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

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on behalf of the CALICE Collaboration

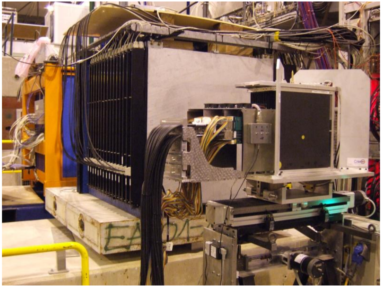
Introduction and outline

CALICE calorimeter prototypes

Highly granular calorimeters developed for the future LC experiments

Test beam campaigns for physics prototypes:

- Check calibration procedures
- Understand detector simulation
- Test Geant4 hadronic models
- Proof the reliability of extrapolation to full detector studies



CALICE test beam setup at CERN

Outline

1. Highly granular Sc-Fe AHCAL
2. Response and resolution
3. Longitudinal center of gravity
4. Mean shower radius

CALICE Sc-Fe AHCAL

CALICE scintillator-steel analogue hadronic calorimeter

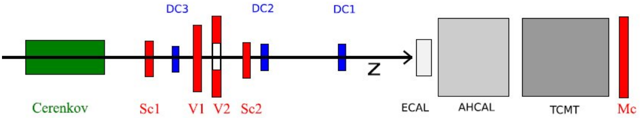
Physics prototype with 7608 cells in $\sim$1 m^3

Longitudinal sampling: 38 layers ($\sim 5.3\lambda_I$), 20 mm Fe + 5 mm Sc per layer

Transverse segmentation: 3x3, 6x6 and 12x12 cm^2 cells with SiPM readout

Test beam setup

Positive hadron beams @ 10-80 GeV in CERN and FNAL, configurations with and w/o ECAL



Čerenkov counter upstream and tail catcher and muon tracker (TCMT) downstream of the calorimeter are used for event selection.

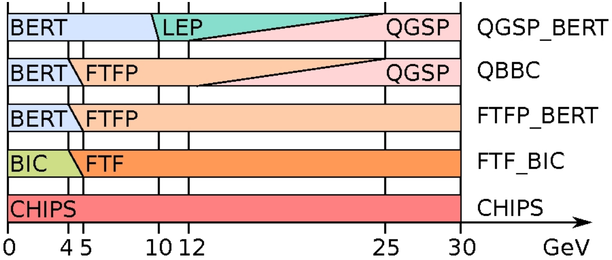
Calibration

Cell response equalized with MIP, the lower threshold 0.5 MIP was applied for analysis

EM scale calibrated with positrons 2011 JINST 6 P04003, 2010 JINST 5 P05004

Geant4 simulations

Simulations with Geant4 version 9.4 patch 03



Simulations with Geant4 version 9.6 patch 01 (performed by Sergey Morozov)

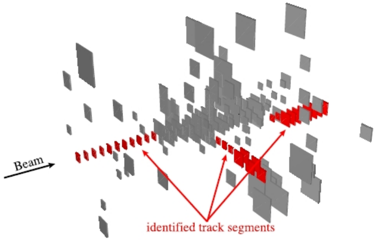
FTFP_BERT physics list is now recommended by Geant4 team.
Version comparison done for two physics lists: FTFP_BERT and QGSP_BERT.
CHIPS physics list is deprecated.

Software tools

Mokka environment, versions 07-07p04 for Geant4 v9.4 and 08-01 for Geant4 v9.6
Digitization of Monte Carlo samples including SiPM response and noise from data runs

Hadronic showers in a highly granular calorimeter

Typical hadronic shower

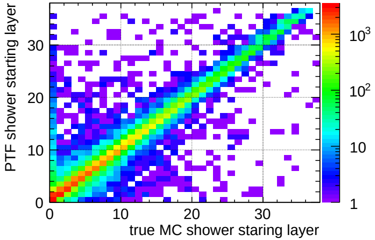


25 GeV π^-
ECAL upstream (cells 1×1 cm^2)

Position of a primary inelastic interaction can be identified on event-by-event basis

