

Pion shower profiles extracted from CALICE data and Geant4 simulations

Marina Chadeeva (ITEP, MEPhI)

on behalf of the CALICE Collaboration

- 1 CALICE prototypes and test beam experiments
- 2 Longitudinal profiles: decomposition and comparison
- 3 Response and h/e ratio from the fit to longitudinal profiles
- 4 Parametrisation of radial profiles



CALICE high-granular calorimeter prototypes

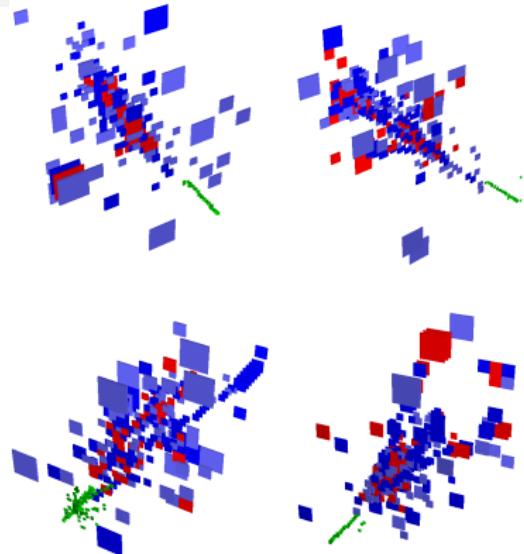
Motivation and goals

- Future HEP experiments
- PFA application: proof of principle
- Check of calibration procedures
- Test of detector simulation

Si-W and Sc-W ECAL, Sc-Fe(W) AHCAL,
GRPC-Fe(W) DHCAL and GRPC-Fe SDHCAL

Scintillator-steel analogue hadronic calorimeter

- 1 m³ physics prototype:
 $38 \text{ layers} \times (20 \text{ mm Fe} + 5 \text{ mm sci}) \approx 5.3\lambda_I$
- active sci planes: 3x3, 6x6, 12x12 cm² cells
 with SiPM readout



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

Unprecedented granularity for validation of hadronic models

Test of PFA with test beam data and G4 9.3: [2011 JINST 6 P07005](#)

Pion response, shower radius, etc. in data and G4 9.4: [2013 JINST 8 P07005](#)

Pion and proton showers from data and simulations with G4 9.4 and 9.6: [CAN-040](#)

CALICE Sc-Fe AHCAL: test beam data and simulations

Test beam with positive hadrons

- @ 30-80 GeV: Si-W ECAL + Sc-Fe AHCAL + TCMT (CERN 2007)
- @ 10-15 GeV: Sc-Fe AHCAL + TCMT (FNAL 2009)

Calibration, event selection and systematics

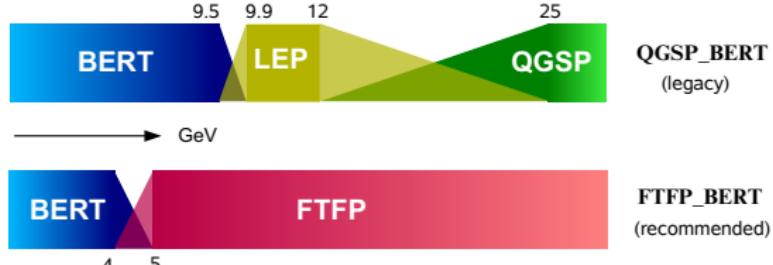
- Cell response equalised with MIPs (0.5-MIP cut for analysis)
- Sample cleaning from muons and positrons
- Čerenkov counter for pion-proton separation
- Correction for bias due to impurity
- Systematic uncertainties from:
 - layer-to-layer variations
 - identification of shower axis
- Selection by shower start in AHCAL:
 - in physical layers 3-6 w/o Ecal
 - in physical layers 2-6 with Ecal

Simulations with Geant4 version 9.6 patch 01: QGSP_BERT and FTFP_BERT

Digitisation:

- intertile crosstalk
- map of dead cells
- SiPM response

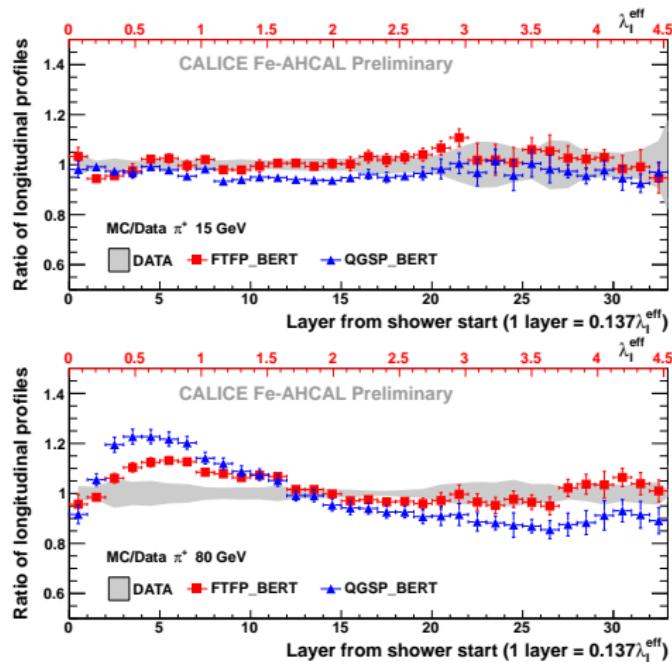
Beam profiles and noise from data runs



Longitudinal shower profiles from shower start

Visible energy ΔE per layer vs. long. distance from the identified shower start in Fe-AHCAL

