CALICE Digital Hadron Calorimeter Results from Fermilab Beam Tests:Calibration

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Digital Hadron Calorimeter (DHCAL)

Concept of the DHCAL

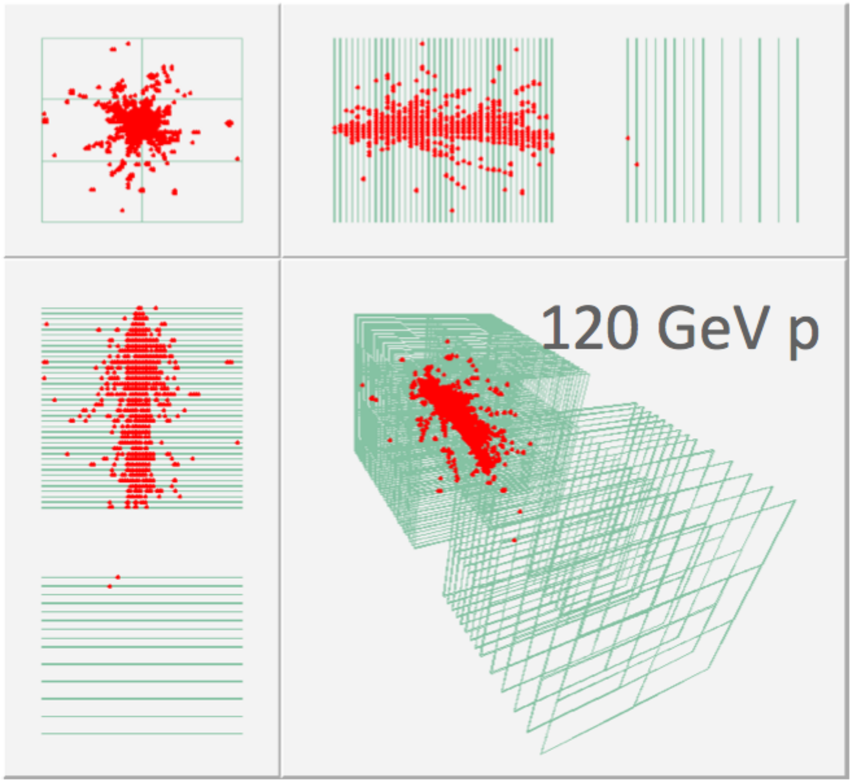
• Imaging hadron calorimeter optimized for use with PFA

• 1-bit (digital) readout

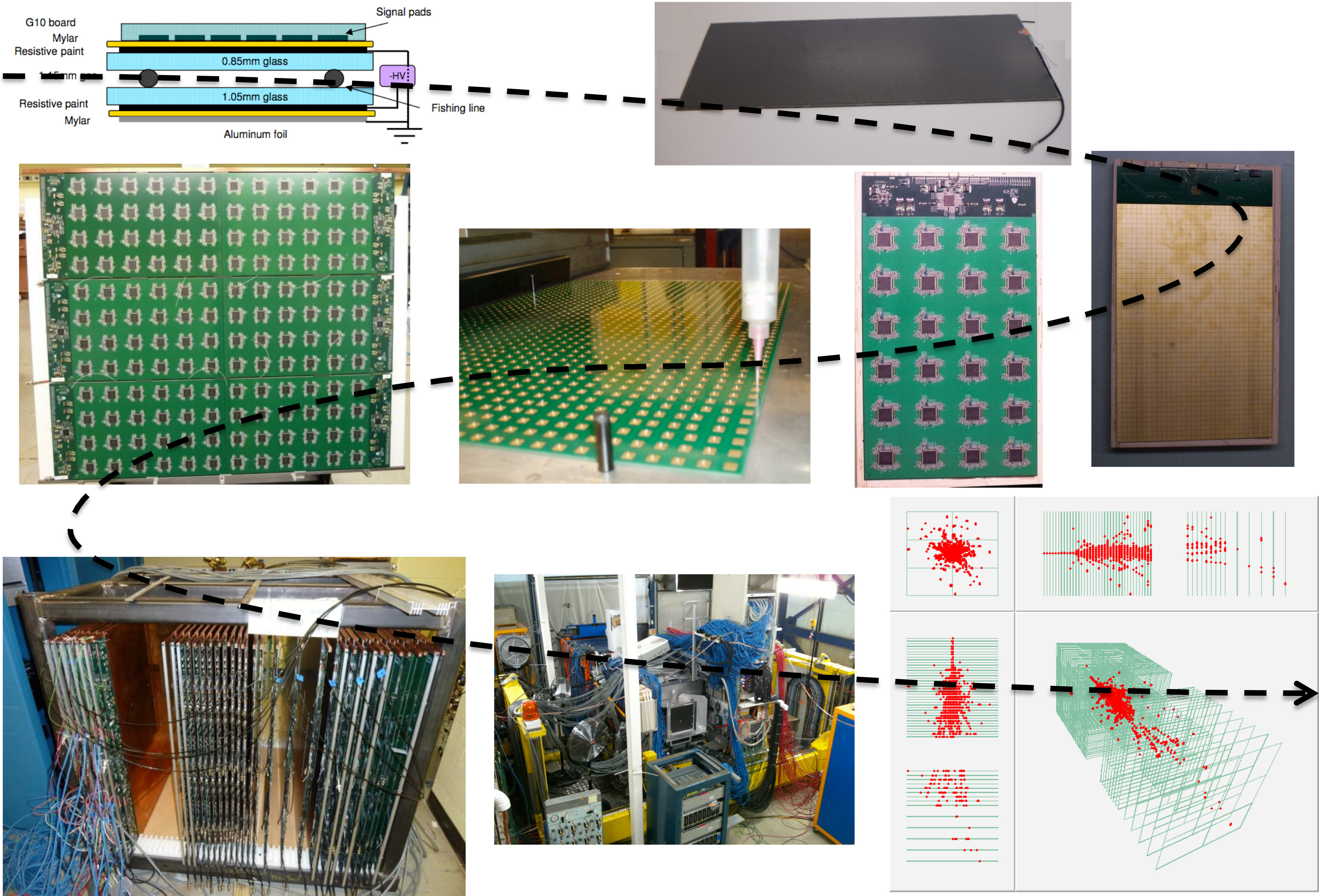
• 1 x 1 cm^2 pads read out individually (embedded into calorimeter!)

