Hadronic Shower Reconstruction in an Imaging Calorimeter

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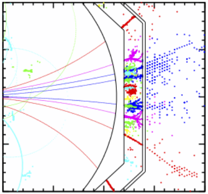
Imaging calorimeters for PFA-based reconstruction

Detectors for a future Linear Colliders



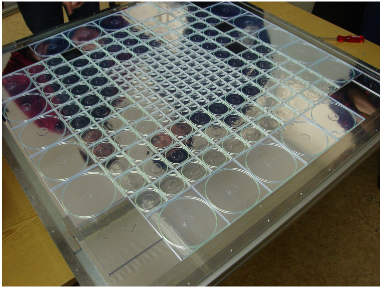
ILD event display

- Goal for detectors at ILC: $\frac{\sigma_{jet}}{E_{jet}} \sim$ 3-4%
- Classic calorimeter approach not sufficient
- Possible solution: Particle Flow Analysis
  $\Rightarrow$ high granularity required

CAlorimeters for LInear Collider Experiments

CALICE calorimeter prototypes

- high transversal and longitudinal granularity
- test of detector concepts
- test of PFA concept
- test of MC models
- study of 3D shower profiles

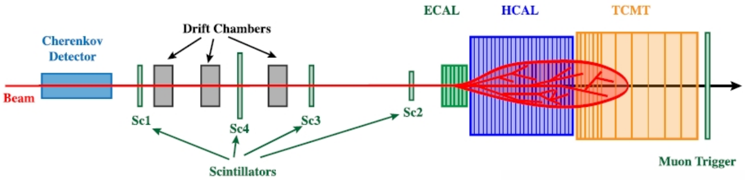


Scintillator tiles assembled in one layer of hadronic calorimeter

CALICE test beam setup

Test beam campaign: since 2006 up to now at DESY, CERN, FNAL
Muons, electrons, hadrons in the energy range 1-180 GeV, different setup configurations

CALICE test beam setup at CERN in 2007

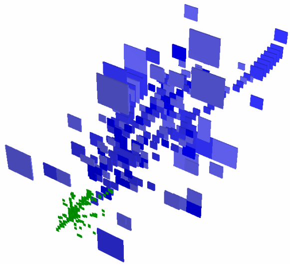


ECAL: Si-W, $\sim 0.8\lambda_I$ (30 layers), 18x18cm^2,
$\sim$10000 cells: 1x1cm^2

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

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

Units of MIP (visible signal from Minimum Ionizing Particle) used to equalize cell-by-cell response

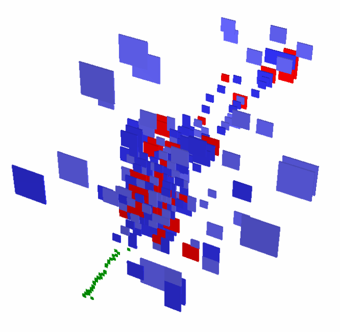


30 GeV pion shower in ECAL and HCAL

Advantages of high granularity

Hadronic shower structure

- First inelastic interaction
- Identification of track segments and high density clusters
- Spatial energy density distribution



30 GeV pion event with track in ECAL and hits above 3.5 MIP shown in red

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

Software compensation: basic idea and techniques

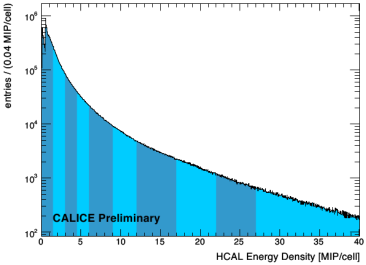
Hadronic shower comprises electromagnetic and hadronic components
with significant event-by-event fluctuations of electromagnetic fraction f_{EM}

Non-compensating calorimeter: different response to electrons and hadrons

$\Rightarrow$ Hadron energy resolution is deteriorated w.r.t. electromagnetic one

