Hadron shower profiles from test beam data and simulations of the CALICE Sc-Fe AHCAL:

update with GEANT4 v9.6

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Outline

Data samples, software and event selection

Test beam data: reconstruction with calice_soft v04-07

CERN 2007 runs, π^+ @ 30-80 GeV (ECAL+AHCAL+TCMT), single runs
FNAL 2009 runs, protons @ 10 and 15 GeV (AHCAL+TCMT)

Simulations (thanks to Sergey Morozov)

Geant4 v9.6p01, Mokka v08_01 (improved TCMT treatment)
Physics lists: QGSP_BERT, FTFP_BERT
calice_soft v04-07 for digitization (846 keV/MIP, 0.15 xtalk for AHCAL)

Event selection (the same procedure for data and MC samples)

- Cut at 0.5 MIP for all hits to reject noise
- Sample cleaning from muons, multiparticle and empty events (CAN-035), additional cuts to reject positrons and multiparticle events in FNAL runs (CAN-040)
- For analysis: shower start at the beginning of AHCAL
  - in layers 2-4 for global observables (details in CAN-040)
  - in layers 3-5 for shower profiles from FNAL data
  - in layers 1-4 for shower profiles from CERN data
- Details of systematic uncertainty estimates in backup slides and CAN-040

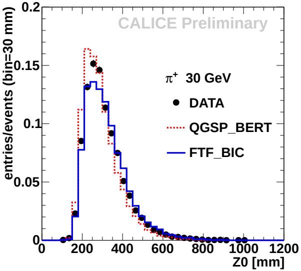
Geant4 v9.4 vs. v9.6: longitudinal CoG

The shower center of gravity in the longitudinal direction for event with shower start position z_{start}:

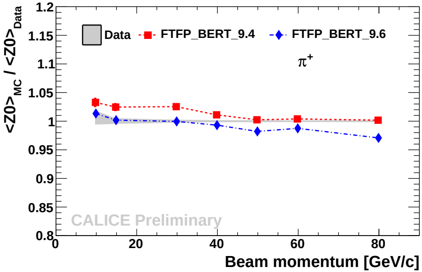
$$\mathbf{Z0} = \frac{\sum e_i \cdot (z_i - z_{\mathrm{start}})}{\sum e_i}$$

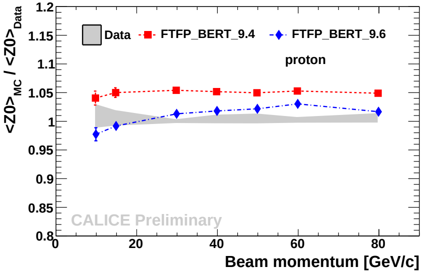
Sum over hits with longitudinal position $z_i \geq z_{\mathrm{start}}$ and signal e_i

Typical distribution of $Z0$ (Geant4 9.4)



from addendum to CAN-040





Geant4 v9.4 vs. v9.6: mean shower radius

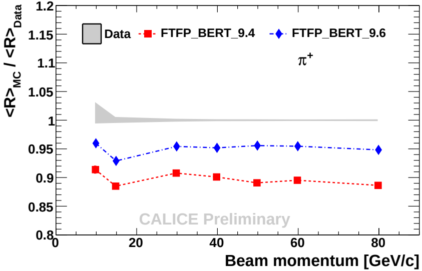
from addendum to CAN-040

Shower radius $\mathbf{R} = \frac{\sum \mathbf{e_i} \cdot \mathbf{r_i}}{\sum \mathbf{e_i}}$

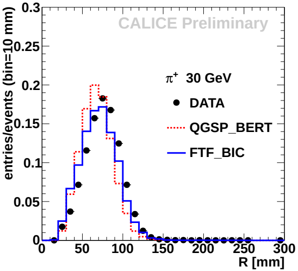
Sum over hits with longitudinal position $\mathbf{z_i} \geq \mathbf{z_{start}}$ and signal $\mathbf{e_i}$

