γ+Jet Measurements in Heavy-Ion Collisions

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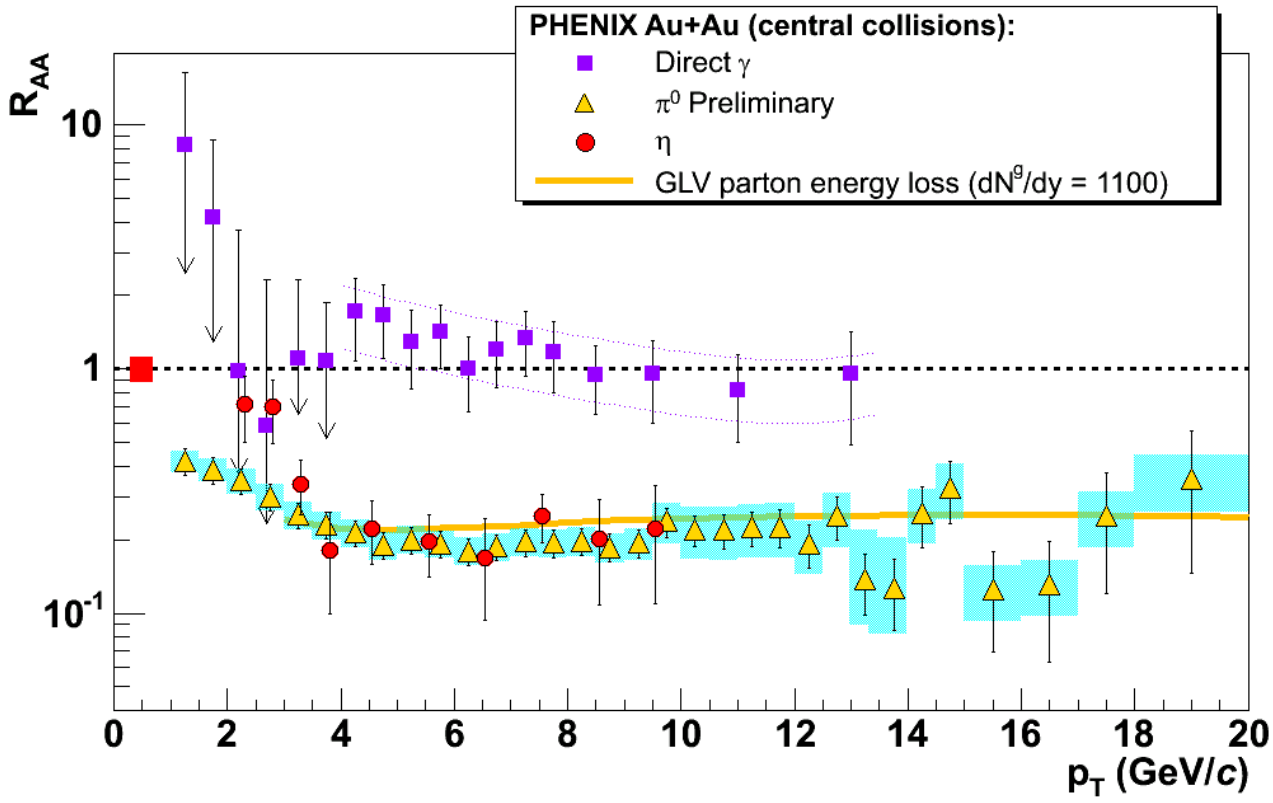
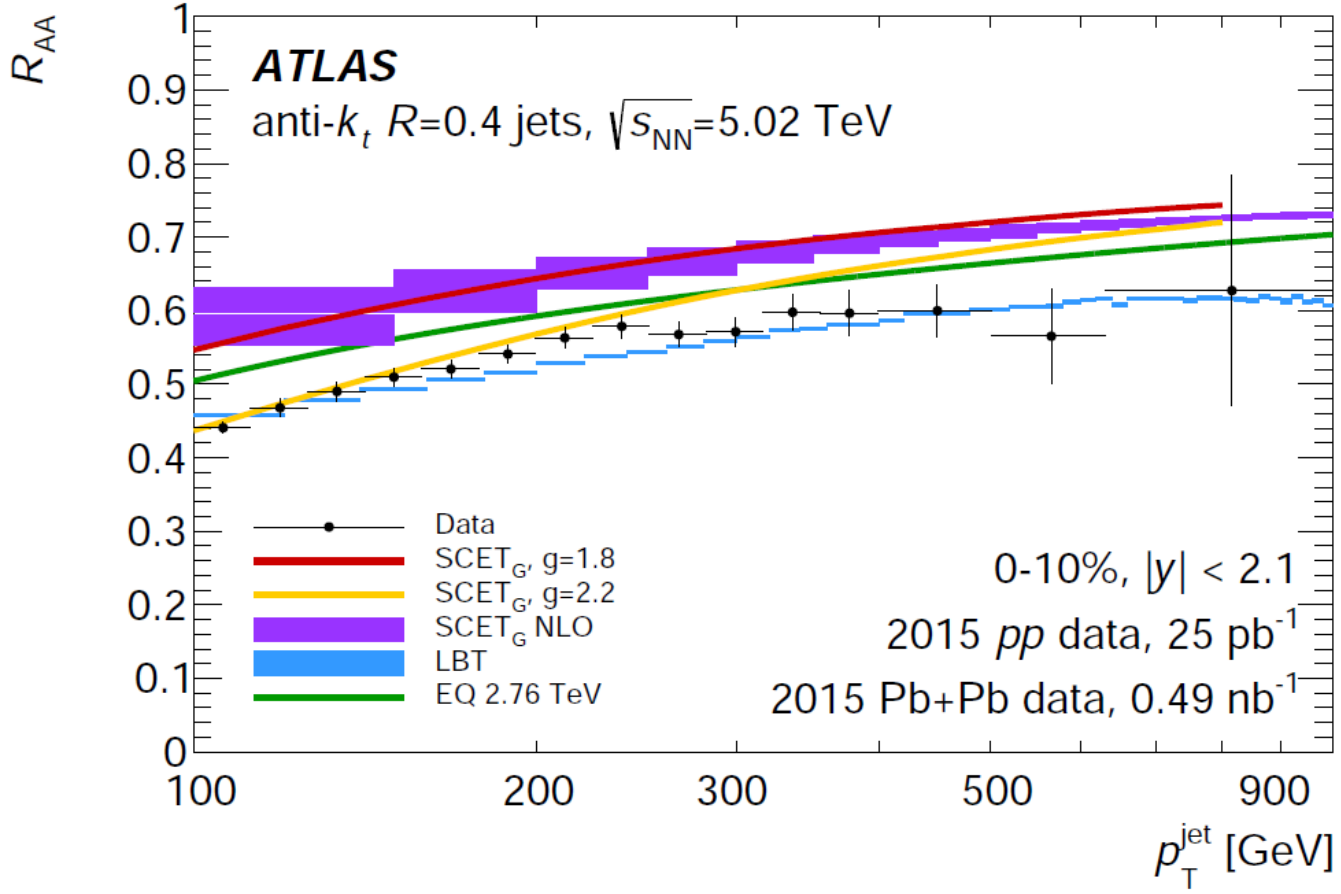
Jet Suppression in Heavy Ions for almost 20 years



Early measurements at RHIC focused on high p_T hadrons as the leading particles coming from jets

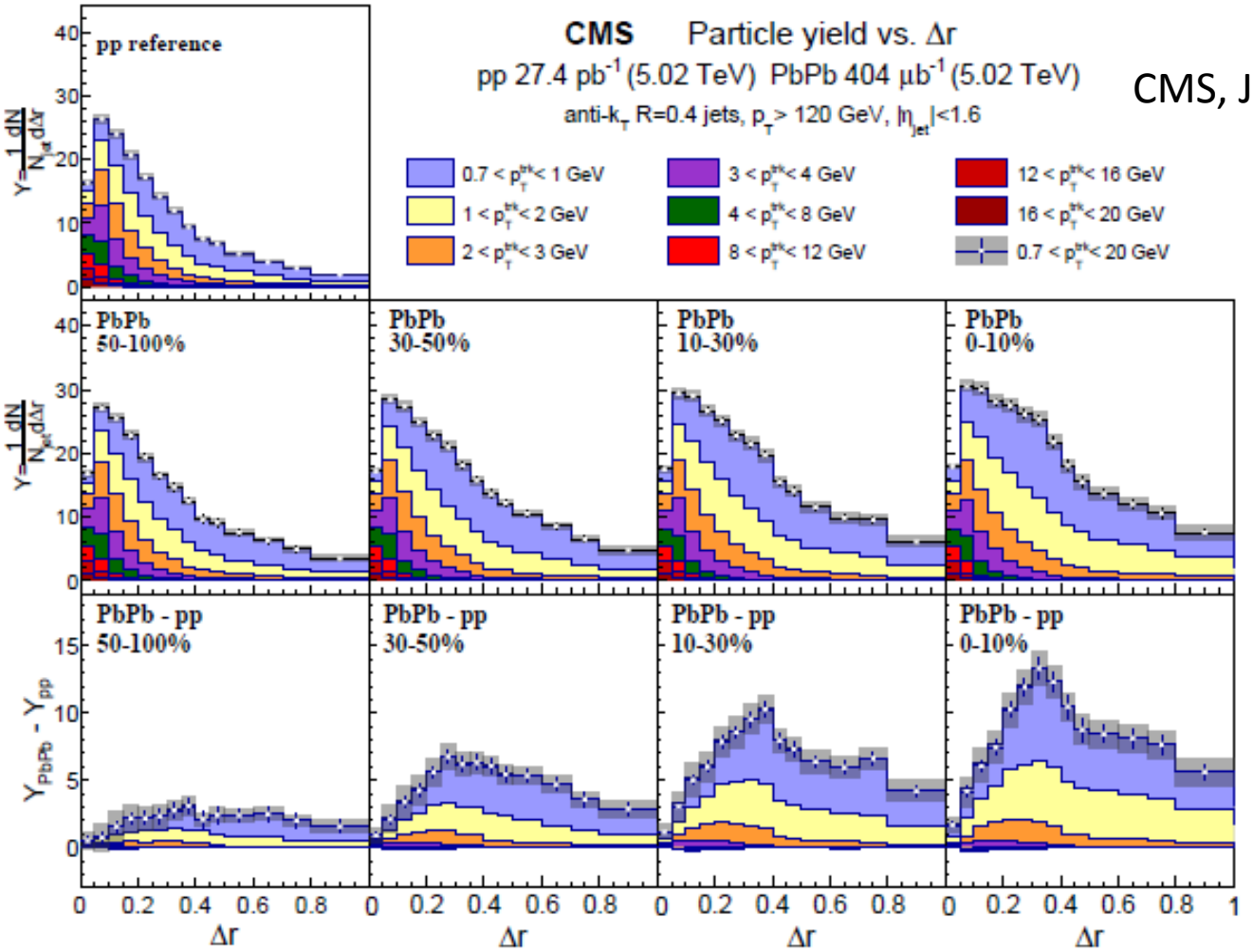
We have come a long way….
Suppression measured for fully reconstructed Jets at the LHC

