Reconstruction and study of hadronic showers with highly granular calorimeters

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LPI, MEPhI

1. CALICE calorimeters for PFA
2. Hadron energy reconstruction
3. Validation of simulations
4. Shower separation
5. Time structure of hadronic showers

ФЕДЕРАЛЬНОЕ ГОСУДАРСТВЕННОЕ БЮДЖЕТНОЕ УЧРЕЖДЕНИЕ НАУКИ
Физический институт имени П.Н.Лебедева Российской академии наук
ФИАН

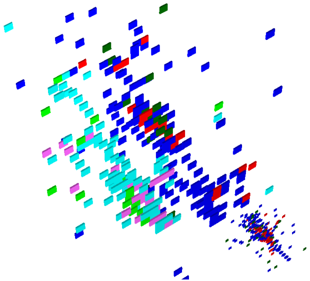
Highly granular calorimetry

Evolution of Particle Flow paradigm

- ALEPH at LEP: *energy-flow reconstruction*
- Detectors for ILC and CLIC: *from energy-flow to particle-flow reconstruction*
  - ambitious goal: excellent jet energy resolution of 3–4% for 100 GeV jets
  - crucial requirement: high longitudinal and transverse segmentation for particle separation
- Current applications: particle-flow reconstruction in CMS detector

CALICE collaboration: technologies for PFA calorimetry

- R&D of highly granular electromagnetic and hadron calorimeters for HEP experiments
- Validation of performance with test beams:
  - particle separation
  - energy resolution
- Study of reconstruction schemas, shower development and shower substructure:
  - software compensation
  - spacial development
  - time structure
- Validation of Geant4 simulations



Overlaid test beam hadron showers with 15 cm between shower axes in CALICE calorimeters

In this talk: focus on hadron calorimeters and hadronic showers

CALICE calorimeters in test beams

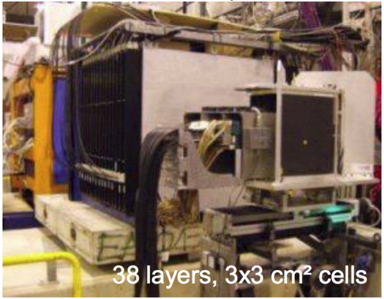
CALICE prototypes

ScECAL: Sc-W EM calorimeter, 4.5x1 cm^2 scint. strips with SiPM readout
SiECAL: Si-W EM calorimeter, 1x1 cm^2 silicon pads
AHCAL ($\sim$1 m^3): Sc-Fe(W) hadron calorimeter, 3x3 cm^2 scint. tiles with SiPM readout
SDHCAL ($\sim$1 m^3): GRPC-Fe hadron calorimeter, 1x1 cm^2 pads, 2-bit readout

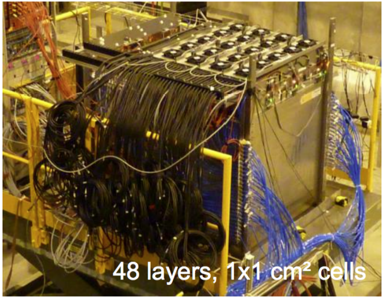
CALICE test beam setups

ECAL(optional) + HCAL + TCMT(optional); μ, e and hadron beams; 1—300 GeV

SiW ECAL + AHCAL (12-bit readout)



SDHCAL (2-bit readout)



Hadron energy reconstruction

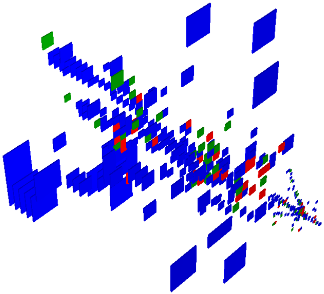
Standard reconstruction for analogue readout

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

- N_s - number of cells in s-th subdetector with signal above 0.5 MIP threshold (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 $\left[\frac{\text{GeV}}{\text{MIP}}\right]$

Hit spectra reflect shower substructure:
EM fraction in the shower core
surrounded by **hadronic fraction**

