Characteristics of hadronic showers in the CALICE AHCAL

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for the CALICE Collaboration

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

Calorimeter for ILC

ITEP MOSCOW

Introduction

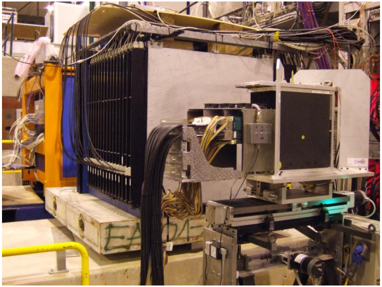
CALICE Collaboration is focused on the development of highly granular calorimeters for the future LC experiments

CALICE test beam campaigns 2006-2012

Muons, electrons and hadrons 1-180 GeV @ DESY, CERN, FNAL

Calorimeter prototypes:
Si-W and Sc-W ECAL
Sc-W and **Sc-Fe AHCAL**
GRPC-Fe and GRPC-W DHCAL
GRPC-Fe SdHCAL

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



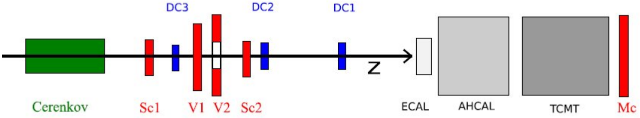
CALICE test beam setup at CERN

In this talk: focus on the CALICE Sc-Fe analogue HCAL prototype ($\sim$1 m^3, 7608 cells)
Longitudinal sampling: 38 layers ($\sim 5.3\lambda_I$), 20mm Fe + 5mm Sc per layer
Transversal segmentation: 3x3, 6x6 and 12x12 cm^2 cells with SiPM readout

CALICE Sc-Fe AHCAL: test beam data and simulations

Test beam data

Positive and negative hadrons @ 8-80 GeV
Different setup configurations (with and w/o ECAL)



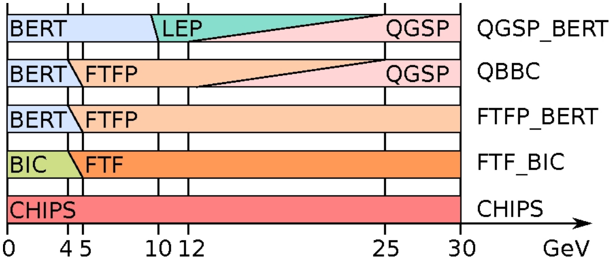
Čerenkov counter upstream and tail catcher and muon tracker (TCMT) downstream of the calorimeter are used for event selection.

Simulations with Geant4 versions 9.3 and 9.4

Unless otherwise specified the version 9.4p03 is used

For the version 9.3 the patch version 9.3p01 is used for CHIPS physics list

All MC samples were digitized for comparison with data



Hadronic showers in a highly granular calorimeter

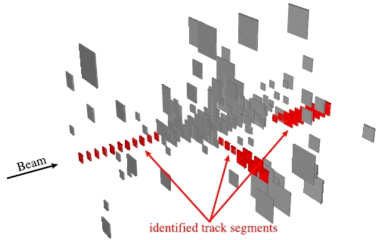
Calibration

Cell response equalized with MIPs
For analysis: $e_{\mathrm{hit}} \geq 0.5$ MIP

EM scale calibrated with positrons

2011 JINST 6 P04003
2010 JINST 5 P05004

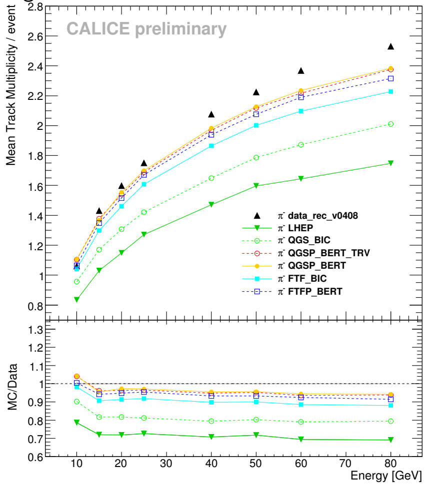
Typical hadronic shower



25 GeV π^-
ECAL upstream (cells $1{\times}1$ cm^2)

MIP-like track segments within a shower

Might be useful for calibration.



