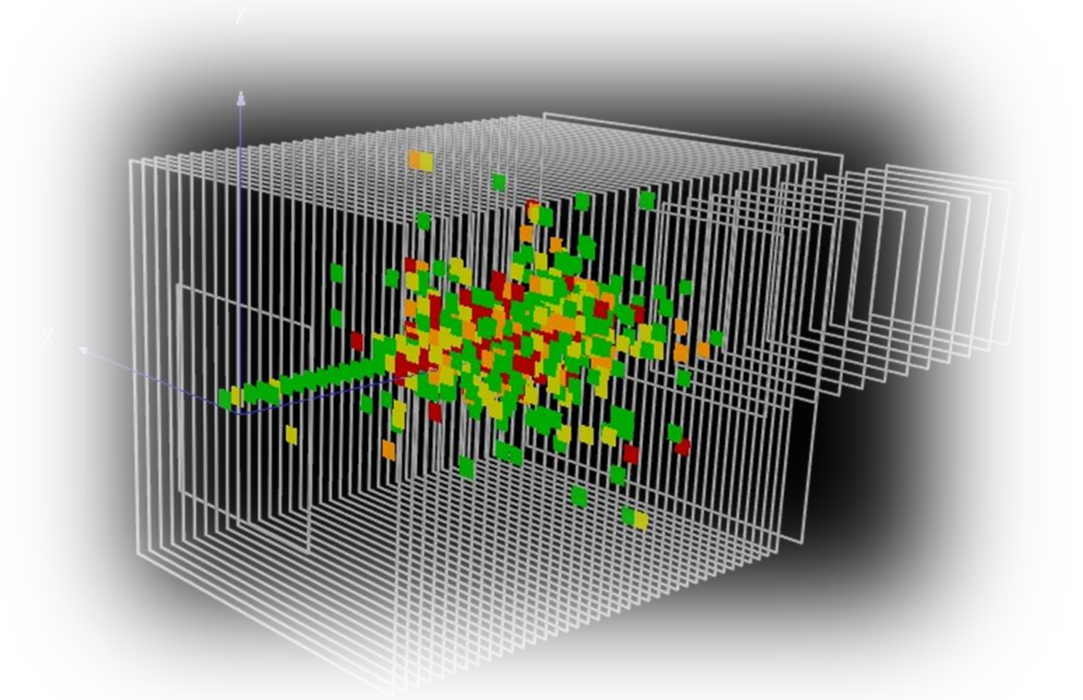
Analysis of shower shapes recorded with the CALICE-AHCAL in 2018 Test Beam Data



Olin Pinto

CALICE Virtual Meeting

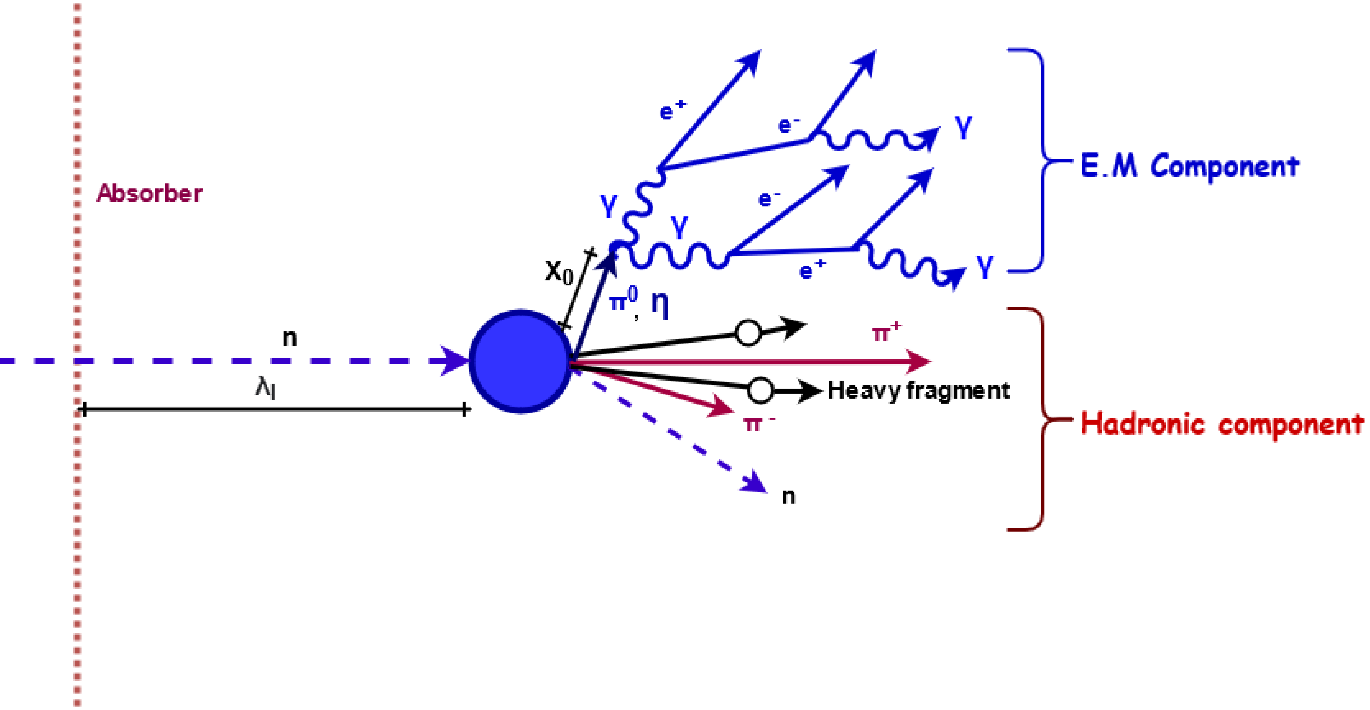
26th March 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Hadronic Showers

