Studies towards optimisation of the Analog Hadronic Calorimeter for future linear collider detectors

＞ Introduction to ILC and ILD
＞ Analog Hadronic Calorimeter (AHCAL) and Particle Flow Concept
＞ AHCAL Optimisation
＞ Software Compensation
＞ Outlook

Huong Lan Tran
for the CALICE-D Collaboration
DPG meeting
Hamburg, 02.03.2016
Introduction to ILC and ILD

• ILC (International Linear Collider):
  • $e^+e^-$ collider of ~ 30 km length
  • Planned energy at $\sqrt{s} = 500 \ GeV$, potential upgrade to 1 $GeV$
  • Using superconducting RF-cavities for acceleration

• ILD (International Large Detector) is one of the two detectors for ILC, design motivated by Particle Flow Concept
  • Vertex detector and tracker with low material budget
  • High granularity calorimeters
Analog Hadronic Calorimeter

- Developed in CALICE collaboration for ILC detectors
- **High granularity** sandwich calorimeter based on scintillator tiles of 3x3 $cm^2$ readout by Silicon Photomultipliers (SiPM)
- Depth of $\sim 1.3m$, corresponding to 38 layers
- **8 million channels in total**
- Principle demonstrated with physics prototype

Particle Flow Calorimeter
- Using Pandora Particle Flow Algorithm (PandoraPFA)
- Goal of 3-4% jet energy resolution achieved (non-achievable with classic calorimeter approach)
  - Particle Flow gain even at high energies
Introduction to Particle Flow & PandoraPFA

- In a typical jet:
  - 60% energy in charged hadrons
  - 30% in photons
  - 10% in neutral hadrons
- Particle Flow:
  - Trace individual particles
  - Measure charged particle energy through track momentum
  - Photon energies measured in ECAL: $\sigma_E / E < 20% / \sqrt{E}$ (GeV)
  - Neutral hadron energies measured in HCAL

PandoraPFA:
- Powerful software tool for Particle Flow Algorithm
- Provide visual option for monitoring
- Well maintained/developed
Motivations for AHCAL (re-)optimisation

• Discussion about overall size of ILD and cost
  • HCAL cell sizes, HCAL thickness, different granularities @ different depth

• New version of PandoraPFA with improved pattern recognition shows better resolution for all jet energies

• Results with software compensation suggest further improvement: Software compensation applied to test beam data from CALICE-AHCAL physics prototype:
  • Improvement of hadronic energy resolution by 20% for single hadrons from 10 to 80 GeV

➢ Re-optimisation of AHCAL with newest version of PandoraPFA and software compensation
Software Compensation

• ILD calorimeters are *non-compensating*
  - Higher detector response for electromagnetic compared to hadronic showers $\frac{e}{h} > 1$
  - Non-linearity for hadronic calorimeter response
  - Degradation of energy resolution

• Software compensation is “offline” way to achieve compensation
  - Electromagnetic showers denser than hadronic showers $\Rightarrow$ energy of hits inside electromagnetic sub-showers are typically higher compared to hits inside hadronic sub-showers.
  - Applying different weights for hits of different energy densities

![Graph showing hit energy density vs. hit energy density with EM hits and HAD hits represented with different weights.](image)
Software Compensation Weights

• 9 hit energy density bins

• In energy reconstruction, hits are weighted:
  
  • Weight of each bin depends on initial energy of particle

\[
E^{SC} = E_{ECAL} + \sum_{i=1}^{9} E^i_{HCAL} \times \omega_i = E_{ECAL} + \sum_{i=1}^{9} E^i_{HCAL} \times (\alpha_i + \beta_i E + \gamma_i E^2)
\]

![Graph showing weight values and bin weight against initial energy (GeV) and energy bin (MIP).](image)
Software Compensation in PandoraPFA

- PandoraPFA uses vertex, tracker and calorimeter information
- Output: Particle Flow Objects (PFO) (including vertex, tracks, clusters)

