Comparison of pion and proton shower profiles in the CALICE Sc-Fe AHCAL

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Outline

1. Data and event selection
2. Systematic uncertainties
3. Longitudinal profiles
4. Radial profiles
5. Electromagnetic fraction
6. Summary
7. Backup slides: systematic uncertainties, fit quality, examples of profiles and profile ratios

Data samples and simulations

Test beam data

CERN 2007 runs, π^+ @ 30-80 GeV (ECAL+AHCAL+TCMT)
FNAL 2009 runs, protons @ 10 and 15 GeV (AHCAL+TCMT)
Reconstruction with calice_soft v04-01

Simulations (by Lars Weuste)

GEANT4.9.4p03, Mokka v07_07p04
Physics lists: QGSP_BERT, QBBC, CHIPS, FTFP_BERT, FTF_BIC
calice_soft v04-05, 816 keV/MIP, 0.1 light crosstalk for AHCAL

Sample cleaning

- Rejection of muons, multiparticle and empty events (CAN-035)
- Additional cuts to reject positrons and multiparticle events in FNAL runs
- Separation of pions from protons using Čerenkov counter
- Selection of events with shower start at the beginning of AHCAL:
    - in layers 2-5 for FNAL data to reject positrons and minimize leakage
    - in layers 1-4 for CERN data to minimize leakage and exclude the first(0) layer with the biggest uncertainty of shower start identification

Systematic uncertainties

Positron contamination in FNAL data

$<1\%$ after positron rejection and requirement of shower start after 2nd AHCAL layer

Pion contamination of proton samples

Beam momentum GeV/c	Purity of proton sample η
10	0.66
15	0.73
30	0.95
40	0.84
50	0.79
60	0.89
80	0.78

Proton profiles are corrected by subtracting the average contribution of pion admixture depending on purity η at the corresponding energy.

The corrected content for *i*-th layer (bin)

$$E_i^{\mathrm{corr}} = E_i^{\mathrm{mix}} \cdot \frac{1}{\eta} - E_i^{\pi} \cdot \frac{1-\eta}{\eta},$$

E_i^{mix} - from *i*-th bin in the mixed sample
E_i^{π} - from *i*-th bin in the pion sample

Layer intercalibration

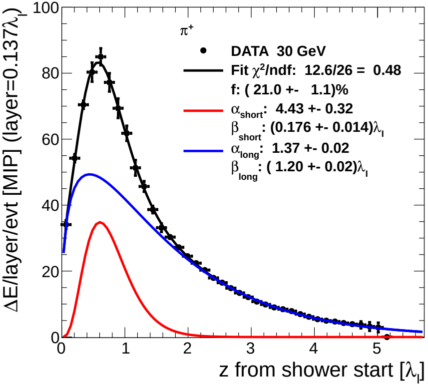
Systematically higher(lower) response for some layers, difference increases with energy. It is most likely due to saturation correction issues for some cells and dead cells. (Estimation details in backup slides.)

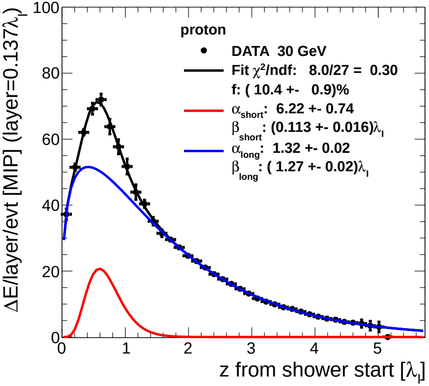
Fit to longitudinal profiles

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

Fit parameters: scaling factor A, fractional contribution f,
multiplicity parameters α_{short} and α_{long}, slope parameters β_{short} and β_{long}

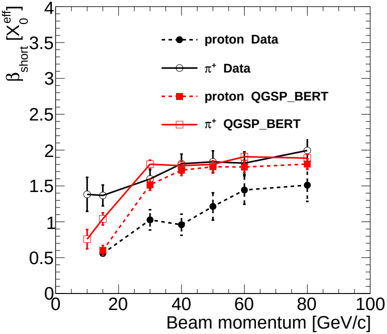
The smaller slope parameter from fit is called β_{short} with corresponding α_{short} and fractional contribution f.