Event display in Si-W ECAL + Fe-AHCAL
30-GeV pion from test beam data
[0.5–3) MIP, **[3–5.5) MIP**, **≥5.5 MIP**



Semi-digital reconstruction (SDHCAL), 2-bit readout (3 thresholds)

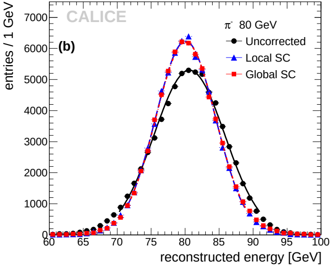
Binary mode: $E_{\text{reco}}^{\text{binary}} = A_1 \cdot N_{\text{hit}} + A_2 \cdot N_{\text{hit}}^2 + A_3 \cdot N_{\text{hit}}^3$

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

$N_{\text{hit}} = N_1 + N_2 + N_3$; constant A_1, A_2, A_3; parametrised α, β γ

Energy reconstruction and software compensation

Motivation: improve energy resolution by taking into account fluctuations of em fraction

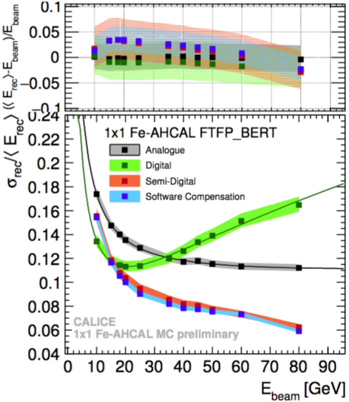


- Correction is applied on an event-by-event basis
- Two software compensation techniques developed:
  - hit energy weighting (Local SC)
  - event energy weighting (Global SC)
  - more details in *JINST 7 P09017 (2012)* and backup
- Improvement of resolution in Fe-AHCAL up to 25%

Simulation of different reconstruction schemas *CAN-049*

- FTFP_BERT physics list (Geant4 9.6)
- Fine granularity: 1×1 cm^2
- Analogue, digital and semi-digital reconstruction

Semi-digital reconstruction shows the same performance as analogue reconstruction with software compensation



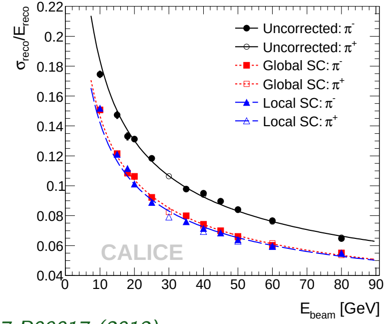
Software compensation in AHCAL

Event energy weighting technique for AHCAL with different absorbers and same active layers

	Fe-AHCAL	**W-AHCAL**	ratio (Fe/W)
Total depth [λ_I]	5.2	4.9	$\sim$1.06
Layer depth [λ_I]	0.137	0.129	$\sim$1.06
Layer depth [X_0]	1.24	2.80	$\sim$0.44
38 active layers: scintillator tiles with SiPM readout			

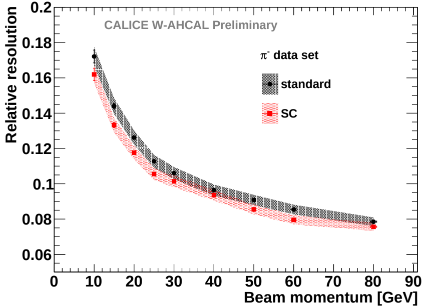
Event selection:
shower start at the beginning of the AHCAL and MIP in ECAL

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



JINST 7 P09017 (2012)

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



CAN-062

More significant improvement in noncompensating calorimeter than in compensating.

Software compensation in combined setup

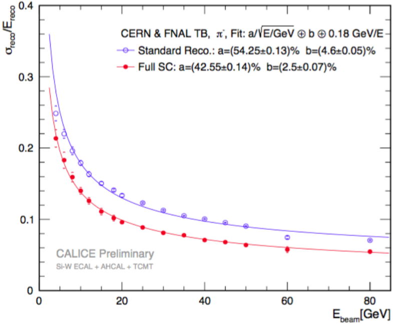
Relative resolution of combined setup: ECAL+AHCAL+TCMT

Hit energy weighting technique is applied to ECAL hits and AHCAL hits.