Ratio of longitudinal profiles for π^+



15 GeV

FTFP_BERT: agreement within uncertainties

QGSP_BERT: little underestimation

80 GeV

Overestimation around shower maximum:

FTFP_BERT: by $\sim 10\%$

QGSP_BERT: by $\sim 20\%$

Fit to longitudinal profiles proposed in R.K. Bock et al. NIM, 186 (1981)

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

A - scaling factor

f - fraction of the "short" component

Γ - gamma function

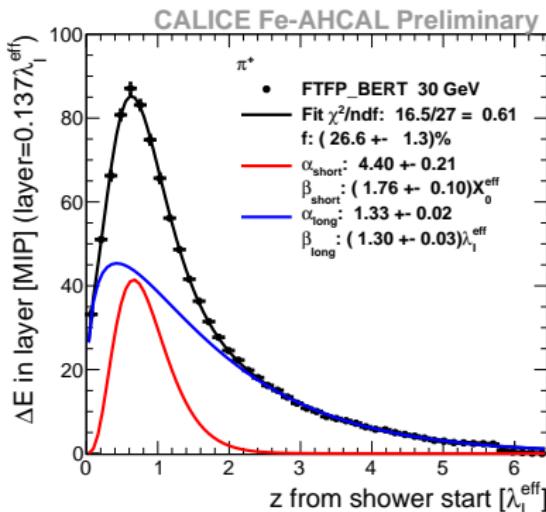
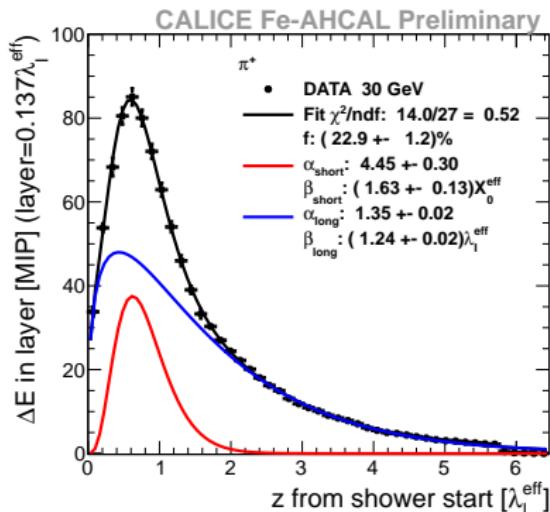
Fit range: $[0.1 \cdot \lambda_I^{\text{eff}}; 4.6 \cdot \lambda_I^{\text{eff}}]$

z - distance from the shower start

α_{short} and α_{long} - shape parameters

$\beta_{\text{short}} < \beta_{\text{long}}$ - slope parameters

$\lambda_I^{\text{eff}} = 231$ mm (~ 7 layers), $X_0^{\text{eff}} = 25.5$ mm

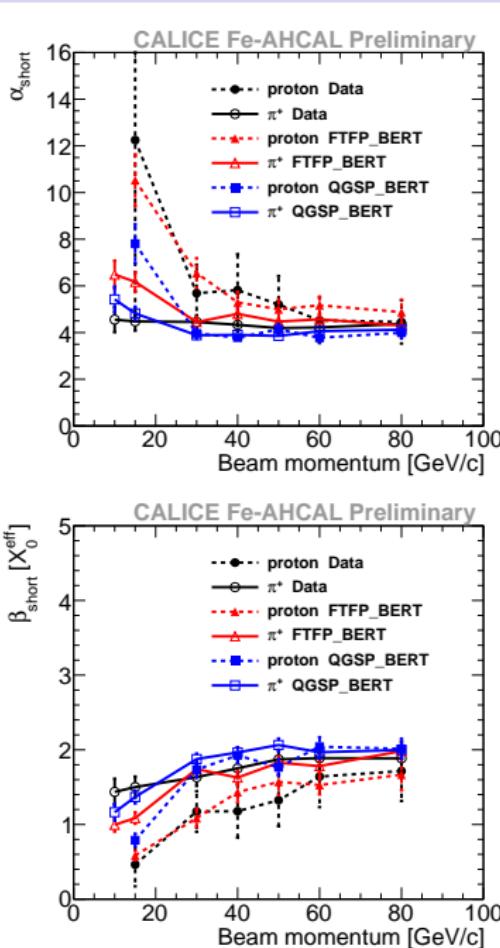
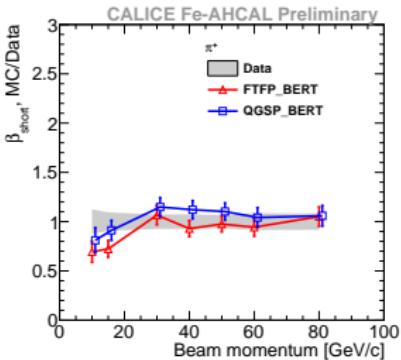
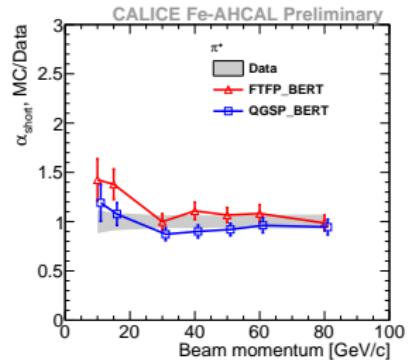


