Performance of highly granular calorimeters in test beams

M.C Fouz (CIEMAT)

For the CALICE Collaboration

ICHEP July 2014, Valencia
Motivation of Highly Granular Calorimeters

**Particle Flow Algorithms (PFA)** allow to **improve the jet energy reconstruction** by **measuring each single particle** (charged particles, photons, neutral hadrons) in the sub-detector providing the best resolution for this particle type.

- **Reconstruct individual particles within jets**
- **Associate calorimeter clusters with correct tracks**

**Requires**

- **Precise tracking system**
- **Calorimeters with high segmentation**
- **Dedicated reconstruction algorithms**

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**Particles in jets**

<table>
<thead>
<tr>
<th>Particles in jets</th>
<th>Fraction of energy</th>
<th>Measured with</th>
<th>Resolution $[\sigma^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged</td>
<td>65 %</td>
<td>Tracker</td>
<td>Negligible</td>
</tr>
<tr>
<td>Photons</td>
<td>25 %</td>
<td>ECAL with 15%/$\sqrt{E}$</td>
<td>$0.07^2 E_{jet}$</td>
</tr>
<tr>
<td>Neutral Hadrons</td>
<td>10 %</td>
<td>ECAL + HCAL with 50%/$\sqrt{E}$</td>
<td>$0.16^2 E_{jet}$</td>
</tr>
<tr>
<td>Confusion</td>
<td></td>
<td></td>
<td>$\leq 0.04^2$ (goal)</td>
</tr>
</tbody>
</table>

The goal for ILC detectors $\Rightarrow \sigma(E)=30%/\sqrt{E}$
A factor 2 better than traditional calorimetric measurements without PFA
The CALICE Collaboration

**Goal:** Development of highly granular “imaging” calorimeters optimized for Particle Flow for jet reconstruction.

Unprecedented granularity “Tracking” calorimeter

Two generations of prototypes

**Physics prototypes**
- Proof-of-principle and study of showers and MC models validation (see Eva Sicking’s talk)

**Technological prototypes**
- Address integration and technical issues for “real” detectors

Tungsten: Narrow showers $X_0=3.5\text{mm}$ $R_M=9\text{mm}$  
- Better separation of particles in jets $\lambda_i/X_0=27.4$ Hadron shower deposits most of $E$ in HCAL

336 physicists/engineers from 57 institutes and 17 countries coming from the 4 regions (Africa, America, Asia and Europe)
**Si-W Electromagnetic Calorimeter (Si-W ECAL)**

**Absorber:** Tungsten sheets wrapped in carbon fiber

**Detector:** Silicon PIN diodes 1x1cm² (Comparable to R₉:0.9 cm)

Si allows high granularity & compactness

Length: 30 layers ~ 24X₀ ~ 1λ₁

3 "stacks", 10 modules each

Different absorber thickness

- 1.4 mm (0.4 X₀)
- 2.8 mm (0.8 X₀)
- 4.2 mm (1.2 X₀)

Lateral size: 18x18cm²

9720 channels

1 sensor plane = 2 detector slabs
Si-W Electromagnetic Calorimeter (Si-W ECAL)

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Detector: Silicon PIN diodes $1 \times 1 \text{cm}^2$ (Comparable to $R_M:0.9 \text{ cm}$)
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1 Slab
2 sensitive layers mounted on the two sides of a H-shaped W supporting structure

**Offset** to reduce dead areas (+ 1.3 mm offset between successive slabs)
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Lateral size: $18 \times 18 \text{cm}^2$

1 sensor plane = 2 detector *slabs*

**SLAB**

1 *Slab*  
2 *sensitive layers* mounted on the two sides of a H-shaped W supporting structure

1 *layer* = 6 (3) *Si wafers* (525$\mu$m thick)

1 *wafer* = 6x6 *pads* $1 \times 1 \text{cm}^2$

*Offset* to reduce dead areas (+ 1.3 mm offset between successive slabs)
1.- Pedestal subtraction

2.- ADC-MIP calibration

Response of *single channels to* $\mu$

Landau convoluted with a Gaussian

MIP signal =

most probable value of the Landau

$\mu$ 32 GeV
1.- Pedestal subtraction

2.- ADC-MIP calibration

Response of single channels to $\mu$ Landau convoluted with a Gaussian MIP signal=
most probable value of the Landau

