Digital Hadron Calorimetry

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On behalf of the CALICE Collaboration

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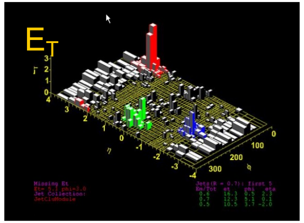
Trend in Calorimetry

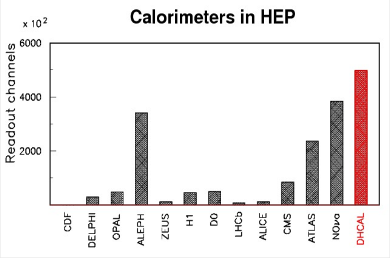
Tower geometry

Energy is integrated over large volumes into single channels

Readout typically with high resolution

Individual particles in a hadronic jet not resolved



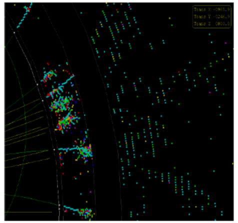


Imaging calorimetry

Large number of calorimeter readout channels (~10^7)

Option to minimize resolution on individual channels

Particles in a jet are measured individually



Particle Flow Algorithms (PFAs)

Attempt to measure the energy/momentum of each particle with the detector subsystem providing the best resolution

Maximum exploitation of precise tracking measurement

- Large radius and length to separate the particles
- Large magnetic field for high precision momentum measurement
- “no” material in front of calorimeters (stay inside coil)
- Small Moliere radius of calorimeters to minimize shower overlap
- High granularity of calorimeters to separate overlapping showers

Emphasis on tracking capabilities of calorimeters

Development of the Digital Hadron Calorimeter

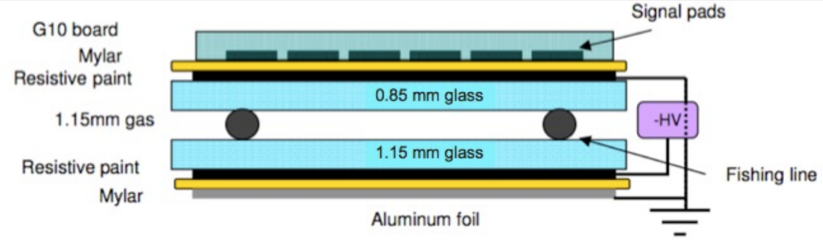
- Develop a tracking Hadron Calorimeter
- Implement digital readout (1-bit) to maximize the number of readout channels
- Place the front-end electronics in the detector

The active medium should:

- Be planar and scalable to large sizes
- Not necessarily be proportional (only yes/no for the traversing particle)
- Be easy to construct, robust, reliable, easy to operate, …

→ Resistive Plate Chambers

Resistive Plate Chambers (RPCs)



Gas: Tetrafluorethane (R134A) : Isobutane : Sulfurhexafluoride (SF_6) with the following ratios 94.5 : 5.0 : 0.5

High Voltage: 6.3 kV (nominal)

Average efficiency: 96 %

Average pad multiplicity: 1.6

The DHCAL Prototype

Description

Hadronic sampling calorimeter

Designed for future electron-positron collider (ILC)

54 active layers (~1 m^2)

Resistive Plate Chambers with 1 x 1 cm^2 pads

→ ~500,000 readout channels

Electronic readout

1 – bit (digital)

