
Justin Frantz - Ohio University


Lake Louise Winter Institute 2020

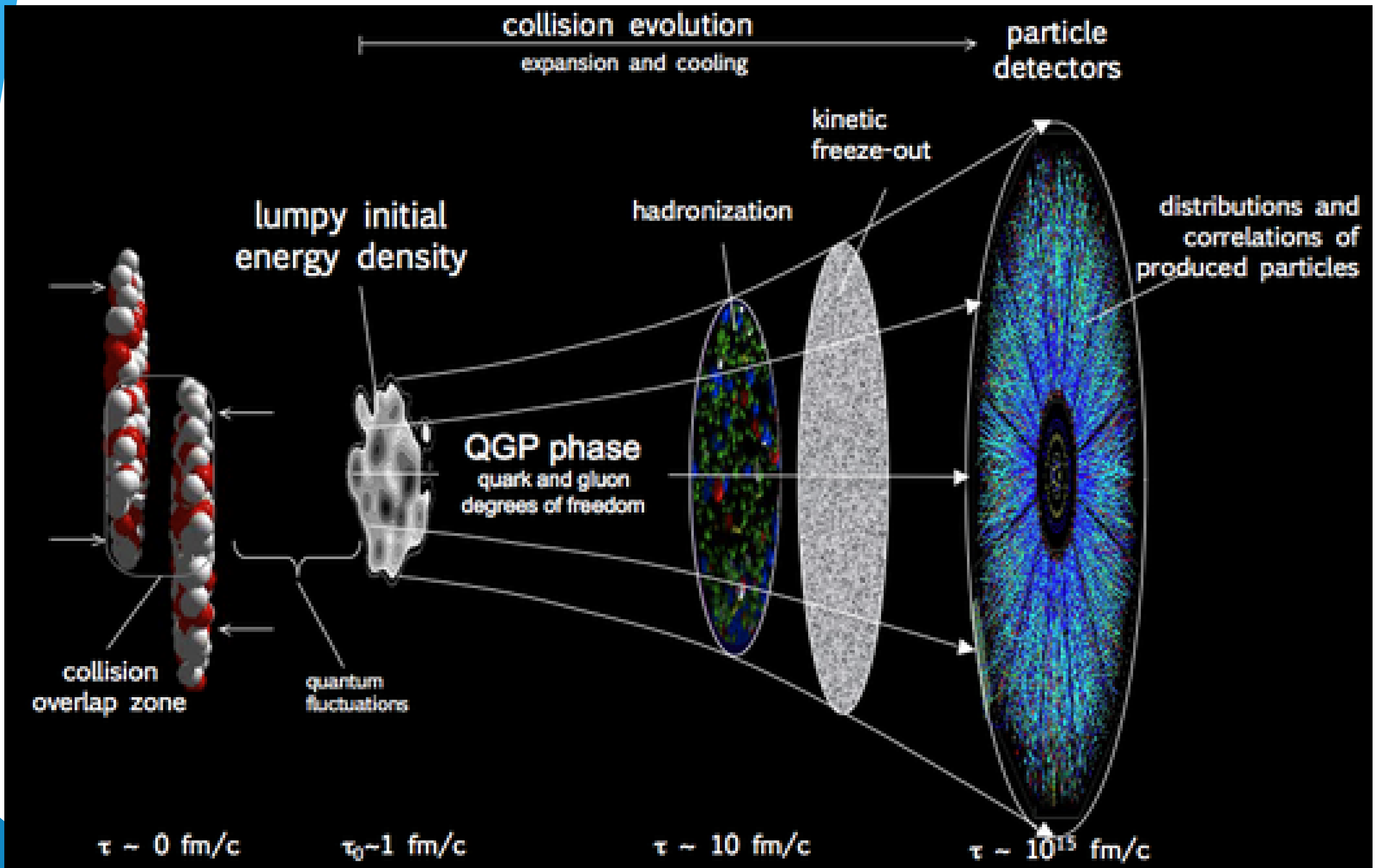
# Recent Results from PHENIX at RHIC

Valentines Day 2/14/2020

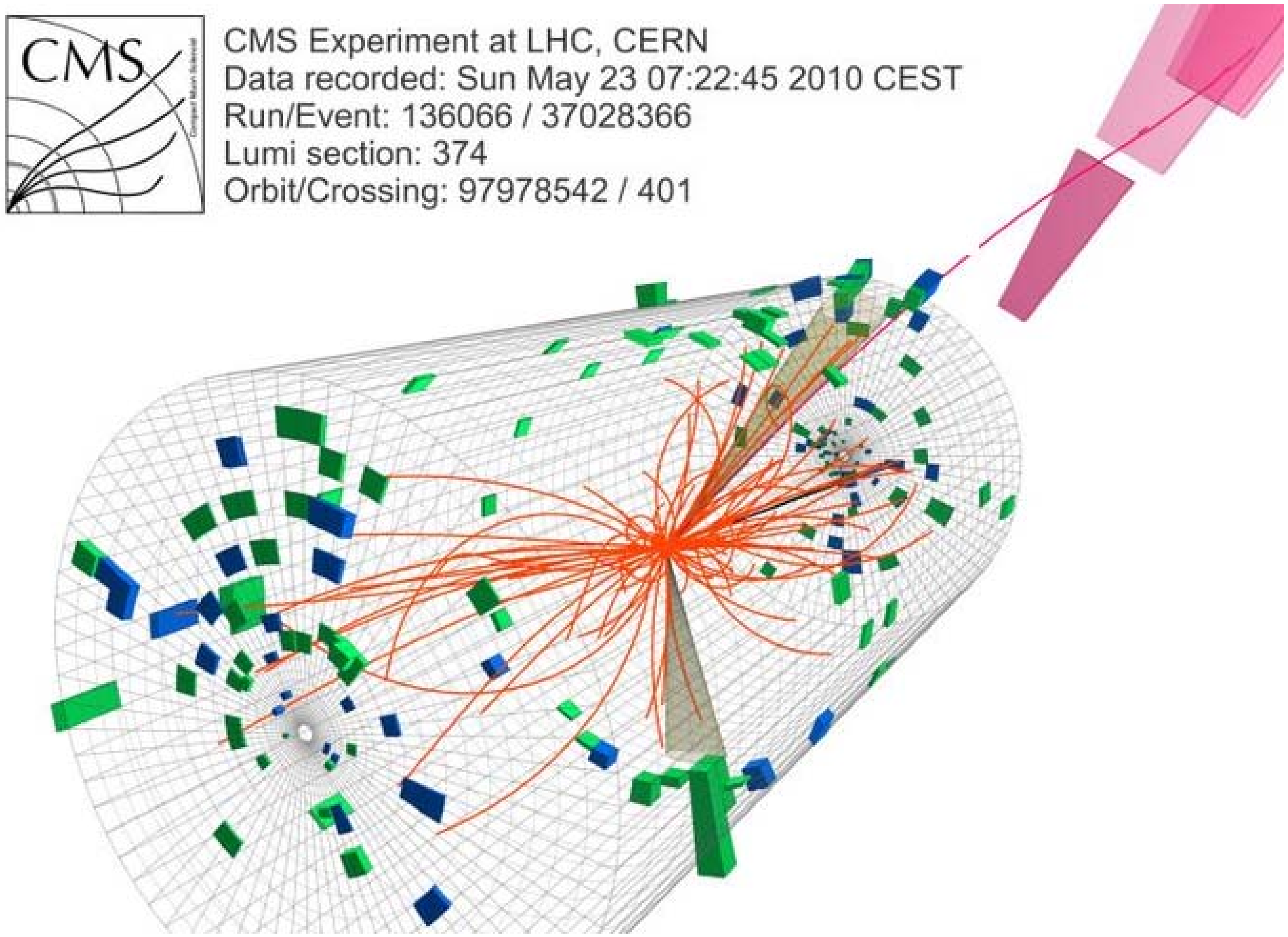
US DOE

# QGP: Quark Gluon Plasma

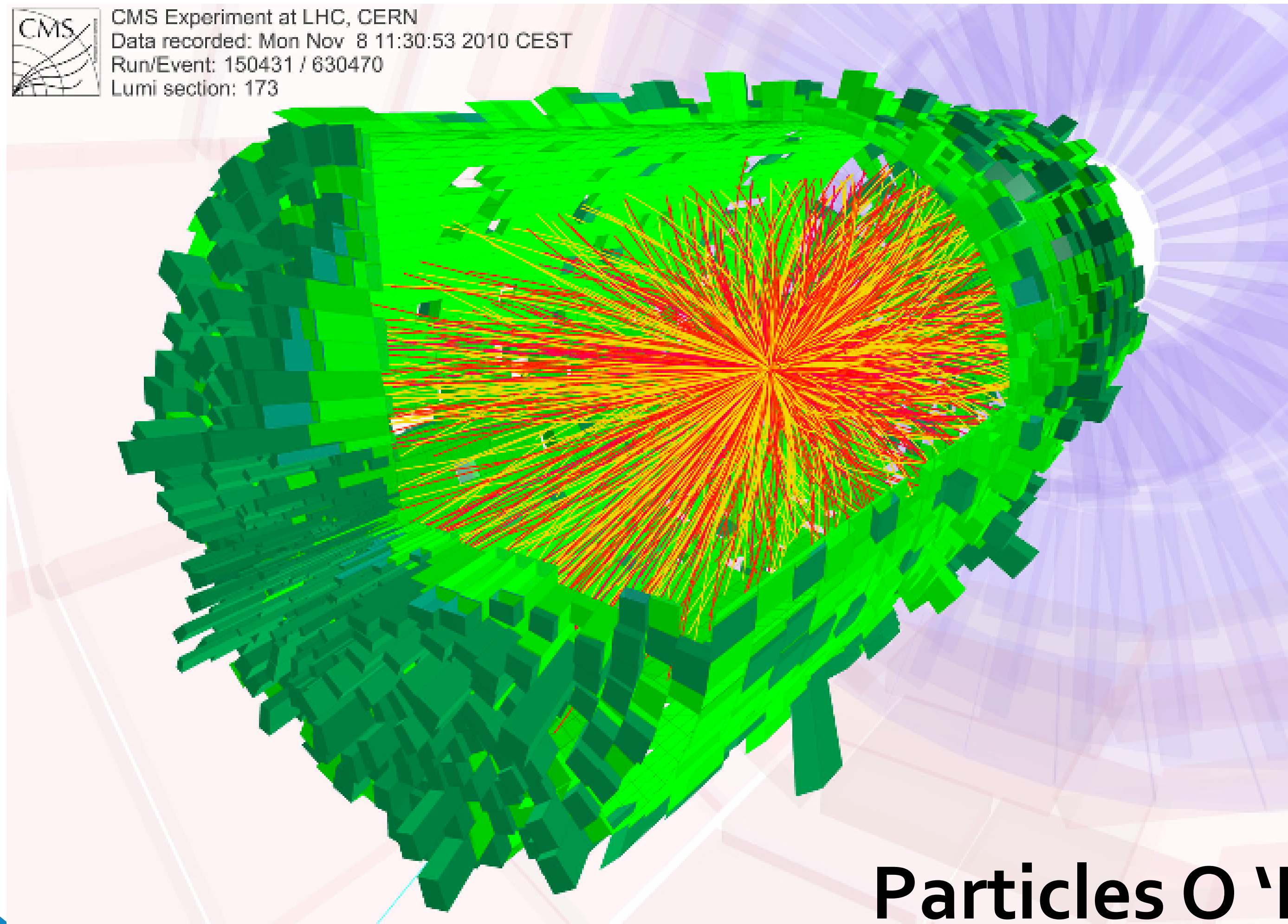
High Energy Nuclear Collisions



# CMS p+p Event


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun May 23 07:22:45 2010 CEST
Run/Event: 136066 / 37028366
Lumi section: 374
Orbit/Crossing: 97978542 / 401