3.- Energy Reconstruction

$E_{raw} = \sum_{i=0}^{9} E_i + 2 \sum_{i=10}^{19} E_i + 3 \sum_{i=20}^{29} E_i$

Stacks weighted according their thickness $E_i =$ Total energy plane $i$
1.- Pedestal subtraction

2.- ADC-MIP calibration
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$E_i = $ Total energy plane $i$

4.- Gap correction

1+1 mm inactive area between wafers (guard ring)
$\Rightarrow$ non-uniform energy response

Mean value of Energy depending on particle incident position

Normalized ECAL response
Si-W ECAL Calibration

1.- Pedestal subtraction

2.- ADC-MIP calibration

Response of single channels to $\mu$
Landau convoluted with a Gaussian
MIP signal=
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$\mu$ 32 GeV

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1+1 mm inactive area between wafers (guard ring)
$\Rightarrow$ non-uniform energy response

8 GeV $e^+$

Mean value of Energy depending on particle incident position

Energy can be corrected by $1/f(x, y)$

8 GeV $e^+$
Si-W ECAL Performance

**Without Gap correction**

\[ E_{\text{mean}} = P_0 + p_1 E_{\text{beam}} \]

\[
\begin{align*}
\chi^2 / \text{ndf} & = 365.94 / 3 \\
p_0 & = -139 \pm 1.2945 \\
p_1 & = 256.21 \pm 0.1594
\end{align*}
\]
Si-W ECAL Performance

\[ E_{\text{mean}} = P_0 + P_1 E_{\text{beam}} \]

Gap correction reduce scattering from linear response

Without Gap correction

With Gap correction

\[ \chi^2 / \text{ndf} = 365.94 / 3 \]
\[ P_0 = 139 \pm 1.2945 \]
\[ P_1 = 259.21 \pm 0.15994 \]

\[ \chi^2 / \text{ndf} = 158.66 / 3 \]
\[ P_0 = -109.97 \pm 0.69923 \]
\[ P_1 = 209.48 \pm 0.10723 \]

\[ \pm 1\% \]
\[ \pm 0.5\% \]
Si-W ECAL Performance

\[ E_{\text{mean}} = P_0 + P_1 E_{\text{beam}} \]

Gap correction reduce scattering from linear response

\[ \sigma_E(E) = \frac{a(\%)}{\sqrt{E}} \oplus b(\%) \]

Without Gap correction

With Gap correction

Gap correction doesn’t correct fully the gap effect.

A gap correction computed per stack or layer may further improve the results

Beam spread subtracted only in CERN results
**Scintillator – W Electromagnetic calorimeter (Sc-W ECAL)**

**Absorber:** Tungsten (88%W 12%Co 0.5%C) 3.5mm thick  
**Detector:** Plastic scintillator  

- **Strip**  
  4.5x1 cm² 3mm thick  
  - WLS (WaveLength Shifting) fiber  
  - MPPC (MultiPixel Photon Counter)  
  - 1600 pixels  
  - MPPCs in strip  

Odd layers orthogonal to even layers  
⇒ 1x1cm² effective granularity  

Less readout channels  
but shower reconstruction more complicated  

- 21.3X₀  
- 2160 Readout channels  
- 30 layers  
- 26 cm  
- 18 cm  

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Sc-W ECAL Calibration

- Pedestal subtraction
Sc-W ECAL Calibration

- Pedestal subtraction

- ADC-MIP calibration
  
  Response of **single channels to μ** Landau convoluted with a Gaussian
  MIP signal= most probable value
  
  \[
  1\text{PMIP} \sim 160 \text{ ADC counts}
  \]

  **Temperature dependence**

  MPPC breakdown voltage & gain depends on temperature
  
  Linear dependence of the ADC-MIP conversion factor with Temperature

  It can be parameterized
Sc-W ECAL Calibration

- Pedestal subtraction

- ADC-MIP calibration

Response of *single channels to μ*
Landau convoluted with a Gaussian
MIP signal= most probable value
1PMIP ~ 160 ADC counts