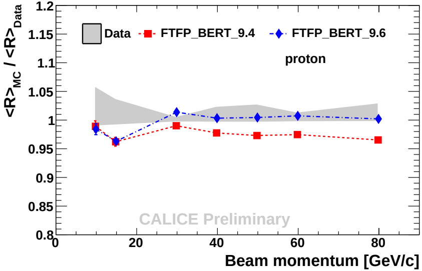
Radial distance $\mathbf{r_i}$ from hit $(\mathbf{x_i}, \mathbf{y_i})$ to shower axis $(\mathbf{x_0}, \mathbf{y_0})$:

$$\mathbf{r_i} = \sqrt{(\mathbf{x_i} - \mathbf{x_0})^2 + (\mathbf{y_i} - \mathbf{y_0})^2}$$



Typical distribution of *R* (Geant4 9.4)





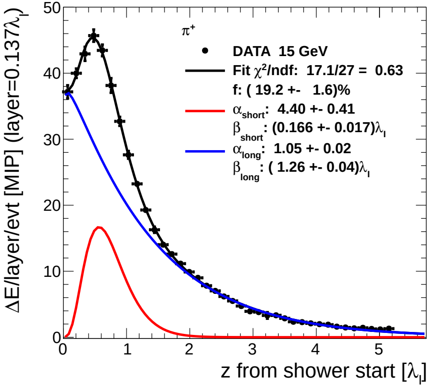
Improvement of FTFP_BERT from 10% to 5% difference from pion data

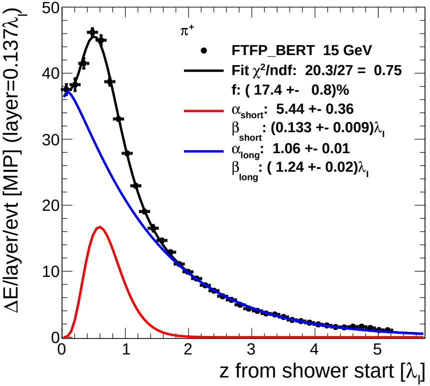
Fit to longitudinal profiles

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

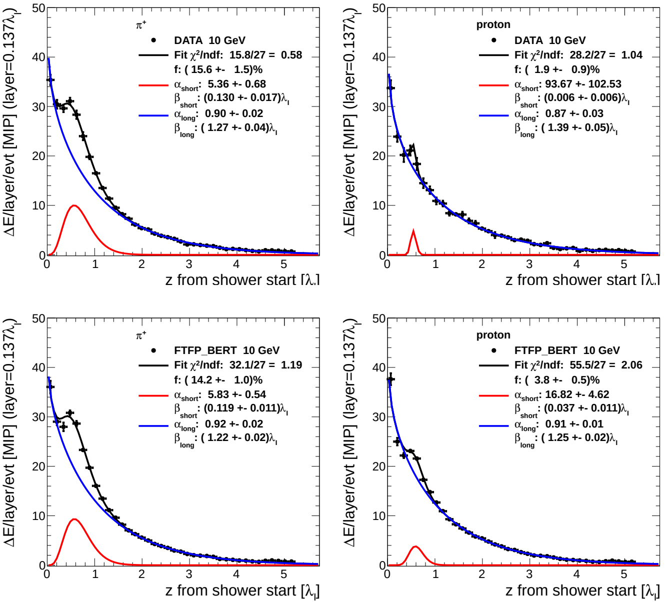
Fit parameters: scaling factor A, fractional contribution f,
multiplicity parameters $\alpha_{\rm short}$ and $\alpha_{\rm long}$, slope parameters $\beta_{\rm short}$ and $\beta_{\rm long}$

The smaller slope parameter from fit is called $\beta_{\rm short}$ with corresponding $\alpha_{\rm short}$ and fractional contribution f. ($\lambda_{\rm I} = 231$ mm)

