Software Compensation in a Highly Granular Calorimeter

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Outline

Use the advantages of a highly granular calorimeter to develop software compensation techniques to improve the energy resolution of the calorimeter.

1. Hadronic Showers in a calorimeter
2. Software Compensation
   - Idea
   - Advantage of high granularity
   - Methods
3. Software Compensation in ILD
   - Detector and reconstruction design
   - Development of software compensation technique
   - Results
4. Summary and Outlook

Hadronic showers

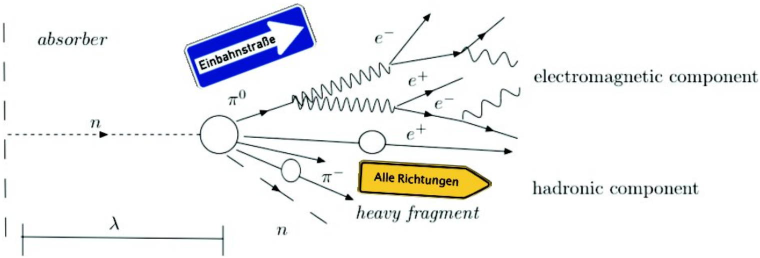
Energy measurement in a sampling calorimeter:

- successive layers of active a passive material
- energy loss of incoming particle depends on particle type (ionization, electromagnetic interaction, hadronic interaction)

Hadronic showers:

- dominated by succession of inelastic hadronic interactions
  $\Rightarrow$ production of secondary particles (π^+, π^-, π^0, n)
- structure/composition of hadronic showers depend on produced particles in the shower
- large event-to-event fluctuations $\rightarrow$ no "typical hadronic shower"
- Two scales for the hadronic shower cascade:
  - strongly interaction part $\rightarrow$ HAD energy scale
  - electromagnetic part $\rightarrow$ EM energy scale

Hadronic showers



- mostly production of π^0 gives electromagnetic shower component
- all energy of electromagnetic shower component is detectable
- hadronic showers: certain fraction of energy is undetectable $\rightarrow$ invisible energy
- invisible energy due to excitation and nuclear breakup
- $\frac{e}{\pi} > 1$ at same energy of e and π for a non-compensation calorimeter
- $\frac{e}{\pi}$ ratio depends on energy

$\Rightarrow$ worsens energy resolution

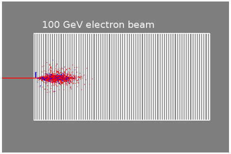
Software compensation

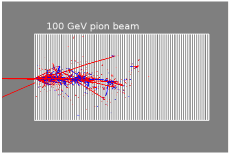
Most experiments have non-compensating calorimeters

$\frac{e}{\pi} = 1$ with software compensation

$\Rightarrow$ distinguish between em. and had. shower parts

- electromagnetic showers tend to be denser than hadronic ones





- Local software compensation technique
  - the higher the hit energy density, the higher the propability to be an em shower component
- Global software compensation technique
  - the higher the cluster energy density, the higher the propability to have a high em component

High granularity

What is the benefit from a highly granular calorimeter?

- Large number of cells, small cell sizes
- More details of hadronic shower components
- Shower variables can be measured with higher precision

$\Rightarrow$ Software Compensation should be very powerful

- CALICE develops calorimeters with high granularity and new technologies
- Test beam data with $\pi^-, \pi^+, p, e^-, e^+$
- Simulated data

CALICE test beam program

Electromagnetic Calorimeter (ECAL)

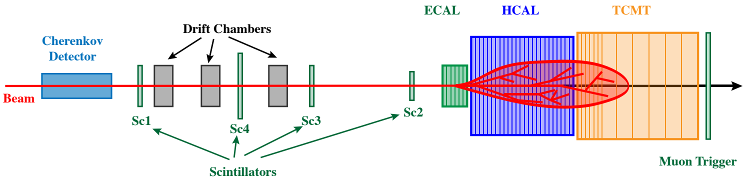
- 30 silicon layers (active area $18\times12\,\mathrm{cm}^2$)
- 1.4 mm, 2.8 mm, 4.2 mm thick tungsten absorber plates $(0.9\,\lambda, 30\,\mathrm{X}_0)$
- each layer divided in 6×6 modules; $1\times1\,\mathrm{cm}^2$ readout-pads

Hadronic Calorimeter (HCAL)

- 38 layers
- 2 cm thick steel absorber plates ($5.3\,\lambda$)
- scintillator tile sizes $3\times3\,\mathrm{cm}^2$ in center, $6\times6\,\mathrm{cm}^2$, $12\times12\,\mathrm{cm}^2$ ($\approx$ 8000 channels)

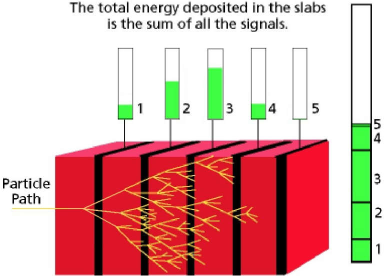
Tail Catcher/ Muon Tracker (TCMT)

