Hadron energy resolution of the CALICE AHCAL and software compensation approaches

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for the CALICE Collaboration

Outline

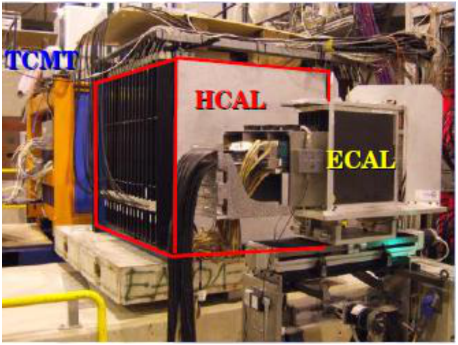
1. CALICE test beam setup and event selection
2. Intrinsic AHCAL energy resolution for single hadrons
3. Software compensation approach and its application
   - Local technique
   - Global technique
4. Comparison of software compensation techniques
   - Linearity and relative resolution
   - Improvement of resolution
5. Summary

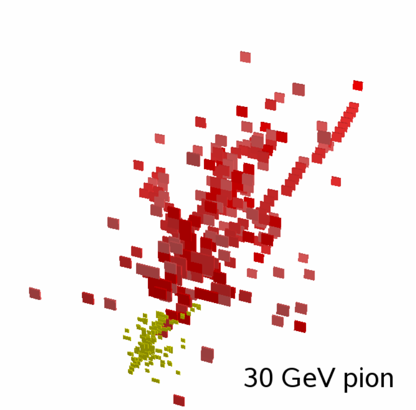
CALICE test beam setup

Test beam at CERN SPS π^- **and** π^+ **10-80 GeV**

ECAL: Si-W, $\sim 0.8\lambda_I$ (30 layers), 18x18cm^2, 1x1cm^2 cells

HCAL: Sc-Fe, $\sim 4.5\lambda_I$ (38 layers), $\sim$1x1m^2, 7608 tiles: 3x3, 6x6, 12x12cm^2





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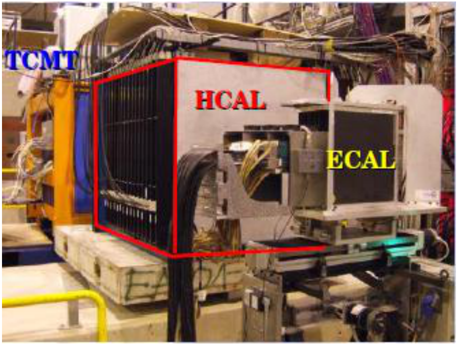
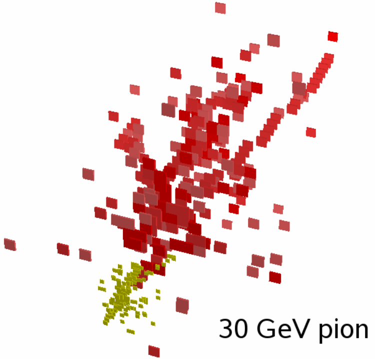
TCMT: Sc-Fe, $\sim 5\lambda_I$ (16 layers), 90x90cm^2, strips

Helpers: drift chambers, Čerenkov and veto





Advantages of high granularity

Hadronic shower structure

Identification of a layer of the first inelastic interaction

- longitudinal shower profiles w/o convolution with the distribution of the first interaction point

Investigation of a shower substructure on event-by-event basis

- track segments inside hadronic shower
- electromagnetic clusters
- energy density spectra

Particle Flow Analysis

Possibility to disentangle showers induced by charged and neutral particles

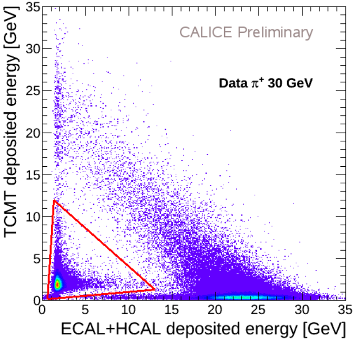
Software compensation

Improvement of the energy resolution by means of software compensation techniques based on the analysis of the detailed energy density spectra

