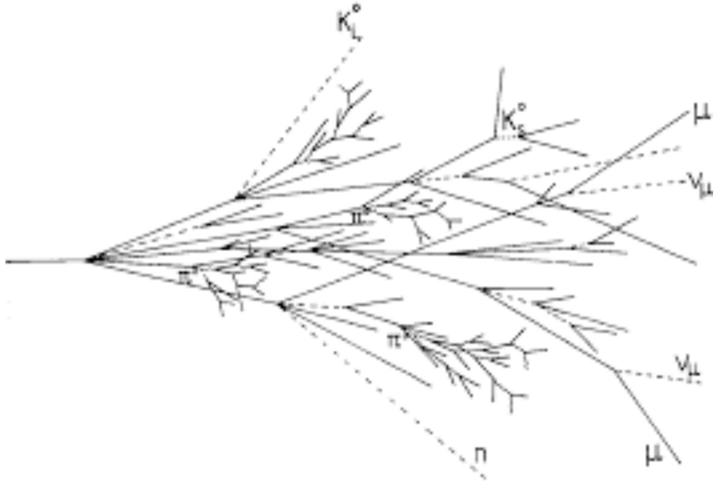
Hadron Calorimetry at the EIC

Brian Page

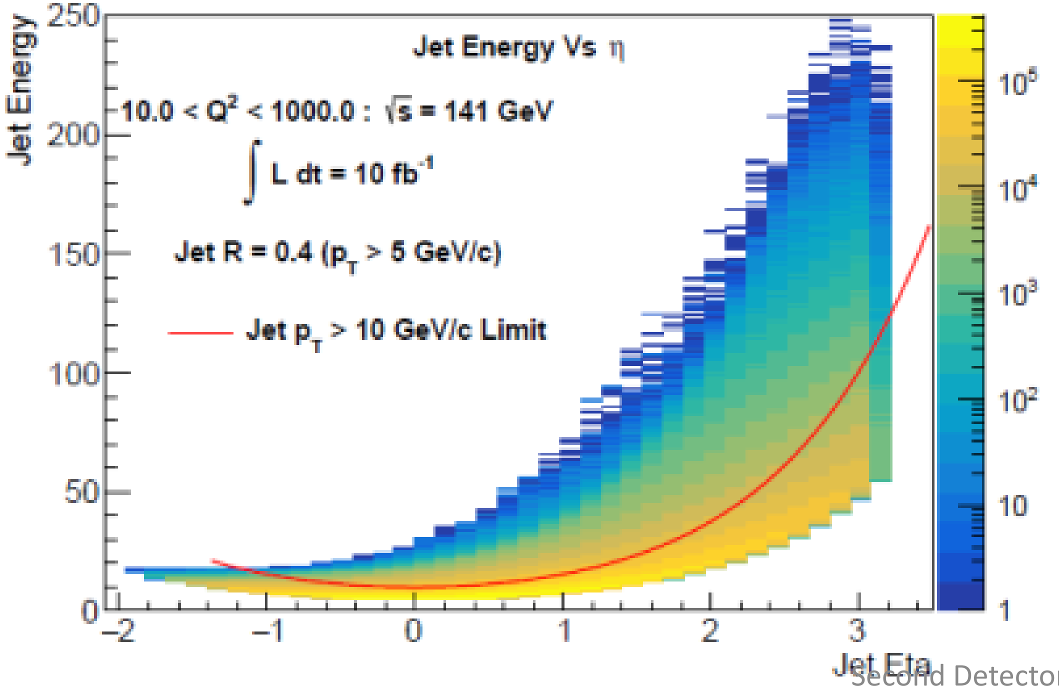
1st International Workshop on a 2nd Detector for the EIC

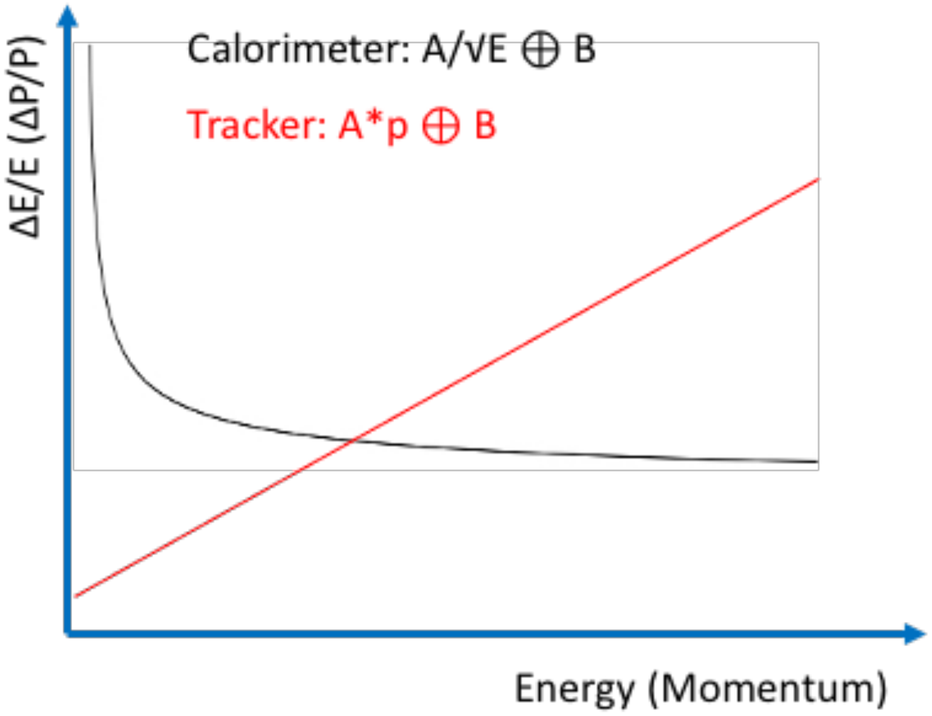
May 18th, 2023



HCal Function at the EIC

- ❑ Particles and jets will have relatively low momenta except in the forward region – track momentum resolution superior to calorimeter resolution for much of the phase space
- ❑ Track momentum + PID = Energy determination
- ❑ Hadron calorimeters needed for measurements of neutral hadrons (neutrons and K_L)
- ❑ Possible muon ID? KLM?

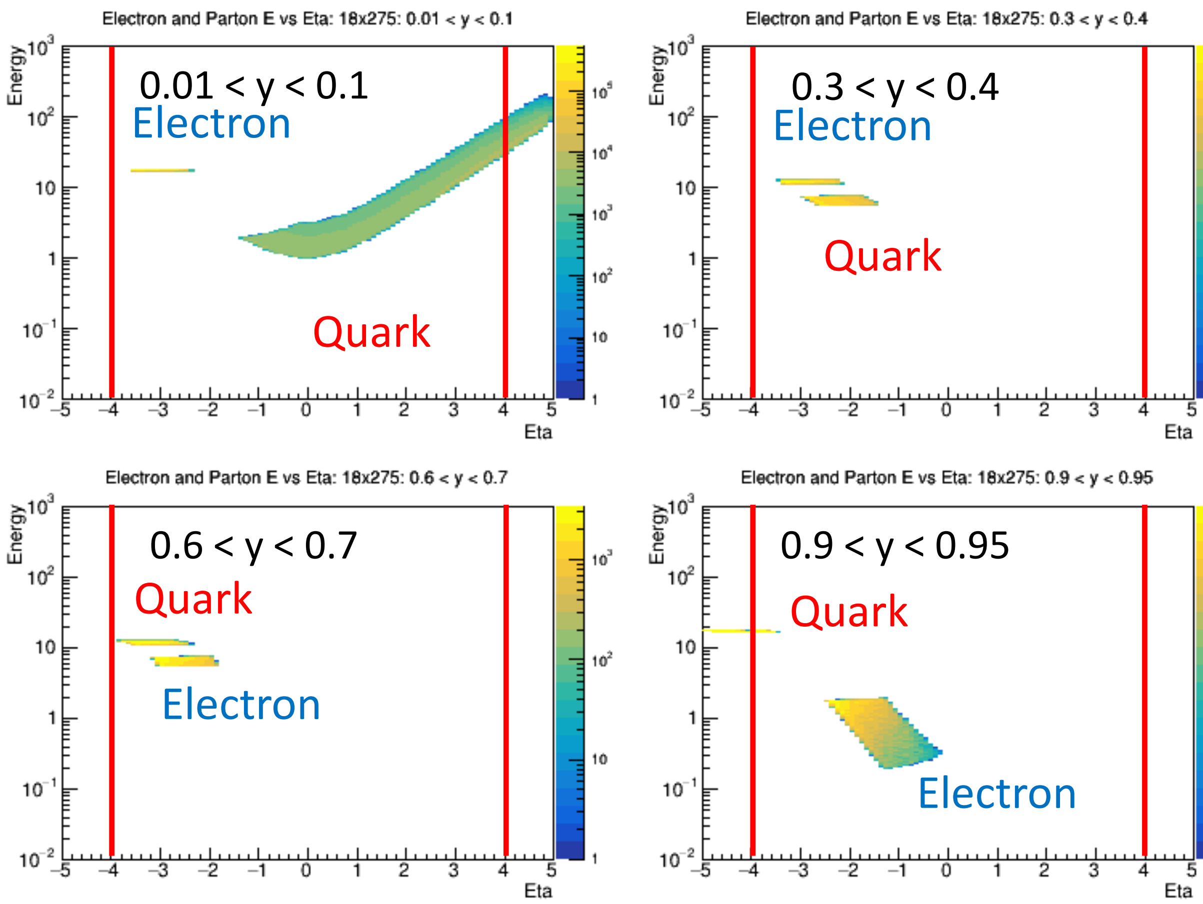




- ❑ As particle energy increases, calorimeter resolution improves while tracker resolution degrades
- ❑ Tracker resolution and acceptance degrades at forward rapidity
- ❑ Particle / jet energies will be highest in the forward (hadron-going) direction
- ❑ Good forward hadron calorimetry will be essential

Electron and Struck Quark (18x275)

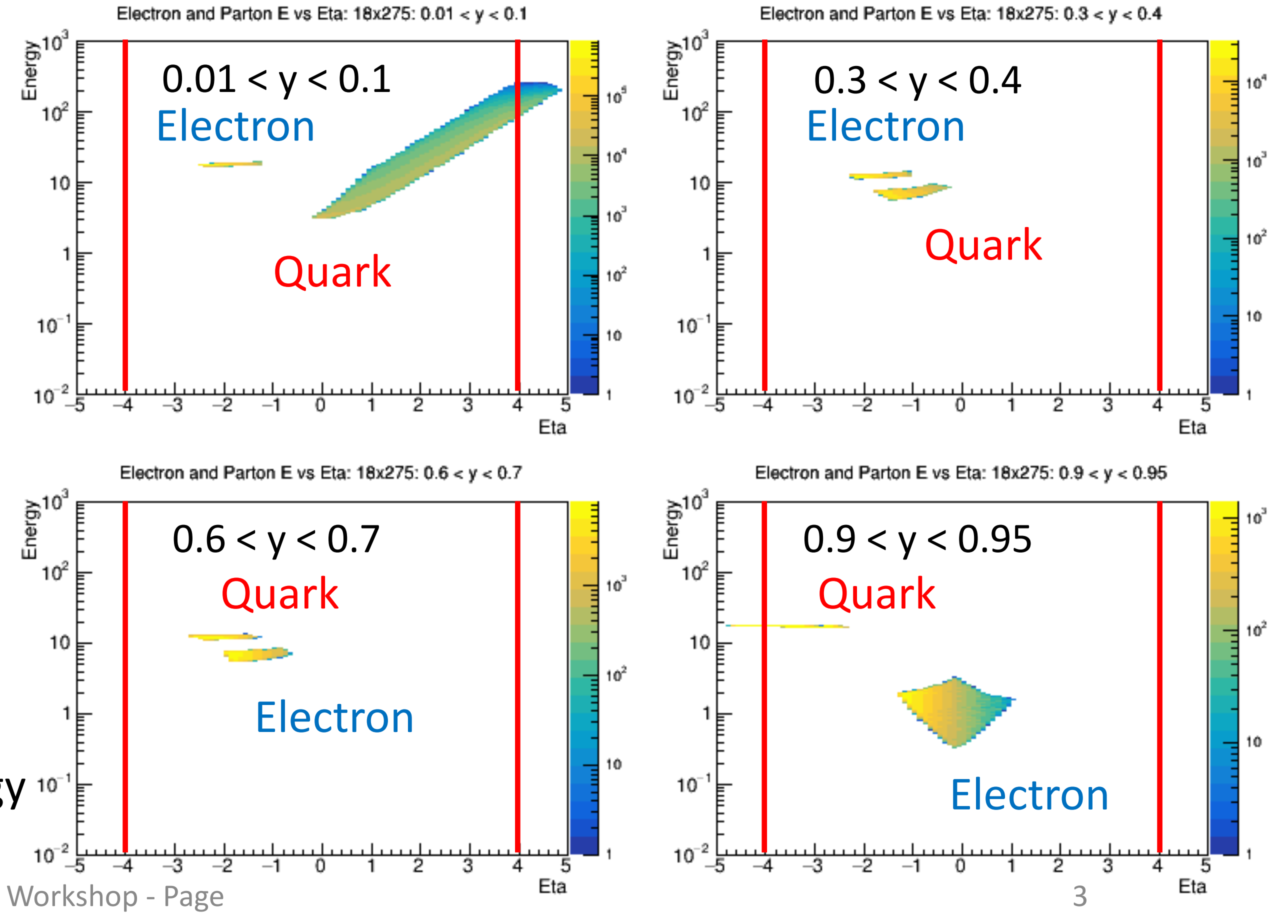
- ❑ Look at energy vs pseudorapidity of the scattered electron and struck quark as a function of y and Q^2
- ❑ For fixed Q^2, as y increases, electron eta increases while parton eta decreases



$1.0 < Q^2 < 10.0$

- ❑ As y -> 0, the struck quark can take the full ion beam energy
- ❑ As y -> 1, the struck quark takes the full electron beam energy
- ❑ Different detector considerations in forward and backward regions

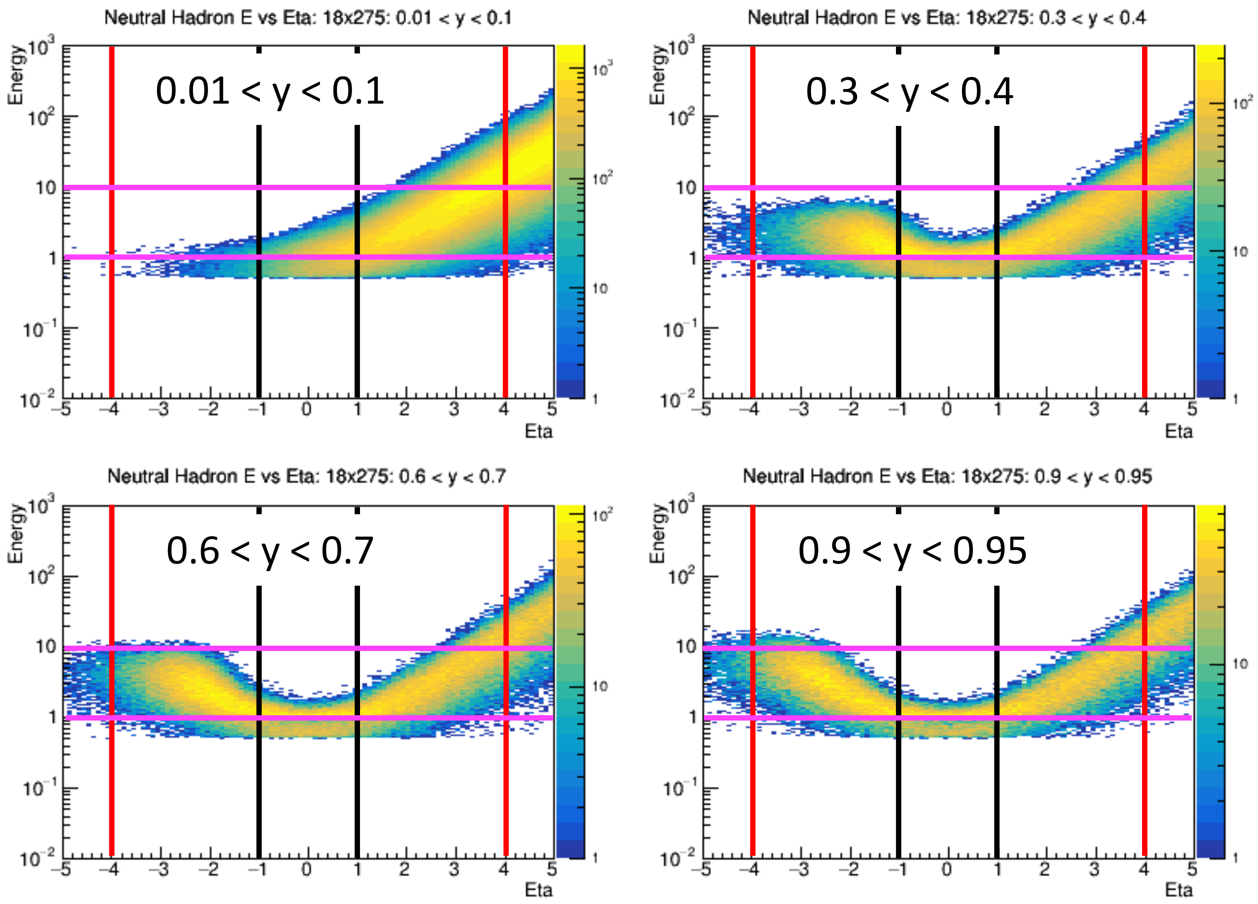
$10 < Q^2 < 100$



Neutral Hadrons (18x275)