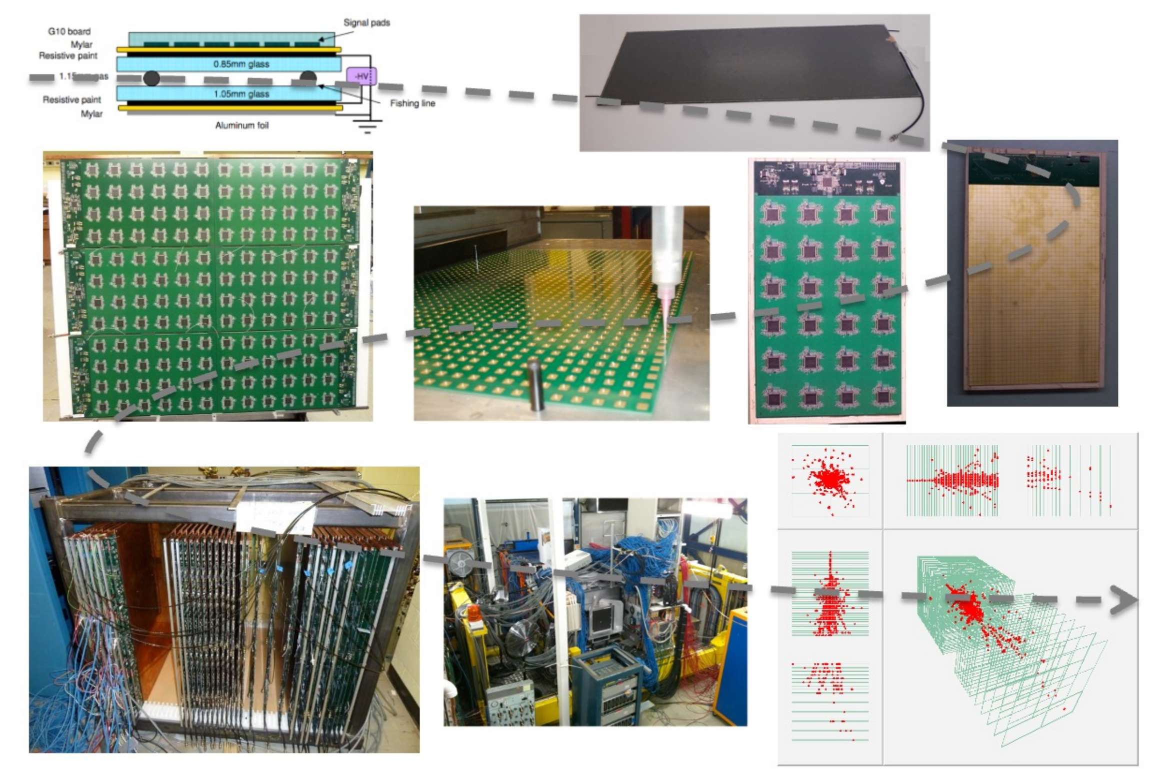
Tests at FNAL

with Iron absorber in 2010 – 2011

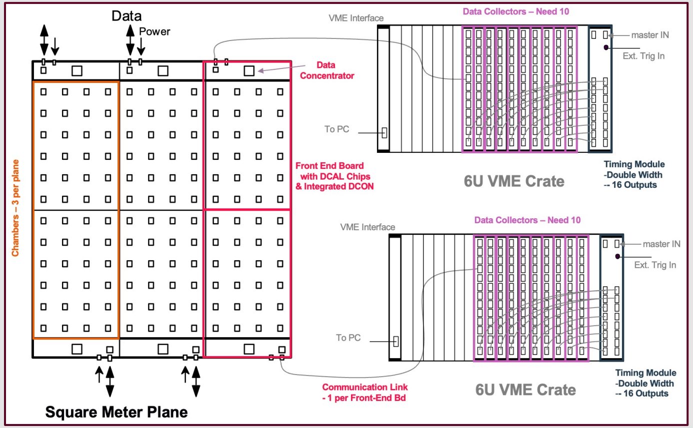
with no absorber in 2011

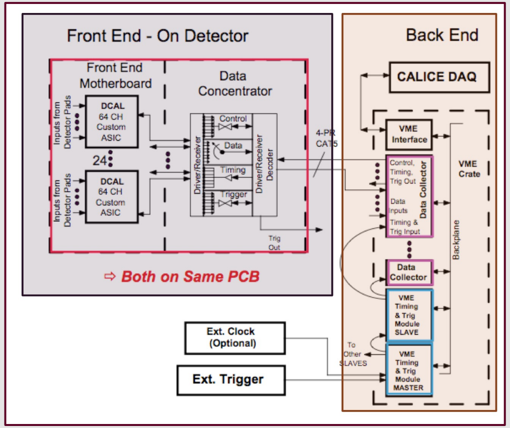
Tests at CERN

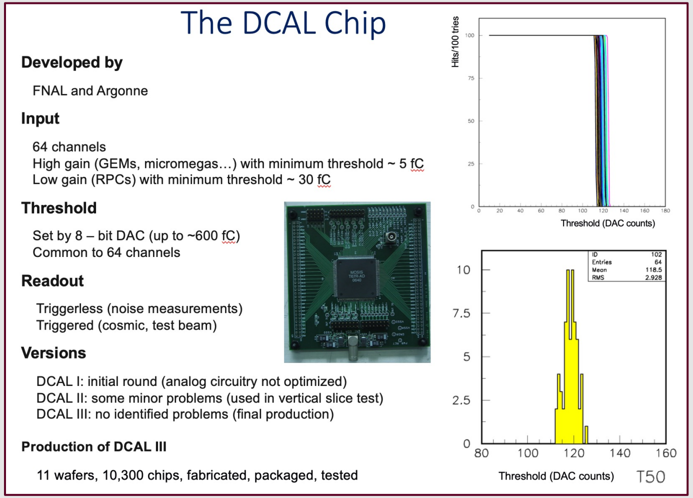
with Tungsten absorber in 2012



Readout Electronics Overview







The DCAL Chip

Developed by

FNAL and Argonne

Input

64 channels
High gain (GEMs, micromegas…) with minimum threshold ~ 5 fC
Low gain (RPCs) with minimum threshold ~ 30 fC

Threshold

Set by 8 – bit DAC (up to ~600 fC)
Common to 64 channels

Readout

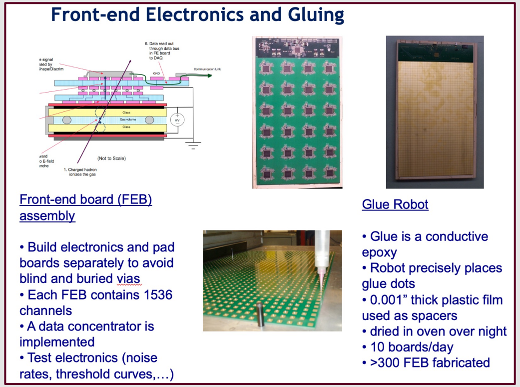
Triggerless (noise measurements)
Triggered (cosmic, test beam)

Versions

DCAL I: initial round (analog circuitry not optimized)
