AHCAL Energy Resolution

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Munich, Germany
for the CALICE Collaboration

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Outline

1. CALICE calorimeter prototypes

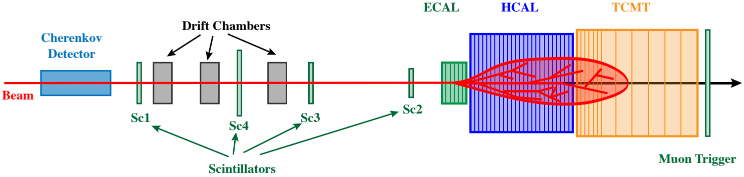
2. Calibration of the AHCAL

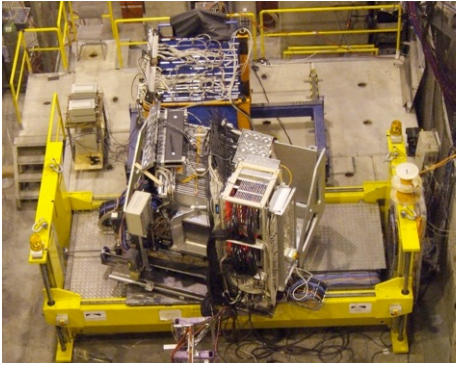
3. Electromagnetic Showers

4. Hadronic Showers - Software Compensation
   - Global Method
     - Cluster Energy Density Weighting
     - Neural Network
   - Local Method
     - Single Cell Energy Weighting

5. Conclusions

CALICE Calorimeter Prototype Program

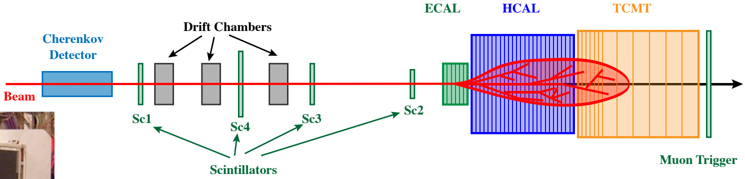


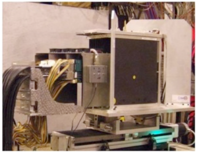


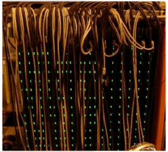
Extensive Test Beam Program

- DESY: 2006
  CERN: 2006, 2007
  FNAL: 2008, 2009
- Particle Types:
  $\mu, e^{\pm}, \pi^{\pm}, p$
- Particle Energies:
  1 GeV to 80 GeV

CALICE Calorimeter Prototype Program





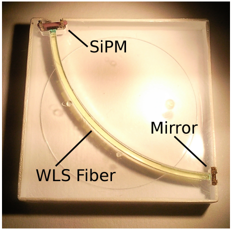


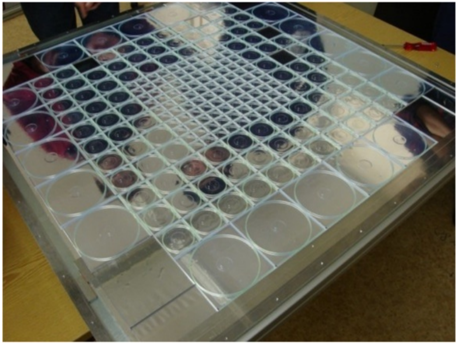
CERN 2007

- ECAL: Silicon-Tungsten Calorimeter
  30 Layers; 1×1 cm^2 readout pads, 1.4, 2.8, 4.2 cm thick absorber plates;
  30 X_0, $1\,\lambda_0$
- HCAL: Scintillator-Steel Calorimeter
  38 Layers; 1.8 cm thick absorber plates,
  $47\,\mathrm{X}_0\;4.5\,\lambda_0$
- TCMT: Scintillator-Steel Calorimeter
  8 layers: 2 cm thick absorber plates, 8 layers: 10 cm thick absorber plates,
  5×100 cm scintillator bars; 5.8 λ_0

