Precision Jet Measurements with sPHENIX

Megan Connors

Jets for 3D Imaging at EIC Workshop

September 27, 2021
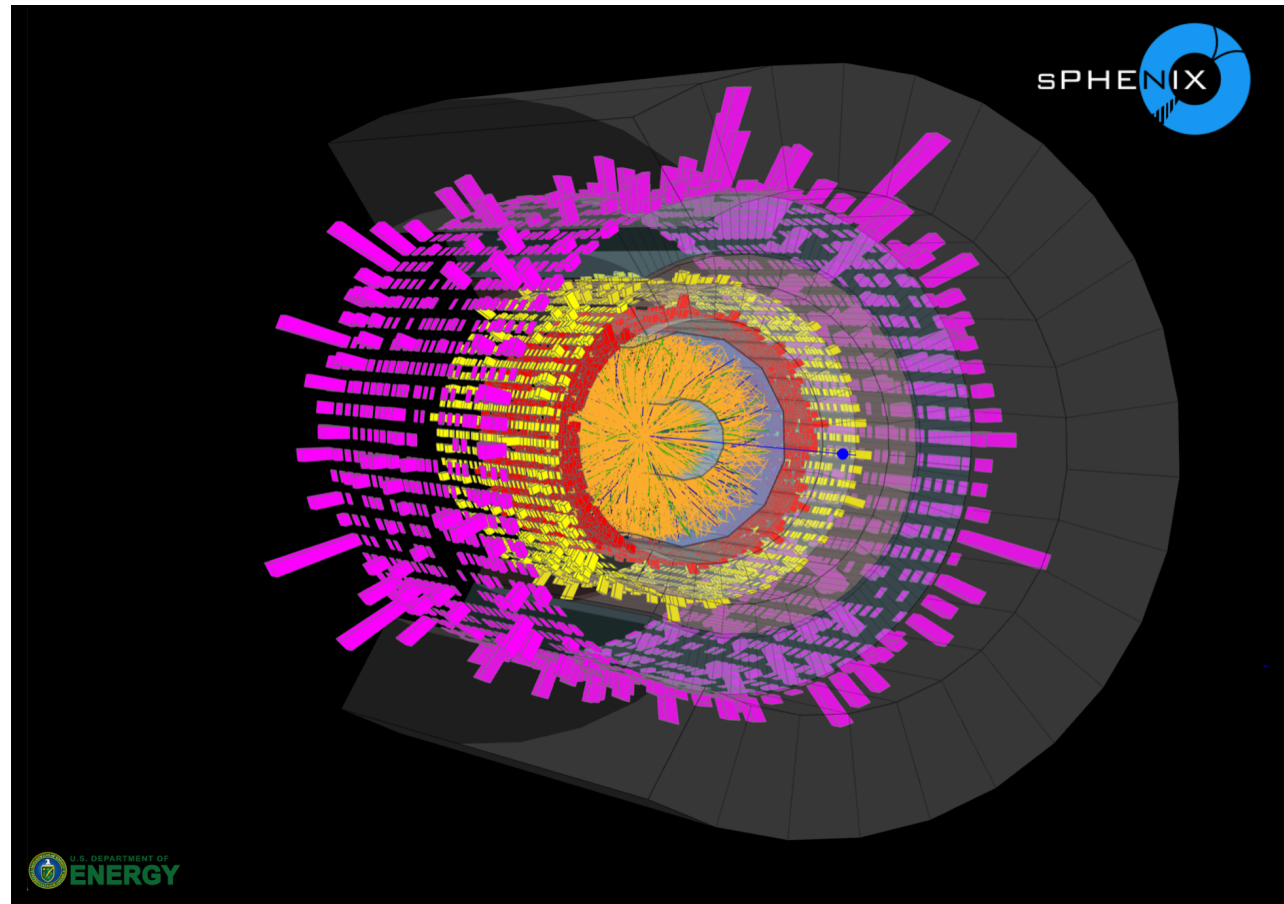
sPHENIX Mission
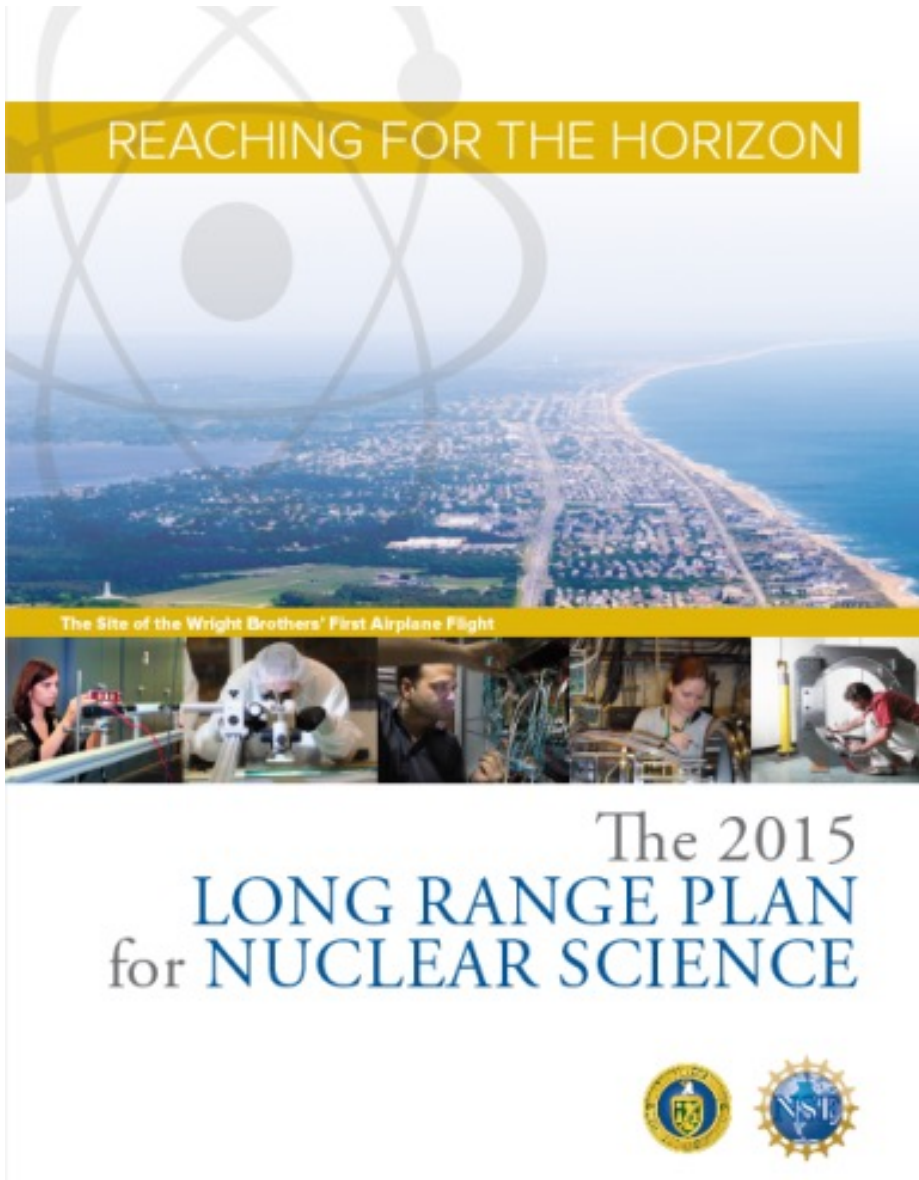
There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX.** (2) Map the phase diagram of QCD with experiments planned at RHIC.
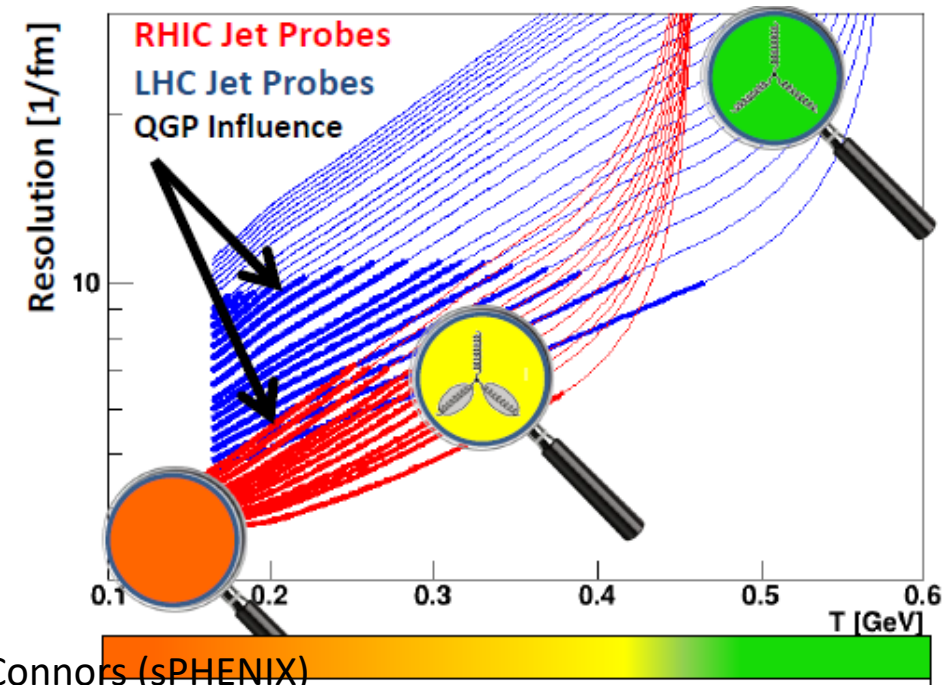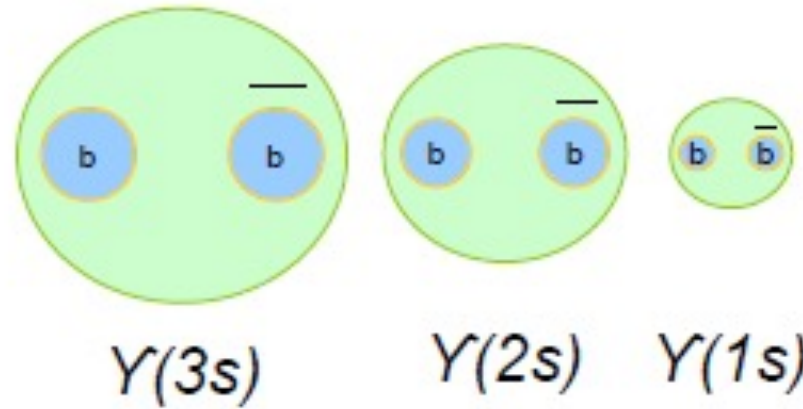
Probe QGP at Multiple Scales

u, d, s

g

c

b
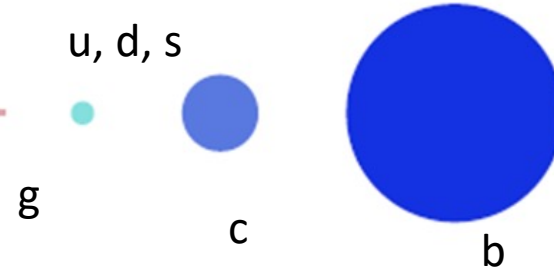
Parton energy loss
vary mass/momentum of probe

$p_{T,1}$

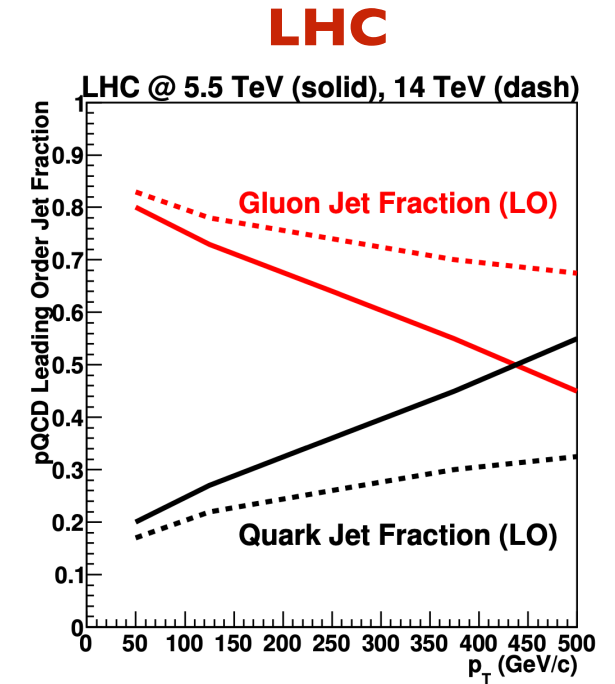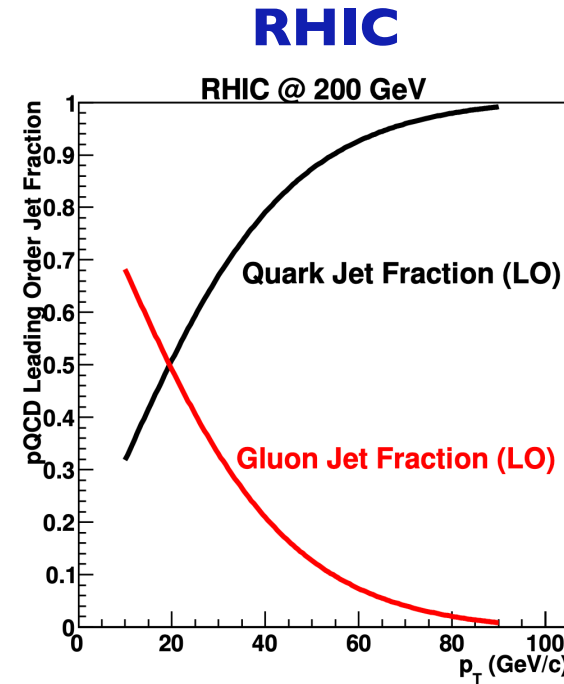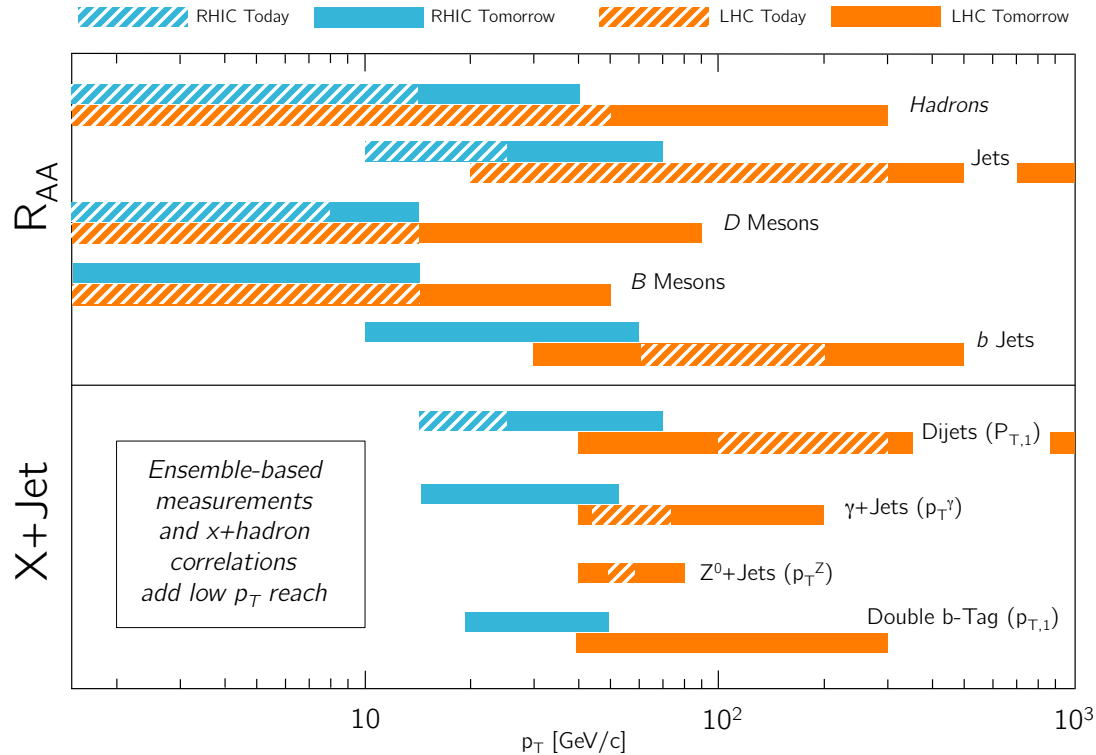$p_{T,2}$

Y(3s)   Y(2s)   Y(1s)
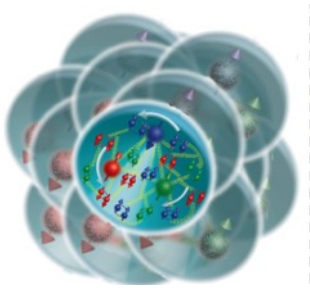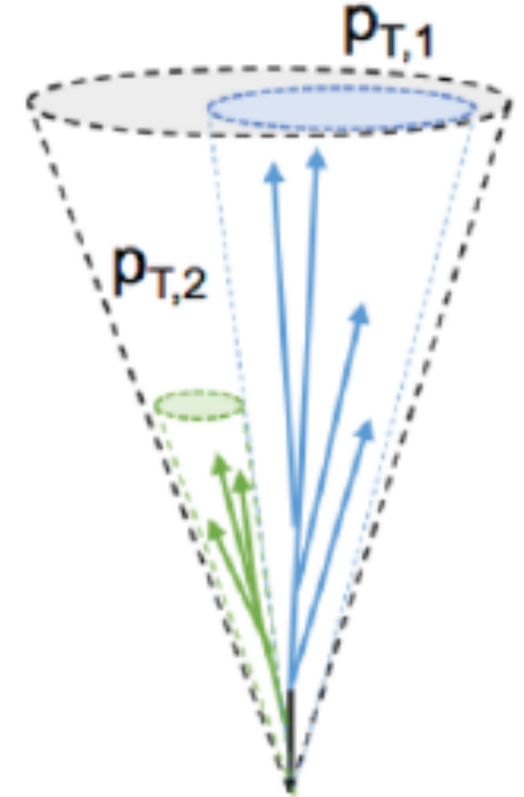
Cold QCD
vary temperature of
QCD Matter