DCAL II: some minor problems (used in vertical slice test)
DCAL III: no identified problems (final production)

Production of DCAL III

11 wafers, 10,300 chips, fabricated, packaged, tested



Front-end Electronics and Gluing

Front-end board (FEB) assembly

- Build electronics and pad boards separately to avoid blind and buried vias
- Each FEB contains 1536 channels
- A data concentrator is implemented
- Test electronics (noise rates, threshold curves,…)

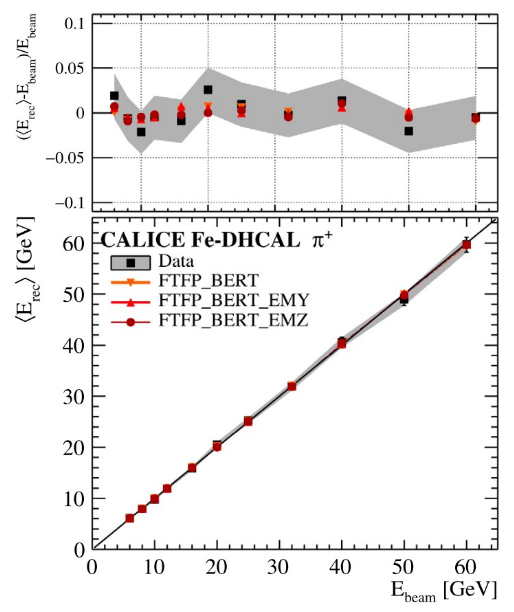
Glue Robot

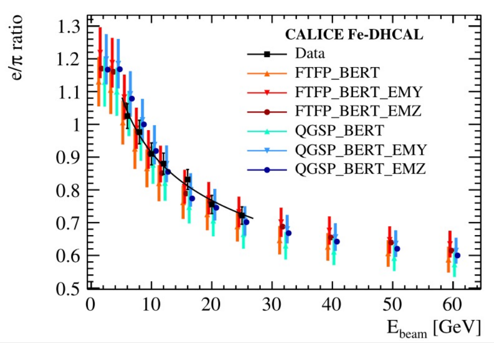
- Glue is a conductive epoxy
- Robot precisely places glue dots
- 0.001” thick plastic film used as spacers
- dried in oven over night
- 10 boards/day
- >300 FEB fabricated

