Digital Hadron Calorimetry

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Calorimetry for the High Energy Frontier

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Lyon, France

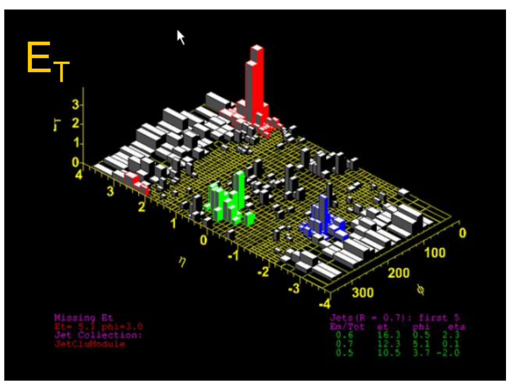
Trend in Calorimetry

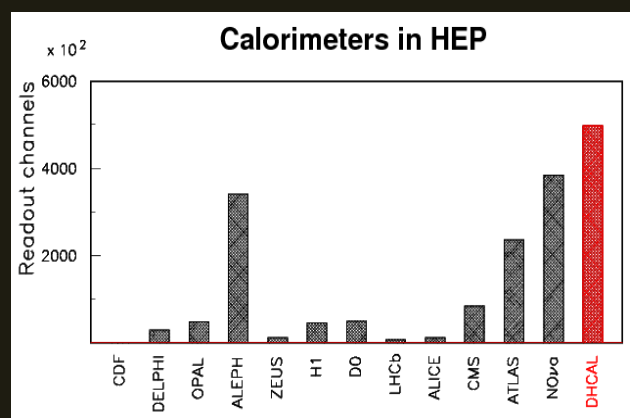
Tower geometry

Energy is integrated over large volumes into single channels

Readout typically with high resolution

Individual particles in a hadronic jet not resolved



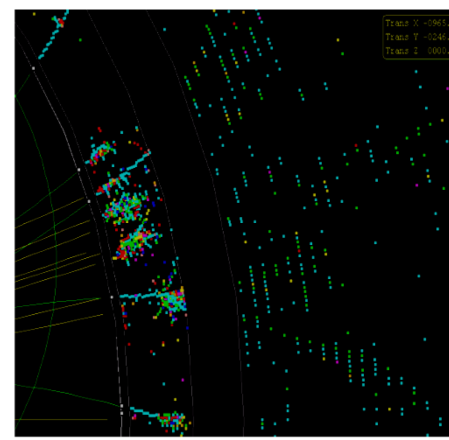


Imaging calorimetry

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

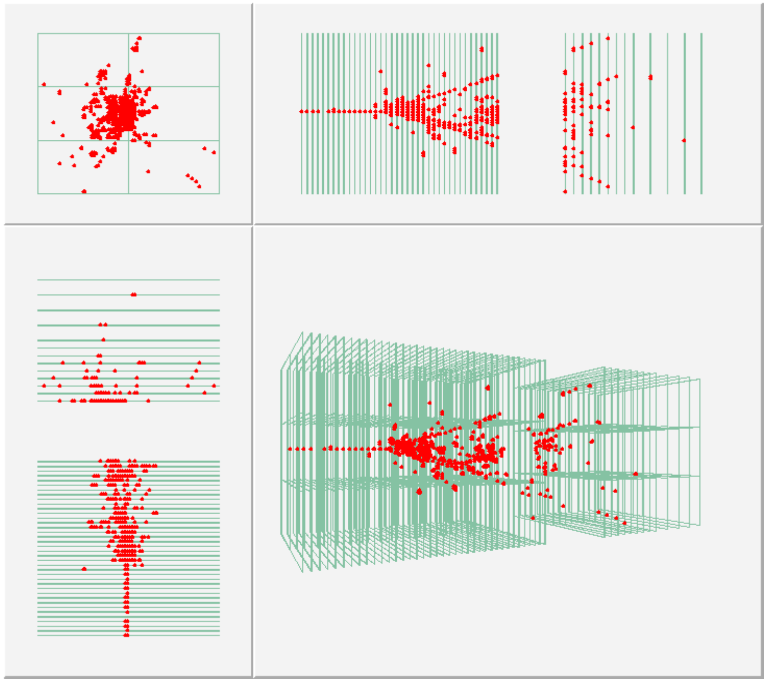
Option to minimize resolution on individual channels