Quarkonium spectroscopy
vary size of probe

Jet structure
Vary momentum/angular
scale of probe

University of Colorado Boulder

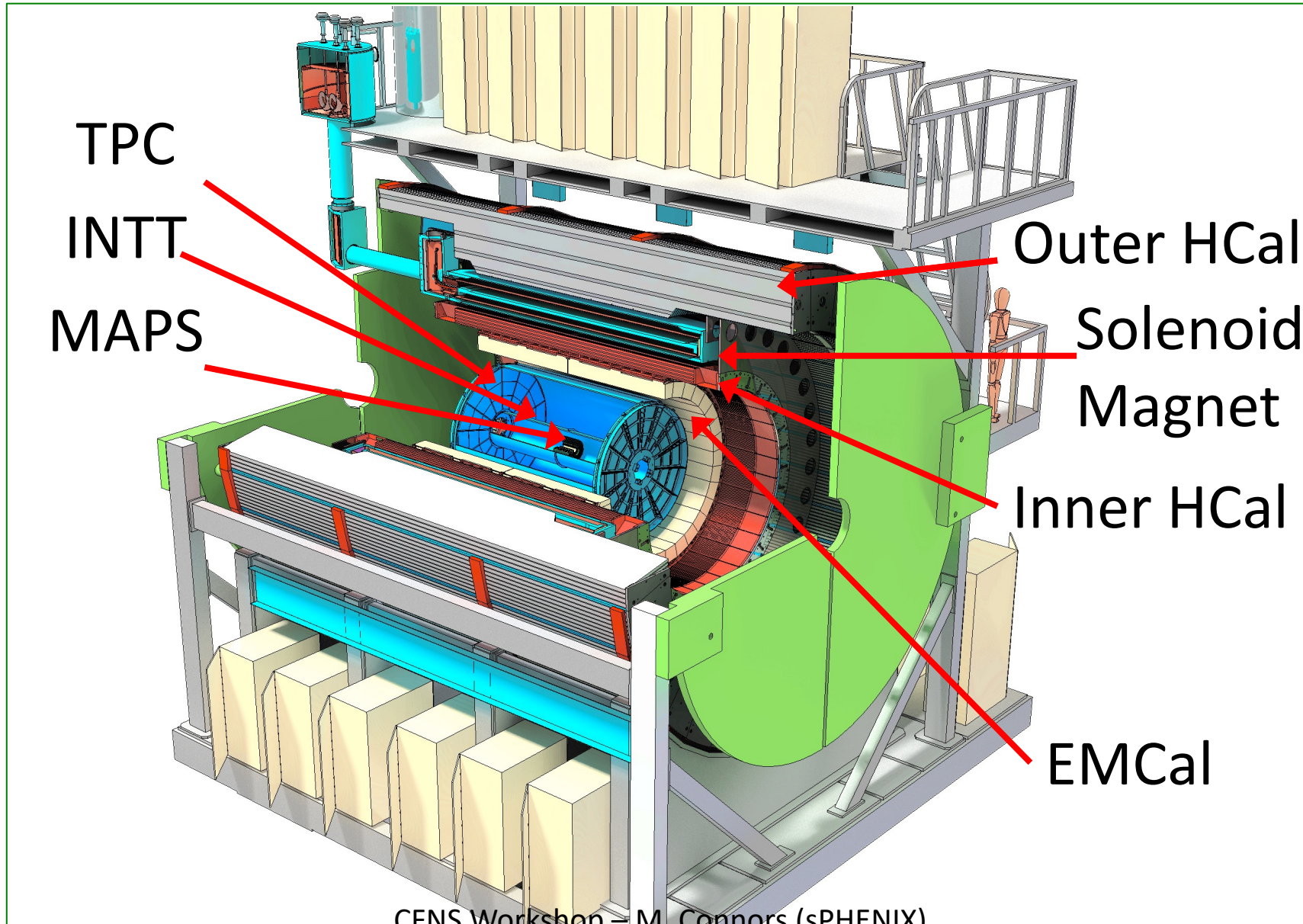# RHIC/LHC Complementarity

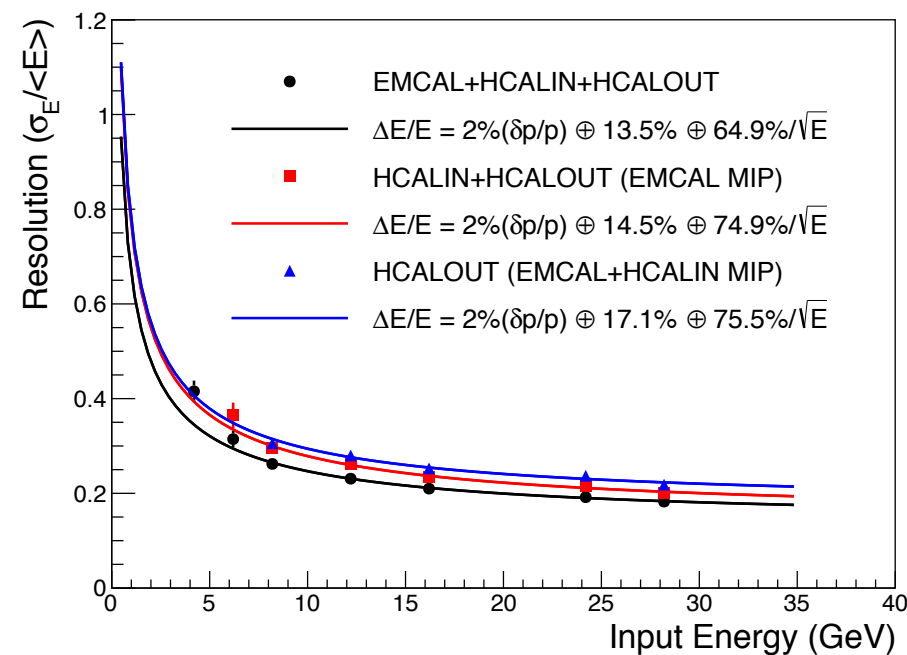- Significant overlap achievable with "tomorrow's" RHIC-LHC jet measurements

- Different mixture of quark and gluon jets at RHIC/LHC

sPHENIX Detectors

TPC

INTT

MAPS

Outer HCal

Solenoid Magnet

Inner HCal

EMCal

Importance of Calorimetry

- Good calorimeters are crucial for measuring jets
- Allow for unbiased, efficient triggering in p+p
- EMCal measures photons for photon tagged jet
- Excellent energy resolution for jets
- Beam Test studies validate simulations
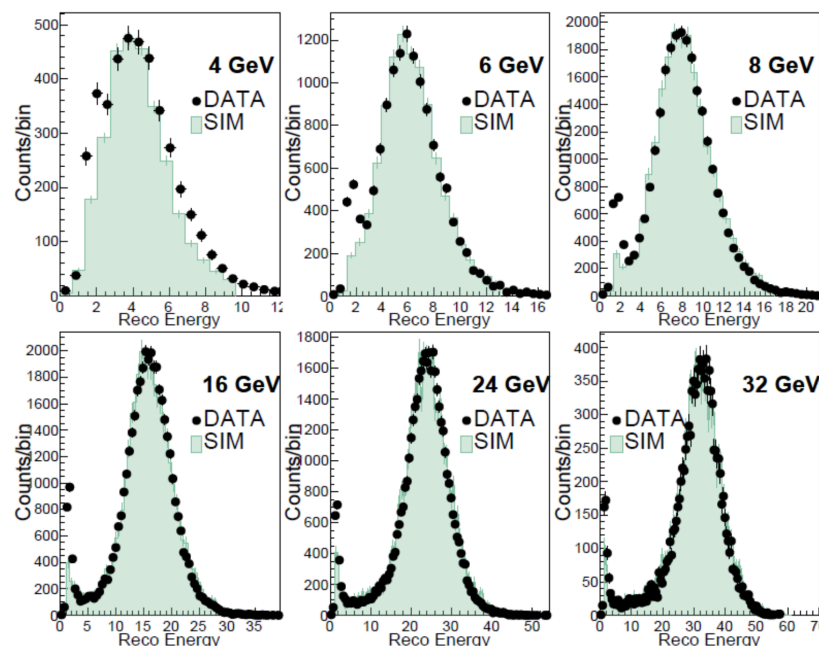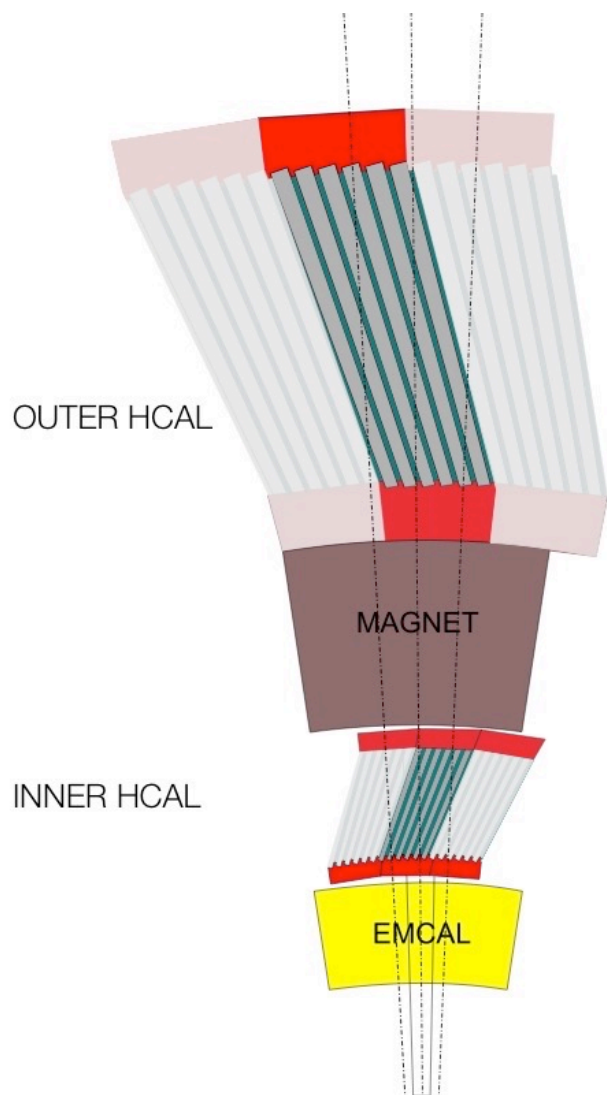
arXiv 2003.13685, arXiv 1704.01461

Jet finding on a ΔηxΔφ = 0.1x0.1 grid

CEMC

IHCal

CEMC

22(η)x64(φ) ~ 1.5k towers

IHCal

OHCal

IHCal

22(η)x64(φ) ~ 1.5k towers

OHCal

OHCal

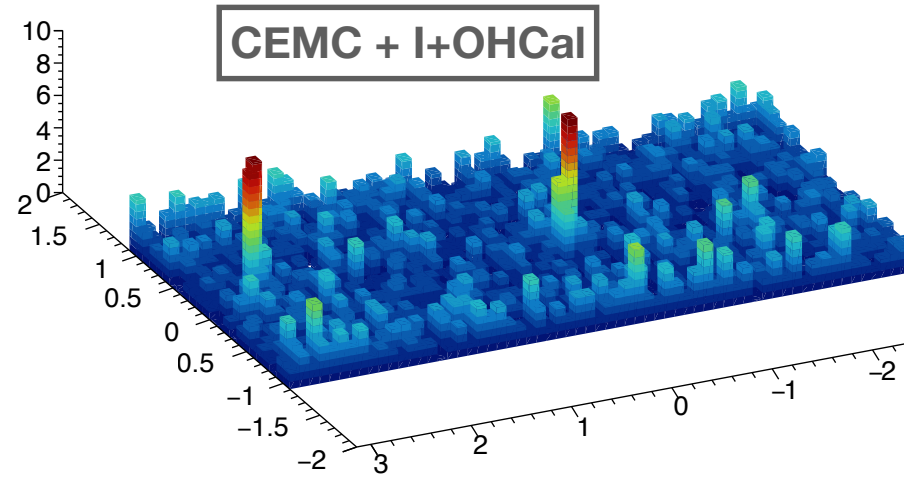CEMC + I+OHCal
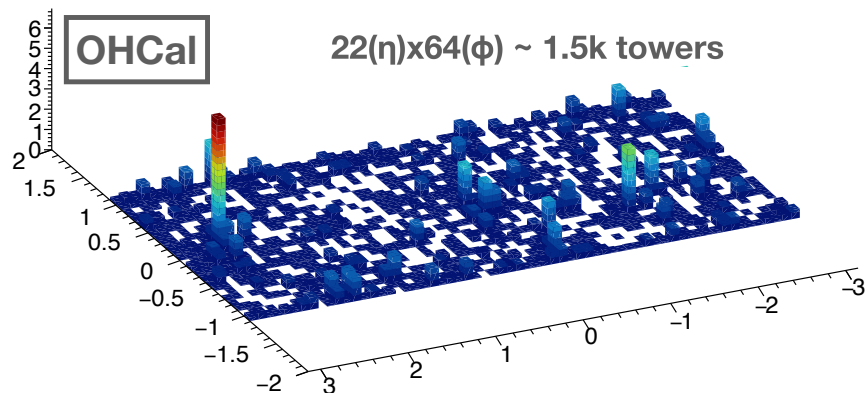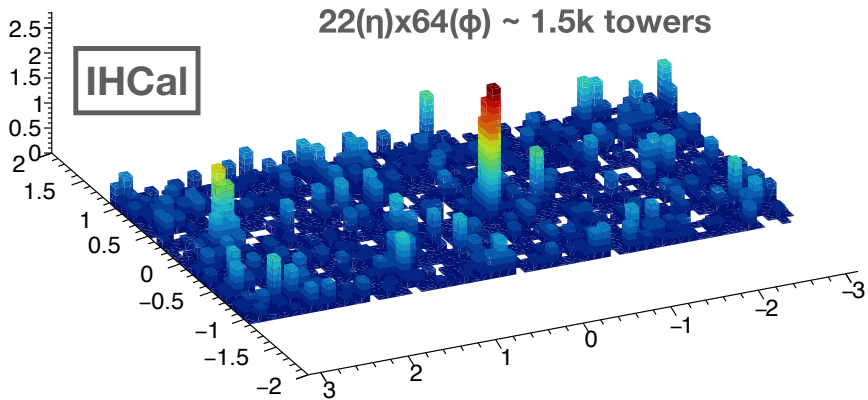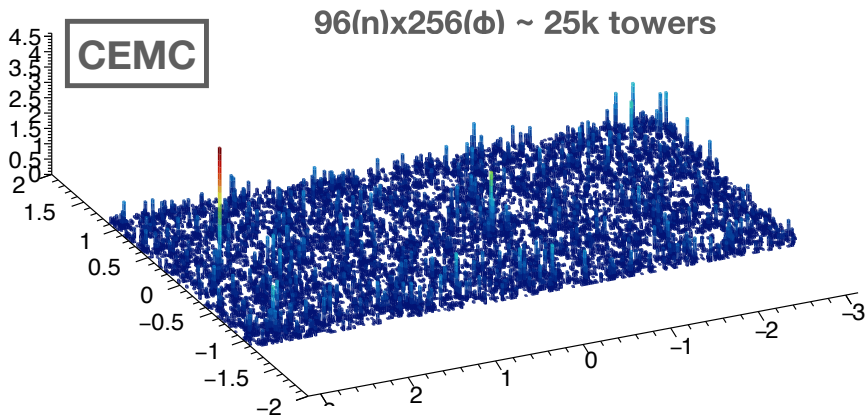
Iterative subtraction procedure:
- Exclude R=0.2 jet seeds
- Determine background in each layer and η-ring