Sketch of hadronic shower



- Mainly charged and neutral pions

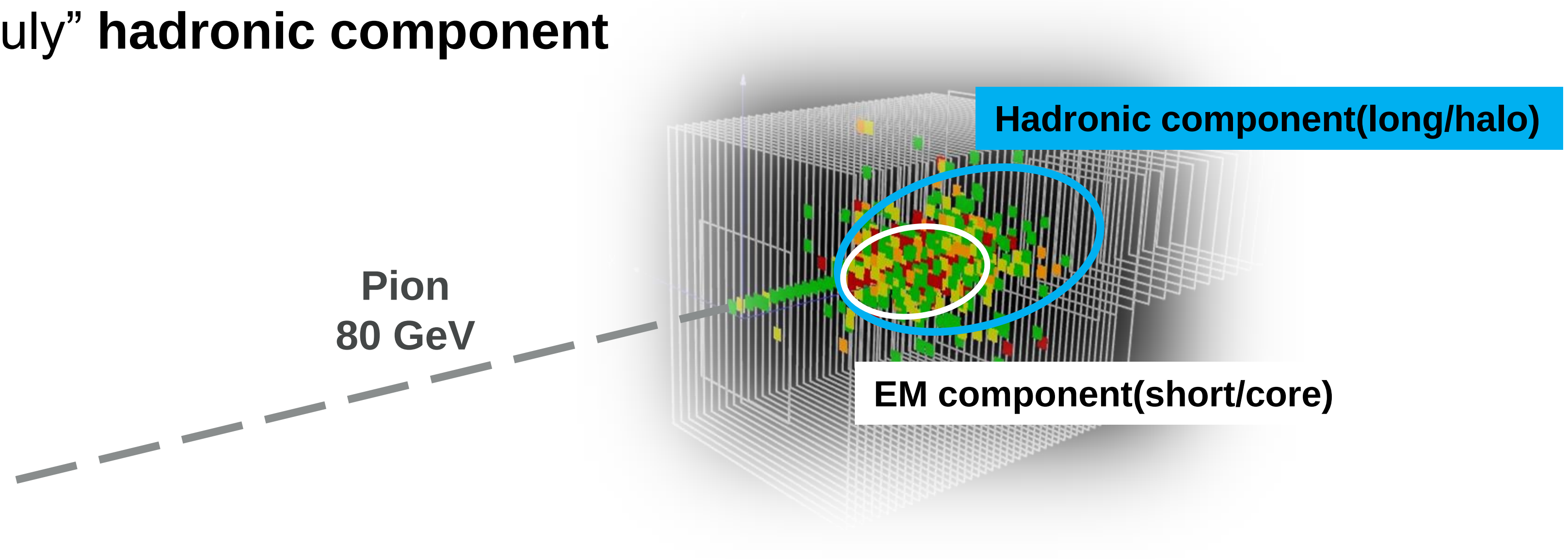
  Large component of secondary particles in hadron cascades are π^0

  - which represent ~ 1/3 of total energy produced in each inelastic collision
  - Initiating electromagnetic subcascades in a hadron shower

  Hadronic showers have a complex structure and are theoretically not as well understood as electromagnetic showers

Motivation

- Shower shapes can be investigated with excellent accuracy, due to fine segmentation of the AHCAL
- The goal is to identify the core/short part of the shower with an **EM component**, and the long/halo part with the "truly" **hadronic component**



- Exploitation of shower shapes allows an estimation of **h/e signal ratio**
  - The ratio of responses to the non-electromagnetic and electromagnetic components of a hadron-induced shower, determines the origin of non-linearity

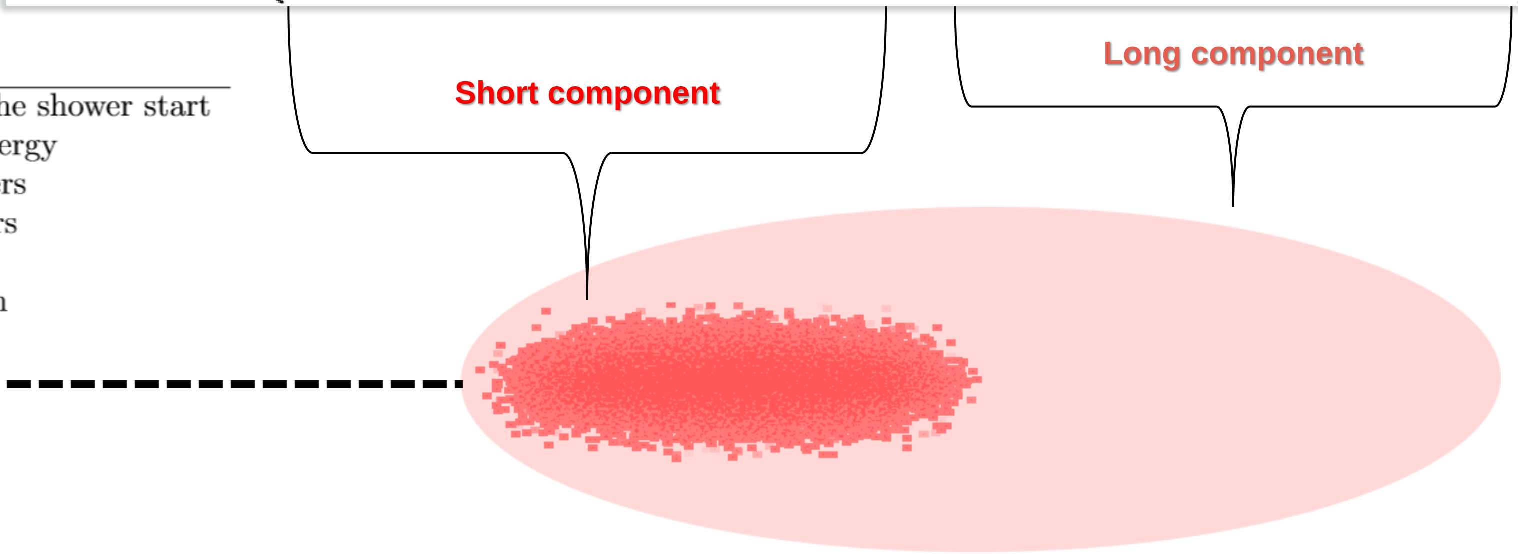
Parametrization

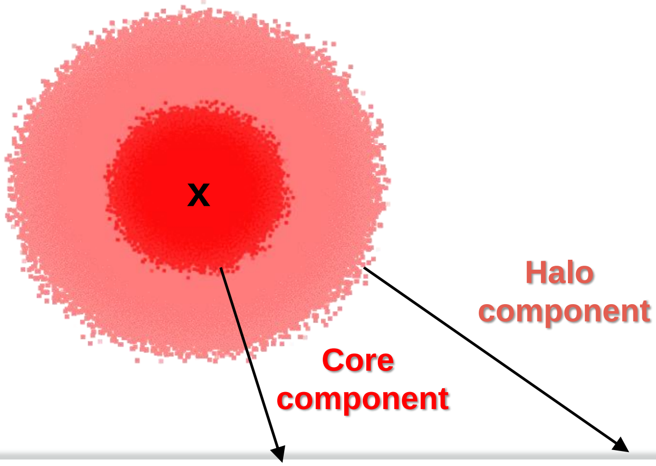
JINST 11 (2016) P06013

Longitudinal profile is the mean energy deposited per layer from the shower start

$$\Delta E(z) = E\cdot\left\{\frac{f}{\Gamma(\alpha_s)}\cdot\left(\frac{Z[X_0]}{\beta_s}\right)^{\alpha_s-1}\cdot\frac{e^{\frac{-Z[X_0]}{\beta_s}}}{\beta_s}+\frac{1-f}{\Gamma(\alpha_l)}\cdot\left(\frac{Z[\lambda_I]}{\beta_l}\right)^{\alpha_l-1}\cdot\frac{e^{\frac{-Z[\lambda_I]}{\beta_l}}}{\beta_l}\right\}$$

Parameter	
z	distance from the shower start
E	mean visible energy
α_s, β_s	shape parameters
α_l, β_l	slope parameters
f	short fraction
Γ	gamma function





Radial profile is the distribution of the energy density as a function of the radial distance to the shower axis