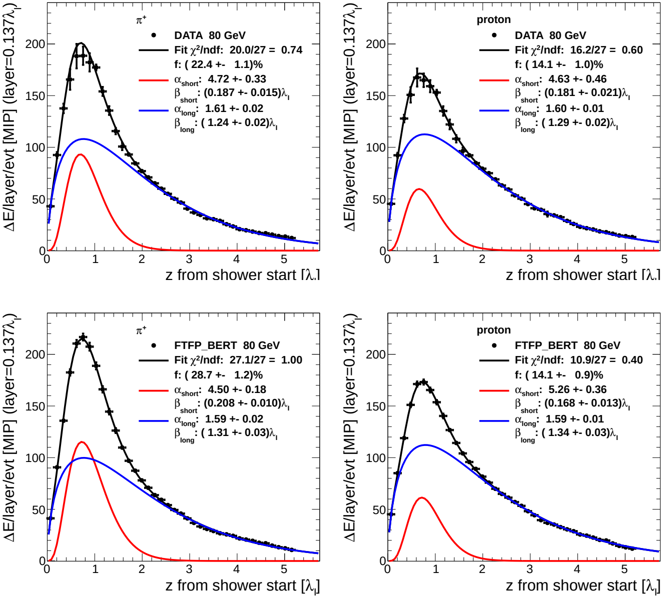




Examples of longitudinal profiles: 10 GeV



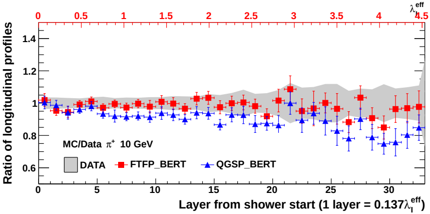
Examples of longitudinal profiles: 80 GeV

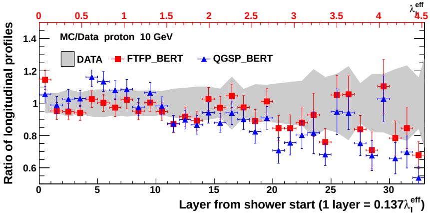


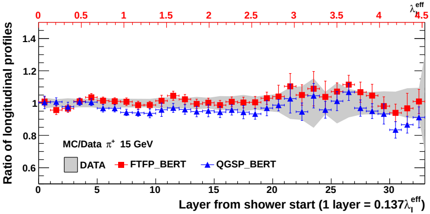
Ratio of longitudinal profiles: 10 and 15 GeV

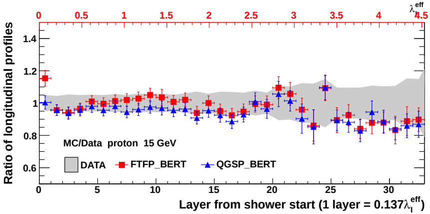
π^+

proton







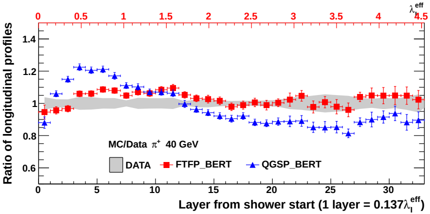


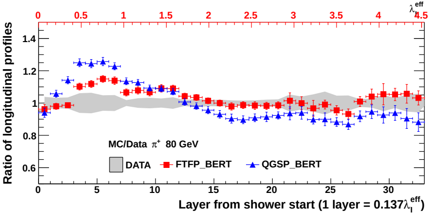
FTFP_BERT on average better
<10% disagreement around shower maximum

FTFP_BERT on average better
Big uncertainties @10 GeV due to low statistics

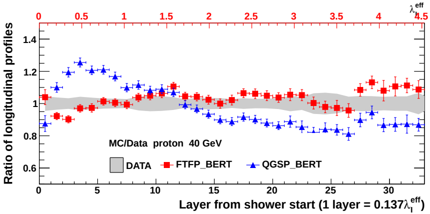
Ratio of longitudinal profiles: 40 and 80 GeV