Combine layers

CEMC + I+OHCal
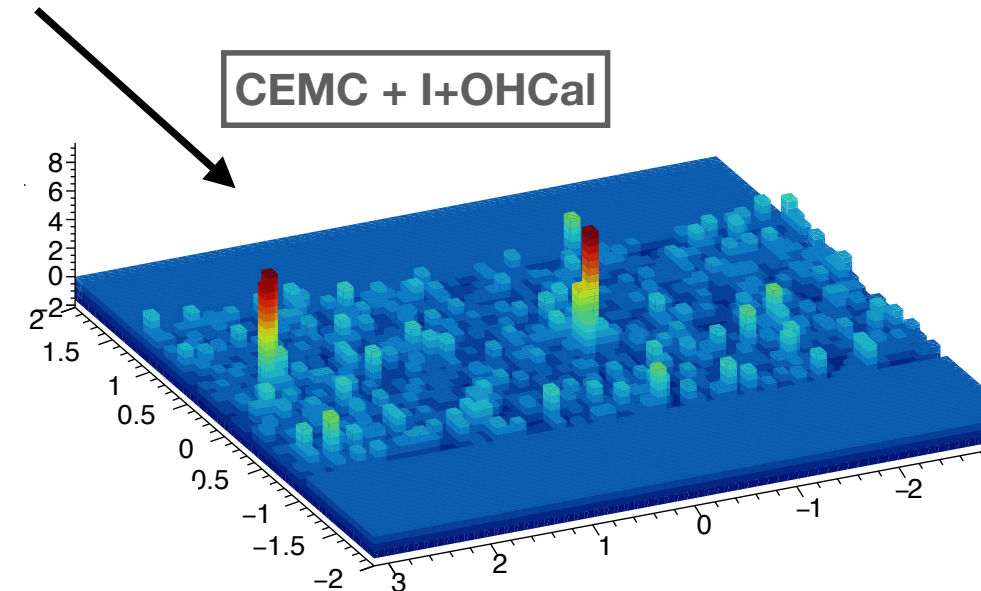
Calorimeter Jets

Jet Energy Scale
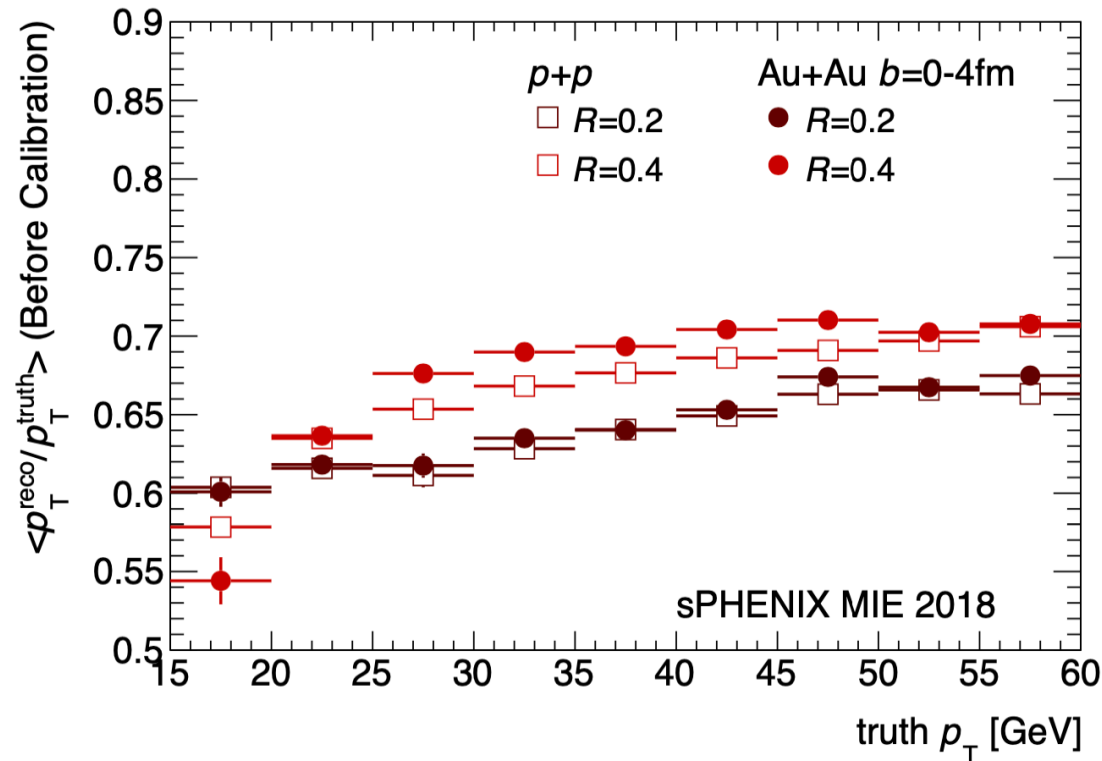
Jet Energy Resolution
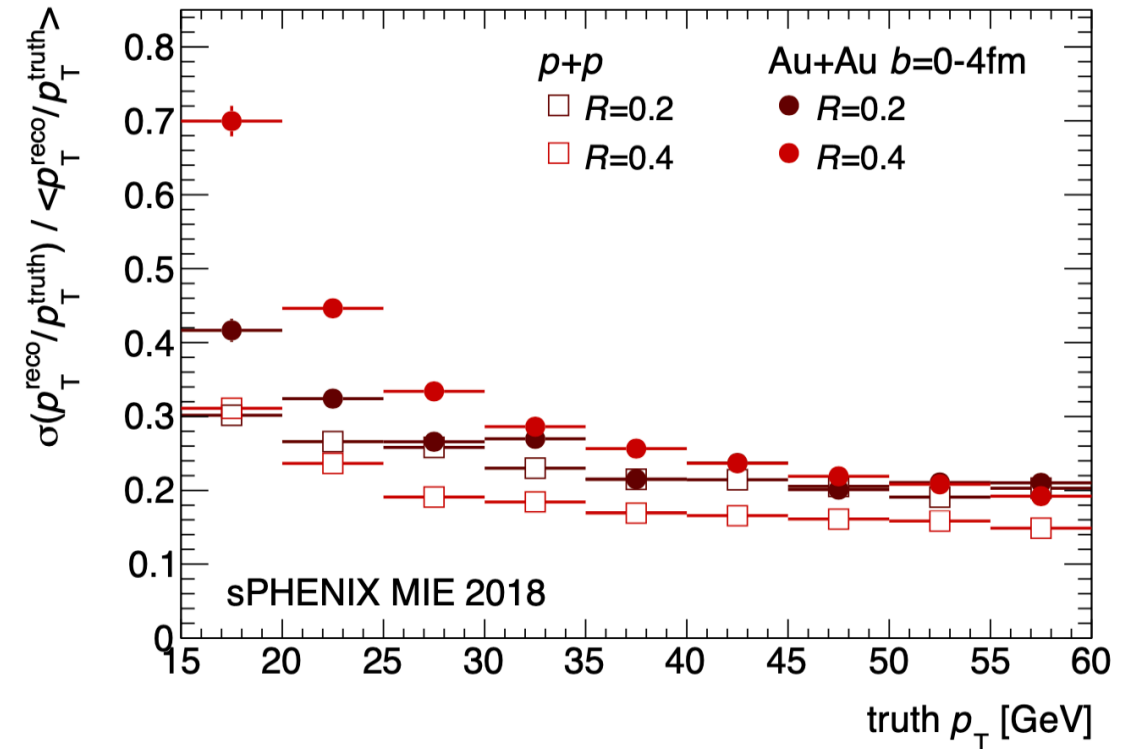
- UE fluctuation at low p_T for large R jets
- Expected jet radius ordering

Importance of Tracking
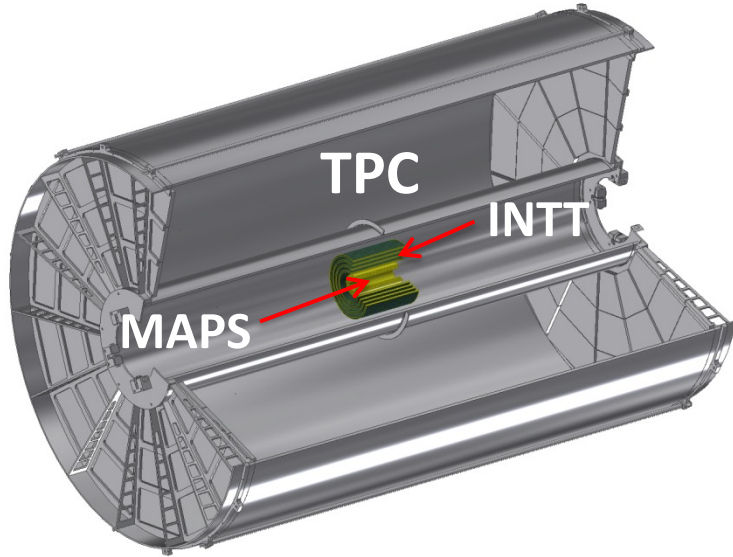
- Specifications driven by Upsilon/HF program
- Benefits to jet program
  - **Particle flow jets**
  - **Excellent momentum resolution for fragmentation functions**
  - **Excellent track pattern recognition for jet substructure studies**
  - **Precise DCA resolution for HF jet tagging**
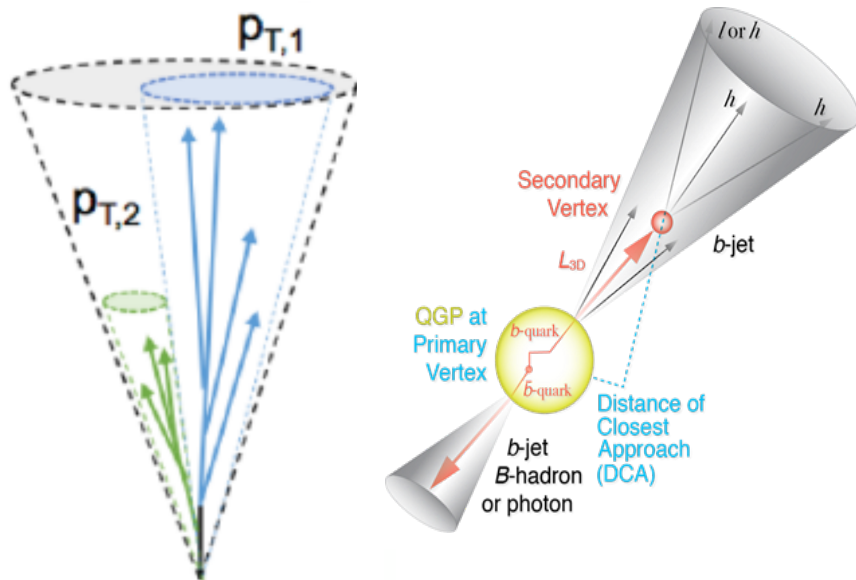
Particle Flow Jets
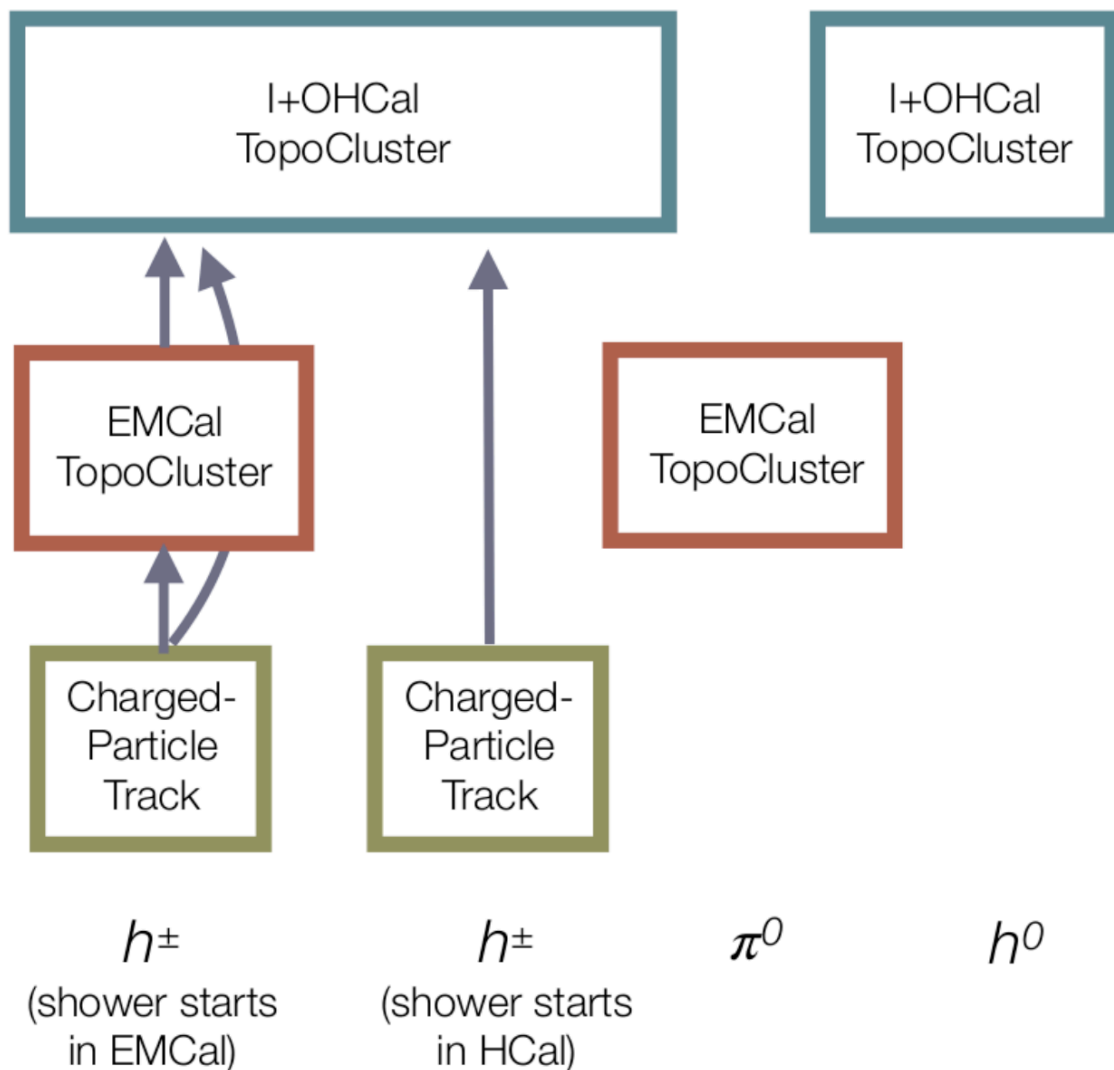
- Combine ideas from ATLAS & CMS

- Uses charged-particle track energy whenever match occurs

Jet Energy Response

sPHENIX G4 Simulation
$R = 0.4$, $p_T^{truth} = 30$ GeV
— Calorimeter Jet (EM-scale)
$\mu = 0.759$, $\sigma / \mu = 0.154$
— Particle Flow Jet
$\mu = 0.959$, $\sigma / \mu = 0.115$

Jet Response (p_T^{reco} / p_T^{truth})
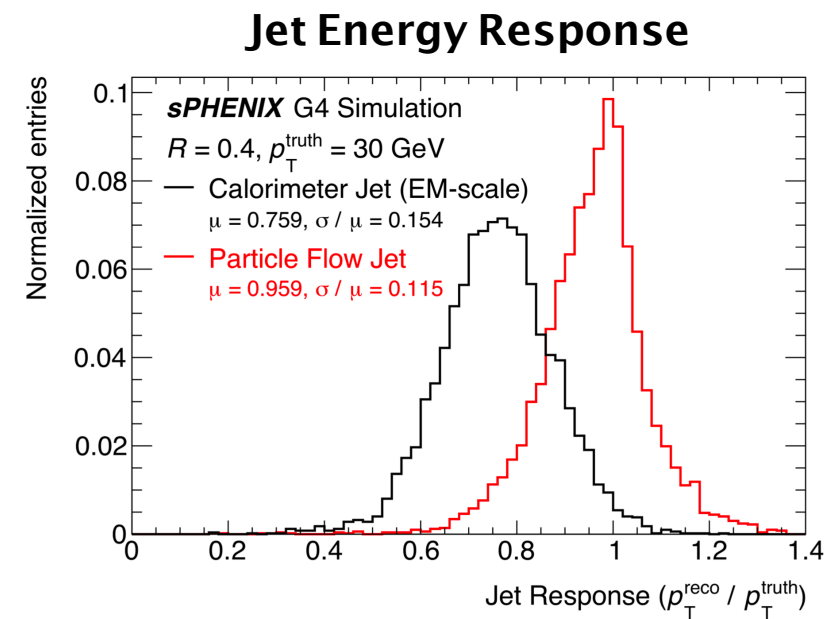
- Tracking information reduces sensitivity to fragmentation, better allows sub-structure measurements

sPHENIX Timeline

2015   2016   2017   2018   2019   2020   2021   2022   2023

sPHENIX science collaboration

DOE CD-0 "Mission need" approval

DOE CD-1/3A Cost, schedule, advance purchase approval

BNL PD-2/3 Final project design approval

Installation & commissioning

sPHENIX → data taking in early 2023
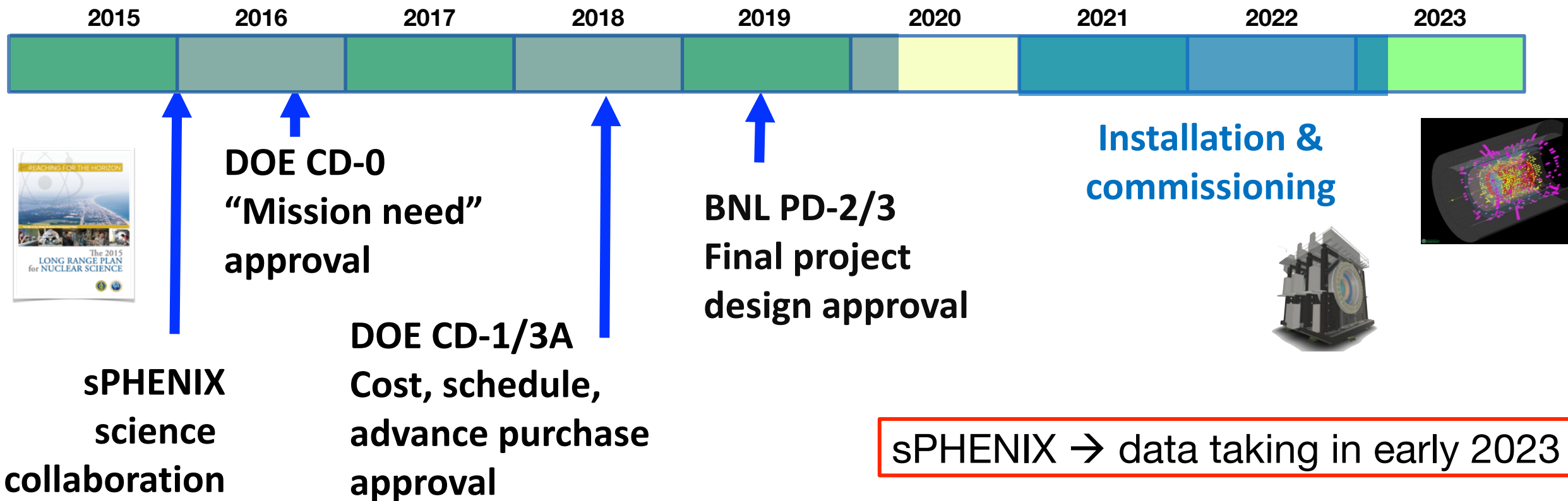
Proposed Plan

- First 3 years of data taking

2023	2024	2025
Au+Au	p+p/p+Au	Au+Au

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $|z| < 10$ cm	Samp. Lum. $|z| < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^\uparrow p^\uparrow$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-str]	45 (62) pb^{-1}
2024	$p^\uparrow$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-str]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	