SiW ECAL+ScFe AHCAL+ScFe TCMT

Test beam data

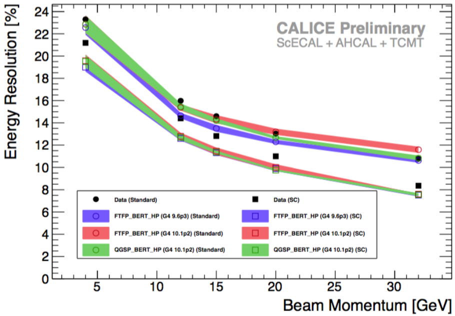
$4 \leq E_{\mathrm{beam}} \leq 80$ GeV *(CAN-058)*



ScW ECAL+ScFe AHCAL+ScFe TCMT

Test beam data and simulations

$4 \leq E_{\mathrm{beam}} \leq 35$ GeV *(CAN-056)*



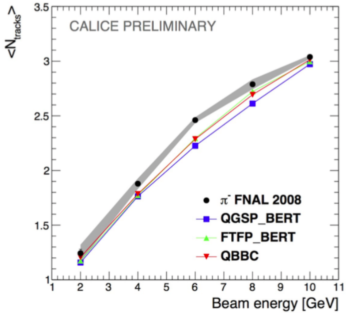
Improvement of stochastic term with software compensation up to $\sim \frac{42\%}{\sqrt{E/\mathrm{GeV}}}$

Validation of simulations: number of track segments

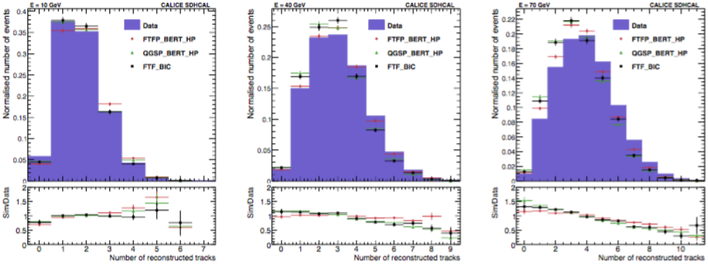
SiW ECAL prototype [CAN-055]

- Test beam data: pions of 2–10 GeV
- Simulations: Geant4 10.1
- Track finding based on clustering
- Good agreement in number of identified tracks
- Smaller energy fraction in interaction region in simulation by ∼10%

[N.B. First studies for the Fe-AHCAL in JINST 8 (2013) P09001]



GRPC-Fe SDHCAL [JINST 12 P05009 (2017)]

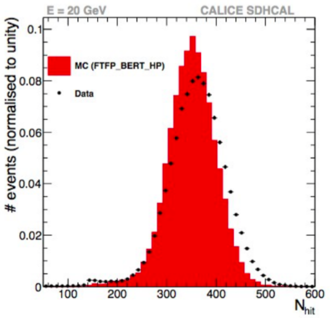


- Test beam data: pions of 10–80 GeV
- Simulations: Geant4 9.6
- Hough Transform for track id
- FTFP_BERT gives better predictions
- Discrepancy between data and simulations increases with energy

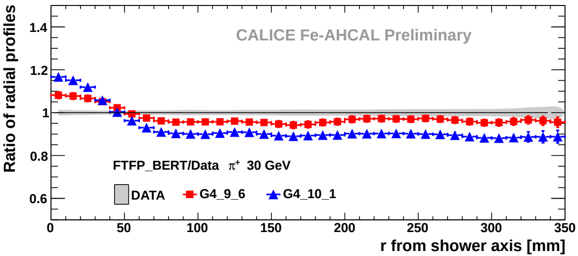
Validation of simulations: shower development

GRPC-Fe SDHCAL prototype [JINST 11 (2016) P04001]

- Test beam data: pions of 10–80 GeV
- Simulations: Geant4 9.6
- Underestimation of the number of hits
- Discrepancy increases with energy
- Same observation in CALICE GRPC DHCAL



Sc-Fe AHCAL [CAN-040b]