Identification of shower starting point

True MC shower start vs found starting layer for 80 GeV π^-, QGSP_BERT from Geant4 9.3



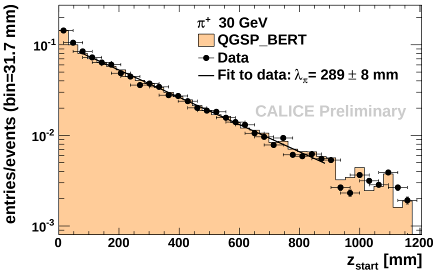
Performance: correlation >90%(85% @ 10 GeV)

Helpful for event selection, minimization of leakage and offline compensation

Figure from CAN-026

Nuclear interaction length

Distributions of found shower start



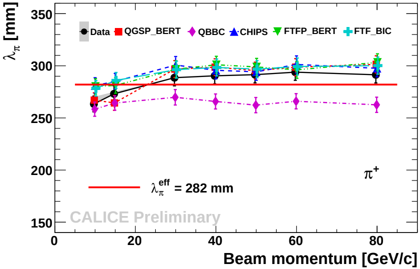
Estimates of λ_π and λ_I

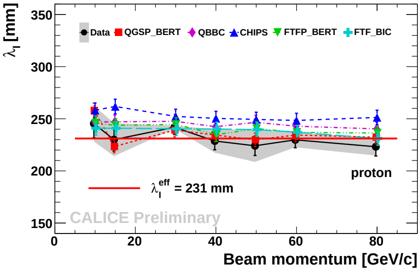
λ^{eff} from PDG data

Gray band shows systematic uncertainties

Data: $\frac{\lambda_\pi}{\lambda_I} \approx 1.23$

Simulations with Geant4 9.4





Response to hadrons

Energy reconstruction

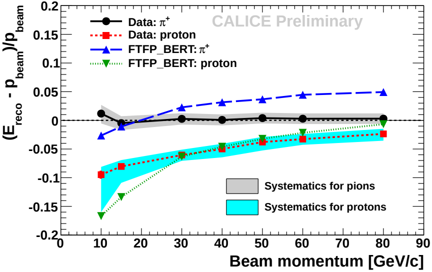
Selected shower start at the beginning of AHCAL (track in ECAL)

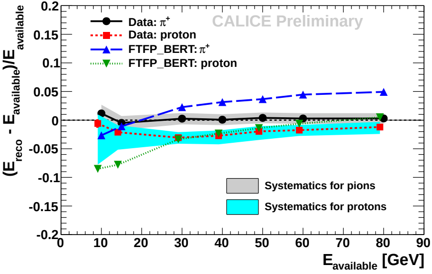
For each event $\mathbf{E_{event} = (E^{track}_{ECAL})_{MIPscale} + 1.2 \cdot (E_{AHCAL} + E_{TCMT})_{EMscale}}$

$E_{\rm reco}$ and $\sigma_{\rm reco}$ obtained from Gaussian fit, response to π^+ and π^- agrees within $\pm 1\%$

$$E^{\rm proton}_{\rm available} = \sqrt{P^2_{beam} + m^2_{\rm proton}} - m_{\rm proton}$$

Linearity of positive hadron response (simulations with Geant4 9.4)

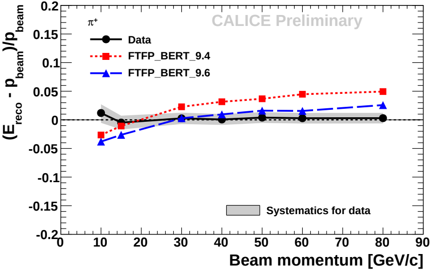


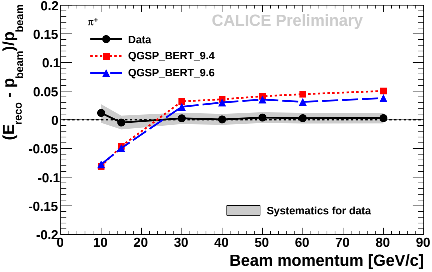


Difference in response ∼1-4% cannot be explained by the baryon conservation law.

