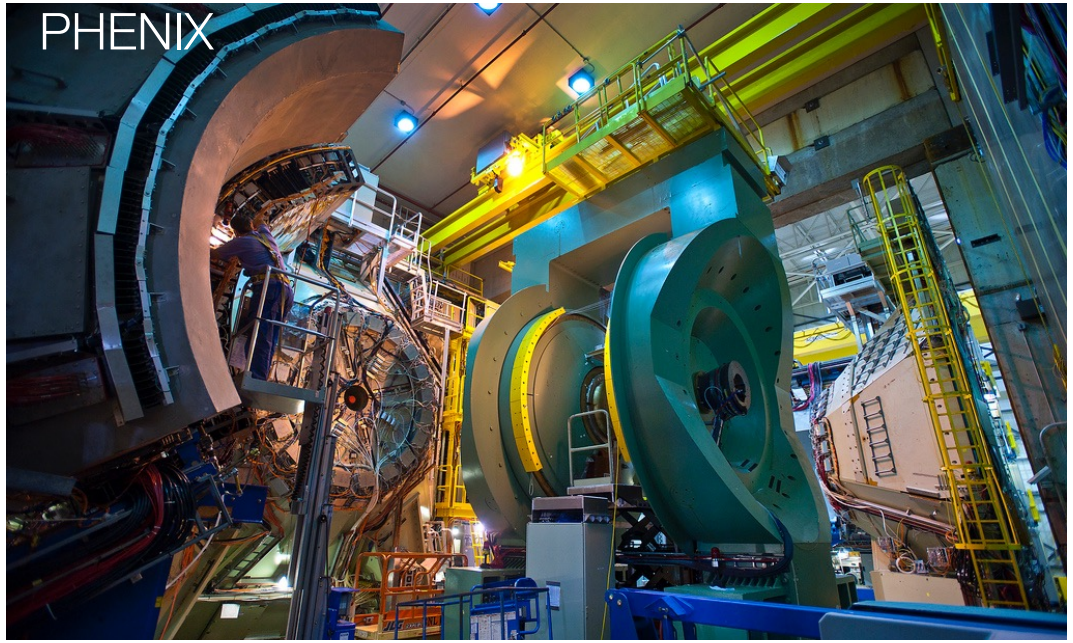
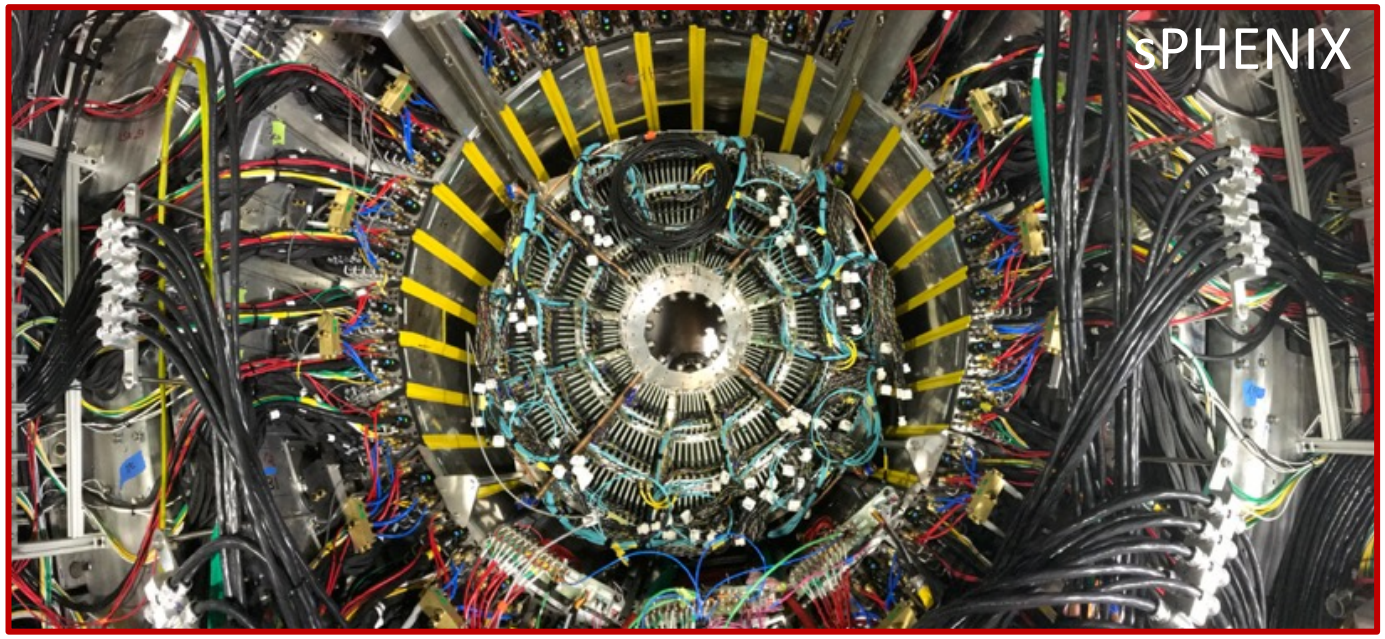
# Jet Quenching:

## The transition from PHENIX discoveries to sPHENIX opportunities




Georgia State University

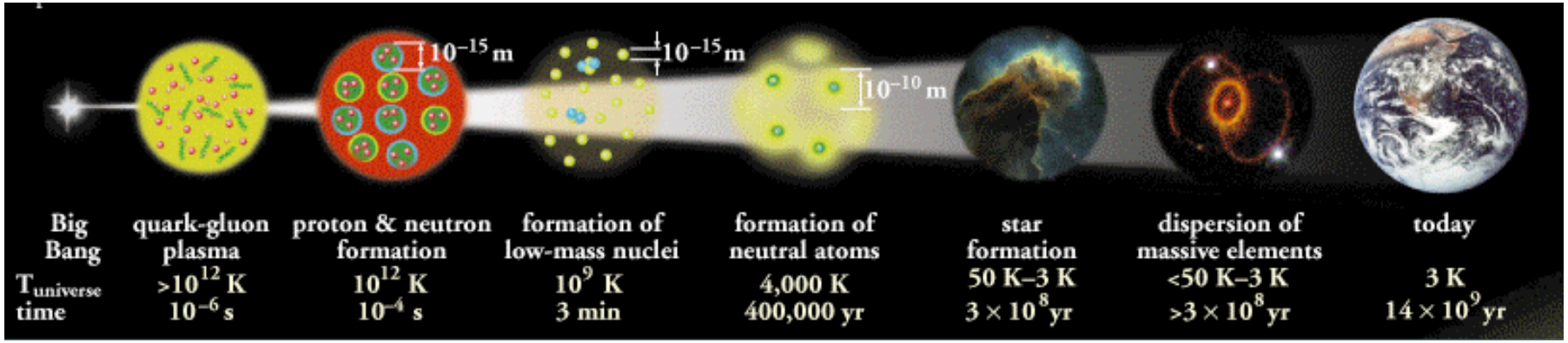
Megan Connors

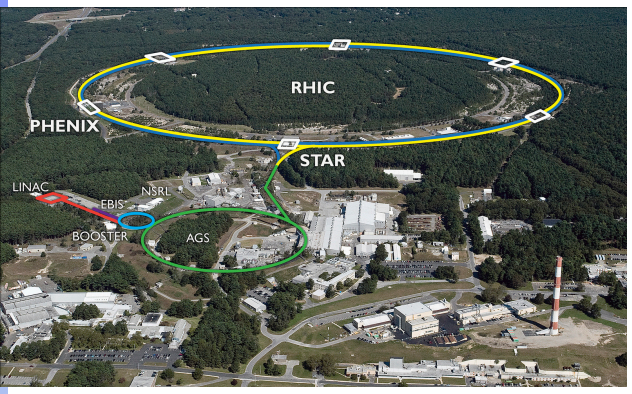
RBRC 25th Anniversary

June 22, 2023

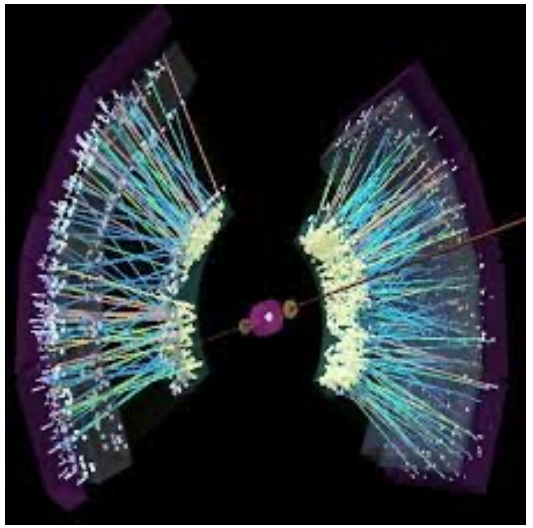
RBRC
RIKEN BNL Research Center

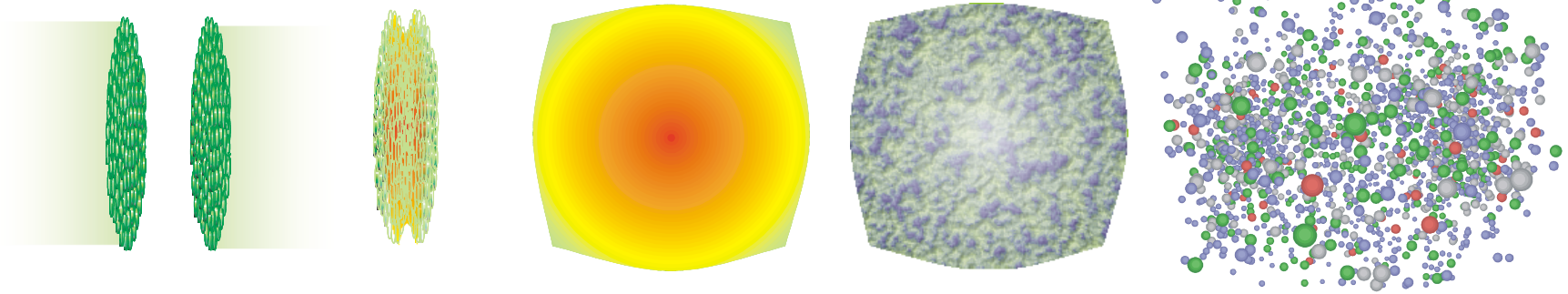
# Recreating the Big Bang



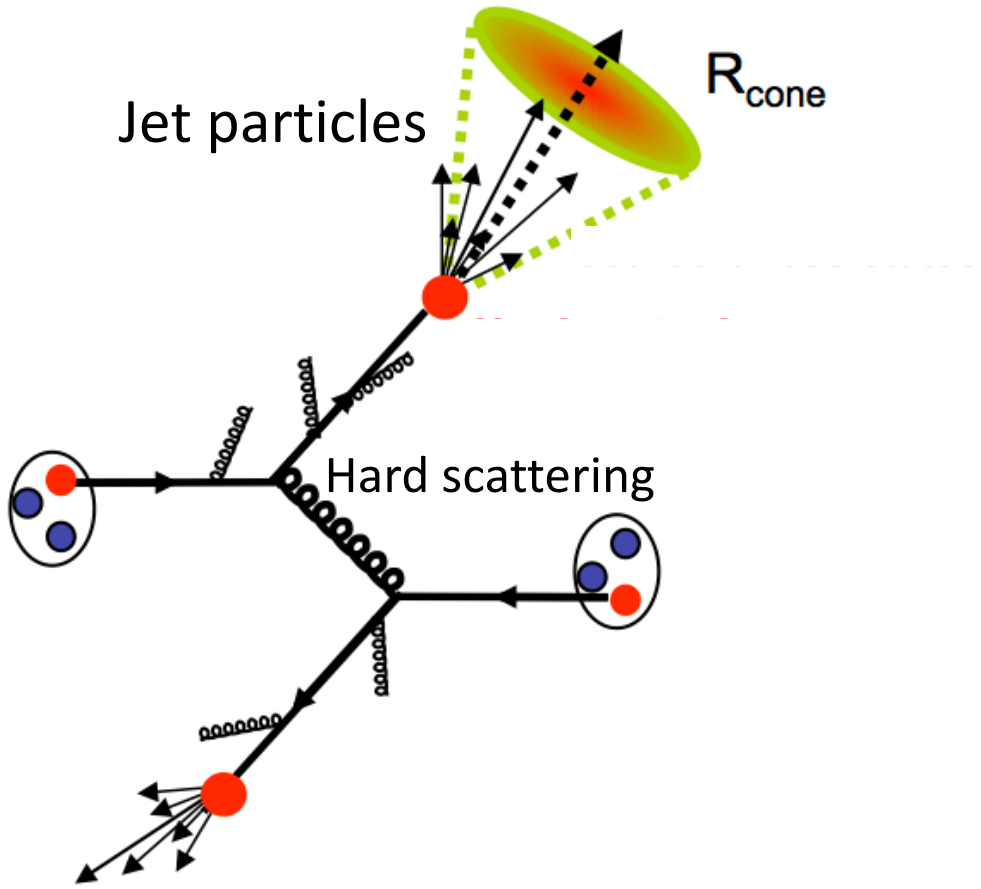




- Quark Gluon Plasma teaches us about the strong force interactions which binds our universe together