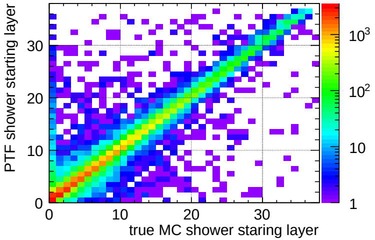
Multiplicity of tracks within hadronic shower in data and simulations (Geant4 9.3)
Figure from CAN-022

Nuclear interaction length

Identification of shower starting point

Position of primary inelastic interaction identified on event-by-event basis.

Helpful for event selection, minimization of leakage and offline compensation



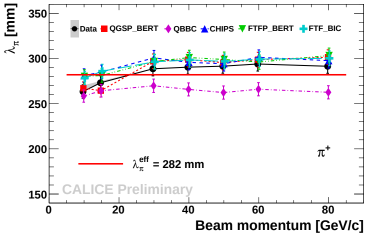
True MC shower start vs found starting layer for QGSP_BERT physics list, 80 GeV π^-

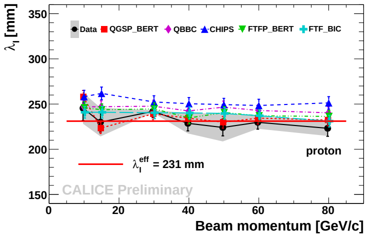
Performance: correlation >90%(85% @ 10 GeV)

Figure from CAN-026

λ_π and λ_I

estimated from found shower start





λ^{eff} from PDG data

Gray band shows systematic uncertainties

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

Response to hadrons

Energy reconstruction

Shower start at the beginning of AHCAL

$$E_{event} = (E^{track}_{ECAL})_{MIP} + 1.2 \cdot (E_{AHCAL} + E_{TCMT})_{EM}$$

E_{reco} and σ_{reco} obtained from Gaussian fit

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

Response to π^+ and π^- agrees within $\pm 1\%$

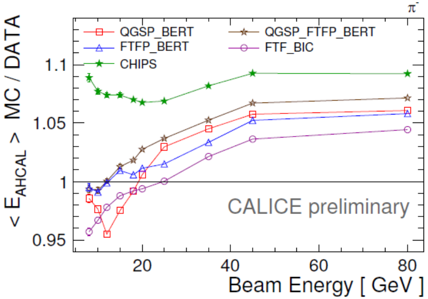
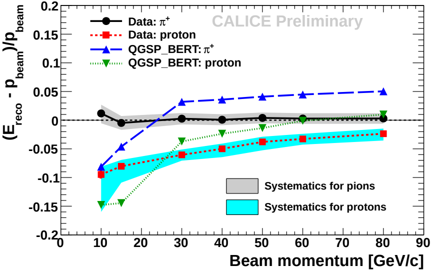
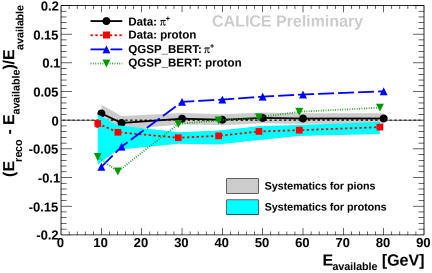


Fig. from EUDET-Memo-2010-15 (Geant4 9.3)

Linearity of positive hadron response vs E_{beam} and $E_{available}$

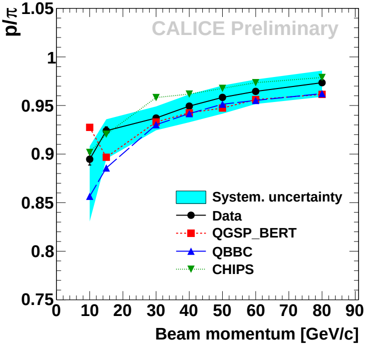


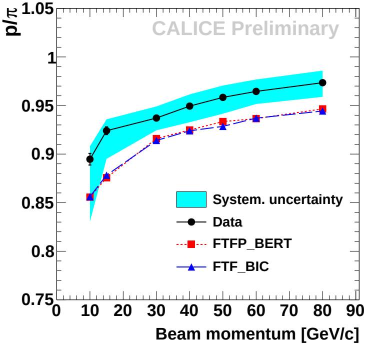


Difference in response ~1-4% cannot be explained by the baryon conservation law.

