DHCAL with Minimal Absorber: Measurements with Positrons

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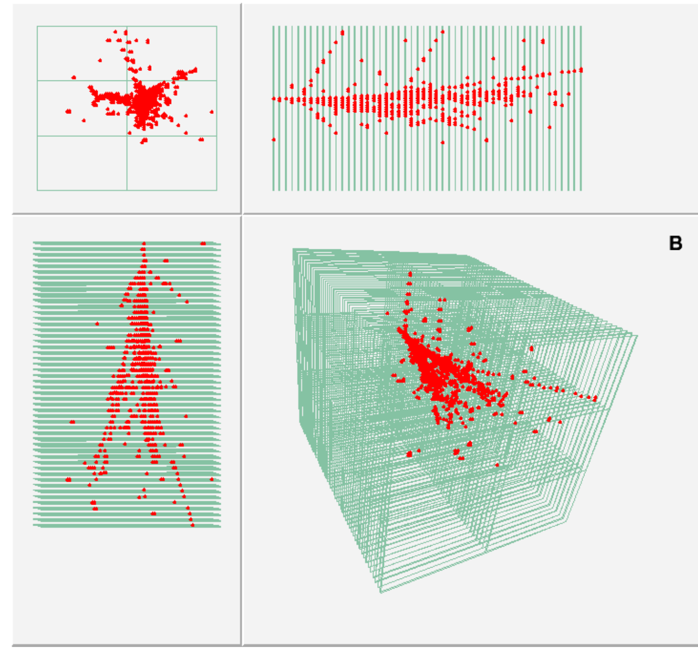
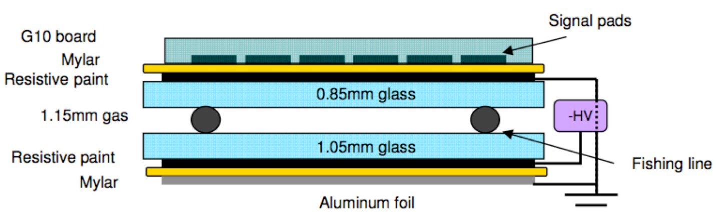
CALOR 2016
20.05.16

The DHCAL prototype



Description

54 active layers
Resistive Plate Chambers with 1 x 1 cm^2 pads
→ ~500,000 readout channels
Main stack and tail catcher (TCMT)



Electronic readout

1 – bit (digital)
Digitization embedded into calorimeter

Tests at FNAL

with Iron absorber in 2010 - 2011

Tests at CERN

with Tungsten absorber 2012

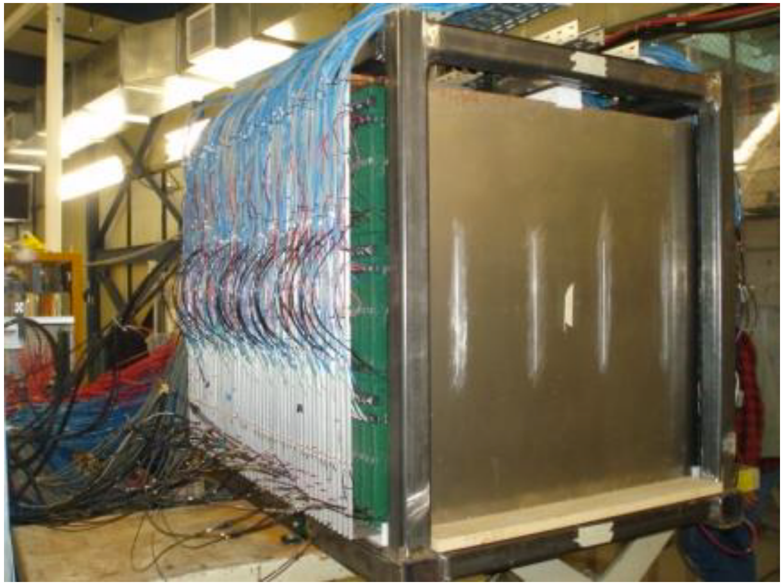
DHCAL with Minimal Absorber

- 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

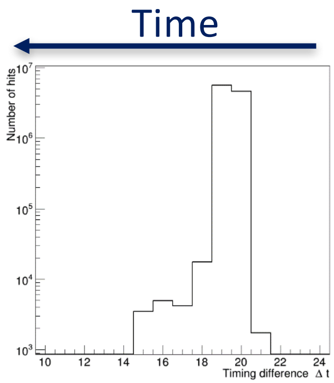
- Data collected at Fermilab Test Beam Facility
- Secondary beam (1-66 GeV/c) mixture of electrons, muons and pions
- Spill duration 4.0 seconds
- Cerenkov counters for PID
- Data collected in November 2011 has a momentum range of 1 - 10 GeV/c

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

Hit and event selection

Pads close to ground lead fire at a relatively high rate

→ Area of 2 x 5 cm^2 around these leads are ignored for both data and simulation (loss for simulation is negligible)



Data recorded in seven time bins (100 ns)

Most hits occur in time bin 19 and 20 (bin difference to trigger)

Remove events if most hits occur outside these two time bins to reduce noise contamination & multiple particles (<1%)

Sometimes the same pad fires several times in the same event

→ Duplicates are assumed to be fake hits and are removed (~0.1%)

