INSTR 2020 @ Budker Institute of Nuclear Physics, Novosibirsk, Russia

CALICE highly granular calorimeters: imaging properties for hadronic shower analysis

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Outline

1. CALICE highly granular calorimeters for PFA
2. Hadronic showers in electromagnetic calorimeter
3. Hadron calorimeters
   - AHCAL prototypes — optical readout
   - (S)DHCAL prototypes — gaseous readout

Highly granular calorimeters: motivation

Planned experiments at lepton colliders

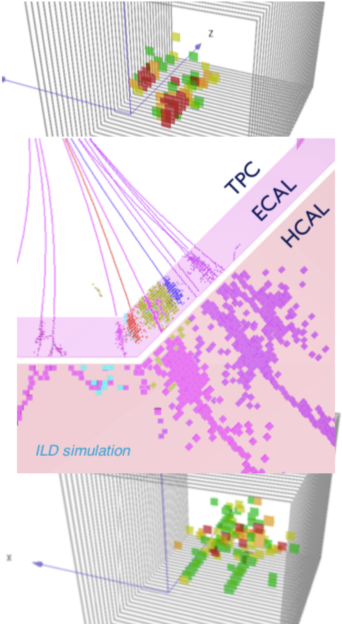
ILC, CLIC, FCCee, CEPC ...
Detector concepts: ILD, SiD ...

- precision frontier: measurements of Higgs couplings, W, Z and top properties, searches for BSM physics
- model-independent analyses possible
- clean environment
- beam polarisation option at linear colliders

Goal: 3-4% jet energy resolution

to distinguish dijets from W and Z hadronic decays

- main tool: **particle-flow** reconstruction
- assumes possibility to disentangle contributions from particles within jets
- **requires high longitudinal and transverse segmentation**



ILD simulation sketch by J. Marshall (@CHEF2017) and event displays from CALICE AHCAL TB

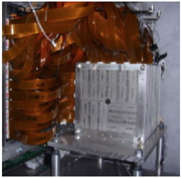
CALICE R&D activities since 2005

CALICE collaboration pioneered developments of highly granular calorimeter concepts

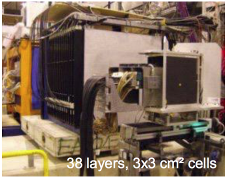
From proof-of-principle with the first generation physics prototypes

Si-W ECAL

Sc-W ECAL



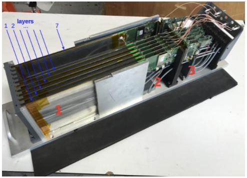
Sc-Fe(W) AHCAL



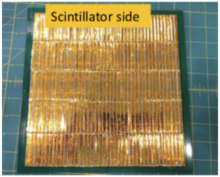
GRPC-Fe DHCAL

To scalability tests with the second generation technological prototypes

Si-W ECAL

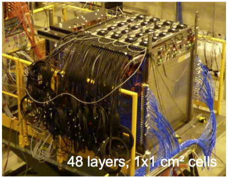


Sc-W ECAL



Sc-Fe AHCAL

GRPC-Fe SDHCAL

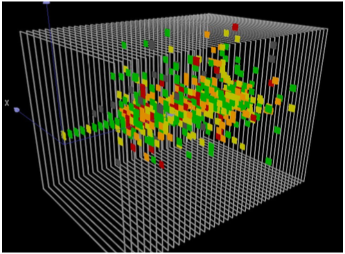


Highly granular calorimeters: goals and tasks

CALICE calorimeter prototypes

experimental data for tests and validations

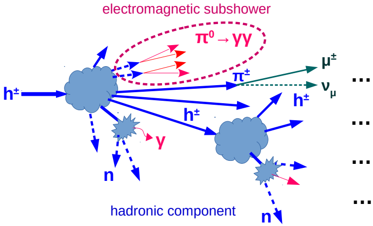
- **Tests of PFA performance**
  - particle separation
  - energy reconstruction incl. software compensation
- **Validation of simulations**
  comparison of Geant4 hadronic models
- **Study of shower substructure**
  - energy density distributions
  - shower development in time