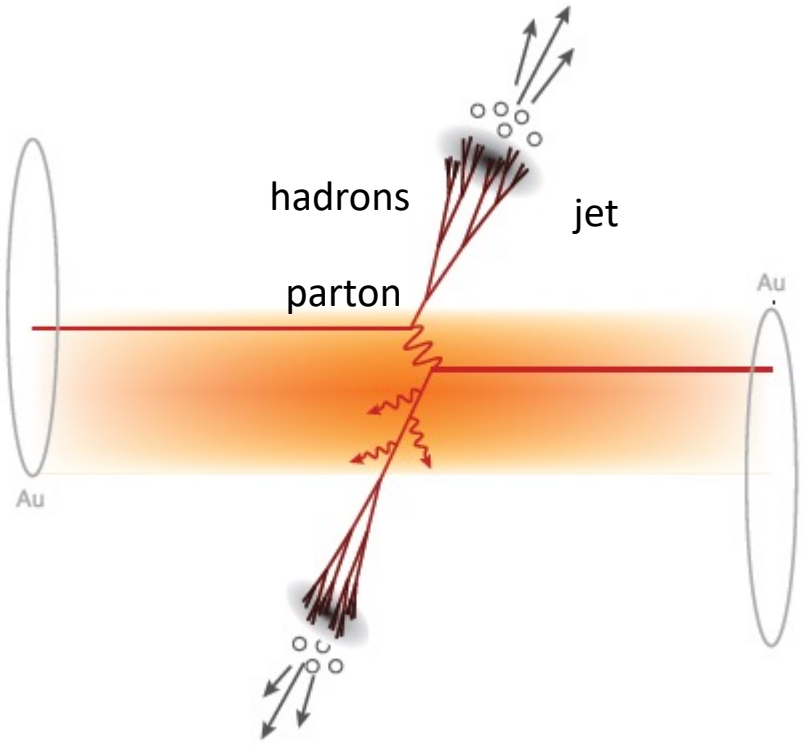


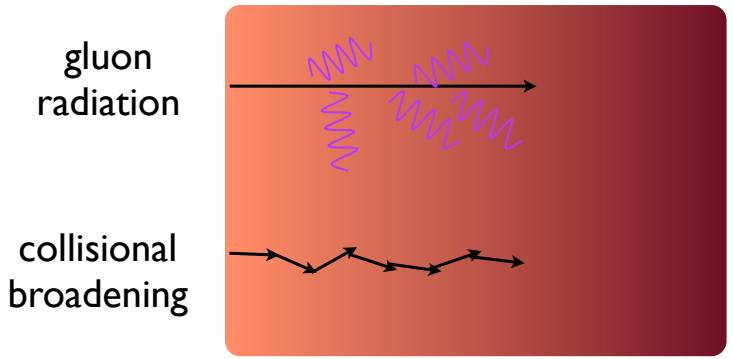
# What is a jet?




- Hard scattering produces back-to-back quarks or gluons
- A collimated spray of particles
- Defined by a jet finding algorithm
- High momentum particles as a proxy

# Jets in the QGP

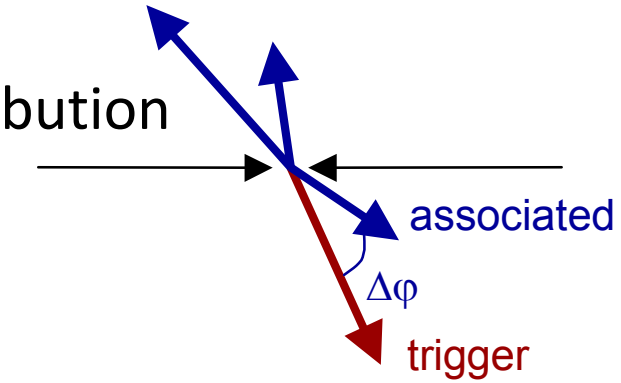



- An internal probe of the QGP produced in heavy-ion collisions
- Measurements modified relative to p+p

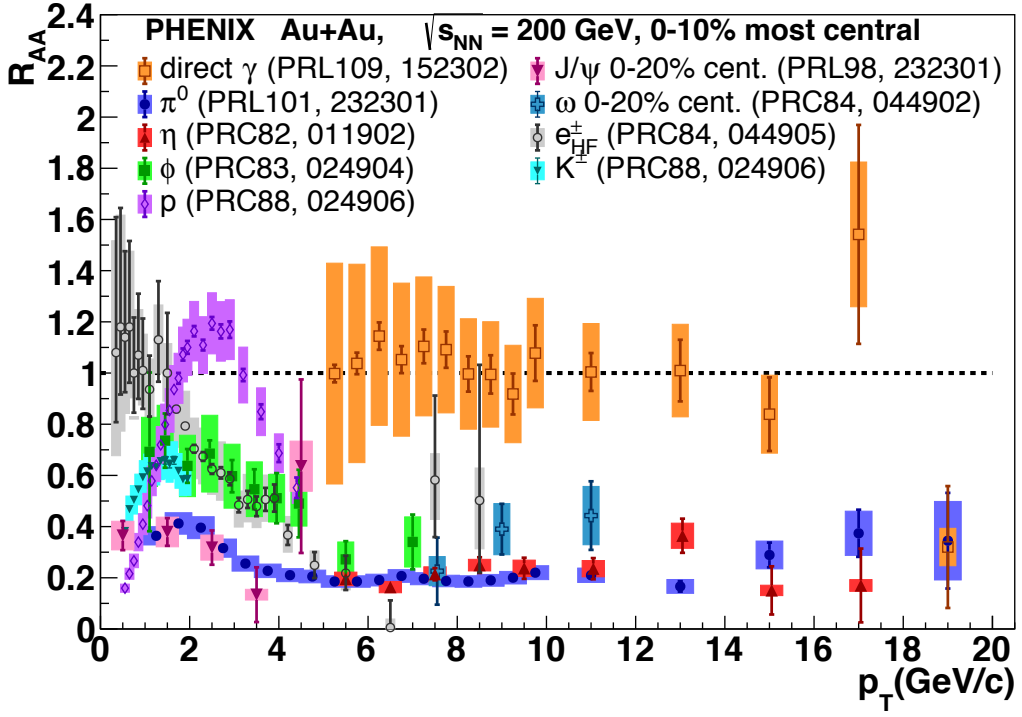
1. Yield: $$R_{AA} = \frac{dN_{jet}^{AA} / dp_T}{\langle N_{coll} \rangle dN_{jet}^{pp} / dp_T} \frac{N_{evt}^{pp}}{N_{evt}^{AA}}$$

2. Angular distribution

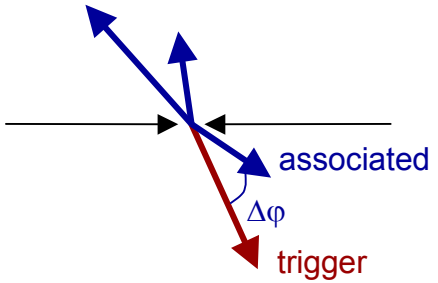


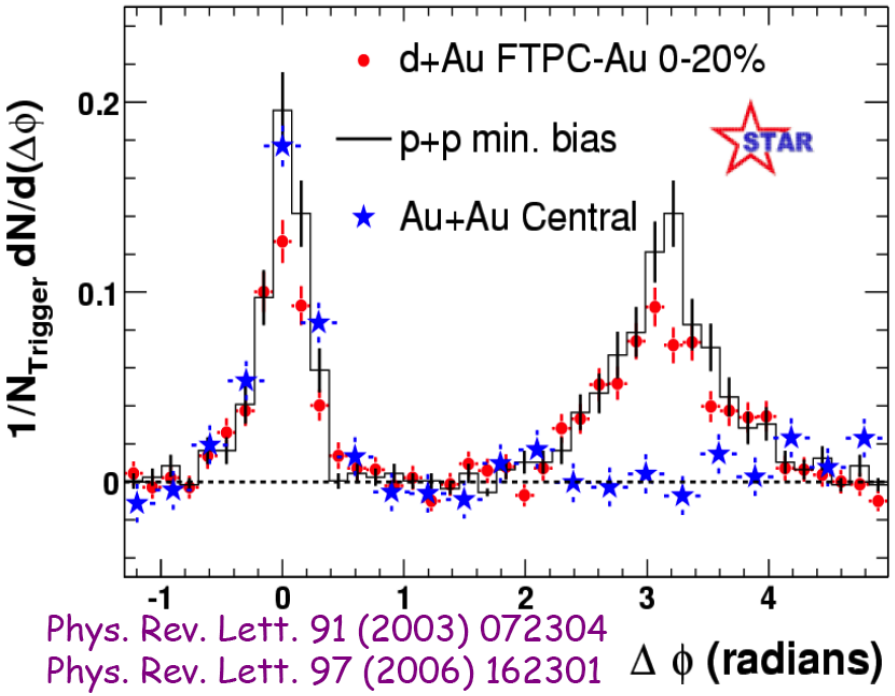
# Jets are suppressed!

- Suppression of high $p_T$ hadrons observed!
- Di-hadron awayside suppressed compared to p+p and d+Au




$$R_{AA} = \frac{dN_{jet}^{AA} / dp_T}{\langle N_{coll} \rangle dN_{jet}^{pp} / dp_T} \frac{N_{evt}^{pp}}{N_{evt}^{AA}}$$