Temperature dependence

MPPC breakdown voltage & gain depends on temperature
Linear dependence of the ADC-MIP conversion factor with Temperature
It can be parameterized

- MPPC saturation. ADC-photon conversion factor

MPPC is non-linear due the
finite number of pixels

\[ N_{\text{fired}} = N_{\text{eff}}^{\text{pix}} \left( 1 - \exp \left( -\frac{\varepsilon N_{\text{in}}}{N_{\text{eff}}^{\text{pix}}} \right) \right) \]

- MPPC output
- \( N_{\text{eff}}^{\text{pix}} = \text{Nb. “effective” MPPC pixels} \)
- \( N_{\text{in}} = \text{Nb. Photons incident on the sensor} \)
- \( \varepsilon = \text{Photon detection eff.} \)

Light pulse from a LED

Temperature should also be taken into account
- Pedestal subtraction

- ADC-MIP calibration
  Response of single channels to $\mu$
  Landau convoluted with a Gaussian
  MIP signal= most probable value
  \[1PMIP \approx 160 \text{ ADC counts}\]

- MPPC saturation. ADC-photon conversion factor
  MPPC is non-linear due the finite number of pixels
  \[N_{\text{fired}} = N_{\text{effpix}} \left(1 - \exp\left(-\frac{\varepsilon N_{\text{in}}}{N_{\text{effpix}}}\right)\right)\]
  \[N_{\text{fired}} = \text{MPPC output}\]
  \[N_{\text{effpix}} = \text{Nb. “effective” MPPC pixels}\]
  \[N_{\text{in}} = \text{Nb. Photons incident on the sensor}\]
  \[\varepsilon = \text{Photon detection eff.}\]

- Energy Reconstruction
  \[E_{\text{total}} = \sum_{l=1}^{30} \sum_{s=1}^{72} \frac{E'_{ls}(T)}{C'_{ls}(T)}\]
  \(l = \text{Layer}\)
  \(s = \text{Strip}\)
  \(E'_{ls}(T) = \text{Measured energy } \cdot \text{corrected for saturation}\)
  \(C'_{ls}(T) = \text{ADC-MIP Calibration}\)
Sc-W ECAL Performance

**Linearity**

T correction applied ONLY to ADC-MIP

Slope = 127.6

Correction of ADC-MIP by T improves linearity
Sc-W ECAL Performance

**Linearity**

T correction applied ONLY to ADC-MIP

T correction applied to ADCP-MIP & Saturation

Correction of ADC-MIP by T improves linearity

Taken also into account T in the correction of saturation increases slope 3%

Slope = 127.6

Slope = 131.3
Sc-W ECAL Performance

**Linearity**

- T correction applied ONLY to ADC-MIP

**Resolution**

- T correction applied to ADPC-MIP & Saturation

**Slope**

- Before Temperature correction: 127.6
- After Temperature correction: 131.3

**Correction of ADC-MIP by T improves linearity**

**Deviation from linear (%)**

- T Corrected
  - FULL: 12.9 ± 0.1 ± 0.4
  - ADC-MIP: 13.13 ± 0.03
  - NONE: 15.15 ± 0.03

**Taken also into account T in the correction of saturation increases slope 3%**

<table>
<thead>
<tr>
<th>T Correct.</th>
<th>a (%)</th>
<th>b (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FULL</td>
<td>12.9 ± 0.1 ± 0.4</td>
<td>1.2 ± 0.1 + 0.4 - 0.2</td>
</tr>
<tr>
<td>ADC-MIP</td>
<td>13.13 ± 0.03</td>
<td>2.41 ± 0.01</td>
</tr>
<tr>
<td>NONE</td>
<td>15.15 ± 0.03</td>
<td>1.44 ± 0.02</td>
</tr>
</tbody>
</table>
Fe-Scintillator HCAL (Fe-AHCAL)

Absorber: Steel (~19 mm)
Detector: Plastic scintillator

38 detector layers
30 (first) layers

5mm thick

SiPM
1156 pixels

WLS (WaveLength Shifting) fiber

3x3 cm²

AHCAL
5.3 \lambda_i
7608 readout channels

6x6 cm²

3D hadronic showers

Possible to identify MIP track segments within shower

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Fe-AHCAL Software compensation techniques