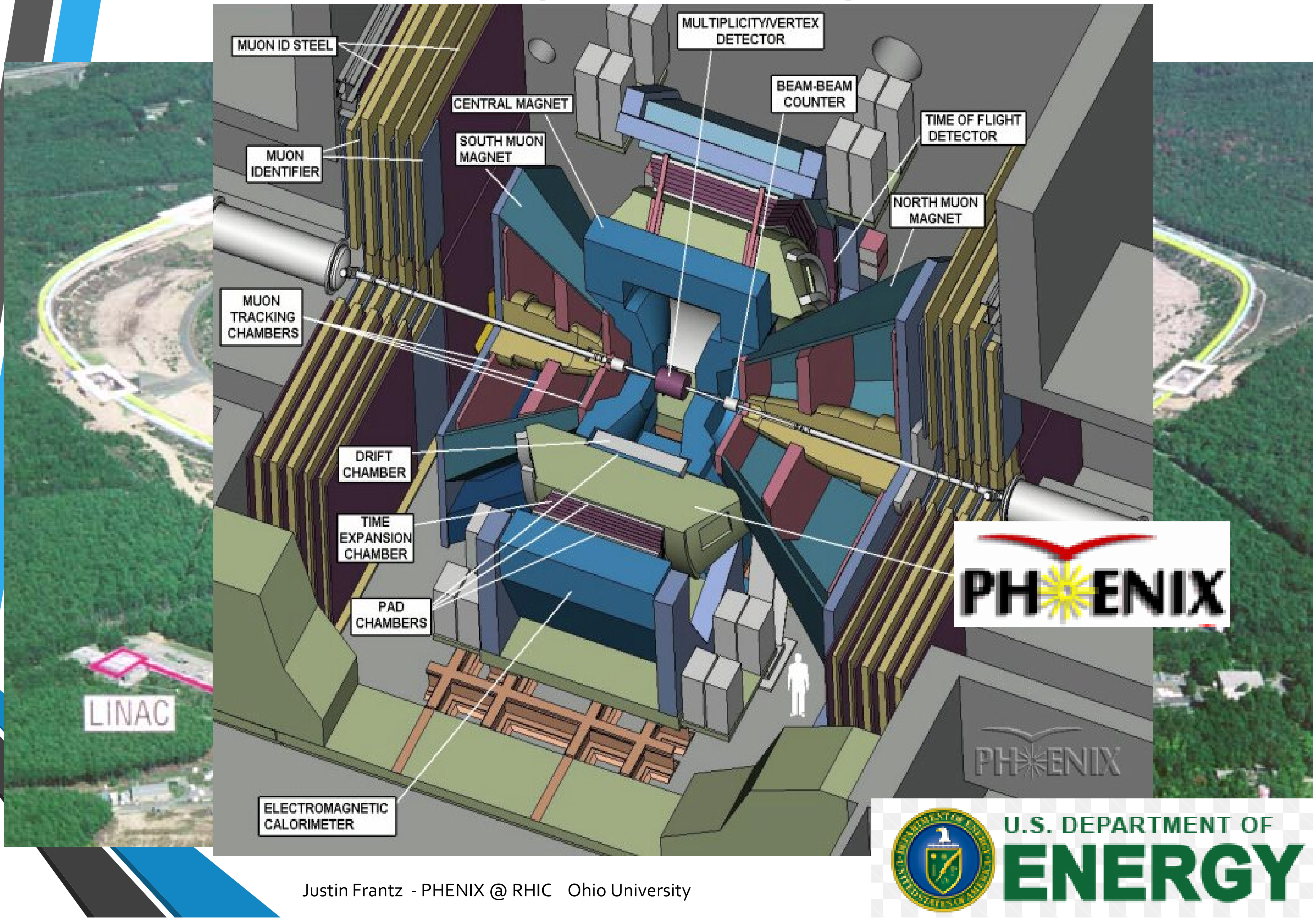
# CMS Heavy Ion Event




**Particles O 'Rama!**

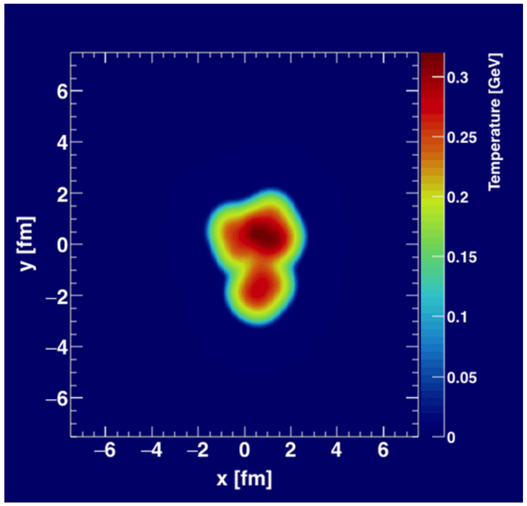
2 particles in, ~50,000 come out

# RHIC, PHENIX, etc.

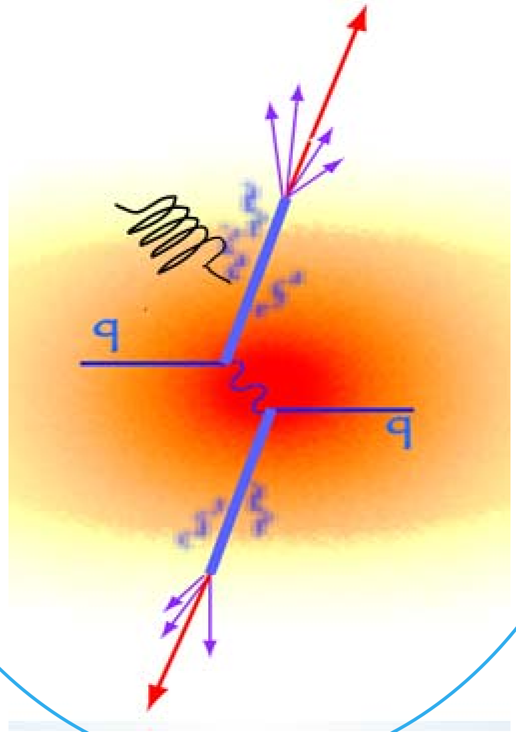


# Three Traditional RHI/PHENIX QGP Measurements

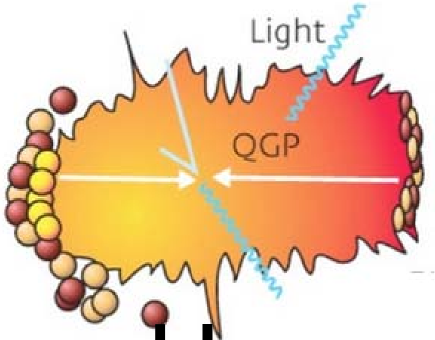
Soft (<2GeV) Particle Hydro Flow




Jet Quenching Suppression



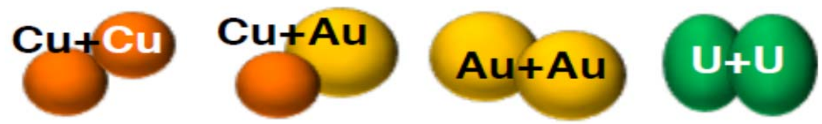
Thermal Soft Photons



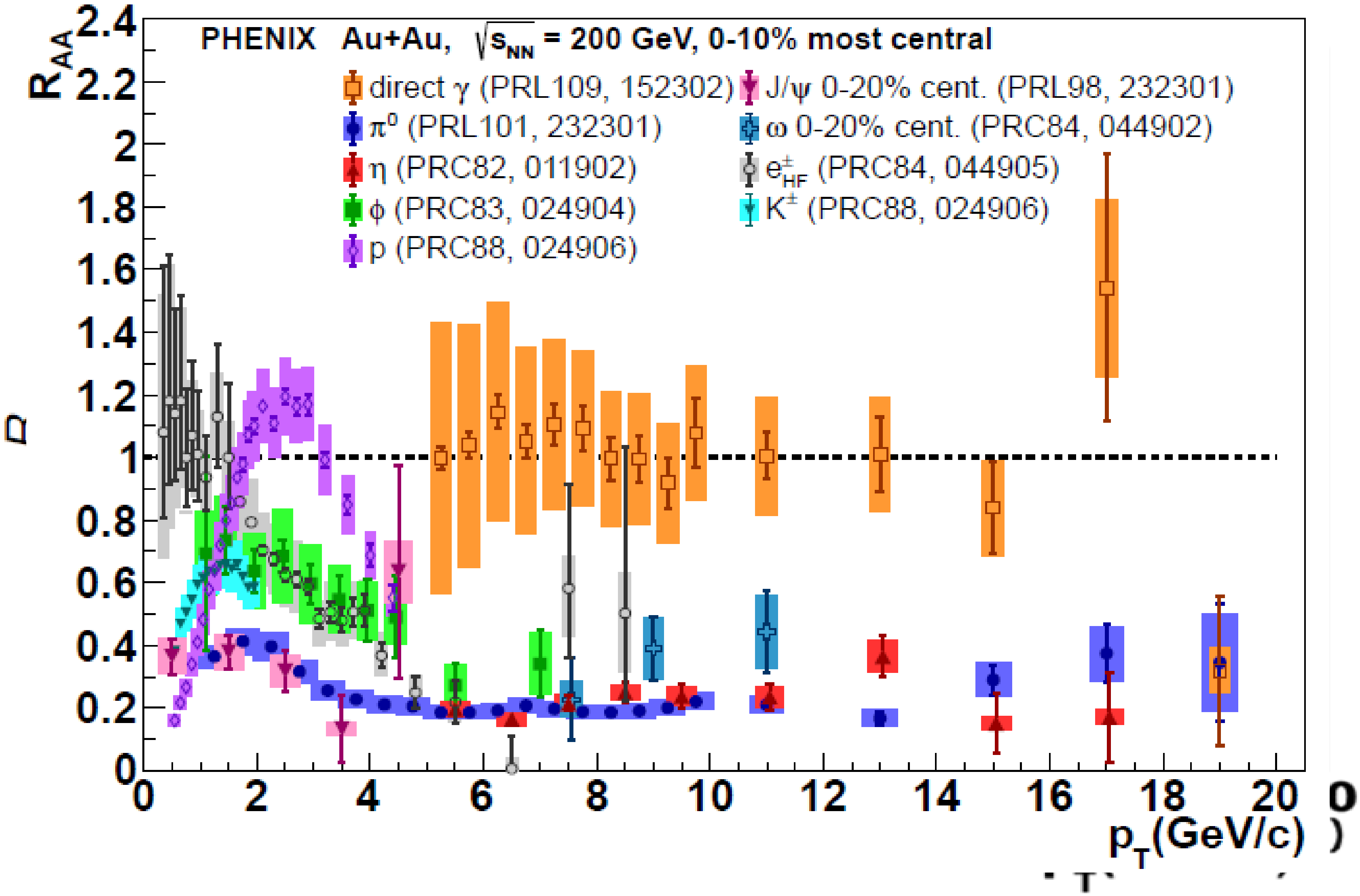

**These observables and many others – QGP!**

# E.g.: Quenching $R_{AA}$ in Large Nucl. systems

All particles suppressed at high $p_T$

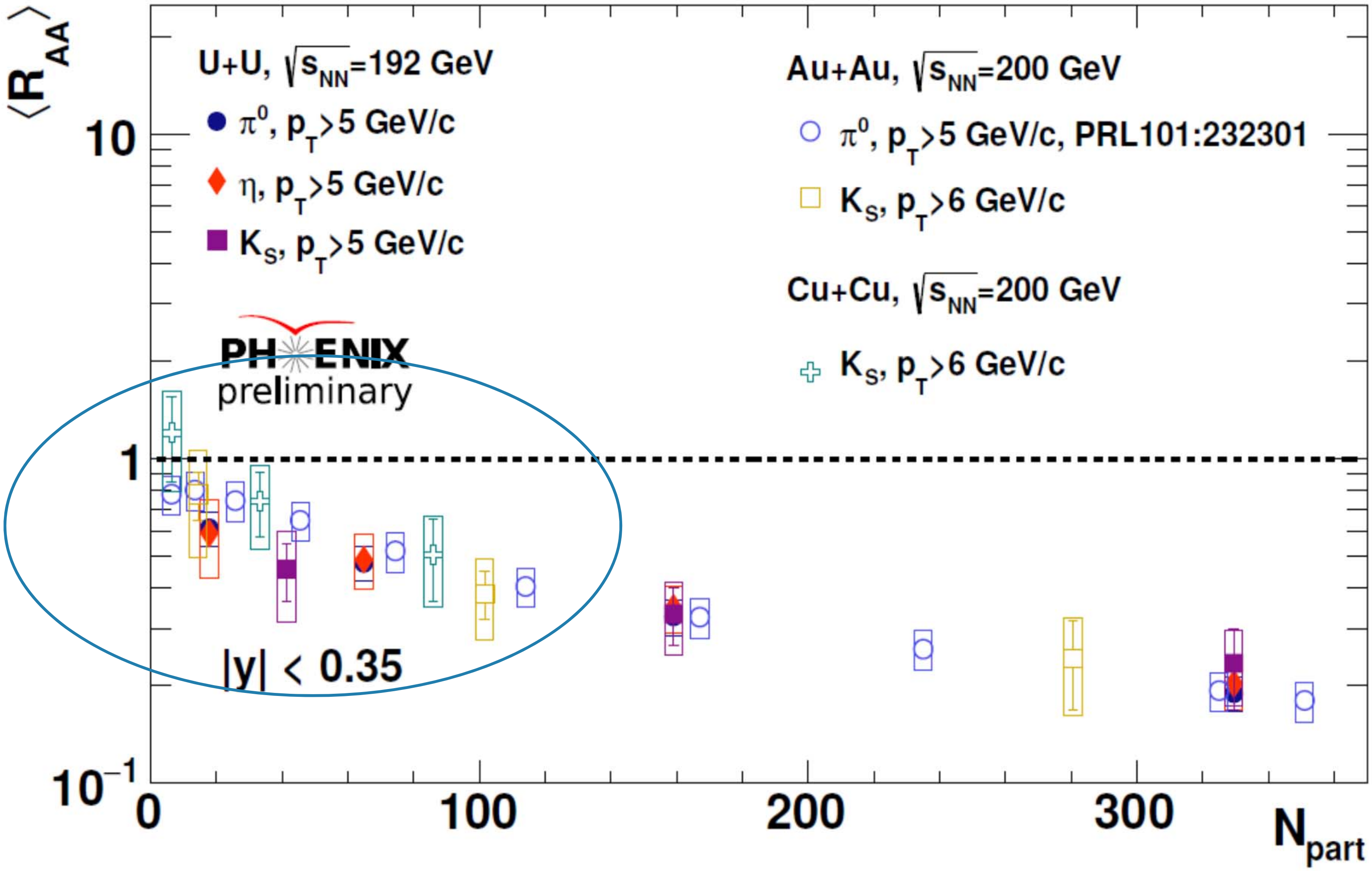



## JET E LOSS SUPPRESSION



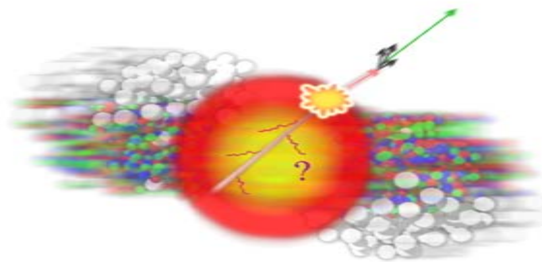
# $R_{AA}$ at High $p_T$

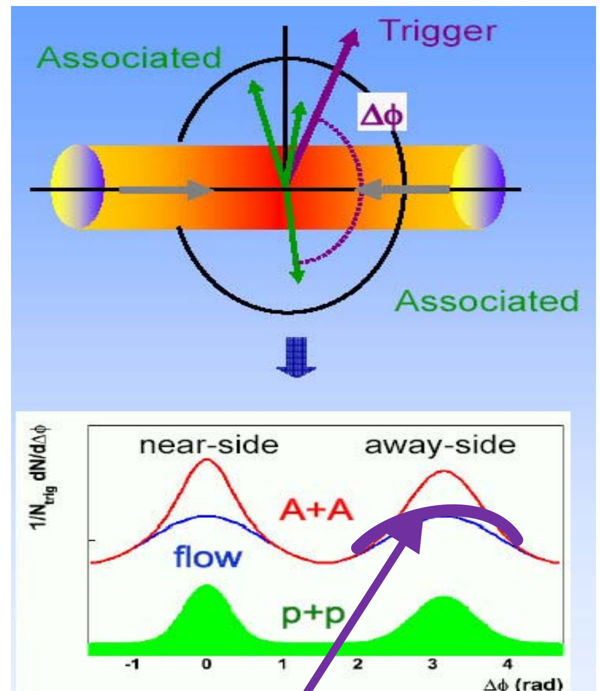
- "Centrality" : Number of Nucleons Participating In Collision $N_{part}$
- We are interested in learning more about this region– is there a complete turn off of QGP effects at some system size?



# Two particle ANGULAR (mostly $\Delta\phi$) JET correlation

**Jets must be produced in back to back (pairs) to** conserve momentum






Awayside suppression

- Trigger particle → high momentum $\pi0$ → proxy for jet
- Partner (Associated) particle → charged hadron from same jet or "awayside" jet
- Correlation function: C(ΔΦ)
- → Convert to Yields of jet associated particles

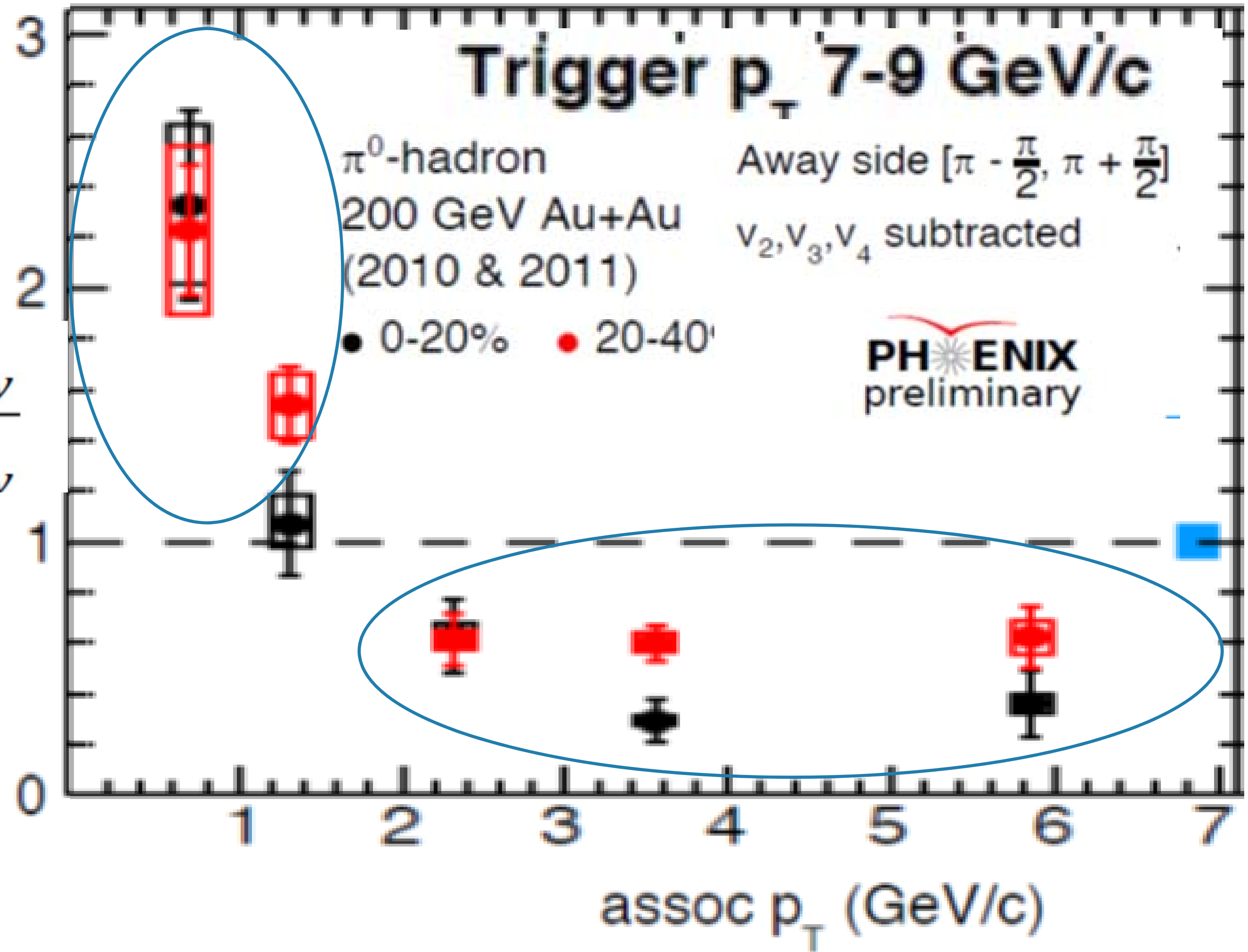
$$C(\Delta\phi) \propto \frac{N^{AB}_{same}(\Delta\phi)}{N^{AB}_{mixed}(\Delta\phi)}$$

← Corrects for imperfect detector

Source: http://puma.uio.no/trine/ALICE-Oslo/angular_correlations.html

# Jet Particle Behavior in A+A

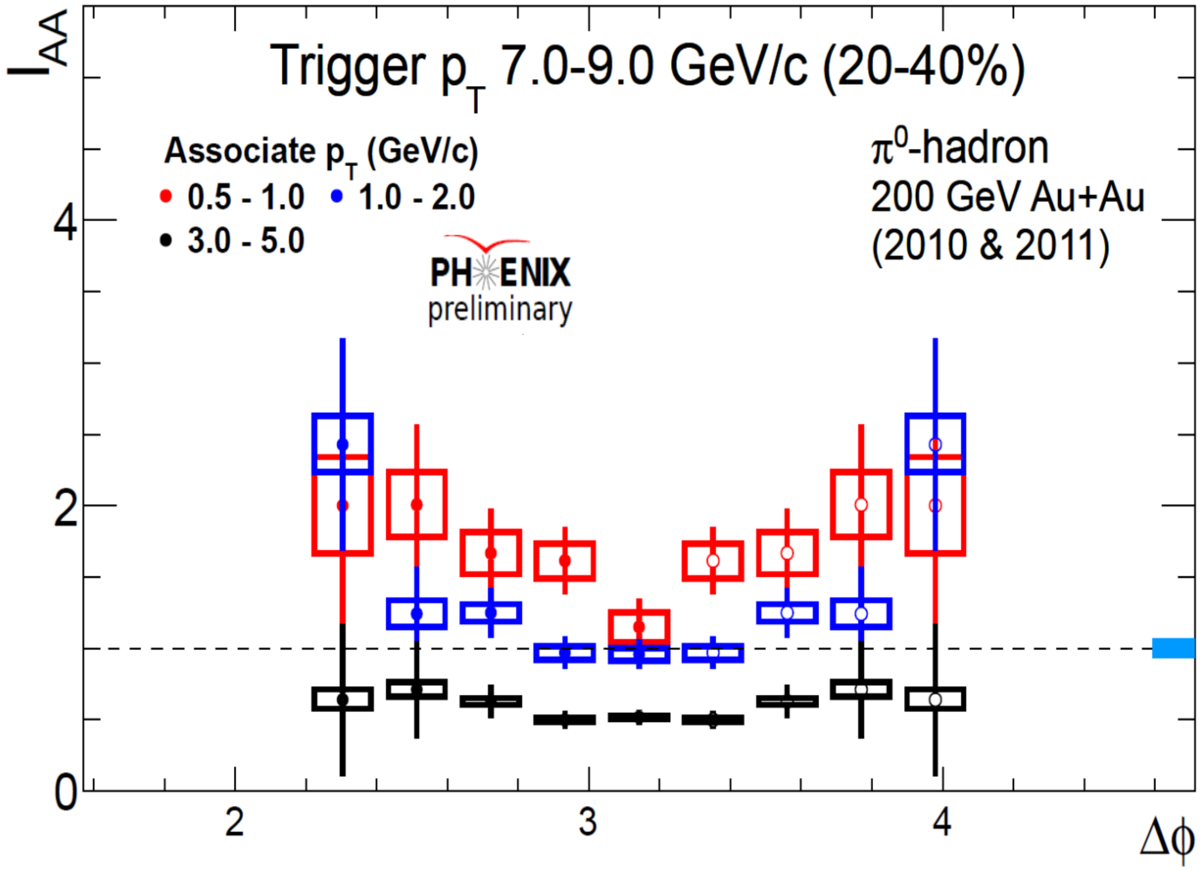
$$I_{AA} = \frac{Y^{AA}_{Away}}{Y^{pp}_{Away}}$$




- Suppression at high $p_T$
- **Enhancement** at low $p_T$ -- where lost jet E goes!