Particles in a jet are measured individually



The DHCAL prototype

60 GeV π+



Description

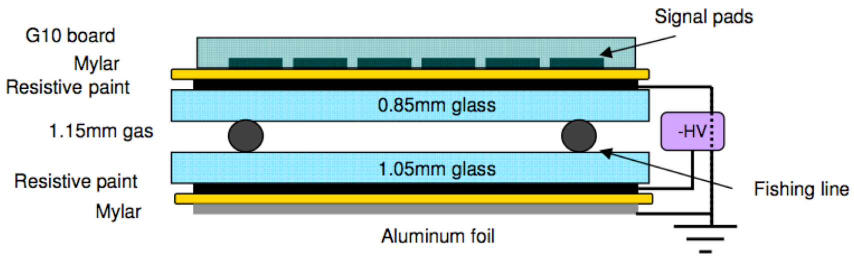
Hadronic sampling calorimeter

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

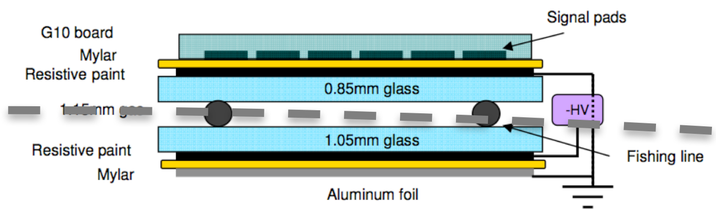
with Iron absorber in 2010 – 2011

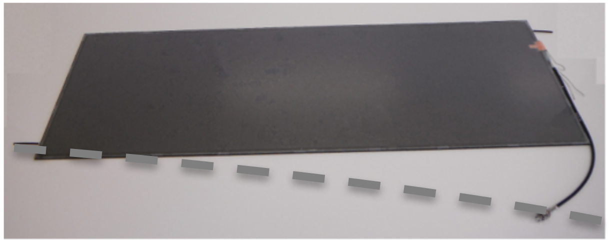
with no absorber in 2011

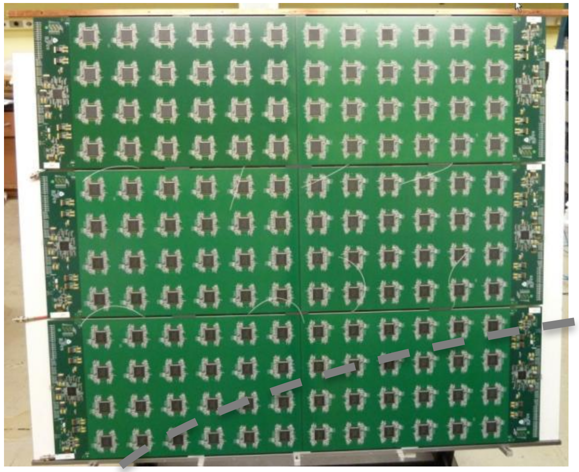
Tests at CERN

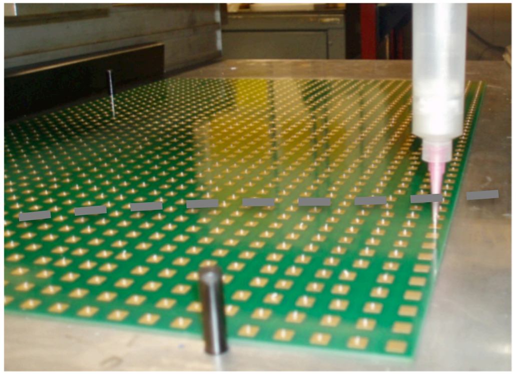
with Tungsten absorber in 2012

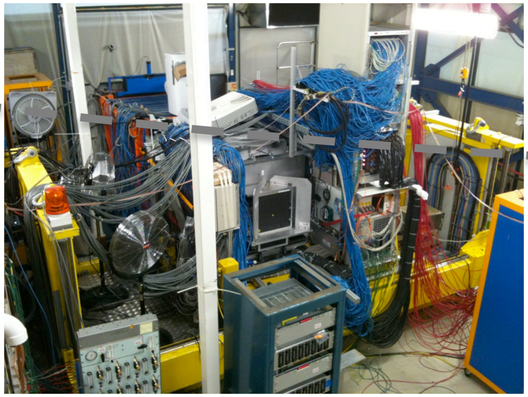
DHCAL Construction

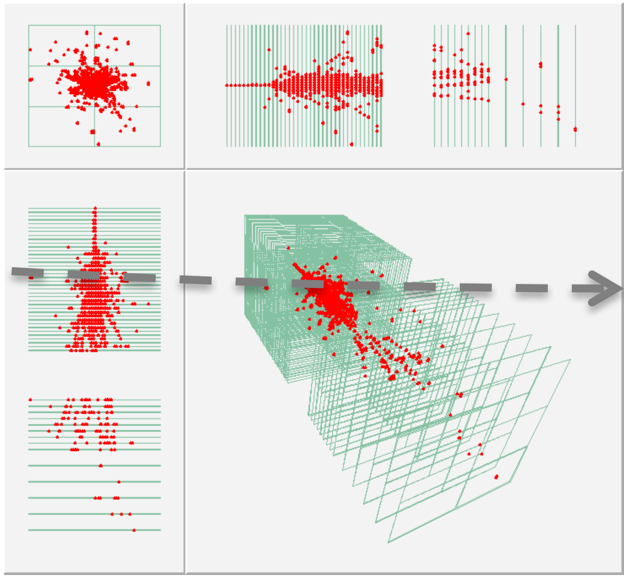












Fe-DHCAL at Fermilab

Fermilab Test Beam Facility

Covers 1 – 120 GeV/c
Mixture of pions, electrons and muons (up to 60 GeV/c)
Primary protons at 120 GeV/c
Čerenkov counter for particle ID
4 s spill every 60 s

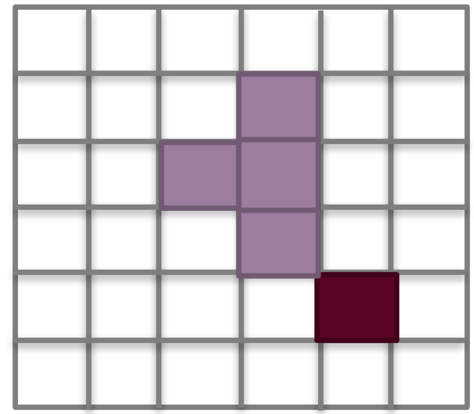
Muon Trigger:
2 x (1 m x 1 m scintillator)

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

Event:
Time stamp, Čerenkov/muon tagger bits

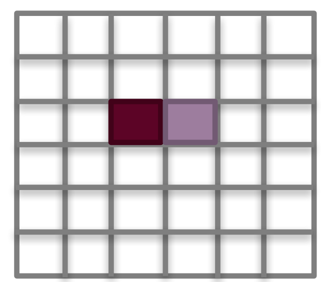
Hit:
x, y, z, time stamp

Nearest neighbor clustering:
Combine hits with a common edge

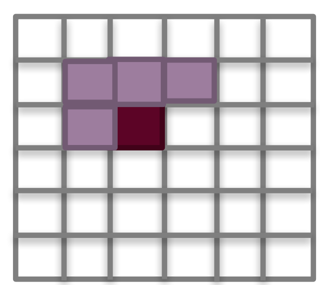


→ Cluster:
x, y, z

Density 3x3:
Number of neighbors in 3x3 pads surrounding the hit



→ 1



→ 4

Calibration Procedures

RPC performance

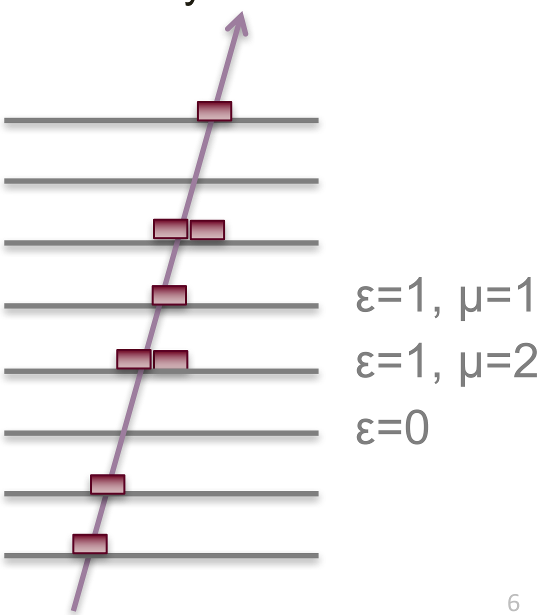
Average efficiency to detect MIP: $\varepsilon_0 \sim 96\%$
Average pad multiplicity: $\mu_0 \sim 1.6$