ATLAS, arXiv:1805.05635



We have come a long way….

Modification of the structure of Jets at the LHC



CMS, JHEP 05 (2018) 006

Why do we look at so many different observables?

What is the end game in the jet business?

From the 80's TV show

From the 80's TV show

We ain't in the coke business, we're in the cash business!

From Heavy-Ion Physicists

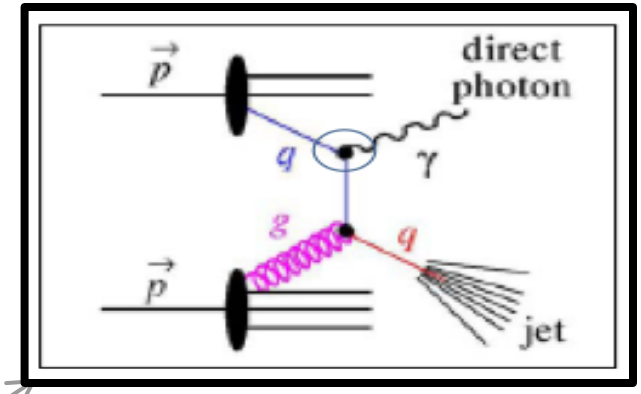
We ain't in the jet business, we're in the QGP business!

Goal is to extract Properties of QGP

- But this is the hard part!
- To learn more about the nature of the medium, we want to understand how a hard probe interacts with it
- So far, single-hadron suppression measurements have led to estimates of the gluon density and $\hat{q}$ (JET Collaboration)
- But we are interested in the particles that emerge from such interactions, not just measure the fraction of the ones that survive without much effect
- *Is the interaction between a hard parton and the quasi-particle medium perturbative?* If Q^2 is large enough
- We know medium is strongly interacting medium
- Medium interaction is handled differently among theory calculations
- LHC has opened up many new possibilities of studying jet structure and the modification of it in the medium
- RHIC is still relevant for exploring the interaction of the "not as hard" partons with the medium – another knob to turn

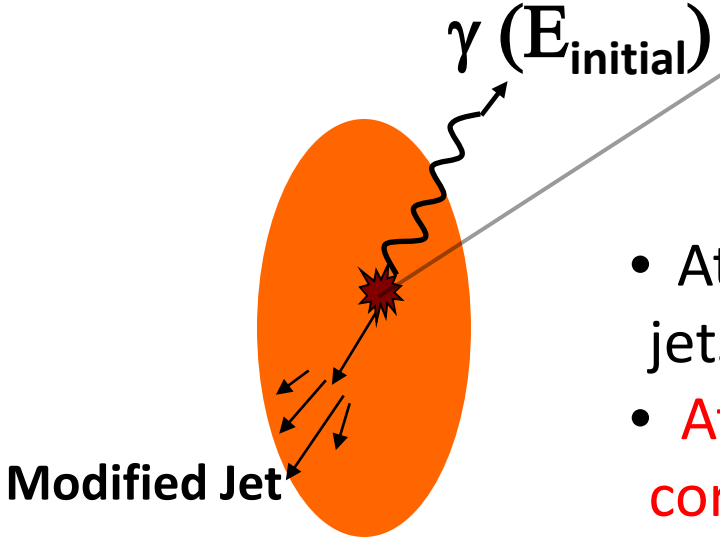
γ-Jet Motivation

Photon does not interact strongly, so the trigger energy is more directly connected to the recoil parton energy



Goal:

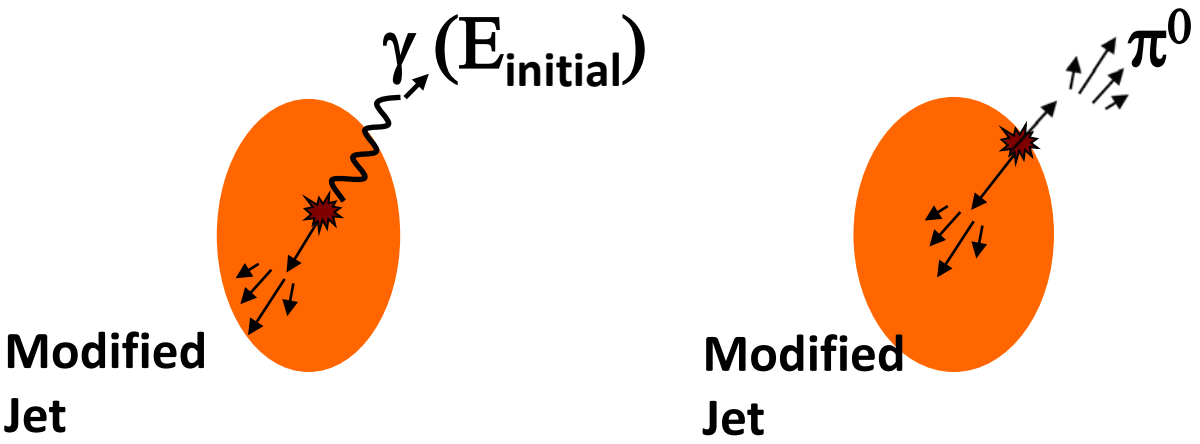
Measure Recoil Jet Energy vs. Initial Energy of Parton, as approximated by trigger-photon energy



- At LHC, studied with fully reconstructed jets on the recoil side of trigger photon
- At RHIC, mostly studied with azimuthal correlations of charged particles with trigger photon

Comparison of Photon- to Hadron-Triggered "Jets"

Hadron triggers are surface biased, so recoil parton has (on average) more medium to traverse

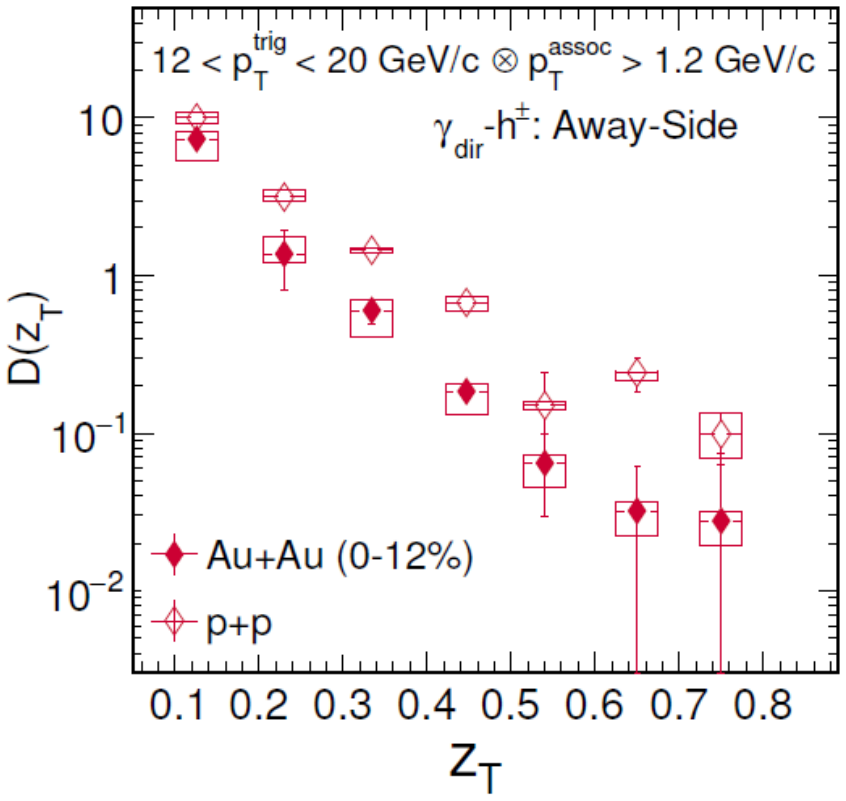


Recoil parton of photon triggers mostly quark jets, recoil of high-p_T π^0 (at RHIC) are mostly gluon jets (D. de Florian et al., PRD 91, 014035 (2015); T. Kaufmann et al., PRD 92, 054015 (2015))– color factor would result in greater energy loss for π^0-triggered jets

