Latest QCD results from PHENIX

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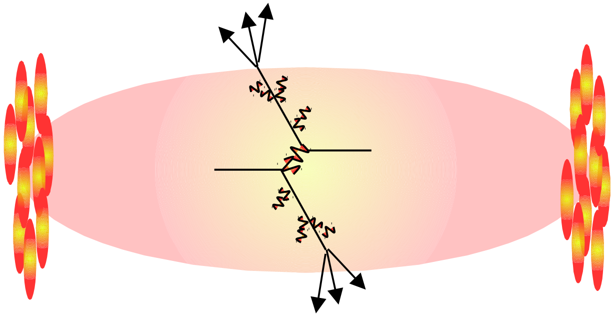
Excited QCD 2012, May 6-12

Probing the medium with high-p_T particles

- The overall goal is to investigate the properties of the hot, dense matter produced in heavy ion collisions
- As hard partonic scattering occurs as the medium is forming, the probes may be modified by medium
- We wish to quantify that modification.



Both jets are subject to interaction with the medium

Our tools

- PHENIX controlled
  - Centrality (system size)
  - Momentum
  - Particle Identification
- Today:
  - Single spectra
  - Triggered Correlations
  - γ (and “Full”) jet reconstruction

- RHIC controlled

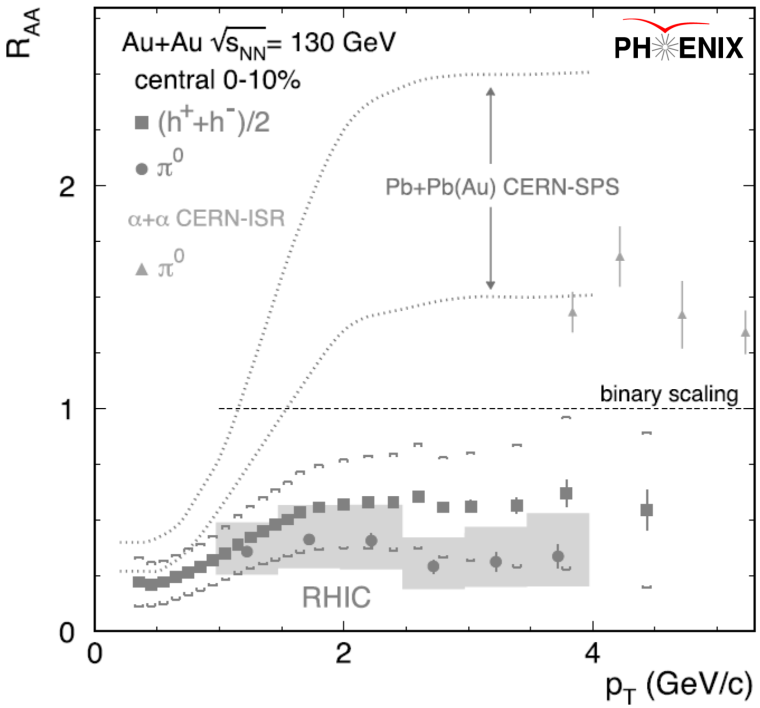
Can turn on and off the hot, dense medium

  - Collision Species
  - Collision Energy

A brief story of high-p_T at RHIC:
Single particle spectra

- Earliest measurements at high-p_T:
  - Large "suppression" observed at high-p_T
  - Interpreted as energy loss in medium - jet quenching
- Difficult to be quantitative:
  - In the level of radiative versus collisional energy loss
  - Is jet quenching a perturbative or non-perturbative process

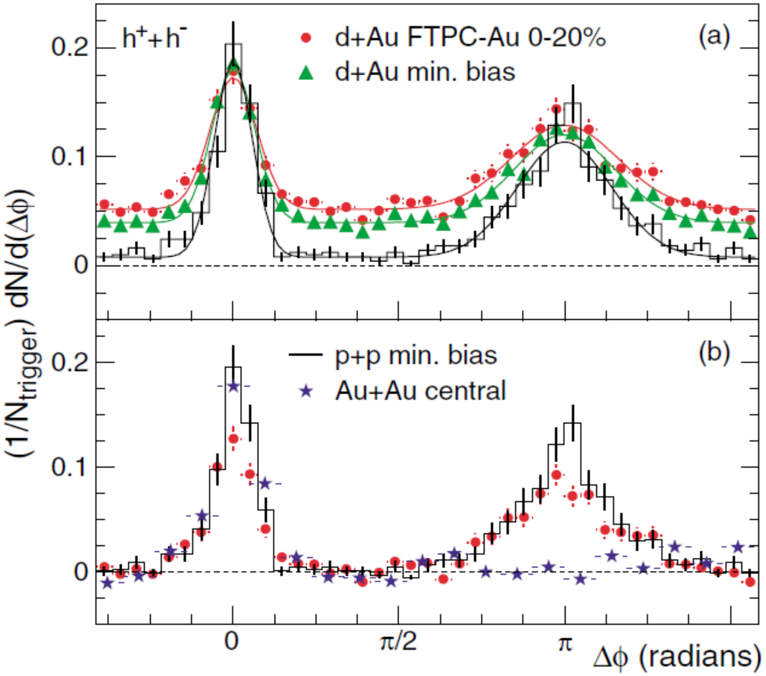
Phys. Rev. Lett. 88, 022301 (2001)



A brief story of high-p_T at RHIC:
Two-particle correlations

- More direct evidence of jet quenching:
  - "disappearance" of backward jet
    - Interpreted as suppression due to parton energy loss
  - "reappearance" at low momenta
    - shape modification on the away side
  - "no quenching" at highest p_T
- Still uncertainties
  - in the energy scale of the jet
  - modifications to the fragmentation functions (expected softening and broadening of the jet)
  - geometrical aspects
    - position of hard scattering in the collision overlap area
    - the path length traversed in medium
    - energy loss by the trigger or near side jet?

STAR: Phys. Rev. Lett. 90, 082302 (2003)
STAR: Phys. Rev. Lett. 91, 072304 (2003)



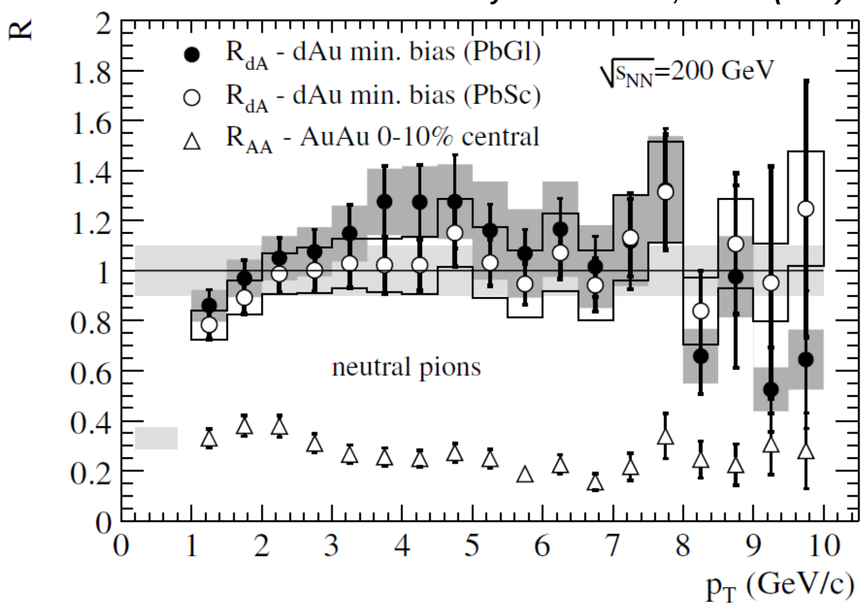
A brief story of high-p_T at RHIC:
Full-jet and γ-jet

- γ-jet: the golden channel for Heavy-ion collisions
  - No trigger/surface bias – opposite side (jet) yield averaged over all path lengths
  - Clean probe: can calibrate energy of the jet
  - Direct measure of the fragmentation function of the jet
  - Any modification of the FF interpreted as parton energy loss in the medium

- Full-jet: a relatively recent probe at RHIC
  - Direct observation of parton-medium interaction and medium response
  - R_{AA}^{jet} → parton medium induced energy loss
  - Di-jet correlations → jet broadening

Testing the jet-quenching hypothesis:
d+Au at RHIC

Phys. Rev. Lett. 91, 072303 (2001)



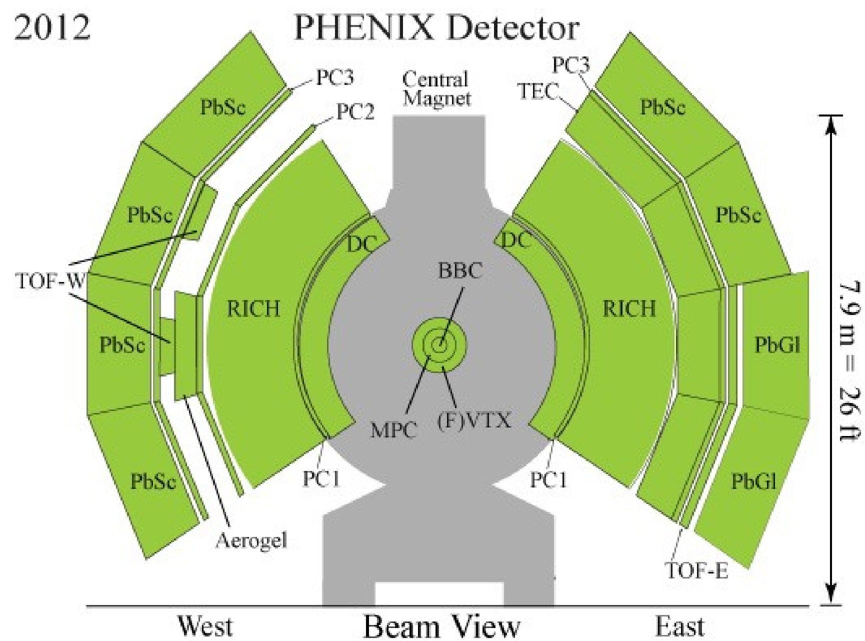
- d+Au versus Au+Au
  - Control experiment
  - “cold” versus “hot” nuclear matter
- Result:
  - Suppression in Au+Au central events not apparent in d+Au collisions
  - Suppression in Au+Au is a “*final state*” effect

Road map for further detailed studies

- Know:
  - Spectral suppression in Au+Au
  - No suppression in d+Au
  - Away-side jet also modified
    - Dependent on trigger-p_T and/or associate p_T
- Don't know:
  - How, why
    - Radiative, collisional energy loss?
  - Systematic dependencies?
    - Path length
    - Color-charge
    - Collision energy
    - System-size
  - Are our measurement methods biased?
    - Can we remove the bias with new methods?

