Hadronic shower properties in highly granular calorimeters with different absorbers

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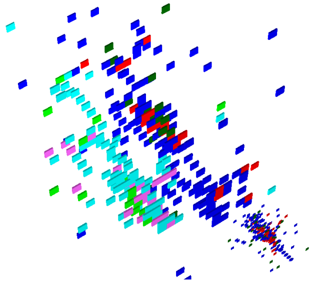
1. CALICE calorimeters for PFA
2. Hadron energy reconstruction with software compensation
3. Spatial shower development
4. Comparison of shower profiles

CALICE calorimeters for PFA

CALICE collaboration activities

https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome

- Goal: test of particle-flow reconstruction
- R&D of highly granular electromagnetic and hadron calorimeters for HEP experiments
  - different readout technologies: analog, semi-digital, digital
  - different active materials: silicon, scintillator-SiPM, RPC
  - different absorbers: stainless steel, tungsten
- Validation of performance with test beams:
  - particle separation
  - energy resolution
- Study of reconstruction schemas, shower development and shower substructure:
  - software compensation
  - spatial development
  - time structure
- Validation of Geant4 simulations



Overlaid test beam hadron showers

- 10 GeV and 30 GeV
- 15 cm between shower axes
- setup: SiW ECAL+Sc-Fe AHCAL

In this talk: focus on scintillator-SiPM hadron calorimeter with different absorbers

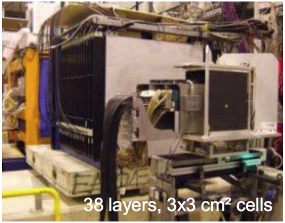
CALICE scintillator-SiPM hadron calorimeters in test beams

CALICE prototypes

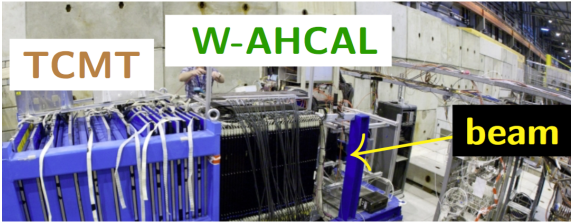
Sc-Fe(W) AHCAL	**Scintillator tiles with SiPMs 3×3 (6×6, 12×12) $\times0.5$ cm^3 (90×90 cm^2)**	**$\sim$5.2(4.9) λ_I 38 layers**
SiW ECAL	Silicon pads 1×1 cm^2 (18×18 cm^2)	$\sim$1 λ_I, 30 layers
Sc-Fe TCMT	Scintillator strips with SiPMs (5×100 cm^2)	$\sim$5.2 λ_I, 16 layers

Beam tests: ECAL(optional) + AHCAL + TCMT(optional); μ, e and hadrons of 1—300 GeV

SiW ECAL + **Fe-AHCAL** + Sc-Fe TCMT



W-AHCAL + Sc-Fe TCMT



	Total depth	Depth per layer	
Fe-AHCAL	$5.2\lambda_I$	$0.137\lambda_I$ ($1.24X_0$)	noncompensating $e/\pi \sim$1.2
W-AHCAL	$4.9\lambda_I$	$0.129\lambda_I$ ($2.80X_0$)	compensating $e/\pi \sim$1

Hadron energy reconstruction and software compensation

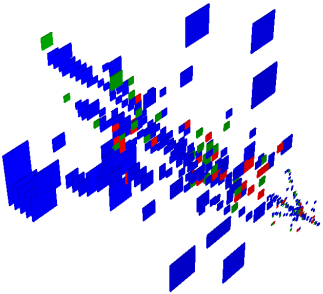
Standard reconstructed

$$E_{\rm std}^{\rm event} = \sum_{s=1}^{M} C_s \cdot \sum_{i=1}^{N_s} e_{is}$$

Mean and σ are extracted from the two-step Gaussian fit within ± 2 RMS

- cell response equalized with MIPs; N_s - number of cells in s-th subdetector above 0.5 MIP (hits)
- e_{is} - amplitude in MIP of i-th hit in s-th subdetector (ECAL, AHCAL, TCMT) with hadronic scale calibration factors C_s in [GeV/MIP]