Small fraction of dead DHCAL chips (<1%)

→ Corresponding areas are removed in simulation

To reduce number of events with multiple particle and upstream interactions

→ Exactly one cluster with at most four hits is required in the first layer (10-20%)

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 Cerenkov signal (not simulated)

Nearly all hits survive selection cuts

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:

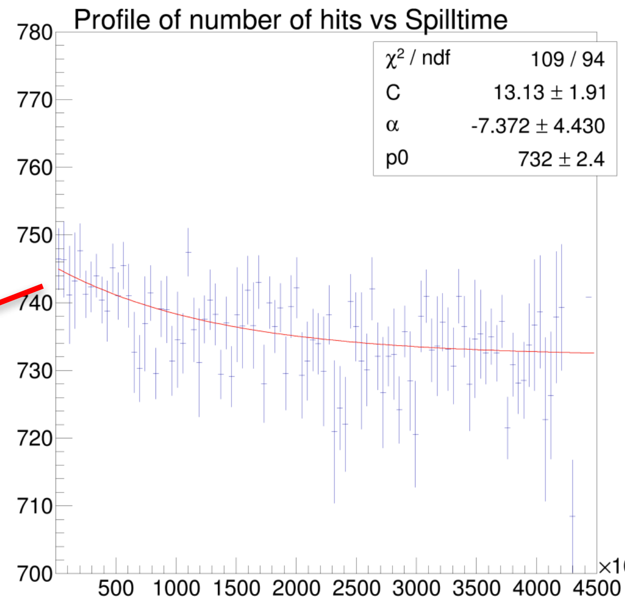
ε_0=0.917, μ_0=1.573

Systematic uncertainties

Sources of error

- Equalization uncertainties (1-4 %)
- Limited rate capability of RPC (only the first half second of each spill are taken for longitudinal shower profiles)

10 GeV e^+



RPC lose efficiency exponentially during spill (1-2 % effect)

Systematic uncertainties

Sources of error

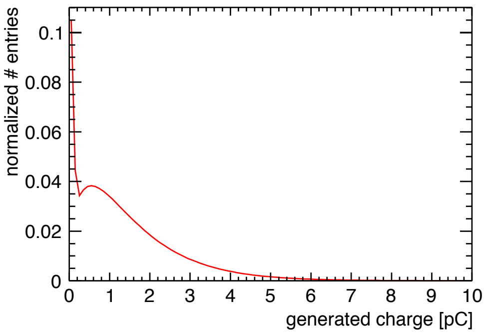
- Calibration uncertainties
- Limited rate capability of RPC (only the first half second of each spill are taken for longitudinal shower profiles)
- Contamination from muons and pions estimated to be less than 1%
- Contamination from accidental noise hit was estimated to 0.2 hits per event in the entire stack
  - Negligible, nevertheless noise events from accidental noise runs are added to simulation

Simulation

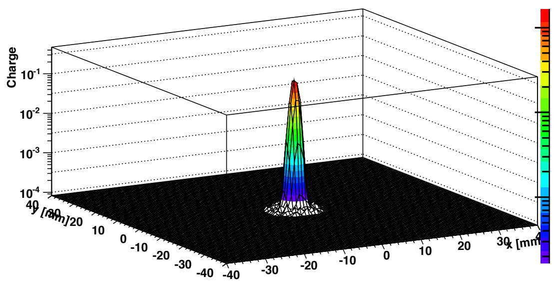
- GEANT4 based simulation gives raw points of ionisation
- Simulation of RPC charge avalanche & read-out by standalone program (RPC_sim)
  - Charge generated randomly following parametrization (taken from analog RPC tests)
  - Radial charge distribution modeled by double-Gaussian

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

  - Close-by avalanches suppression ($\boldsymbol{d_{cut}}$)
  - Threshold to convert charge to hits (**TT**)
- Tuning
  - σ_1, σ_2, R and TT tuned using muons
  - $\boldsymbol{d_{cut}}$ 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'
  - Main differences:
    - Reduced range size in computation of the step limit by ionization process and improved treatment of multiple scattering