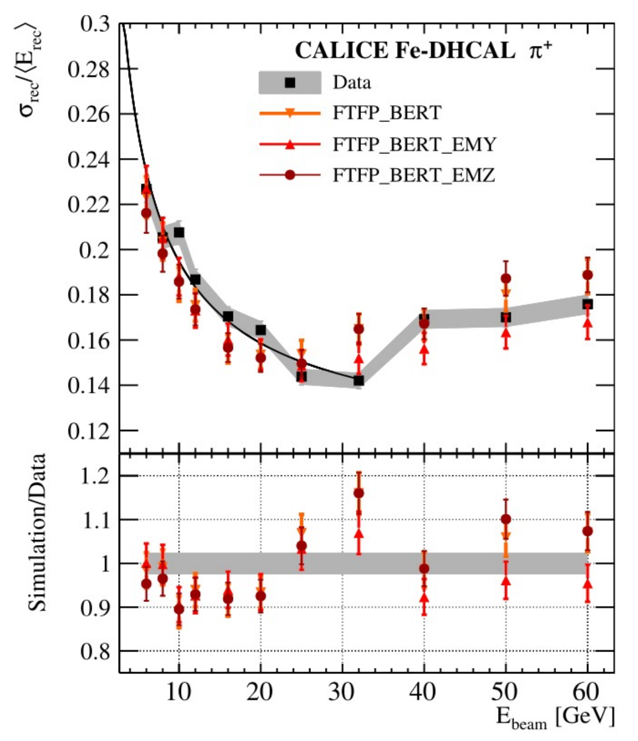
Cassette Assembly

- Cassette is compressed horizontally with a set of 4 (Badminton) strings
  - Strings are tensioned to ~20 lbs each
  - ~45 minutes/cassette

Fe-DHCAL at Fermilab

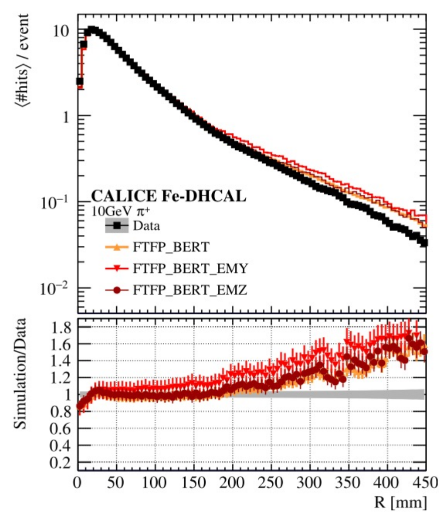


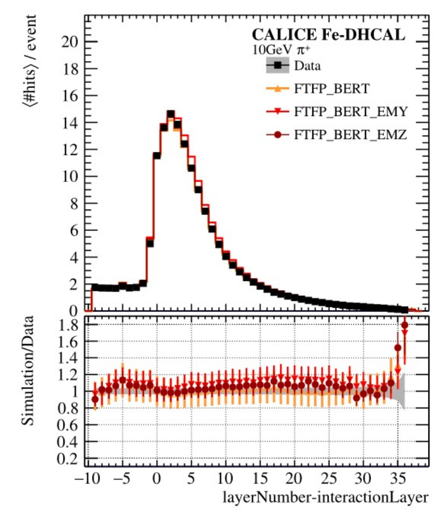




$$\frac{\sigma}{E} = \frac{(51.5 \pm 1.5)\%}{\sqrt{E}} \oplus (10.6 \pm 0.5)\%$$

M. Chefdeville, et.al., Nucl. Instr. And Meth. A 939, 89, 2019



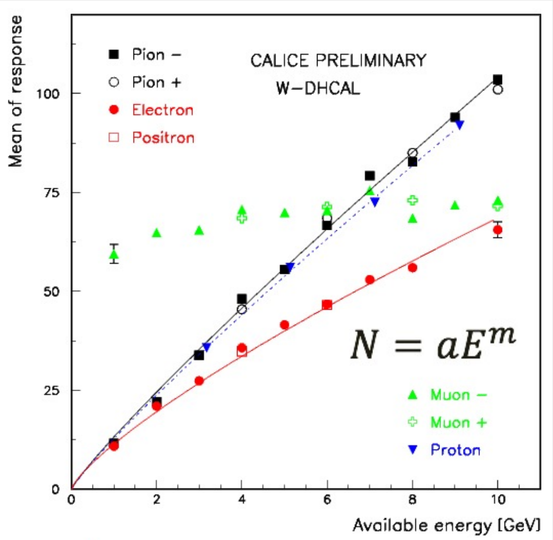


W-DHCAL at CERN

PS

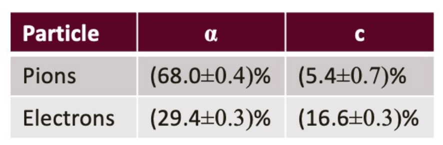
Covers 1 – 10 GeV/c
Mixture of pions, electrons, protons, (Kaons)
Two Cerenkov counters for particle ID
1-3 400-ms-spills every 45 second
Data taking with ~500 triggers/spill

m= 0.90 (**hadrons**),
0.78 (**electrons**)