p/π ratio from test beam data and simulations

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





Good prediction by QGSP_BERT, QBBC and CHIPS

Underestimated by FTFP_BERT and FTF_BIC

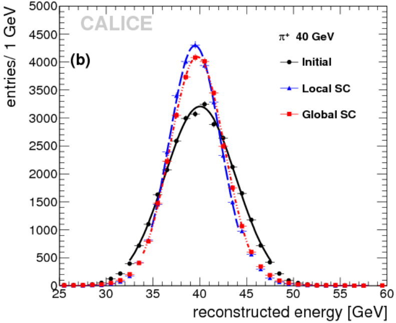
Energy resolution

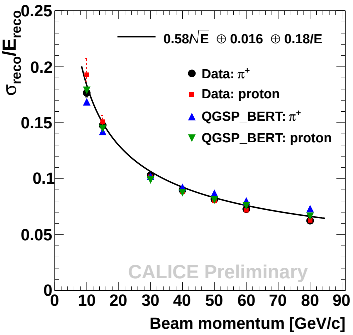
Intrinsic resolution: $\frac{58\%}{\sqrt{E/\mathrm{GeV}}} \oplus 1.6\% \oplus \frac{0.18}{E/\mathrm{GeV}}$

π and proton data in agreement within uncertainties

Better prediction for all hadrons by QGSP_BERT

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





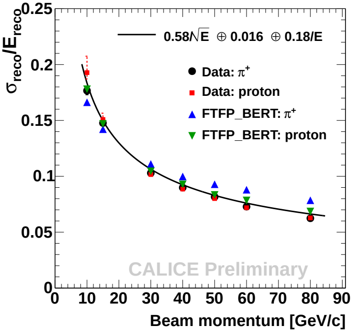


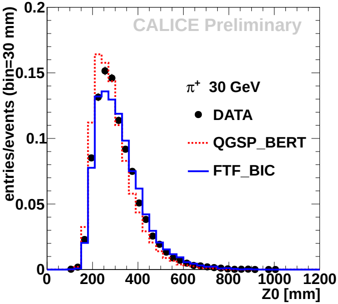
Figure from 2012 JINST 7 P09017

Longitudinal shower development: pions

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

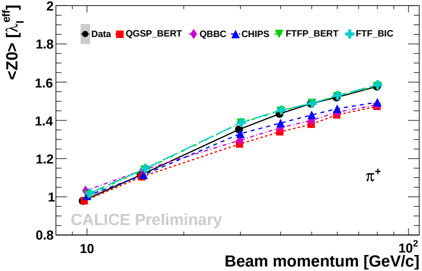
$$\mathbf{Z0} = \frac{\sum e_i \cdot (z_i - z_{\mathrm{start}})}{\sum e_i}$$

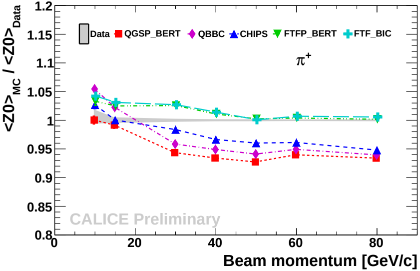
Sum over hits with longitudinal position $z_i \geq z_{\mathrm{start}}$