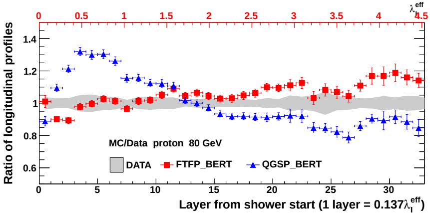
π^+





proton

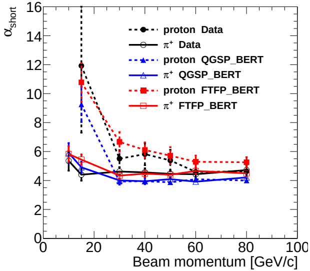


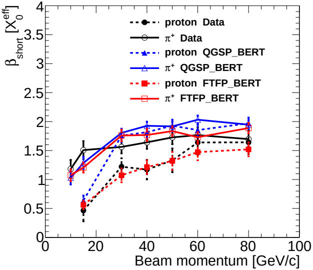


FTFP_BERT much better
5-10% difference @ shower maximum
Shorter shower in QGSP_BERT

FTFP_BERT much better, although shower start seems to be found earlier than in data
Huge disagreement with QGSP_BERT

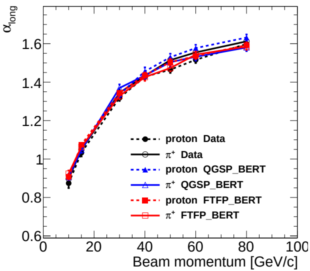
Parameters of longitudinal profiles

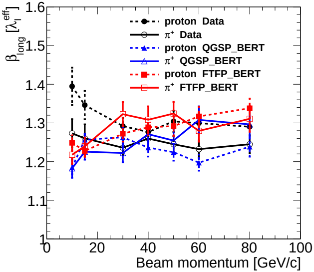




"Short" component

No energy dependence above 30 GeV for pions.
Good agreement between MC and data.
Protons approach pions with increasing energy.
$\beta_{\mathrm{short}} \sim 1.5 \cdot X_0^{\mathrm{eff}}$



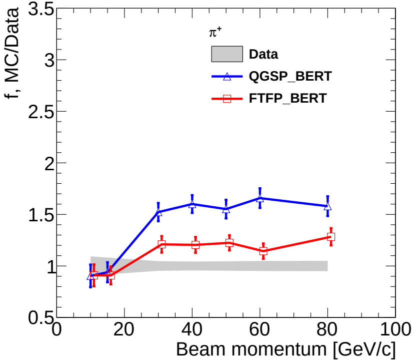


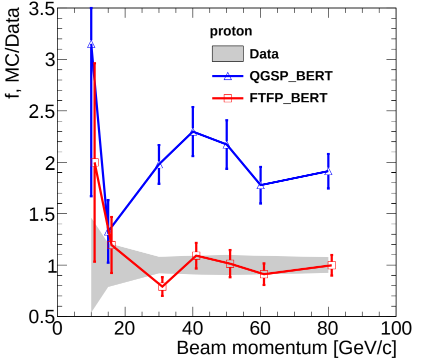
"Long" component

Logarithmic rise of α_{long}.
Almost constant β_{long}.
Bigger difference between pions and protons in data.
$\beta_{\mathrm{long}} \sim 1.3 \cdot \lambda_{\mathrm{I}}^{\mathrm{eff}}$

Fraction of the "short" component

Fractional contribution f of the component with α_{short} and β_{short}
No significant changes from GEANT4 9.4 to 9.6