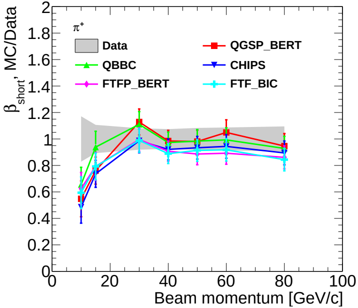


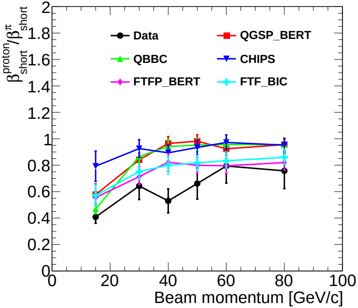


Parameter β_{short}

Slope parameter β_{short} in units of X_0^{eff}
Sc-Fe AHCAL: $X_0^{\mathrm{eff}} = 25.5$ mm $\approx 0.1\lambda_{\mathrm{I}}^{\mathrm{eff}}$







β_{short} increases with energy. MC tends to underestimate data for pions. MC underestimates difference between π^+ and protons.

α_{short} is energy independent above 20 GeV.

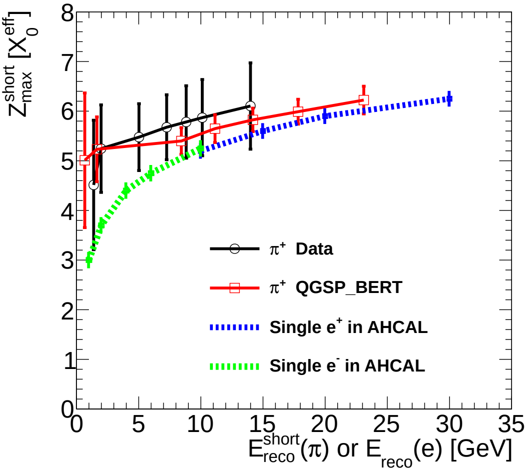
"Short" longitudinal component

$Z_{\rm max}^{\rm short} = (\alpha_{\rm short} - 1) \times \beta_{\rm short}$ **is a position of the maximum of "short" component.**

$E_{\rm reco}^{\rm short}$ **is an integral under the "short" part of longitudinal profile (energy of the "short" component).**

Points for single positrons in AHCAL are from CALICE paper: 2011 JINST 6 P04003.

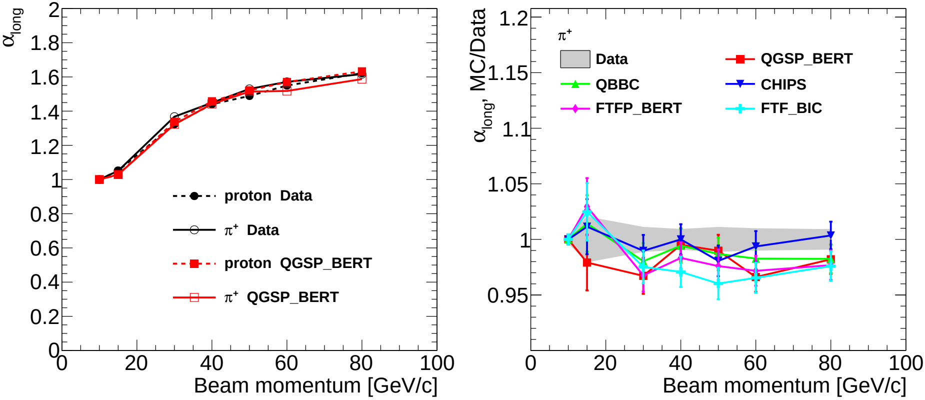
Points for single electrons in AHCAL are from dissertation of Nils Feege.



Parameters of "short" component of pion showers are in good agreement with those of electromagnetic showers from single electrons/positrons in the AHCAL.

Parameter α_{long}

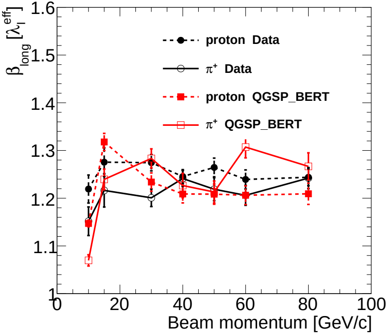
Multiplicity parameter α_{long}



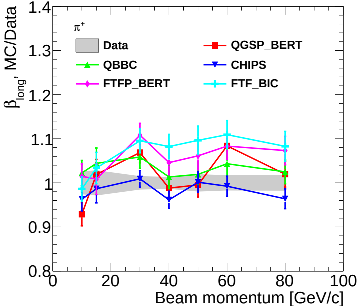
α_{long} increases logarithmically with energy and coincides within uncertainties for pions and protons. Difference between MC and data does not exceed 5%.