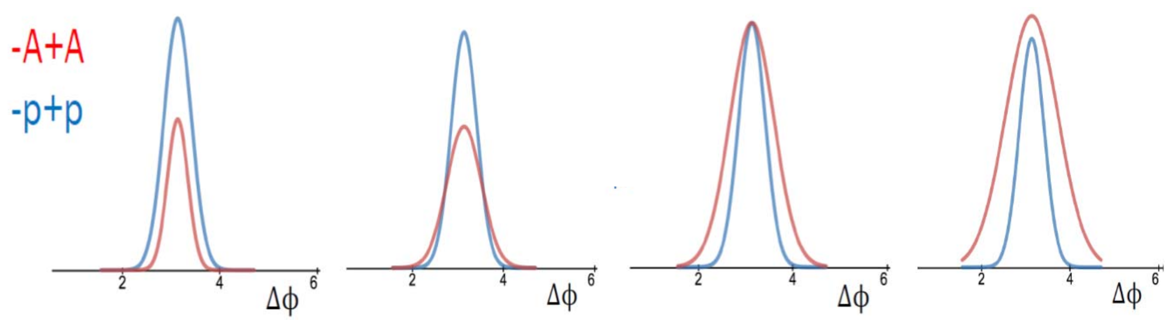
Thermalized by Plasma

# Enhancement At Large Jet Angles



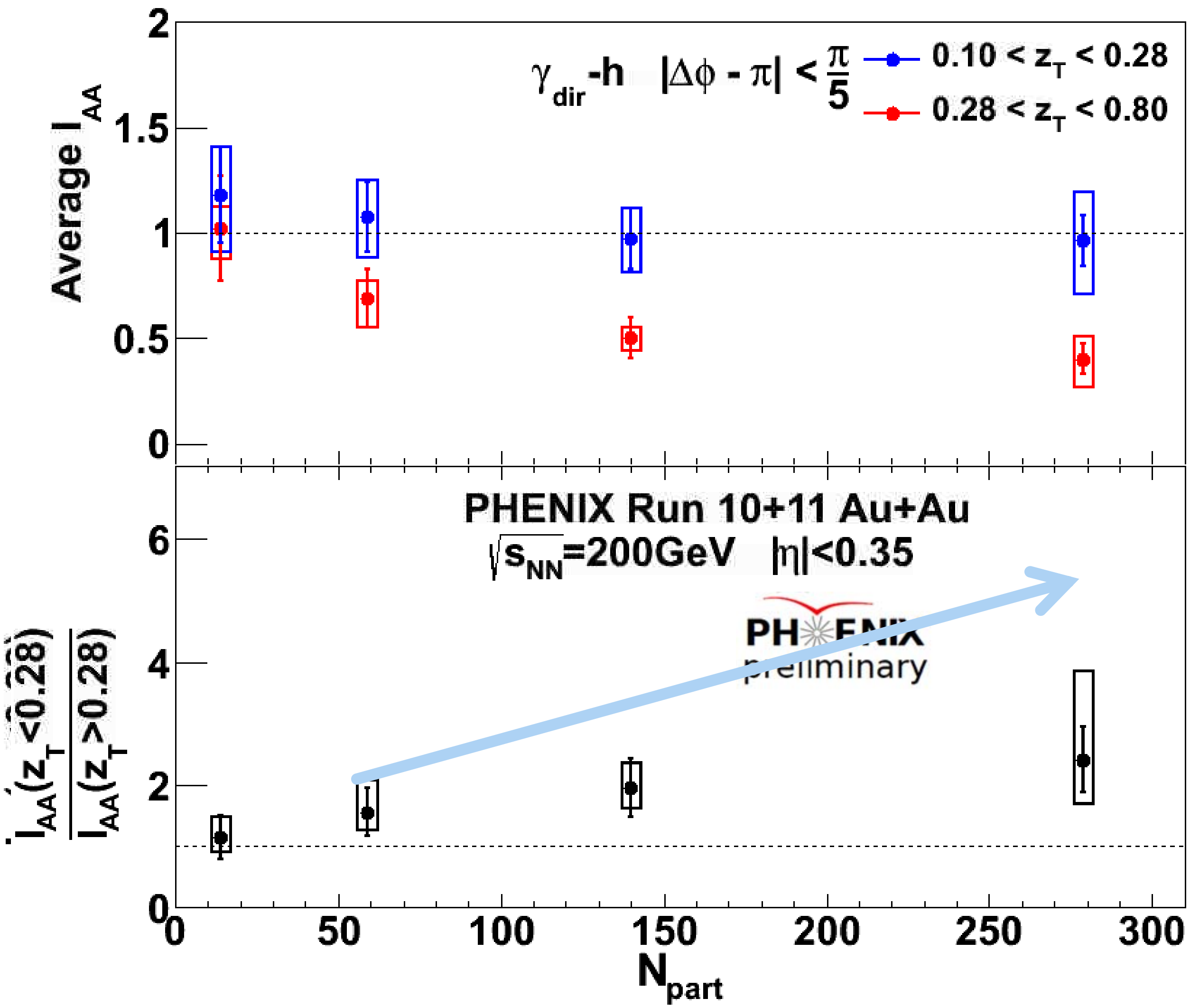

- $I_{AA}$ vs $\Delta\phi$ to explore substructure of jet w/ $\pi^0$–h correlations
- Enhancement at large angles
- Consistent with soft gluon radiation

$$I_{AA} = \frac{Y^{AA}_{Away}}{Y^{pp}_{Away}}$$



# Centrality Dependence of Enhancement

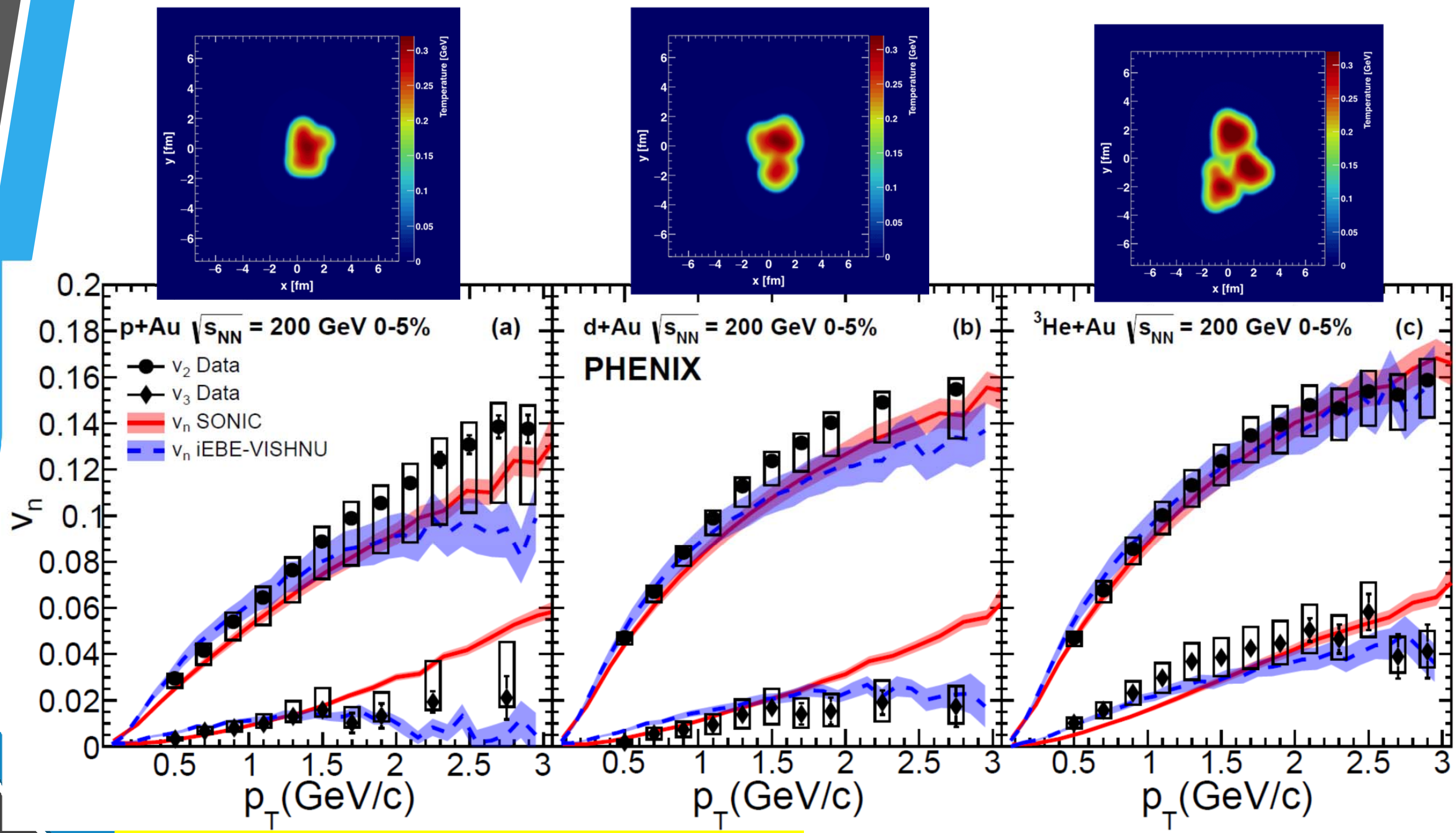
- $1^{st}$ measurement of centrality dependence of low $z_T$ enhancement
- To judge true centrality dependence of enhancement, must account for overall reduction of jets due to suppression
- Energy recovery factor – High $z_T$/ low $z_T$ ratio – shows monotonic increase toward central events




**Many measurements like this one: hard to get good precision in peripheral A+A … another idea to look for turn off QGP effects….**

# Go to Smallest  Systems ! – E.g. Soft Flow

**Recent High profile idea of go directly to the VERY SMALLEST systems**
**QGP-like flow observed there – QGP droplets!**

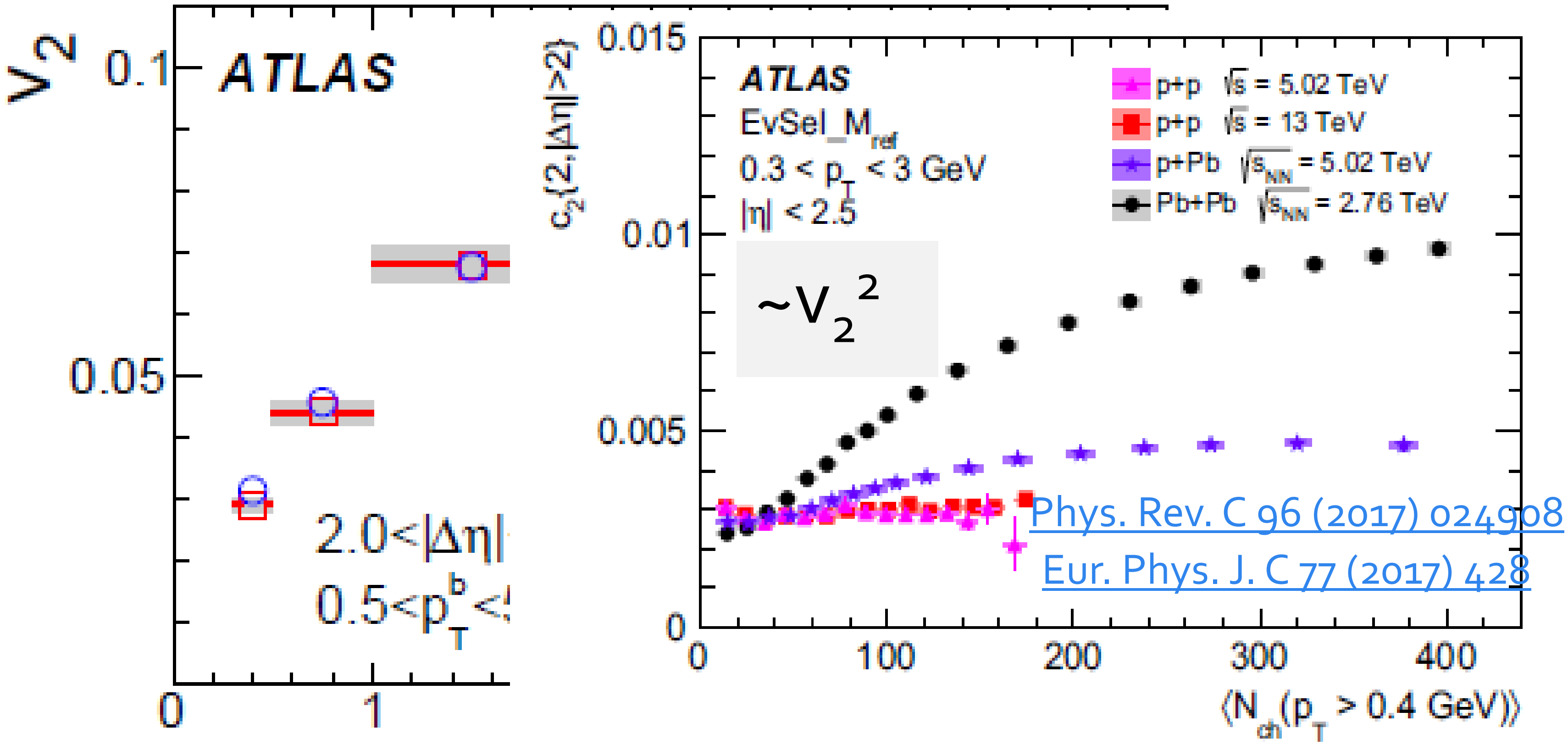



*Nature Physics* **15**, pages214–220 (2019)

Models  w/ QGP Hydro match well

# Even in high multiplicity p+p !!!  (?)

Num of participating partons (low x) / produced particles increase w/ E– collective “QGP” to be expected???




- Also in p+p!!!   Same Flow Parameter $p_T^a$ [GeV]
- Use N charge particle as proxy for “centrality”

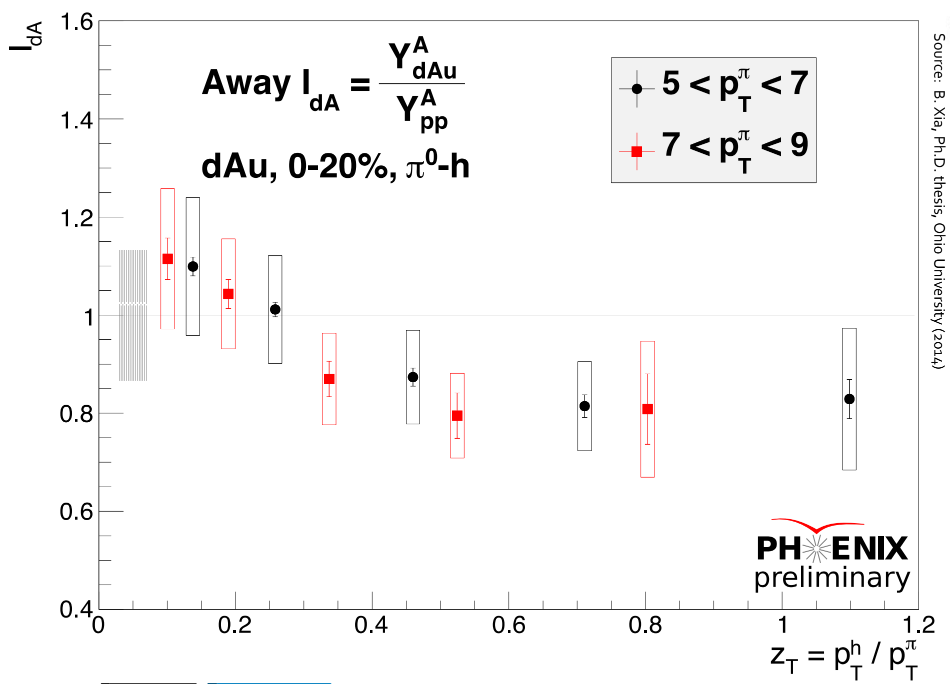
However, big “non-flow” effects – behavior different, still not conclusive

# Jet Quenching in Small Systems?

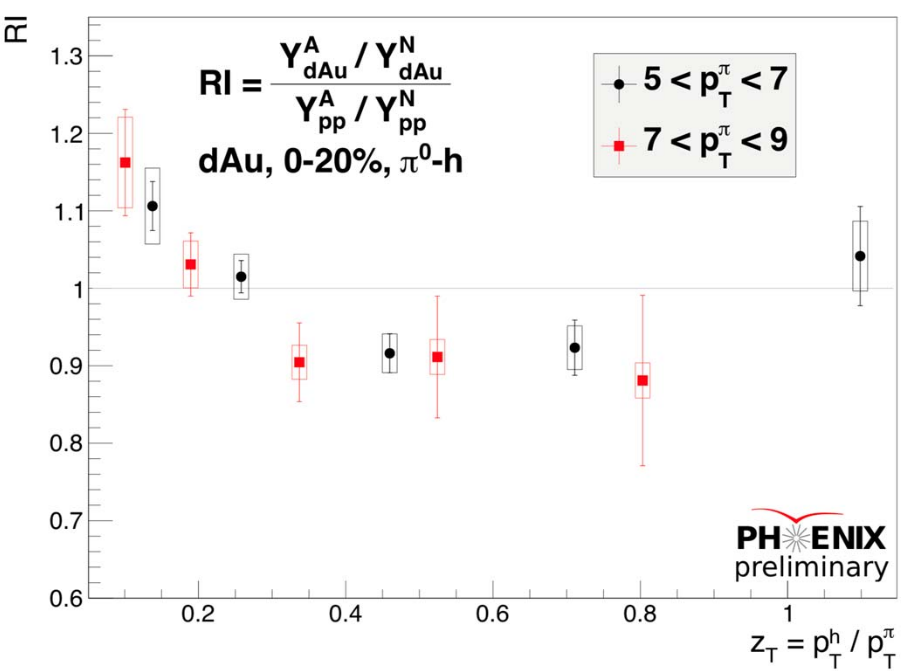
- By now many have looked for jet quenching also in small systems – but expect small effect
- Need more precision: Double Ratio RI instead of IAA