Software compensation (SC) reconstruction

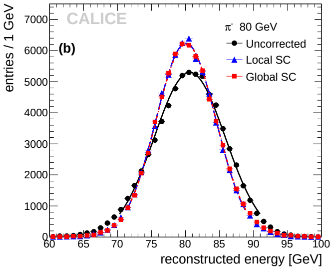


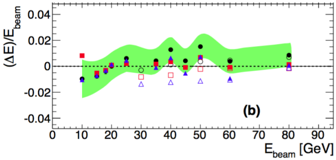
- Motivation: improve energy resolution by taking into account fluctuations of em fraction
- Correction is applied on an event-by-event basis
- Two software compensation techniques developed:
  - hit energy weighting (Local SC)
  - event energy weighting (Global SC)
  - test on standalone calorimeter (shower start in AHCAL)
  - improvement of resolution in Fe-AHCAL up to 25%
  - more details in *JINST 7 P09017 (2012)* and backup
- Improvement of pion energy resolution with local SC in combined setup up to $\sim 42\%/\sqrt{E/\mathrm{GeV}}$ (*CAN-058*)
- Implementation of SC in ILD simulations: improvement of jet energy resolution (*Eur.Phys.J. C77 (2017) 10, 698*)

Pion energy distributions and linearity of response

Test beam data: pions 10–80 GeV, SC applied to AHCAL hits
Selections: shower start (first inelastic interaction) in the first layers of AHCAL, mip in ECAL

Fe-AHCAL ($e/\pi \sim 1.2$) with tail catcher





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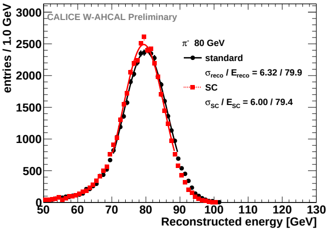
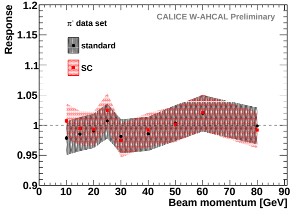
W-AHCAL ($e/\pi \sim 1$) no tail catcher





CAN-062

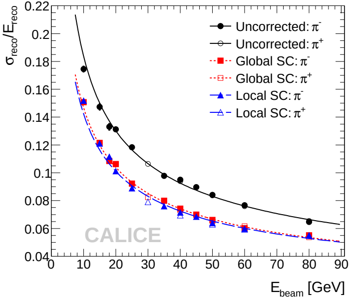
Linearity of response within $\pm 2\%$ with and without software compensation

Energy resolution for single hadrons

Noncompensating (Fe-AHCAL) versus compensating (W-AHCAL) calorimeter

- Test beam data: pions 10–80 GeV
- Energy weighting technique (global software compensation)
- Shower start at the beginning of the AHCAL to minimise leakage
- Hit spectra for software compensation from AHCAL only

Fe-AHCAL ($e/\pi \sim 1.2$) with tail catcher



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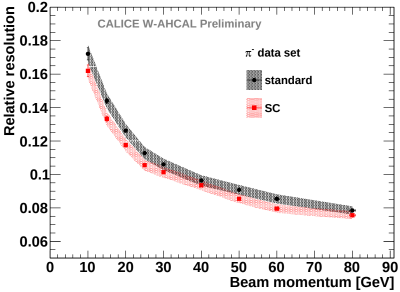
W-AHCAL ($e/\pi \sim 1$) no tail catcher



CAN-062

More significant improvement in noncompensating calorimeter than in compensating ⇒
⇒ SC corrects presumably for the fluctuations of EM fraction in hadronic showers

Hadronic shower characteristics

Longitudinal centre of gravity

$$Z0 = \frac{\sum_{i=1}^{N_{\rm sh}} e_i \cdot (z_i - z_{\rm start})}{\sum_{i=1}^{N_{\rm sh}} e_i}$$

z_i – longitudinal coordinate of hit e_i

$z_{\rm start}$ – longitudinal position of shower start

important for estimation of leakage

Shower radius

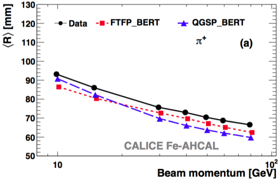
$R = \frac{\sum_{i=1}^{N_{\rm sh}} e_i \cdot r_i}{\sum_{i=1}^{N_{\rm sh}} e_i}$, $N_{\rm sh}$ – number of hits in shower

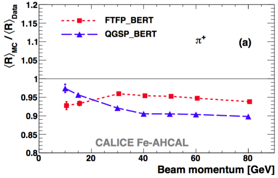
Radial distance of hit e_i from shower axis (x_0, y_0):

$r_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}$

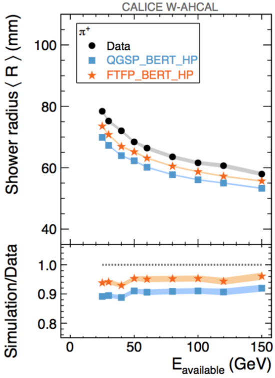
important for particle separation in PFA