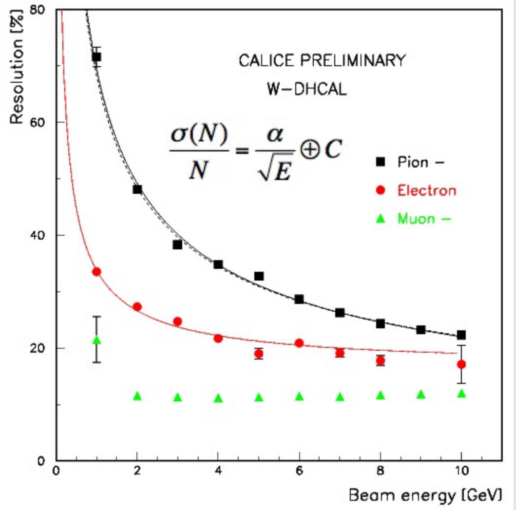


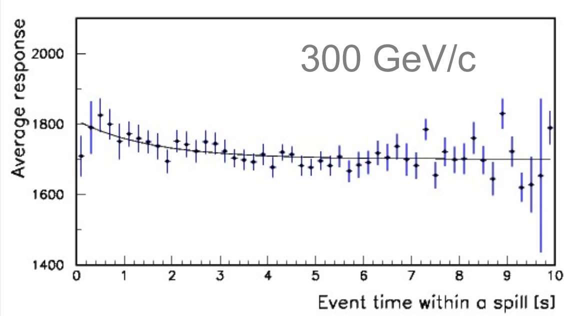
SPS

Covers 12 – 300 GeV/c
Mostly set-up to either have electrons or pions (18 Pb foil)
Two Cerenkov counters for particle ID
9.7-s-spills every 45 – 60 seconds
RPC rate capability a problem



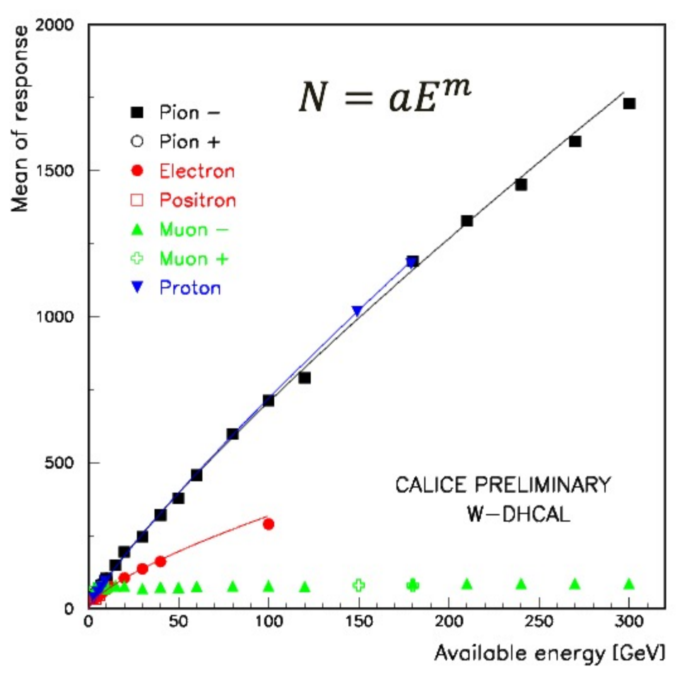
Particle	α	c
Pions	(68.0±0.4)%	(5.4±0.7)%
Electrons	(29.4±0.3)%	(16.6±0.3)%