Calibration procedures used are similar to the Sc-ECAL

Software compensation motivation:

Hadron shower ➔ Two components (e.m & purely hadronic)
Different response and fluctuations from event to event

2 Techniques developed
Fe-AHCAL Software compensation techniques

Calibration procedures used are similar to the Sc-ECAL

Software compensation motivation:

Hadron shower ➜ Two components (e.m & purely hadronic)
Different response and fluctuations from event to event

2 Techniques developed

Local Software compensation (LSC)

Weights ($\omega_i$) in every cell based on the local energy density ($\rho = E_{cell}/Volume_{Cell}$)

(density indicates probability than the cell belongs to an e.m or hadronic sub-shower)

$$E_{LSC} = E_{track}^{ECAL} + \frac{e}{\pi} \left( \sum_i (E_{HCAL,i} \omega_i) + E_{TCM} \right)$$

$$\frac{e}{\pi} = 1.19$$

$$\omega_i = f(\rho_i, E_{beam})$$

obtained by minimizing

$$\chi^2 = \sum_i (E_{LSC,i} - E_{beam})^2$$

Corrections based on the signal recorded without using the beam energy
Fe-AHCAL Software compensation techniques

Software compensation motivation:

- Hadron shower: Two components (e.m & purely hadronic)
  - Different response and fluctuations from event to event

2 Techniques developed

- **Local Software compensation (LSC)**
  - Weights \( \omega_i \) in every cell based on the **local energy density** \( \rho = \frac{E_{\text{cell}}}{\text{Volume}_{\text{Cell}}} \)
  - Density indicates probability than the cell belongs to an e.m or hadronic sub-shower
  - \[ E_{\text{LSC}} = E_{\text{ECAL}}^{\text{track}} + \frac{e}{\pi} \left( \sum_i (E_{\text{HCAL},i} \omega_i) + E_{\text{TCM}} \right) \]
  - \( e = 1.19 \)
  - \( \omega_i = f(\rho_i, E_{\text{beam}}) \)
  - Obtained by minimizing
  - \[ \chi^2 = \sum_i (E_{\text{LSC},i} - E_{\text{beam}})^2 \]

- **Global Software compensation (GSC)**
  - Single Global weight based on the fraction of hits with energy \( E_h \) below an energy threshold \( e_{\text{bin}} \)
  - \[ C_{\text{glob}} = \frac{N(E_h < e_{\text{bin}})}{N(E_h < < E_h>)} \]
  - \( < E_h > \) Mean value of \( E \) of single hit
  - \( e_{\text{bin}} \) optimized for full E range (based on linearity)

Corrections based on the signal recorded without using the beam energy
Fe-AHCAL Performance

Dotted line \( \Rightarrow \) \( E_{\text{reco}} = E_{\text{beam}} \)

\[ \pm 1.5\% \text{ linearity for both (GSC & LSC)} \]
Fe-AHCAL Performance

Dotted line
\[ \frac{\sigma_{E_{\text{reco}}}}{E_{\text{reco}}} = \frac{a}{\sqrt{E_{\text{beam}}}} \oplus b \oplus \frac{c}{E_{\text{beam}}} \]

\[ \text{c fixed to 0.18} \]

\[ \Rightarrow \text{measured noise contribution} \]

<table>
<thead>
<tr>
<th></th>
<th>a (%)</th>
<th>b (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncorrected</td>
<td>57.6 ± 0.4</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td>GSC</td>
<td>45.8 ± 0.3</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td>LSC</td>
<td>44.3 ± 0.3</td>
<td>1.8 ± 0.3</td>
</tr>
</tbody>
</table>

Software compensation algorithms improve significantly the energy resolution.

\( \pm 1.5\% \) linearity for both (GSC & LSC)

\( \Rightarrow \) Ereco = Ebeam

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**Fe-RPC Digital HCAL (DHCAL)**

**Absorber:** Steel (16 mm steal plate + (2mm steel & 2mm copper cassette) )

**Detector:** GRPC (Glass Resistive Plate Chambers) operating in avalanche mode

- 1x1 cm² pads
- Digital Readout: Gives which and how many pads have a signal about a threshold

Electronics embedded in the detector planes

- 1 Layer = 3 RPCs
- 3X(32x96cm²)
- 38 active layers

**Full AHCAL prototype < 8000 channels**

- 1 Layer = 9216 readout channels!!

