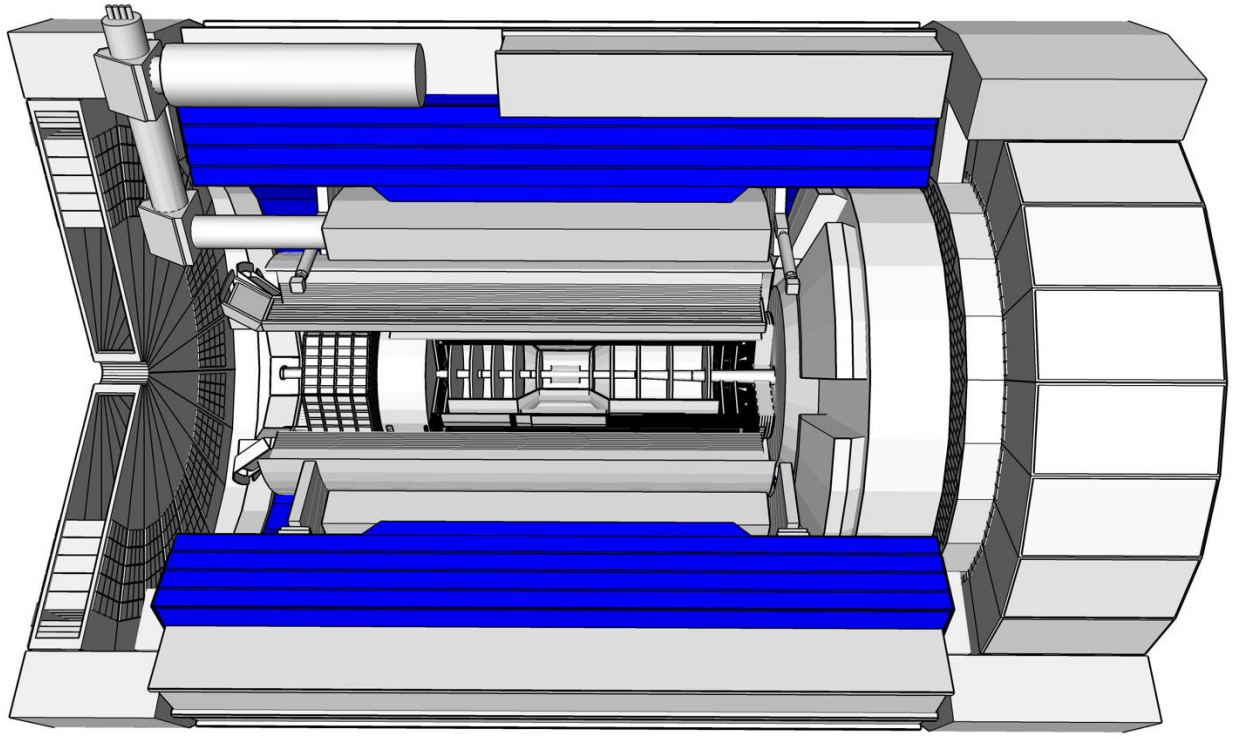
The Barrel Hadronic Calorimeter - BHCal



August 1, 2025

DSLs: S. Bathe (Baruch) & M. Sarsour (GSU)

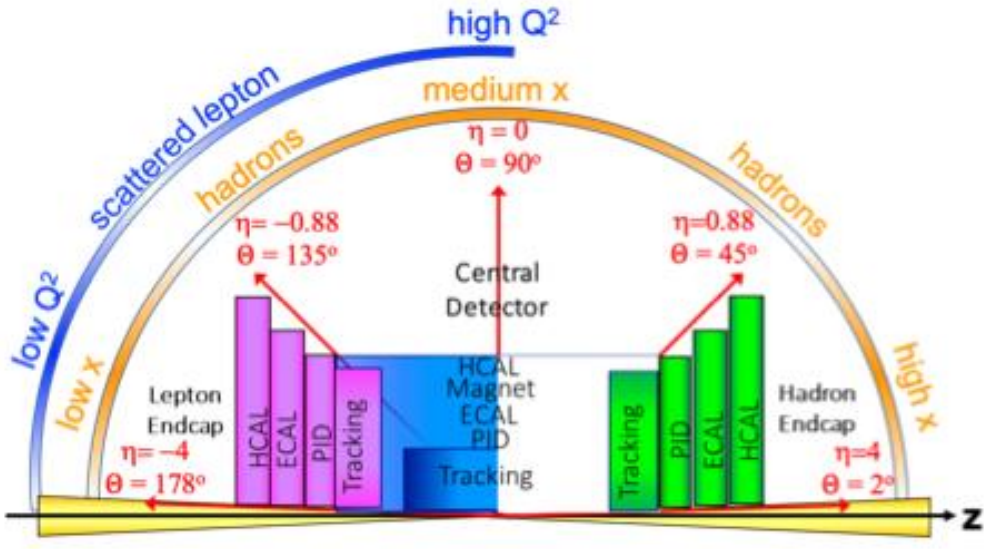
Team: ANNL, Baruch, BNL, GSU, ISU, ORNL , UNH, NMSU

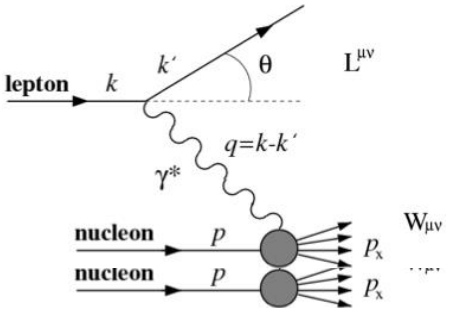
The Barrel Hadronic Calorimeter - BHCal

- The requirements for the barrel hadronic calorimeter (BHCal) in the Yellow Report are primarily motivated by single jet measurements. Improving jet energy scale and resolution through precise measurement of the jet's neutral component

- The BHCal offers several additional performance benefits, including:
  - Reconstruction of neutral hadrons, such as neutrons
  - Reconstruction of event kinematics and the hadronic final state
  - Tagging of charged-current DIS events
  - Muon identification