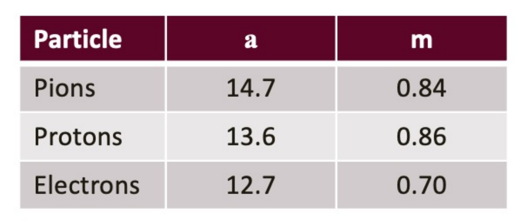




~6 % loss of hits
(in the following not yet corrected)
Time constant ~ 1 second

W-DHCAL at CERN – Combined PS and SPS Measurements



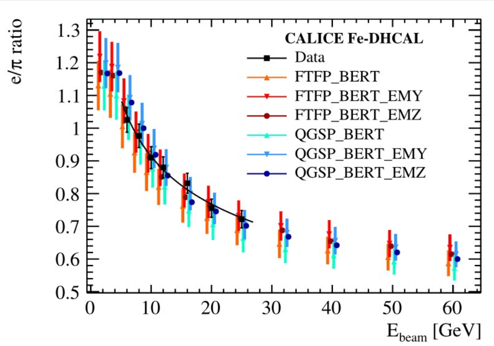


Particle	a	m
Pions	14.7	0.84
Protons	13.6	0.86
Electrons	12.7	0.70

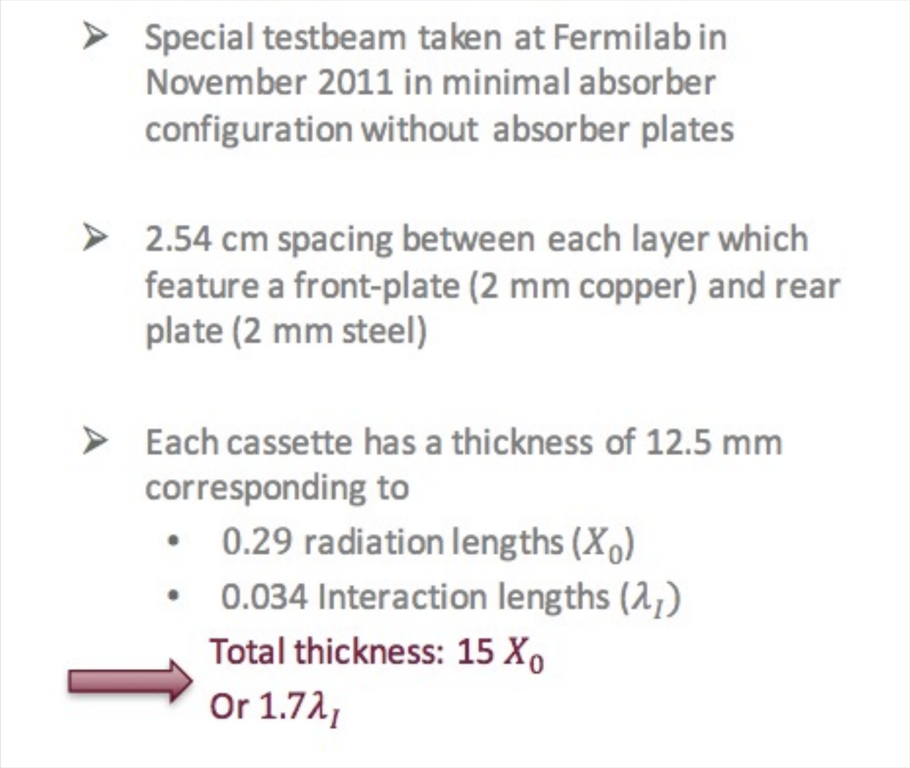
W-DHCAL with 1 x 1 cm^2

Highly over-compensating for the entire energy range (compare to the Fe-DHCAL compensation curve below).

Smaller pads would increase the electron response more than the hadron response, therefore would alter the compensation characteristics.



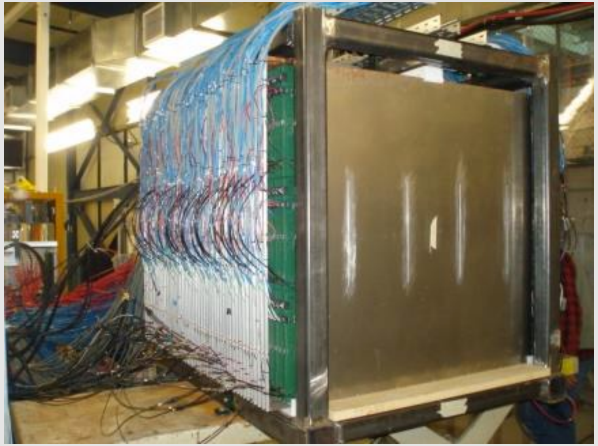
Min-DHCAL, DHCAL with Minimal Absorber, at Fermilab

