Parametrisation of hadron shower profiles in the CALICE Sc-Fe AHCAL

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Outline

1. Data and event selection
2. Systematic uncertainties
3. Ratio of profiles
4. Parametrisation of longitudinal profiles
5. Parametrisation of radial profiles
6. Summary

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 v04-07

Simulations (by Sergey Morozov)

GEANT4.9.6p01, Mokka v08_02
Physics lists: QGSP_BERT and FTFP_BERT
calice_soft v04-07, 846 keV/MIP, 0.15 light crosstalk for the AHCAL

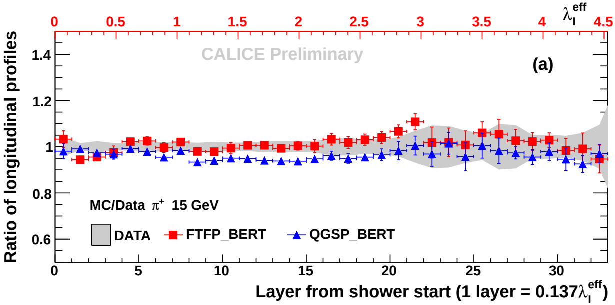
Sample cleaning

- 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 physical layers 3-6 for FNAL data to reject positrons and minimize leakage
  - in physical layers 2-5 for CERN data to minimize leakage and exclude the first layer with the biggest uncertainty of shower start identification

Systematic uncertainties (details in backup slides)

- **Layer-to-layer variations**
  - increase with energy up to ∼10% at 80 GeV
  - main origin: saturation correction issues
- **Identification of shower start layer in the AHCAL**
  - stability of the algorithm w/o ECAL confirmed by simulations
- **Identification of shower axis for radial profiles**
  - higher accuracy with track in ECAL (granularity 1×1 cm^2)
  - lower accuracy w/o ECAL: CoG or track in AHCAL, variations up to ∼10%
- **Pion contamination of proton samples**
  - sample purity varies from 74% to 95%
  - profiles corrected with propagated uncertainty
- **Positron contamination**
  - crucial for runs w/o ECAL
  - negligible impact if shower start behind 2nd AHCAL layer
- **Leakage from the AHCAL**
  - impact of fit range upper limit (4-7$\lambda_{\mathrm{I}}^{\mathrm{eff}}$) much smaller than fit errors

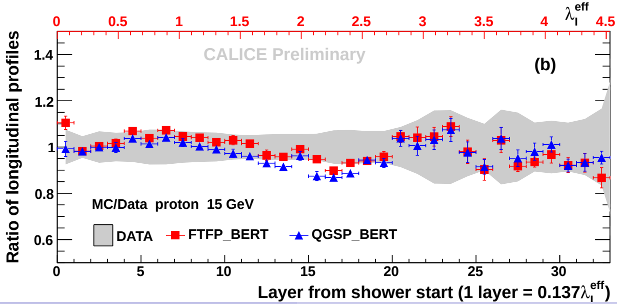
Ratio of longitudinal profiles @ 15 GeV



Pions

FTFP_BERT: good agreement

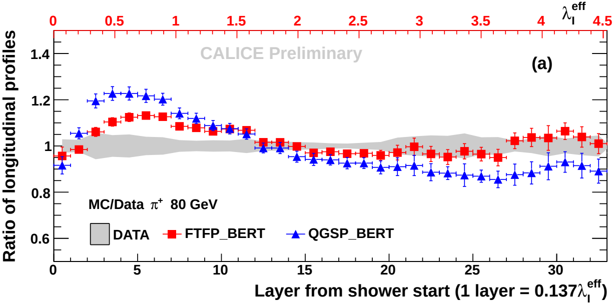
QGSP_BERT: ↓ by 5%



Protons

Agreement within uncertainties

Ratio of longitudinal profiles @ 80 GeV

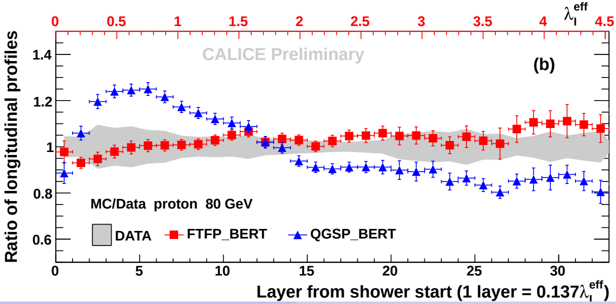


Pions

Around shower maximum:

FTFP_BERT: ↑ by 10%

QGSP_BERT: ↑ by 20%

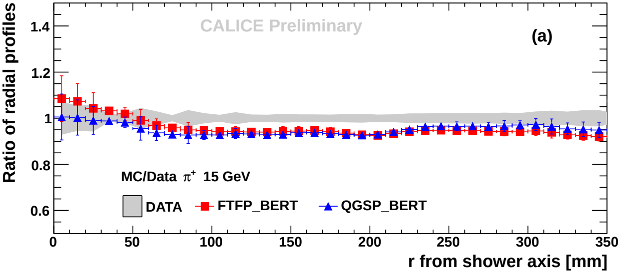


Protons

FTFP_BERT: agreement within uncertainties

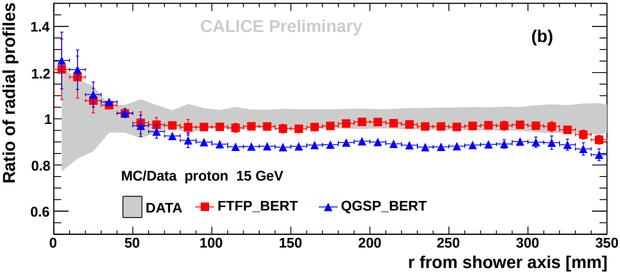
QGSP_BERT: ↑ by 20% around shower maximum

Ratio of radial profiles @ 15 GeV



Pions

↓ by 5-10% in the middle

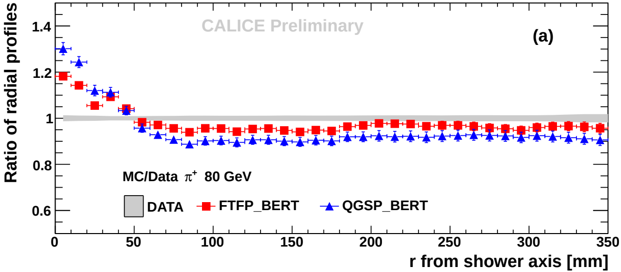


Protons

FTFP_BERT: agreement within uncertainties

QGSP_BERT: ↓ by 10% in the middle

Ratio of radial profiles @ 80 GeV

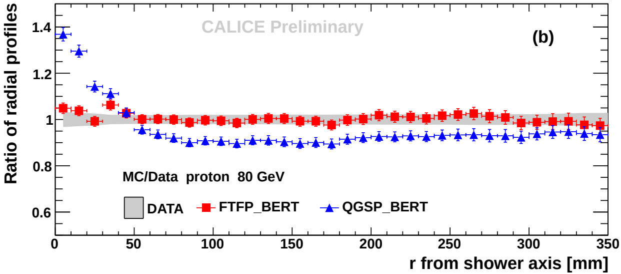


Pions

Shower core:

FTFP_BERT: ↑ by 20%

QGSP_BERT: ↑ by 30%



Protons

FTFP_BERT: agreement within uncertainties

QGSP_BERT: ↑ by 40% in the shower core

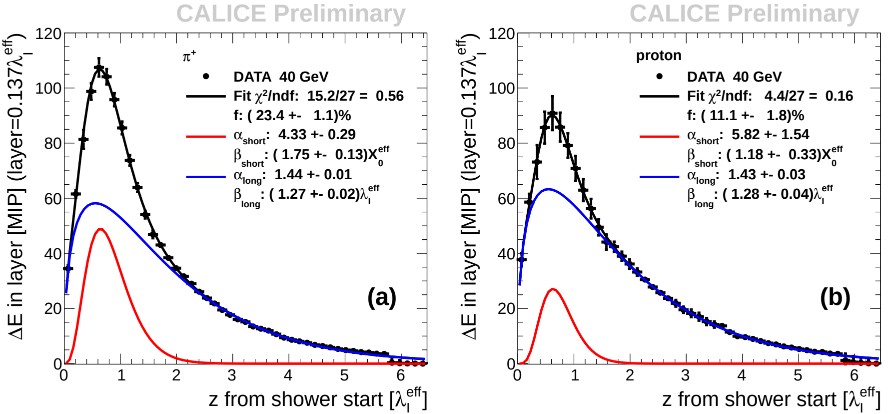
Fit to longitudinal profiles

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

A - scaling factor, f - fractional contribution of the "short" component,

α_{short} and α_{long} - shape parameters, $\beta_{\mathrm{short}} < \beta_{\mathrm{long}}$ - slope parameters,

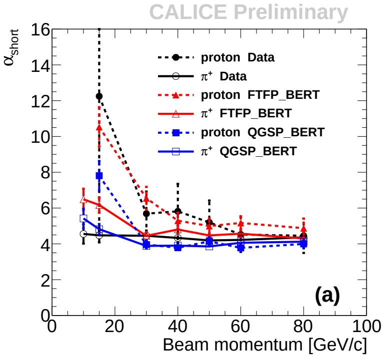
fit range: $[0.1 \cdot \lambda_{\mathrm{I}}^{\mathrm{eff}}; 4.6 \cdot \lambda_{\mathrm{I}}^{\mathrm{eff}}]$



Shape parameter α_{short}

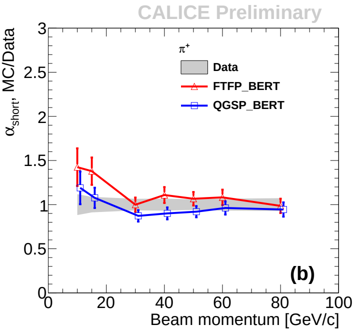
No energy dependence above 20 GeV

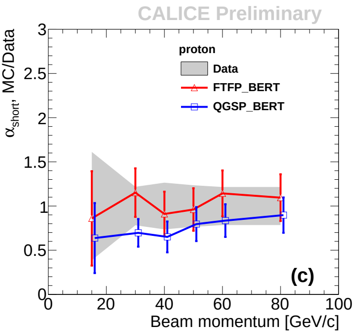
Data and MC agreement for pions above 20 GeV



Unreliable estimates for protons:

- low statistics
- small fraction of the "short" component
- high uncertainties due to pion contamination



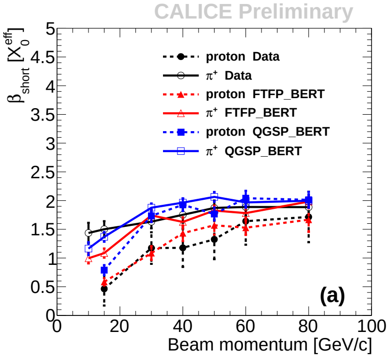


Slope parameter β_{short}

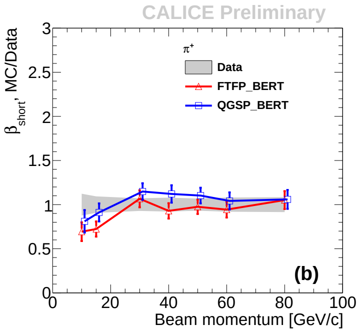
Slow rise with energy

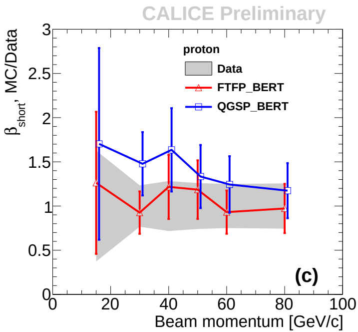
Data and MC agreement for pions within uncertainties (10-15%)

Unreliable estimates for protons



$X_0^{\text{eff}} = 25.5$ mm ≈0.8 layer of the Sc-Fe AHCAL



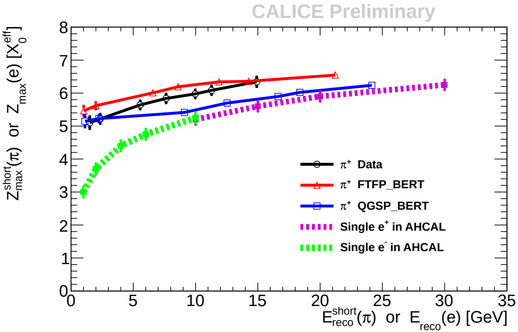


"Short" component and single electron shower

Shape of the "short" component of pion shower is comparable with that of electromagnetic showers from single electrons.