The Barrel Hadronic Calorimeter - BHCal

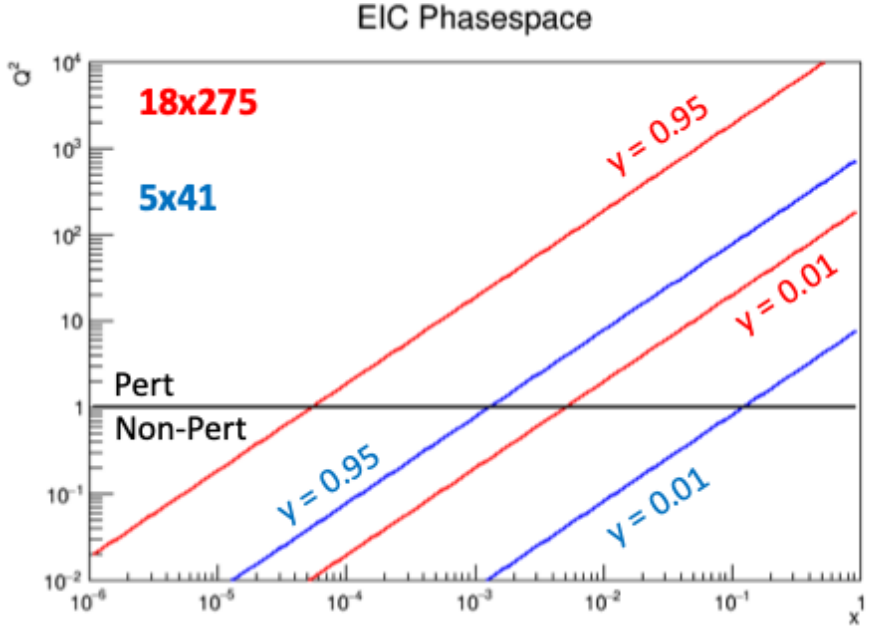




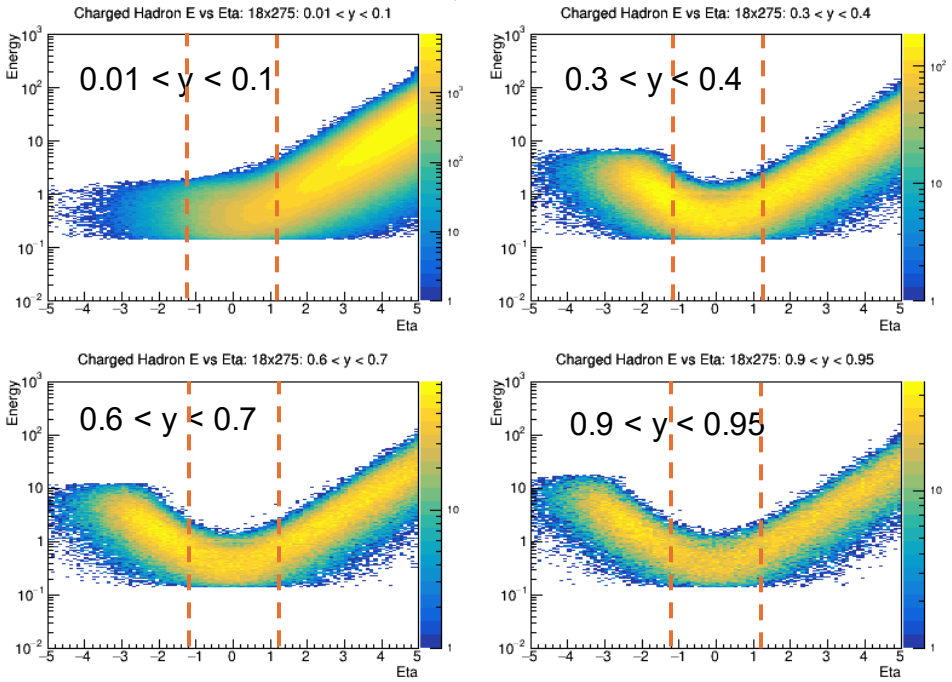
$$Q^2 = -q^2 = -(k - k')^2$$

$$W^2 = (q + P)^2$$

$$y = \frac{q \cdot P}{k \cdot P} \qquad x = \frac{Q^2}{2p \cdot q}$$



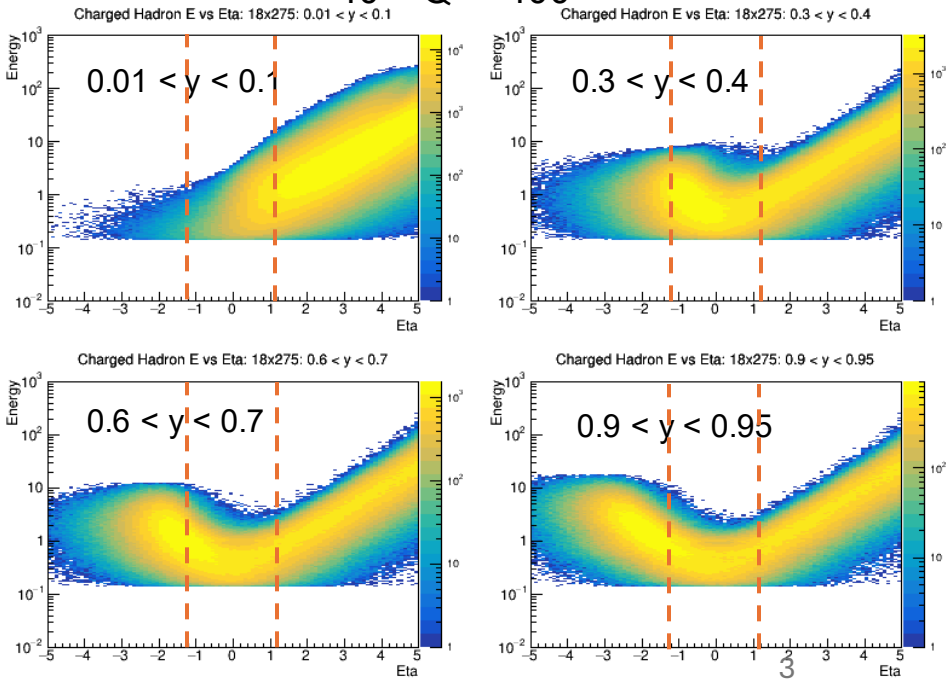
0.1 < Q² < 1.0



Brian Page,
CFNS workshop 2023

(Charged) Particle Distributions (18x275)