CALICE Analog HCAL

- Iron absorber structure
- Active layers: scintillator tiles
  - Tile sizes: $3{\times}3\,\text{cm}^2$, $6{\times}6\,\text{cm}^2$, $12{\times}12\,\text{cm}^2$
  - Light collection via wavelength shifting fiber
  - Readout via SiPM

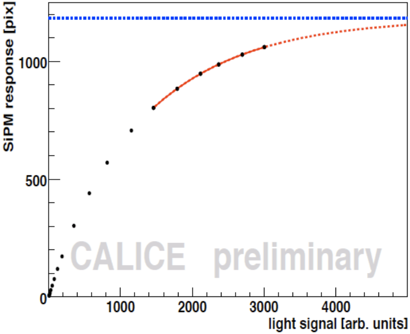




- High granularity in AHCAL center → in the shower core

Calibration of the AHCAL

- Signal Saturation
  - SiPM pixel number limited → only limited number of photons can be counted
- Auto-calibration of SiPM gain:
  - Low-intensity LED light coupled into each detector cell
  - Gain measurement
- MIP-Calibration with Muons
  - Complete detector illuminated with high energy muons
  - Equalization of cell response by matching the MPV position
- Temperature effect correction
  - SiPM gain
  - SiPM amplitude



⇒ All effects included into event reconstruction and Monte Carlo digitization.

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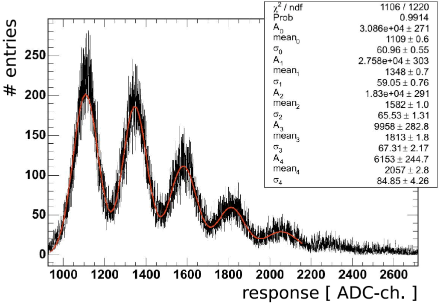

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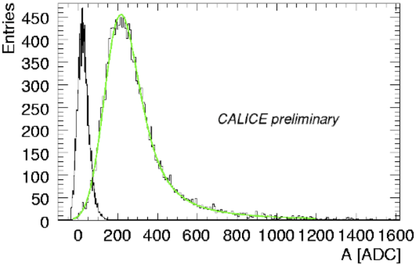

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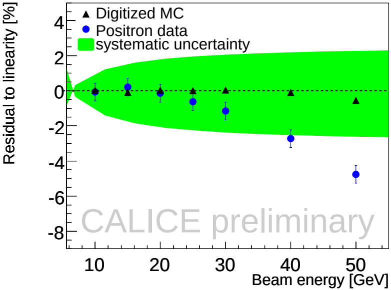
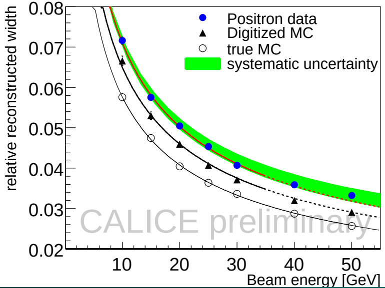
Electromagnetic Showers in the AHCAL





Positron test beam data from 10 GeV to 50 GeV

Comparison to Monte Carlo data

- Data taking without ECAL in front of HCAL
- Linearity of detector response of 1.5 % up to 30 GeV
- Non-Linearity at higher energies not yet reproduced in MC → Saturation handling
- Energy Resolution Data

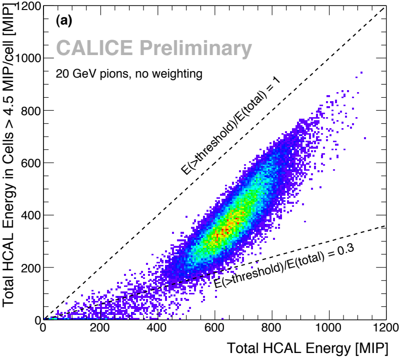
  Fit in the range from 10 GeV to 30 GeV with: $\frac{\sigma}{E[GeV]} = \frac{a}{\sqrt{E[GeV]}} \oplus b$

  a $=$ 22.5 $\pm$ 0.1(stat) $\pm$ 0.4(syst) %
  b $=$ 0.0 $\pm$ 0.1(stat) $\pm$ 0.1(syst) %