- 16 scintillator layers (active area $1\times1\,\mathrm{m}^2$)
- 1.9 cm, 10.2 cm thick absorber plates ($5.8\,\lambda$)
- each layer 20 $100\times5\,\mathrm{cm}^2$ scintillators



Energy Measurement

- Hadronic interactions take place in the absorber layers
- Energy loss mostly due to ionization in the active layers



CALICE

- In active layer the energy is measured in units of the energy deposition of one penetrating minimum ionizing particles (MIP)
- One MIP deposits approx. 30 MeV in one active HCAL cell
- Conversion factor k transforms from the calibration scale to the energy scale $E_{\text{rec}}[\text{GeV}] = \sum_{hit} E_{hit}[\text{MIP}] \cdot k$
- k is constant

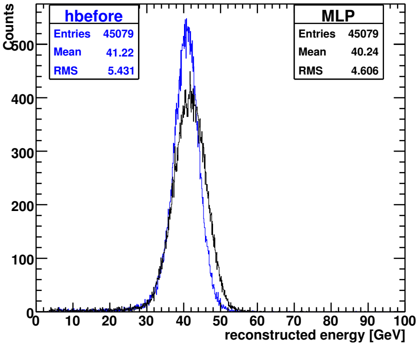
Methods

1. Single Hit Weighting:
   - Local technique
   - Treats every hit separately $\rightarrow$ every hit gets a different weight in the overall energy sum $E_{\text{rec}}[\text{GeV}] = \sum_{hit} E_{hit}[\text{MIP}] \cdot \omega_{hit}$
   - Weights ω_{hit} depend on the hit energy density and the initial reconstructed energy $\sum_{hit} E_{hit}$
2. Cluster Weighting:
   - Global method
   - Cluster is treated as a whole
   - One weight per cluster $E_{\text{cluster}}[\text{GeV}] = E_{\text{cluster}}[\text{MIP}] \cdot \omega_{\text{cluster}}$
   - Weights ω_{cluster} depend on cluster energy density and initial reconstructed energy $E_{\text{cluster}}[\text{MIP}]$
3. Neural Network:
   - Global method
   - Cluster variables determination (cluster energy, cluster volume, cluster length, cluster width,...)
   - Cluster variables are feed to a neural net
   - Output of neural net is cluster energy $E_{\text{cluster}}[\text{GeV}]$

Methods

Goodness criteria:

- Improvement in width of the reconstructed energy
  Histogram for a 40 GeV π^-



Methods

Goodness criteria:

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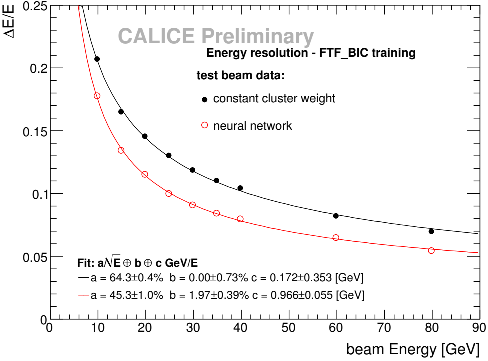
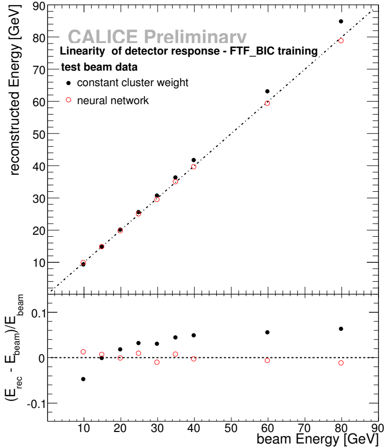
  Histogram for a 40 GeV π^-
- Software compensation should work for data and MC independent of the data set from which the weights are extracted





From CALICE to ILD

- Improvement of energy resolution due to high granular calorimeter
- CALICE ECAL and HCAL very similar to ILD calorimeter
- Software Compensation extracted from Monte Carlo works for test beam data
- Software Compensation should work in ILD

The International Large Detector (ILD) for the ILC

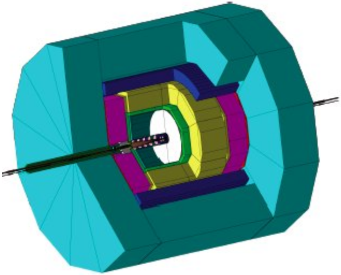
ILC:

- e^+e^- machine
- E_{cms} up to 500 GeV
- peak luminosity $2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

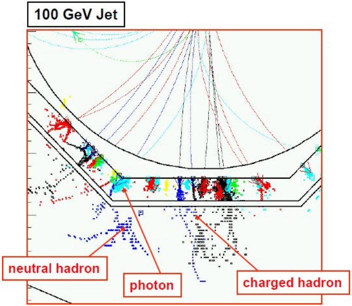
ILD one Detector design:

- Vertex detector
- TPC (224 points per track, 1.8 m outer radius)
- SiW ECAL (cell size $1 \times 1\,\mathrm{cm}^2$)
- Analog Scint/Fe HCAL (cell size $3 \times 3\,\mathrm{cm}^2$)
- Magnet for field of 3.5 Tesla
- Iron retrun yoke