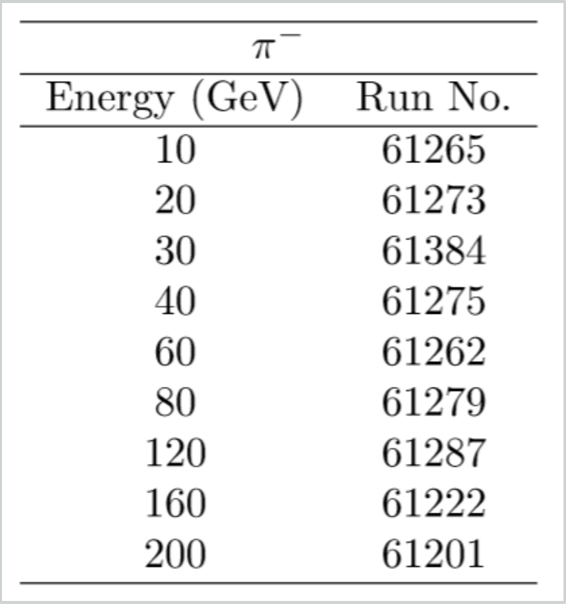
$$\frac{\Delta E}{\Delta S}(r) = \frac{E}{2\pi}\cdot\left\{f\cdot\frac{e^{\frac{-r}{\beta_c}}}{\beta_c^2}+(1-f)\cdot\frac{e^{\frac{-r}{\beta_h}}}{\beta_h^2}\right\}$$

Parameter	
r	distance from the shower axis
E	mean visible energy
β_c, β_h	slope parameters
f	core fraction

Samples and Selection

Samples

- Data for Pions are from June 2018 recorded at SPS CERN test beam
- Reconstruction of samples are done using *CaliceSoft v04-14-02*
- Simulations of half a millions events done using *QGSP_BERT_HP* & *FTFP_BERT_HP* physics list from *GEANT4 v10.03.p02* for all available energies



π^-	
Energy (GeV)	Run No.
10	61265
20	61273
30	61384
40	61275
60	61262
80	61279
120	61287
160	61222
200	61201

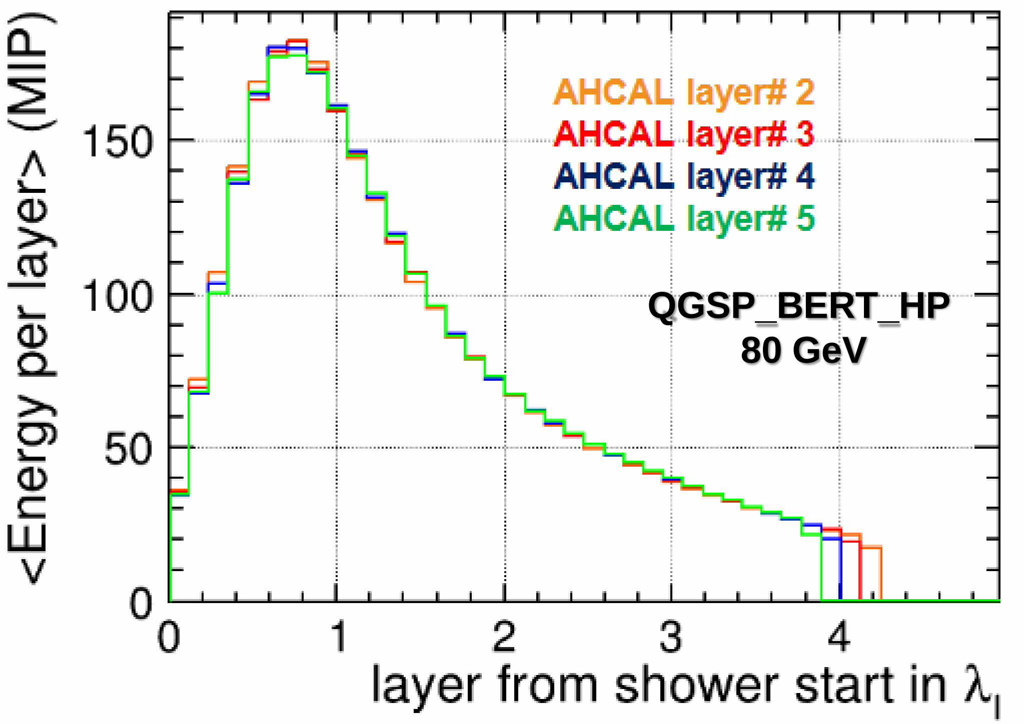
Selection

- Applied PID using BDT for hadrons to remove beam contamination
- Require that the shower start is in layer 2-6

Event selection

- Exclusion of events with shower start beyond sixth layer to minimize leakage
- Require single track and track hit match in layer 1 || 2 || 3
- Apply Gap Rejection: 2.0 mm
- Selected Events in MC within the statistics available in data, due to the acceptance area of trigger scintillator and wire chamber (~10 x 10 cm^2)

Systematic Uncertainties

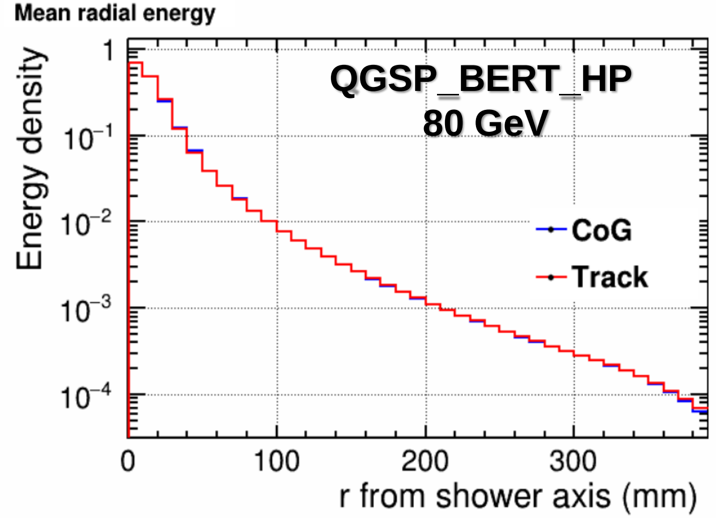


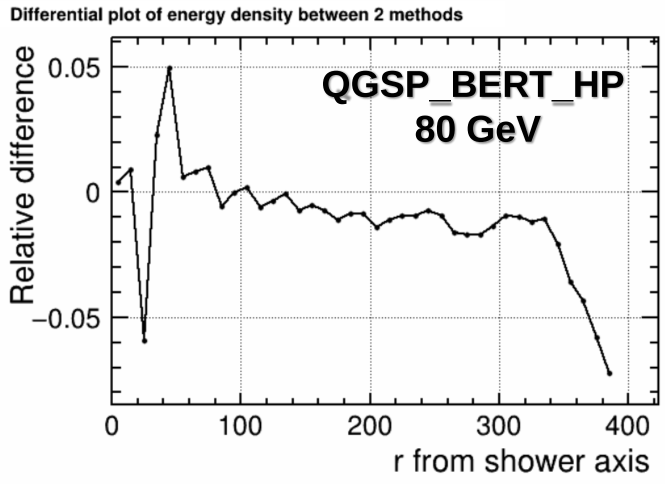
Longitudinal: layer-to-layer variations

- Significant contribution comes from layer-to-layer variations
  - Uncertainties in SiPM response function
- Averaging the contribution from different physical layers minimizes the layer-to-layer variation