10 < Q² < 100

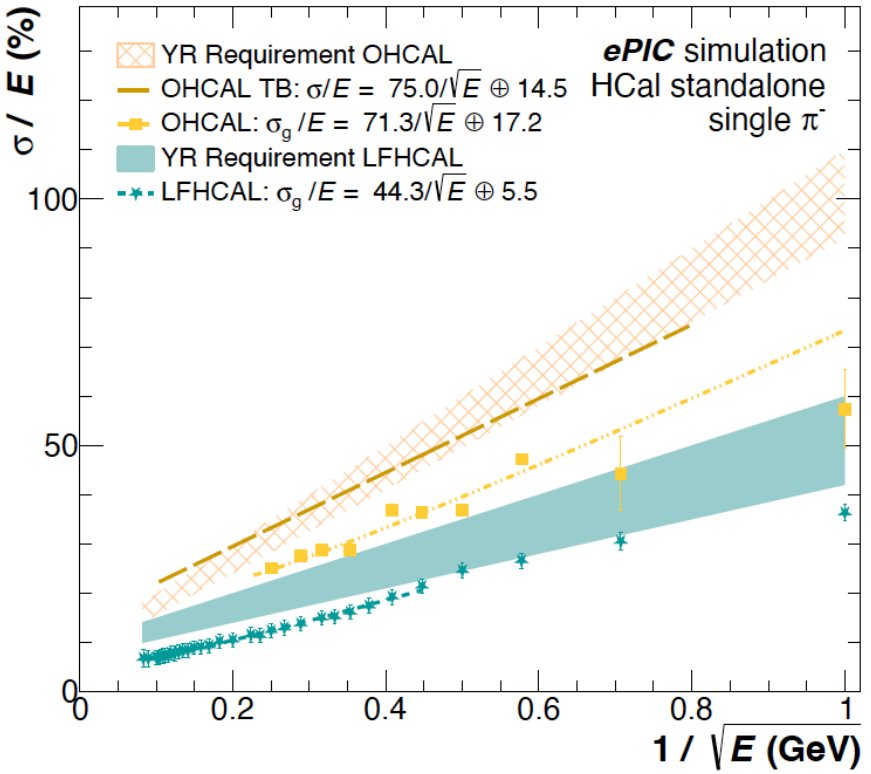


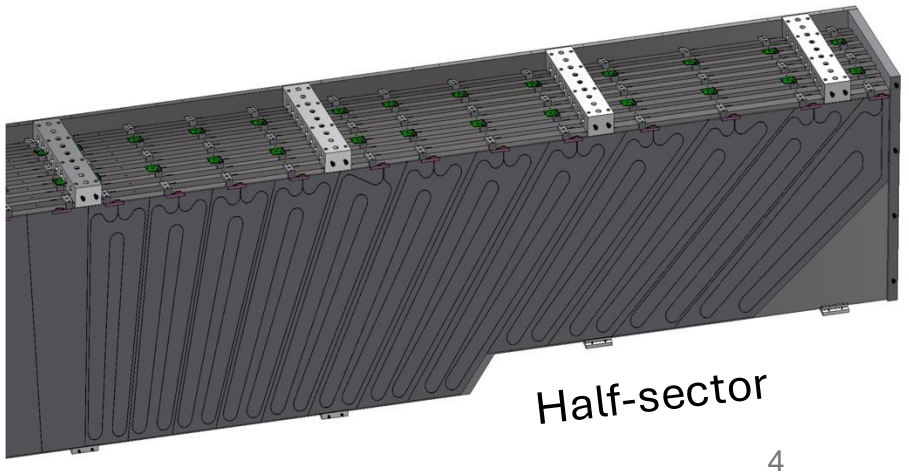
BHCal Requirements

- The Yellow Report indicates that $\frac{\sigma_E}{E} \approx \frac{(80-100)\%}{\sqrt{E}} \oplus (7-10)\%$ will be adequate.

- sPHENIX Outer Hadronic Cal. (OHCAL) with $\frac{\sigma_E}{E} \approx \frac{75\%}{\sqrt{E}} \oplus 14.5\%$
  - Tilted-plate: alternating steel & scintillating tile (+ WLS fibers)
    - $|\eta| < 1.1$ & 2π coverage.
    - 32 sectors – 6 m long, 16 tons each
    - 48 towers/sector @ 5 tiles/tower ($\Delta\eta \times \Delta\varphi \sim 0.1 \times 0.1$)

→ **ePIC** will refurbish sPHENIX OHCal, but read out each tile ($\Delta\eta \times \Delta\varphi \sim 0.1 \times 0.02$)

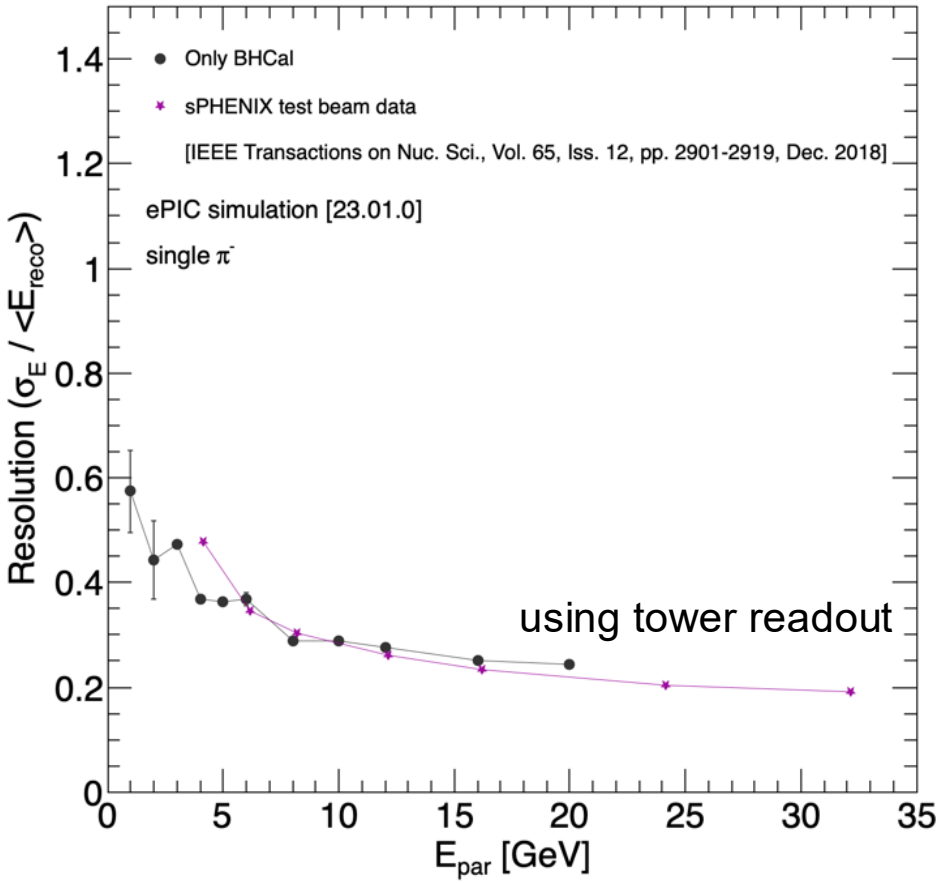


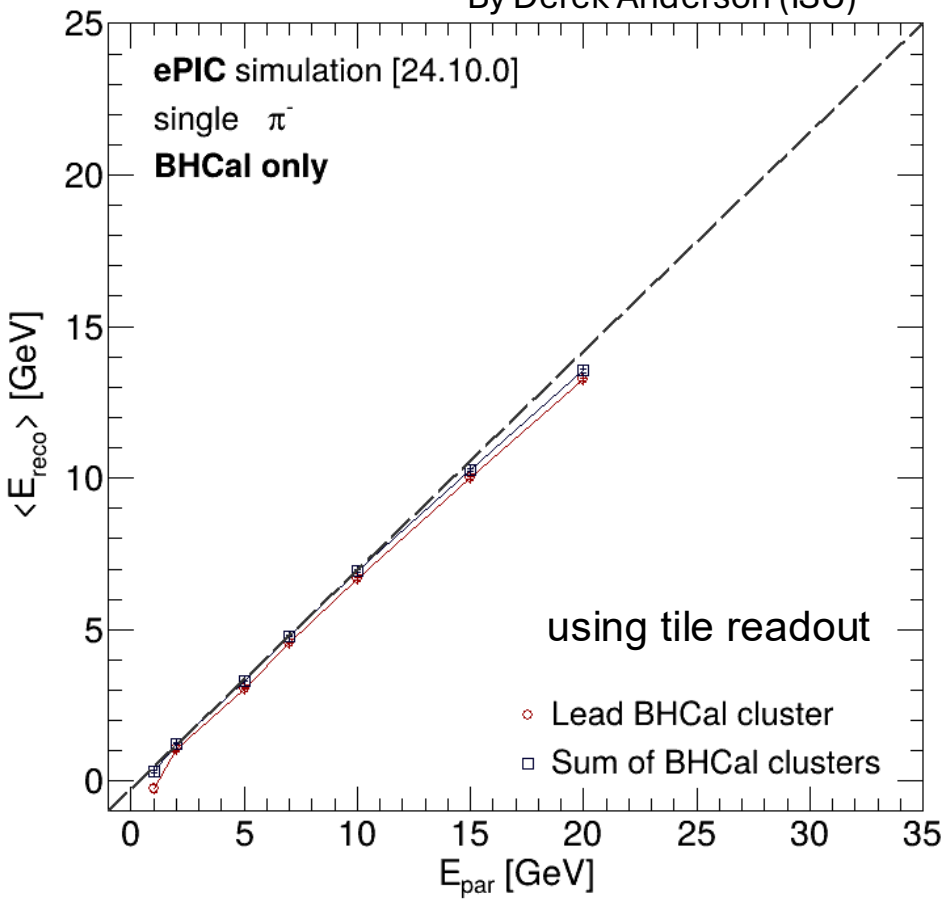


BHCal in ePIC Simulation Framework

- BHCal implemented in DD4hep simulation of ePIC
  - Resolution&Linearity from ePIC simulation vs. sPHENIX test beam data (*IEEE Transactions on Nuc. Sci., Vol.* ***65****, 2901 – 2919 (2018)*)