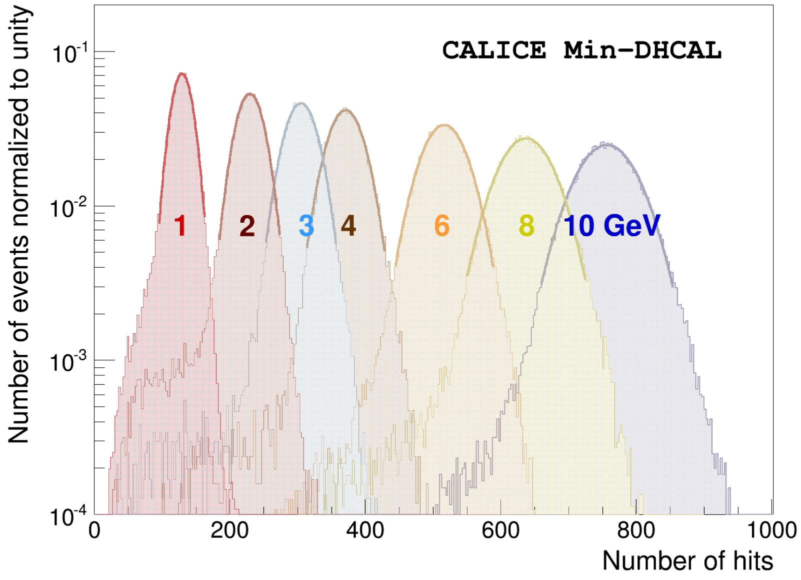
Charge distribution in x-y



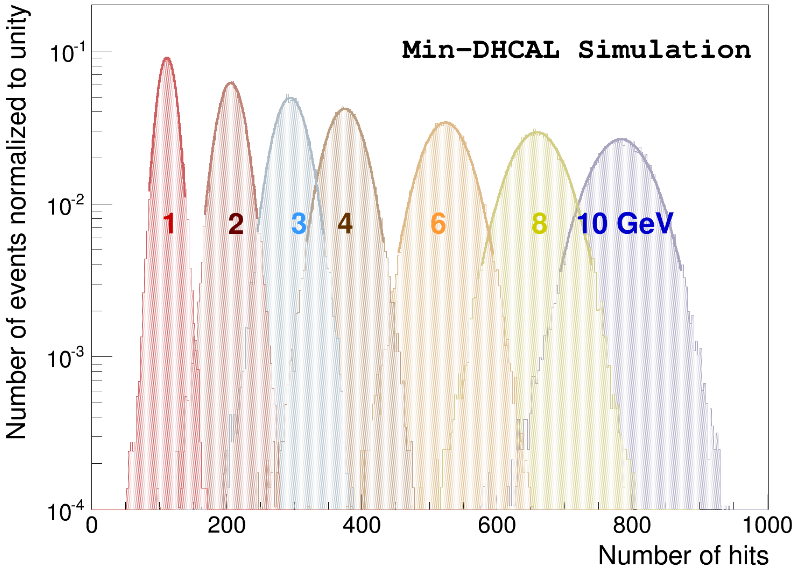
Response to positrons

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

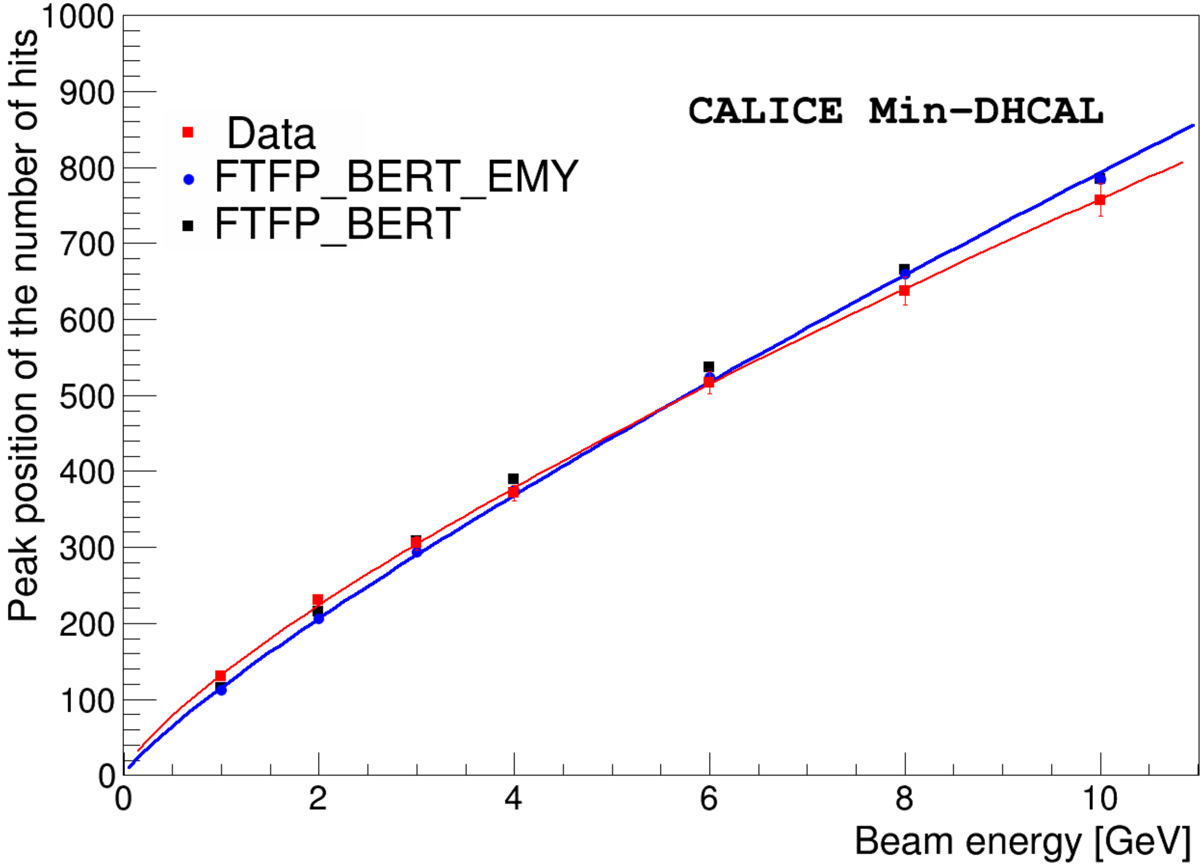
$$N = a * E^m$$

Data

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

FTFP_BERT_EMY

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



Simulation features less hits for low energies and more for higher energies than data