Event selection and data samples

Sample cleaning

- Muons: initial admixture 4-30%
  in the cleaned sample <0.5%
- Multiparticle: 1-2%
- Electrons from π^-: Čerenkov counter
- Protons from π^+: Čerenkov counter



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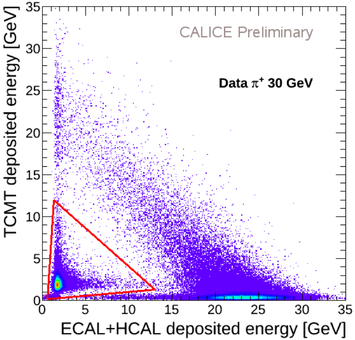

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Training and test subsamples

Samples from different runs of the same beam energy and particle charge are merged
Merged samples are split into two subsamples (even and odd event numbers)
Statistically independent samples are used to test software compensation approaches

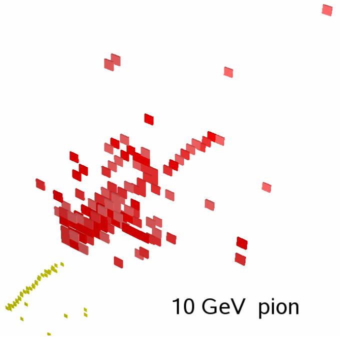
- set of even subsamples is used to adjust software compensation factors
- adjusted compensation factors are applied to the set of odd subsamples

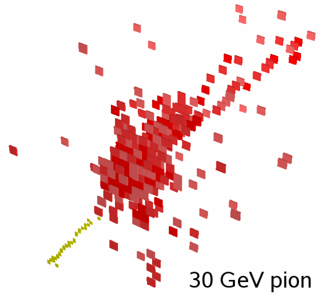
Event selection for software compensation study

Hadronic shower start in the first 5 layers of the HCAL

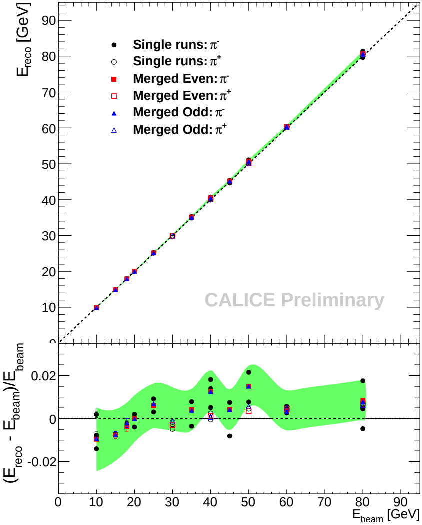
Additional constraint to select showers mostly contained in the HCAL

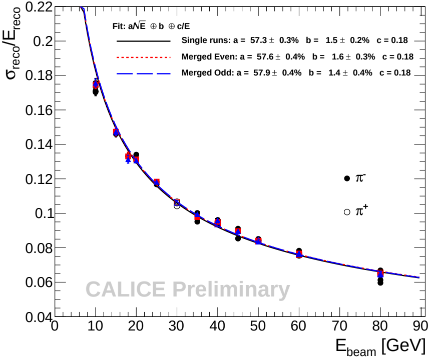
- track in ECAL
- detailed energy density spectrum in the fine-granular HCAL
- minimum longitudinal leakage into TCMT (around 6% at 80 GeV)
- $\sim \frac{1}{4}$ of pion events remains





Intrinsic AHCAL resolution for single hadrons





Systematic uncertainties

$\delta E_{\mathrm{reco}} = 0.9\%$ ($\oplus \delta E_{\mathrm{beam}}$ for residuals)

Fit results coincide within errors

Stochastic term: $\sim \frac{57.5\%}{\sqrt{E/\mathrm{GeV}}}$

Constant term: $\sim 1.5\%$

Noise fixed at 0.18 GeV for full setup

Similar resolution for π^- and π^+

Software compensation

Non-compensating calorimeters

- Hadronic shower comprises electromagnetic and hadronic component
- A part of the hadronic component (neutrons, etc.) remains undetectable
- Electromagnetic fraction exhibits significant event-by-event fluctuations

⇒ Different response to electrons and hadrons of the same energy
⇒ Hadron energy resolution is deteriorated w.r.t. electromagnetic one