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

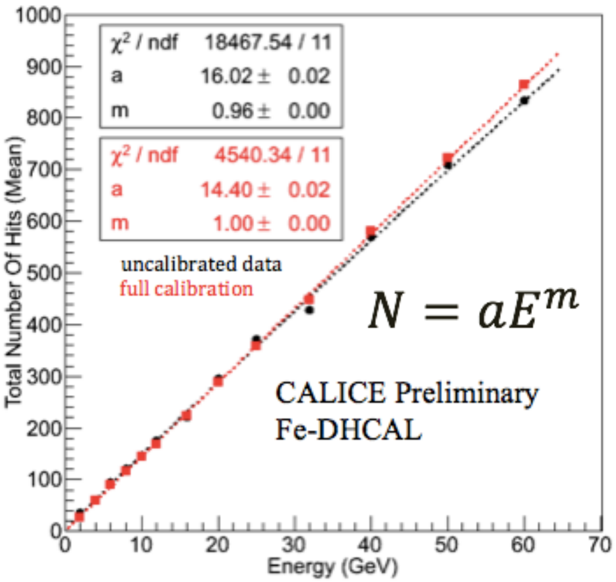
H_i: Number of hits in layer i

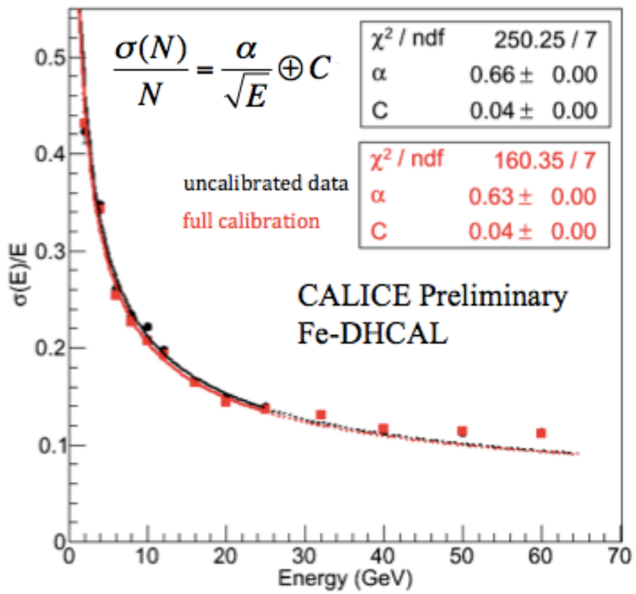
2. Density-weighted Calibration: Developed due to the fact that a pad will fire if it gets contribution from multiple traversing particles regardless of the efficiency of this RPC. Hence, the full calibration will overcorrect. Classifies hits in density bins (number of neighbors in a 3 x 3 array).

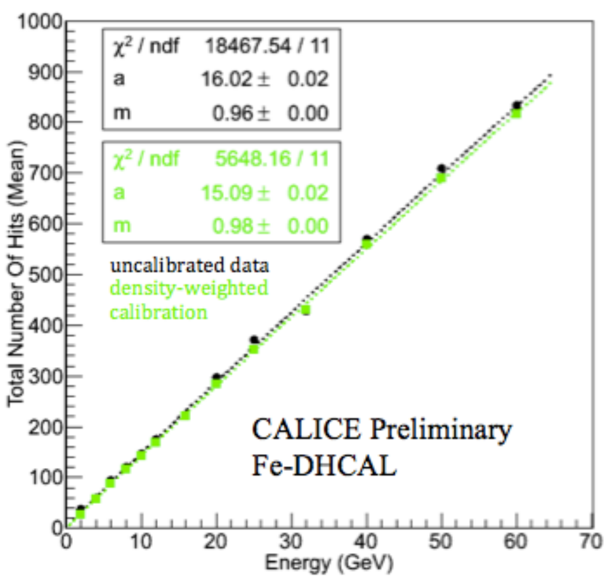
3. Hybrid Calibration: Density bins 0 and 1 receive full calibration.