PHENIX detector
Brief Overview

- Two mid-rapidity spectrometer arms: $|\eta|<0.35$ and $\Delta\phi=\pi/2$
- Main detectors used
  - Drift Chamber (DC), Pad Chamber (1&3), Cherenkov Detector(RICH)
    - Momentum measurement for charge particles, electron Id
  - EMCal (Pb-glass & Pb-scintillator)
    - Energy for photons (π^0, η)
  - TOF
    - PID at large momentum
  - VTX, FVTX
    - Upgrades for heavy flavor

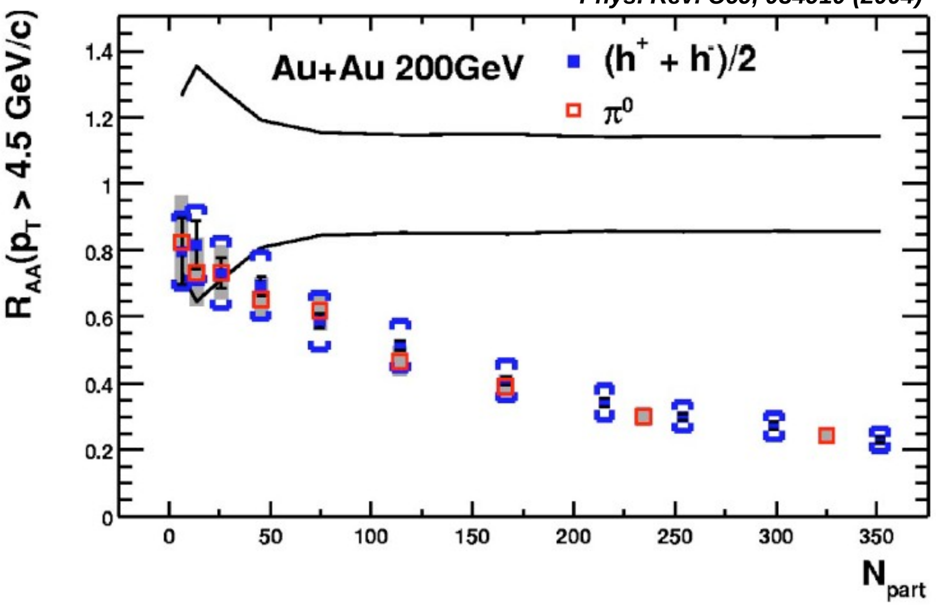


Run 12 central arm configuration

Systematic Studies:
single spectra

- Path-length dependencies
- Simplest:suppression is dependent on the number of participants, N_{part}
- Similar dependence observed for π^0 and $h^{\pm}$ at high-p_T

Phys. Rev. C69, 034910 (2004)

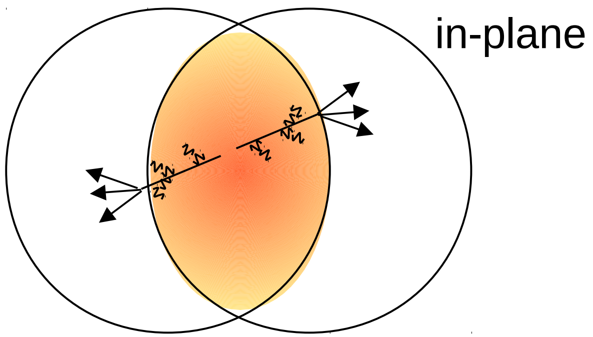


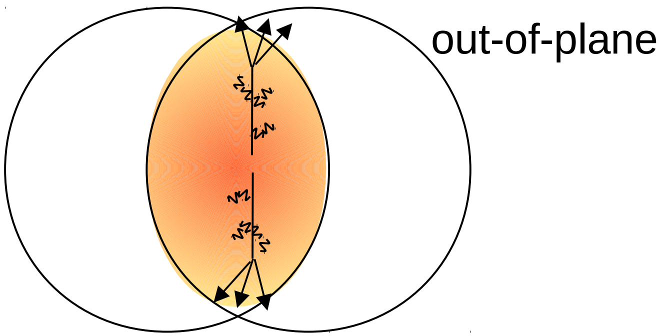
Systematic Studies:
single spectra

- Path-length dependencies

More precision:

- Currently observed
  - Average suppression
  - Integrated over the whole medium
- Separate in-plane versus out-of-plane
  - Controlled probe of energy loss due to medium



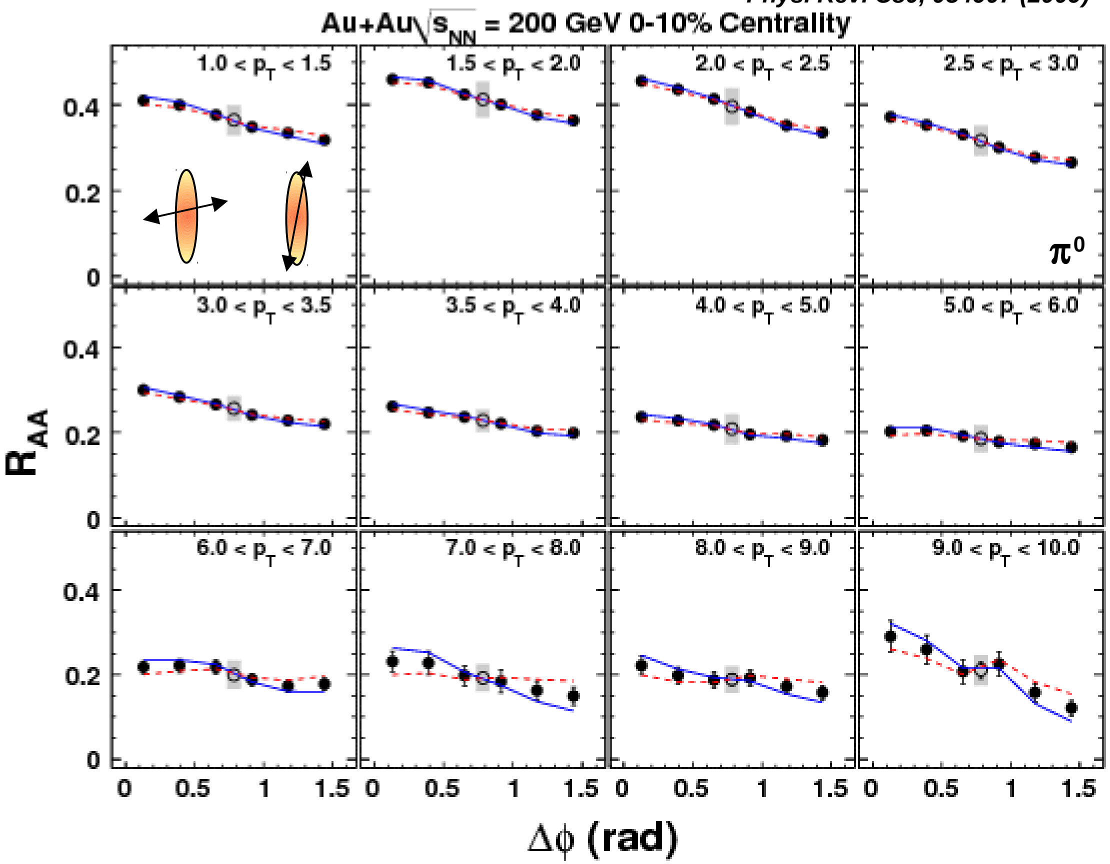


Systematic Studies

single spectra

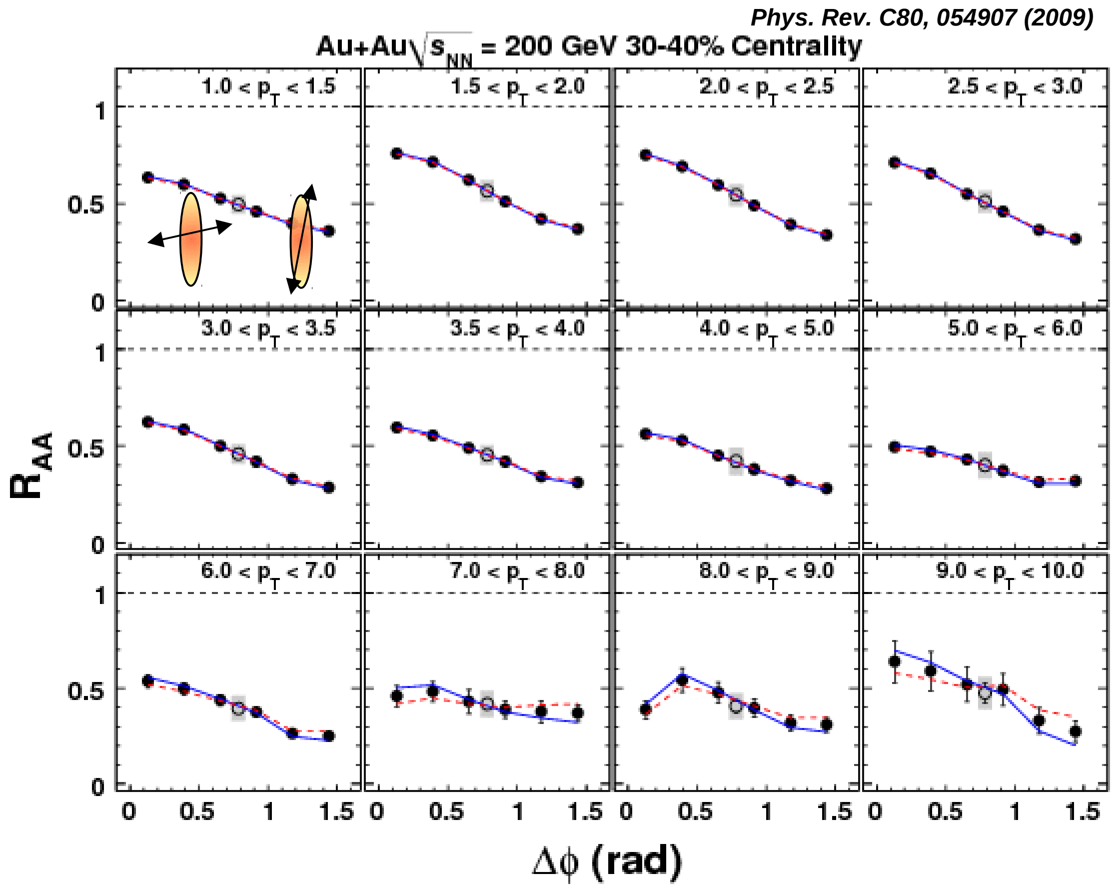
- Path-length dependencies
- In- versus out-of-plane dependence observed in central

Phys. Rev. C80, 054907 (2009)



Systematic Studies:
single spectra

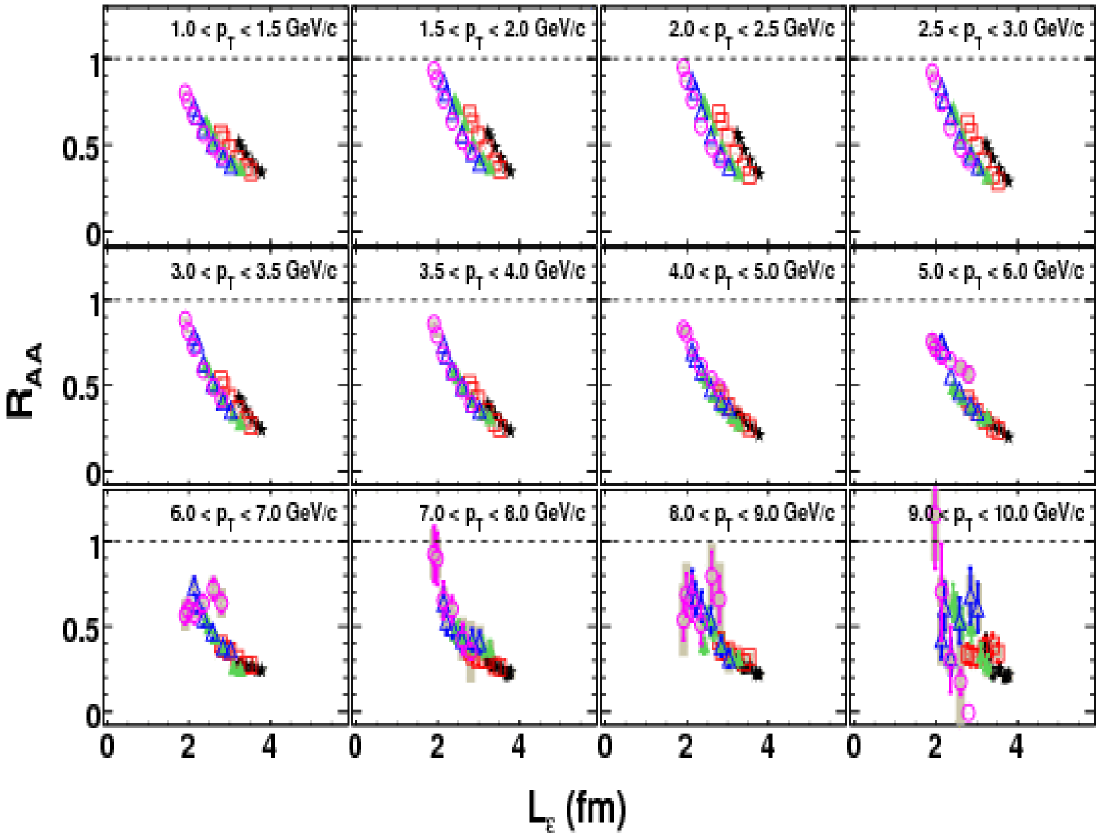
- Path-length dependencies
- In- versus out-of-plane dependence observed in central and mid-central