The last 9 points are from the 1st TCMT section with the same sampling as the Fe-AHCAL.

"Short" parameters α_{short} and β_{short}

"Short" parameters of pion-induced showers:

- α_{short} : no energy dependence above 20 GeV;
- β_{short} : slow increase with energy;
- **MC and data agree within uncertainties above 20 GeV (10-15%).**



Unreliable estimates for proton-induced showers:

- low statistics and high systematics;
- small fraction of the "short" component.

Shape of the "short" component of pion-induced shower

"Short" component of pion shower:

$$Z_{\max}^{\text{short}}(\pi) = (\alpha_{\text{short}} - 1) \times \beta_{\text{short}}$$

longitudinal maximum of the "short" component of pion shower

$$E_{\text{reco}}^{\text{short}}(\pi)$$

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

Pure electromagnetic shower:

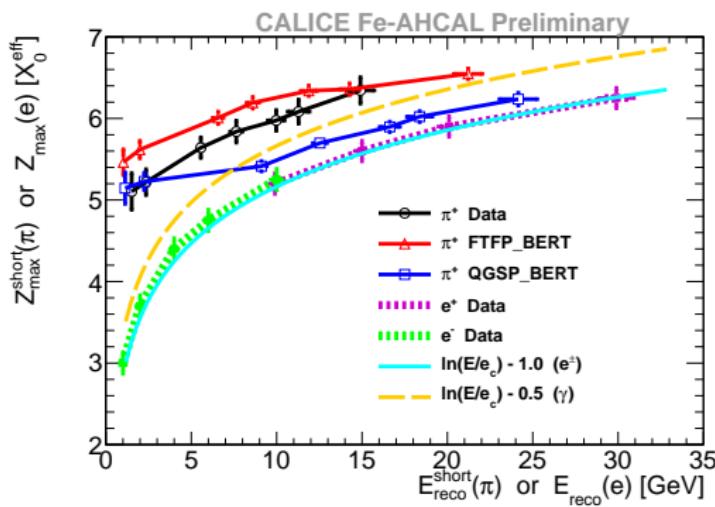
$$Z_{\max}(e)$$

maximum obtained from the parametrisation of longitudinal profiles of the showers induced by single electrons (positrons) in the Fe-AHCAL

$$E_{\text{reco}}(e)$$

mean reconstructed energy of single electrons (positrons) in the Fe-AHCAL (agrees with E_{beam} within 1-2%)

"Short" component is comparable to electromagnetic shower from single electron (gamma) in shape.



Data on e^+ in Fe-AHCAL: 2011 JINST 6 P04003

Data on e^- in Fe-AHCAL: DESY-THESIS-2011-048

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

Tail parameters α_{long} and β_{long}

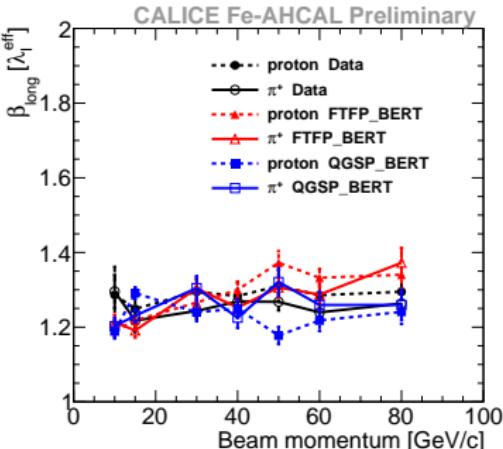
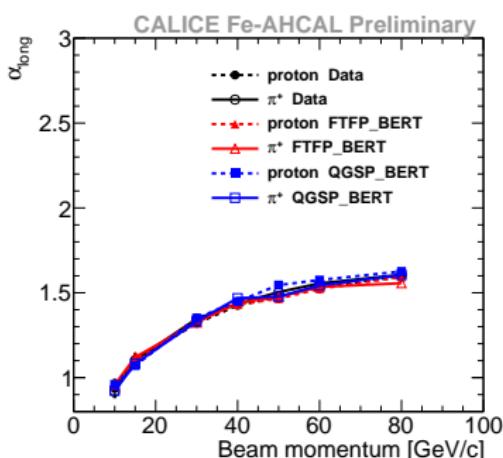
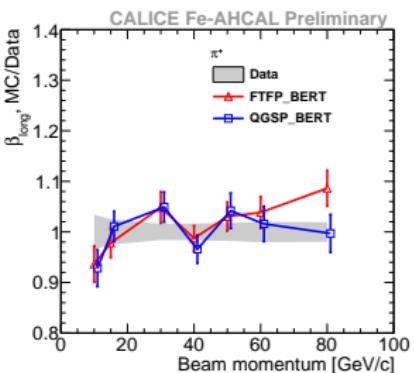
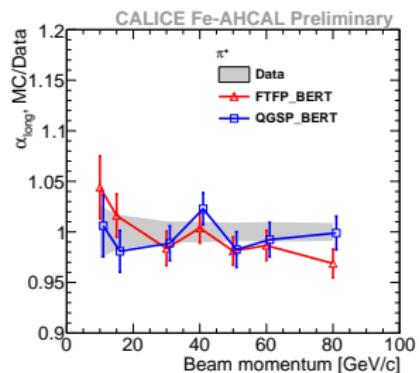
Sc-Fe AHCAL: $\lambda_I^{\text{eff}} = 231 \text{ mm} (\sim 7 \text{ layers})$