By Derek Anderson (ISU)



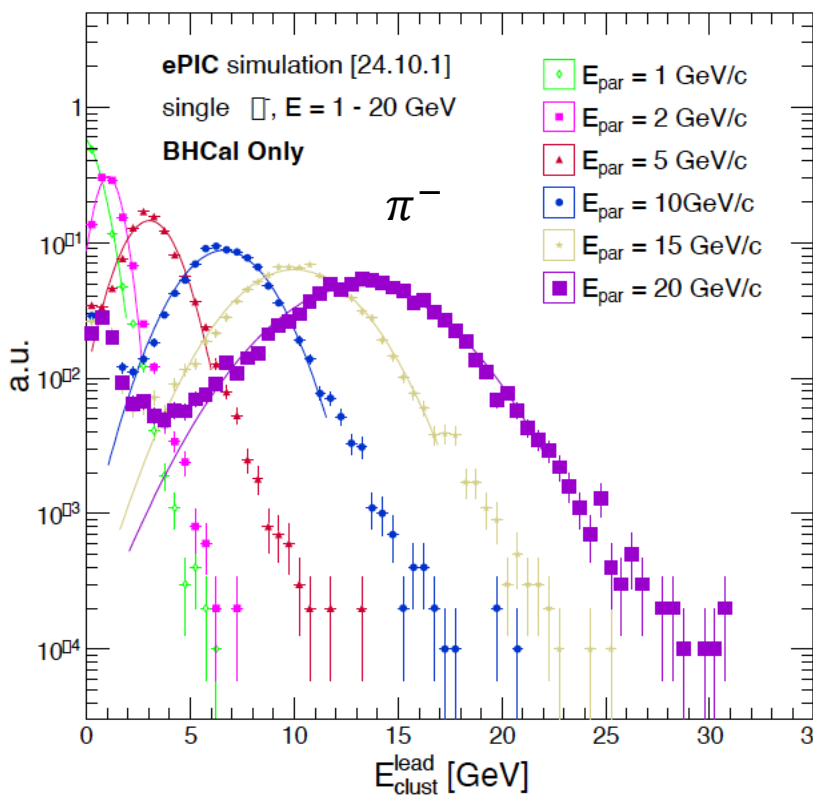


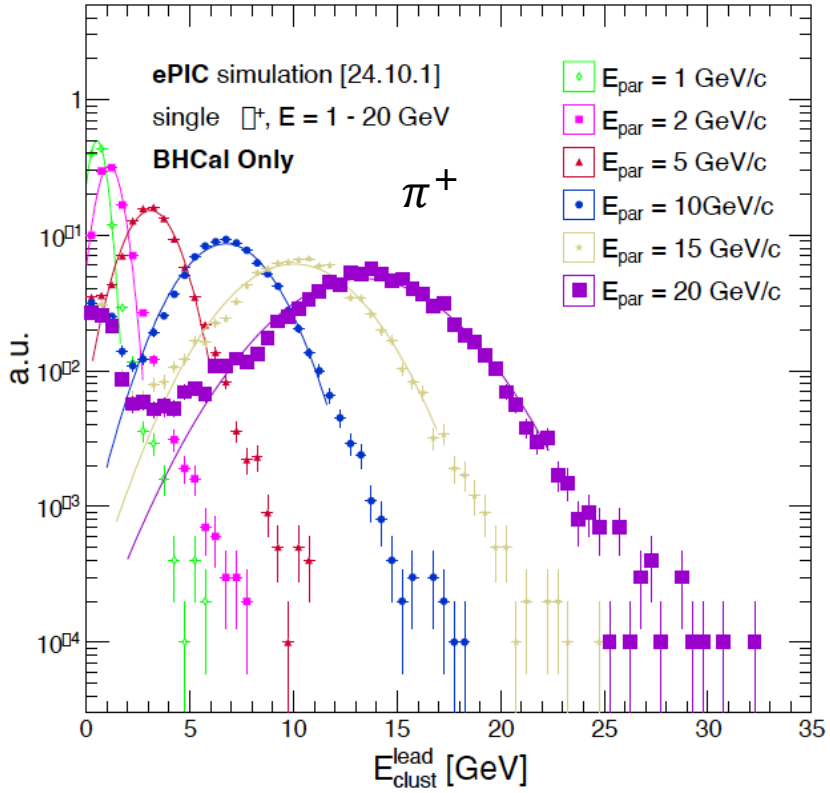
❖ Ongoing: include CAD geom. through GDML files + per-tile simulations (clustering, ... etc).

The Barrel Hadronic Calorimeter - BHCal

❑ Hadrons energy reconstruction

Reconstructed energy of the leading (highest energy) cluster / Individual tiles clustering



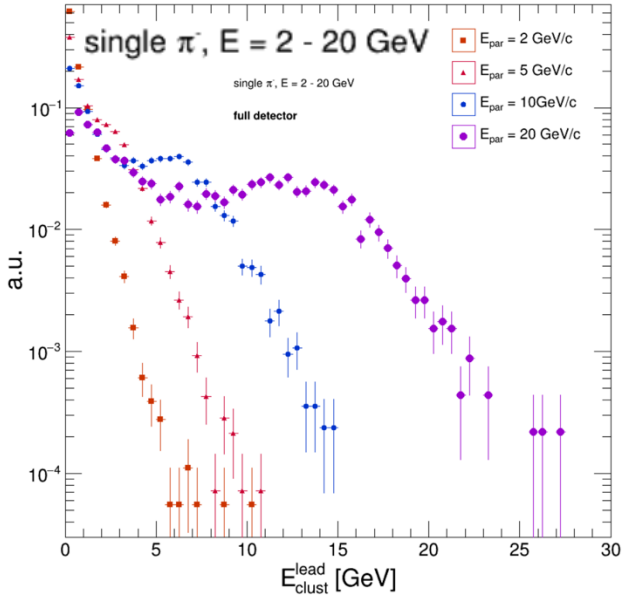


- *Energies are shown at the EM scale*
- *The simulation of the BHCal produces reasonable hadronic energy spectra.*

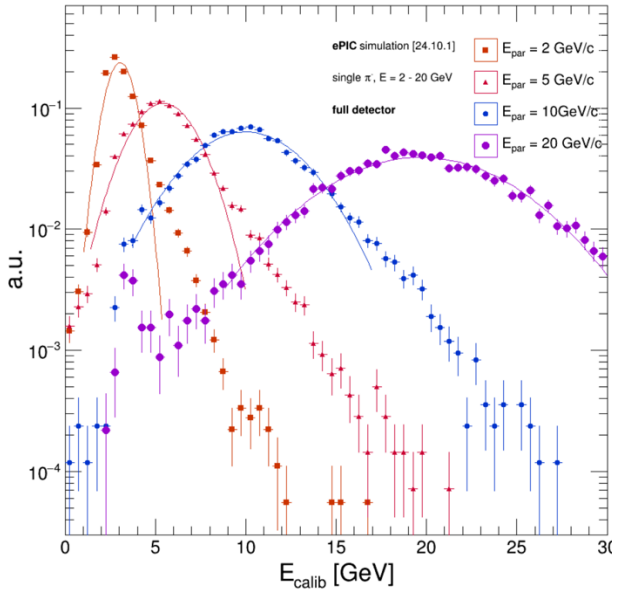
- Significant smearing by energy loss in dead material and due to nuclear binding, fluctuations in the hadronic shower, and clustering inefficiencies.