Typical distribution of $Z0$

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





Better predictions with Fritiof-based PL

Longitudinal shower development: protons

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

Pion to proton comparison

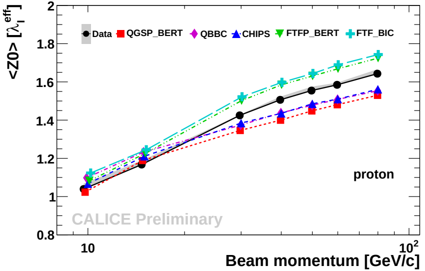
Longitudinal CoG of proton shower on average $\sim$5% deeper in data

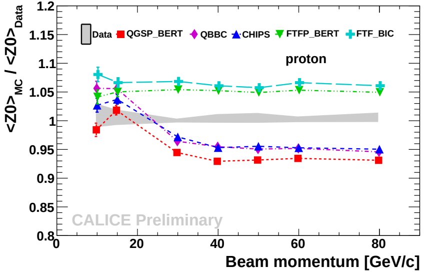
$\langle \mathbf{Z0} \rangle_{\text{proton}} / \langle \mathbf{Z0} \rangle_{\pi} \approx 1.05$

Simulations to data comparison

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

underestimated by QGSP_BERT, QBBC and CHIPS by $\sim$5% above 20 GeV



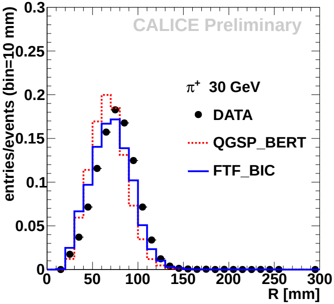


Radial shower development: pions

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

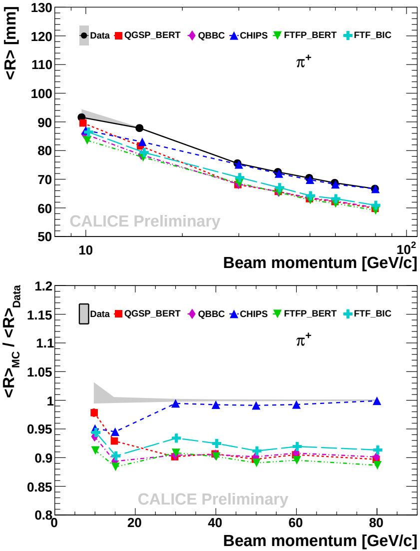
Sum over hits with longitudinal position $z_i \geq z_{start}$

Radial distance $\mathbf{r_i}$ 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 in the center of front plane



Underestimated by ~10% (except for CHIPS)

Radial shower development: protons

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

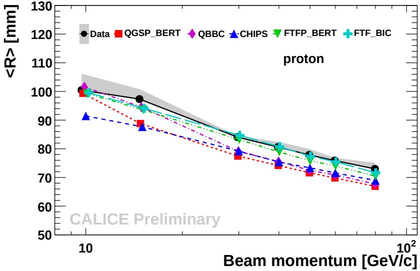
Proton showers on average ~10% wider

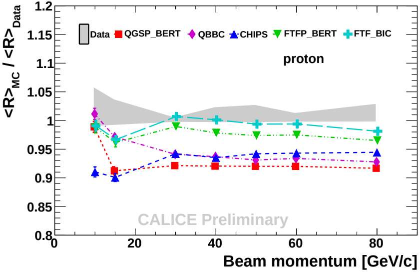
$\langle \mathbf{R} \rangle_{\mathbf{proton}} \, / \, \langle \mathbf{R} \rangle_{\pi} \approx 1.1$

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



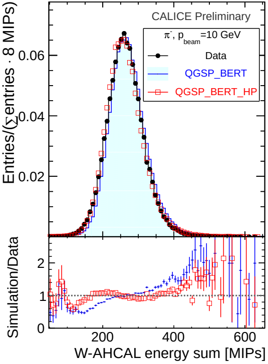


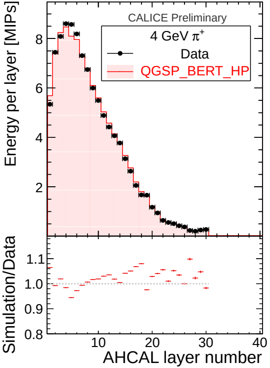
Highly granular Sc-W AHCAL

Compact hadronic calorimeter for CLIC

1.6 cm steel plates of Sc-Fe AHCAL replaced by 1 cm tungsten plates: 30 layers, $1\times1\times0.75$ m^3, depth $\sim3.9\lambda_\mathrm{I}$