Mean shower radius in Fe-AHCAL





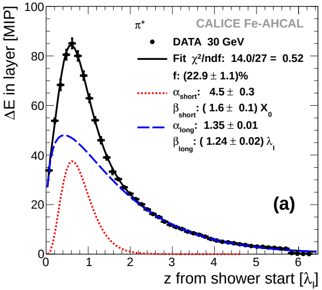
Mean shower radius in W-AHCAL



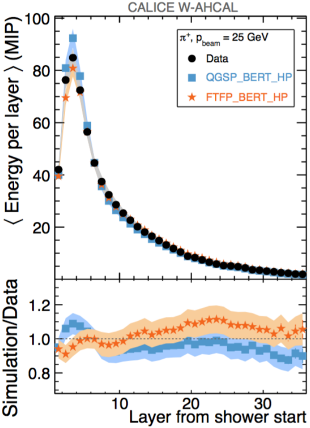
G4 v9.6 underestimates mean shower radius, better predictions from FTFP_BERT phys. list

Longitudinal profiles from shower start

Fe-AHCAL *JINST 11 (2016) P06013*



W-AHCAL *JINST 10 P12006 (2015)*



Parametrisation (decomposition) of profiles

- sum of two Gamma-distributions
- to disentangle EM and hadronic components

Preliminary conclusions based on profile parametrisation for different absorbers

- In higher-Z material (W): lower EM fraction, higher (lower) multiplicity for EM (hadronic) component
- Very similar longitudinal tail slopes for both absorbers

Simulations overestimate electromagnetic fraction in hadronic showers.
Discrepancy between data and simulations increase with increasing particle energy

Summary

Beam tests of CALICE highly granular calorimeter prototypes

- Scintillator-SiPM hadron calorimeter assembled from about 8000 tiles were constructed and exposed to test beams in 2006-2011 with steel and tungsten absorbers.
- **Software compensation techniques help to decrease the contribution of stochastic term to resolution of noncompensating Sc-Fe AHCAL from $\frac{\sim 58\%}{\sqrt{E/\mathrm{GeV}}}$ to $\frac{\sim 45\%}{\sqrt{E/\mathrm{GeV}}}$,** improvement is much smaller for compensating Sc-W AHCAL as expected.

Shower properties and validation of simulations

- Simulations predict narrower hadronic showers than observed in data.
- FTFP_BERT physics list from Geant4 9.6 gives the best predictions (tests of Geant4 10.x ongoing).
- Good predictions of resolution, longitudinal development and substructure below 20 GeV.
- **Discrepancies between data and simulations increase with energy.**
- **Deposition in the shower core (em fraction) is overestimated by simulations.**

Next generation prototypes

- CALICE AHCAL technological prototype for the ILD in beam tests since 2017
- New features compared to the AHCAL physics prototype discussed above:
  - tiles with dimple and direct readout by SiPM
  - embedded electronics with power pulsing mode and time measurement

Backup slides

Energy reconstruction with software compensation

Software compensation techniques for analogue readout [*JINST 7 P09017 (2012)*]

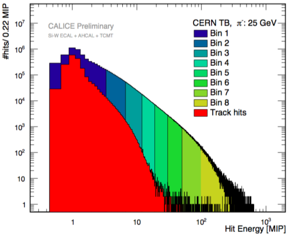
- Correction is applied on event-by-event basis
- Calibration factor C_{trk} for track hits and hadron scale calibration C_s for shower cluster

Hit weighting technique (local compensation)

$$E^{\mathrm{event}}_{\mathrm{SClocal}} = C_{\mathrm{trk}} \cdot \sum_{t=1}^{N_{\mathrm{trk}}} e_t + \sum_{s=1}^{M} C_s \cdot \sum_{j}^{K_s} w_{js}(E^{\mathrm{event}}_{\mathrm{std}}) \cdot \sum_{i}^{N_{js}} e_{ijs}$$

- Hit spectrum in s-th subdetector is divided in K_s bins.
- Hit amplitudes e_{ijs} in bin j in subdetector s are weighted with w_{js} $(1 \le i \le N_{js}$, typical $K_s = 8)$.
- Hit weights are energy dependent, parametrisation is performed using test beam data.

