Highly granular analogue hadron calorimeter: software compensation and shower decomposition

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on behalf of the CALICE Collaboration

1. CALICE prototypes and test beam experiments
2. Longitudinal profiles: decomposition and comparison
3. Radial shower development

Highly granular calorimeters

CALICE collaboration

Calorimeter R&D for future HEP experiments

- High granularity: test of technologies

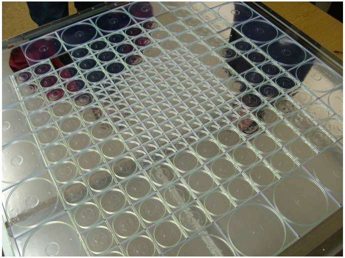
  Si-W and Sc-W ECAL, Sc-Fe(W) AHCAL, GRPC-Fe(W) DHCAL and GRPC-Fe SDHCAL
- Check of calibration procedures
- Particle Flow Approach: proof of principle

Advantages of high granularity

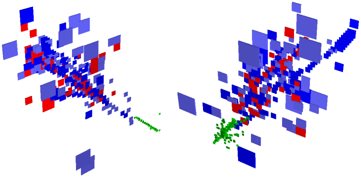
- First inelastic interaction id
- Spatial energy density distributions
- Software compensation

Validation of hadronic models

Test of PFA: *2011 JINST 6 P07005*
Pion showers: *2013 JINST 8 P07005*
Pion vs proton: *2015 JINST 10 P04014*



Active plane of the CALICE AHCAL



30-GeV pions from test beam data: Si-W ECAL and Sc-Fe AHCAL with marked hits >3.5 MIP

Test beam data and simulations

Experimental setup and test beam activities

- Test beam campaigns at DESY, CERN, FNAL
  Electron, muon, hadron beams @ 1-130 GeV
- Combined setup with Ecal and tail catcher (longitudinal depth $\sim 11\ \lambda_I$)
  Čerenkov counter upstream calorimeters

Calibration

- Cell response equalised with MIPs (0.5-MIP cut for analysis)
- EM scale calibrated with positrons
  2011 JINST 6 P04003

Scintillator-steel analogue hadron calorimeter CALICE Fe-AHCAL

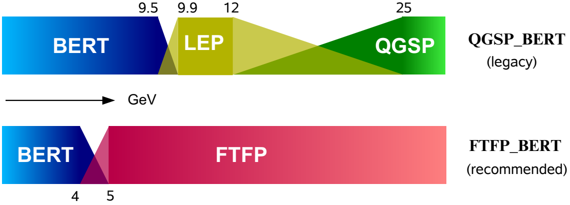
- $\sim 1\ m^3$ sandwich structure: 38 layers $\times$ (20 mm Fe + 5 mm sci) $\approx 5.3\ \lambda_I$
- $90 \times 90\ cm^2$ active planes assembled from 3×3, 6×6, $12\times12\ cm^2$ scintillator tiles
- 7608 cells with individual readout by SiPMs

Simulations with Geant4 version 9.6 patch 01 for shower profile comparisons

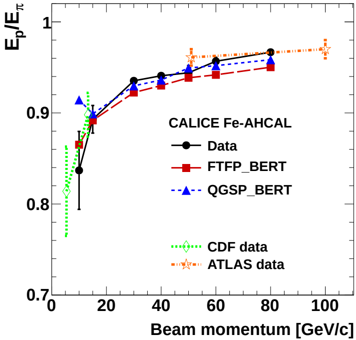
Digitisation:

- intertile crosstalk
- map of dead cells
- SiPM response

Beam profiles and noise from data runs



Response and resolution studies



Energy reconstruction

$$E_{\mathrm{event}} = E^{\mathrm{track}}_{\mathrm{ECAL}} + E_{\mathrm{AHCAL}} + E_{\mathrm{TCMT}}$$

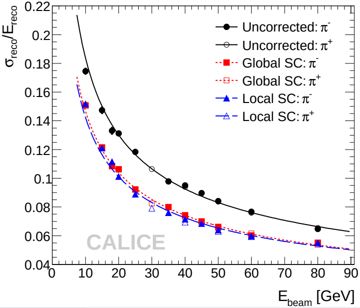
- Event selection for analysis: track in ECAL and shower start at the beginning of Fe-AHCAL
- E_{reco} and σ_{reco} from Gaussian fit
- Non-compensating calorimeter: $\frac{e}{\pi}$ ≈1.2
- p/π ratio from *2015 JINST 10 P04014*