Double Ratio: $R_I = \frac{Y^{AA}_{away}/Y^{AA}_{near}}{Y^{pp}_{away}/Y^{pp}_{near}}$

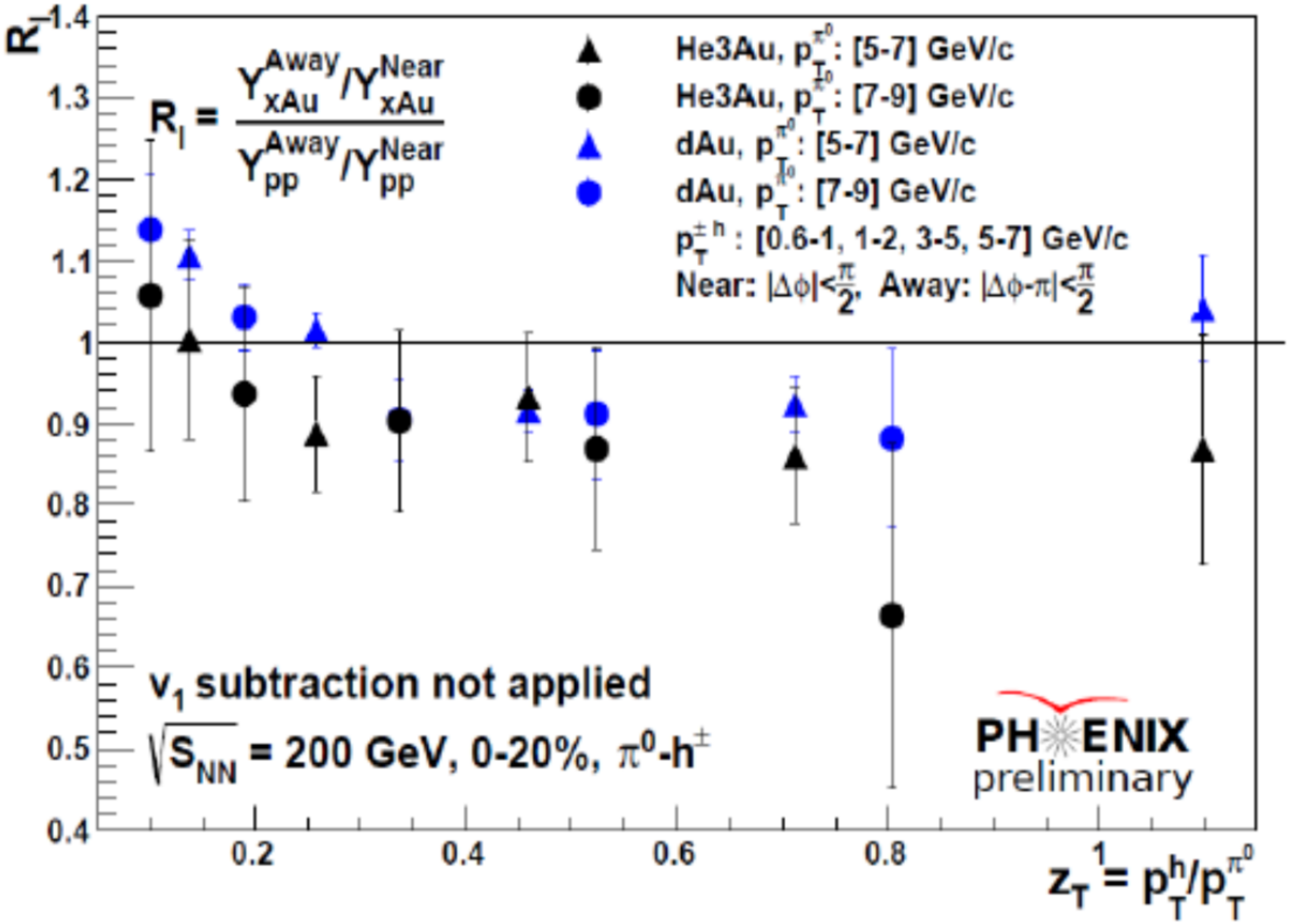
**$I_{dAu}$, 0-20 % centrality**
**Run8 d+A at $\sqrt{s_{NN}} = 200\ GeV$**




**RI, 0-20 % centrality,**
**Run8 d+A at $\sqrt{s_{NN}} = 200\ GeV$**

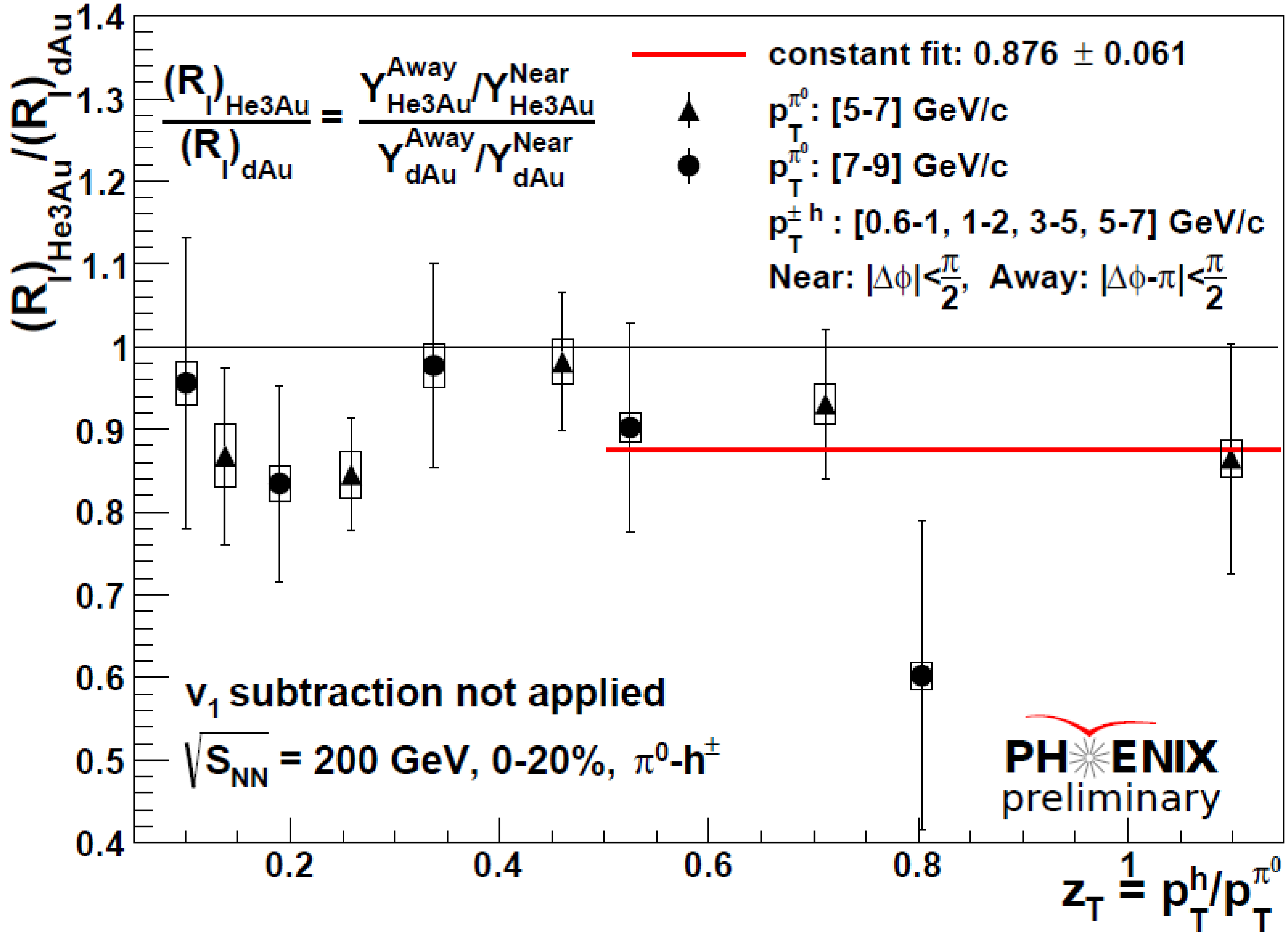


# Jet Modification in Small Systems




- Hints of suppression in small systems at high $z_T$ and enhancement at low $z_T$
- Similar to energy loss effect observed for jets in A+A

# Jet Modification in Small Systems

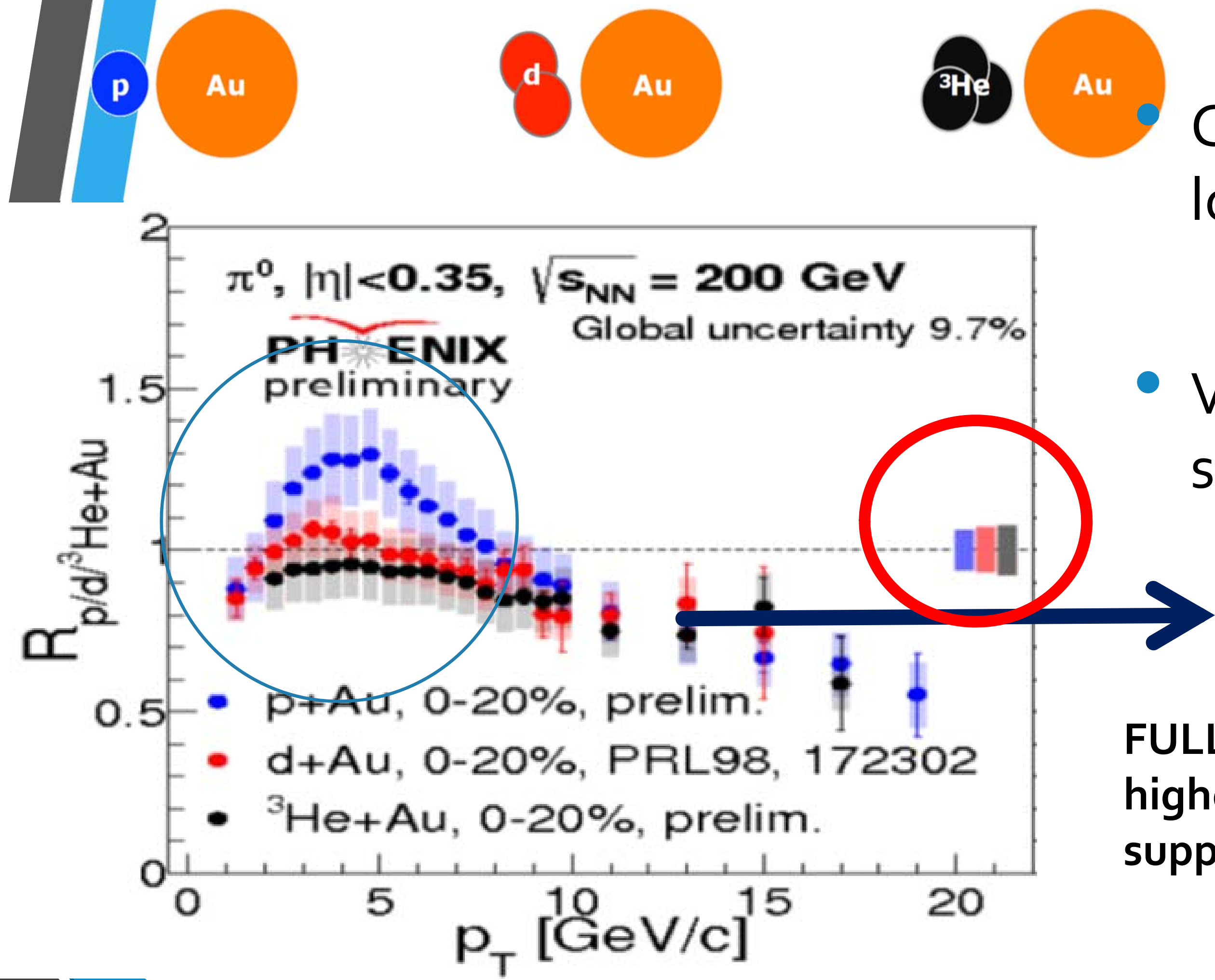



- Right ordering with system size: (more suppression for larger size)

# Actual QGP Jet Quenching?

- **There are number of "KNOWN" NUCLEAR EFFECTS we need to rule out… some we can , others we need more input from theory**
- **However this has implications beyond Heavy Ion Physics: new observables to constrain longstanding nuclear physics effects -- a theme for several observables**
- Example "Trivial" "Cold Nuclear Effects:
- "Hydro" v3, v1
- ~~Enhanced Nuclear $k_T$~~
- ~~Initial State nuclear modified PDF (nPDF) effects~~
- ~~Rapidity Effects Mismatching p+p vs A+B?~~
- Color Transparency ?
- "Cronin" Nuclear Effects

# $R_{AB}$ Collision dependences

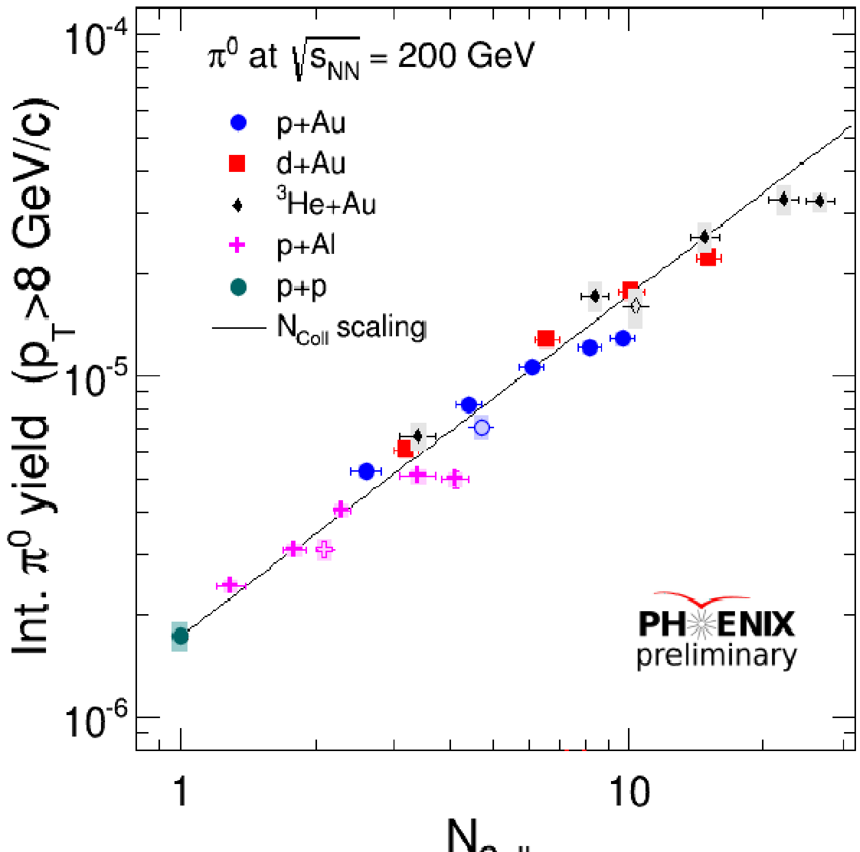


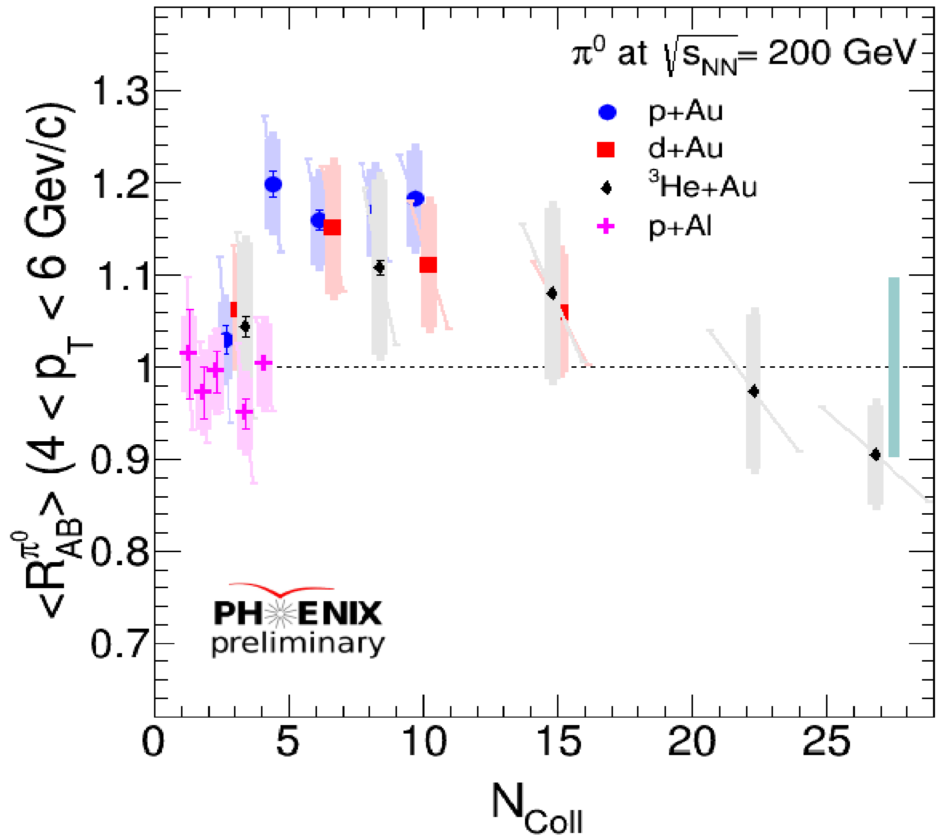

- Cronin enhancement at low $p_T$
  - Projectile dependence
- Very small Suppression seen at high $p_T$