α_{long} : logarithmic rise with energy

β_{long} : no energy dependence

MC and data agree within uncertainties

(except for FTFP_BERT @ 80 GeV)



Tail parameters of pion and proton showers agree within uncertainties (except for QGSP_BERT @ 50 GeV).

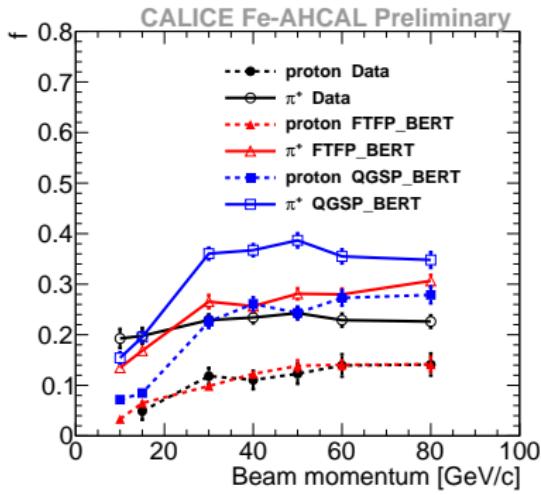
Fraction of the "short" component

Steeper energy dependence predicted by MC

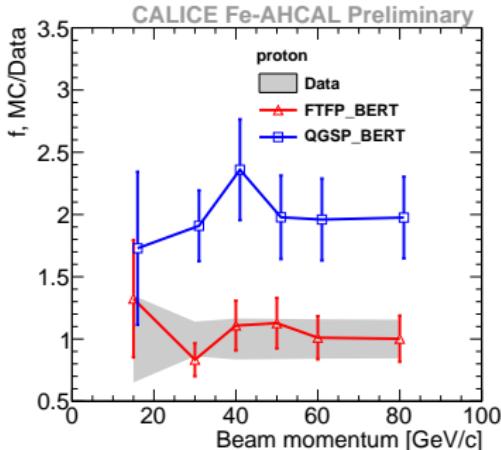
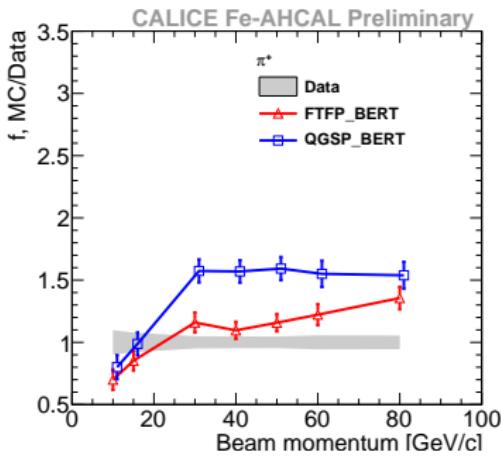
MC overestimates the fraction of "short" component:

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

Better predictions by FTFP_BERT



Good predictions by FTFP_BERT for protons



Calorimeter response from the fit to longitudinal profiles

Can we estimate the response from extrapolation of the fit?

Fe-AHCAL depth: $\sim 5.3 \cdot \lambda_I^{\text{eff}}$, available fit range: up to $4.6 \cdot \lambda_I^{\text{eff}}$

Reconstructed energy from fit $E_{\text{reco}}^{\text{fit}}$

$E_{\text{sh}}^{\text{fit}}$ - integral up to infinity under the curve from the fit to longitudinal profiles

$$E_{\text{reco}}^{\text{fit}} = E_{\text{track}} + C_{\text{em}}^H \cdot E_{\text{sh}}^{\text{fit}}$$