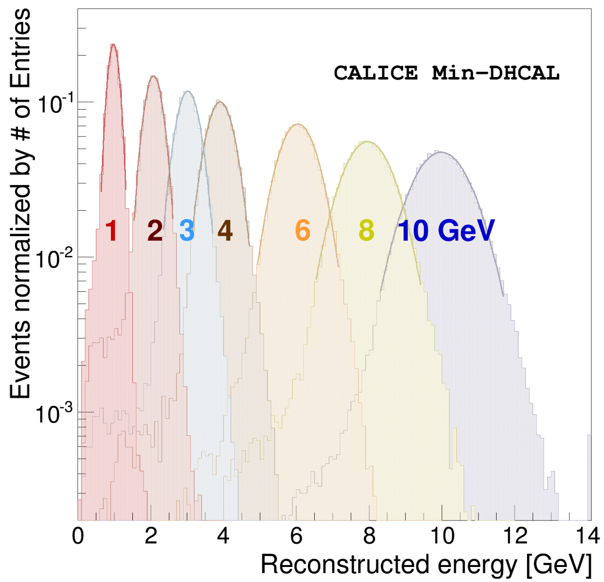
Saturation due to large pad size compared to the dense electromagnetic showers

Inverse fit function used to reconstruct energy

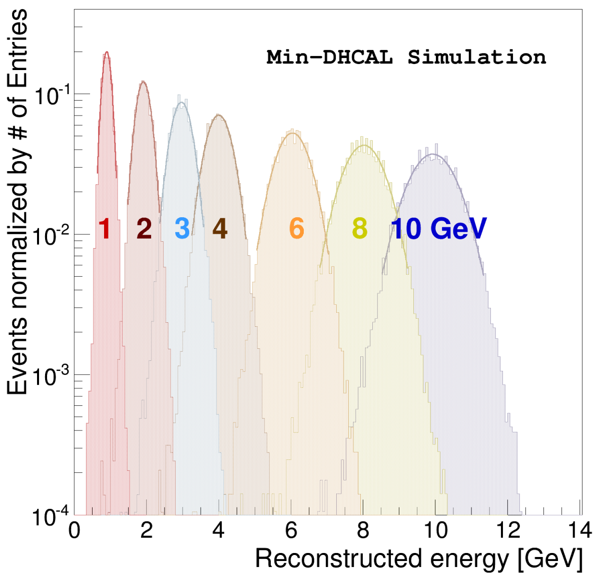
Reconstructed energy of positrons

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

Data

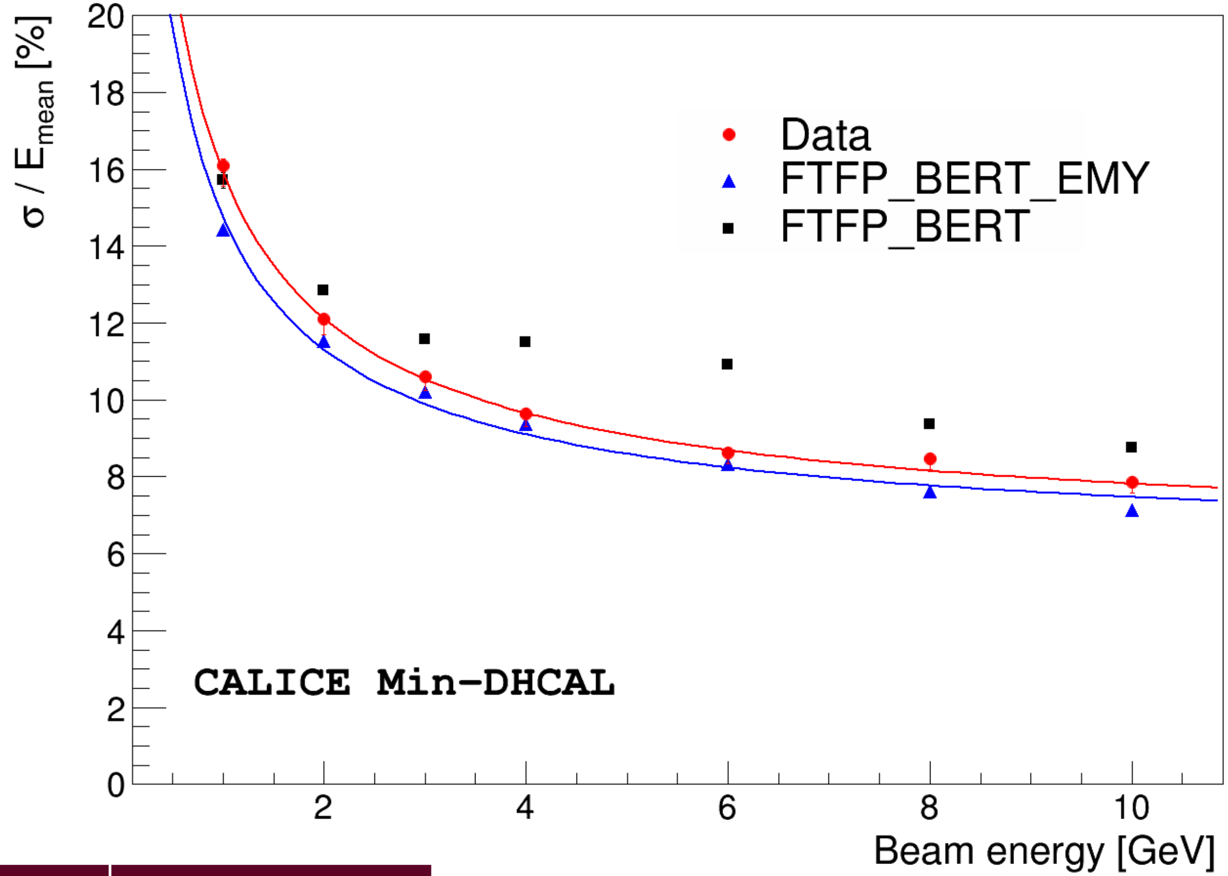


Simulation (FTFP_BERT_EMY)