BHCal - Hadrons energy reconstruction

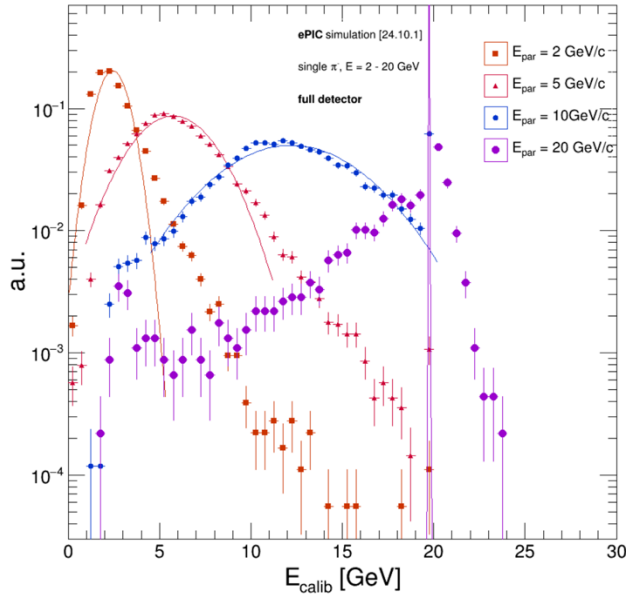
Uncalibrated

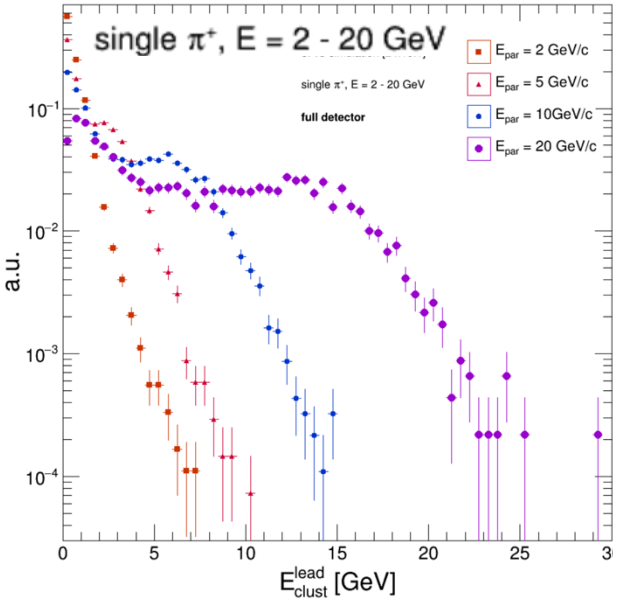


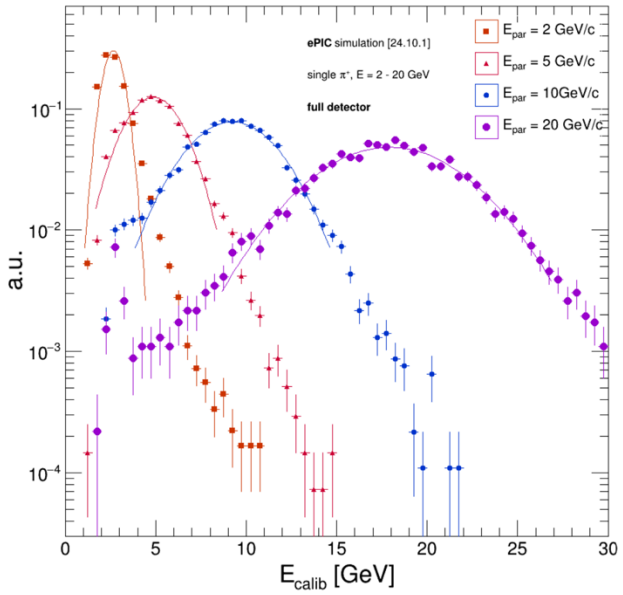
LD-calibrated

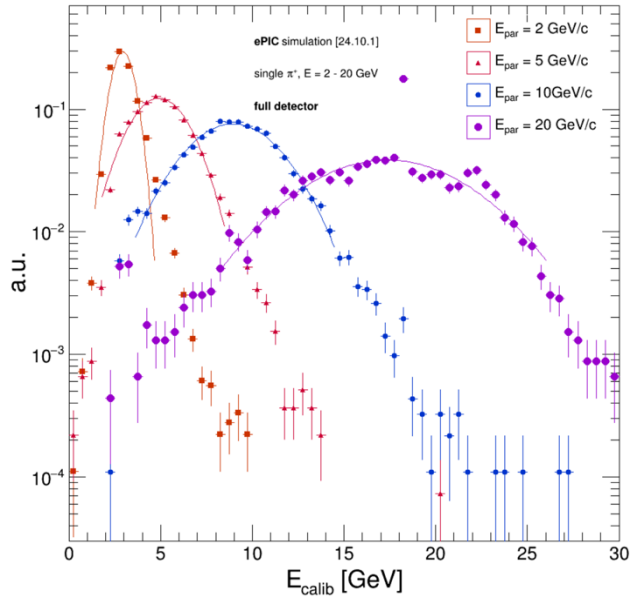


MLP-calibrated





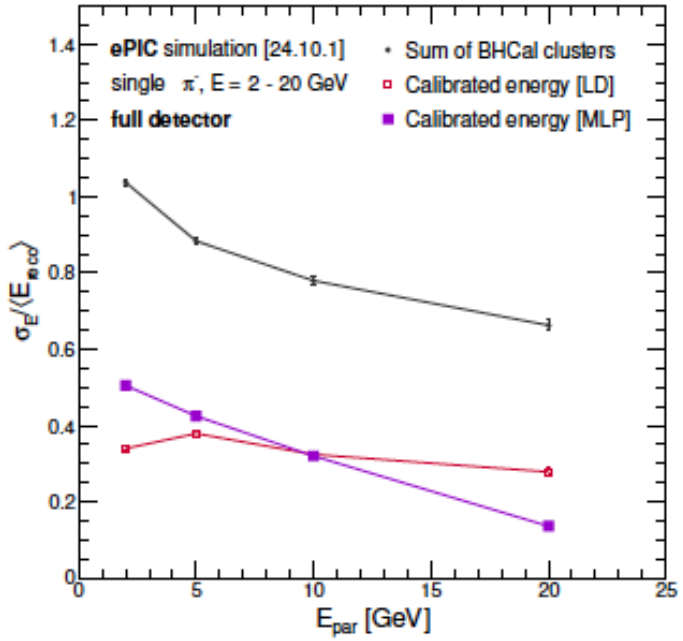


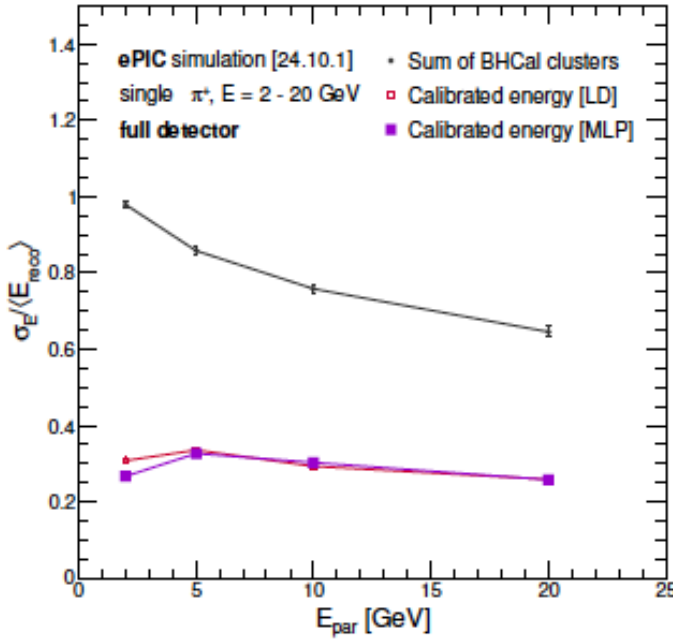


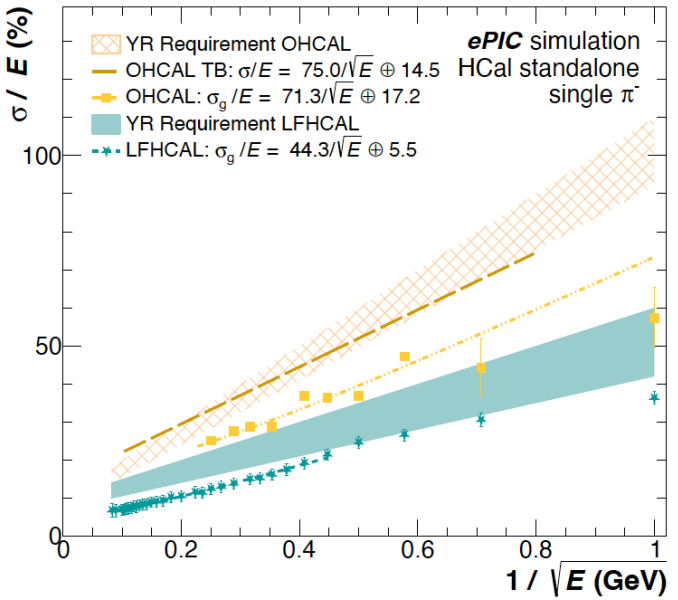
- Smearing Effects are worse with full detector.