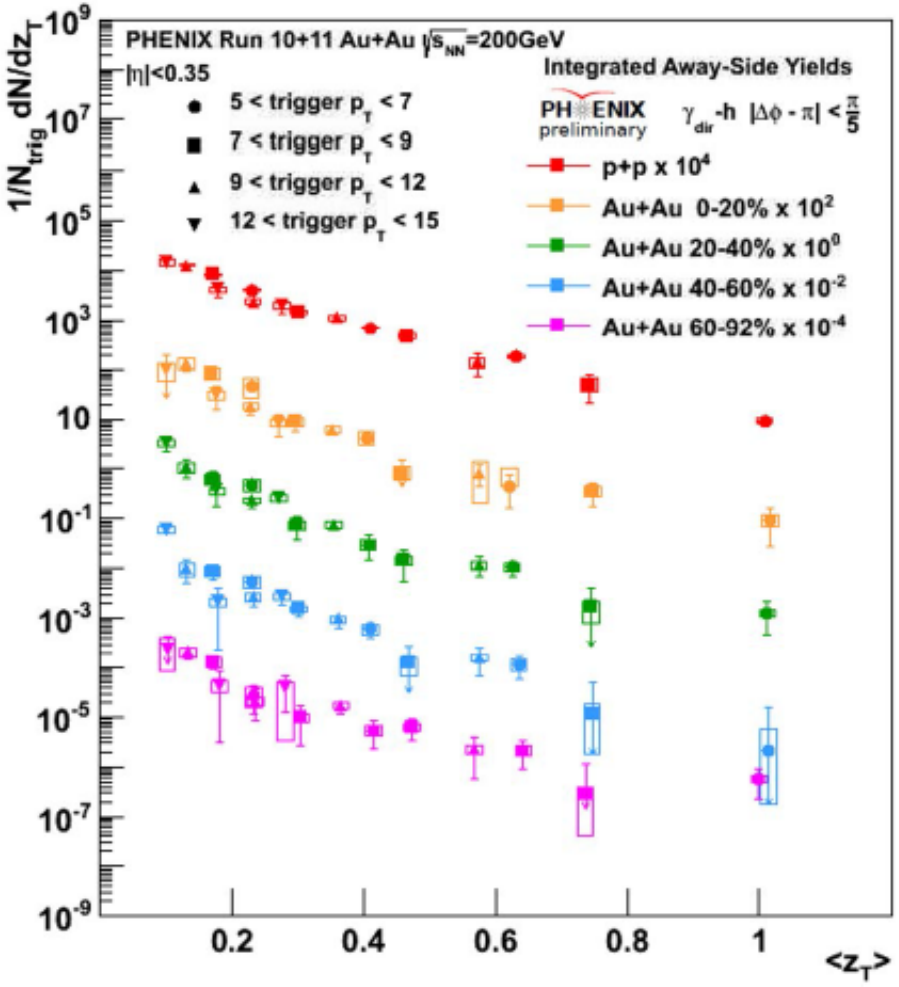
Fragmentation Functions via γ-h Correlations at RHIC

STAR

Phys. Lett. B **760** (2016) 689



PHENIX preliminary



Suppression of jet-like yields on recoil side of π^0 triggers vs. γ_{dir} triggers

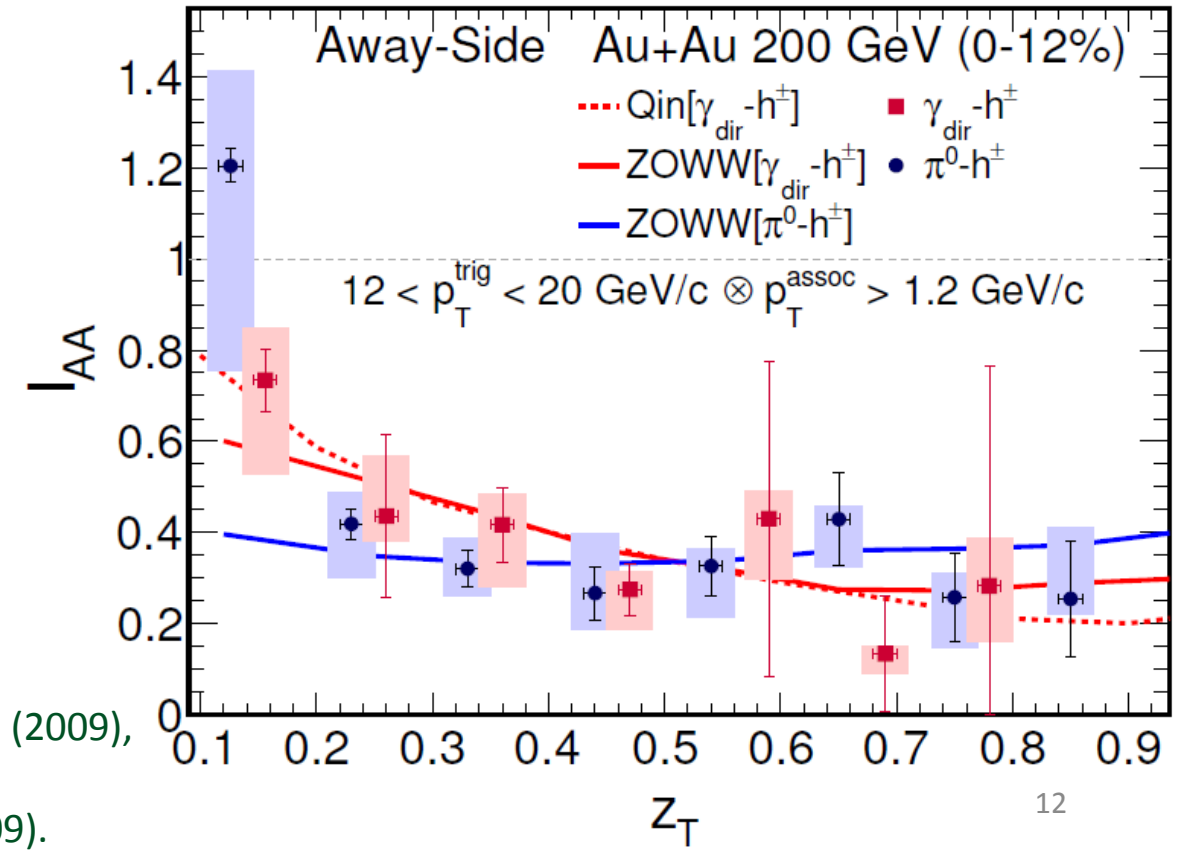
Suppression measured via I_{AA} = ratio of per-trigger yields in central Au+Au to minimum-bias p+p collisions

Suppression consistent for hadron triggers and photon triggers within uncertainties
Suppression appears to be less significant at low z_T, low p_T^{assoc}

No significant differences seen due to expected effects:
1) difference in surface vs. volume emission and
2) color factor in energy loss