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

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

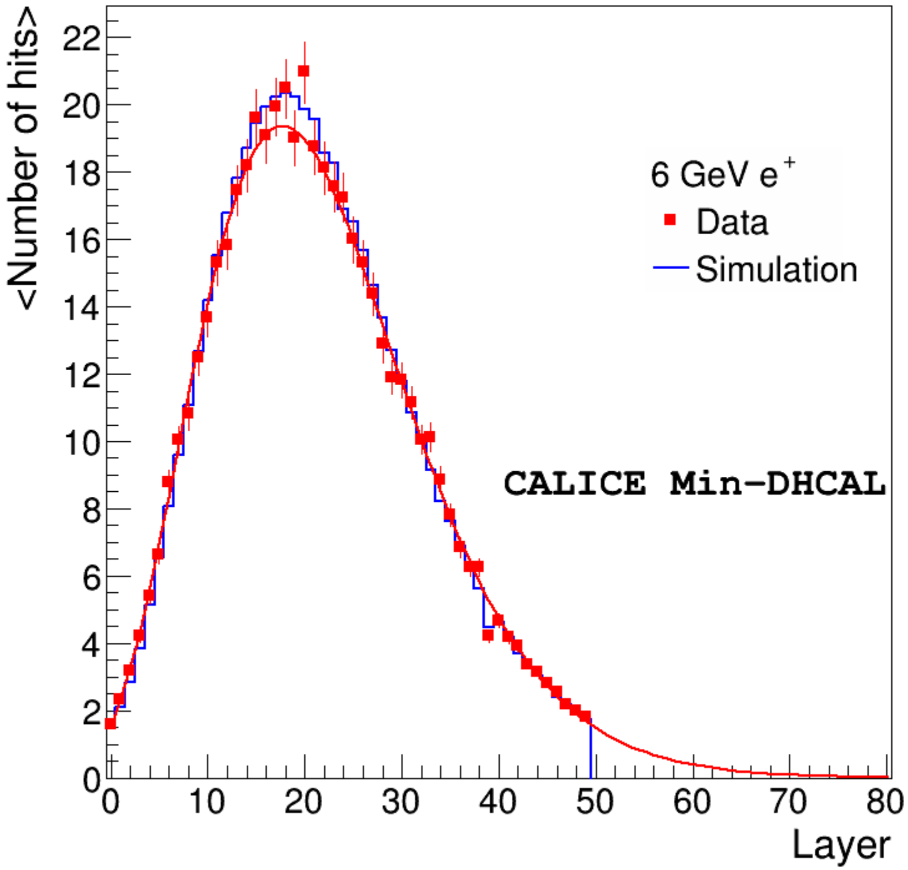
γ shape parameter

β scale parameter

μ location parameter

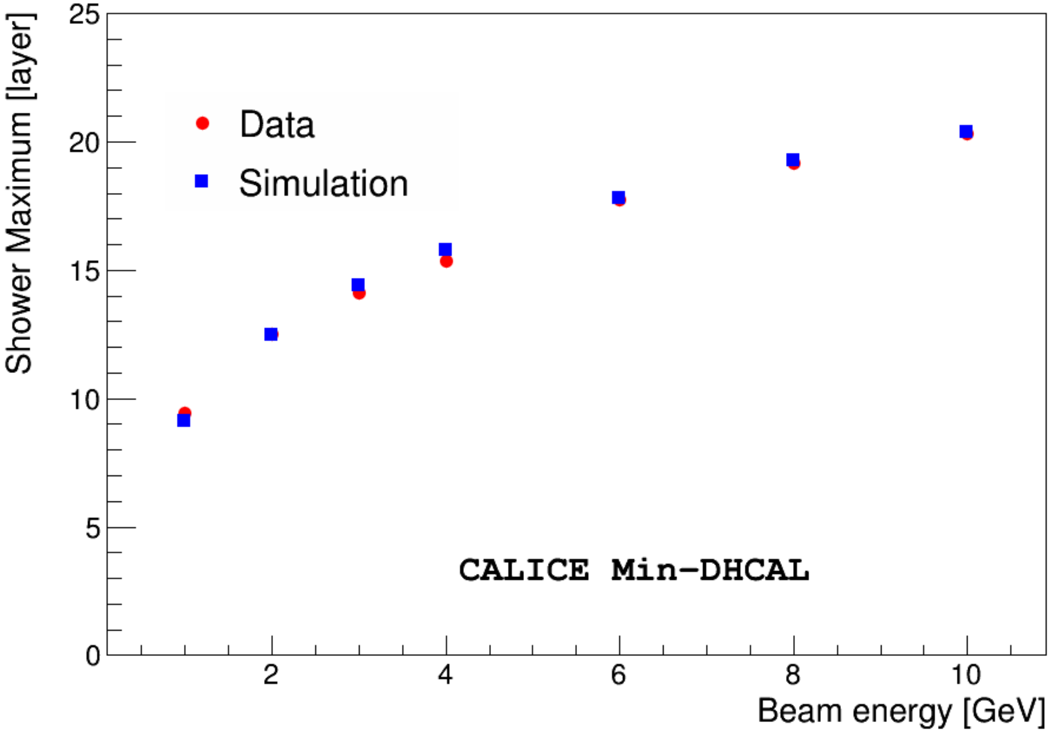
Mean response is corrected for leakage

