Energy reconstruction study in a High Granularity Semi-Digital Hadronic Calorimeter for ILC

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Outline

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   - The Semi Digital Hadronic Calorimeter prototype

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   - Tests beam at Cern
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3 Hadronic energy reconstruction techniques in SDHCAL
   - Energy reconstruction: Quadratic Parametrisation
   - Energy reconstruction: Artificial Neural Network

4 Particle identification using ANN

5 Conclusion
The Semi-Digital Hadronic CALorimeter (SDHCAL) is one of the calorimeters developed within the CALICE collaboration proposed for the Future International Linear Collider experiments.

ILC should be equipped with high precision detectors.

Excellent Jet energy Resolution $3\%/E_{jet}$

$$\sigma_{jet} = \sqrt{\sigma_{Track}^2 + \sigma_{Had}^2 + \sigma_{elm}^2 + \sigma_{confusion}^2}$$

PFA: Construction of individual particles and estimation of their energy/momentum in the most appropriate sub-detector.

Construction of Highly Granular Calorimeters to separate overlapping showers.
PFA Hadronic Calorimeters

- **DHCAL**: Binary readout
  - 1-bit readout electronics (1 threshold)
  - Lateral segmentation of 1 cm²

- **SDHCAL**: 2-bit electronics (3 thresholds)
  - Lateral segmentation of 1 cm²

- **Analog HCAL readout directly by SiPM and embedded electronics**

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*Energy reconstruction in SDHCAL*

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Sampling calorimeter

Size: 48 stainless steel plates + 48 active layers $\Rightarrow 1 \times 1 \times 1.3 m^3$

Active layer
- Gaseous detector: GRPC (Glass Resistive Plate Chamber) of $1 m^2$
- Gas mixture: tetrafluoroethane (TFE, 93%), isobutane (5%) and SF$_6$ (2%)
- HV: $\sim 6.9 kV$ in avalanche mode

Readout
- 96 $\times$ 96 pads of $1 cm^2$ per layer $\iff$ more than 460000 channels for the whole prototype
- Semi-digital readout: 3 thresholds on the induced charge to have a better idea on the deposited energy

Absorber: $48 \times 20 mm$ stainless steel $\iff \sim 6 \lambda$
A technological prototype was built with a self-supporting mechanical structure, fulfilling almost all the ILD requirements

- compactness
- homogeneity
- low power consumption

Power pulsing mode: Important feature of ILC detectors to reduce power consumption and heating for highly-granular detectors
Electronics switched on just before the bunches train and off after
Tests beam summary

- August-September 2012 on H6 line for 2 weeks
- November 2012 on H2 line for 1 week
- December 2014 on H6 line for 1 week
- Large beam size, low particle rate < 1000 particle/spill
- Triggerless acquisition: all hits are recorded until a ramfull occurs, then data transferred and acquisition starts again
- Power pulsing
- **Efficiency**: probability to find at least 1 hit within 3cm of the reconstructed track in the studied layer. $\bar{\epsilon} \sim 96\%$

- **Multiplicity**: mean number of hits matched on studied layer within 3cm of the impact track $\bar{\mu} \sim 1.7$
Event selection

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<td>$E_{\text{miss}} &lt; 10 \text{ GeV}$</td>
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<td>Muon rejection</td>
<td>$N_{\text{hit}} / N_{\text{layer}} &gt; 2.2$</td>
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<tr>
<td>Radiative muon rejection</td>
<td>$N_{\text{hit}} / N_{\text{layer}} \times \text{RMS} &gt; 5 \text{ cm} &gt; 20%$</td>
</tr>
<tr>
<td>Neutral rejection</td>
<td>$N_{\text{hit}} \text{ in first 5 layers} \geq 4$</td>
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No containment cuts

![Histograms showing event selection](image)

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![Histograms showing event selection](image)
the beam parameters were optimized to get spills containing less than 1000 particles.

For some runs with rather high intensity, the number of hits go down with time within a spill especially with the number of hits associated to the second and the third thresholds.

Limitation of the GRPC rate capability

Degradation of the energy resolution.
We correct for using a simple formula \(N_{\text{corr}} = N_i - S_{\text{lope}} \times T_{\text{imeInSpill}}\).

\(N_i\) : number of hits for each event
Energy reconstruction: Quadratic parametrisation

- \( E_{\text{rec}} = \alpha(N_{\text{tot}}) \times N_1 + \beta(N_{\text{tot}}) \times N_2 + \gamma(N_{\text{tot}}) \times N_3 \) in case of S.D readout.
- \( E_{\text{rec}} = C N_{\text{tot}} + D N_{\text{tot}}^2 + F N_{\text{tot}}^3 \) in case of Binary readout
- \( N_1, N_2, N_3 \): number of hits for thresholds 1, 2, 3 (0.114pC, 5pC, 15pC)
- \( N_{\text{tot}} = N_1 + N_2 + N_3 \)
- \( \alpha(N_{\text{tot}}) = \alpha_1 + \alpha_2 \times N_{\text{tot}} + \alpha_3 \times N_{\text{tot}}^2 \)
- \( \beta(N_{\text{tot}}) = \beta_1 + \beta_2 \times N_{\text{tot}} + \beta_3 \times N_{\text{tot}}^2 \)
- \( \gamma(N_{\text{tot}}) = \gamma_1 + \gamma_2 \times N_{\text{tot}} + \gamma_3 \times N_{\text{tot}}^2 \)
- \( \alpha, \beta, \gamma \): quadratic weights of \( N_{\text{tot}} \) obtained from like \( \chi^2 \) minimisation:
- \( \chi^2 = \sum_{i=1}^{N} \frac{(E_{\text{beam}} - (E_{\text{rec}}))^2}{E_{\text{beam}}} \)

shower development pion 50 GeV
Binary-based study

![Graph a) and b)](image-url)
• Systematics
• Changing the cuts (5% changes)
• Differences observed in simulation with and without cuts
• Beam energy (2%). this includes difference coming from proton/pion (in case of H6 data)
• Difference between fit using CB and Gaussian fits)
Multi-threshold vs Binary

