TIPP'17

Digital Electromagnetic Calorimetry with Extremely Fine Spatial Segmentation

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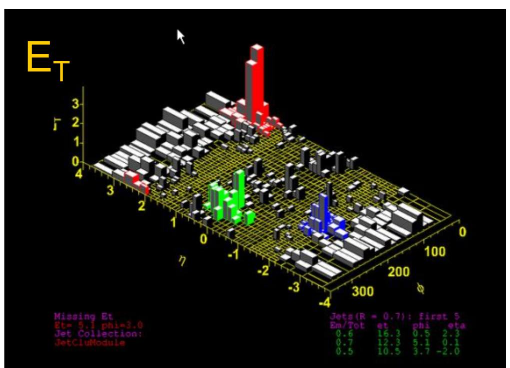
Trend in Calorimetry

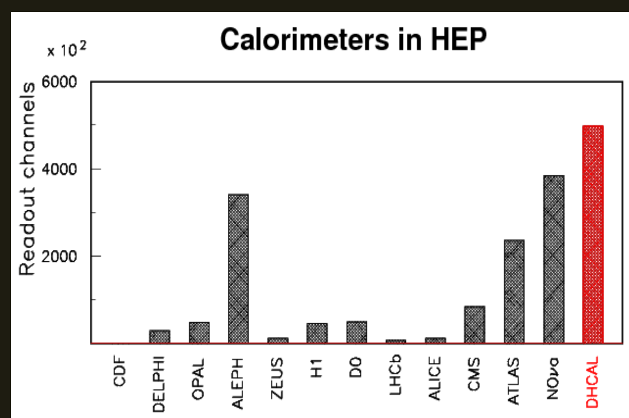
Tower geometry

Energy is integrated over large volumes into single channels

Readout typically with high resolution

Individual particles in a hadronic jet not resolved



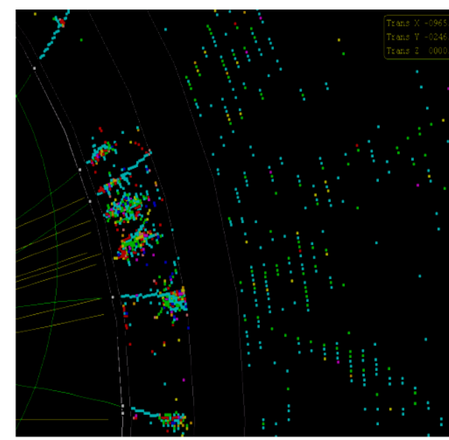


Imaging calorimetry

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

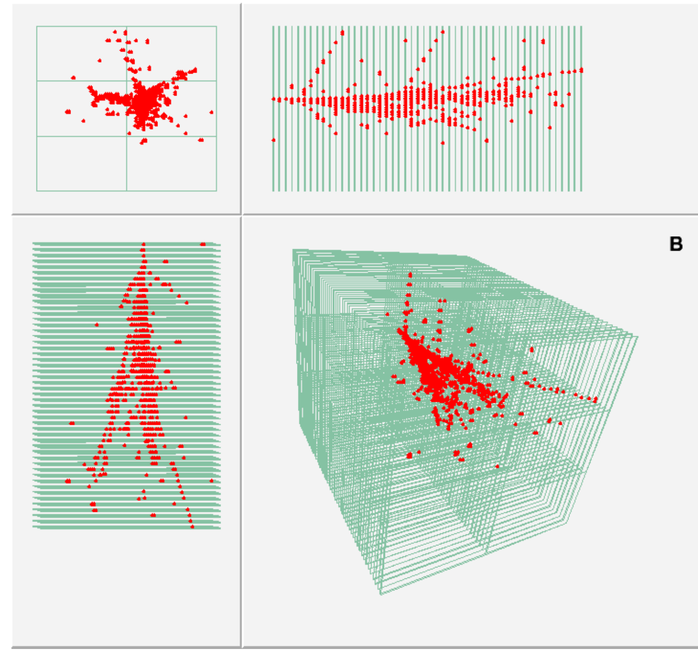
Option to minimize resolution on individual channels