**DHCAL before cabling**

**RAW Event**

**Pion shower**

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Using muon tracks compute efficiency ($\varepsilon$) and multiplicity ($\mu$) (#hits in a cluster)

- $H_i$: Total number of hits for layer $i$
- $\varepsilon_0\mu_0$: Average $\varepsilon$ & $\mu$ for prototype
- $\varepsilon_i\mu_i$: Average $\varepsilon$ & $\mu$ for layer $i$

$$H = \sum_i \frac{\varepsilon_0\mu_0}{\varepsilon_i\mu_i} H_i$$
DHCAL Calibration

Using muon tracks compute efficiency ($\varepsilon$) and multiplicity ($\mu$) (#hits in a cluster)

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Density-weighted calibration

Pad calibration factors depend on local hit density
DHCAL Calibration

**Full Calibration**

- **Using muon tracks compute efficiency (ε) and multiplicity (µ) (#hits in a cluster)**
  - $H_i$ → Total number of hits for layer $i$
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$$H = \sum_i \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} H_i$$

**Density-weighted calibration**

- Pad calibration factors depend on local hit density

1. Produce **MC samples digitized** with $\varepsilon_i \mu_i$ and $\varepsilon_0 \mu_0$
DHCAL Calibration

Using muon tracks compute efficiency ($\varepsilon$) and multiplicity ($\mu$) (#hits in a cluster)  

- **Full Calibration**
  - $H_i$ \(\Rightarrow\) Total number of hits for layer $i$
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**Density-weighted calibration**

1.- Produce **MC samples digitized** with $\varepsilon_i\mu_i$ and $\varepsilon_0\mu_0$
2.- **Classify** hits into **density bins (0-8)**

(#neighbors hits around 3x3 array)

Pad calibration factors depend on local hit density

1. Produce **MC samples digitized** with $\varepsilon_i\mu_i$ and $\varepsilon_0\mu_0$
2. Classify hits into **density bins (0-8)**

(#neighbors hits around 3x3 array)

Density 4  Density 1
DHCAL Calibration

Using muon tracks compute efficiency ($\varepsilon$) and multiplicity ($\mu$) (#hits in a cluster)

Full Calibration

- **Total number of hits for layer $i$**: $H_i$
- **Average $\varepsilon$ & $\mu$ for prototype**: $\varepsilon_0 \mu_0$
- **Average $\varepsilon$ & $\mu$ for layer $i$**: $\varepsilon_i \mu_i$

$$H = \sum_i \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} H_i$$

Density-weighted calibration

Pad calibration factors depend on local hit density

1. Produce **MC samples digitized** with $\varepsilon_i \mu_i$ and $\varepsilon_0 \mu_0$
2. **Classify** hits into **density bins (0-8)** (#neighbors hits around 3x3 array)
3. **Compare density** hits both **MC samples**
   - $C = $ Correction

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DHCAL Calibration

Full Calibration

- Using muon tracks compute efficiency ($\varepsilon$) and multiplicity ($\mu$) (#hits in a cluster)
  
  $H_i \rightarrow$ Total number of hits for layer $i$
  
  $\varepsilon_0 \mu_0 \rightarrow$ Average $\varepsilon$ & $\mu$ for prototype
  
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$H = \sum_i \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} H_i$

Density-weighted calibration

- Pad calibration factors depend on local hit density

1. Produce **MC samples digitized** with $\varepsilon_i \mu_i$ and $\varepsilon_0 \mu_0$

2. Classify hits into **density bins (0-8)**
   (#neighbors hits around 3x3 array)

3. Compare density hits both **MC samples**
   
   $C = $ Correction

4. For each density beam plot $C$ vs $R = \frac{\varepsilon_i \mu_i}{\varepsilon_0 \mu_0}$

   $R_{\pi} = \frac{\varepsilon_i^{0.3} \mu_i^{1.5}}{\varepsilon_0^{0.3} \mu_0^{1.5}}$
   