Technological prototypes

solutions on the way to large-scale detectors

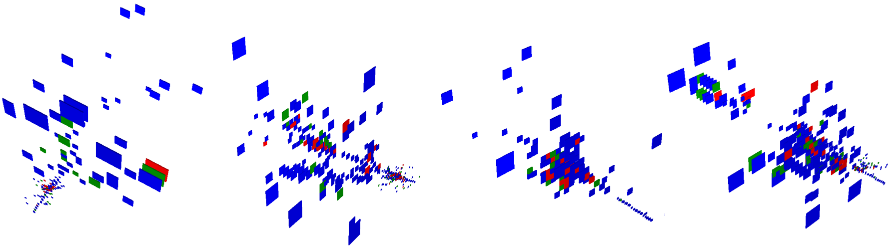
- optimal transverse segmentation from ILD simulations:
  - 5×5 mm^2 in Ecal (>80 mln. channels)
  - 30×30 mm^2 in Hcal ($\sim$8 mln. channels)
- mass production and assembling
- calibration approaches and tools
- tests of readout and operation modes with embedded electronics



Hadronic shower development

Hadron-induced showers in imaging calorimeters

test beam data from combined setup of physics prototypes: SiW ECAL(1×1 cm^2) + Fe-AHCAL



10 GeV | 30 GeV | 10 GeV | 30 GeV

Global parameters

- position of first inelastic interaction: shower start
- shower radius (energy weighted)
- longitudinal centre of gravity

Shower substructure

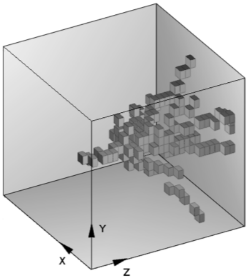
- tracks within a shower
- hit energy spectra
- longitudinal and radial profiles
- hit time distributions

Si-W ECAL physics prototype

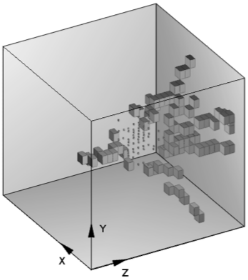
Highly granular electromagnetic calorimeter with semi-conductor readout

- sandwich-like structure, 30 layers of silicon, alternating with tungsten absorber
- overall depth is $24X_0$ or $\sim 1\lambda_I \Rightarrow \sim$60% of hadrons interact in ECAL
- transverse size 18×18 cm^2 with very high segmentation to 1×1 cm^2 pads
- 3 segments with different absorber thickness - converted into pseudolayers for analysis

Event display of 10 GeV pion in SiW ECAL with removed interaction region (right)



(a) *Before removing the interaction region.*



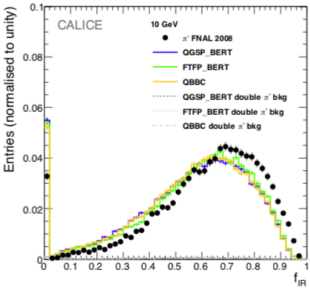
(b) *After removing the interaction region.*

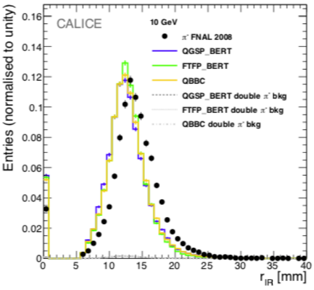
Fine segmentation allows hadronic shower analysis and validation of G4 hadronic models

Hadronic showers in Si-W ECAL physics prototype

Characterisation of different stages of hadronic showers *[NIM A937 (2019) 41-52]*

- test beams in a combined setup with AHCAL, pions in the energy range 2–10 GeV
- comparisons with simulations using Geant4 version 10.1
- analysis includes discrimination between interacting pions and MIP-like events, identification and characterisation of interaction region (IR)
- **important studies for validation of Geant4 hadronic models and developments of shower separation algorithms**