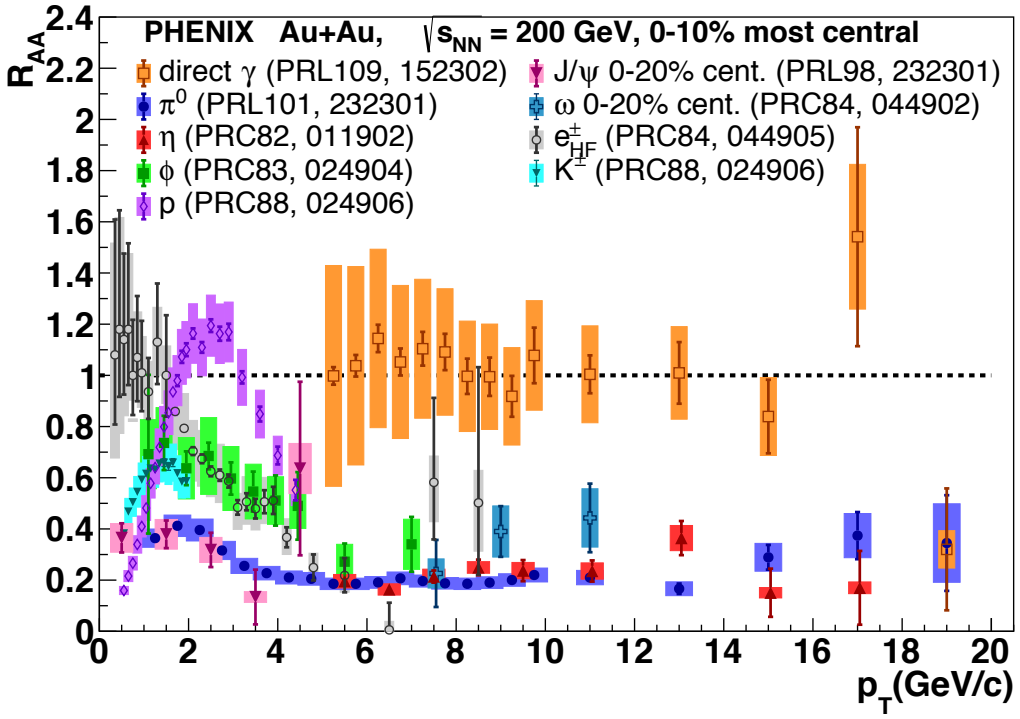


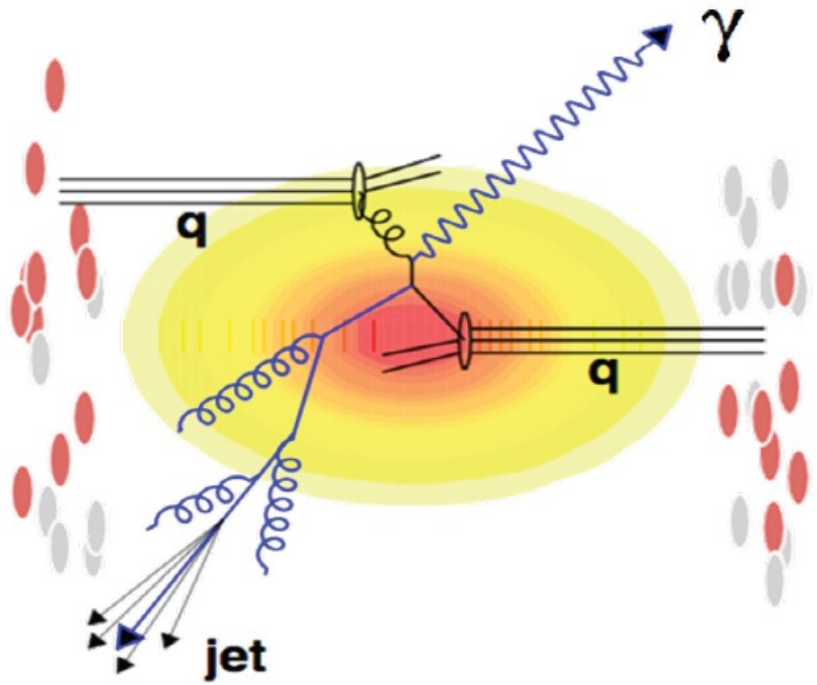




Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

# The golden channel: photon tagged jets

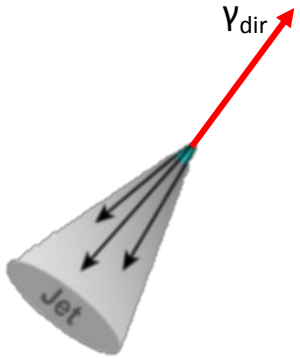
- Direct photons do not interact via strong force: give $R_{AA}=1$
- Opposing jets are predominately quark jets



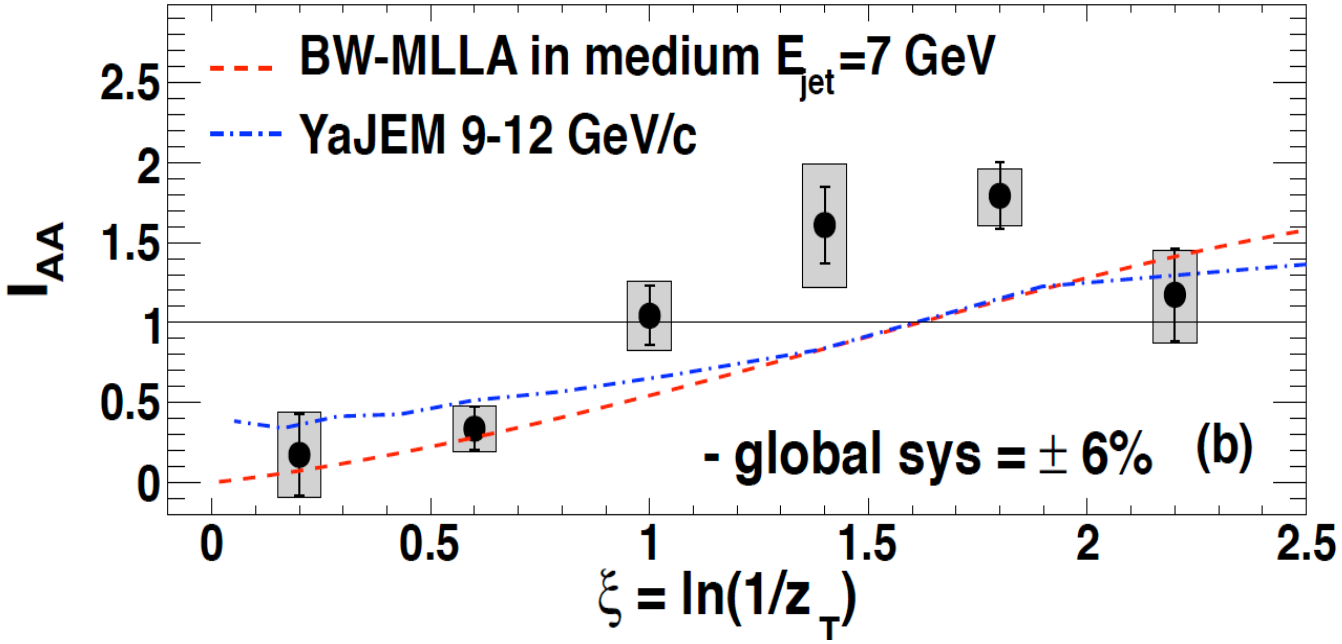




γ energy ≈ jet energy

# Where does the lost energy go?




$$I_{AA} = \frac{Y_{AA}}{Y_{pp}}$$



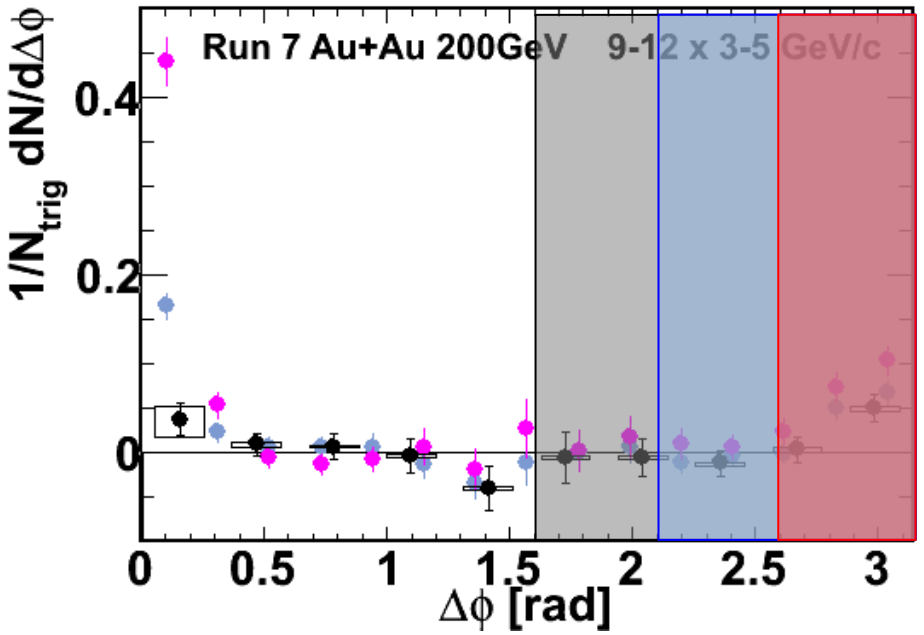

- Suppression at low $\xi$ (high $p_T$) and enhancement at high $\xi$ (low $p_T$)
  - Increase in the number of low momentum particles
- Qualitative agreement with models at the time