**d+Au FULL JET**

**FULL JET RECO goes to much higher pt --confirms small /~no suppression at high pt**

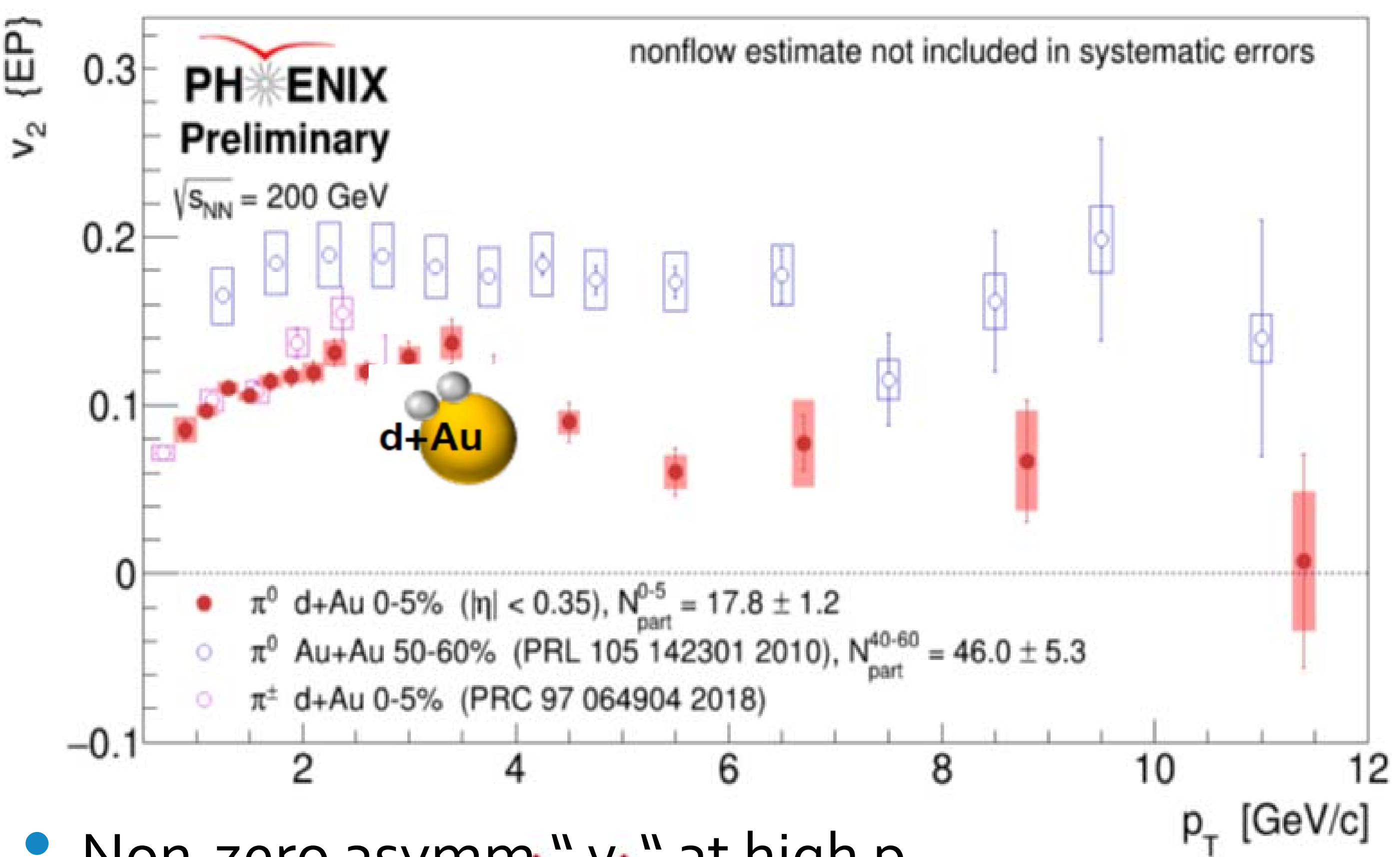
# Scaling of Cronin Region in RAA

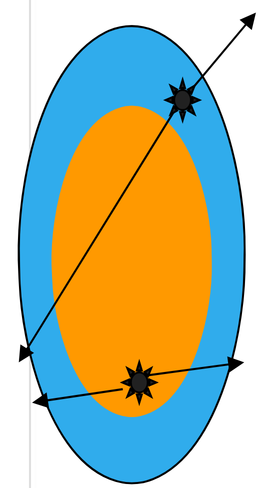



- Cronin region follows $N_{coll}$ scaling
- Interesting observable to study Cronin with:
- **The point:** we need to understand "normal nuclear effects"

# High pt $v_2$ for Hard Probes in Small System



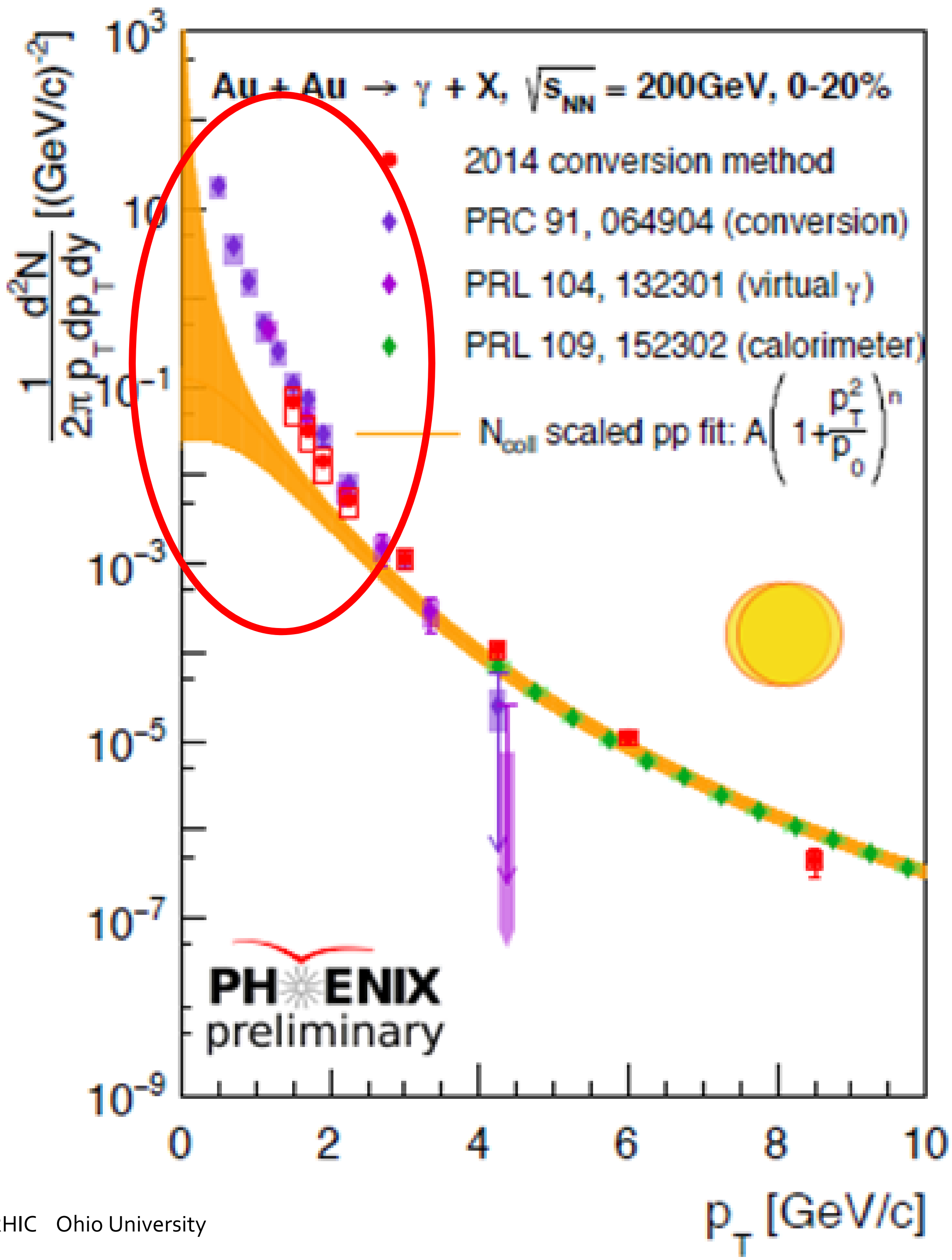



- Non-zero asymm "$v_2$" at high $p_T$
- In Au+Au this is attributed to pathlength dependent energy loss

Another piece of evidence for AuAu like Jet Eloss?

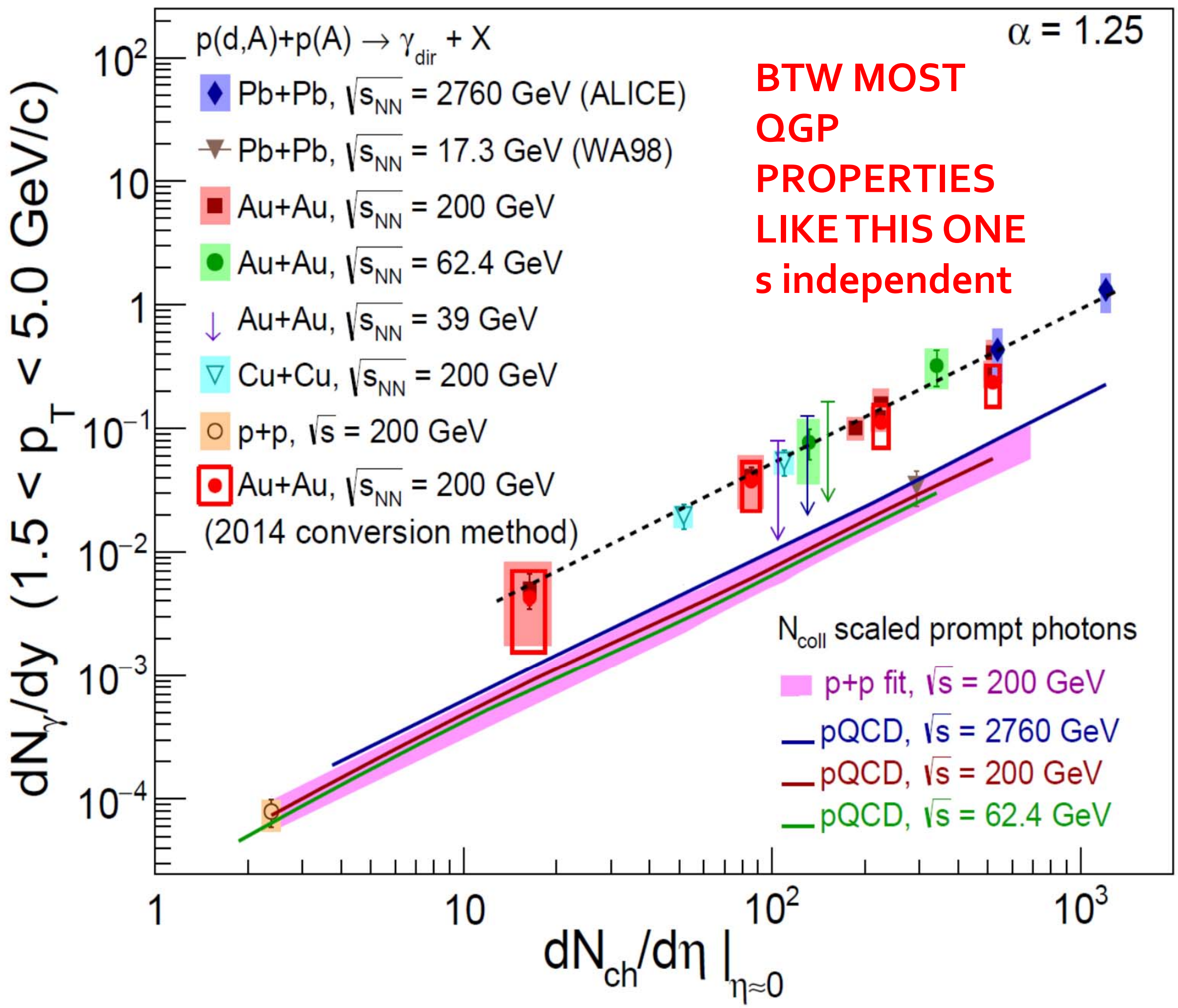
# Thermal Photons in A+A Collisions

- PHENIX has long history of making direct photon measurements
- High pt exactly in line with scaled p+p (no suppression : colorless probe)
- **LOW PT Photons attributed to Thermal "Blackbody" PLASMA radiation**

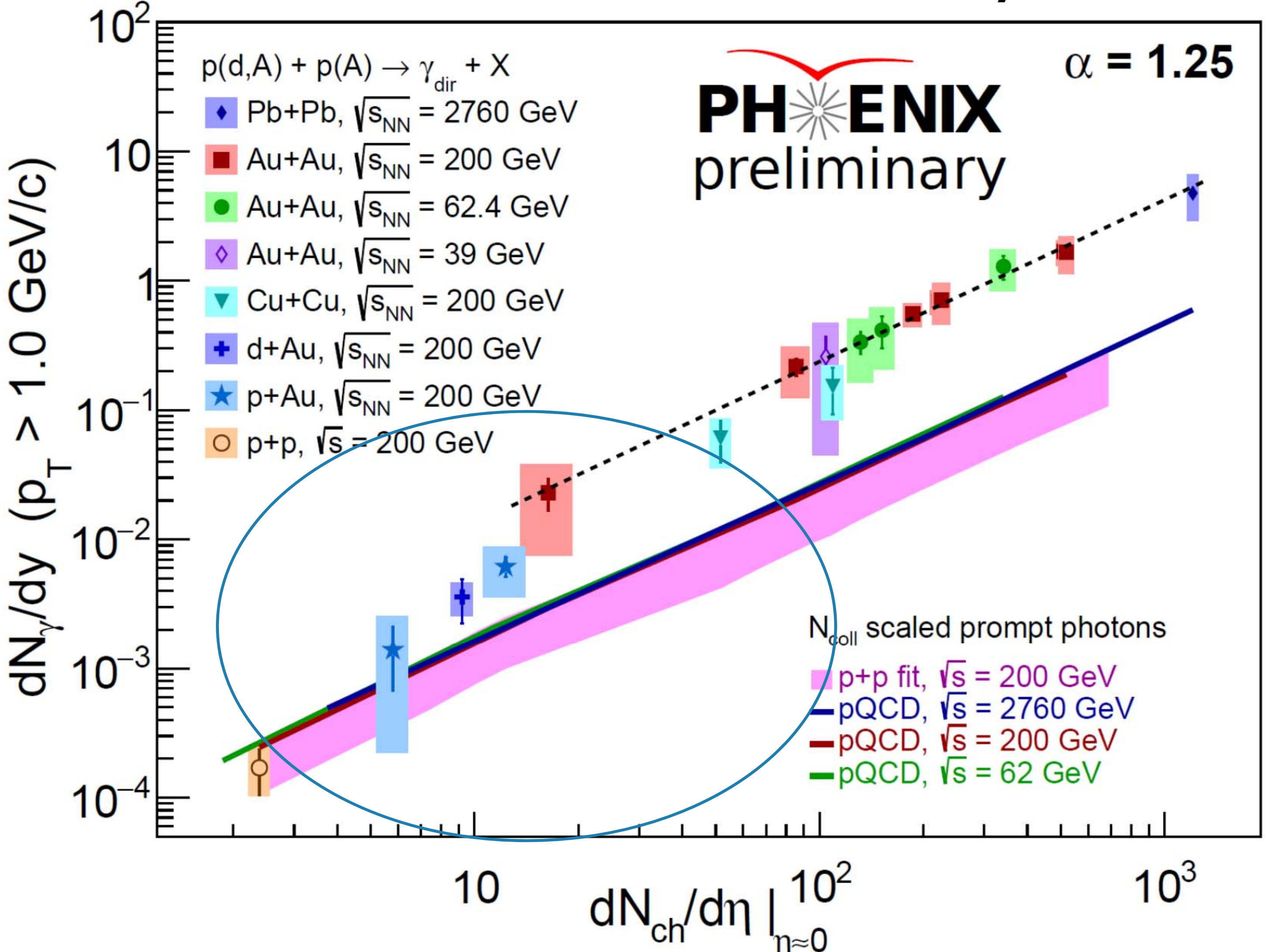


# Scaling of Thermal Photons in A+A Collisions

- Some mysteries – e.g. large flow
- look for scaling properties
- Similar scaling for heavy ion collision systems measured by PHENIX and ALICE



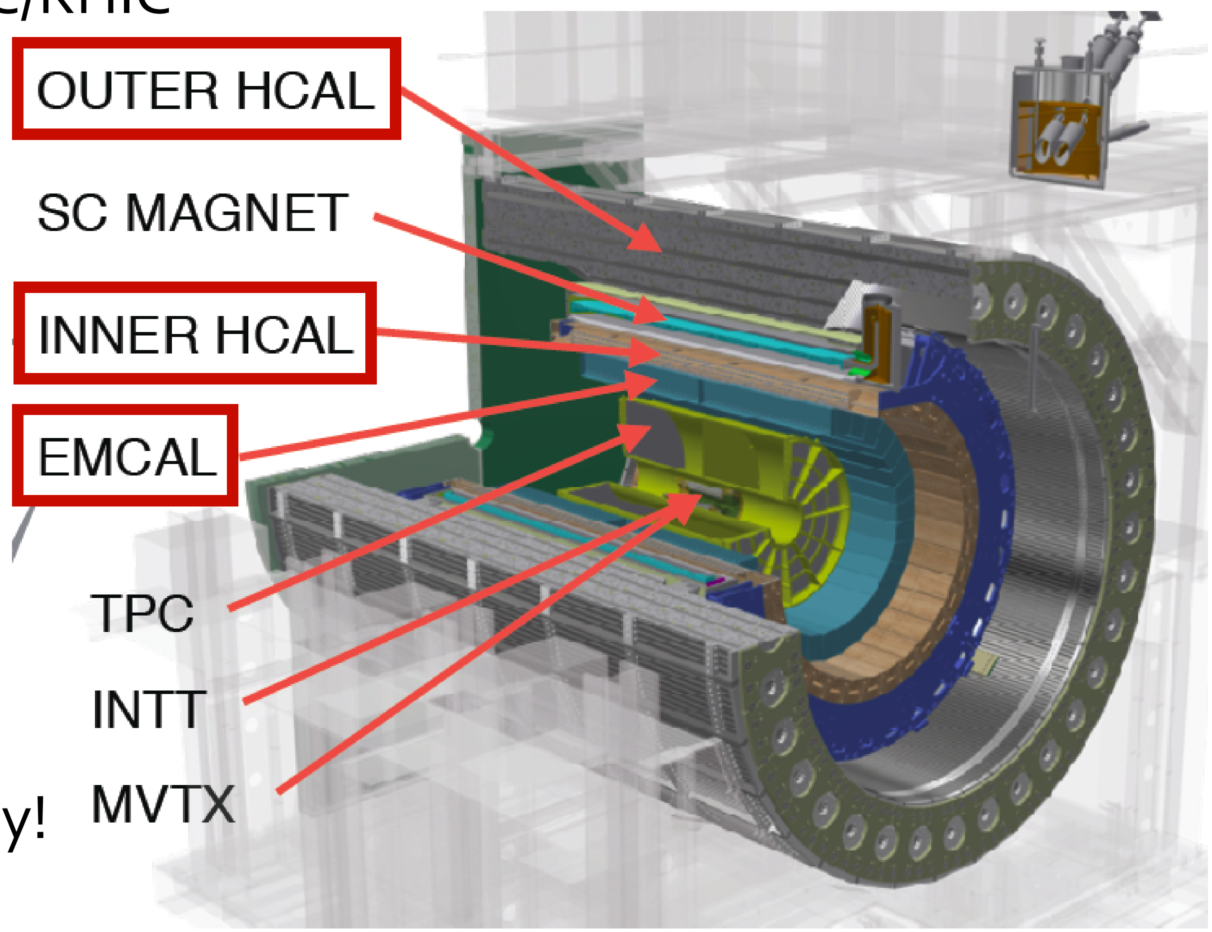
# Thermal Photons in Small Systems




Smooth trend between small and large systems

# Future: sPHENIX - New Collaboration

- New Detector/Collaboration in same hall as PHENIX!
- Will RUN in 2023!
- Optimized for LHC/RHIC Jet Comparison
  - Hcal
  - better uniformity
  - QGP at two diff Temperature profiles!
- Build of detector already underway!