Systematic Studies:
single spectra

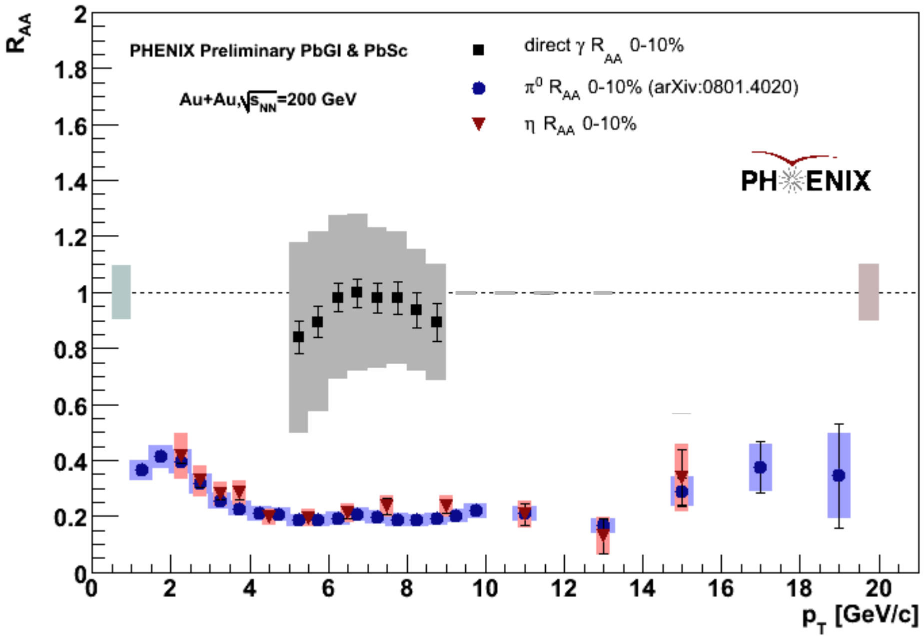
Phys. Rev. C80, 054907 (2009)

- Path-length dependencies
- In- versus out-of-plane dependence observed in central and mid-central
- Suppression strongly correlated to the path length, not just system size (Npart)
  - Becomes more sharply defined with more sophisticated "path length"



Systematic Studies:
direct-γ spectra

- Question:
  - Is this really a suppression?
- Solution:
  - Measure direct-γ, which do not couple to the medium
- Answer:
  - Direct photons are not suppressed – scale with N_{coll} (circa 2005)



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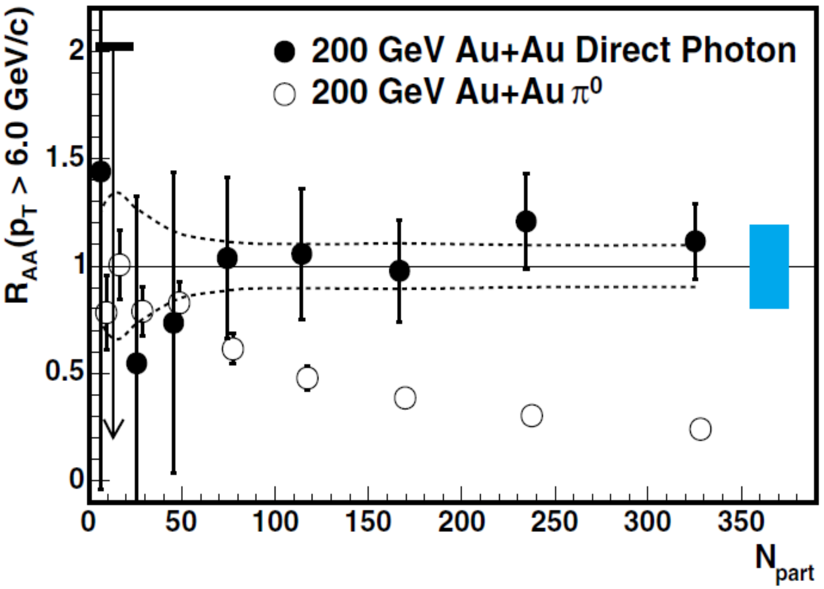
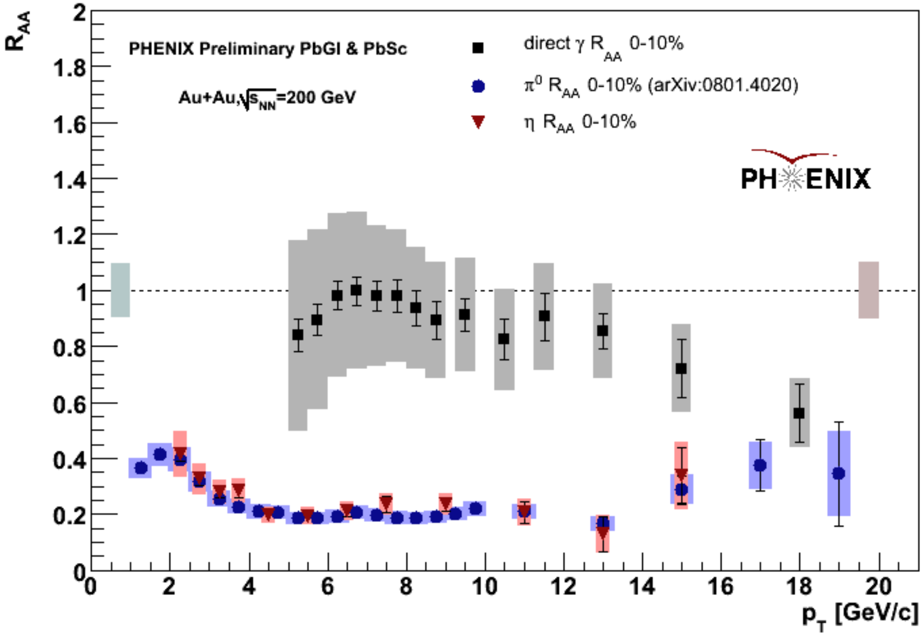


Systematic Studies:
direct-γ spectra

- Question:
  - Is this really a suppression?
- Answer:
  - Direct photons are not suppressed – scale with N_{coll} (circa 2005)
- Updated (circa 2011):
  - Direct photons do not scale with N_{coll} at very high-p_T



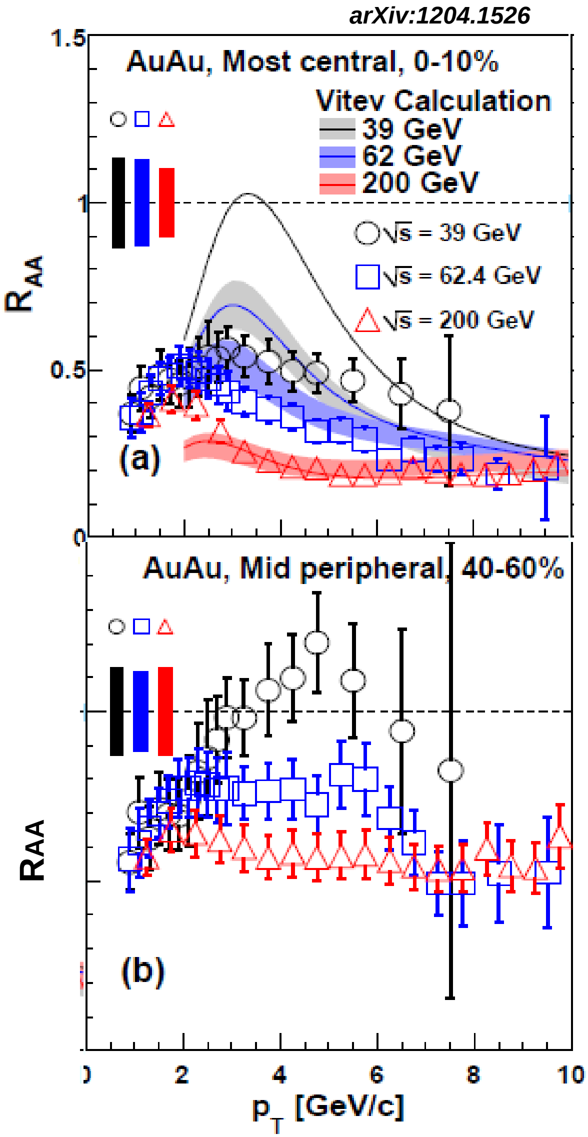
Systematic Studies:
energy scan

"High" energy scan

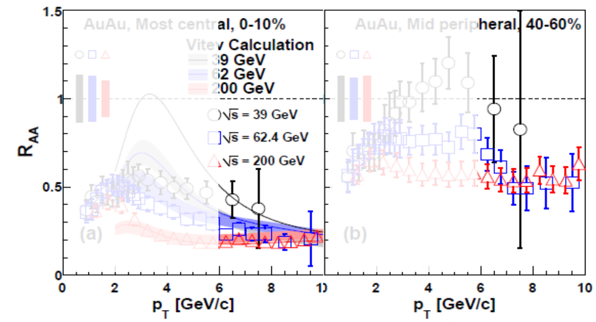
- Probe energy dependence of R_{AA}
  - $\sqrt{s_{NN}}$=200, 62.4 and 39 GeV
    - "suppression" observed
  - $\sqrt{s_{NN}}$=39 GeV
    - "enhancement" peripheral

("Low" energy scan

- $\sqrt{s_{NN}}$<20 GeV
- Focus on studying the QCD phase diagram
- outside the scope of this talk.)

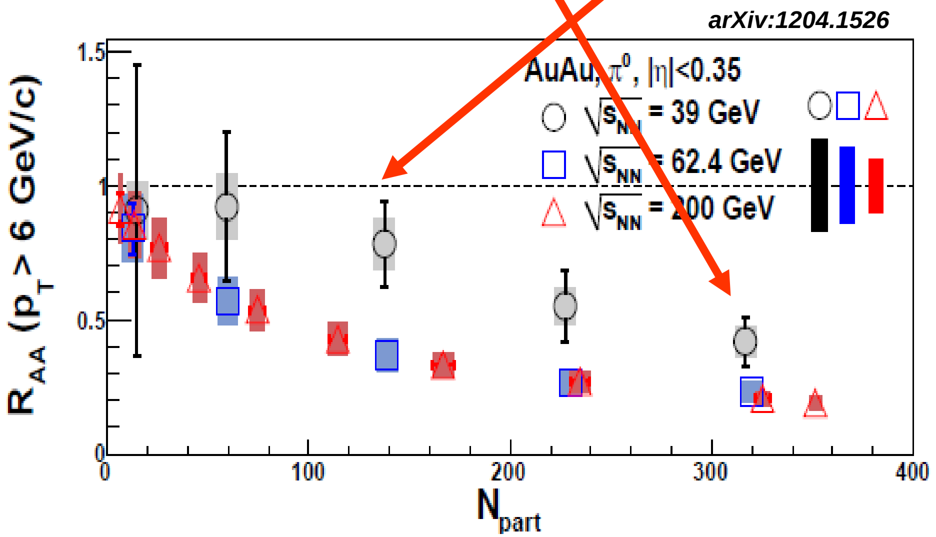


Systematic Studies:
energy scan



"High" energy scan

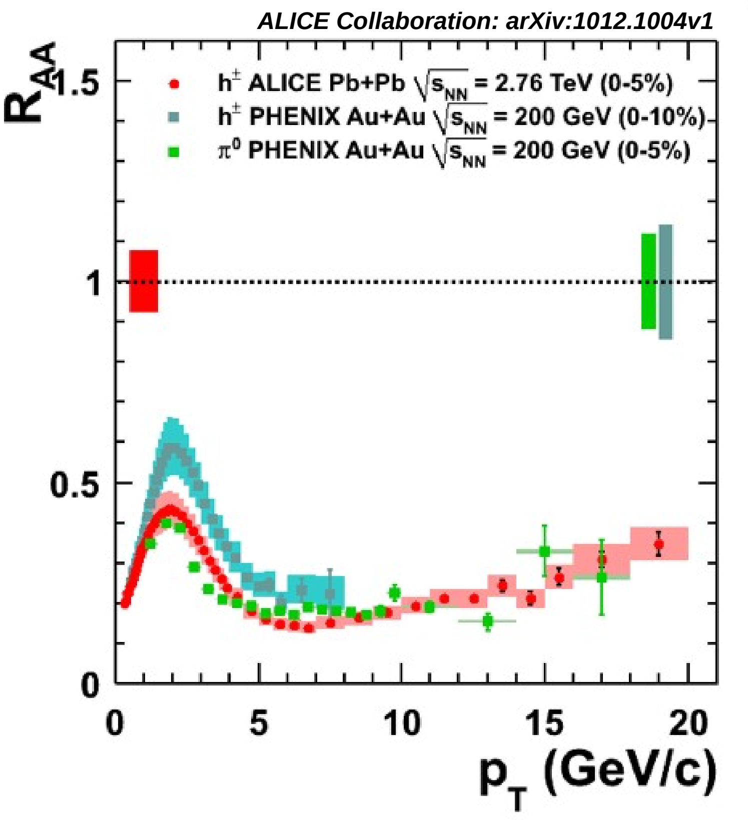
- Probe energy dependence of R_{AA}
  - $\sqrt{s_{NN}}$=200, 62.4 and 39 GeV
    - "suppression" observed
- Path length dependence observed, and similar for energies > 39 GeV