Particles in a jet are measured individually



The DHCAL prototype

8 GeV e+



Description

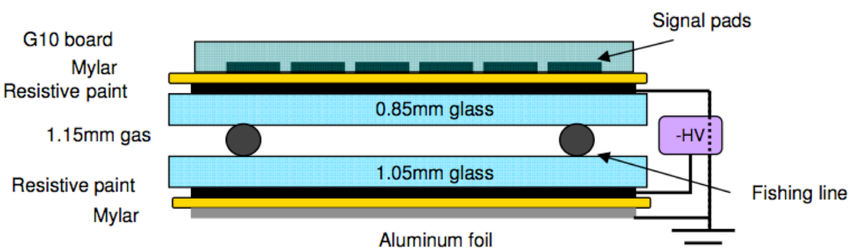
Hadronic sampling calorimeter

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

Tests at CERN

with Tungsten absorber 2012

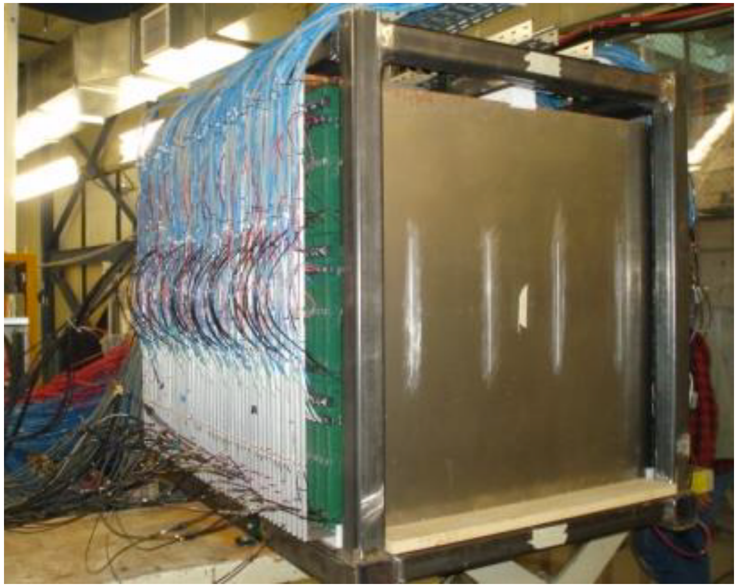
DHCAL with Minimal Absorber

- 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!

Data sample collected at Fermilab

- Data collected at Fermilab Test Beam Facility
- Secondary beam mixture of electrons, muons and pions
- Spill duration 4.0 seconds
- Čerenkov counters for PID
- Data collected in November 2011 has a momentum range of 1 - 10 GeV/c

Momentum [GeV/c]	Number of events
1	107 k
2	117 k
3	62 k
4	84 k
6	109 k
8	109 k
10	226 k
TOTAL	814 k

Event selection

Data	Momentum [GeV/c]	1	2	3	4	6	8	10
	Timing cuts	99.9	99.8	99.9	99.8	99.95	99.95	99.96
	Requirements on first layer	88.5	87.0	80.3	80.3	88.1	86.6	88.2
	At least 6 active layers	88.1	86.4	80.0	79.8	88.0	86.5	88.1
	Čerenkov signal	60.3	31.7	40.0	30.7	53.9	41.7	33.0
Simulation	Timing cuts	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	Requirements on first layer	98.3	97.9	97.9	97.6	97.2	97.1	96.8
	At least 6 active layers	98.3	97.9	97.9	97.6	97.2	97.1	96.8

PID provided by Čerenkov signal (not simulated)

Percentage of events surviving the various event selection criteria

Equalization of the RPC response

- Through-going muons are used to equalize the response of the 150 RPCs
- Efficiency ε and multiplicity μ are calculated for ever RPC
- Calibration factors c_i for RPC i are the product of the average multiplicity μ_0 and efficiency ε_0 divided by the multiplicity and efficiency of RPC i

$$c_i = \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i}$$

- Then the corrected number of hits N_i' is calculated as:

$$N_i' = c_i N_i$$

Average values for November data:

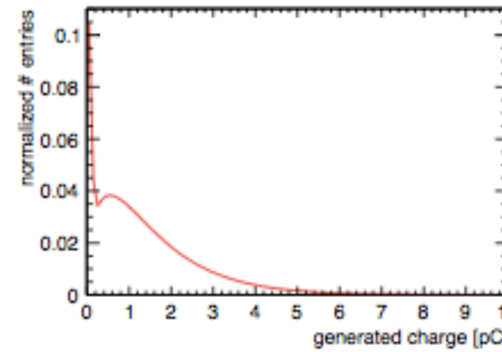
$\boxed{\varepsilon_0 = 0.917,\ \mu_0 = 1.573}$

Simulation

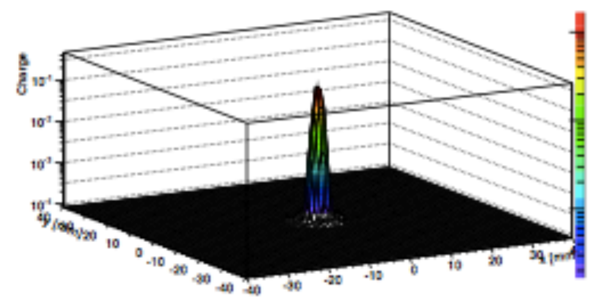
- GEANT4 based simulation gives raw points of ionisation
- Simulation of RPC charge avalanche & read-out by standalone program (RPC_sim)
  - Charge generated randomly following parametrization (taken from analog RPC tests)
  - Radial charge distribution modeled by double-Gaussian