Energy fraction in IR underestimated by G4

Radius of IR underestimated by G4

CALICE Scintillator-SiPM analog hadron calorimeter

Physics AHCAL prototype

38 layers, ∼8000 tiles, assembled by hand

- tiles with WLS fibers
- side coating against crosstalk
- SiPMs mounted by hand
- 3×3×0.5, 6×6×0.5, 12×12×0.5 cm^3 tiles
- External electronic boards
- sensors for temperature measurement
- 2 cm (1 cm) steel (tungsten) absorber

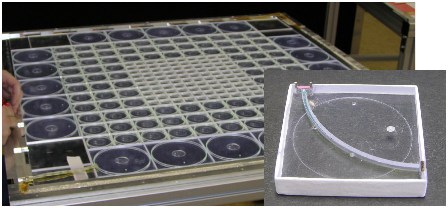
Successful tests and proof-of-principle!

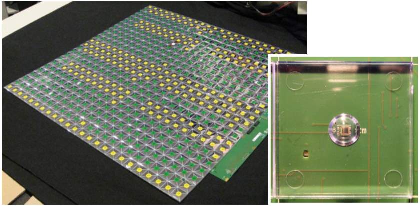
Technological AHCAL prototype

38 layers, ∼22000 tiles, automatic assembly

- tile w/dimple optimised for uniformity
- each tile wrapped in reflective foil
- SMD SiPMs, automatically soldered
- all tiles 3×3×0.3 cm^3
- Embedded electronics, power puls. option
- tool for temperature compensation
- 2 cm steel plates as absorber

Technology ready for mass production!





AHCAL technological prototype in test beams

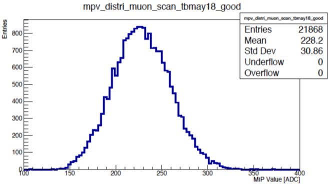
Prototype layout

- scalable detector design with SiPM-on-tile
- 38 active layers interleaved by steel absorber ($\sim 4.5\lambda_{\mathrm{I}}$ in total)
- transverse size 72×72 cm^2, 576 tiles/layer
- injection moulded tiles $3\times3\times0.3$ cm^3, produced by Uniplast (Vladimir, Russia)
- surface-mounted SiPMs (2668 pixels), negligible noise at 0.5 MIP threshold

Test beam at CERN SPS in 2018

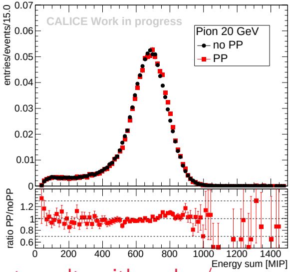
- wide muon beam for MIP calibration
- energy scan:
  - electrons @ 10–100 GeV
  - negative pions @ 10–200 GeV
- runs with and without power pulsing (PP) turn off electronics for ILC idle time
- shifted beam positions

MIP calibration



Good calibration for 99.9% of channels!

Power pulsing mode tests



Consistent results with and w/o power pulsing

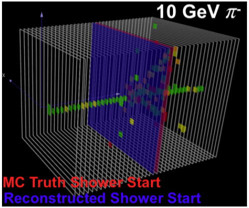
Large amount of high quality data stored for performance and shower analysis studies!

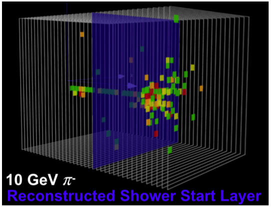
AHCAL: shower start finding algorithm

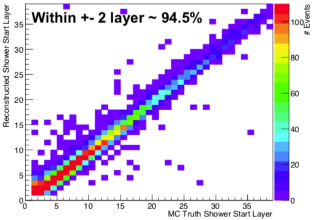
Developed for the analysis of test beam data

- Application for particle identification, hadronic shower studies, leakage estimates
- Idea: comparison of visible energy and number of hits with mip-like deposition
  - calculate visible energy, E_i, and number of hits, N_i, in i-th layer
    reminder: visible energy in units of MIP, hit is the cell with visible energy above 0.5-MIP threshold
  - average visible energy E_i within a sliding window of m layers up to k-th layer: $M_k = \sum_{j=0}^{m-1} E_{k-j}/m$
  - calculate sum of averaged visible energy in two successive layers: $M_k + M_{k+1}$
  - calculate sum of number of hits in two successive layers $N_k + N_{k+1}$
  - identify shower start if both values are above their thresholds
  - both thresholds are energy dependent (beam energy) and tuned using simulations
- Thresholds and their energy dependence are adjusted using Geant4 simulations