Model calculations in agreement with data

STAR, Phys. Lett. B **760** (2016) 689

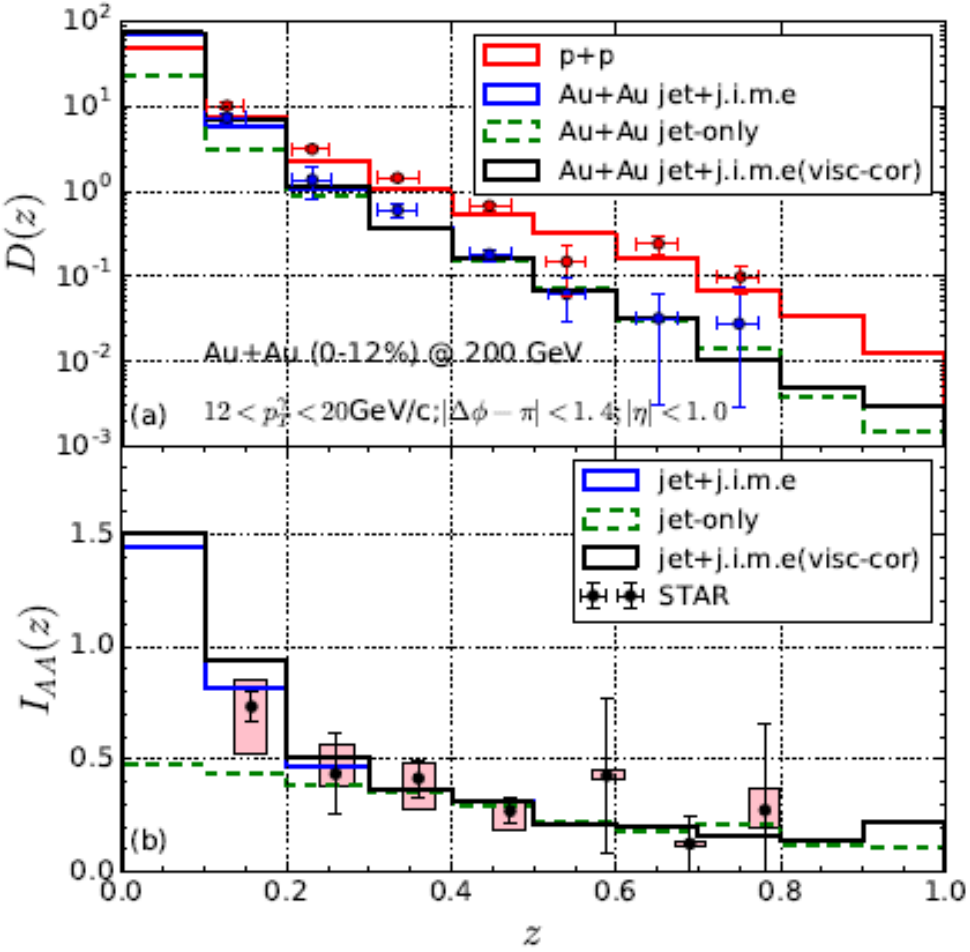


ZOWW: H. Zhang et al., PRL 103, 032302 (2009), X.-F. Chen et al., PRC 81, 064908 (2010)
Qin: G.-Y. Qin et al., PRC 80, 054909 (2009).

More Recent Model Calculation

- Coupled Linear Boltzmann Transport Hydro model (W. Chen, Phys.Lett. B777 (2018) 86-90)

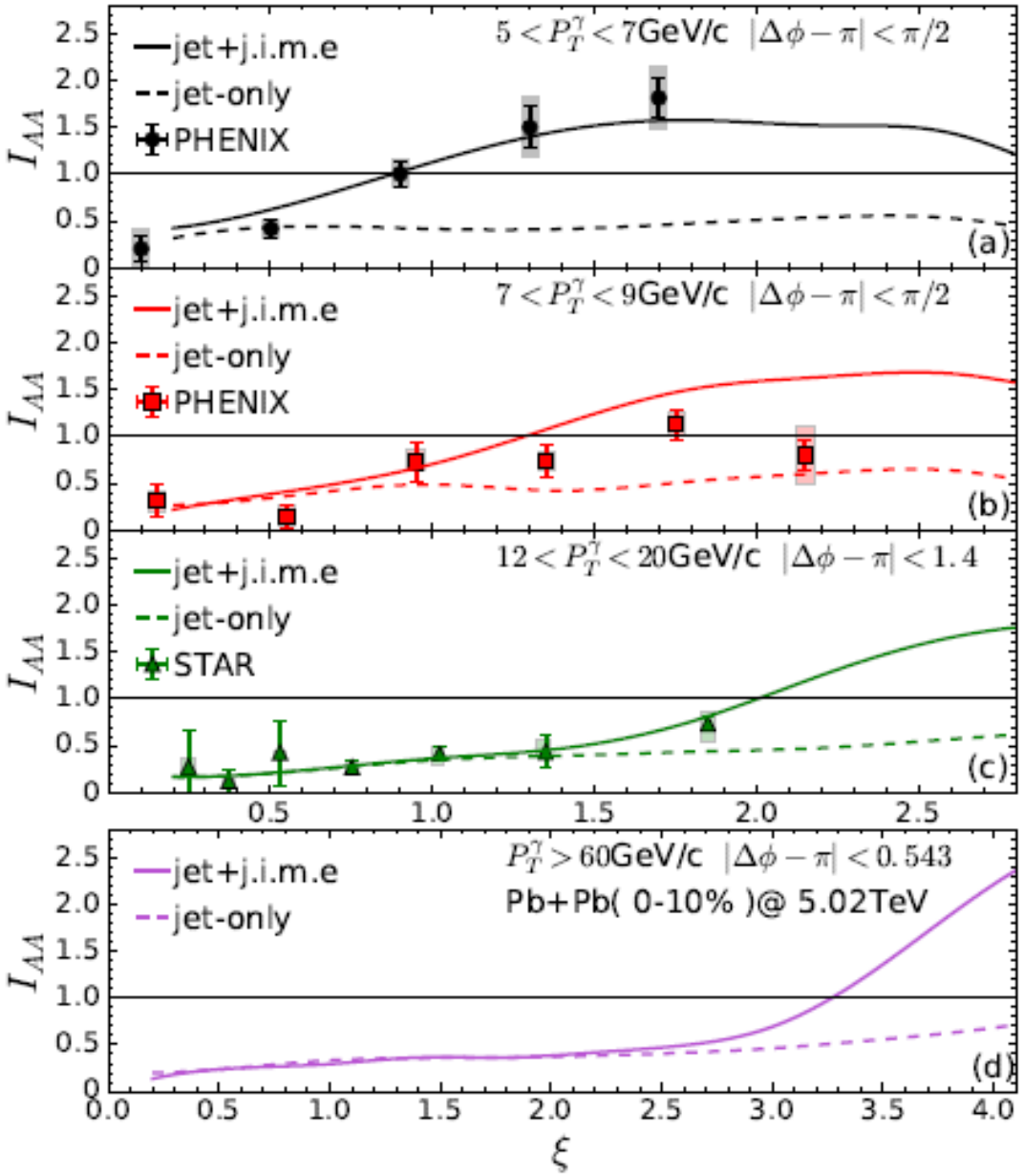
- Calculation rises at low z_T, if including transport of medium recoil partons



Model Comparison to PHENIX and STAR Data

Same calculation compared to PHENIX data (PHENIX, Phys. Rev. Lett. 111, 032301)

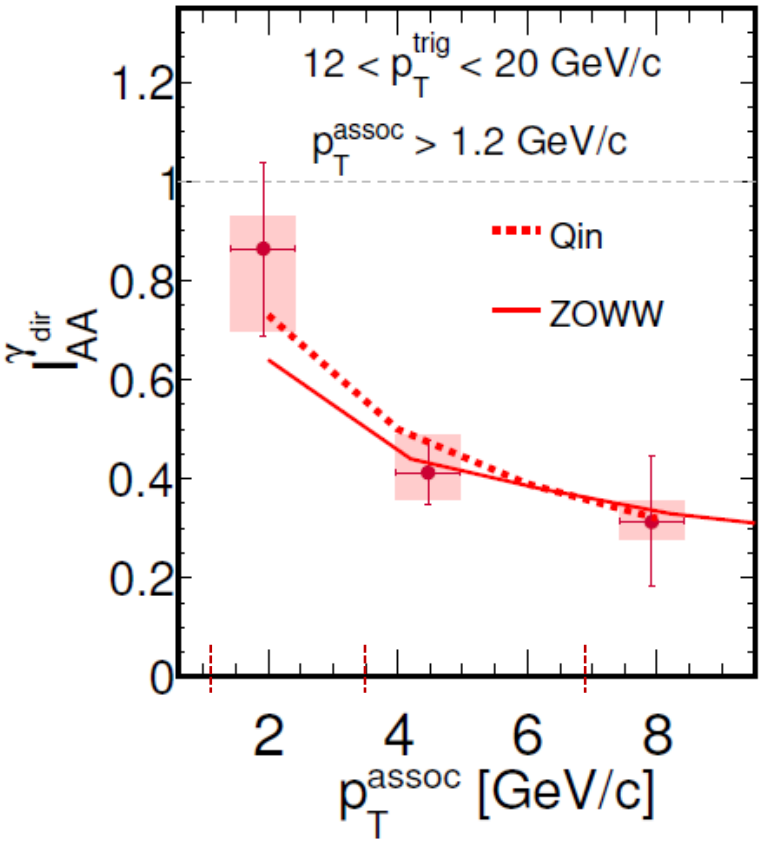
shows agreement only if including transport of medium recoil partons



Suppression of recoil-jet yields as a function of p_T^{assoc}

- If enhancement occurs at a fixed p_T, rather than z_T, should see a stronger effect when I_{AA} is viewed as a function of associated charged-particle p_T.
- Suppression is less significant at low p_T^{assoc}
- If enhancement occurs at low p_T, it must be for $p_T < \sim 3$ GeV/c