Radial: Identification of shower axis

- The uncertainty is related to the difference between the two methods of shower-axis reconstruction
  - Event centre of gravity
  - Identification of incoming track



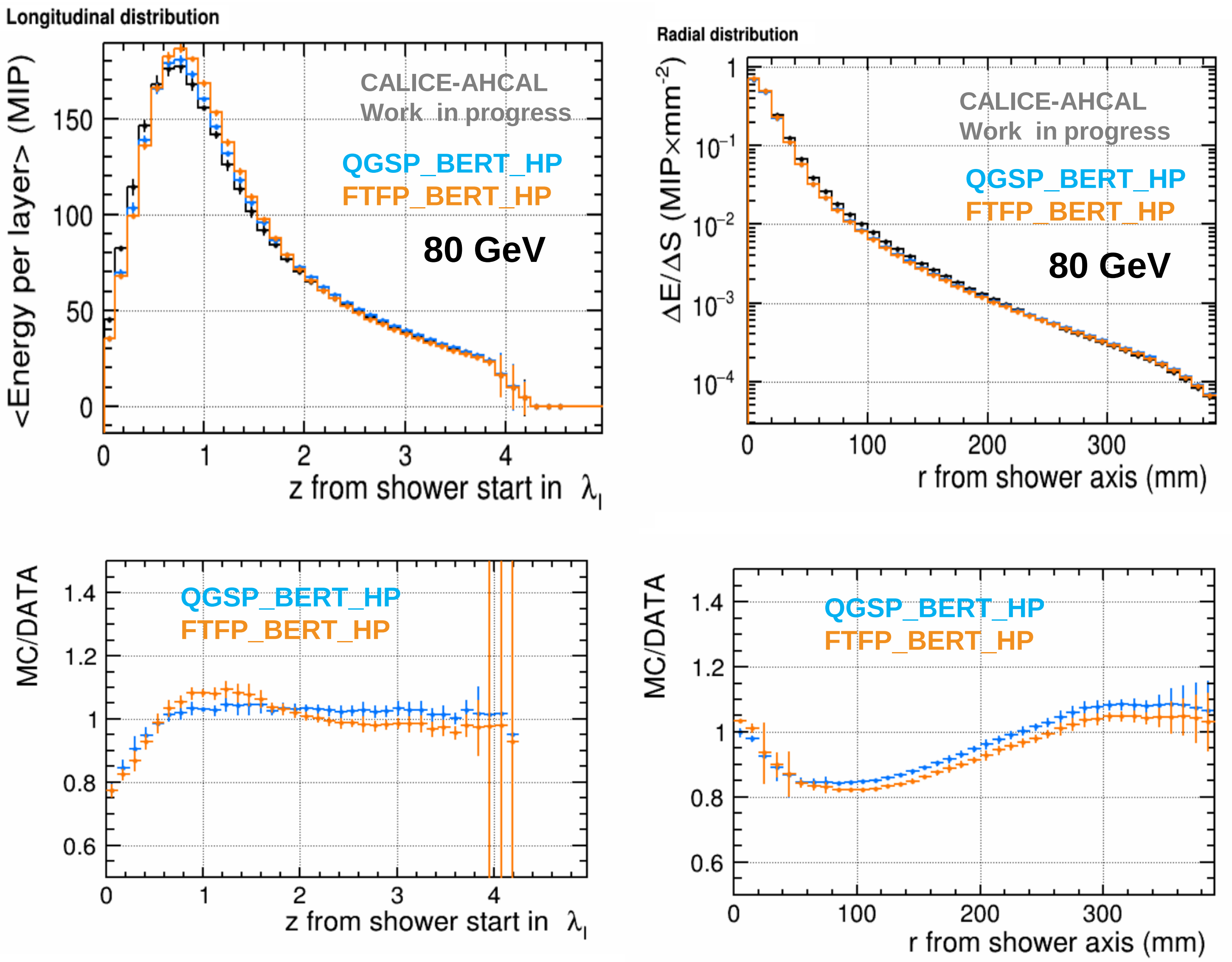


Shower shapes

Data and MC comparisons

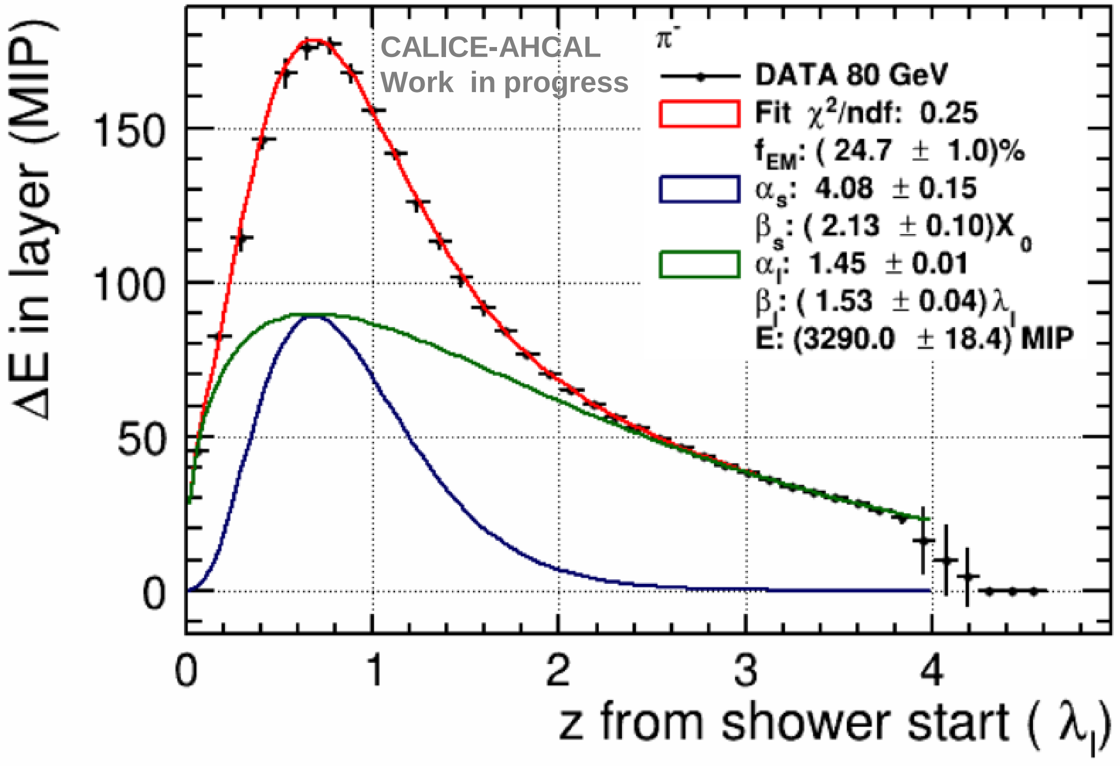
- Data is compared between two recommended *GEANT4 (v10.03.p02)* physics lists, **QGSP_BERT_HP** & **FTFP_BERT_HP**