6 GeV e^+



Longitudinal shower shape

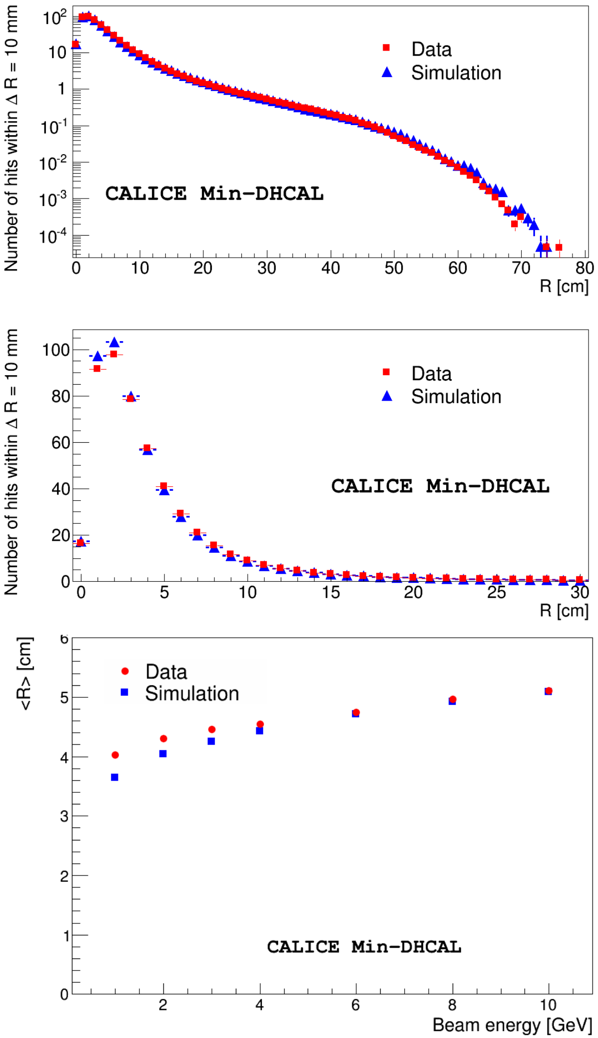
Excellent agreement for shower maximum



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
- Good agreement observed for data and simulation
- Good agreement also observed for mean distance