OHCal
IHCal
EMCal
MAPS+IT+TPC

sPHENIX G4 simulation
Pythia8, 50 GeV dijet event

Pythia8 γ+jet, $p_T^\gamma > 30$ GeV, $p_T^{jet} > 20$ GeV

$\mu = 0.798$
$\sigma = 0.102$

$(1/N_\gamma)(dN/d(p_T^{reco}/p_T^{truth}))$
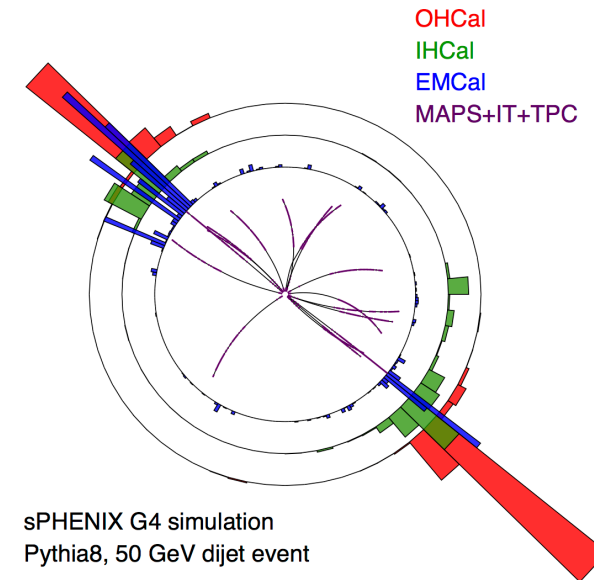
Jet Statistics with Heavy Ions
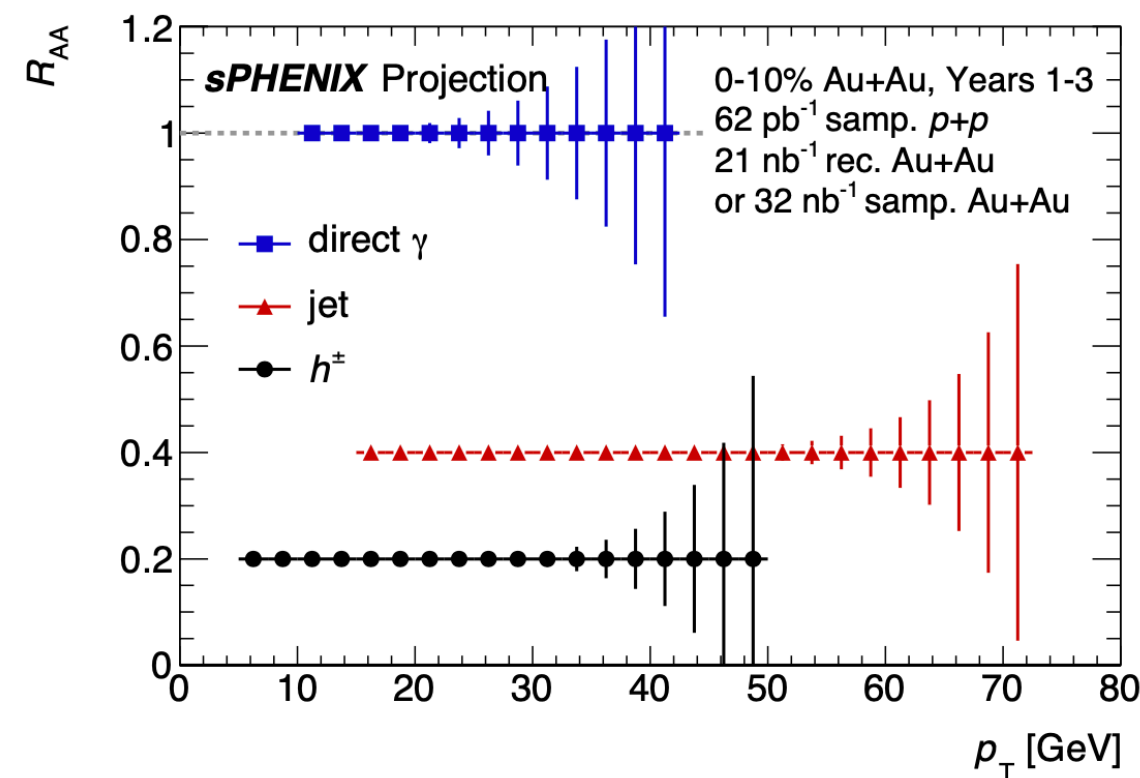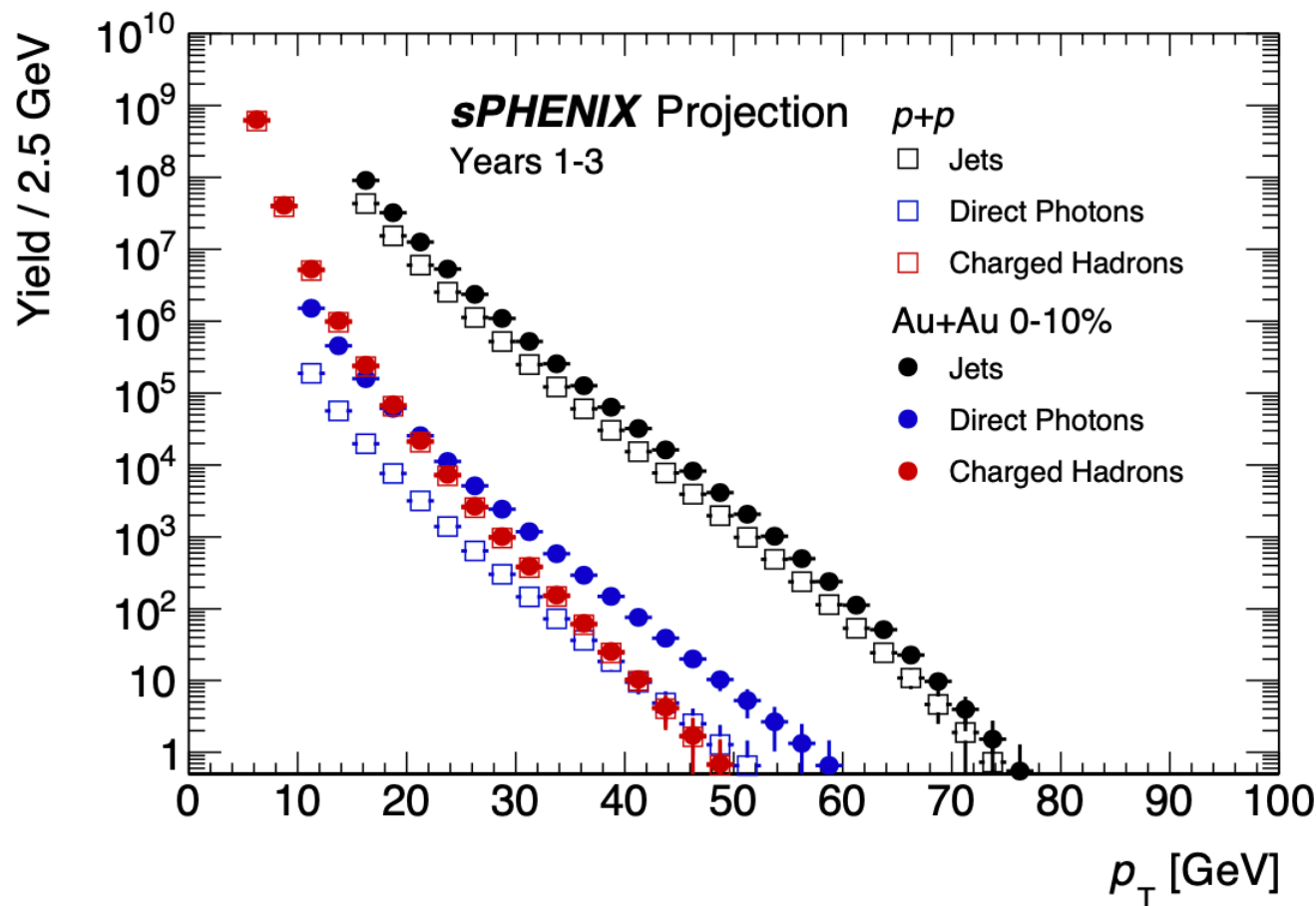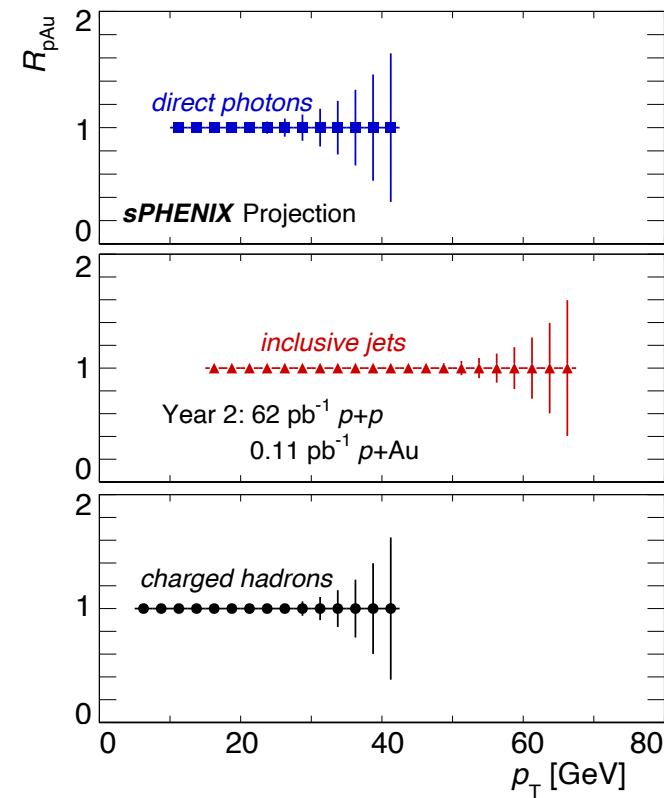

Central Yields p_T Range

10^7 jets   > 20 GeV/c

10^6 jets   > 30 GeV/c

10^4 γ_{dir} > 20 GeV/c

10^4 b-jets > 20 GeV/c
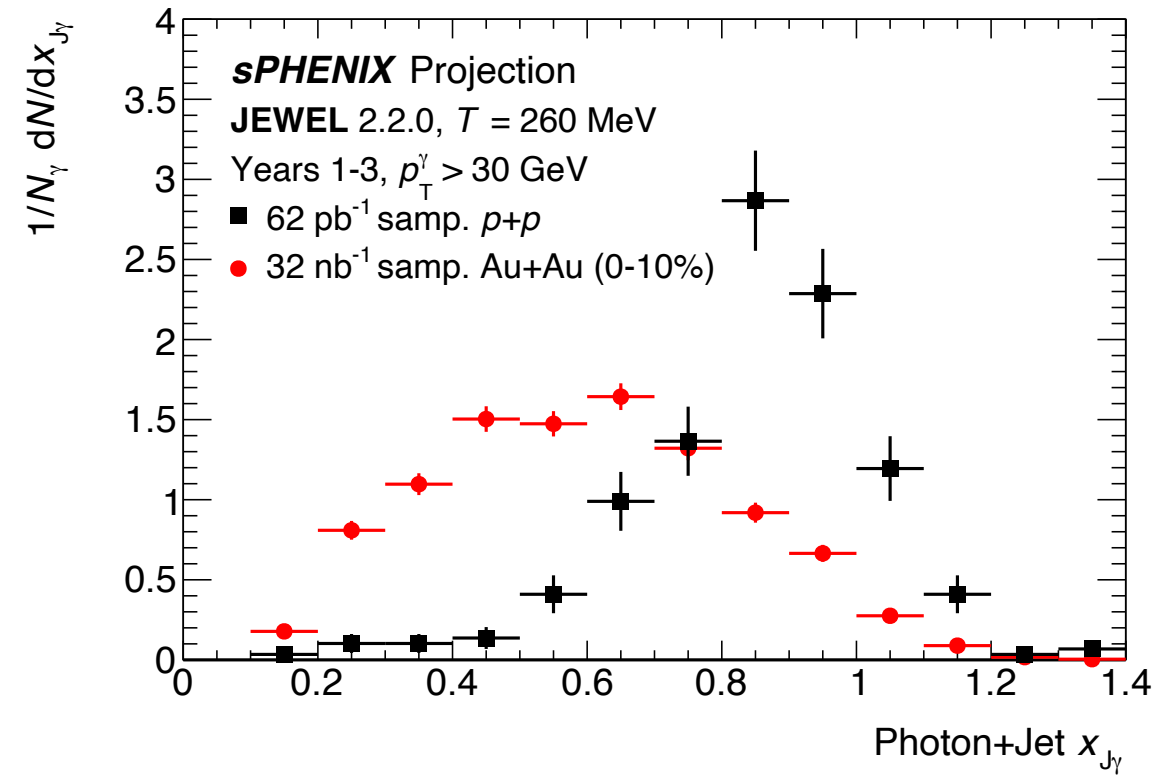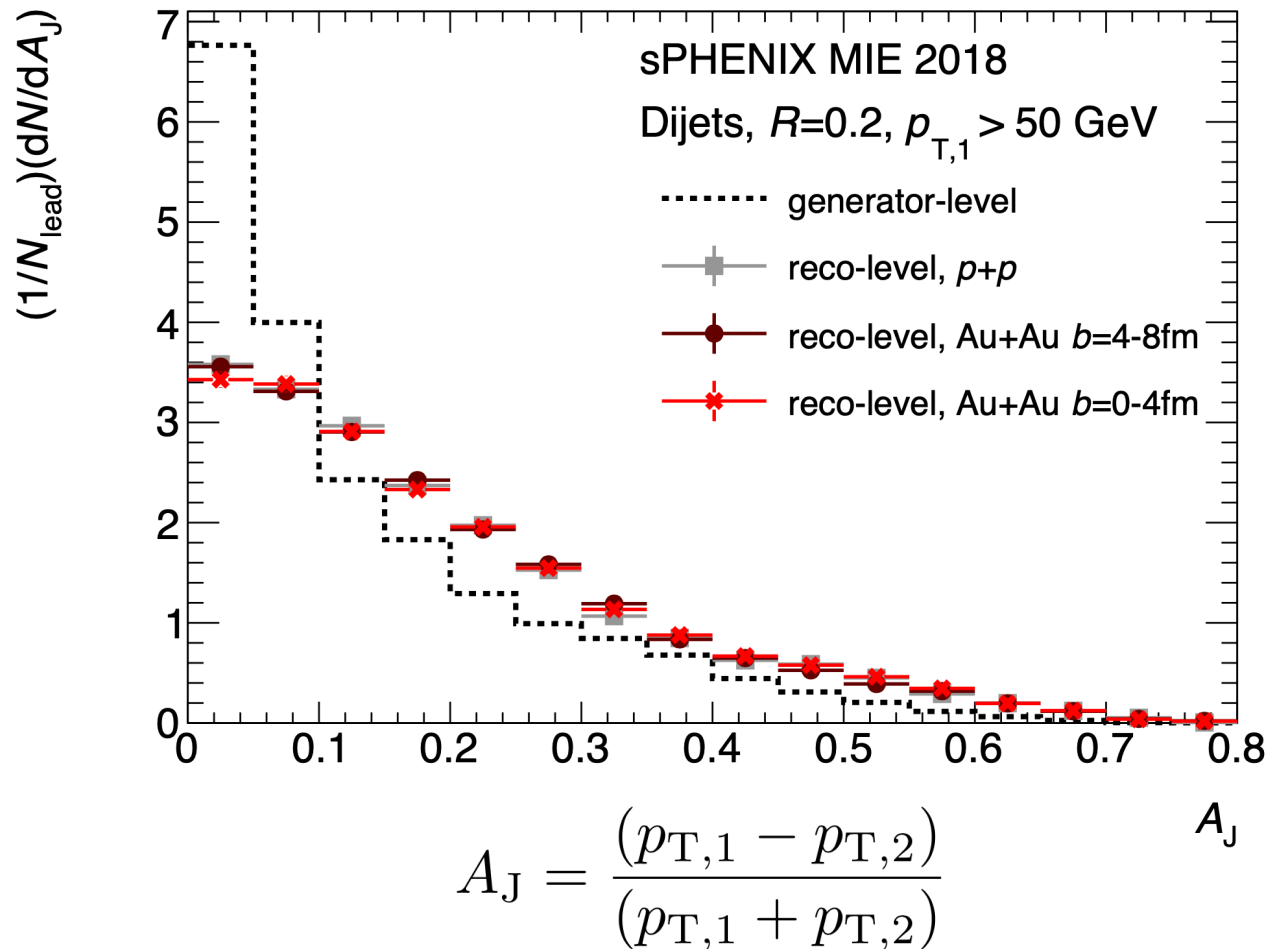
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Jets Statistics with Cold QCD