- Both simulations predict higher energy deposition around the shower maximum compared to data
- The tail of the shower are reasonably well reproduced by simulations

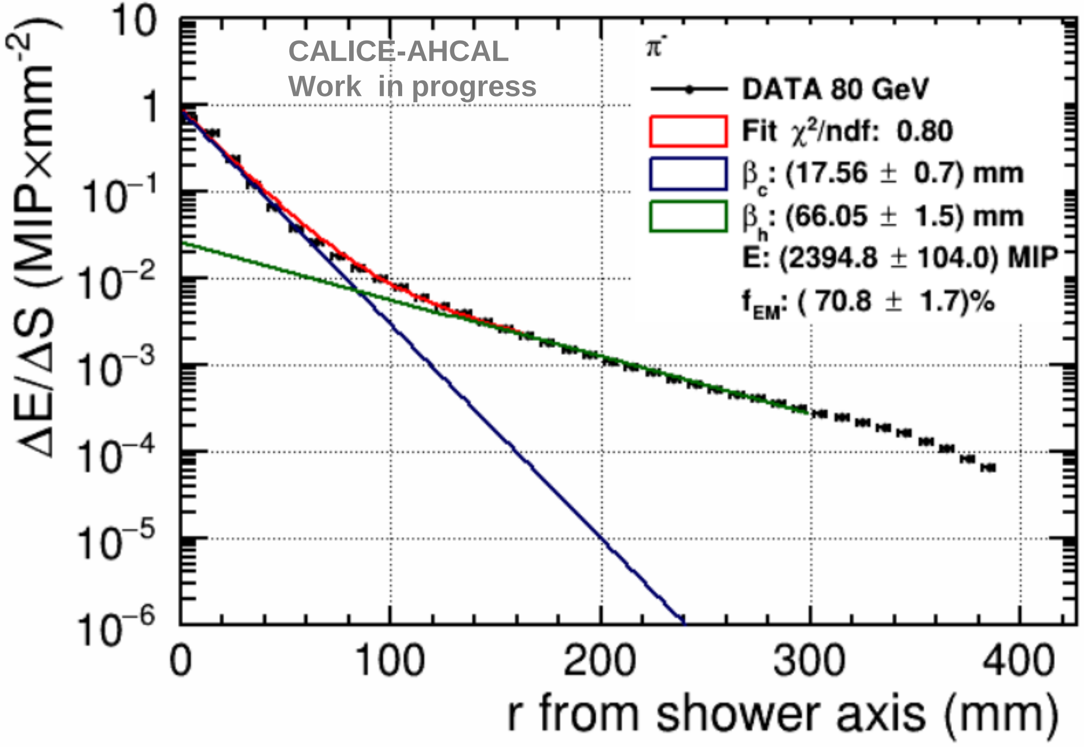


Shower Shapes

Longitudinal distribution



Radial distribution



The longitudinal fit range corresponds to a depth of $4\lambda_l$ from the shower start and for radial up to a width of 300 mm with a step size of 10 mm

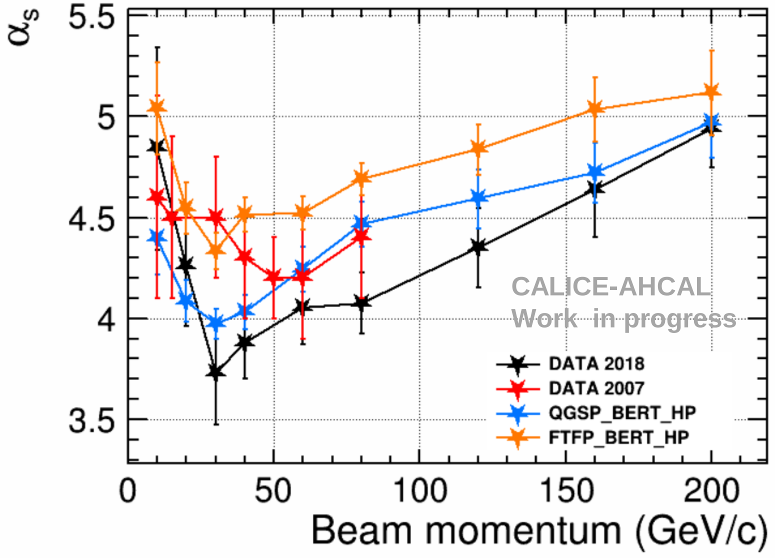
ENERGY DEPENDANCE OF SHOWER PROFILE PARAMETERS

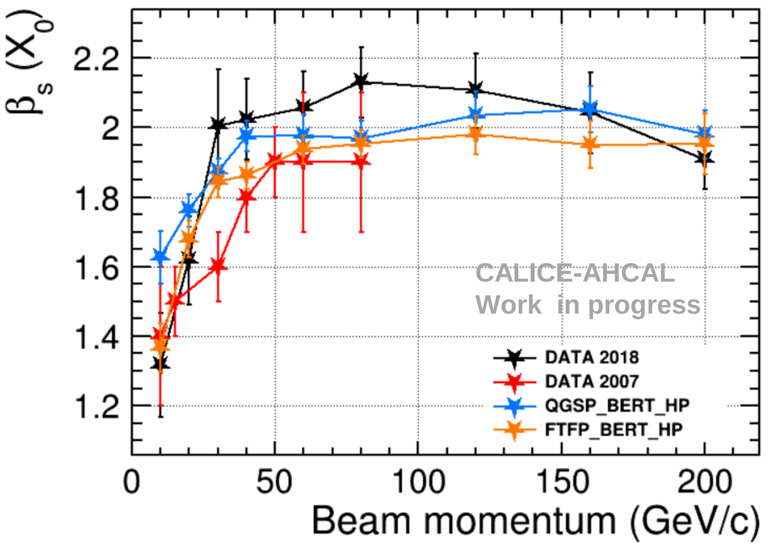
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