STAR, Phys. Lett. B **760** (2016) 689

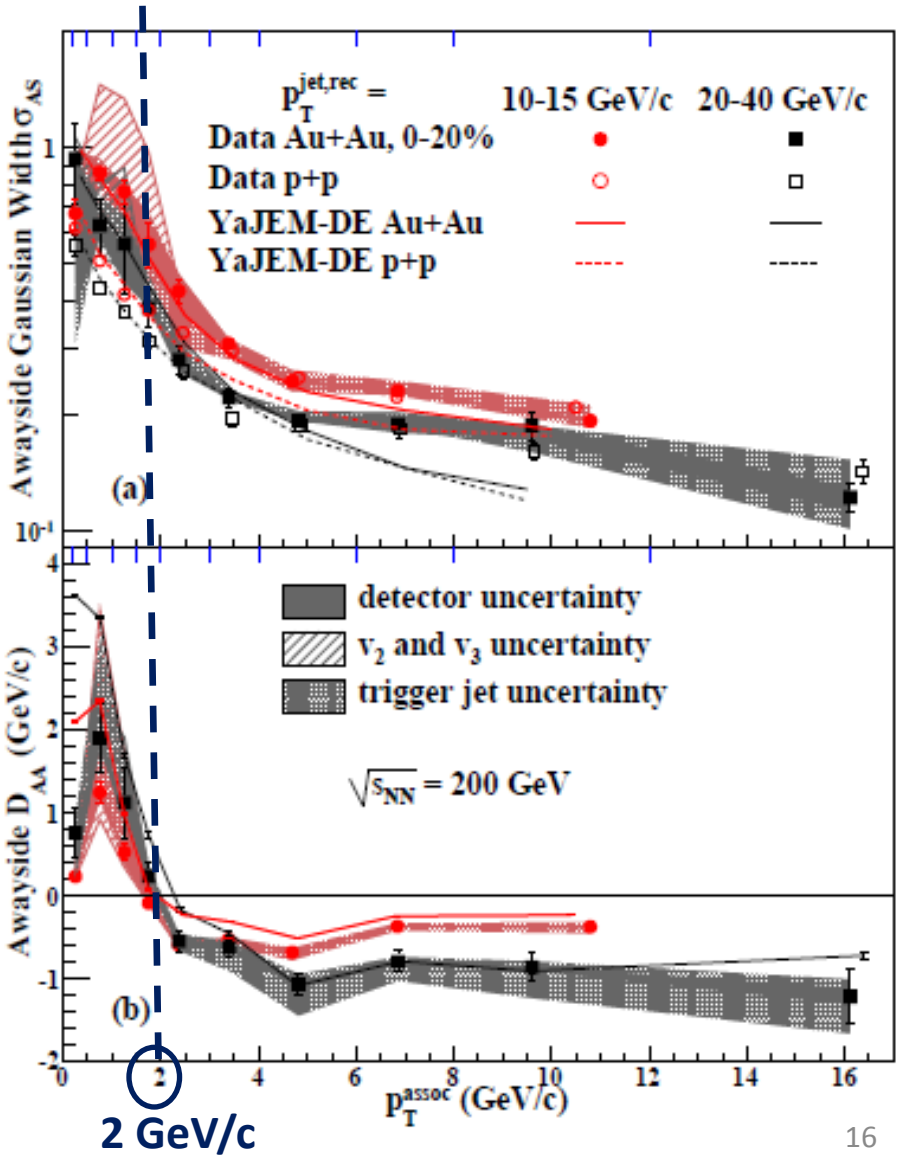


Recovery of Energy at Large Angles?

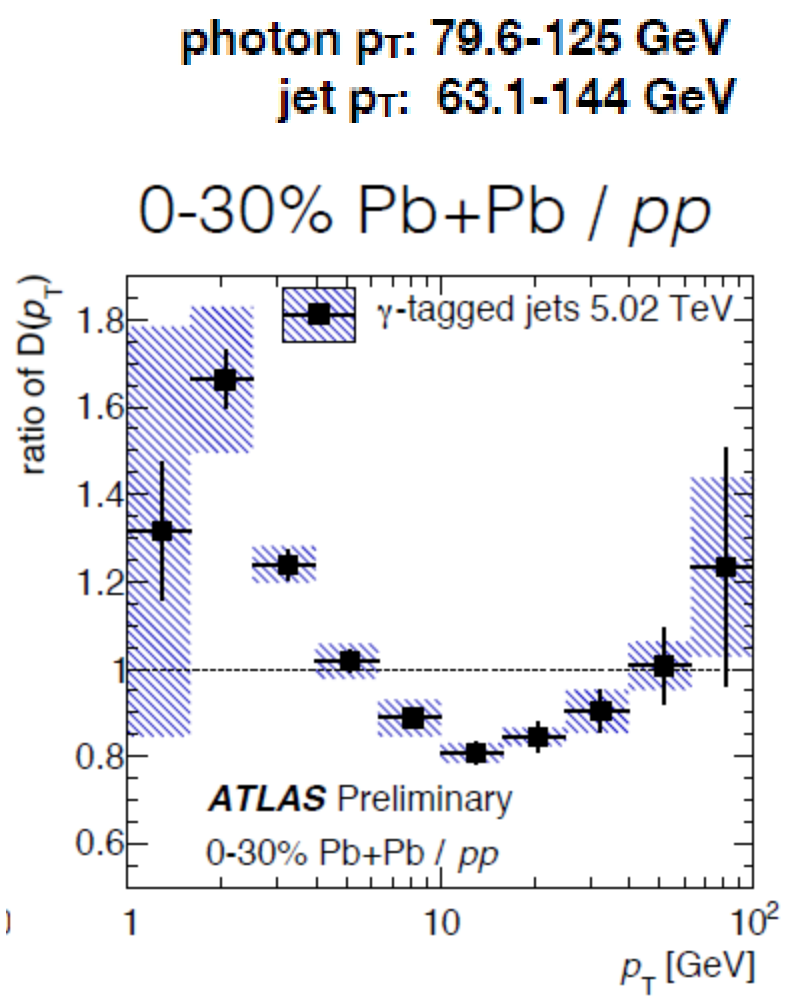
Measurement: Require a (reconstructed) Jet Trigger and quantify yields of the associated charged hadrons on the recoil side

Results from STAR Jet-hadron correlations (for two different ranges of jet energies) also indicate that the lost energy is recovered only for $p_T^{assoc} < 2$ GeV/c

STAR, Phys.Rev.Lett. 112, 122301 (2014)



Low-pT Enhancement at LHC at similar p_T



- Fragmentation function measured at ATLAS with photon-jet back-to-back pairs in Pb+Pb and p+p collisions
- Ratio of Yields as a function of charged-particle p_T within the recoil jet
- A modest suppression observed for charged particles with p_T ≈5-40 GeV/c
- Enhancement for p_T<3-4 GeV/c

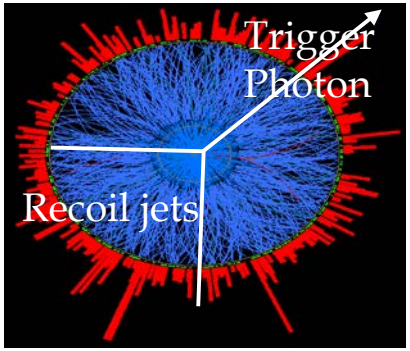
Summary I

- Suppression of recoil-jet yields (I_{AA}) were measured by STAR via γ-triggered vs. π^0-triggered charged-hadron correlations show similar level of suppression for p_T^{trig}=12-20 GeV/c, p_T^{assoc}>1.2 GeV/c.
  - Expected difference in π^0 triggered vs. γ-triggered suppression due to surface vs. volume emission and due to the color factor in energy loss is not seen at high z_T, where we are only measuring the fraction of jet particles surviving without much medium interaction
  - Suppression is smaller at low z_T (z_T<0.2, corresponding to p_T^{assoc}<2.4 GeV/c)
- I_{AA} measured by PHENIX γ-triggered charged-hadron correlations show suppression at high p_T (z_T), but enhancement at lower p_T (z_T) for p_T^{trig}=5-9 and 9-12 GeV/c
- Comparison with other measurements suggests that recovered energy appears at p_T^{assoc}<2 GeV/c, independent of p_T^{trig}.

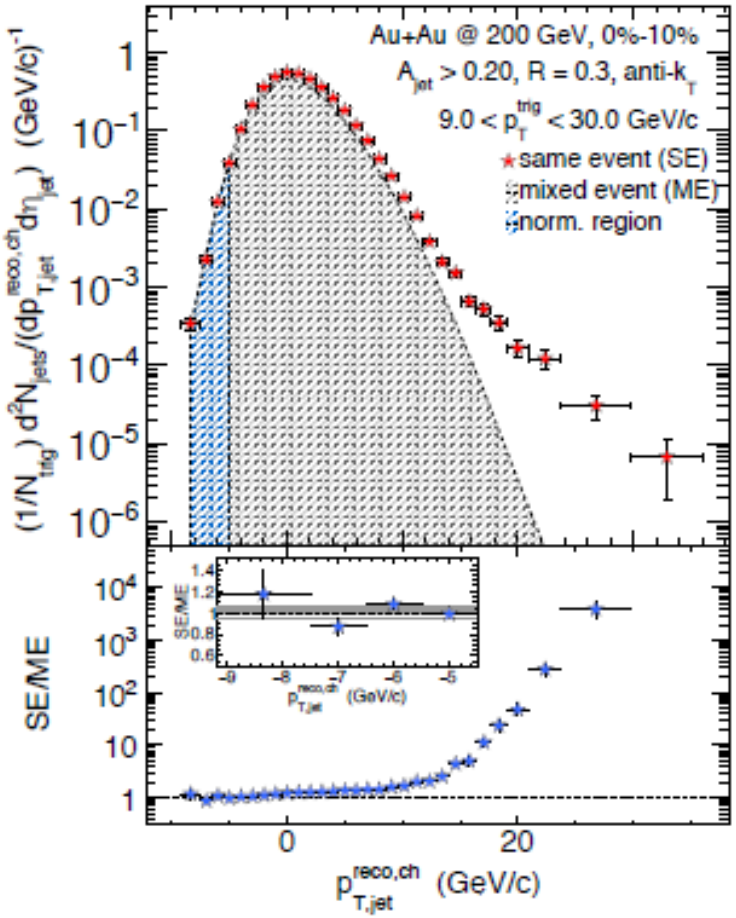
Summary II

- Enhancement in PHENIX at low z_T is consistent with this observation
- Model comparison shows enhancement at low z_T (p_T), if medium recoil partons are included in transport
- γ-triggered Jet Reconstruction at RHIC coming soon at STAR and with higher precision in the future at sPHENIX…
- Measurements and the theoretical calculations to extract medium properties are complicated and tedious. We need many different measurements (with different biases and kinematics) to test the theory in different aspects!