E_{track} - energy deposited before shower start

C_{em}^H - em calibration factor for Fe-AHCAL

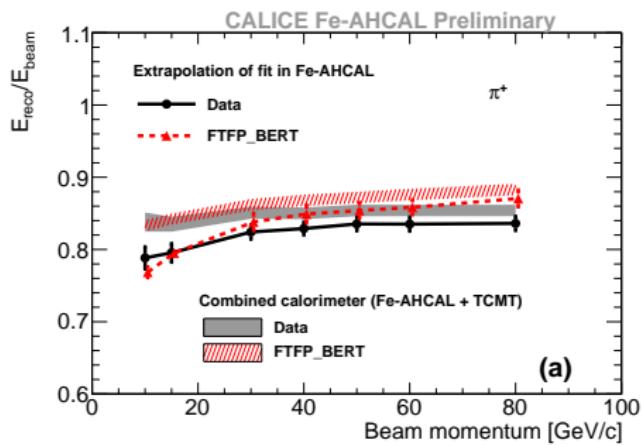
Reconstructed energy from combined calorimeter $E_{\text{reco}}^{\text{comb}}$

$$E_{\text{event}} = E_{\text{track}} + C_{\text{em}}^H \cdot E_{\text{vis}}^H + C_{\text{em}}^T \cdot E_{\text{vis}}^T$$

$E_{\text{vis}}^H, E_{\text{vis}}^T$ - visible energy in AHCAL, TCMT

C_{em}^T - em calibration factor for TCMT

$E_{\text{reco}}^{\text{comb}}$ from Gaussian fit of energy distribution



**Agreement within uncertainties above 30 GeV
Contribution from TCMT noise (~ 0.5 GeV)**

$$E_{\text{track}} = \begin{cases} 0.40 \pm 0.09 \text{ GeV} & \text{with ECAL} \\ 0.06 \pm 0.02 \text{ GeV} & \text{w/o ECAL} \end{cases}$$

Extraction of h/e ratio from shower decomposition

Hadron shower energy = electromagnetic component ($\pi^0 \rightarrow 2\gamma$) + hadronic component



Response:
Fraction:
Reconstructed in em scale:

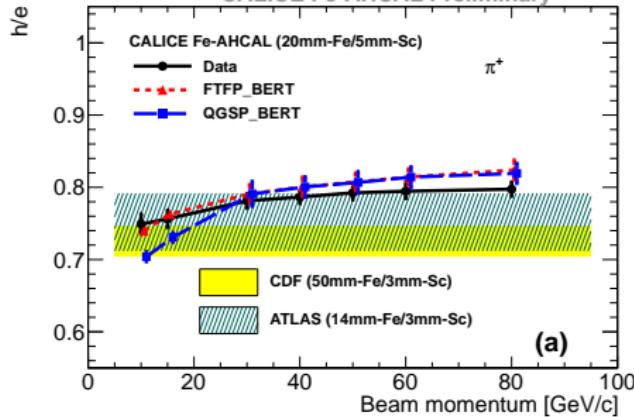
$$\begin{aligned} e \\ f_{\text{em}} \\ E_{\text{em}} = f_{\text{em}} \cdot E_{\text{ini}} \end{aligned}$$

Assumption from fit:
integral up to infinity

$$\begin{aligned} E_{\text{em}} = E_{\text{reco}}^{\text{short}} \\ \text{under "short" component} \end{aligned}$$

$$\begin{aligned} h \\ f_{\text{had}} = 1 - f_{\text{em}} \\ E_{\text{had}} = (h/e) \cdot f_{\text{had}} \cdot E_{\text{ini}} \end{aligned}$$

$$\begin{aligned} E_{\text{had}} = E_{\text{reco}}^{\text{long}} \\ \text{under "long" component} \end{aligned}$$



$$\frac{h}{e} = \frac{E_{\text{reco}}^{\text{long}}}{E_{\text{ini}} - E_{\text{reco}}^{\text{short}}}$$

$$E_{\text{ini}} = E_{\text{beam}} - E_{\text{track}}$$

h/e from fit increases with energy:

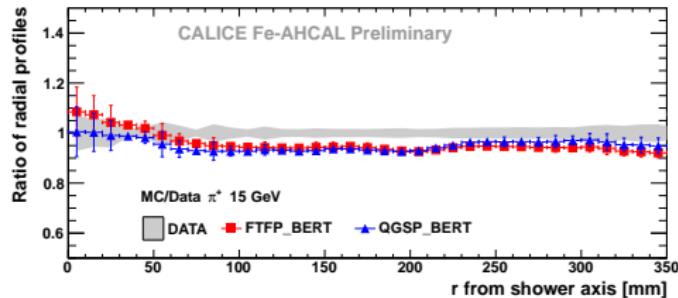
- simplified representation: higher energy \Rightarrow increasing contribution of em fraction to the "long" component
- changing topology: higher energy \Rightarrow narrower showers \Rightarrow better sampling

[Experimental data of CDF and ATLAS from FERMILAB-Conf-97/414-E and NIM, A606, 2009, 362]