- Utilizing p+Au and p+p data from year 2

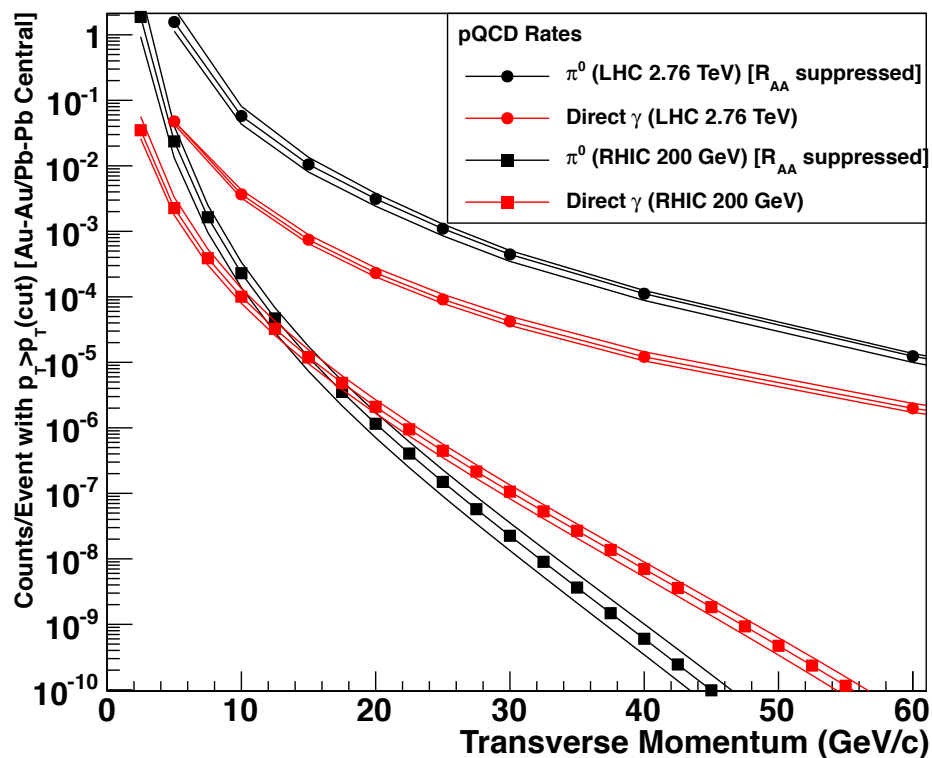- Extends previous RHIC photon/hadron measurements beyond 20 GeV/c
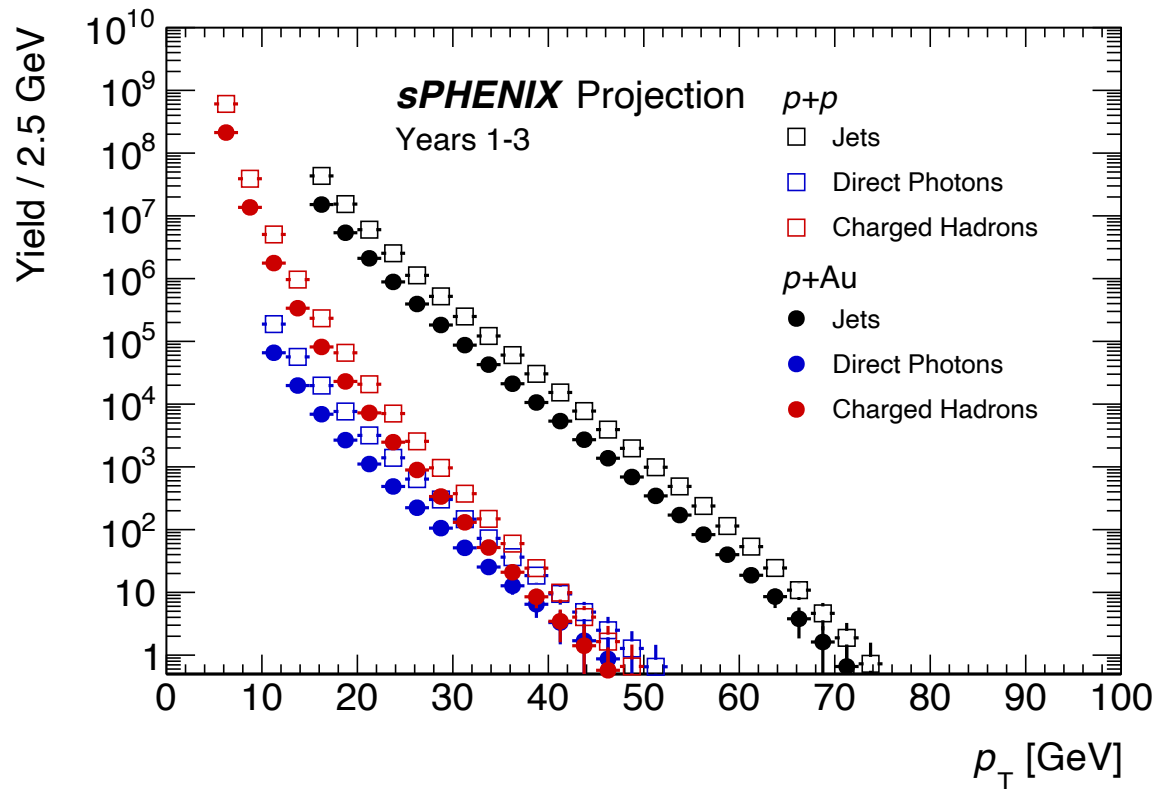
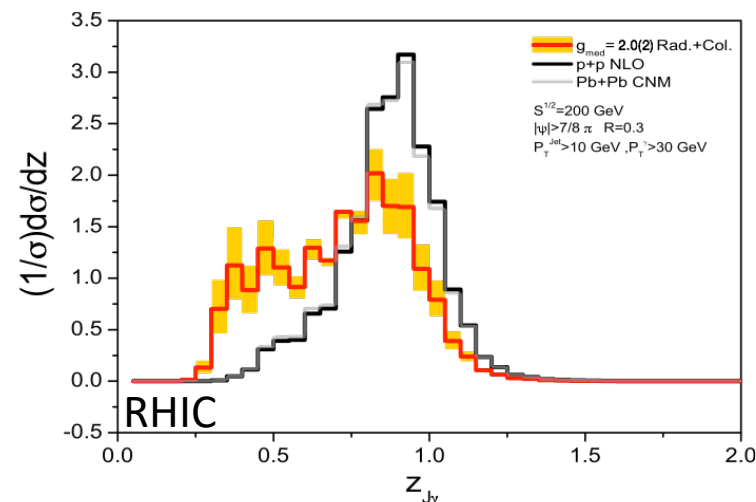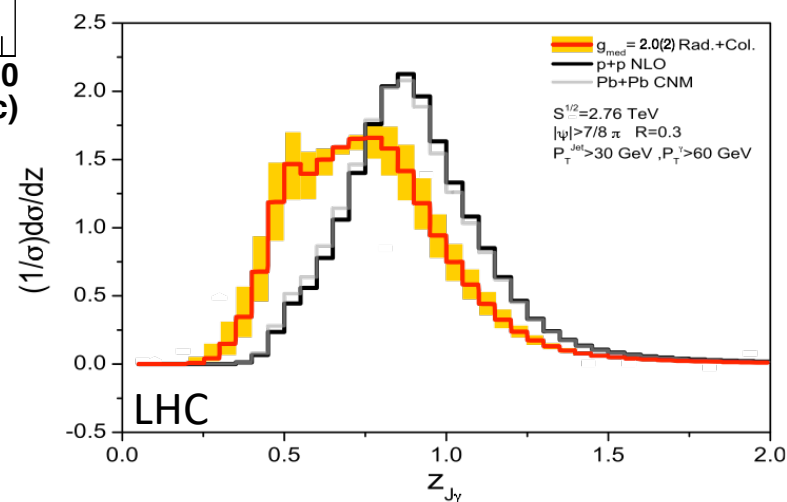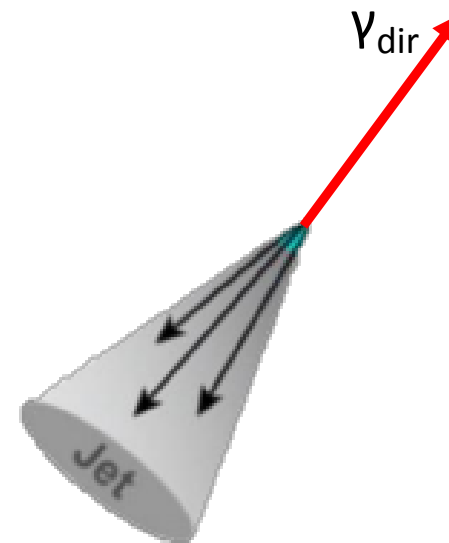# First Observables

- Dijet and photon-jet Asymmetries can be measured with Calorimeter jets

$$A_{\mathrm{J}} = \frac{(p_{\mathrm{T},1} - p_{\mathrm{T},2})}{(p_{\mathrm{T},1} + p_{\mathrm{T},2})}$$

Photon-jets at RHIC

LHC

RHIC

γ_{dir}

Photon tagged jet fragmentation functions

$$z = p_h \big/ p_{jet}^i$$

$$z = p_h \big/ p_{jet}^f$$

PAS-HIN-16-002

increasing centrality
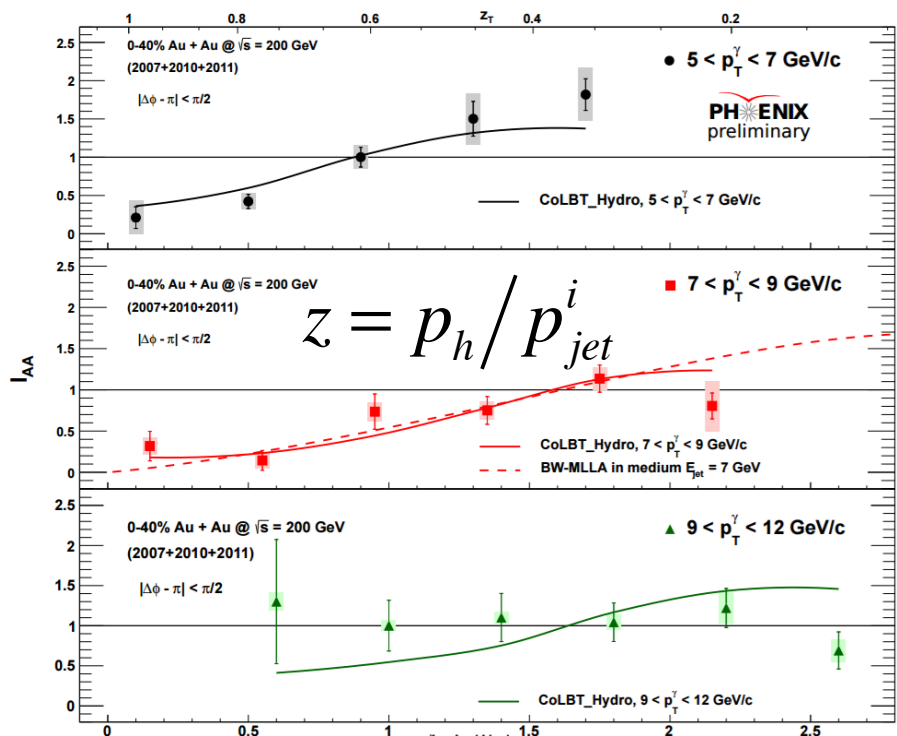
- Photon tags initial hard scattering kinematics

- Jet reconstructed after energy loss
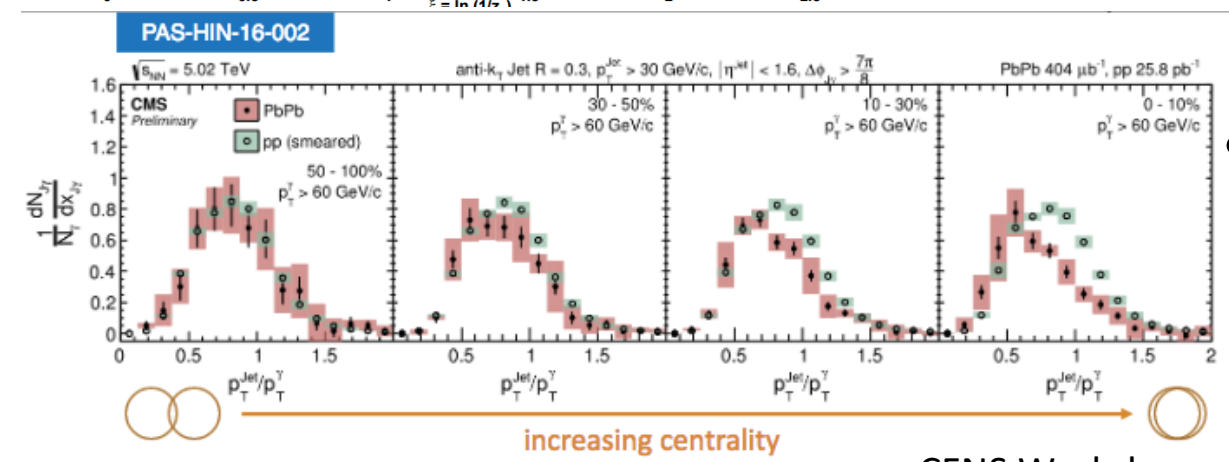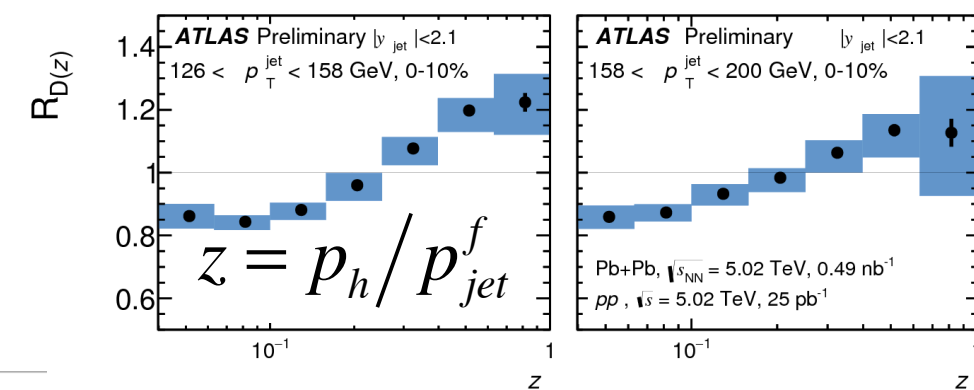
- Photon-tagged jets directly probe ΔE

$$p_{jet}^f \big/ p_{jet}^i$$

Photon-jet in sPHENIX

- Fragmentation Functions studied in sPHENIX

- γ-jet fragmentation functions require:

  - **Photon reconstruction in EMCal**

  - **Jet reconstruction (EMCal+HCals)**

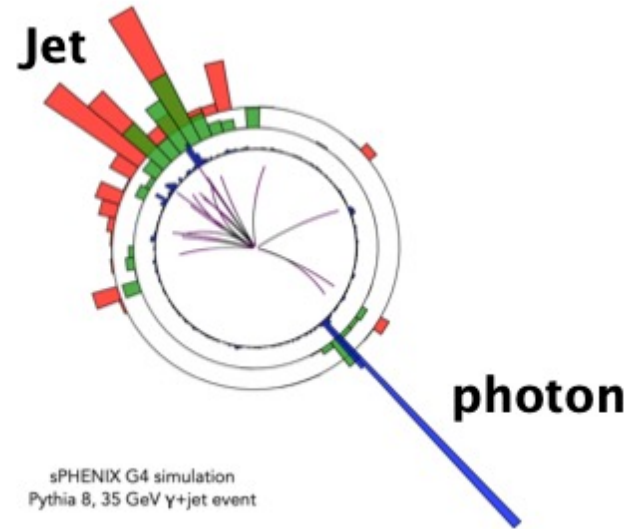 - **Tracking (MAPS+INTT+TPC)**
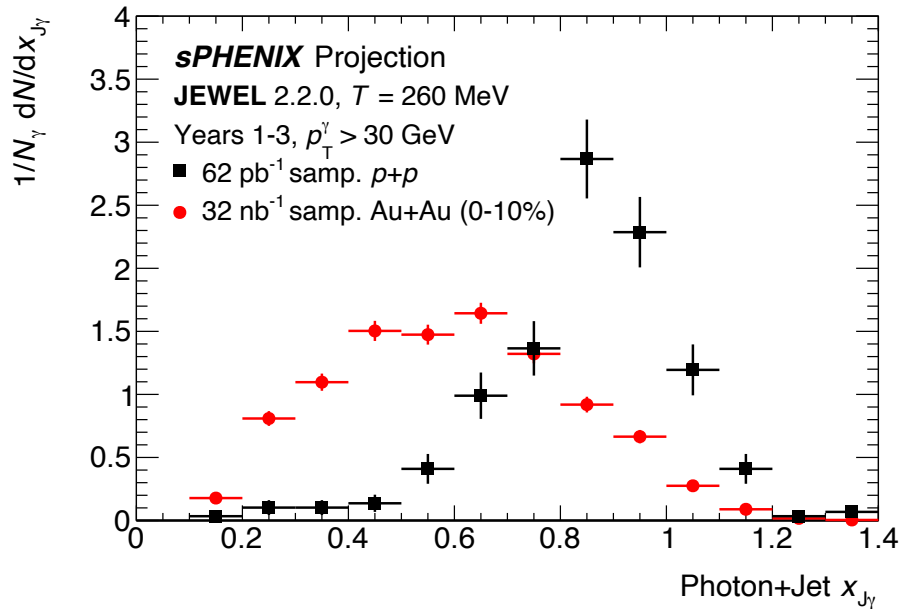
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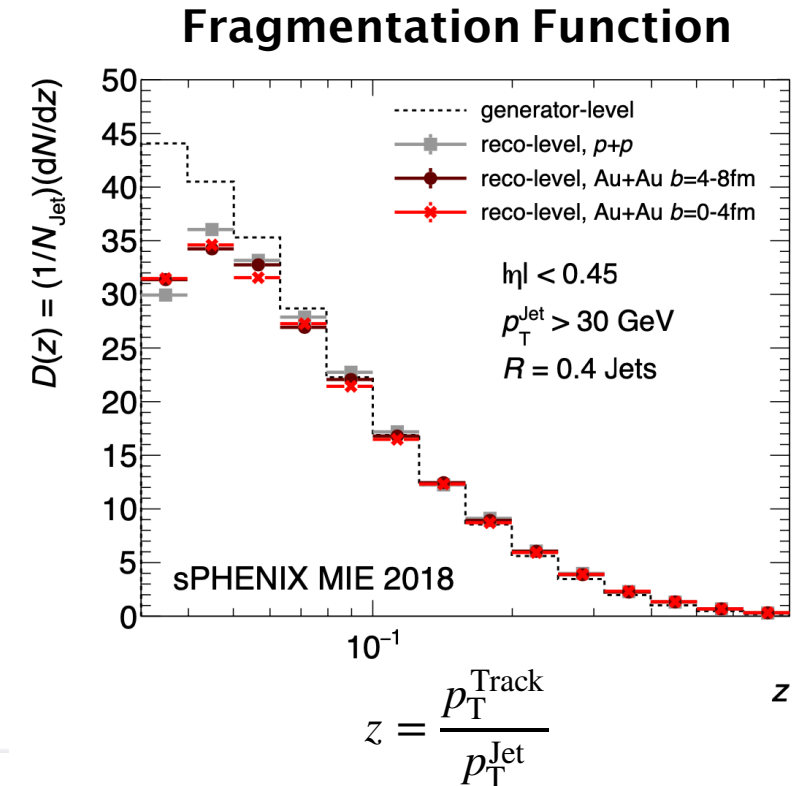
Jet Substructure