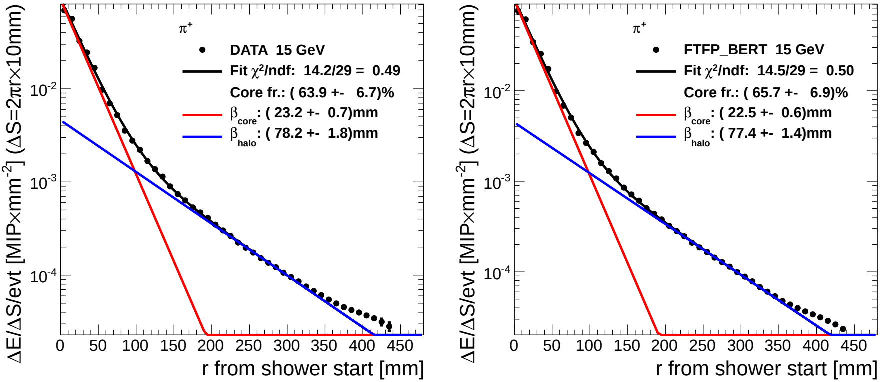
Overestimated by FTFP_BERT by ~20% above 20 GeV.

Good prediction by FTFP_BERT in all studied energy range.

f **is overestimated by QGSP_BERT by more than 50% above 20 GeV.**

Fit to radial profiles

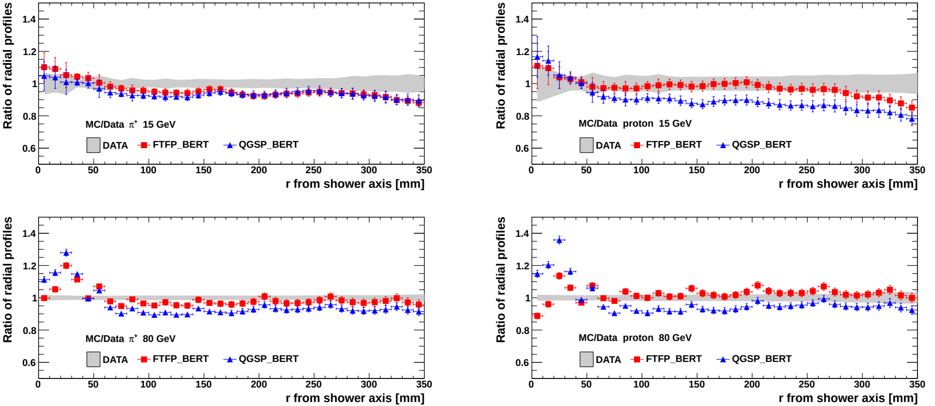
$\frac{\Delta E}{\Delta S}(r) = A_{\rm core} \cdot \exp(-r/\beta_{\rm core}) + A_{\rm halo} \cdot \exp(-r/\beta_{\rm halo})$
$\Delta S = 2\pi r \Delta r$ $\quad\quad \sigma_r = 2$ mm (accuracy of shower axis)
scaling factors $A_{\rm core}$ and $A_{\rm halo}$, slope parameters $\beta_{\rm core} < \beta_{\rm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



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

Ratio of radial profiles: 15 and 80 GeV

π^+ proton



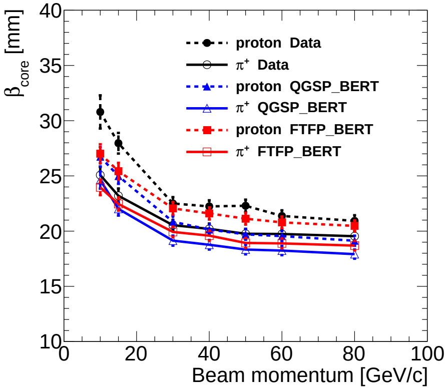
FTFP_BERT in better agreement with data

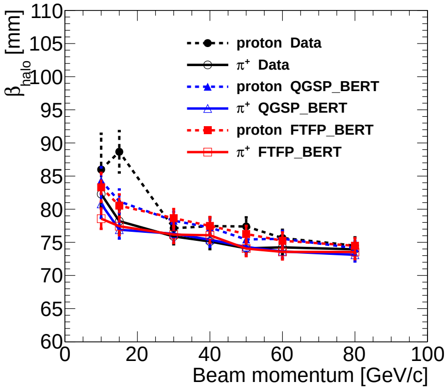
Structure at 80 GeV due to low signal in peripheral region (narrow showers)