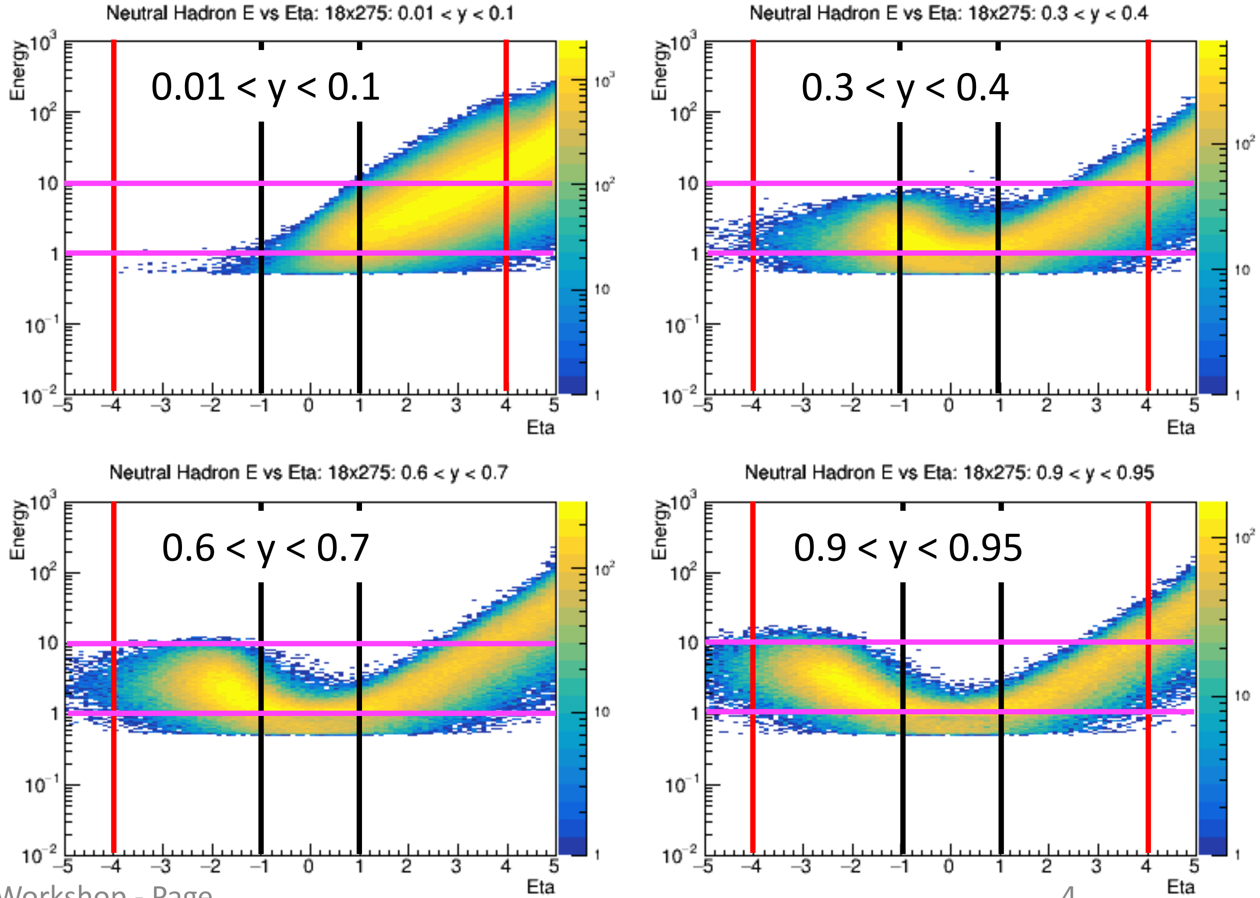
- ❑ Neutral hadron energy vs eta distributions all show roughly similar features – high energy forward, low at mid-rapidity, and a slight rise in the backward region

- ❑ Charged hadron and gamma distributions are very similar



$1 < Q^2 < 10$

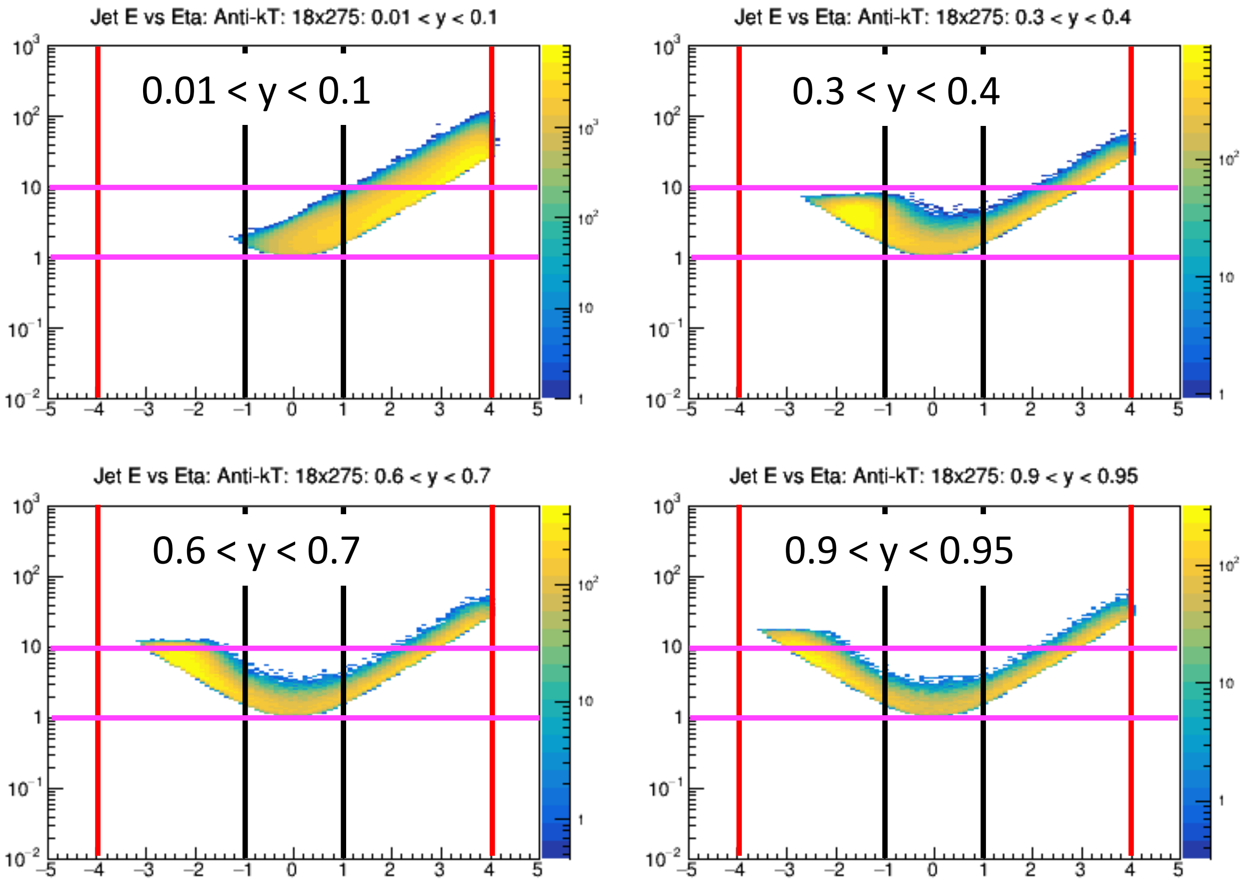
$10 < Q^2 < 100$



- ❑ Show approximate acceptance in red, mid-rapidity range (-1 < eta < 1) in black, and 1 & 10 GeV energies in magenta

Reconstructed Jets (18x275)

- Reconstruct jets from all stable particles using Anti-kT algorithm with R = 1.0
- Q2 > 100 will fill in somewhat higher energy jets at forward/mid-rapidity, but energies are generally small



$1 < Q^2 < 10$

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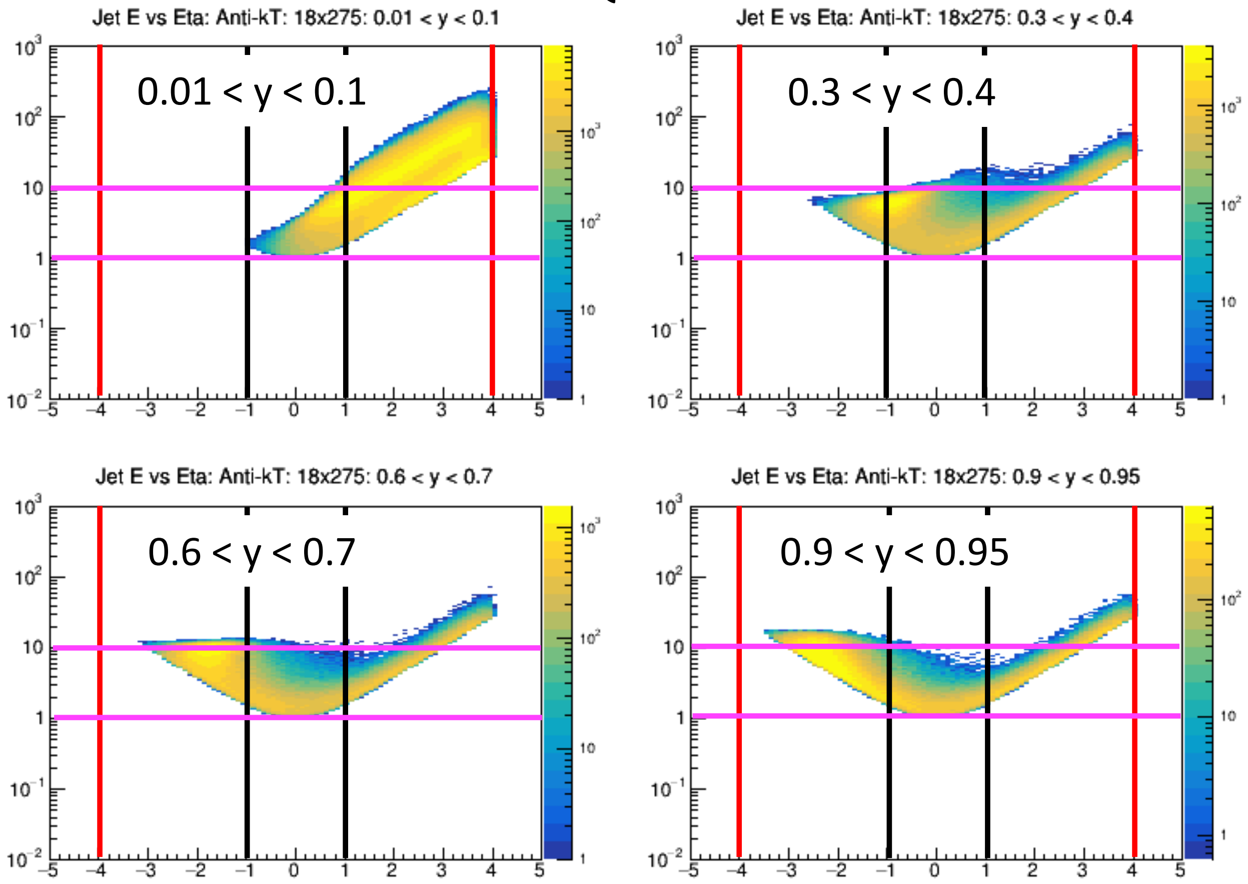
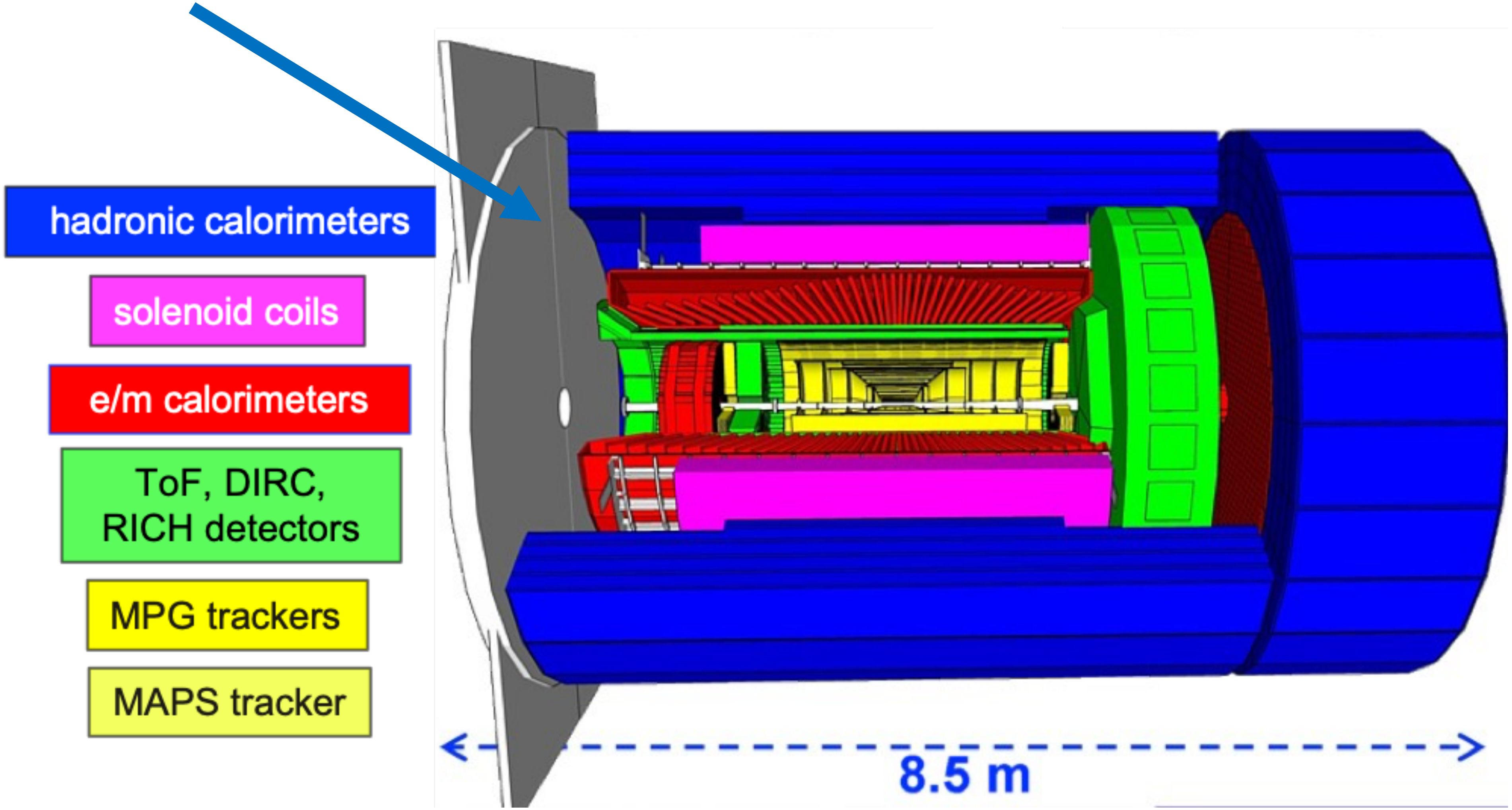