Cluster-Track energy comparison: if failed, re-clustering

Track-Cluster comparison

Two places where SC can improve

Neutral hadron PFOs registered with software compensated energy

Clusters  →  Tracks  →  Vertices

PFOs
• Correction of neutral hadron PFOs energy
• Initial estimation of cluster’s energy used for determination of weights
• Apply to set of Kaon0L and neutron samples from 10 to 95 GeV

- RMS significantly reduced
Single Particle Energy Reconstruction

- Improves linearity in whole range
- Improves resolution by ~20% (similar to results obtained for physics prototype)

➢ Testbeam results reproduced!
Jet Energy Resolution

- Software compensation applied for jets
  - Only for neutral hadrons, after clustering and re-clustering step
  - Only hits in HCAL are weighted

Reconstructed energy distribution closer to simulated energy and width of distribution smaller

- Improves jet energy resolution in whole range

$\sqrt{s} = 200 \text{ GeV}$

$h_{PFO}$

<table>
<thead>
<tr>
<th>Entries</th>
<th>6005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>197.7</td>
</tr>
<tr>
<td>RMS</td>
<td>6.62</td>
</tr>
</tbody>
</table>

$E_{SC}$

<table>
<thead>
<tr>
<th>Entries</th>
<th>6005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>199.3</td>
</tr>
<tr>
<td>RMS</td>
<td>6.251</td>
</tr>
</tbody>
</table>

$\frac{3 \times 3 \text{ cm}^2}$
JER vs cell size

• Over all improvement with software compensation

Work in progress
Outlook

Towards cost optimisation

- Look at jet energy resolution as a function of number of channels
- Plot shows that 3x3 cm$^2$ cell size is still a very reasonable choice
Summary & Outlook

• Software compensation:
  • Implemented in PandoraPFA
  • Improves single particle and jet energy resolution
  • Next step: SC in re-clustering

• AHCAL cell size optimisation:
  • 3x3 cm$^2$ still a very reasonable choice

• Final goal:
  • Longitudinal sampling
  • Different cell size w.r.t. different depth
  • ILD optimisation: overall detector radius
Back-up slides
Particle Flow Calorimetry

★ In a typical jet:
- 60% of jet energy in charged hadrons
- 30% in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
- 10% in neutral hadrons (mainly $n$ and $K_L$)

★ Traditional calorimetric approach:
- Measure all components of jet energy in ECAL/HCAL!
- ~70% of energy measured in HCAL: $\sigma_E/E \approx 60%/\sqrt{E(\text{GeV})}$
- Intrinsically “poor” HCAL resolution limits jet energy resolution

★ Particle Flow Calorimetry paradigm:
- Charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_E/E < 20%/\sqrt{E(\text{GeV})}$
- Neutral hadrons (ONLY) in HCAL
- Only 10% of jet energy from HCAL → much improved resolution
AHCAL Optimisation & Software Compensation

- Perform on events with jets from decay of off-shell mass Z bosons to light quarks
- Typically 2 mono energetic back-to-back jets
- Jet energy resolution = $\frac{RMS_{90}}{Mean_{90}}$

Typical 500 GeV Off-Shell mass Z boson decay.
Why Compensation?

- ILD calorimeters are **non-compensating**

Typical hadronic shower

Detected via energy loss of electrons and photons in active medium

Hadronic components:
- Energy loss of charged hadrons, photons, neutrons…
- *Invisible energy*: nuclear binding energy or target recoil

➢ Smaller calorimeter response for this part

**Consequences:**
- Higher detector response for electromagnetic compared to hadronic showers \( \frac{e}{\hbar} > 1 \)
- Non-linearity for hadronic calorimeter response
- Degradation of energy resolution
Methods to achieve Compensation

- Reducing electromagnetic response
- Increasing hadronic response

Achievable with detector design
- Increase nuclear fission with absorber material
  - Example: ZEUS detector using $^{238}$U
- Manipulating response to (slow) neutrons
- Sampling fractions
- …