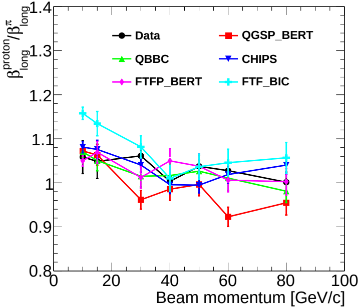
Parameter β_{long}

Slope parameter β_{long} in units of $\lambda_{\mathrm{I}}^{\text{eff}}$
Sc-Fe AHCAL: $\lambda_{\mathrm{I}}^{\text{eff}} = 231.1$ mm $\approx$ 7 layers



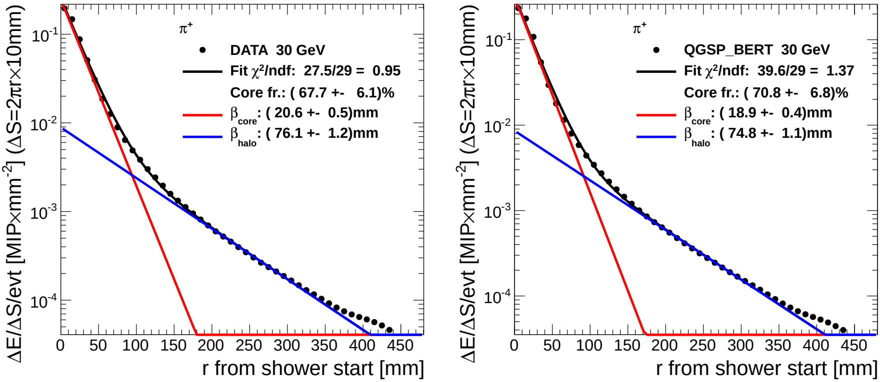
β_{long} is energy independent, most PL (except for CHIPS) tend to overestimate β_{long}. Difference between π^+ and protons decreases with energy.





Fit to radial profiles

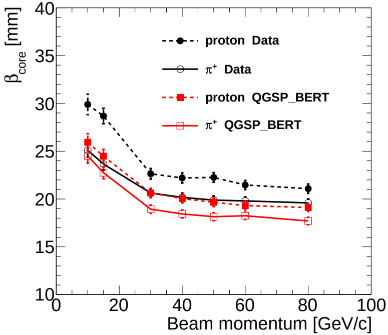
$\frac{\Delta E}{\Delta S}(r) = A_{\mathrm{core}} \cdot \exp(-r/\beta_{\mathrm{core}}) + A_{\mathrm{halo}} \cdot \exp(-r/\beta_{\mathrm{halo}})$
$\Delta S = 2\pi r \Delta r$ $\quad\quad$ $\sigma_r = 2$ mm (accuracy of shower axis)
scaling factors A_{core} and A_{halo}, slope parameters $\beta_{\mathrm{core}} < \beta_{\mathrm{halo}}$

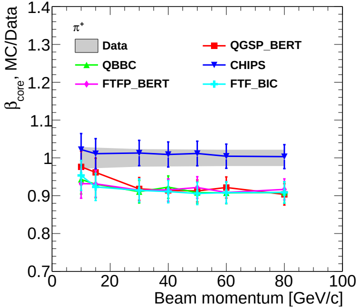


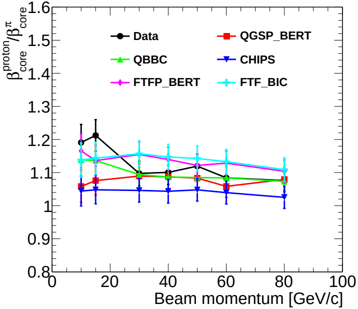
Radius R_{core} corresponds to the intersection of two exponents.
R_{core} is ∼100-110 mm below 20 GeV and ≈95 mm from 30 GeV and above.