Response to hadrons in Geant4 9.4 and Geant4 9.6

π^+





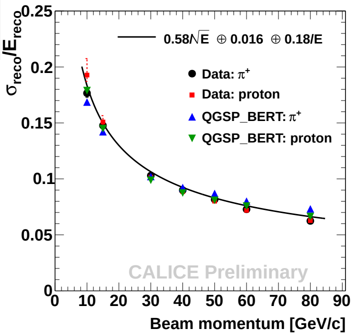
Improved FTFP_BERT predictions at higher energies

Better agreement with data at lower energies for FTFP_BERT in both versions

Protons

Minor changes in right direction for both physics lists

Fractional energy resolution



Experimental resolution

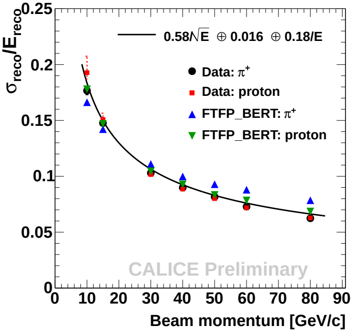
Estimated for $\pi^\pm$ data with fixed noise term:

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

π and proton data in agreement within uncertainties

Improved by software compensation to $\frac{45\%}{\sqrt{\mathrm{E/GeV}}}$

2012 JINST 7 P09017



Geant4 simulations

Minor differences between Geant4 9.4 and Geant4 9.6

Geant4 physics lists predict lower stochastic term and higher constant term

Better prediction for all hadrons by QGSP_BERT

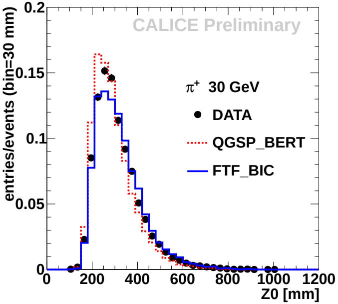
Better prediction for protons than for pions

Longitudinal center of gravity of pion showers

Shower CoG in longitudinal direction for event with shower start position z_{start}:

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

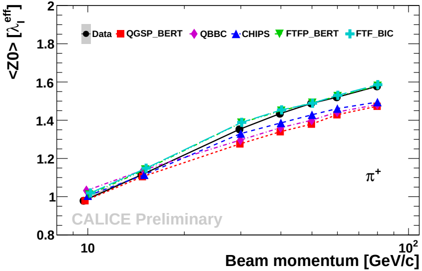
Sum over hits with longitudinal position $\mathbf{z_i \geq z_{start}}$ and signal $\mathbf{e_i \geq 0.5}$ MIP

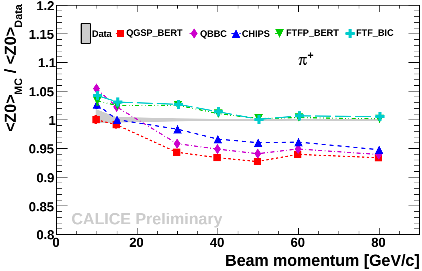


Typical distribution of $Z0$

NB: AHCAL depth $\sim 5.3\lambda_I^{\mathrm{eff}}$ ($\lambda_I^{\mathrm{eff}} = 231$ mm)

Simulations with Geant4 9.4





Longitudinal center of gravity of proton showers

Main contribution to systematic uncertainty from contamination with pions (5-35%)
Relative bias of $\langle Z0 \rangle$ up to ∼3% (gray band)

Pion to proton comparison

Longitudinal CoG of proton shower on average ∼5% deeper in data

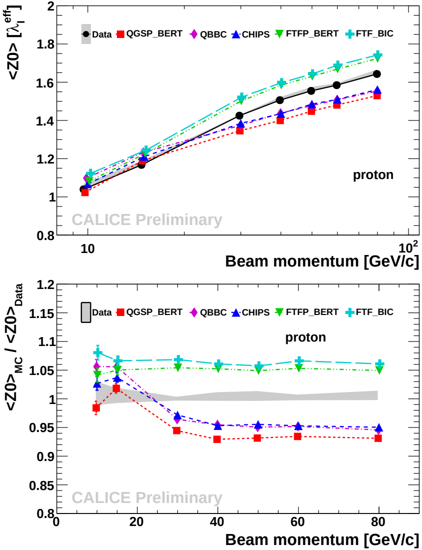
$\langle \mathbf{Z0} \rangle_{\text{proton}} / \langle \mathbf{Z0} \rangle_{\pi} \approx 1.05$