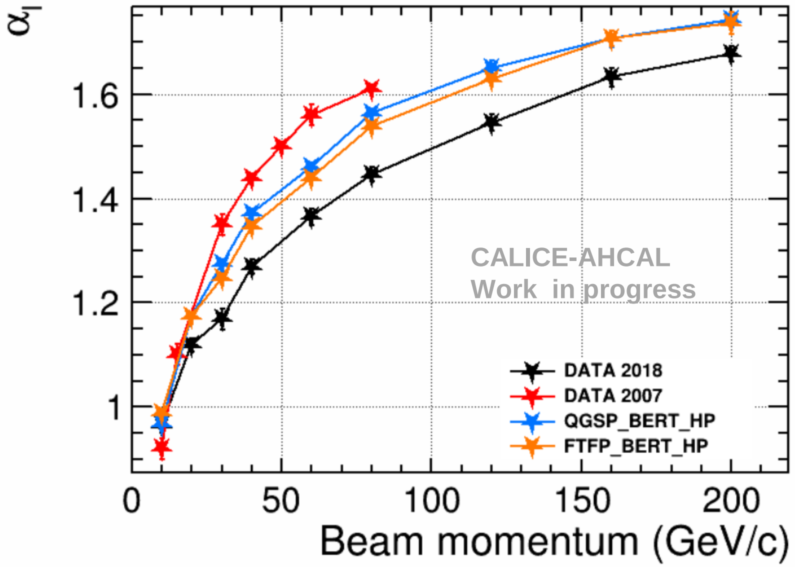
Longitudinal Parameters

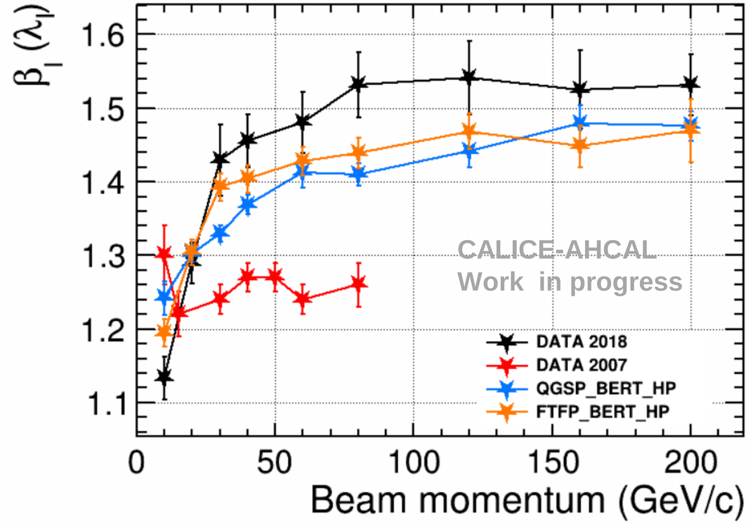
“short” & “long” parameters

- Parameters for short component (α_s and β_s) agree reasonably well between <u>physics prototype</u> and the current analysis as well as MC and data
    - but have rather large uncertainties
- Parameters for long component (α_l and β_l) agree less well



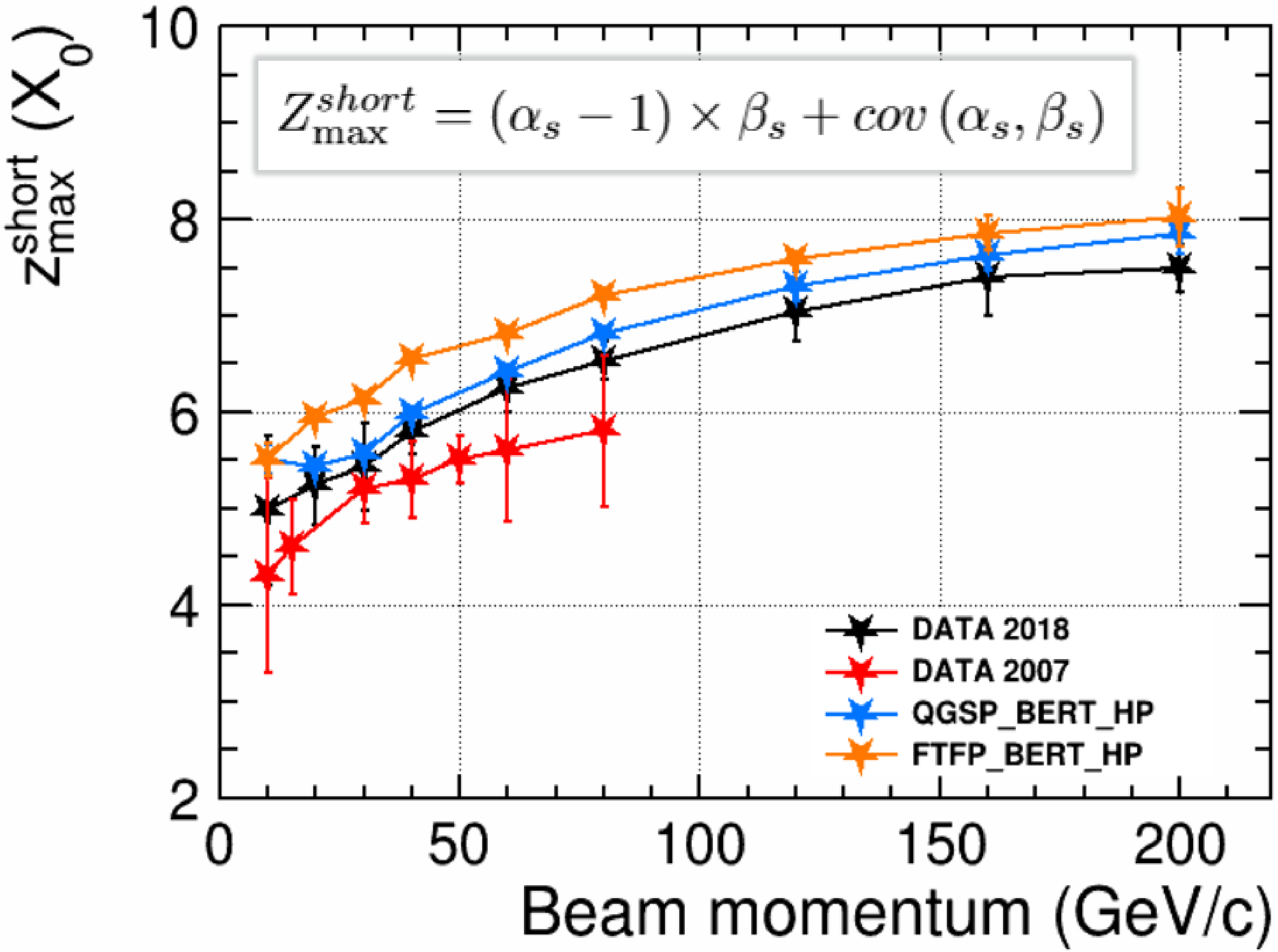






Maximum Position of the "short" Component

- The maximum position of the "short" component, Z_{max}^{short} is extracted from longitudinal profile induced by pions
- Data samples exhibits a logarithmic rise as expected
- Consistent difference between data and simulation for increasing energies



h/e Signal Ratio

The ratio of responses to the non-electromagnetic and electromagnetic components of a hadron-induced shower