Parameter β_{core}

β_{core} describes the behavior near shower axis.
Sc-Fe AHCAL: $R_{\mathrm{M}}^{\mathrm{eff}} = 24.5$ mm (inner tile 30 mm)



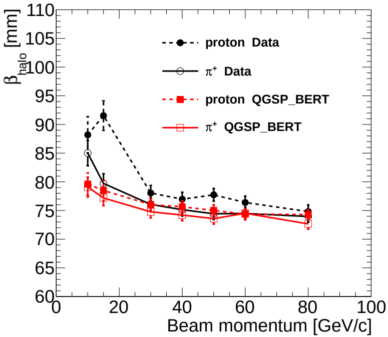




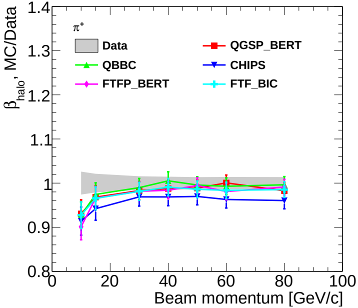
β_{core} decreases fast till 30 GeV.
Most PL (except for CHIPS) underestimate β_{core} for pions by $\sim$10%.
β_{core} is by $\sim$5-15% larger for protons.

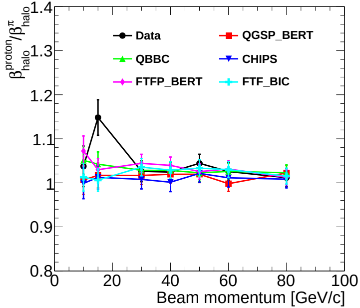
Parameter $\beta_{\rm halo}$

$\beta_{\rm halo}$ describes the behavior far from shower axis.



$\beta_{\rm halo}$ decreases slowly with energy.
MC and data in agreement (except for CHIPS).
$\beta_{\rm halo}$ for pions and protons coincides within uncertainties (the behavior at 15 GeV for proton data not understood yet).

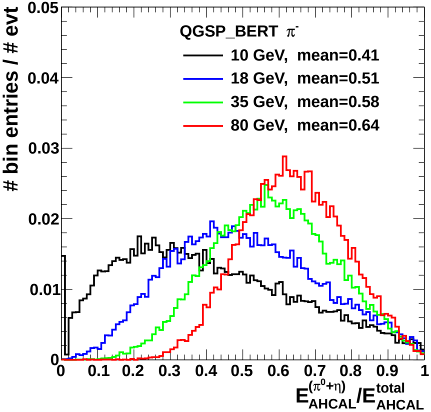




Radial core fraction and EM fraction from MC

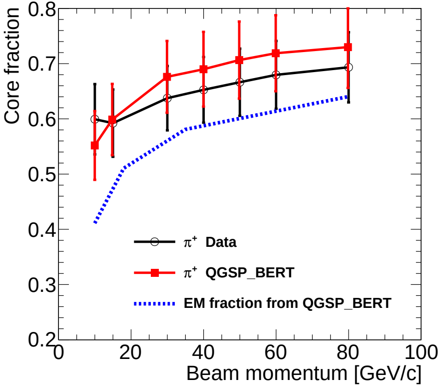
EM fraction (GEANT4.9.3):

ratio of the energy $E^{(\pi^0+\eta)}_{\mathrm{AHCAL}}$ from π^0 and η to the total energy $E^{\mathrm{total}}_{\mathrm{AHCAL}}$ measured in AHCAL (only events with the true first interaction in the first five AHCAL layers).



Observable: radial core fraction

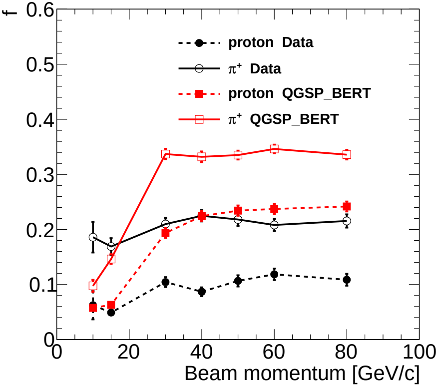
is a fractional integral contribution from the component with β_{core} within R_{core}.

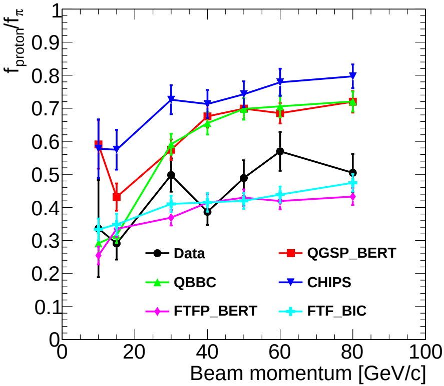


Core fraction overestimates the real EM fraction by 10-15%.