• Resistive Plate Chambers (RPCs) as active elements, between steel/ tungsten

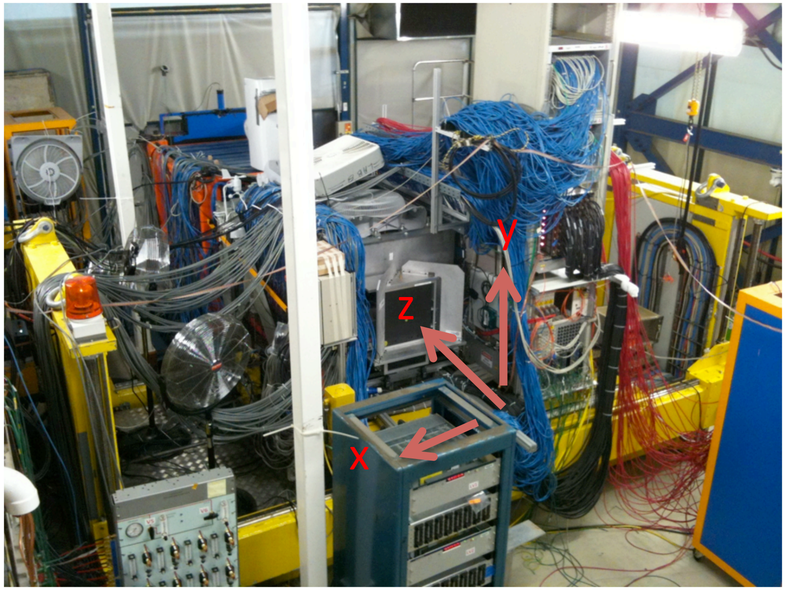
- Each layer with an area of ~ 1 x 1 m^2 is read out by 96 x 96 pads.
- The DHCAL prototype has up to 54 layers including the tail catcher (TCMT) ~ 0.5 M readout channels (world record in calorimetry!)



DHCAL Construction

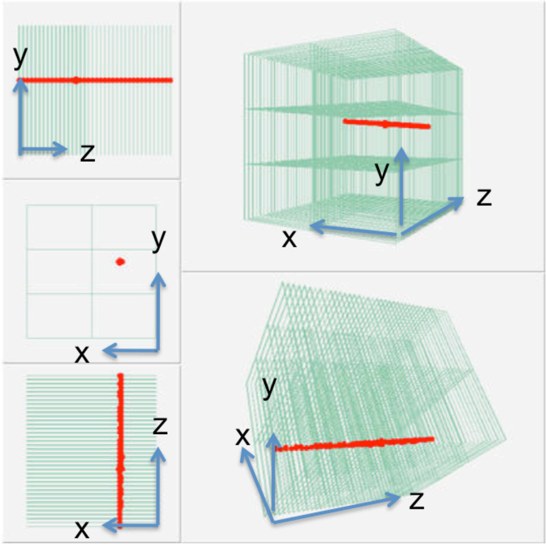


DHCAL Data



Muon Trigger:
2 x (1 m x 1 m scintillator)

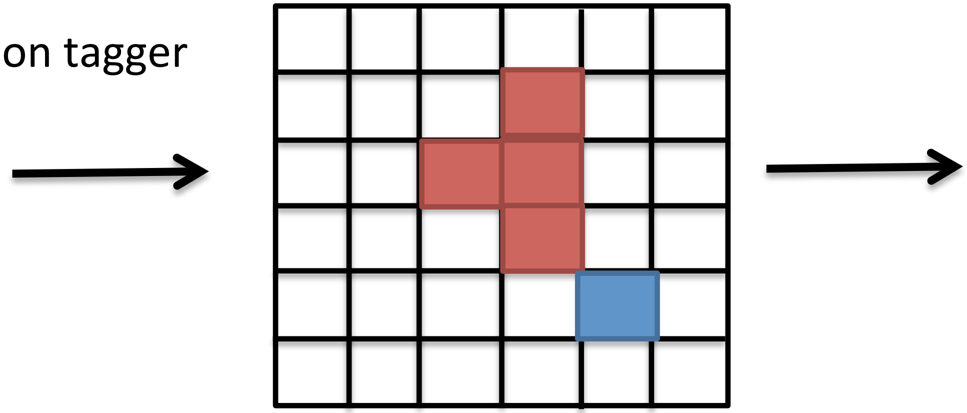
Secondary Beam Trigger:
2 x (20 cm x 20 cm scintillator)



Nearest neighbor clustering

Event:
Time stamp, Čerenkov/muon tagger bits

Hit:
x, y, z, time stamp



Cluster:
x, y, z

Calibration/Performance Parameters

Efficiency (ε) and pad multiplicity (μ)

Track Fits:

- specifically for muon calibration runs
- Identify a muon track that traverse the stack with no identified interaction
- Measure all layers

Track Segment Fits:

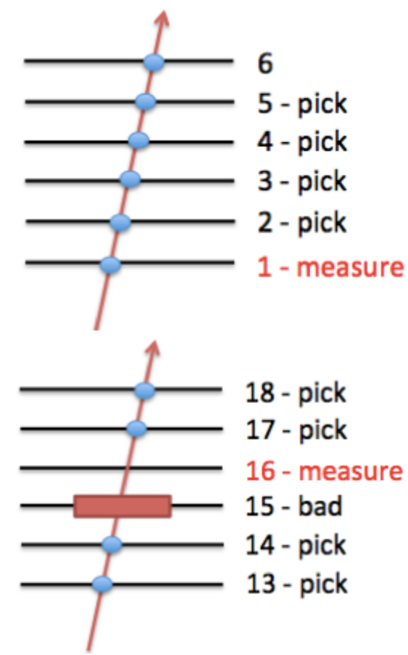
- for online calibration
- Identify a track segment of four layers with aligned clusters within 3 cm
- Measure only one layer (if possible)

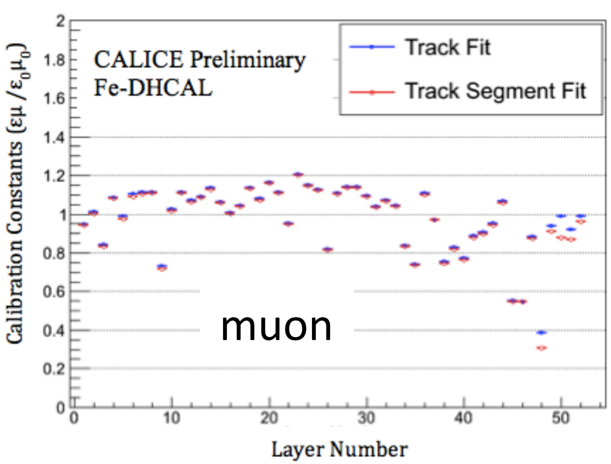
- Fit to the parametric line: $x=x_0+a_x t$; $y=y_0+a_y t$; $z=t$

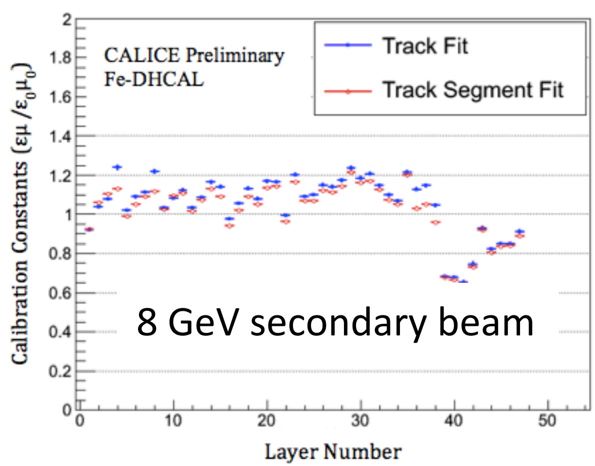
A cluster is found in the measurement layer within 2 cm of the fit point?

Yes → ε=1, μ=size of the found cluster

No → ε=0, No μ measurement







Calibration Procedures

RPC performance

Average efficiency to detect MIP: $\varepsilon_0 \sim 96\%$
Average pad multiplicity: $\mu_0 \sim 1.6$

1. Full Calibration: $$H_{calibrated} = \sum_{i=RPC_0}^{RPC_n} \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} H_i$$

2. Density-weighted Calibration: Developed due to the fact that a pad will fire if it gets contribution from multiple traversing particles regardless of the efficiency of this RPC. Hence, the full calibration will overcorrect. Classifies hits in density bins (number of neighbors in a 3 x 3 array).

3. Hybrid Calibration: Density bins 0 and 1 receive full calibration.

Density-weighted Calibration Overview

Warning: This is rather COMPLICATED

Derived entirely based on Monte Carlo

Assumes correlation between

Density of hits $\leftrightarrow$ Number of particles contributing to signal of a pad

Mimics different operating conditions with

Different thresholds

Utilizes the fact that hits generated with the

Same GEANT4 file, but different operating conditions can be correlated

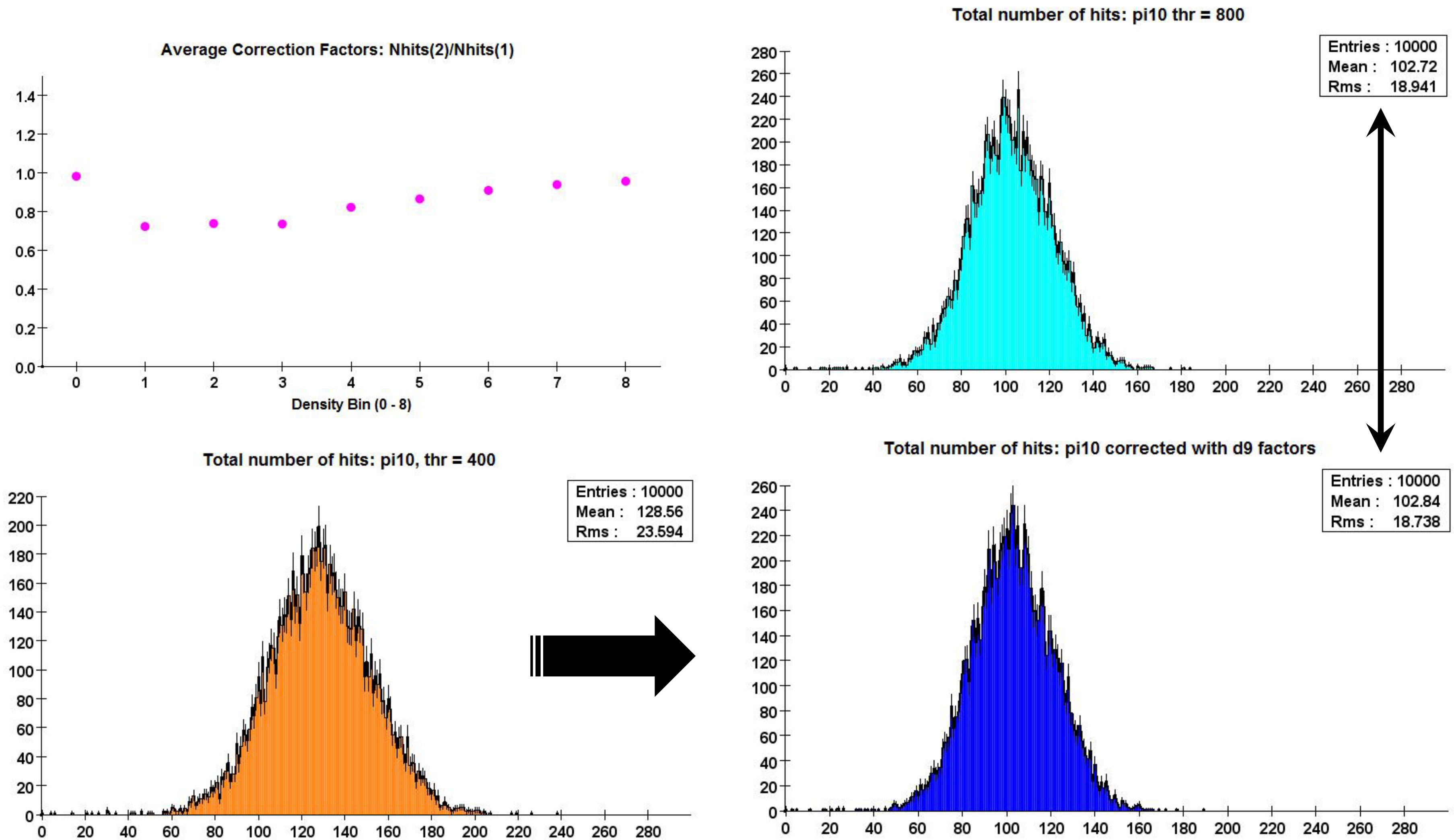
Defines density bin for each hit in a 3 x 3 array