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

  - 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



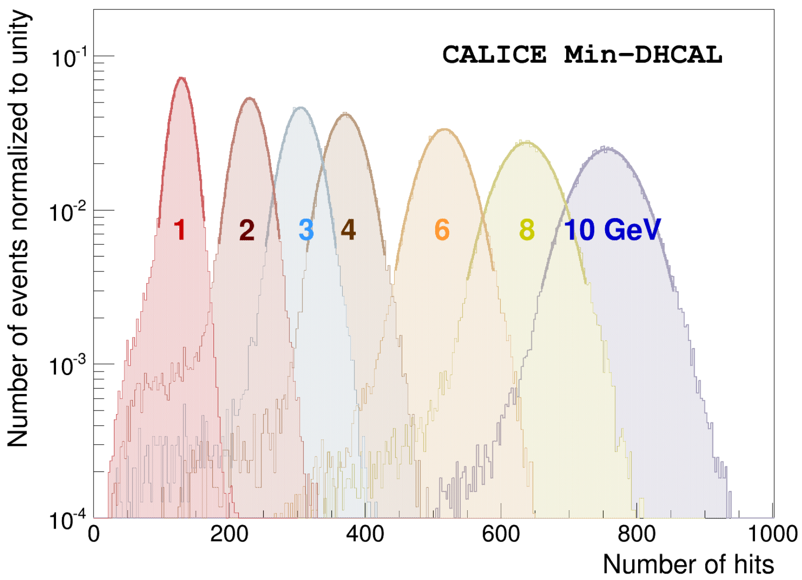
Charge distribution in x-y



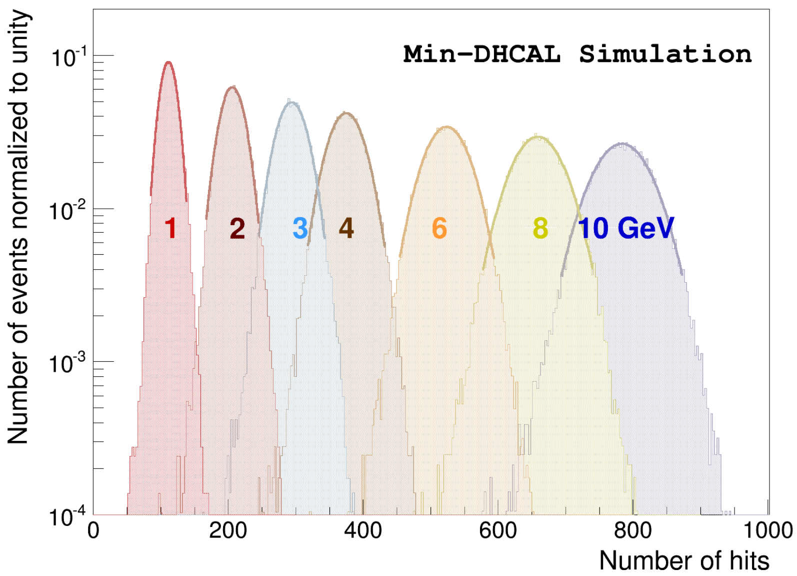
Response to positrons

Gaussian fit in a $\pm 2\sigma$ range to estimate the mean response as a function of the energy

Data



Simulation (FTFP_BERT_EMY)