γ-Jet Measurement in STAR ongoing



STAR, Phys. Rev. C **96** (2017) 24905



Hadron-triggered Recoil Jets measured by STAR using mixed events to measure combinatorial jets

Backup

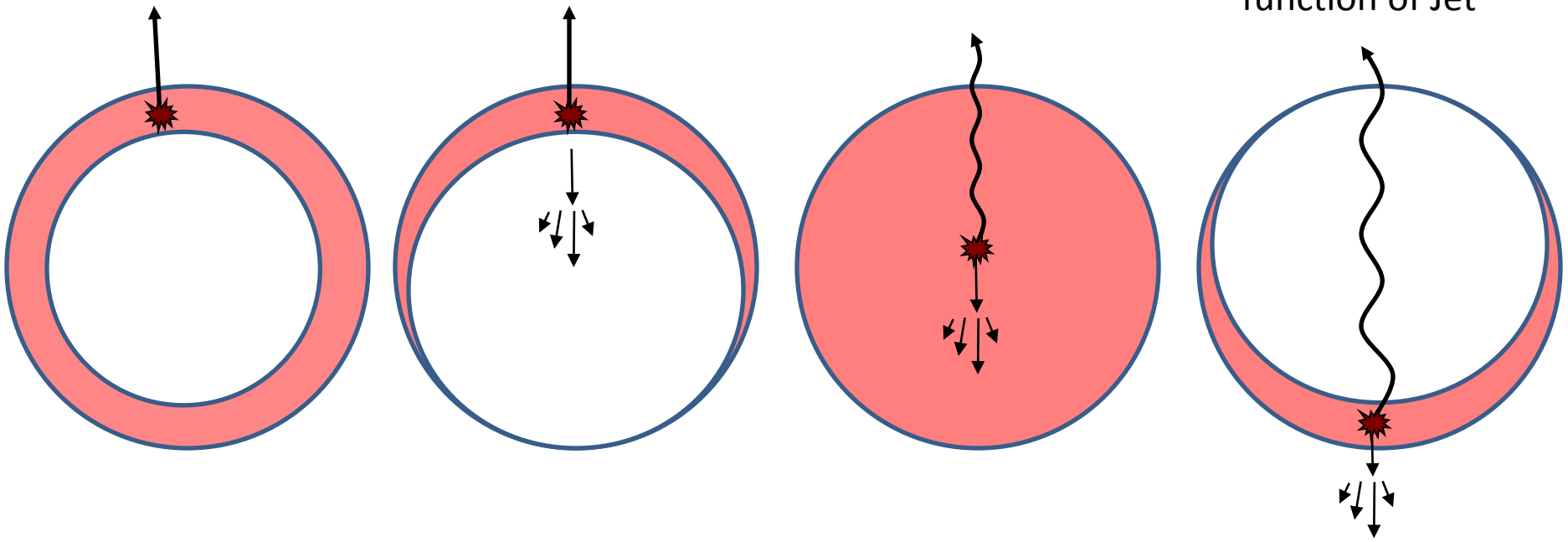
Biases (Selections) in "Jet" Measurements

Single Hadron at High p_T as proxy for jet (leading particle of jet)

High-p_T Hadron-Triggered Correlations for measuring jets

High-p_T Photon-Triggered Correlations or Jets for measuring jet modification with unbiased trigger

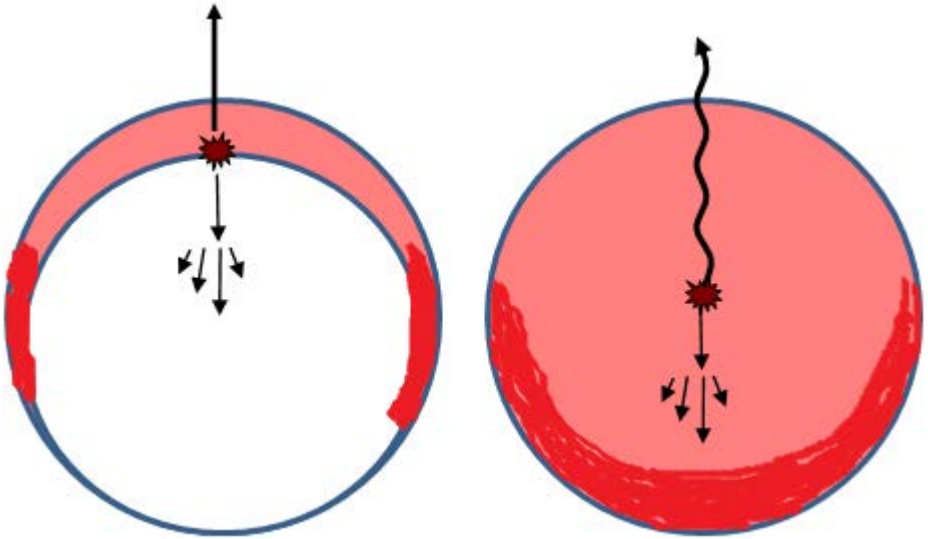
Trigger on High-p_T Photon+Recoil Jet with p_T threshold cut for measuring modified fragmentation function of Jet



Biases in Jet-Like Correlation Measurements

High-p_T π^0-Triggered Correlations for measuring jets

High-p_T Photon-Triggered Correlations for measuring jet modification of unbiased trigger

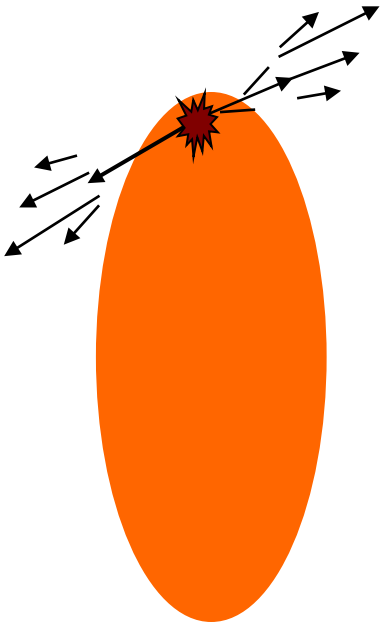


At high z_T, not much energy loss, i.e. I_{AA} is just the fraction of recoil jets that made it out without energy loss.

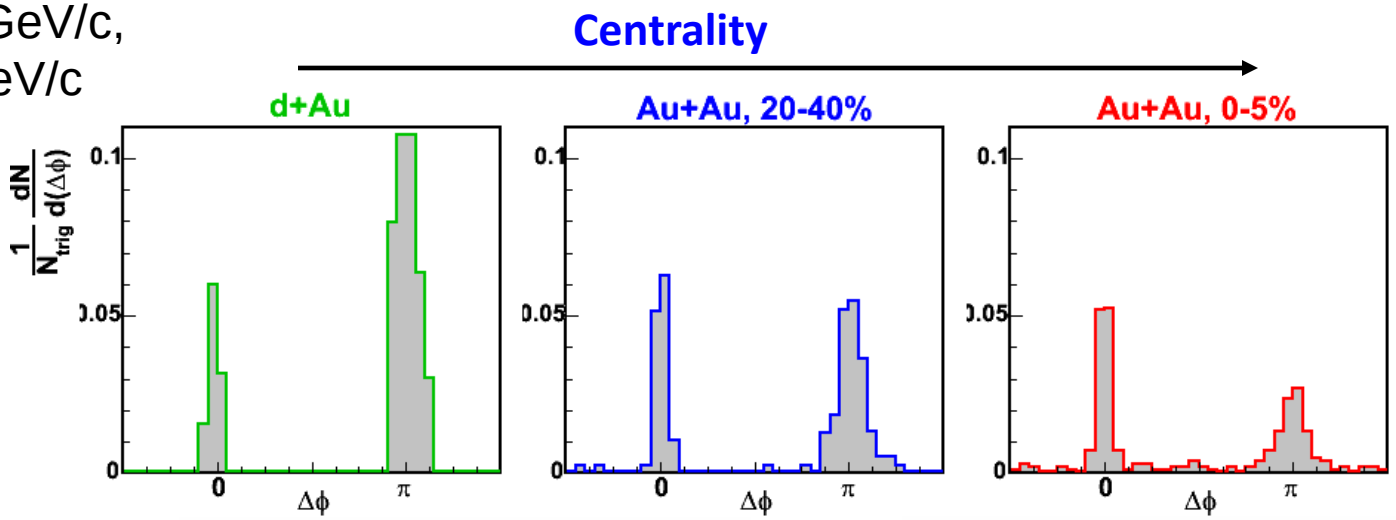
Di-hadron correlations

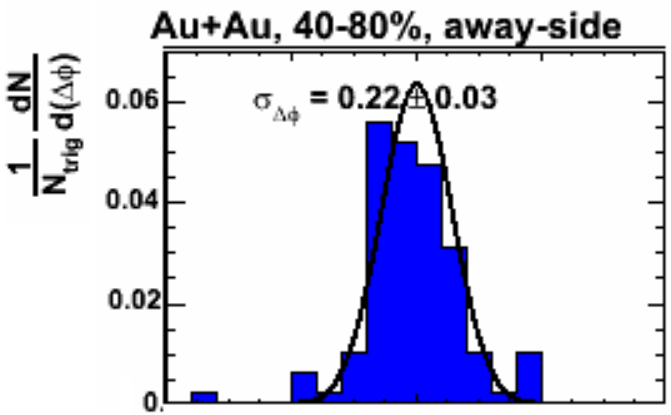
High-pT hadrons on away side are surviving hadrons which don't show modification due to medium interaction