Bin 0 – 0 neighbors, bin 1 – 1 neighbor …. Bin 8 – 8 neighbors

Weighs each hit

To restore desired density distribution of hits

Density-weighted Calibration Example: 10 GeV pions: Correction from T=400→ T=800



Mean response and the resolution reproduced.
Similar results for all energies.

Density-weighted Calibration:
Expanding technique to large range of performance parameters

GEANT4 files

Positrons: 2, 4, 10, 16, 20, 25, 40, 80 GeV
Pions: 2, 4, 8, 10, 10, 25, 40, 80 GeV

Digitization with RPC_sim

Thresholds of 200, 400, 600, 800, 1000 (~ x 1fC)

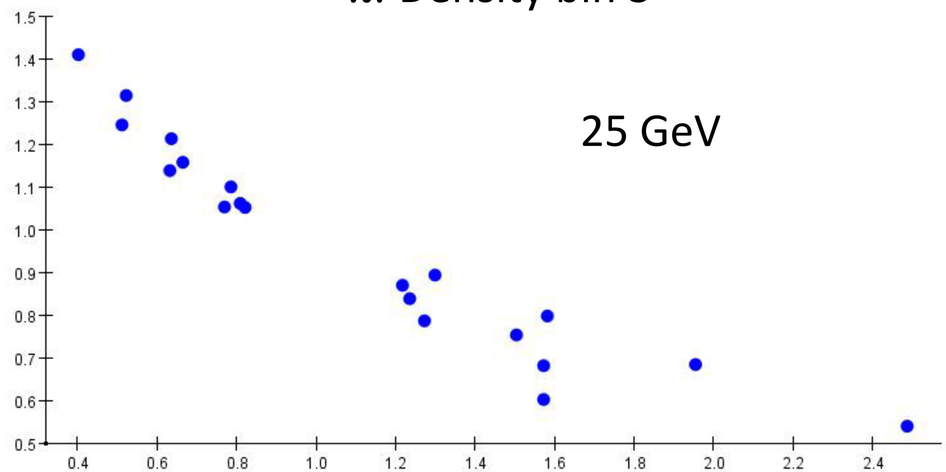
Calculate correction factors (C)

- for each density bin separately
- as a function of ε_i, μ_i, ε_0 and μ_0 (i : RPC index)

Plot C as a function of $R = (\varepsilon_i\mu_i)/(\varepsilon_0\mu_0)$

→ Some scattering of the points

π: Density bin 3



$R = (\varepsilon_i\mu_i)/(\varepsilon_0\mu_0)$

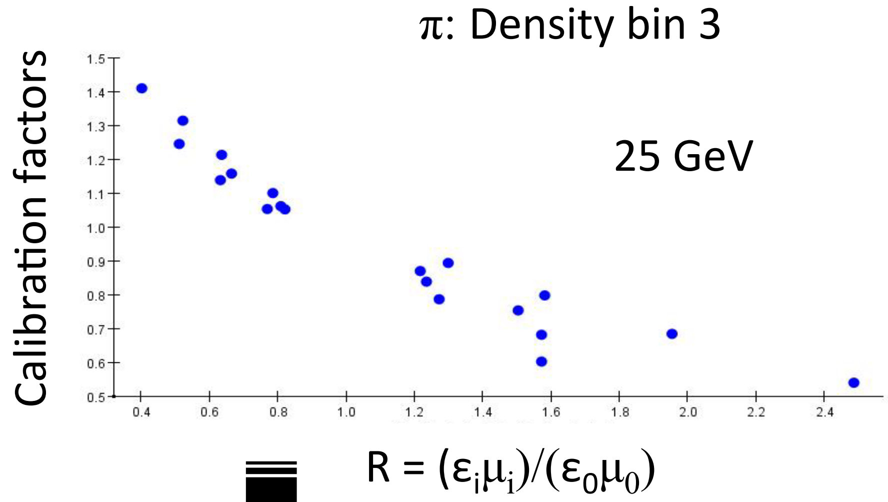
Density-weighted Calibration: Empirical Function of ε_i, μ_i, ε_0, μ_0