- BHCal calibration is needed - from the EM scale to the hadronic scale utilizing information from additional subsystems.
- Two simple machine-learning models used:
  - Linear-Discriminant (LD)
  - Multi-Layer Perceptron (MLP)

BHCal -

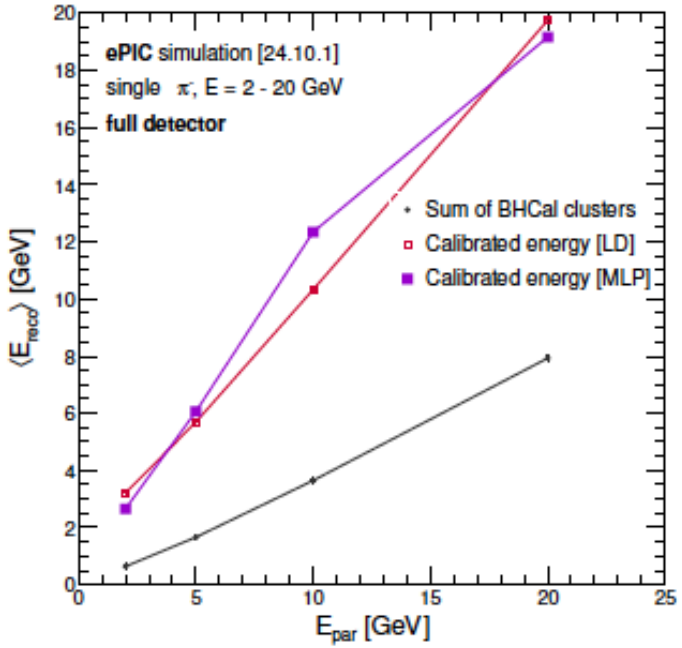
Hadrons energy reconstruction

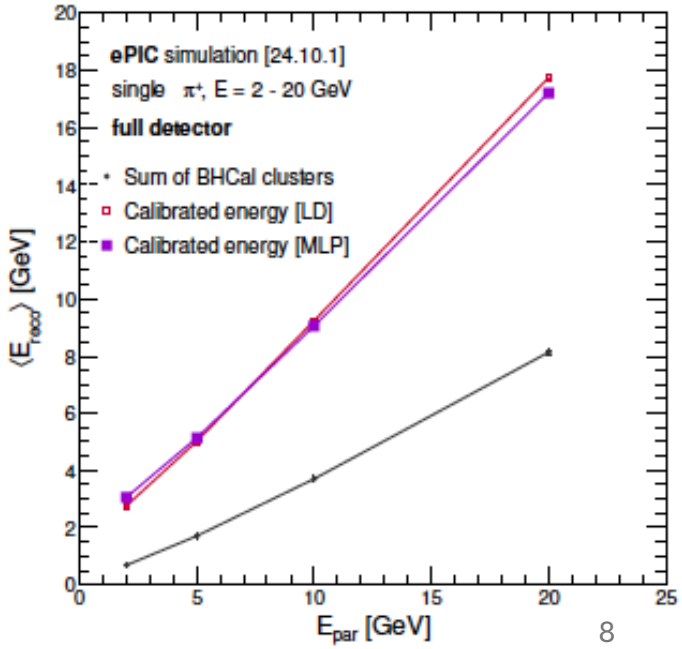






- The linearity and resolution from simply summing all of the clusters in the BHCal.
- Shows the impact of the calibration
- BHCal meets the yellow report requirement for energy resolution.