Response to positrons

Data and simulation agree reasonably well for all energies

Good agreement achieved for both FTFP_BERT_EMY and FTFP_BERT

Fitted with power law

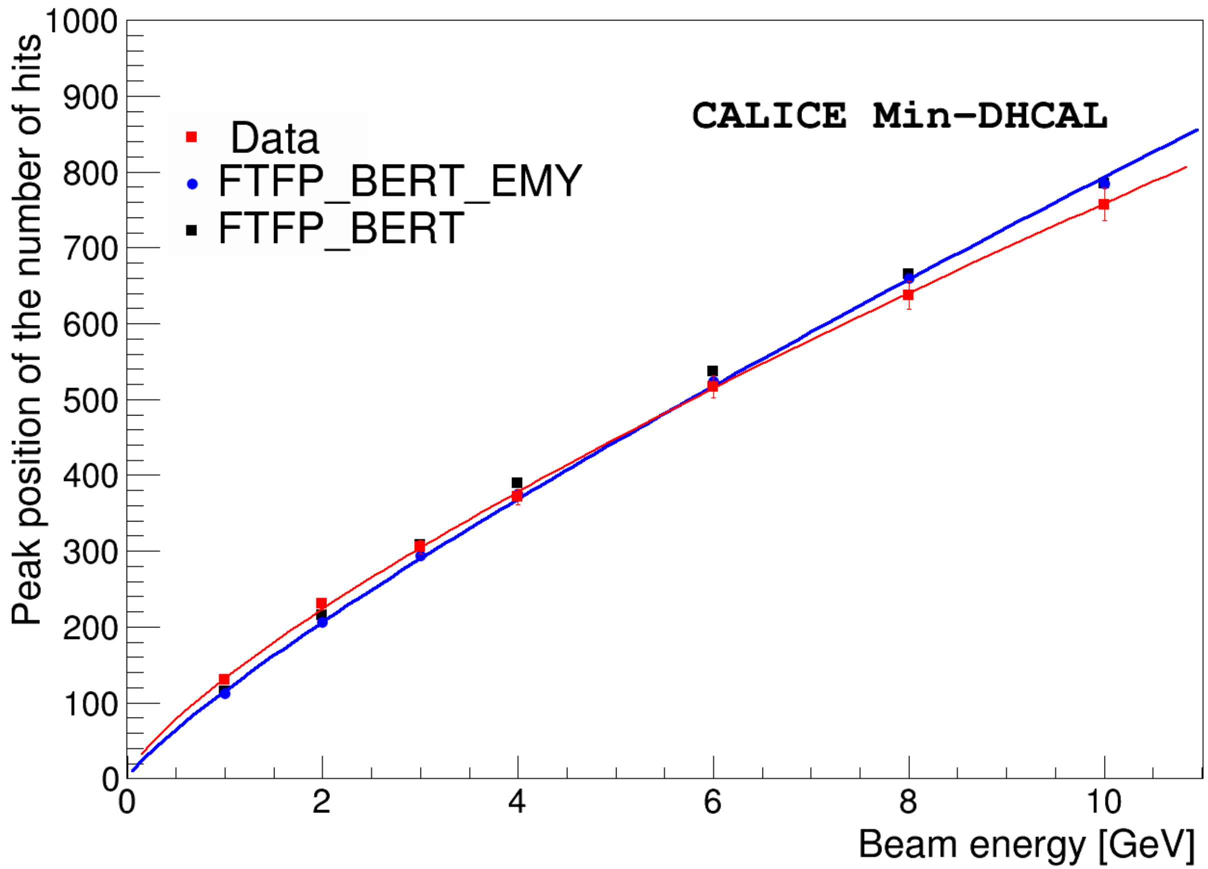
$$N = a * E^m$$

Data

$$m = 0.76 \pm 0.02$$
$$a = 131.8 \pm 2.8$$

FTFP_BERT_EMY

$$m = 0.836 \pm 0.001$$
$$a = 115.8 \pm 0.1$$



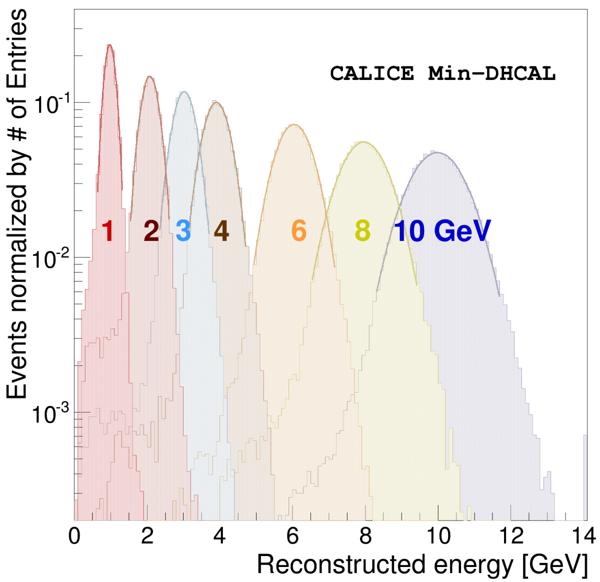
Saturation due to large pad size compared to the dense electromagnetic showers

Inverse fit function used to reconstruct energy

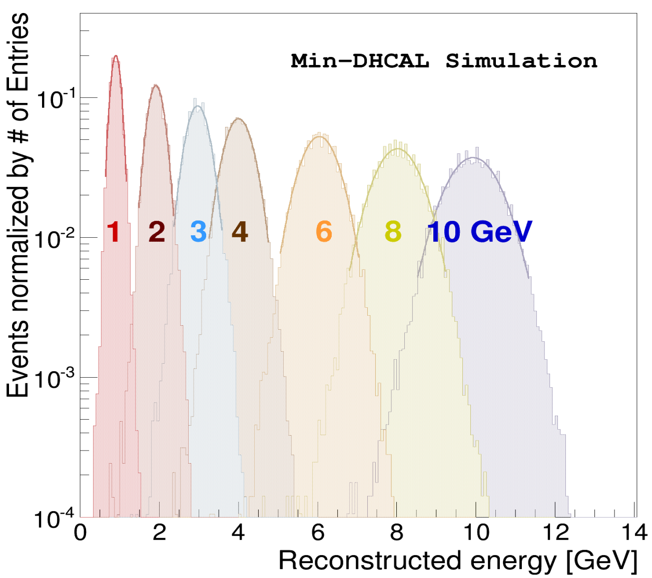
Reconstructed energy of positrons

Gaussian fit in a $\pm 2\sigma$ range to estimate the resolution

Data



Simulation (FTFP_BERT_EMY)