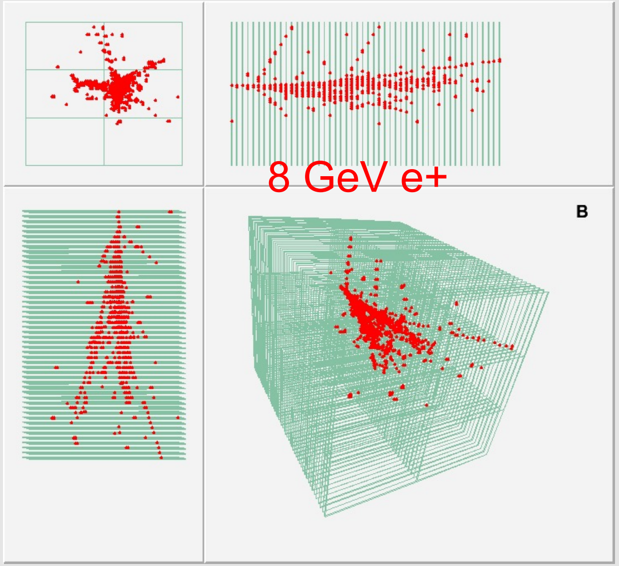


- Special testbeam taken at Fermilab in November 2011 in minimal absorber configuration without absorber plates
- 2.54 cm spacing between each layer which feature a front-plate (2 mm copper) and rear plate (2 mm steel)
- Each cassette has a thickness of 12.5 mm corresponding to
  - 0.29 radiation lengths (X_0)
  - 0.034 Interaction lengths (λ_I)