Systematic Studies:
energy scan

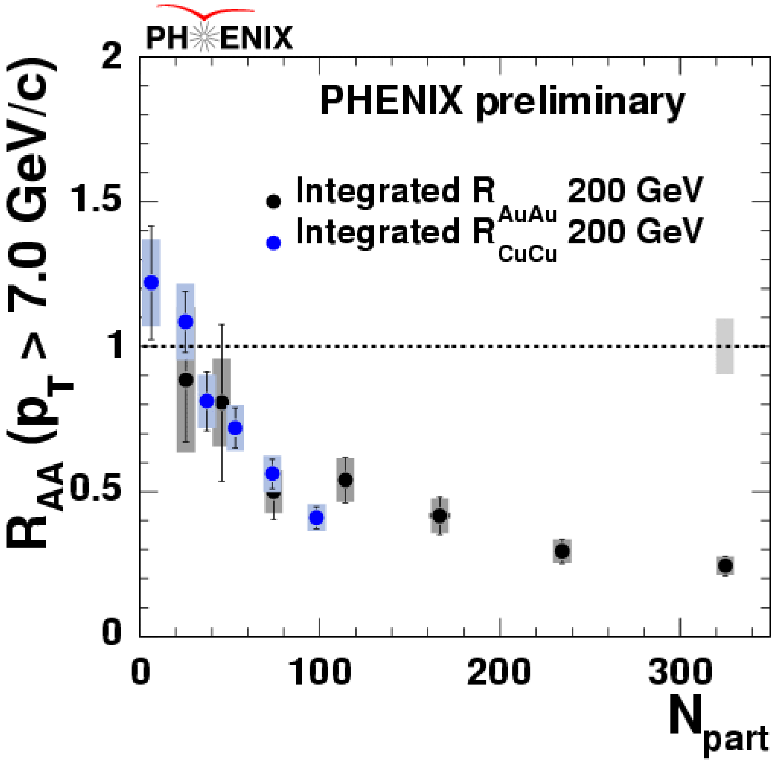
Ultimate energy scan:

- Comparison to LHC
  - Same old same old
  - nothing changes? Why?



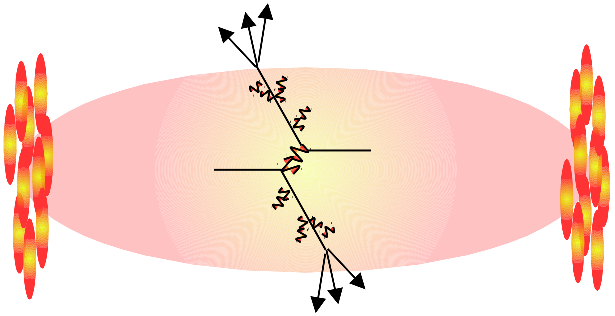
Systematic Studies:
species scan

- We have seen d+Au
  - What about other smaller systems?
- Same old same old
  - R_{AA} for π^0 scale with N_{part}
  - Approximate path length dependence holds

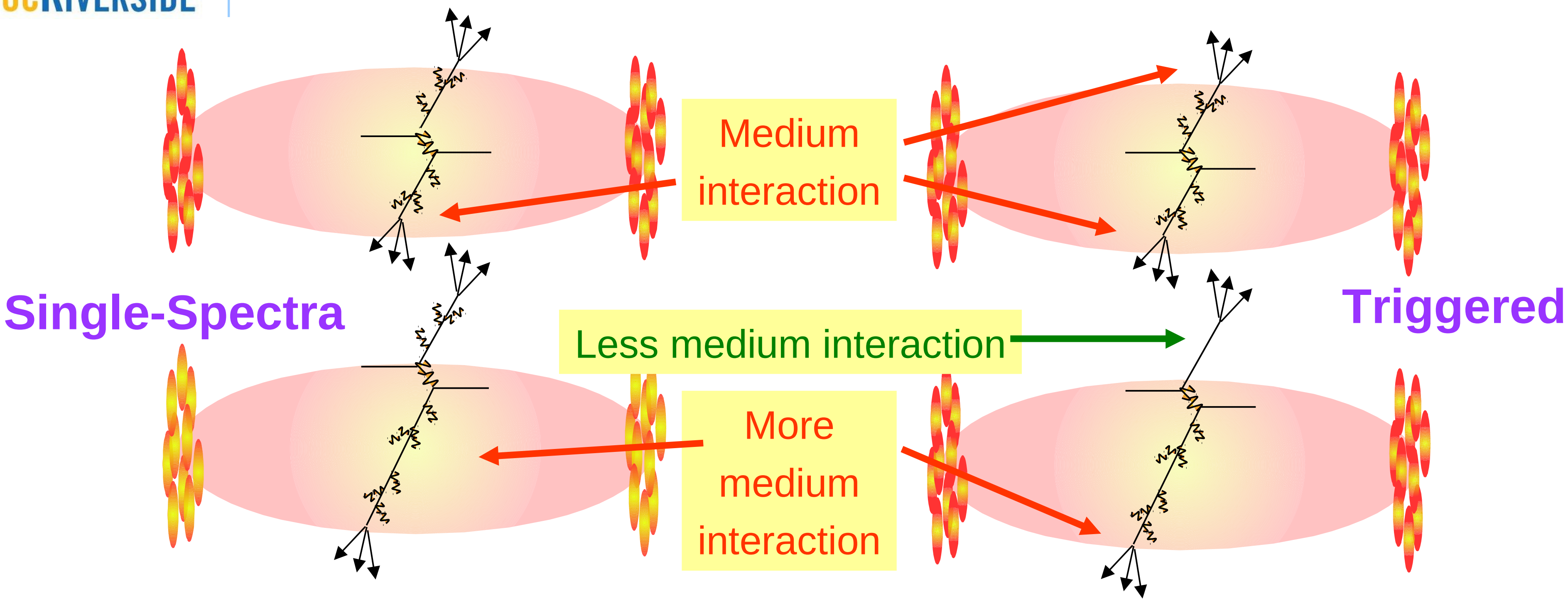


Triggered correlations

- Advantage:
  - Jet like
  - Can tune trigger and associates to probe different kinematic regions
- Disadvantage
  - Need large statistics
  - Need wide coverage
- Advantage ***AND*** Disadvantage
  - Surface bias

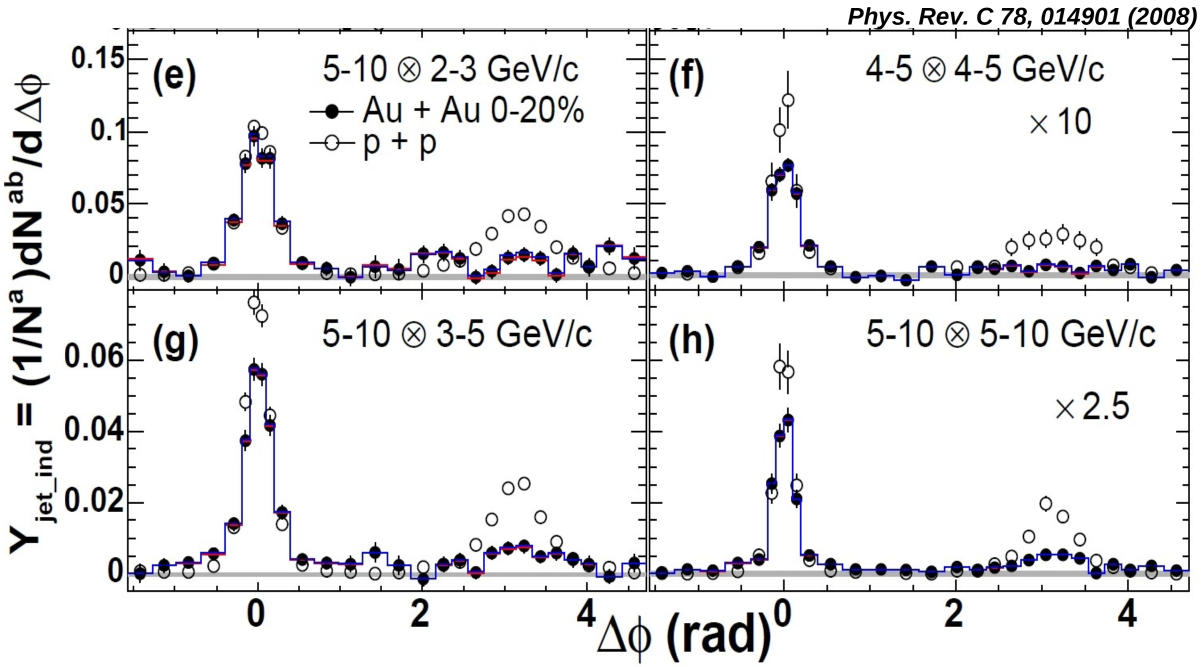


Surface bias single spectra versus h-h correlations



- No trigger / no surface bias
  - Probe full medium
  - Path length is not fixed
- Triggered / have surface bias
  - Owing to preferred interactions from edge of medium
  - Associate path length “fixed”

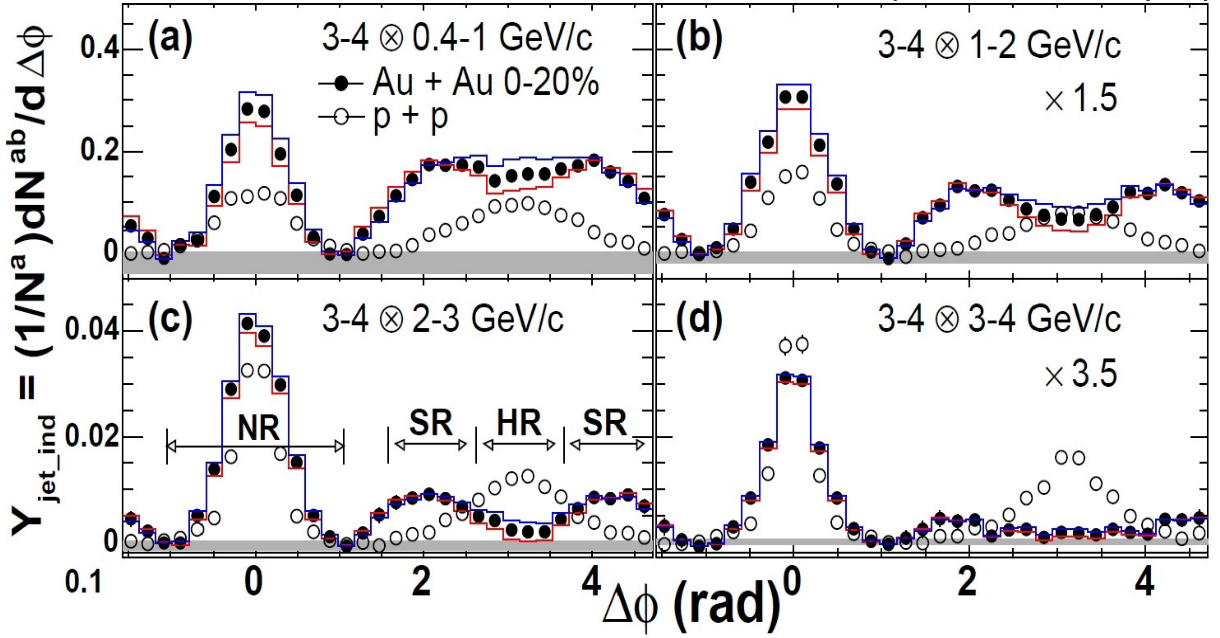
Systematic Studies:
triggered correlations