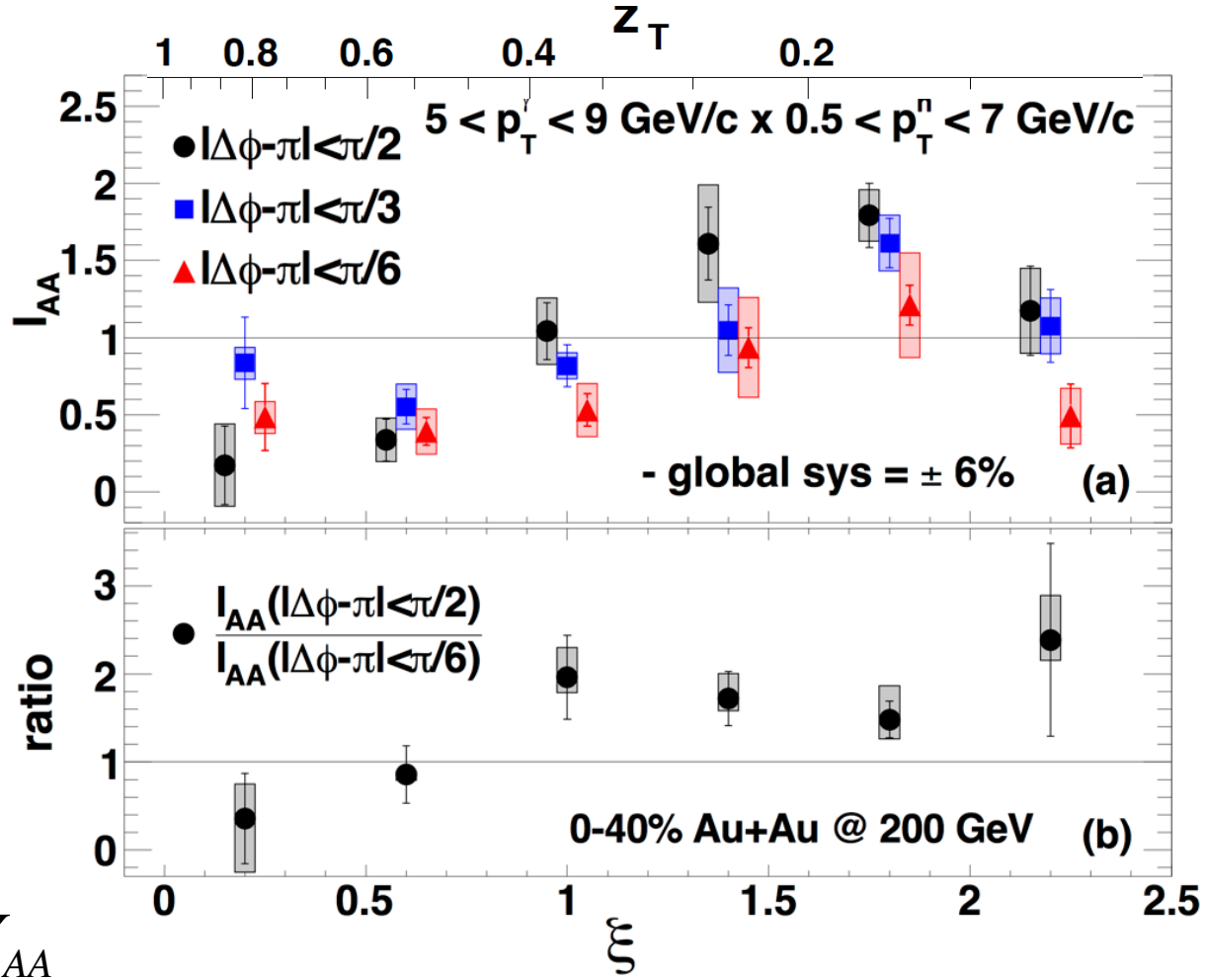
Phenix PRL 111, 032301

# Jet broadening

Phenix PRL 111, 032301

- More enhancement at wider angles

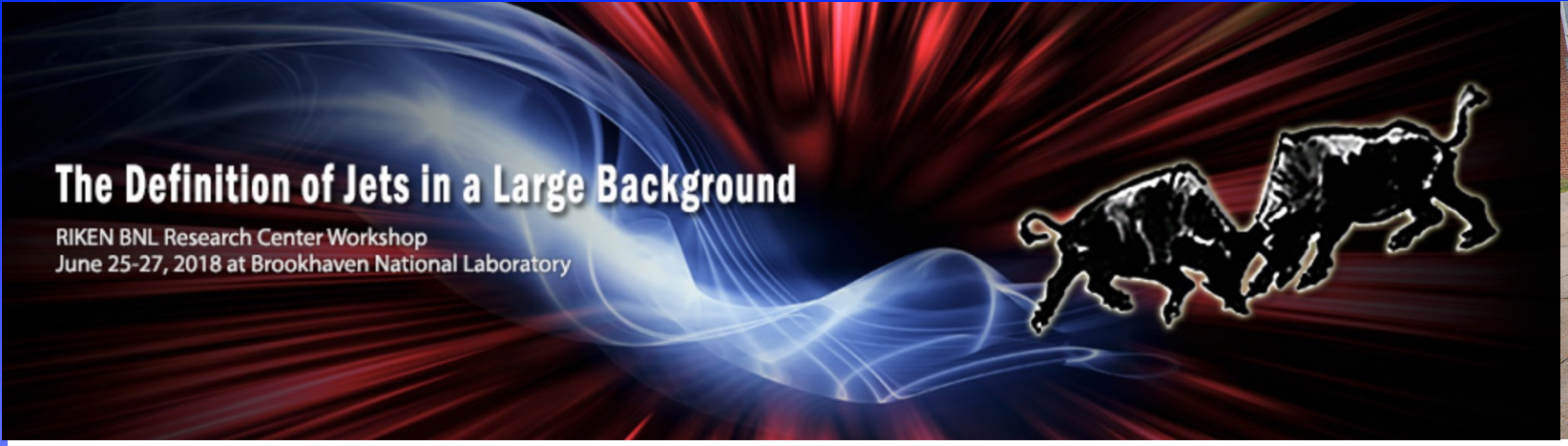


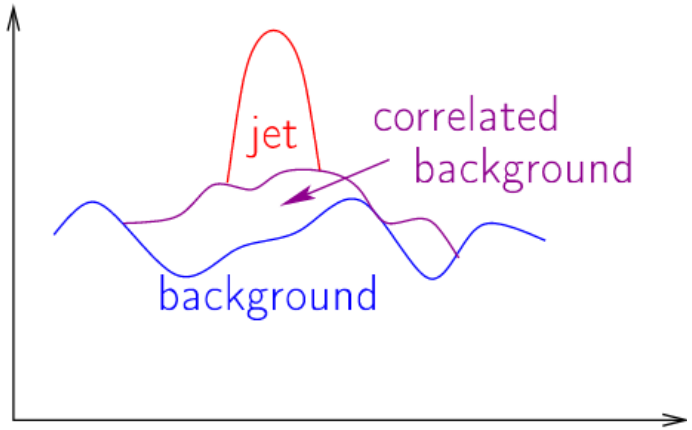

$$I_{AA} = \frac{Y_{AA}}{Y_{pp}}$$

# Fast forwarding

- LHC results on jet quenching with reconstructed jets
  - Jet review paper: Rev. Mod. Phys. 90, 025005 (2018)
- After working on ALICE as a post-doc, I joined the RBRC in Fall 2015 as an assistant professor at GSU
- I rejoined PHENIX and started working on sPHENIX




- Explore the procedures for extracting jets from the large underlying event in heavy-ion collisions
- Make sure measurements include “correlated background” or “medium response” which results from the energy of the jet deposited into the QGP
- Productive discussions about new observables



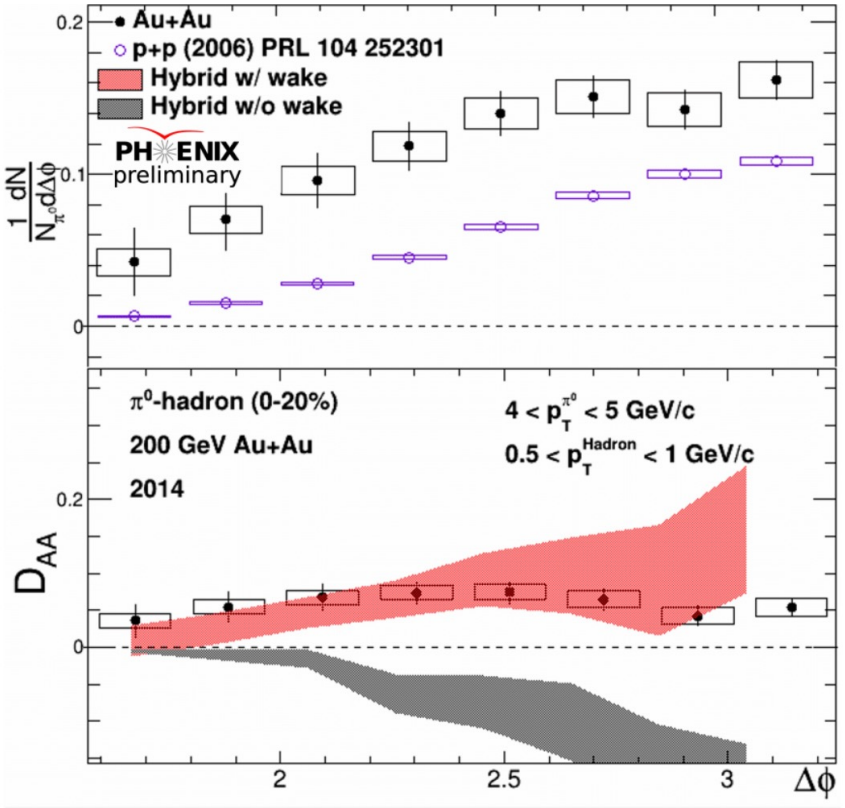

https://www.bnl.gov/jets18/

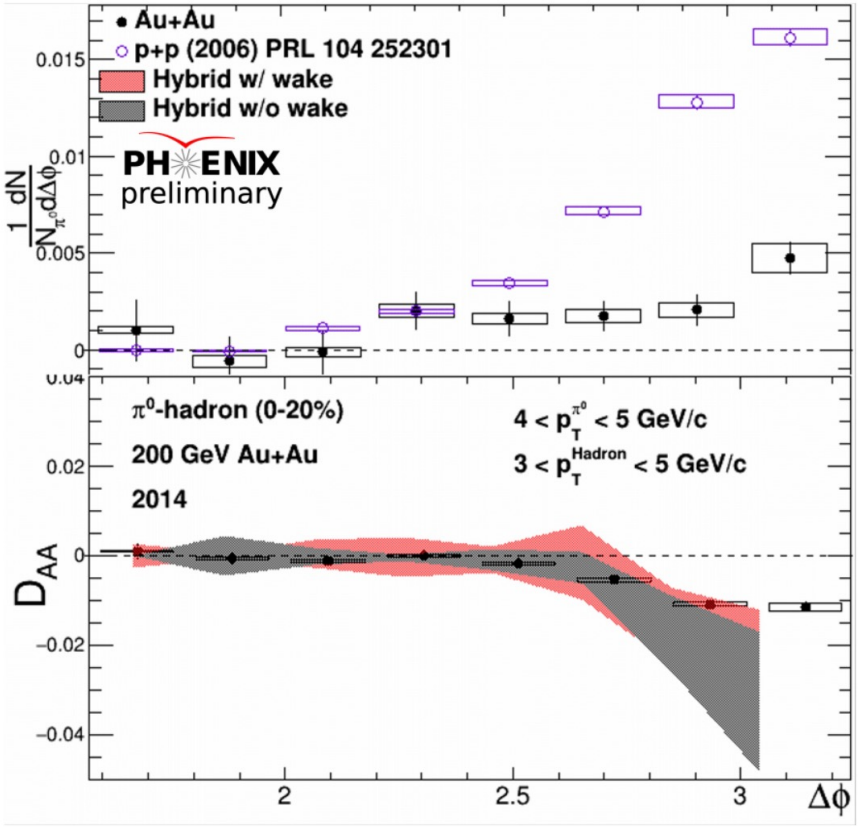
# Medium response

- Awayside yields for dihadron correlations from PHENIX run 14
- Agrees with model that includes medium response
- Similar results from LHC Z-h correlations
- Medium response more significant for low $p_T$

$$D_{AA} = Y_{AA} - Y_{pp}$$

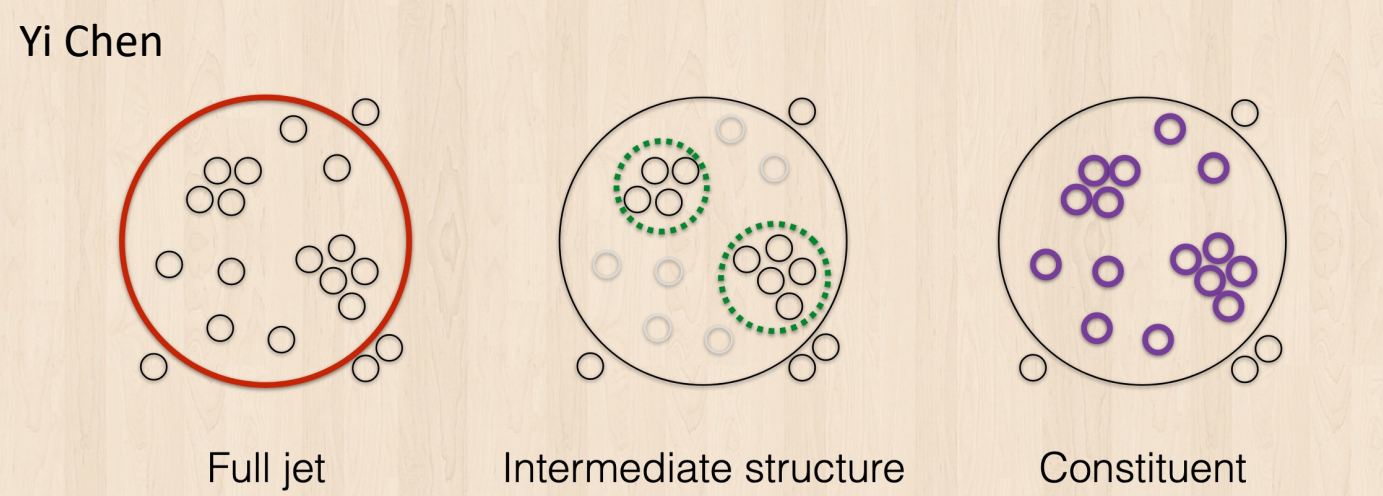
Anthony Hodges
GSU PhD 2022



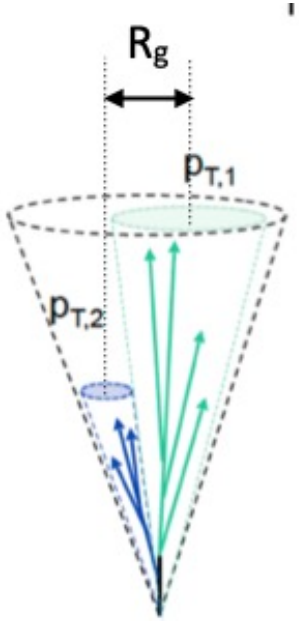




Award 1848162: CAREER: Jet Measurements and a Novel Hadronic Calorimeter at the Relativistic Heavy Ion Collider