Energy resolution and software compensation

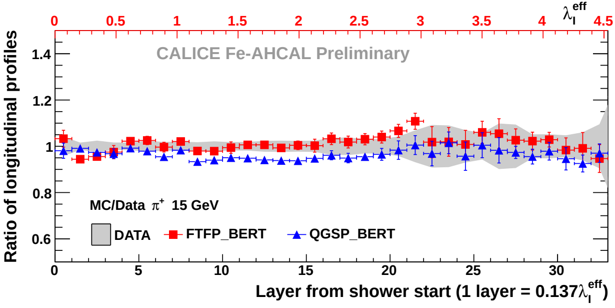
Intrinsic resolution: $\frac{58\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1.6\% \oplus \frac{0.18}{E/\mathrm{GeV}}$

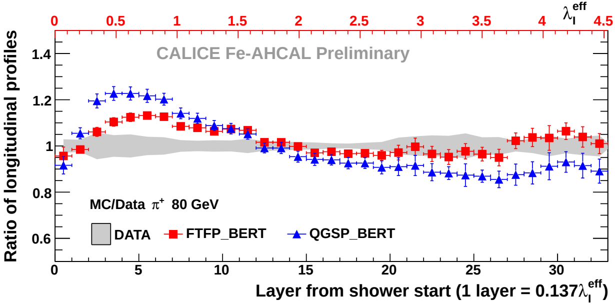
Software compensation *2012 JINST 7 P09017*

- **Local method**: weighting of individual hits
  Global method: event energy weighting
- event-by-event energy correction
- prior knowledge of particle energy not required
- **improvement of stochastic to** $\frac{45\%}{\sqrt{\mathbf{E/GeV}}}$



Longitudinal shower development: MC/Data





Longitudinal profile: visible energy ΔE per layer vs. long. distance from the identified shower start

15 GeV

FTFP_BERT: agreement within uncertainties

QGSP_BERT: little underestimation

80 GeV

Overestimation around shower maximum:

FTFP_BERT: by ∼10%

QGSP_BERT: by ∼20%

Discrepancy between data and simulations increases with energy

Parametrisation of longitudinal profiles

$$\Delta E = A\left\{ \frac{f\cdot \exp\left(-\frac{z}{\beta_{\mathrm{short}}}\right)}{\beta_{\mathrm{short}}\cdot\Gamma(\alpha_{\mathrm{short}})}\cdot\left(\frac{z}{\beta_{\mathrm{short}}}\right)^{\alpha_{\mathrm{short}}-1} + \frac{(1-f)\cdot\exp\left(-\frac{z}{\beta_{\mathrm{long}}}\right)}{\beta_{\mathrm{long}}\cdot\Gamma(\alpha_{\mathrm{long}})}\cdot\left(\frac{z}{\beta_{\mathrm{long}}}\right)^{\alpha_{\mathrm{long}}-1}\right\}$$

proposed in *R.K. Bock et al. NIM, 186 (1981)*

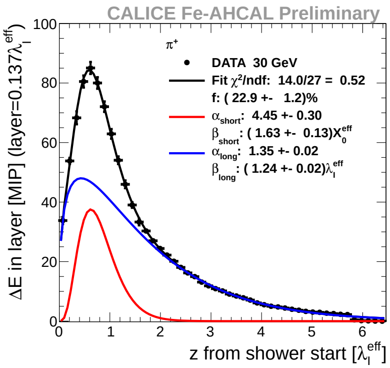
A - scaling factor
f - fraction of the "short" component
Γ - gamma function

z - distance from shower start
α_{short} and α_{long} - shape parameters
$\beta_{\mathrm{short}} < \beta_{\mathrm{long}}$ - slope parameters

- Fit range: $[0.1\cdot\lambda_{\mathrm{I}}^{\mathrm{eff}}; 4.6\cdot\lambda_{\mathrm{I}}^{\mathrm{eff}}]$
- $\lambda_{\mathrm{I}}^{\mathrm{eff}} = 231$ mm, $X_0^{\mathrm{eff}} = 25.5$ mm
- Last 9 bins from TCMT section with the same sampling as Fe-AHCAL

MC to Data comparison

- **MC and data agree within uncertainties for shape and slope parameters: 10-15% for "short", <5% for "long"**
- **MC tends to overestimate parameter *f***



"Short" component of pion-induced shower

"Short" component of pion shower

$$\mathbf{Z}^{\mathrm{short}}_{\mathrm{max}}(\pi) = (\alpha_{\mathrm{short}} - 1) \times \beta_{\mathrm{short}}$$

longitudinal maximum of the "short" component of pion shower

$\mathbf{E}^{\mathrm{short}}_{\mathrm{reco}}(\pi)$

integral under the "short" component (electromagnetic calibration is used to convert MIP to GeV).