$\Rightarrow$ excellent spatial resolution
$\Rightarrow$ optimized for Particle Flow

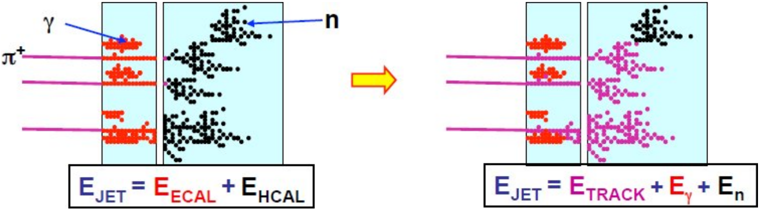


Principle of Particle Flow with PandoraPFA



Concept:

- momenta of charged particles measured with tracking detectors
- energy of photons and neutral hadrons measured with calorimeter system
- assign correct hits to reconstructed particle $\rightarrow$ separation of nearby showers



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    Minimization of function $\chi = E_{\mathrm{true}} - E_{\mathrm{rec}}$

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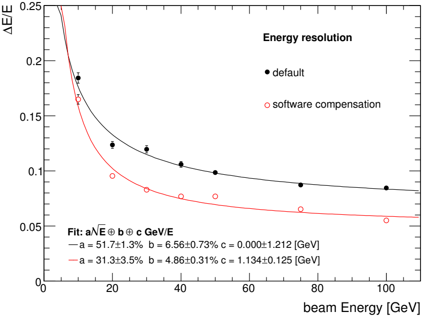
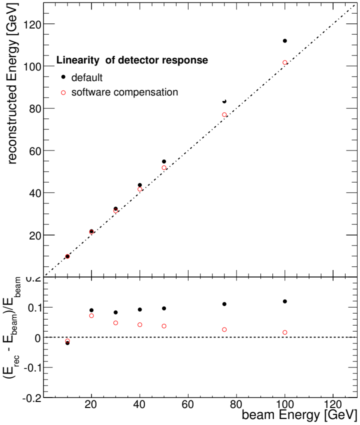
Weight parameterization application/ Input:

- hit energy density
- hadronic cluster energy

Improvement:

Software Compensation applied on simulated K_L^0 events:

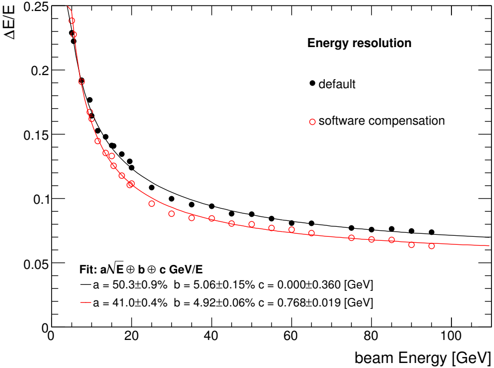




Test of calorimeter performance

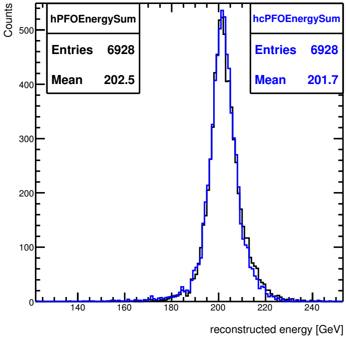
- Test on independent data set n, K_L^0 at various energies
- Resolution given by the calorimeters only

$\Rightarrow$ Energy resolution improvement approx. 20 %



$e^+e^- \to Z \to q\bar{q}$

- Use realistic e^+e^- events at various energies
  $\Rightarrow e^+e^- \to Z^* \to q\bar{q}(uds)$
- Full particle flow performance
  Only energy of neutral hadrons is taken from the calorimeters
- Gaussian fit for E_{rec}, RMS90 for width



E_{cms} [GeV]	91	200	360	500
Default				
RMS90/E_{rec} [%]	2.82±0.02	2.49±0.02	2.61±0.02	2.81±0.02
Software Compensation				
RMS90/E_{rec} [%]	2.79±0.02	2.38±0.02	2.51±0.02	2.70±0.02
Improvement [%]	1.06	4.42	3.83	3.91

How much improvement do we expect?

- Software compensation improves neutral hadrons by approx. 20 %
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⇒ Expect approx. 2 % resolution improvement for E_{cms}

Check MC particleID of leading cluster particle for particles marked as neutral hadrons.

E_{cms}	200 GeV
Photons	24 %
Charged EM particles	2 %
Charged HAD particles	22 %
Neutral HAD particles	52 %

- Photons and electrons in the ECAL should be on the electromagnetic energy scale
- Software Compensation could correct energy of photons in the ECAL from the hadronic scale to the electromagnetic scale

Summary and Outlook

So far...

- Different software compensation techniques work for Monte Carlo and test beam data
- Software compensation integrated into particle flow reconstruction
  - Software Compensation improve energy determination of neutral hadrons
  - Software Compensation corrects energy scale of wrongly assigned particles

Coming up...

- Improvement of software compensation technique
- Help to improve/cross check particle flow algorithm
- Physics analysis with and without software compensation applied