Energy Reconstruction of hadron showers with the CALICE SDHCAL prototype

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Outline

**SDHCAL technological prototype**

✓ Short description
✓ Energy reconstruction method
✓ Improvement with PID techniques
✓ Further improvements on energy reconstruction

Summary
The SDHCAL-GRPC is one of the two HCAL options based on PFA and proposed for **ILD of ILC/CEPC**. Modules are made of 48/40 RPC chambers equipped with **semi-digital, power-pulsed electronics** readout and placed in **self-supporting mechanical** structure to serve as absorber as well.

The structure proposed for the SDHCAL:
- is very compact with negligible dead zones
- Eliminates projective cracks
- Minimizes barrel / endcap separation
  (services leaving from the outer radius)

**SDHCAL Technological Prototype** should be as much as possible similar to the ILD module and able to study **hadronic showers**

**Challenges**
- Homogeneity for large surfaces
- Thickness of only few mms
- Lateral segmentation of 1 cm X 1 cm
- Services from one side
- Embedded power-cycled electronics
- Self-supporting mechanical structure
48 layers (-6λ₁)
1 cm X 1 cm granularity
3-threshold, 500000 channels
Power-Pulsed
Triggerless DAQ system
Self-supporting mechanical structure
SDHCAL prototype was exposed to beam particles at CERN PS, SPS in 2012, 2015, 2017 and 2018.

Electron rejection: shower starting after the fourth layer (6 radiation length)
SDHCAL prototype was exposed to beam particles at CERN PS, SPS in 2012, 2015, 2017 and 2018

Muon rejection: average number of hits/layer < 2
SDHCAL high granularity is conceived for PFA

It helps to optimize the connection of hits belonging to the same shower by using first the topology and then the energy information

**ArborPFA algorithm**: It connect hits and then their clusters using distance and orientation information then correct using tracker information (momentum)
Energy reconstruction

$$E_{\text{rec}} = \alpha (N_{\text{tot}}) N_1 + \beta (N_{\text{tot}}) N_2 + \gamma (N_{\text{tot}}) N_3$$

$$N_{\text{tot}} = N_1 + N_2 + N_3$$

$\alpha$, $\beta$, $\gamma$ are quadratic functions of $N_{\text{tot}} = N_1 + N_2 + N_3$

They are computed by minimizing:

$$\chi^2 = (E_{\text{beam}} - E_{\text{rec}})^2 / E_{\text{beam}}$$

Hough-Transform

Track segments reconstruction using 3D-Hough Transform helps to apply different treatment to the hits of these segments.

$$E_{\text{rec}} = \alpha (N_{\text{tot}}) N'_1 + \beta (N_{\text{tot}}) N'_2 + \gamma (N_{\text{tot}}) N'_3 + c \ N_{\text{HT}}$$

$$N_{\text{tot}} = N'_1 + N'_2 + N'_3 + N_{\text{HT}}$$
Energy reconstruction

Particle Identification

Due to the absence of Cerenkov detectors in front of the SDHCAL, the use of an electron selection (shower starting > $d = 6 \lambda_0$) was rather powerful but led to an important loss of hadrons ($d = 1 \lambda_0$).

To reject electrons and muons without losing hadrons we use the excellent granularity of SDHCAL to discriminate the three species. Several discriminatory variables were selected:

1- First layer of the shower (begin)
2- Number of tracks in the shower (trackMultiplicity)
3- Ratio of shower layers over total fired layers ($nSHowerLayer/Nlayers$)
4- Shower density (density)
5- Shower radius (radius)
6- Maximum shower position (length)
7- Ratio of $N_3/N_{tot}$
8- Average number of clusters

➢ BDT technique was used.
➢ Simulated events of electrons, muons and pions were used for training/validation before to apply to data.
➢ To avoid a possible bias due to discrepancy between data/simulation of electrons showers in the SDHCAL, pure electrons and muons data events were also used
First layer of the shower

# of showers normalized

3-10
2-10
1-10
1
10

Pion data
Pion simulation
Muon data
Muon simulation
Electron data
Electron simulation

CALICE SDHCAL

Shower layers/Fired layers

Number of tracks

# of showers normalized

Pion data
Pion simulation
Muon data
Muon simulation
Electron data
Electron simulation

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Shower density

Maximum Shower position (mm)

Shower Radius (cm)
Electron and muon rejection > 99%
Excellent agreement between data and simulation of pion events.
The BDT-based PID was first applied to the SPS 2015(10-80 GeV) samples.
The BDT-based PID technique was also applied to the PS (3-12 GeV) samples.
Comparison of reconstructed energy of 10 GeV PS (no electron contamination) and 10 GeV SPS (after rejection of electron contamination)
Further improvements on the energy reconstruction

Detector homogeneity

The homogeneity of the detector response is important to achieve better energy reconstruction.