   $R_e = \frac{\varepsilon_i^{0.3} \mu_i^{2.0}}{\varepsilon_0^{0.3} \mu_0^{2.0}}$

Correction factor vs $R_{\pi}$

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DHCAL Calibration

Using muon tracks compute efficiency ($\varepsilon$) and multiplicity ($\mu$) (#hits in a cluster)

$$ H_i \rightarrow \text{Total number of hits for layer } i $$

$$ \varepsilon_0 \mu_0 \rightarrow \text{Average } \varepsilon \text{ & } \mu \text{ for prototype} $$

$$ \varepsilon_i \mu_i \rightarrow \text{Average } \varepsilon \text{ & } \mu \text{ for layer } i $$

$$ H = \sum_i \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} H_i $$

**Density-weighted calibration**

Pad calibration factors depend on local hit density

1.- **Produce MC samples digitized** with $\varepsilon_i \mu_i$ and $\varepsilon_0 \mu_0$

2.- **Classify** hits into **density bins (0-8)** (#neighbors hits around 3x3 array)

3.- **Compare density** hits both MC samples

   $\Rightarrow \text{ C = Correction}$

4.- For each density beam plot C vs $R = f(\varepsilon_i \mu_i / \varepsilon_0 \mu_0)$

   $$ R_\pi = \frac{\varepsilon_i^{0.3} \mu_i^{1.5}}{\varepsilon_0^{0.3} \mu_0^{1.5}} \quad R_e = \frac{\varepsilon_i^{0.3} \mu_i^{2.0}}{\varepsilon_0^{0.3} \mu_0^{2.0}} $$

5.- **Fit C vs R** independently for each density bin

   $$ C = p_0 R^{p_1} $$

Correction to be applied

**Correction factor vs $R_\pi$**

CALICE Simulation Fe-DHCAL

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DHCAL Calibration

Using muon tracks compute efficiency ($\varepsilon$) and multiplicity ($\mu$) (#hits in a cluster)

- **Full Calibration**
  - $H_i$ → Total number of hits for layer $i$
  - $\varepsilon_0\mu_0$ → Average $\varepsilon$ & $\mu$ for prototype
  - $\varepsilon_i\mu_i$ → Average $\varepsilon$ & $\mu$ for layer $i$
  - $H = \sum_i \frac{\varepsilon_0\mu_0}{\varepsilon_i\mu_i} H_i$

**Density-weighted calibration**

1. Produce **MC samples digitized** with $\varepsilon_i\mu_i$ and $\varepsilon_0\mu_0$
2. Classify hits into **density bins (0-8)** (#neighbors hits around 3x3 array)
3. Compare density hits both **MC samples**
   - $C =$ Correction
4. For each density beam plot $C$ vs $R$ = $f(\varepsilon_i\mu_i / \varepsilon_0\mu_0)$
   - $R_\pi = \frac{\varepsilon_i^{0.3}\mu_i^{1.5}}{\varepsilon_0^{0.3}\mu_0^{1.5}}$
   - $R_e = \frac{\varepsilon_i^{0.3}\mu_i^{2.0}}{\varepsilon_0^{0.3}\mu_0^{2.0}}$
5. Fit $C$ vs $R$ independently for each **density bin**
   - $C = p_0 R^{p_1}$
   - Correction to be applied

**Hybrid calibration**

- If density 0 or 1 → apply **Full calibration**
- If density>1 → apply **Density-weighted calibration**
The 3 calibration methods produce a more uniform response for runs at same energy respect to uncalibrated.

Resolution

$$\frac{\sigma(E)}{E} = \frac{\alpha}{\sqrt{E}} \oplus C$$

<table>
<thead>
<tr>
<th></th>
<th>(\alpha)</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>0.66</td>
<td>0.04</td>
</tr>
<tr>
<td>Density weighed</td>
<td>0.63</td>
<td>0.04</td>
</tr>
<tr>
<td>Hybrid</td>
<td>0.64</td>
<td>0.03</td>
</tr>
</tbody>
</table>

DHCAL Performance

Nhits vs Beam Energy (Fit to \(N = aE^m\))