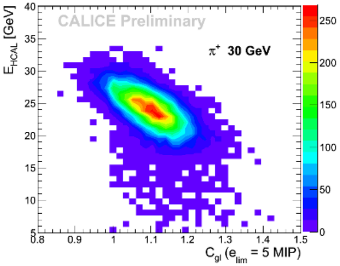
Software compensation: take into account f_{EM} fluctuations to improve resolution

Local Compensation technique (LC)
weighting of signals of individual cells depending on the cell energy density



Energy density spectrum

Global Compensation technique (GC)
applying one weight calculated from the energy density spectrum to energy sum



Correlation between global compensation factor and HCAL energy sum

Both methods: energy dependent weights, parameters of the energy dependence extracted from test beam data, **do not require a prior knowledge of particle energy**

Software compensation for π^- and π^+ test beam data

Hadron energy reconstruction

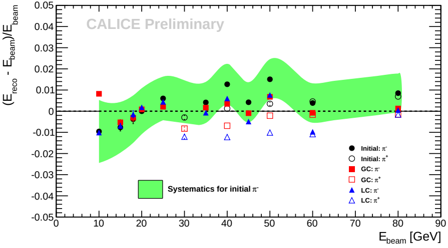
$E_{\mathrm{reco}} = E_{\mathrm{ECAL}}^{\mathrm{track}} + E_{\mathrm{HCAL}} + E_{\mathrm{TCMT}}$

Selected events with track in ECAL

E_{HCAL} non-corrected or corrected

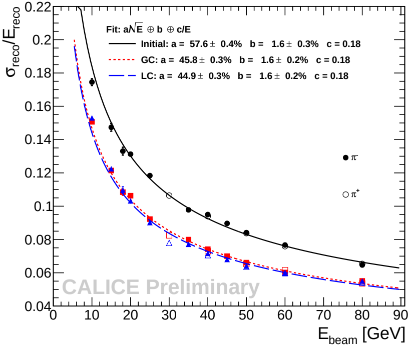
Weights for software compensation:

- depend on total event energy
- calculated from uncorrected E_{reco}
- energy dependence parameters extracted from data



Relative residuals to beam energy

Hadron energy resolution



Stochastic: from ~58% ↓ to ~45%

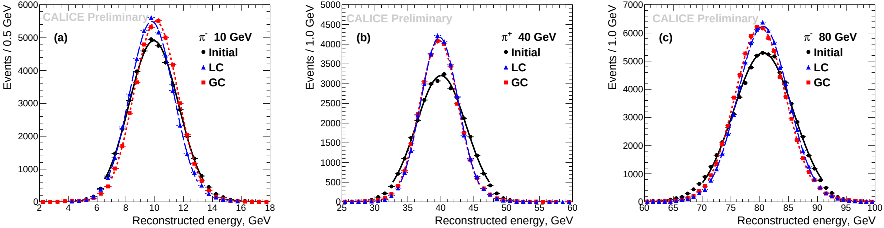
Constant: 1.6% - not changed

Noise: 0.18 GeV fixed for full setup

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

Software compensation: improvement of resolution

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

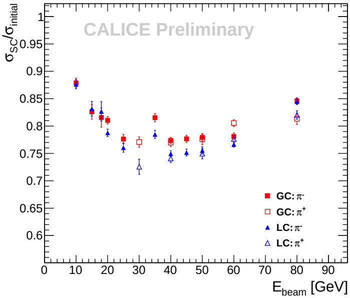


Relative improvement of absolute resolution
12% $< \sigma_{\mathbf{SC}}/\sigma_{\mathbf{initial}} <$ **25%**

Similar improvement for π^- and π^+

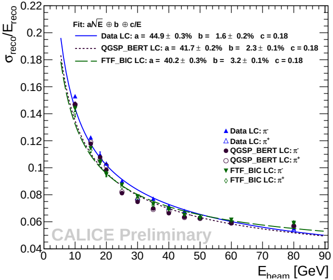
Local approach gives 3% better improvement
in the energy range 25-60 GeV than the global one