Approaches to improve resolution

Hardware compensation (material, sampling fraction, etc.)
Software or "off-line" compensation

- based on the expectation of higher energy density inside electromagnetic component comparing to a hadronic one
- successfully implemented for
    - WA1 iron-Sc sampling calorimeter (H. Abramowicz *et al.* NIM 180 (1981) 429-439)
    - H1 LAr calorimeter (C. Issever, K. Borras, D. Wegener, NIM A545 (2005) 803-812)

Software compensation for the CALICE AHCAL

CALICE analogue hadronic calorimeter

Non-compensating with average $\frac{e}{\pi} \approx 1.2$ (for 10-80 GeV)
High-granular ⇒ gives a detailed energy density spectrum

Software compensation

Two techniques were developed with different approaches:

Local
different weights are applied to the signals in individual cells depending on their energy density

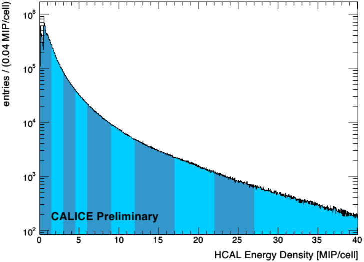
Global
one compensation factor calculated from the energy density spectrum is applied to the energy sum

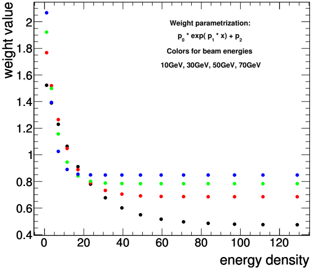
Both techniques

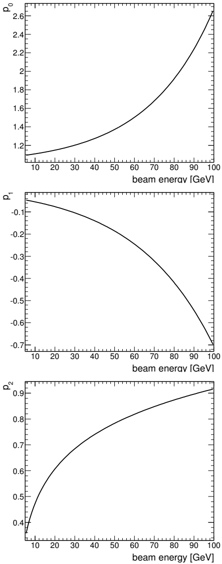
- **allow event-by-event energy correction**
- **do not require a prior knowledge of particle energy**

Local compensation technique (LC)

- Energy density (*ED*) distribution is divided into energy density bins
- $E_{SC} = E_{ecal,sum} + \sum_{\text{hit}} E_{\text{hit}} \cdot \omega_{\text{hit}} + E_{tcmt,sum}$
- The weights depend on *ED* and initial reconstructed event energy *E* (p_0, p_1, p_2 are energy dependent):
  $\omega_{hit} = p_0(E) \cdot \exp(p_1(E) \cdot ED) + p_2(E)$
- Shape of parameters p_0, p_1, p_2 is found via an iterative procedure using beam energy.

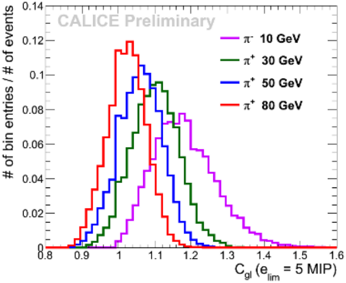






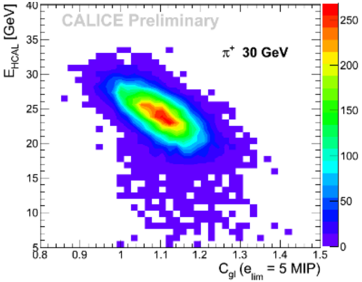
Global compensation technique (GC)

- Global compensation factor C_{gl} calculated on event-by-event basis:
  - number of shower hits N_{av} with $e_{hit} < \langle e \rangle$, $\langle e \rangle$ is a mean of shower hit energy spectrum
  - number of shower hits N_{lim} with $e_{hit} < e_{lim}$, $e_{lim} = 5$ MIP
  - $C_{gl} = \frac{N_{lim}}{N_{av}}$