- Jet grooming one of many techniques to explore substructure of jets

- Groomed jets explore the evolution of the parton shower
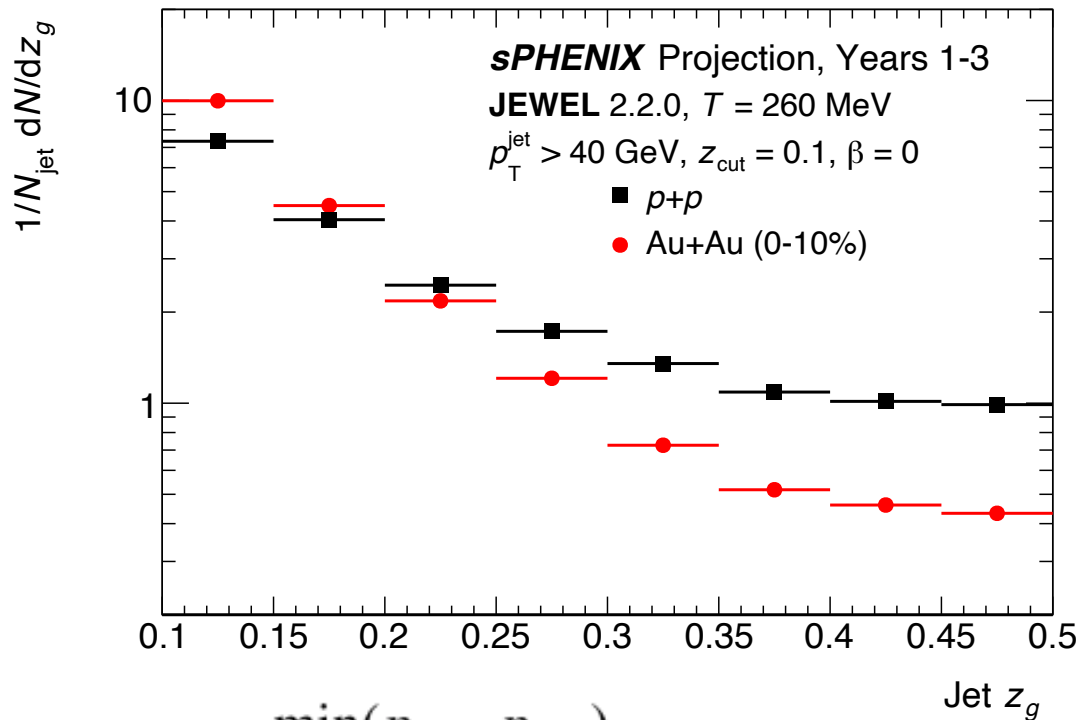
$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$$
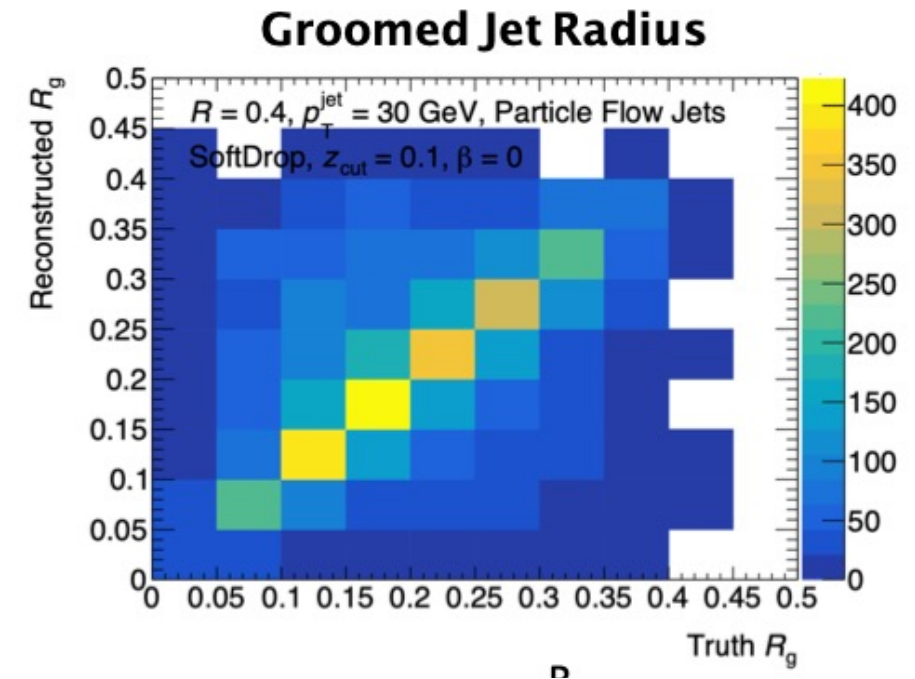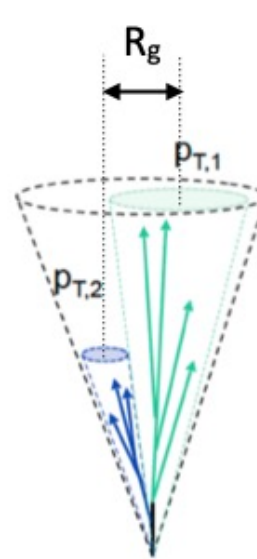
Event Plane Studies

- Event Plane Detector will improve resolutions to enable more precise jet v_2 studies
  - **Address R_{AA} v_2 puzzle in heavy ions**
  - **Jet v_2 in p+Au to deepen understanding of small systems**
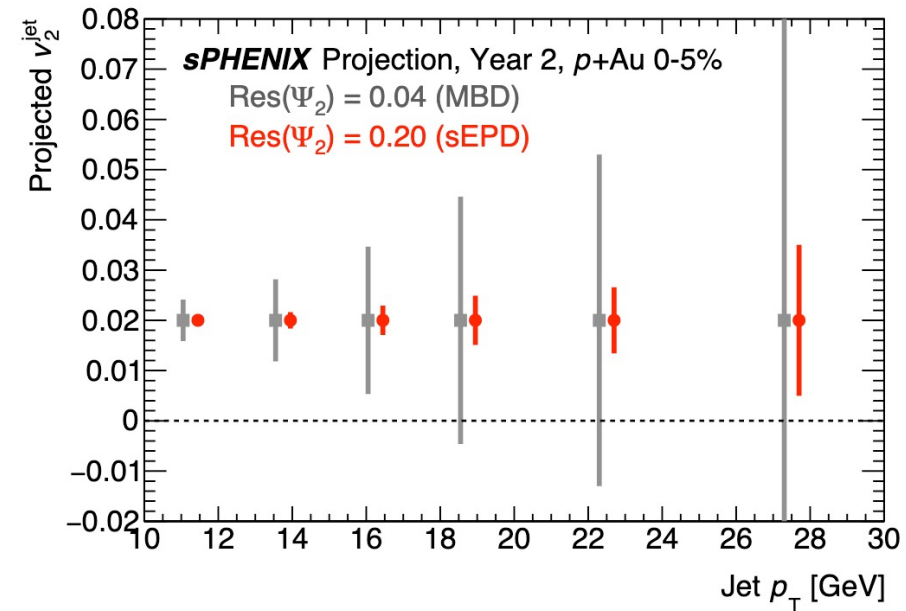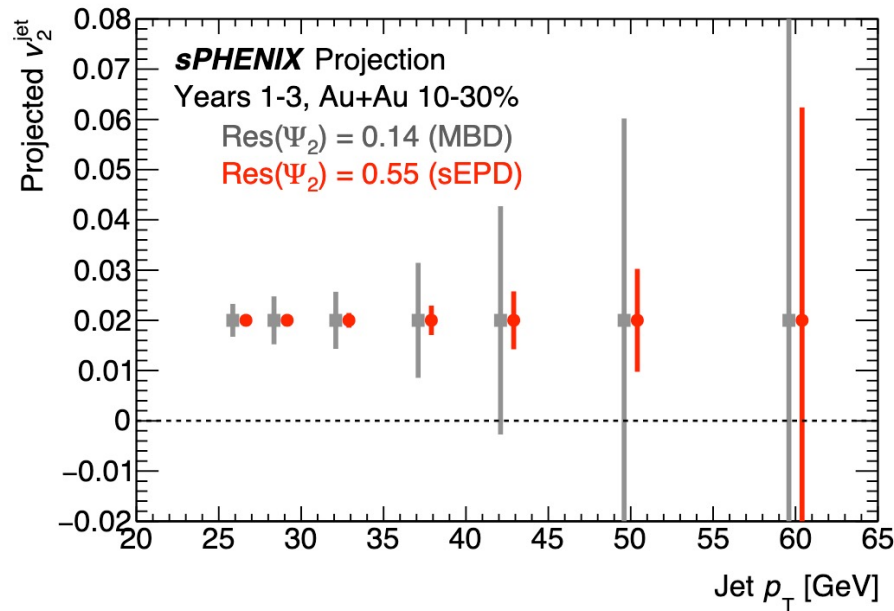
Event Plane with Photon-jets

- Jet-hadron correlations at ALICE measured no significant pathlength dependence

- Can we quantify this better at RHIC? With other observables?

- Can explore reaction plane dependence of $x_{J\gamma}$

ALICE jet-h
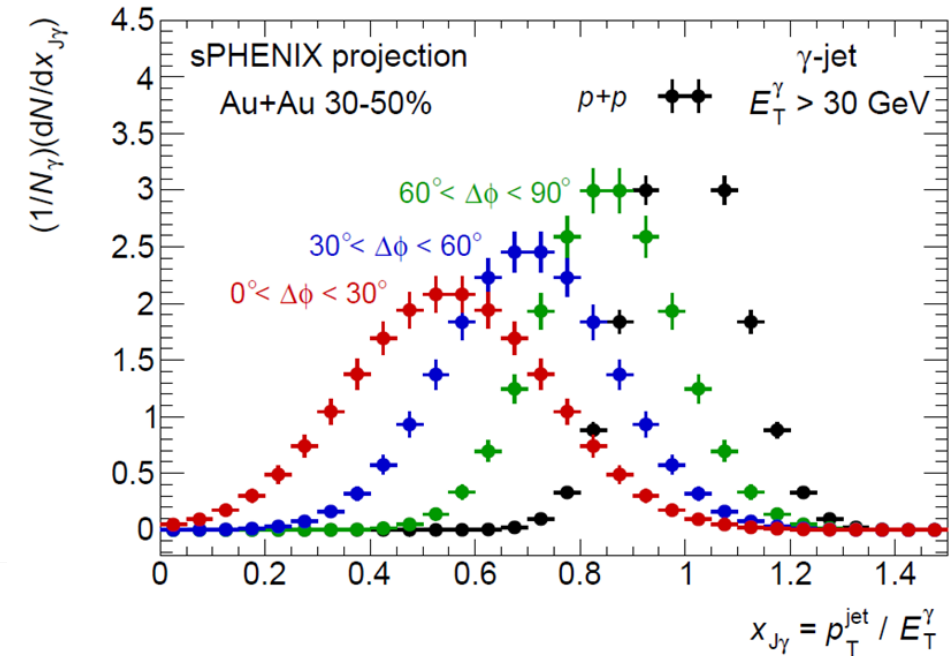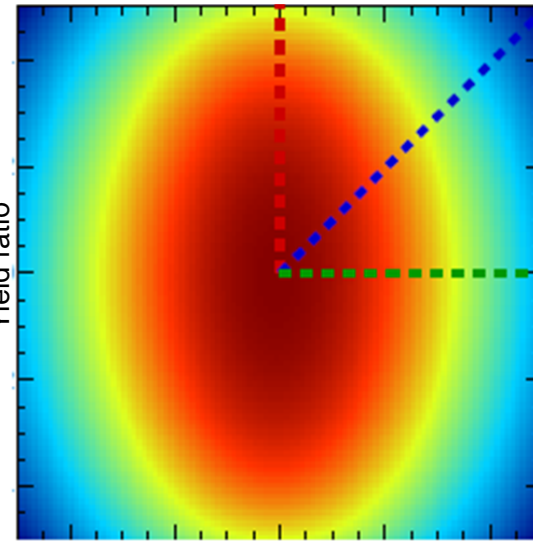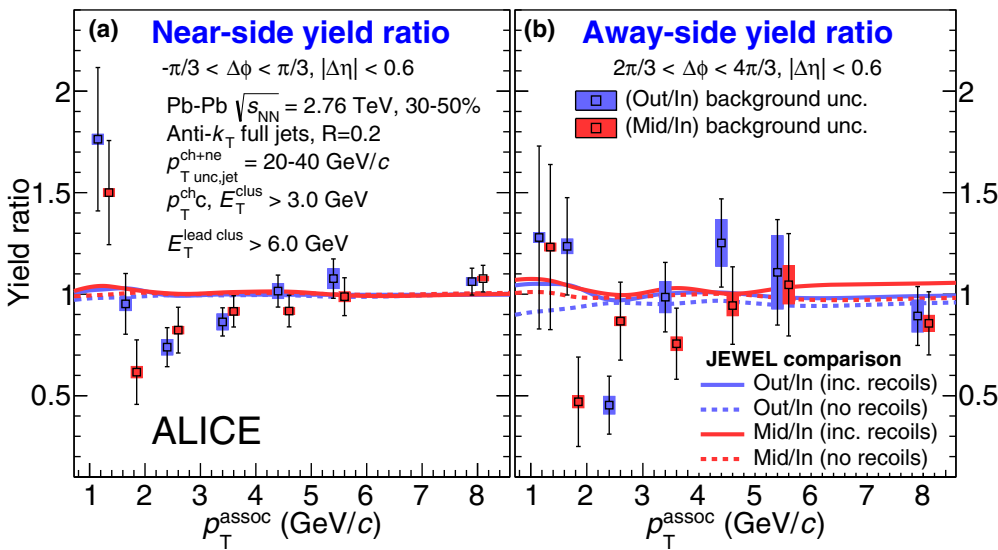
b-tagged Jets

- Sensitivity to collisional vs radiative energy loss

- First b-jet measurement at RHIC

- Complimentary to LHC jets, accessing lower p_T region with larger heavy quark mass effect.

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22
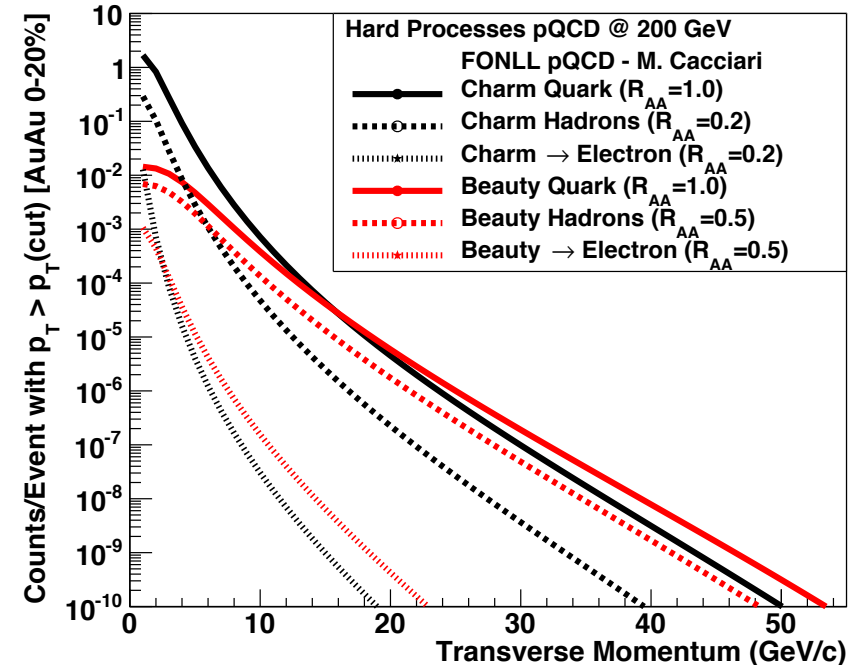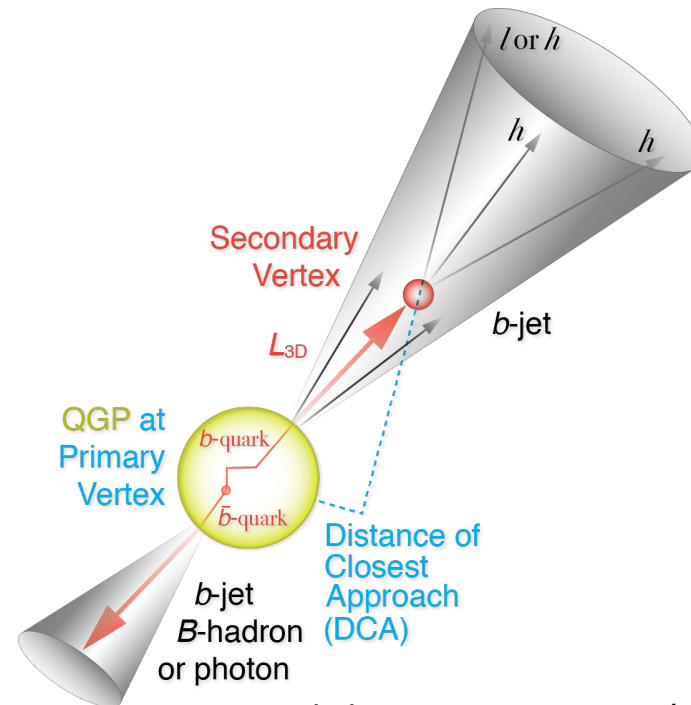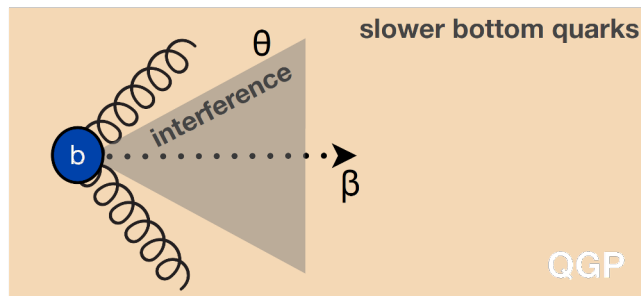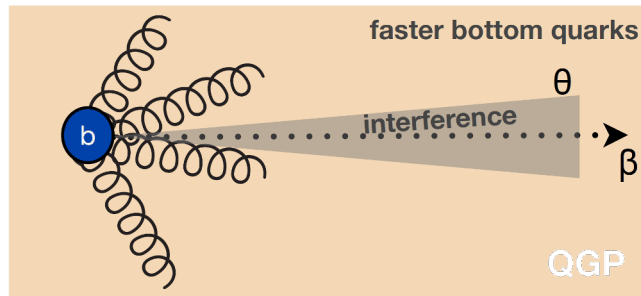
b-jet Projections