A new calibration method based on varying the thresholds rather than the electronic gain was found to be powerful. Muon runs with different thresholds, Thr1: 0.1-0.42 pC, Thr2: 0.4-5, Thr3:4.7-24, and efficiency and multiplicity were measured for each value. The values of the three thresholds of each ASIC were fixed to obtain same multiplicity (first threshold) and the same efficiency for thr2 and thr3.
Further improvements on the energy reconstruction

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\[ \varepsilon(t; q, \delta, \varepsilon_0) = \varepsilon_0 \cdot \left( 1 - \int_0^q P(q; \bar{q}, \delta) dq \right) \]
\[ P(q; \bar{q}, \delta) = \frac{1}{\Gamma\left(\frac{3}{\delta}\right) \delta^{\frac{3}{\delta}} - 1} e^{-\frac{q}{\delta}} \]
\[ \mu(t; f, p, c) = f \cdot t^p + c \]
Further improvements on the energy reconstruction

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Further improvements on the energy reconstruction

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Before

3.9%

After

1.4%

We will apply the new method to the data to be collected in 2022.
Further improvements on the energy reconstruction

Multi-Variate Techniques

Several MVT methods (NN and BDT) were used to exploit, in addition to $N_1$, $N_2$ and $N_3$, the hadronic shower shape information related to its energy thanks to the high granularity of the SDHCAL.

<table>
<thead>
<tr>
<th>Input Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$nHit_1$</td>
<td>The number of hits only exceeding the threshold 1</td>
</tr>
<tr>
<td>$nHit_2$</td>
<td>The number of hits exceeding the threshold 2 but not threshold 3</td>
</tr>
<tr>
<td>$nHit_3$</td>
<td>The number of hits exceeding the threshold 3</td>
</tr>
<tr>
<td>$nHit$</td>
<td>$nHit = nHit_1 + nHit_2 + nHit_3$</td>
</tr>
<tr>
<td>$nHough$</td>
<td>Number of hits used to do Hough Transformation</td>
</tr>
<tr>
<td>$nCluster$</td>
<td>Number of clusters</td>
</tr>
<tr>
<td>$nTrack$</td>
<td>Number of tracks</td>
</tr>
<tr>
<td>$nLayer$</td>
<td>Number of layers fired</td>
</tr>
<tr>
<td>Density</td>
<td>The density of hits</td>
</tr>
<tr>
<td>$meanRadius$</td>
<td>Mean of distance between tracks and hits</td>
</tr>
<tr>
<td>$InterLayer$</td>
<td>Number of layers when $meanRadius &gt; 5cm$</td>
</tr>
<tr>
<td>$begin$</td>
<td>The number of the layer where the shower starts</td>
</tr>
</tbody>
</table>
Several MVT methods were used to exploit in addition to $N_1$, $N_2$ and $N_3$ the shape information that is related to the shower energy thanks to high granularity of SDHCAL. Simulated pion events within SDHCAL were used for this study.

**Further improvements on the energy reconstruction**

MLP seems to perform better.
Hadron identification

The energy reconstruction method was applied to hadron events. No distinction was made between pions and protons or others. Hadronic showers of pions and protons are not identical.

Better construction can be made if one can identify the nature of the hadron.

2022 beam test will be dedicated to study pion vs proton and kaon showers using Cerenkov detectors. Then BDT technique will be used to develop hadron PID and then energy construction algorithm with different $(\alpha, \beta, \gamma)$ parameters could be used.
Summary

➢ SDHCAL concept with its high granularity provides an excellent tool not only to apply PFA by separating nearby showers but also to measure their energy.

➢ Different techniques were used to measure hadronic shower energy excellent linearity and very good resolution are obtained

➢ The exploitation of the hadronic shower shape thanks to the high granularity is an excellent asset to identify particles and then better measure their energy.

➢ In the future SDHCAL will exploit precise time information using MRPC. The time information will improve on energy reconstruction by separating delayed neutrons contribution and better estimating it.
Standard: $\varepsilon = 0.95 \pm 0.04$

After homogenization: $\varepsilon = 0.96 \pm 0.05$
Time correction
SDHCAL High-granularity impact

Hough Transform is an example to extract tracks within hadronic showers and to use them to control the calorimeter in situ

\[ \rho_{xz} = z \sin(\theta) + x \cos(\theta) \]

Excellent agreement with efficiency/multiplicity results obtained with cosmic and beam-muons. Excellent agreement data/MC
\[ \langle \varepsilon \rangle : 0.89 \pm 0.04 \]
Timing could be an important factor to identify delayed neutrons and better reconstruct their energy.