Simulations to data comparison

$\langle \mathbf{Z0} \rangle_{\text{proton}}$ overestimated by FTFP_BERT and FTF_BIC by ∼5%

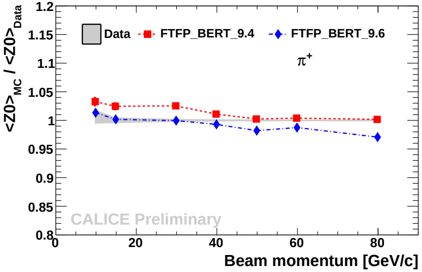
underestimated by QGSP_BERT, QBBC and CHIPS by ∼5% above 20 GeV

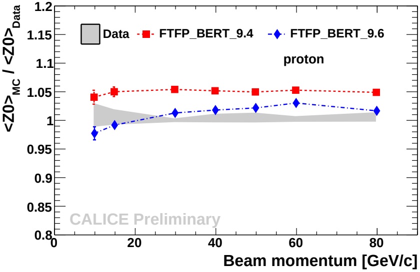
Simulations with Geant4 9.4



Longitudinal center of gravity: Geant4 9.4 vs Geant4 9.6

FTFP_BERT





Improvement below 40 GeV **Improvement above 10 GeV**

QGSP_BERT

Minor changes in wrong direction for both pions and protons

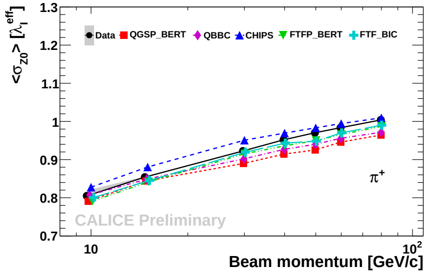
r.m.s. of longitudinal center of gravity σ_{Z0}

The r.m.s. of CoG in longitudinal direction

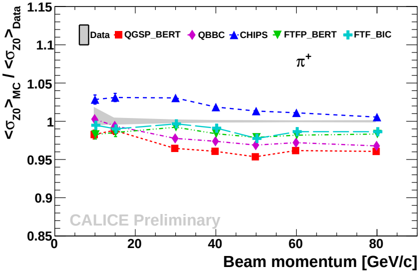
$$\sigma_{Z0} = \sqrt{\frac{\sum e_i \cdot (z_i - z_{start} - \langle Z0 \rangle)^2}{\sum e_i}}$$

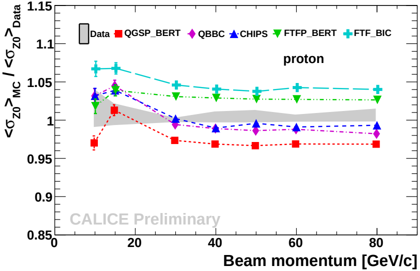
Sum over hits with longitudinal position $z_i \geq z_{start}$ and signal $e_i \geq 0.5$ MIP