# Reconstructed jets and substructure

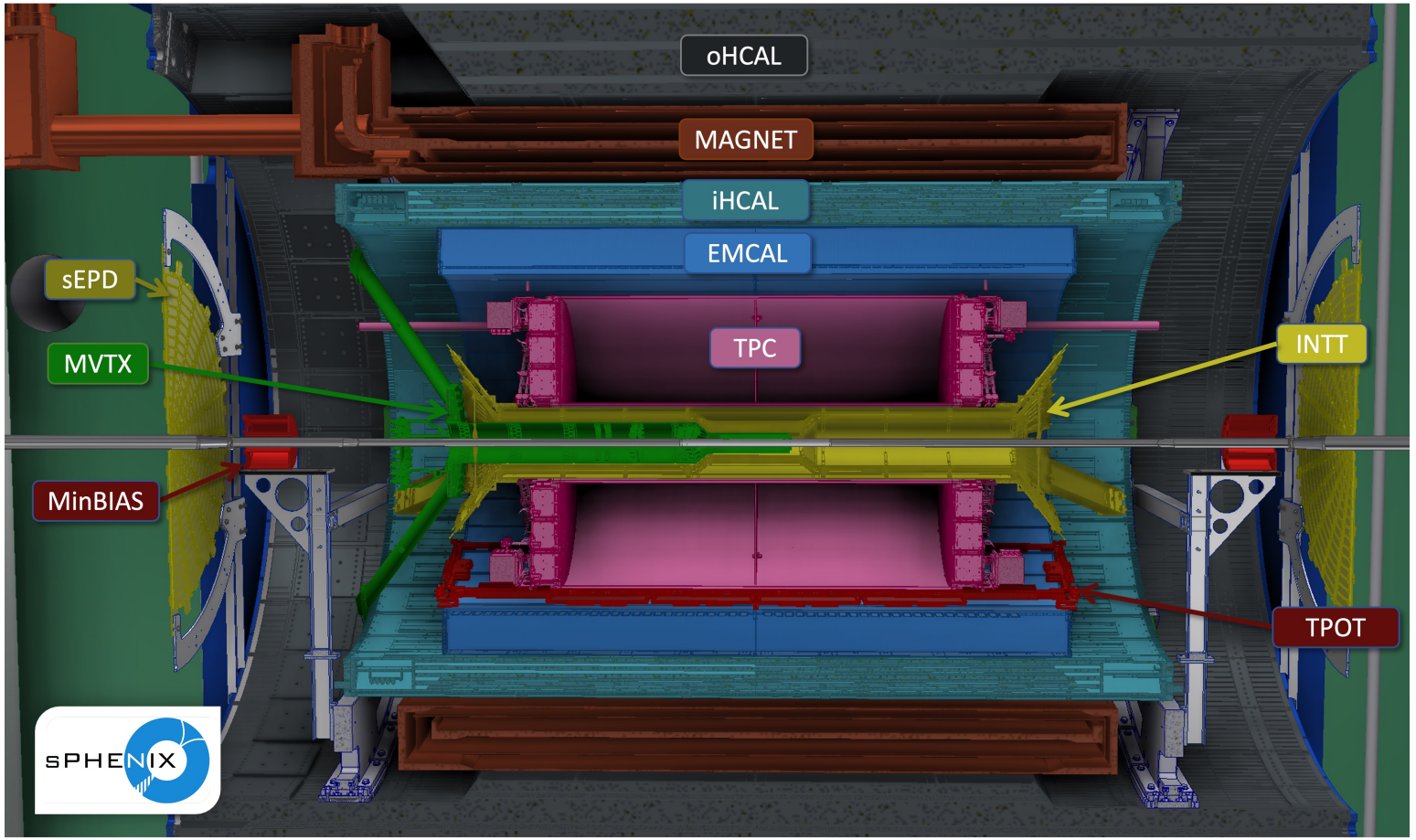



$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$$



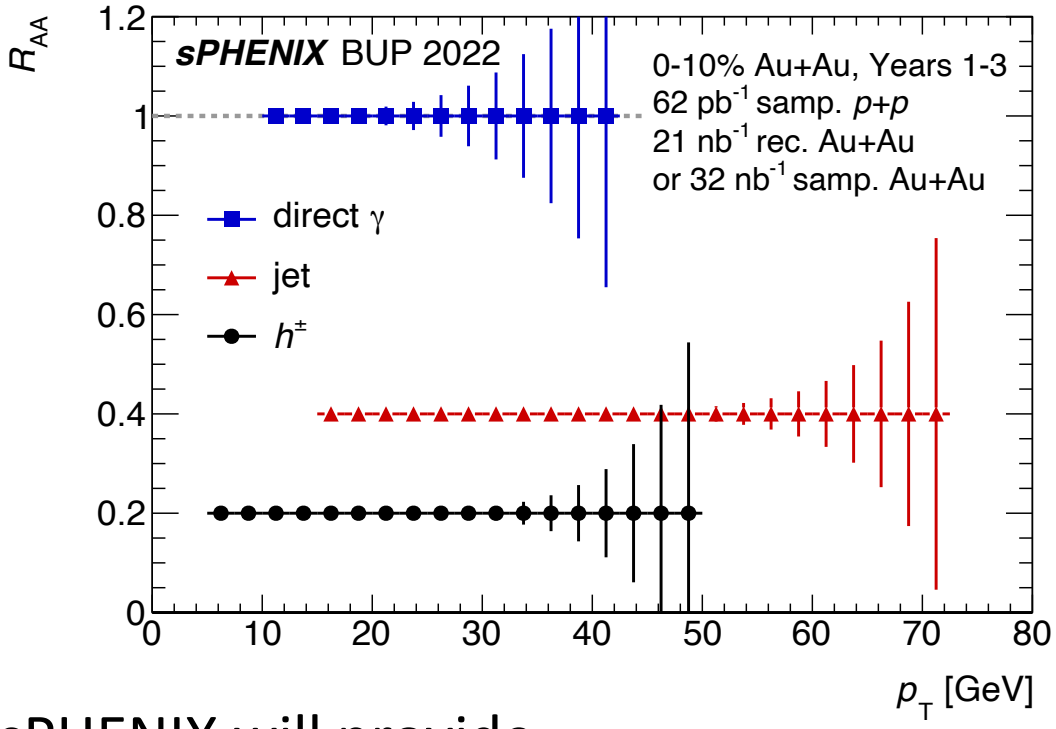

- Photon tagged jets directly probe the lost energy and help disentangle quark/gluon jet effects
- Reconstructed jets require large uniform detector acceptance and high statistics
- Substructure requires good resolution of particles within the jet

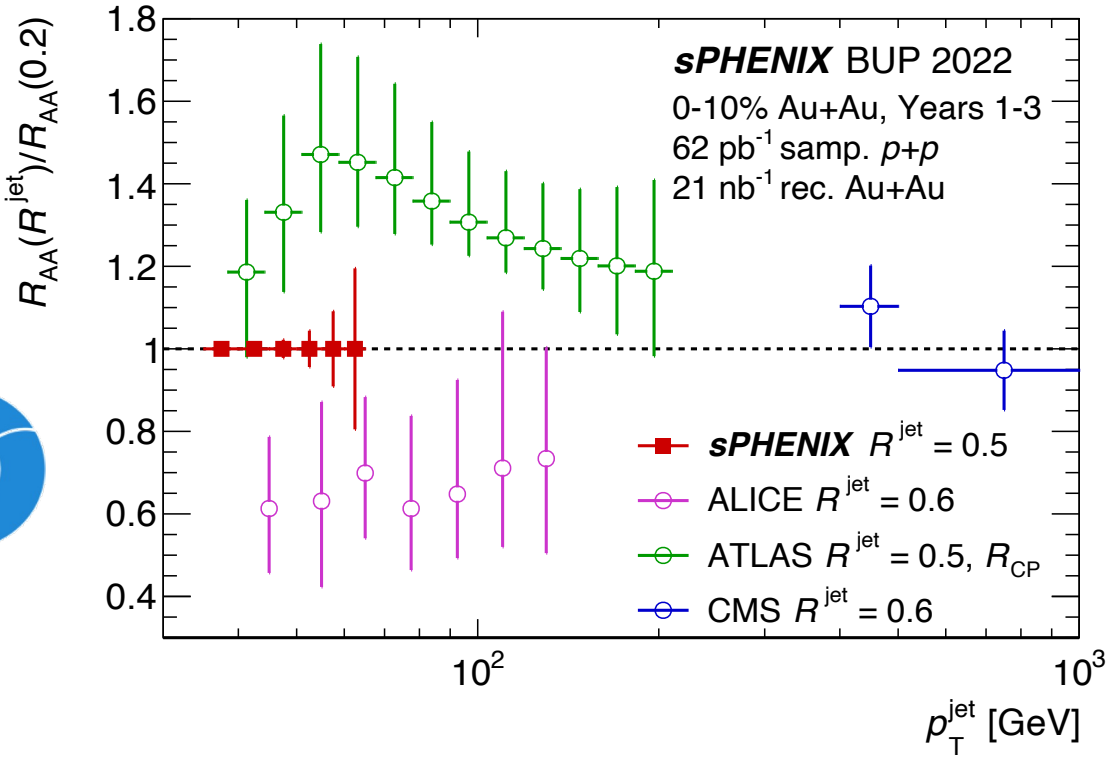
# A jet detector at RHIC




- Full azimuthal acceptance
- High Data Acquisition rate
- Calorimeters for jet energy measurements
- Tracking for HF tagging and jet substructure measurements

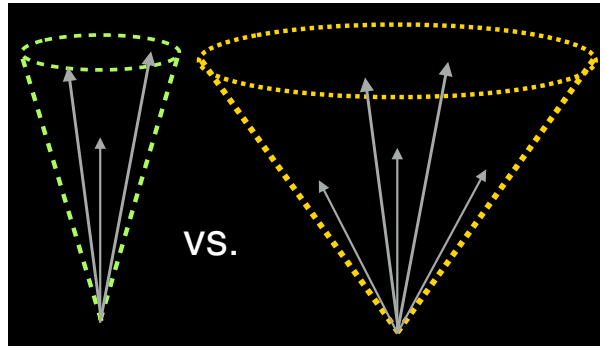
# Full jet studies



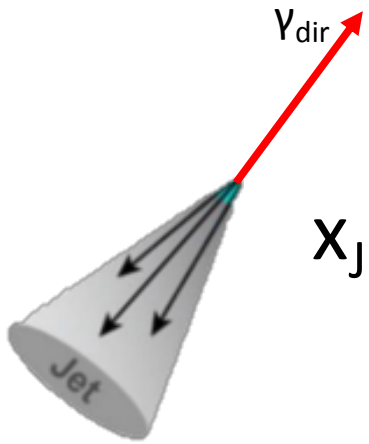

sPHENIX will provide

- significant extension in kinematics and overlap with LHC
- jet cone size $R_{AA}$ comparisons at low $p_T$ where differences at LHC experiments exist

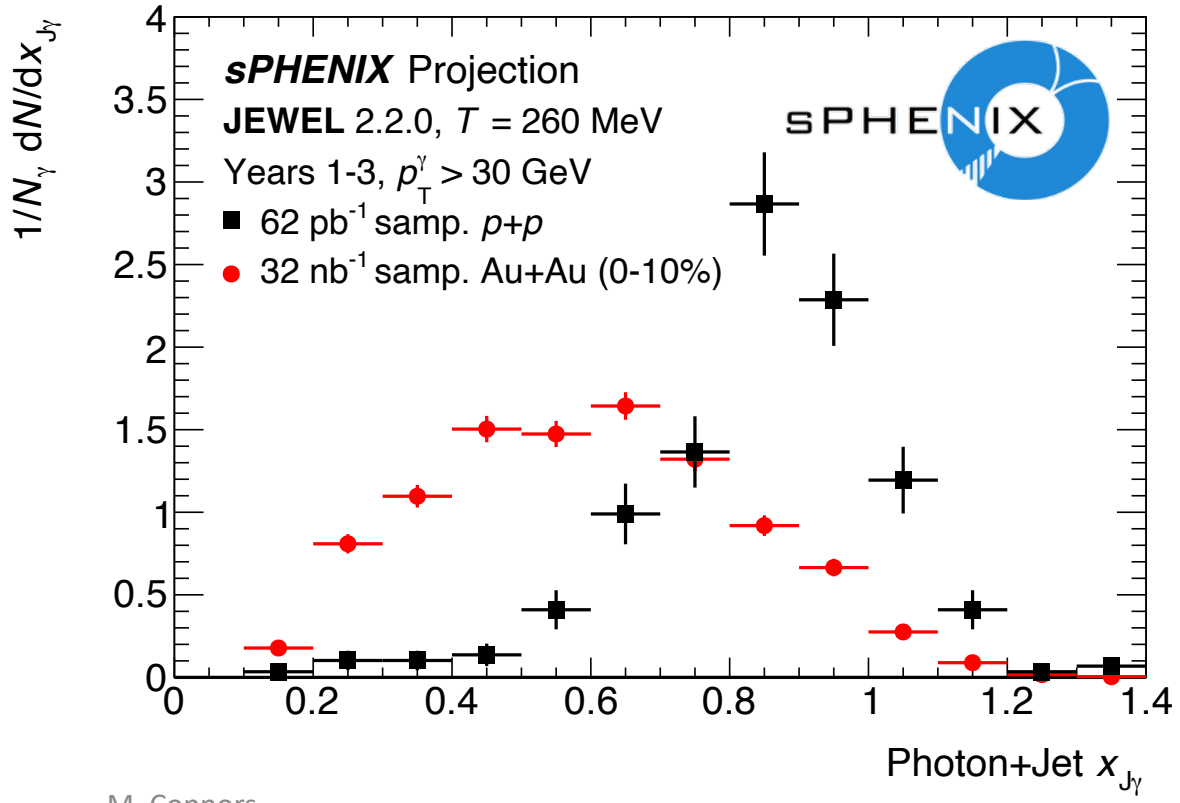


# Photon-Jet Imbalance

- Photon tagged jets are a key component to the sPHENIX program
- Projected statistical precision shown for the energy imbalance