# Conclusions

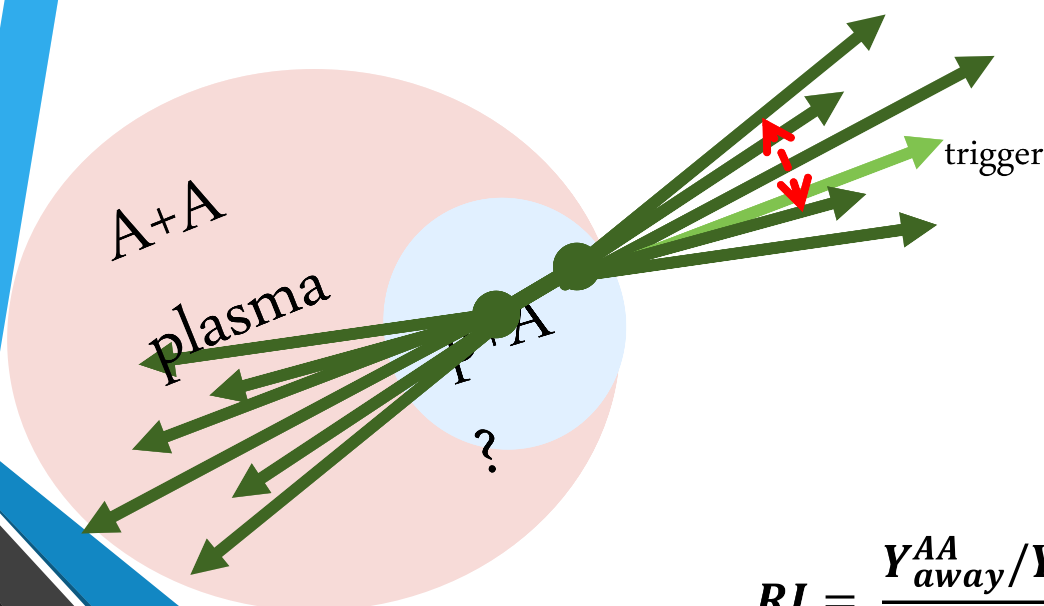
- PHENIX continues to characterize QGP with more and more precision/ new probes
- Some progress in different kinds of probes in determining if there is a smaller limit to various QGP "signature" effects
- Main Observable: Flow Seen in A LOT of small systems
  - Possible confirmation in Jet Energy Loss Quenching Effect
  - Possible confirmations in thermal photons
  - Other observable: Quarkonia modification (melting )

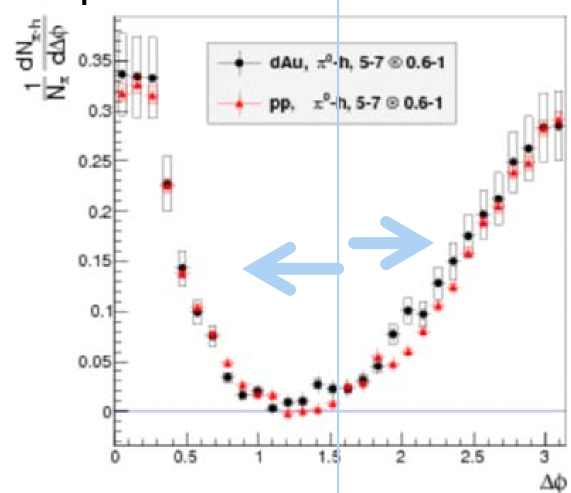
# BACKUP

- BACKUP

# NS/AS Ratios: A Nice Observable for searching for small $E_{loss}$ ?

- Assume well-known surface bias picture for Au+Au should apply as the system goes peripheral—possibly even in “small systems” p+Au, d+Au, He+Au
- Look for Differences in Awayside Modification compared to Nearside



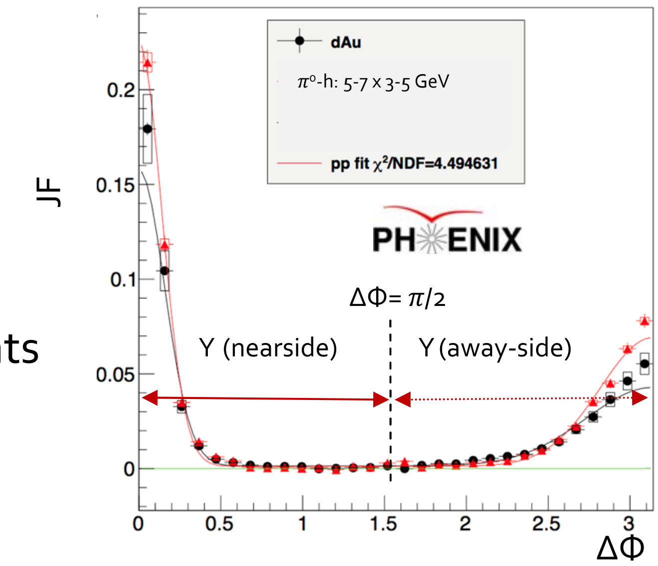

$$RI = \frac{Y^{AA}_{away}/Y^{AA}_{near}}{Y^{pp}_{away}/Y^{pp}_{near}}$$

Black
**Red**

# Jet Pair Quantification

**PTY Nuclear Modification Factor ($I_{AA}$) =$Y^{AA}$ /$Y^{pp}$ (Away side)**

- Y roughly represents the number of particles produced per jet
- Y is Per Trigger: any deviation from unity represents modification
- AA/pp Partner $h^{\pm}$ SINGLES EFFICIENCIES vs $p_T$ NEEDED
- Uncertainty dominated by singles charge hadron efficiency



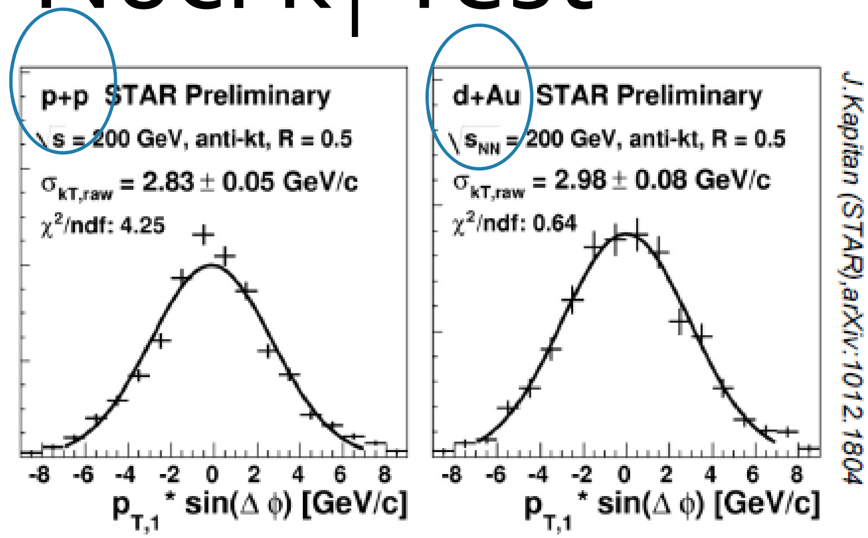

Source: B. Xia, Ph.D. thesis, Ohio University (2014)

**Double Ratio:** $$RI = \frac{Y^{AA}_{away}/Y^{AA}_{near}}{Y^{pp}_{away}/Y^{pp}_{near}}$$

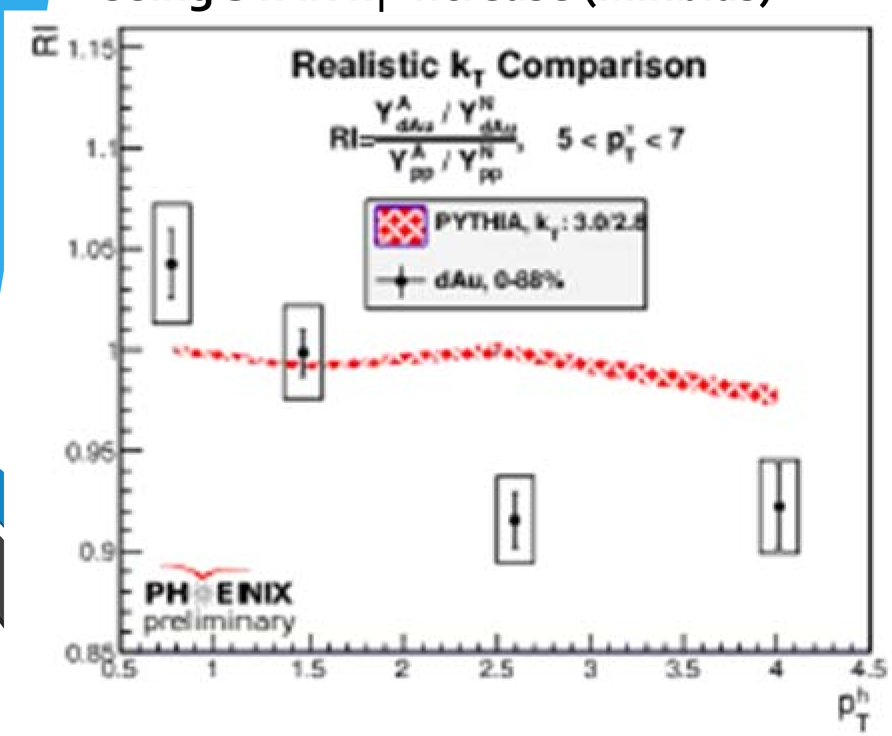
- **NO EFFICIENCIES NEEDED (Cancels in AS/NS)**
  - Dominant systematic errors due to single charge hadron efficiency are completely removed
- Surface Bias: levels of modification mostly unchanged (going from IAA to RI)
- Contribution of $v_{2n}$ even harmonics from hydrodynamic flow **is zero** (e.g. $v_2$)
- Contribution of higher order odd harmonics (>= $v_3$) can be neglected--only sensitive to $v_1$

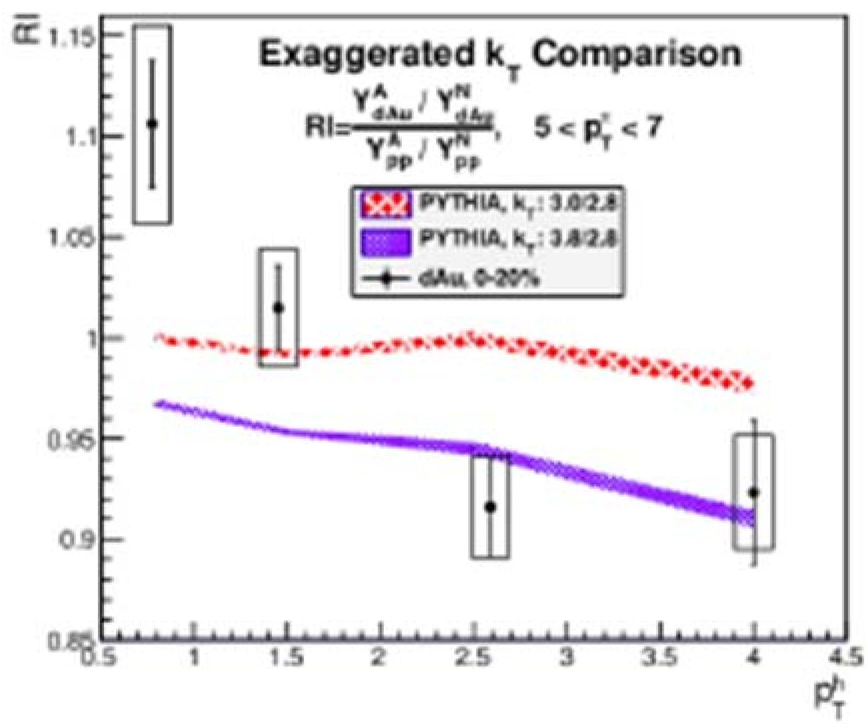
# OLD PYTHIA6 Nucl $k_T$ Test

- Using $k_T$ constraints from STAR jet measurements → No effect for 0-100% Minbias
- However, $k_T$ smear larger in Central?



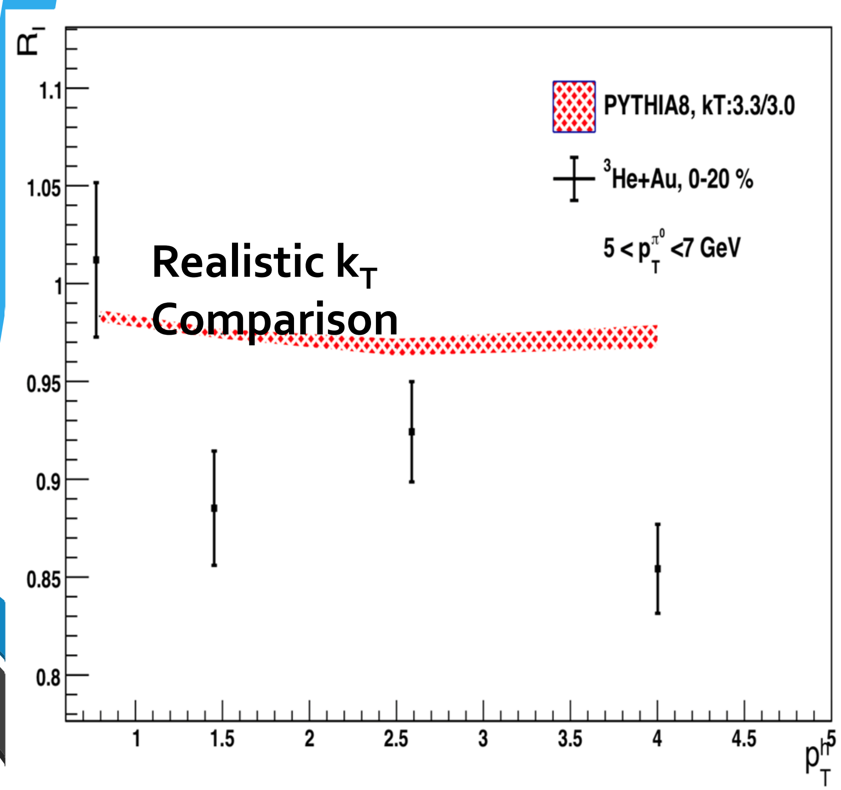

**Using STAR $k_T$ Increase (Minbias)**

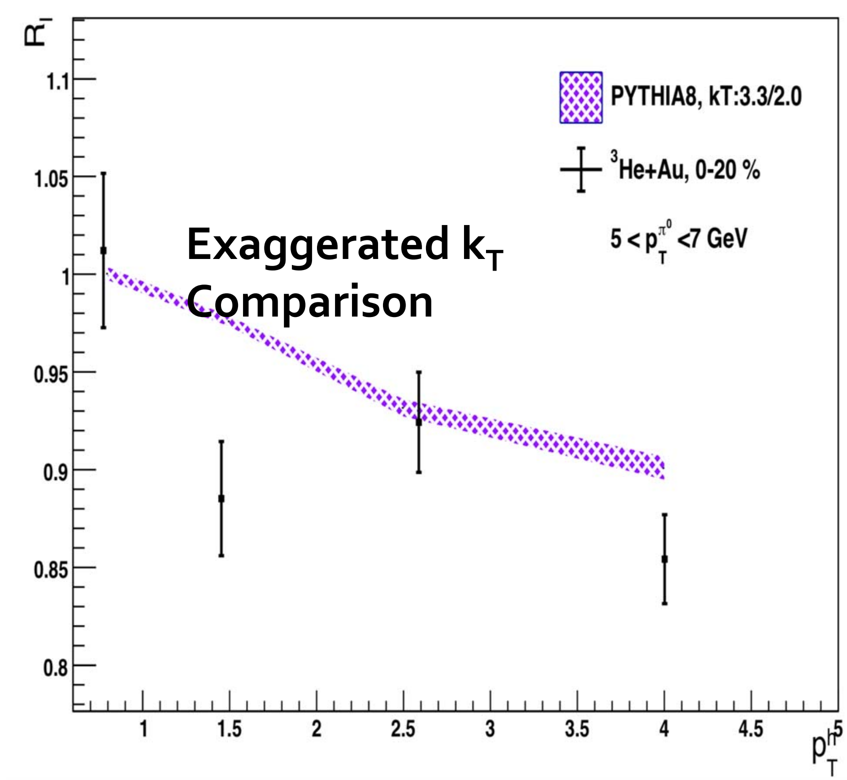


# UPDATED PYTHIA 8 Nuclear $k_T$ test

- Using $k_T$ constraints from STAR jet measurements → No effect for 0-100% Minbias
- However, $k_T$ smear larger in Central HeAu→ Exaggerated has some shape similarity **but this is very large kT**