Fit to a cte all runs same E

\(\chi^2/ndf vs E\)
W-DHCAL

Absorber: 3.3 $X_0$ per layer

**Tungsten** (10 mm) + (2mm steel & 2mm Cu cassette)

Saturation at low momenta due to the smaller $X_0$ and $R_M$ in W (higher density) & binary readout

~30% less hits in W respect to Fe

Overcompensation

$$\sigma(E) = \frac{a}{\sqrt{E}} + b$$

<table>
<thead>
<tr>
<th>a (%)</th>
<th>b (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.4</td>
<td>16.6</td>
</tr>
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<td>68.0</td>
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**Tungsten** (10 mm) + (2mm steel & 2mm Cu cassette)

~30% less hits in W respect to Fe

Saturation at low momenta due to the smaller $X_0$ and $R_M$ in W (higher density) & binary readout

Not seen for W-AHCAL

Pads size need to be reduced

Overcompensation

\[
\sigma(E) E = \frac{a}{\sqrt{E}} \oplus b
\]

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<thead>
<tr>
<th></th>
<th>a (%)</th>
<th>b (%)</th>
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</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>29.4</td>
<td>16.6</td>
</tr>
<tr>
<td>Pions</td>
<td>68.0</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Not calibrated
Semi-Digital Hadronic Calorimeter (SDHCAL)

Absorber: **Steel** (20 mm)
Detector: **GRPC (Glass Resistive Plate Chambers)** operating in **avalanche mode**

1x1 cm$^2$ pads. **Semi-Digital Readout**, 2 bits - **3 thresholds**

Technological prototype

144 ASICs = 9216 channels/1m$^2$

48 active layers 1x1 m$^2$ GRPCs ~ 6 $\lambda_i$

- Large detector (1x1 m$^2$) with almost no dead zones
- Large electronics board
- One-side services
- Self-supporting mechanical structure
- Power-pulsed electronics

Absorber plates
Planarity < 500 $\mu$m
Thickness tolerance 50 $\mu$m
Triggerless acquisition mode ➔ Time Clustering for event building
It includes also cosmics. Particle identification (muons, electrons, pions) is applied
Triggerless acquisition mode ➔ Time Clustering for event building
It includes also cosmics. Particle identification (muons, electrons, pions) is applied

<table>
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<tr>
<th>Energy Reconstruction – Binary mode</th>
<th>( E_{\text{reco}} = (C+D \cdot N_{\text{tot}}) \cdot N_{\text{tot}} )</th>
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</table>

<table>
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<tr>
<th>( N_{\text{tot}} = N_1 + N_2 + N_3 )</th>
<th>Number of pads with signal</th>
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<tr>
<td>( N_1 = \text{Nhits crossing only the first (lower) threshold} )</td>
<td>( N_2 = \text{Nhits crossing the 2^{nd} threshold but not the 3^{rd}} )</td>
</tr>
<tr>
<td>( N_3 = \text{Nhits crossing the 3^{rd} (higher) threshold} )</td>
<td>( C=0.0543, : D=0.09 \times 10^{-4} ) Determined from data (Ebeam vs Nhit)</td>
</tr>
</tbody>
</table>

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M.C Fouz
**SDHCAL Energy calibration**

**Triggerless acquisition mode** ➔ **Time Clustering for event building**

It includes also cosmics. **Particle identification** (muons, electrons, pions) is applied.

### Energy Reconstruction – Binary mode

\[ E_{\text{reco}} = (C + D \cdot N_{\text{tot}}) \cdot N_{\text{tot}} \]

- Allows restoring linearity
- \( N_{\text{tot}} = N_1 + N_2 + N_3 \) Number of pads with signal
- \( N_1 \) = Nhits crossing only the first (lower) threshold
- \( N_2 \) = Nhits crossing the 2\(^{nd}\) threshold but not the 3\(^{rd}\)
- \( N_3 \) = Nhits crossing the 3\(^{rd}\) (higher) threshold
- \( C = 0.0543, \ D = 0.09 \times 10^{-4} \) Determined from data (Ebeam vs Nhit)

### Energy Reconstruction – Multithreshold mode

\[ E_{\text{reco}} = \alpha N_1 + \beta N_2 + \gamma N_3 \]