- sPHENIX b-tagged R_{AA} compared to LIDO and pQCD calculations demonstrates anticipated precision
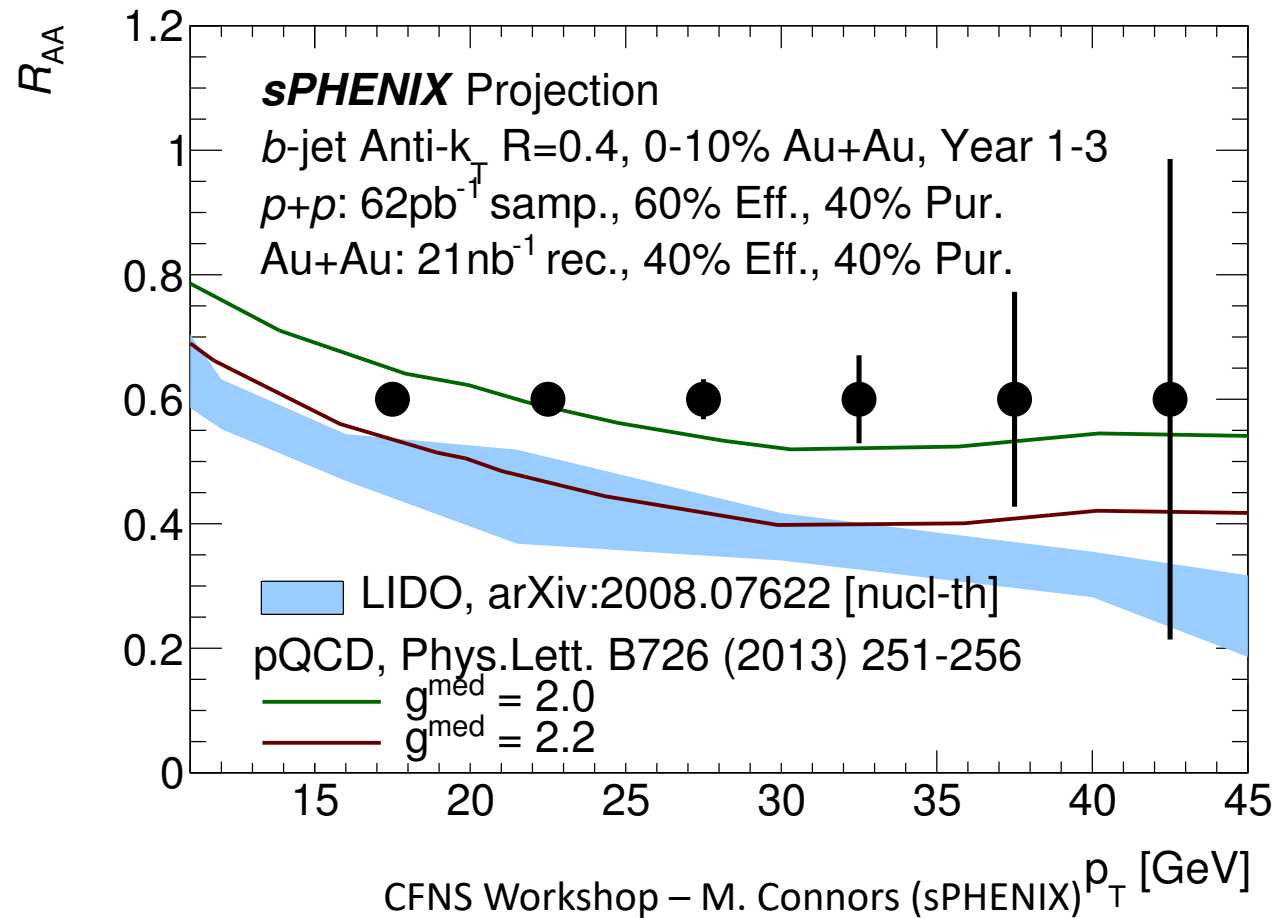
b-jet Projections

- sPHENIX b-tagged di-jets compared to calculations from SCET$_{MG}$ framework

- Precision capable of constraining theoretical parameters
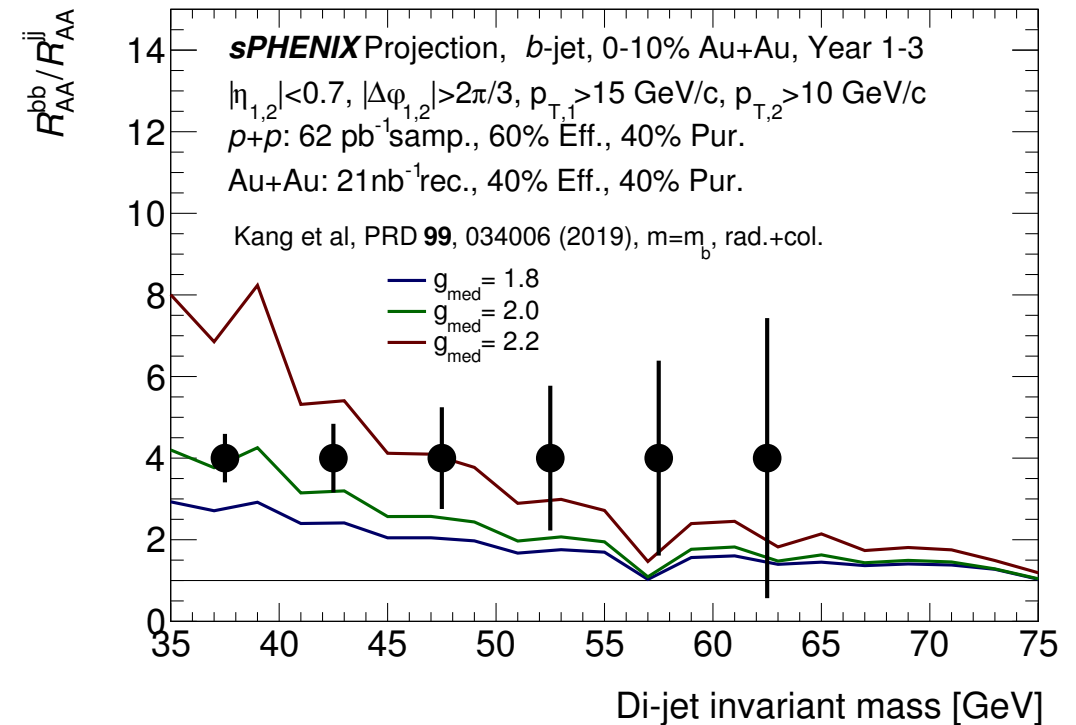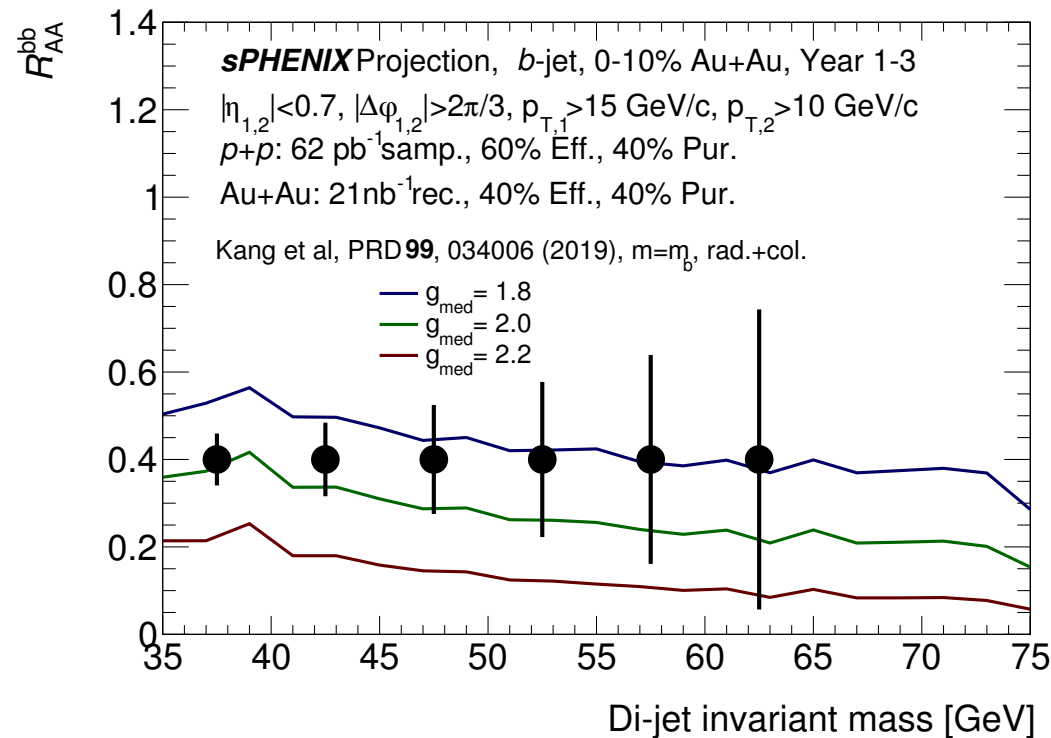
Baby Pictures

sPHENIX Construction @ 1008
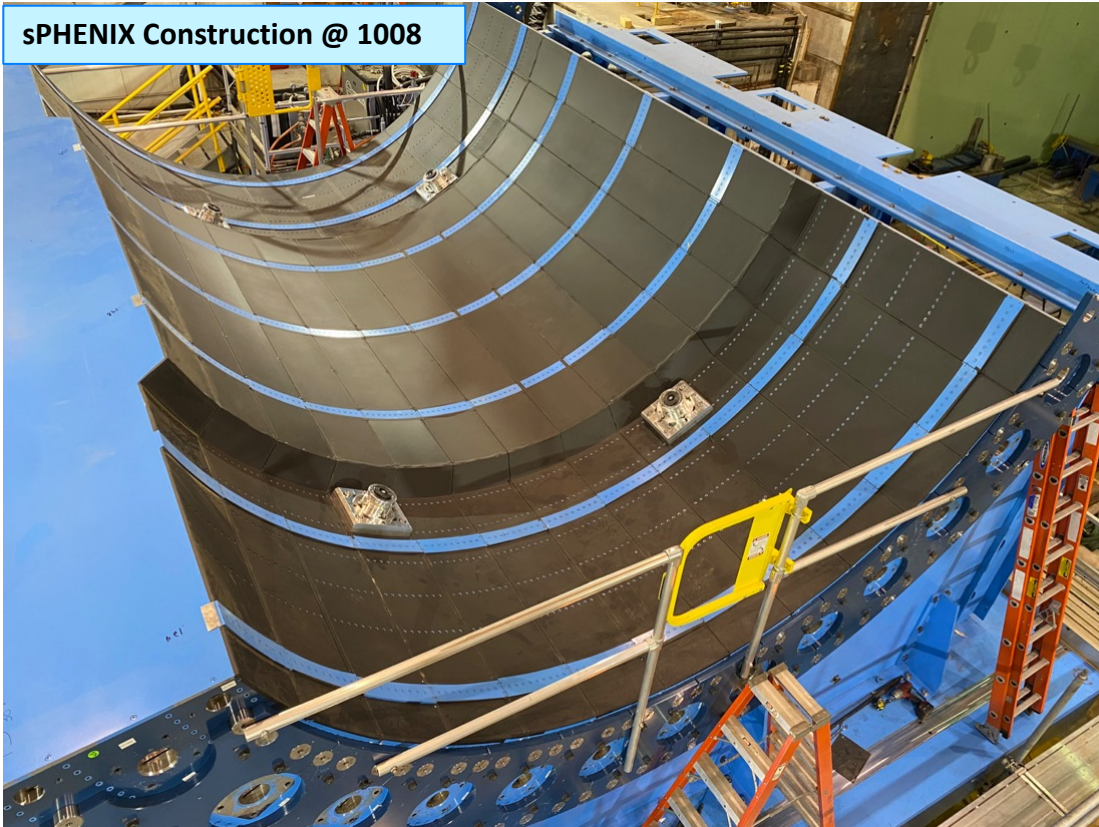
OHCal Assembly @ BNL

TPC Fee Slice Test
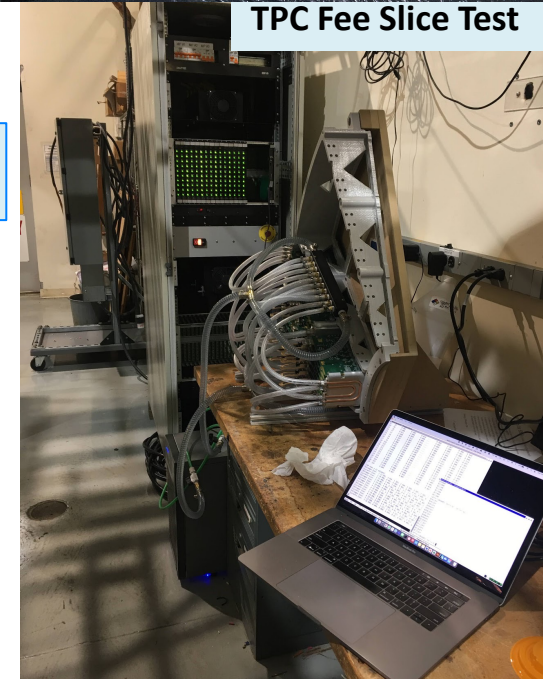
EMCal sector testing @ BNL

MVTX Staves @CERN

INTT ladders/HDIs @ BNL

iHCal tile testing @ GSU

7/9/2021

CFNS W   IX)

From RHIC to EIC
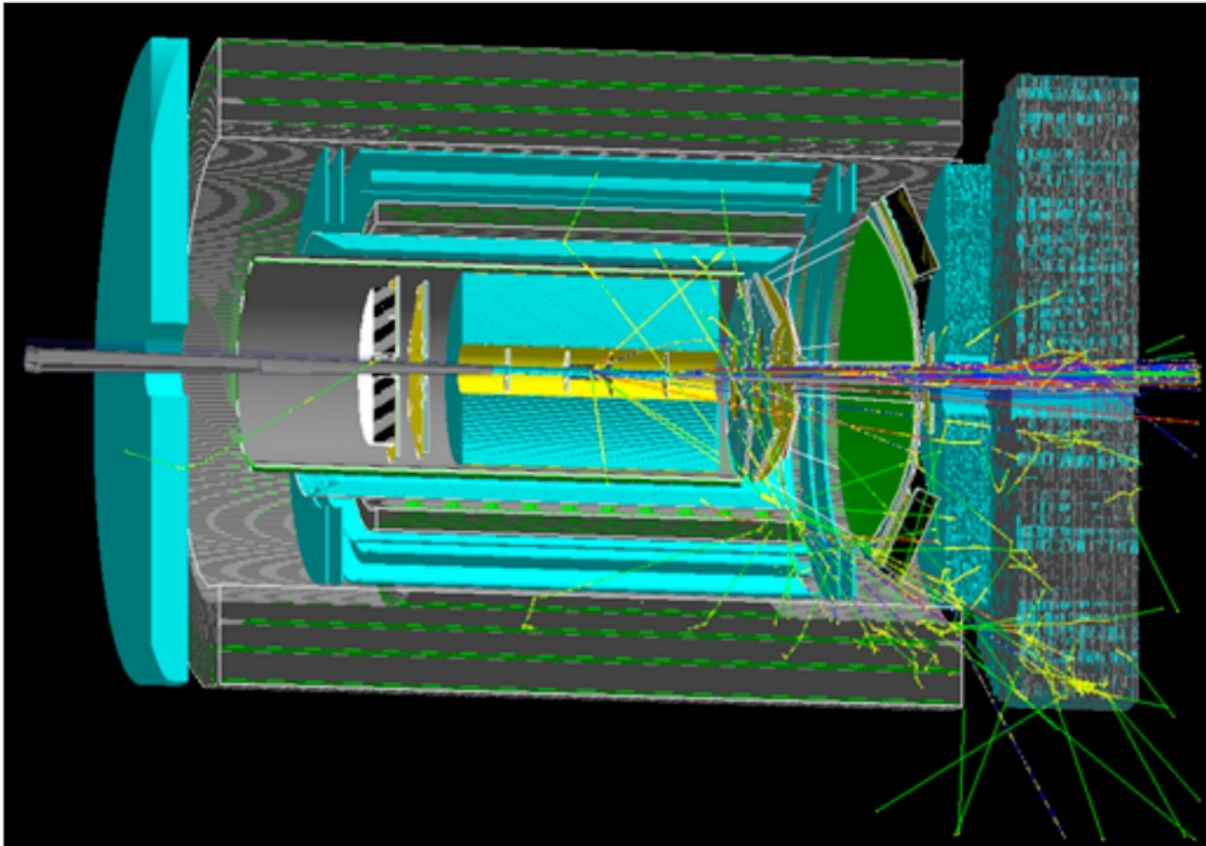
G4 Simulation, DIS e+p event @ 18 on 275 GeV, 25mrad crossing, x ~ 0.5, Q^2 ~ 5000 GeV^2

2014 white paper

Concept for an Electron Ion Collider (EIC) detector built around the BaBar solenoid

The PHENIX Collaboration
February 3, 2014

2018 design study

An EIC Detector Built Around The sPHENIX Solenoid

A Detector Design Study

For the EIC Detector Study Group
and the sPHENIX Collaboration

October 2018
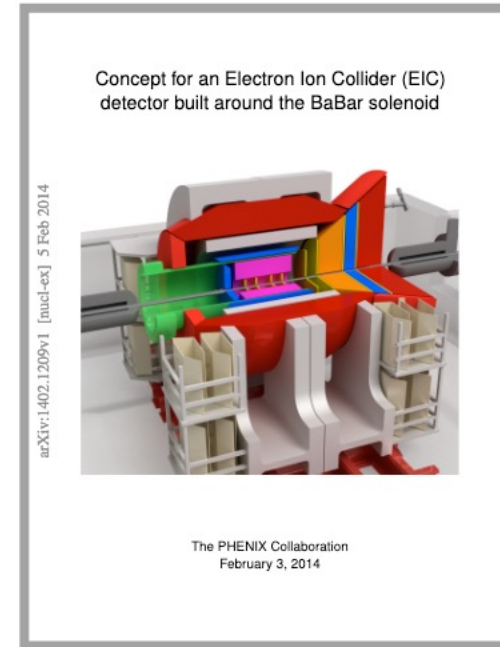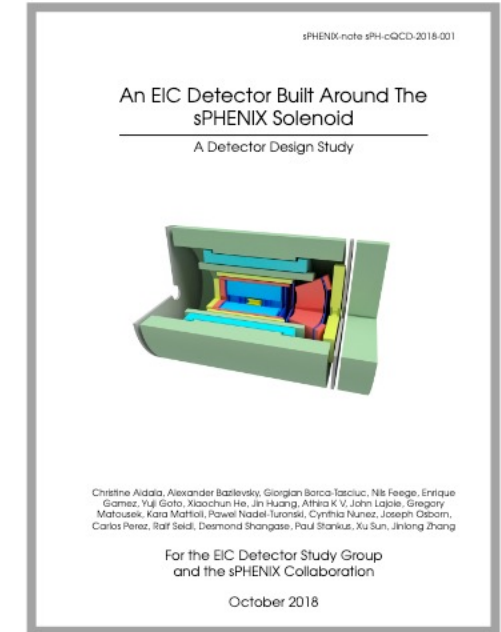
See Morning talk by John Lajoie