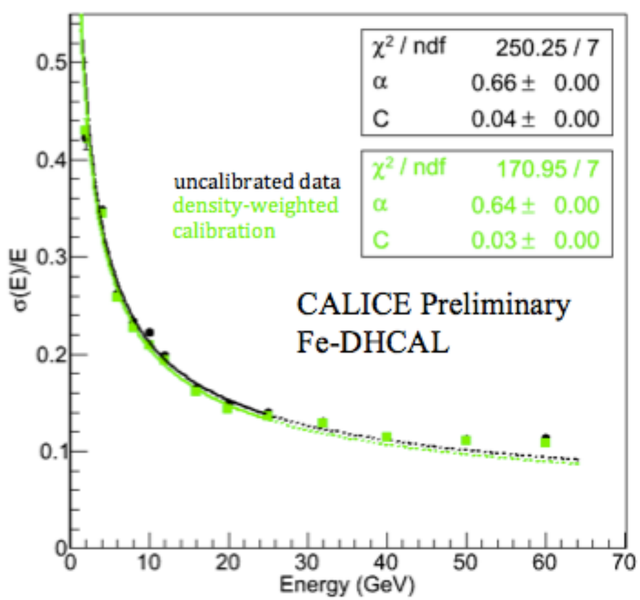


Fe-DHCAL Pion Response and Energy Resolution









Uncalibrated response

4% saturation

Full calibration

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

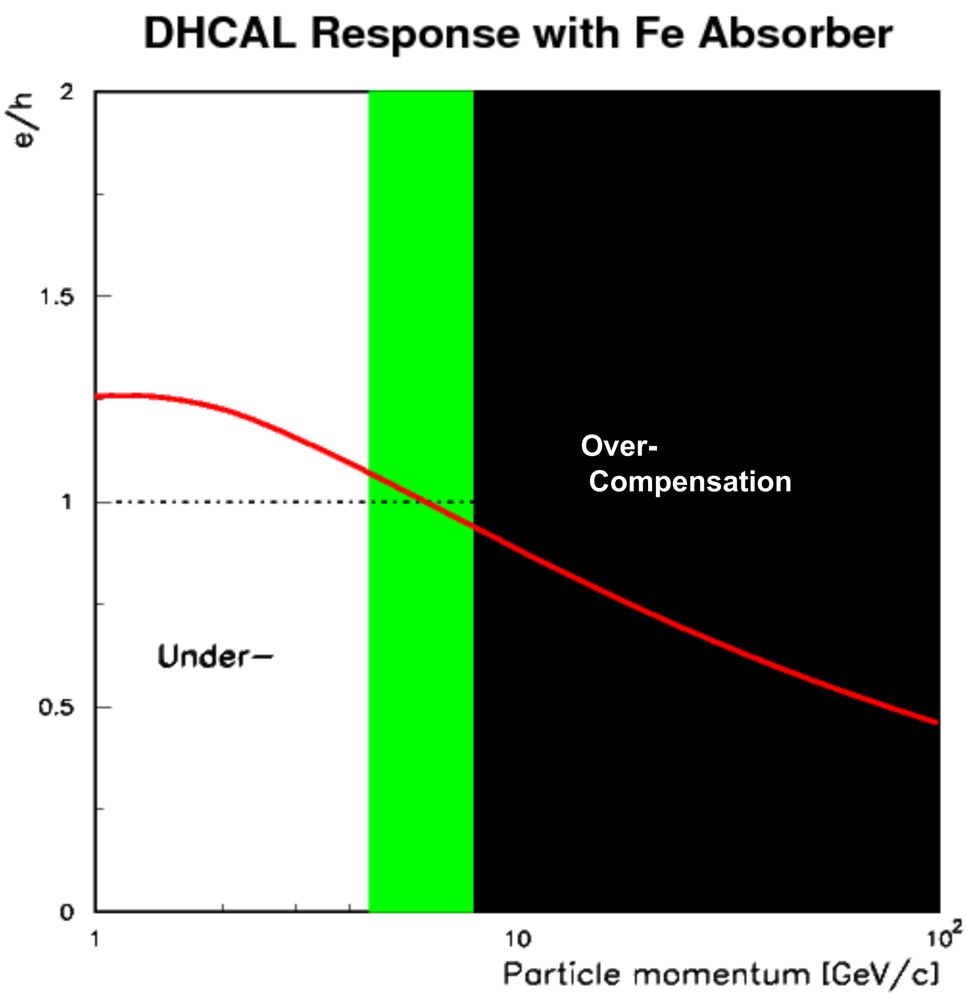
Density- weighted calibration

1 – 2% saturation (in agreement with predictions)

Monte Carlo prediction

Around 58%/√E with negligible constant term

Fe-DHCAL – Response



The **DHCAL** is different…

Higher order corrections (Software compensation) might increase the **range of compensation**

e: Response to electromagnetic interactions
h: Response to hadronic interactions

e/h=1 ➔ compensating

W-DHCAL at CERN

PS

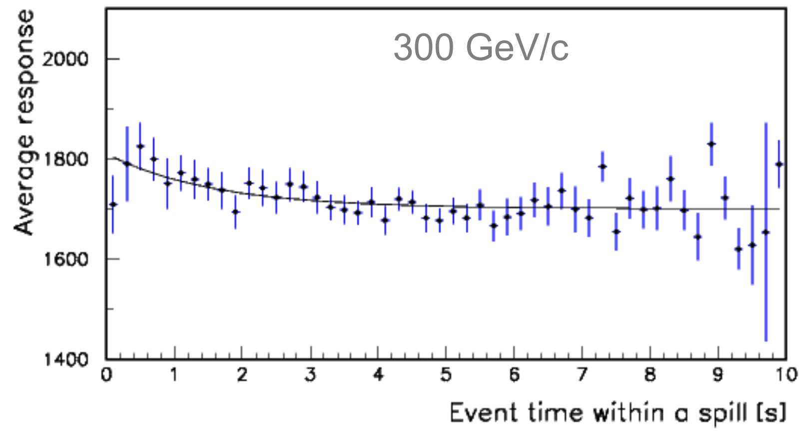
Covers 1 – 10 GeV/c
Mixture of pions, electrons, protons, (Kaons)
Two Cerenkov counters for particle ID
1-3 400-ms-spills every 45 second (RPC rate capability OK)
Data taking with ~500 triggers/spill

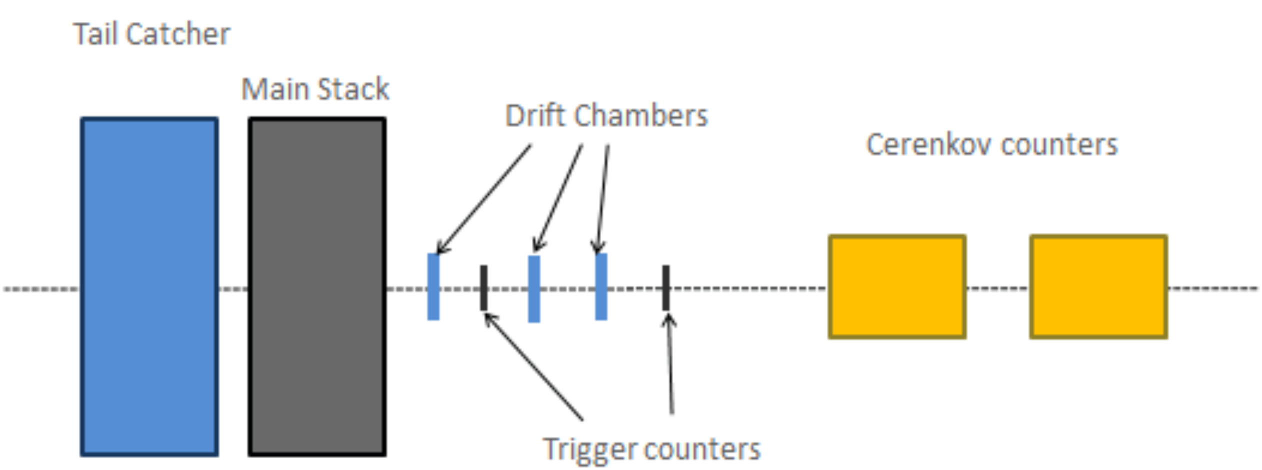
SPS

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
(running with limited rate: 250 – 500 triggers/spill)