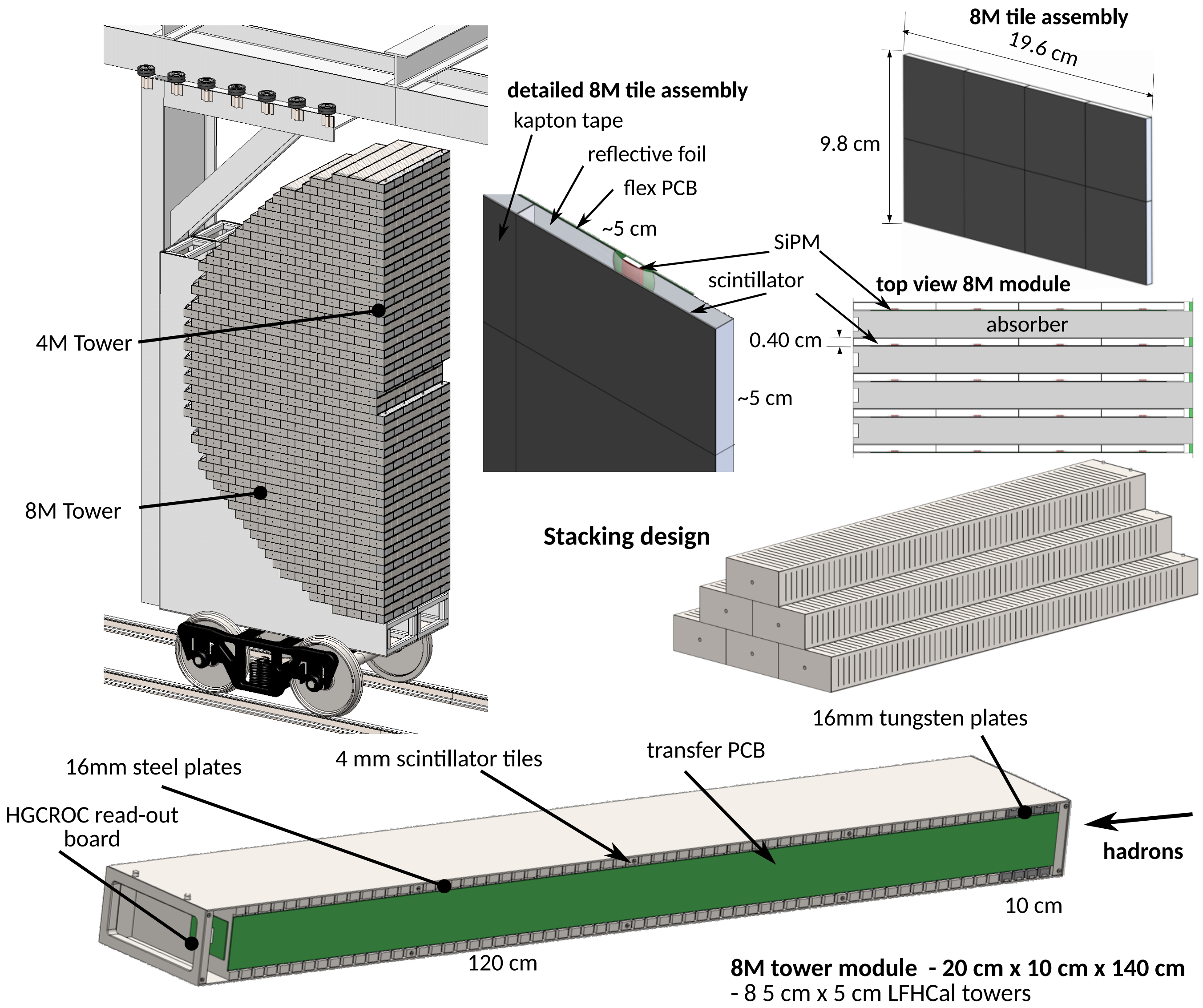
Hadron Calorimetry at ePIC

Backward Endcap flux return instrumented as well



Hadron Calorimetry at ePIC

- ❑ Forward Calorimetry System
  - ➢ W/Scint & Fe/Scint sampling calorimeter
  - ➢ Tungsten layers on front face as collimator
  - ➢ Multiple towers per module to increase granularity and reduce dead area
  - ➢ Longitudinal segmentation -> particle flow



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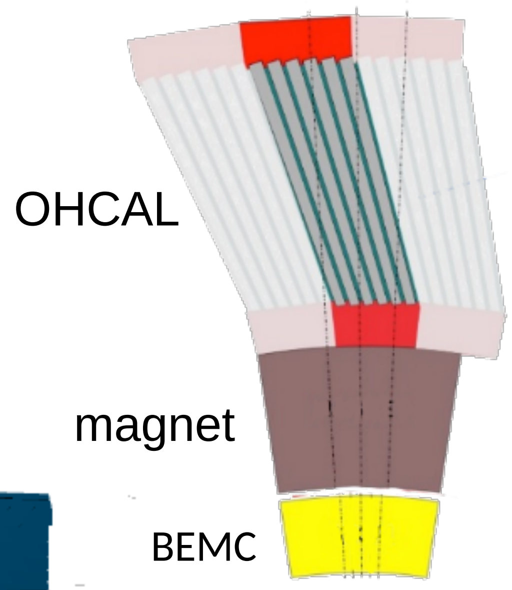
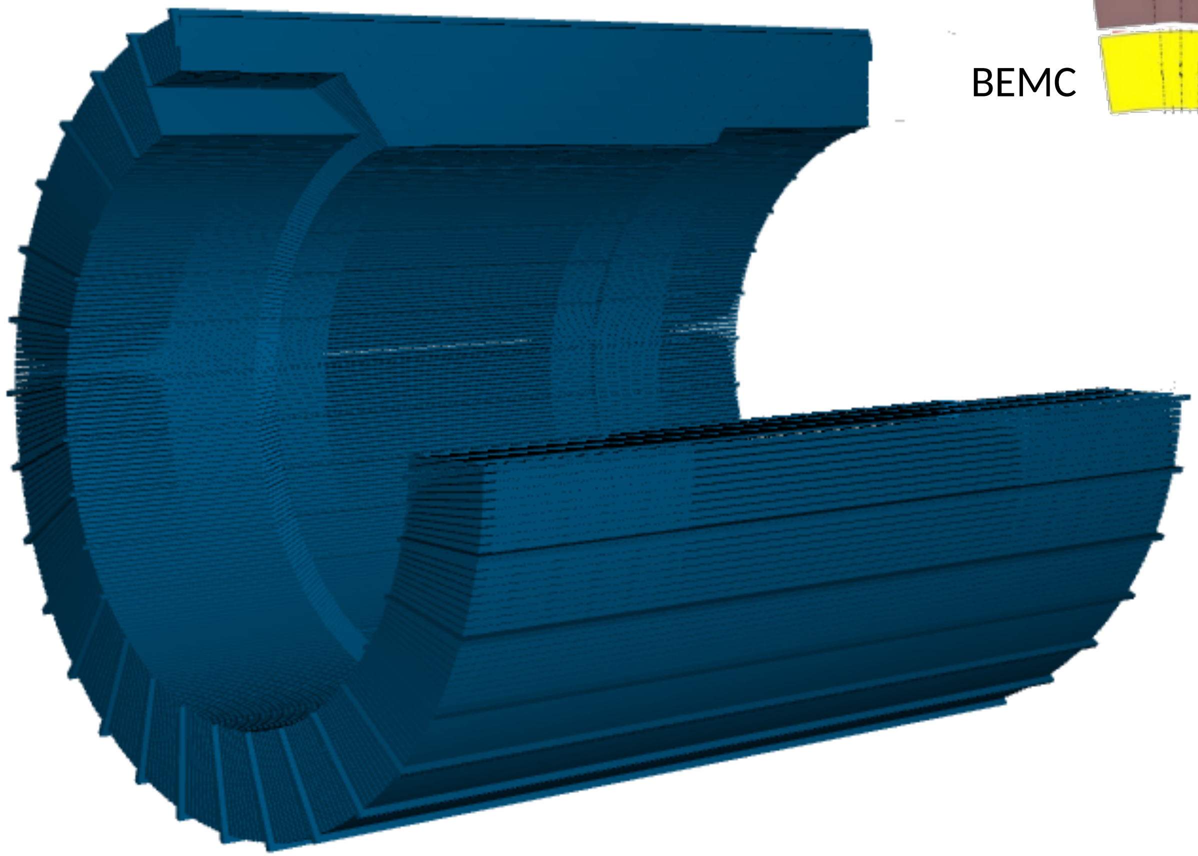
- ❑ Barrel HCal System
  - ➢ Fe/Scint sampling calorimeter
  - ➢ Partial reuse of sPHENIX calorimeter
  - ➢ Also serves as magnet flux return





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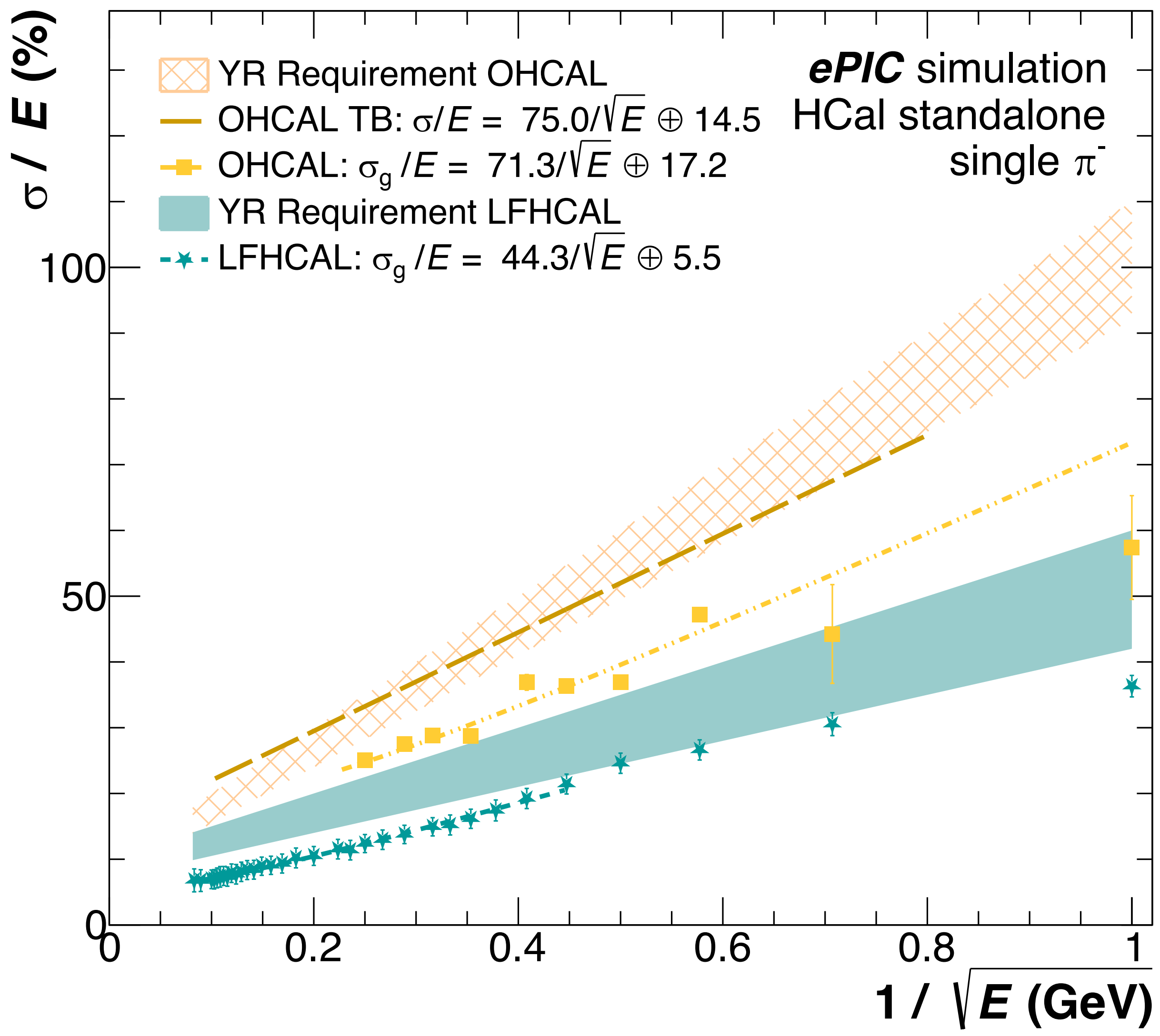

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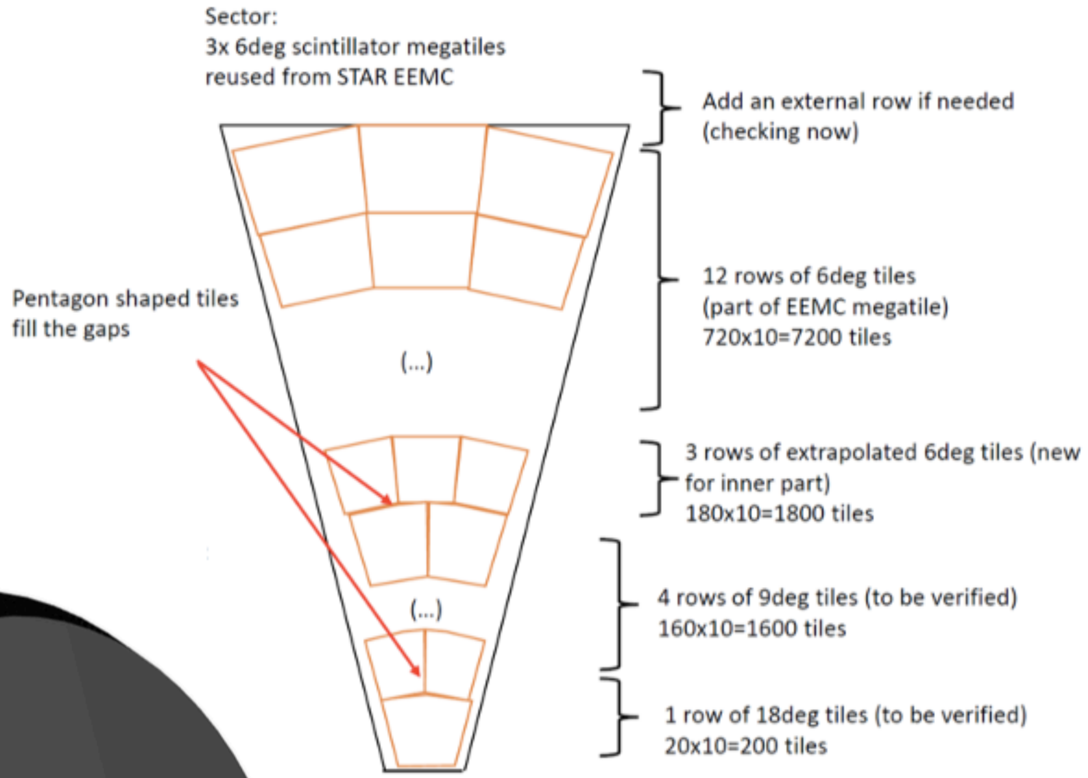
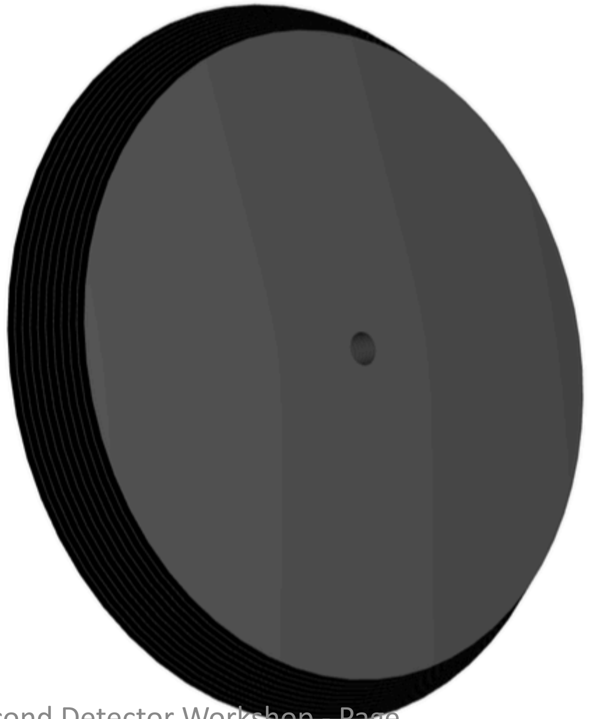
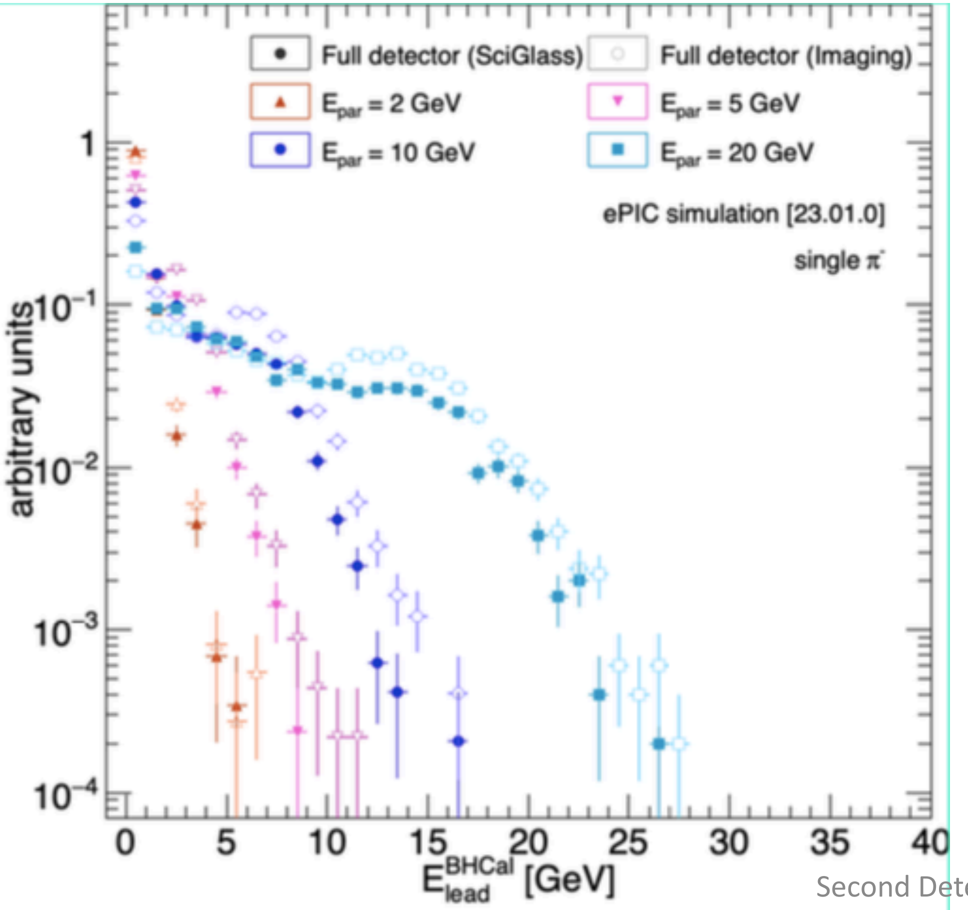
- Barrel HCal System
  - Fe/Scint sampling calorimeter
  - Partial reuse of sPHENIX calorimeter
  - Also serves as magnet flux return
- Backward HCal System
  - Currently envisioned as a tail catcher for identifying neutral hadrons
  - Scint tile design under active investigation