Hadronic Showers

Detector Response

- CALICE: non-compensating sampling calorimeter
- Calorimeter response to hadrons is smaller than to electrons of the same energy
- CALICE AHCAL $\frac{e}{\pi} \sim 1.2$



Software Compensation

$\Rightarrow$ Identification of electromagnetic and hadronic shower component fractions

$\Rightarrow$ Improve energy resolution

$\Rightarrow$ Improve linearity of detector response

Method:

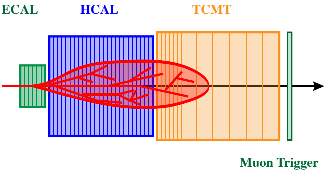
- Electromagnetic showers tend to be denser than purely hadronic ones
- Correlations between reconstructed energy and energy in high density shower regions

$\Rightarrow$ Test Local and Global Techniques

Cluster-Based Software Compensation

Two global methods based on cluster as a whole - no subcluster analysis
Look at global cluster properties

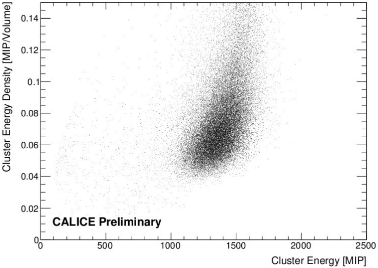
1. Shower reconstruction in AHCAL and TCMT
   Showers are required to start in the AHCAL
2. Determination of shower variables
   from test beam and simulated data
3. Analyses developed on Monte Carlo data
   FTF_BIC
   - Energy density weighting technique
   - Neural Network from TMVA
4. Application of weight or trained neural network
   on test beam data



Cluster Energy Density Weighting Technique

Hadronic Showers with high energy density ρ
$\Rightarrow$ Higher electromagnetic content
$\Rightarrow$ Higher reconstructed energy

$$E_{rec}[GeV] \quad = \quad E_{rec}[MIP] \cdot \omega(\rho, E)$$



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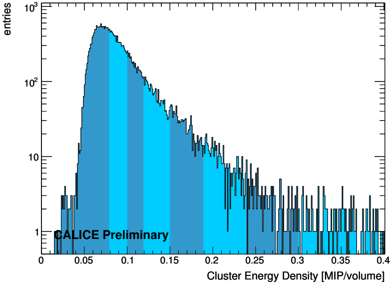
- Individual weights with minimization of function
  $\chi^2 = E_{rec} \cdot \omega - E_{beam}$



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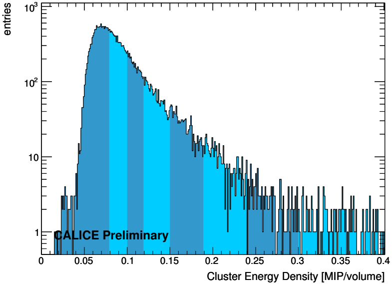
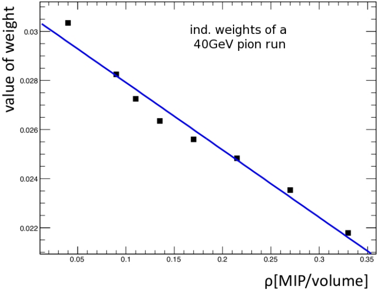
- Parameterization of the individual weights via $\omega = a(E) \cdot \rho + b(E)$





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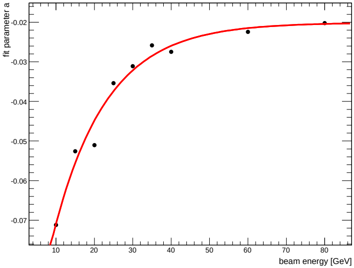
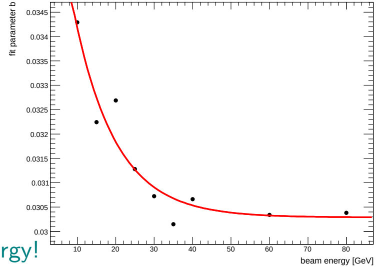
- Individual weights with minimization of function $\chi^2 = E_{rec} \cdot \omega - E_{beam}$
- Parameterization of the individual weights via $\omega = a(E) \cdot \rho + b(E)$
- Parameterization of energy dependence with function for $a(E)$ und $b(E)$, $E = E_{rec}$