Pure em shower in Fe-AHCAL

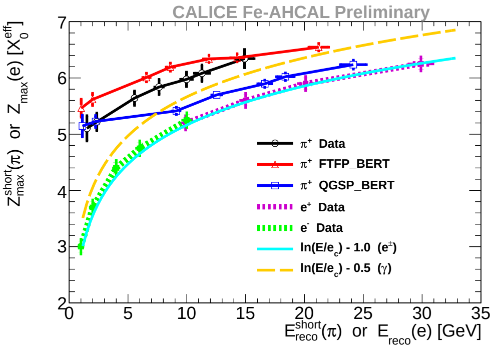
$\mathbf{Z}_{\mathrm{max}}(\mathbf{e})$

position of shower maximum from parametrisation of long. profiles for single electrons (positrons)

$\mathbf{E}_{\mathrm{reco}}(\mathbf{e})$

mean reconstructed energy of single electrons (positrons) (agrees with $\mathbf{E}_{\mathrm{beam}}$ within 1-2%)

Shape of "short" component is comparable to that of em shower from single gamma (electron).



Data on e^+ in Fe-AHCAL: *2011 JINST 6 P04003*
Data on e^- in Fe-AHCAL: *DESY-THESIS-2011-048*

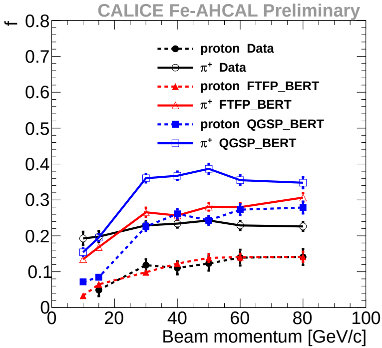
For parametrisation of $\mathbf{Z}_{\mathrm{max}}$: **E** in GeV, $\mathbf{e_c} = \mathbf{21}$ MeV
(C. Leroy and P.-G. Rancoita, 2000, Rep. Prog. Phys. ***63****, 505)*

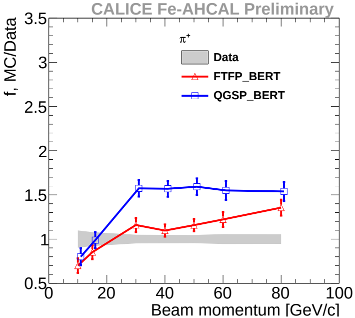
Fraction of the "short" component

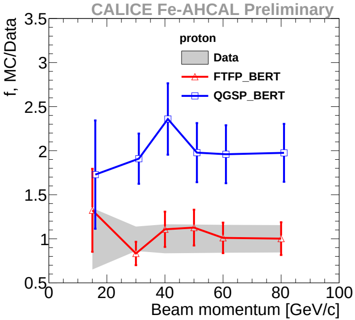
MC overestimates the fraction of "short" component:

- **up to 25% by FTFP_BERT**
- **up to 50% by QGSP_BERT**

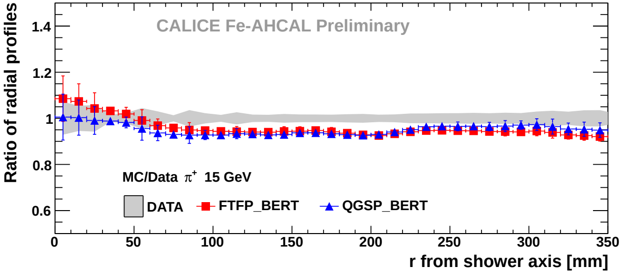
Better predictions by FTFP_BERT
Good predictions by FTFP_BERT for protons





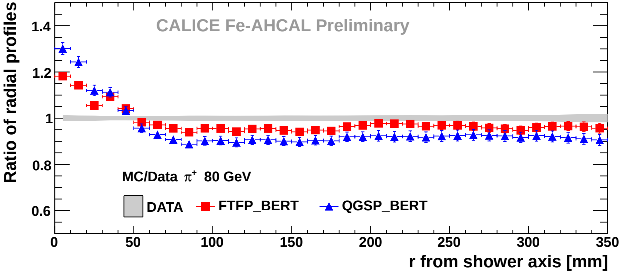


Radial shower development: MC/Data, pions



Radial profile:
visible energy density in the cylinder of radius r and width Δr vs. radial distance r from shower axis