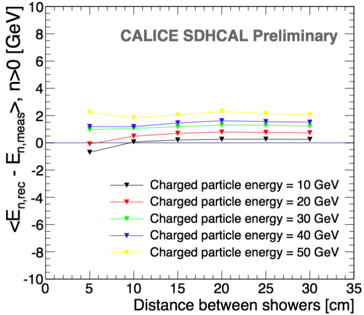


- Test beam data: pions of 10–80 GeV
- Simulations: Geant4 9.6 and 10.1
- Radial profile: energy density in the rings around shower axis integrated over longitudinal direction
- Energy in the shower core is overestimated by simulations
- Discrepancy between data and simulations increases with energy

Shower separation

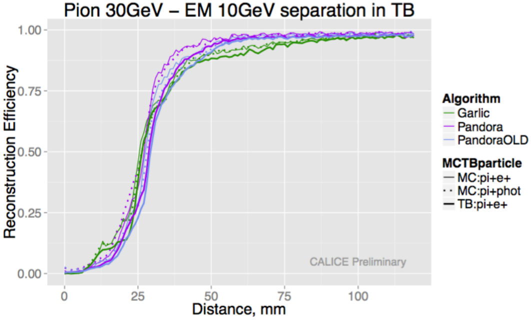
Hadron-hadron separation [CAN-054]

- **Test beam** pions of 10–80 GeV in SDHCAL
- Single-particle events overlaid with shift 5–30 cm between shower axes
- Reconstruction using **ArborPFA**
- Bias of the energy of 10 GeV neutral hadron reconstructed in neighbourhood of charged hadron:
  Bias increases with charged particle energy and is independent of distance above 10 cm.



Electron-hadron separation [CAN-057]

- Test beam setup: SiW ECAL + Fe-AHCAL
  Hadron- and electron-induced showers
- Showers overlaid with a shift between shower axes from few mm to hundred mm
- One em reconstructed cluster is required with energy within 20% of its measured energy
- Comparable separation performance of **Garlic, ArborPFA and PandoraPFA**



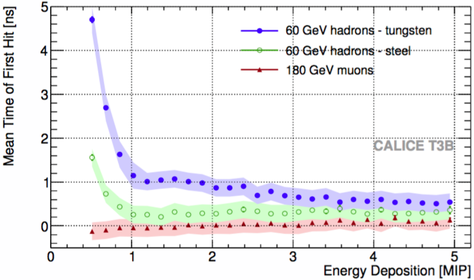
Time structure of hadronic showers

Time measurements: relevant for background suppression
Intrinsic time structure: important for calorimeter development and simulations

CALICE T3B experiment: first step to measuring the time structure of hadronic showers

- Setup of 15 small plastic scintillator tiles with SiPM readout and subnanosecond time resolution over a time window of 2.4 μs
- Placed behind scintillator-tungsten AHCAL and GRPC-steel SDHCAL [*JINST 9 P07022 (2014)*]
- Time structure of hadronic showers was measured on a statistical basis
- Validation of Geant4 simulations: importance of using HP package for tungsten absorber

Mean time of first hit vs. hit energy



3 times larger delay of low-energy hits in tungsten than in steel

Next generation AHCAL prototype with time measurement

3$\times$3 cm^2 tiles with direct readout by SiPM ($\sim$22000 channels), embedded electronics, power-pulsing mode and **timing** — test of scalability to large-scale detectors

Details in the talk of Yuji Sudo "Scalability of technologies for highly granular calorimeters"

Summary

Proof of Particle Flow concept with CALICE highly granular calorimeter prototypes

- Good performance of two particle separation demonstrated on test beam data
- Noticeable effect of software compensation on energy resolution for single hadrons:
  - **improvement of resolution for the combined setup with Sc-Fe AHCAL is up to** $\sim \frac{42\%}{\sqrt{E/\mathrm{GeV}}}$
  - improvement is much smaller in compensating calorimeter than in noncompensating as expected
  - N.B.: Implementation of software compensation in simulations of the full-scale ILD detector results in improvement of jet energy resolution *Eur.Phys.J. C77 (2017) no.10, 698*

Validation of hadronic models

Detailed study of hadronic showers with unprecedented longitudinal and transverse granularity

- 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
- **Discrepancy between data and simulations increases with energy**, deposition in the shower core is overestimated by simulations.