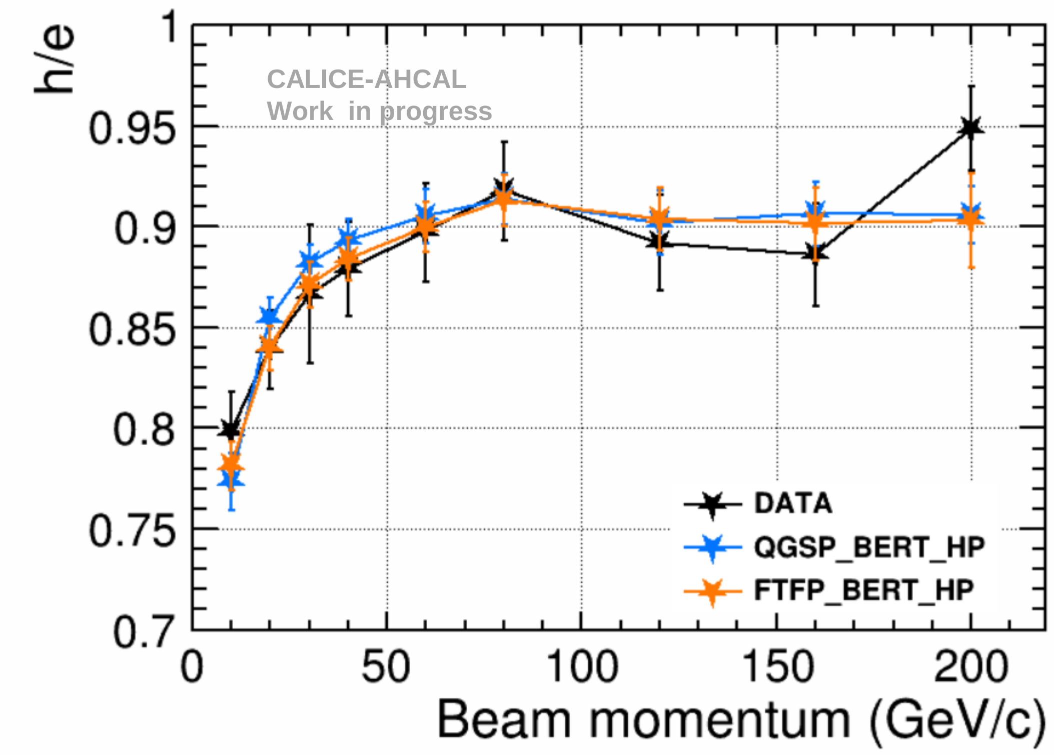
- Degree of non-compensation is determined by h/e value of the calorimeter
- h/e signal ratio is not directly measurable
- The value of h/e is extracted from the fit to longitudinal profile

$$\frac{h}{e} = \frac{E_{had}^{fit}}{E_{beam} - E_{em}^{fit}}$$

Electromagnetic calibration constant 0.02278 GeV/MIP

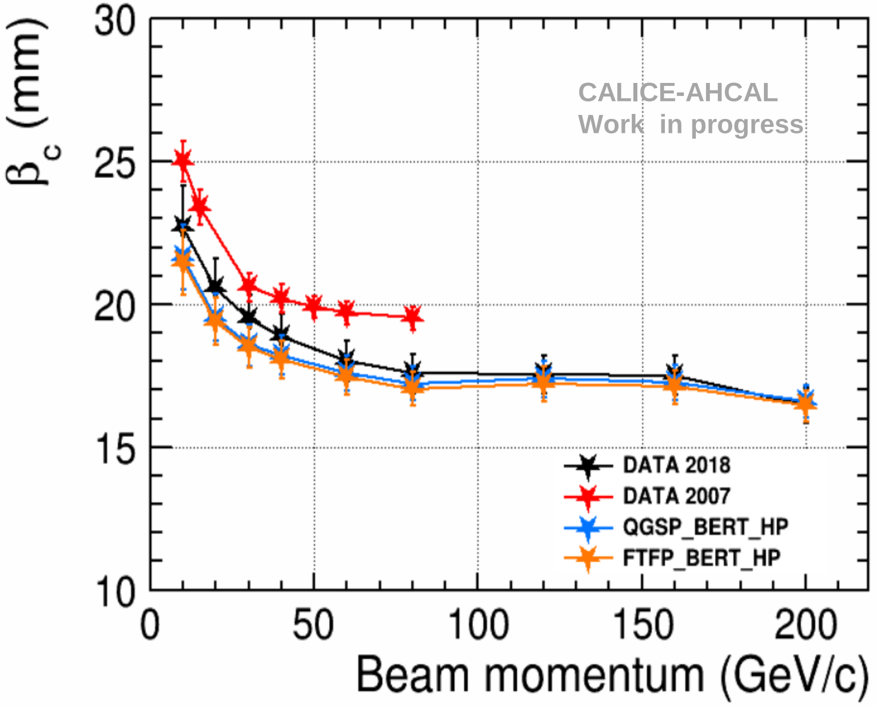
$$E_{had}^{fit} = E_{reco} \cdot (1 - f_{em}) \cdot C_{\mathrm{em}}, \quad E_{em}^{fit} = E_{reco} \cdot f_{em} \cdot C_{\mathrm{em}}$$

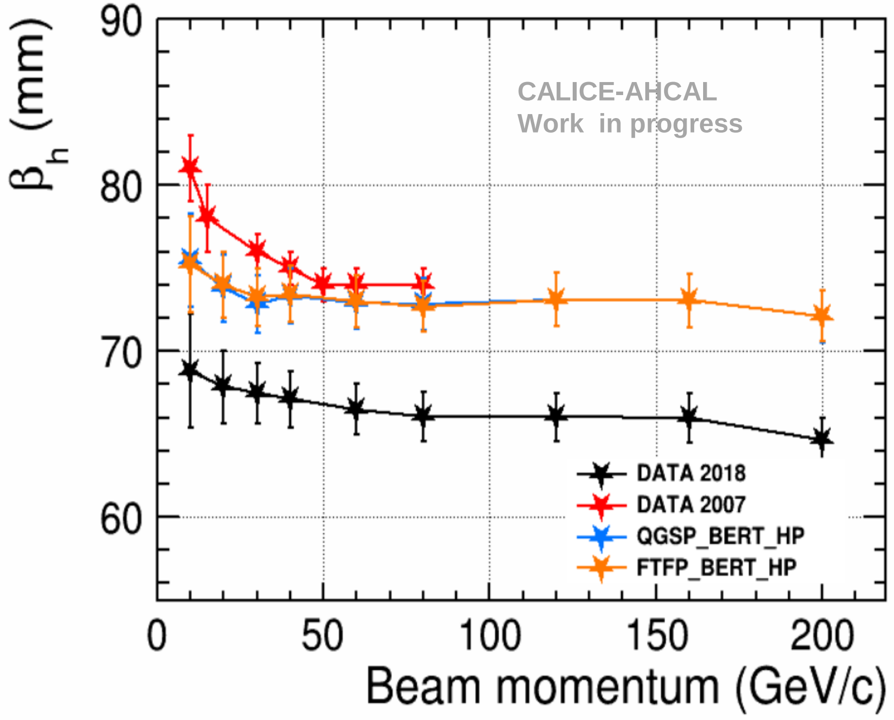
- h/e signal ratio is energy independent at higher energies as expected