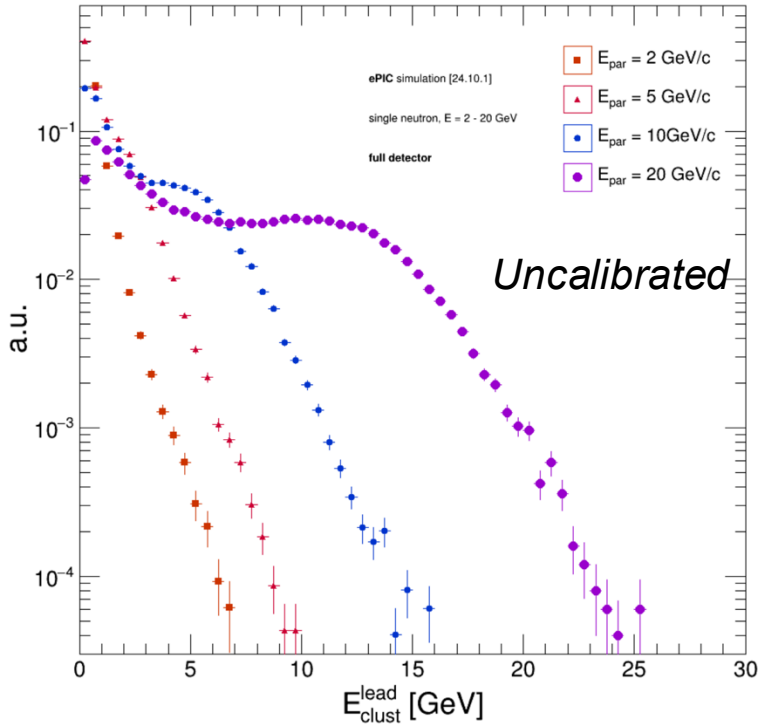


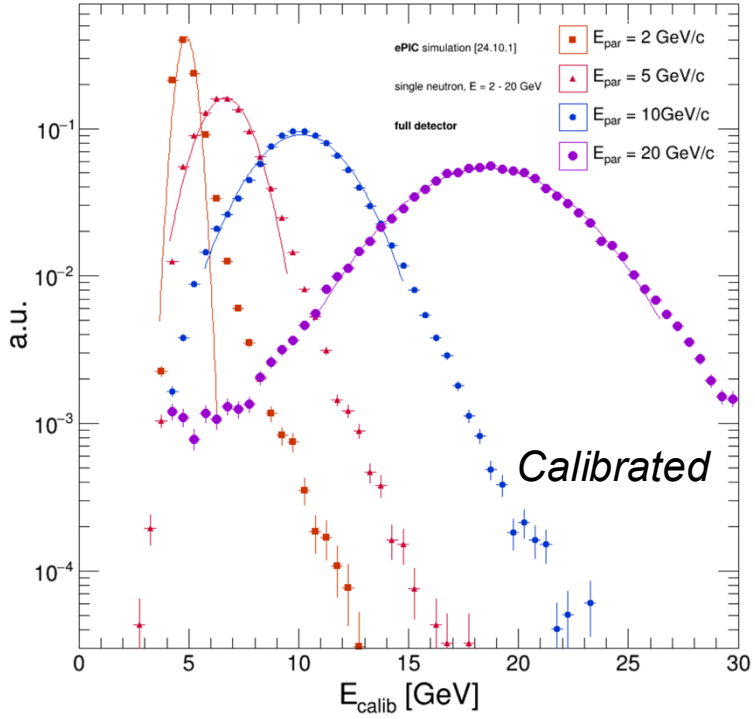


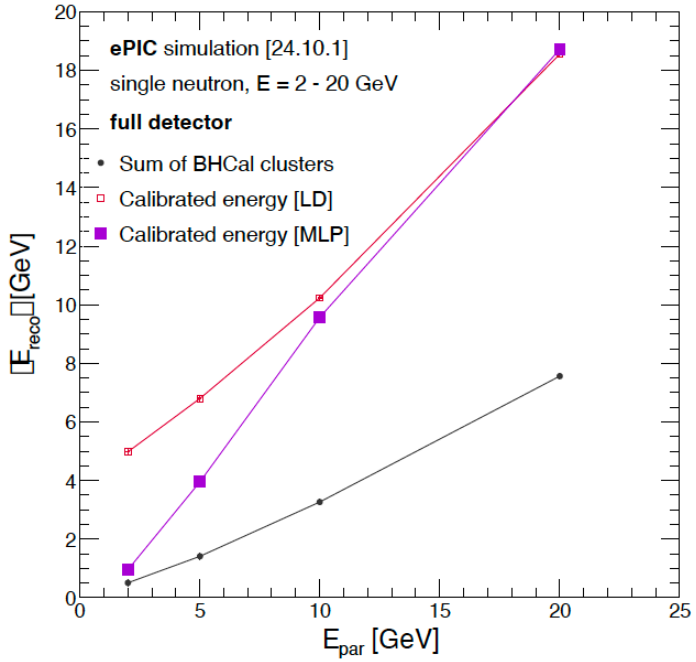
The Barrel Hadronic Calorimeter - BHCal

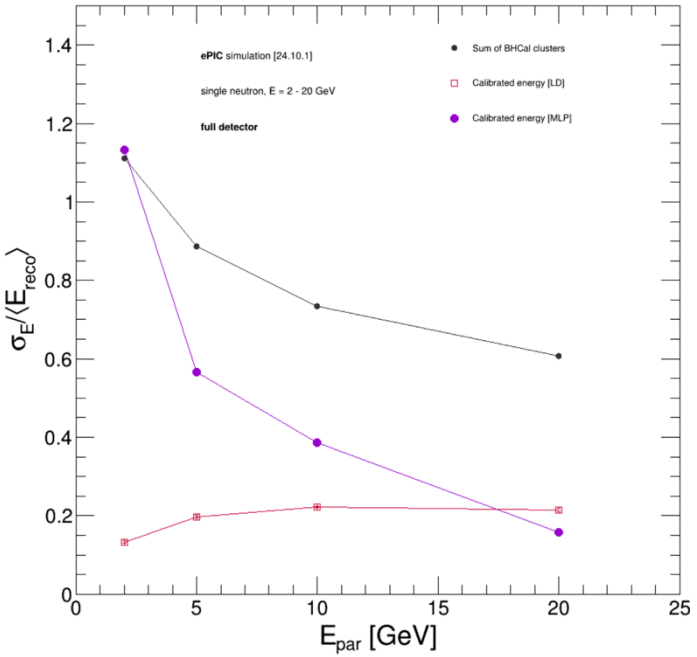
❑ Neutral hadrons - neutrons

Single neutron, E = 2-20 GeV / Full detector









- Distinct low energy tails in the energy spectra.
  Cluster splitting? fluctuations in the hadronic shower? or inadequacies in the model?
- Efforts to understand these tails are ongoing.