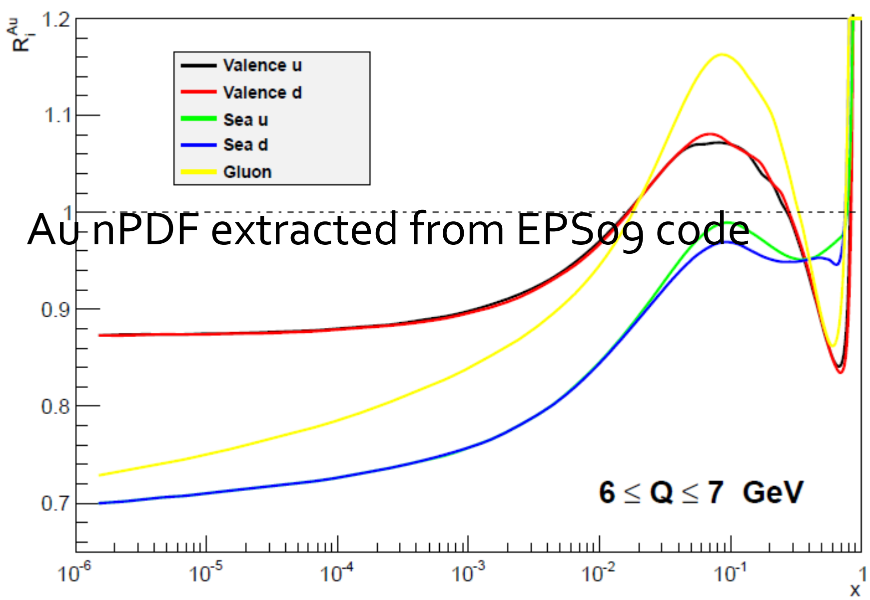


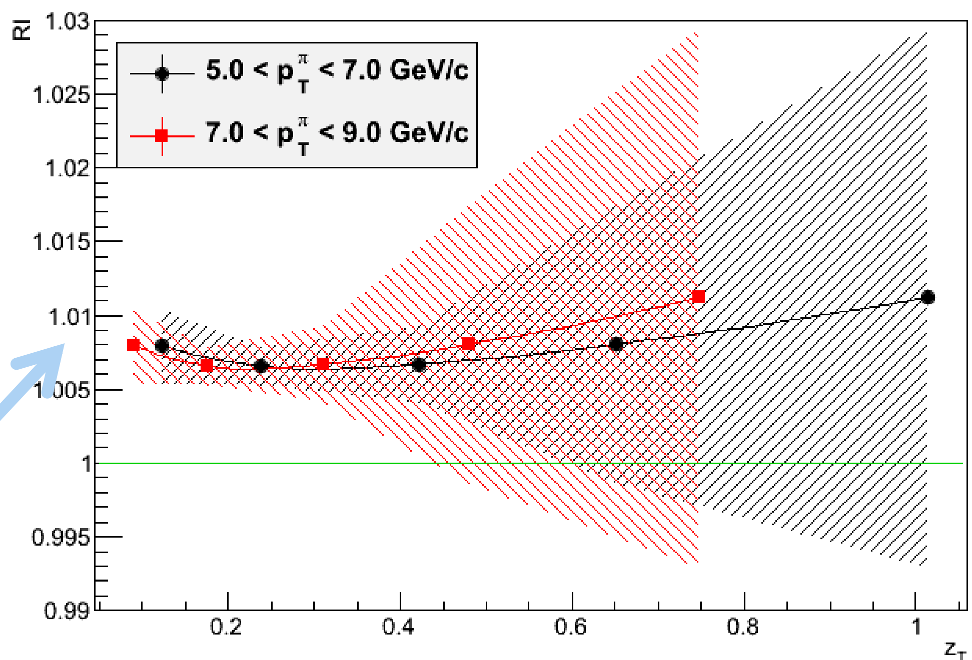
# OLD EPS09 Initial State Nuclear PDF's?

- nPDF effects would seem unlikely to cause this, since they probably often affect *both* jets in a di-jet
- Studies with EPS09 (and 09s) confirm this expectation
  - NOTE UNITS: << 1% negligible effect

RI Extracted from EPS09 Study



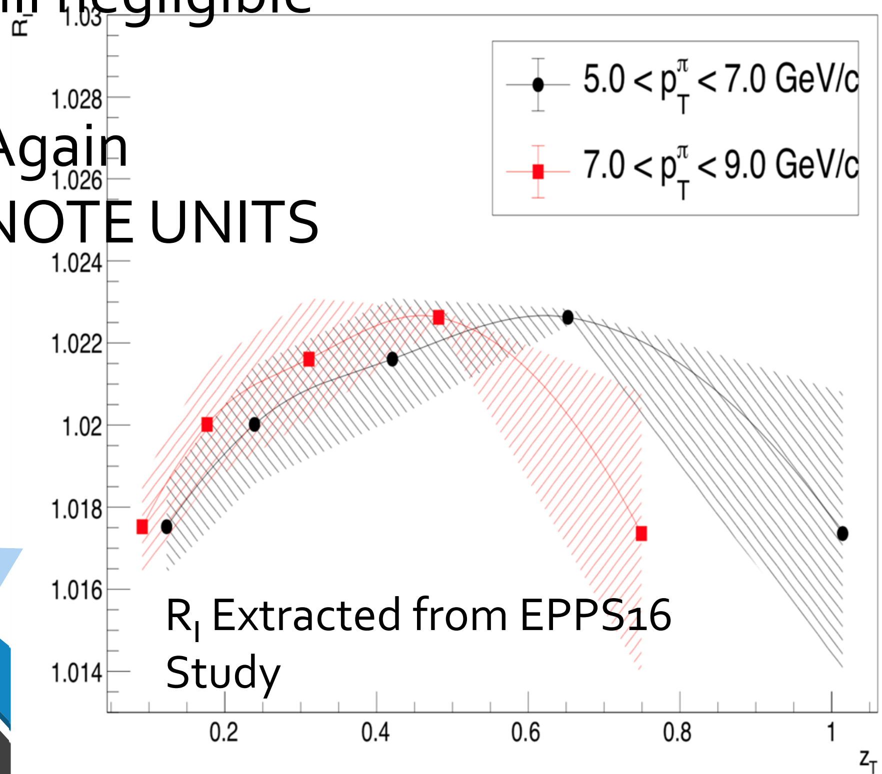

Au nPDF extracted from EPS09 code



# UPDATED EPPS16 & "Real" He+Au nPDF

- Previously only p+Au test for scale – He Wave Fn make a difference?
- Studies with EPPS16 and full HeAu
- Still negligible

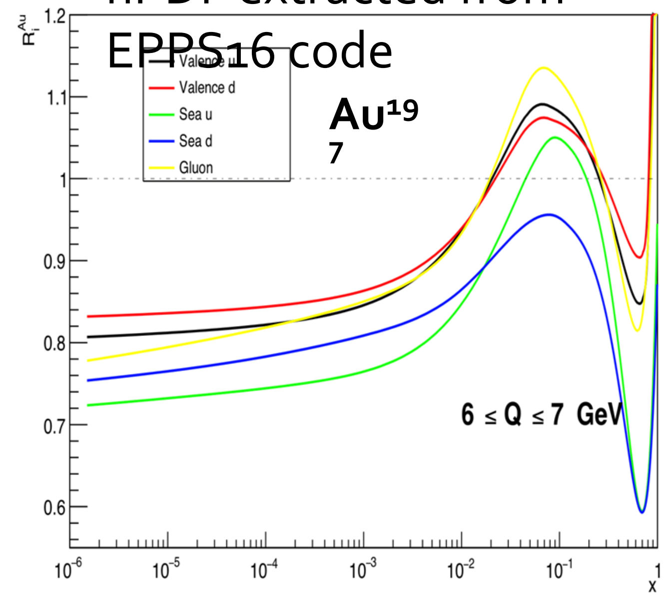
Again
NOTE UNITS

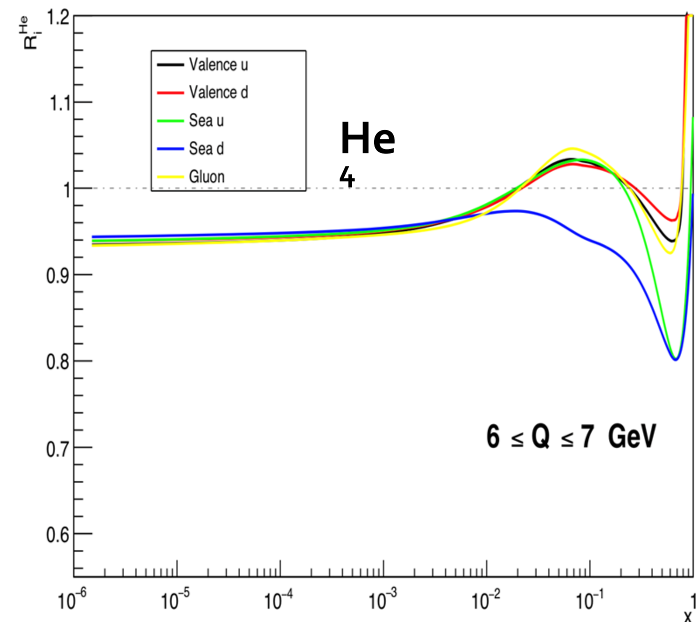



$R_I$ Extracted from EPPS16 Study

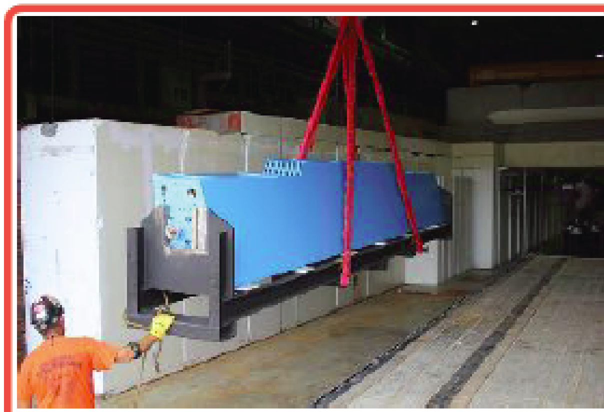
RESULT

nPDF extracted from EPPS16 code

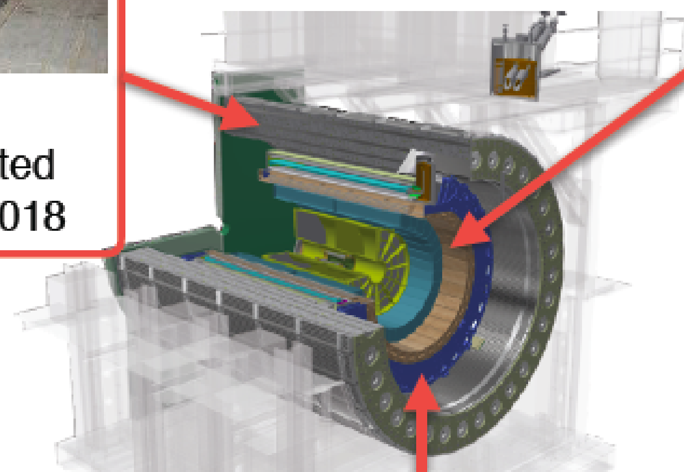


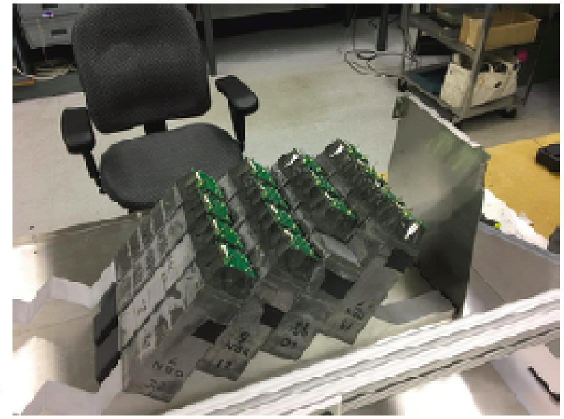



# sPHENIX Build Underway!



**OHCAL**
Production sectors started arriving at BNL in Sep 2018





**EMCAL**
**Sector 0 production underway**

**SC Magnet**
Full field magnet test at 1.4 T at BNL in Feb 2018

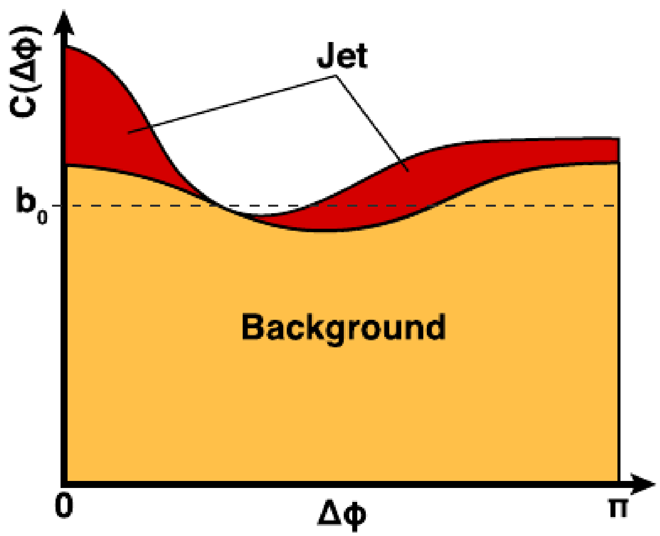
# 2-p Correlation Analyses - Methods

- Statistical Methods: subtraction:  Not EvByEv
- Need to measure per-trigger yield function)

$$C(\Delta\phi_{AB}) = J(\Delta\phi_{AB}) + b_0 \frac{dN^{AB}_{comb}}{d\Delta\phi_{AB}}$$

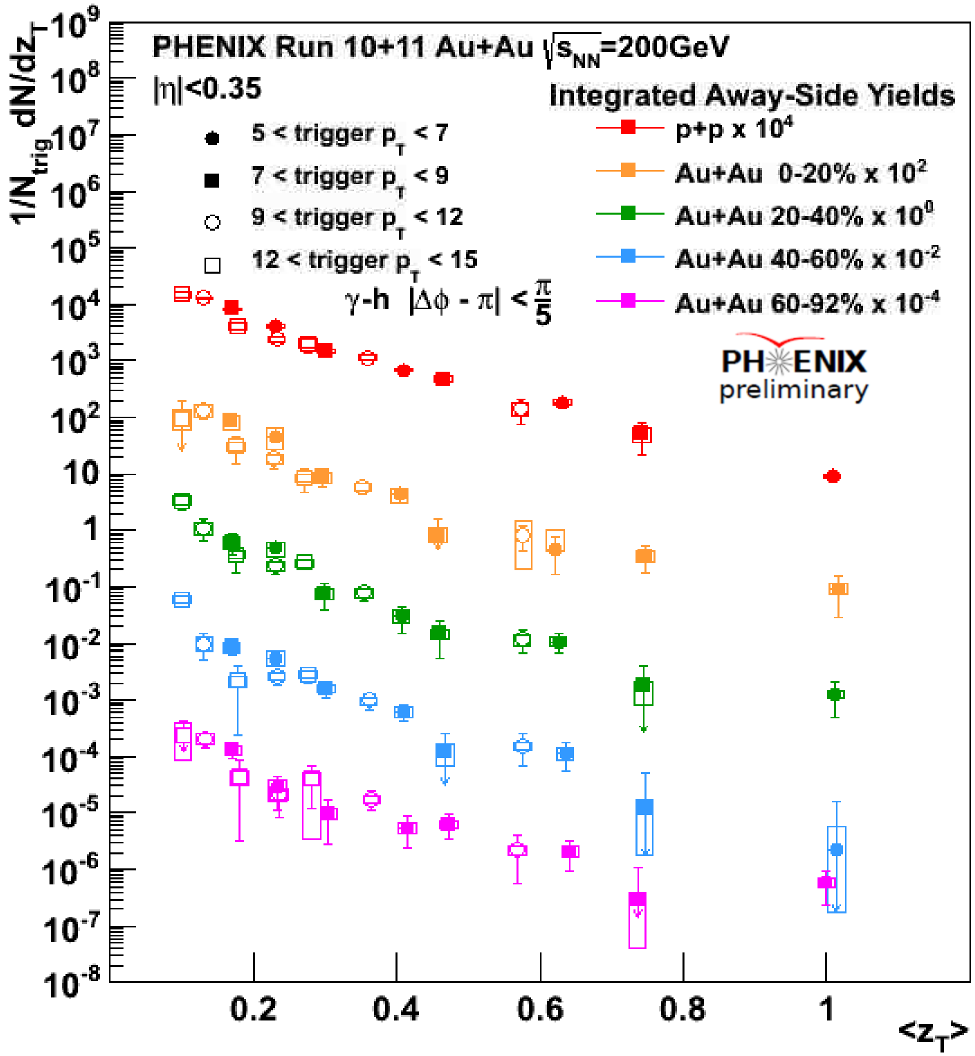
  - Correlation Function – bkgd (Flow)

$$\frac{dN^{AB}_{comb}}{d\Delta\phi_{AB}} \propto 1 + 2v_2^A v_2^B \cos(2\Delta\phi_{AB}) \; + v_{n>3}$$