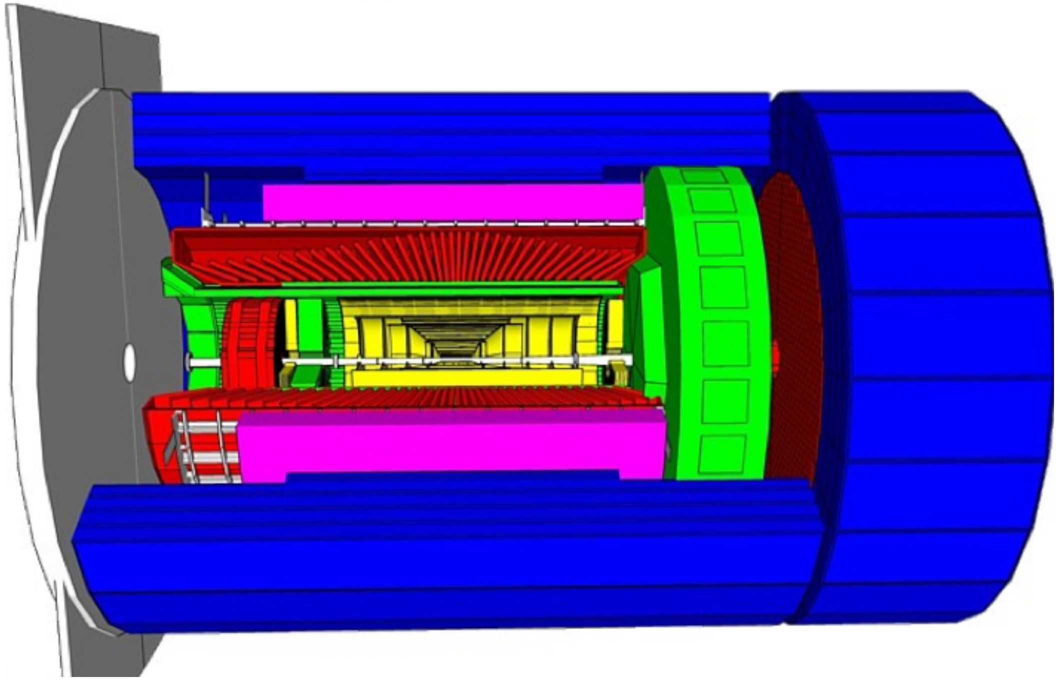




Barrel Calorimeter: Incident Energy

- Particles / Jets in the barrel region (~ -1 < eta < 1) are quite soft (E < 10 GeV) and
- Have to go through ECal and magnet before reaching the HCal
- How much of the shower reaches the HCal to be measured?





Studies carried out by Derek Anderson

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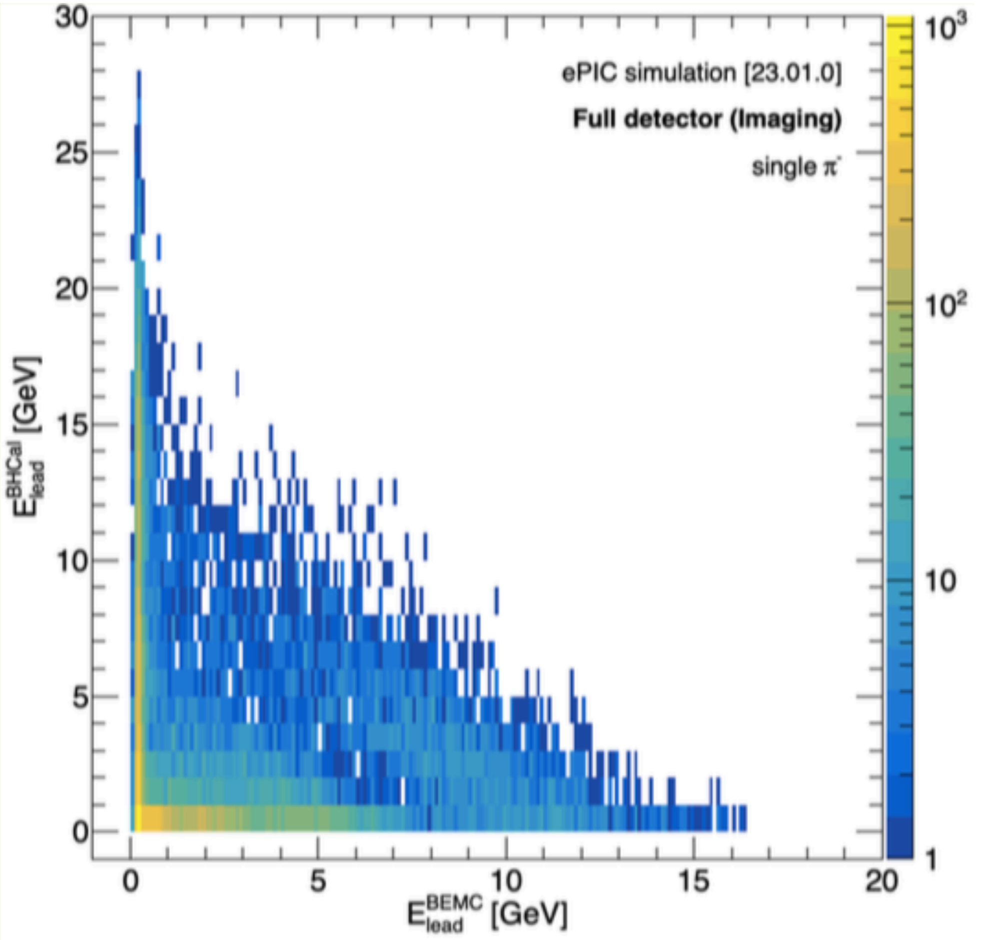
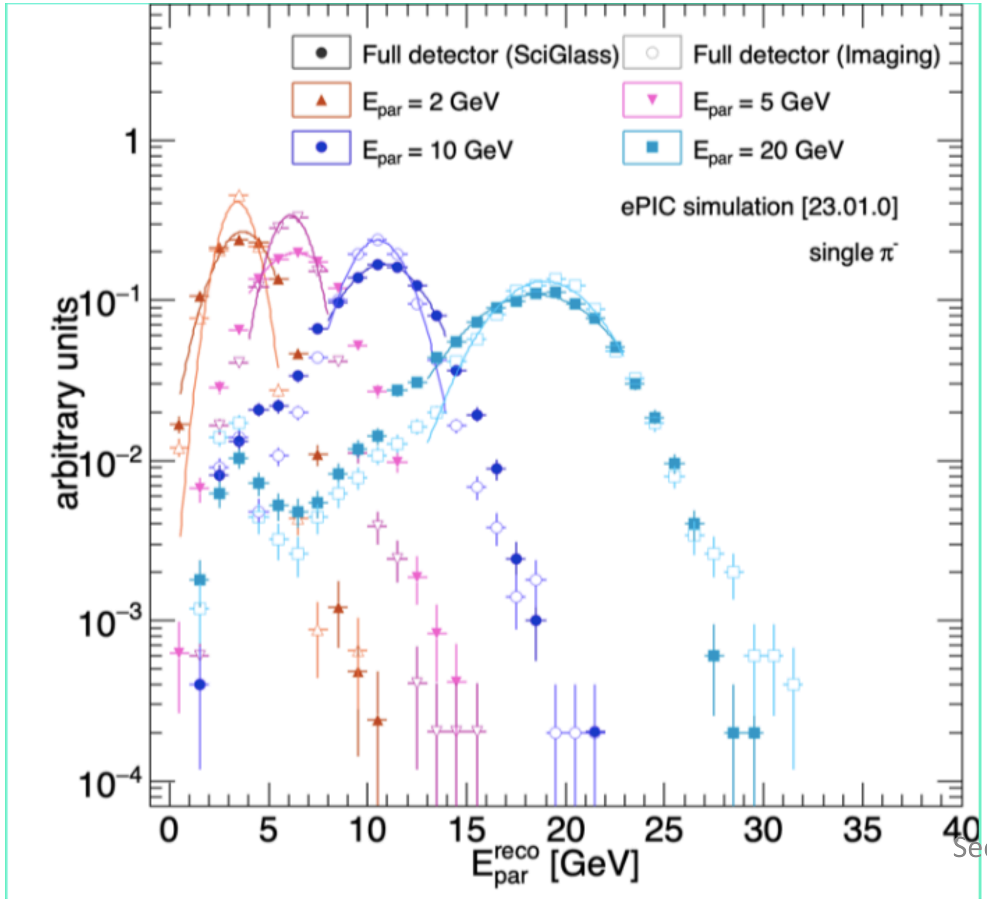
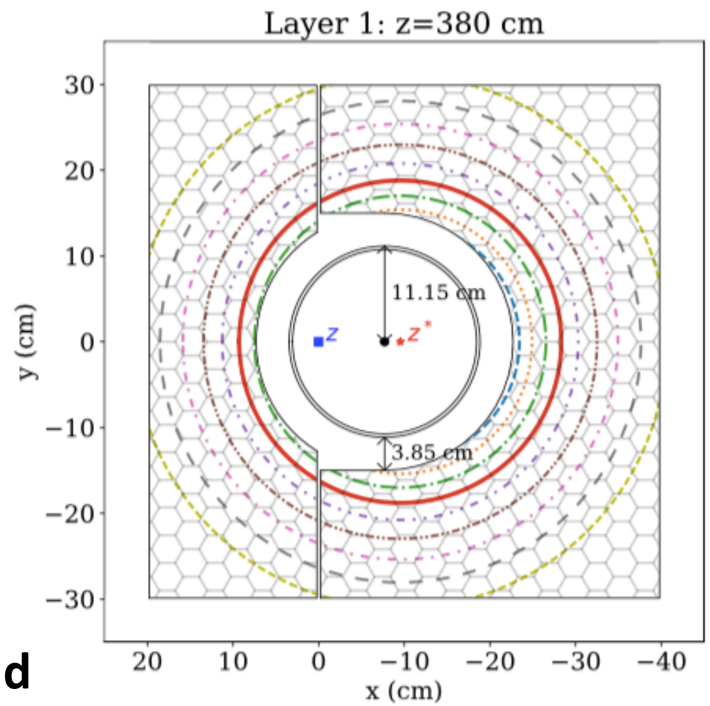




- ❑ Use ECal and HCal cluster / hit information in a multivariate regression analysis to calibrate response
- ❑ Could this be improved with more calorimetry in front of the magnet? See better resolution for imaging ECal which has greater interaction depth.

Crossing Angle and Forward Acceptance

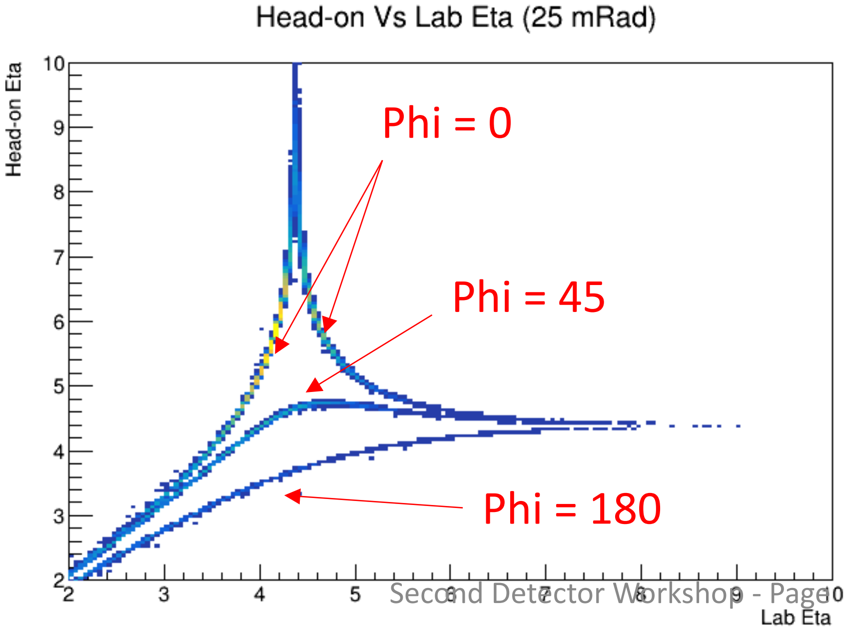
- The presence of a crossing angle complicates the acceptance in the forward region
  - Difference between ”detector symmetry” axis (centered on electron beam), “physics” axis (proton beam) and center of beam pipe
  - Beam pipe changes dimension as a function of z through the length of the forward calorimeter
  - How do we get calorimeter as close as possible to the beam pipe to maximize acceptance?

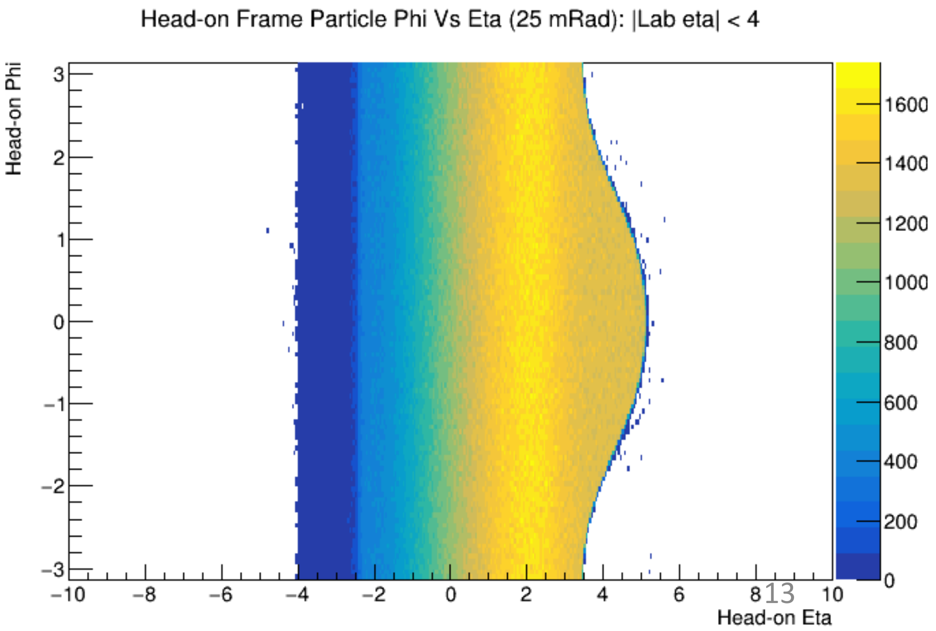


arXiv:2208.05472

Xing Angle = 25 mRad

- Can boost to a frame where beams are colinear (or just define coordinates w.r.t. hadron beam) – setting acceptance cuts in lab frame can lead to phi-dependent acceptance





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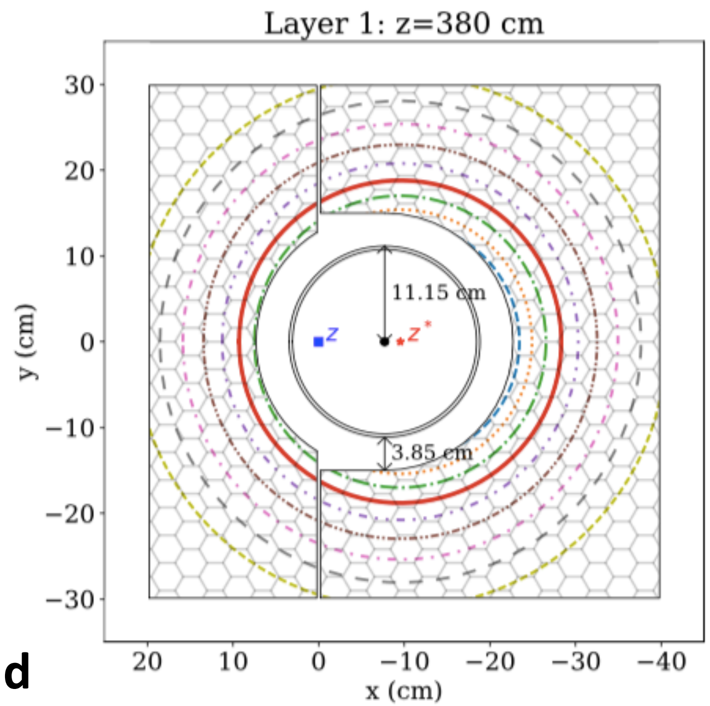