- High-p_T – high-p_T correlation
  - Away-side suppression relative to p+p collisions

Systematic Studies:
triggered correlations

Phys. Rev. C 78, 014901 (2008)

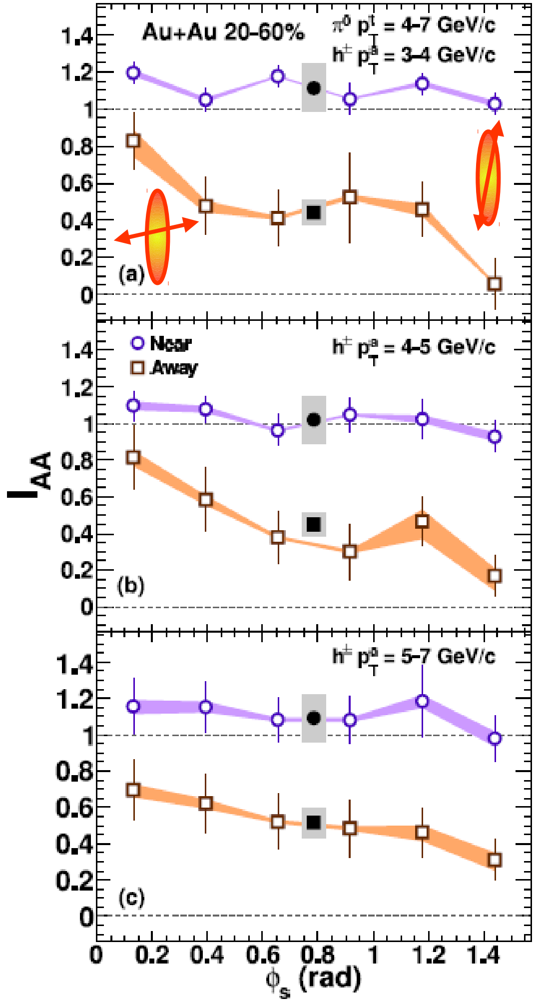


- High-p_T – low-p_T correlation
  - Away-side shape modification relative to p+p collisions

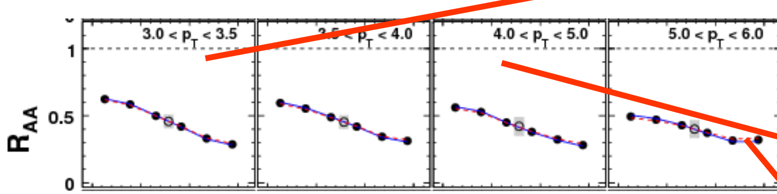
Systematic Studies:
triggered correlations

- Form a nuclear modification factor, like R_{AA} (now a conditional $R_{AA} \rightarrow I_{AA}$)
  - Associates:
    - Clear path length dependence
    - p_T dependent
  - Trigger:
    - No dependence – surface bias?
- How does this compare to R_{AA}?

arXiv:1010.1521



Systematic Studies:
triggered correlations



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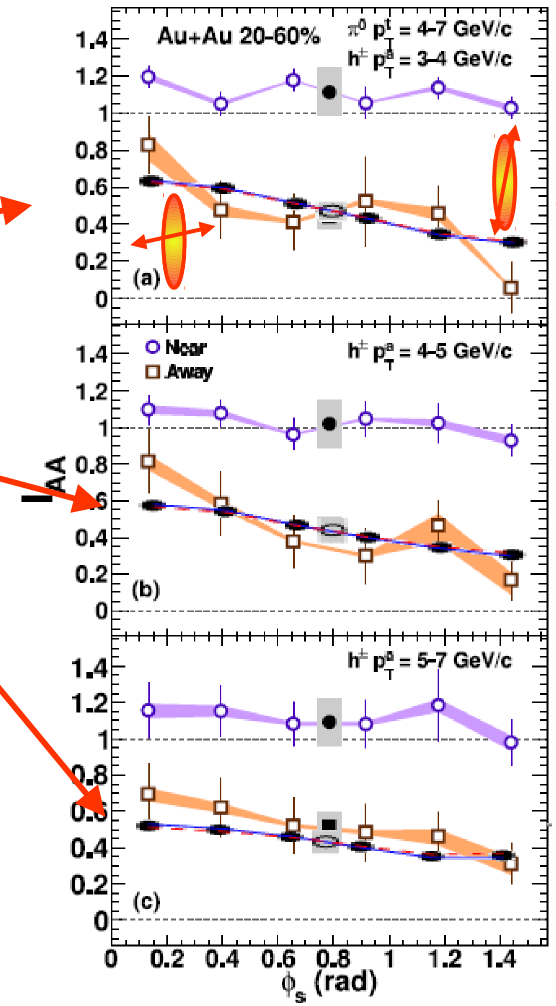
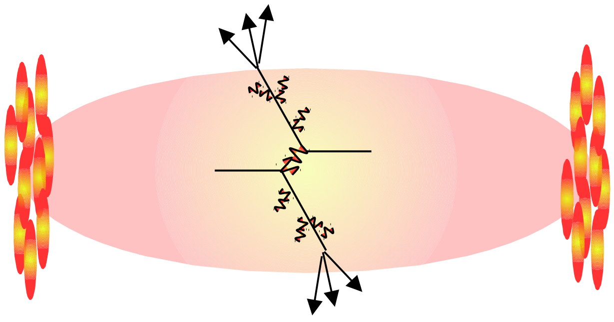


- How does this compare to R_{AA}?
  - Same (?)
  - But we are sampling ***more*** medium with the conditional I_{AA}?

- We should try something else …

γ-jet reconstruction

- γ-jet
  - No γ-medium interaction
- Two advantages:
  - No trigger surface bias
  - Energy calibration of associate-jet
- With no surface bias:
  - Expect a ***smaller*** modification to away-side
    - Smaller average path length as triggers may come from any point in the medium

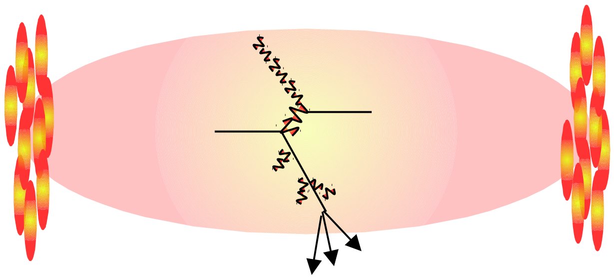


Hadron-triggered correlations:

Both jet subject to interaction with the medium

Surface bias probable (trigger jet must emerge)

Associated path length "fixed"



Photon-triggered correlations:

Only hadronic jet subject to interaction with the medium

No surface bias

Associated path length not fixed

γ-jet reconstruction

- γ-jet
  - No γ-medium interaction
- Two advantages:
  - No trigger surface bias
  - Energy calibration of associate-jet
- With no surface bias:
  - Expect a ***smaller*** modification to away-side
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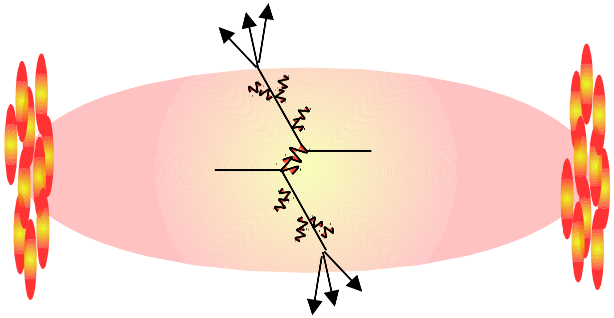

Hadron-triggered correlations:
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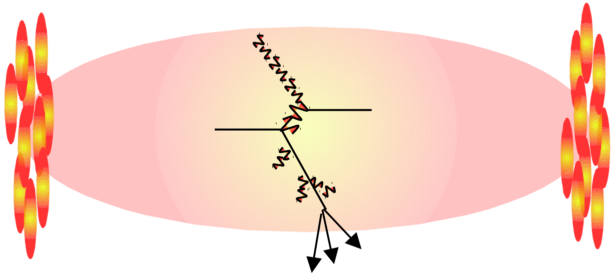
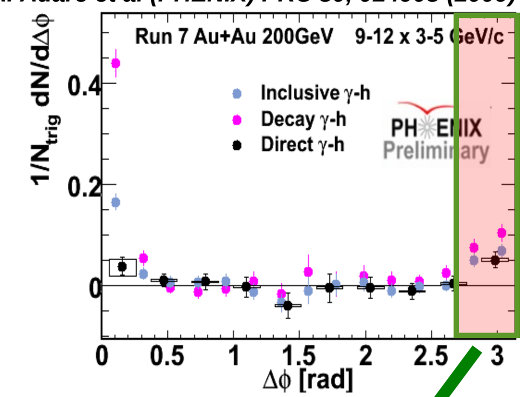


Photon-triggered correlations:
Only hadronic jet subject to interaction with the medium
No surface bias
Associated path length not fixed

Hadronic jet FF in Au+Au

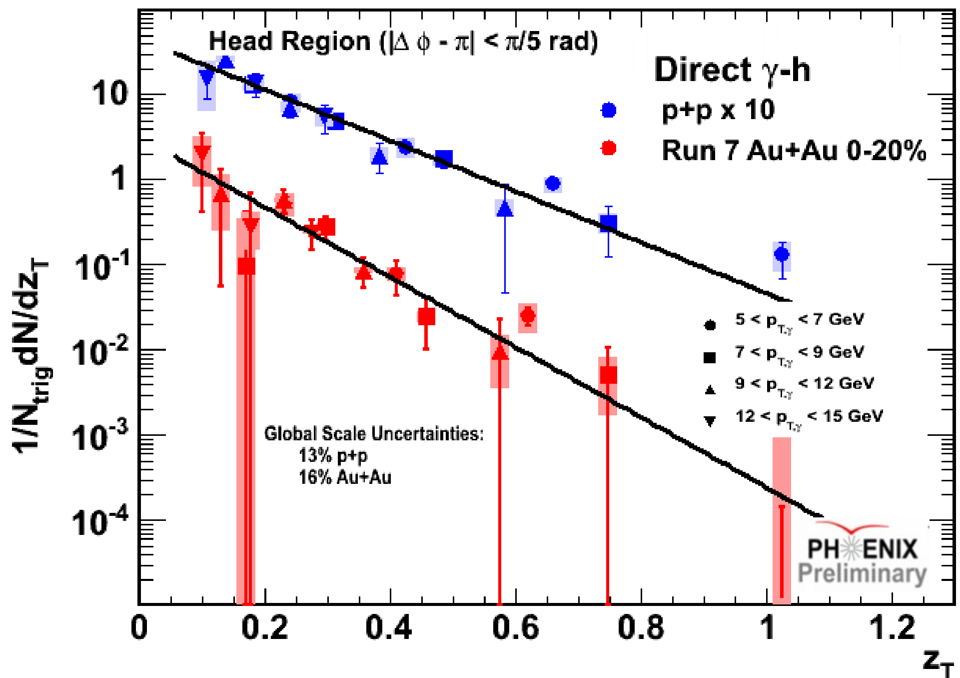
A. Adare et al (PHENIX) PRC 80, 024908 (2009)