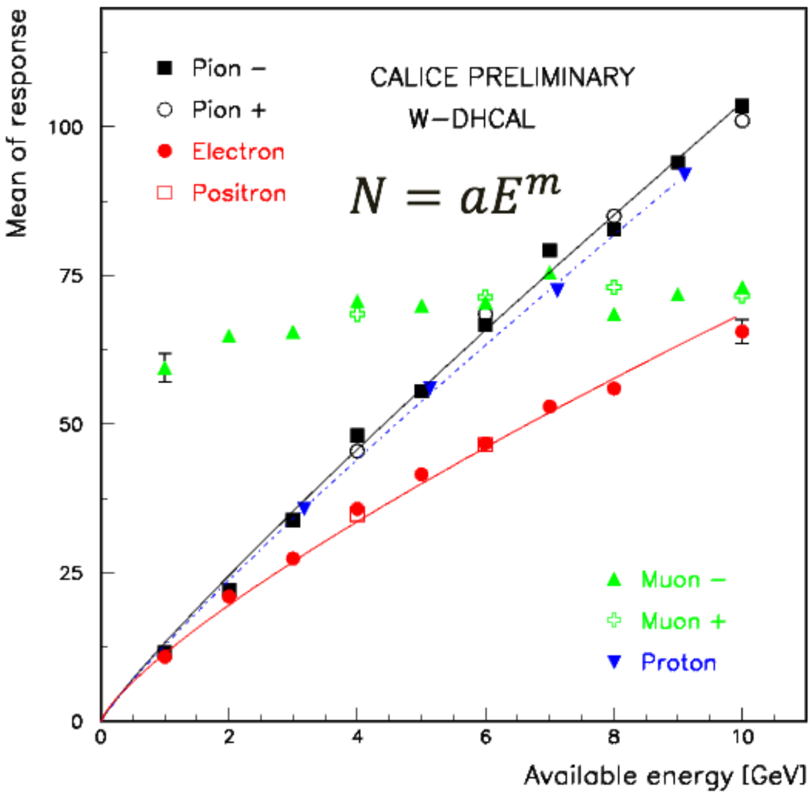
RPC rate limitations

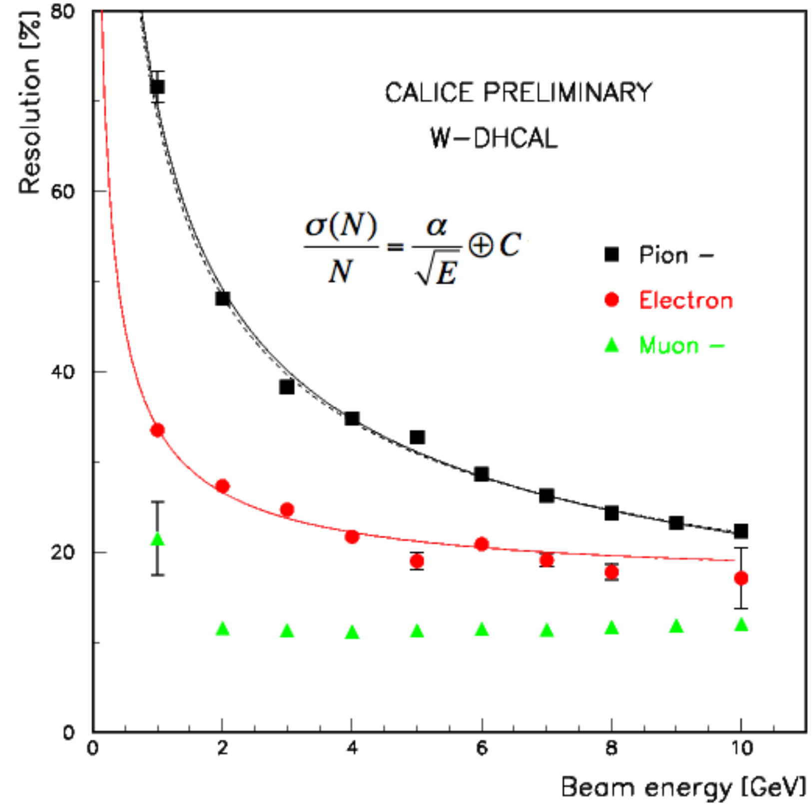
~6 % loss of hits
(in the following not yet corrected)
Time constant ~ 1 second





W-DHCAL Response at the PS (1 – 10 GeV)





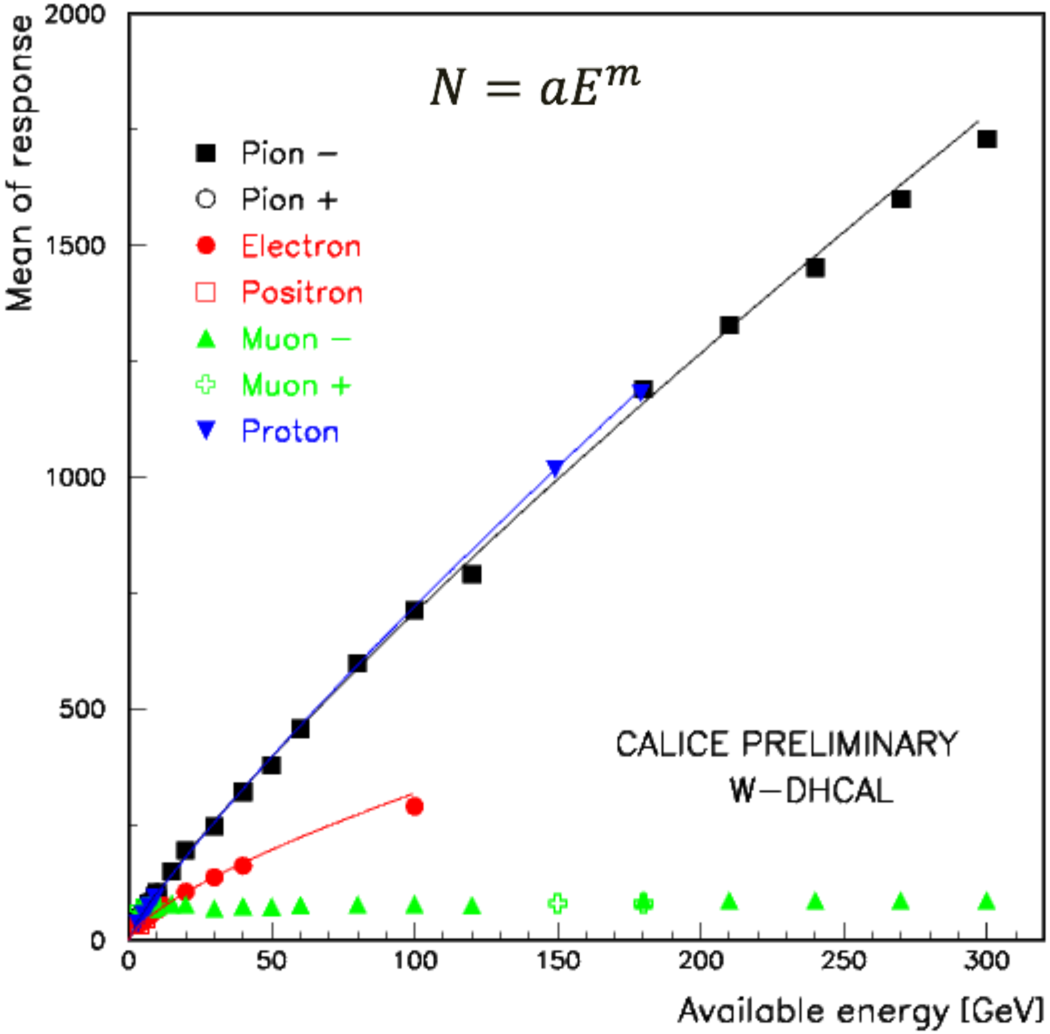
Fluctuations in muon peak
Data not yet calibrated