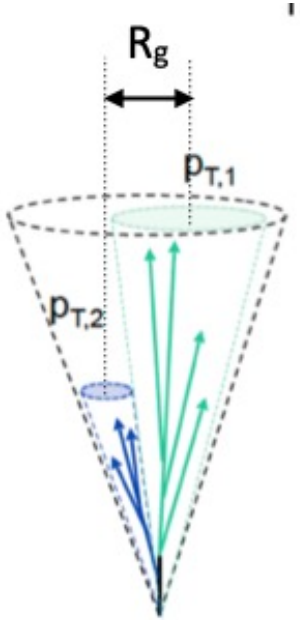

$x_{J\,\gamma} = p_{Tjet}/p_{T\gamma}$

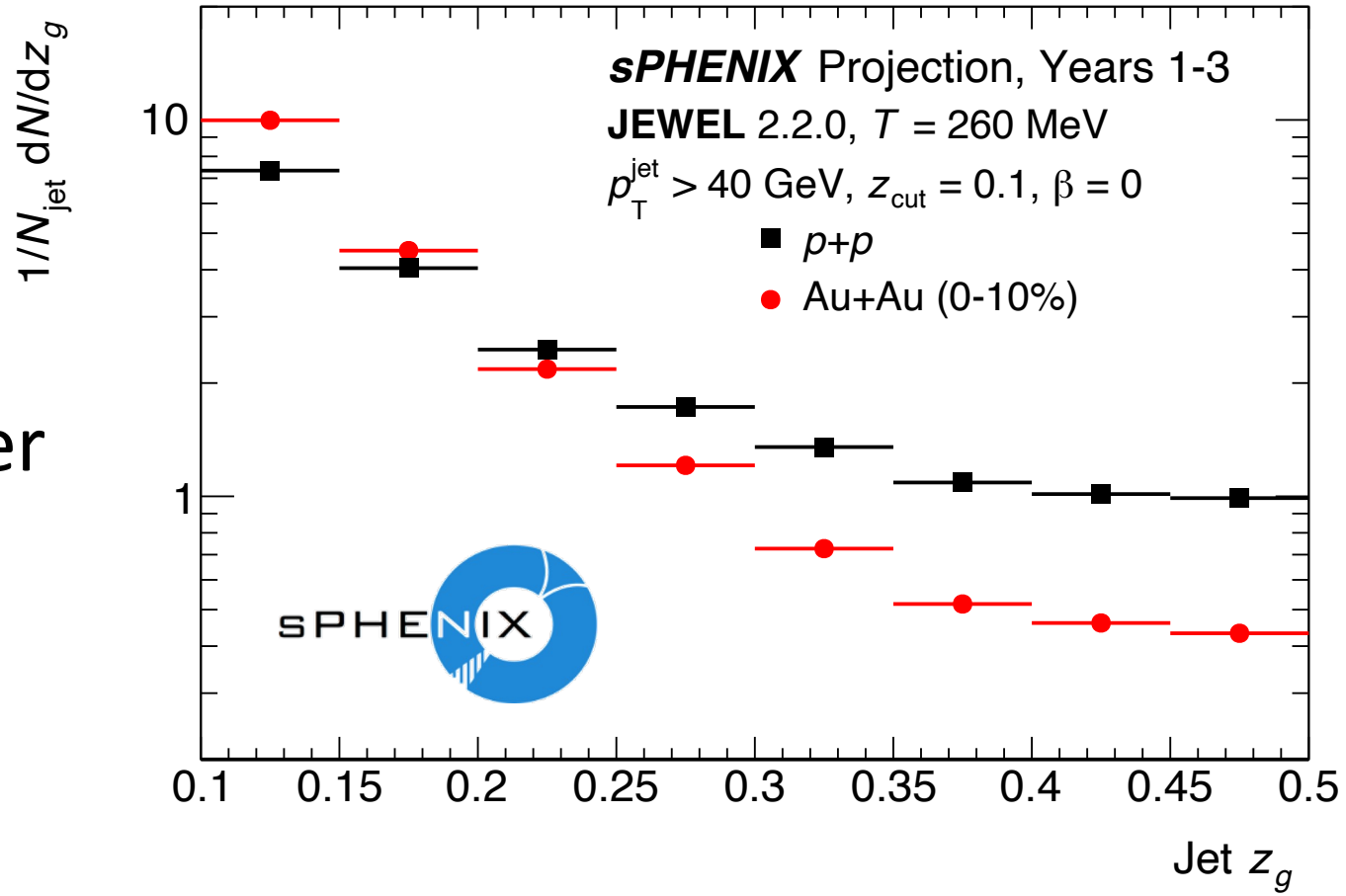


# Jet substructure

- Jet grooming one of many techniques to explore substructure of jets
- Groomed jets explore the evolution of the parton shower

$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$$



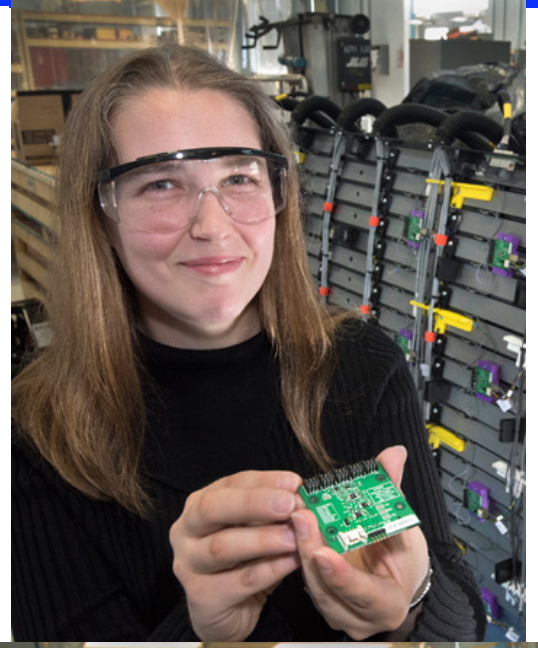



# Introducing…sPHENIX!

**A new collaboration takes aim at understanding how the ultra-hot, ultra-dense plasma that formed our early universe gets its intriguing properties.**

June 15, 2016

[BNL newsroom sPHENIX link]

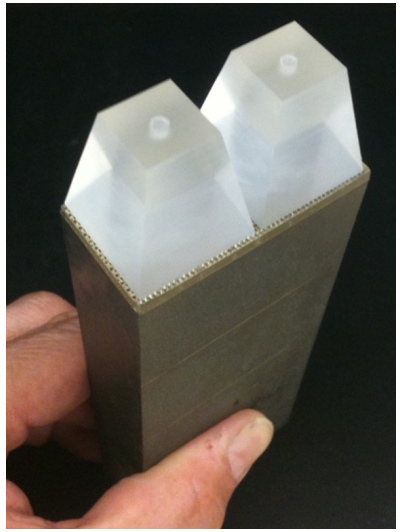


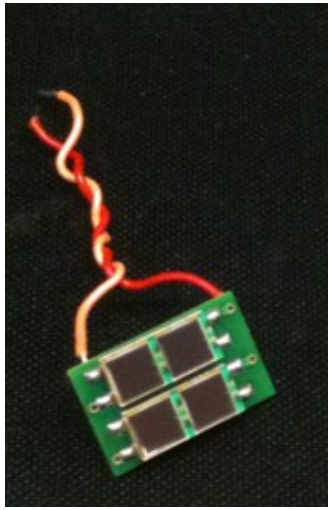
> We will take what we learn about how well the detector will perform based on the testing at Fermilab, and then use that knowledge to finalize the design.
>
> — RIKEN-BNL Research Center Fellow and sPHENIX member Megan Connors

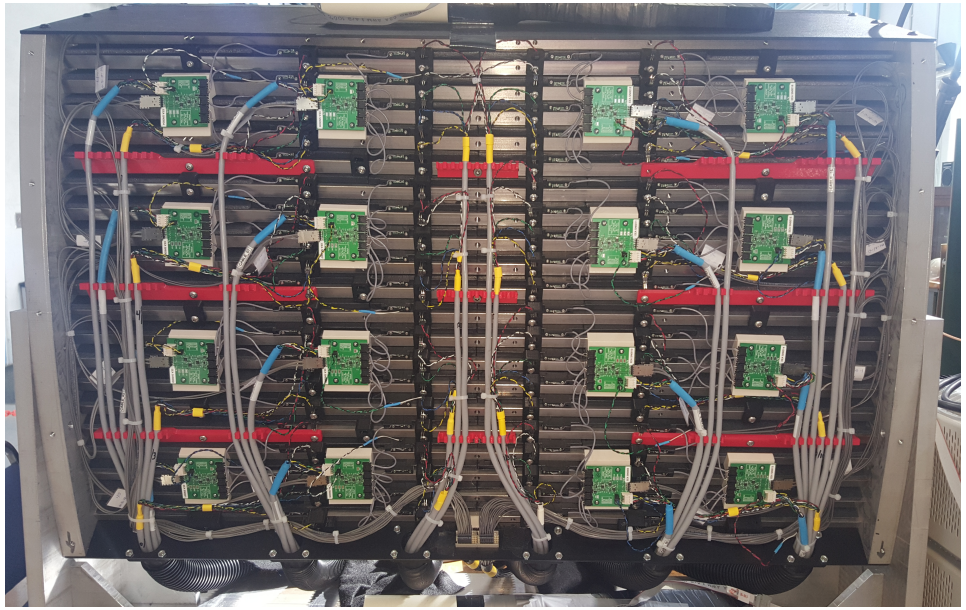
[BNL Newsroom Calo link]

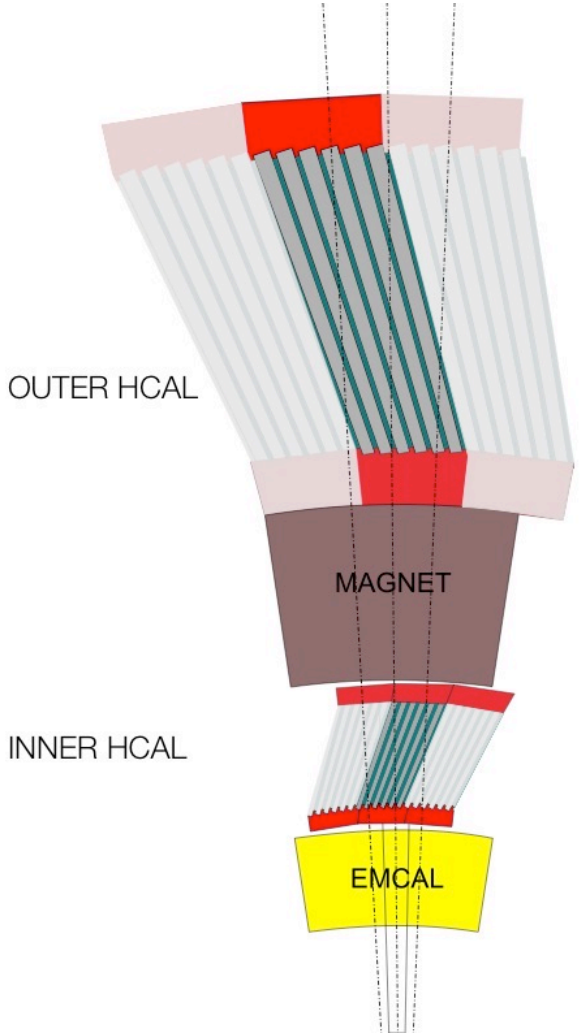
- 2016 BNL news stories highlighting newly formed collaboration and calorimeter developments