$Z_{\max}^{\rm short}(\pi) = (\alpha_{\rm short} - 1) \times \beta_{\rm short}$ - position of the maximum of the "short" component of pion shower with energy $E_{\rm reco}^{\rm short}(\pi)$ (integral under the "short" component).

$Z_{\max}(e)$ - position of the maximum of single electron shower with energy $E_{\rm reco}(e)$

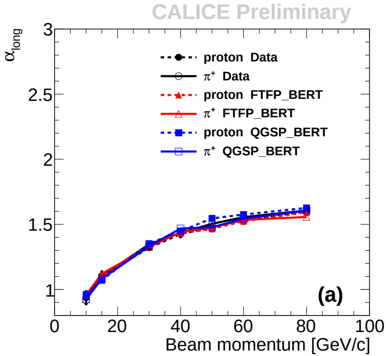


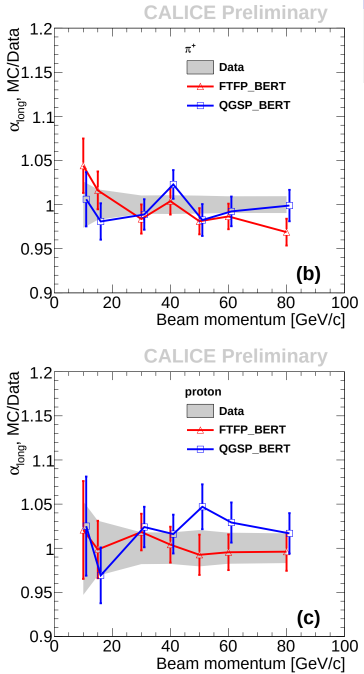
Points for single positrons in the AHCAL: 2011 JINST 6 P04003.
Points for single electrons in the AHCAL: dissertation of Nils Feege.