Event display from AHCAL technological prototype (pictures by J. Mikhaeil and D. Heuchel)







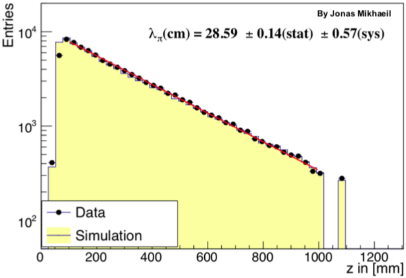
AHCAL: estimates of nuclear interaction length

Application of shower start finding

- **Performance of the algorithm: $\sim$80% ($\sim$95%) within $\pm$1 ($\pm$2) layer(s) from MC truth**
- Extracted value of nuclear interaction length for different particle types gives consistent results with PDG and estimates from material composition
- **Improved performance for technological prototype: lower noise and optimisations**

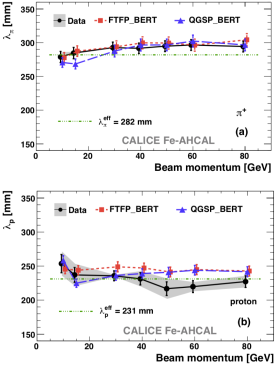
Shower start position distribution

30 GeV pions in technological prototype



$\lambda_{\pi}^{\mathrm{eff}} = 27.76$ cm from PDG data

Pions and protons in physics prototype

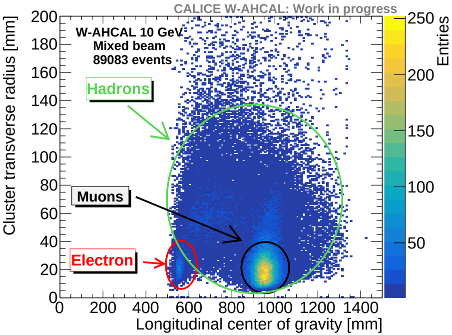


AHCAL: hadron identification

Calorimeter-based particle ID

- Hadronic shower studies require high purity samples, even more challenging case without electromagnetic calorimeter and tail catcher
- Test beams are usually mixed, comprising more than two particle species, there is typically admixture of electrons and muons in hadron beams
- Fine segmentation provides observables for particle (cluster) characterisation

Tungsten AHCAL in mixed test beam



Observables for particle ID

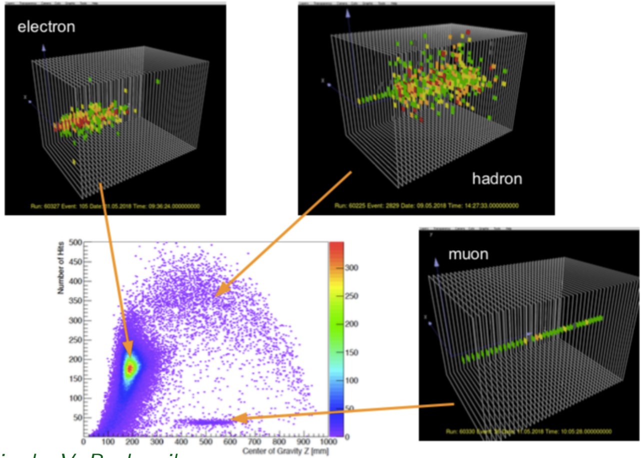
- number of hits in cluster, N
- cluster centre of gravity in longitudinal direction: $zCoG = \frac{\sum_{i=1}^{N} e_i \cdot z_i}{\sum_{i=1}^{N} e_i}$

  z_i – coordinate of hit with amplitude e_i
- cluster radius (transverse size): $R = \frac{\sum_{i=1}^{N} e_i \cdot r_i}{\sum_{i=1}^{N} e_i}$, r_i – radial distance of hit e_i from shower axis (x_0, y_0)
- shower start position
- energy fraction in first $25X_0$
- energy fraction in shower core
- energy fraction in track hits