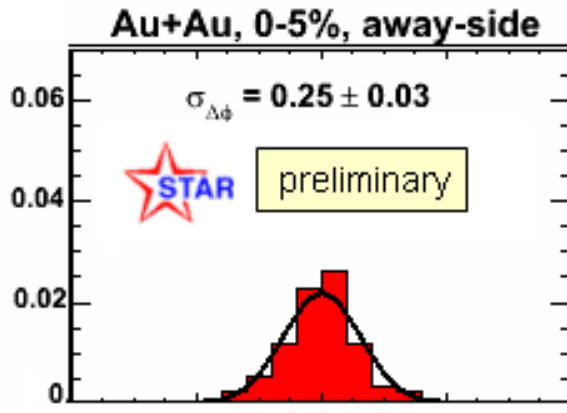
$8 < p_{T,trig} < 15$ GeV/c,
$p_{T,assoc} > 6$ GeV/c



just tangential emission?



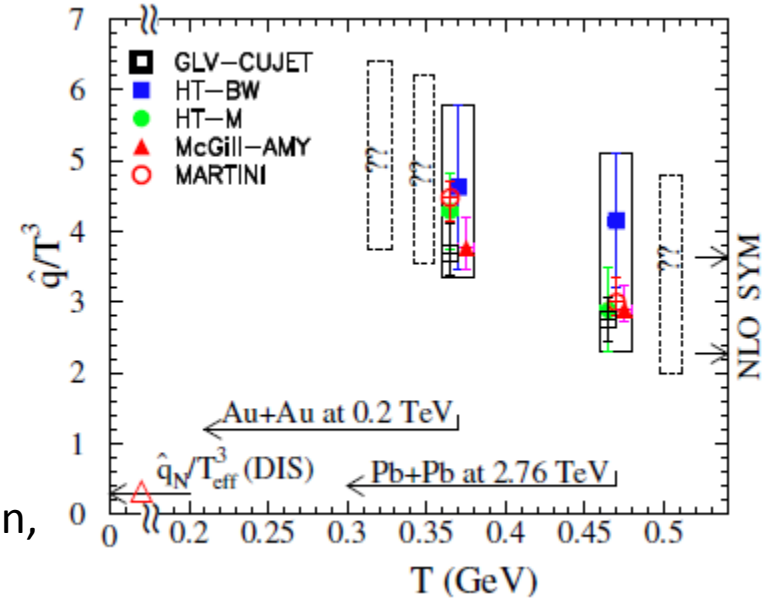




R_{AA} vs models – Extracting the "jet" Transport Coefficient

$$\hat{q} = \frac{d(p_T)^2}{dt}$$

$$\frac{\hat{q}}{T^3} \propto \frac{1}{\eta/s}$$



Burke et al, JET Collaboration, arXiv:1312.5003

Several **pQCD** formalisms/approximations for parton energy loss exist
Allows to determine medium properties, parton transport coefficient for a 10 GeV parton at the center of Au+Au collision

RHIC:

$\hat{q} = 1.2 \pm 0.3 \ GeV^2/fm$

(T=370 MeV)

$$\frac{\hat{q}}{T^3} = 4.6 \pm 1.2$$

LHC:

$\hat{q} = 1.9 \pm 0.7 \ GeV^2/fm$

(T=470 MeV)

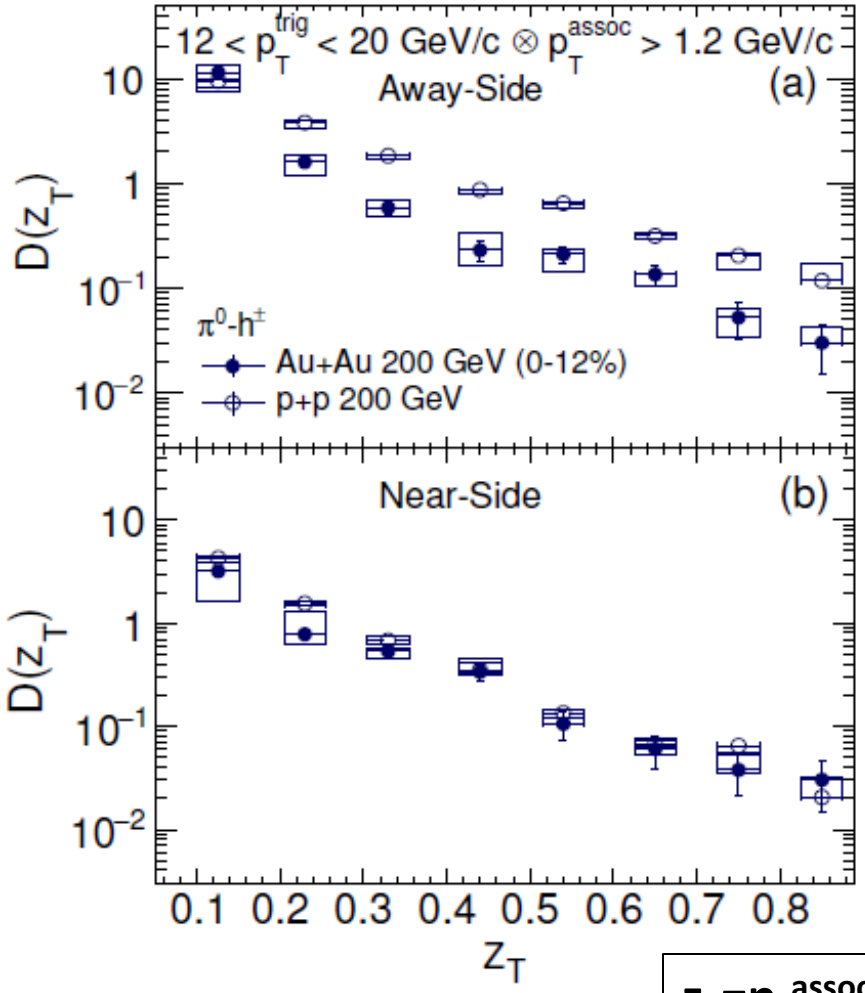
$$\frac{\hat{q}}{T^3} = 3.7 \pm 1.4$$

Cold Nuclear Matter:

$$\hat{q}_N \approx 0.02 \ GeV^2/fm$$

Charged-Particle Yields Associated with π^0 Triggers (STAR)

p_T^{trig} = 12-20 GeV/c, $p_T^{assoc} \geq 1.2$ GeV/c



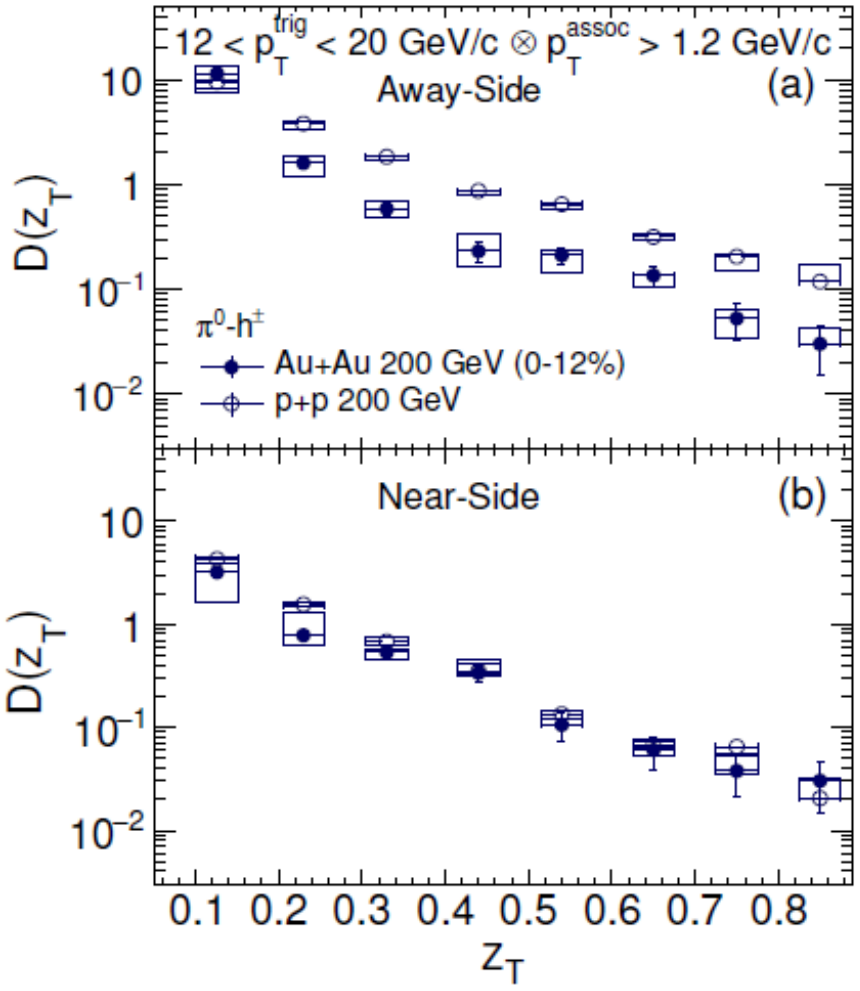
On the away side, yields in central Au+Au suppressed relative to yields in p+p