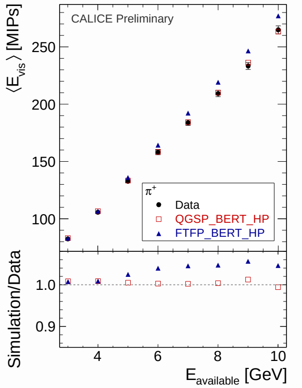
Test beam campaign at CERN in 2010-2012
Data analysis in progress





HP package is important for simulations of W-AHCAL

π^+ @ 3-10 GeV



Simulations with Geant4 v9.3p03

Accuracy of QGSP_BERT_HP predictions $\pm1\%$
Figures from CAN-036

Summary

Parameters of hadronic showers in the highly granular scintillator-steel analogue hadronic calorimeter were analyzed for test beam data in the energy range 8-80 GeV and compared with Geant4 simulations.

- 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.
- Longitudinal CoG of hadronic shower is underestimated by QGSP_BERT, QBBC and CHIPS physics lists by ∼5% above 20 GeV; FTF_BERT and FTF_BIC physics lists give good predictions for pions and overestimate longitudinal CoG for protons by ∼5%.
- Mean shower radius tends to be underestimated by ∼5-10%. The best prediction for pions above 20 GeV is given by CHIPS, for protons - by FTF_BIC.
- High Precision package is important for simulations of tungsten calorimeter.

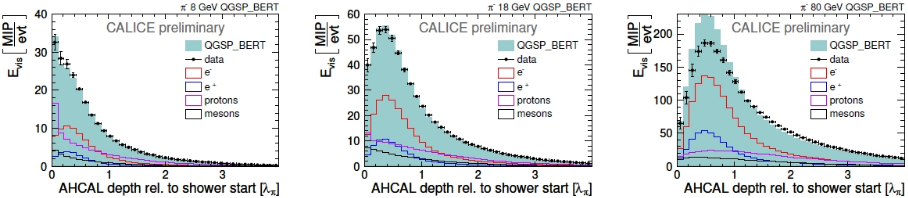
In progress

- Study of parametrization of longitudinal and radial shower profiles
- Analysis of high energy hadron data for Sc-W AHCAL

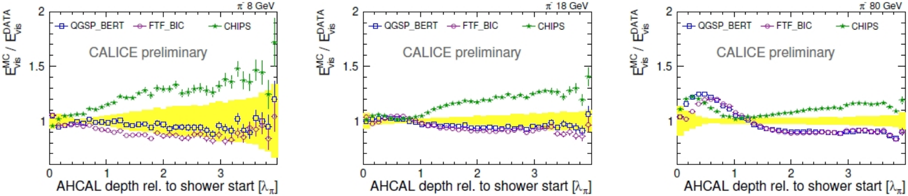
Backup slides

Hadronic shower substructure

Longitudinal profiles from shower start and shower decomposition from QGSP_BERT



MC/Data ratio of longitudinal profiles (Geant4 9.3)



QGSP_BERT and FTF_BIC in agreement within uncertainties up to 20 GeV

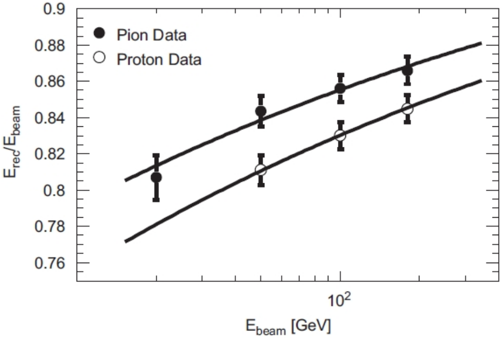
∼20% overestimation in shower maximum at 80 GeV