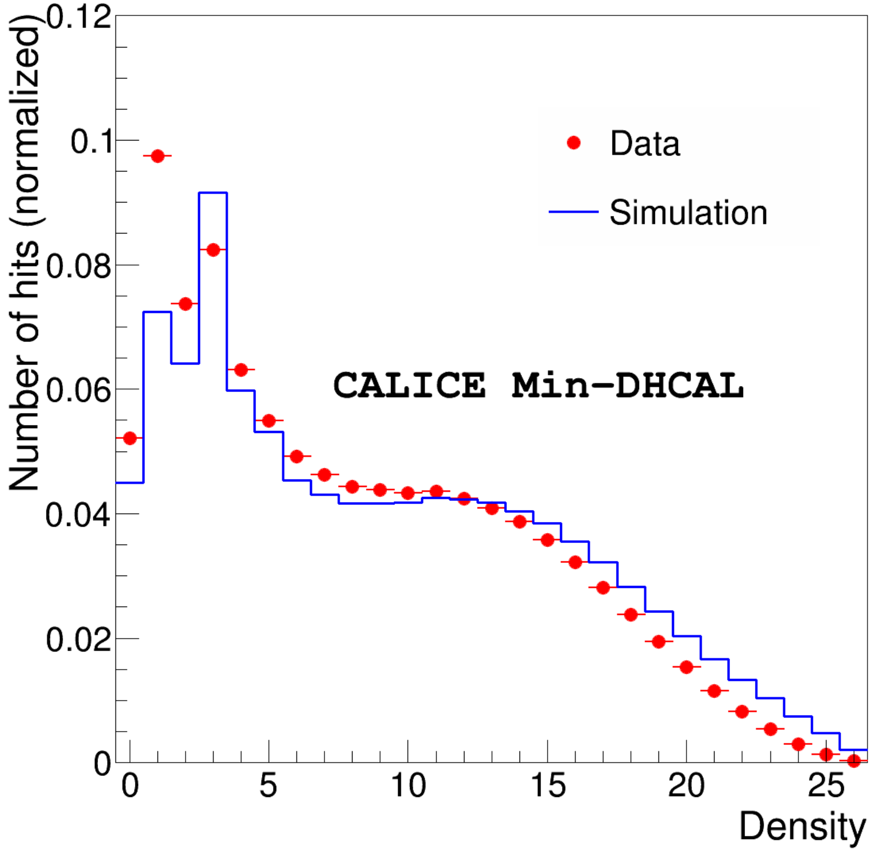
6 GeV e^+



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



Conclusion

- Data taken with the DHCAL with minimal absorber at Fermilab are compared to simulations
- Fine segmentation allows detailed study of electromagnetic showers
- Standard FTFP_BERT fails to reproduce data well
- EMY option allows big improvement in the agreement
- Results are published (B. Freund *et al* 2016 *JINST* **11** P05008 http://dx.doi.org/10.1088/1748-0221/11/05/P05008)
- Analysis of pion data is underway

Backup

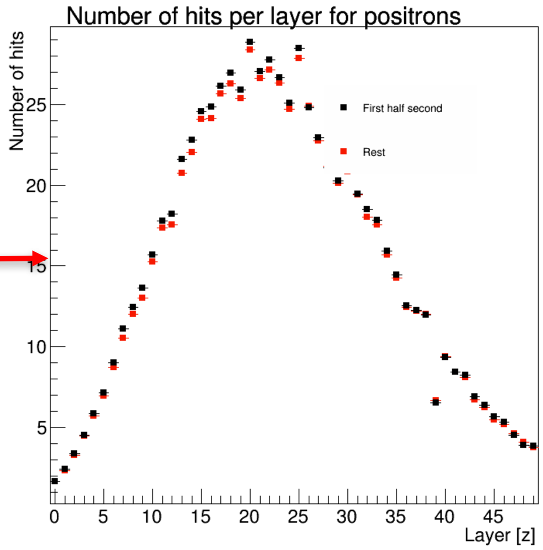
Systematic uncertainties

Sources of error

- Calibration uncertainties
- Limited rate capability of RPC (only the first half second of each spill are taken for longitudinal shower profiles)

Longitudinal shower profiles sensitive to this effect, applied only as positive systematic error

10 GeV e^+

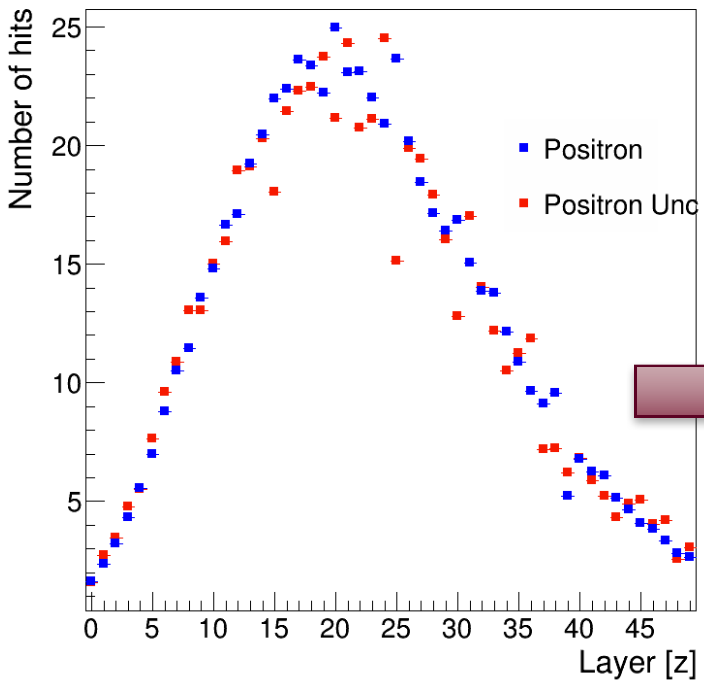


Systematic uncertainties

Sources of error

- Calibration uncertainties

8 GeV e^+



- Assign half the average difference between calibrated and uncalibrated data as systematic uncertainty