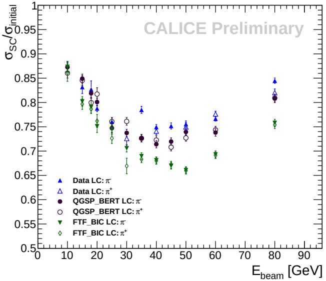
Global uses twice as less parameters as the local



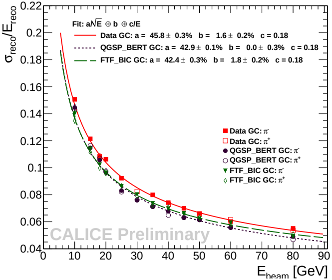
Software compensation: simulated samples and data

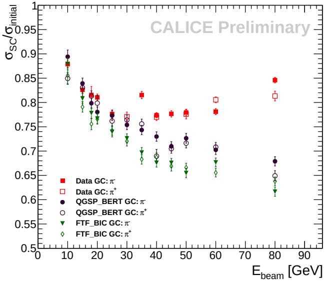
Local compensation





Global compensation





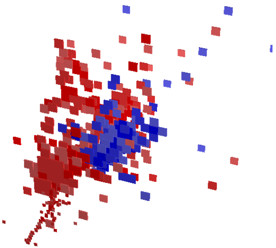
GEANT 4.9.4
QGSP_BERT
FTF_BIC

parameters for compensation extracted from data

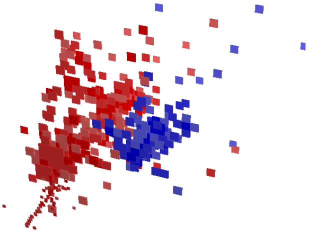
Local: MC follows data

Global: MC predicts further improvement above 40 GeV

PFA test using test beam data



10 GeV and 30 GeV pion showers at 12 cm

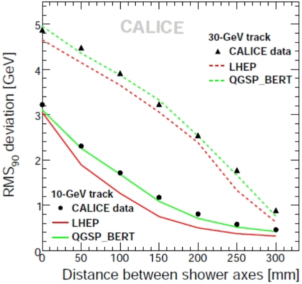


10 GeV and 30 GeV pion showers at 24 cm

Pairs of single particle events from the CALICE prototype are superimposed and mapped into ILD geometry

PandoraPFA was used as a reconstruction tool

Goal is to compare disentangling efficiency: test beam data vs. GEANT 4.9.2 simulations



Estimated confusion term: RMS deviation of a neutral cluster reconstructed energy from its measured energy in the vicinity of a charged cluster

Confusion term agrees for QGSP_BERT and data

Summary

Hadron energy resolution of the CALICE scintillator-steel analogue HCAL was estimated for π^- and π^+ test beam data samples in the range from 10 to 80 GeV

intrinsic resolution: $\frac{57.5\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1.6\% \oplus \frac{0.18}{E/\mathrm{GeV}}$, linearity of response within $\pm 2\%$

Local and global software compensation techniques were developed for the CALICE AHCAL and applied to test beam data

contribution from stochastic term reduced down to $\sim \frac{45\%}{\sqrt{E/\mathrm{GeV}}}$

PFA performance was compared for CALICE test beam data and GEANT 4.9.2 simulated samples

similar performance observed for QGSP_BERT model and data

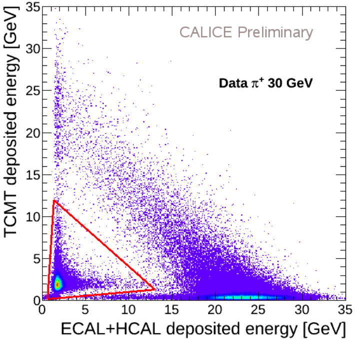
$\Rightarrow$ **extrapolation to jets in the complete detector is reliable**