- Calibrated probe

$$p_T^{\gamma} \approx p_T^{jet}$$

- $D_{AA}(z_T)$ and I_{AA} extracted from the "head" region on the away side of the γ+hadron correlation
- z_T scaling in Au+Au
- FF modification in AuAu

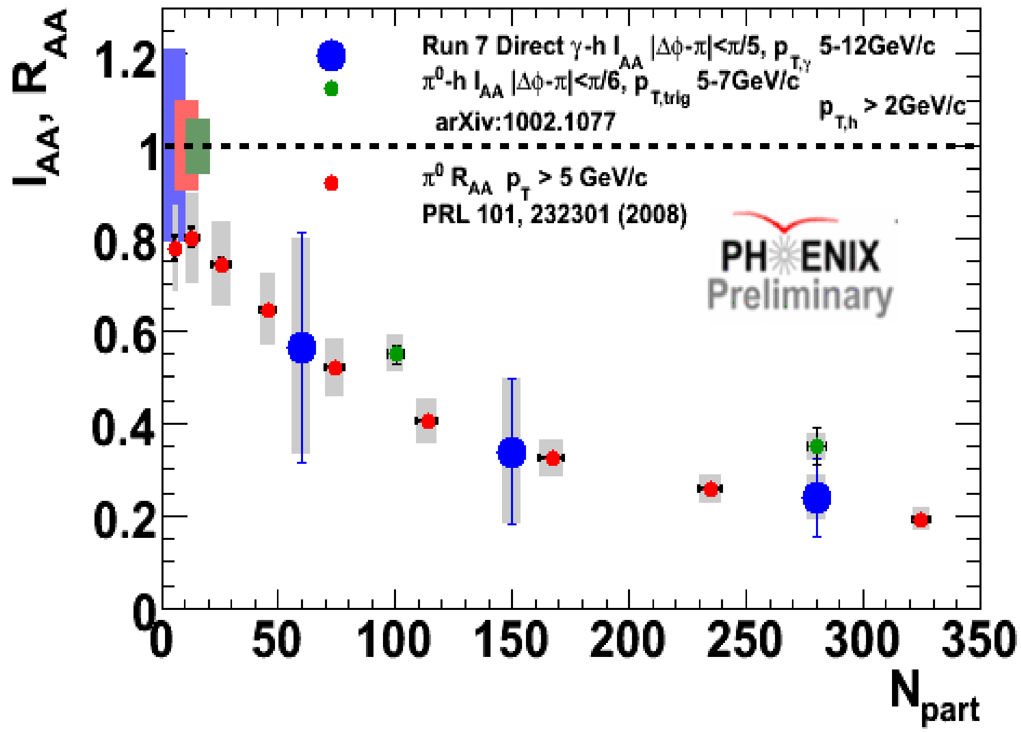


- Y-axis $D_q(z_T) = \frac{1}{N_{evt}} \frac{dN(z_T)}{dz_T}$
- X-axis $z_T = \frac{p_T^h}{p_T^{\gamma}}$

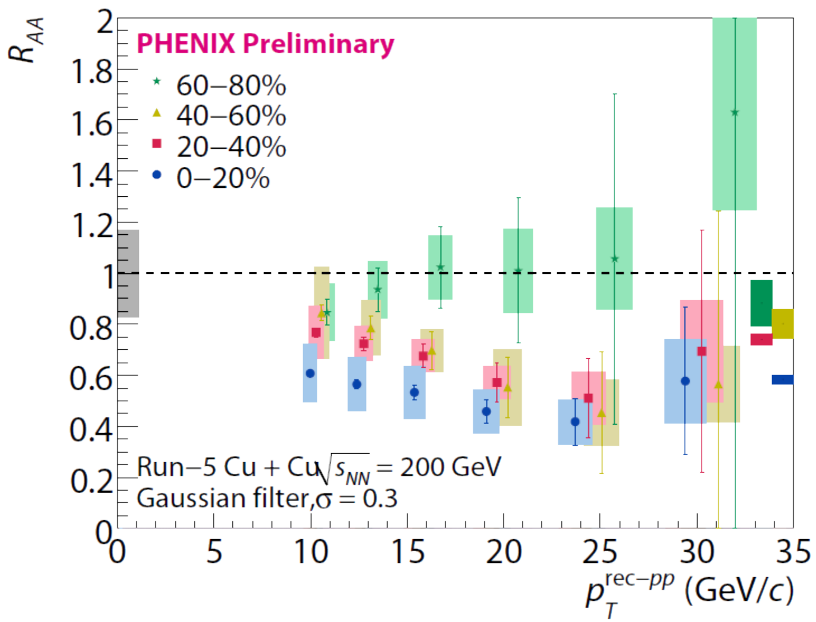
Medium modification of hadronic jet

- Centrality dependence of γ-hadron I_{AA}
  - Consistent with π^0-hadron I_{AA}
  - Consistent with $R_{AA}(\pi^0)$

- Same level of suppression
  - Not expected
  - Is there surface bias?
  - Is there a path-length effect?
  - Is there suppression at all?



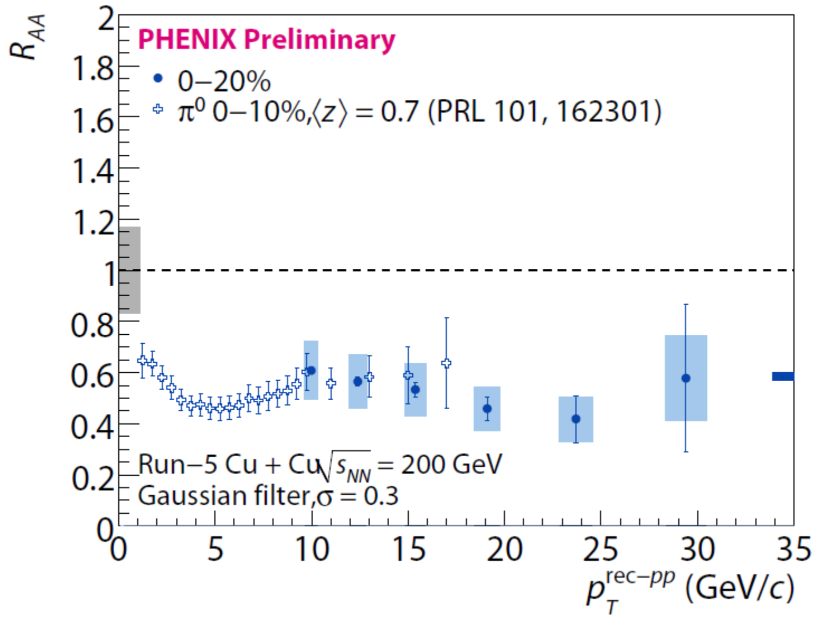
Full jet reconstruction



$$R_{AA} = \frac{(1/N_{evt}) \times (d^2 N_{Cu}/dp_T\, dy)}{\langle T_{AB} \rangle \times d^2 \sigma_{pp}/dp_T\, dy}$$

- Measure the total energy loss of the parton
  - No ambiguity from the FF modification or
  - Energy scale of the jet
- Jet R_{AA} versus p_{T},
  - Energy scale is of the reconstructed *pp* jet
- Modification is observed in central collisions
  - Gradually increasing with centrality
  - Appear unmodified in peripheral

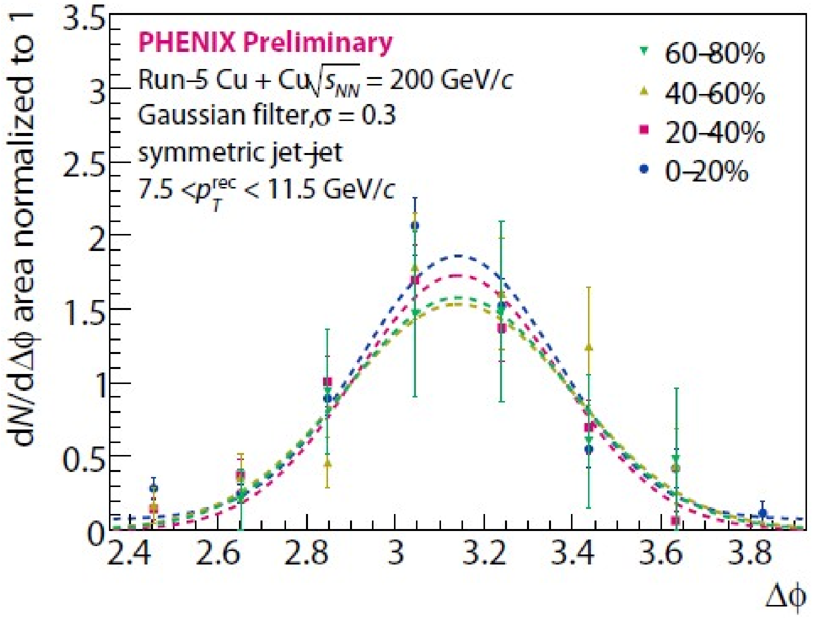
Jet modification



- Strong jet modification is observed for central Cu
- **Same level** as single-π^0 spectra for overlapping p_T range
  - Within energy scale and point systematics
  - Note: R_{AA} single-π^0 spectra at a different energy scale than reconstructed jets
    - π^0 are relatively squashed down
    - (a 10 GeV π^0 came from a >10 GeV jet)

Does the jet broaden in the medium?

- Dijet studies
  - No centrality difference
  - Surviving parton traversing medium has very small transverse k_T broadening?
  - Jets are not deflected more in central than in peripheral



Summary

- PHENIX has made a wide range of high-p_T measurements
  - Single Spectra
  - Triggered Correlations
  - Direct photons
  - Full jet reconstruction

- Have observed a clear path length dependence to the modification of the spectra relative to *pp* interactions
- Path length dependencies are surprisingly similar for
  - Single and triggered distributions
  - Hadron and photon triggered correlations
  - Reconstructed jets
- Needs more systematic studies to complete the parton energy loss picture

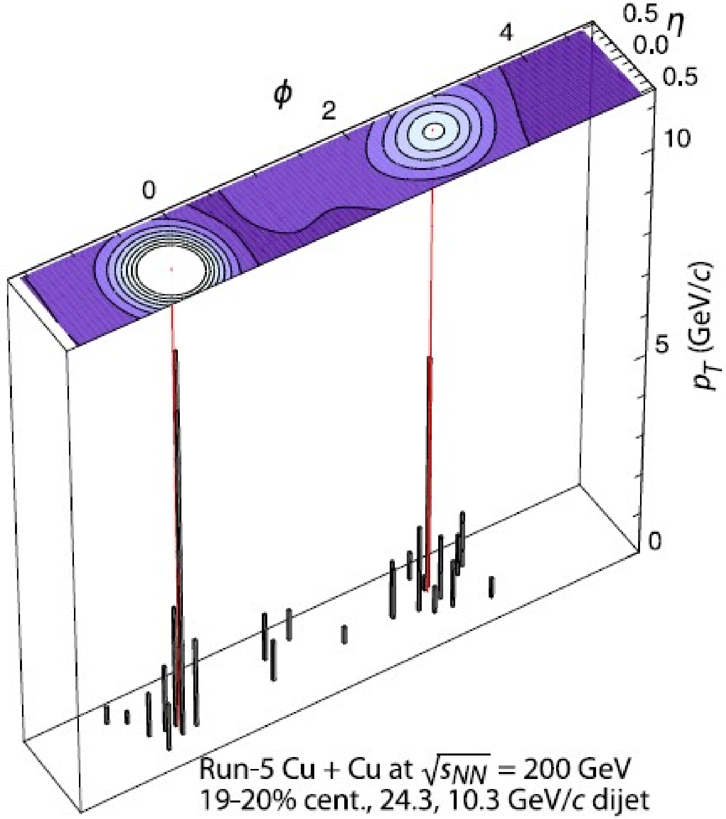
Backup

Full jet reconstruction

- Gaussian filter
  - Cone-like algorithm
    - without sharp angular cut-of
  - Gaussian distributed weights, kernel size σ
    - Enhances the center signal to the periphery → optimizes signal-to-background