- \( \alpha, \beta, \gamma = f(N_{\text{tot}}) \) (Quadratic function)
- \( \alpha, \beta, \gamma \) are obtained by minimizing \( \chi^2 \) from a data subsample

\[
\chi^2 = \sum_{i=1}^{N} \frac{(E_{\text{beam}}^i - E_{\text{reco}}^i)^2}{E_{\text{beam}}^i}
\]

**ICHEP July 2014, Valencia**

M.C Fouz
Time Spill correction

GRPC efficiency decreases at high rate. Efficiency decrease with time in spill due to charge accumulative effects. This can be corrected

\[ N_{\text{TOTcor}} = N_1 - \text{Slope}_1 \times \text{Time} + N_2 - \text{Slope}_2 \times \text{Time} + N_3 - \text{Slope}_3 \times \text{Time} \]
SHDCAL Energy Calibration

**Time Spill correction**

GRPC efficiency decreases at high rate. Efficiency decrease with time in spill due to charge accumulative effects. This can be corrected

\[ N_{TOT\text{cor}} = N_1 - \text{Slope}_1 \times \text{Time} + N_2 - \text{Slope}_2 \times \text{Time} + N_3 - \text{Slope}_3 \times \text{Time} \]

**Track hits correction.**

Single tracks can produce a signal bigger than 2\text{nd} or 3\text{rd} threshold and can bias the measurement.

Identifying those tracks, removing the hits belonging to them from \( N_1, N_2, N_3 \) and giving them the same weight can improve the results

\[ E_{\text{reco}} = \alpha N_1' + \beta N_2' + \gamma N_3' + c N_T \]
SHDCAL Energy Calibration

**Time Spill correction**

GRPC efficiency decreases at high rate. Efficiency decrease with time in spill due to charge accumulative effects. This can be corrected

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\[
E_{\text{reco}} = \alpha N1' + \beta N2' + \gamma N3' + c N_T
\]

**Density weighting**

Separate the hits in **high-density** (e.m) and **low-density** (had) and give different weights

Density computed in a volume \( 1.5(x) \times 1.5 (y) \times 3.1 \text{ cm}^3 \)

\( >9 \Rightarrow \text{High density} \)

<table>
<thead>
<tr>
<th>High density part</th>
<th>Low density part</th>
<th>Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_h N1_h + \beta_h N2_h + \gamma_h N3_h )</td>
<td>( \alpha_l N1_l + \beta_l N2_l + \gamma_l N3_l )</td>
<td>( c N_T )</td>
</tr>
</tbody>
</table>
Multi-threshold mitigate the saturation effects at higher energies and improve the resolution respect to binary.

**Time Spill, track & density correction NO applied**

**Multi-threshold**

**Corrections improve the resolution**
Other prototypes being developed

R&D on Micromegas & GEM Alternative to GRPC

Micromegas 1x1 m²

ECAL Technological prototypes

GEM

Long layers

New Si sensor design

Alveolar structure for ECAL 1.5m long (3/5 of a ILD module)

AHCAL Technological prototype

2.2 m HCAL Base Unit

New Si sensor design

New Scintillator strips

No WLS

Fiberless

New Tiles

MPPC

Integrated electronics for ScECAL
CALICE Collaboration is developing imaging calorimeters for the application of Particle Flow Techniques.

**Different types of prototypes** have been tested extensively with particle beams to prove the principle of the different technologies (Silicon, Scintillator, RPCs, Micromegas, GEM).

**Different methods of calibration and software compensation** are being developed profiting from the high granularity and tracking capabilities of the devices allowing **to improve the performance**.

The prototypes show **good resolutions** and **excellent tracking capabilities**.

The **technologies have been validated** and the collaboration is now tackling the remaining **technological issues**.
Backup
Absorber: Tungsten (92.99%W 5.25%Ni 0176%Cu) 1cm thick + 0.2 cm steel (detector cassettes)

Resolution $\Rightarrow (29.6 \pm 0.5)\%/\sqrt{E(\text{GeV})}$

Fe-AHCAL $\Rightarrow (21.9 \pm 1.4)\%/\sqrt{E(\text{GeV})}$

W-AHCAL coarse sampling 2$X_0$ vs 1.2$X_0$