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Xing Angle = 35 mRad

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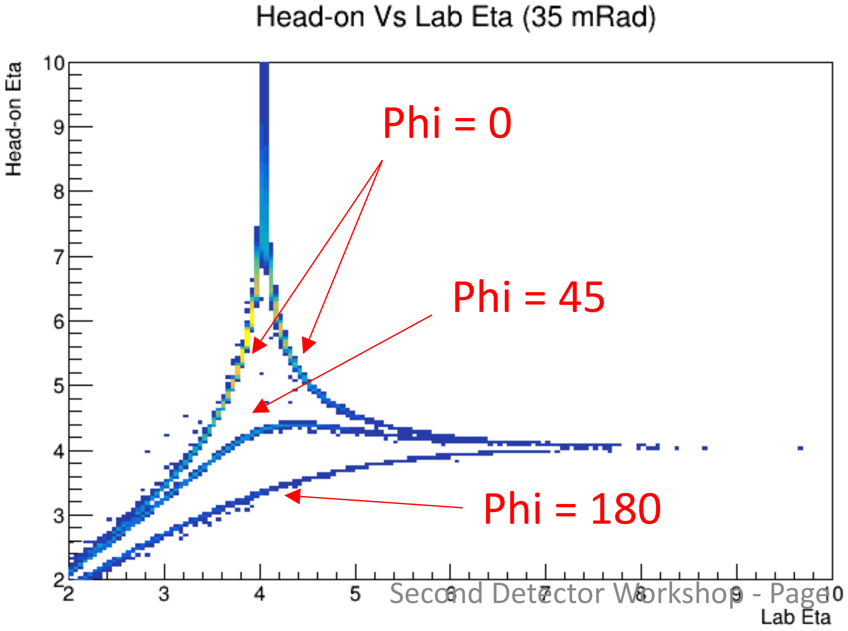
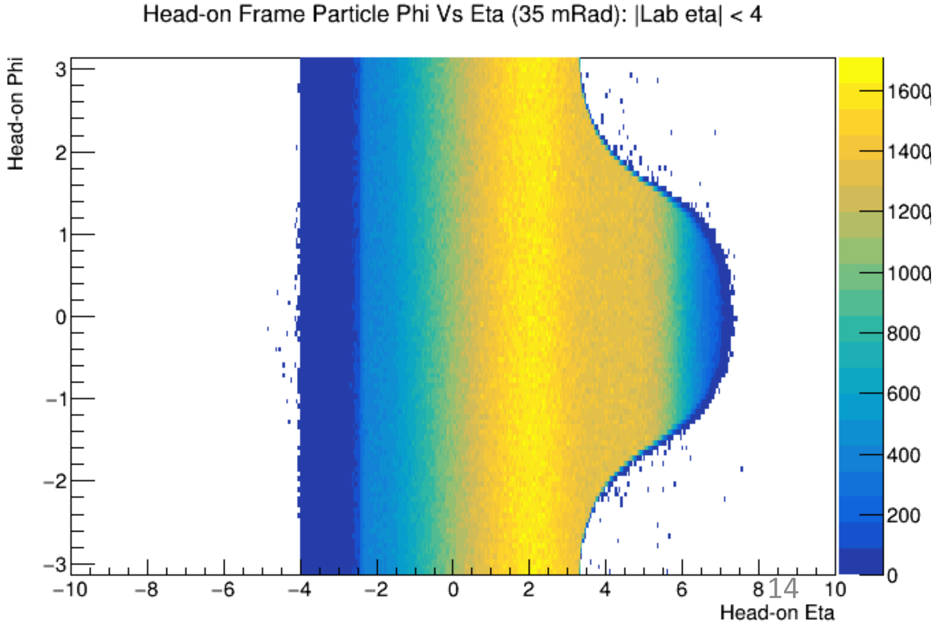
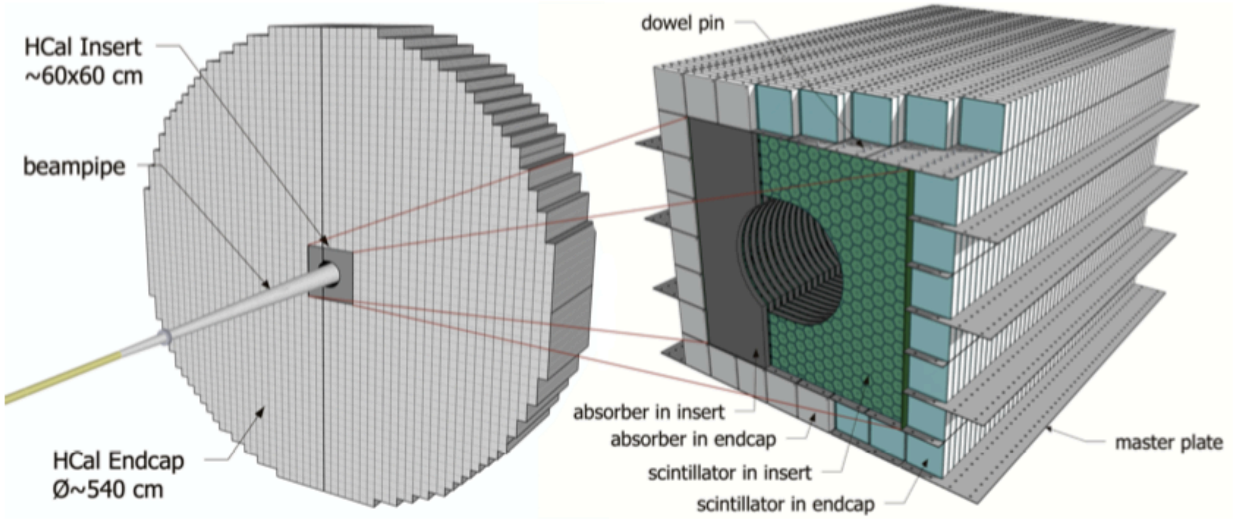




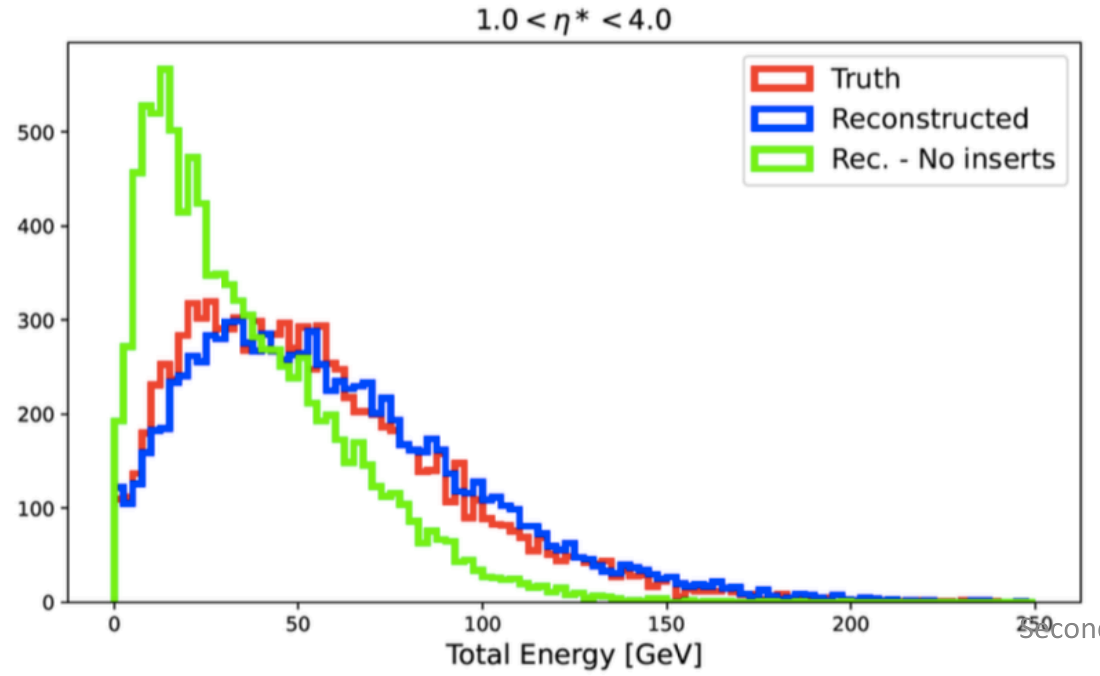
Forward Acceptance: Calorimeter Insert

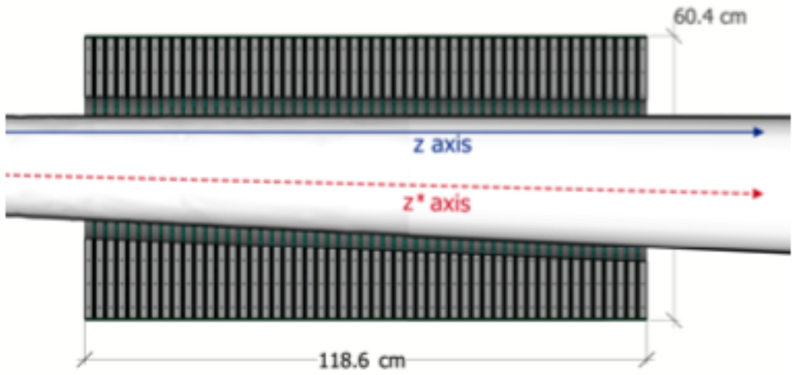
arXiv:2208.05472

- Calorimeter should sit as close as possible to the beam to maximize acceptance
  - Reduce phi-dependent acceptance effects as discussed above
  - Improve reconstruction of the total energy in event -> kinematic reconstruction



- Proposal in ePIC for a high-granularity insert whose geometry changes in z to follow the beam pipe





Larger crossing angle at the second IR will exacerbate forward HCal acceptance challenges -> Consider beam pipe design, high-eta calorimeter design, and even calorimeter z position to maximize acceptance

Conclusions

- Structure of DIS events at the EIC dictates that different detector regions will see particles/jets with significantly different energies

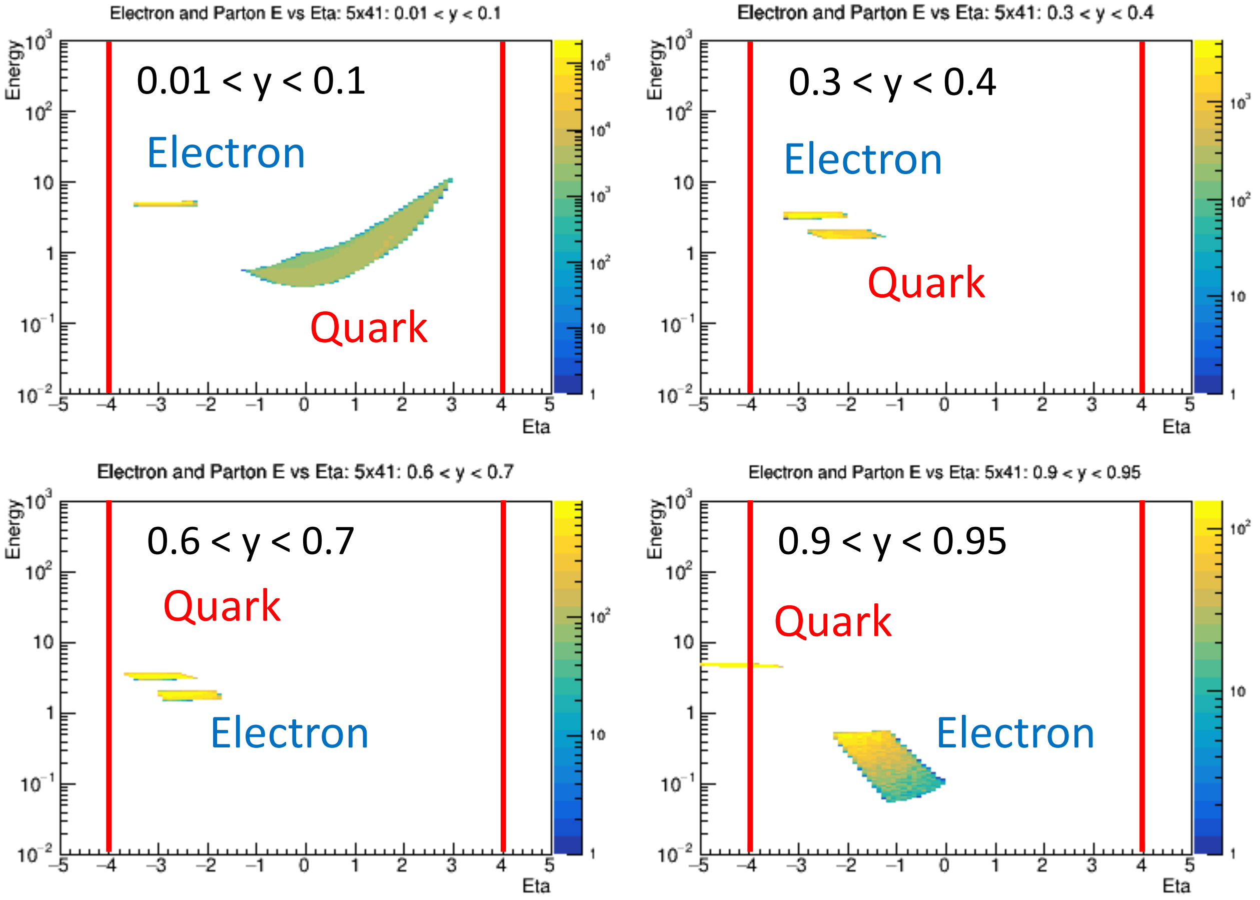
- Need to take this into account when deciding the function, and therefore the form, of calorimeter systems at a second detector

- Helps outline potential areas of complementarity
  - Some amount of 'inner calorimetry'?
  - Energy measurements vs neutral hadron ID / veto?
  - KLM / Muon tagging capability?

- Larger crossing angle will pose challenges for forward acceptance – think holistically about beam pipe design, calorimeter design and position to maximize coverage

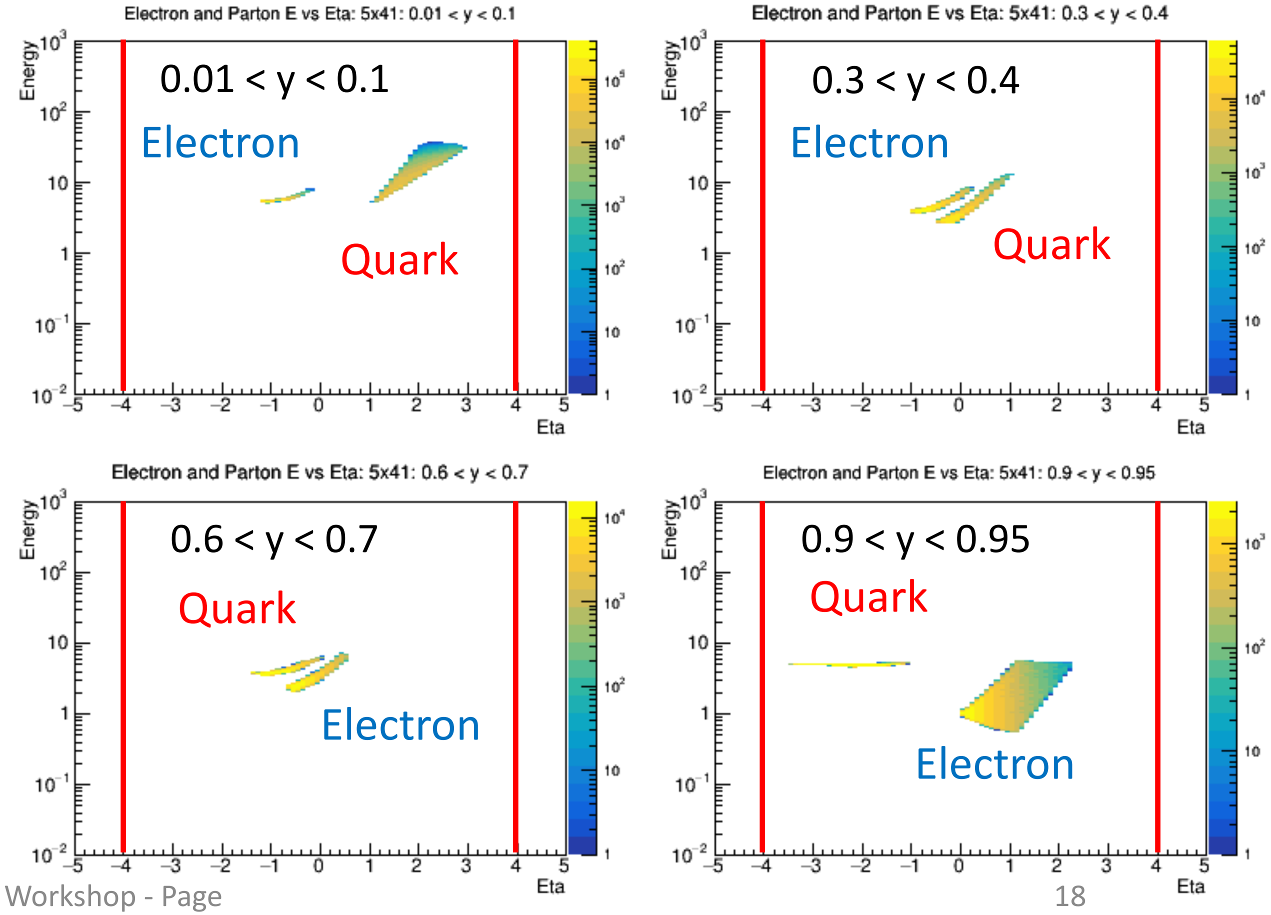
Backup

Electron and Struck Quark (5x41)