Developing story: highly granular calorimeter prototypes in test beams and future projects

- CALICE AHCAL technological prototype for the ILD
- CMS HGCAL, ATLAS HGTD, FCC-hh calorimeter system

Backup slides

Energy reconstruction with software compensation

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

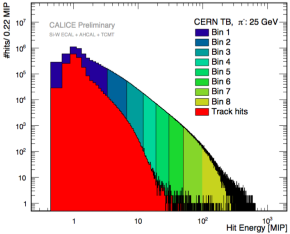
- Correction is applied on event-by-event basis
- Calibration factor C_{trk} for track hits and hadron scale calibration C_s for shower cluster

Hit weighting technique (local compensation)

$$E^{\mathrm{event}}_{\mathrm{SClocal}} = C_{\mathrm{trk}} \cdot \sum_{t=1}^{N_{\mathrm{trk}}} e_t + \sum_{s=1}^{M} C_s \cdot \sum_{j}^{K_s} w_{js}(E^{\mathrm{event}}_{\mathrm{std}}) \cdot \sum_{i}^{N_{js}} e_{ijs}$$

- 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)

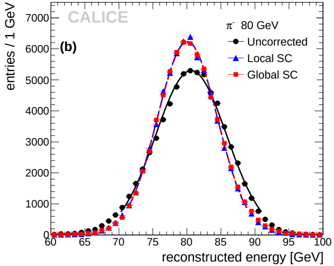
$$E^{\mathrm{event}}_{\mathrm{SCglobal}} = C_{\mathrm{trk}} \cdot \sum_{t=1}^{N_{\mathrm{trk}}} e_t + E^{\mathrm{event}}_{\mathrm{cor}} \cdot P(a_G, E^{\mathrm{event}}_{\mathrm{cor}})$$

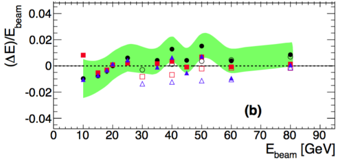
$$E^{\mathrm{event}}_{\mathrm{cor}} = \sum_{s=1}^{M} C_s \cdot W^{\mathrm{event}}_s \cdot \sum_{i}^{N_s} e_{is}$$

- Weights W^{event}_s are calculated from hit energy spectrum shape.
- Coefficients a_G of second-order polynomial P are estimated from test beam data.

Application to calorimeters with different level of compensation

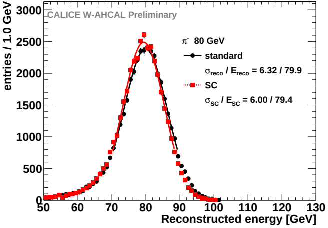
Fe-AHCAL ($e/\pi \sim 1.2$) with tail catcher

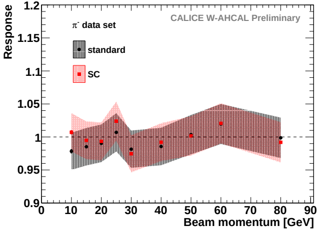




JINST 7 P09017 (2012)

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





CAN-062

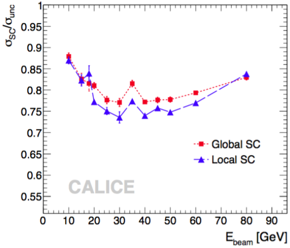
Linearity of response within $\pm 2\%$ with and without software compensation

Software compensation in AHCAL: improvement of resolution

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

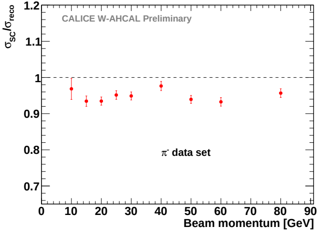
Fe-AHCAL ($e/\pi \sim 1.2$) with tail catcher



Improvement of resolution ∼**10–25%**

JINST 7 P09017 (2012)