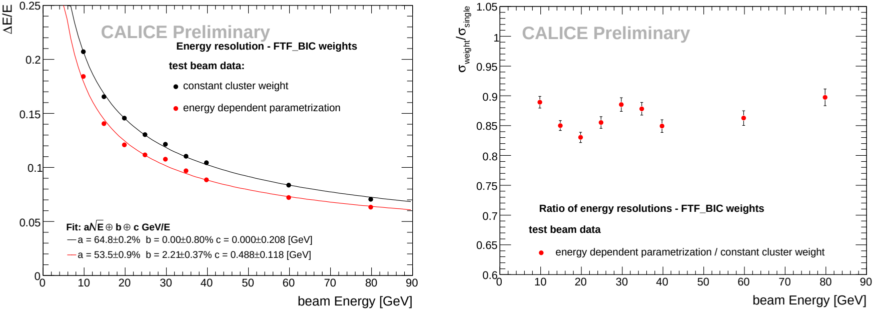




⇒ Determination of weights independent of beam energy!

Cluster Energy Density Weighting - Results

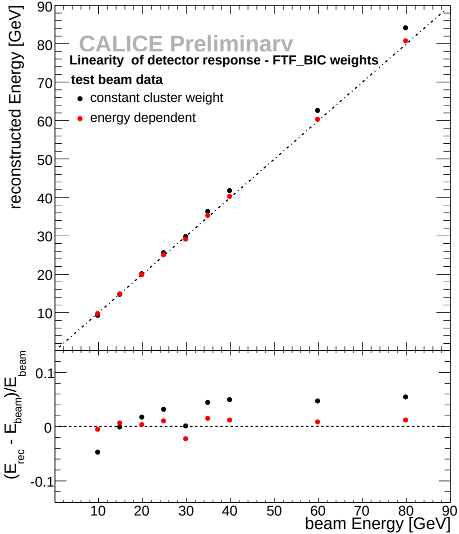
Energy Resolution:



- Weight parametrization from Monte Carlo derived
- Weights applied on test beam data
- Energy resolution improvement: → approx. 15 %

Cluster Energy Density Weighting - Results

Linearity of detector response:



- Significant improvement of linearity of detector response
  → better than 4 %
- Test beam data: π^+ and π^- runs. Elimination of proton content of π^+ runs should improve the linearity even further.

Neural Network of TMVA

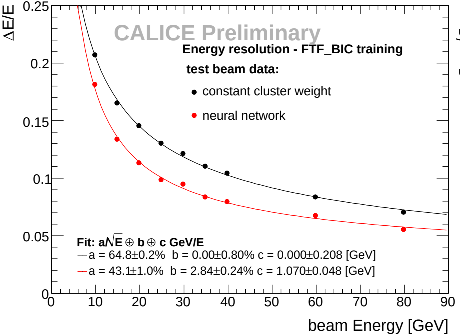
TMVA - Toolkit for Multivariate Data Analysis

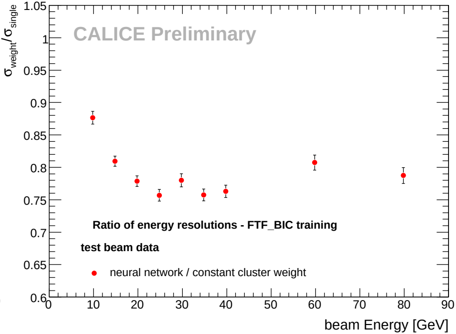
- Training with Monte Carlo events with continuous energy of hadronic model FTF_BIC
- 6 input variables
  - Reconstructed energy
  - Cluster volume
  - Cluster length
  - Mean cluster width
  - Cluster energy in last 5 AHCAL layers
  - Cluster energy in Tail Catcher
- Target variable: beam energy
- Output value: reconstructed energy

⇒ Trained Neural Network applied on test beam data

Neural Network Technique - Results

Energy Resolution:

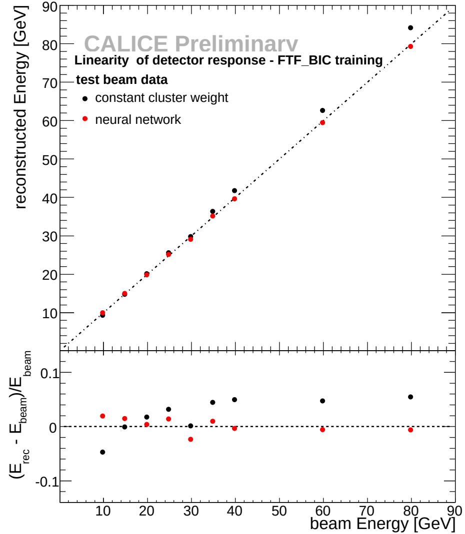




- Energy resolution improvement: → approx. 23 %

Neural Network Technique - Results

Linearity:



- Significant improvement of linearity of detector response
  → better than 3 %

Single Cell Weighting - Technique

Simple reconstruction without weighting

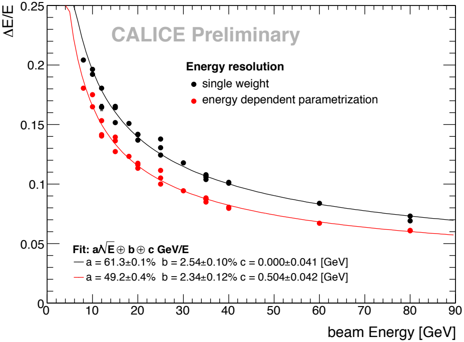
- One calibration factor (MIP to GeV) per subdetector (ECAL, AHCAL, TCMT)
- Noise rejection applied

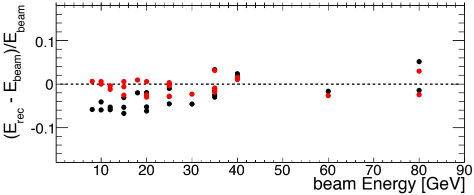
Weight calorimeter cells according to their energy content ⇒ Apply higher weights to cells with low energy density

- Weights are energy dependent
- No knowledge of beam energy needed to apply weights

Results:

- Energy resolution improvement: → approx. 18 %
- Linearity of detector response better than 4 %



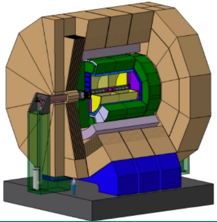


Conclusions

- Calibration of analog AHCAL with SiPM redout
- Energy Reconstruction of electromagnetic data
  ⇒Test beam and simulated data in the AHCAL
- Energy Reconstruction of hadron data
  ⇒High granularity can be used for software compensation
  Local and global software compensation methods
  - Cluster energy density weighting technique:
    ⇒ 15 % energy resolution improvement for AHCAL and TCMT
  - Neural Network:
    ⇒ 23 % energy resolution improvement for AHCAL and TCMT
  - Tile energy density weighting technique:
    ⇒ 18 % energy resolution improvement for the complete CALICE setup
- Optimum maybe in between both methods

Outlook

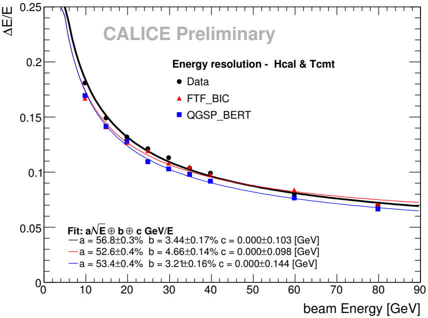
- Application of method on full ILD simulations
  and ILD reconstruction software PandoraPFA