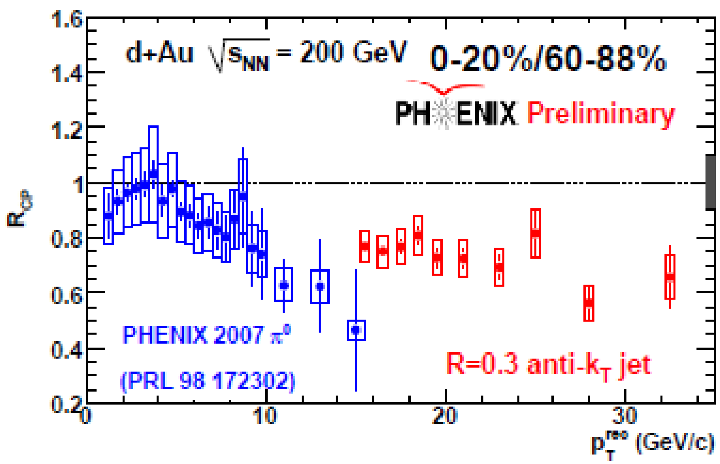
$$\iint_{\mathbb{R}\times S^1} d\eta' d\varphi' p_T(\eta', \varphi') \exp\left[-\frac{(\eta-\eta')^2 + (\varphi-\varphi')^2}{2\sigma^2}\right]$$

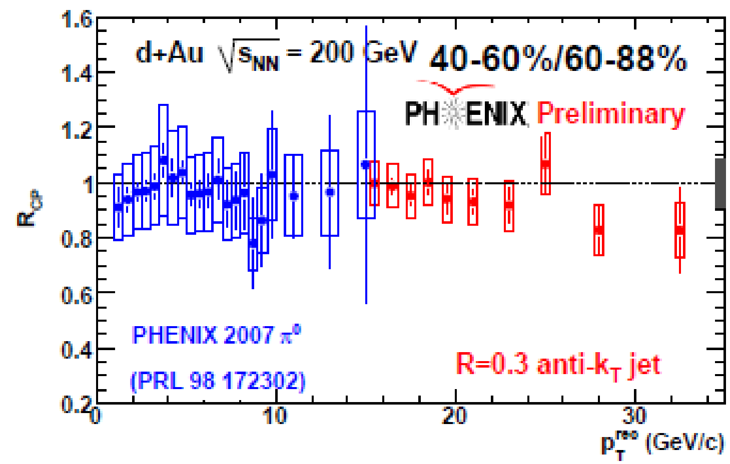
- Background:
  - Fake jet rejection scheme
    - No statistical subtraction
    - Trade-off between reconstruction efficiency and acceptable rejection rate



Lego: final state particle pt
Top contour: filter output
Red lines: reconstructed jets

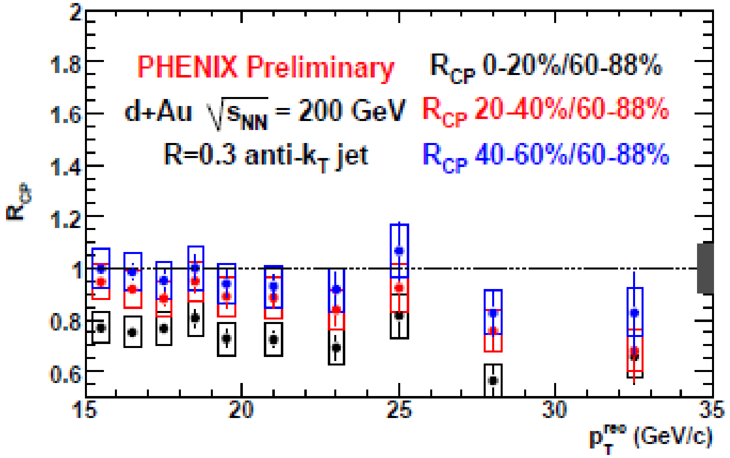
Jets in d+Au at 200 GeV

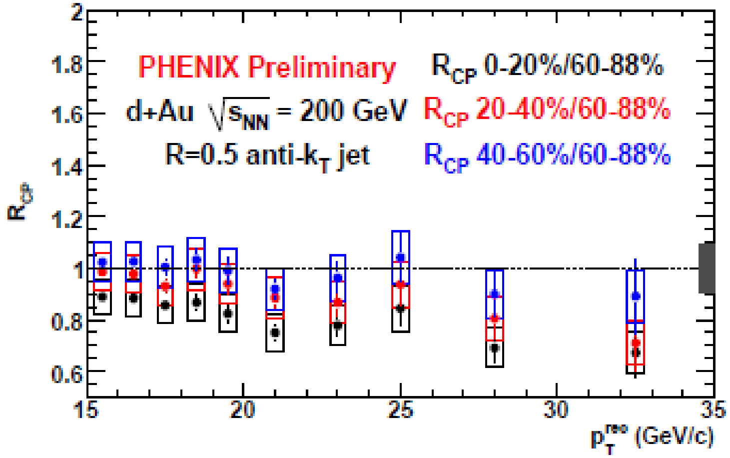




- Jet R_{cp} versus p_T
  - Energy scale is of the reconstructed *pp* jet
- Suppression is observed in central collisions
  - Gradually increasing with centrality
  - Appear unmodified in peripheral
  - Consistent with single particle pi0
  - Cold nuclear matter energy loss?

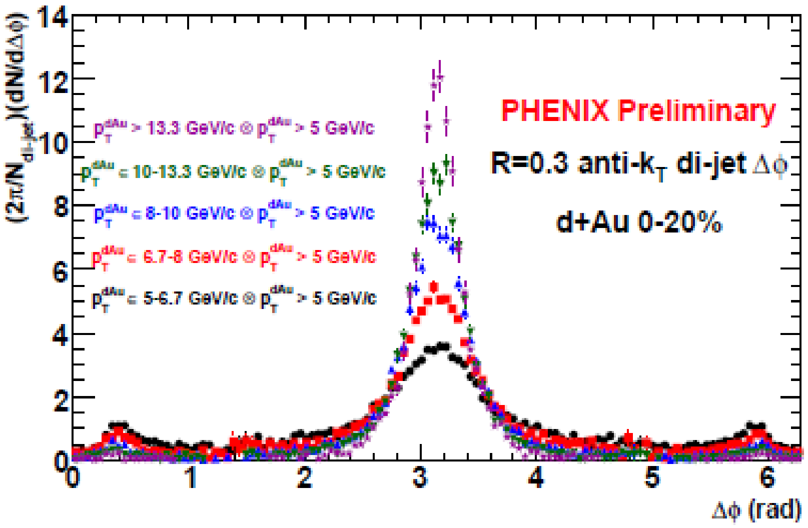
Jets in d+Au





- Jet R_{cp} versus p_T
  - Energy scale is of the reconstructed *pp* jet
- Suppression is observed in central collisions
  - Gradually increasing with centrality
  - Appear unmodified in peripheral
  - Consistentbetween cone size

Di-jets in d+Au



- Multiple scattering in cold nuclear matter

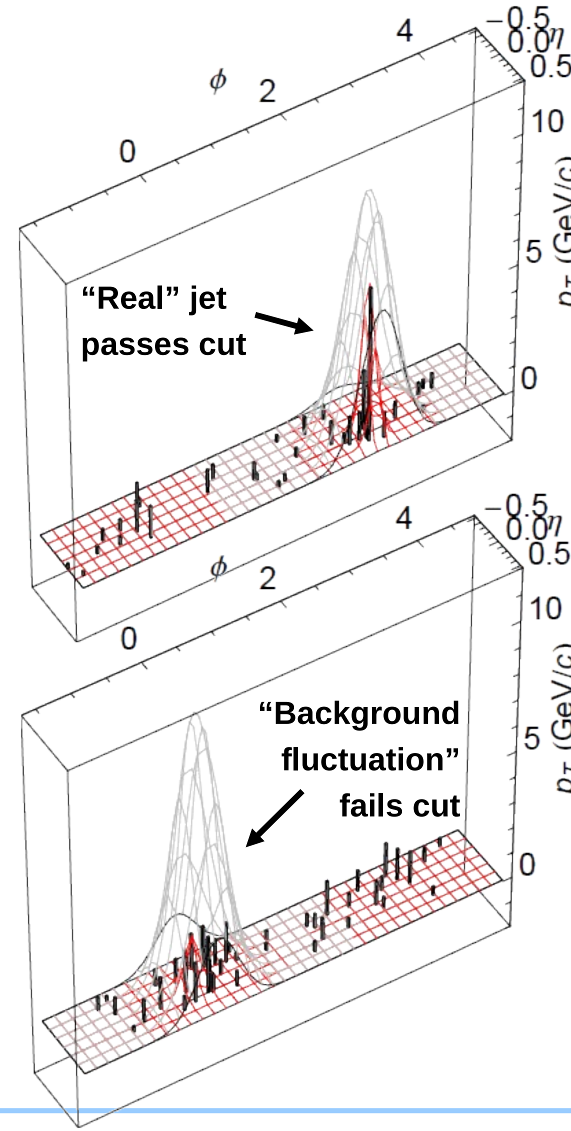
(Direct) Fake jet rejection

- Inspired by the Gaussian filter algorithm: cut on the shape of the jet

$$g_{\sigma_{dis}}(\eta, \varphi) = \sum_{i \in \text{fragment}} p_{T,i}^2 \exp\left[-\frac{(\eta_i - \eta)^2 + (\varphi_i - \varphi)^2}{2\sigma_{dis}^2}\right]$$

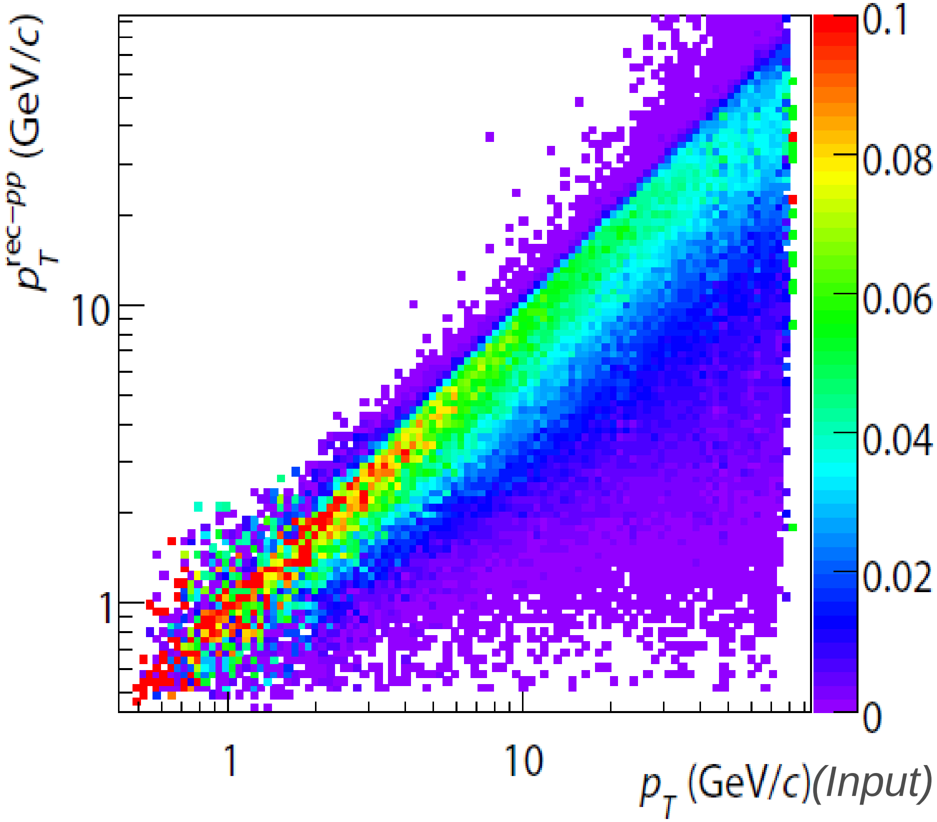
Discriminant:

- Weighted p_T^2 sum with a Gaussian distribution
  - η,ϕ is the reconstructed jet axis
- Size of Gaussian kernel $\sigma_{dis} = 0.1$
  - ~ characteristic background particle separation $[dR_{back} = \sqrt{(2\pi/(dN/d\eta))}]$
- Allow jet axis to shift until $g_{\sigma(dis)}$ is maximized (g')
- Cut on $g'_{0.1} > 17.8\ (\text{GeV}/c)^2$
  - Fixed discriminant threshold → nearly centrality independent efficiency



Jet energy correction

- Correction to true jet energy scale
  - Difficult via multiplicative factor
  - Unfolding of the measured spectrum by using an energy transfer matrix
    - Regularized inversion of the reconstructed to the “true” spectra using singular value decomposition (SVD), GURU*



Reconstructed/true *jet transfer matrix for pp at 200 GeV.*

Gaussian filter with σ=0.3

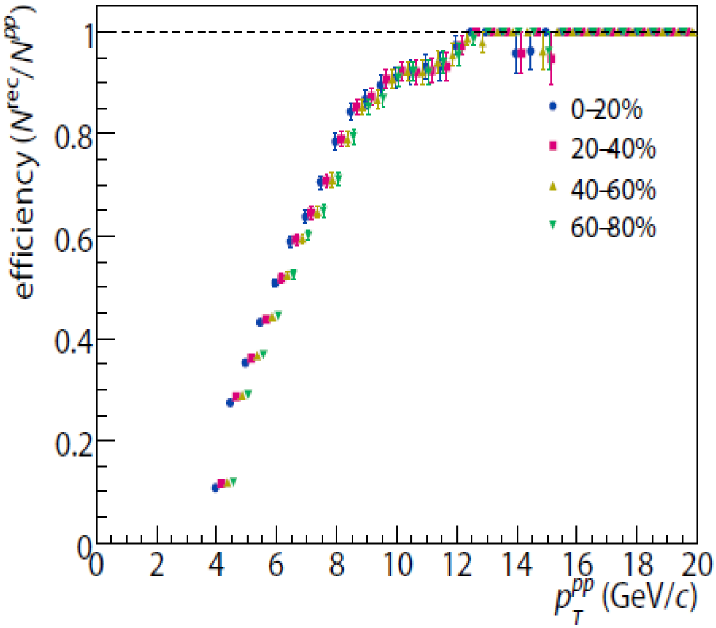
GEANT Pythia 6.4.20 simulation.

**** Nucl. Instrum. Meth. A372, 469 (1996)***

Jet reconstruction efficiency
200 GeV Cu+Cu collisions

Jet reconstruction efficiency

- *pp* jets embedded into Cu+Cu data
- Includes fake rejection
  - $g'_{0.1}$>17.8 (GeV/*c*)
  - Jets with p_T>16 GeV/*c* are above the discriminant threshold for fake jets
    - Little effect on R_{AA}, spectra above this p_T
- Nearly centrality independent



Jet reconstruction efficiency for g'0.1>17.8 (GeV/c)².

Embedding of pp into Cu+Cu data. Efficiency includes the fake rejection.

Fragmentation functions

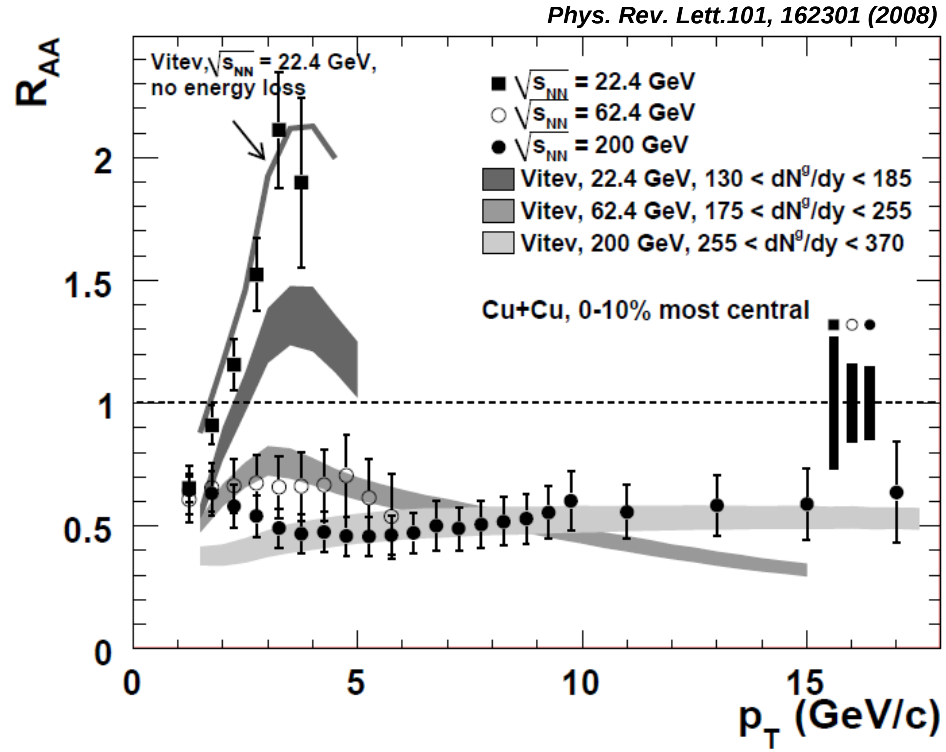
- $z = p_{particle||} / p_{jet}$
  - p_{jet} must be the true jet energy to perform "apple-to-apple" division, otherwise z is shifted
- 2D unfolding needed to simultaneously unfold ($p_{particle||}$, p_{jet})
  - Phenix developed a n-D generalization to GURU
  - First time 2D regularized SVD unfolding is applied in HEP/NP

- Result for Run-5 p + p minimum bias only
- Direct comparison to (perfect detector) PYTHIA at p^{jet}_T =15 GeV/c
- Particle species:
  - Non-ID charged tracks (rejecting e^-, mostly from γ beam-pipe conversions)
  - Neutral clusters (electromagnetic)
- Single particle resolution not yet unfolded (very small effect)
  - $\delta p/p = 0.7\% \oplus 1.0\% p/(GeV/c)$
- Uncertainty in the absolute energy scale of the calorimeter clusters
  - ± 3%(syst)

Systematic Studies:
species, energy scan

"High" energy scan

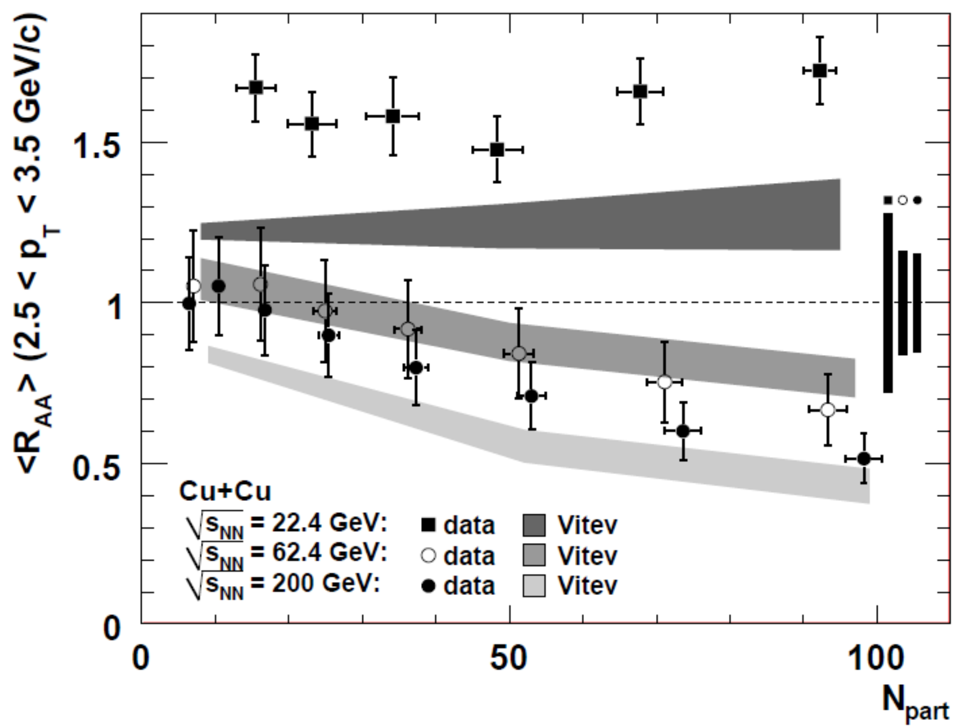
- Probe energy dependence of R_{AA}
  - $\sqrt{s_{NN}}$=200 and 62.4 GeV
    - "suppression" observed
  - $\sqrt{s_{NN}}$=22.4 GeV
    - "enhancement"



Systematic Studies:
energy scan

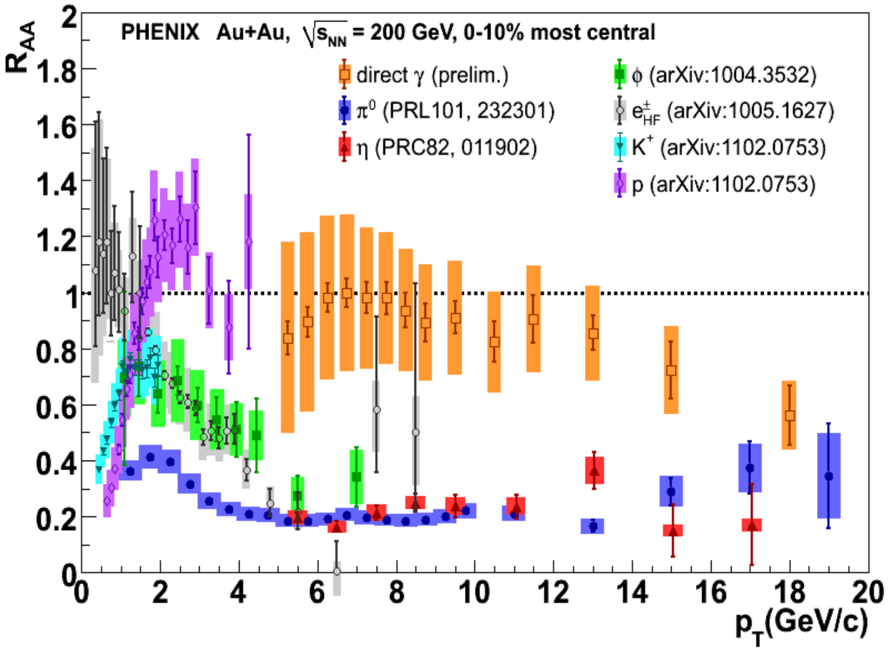
"High" energy scan

- Probe energy dependence of R_{AA}
  - $\sqrt{s_{NN}}$=200 and 62.4 GeV
    - "suppression" observed
  - $\sqrt{s_{NN}}$=22.4 GeV
    - "enhancement"
- Path length dependence observed, and similar, at higher energies



Systematic Studies:
identified single spectra

- Further examination
  - Color-charge dependence
  - Via Particle-ID
- Strong species dependence of R_{AA}
  - Proton modification distinct from meson



FF modified in Au+Au?

Fit function: $\frac{dN}{dz_T} = N e^{-b z_T}$

- z_T scaling in Au+Au
- Universal fit for all jet energies to compare with *pp*
- Slopes difference
  - p+p, b=6.9±0.8

    quark fragmentation b=8,
    gluon fragmentation b=11
  - Au+Au, b=9.5±1.4
- Au+Au slope is 1.3σ larger than *pp*