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

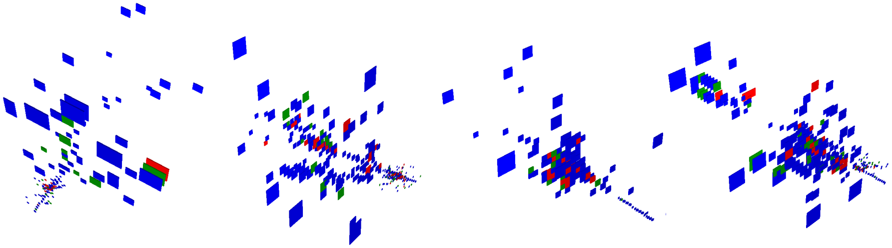


Improvement of resolution ∼**5%**

CAN-062

Software compensation corrects presumably for the fluctuations of electromagnetic fraction in hadronic showers.

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

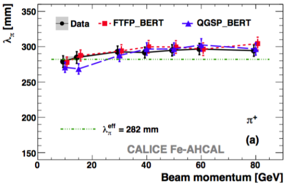


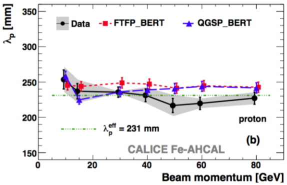
10 GeV 30 GeV 10 GeV 30 GeV

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.



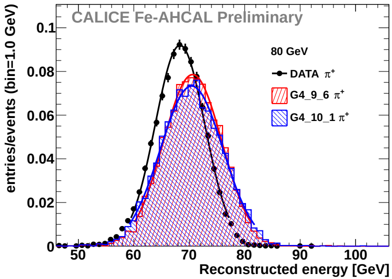


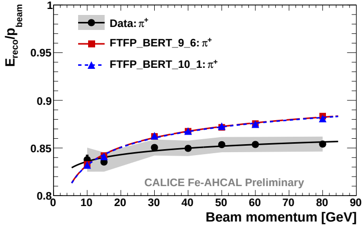
JINST 10 P04014 (2015)

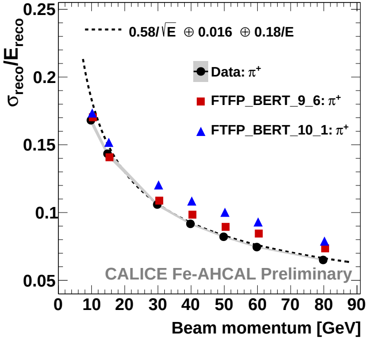
Validation of simulations: response and resolution

CALICE Fe-AHCAL

- Conditions
  - Combined test beam setup:
    SiW ECAL + **Fe-AHCAL** + TCMT
  - Focus on AHCAL: MIP in ECAL required
  - Geant4 versions 9.6 and 10.1
- Results
  - Steeper behaviour of response in MC
  - MC overestimates energy fluctuations
  - Discrepancy increases with energy







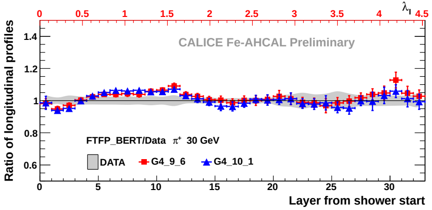
CAN-040b

Hadronic shower development: profiles

CALICE Fe-AHCAL

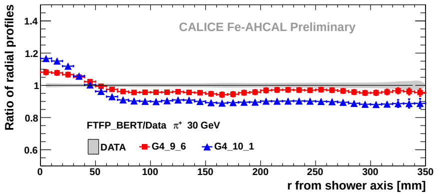
- Fine longitudinal segmentation: $\sim 0.14\ \lambda_I$ per layer
- Fine transverse granularity: 3×3 cm^2 tiles in the central part
- Combined test beam setup: SiW ECAL + **Fe-AHCAL** + TCMT (MIP in ECAL)
- Longitudinal profile from the identified first inelastic interaction
- Radial profile with respect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

Longitudinal profile (30 GeV pion)



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

Radial profile (30 GeV pion)



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