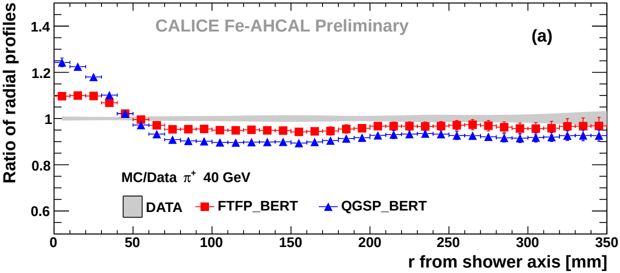
15 GeV
Within uncertainties (∼10%) in the shower core
Underestimation in the middle



80 GeV
Overestimation of core
FTFP_BERT: by ∼20%
QGSP_BERT: by ∼30%

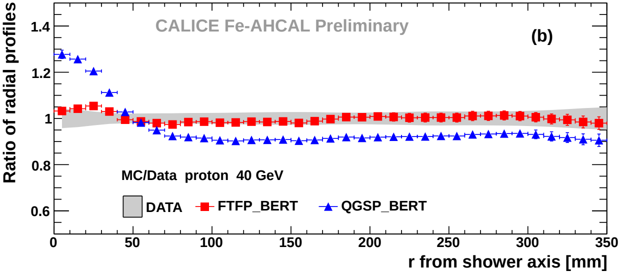
Discrepancy between data and simulations increases with energy

Ratio of radial profiles: pions and protons



Mean shower radius for hadrons @ 10-80 GeV:

- ∼60-110 mm
- ∼65% of shower energy
- decreases logarithmically with increasing energy



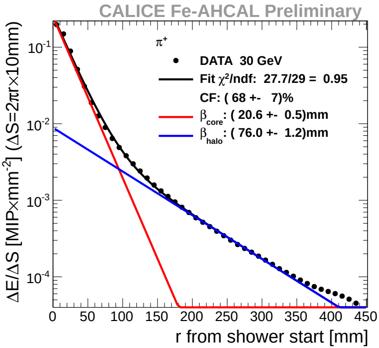
Proton-induced showers tend to be by ∼10% wider (mean shower radius) than pion-induced showers. FTFP_BERT agrees with data for protons within uncertainties in the energy range 10-80 GeV.

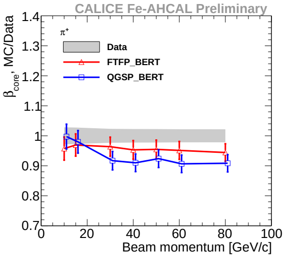
Fit to radial profiles

$$\frac{\Delta E}{\Delta S}(r) = A_{\mathrm{core}} \cdot \exp(-r/\beta_{\mathrm{core}}) + A_{\mathrm{halo}} \cdot \exp(-r/\beta_{\mathrm{halo}})$$

A_{core} and A_{halo} - scaling factors
$\beta_{\mathrm{core}} < \beta_{\mathrm{halo}}$ - slope parameters
Fit range: [0; 340] mm
tiles 12×12 cm^2 excluded from fit

r - distance from the shower axis
accuracy of the shower axis $\sigma_r = 2$ mm
$\Delta S = 2\pi r \Delta r$, $\Delta r = 10$ mm
CF - fractional contribution of "core"





MC tends to underestimate β_{core} above 20 GeV:

- FTFP_BERT by ∼5%
- QGSP_BERT by ∼10%

Summary

CALICE highly granular calorimeter prototypes

R&D of highly granular calorimeters for future HEP applications
Highly granular scintillator-steel analogue hadron calorimeter Sc-Fe AHCAL:
90cm×90cm×5λ_{I}, 7608 cells with individual SiPM readout

Response and resolution studies of the Sc-Fe AHCAL

Response to hadrons and energy resolution study in the energy range 10-80 GeV
Software compensation techniques, which allow improvement of resolution by ∼15%

Spatial shower development in the highly granular Sc-Fe AHCAL

Identification of shower start position for hadron-induced showers
Parametrisation of profiles from shower start with two-component functions
Analysis for positive hadrons @ 10-80 GeV
Comparison with FTFP_BERT and QGSP_BERT from GEANT4 9.6:

- good agreement between MC and data below 20 GeV
- good predictions of the longitudinal tail and radial halo parameters
- increase of discrepancies with energy:
  - underestimation of the core slope parameter of radial profiles by ∼5-10%
  - overestimation of the fractional contribution of the "short" component of longitudinal profiles
- FTFP_BERT gives better prediction of hadron shower profiles than QGSP_BERT