Overestimation by FTFP_BERT (QGSP_BERT) up to 20%(40%) in the core at 80 GeV

Slope parameters of radial profiles

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

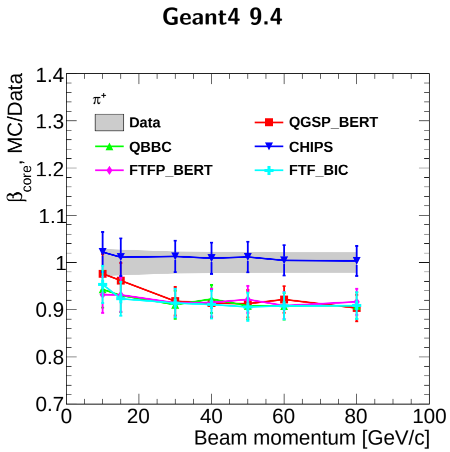


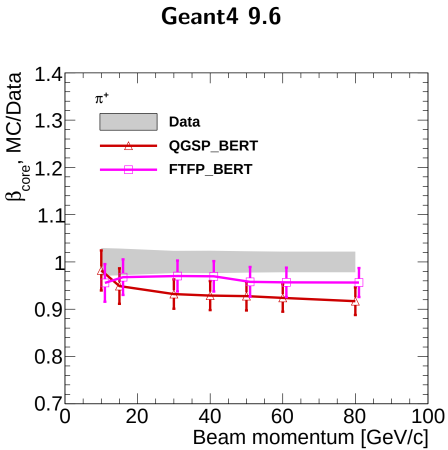


No energy dependence above 30 GeV.
β_{core} by ∼10-20% larger for protons.
MC below data.

Weak energy dependence.
Agreement between MC and data.
Outlier in proton data at 15 GeV.

Parameter β_{core} from GEANT4 9.4 to 9.6





Most PL (except for CHIPS) underestimate β_{core} for pions by $\sim$10%.

The difference of FTFP_BERT from data in GEANT4 9.6 decreased down to 5%

Summary

Data and software

- Positive hadron runs in the energy range from 10 to 80 GeV
- Updated calice_soft v04-07 for reconstruction and digitization
- Simulations with GEANT4 9.6p01
- Selection of events with shower start at the beginning of AHCAL

MC and data comparison

- FTFP_BERT gives better predictions of shower profiles than QGSP_BERT.
- **Longitudinal development.** No significant changes from 9.4 to 9.6. The fractional contribution of the "short" component is the main difference between data and MC above 20 GeV – up to 20% (50%) for FTFP_BERT (QGSP_BERT).
- **Radial development.** Noticeable progress for FTFP_BERT in GEANT4 9.6. The underestimation of core slope parameter for pion showers decreased from 10% to $\sim$5%. This translates into better agreement of mean shower radius.

Backup slides

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)

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

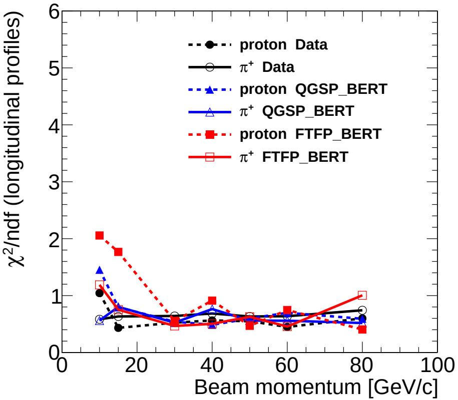
E_i^{mix} - from i-th bin in the mixed sample
E_i^{π} - from i-th bin in the pion sample

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. (More details in the talk on CALICE Collaboration meeting in Hamburg, March 2013.)

Fit quality

Longitudinal profiles



Radial profiles