# Calorimeters Reference Design

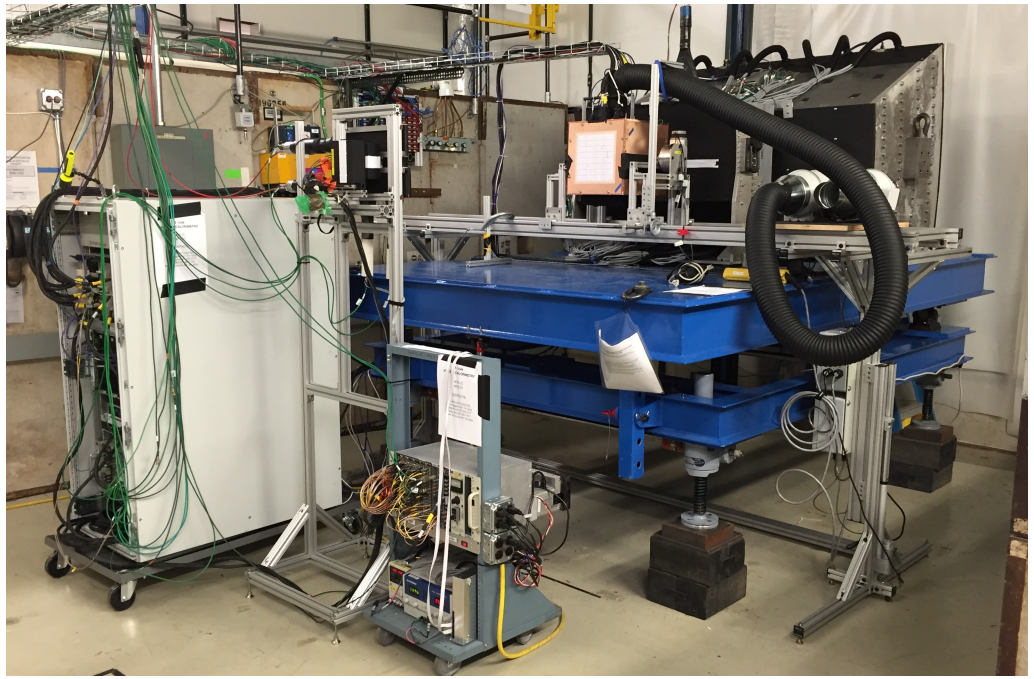


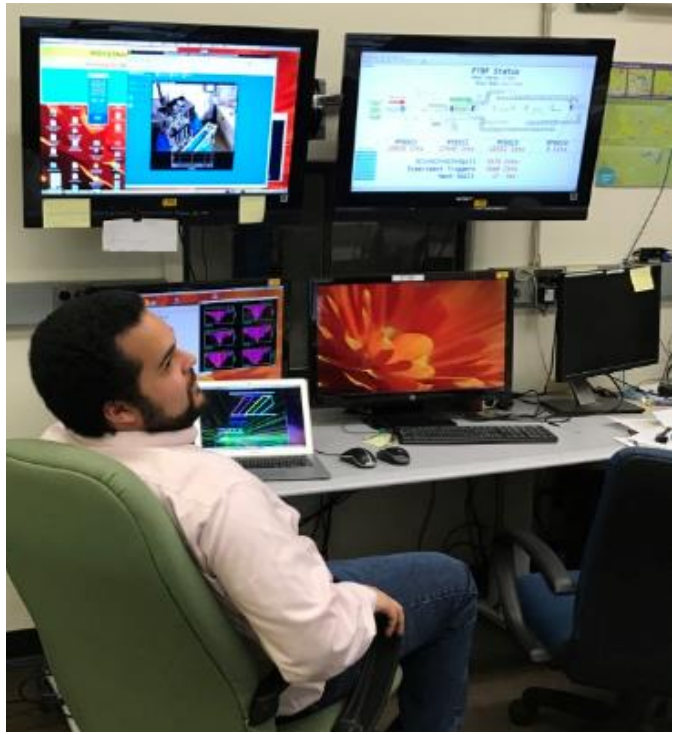




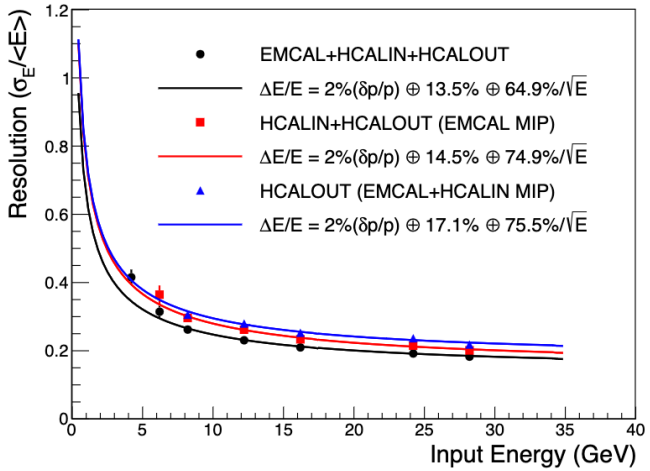


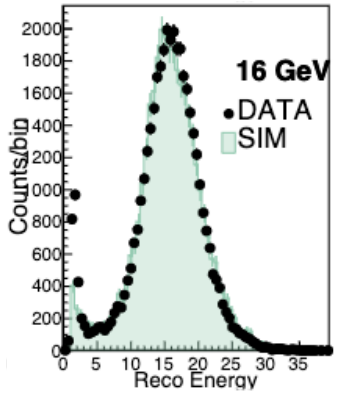
# Prototype Testing



- Fermilab Test Beam Facility
- Simulation reproduces the data
- Satisfies the sPHENIX performance requirements

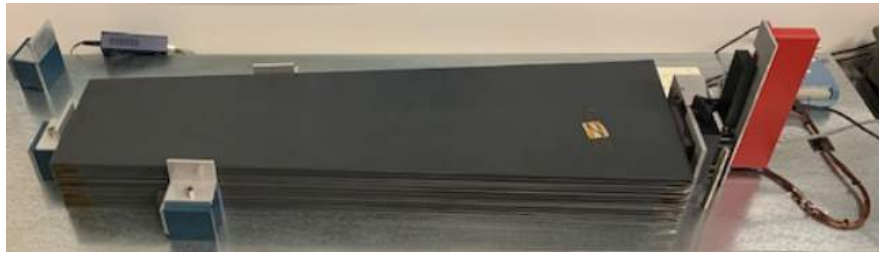


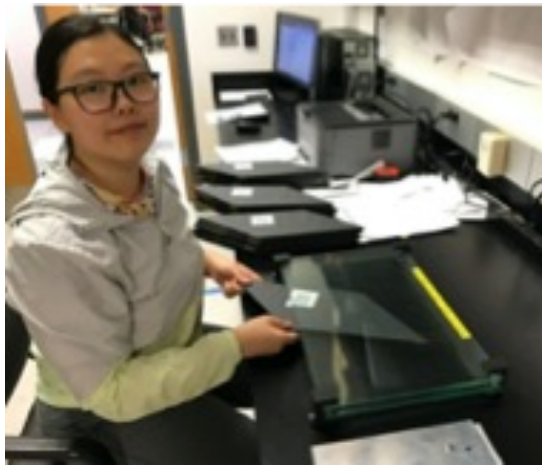
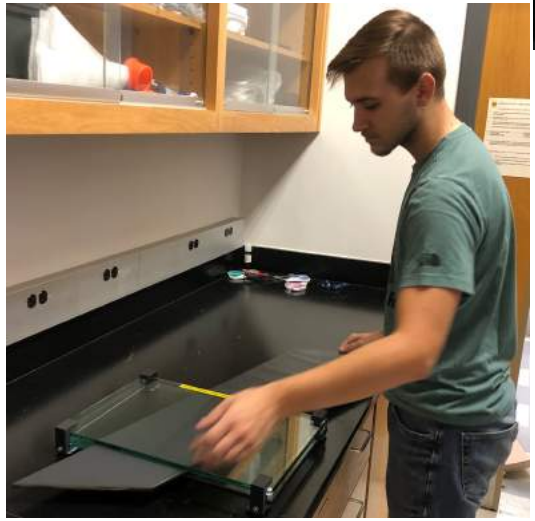
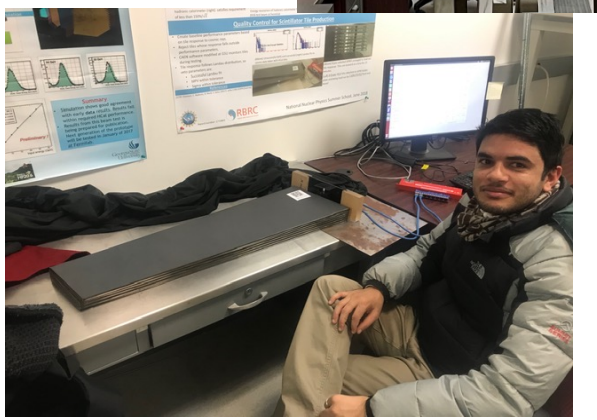

IEEE TNS, Vol 65, No. 12, p 2901, (2018)
IEEE TNS, Vol 68, No. 2, p. 173, (2021)

# GSU Students Testing Tiles

- >12 GSU undergrads worked with the tiles 2017-2021



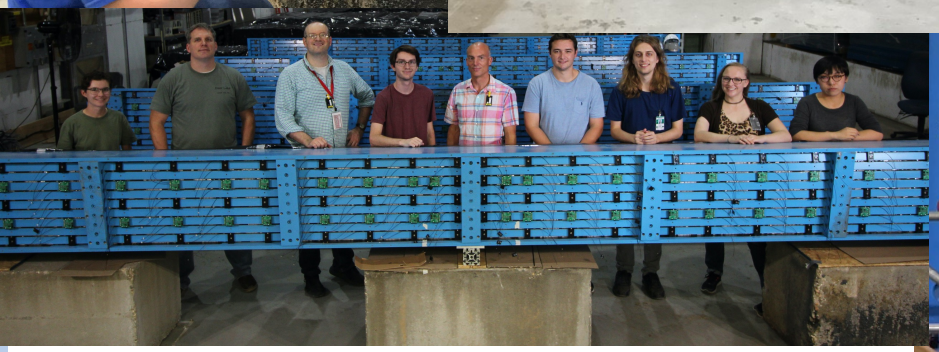





Funding for Hcal tiles and student labor through sPHENIX project

# Tiles to Calorimeter

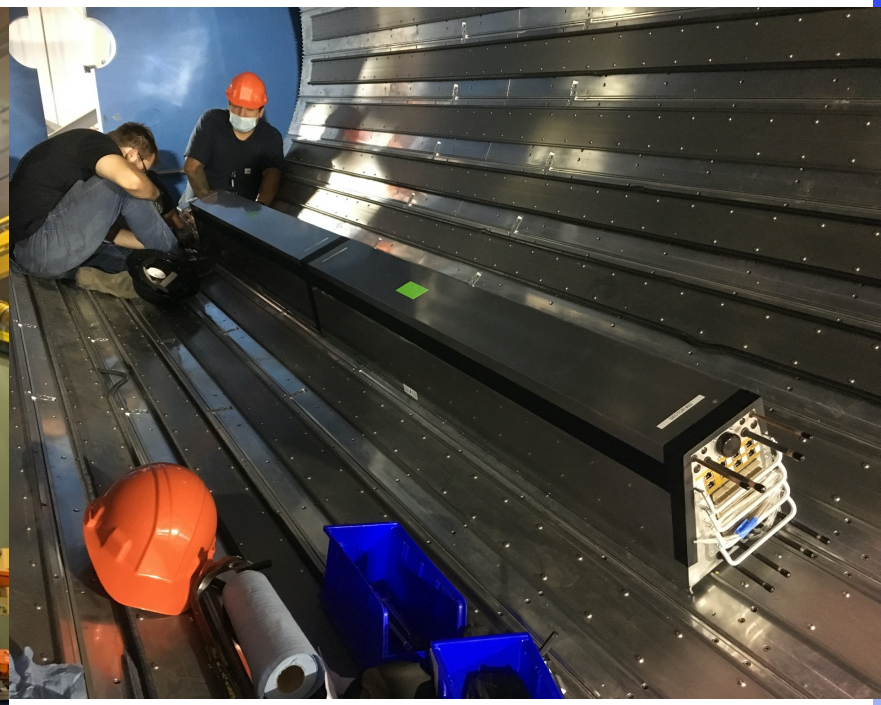
- Shipped tested tiles to BNL to be assembled in steel/aluminum sectors
- Outer Hcal was the first sPHENIX detector to be installed