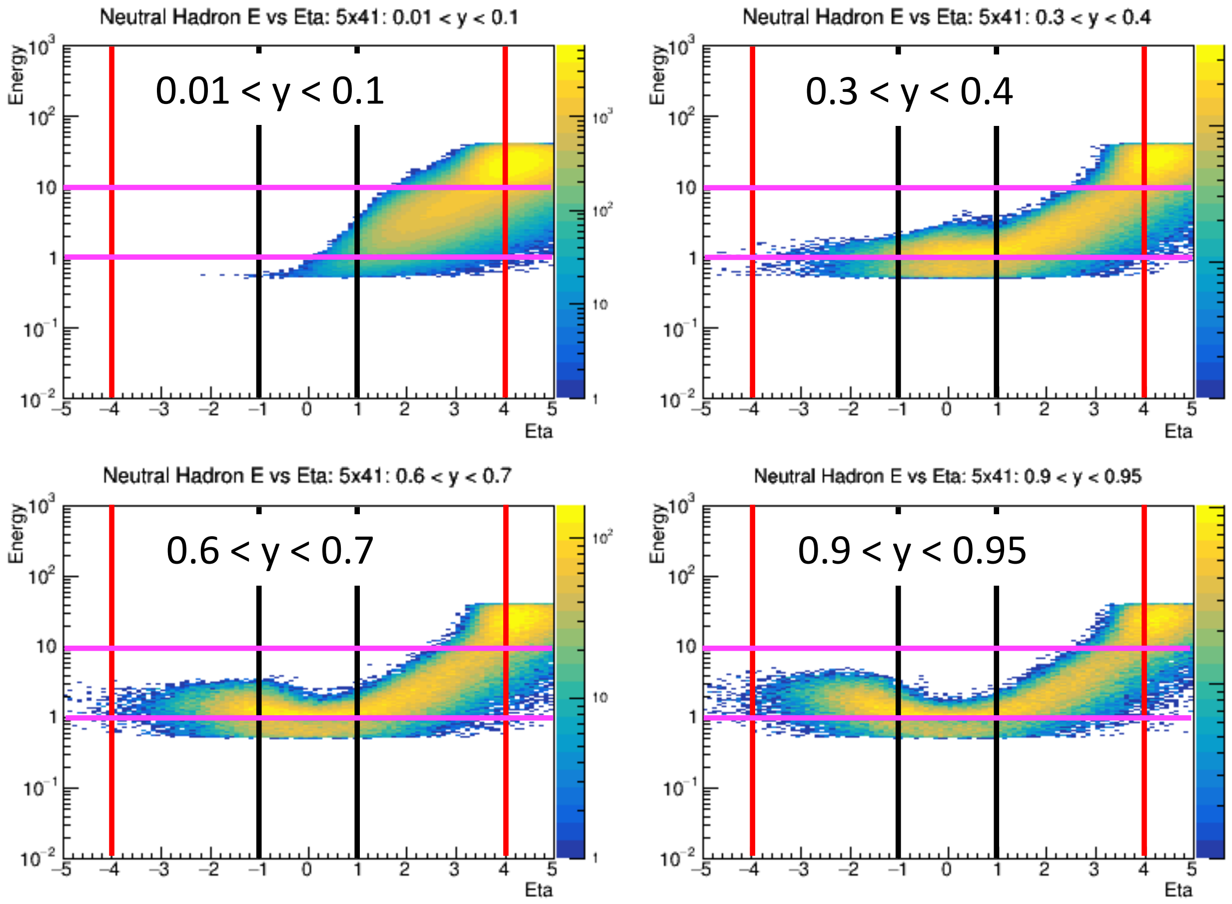


$0.1 < Q^2 < 1.0$

$10 < Q^2 < 100$

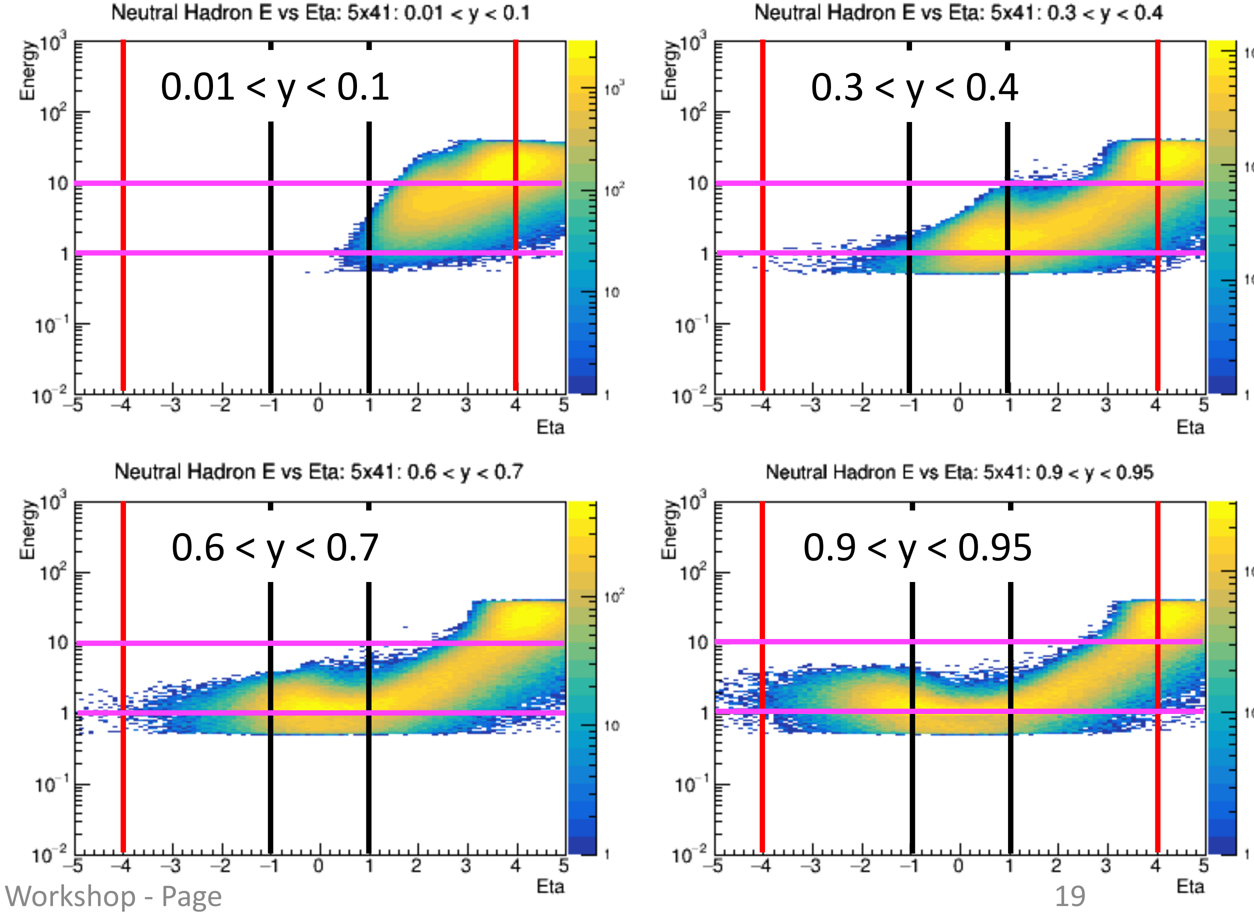


Neutral Hadrons (5x41)

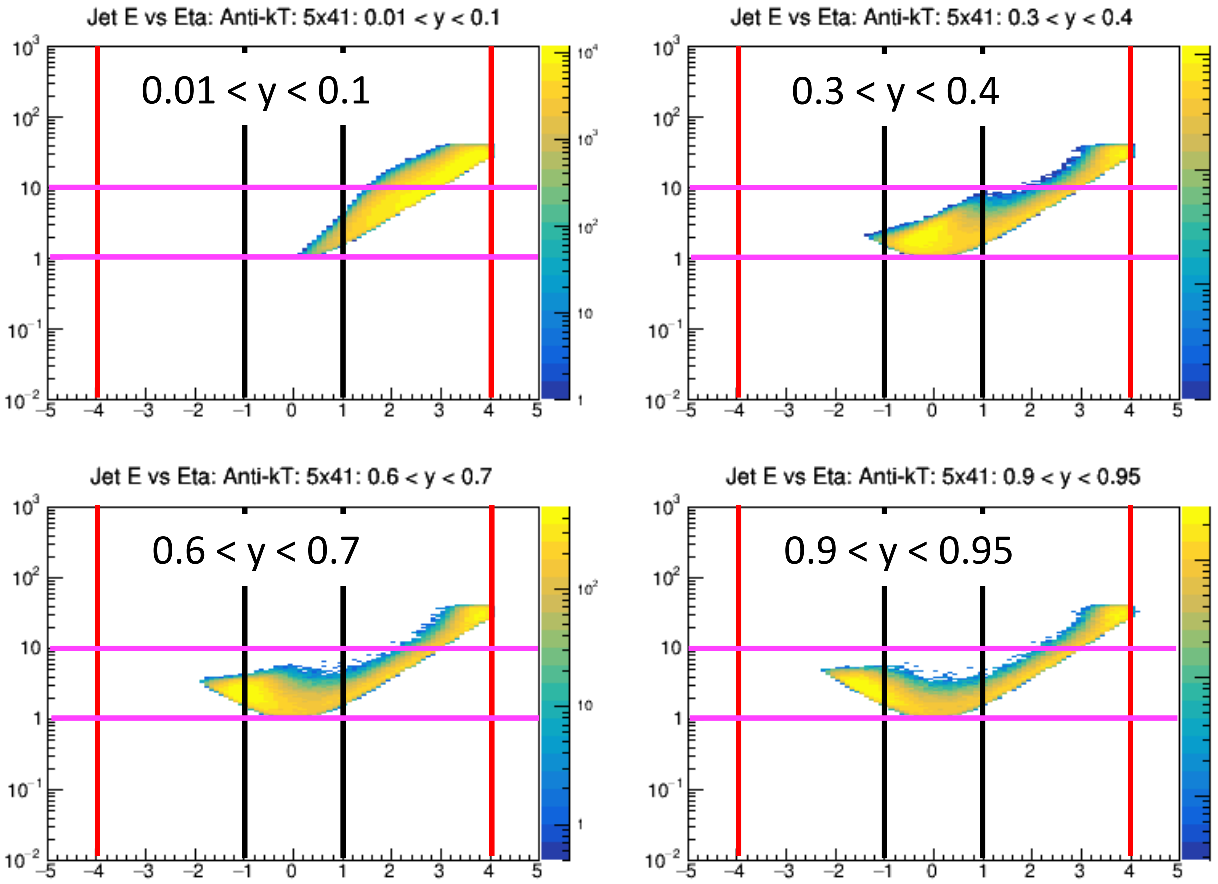


$1 < Q^2 < 10$

$10 < Q^2 < 100$



Reconstructed Jets (18x275)



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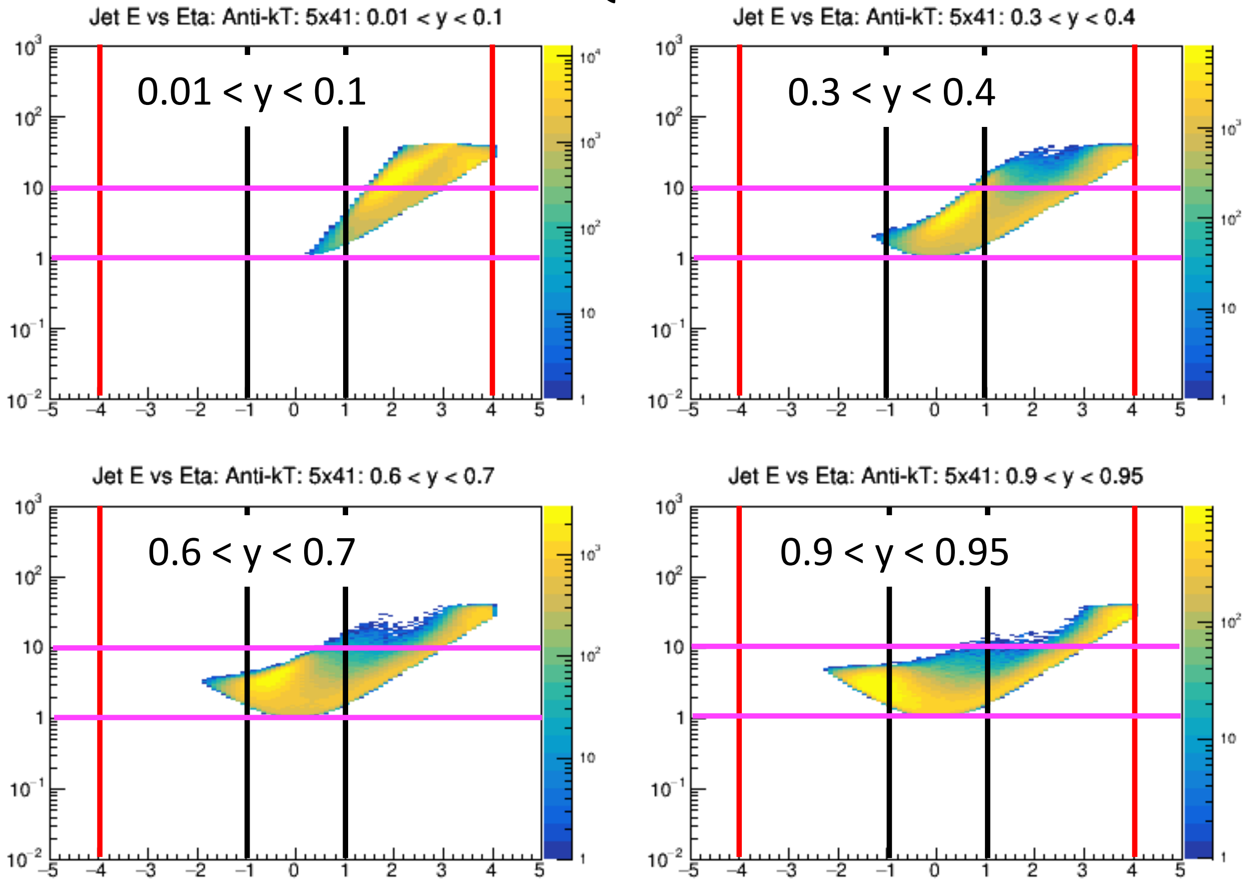
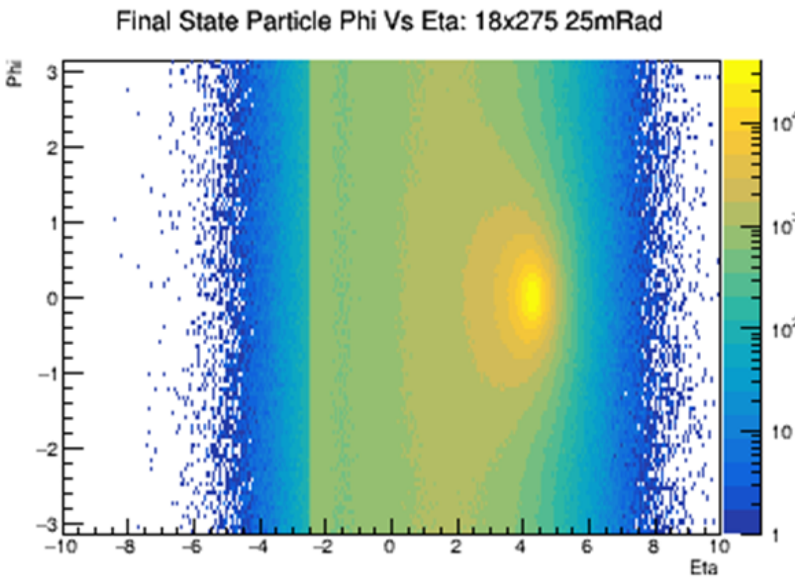
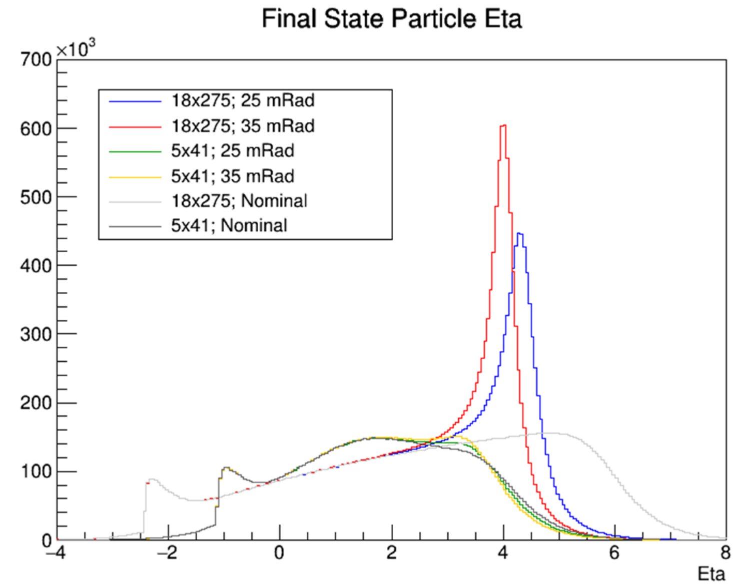
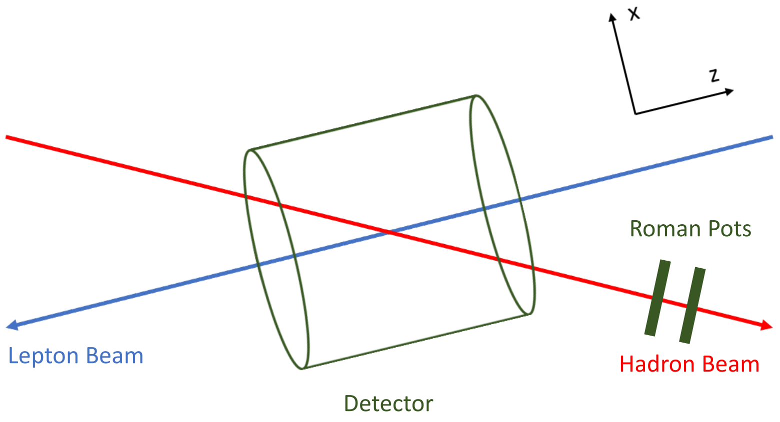