Shape parameter α_{long}

Logarithmic rise with energy

Agreement between MC and data within 4%

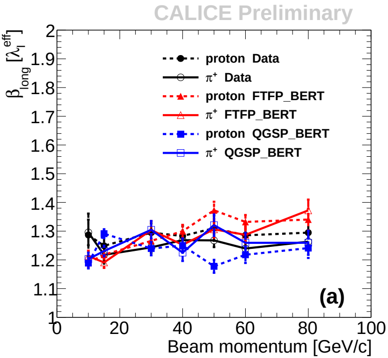




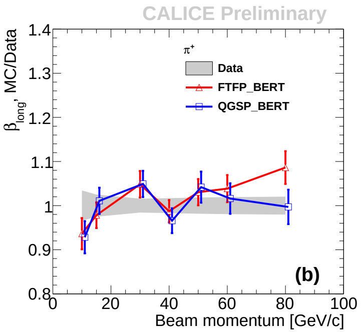
Slope parameter β_{long}

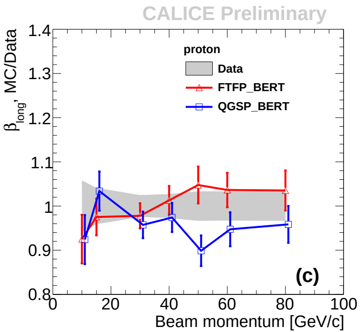
No energy dependence

Agreement between data and MC within 7%



$\lambda_I^{\mathrm{eff}} = 231$ mm ≈7 layers of the Sc-Fe AHCAL





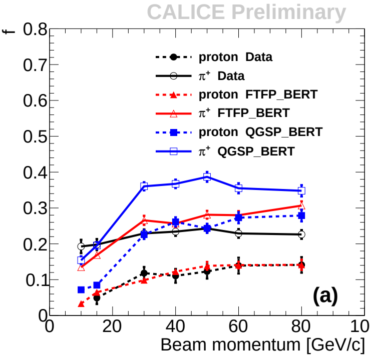
Fraction of the ”short” component

Steeper energy dependence predicted by MC

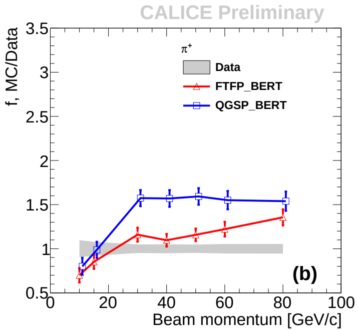
Overestimated by simulations:

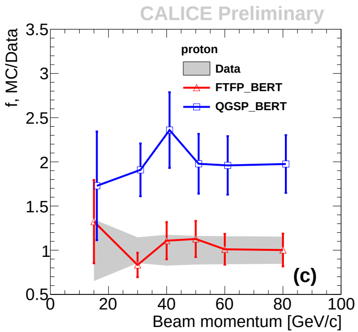
- **up to 25% by FTFP_BERT**
- **up to 50% by QGSP_BERT**

Better predictions by FTFP_BERT



Very good predictions by FTFP_BERT for protons





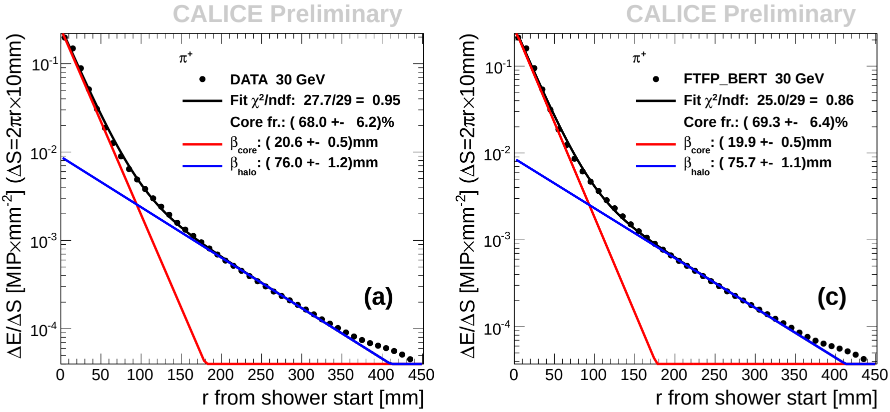
Fit to radial profiles

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

$\Delta S = 2\pi r \Delta r$ $\sigma_r = 2$ mm (accuracy of shower axis)

scaling factors A_{core} and A_{halo}, slope parameters $\beta_{\mathrm{core}} < \beta_{\mathrm{halo}}$

fit range: [0; 340] mm



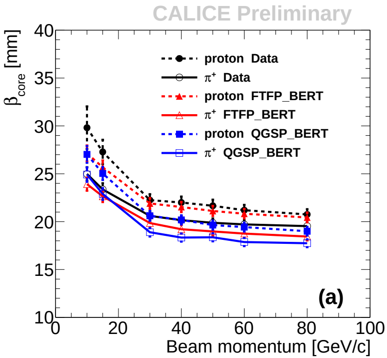
Core fraction: integral contribution of the "core" component.

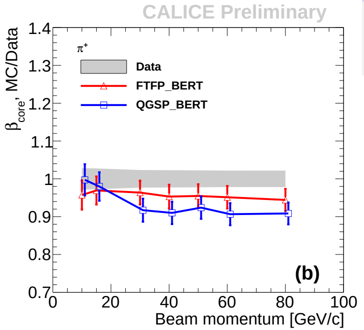
Slope parameter β_{core}

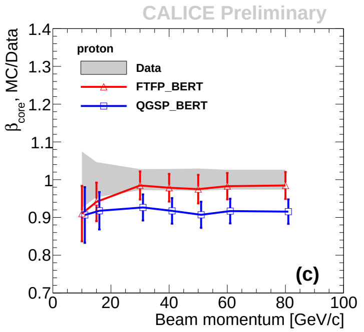
Decreases with energy

Underestimated by simulations:

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







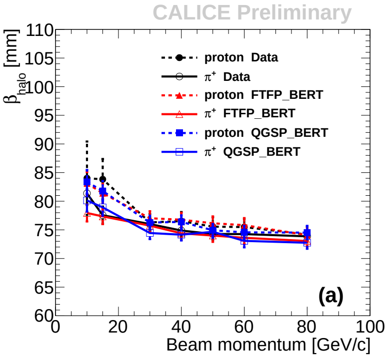
∼10% wider core for protons

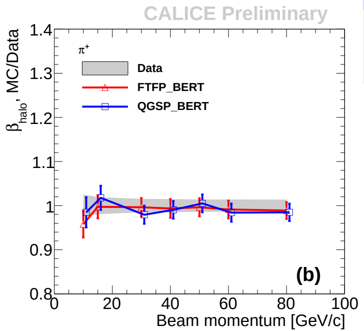
Good predictions by FTFP_BERT for protons

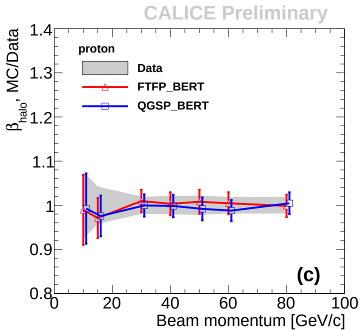
Slope parameter β_{halo}

Slow decrease with increasing energy

Agreement between data and MC within 2-5%







Summary

Shower parametrisation

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 the "short" component that might be related to overestimated π^0 production.
- Radial development: MC underestimates core slope parameter by $\sim$5-10% which might be related to angular distribution of secondaries.

Backup slides

Layer-to-layer variations

Observation:

jagged profile, variations increase with energy

Origin:

- dead and noisy cells (few %, some layers more affected, reproduced in MC)
- **saturation correction issues** (cells with unknown scaling factor and gain, not reproduced in MC)

Estimation:

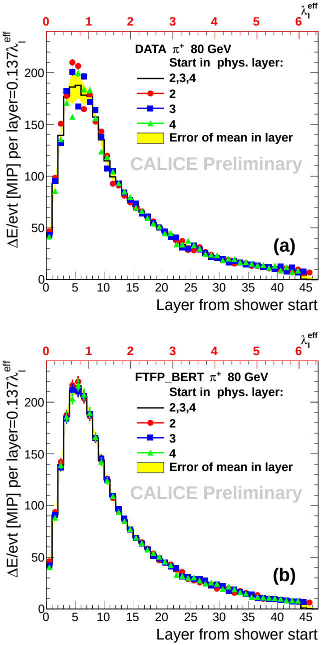
Find average of several normalised profiles from fixed shower starts

⇓

Calculate mean and variance in each bin

⇓

Error of mean = systematic uncertainty



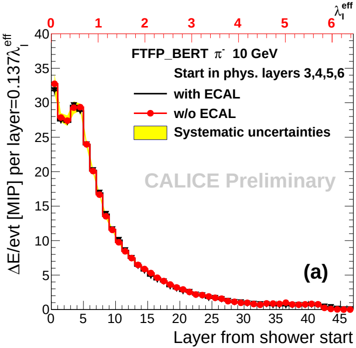
Identification of shower start layer

Uncertainties of the algorithm:

- distribution of (found start - true start): r.m.s.≈1 layer
- increases with decreasing energy
- higher for several first layers
  ⇒ higher for runs w/o ECAL

Impact:

- negligible for data and MC comparison: found start layer used in both cases
- profile shape might be affected for low energy samples taken w/o ECAL



Estimation:
Crosscheck with simulations: difference within layer-to-layer variations

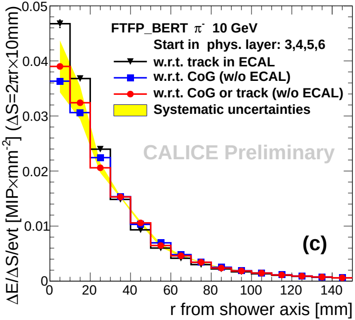
Identification of shower axis

Algorithm with ECAL:

- track in ECAL (granularity 1×1 cm^2, 25-30 track hits)

Algorithm w/o ECAL:

- track in AHCAL if start behind fourth physical layer (granularity 3×3 cm^2, >4 track hits)
- shower centre of gravity (>100 shower hits)



Problem w/o ECAL:

- both approaches not accurate
- CoG underestimates contribution near shower axis

Rough estimate:
from variance extracted from difference between different approaches

N.B.: found start for all ⇒ negligible impact on data and MC comparison

Pion contamination of proton samples

Estimation of proton sample purity η is based on independent muon identification procedure as described in CAN-040.