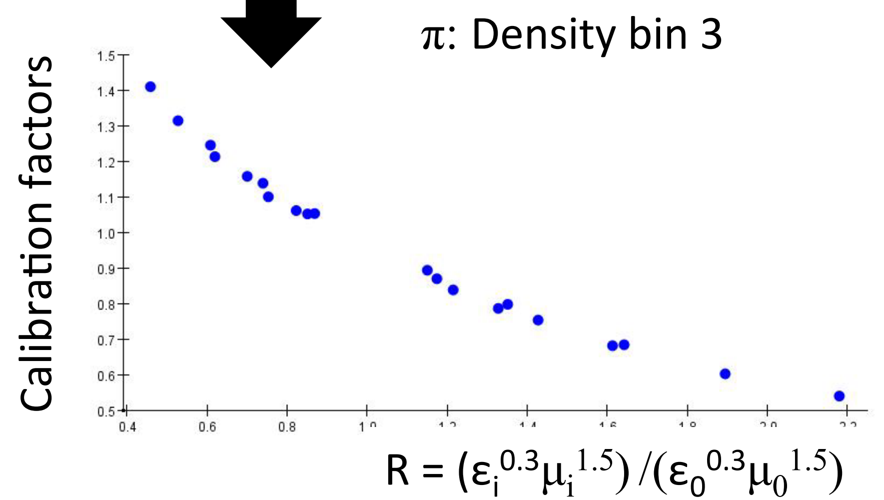
Positrons

$$R_e = \frac{\varepsilon_i^{0.3}\mu_i^{2.0}}{\varepsilon_0^{0.3}\mu_0^{2.0}}$$

Pions

$$R_\pi = \frac{\varepsilon_i^{0.3}\mu_i^{1.5}}{\varepsilon_0^{0.3}\mu_0^{1.5}}$$