Resolutions corrected for non-linear response

Response non-linear
Data fit empirically with aE^m
m= 0.90 (**hadrons**), 0.78 (**electrons**)

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

W-DHCAL Response at the PS (1 – 10 GeV) and SPS (12 – 300 GeV) Combined



W-DHCAL with 1 x 1 cm^2

Highly over-compensating (smaller pads would increase the electron response more than the hadron response)

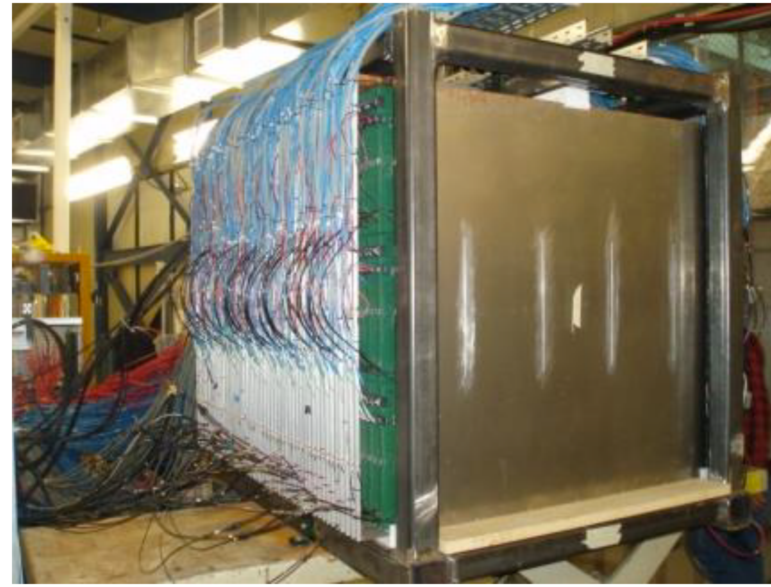
Particle	a	m
Pions	14.7	0.84
Protons	13.6	0.86
Electrons	12.7	0.70

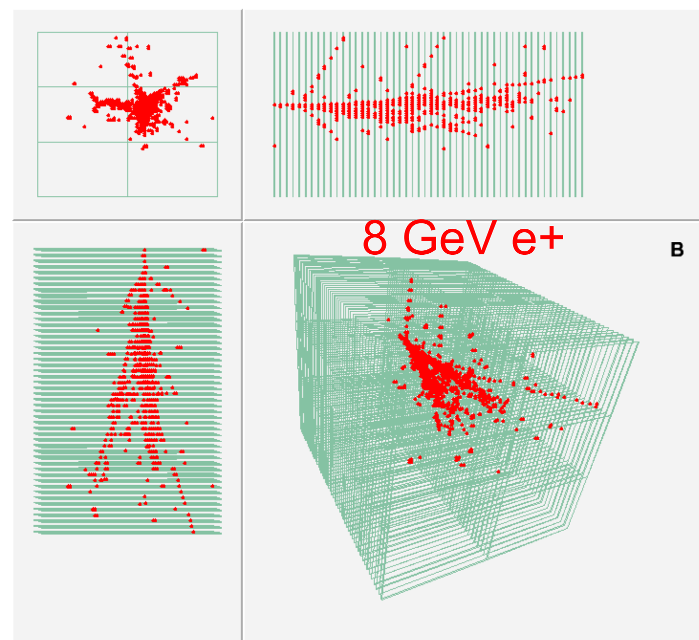
DHCAL with Minimal Absorber: Min-DHCAL

- 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

Unprecedented details of low energy electromagnetic showers!



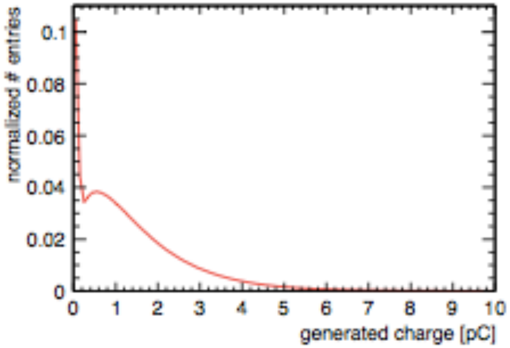


DHCAL Simulation

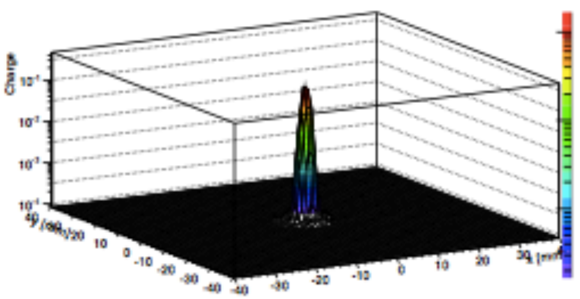
- GEANT4 based simulation gives raw points of ionisation
- Simulation of RPC charge avalanche & read-out by standalone program (RPC_sim)
  - Charge generated randomly following parametrization (taken from analog RPC tests)
  - Radial charge distribution modeled by double-Gaussian

$$f(r) = (1-R) * e^{-\frac{r^2}{(2\sigma_1)^2}} + R * e^{-\frac{r^2}{(2\sigma_2)^2}}$$

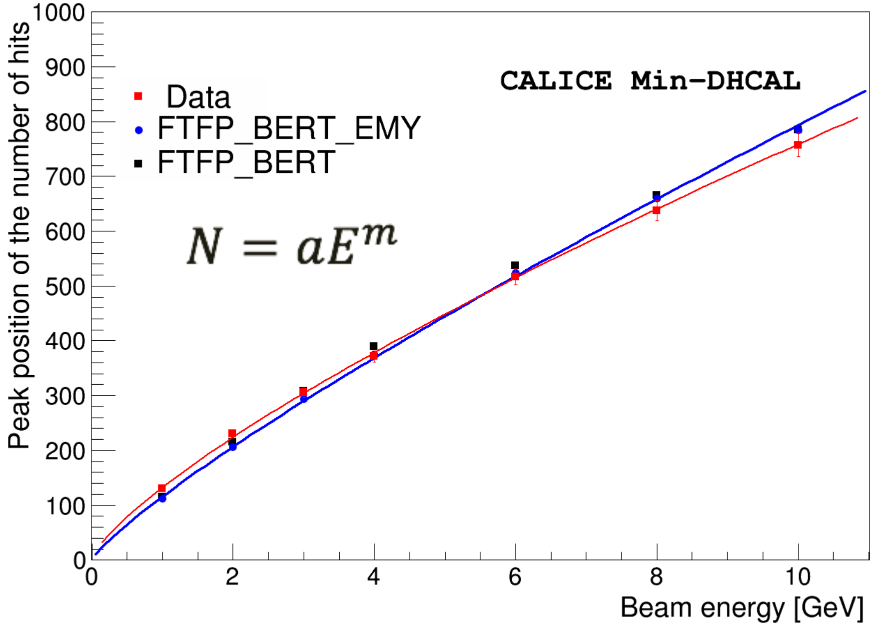
  - Close-by avalanches suppression (d_{cut})
  - Threshold to convert charge to hits (TT)
- Tuning
  - σ_1, σ_2, R and TT tuned using muons
  - d_{cut} tuned using positrons (3 & 10 GeV)
- Initially FTFP_BERT physics list was used
  - ➢ Led to unsatisfactory agreement (see later)
- Now using 'Option 3' or '_EMY' (optimized for low energies)
  - Main differences:
    - Reduced range size in computation of the step limit by ionization process and improved treatment of multiple scattering