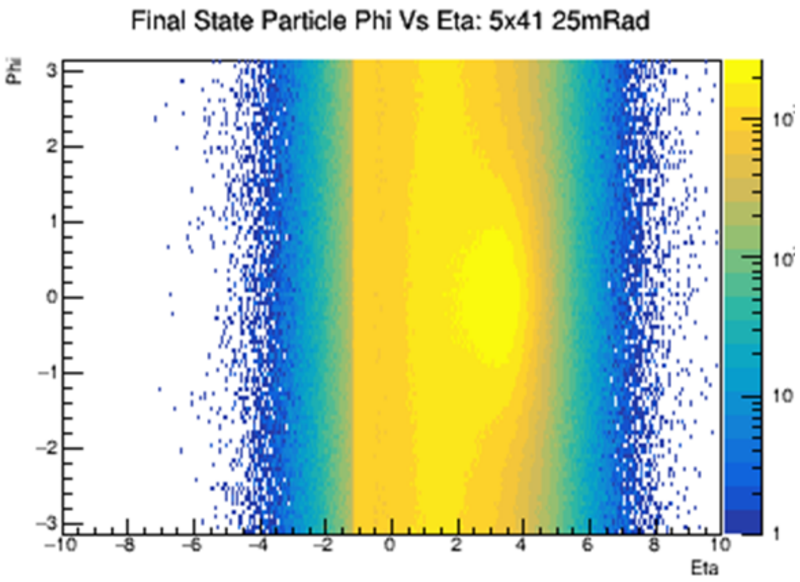
Final State Particle Distributions

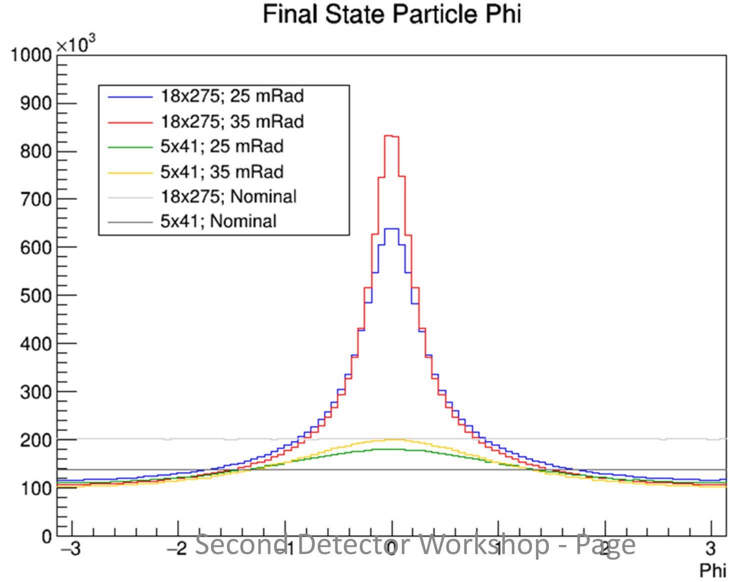






- Detector solenoid must align with electron beam to minimize synchrotron radiation: “lab frame” -> electron beam = z-axis



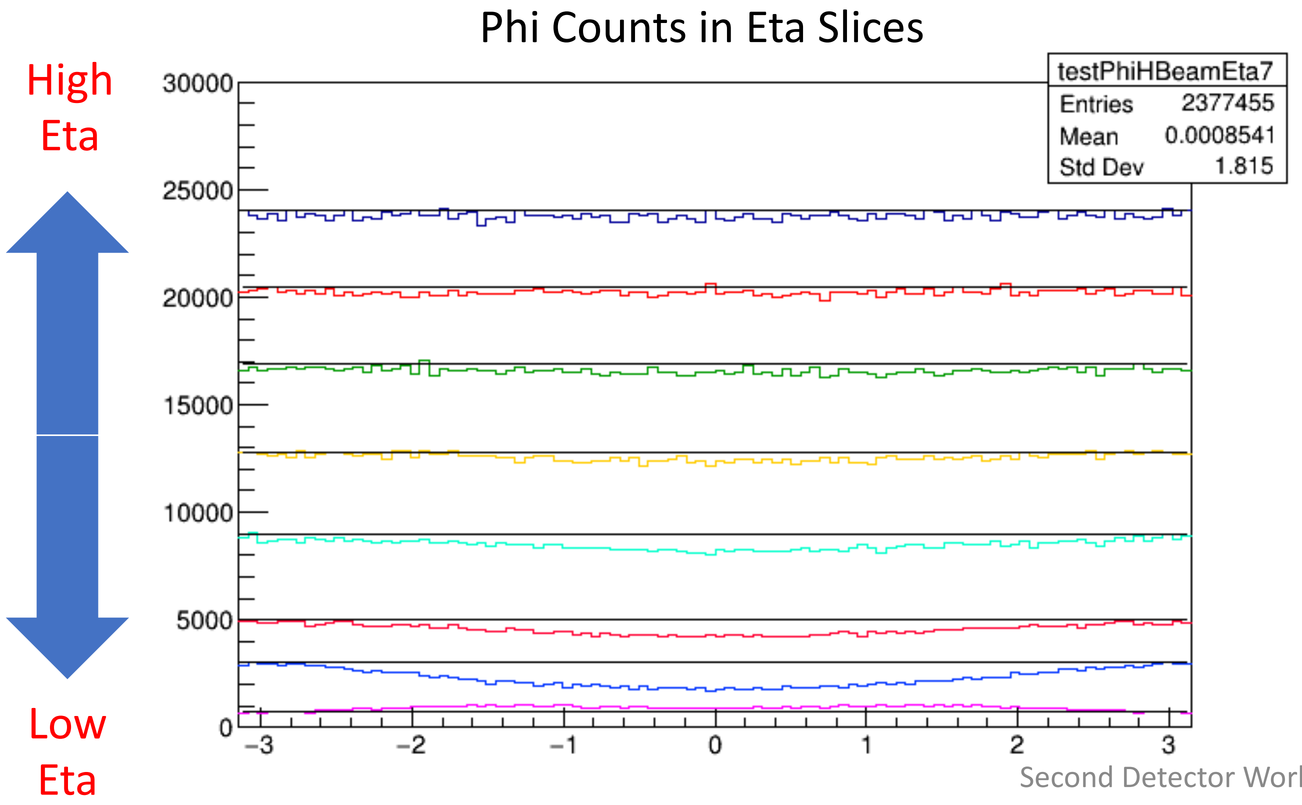


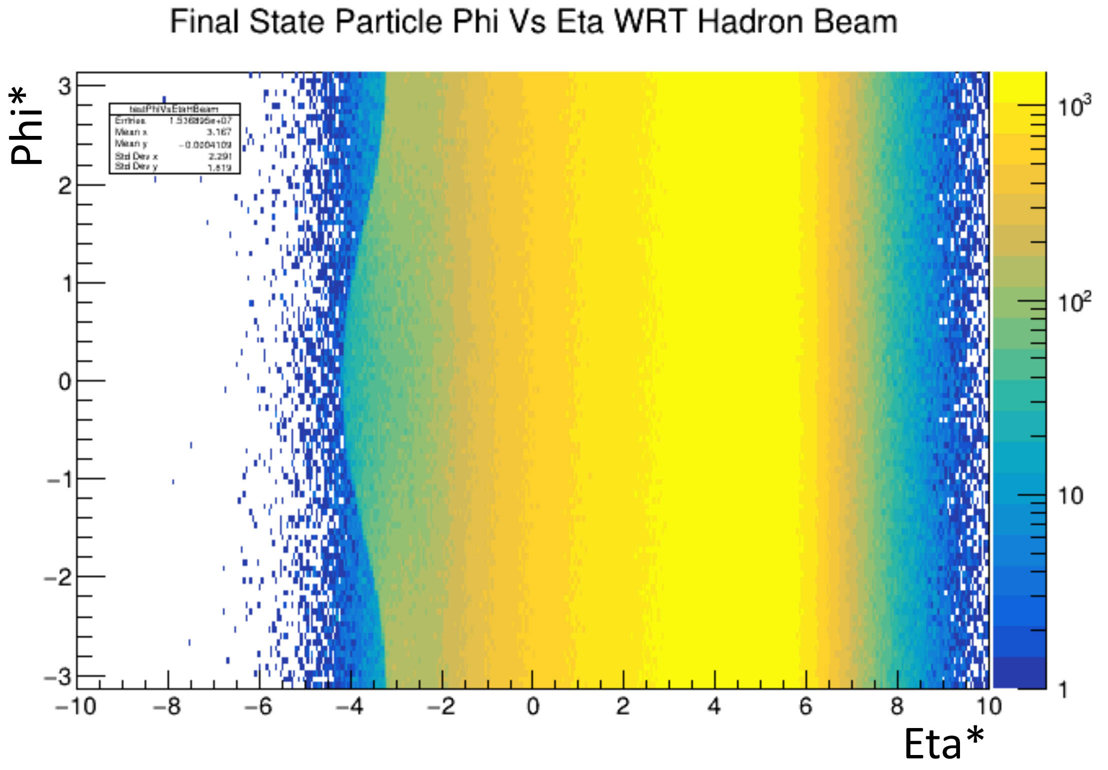
- When measuring in lab frame coordinates – see a hot spot in eta/phi corresponding to the beam direction
- More pronounced for more relativistic beams
- How do we mitigate these features?

Coordinates W.R.T. Hadron Beam

- ”Physics” in the forward region should be consistent around the hadron beam regardless of where the beam is pointing

- In some sense, the features seen above are simply artifacts of measuring about the ”wrong” axis -> instead, define eta and phi with respect to the hadron beam direction (Eta*, Phi*)





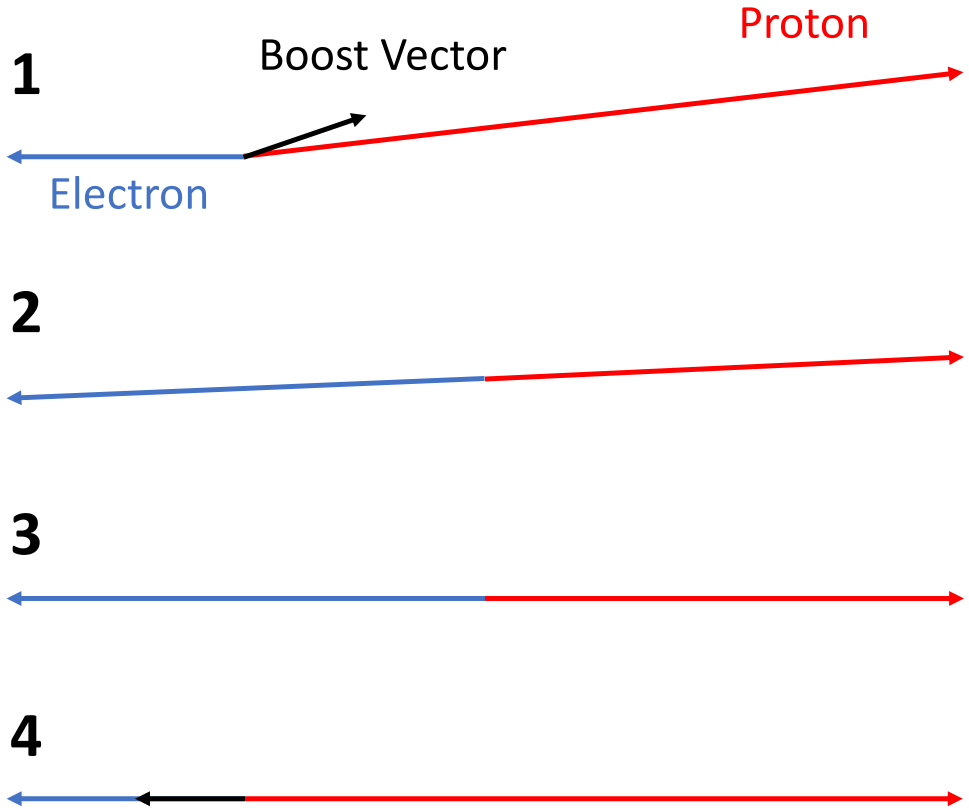
- When defined w.r.t. the hadron beam, the concentrations in eta and phi disappear

- However, because there is no common beam axis, the particle distribution along the electron-going direction becomes distorted

- Can avoid these distortions by boosting to a frame in which the beams are collinear

Head-On (Minimum Boost) Frame

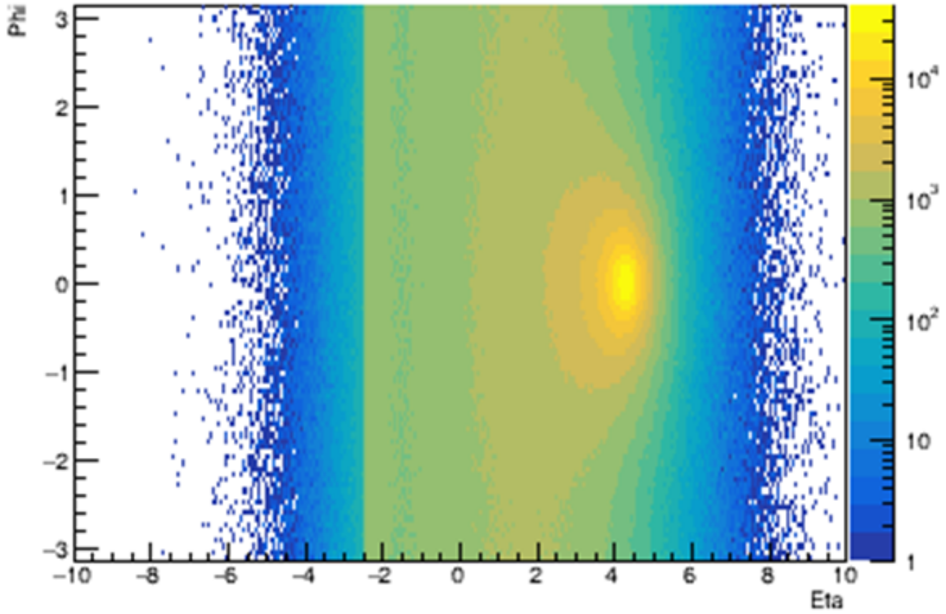
- ❑ Can boost and rotate into a frame in which the beams are collinear (no crossing angle) and energies are very close to the original (minimum boost)
- ❑ This should give an undistorted distribution of particles at high and low eta simultaneously



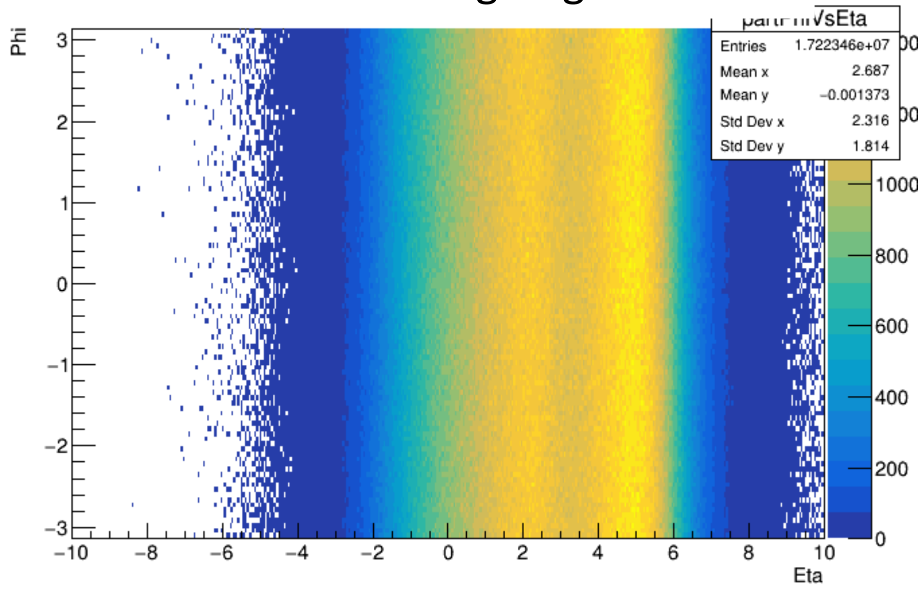
1. Initial Configuration in the Lab Frame includes a relative angle between the beams
2. Boost by sum of beam 4-momenta to get to CM Frame
3. Rotate about y-axis to eliminate x-component of momentum
4. Boost back along z to (nearly) restore original beam energies

Head-On Frame Particle Distributions

Lab Frame Distribution

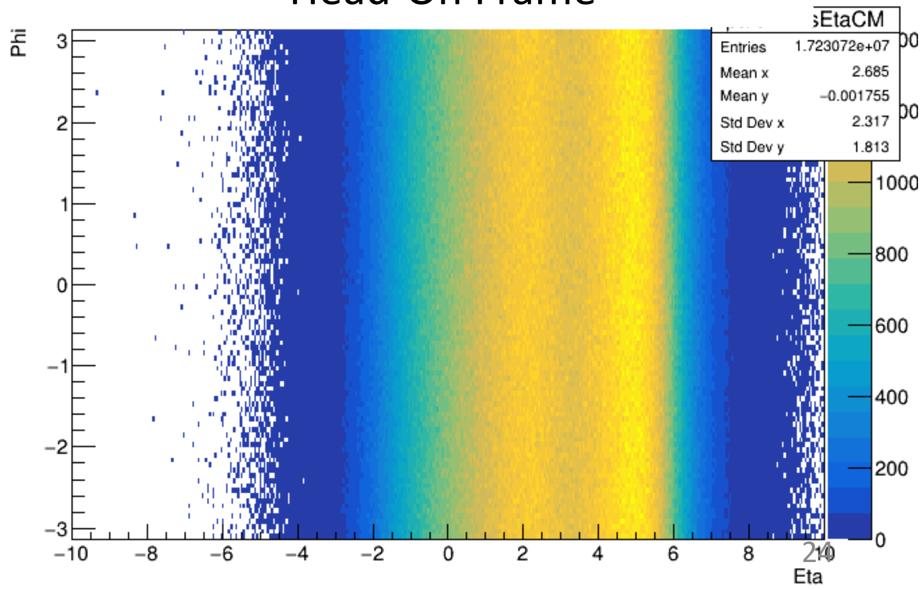


No Crossing Angle



Transform to Head-On

Head-On Frame



- Transformation to the head-on frame removes all features in the final state particle distribution for forward and backward regions simultaneously
- Resulting distribution matches that from default simulation with no crossing angle introduced

Detector Acceptance Considerations

- The head-on frame distributions shown previously assumed infinite acceptance – what effect will finite detector acceptance have?