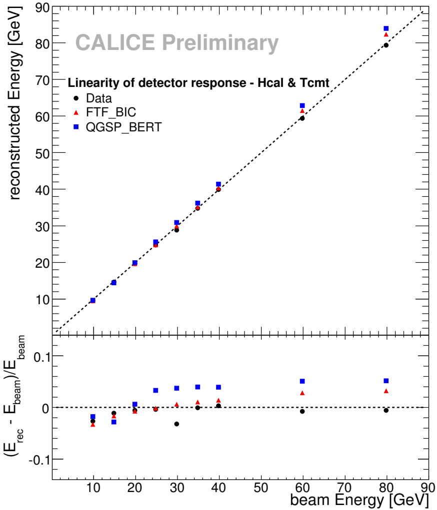


Backup slides

Energy Resolution and Linearity for all energy in AHCAL and TCMT

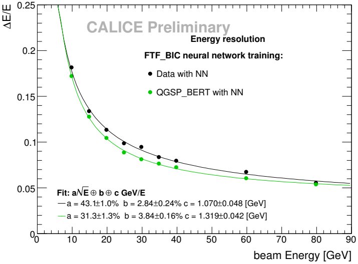
- No clustering
- No software compensation
- MIP to GeV factor 0.028

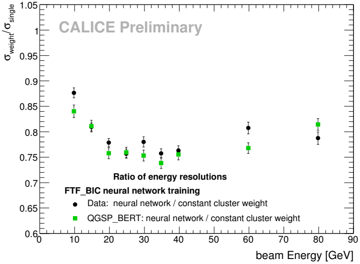


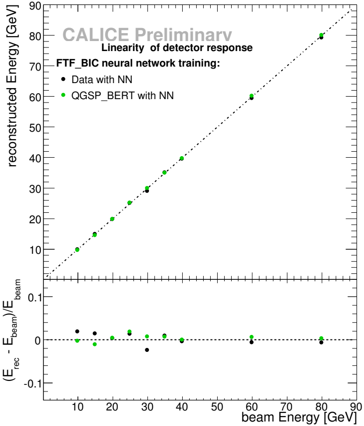


Energy Resolution and Linearity for test beam data and QGSP_BERT Monte Carlo with Neural Network

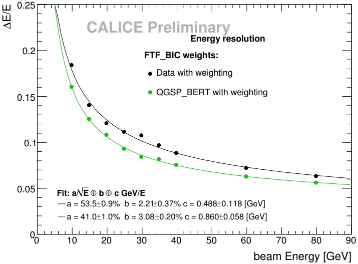
- Neural Network trained with FTF_BIC simulated data

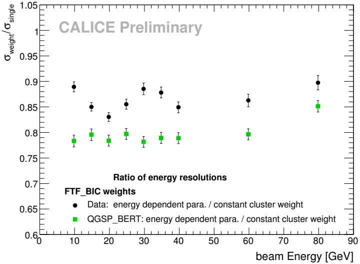




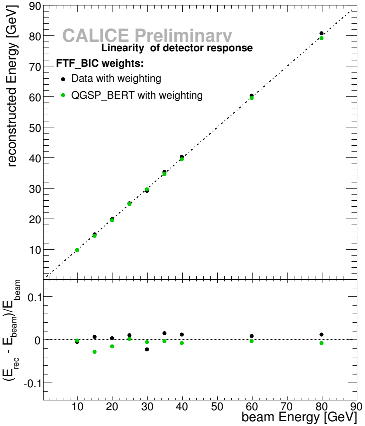


Energy Resolution and Linearity for test beam data and QGSP_BERT Monte Carlo with Cluster Energy Density Weighting



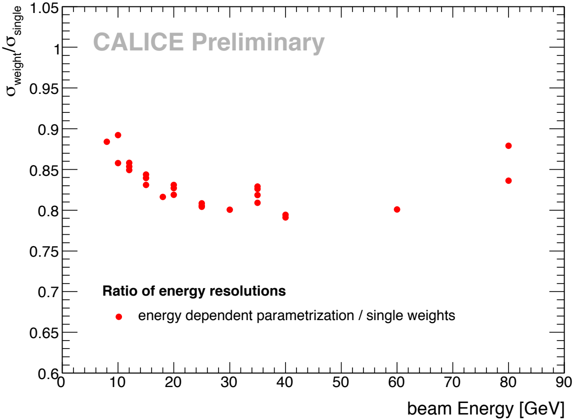


Weights extracted from FTF_BIC simulated data



Energy Resolution Improvement for complete CALICE setup

- Single Tile Energy Weighting Technique
- Weights extracted from data
- No clustering



Monte Carlo Energy Correction