Charge distribution in x-y

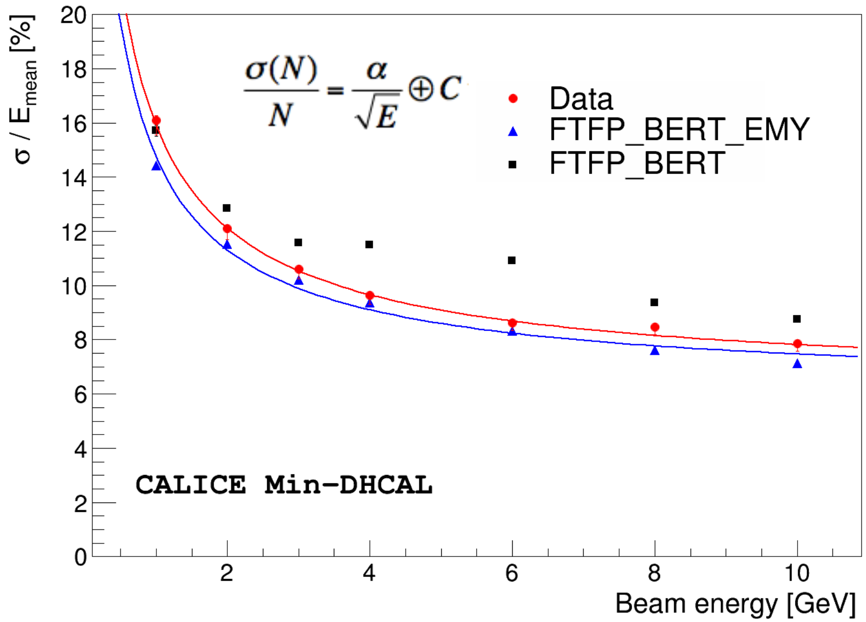


Min-DHCAL Response to Positrons



Data and MC agree reasonably well for all energies

	a	m
Data	131.8 ± 2.8	0.76 ± 0.02
FTFP_BERT_EMY	115.8 ± 0.1	0.84 ± 0.00

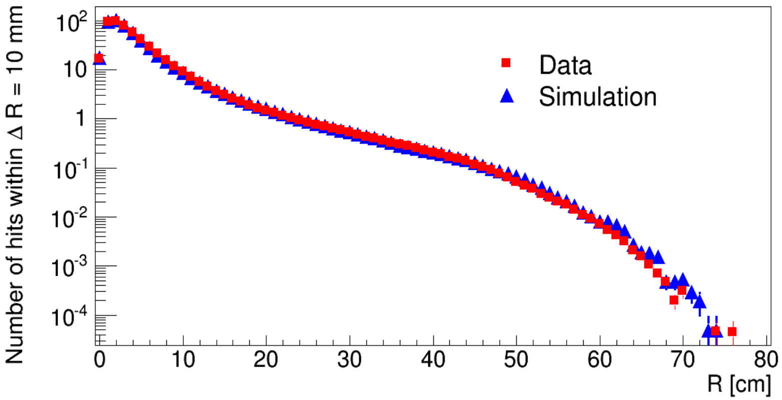


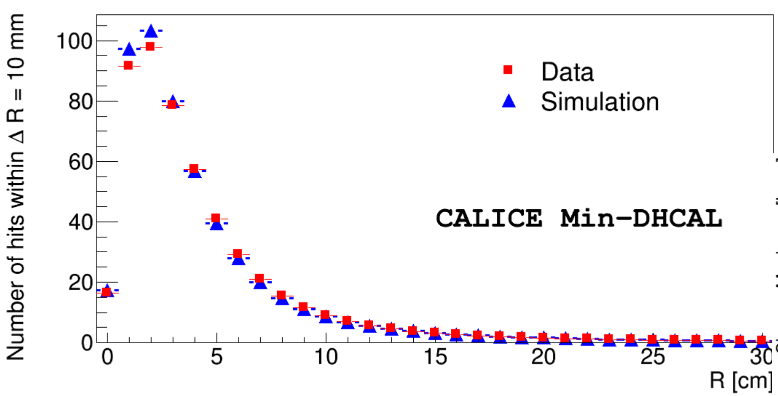
Data and MC agree well only for EMY physics list