![Graphs showing energy reconstruction precision](image)

- **Multi-thr. mode**
- **Binary mode**

- Energy reconstruction in SDHCAL

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Energy reconstruction: Artificial Neural Networks

- **TMultiLayerPerceptron of root package.**
- **2 hidden layers with 6 and 2 neurons.**
- **The input variables:** $N_1, N_2, N_3$.
- **The output variable is the reconstructed energy:** $E_{\text{rec}}$.
- **Monte Carlo Simulation**
  - Training Samples: Odd energies, 1-99 GeV (50 training samples)
  - Test Samples: Even energies, 10-90 GeV (40 test samples)
ANN results in MonteCarlo Simulation
ANN results in Data

- Architecture of the ANN: One hidden layer of 8 neurons.
- The input variables: $N_1, N_2, N_3$.
- The output variable is the reconstructed energy: $E_{\text{rec}}$.
- Data SPS H2 and H6 taken during 2012
  - Training Samples: Trained with Simulation samples, odd energies: 1-99 GeV
  - Test Samples: 2012 tests beam data:
    Energies (5, 7.5, 10, 15, 20, 25, 30, 40, 50, 60, 70, and 80 GeV)
  - An improvement in energy resolution reaching 13% at high energies comparing to quadratic method
Muon/electron identification using ANN in MC

- TMVA of root.
- Method: Multilayer perceptron MLP.
- Training
  - 28000 electron: energies: 2, 3, 8, 10, 15, 20, 25, 30, 40, 50, 60, 70, and 80 GeV
  - 14000 pion with energies 10, 20, 30, 40, 50, 60, 70, and 80 GeV
  - 9000 muons events with energies: 0.5, 2 and 10 GeV
- Variables: the total number of hits, start, width, mean radius, longitudinal centre of gravity of the shower

Variables: the total number of hits, start, width, mean radius, longitudinal centre of gravity of the shower.
Muon/electron identification using ANN in MC
The SDHCAL prototype is built and successfully tested in tests beam.
Good data quality and stability were observed.
Analytic energy reconstruction method is well understood: Good energy resolution with satisfactory linearity.
ANN technique used for energy estimation giving promising results.
ANN used in particles identification giving similar results to classic event selection with a slight improvement in energy resolution but a better linearity.
Charged particles: 65% 
precise measurement by Tracker

Photons: 25% measured by EM calorimeters

Neutral hadrons: 10% measured by HCAL

Tracker measure the Energy deposited of charged particles then eliminate them of the calorimeters.

Calorimeters are used to measure Neutral particles once deposited energy of charged particles eliminated

\[
\frac{\sigma E}{E} = \frac{21}{\sqrt{E/\text{GeV}}} \Theta 0.7 \Theta 0.004E \Theta 2.1 \left( \frac{E}{100 \text{ GeV}} \right)^{0.3} \%
\]
To distinguish between $Z, W^\pm$ jets, the ILD energy resolution should be comparable to the width of the bosons mass spectrum $< 30\%/\sqrt{E}$.

$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\text{GeV}}} \oplus 0.7 \oplus 0.004 \oplus 2.1 \left( \frac{E}{100 \text{ GeV}} \right)^{0.3} \%$$

**Calorimeters** **Tracker** **Leakage** **Confusion**

High granular calorimeters allow the minimisation of the confusion term in energy resolution.

\[
\begin{align*}
\text{mZ/mW} &= 1.13 \\
\text{mZ} - \text{mW} &= 10.7698 \text{ GeV} \\
\text{mZ} &= 80.42 \text{ GeV} \\
\Gamma_W &= 2.046 \pm 0.049 \text{ GeV} \\
\Gamma_Z &= 2.4952 \pm 0.0041 \text{ GeV}
\end{align*}
\]
Multithreshold-based study

![Graph a)](image1)

![Graph b)](image2)
Multithreshold-based study

Energy reconstruction in SDHCAL

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NN regression estimation

![Graph showing energy reconstruction in SDHCAL](image)
NN Identification

CALICE Preliminary SDHCAL

\[ \sigma_{\text{rec}}/E_{\text{rec}} \]

E$_{\text{beam}}$ [GeV]

CALICE Preliminary SDHCAL

\[ \sigma_{\text{rec}}/E_{\text{rec}} \]

E$_{\text{beam}}$ [GeV]
NN Identification

Energy reconstruction in SDHCAL

CALICE Preliminary SDHCAL

$E_{\text{reco}}$ [GeV] vs $E_{\text{beam}}$ [GeV]

$\Delta E/E_{\text{beam}}$ vs $E_{\text{beam}}$ [GeV]

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Energy reconstruction in SDHCAL

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Event selection

- **Pions Data are contaminated with muons, cosmics, electrons** → **Event selection**
  - **Electron rejection**: Shower Start > 4
  - **Muon rejection**: $N_{\text{hit}} / N_{\text{layer}} > 2.2$
  - **Neutral rejection**: $N_{\text{hit}}$ in the first 5 layers > 4