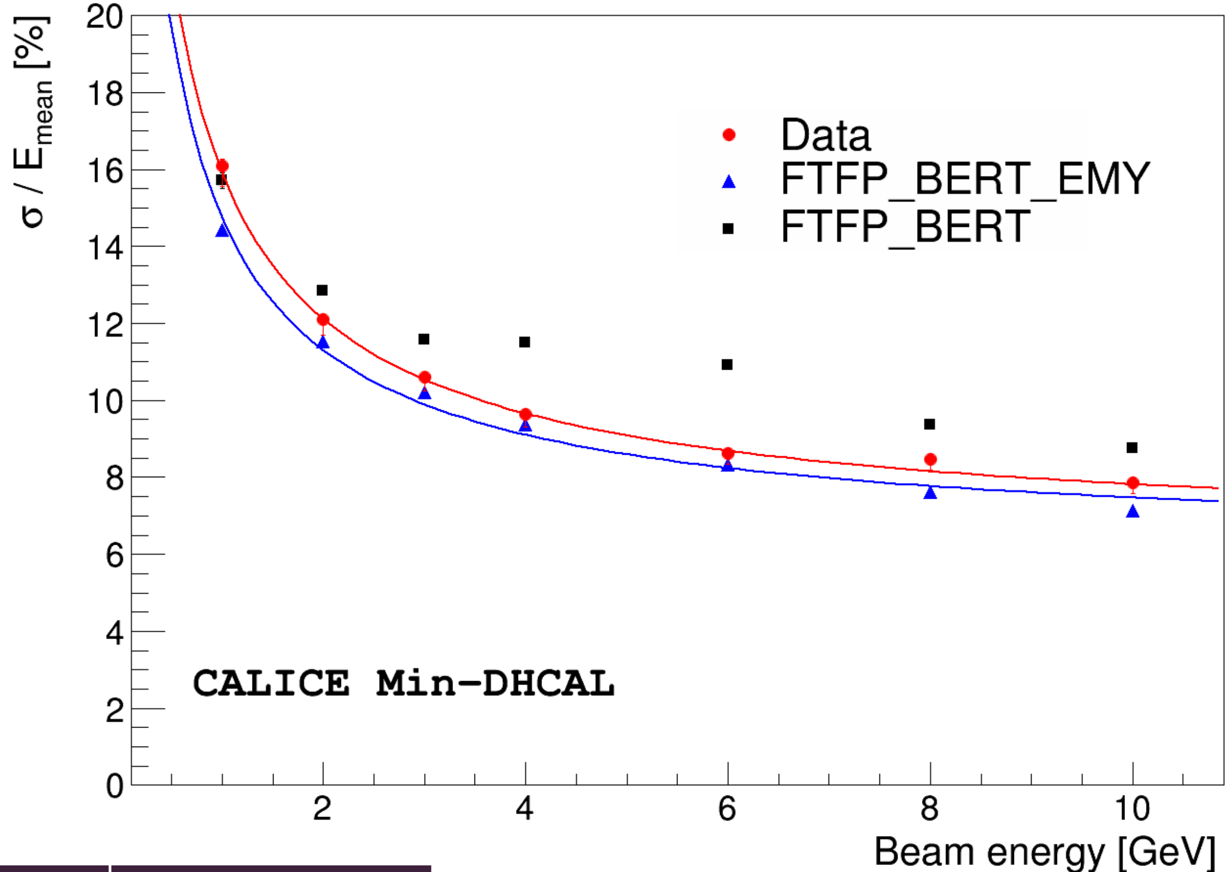


Electromagnetic Energy Resolution

Good agreement only for EMY physics list

Fit with standard parametrization

$$\frac{\sigma}{E} = c \oplus \frac{\alpha}{\sqrt{E/GeV}}$$



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

Longitudinal shower shape

Good agreement for simulation and data

Fit with gamma distribution to estimate average leakage and shower maximum

$$\frac{dN}{dz} = N_0 \frac{\left(\frac{z-\mu}{\beta}\right) e^{-\frac{z-\mu}{\beta}}}{\beta\Gamma(\gamma)}$$

