Hadronic shower properties in highly granular calorimeters with different absorbers

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1. CALICE calorimeters for PFA
2. Hadron energy reconstruction with software compensation
3. Spatial shower development
4. Comparison of shower profiles
CALICE collaboration activities

https://twiki.cern.ch/twiki/bin/view/CALICE/WebHome

- Goal: test of particle-flow reconstruction
- R&D of highly granular electromagnetic and hadron calorimeters for HEP experiments
  - different readout technologies: analog, semi-digital, digital
  - different active materials: silicon, scintillator-SiPM, RPC
  - different absorbers: stainless steel, tungsten
- Validation of performance with test beams:
  - particle separation
  - energy resolution
- Study of reconstruction schemas, shower development and shower substructure:
  - software compensation
  - spatial development
  - time structure
- Validation of Geant4 simulations

Overlaid test beam hadron showers
- 10 GeV and 30 GeV
- 15 cm between shower axes
- setup: SiW ECAL+Sc-Fe AHCAL

In this talk: focus on scintillator-SiPM hadron calorimeter with different absorbers
CALICE scintillator-SiPM hadron calorimeters in test beams

**CALICE prototypes**

<table>
<thead>
<tr>
<th>Calorimeter Type</th>
<th>Description</th>
<th>Interaction Length (μm)</th>
<th>Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc-Fe(W) AHCAL</td>
<td>Scintillator tiles with SiPMs</td>
<td>5.2 (4.9)</td>
<td>38 layers</td>
</tr>
<tr>
<td>SiW ECAL</td>
<td>Silicon pads</td>
<td>∼1</td>
<td>30 layers</td>
</tr>
<tr>
<td>Sc-Fe TCMT</td>
<td>Scintillator strips with SiPMs</td>
<td>∼5.2</td>
<td>16 layers</td>
</tr>
</tbody>
</table>

**Beam tests:** ECAL (optional) + AHCAL + TCMT (optional); μ, e and hadrons of 1—300 GeV

**SiW ECAL + Fe-AHCAL + Sc-Fe TCMT**

**W-AHCAL + Sc-Fe TCMT**

<table>
<thead>
<tr>
<th>Calorimeter Type</th>
<th>Total Depth</th>
<th>Depth per Layer</th>
<th>e/π Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-AHCAL</td>
<td>5.2λ₁</td>
<td>0.137λ₁ (1.24X₀)</td>
<td>noncompensating e/π ∼1.2</td>
</tr>
<tr>
<td>W-AHCAL</td>
<td>4.9λ₁</td>
<td>0.129λ₁ (2.80X₀)</td>
<td>compensating e/π ∼1</td>
</tr>
</tbody>
</table>
Hadron energy reconstruction with software compensation

**Standard reconstructed**

\[
E_{\text{std}}^{\text{event}} = \sum_{s=1}^{M} C_s \cdot \sum_{i=1}^{N_s} e_{is}
\]

- Cell response equalized with MIPs; \(N_s\) - number of cells in \(s\)-th subdetector above 0.5 MIP (hits)
- \(e_{is}\) - amplitude in MIP of \(i\)-th hit in \(s\)-th subdetector (ECAL, AHCAL, TCMT) with hadronic scale calibration factors \(C_s\) in [GeV/MIP]

Mean and \(\sigma\) are extracted from the two-step Gaussian fit within ±2 RMS

**Software compensation (SC) reconstruction**

- Motivation: improve energy resolution by taking into account fluctuations of em fraction
- Correction is applied on an event-by-event basis
- Two software compensation techniques developed:
  - Hit energy weighting (Local SC)
  - Event energy weighting (Global SC)
  - Test on standalone calorimeter (shower start in AHCAL)
  - Improvement of resolution in Fe-AHCAL up to 25%
  - More details in *JINST 7 P09017 (2012)* and backup

- Improvement of pion energy resolution with local SC in combined setup up to \(\sim 42% / \sqrt{E/\text{GeV}}\) (*CAN-058*)

Hadron energy reconstruction with software compensation

Pion energy distributions and linearity of response

Test beam data: pions 10–80 GeV, SC applied to AHCAL hits
Selections: shower start (first inelastic interaction) in the first layers of AHCAL, mip in ECAL