# Away-side Prompt $\gamma$-h Yield

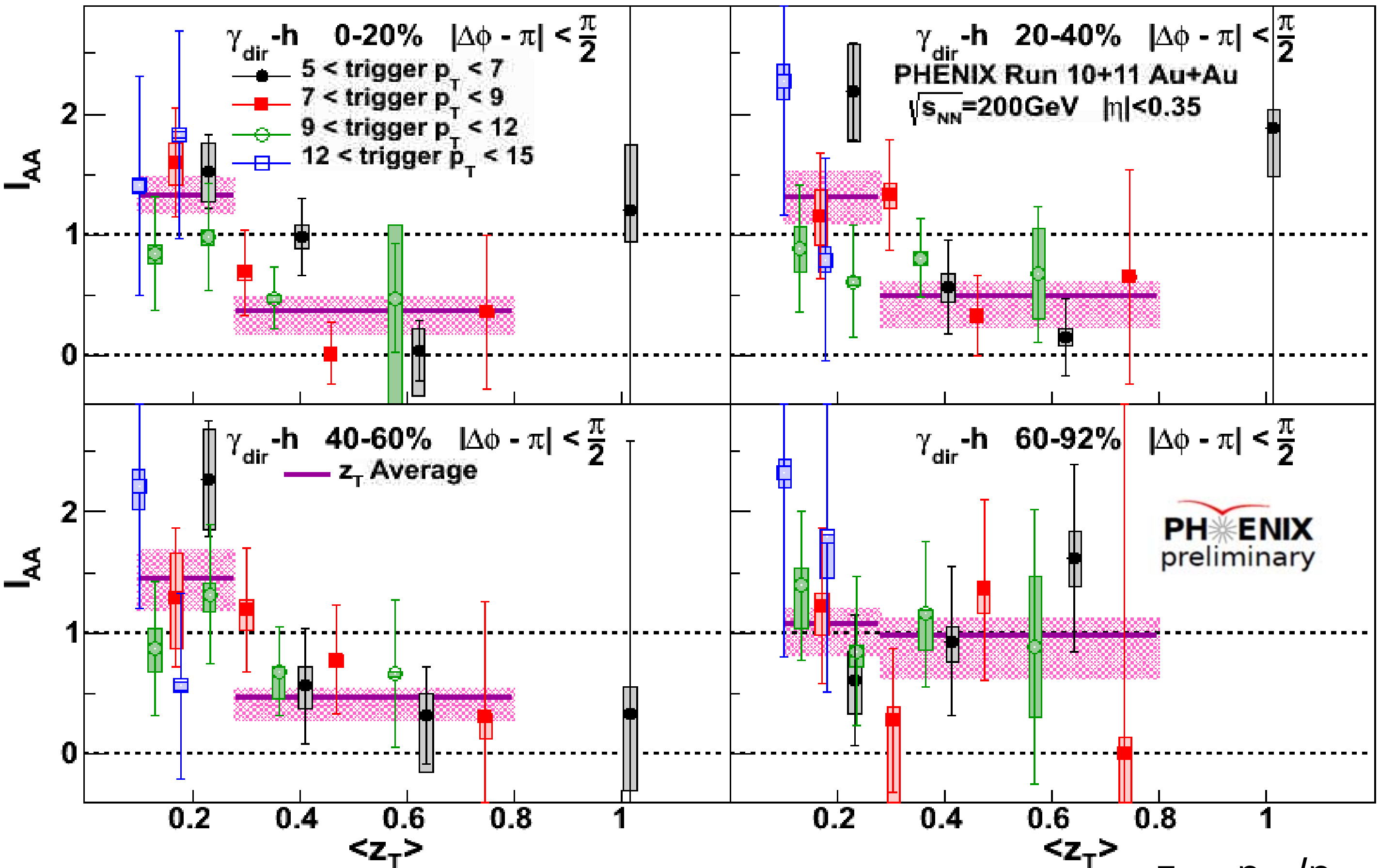
- Integrate away-side of per-trigger yield
- Seems to scale with $z_T = p_{Th}/p_{T\gamma}$



# $I_{AA}$ as a function of $z_T$

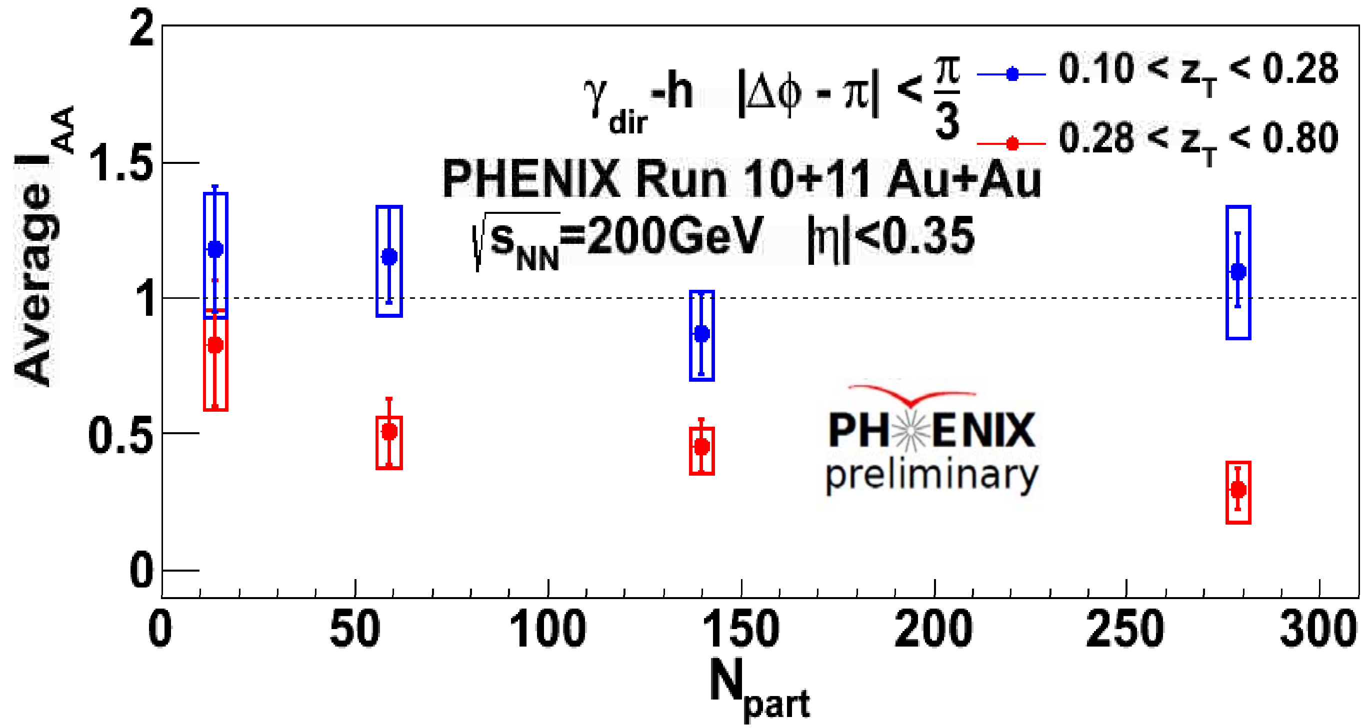
$$I_{AA}(p_T^\gamma, p_T^h) = \frac{Y^{Au+Au}(p_T^\gamma, p_T^h)}{Y^{p+p}(p_T^\gamma, p_T^h)}$$

- Fit all $I_{AA}$ points in two $z_T$ regions to a constant to extract the average $I_{AA}$ for each $z_T$ region and centrality bir




$z_T = p_{Th}/p_{T\gamma}$

# Average $I_{AA}$ vs. Centrality

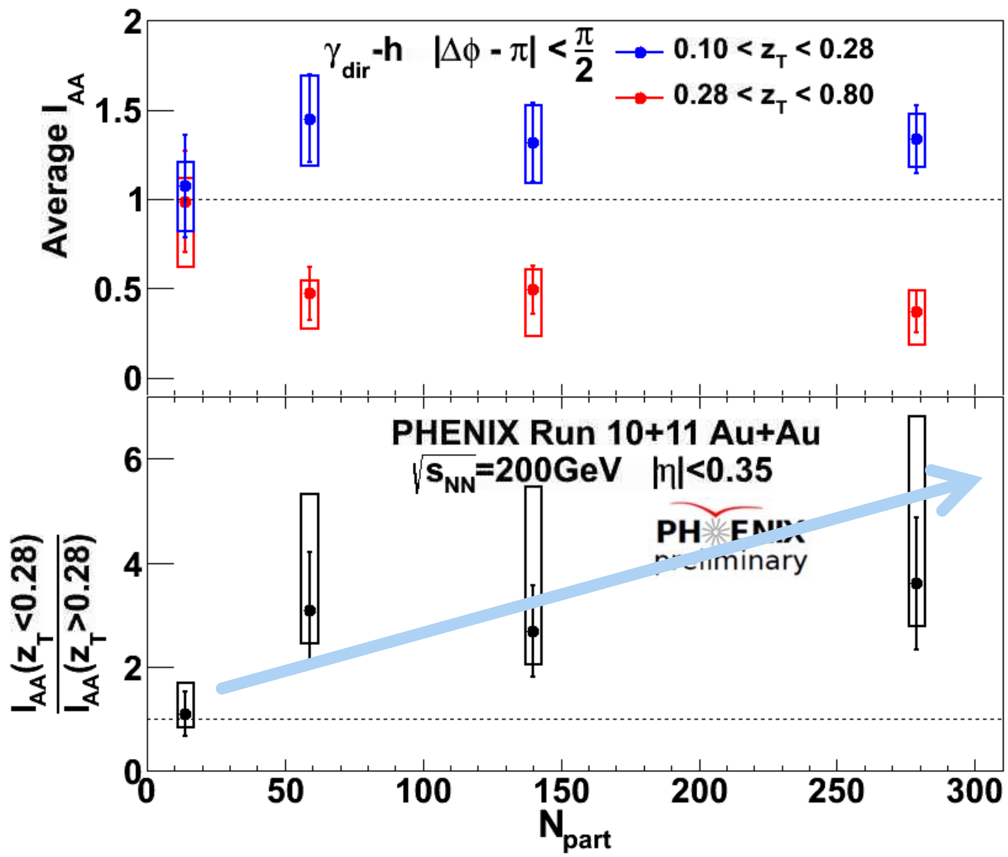



- Low $z_T$ and High $z_T$ behaviors different.
- High $z_T$ suppression for all centrality bins
- Low $z_T$ NOT SUPPRESSED, relatively flat with centrality-- $E_{loss}$ Recovery

Isolation cut allows more precise analysis of the semi-peripheral and peripheral centralities

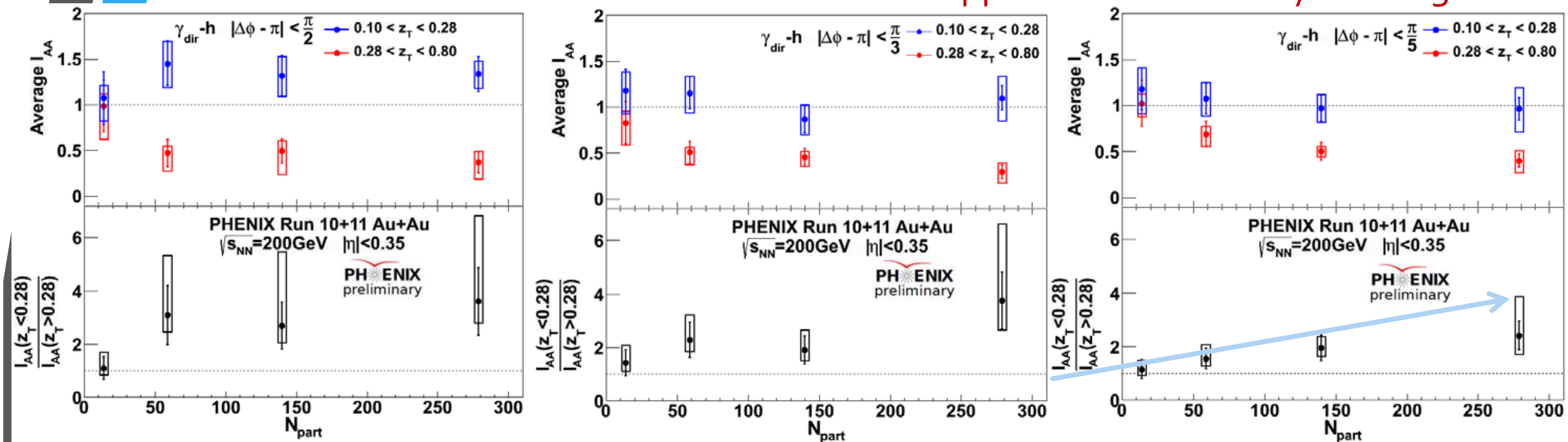
# Average $I_{AA}$ – π/2 away-side

- High $z_T$ energy loss enhances low $z_T$ production
- 1st measurement of centrality dependence of low $z_T$ enhancement
- To judge true centrality dependence of enhancement, must account for overall reduction of jets due to suppression
- Energy recovery factor – High $z_T$/ low $z_T$ ratio – shows monotonic increase toward central events



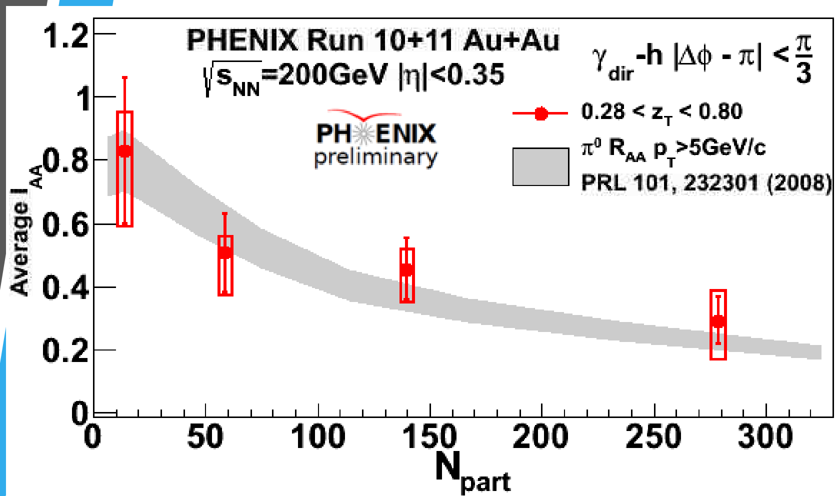
# Average $I_{AA}$

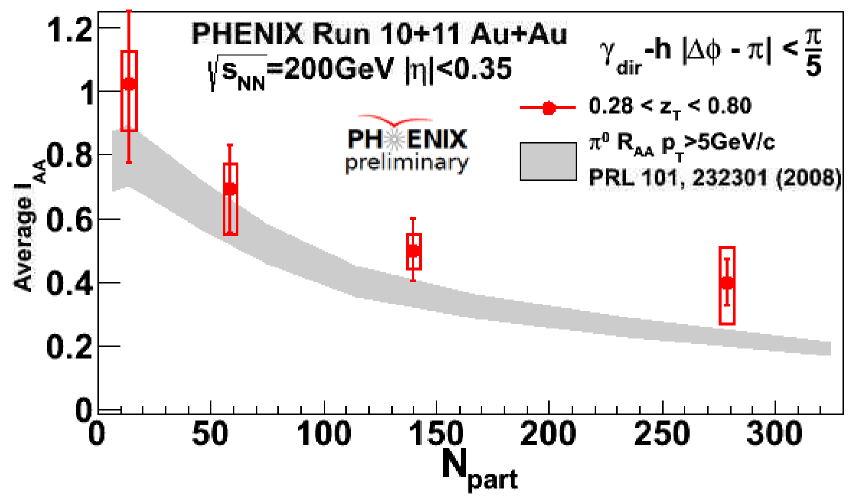
Enhancement and suppression for all away-side regions!



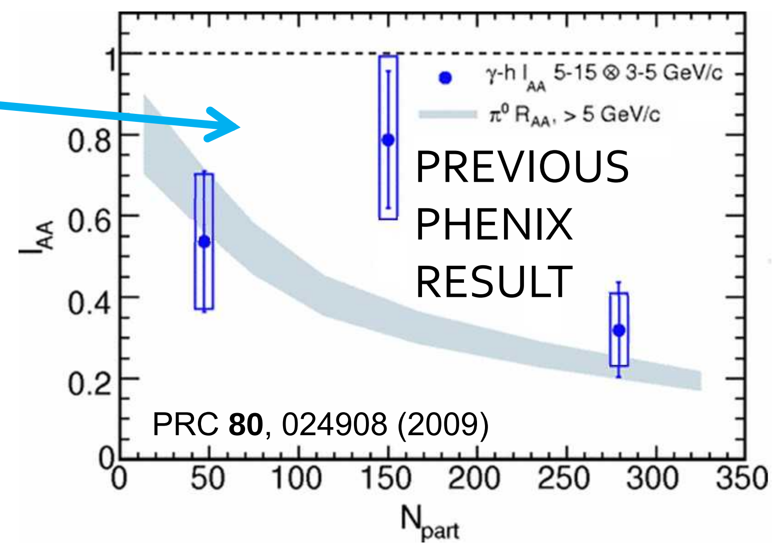

- Increasing low z enhancement for wider integration regions (blue points right to left)
  - Seen by previous gamma-jet and LHC jet reconstruction analyses
- Both high z suppression and low z enhancement
- Enhancement above suppressed jet level (black ratio) monotonically increasing towards central events for all away-sides

# Back to $\gamma$-h Yields High $z_T$ Average $I_{AA}$ Centrality Dependence




- Isolation cut/New stats substantial improvement in precision
- Detailed centrality shape of suppression
- High $z_T$ Average $I_{AA}$ and $\pi^0$ $R_{AA}$ approximately match
  - Photon tagged jet geometric distribution ($E_{loss}$ geometry) is exactly the same as single inclusive jet geometric distribution - so $R_{AA} \approx \gamma$-jet $I_{AA}$ expected



# Implication: Causes?

**Results are pretty well tested and confirmed in He+Au – Need Theory Input—Important Question!**

- Many potential Trivial or Cold Nuclear Explanations—but also shares qualitative features of Eloss
- "Trivial" explanations we could test:
  - ✓ "Hydro" v3, v1
  - ✓ Trivial Rapidity Distributions Mismatching p+p vs d+Au?
  - ✓ HIJING show anything like this?

None of these could reproduce the effect

- "Cold Nuclear Effects":
  - ✓ Enhanced Nuclear $k_T$
  - ✓ Initial State nPDF effects (partial—EPS09(s) only checked)
  - Check other npdf's?
  - Get bonafide theory calcs from theorists (need input from theorists)
- Could QGP/Hot Eloss Cause This?
  - Get bonafide theory calcs from theorists (need input from theorists)