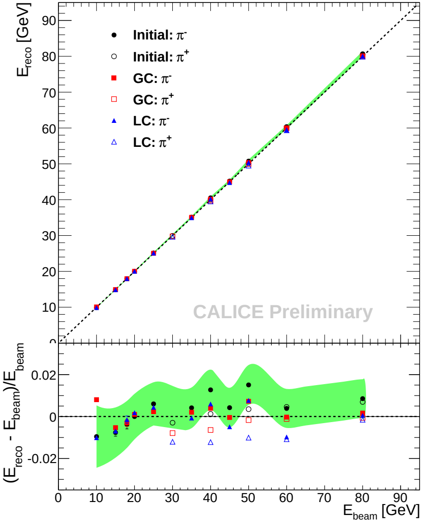


- Mean of global compensation factor C_{gl} is energy dependent; coefficients a_0, a_1, a_2 to describe this dependence are derived using beam energy

- Reconstructed energy:
  $E_{GC} = E_{ecal} + E_{sh} \cdot (a_0 + a_1 E_{sh} + a_2 E_{sh}^2)$,
  where $E_{sh} = C_{gl} \cdot (E_{hcal} + E_{tcmt})$

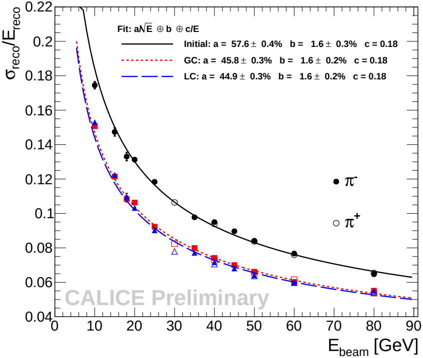


Comparison of local and global compensation



Systematics for initial sample

Different linearity for π^+ and π^-



Stochastic term decreased w.r.t. initial: $\sim \frac{45\%}{\sqrt{E/\mathrm{GeV}}}$ **(little better for LC)**

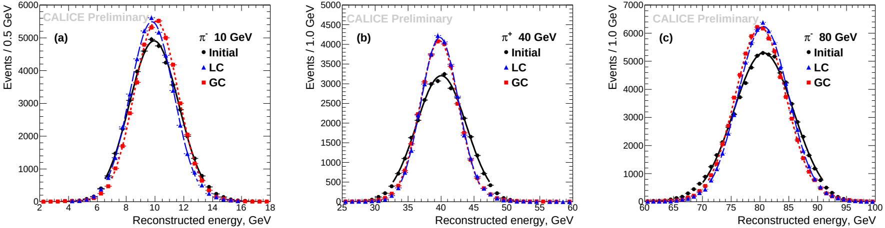
Constant term: not changed

Noise fixed at 0.18 GeV for full setup

Similar improvement of relative resolution for π^- and π^+

Improvement of resolution

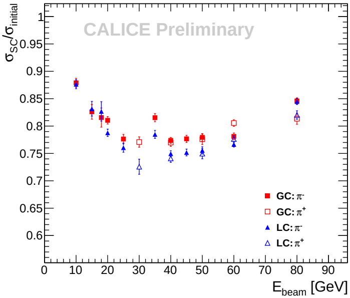
Energy distributions before and after compensation ($\frac{\chi^2}{NDF} < 2$ for Gaussian fits)



Relative improvement of absolute resolution
12% $< \sigma_{\mathrm{SC}}/\sigma_{\mathrm{initial}} <$ **25%**

Similar improvement for π^- and π^+
Outlier at 35 GeV

Local approach gives 3% better improvement
in the energy range 25-60 GeV than the global one



Summary

Hadron energy resolution of the CALICE AHCAL

- π^- and π^+ samples analyzed for beam energies from 10 to 80 GeV
- **intrinsic resolution:** $\frac{57.5\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1.6\% \oplus \frac{0.18}{E/\mathrm{GeV}}$
- similar resolution for π^- and π^+, linearity within $\pm 2\%$

Software compensation for the CALICE AHCAL

- two software compensation techniques developed based on different approaches, both show similar improvement of single particle energy resolution
- **stochastic term improved down to** $\sim \frac{45\%}{\sqrt{E/\mathrm{GeV}}}$

Local compensation
- individual cell signal weighting
- 3% better relative improvement for 25-60 GeV than in global

Global compensation
- one weight for event energy
- twice as less parameters as in local approach

- relative improvement varies from 12% to 25%
- similar improvement for π^- and π^+