On the near side, yields in central Au+Au consistent with yields in p+p

$z_T = p_T^{assoc}/p_T^{trig}$

Hadron Trigger Energy vs. Jet Energy

STAR



We can estimate the fraction of the parton energy carried by the π^0 trigger by summing the additional energy carried by the associated charged particles on the near side

Integrating z_T times a function fit to the near-side $D(z_T)$ distribution results in ***Int***$=0.17 \pm 0.04$. This means that $1/(1+\textbf{\textit{Int}})=p_T^{trig}/(p_T^{trig}+\Sigma p_T^{assoc})=85\pm3\%$

Since the associated particles are charged particles only, we repeat analysis in PYTHIA, find agreement for charged-particle result, then extend it to include neutral energy: $p_T^{trig}/p_T^{jet}=80\pm5\%$

Away-side yields in p+p collisions as a function of "true" z_T

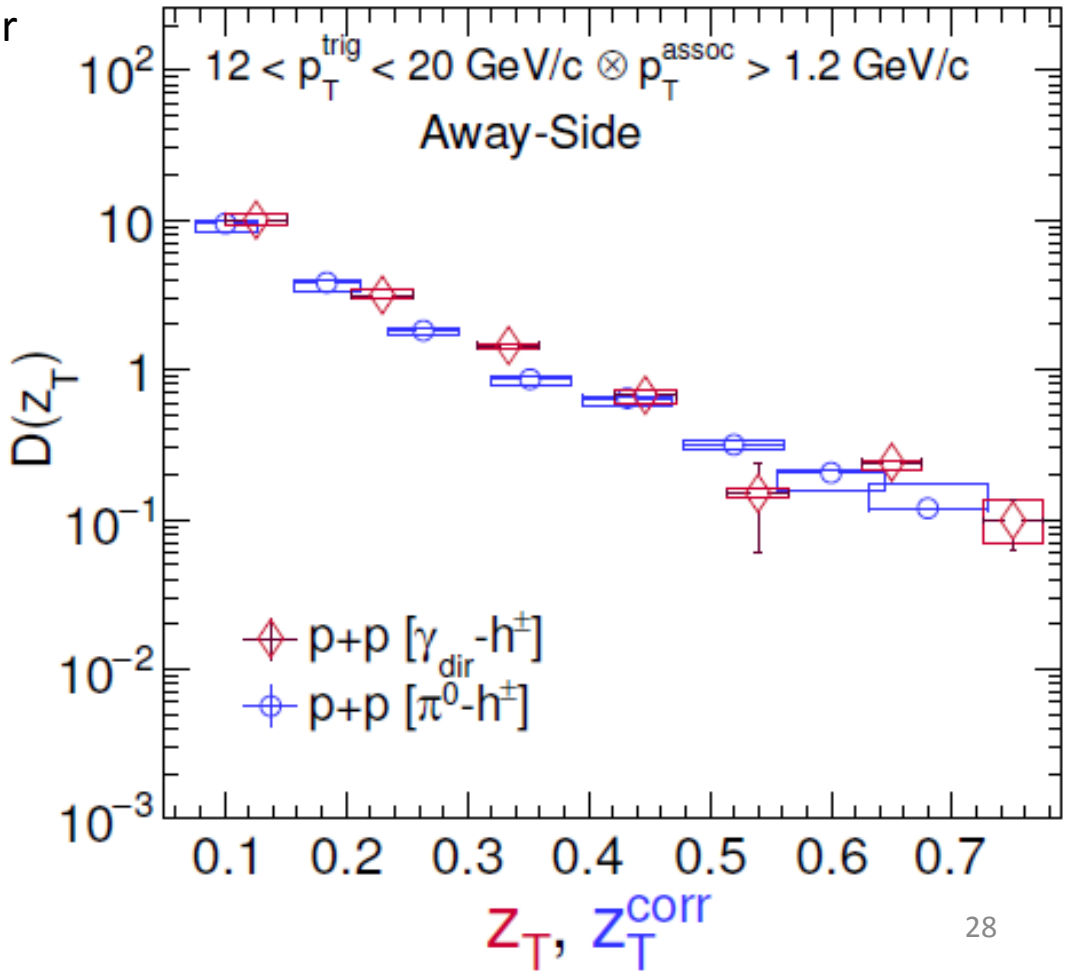
Near-side $D(z_T)$ measurement for π^0 triggers supports PYTHIA estimate that π^0 trigger particle carries 80±5% of jet energy for p_T^{trig}=12-20 GeV/c

Now we can "correct for" $p_T^{\pi^0}/p_T^{jet}$=0.8

→$z_T^{corr}=p_T^{assoc}/p_T^{jet}$ for π^0 triggers

and compare away-side yields for π^0 and direct-γ triggers directly

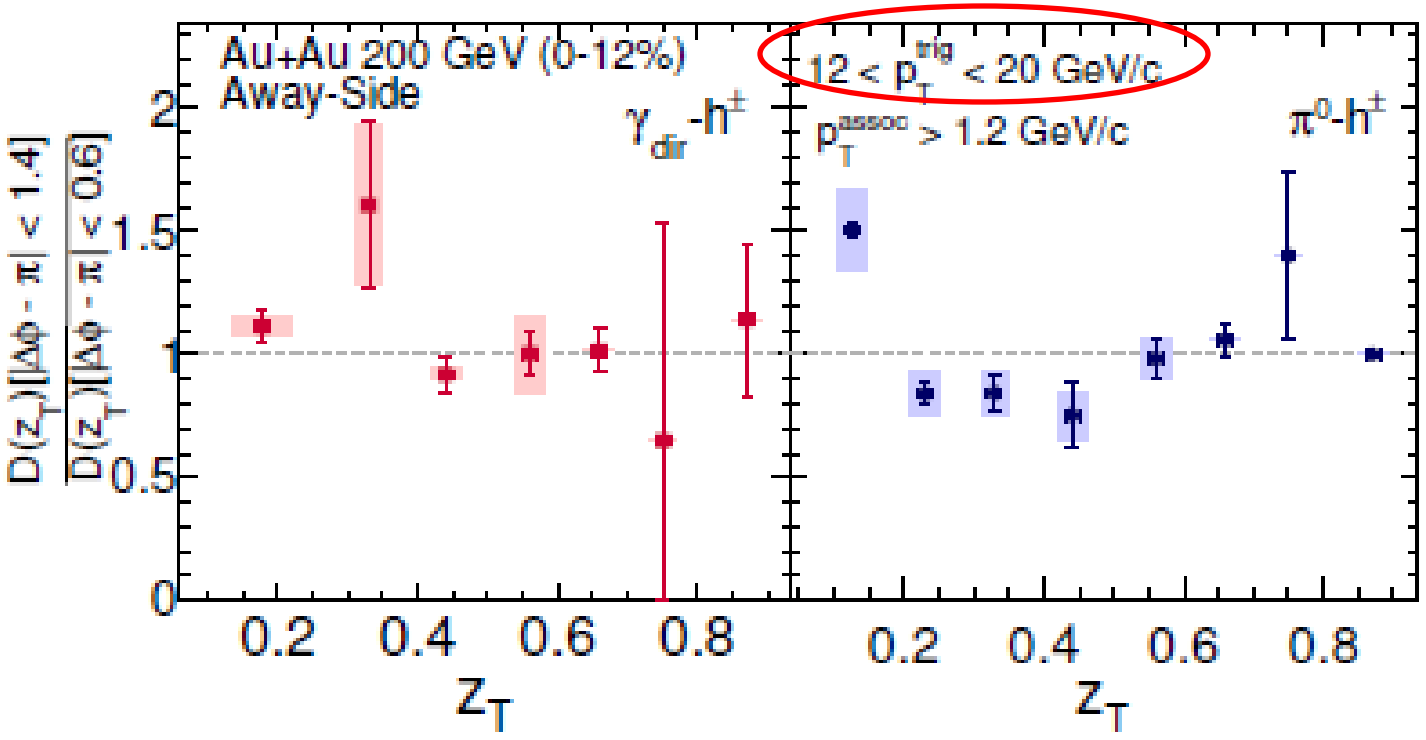
$z_T^{corr}=p_T^{assoc}/p_T^{jet}$



Recovery of Energy at Large Angles?

Compare away-side yields within ±35° vs. ±80°

No significant effect seen, except in lowest z_T bin for π^0 triggers



PHENIX reported effect for z_T<0.4, but **p_T^{trig} = 5-9 GeV/c**

→ p_T^{assoc} < 2 GeV/c (PHENIX, Phys. Rev. Lett. 111, 032301 (2013))