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



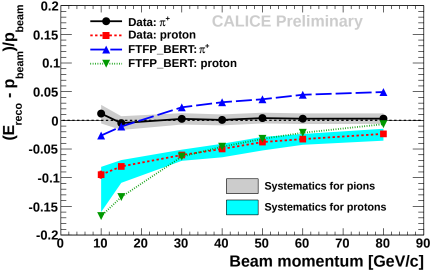
50 GeV point for comparison of $\frac{p}{\pi}$ in data:

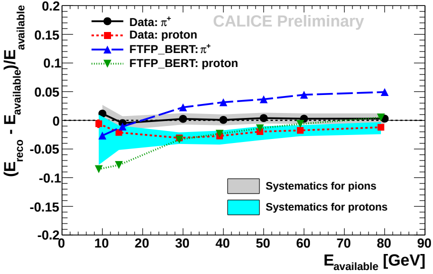
CALICE: $0.958^{+0.012}_{-0.016}(\text{syst.}) \pm 0.001(\text{stat.})$

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

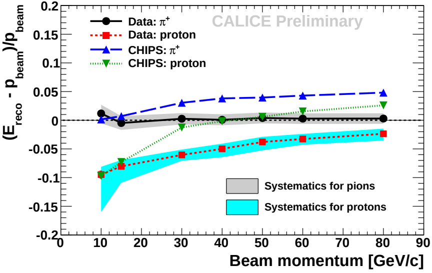
Response of Sc-Fe AHCAL to hadrons: data, FTFP_BERT, CHIPS

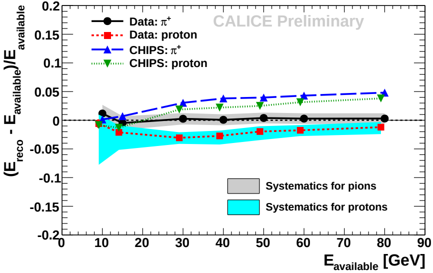
FTFP_BERT physics list





CHIPS physics list





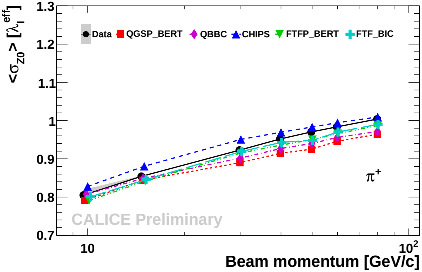
Longitudinal shower development: r.m.s. of Z0

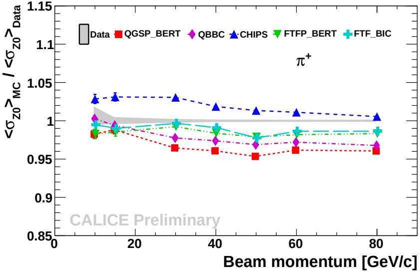
MC to Data

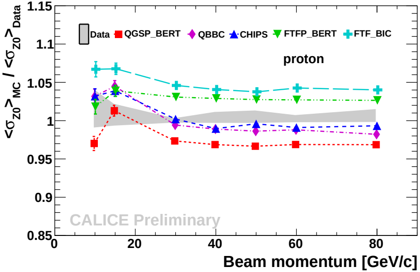
The r.m.s. of CoG in longitudinal direction

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

Shower cluster includes hits with $e_i > 0.5$ MIP and longitudinal position $z_i \geq z_{start}$







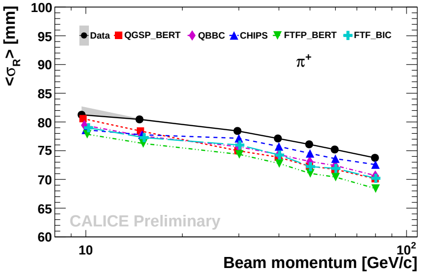
Radial shower development: r.m.s. of R

The r.m.s. of shower radius:

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

Shower cluster includes hits with $e_i > 0.5$ MIP and longitudinal position $z_i \geq z_{start}$

r_i - the radial distance from hit to shower axis.



MC to Data