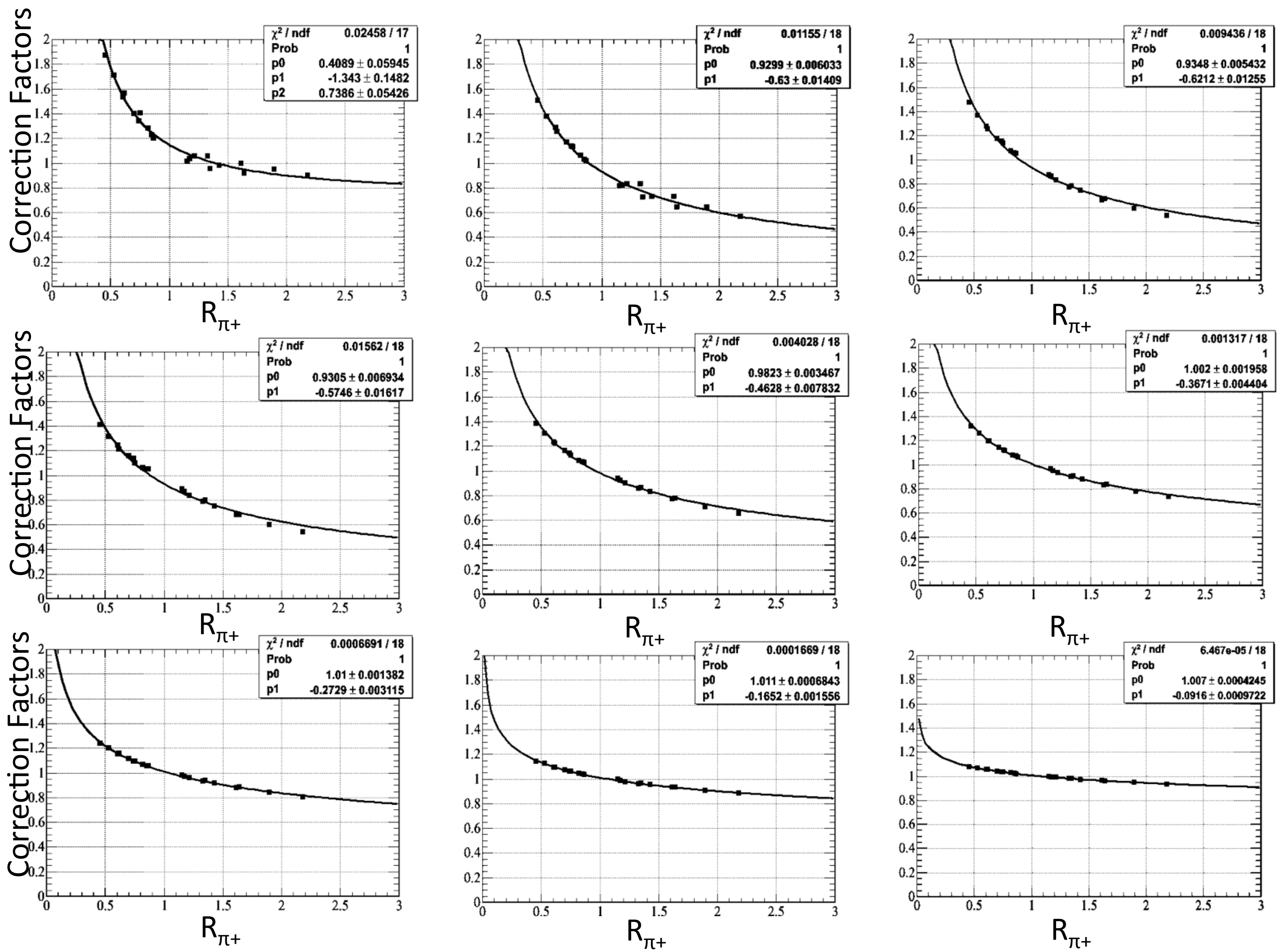




Density-weighted Calibration: Fits of Correction Factors as a Function of R

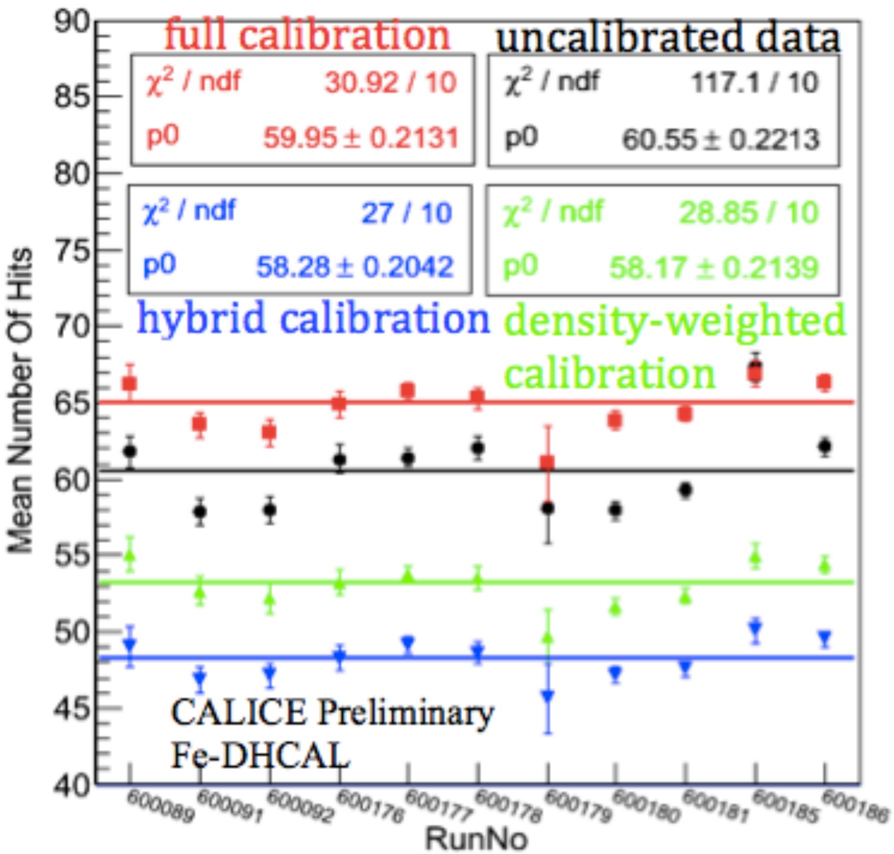
Power law $C = \alpha R_p^{\beta}$

Fit results for p=pion, similar results for p=positron

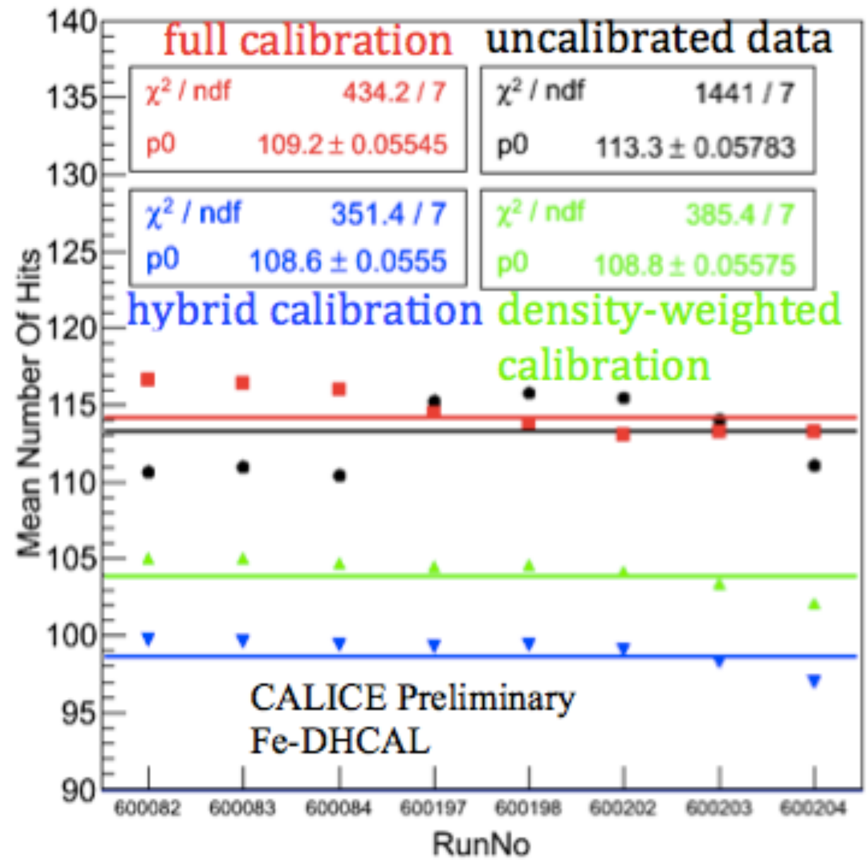


Calibrating Different Runs at Same Energy

4 GeV π^+



8 GeV e^+

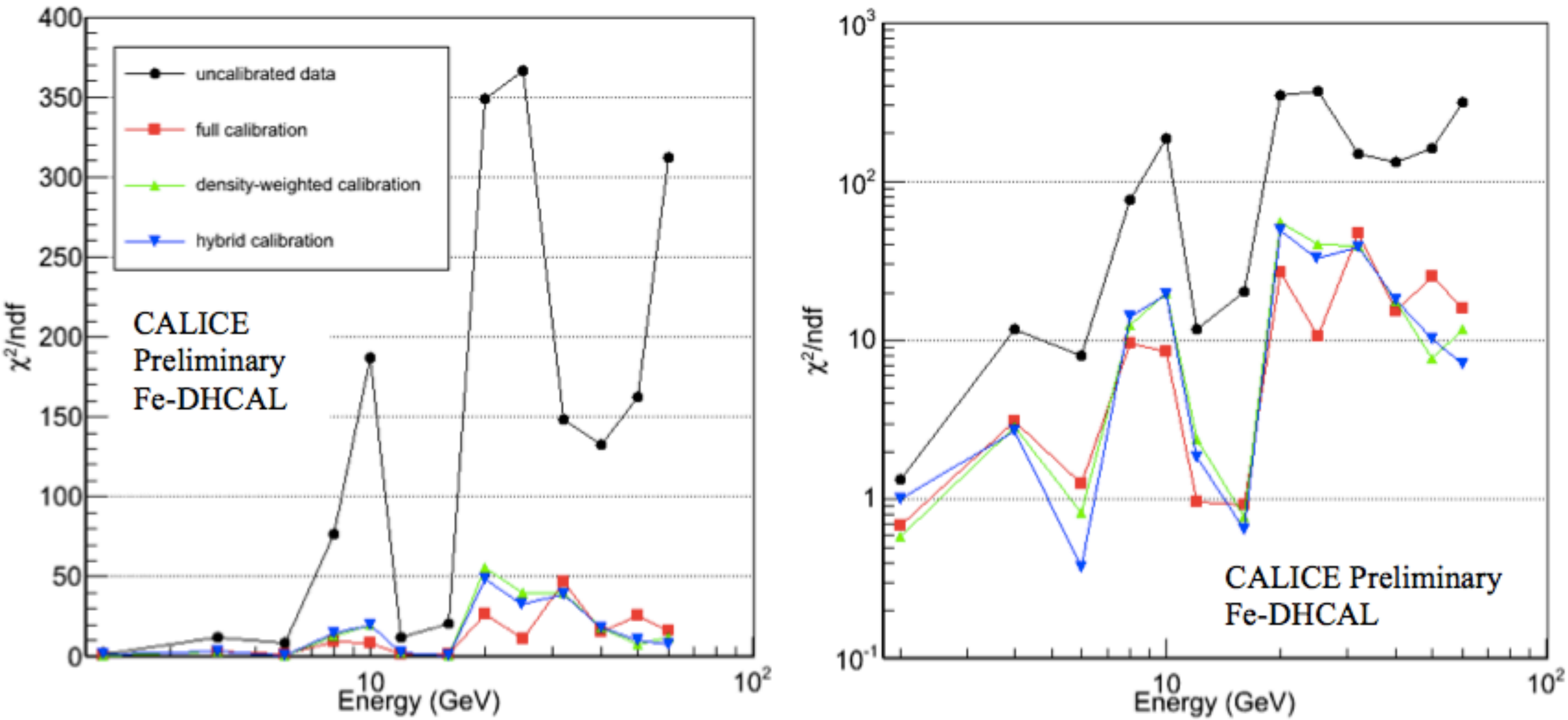


Uncalibrated response (0)