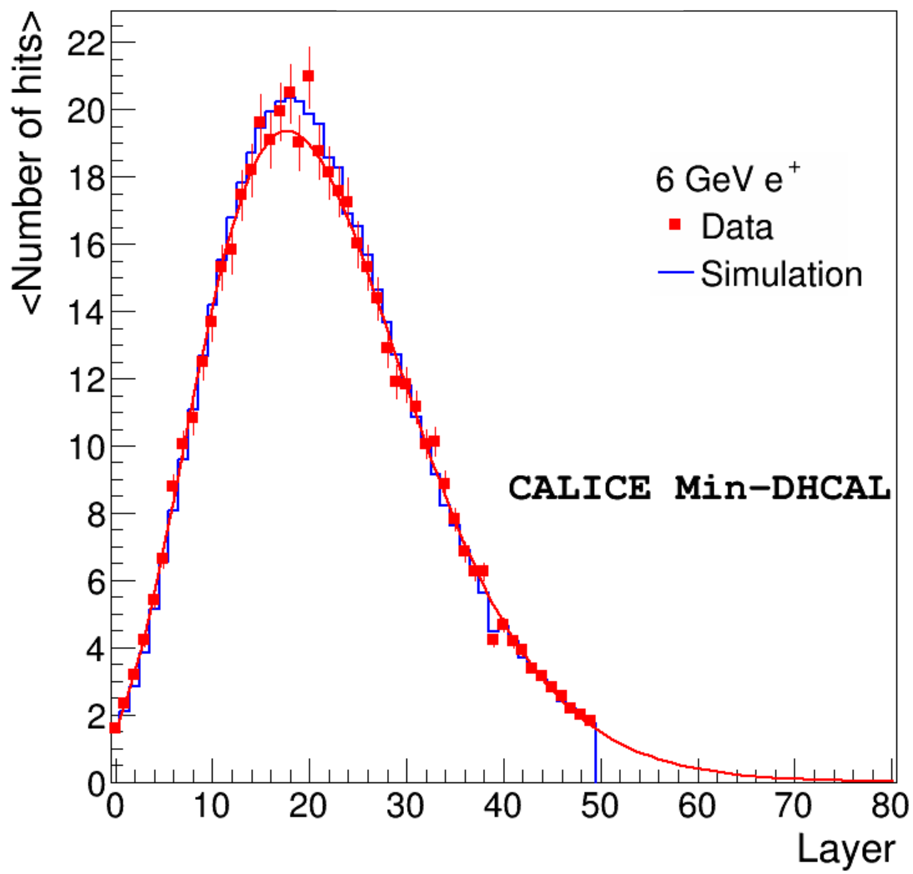
γ shape parameter

β scale parameter

µ location parameter

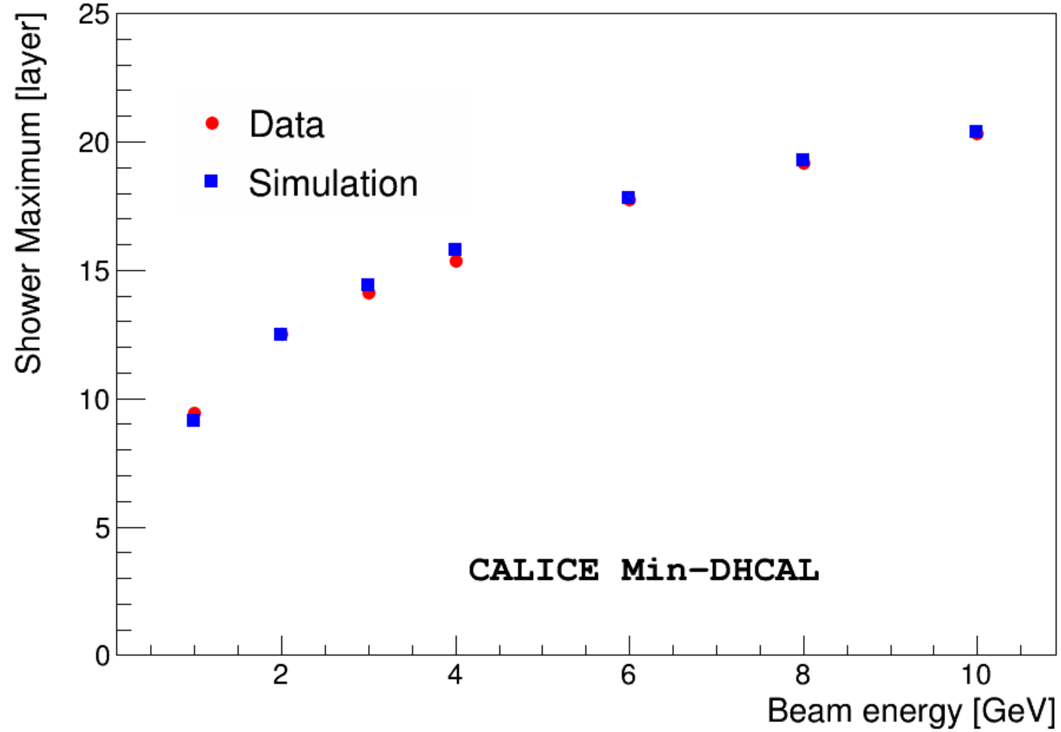
Mean response is corrected for leakage

6 GeV e^+



Longitudinal shower shape

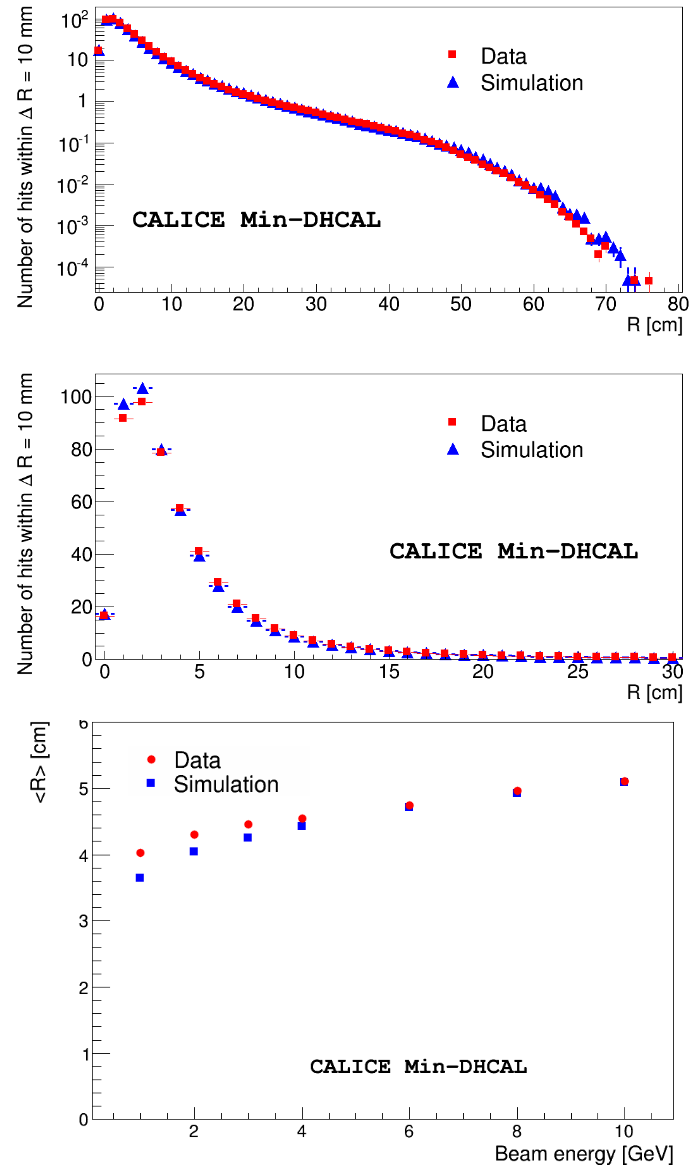
Excellent agreement for shower maximum



Transverse shower shape

- Hits in first 5 layer are fit to a straight line to determine shower axis