Summary

- sPHENIX will usher in new suite of precise jet measurements probing the QGP and cold nuclear matter at RHIC

- This will provide an overlap of kinematic reach between RHIC and LHC to further constrain theoretical models

- A lot of physics opportunities for jet, jet structure and HF jets

- sPHENIX is on schedule to start data collection in 2023!
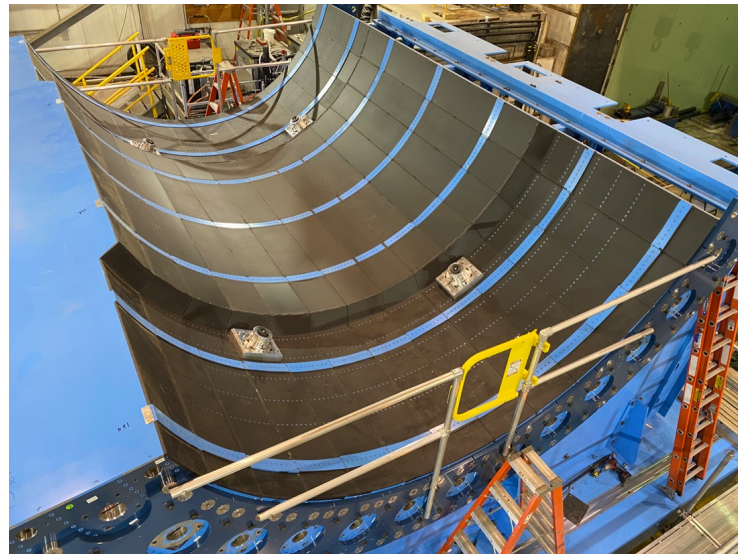
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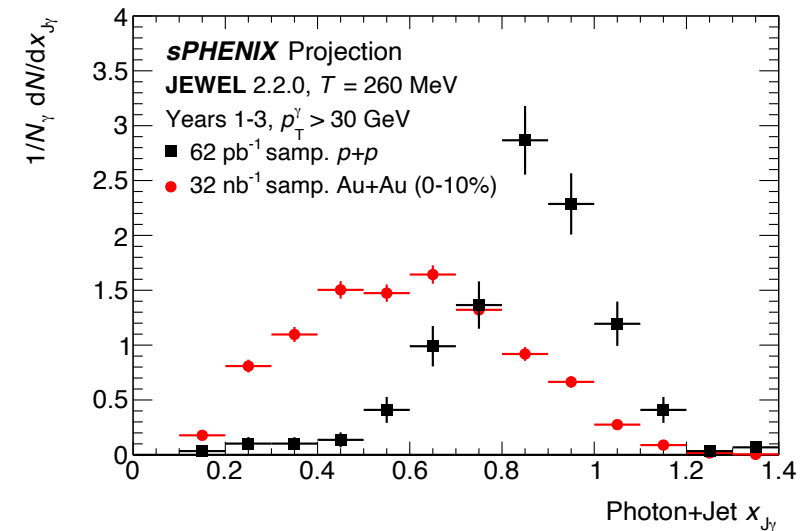
Back up Slides

Opportunities beyond 3-year plan

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $|z| < 10$ cm	Samp. Lum. $|z| < 10$ cm
2026	$p^\uparrow p^\uparrow$	200	28	15.5	1.0 pb^{-1} [10 kHz] 80 pb^{-1} [100%-*str*]	80 pb^{-1}
–	O+O	200	–	2	18 nb^{-1} 37 nb^{-1} [100%-*str*]	37 nb^{-1}
–	Ar+Ar	200	–	2	6 nb^{-1} 12 nb^{-1} [100%-*str*]	12 nb^{-1}
2027	Au+Au	200	28	24.5	30 nb^{-1} [100%-*str*/DeMux]	30 nb^{-1}

UE Subtraction


```
┌─────────────────┐         ┌──────────────────────────────────────────┐
│ Run jet reco    │         │ Determine set of R=0.2 seed jets           │
│ algorithm on    │────────▶│  1st pass: towers in jet satisfy  E_T,max  │
│ 0.1x0.1         │         │                                  ──────── >3│
│ calorimeter     │         │                                   < E_T >   │
│ cells           │         │  2nd pass: jet E_T > 20                     │
└─────────────────┘         └──────────────────────────────────────────┘
```

Determine set of R=0.2 seed jets
1st **pass:** towers in jet satisfy $\frac{E_{T,max}}{< E_T >} > 3$
2nd **pass:** jet E$_T$ > 20

Determine v$_2$ for event
- exclude towers within $\Delta\eta < 0.4$ of seed jet

Determine background E$_T$ in η strips
- demodulate by v$_2$
- exclude towers within $\Delta R < 0.4$ of seed jet

Subtract background from jets tower-by-tower
- first remodulate background by v$_2$

Subtract background from event tower-by-tower
- first remodulate background by v$_2$

Run jet reco algorithm

Output: background subtracted reco jets of various R values
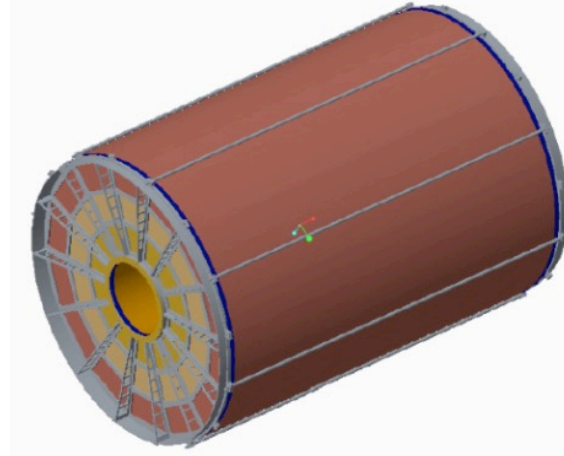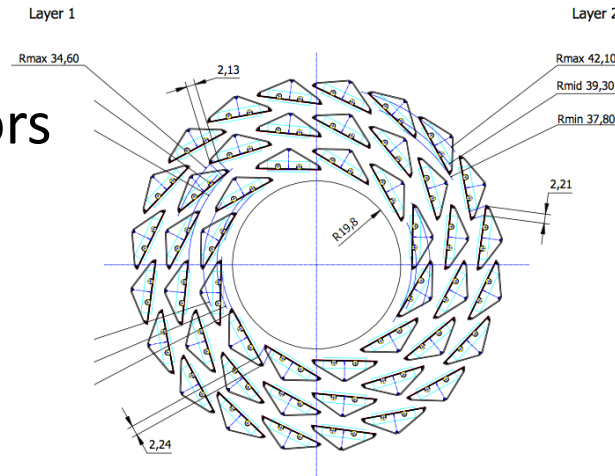
r,

UE subtraction

- Demonstrated control of flow modulation in UE subtraction
  - **Reduced event-plane JES dependence**
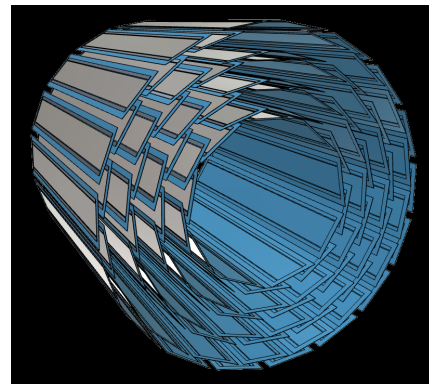 - **Removed artificial increase of JER**
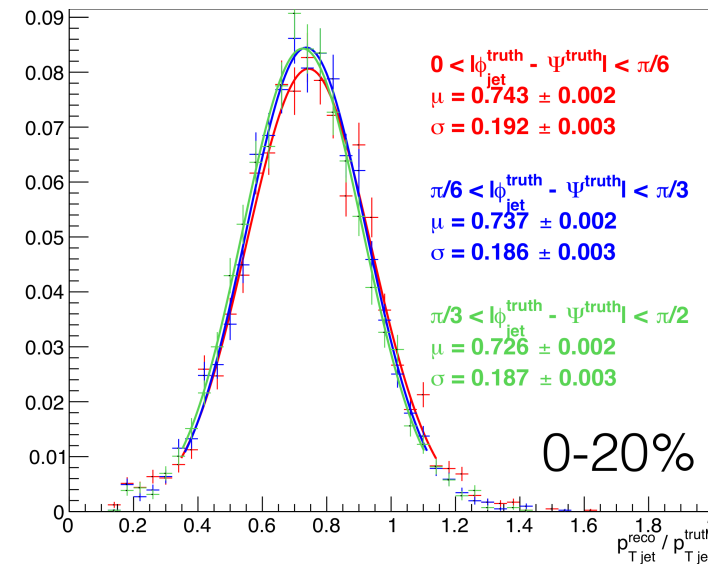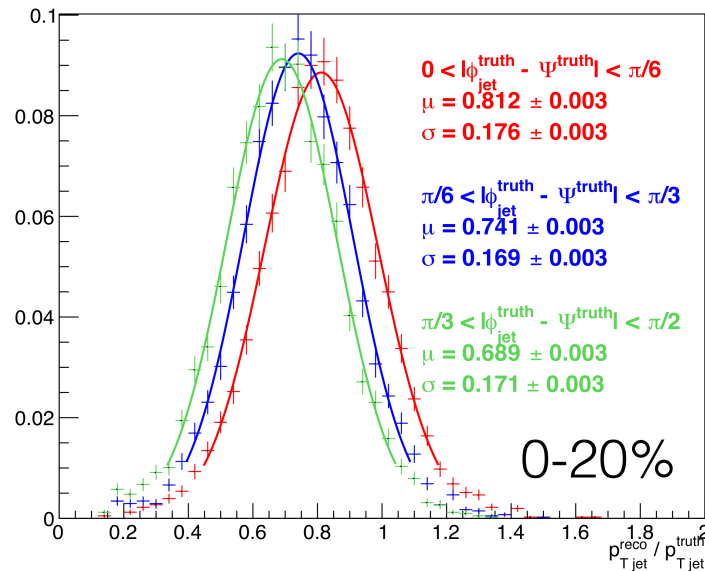
Tracking Subsystems

MAPS

- 3 layers Si sensors
- Based on ALICE ITS upgrade
- $DCA_{xy} < 70\ \mu m$
- $|z_{vtx}| < 10$ cm

INTT

- 4 layers Si strips
- Use PHENIX electronics
- Pattern recognition, DCA, connect tracking systems, reject pile-up

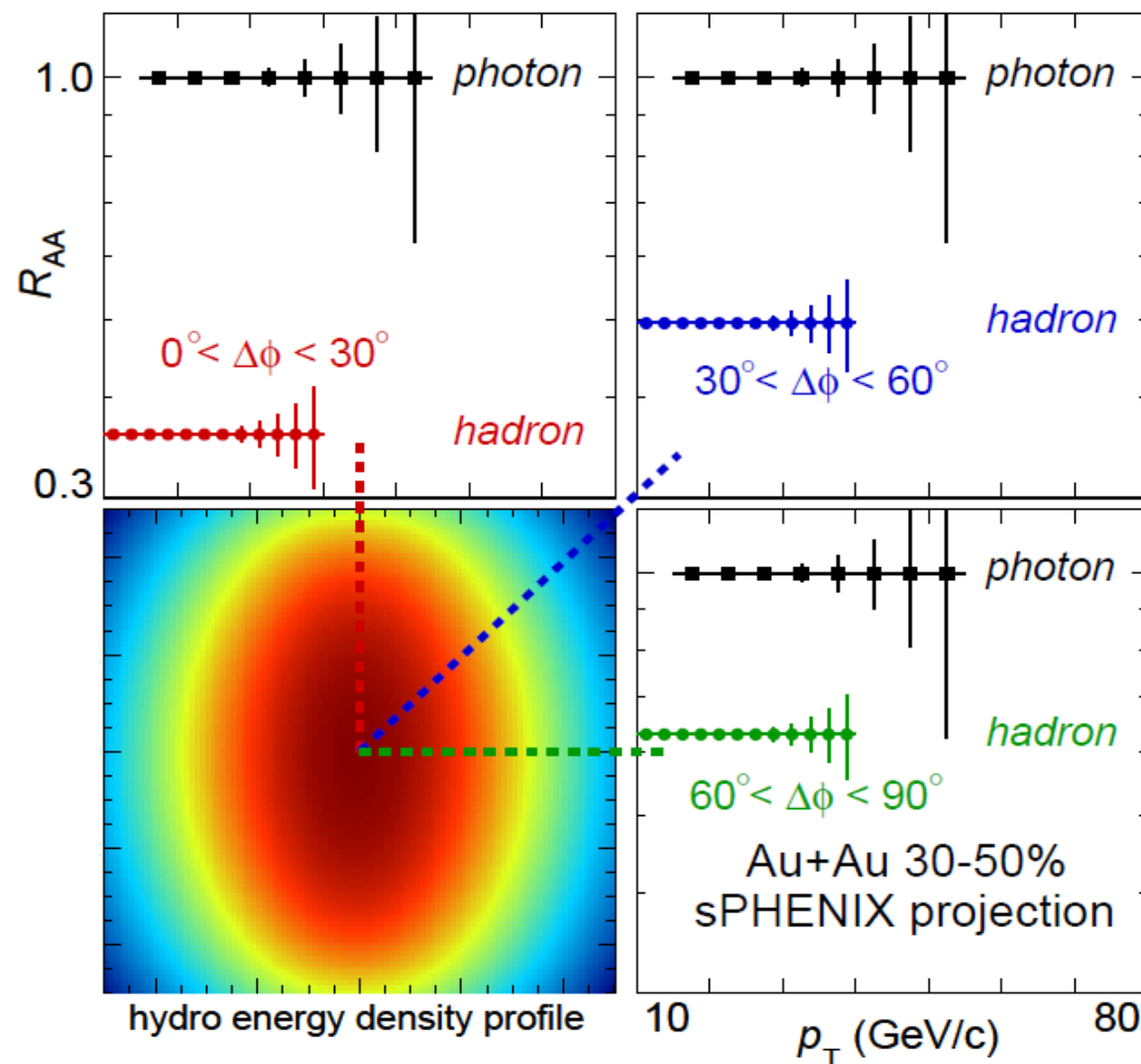## TPC

- Radius 20–78 cm
- ~250 µm effective hit resolution
- Continuous (non-gated) readout
- Pattern recognition, momentum resolution, p_T 0.2-40 GeV/c

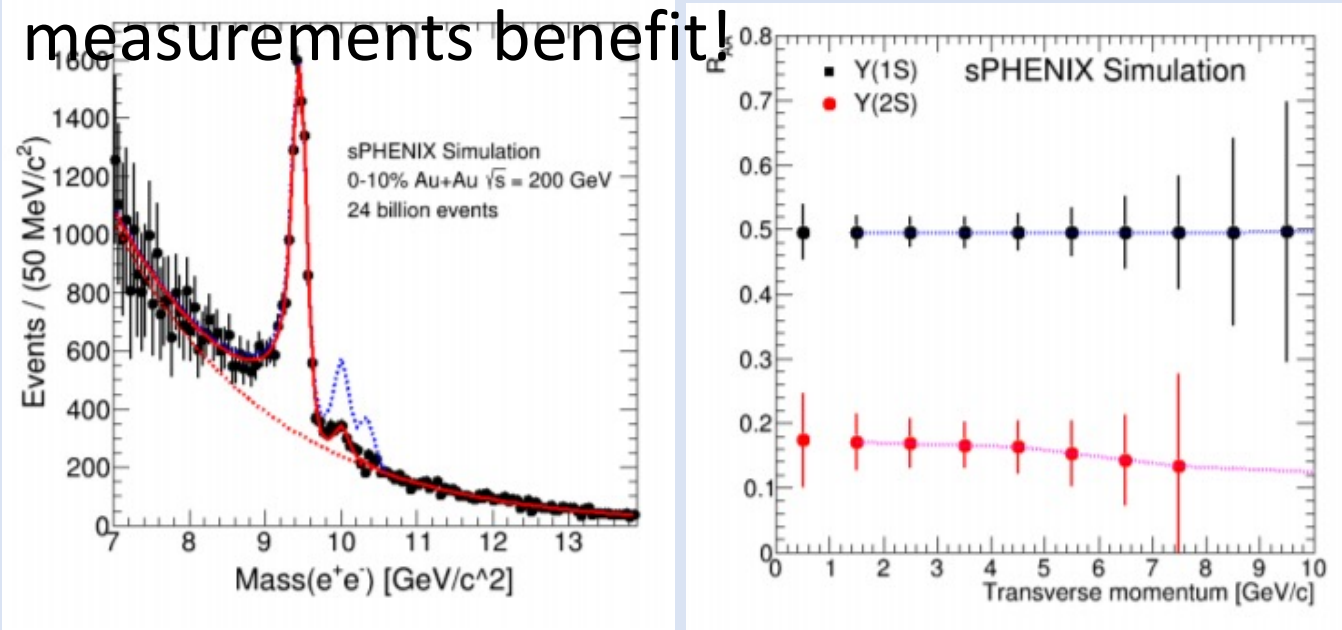# More Statistics = More Differential

- Pathlength studies

- Important constraints for models that describe inclusive R_{AA}

Upsilons at sPHENIX

ϒ + heavy flavor jet physics drive tracking requirements → Jet structure measurements benefit!

- Differential suppression of ϒ(nS) → T dependence of QGP Debye screening length
- **ϒ(1S) width key FOM** in INTT configuration

- Mass resolution of precision tracking allows **clear separation of ϒ states**!
- Precision measurements of ϒ(1S) and ϒ(2S) R_{AA}
  - Upsilon melting observations for $0 < p_T < 7$ GeV