Beam momentum GeV/c	Purity of proton sample η
10	0.74 ± 0.17
15	0.80 ± 0.11
30	0.95 ± 0.01
40	0.84 ± 0.07
50	0.78 ± 0.08
60	0.86 ± 0.06
80	0.83 ± 0.04

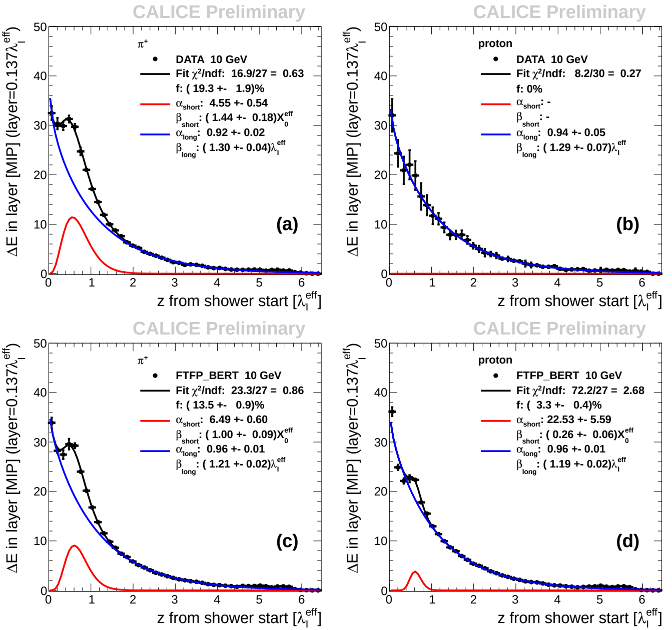
Proton profiles are corrected by subtracting the average contribution of pion admixture depending on purity η at the corresponding energy.

The corrected content for i-th layer (bin)

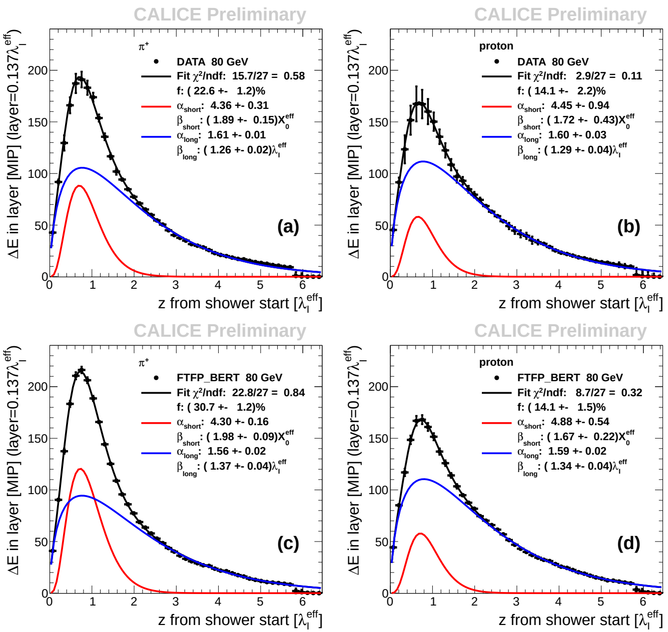
$$E_i^{\mathrm{corr}} = E_i^{\mathrm{mix}} \cdot \tfrac{1}{\eta} - E_i^{\pi} \cdot \tfrac{1-\eta}{\eta},$$

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

Examples of longitudinal profiles: 10 GeV



Examples of longitudinal profiles: 80 GeV



Fit quality

Longitudinal profiles **Radial profiles**