- Distance R is calculated with respect to shower axis
- Relatively good agreement observed for data and simulation

6 GeV e^+

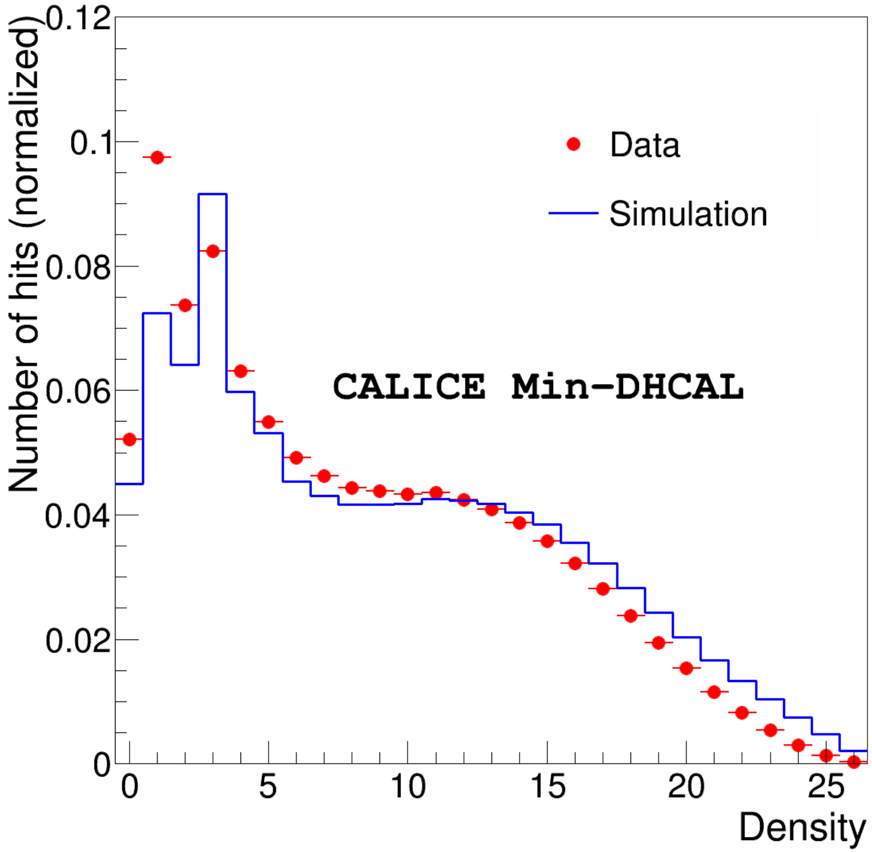


Hit density

Density is defined as number of neighbors in 3x3x3 cube around the hit (0 to 26)

Density information can be used to linearize the response

Some limitations in the simulation still persist.