Total thickness: 15 X_0

Or 1.7λ_I

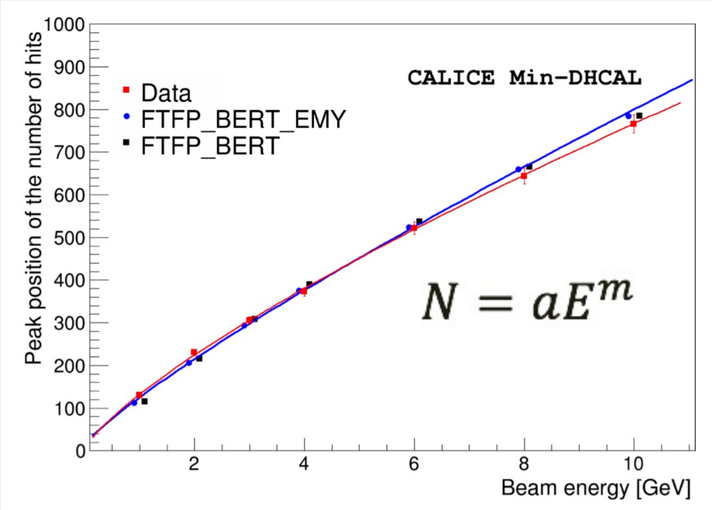


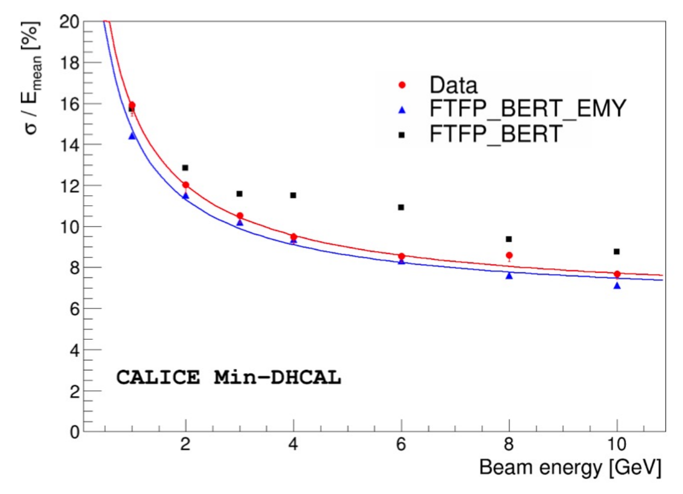


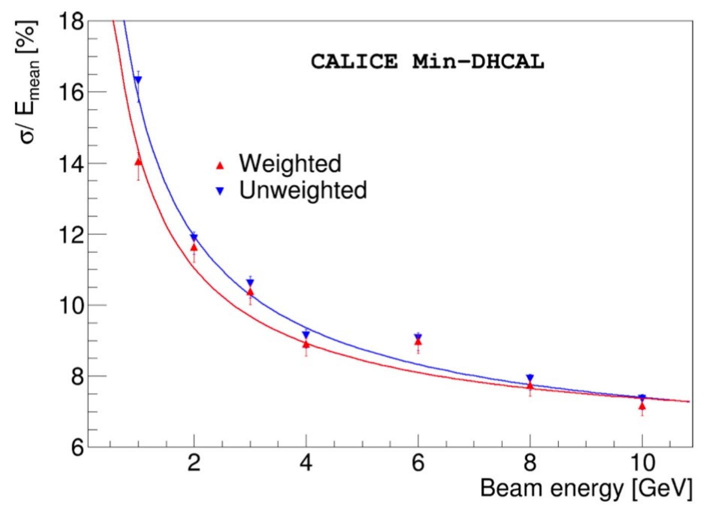
8 GeV e+

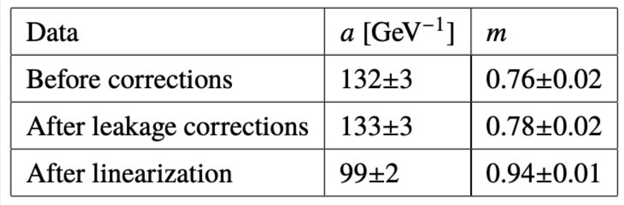
Unprecedented details of low energy electromagnetic showers!

Min-DHCAL Positrons

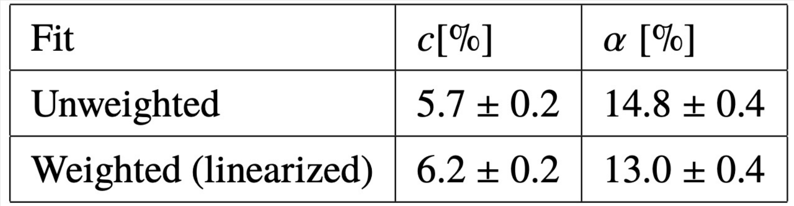








Data	a [GeV^{-1}]	m
Before corrections	132±3	0.76±0.02
After leakage corrections	133±3	0.78±0.02
After linearization	99±2	0.94±0.01



Fit	c[%]	α [%]
Unweighted	5.7 ± 0.2	14.8 ± 0.4
Weighted (linearized)	6.2 ± 0.2	13.0 ± 0.4

B. Freund et.al., JINST 11 P05008, 2016

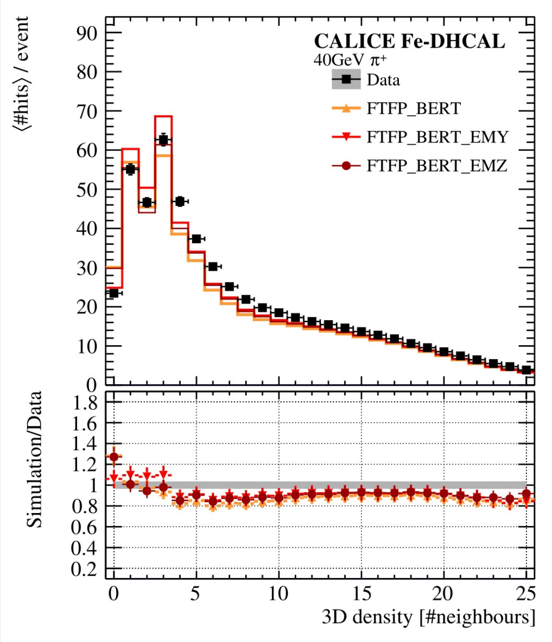
Simulation of the DHCAL Response

- is particularly challenging
- shows significant improvements in newer versions of Geant4 and EM physics packages
- Involves several interconnected steps:

1. The primary ionization locations in the gas gaps of the RPCs are obtained from Geant4.

2. The ionization charges are sampled from the distribution obtained with the analog readout of a DHCAL RPC.

3. A dedicated software called RPCSim was developed to distribute the generated charge over the pads, apply the threshold and reconstruct the hits.



3D density of hits for 40 GeV π^+ showers in the DHCAL with iron absorbers (Fe-DHCAL)

The disagreements are at the very fine level of detail which is not available in conventional calorimeters. ➔ Work ongoing.

Conclusions

- ❑ The first Digital Hadron Calorimeter was built and tested successfully. By construction, the DHCAL was the first large-scale calorimeter prototype with embedded front-end electronics, digital readout, pad readout of RPCs and extremely fine segmentation.

- ❑ Fine segmentation allows the study of electromagnetic and hadronic interactions with unprecedented level of spatial detail, and the utilization of various techniques not implemented in the community so far (software compensation, leakage correction, …).

- ❑ Standard Geant4 simulation package fails to reproduce data well. Some optional packages allow big improvement in the agreement. The disagreements are at the very fine level of detail which is not available in conventional calorimeters.

- ❑ Various analyses and further tests of Geant4 simulation packages are underway.

The concept of Digital Hadron Calorimetry is validated.

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