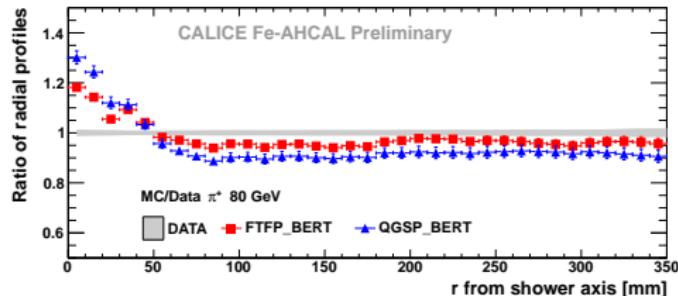
Radial shower profiles

Radial profiles: visible energy density $\Delta E / \Delta S$ in the ring with radius r and width Δr vs. radial distance r from shower axis, $\Delta S = 2\pi r \Delta r$ ($\Delta r = 10$ mm)

Ratio of radial profiles for π^+



15 GeV
Agreement within uncertainties (~10% in the shower core)
Underestimation in the middle



80 GeV
Overestimation in the shower core:
FTFP_BERT: by ~20%
QGSP_BERT: by ~30%

Fit to radial profiles

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

A_{core} and A_{halo} - scaling factors

$\beta_{\text{core}} < \beta_{\text{halo}}$ - slope parameters

Fit range: [0; 340] mm

tiles $12 \times 12 \text{ cm}^2$ excluded from fit

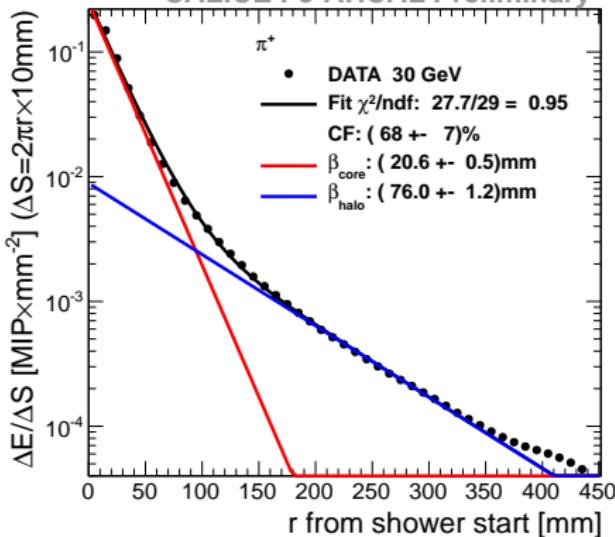
r - distance from the shower axis

accuracy of the shower axis $\sigma_r = 2 \text{ mm}$

CF - fractional contribution of the integral under the "core" component

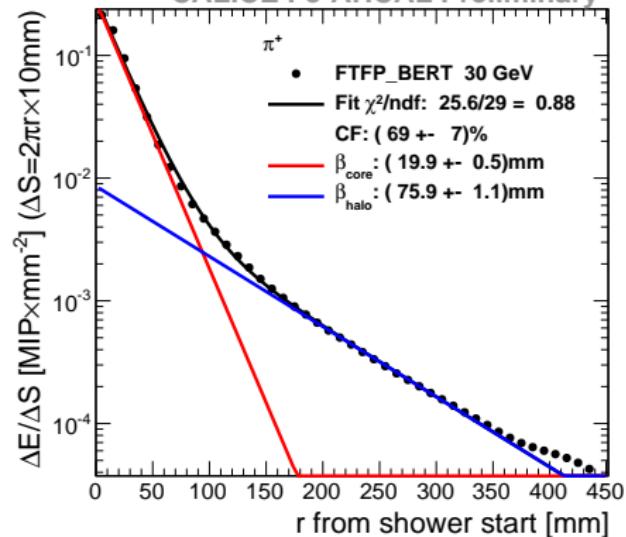
DATA

CALICE Fe-AHCAL Preliminary



FTFP_BERT

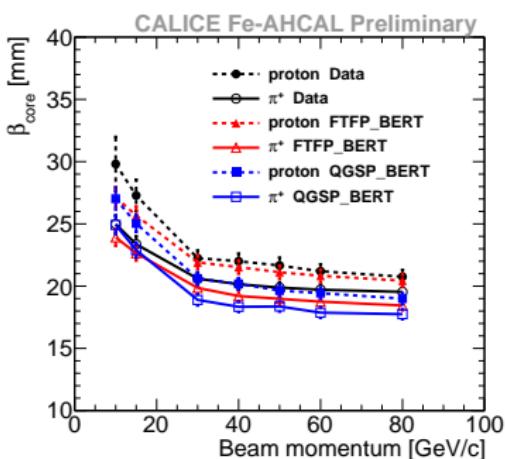
CALICE Fe-AHCAL Preliminary



Radial slope parameters

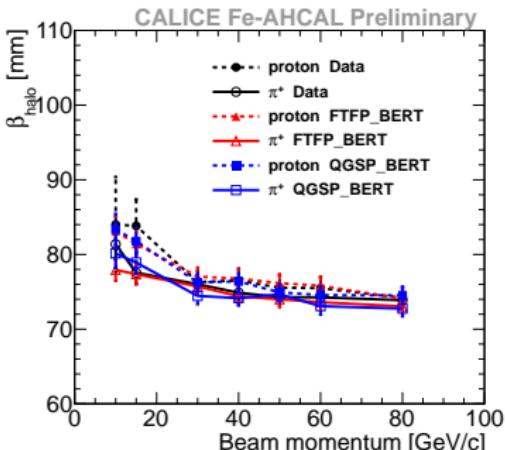
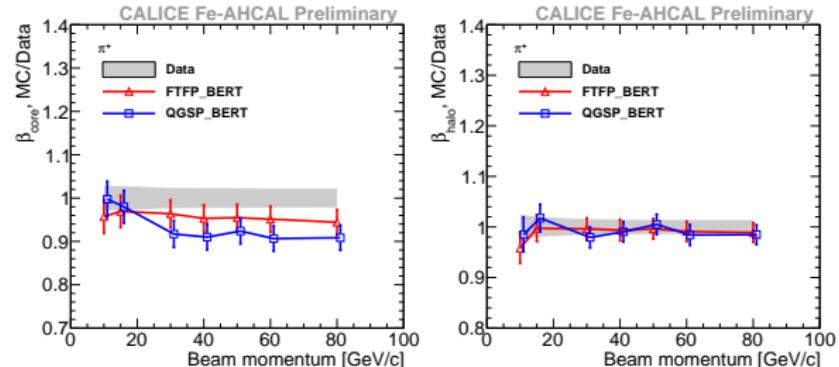
β_{core} :

- decreases with energy
- underestimated by MC:**
 - FTFP_BERT by $\sim 5\%$
 - QGSP_BERT by $\sim 10\%$
- systematically larger for protons than for pions



β_{halo} :

- slow energy dependence