$\langle Z0 \rangle$ - mean longitudinal CoG



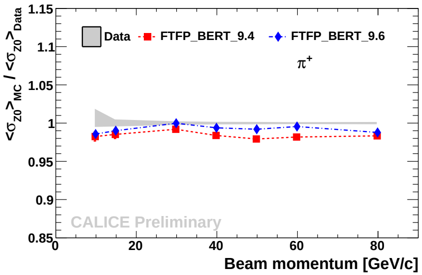
Simulations with Geant4 9.4

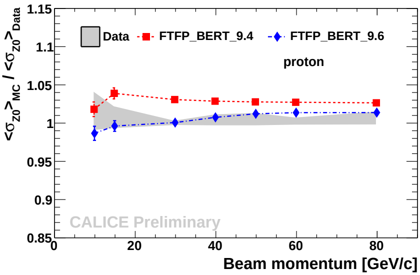




r.m.s. of longitudinal center of gravity: Geant4 9.4 vs Geant4 9.6

FTFP_BERT





Small changes but in right direction

Good agreement with data in Geant4 9.6

QGSP_BERT

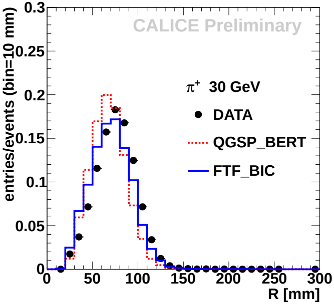
Minor changes in wrong direction for both pions and protons

Mean shower radius for pion showers

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

Sum over hits with longitudinal position $z_i \geq z_{start}$ and signal $e_i \geq \mathbf{0.5}$ MIP

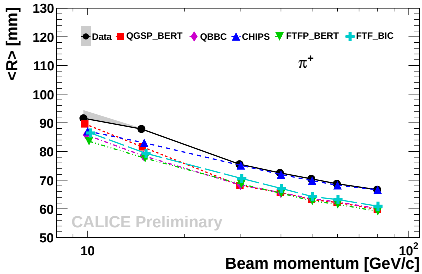
Radial distance r_i from hit (x_i, y_i) to shower axis (x_0, y_0): $r_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}$

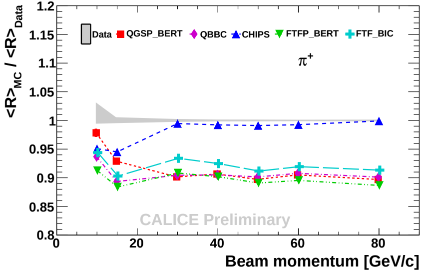


Typical distribution of *R*

NB: AHCAL half width ~450 mm,
beam around the center of AHCAL front plane

Simulations with Geant4 9.4





Mean shower radius for proton showers

Main contribution to systematic uncertainty from contamination with pions (5-35%)
Relative bias of $\langle R \rangle$ up to ~6% (gray band)

Pion to proton comparison

Proton showers on average ~10% wider

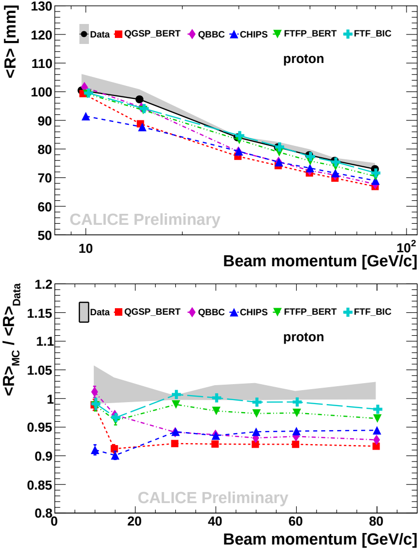
$\langle \mathbf{R} \rangle_{\mathrm{proton}} \,/\, \langle \mathbf{R} \rangle_{\pi} \approx 1.1$

Simulations to data comparison

Mean shower radius for protons underestimated above 10 GeV by ~10% by QGSP_BERT, QBBC and CHIPS

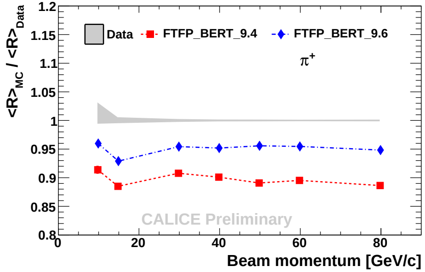
Better predictions with FTF_BIC physics list

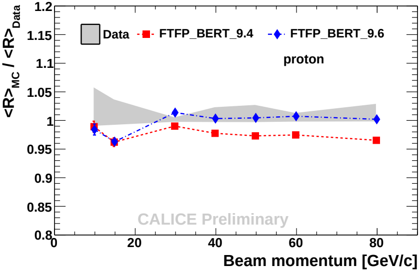
Simulations with Geant4 9.4



Mean shower radius: Geant4 9.4 vs Geant4 9.6

FTFP_BERT





Difference from data reduced to 5%!