Fractional contribution *f*

Fractional contribution *f* of the component with α_{short} and β_{short}

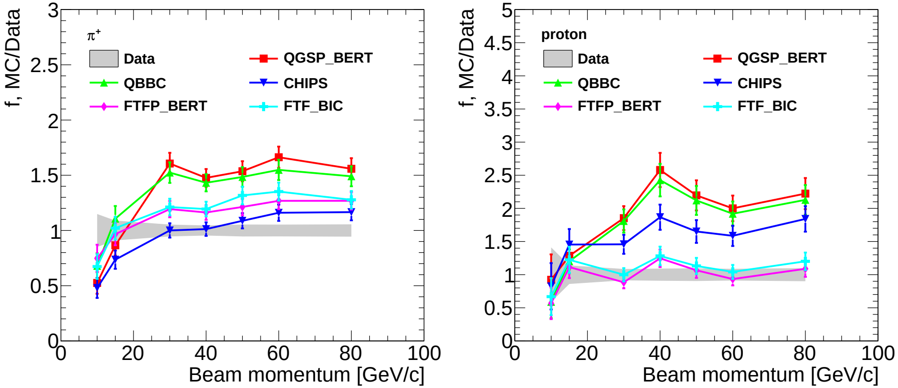




Energy dependence more pronounced in MC. Fraction *f* is significantly lower for protons. The difference between pions and protons tends to decrease with energy.
***f* underestimates the real EM fraction (extracted from MC) ∼4 times below 20 GeV and ∼2 times at higher energies.**

Fractional contribution *f*: MC/Data

Fractional contribution *f* of the component with α_{short} and β_{short}



f **is overestimated by MC above 20 GeV (exceptions: CHIPS for pions and Fritiof for protons) - it is the main source of difference between MC and data.**

Summary

Shower parametrization

Hadronic shower profiles can be well described by the sum of two contributions: sum of gamma distributions for longitudinal and sum of exponents for radial development.

Difference between pions and protons

Core slope parameter of proton-induced showers is larger than for pions (wider proton showers). Fractional contribution of the "short" component is 2-4 times lower for protons. No difference in tails of longitudinal profiles and halo region of radial profiles.

MC and data comparison

- Longitudinal development: the main difference is in fractional contribution of "short" component.
- Radial development: MC underestimates core slope parameter by $\sim$10%.

Electromagnetic fraction

The core fraction of radial profile overestimates the mean electromagnetic fraction in pion showers by 10-15%. The extracted "short" component of longitudinal profile contains no more than half of electromagnetic component.

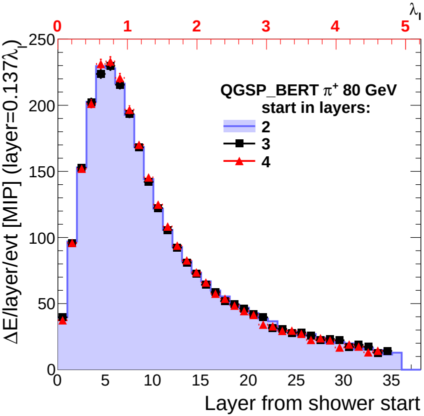
Backup slides

Visualization of intercalibration systematics

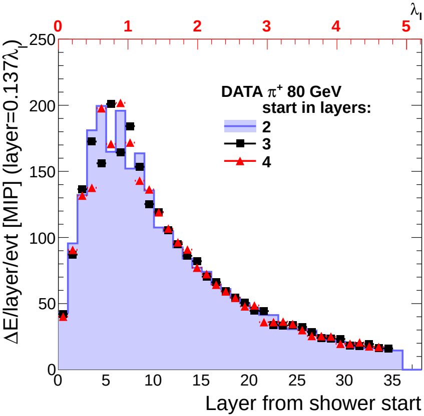
Profiles from shower start are more smooth than from calorimeter front.
For small number of selected start layers (3 or 4) irregularities are still visible in data.

Comparison of profiles for one selected start layer:

Crosscheck with MC: profile shape is independent on selected start layer.