ZEUS Uranium-Scintillator calorimeter

ZEUS e/h response ratio
$= 1$ within 1% for $E > 3$ GeV
Methods to achieve Compensation

- Reducing electromagnetic response
- Increasing hadronic response
- “Offline” compensation: **Software Compensation**
  - Electromagnetic showers denser than hadronic showers => energy of hits inside electromagnetic sub-showers are typically higher compared to hits inside hadronic sub-showers.
  - Cut out high energy hits to reduce EM response *
  - Applying different weights for hits of different energy densities

![Diagram showing weights for HAD and EM hits](image-url)
Software Compensation

- **Idea:** Applying different weights for hits of different energy densities

- **Weight** defined as:

\[ \omega(\rho) = p_1 \cdot \exp(p_2 \cdot \rho) + p_3 \]

where \( \rho \) is hit energy density, \( p_1, p_2, p_3 \) are *beam energy dependent parameters*

- Energy of cluster then computed in software compensation method as:

\[ E_{SC} = \sum_{\text{hits}} E_{ECAL} + \sum_{\text{hits}} (E_{HCAL} \cdot \omega(\rho)) \]

- Weights determined through minimising a \( \chi^2 \) function:

\[ \chi^2 = \sum_{\text{events}} (E_{SC} - E_{beam})^2 \]

- In following slides: Results on standard ILD detector (with 3x3 cm² AHCAL)
**Hit Energy Density and Weights**

Samples:
- Kaon0L and neutrons from 10 to 95 GeV generated from IP, targeted only to barrel part
- Select only events with 1 cluster
  - Events where hadronic showers started already in EM calorimeter: only HCAL hits are weighted
  - Cluster with no hit in muon chamber

**Weight determination:**
- Through $\chi^2$ minimisation
- For each beam energy, weights are defined with three parameters $p_1, p_2, p_3$ given by $\chi^2$
  \[
  \omega(\rho) = p_1 \cdot \exp(p_2 \cdot \rho) + p_3
  \]
- For each of $p_1, p_2, p_3$ obtain 10 values at 10 energies $\Rightarrow$ fit as function of energy
Outlook - Using my numbers

Towards cost optimisation

- Look at jet energy resolution as a function of number of channels
- Plot shows clear preference for 3x3 cm$^2$ cell size
- Software compensation to be applied

![Graph showing jet energy resolution as a function of number of channels, with a preference for 3x3 cm$^2$ cell size. The graph includes data for different energies (91 GeV, 200 GeV, 360 GeV, and 500 GeV). The graph also indicates before and after software compensation.]
• Semi-digital reconstruction:
  • Counting hits at 3 thresholds N1, N2, N3
  • \( N_{tot} = N1 + N2 + N3 \)
  • \( \text{EnergySD} = \alpha N1 + \beta N2 + \gamma N3 \)

where:

\[
\begin{align*}
\alpha &= \alpha_1 + \alpha_2 N + \alpha_3 N^2 \\
\beta &= \beta_1 + \beta_2 N + \beta_3 N^2 \\
\gamma &= \gamma_1 + \gamma_2 N + \gamma_3 N^2
\end{align*}
\]

Software compensation mimics Semi-Digital:

• Define bin

• Energy total = \( \text{Sum}_\text{bin} (\text{weight}_\text{bin} \times \text{SumEnergy}_\text{bin}) \)

• \( \text{weight}_\text{bin} = a + bE + cE^2 \)
Semi-digital Reconstruction

Weights
- Beam Energy: 10 GeV
- Beam Energy: 30 GeV
- Beam Energy: 60 GeV
- Beam Energy: 80 GeV
- Beam Energy: 95 GeV

Weights values

Weight values

E_{\text{reco}} [\text{GeV}]

hPFO

Entries 19949
Mean 60.43
RMS 5.924

PFO + SC

Entries 19949
Mean 59.58
RMS 4.93