Good agreement with data above 20 GeV in Geant4 9.6

QGSP_BERT

No changes in QGSP_BERT

r.m.s of shower radius σ_R

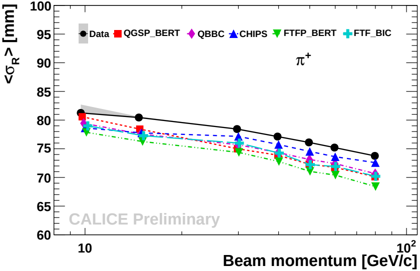
Simulations with Geant4 9.4

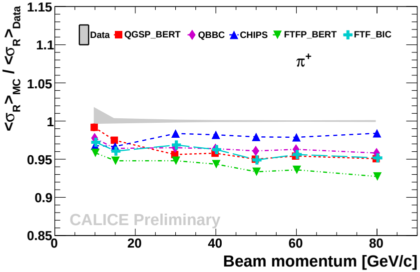
The r.m.s. of shower radius:

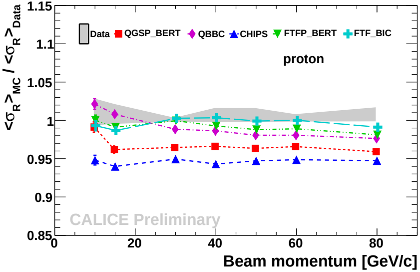
$$\sigma_R = \sqrt{\frac{\sum e_i (r_i - \langle R \rangle)^2}{\sum e_i}}$$

Sum over hits with longitudinal position $z_i \geq z_{start}$ and signal $e_i \geq 0.5$ MIP

$\langle R \rangle$ - mean shower radius

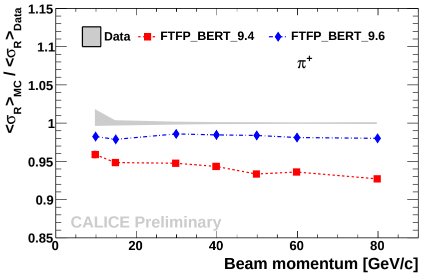


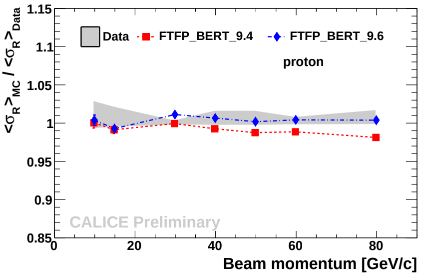




r.m.s. of shower radius: Geant4 9.4 vs Geant4 9.6

FTFP_BERT





Improvement in all studied energy range

Good agreement with data in Geant4 9.6

QGSP_BERT

Minor changes in the right direction

Summary

Parameters of hadronic showers in the highly granular Sc-Fe AHCAL were analyzed for test beam data in the energy range 10-80 GeV and compared with Geant4 simulations.

Pion and proton showers

- Lower response for protons can be largely (except for 1-4%) explained by available energy.
- Longitudinal center of gravity of proton shower is on average 5% deeper in the calorimeter.
- Mean shower radius for protons is about 10% larger than for pions.

Simulations to data comparison

- Simulations show steeper energy dependence of response for pions than observed in data.
- The best prediction of fractional energy resolution for hadrons is given by QGSP_BERT.
- Fritiof-based models give better predictions of longitudinal CoG for pions.
- Mean shower radius for pions tends to be underestimated (except for by CHIPS).