Hit energies in SiW ECAL



Event energy weighting technique (global compensation)

$$E^{\mathrm{event}}_{\mathrm{SCglobal}} = C_{\mathrm{trk}} \cdot \sum_{t=1}^{N_{\mathrm{trk}}} e_t + E^{\mathrm{event}}_{\mathrm{cor}} \cdot P(a_G, E^{\mathrm{event}}_{\mathrm{cor}})$$

$$E^{\mathrm{event}}_{\mathrm{cor}} = \sum_{s=1}^{M} C_s \cdot W^{\mathrm{event}}_s \cdot \sum_{i}^{N_s} e_{is}$$

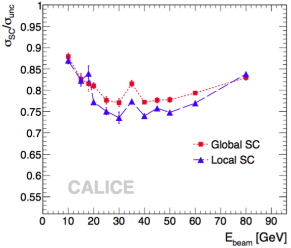
- Weights W^{event}_s are calculated from hit energy spectrum shape.
- Coefficients a_G of second-order polynomial P are estimated from test beam data.

Software compensation in AHCAL: improvement of resolution

Noncompensating (Fe-AHCAL) versus compensating (W-AHCAL) calorimeter

- Same active layers (scintillator tiles with SiPM readout) and different absorbers
- Energy weighting technique (global compensation)
- Shower start at the beginning of the AHCAL to minimise leakage
- Hit spectra for software compensation from AHCAL only
- Energy from tail catcher added to the energy sum for Fe-AHCAL

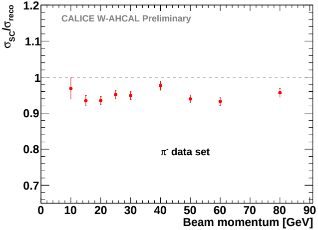
Fe-AHCAL ($e/\pi \sim 1.2$) with tail catcher



Improvement of resolution $\sim$**10–25%**

JINST 7 P09017 (2012)

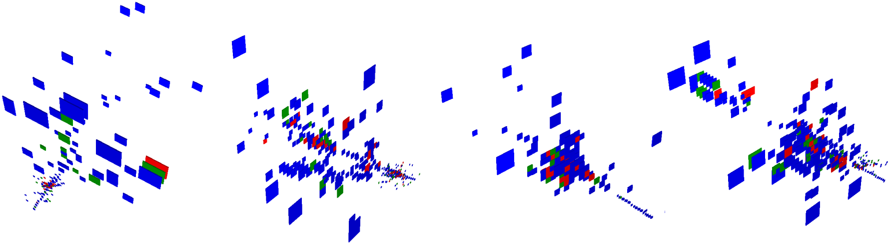
W-AHCAL ($e/\pi \sim 1$) no tail catcher



Improvement of resolution $\sim$**5%**

CAN-062

Diversity of hadron-induced showers: test beam data in SiW ECAL + Fe-AHCAL

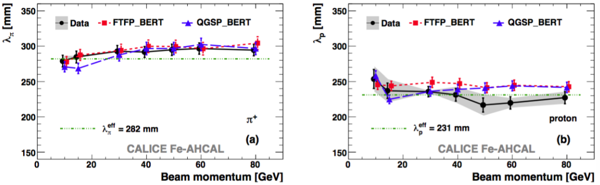


10 GeV | 30 GeV | 10 GeV | 30 GeV

Estimation of interaction length for pions and protons

based on identification of shower start position.

Good agreement with Geant4 predictions and estimations of effective values using material properties.



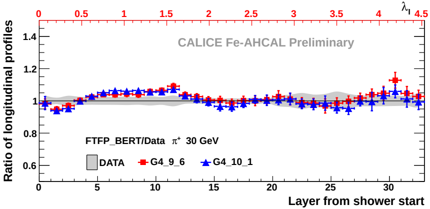
JINST 10 P04014 (2015)

Hadronic shower development: profiles

CALICE Fe-AHCAL

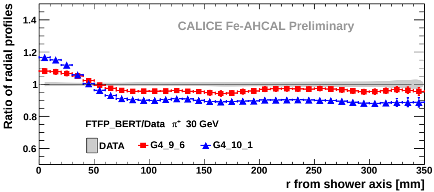
- Fine longitudinal segmentation: $\sim$0.14 λ_I per layer
- Fine transverse granularity: 3×3 cm^2 tiles in the central part
- Combined test beam setup: SiW ECAL + **Fe-AHCAL** + TCMT (MIP in ECAL)
- Longitudinal profile from the identified first inelastic interaction
- Radial profile with respect to shower axis (incoming track or cluster centre of gravity)
- Comparison of data with Geant4 versions 9.6 and 10.1 *(CAN-040b)*

Longitudinal profile (30 GeV pion)



Discrepancy within 5%,
increases up to 10% at 80 GeV.

Radial profile (30 GeV pion)



Discrepancy within 10(18)% in the core,
increases up to 20(25)% at 80 GeV.