- data and MC agree within uncertainties**
- pions and protons agree within uncertainties**



Summary

**Parametrisation of shower profiles of positive hadrons @ 10-80 GeV
in the CALICE Sc-Fe AHCAL using two-component functions**

Summary

Parametrisation of shower profiles of positive hadrons @ 10-80 GeV
in the CALICE Sc-Fe AHCAL using two-component functions

Validation of hadronic models from Geant4 version 9.6 (FTFP_BERT and QGSP_BERT)

- good agreement with data below 20 GeV
- good predictions of the longitudinal tail and radial halo in the energy range studied
- discrepancy increases with energy:
 - underestimation of the core slope parameter of radial profiles by \sim 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

Summary

Parametrisation of shower profiles of positive hadrons @ 10-80 GeV
in the CALICE Sc-Fe AHCAL using two-component functions

Validation of hadronic models from Geant4 version 9.6 (FTFP_BERT and QGSP_BERT)

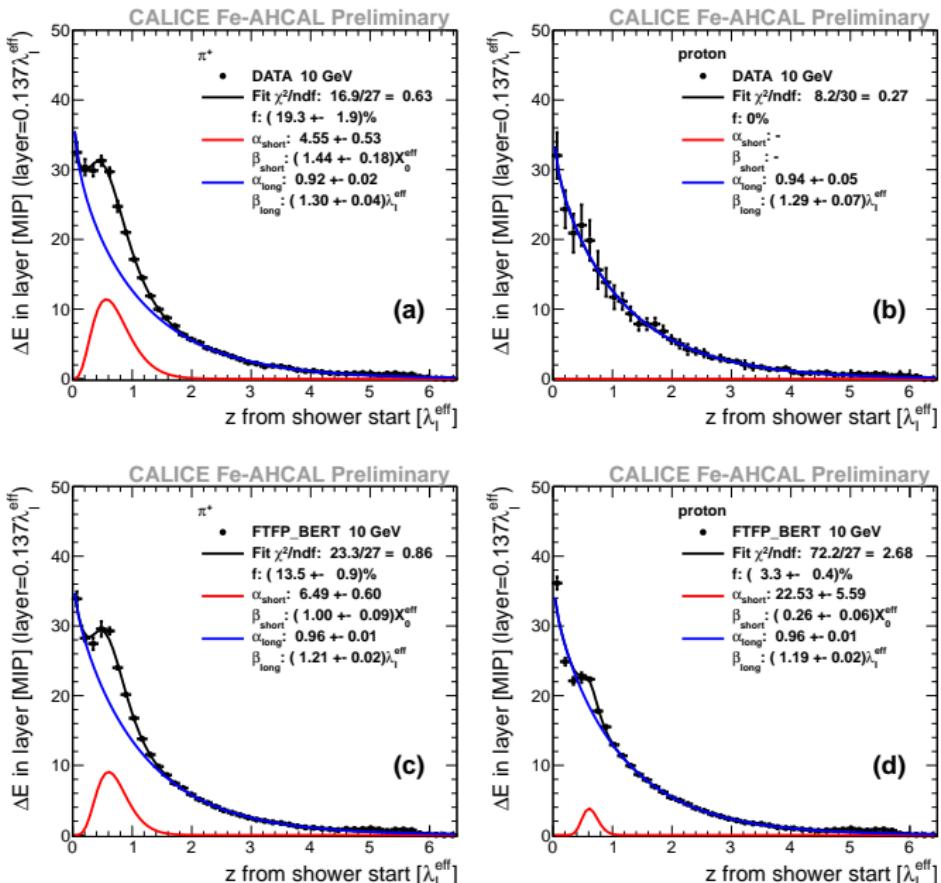
- good agreement with data below 20 GeV
- good predictions of the longitudinal tail and radial halo in the energy range studied
- discrepancy increases with energy:
 - underestimation of the core slope parameter of radial profiles by \sim 5-10%
 - overestimation of the fractional contribution of the "short" component of longitudinal profiles
- FTFP_BERT gives better prediction of hadron shower profiles than QGSP_BERT