AHCAL: particle identification tool under development

BDT-based classification algorithm

- No observable has enough discrimination power in the wide energy range
- BDT trained on simulated samples using set of 8 variables as an input
  Preliminary performance: ∼96% efficiency with <0.5% of misidentified pions for the mixed sample with muons and electrons in the energy range 10—100 GeV



plots and studies by V. Bocharnikov

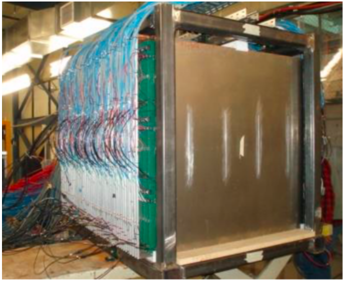
CALICE (Semi)Digital Hadron Calorimeter prototypes

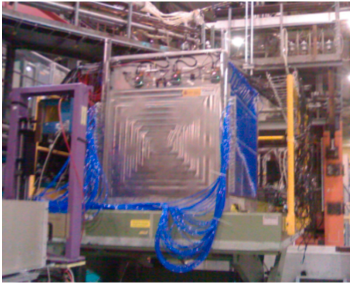
Digital HCAL prototype (DHCAL)

- sampling calorimeter with GRPC
- 38 layers, $1{\times}1$ cm^2 pads, **1-bit readout**
- transverse size $\sim 1{\times}1$ m^2
- steel absorber, $\sim 5.3\lambda_{\rm I}$ ($\sim 11\lambda_{\rm I}$ with tail catcher)
- test beams in 2010-11 at Fermilab
- electrons, muons and hadrons, 2–60 GeV

Semi-Digital HCAL prototype (SDHCAL)

- sampling calorimeter with GRPC
- 48 layers, $1{\times}1$ cm^2 pads, **2-bit readout**
- transverse size $\sim 1{\times}1$ m^2
- steel absorber, $\sim 5.76\lambda_{\rm I}$
- embedded electronics, power pulsing
- test beams in 2012-2018 at CERN
- electrons, muons and hadrons, 5–80 GeV



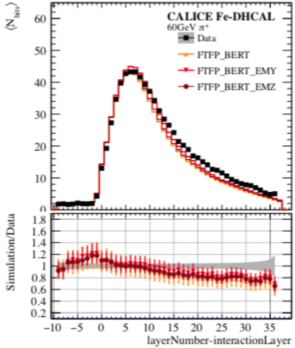


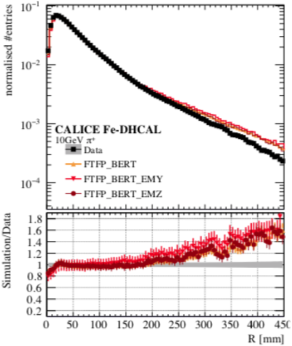
Extremely fine segmentation for hadron calorimetry: $\sim$500000 channels!

Hadronic showers in the DHCAL: validation of simulations

- **Geant4 version 10.1**
- simulated RPC response tuned to muon and electron data
- resolution is limited by saturation effect (hit counting regime)
- large differences between physics lists
- **EMZ physics list** — the best agreement with data for positrons

- for all models, simulated hadron showers tend to be broader
- good agreement of longitudinal behaviour below 30 GeV and shorter simulated showers above
- **QGSP_BERT_EMZ** —the best agreement with data for pion showers
- plots from *[NIM A937 (2019) 41-52]*