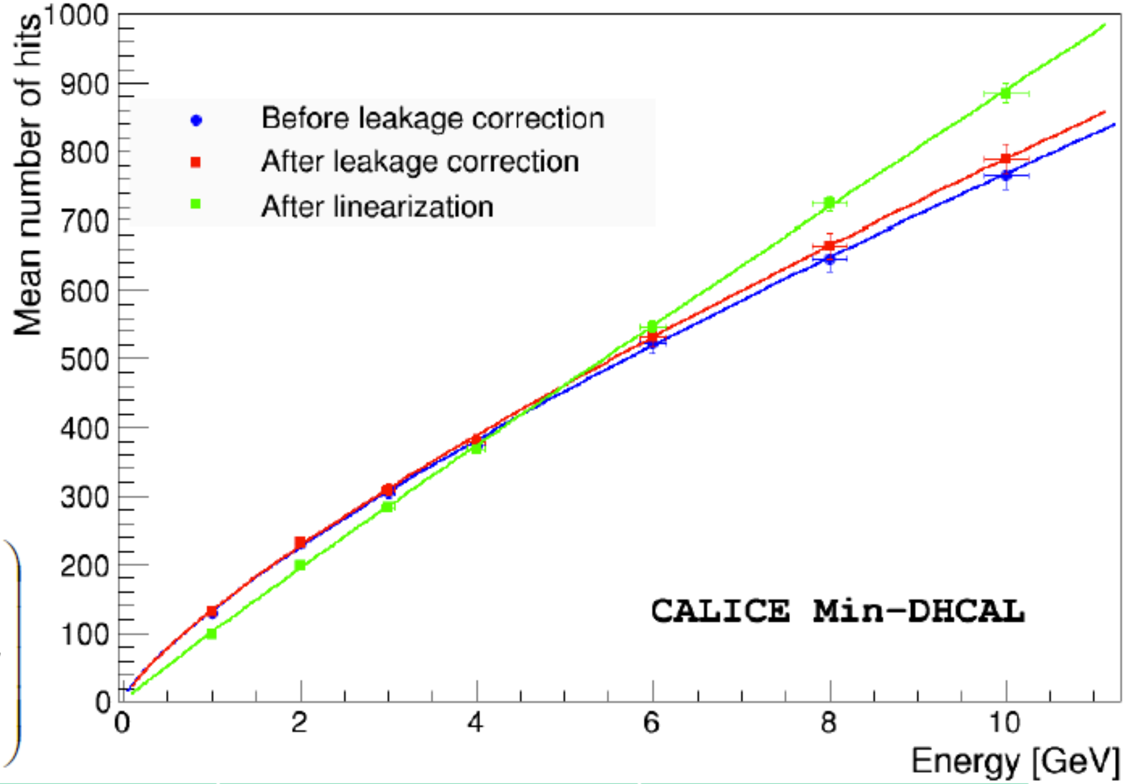
- Error applied symmetrically in general but only downwards for resolution

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	After leakage	Linearized
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

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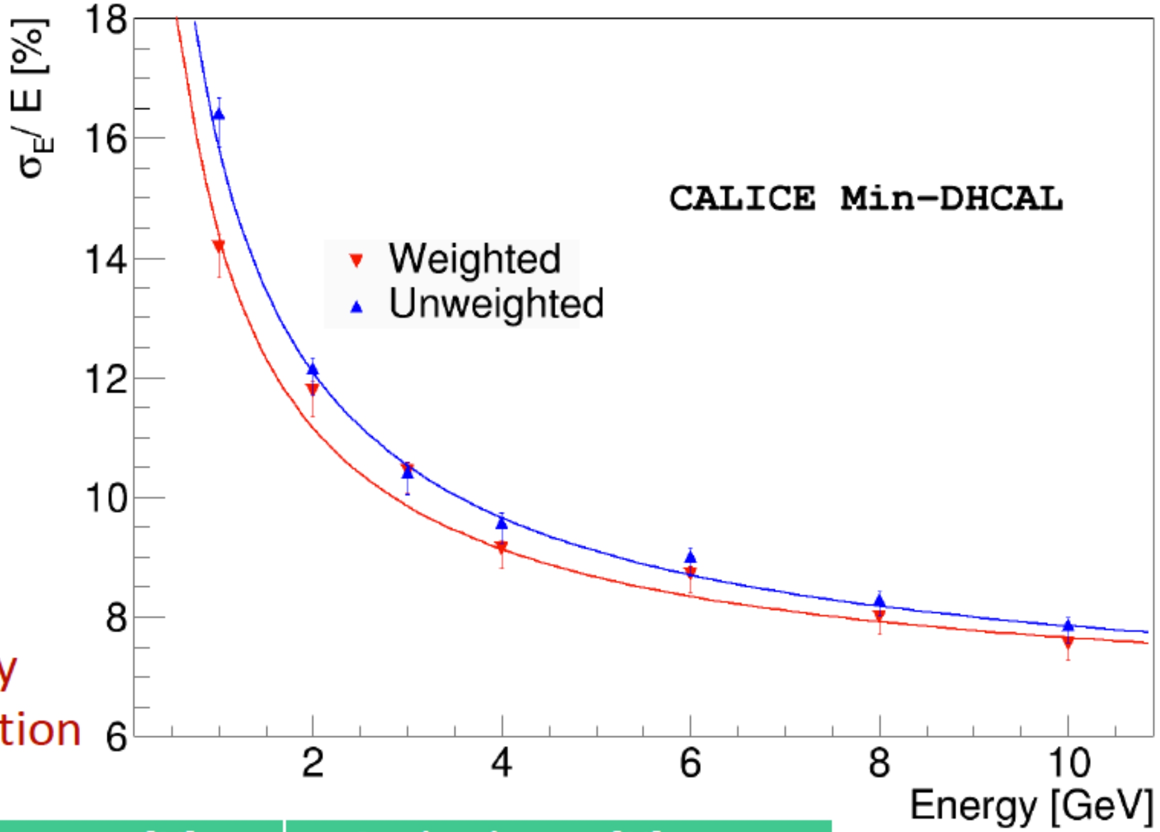
Linearization

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

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