Full calibration (5)
Density – weighted calibration (-5)
Hybrid calibration (-10)

(Offsets applied to the values for better visibility)

Comparison of Different Calibration Schemes

χ^2/ndf of constant fits to the means for different runs at same energy

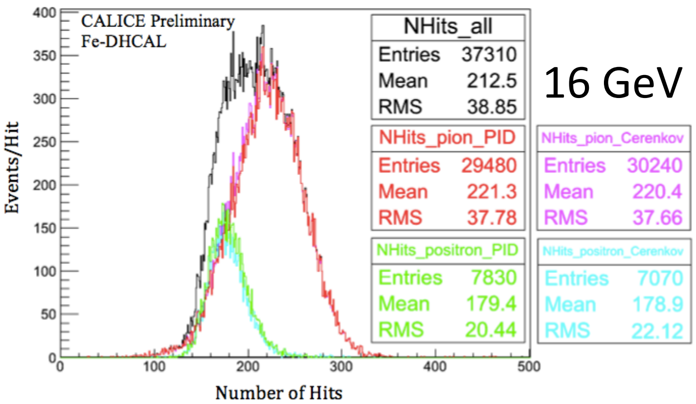


→ **All three schemes improve the spread**

Particle Identification (PID)

0. Čerenkov counter based PID (good for 6, 8, 10, 12, 16, and 20 GeV)