	C [%]	α [%]
Data	6.3 ± 0.2	14.3 ± 0.4
FTFP_BERT_EMY	6.2 ± 0.1	13.4 ± 0.2

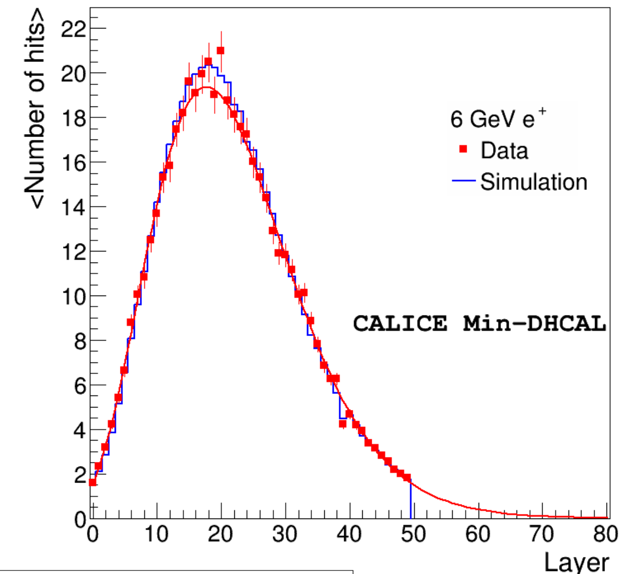
Min-DHCAL Electromagnetic Shower Shapes

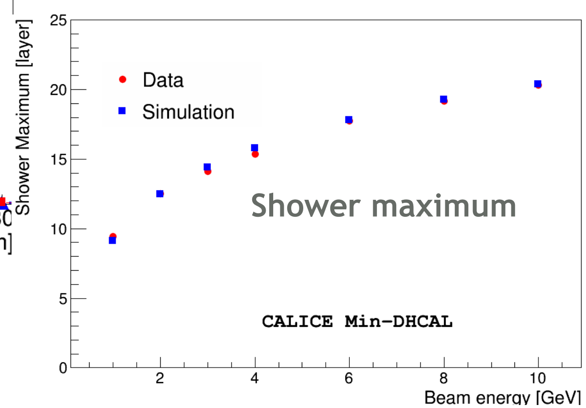
Transverse shower shape



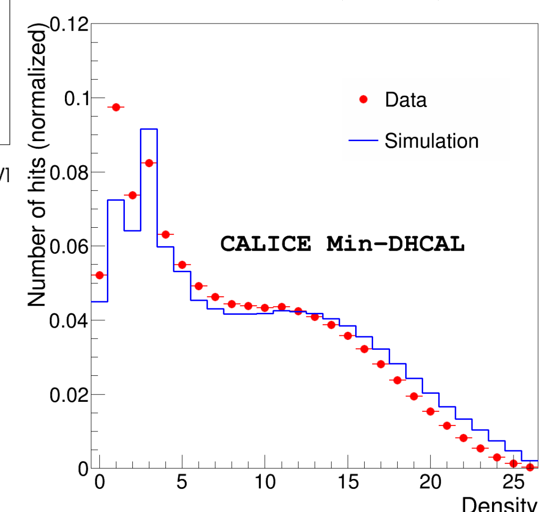


Longitudinal shower shape





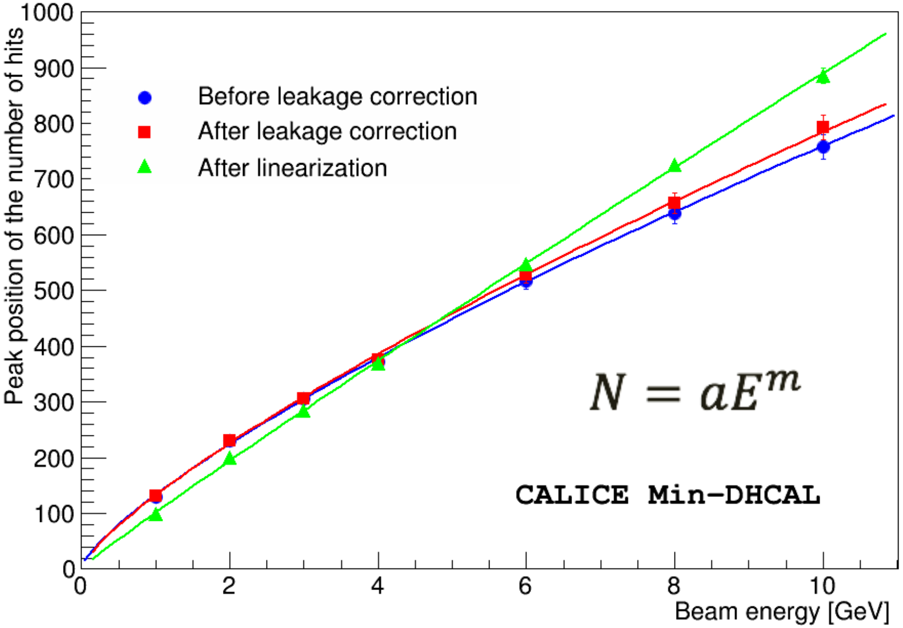
Hit density (3x3x3)



Good agreement between data and MC for longitudinal and radial shower shapes

Comparison of hit densities indicates that some limitations in the simulation still persist.

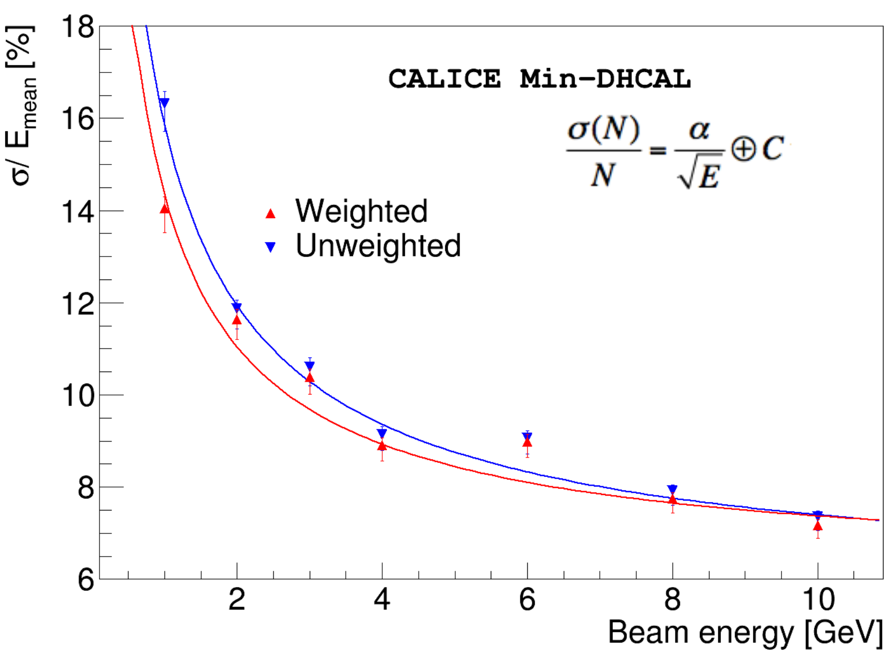
Min-DHCAL Electromagnetic Response Linearization



Leakage correction is from longitudinal shower shapes; linearization is using 3x3x3 hit densities (D_j) to minimize

$$\chi^2 = \sum_{i=1}^{7} \frac{\left(\sum_{j=0}^{26} w_j D_{ij} - \alpha E_i^{beam} \right)^2}{E_i^{beam}}$$

	Before Leakage Corr.	After Leakage Corr.	After Linearization
a	131.8 ± 3.5	132.1 ± 3.5	100.2 ± 2.2
m	0.76 ± 0.02	0.78 ± 0.02	0.95 ± 0.02



Linearization improves the resolution by 2-10 %.

Weights can then be used to linearize the electromagnetic subshowers in pion interactions
➔ expect significantly improved resolution.

	Constant term [%]	Stochastic term [%]
Unweighted	6.4 ± 0.2	14.5 ± 0.4
Weighted	6.5 ± 0.2	12.8 ± 0.3

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.

The concept of Digital Hadron Calorimetry is validated.