Progress in FTFP_BERT: from Geant4 version 9.4 to version 9.6

- Improvement of pion response at higher energies (50-80 GeV)
- Improved predictions of longitudinal CoG below 40 GeV but slightly worse at higher energies
- Much better predictions of mean shower radius for pions (5% difference instead of 10% in Geant4 9.4) and good agreement with data for protons

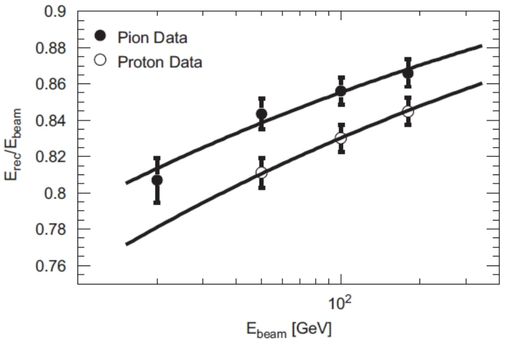
Backup slides

p/π ratio

Comparison with ATLAS TileCal test beam data

ATLAS Sc-Fe TileCal (14 mm Fe + 3 mm Sc)/period

Figure from NIM A615 (2010) 158-181



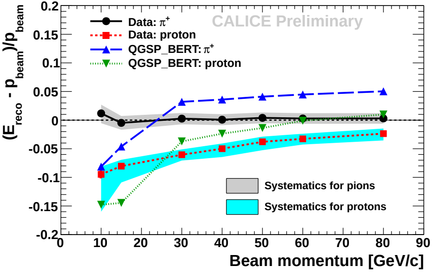
50 GeV point for comparison of $\frac{p}{\pi}$ in data:

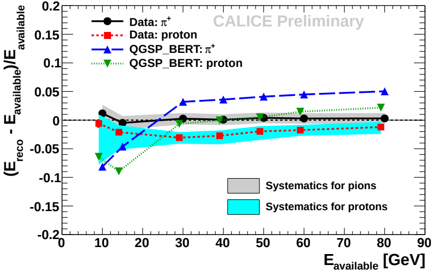
ATLAS: $0.961 \pm 0.009(\text{syst.}) \pm 0.002(\text{stat.})$

CALICE: $0.958^{+0.012}_{-0.016}(\text{syst.}) \pm 0.001(\text{stat.})$

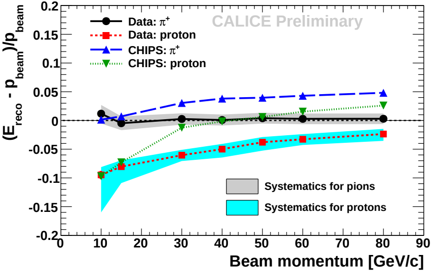
Response of Sc-Fe AHCAL to hadrons: data, QGSP_BERT, CHIPS

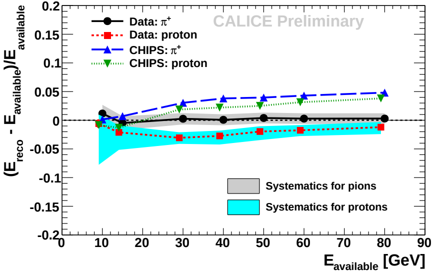
QGSP_BERT physics list from Geant4 9.4





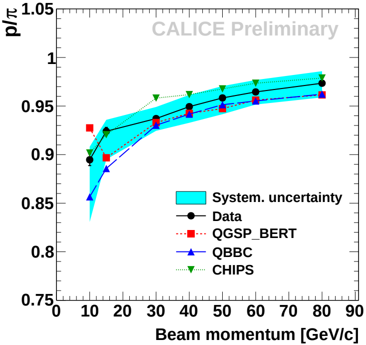
CHIPS physics list from Geant4 9.4





p/π ratio from test beam data and simulations with Geant4 9.4

$p/\pi = E^{proton}_{reco} / E^{\pi}_{reco}$



Good prediction by QGSP_BERT, QBBC and CHIPS,

Underestimated by FTFP_BERT and FTF_BIC,

Improvement in Geant4 9.6

Noticeably improved for FTFP_BERT above 30 GeV
Improved for QGSP_BERT at 10 GeV