Applications

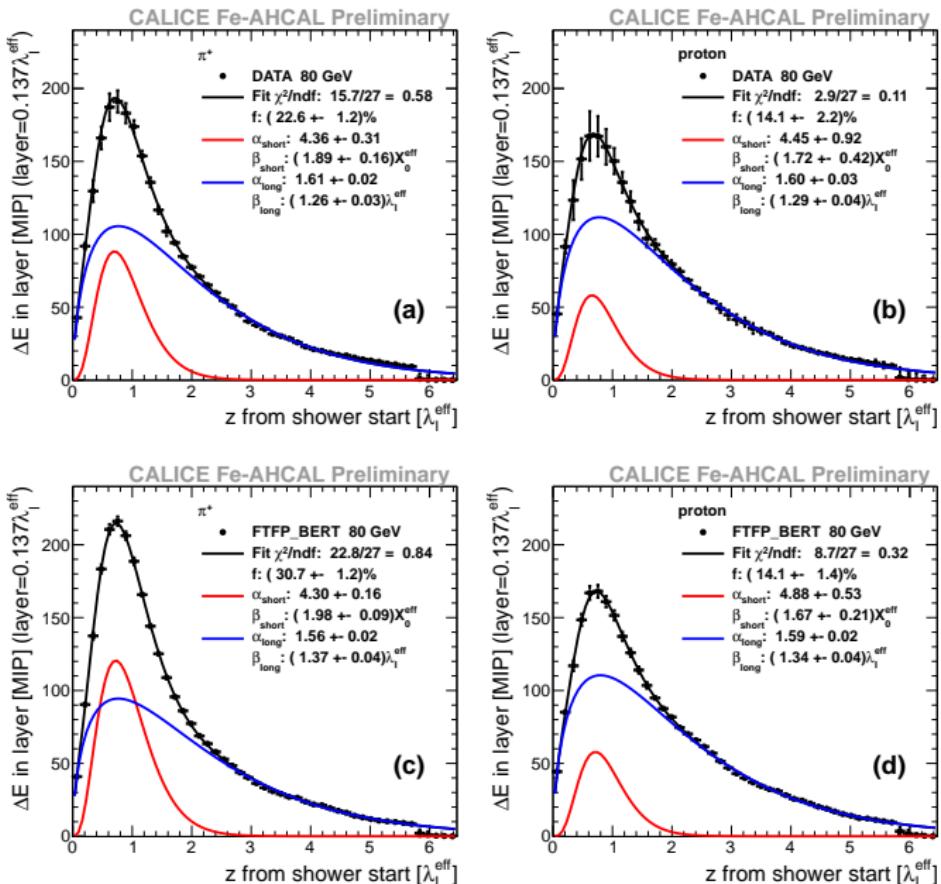
- Extrapolation of the fit to longitudinal profiles gives a reliable estimate of the calorimeter response w/o tail catcher — can be useful for calibration.
- Two-component shower decomposition allows to get a reasonable estimate of the calorimeter characteristic h/e .

Backup slides

Examples of longitudinal profiles: 10 GeV

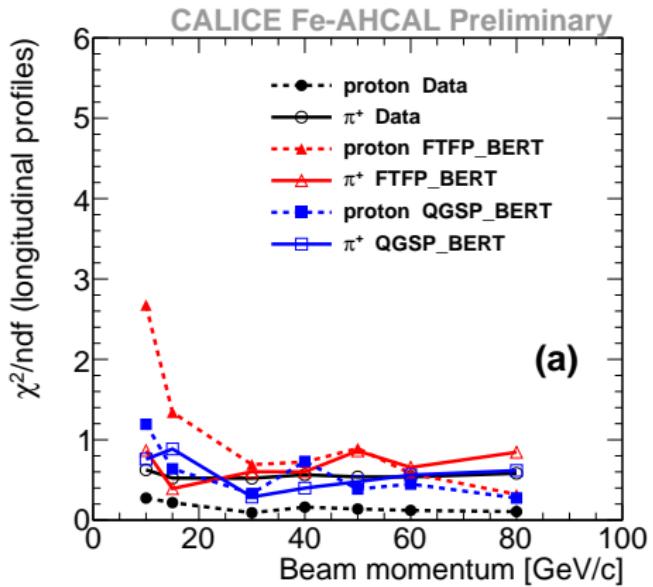


Examples of longitudinal profiles: 80 GeV



Fit quality

Longitudinal profiles



Radial profiles