# sPHENIX in Summer 2022

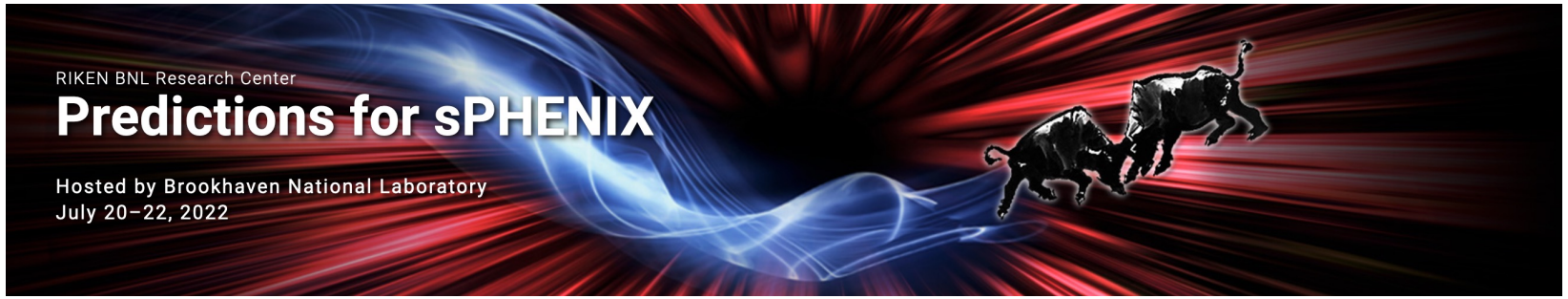
- Inner HCal installed



- EMCal installation

*GSU undergrads support from DOE NP trainee program prepared calorimeter cables*

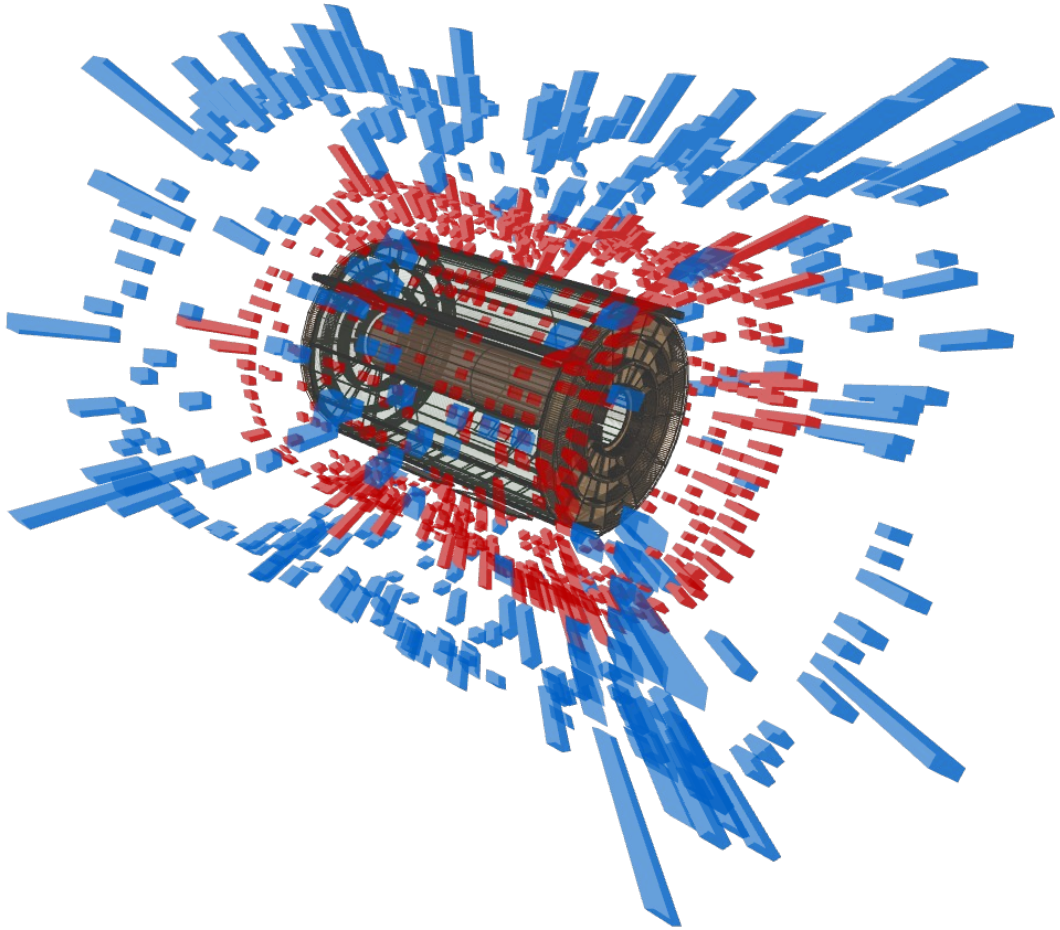
# Preparing for data and physics




- RBRC Workshop bringing together theorists and experimentalists to discuss model predictions and potential new measurements
- Collected theory calculations after the workshop into a paper which has been submitted for publication:
  - https://arxiv.org/abs/2305.15491

# First sPHENIX data in 200 GeV Au+Au collisions

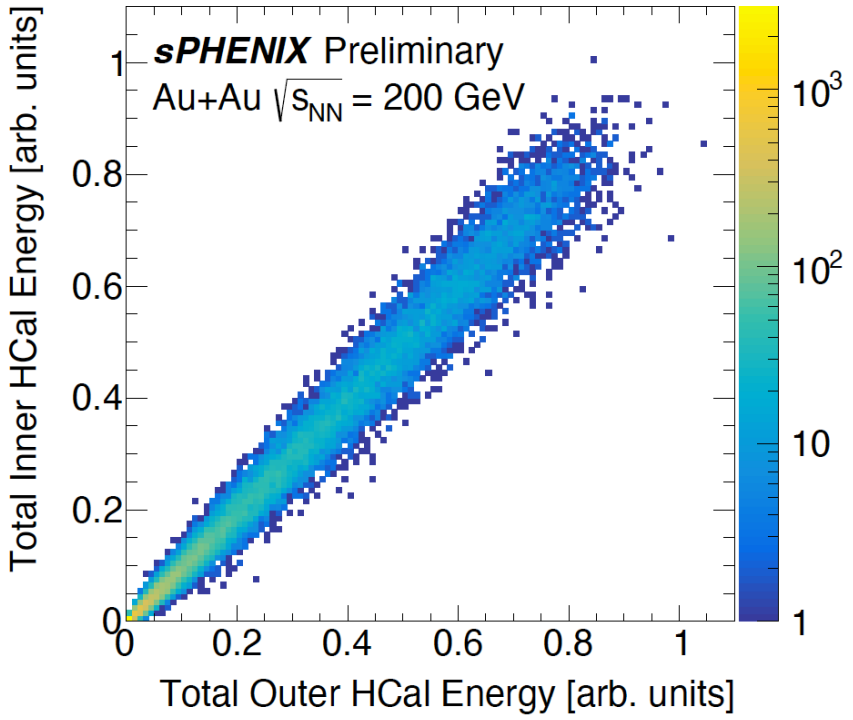
sPHENIX Experiment at RHIC
Data recorded: 2023-05-22, 02:07:00 EST
Run / Event: 7156 / 12
Collisions: Au + Au @ 200 GeV



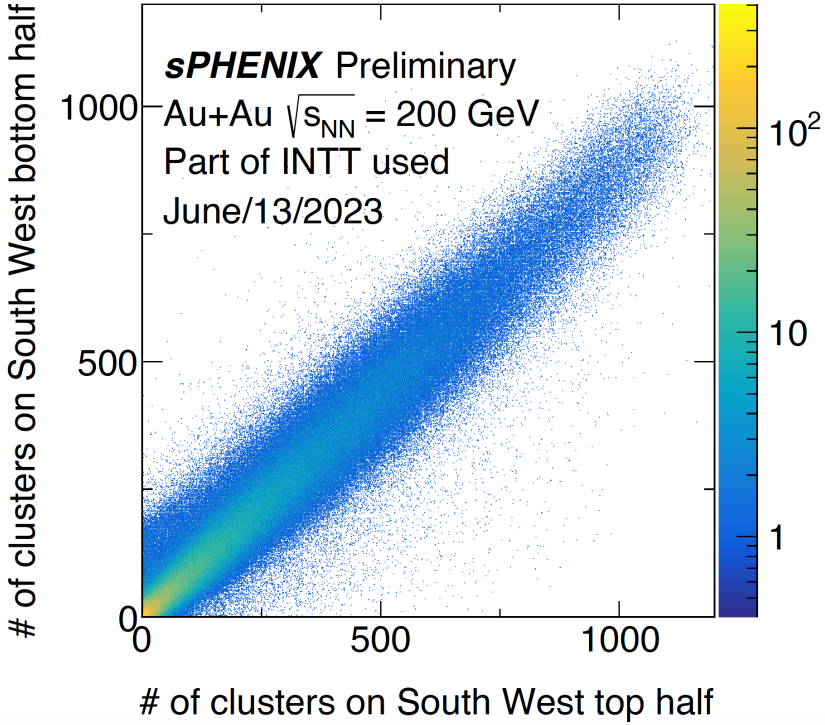
- Event display of the sPHENIX hadronic calorimeter in 200 GeV Au+Au data
  - Shows Energy in the inner and outer HCals
- Ongoing commissioning and calibration of the sPHENIX detector

# First sPHENIX data in 200 GeV Au+Au collisions

**Energy correlation of iHCAL and oHCAL**




**Cluster correlation of different regions of the INTT**



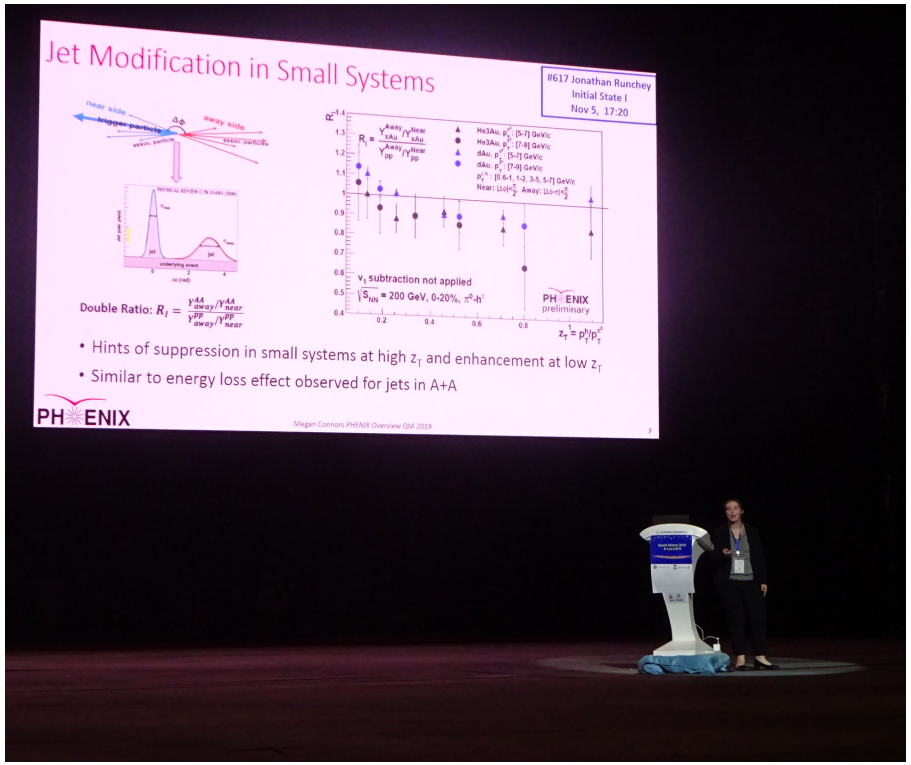

*GSU students Summer 2023*

- Correlations of detectors show successful readout

# Summary

- Jet quenching observed as a suppression in the yield of high $p_T$ particles/jets and a broadening of distributions of jet particles
- Open questions that can be addressed with sPHENIX
- sPHENIX commissioning currently underway and first glimpse of data has been shared
- Looking forward to future sPHENIX results
- Future for jets & the hadronic calorimeter at EIC
- The support from RBRC is greatly appreciated

# *Thank you to the RBRC…*




- *Support for travel to conferences*
- *Support for visits to BNL*
- *Support for student trips to BNL*
- *Workshops*
- *Many opportunities*