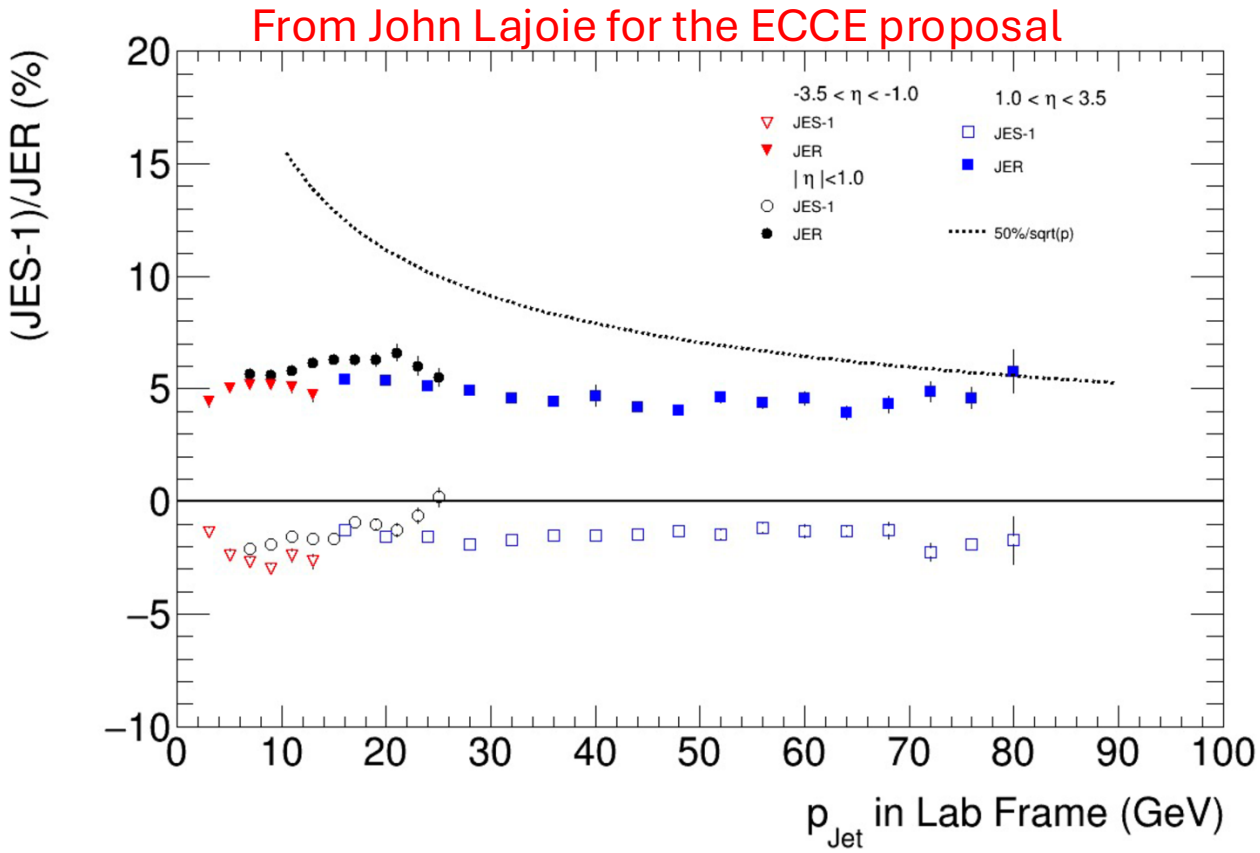
The Barrel Hadronic Calorimeter - BHCal

- **Constraining the jet energy scale (JES) and jet energy resolution (JER).**

- BHCal provides an additional handle of the neutral hadronic component of jets, and thus aids in constraining the jet energy scale (JES) and jet energy resolution (JER).

- *Redo of this study with ePIC software and geometry*

From John Lajoie for the ECCE proposal



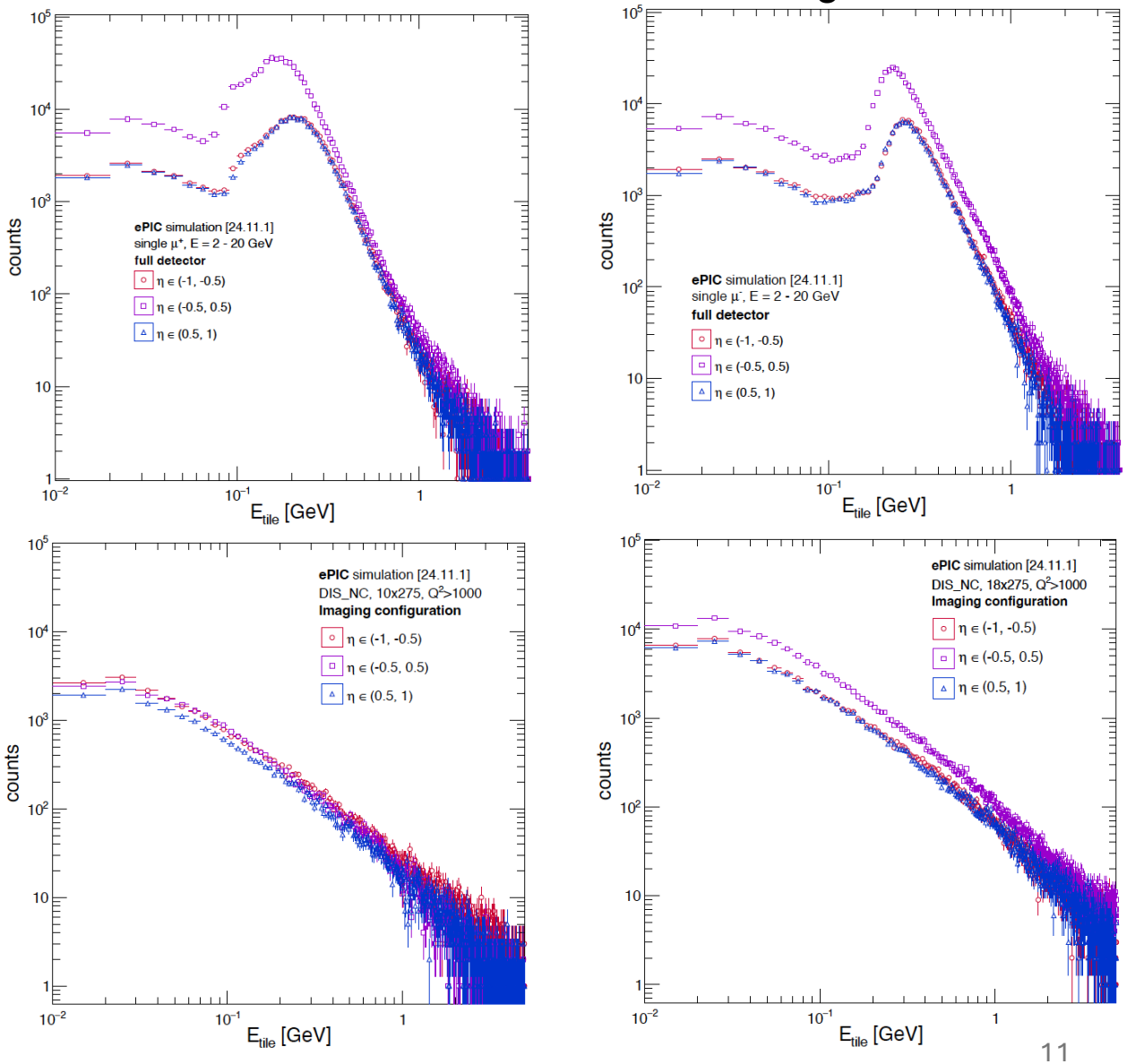
The Barrel Hadronic Calorimeter - BHCal

❑ Muon identification

- A clear peak at ~250 MeV is observed in the reconstructed tile energies, which lies well above the minimum energy expected to be measured by the BHCal.

- Reconstructed tile energies for all particles in NC DIS events for beam energies of 10 × 100 and 18 × 275: the energy distribution is dominated by particles that do not behave as minimum ionizing particles (MIPs) through both calorimeters. As a result, the clear MIP peak seen in single-muon events is significantly diluted or absent.

Reconstructed tile energies



Summary & Outlook

- The Barrel Hadronic Calorimeter (BHCal) plays a crucial role in single jet measurements by providing sensitivity to the neutral hadronic component of jets. It also offers several additional benefits, such as:
  - Enhanced muon and neutron identification
  - Improvements in jet energy scale (JES) and jet energy resolution (JER)
  - Better reconstruction of event kinematics and the hadronic final state
  - Tagging of charged-current deep-inelastic scattering (DIS) events

- BHCal Simulation Status:
  Our current simulation efforts focus on two main areas:
  - After migrating the BHCal geometry to GDML files, a previously unnoticed hole in the geometry was discovered. The cause of this issue is still under investigation.
  - Working on optimizing the clustering algorithm to function at the single-tile level, rather than the tower level, to enhance resolution and performance.

- Determine the JES, JER, and other key performance metrics. This includes studies of DIS kinematic variables using the Jacquet-Blondel method, all within the ePIC software framework and updated geometry.

Backup Slides

BHCal – Muon ID

Initial studies: Log Likelihood Difference Using Barrel HCal E/p and Shower Radius? *Not sure here – does he use E/p<<1?*