Data: differences exceed statistical uncertainties



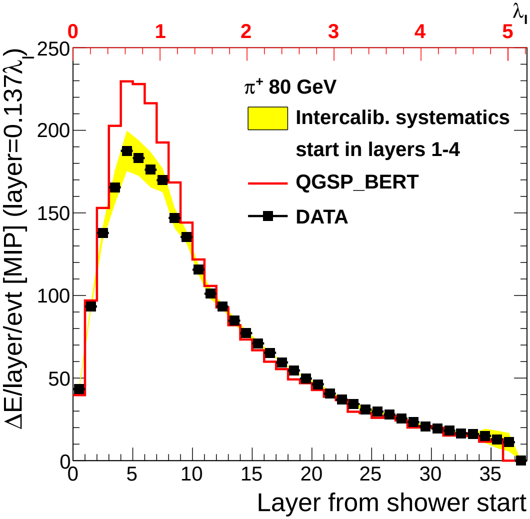
Estimation of intercalibration systematics

Resulting profile is an average of several (e.g. 4) single-start-layer profiles.

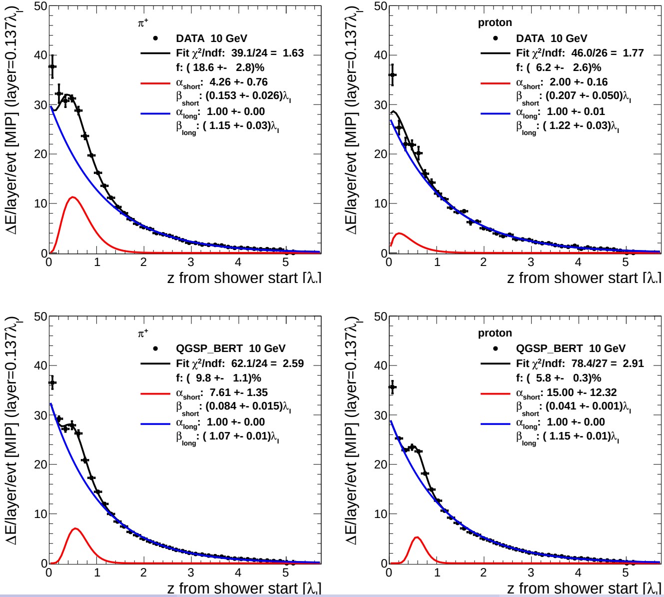
Systematic uncertainty (yellow band) is estimated as an error of mean calculated independently for each layer.

The biggest uncertainty is obtained for 80 GeV data.

Very small impact on radial profiles as expected.