Fe-AHCAL \((e/\pi \sim 1.2)\) with tail catcher

W-AHCAL \((e/\pi \sim 1)\) no tail catcher

Linearity of response within ±2% with and without software compensation
Energy resolution for single hadrons

Noncompensating (Fe-AHCAL) versus compensating (W-AHCAL) calorimeter

- Test beam data: pions 10–80 GeV
- Energy weighting technique (global software compensation)
- Shower start at the beginning of the AHCAL to minimise leakage
- Hit spectra for software compensation from AHCAL only

Fe-AHCAL ($e/\pi \sim 1.2$) with tail catcher

W-AHCAL ($e/\pi \sim 1$) no tail catcher

More significant improvement in noncompensating calorimeter than in compensating ⇒ SC corrects presumably for the fluctuations of EM fraction in hadronic showers

$JINST$ 7 P09017 (2012)

CAN-062
Spatial shower development

Hadronic shower characteristics

Longitudinal centre of gravity

\[ Z_0 = \frac{\sum_{i=1}^{N_{\text{sh}}} e_i \cdot (z_i - z_{\text{start}})}{\sum_{i=1}^{N_{\text{sh}}} e_i} \]

- \( z_i \) – longitudinal coordinate of hit \( e_i \)
- \( z_{\text{start}} \) – longitudinal position of shower start

Important for estimation of leakage

Shower radius

\[ R = \frac{\sum_{i=1}^{N_{\text{sh}}} e_i \cdot r_i}{\sum_{i=1}^{N_{\text{sh}}} e_i}, \quad N_{\text{sh}} \quad \text{– number of hits in shower} \]

- \( r_i \) – radial distance of hit \( e_i \) from shower axis \((x_0, y_0)\):
  \[ r_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2} \]

Important for particle separation in PFA

Mean shower radius in Fe-AHCAL

- Data
- FTFP_BERT
- QGSP_BERT

G4 v9.6 underestimates mean shower radius, better predictions from FTFP_BERT phys. list
Comparison of shower profiles

Longitudinal profiles from shower start

**Fe-AHCAL** *JINST 11 (2016) P06013*

- **Parametrisation (decomposition) of profiles**
  - sum of two Gamma-distributions
  - to disentangle EM and hadronic components

**Preliminary conclusions based on profile parametrisation for different absorbers**
- In higher-Z material (W): lower EM fraction, higher (lower) multiplicity for EM (hadronic) component
- Very similar longitudinal tail slopes for both absorbers

**Simulations overestimate electromagnetic fraction in hadronic showers.**
Discrepancy between data and simulations increase with increasing particle energy

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**Calice Fe-AHCAL**

\[ \chi^2/\text{ndf}: 14.0/27 = 0.52 \]

- \( f: (22.9 \pm 1.1)\% \)
- \( \alpha_{\text{short}}: 4.5 \pm 0.3 \)
- \( \beta_{\text{short}}: (1.6 \pm 0.1) X_0 \)
- \( \alpha_{\text{long}}: 1.35 \pm 0.01 \)
- \( \beta_{\text{long}}: (1.24 \pm 0.02) \lambda_i \)

**W-AHCAL** *JINST 10 P12006 (2015)*

**Simulations**

- Data
- QGSP_BERT_HP
- FTFP_BERT_HP

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8 / 9
Summary

Beam tests of CALICE highly granular calorimeter prototypes

- Scintillator-SiPM hadron calorimeter assembled from about 8000 tiles were constructed and exposed to test beams in 2006-2011 with steel and tungsten absorbers.
- Software compensation techniques help to decrease the contribution of stochastic term to resolution of noncompensating Sc-Fe AHCAL from $\sqrt[2]{E/\text{GeV}} \sim 58\%$ to $\sqrt[2]{E/\text{GeV}} \sim 45\%$, improvement is much smaller for compensating Sc-W AHCAL as expected.