- Displacement between beams means that acceptance cuts in the lab frame (w.r.t. the electron beam) will introduce phi-dependent acceptance features in head-on frame

- Try defining acceptance cuts w.r.t. the hadron beam instead

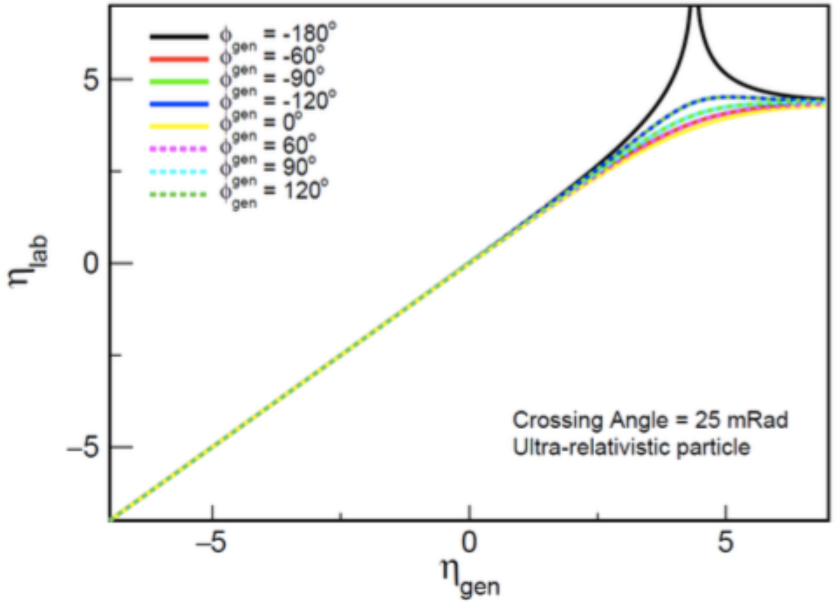
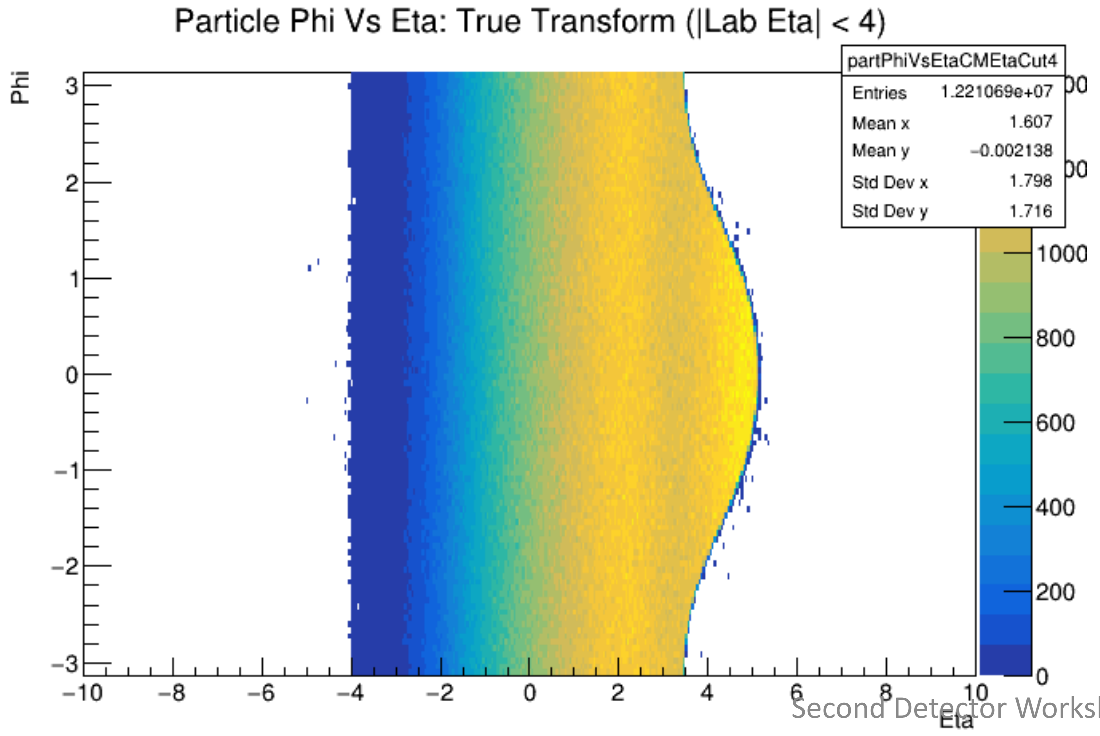
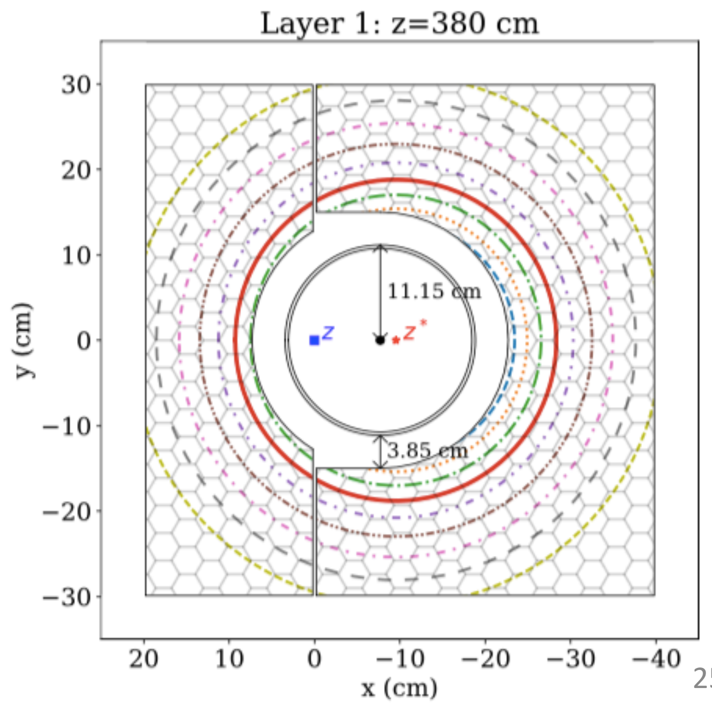


Figure by Barak Schmookler





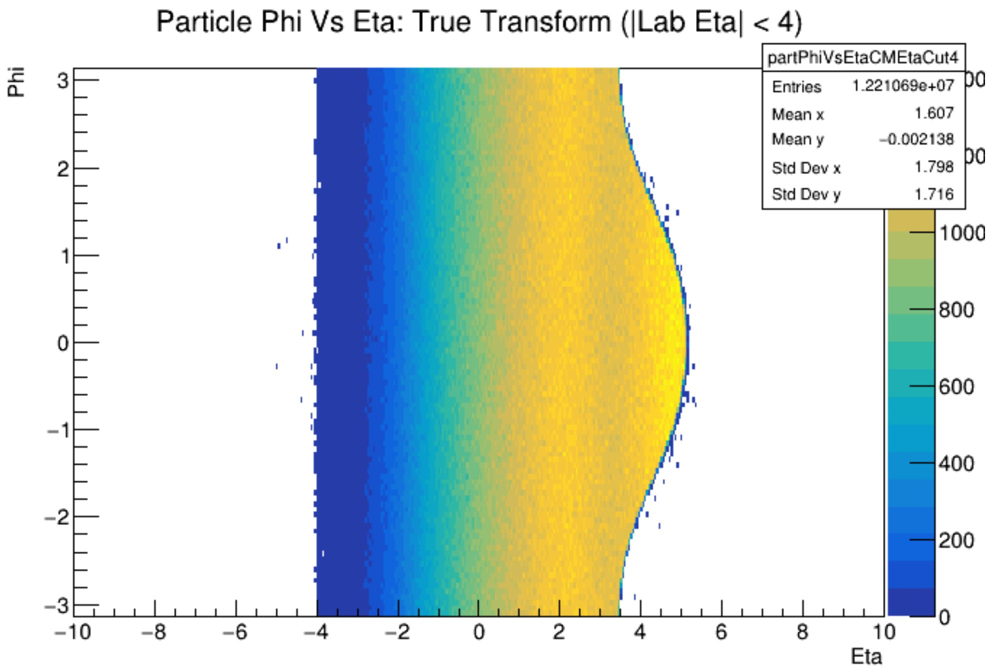
arXiv:2208.05472

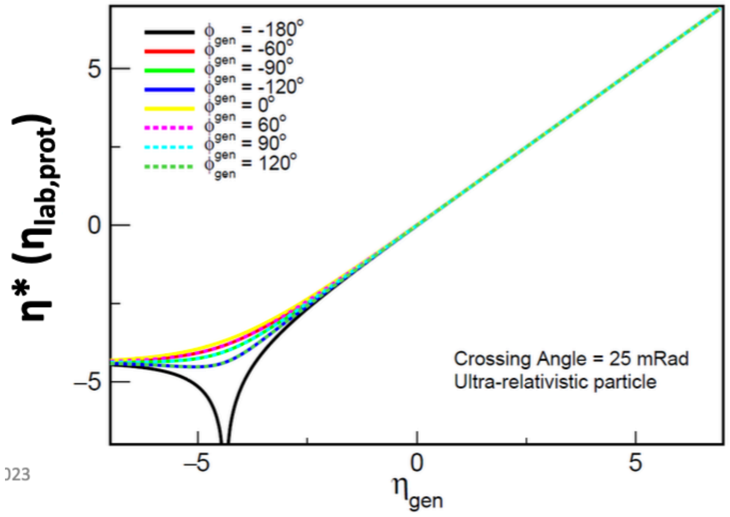
Defining Acceptance Cuts

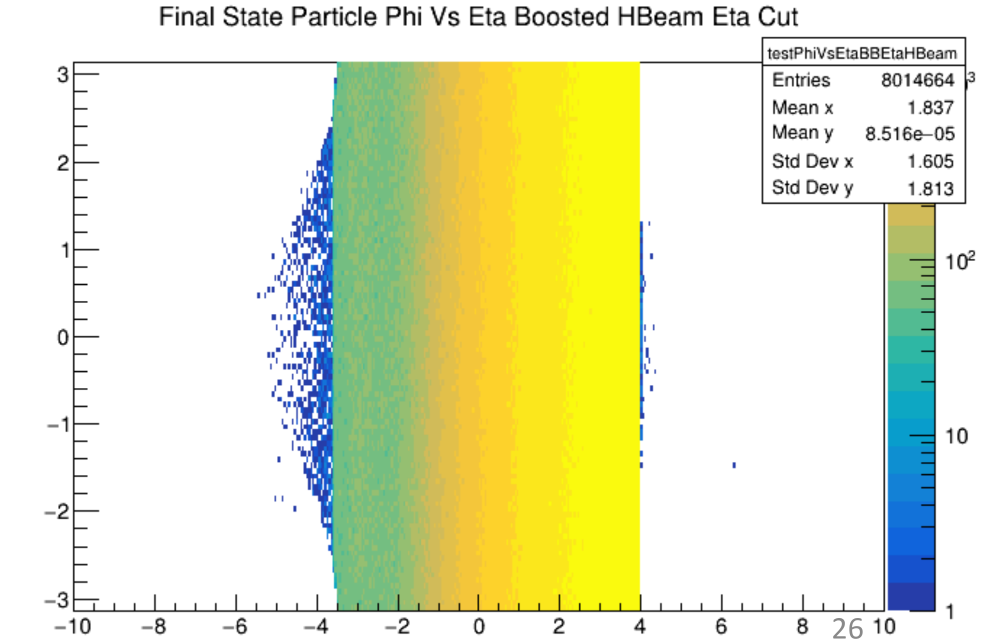
- The beam line shape in the endcap region is complicated, but mostly follows the hadron beam direction

- The z-axis in the head-on frame corresponds to the direction of the lab frame proton beam -> defining detector acceptance w.r.t. the hadron beam should eliminate the phi-dependent artifact

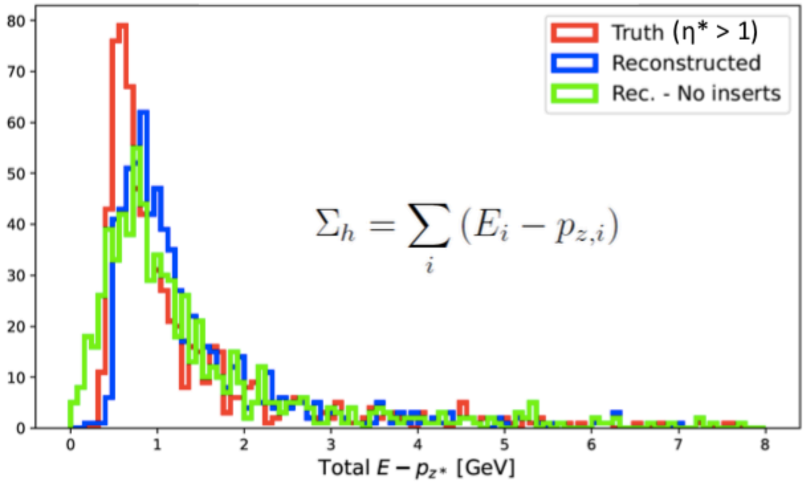
- Both plots on the right show the phi vs eta distribution where these quantities are defined in the head-on frame
  - Top plot applies a cut for |eta| < 4 where eta is defined relative to the electron beam
  - Bottom plot applies a cut for |eta| < 4 where eta is defined relative to the hadron beam

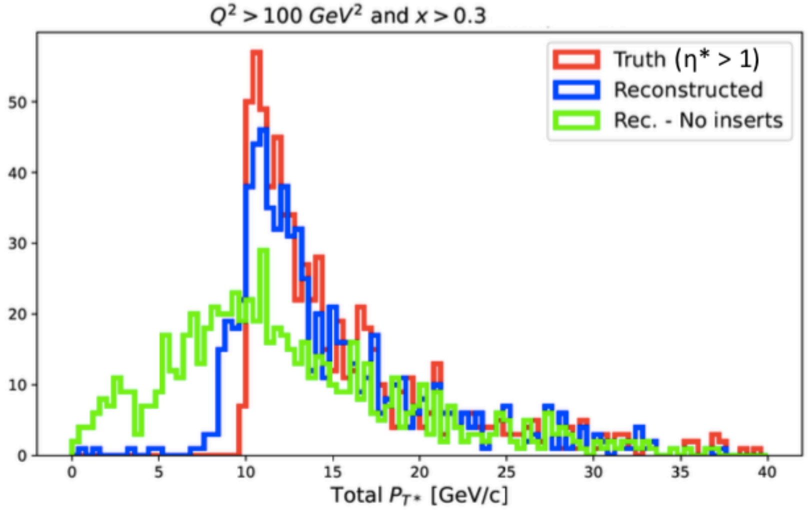






Calorimeter Insert and Kinematic Reconstruction





$$y_h = \frac{\Sigma_h}{2E_e}$$

$$Q_h^2 = \frac{p_{t,h}^2}{1 - y_h}$$