1. Topological PID: Starts with the trajectory fit (used for 2, 4, 25 and 32 GeV)

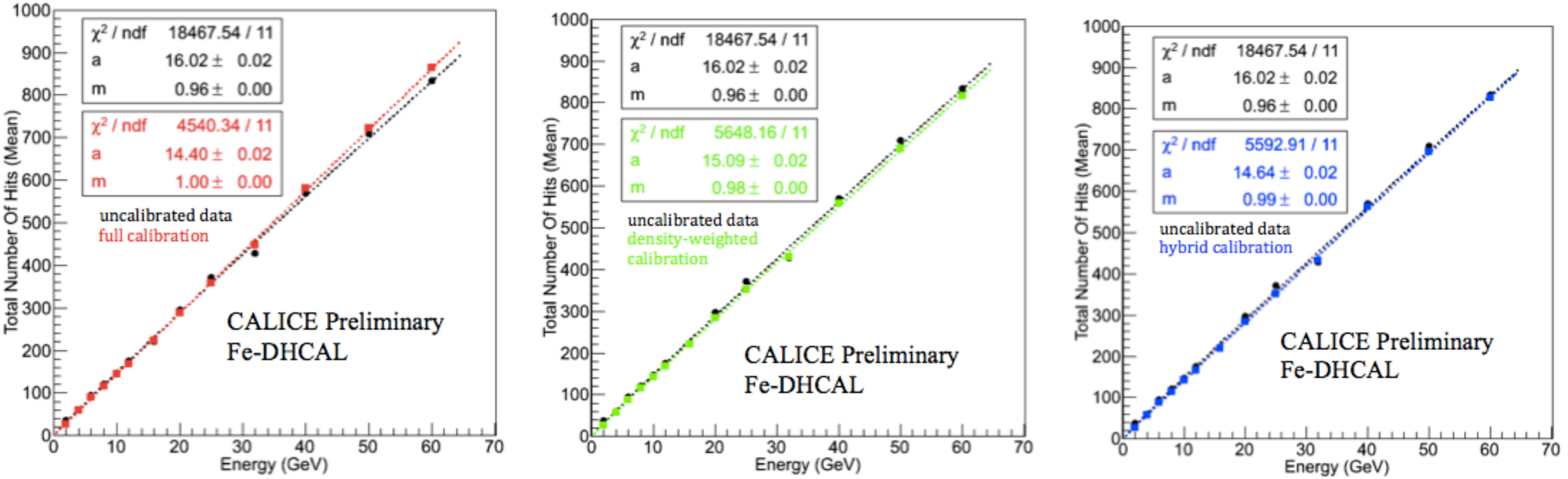


Visually inspect the positron events in the ~10% excess in the topological PID
→ They are positrons
→ 10 % compatible with the inefficiency of the Čerenkov counter
→ Topological PID works nicely!

Topological Variables

- Interaction Layer *IL*: If there are hits with a *ΔR* between 1.5 and 20 cm with respect to the trajectory point in two consecutive layers *i* and *i*+1, the interaction layer is identified as *i*-1.
- Longitudinal Barycenter: Average z-position of the event: $LB = \frac{\sum N_i z_i}{\sum N_i}$ (sum is over all layers).
- Average cluster size: $AC = \frac{N_{Hits}}{N_{Clusters}}$
- Last layer with at least one hit: *LL*
- Lateral shower shape: $R_{rms} = \sqrt{\frac{\sum r_i^2}{N}}$ where r_i is the distance from the trajectory line and N is the total number of hits in the entire stack.
- R_{90}: 90% confinement radius measured with respect to the trajectory (i.e. 90% of the hits in the event are contained in a cylinder of radius R_{90} where the cylinder axis is coincident with the particle trajectory).
- Compactness Index: $\frac{\sqrt{\sum |\vec{r}_i - \vec{r}_{BC}|^2}}{N}$ where $\vec{r}_i$ is the position vector of the hit and $\vec{r}_{BC}$ is the position vector on the trajectory at the longitudinal barycenter. The sum is over all hits.
- $\frac{N_{10}}{N_{20}}$: (Number of hits within 10 cm) / (Number of hits within 20 cm) of the particle trajectory.

Linearity of Pion Response: Fit to N=aE^m



Uncalibrated response

4% saturation

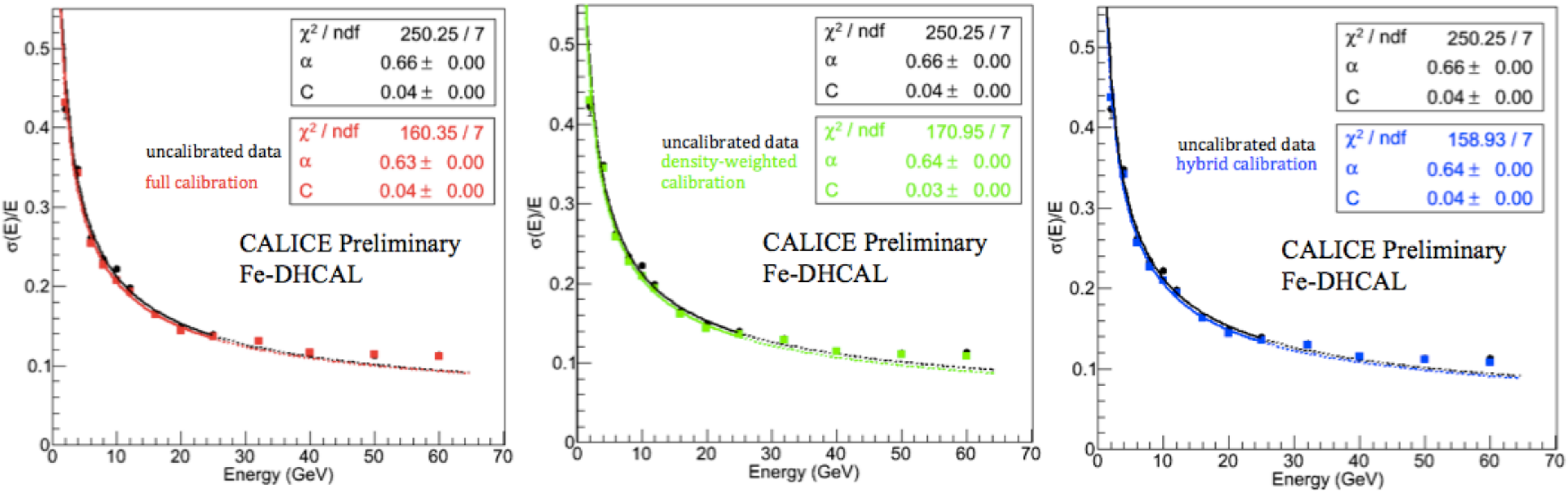
Full calibration

Perfectly linear up to 60 GeV (in contradiction to MC predictions)

Density- weighted calibration/Hybrid calibration

1 – 2% saturation (in agreement with predictions)

Resolution for Pions



Calibration

$$\frac{\sigma(N)}{N} = \frac{\alpha}{\sqrt{E}} \oplus C$$

Improves result somewhat

Monte Carlo prediction

Around 58%/√E with negligible constant term

Saturation at higher energies

→ Leveling off of resolution

Summary

- First DHCAL built and tested successfully
- Calibration of the DHCAL is not a trivial process
- High granularity allows utilization of various topological variables

Concept validated both technically as well as from the physics point of view