Particle identification in the SDHCAL

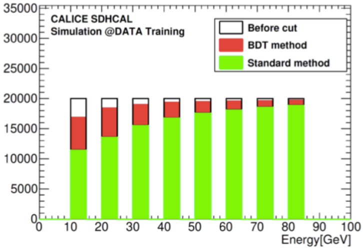
Analysis note CALICE-CAN-2019-001

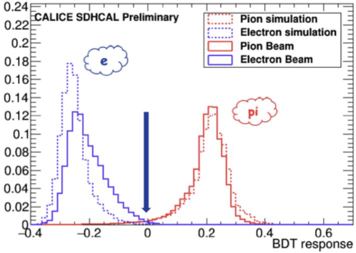
Test beam data and simulations

- test beam data from CERN SPS (2015):
  muons,
  electrons 10–50 GeV,
  pions 10–80 GeV
- simulations with Geant4 version 9.6
- BDT trained with simulations
- reliability of results demonstrated with data

Input variables for BDT

- first layer of the shower
- number of tracks in the shower
- ratio of shower layers over total fired layers
- shower density (hit density)
- shower radius
- position of shower maximum





Improvement of statistics using BDT-based particle ID, especially at low energies

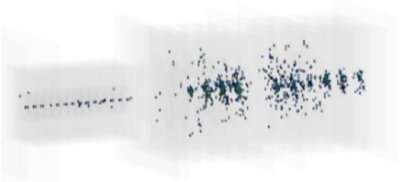
Summary

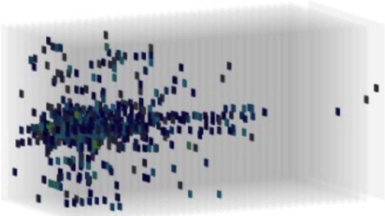
Highly granular calorimeter concept: developments and tests

- Proved with the beam tests of CALICE **physics prototypes** https://twiki.cern.ch/twiki/bin/view/CALICE/CALICEResults
- **Technological prototypes** under development and tests, demonstrate scalability, readiness to mass production and very good performance
- Unique results on **hadronic shower studies**: shower substructure, validation of simulations, sophisticated reconstruction techniques

Beam tests of the combined setup: CMS HGCAL + CALICE AHCAL prototypes

Tested CALICE technologies approved as a baseline concept for the CMS endcap hadron calorimeter upgrade for the HL-LHC, combined beam tests of the CALICE AHCAL and CMS HGCAL prototypes in 2018 have shown promising results





Backup slides

AHCAL: hadron energy reconstruction

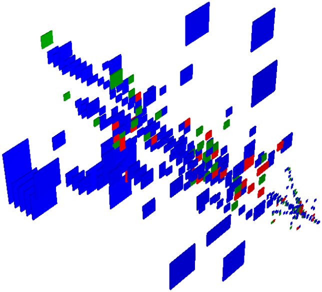
Standard reconstruction

$$E^{\text{event}}_{\text{std}} = \sum_{s=1}^{M} C_s \cdot \sum_{i=1}^{N_s} e_{is}$$

Mean and σ are extracted from the two-step Gaussian fit within ± 2 RMS

- 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]

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)*
- Improvement of pion energy resolution with local SC in combined setup up to $\sim 42\%/\sqrt{E/\mathrm{GeV}}$ (*CAN-058*)
- Implementation of SC in ILD simulations: improvement of jet energy resolution (*Eur.Phys.J. C77 (2017) 10, 698*)

SDHCAL: hadron energy reconstruction

GRPC-Fe SDHCAL prototype *JINST 11 P04001 (2016)*

- Unprecedented transverse granularity: 1x1 cm^2 pads
- 2-bit readout (3 thresholds) $\sim$5.5 λ_I

Energy reconstruction in binary mode:

$$E_{\mathrm{reco}}^{\mathrm{binary}} = A_1 \cdot N_{\mathrm{hit}} + A_2 \cdot N_{\mathrm{hit}}^2 + A_3 \cdot N_{\mathrm{hit}}^3$$

Energy reconstruction in multithreshold mode:

$$E_{\mathrm{reco}}^{\mathrm{multithr}} = \alpha(N_{\mathrm{hit}}) \cdot N_1 + \beta(N_{\mathrm{hit}}) \cdot N_2 + \gamma(N_{\mathrm{hit}}) \cdot N_3$$

N_1, N_2, N_3 – number of hits in 1st, 2nd and 3d threshold range, respectively, $N_{\mathrm{hit}} = N_1 + N_2 + N_3$