Shower properties and validation of simulations

- Simulations predict narrower hadronic showers than observed in data.
- FTFP\_BERT physics list from Geant4 9.6 gives the best predictions (tests of Geant4 10.x ongoing).
- Good predictions of resolution, longitudinal development and substructure below 20 GeV.
- Discrepancies between data and simulations increase with energy.
- Deposition in the shower core (em fraction) is overestimated by simulations.

Next generation prototypes

- CALICE AHCAL technological prototype for the ILD in beam tests since 2017
- New features compared to the AHCAL physics prototype discussed above:
  - tiles with dimple and direct readout by SiPM
  - embedded electronics with power pulsing mode and time measurement
Backup slides
Energy reconstruction with software compensation

Software compensation techniques for analogue readout \[ JINST 7 P09017 (2012) \]

- Correction is applied on event-by-event basis
- Calibration factor $C_{trk}$ for track hits and hadron scale calibration $C_s$ for shower cluster

Hit weighting technique (local compensation)

$$ E_{SClocal}^{\text{event}} = C_{trk} \cdot \sum_{t=1}^{N_{trk}} e_t + \sum_{s=1}^{M} C_{s} \cdot \sum_{j=1}^{K_{s}} w_{js} (E_{\text{std}}^{\text{event}}) \cdot \sum_{i=1}^{N_{js}} e_{ijs} $$

- Hit spectrum in $s$-th subdetector is divided in $K_{s}$ bins.
- Hit amplitudes $e_{ijs}$ in bin $j$ in subdetector $s$ are weighted with $w_{js}$ ($1 \leq i \leq N_{js}$, typical $K_{s} = 8$).
- Hit weights are energy dependent, parametrisation is performed using test beam data.

Hit energies in SiW ECAL

Event energy weighting technique (global compensation)

$$ E_{SCglobal}^{\text{event}} = C_{trk} \cdot \sum_{t=1}^{N_{trk}} e_t + E_{cor}^{\text{event}} \cdot P(a_G, E_{cor}^{\text{event}}) $$

$$ E_{cor}^{\text{event}} = \sum_{s=1}^{M} C_{s} \cdot W_{s}^{\text{event}} \cdot \sum_{i=1}^{N_{s}} e_{is} $$

- Weights $W_{s}^{\text{event}}$ are calculated from hit energy spectrum shape.
- Coefficients $a_G$ of second-order polynomial $P$ are estimated from test beam data.
Noncompensating (Fe-AHCAL) versus compensating (W-AHCAL) calorimeter

- Same active layers (scintillator tiles with SiPM readout) and different absorbers
- Energy weighting technique (global compensation)
- Shower start at the beginning of the AHCAL to minimise leakage
- Hit spectra for software compensation from AHCAL only
- Energy from tail catcher added to the energy sum for Fe-AHCAL

Fe-AHCAL \((e/\pi \sim 1.2)\) with tail catcher

- Improvement of resolution \(\sim 10\text{--}25\%\)
  
  \textit{JINST 7 P09017 (2012)}

W-AHCAL \((e/\pi \sim 1)\) no tail catcher

- Improvement of resolution \(\sim 5\%\)
  
  \textit{CAN-062}
Shower development: first inelastic interaction

Diversity of hadron-induced showers: test beam data in SiW ECAL + Fe-AHCAL

Estimation of interaction length for pions and protons based on identification of shower start position.

Good agreement with Geant4 predictions and estimations of effective values using material properties.

JINST 10 P04014 (2015)
Hadronic shower development: profiles

**CALICE Fe-AHCAL**

- Fine longitudinal segmentation: $\sim 0.14 \lambda_I$ per layer
- Fine transverse granularity: $3 \times 3$ cm$^2$ tiles in the central part
- Combined test beam setup: SiW ECAL + **Fe-AHCAL** + TCMT (MIP in ECAL)
- Longitudinal profile from the identified first inelastic interaction
- Radial profile with respect to shower axis (incoming track or cluster centre of gravity)
- Comparison of data with Geant4 versions 9.6 and 10.1 (*CAN-040b*)

Discrepancy within 5%, increases up to 10% at 80 GeV.

**Longitudinal profile (30 GeV pion)**

**Radial profile (30 GeV pion)**

Discrepancy within 10(18)% in the core, increases up to 20(25)% at 80 GeV.