Examples of longitudinal profiles: 10 GeV

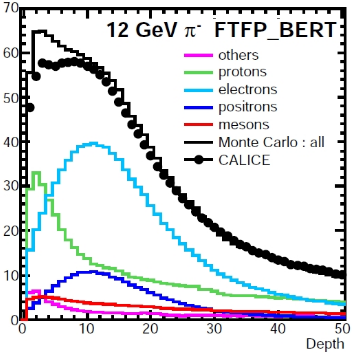


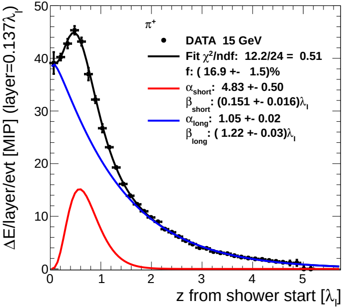
Comparison with Si-W ECAL study

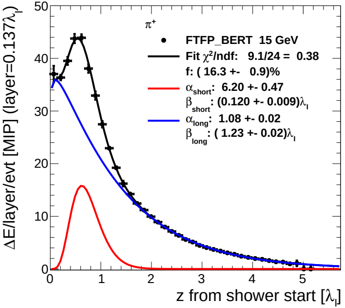
π^+ **in Sc-Fe AHCAL** $\Rightarrow$

π^- **in Si-W ECAL**

$\Downarrow$







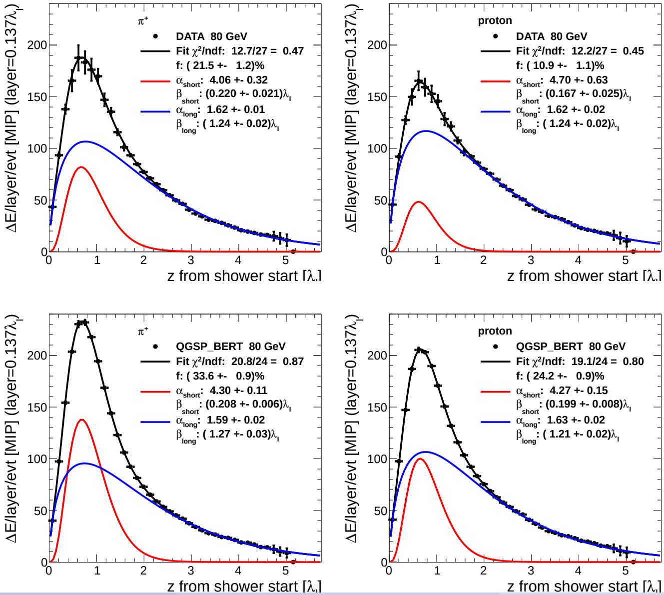
CALICE paper: 2010 JINST 5 P05007

π^- showers in Si-W ECAL from shower start

1 bin = 1.4 mm of tungsten ($0.016\lambda_\mathrm{I}$)

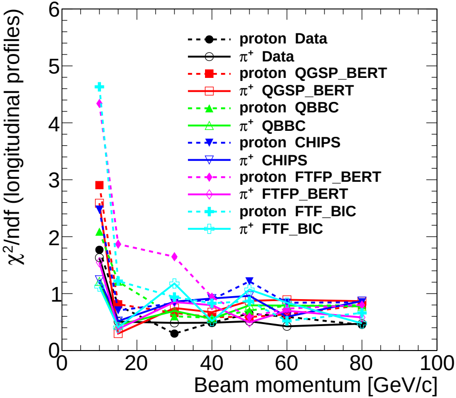
8 bins $\approx$ 1 AHCAL layer ($0.137\lambda_\mathrm{I}$)