Backup slides

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

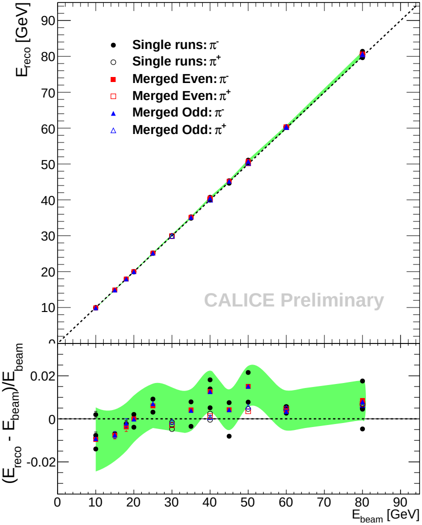


Training and test subsamples

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

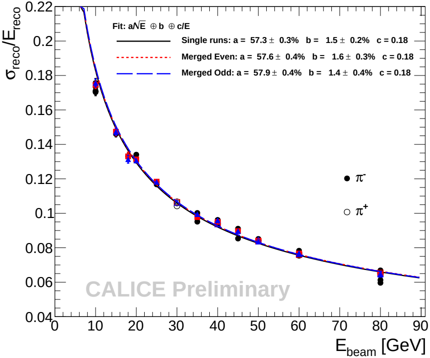
- set of even subsamples is used to adjust software compensation factors
- adjusted compensation factors are applied to the set of odd subsamples

Intrinsic AHCAL resolution for single hadrons



Systematic uncertainties

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



Fit results coincide within errors

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

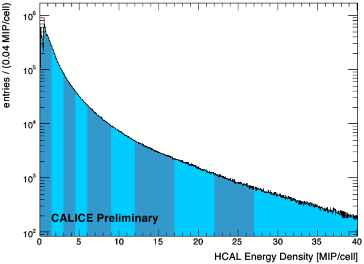
Constant term: $\sim$1.5%

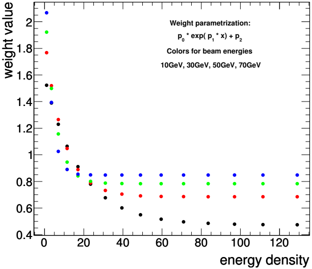
Noise fixed at 0.18 GeV for full setup

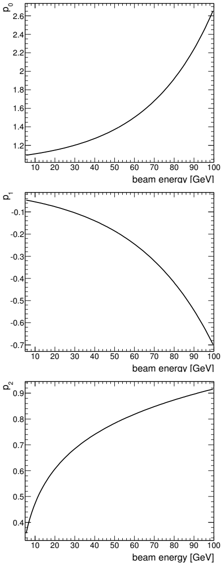
Similar resolution for π^- and π^+

Local Compensation technique (LC)

- Energy density (*ED*) distribution is divided into energy density bins
- $E^{SC}_{reco} = E_{ECAL} + \sum_{hit} E_{hit} \cdot \omega_{hit} + E_{TCMT}$
- 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.

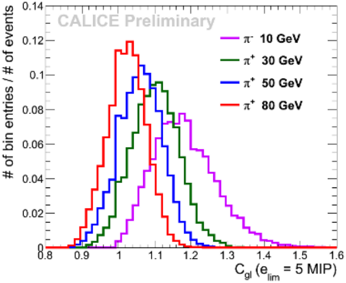




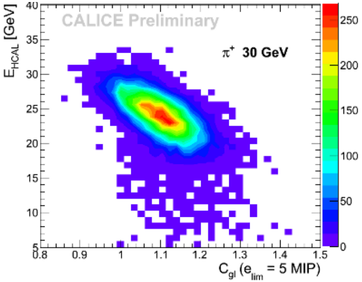


Global Compensation technique (GC)

- 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: $E^{GC}_{reco} = E_{ECAL} + E_{sh} \cdot (a_0 + a_1 E_{sh} + a_2 E^2_{sh})$, where $E_{sh} = C_{gl} \cdot (E_{HCAL} + E_{TCMT})$