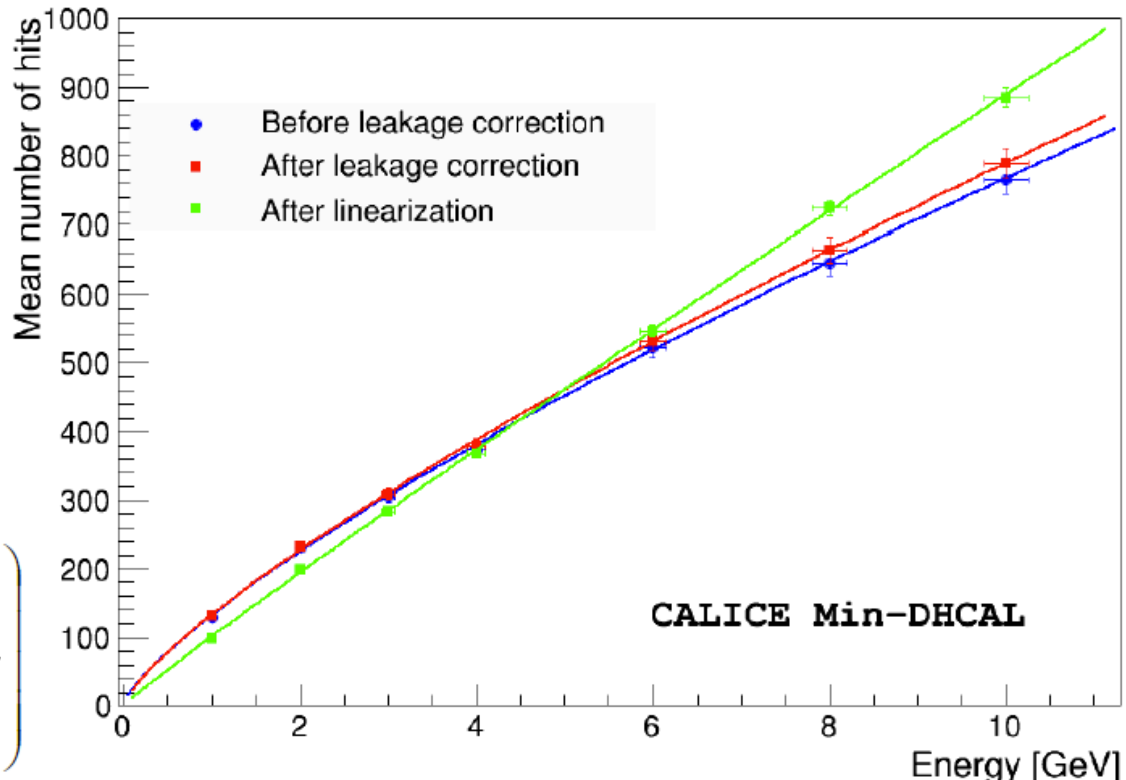


Linearization

Density information can be used to linearize response

Every density bin D_i is multiplied with a weight w_i found by minimizing the χ^2 function

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



Fit parameters

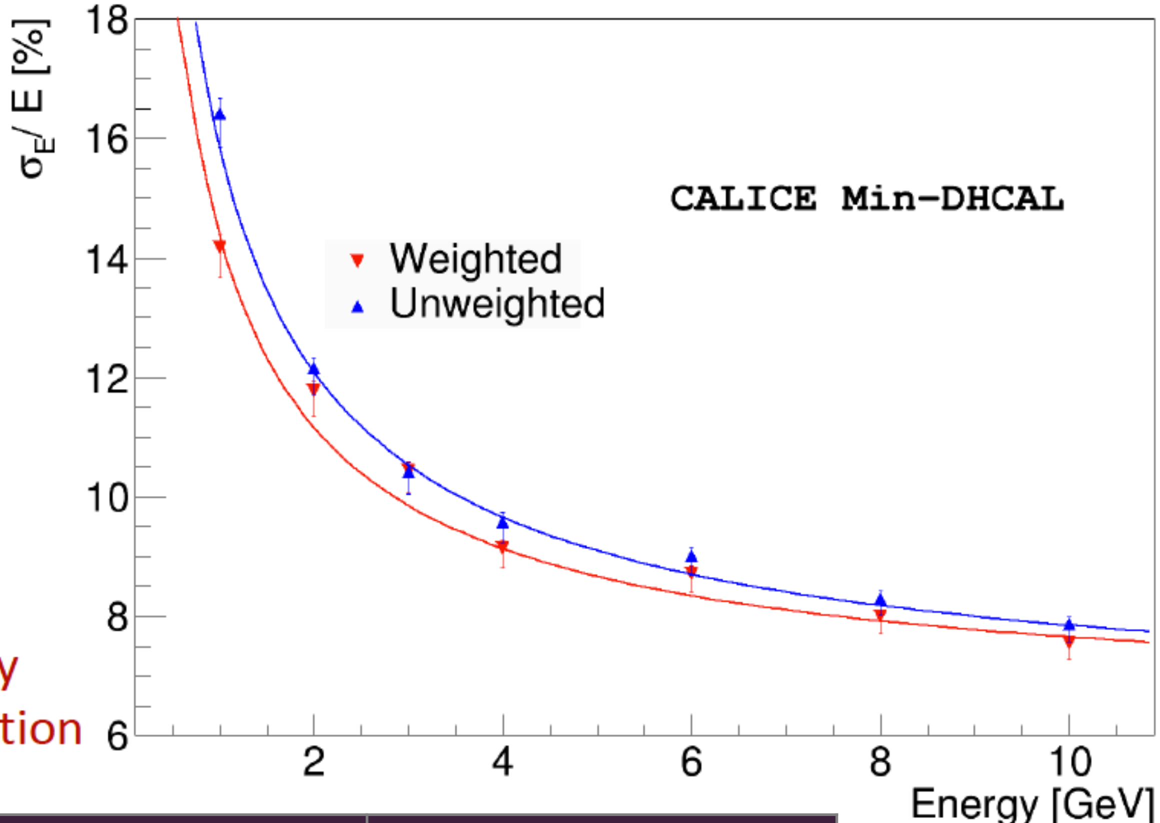
	Before Leakage Corr.	After Leakage Corr.	After Linearization
a	131.8 ± 3.5	132.1 ± 3.5	100.2 ± 2.2
m	0.76 ± 0.02	0.78 ± 0.02	0.95 ± 0.02

Linearization

Improves the resolution 2-10%

Weights can then be used to linearize electromagnetic subshowers in pion events

➡ 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

- Fine segmentation allows the study of electromagnetic interactions with unprecedented level of spatial detail
- Data taken with the DHCAL with minimal absorbers at Fermilab are compared to simulations
- Standard Geant4 electromagnetic simulation package fails to reproduce data well
- EMY option allows big improvement in the agreement
- Analysis of pion data is underway

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