Examples of longitudinal profiles: 80 GeV

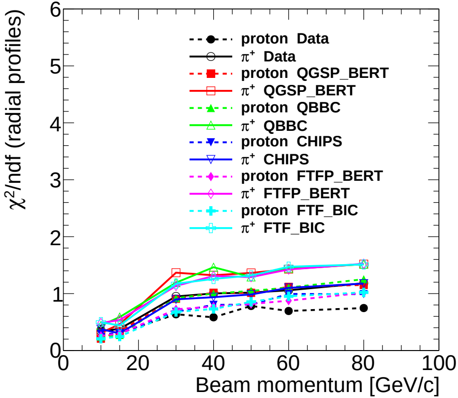


Fit quality

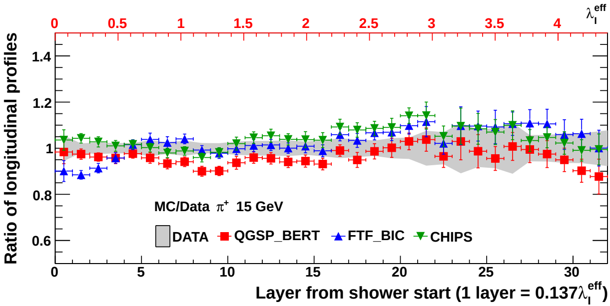
Longitudinal profiles



Radial profiles



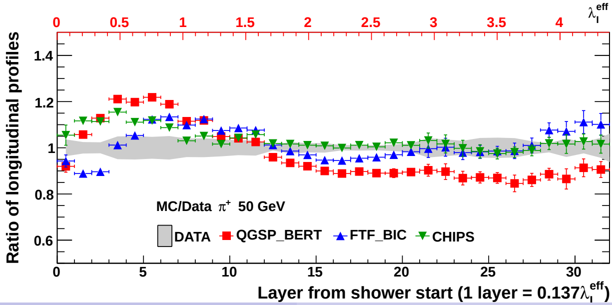
Ratio of longitudinal profiles: π^+



15 GeV

FTF_BIC: ∼12% ⇓ at maximum

QGSP_BERT and **CHIPS**: good agreement with data



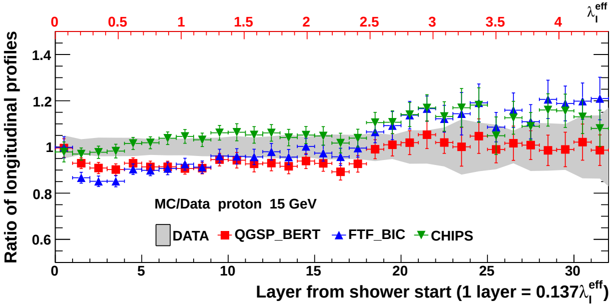
50 GeV

FTF_BIC: maximum shifted w.r.t. data

QGSP_BERT: ∼20% ⇑ at maximum, ∼10% ⇓ of tail

CHIPS: ∼15% ⇑ at maximum

Ratio of longitudinal profiles: proton

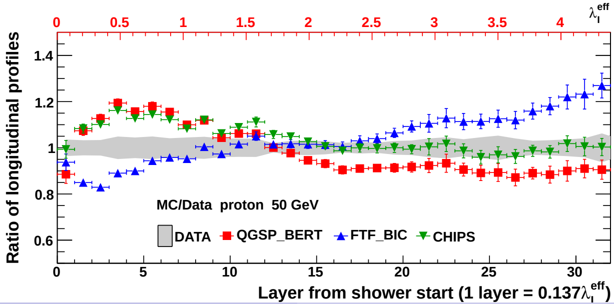


15 GeV

FTF_BIC: up to 15% ⇓ at maximum

QGSP_BERT: ∼10% ⇓ at maximum

CHIPS: good agreement with data



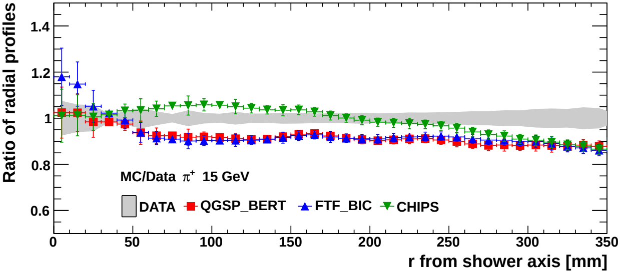
50 GeV

FTF_BIC: up to 20% ⇓ at maximum and ⇑ of tail

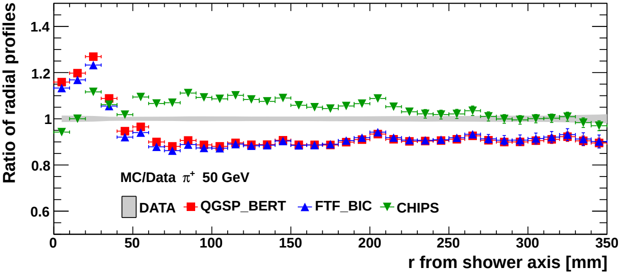
QGSP_BERT: up to 20% ⇑ at maximum, ∼10% ⇓ of tail

CHIPS: up to 20% ⇑ at maximum

Ratio of radial profiles: π^+

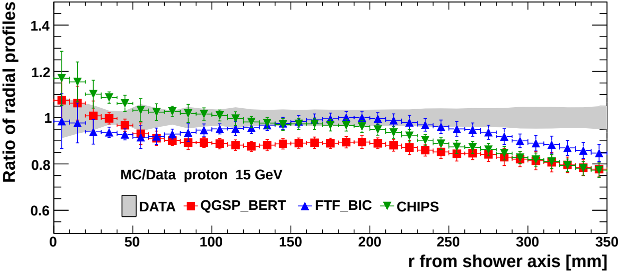


15 GeV
FTF_BIC and
QGSP_BERT: up to 10% ⇓ out of the core
CHIPS: ∼5% ⇑ in the middle



50 GeV
FTF_BIC and
QGSP_BERT: ∼20% ⇑ in the core, ∼10% ⇓ in halo region
CHIPS: ∼10% ⇑

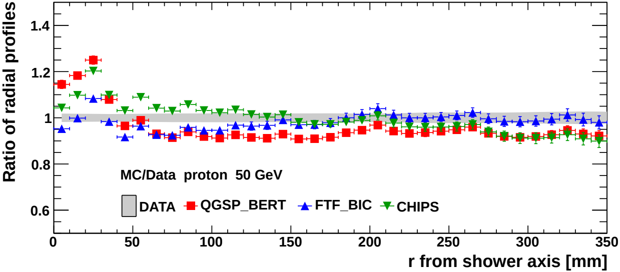
Ratio of radial profiles: proton



15 GeV

QGSP_BERT: ⇓ in the halo

CHIPS: ⇑ in the core



50 GeV

All physics lists overestimate energy density in the core. Better agreement for **FTF_BIC**