Radial Parameters

Core & Halo





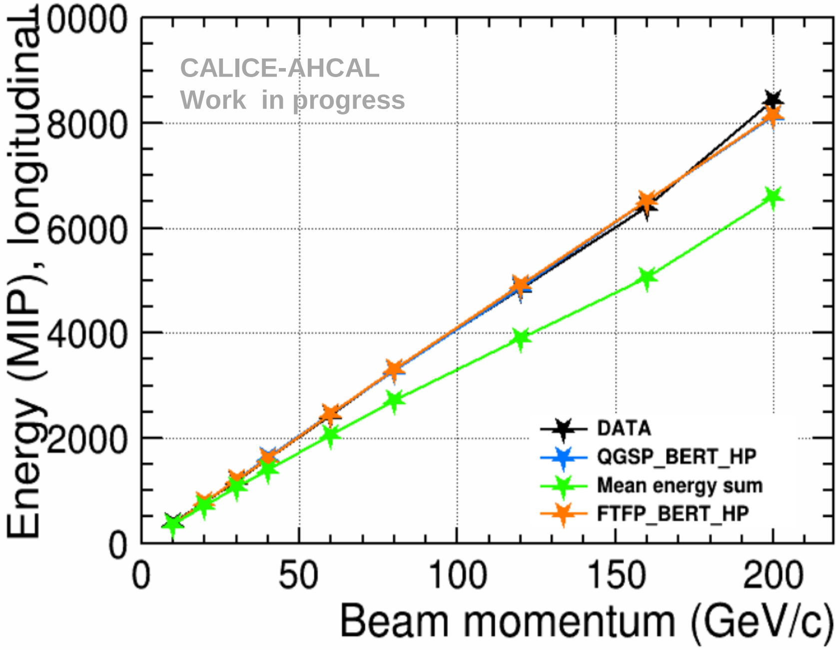
Parameter β_c

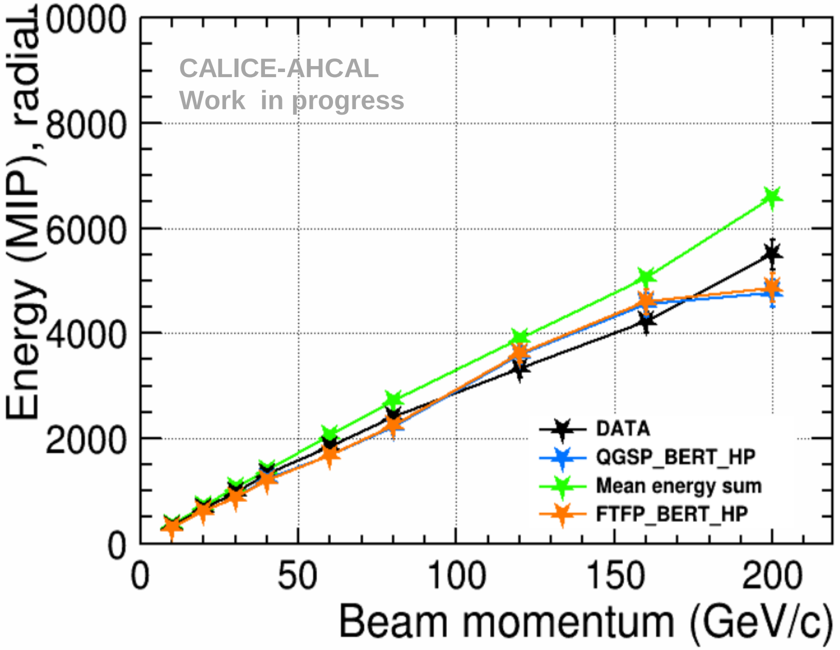
- Decrease at a faster rate at low energies compared to the energies above 30 GeV, this behaviour being well reproduced by simulations
- No energy dependence above 30 GeV

Parameter β_h

- Almost no energy dependence above 30 GeV also predicted by simulations
- In general, simulations obtains a larger halo component and the difference in the parameter increases with increasing energy

Energy- Scaling Parameter

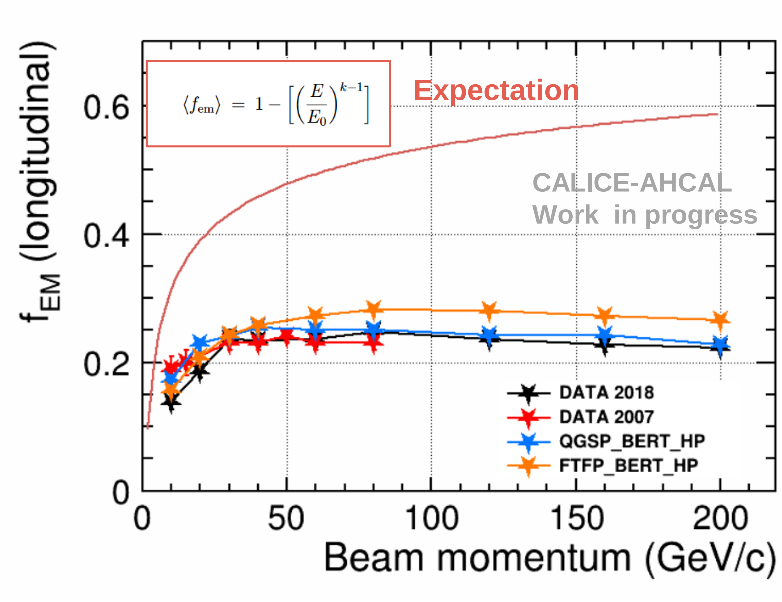


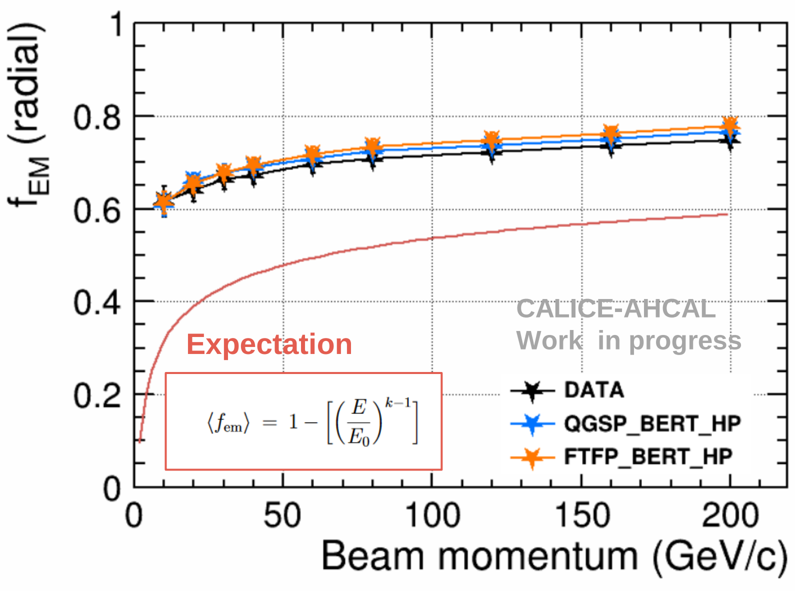


Parameter E

- This parameter is obtained from the longitudinal and radial fit function and is equal to the integral under the curves up to infinity as this corresponds to the mean visible energy in units of MIP
- Showers are radially well contained but longitudinal clearly not

Fraction of short/core component: “Average EM fraction”





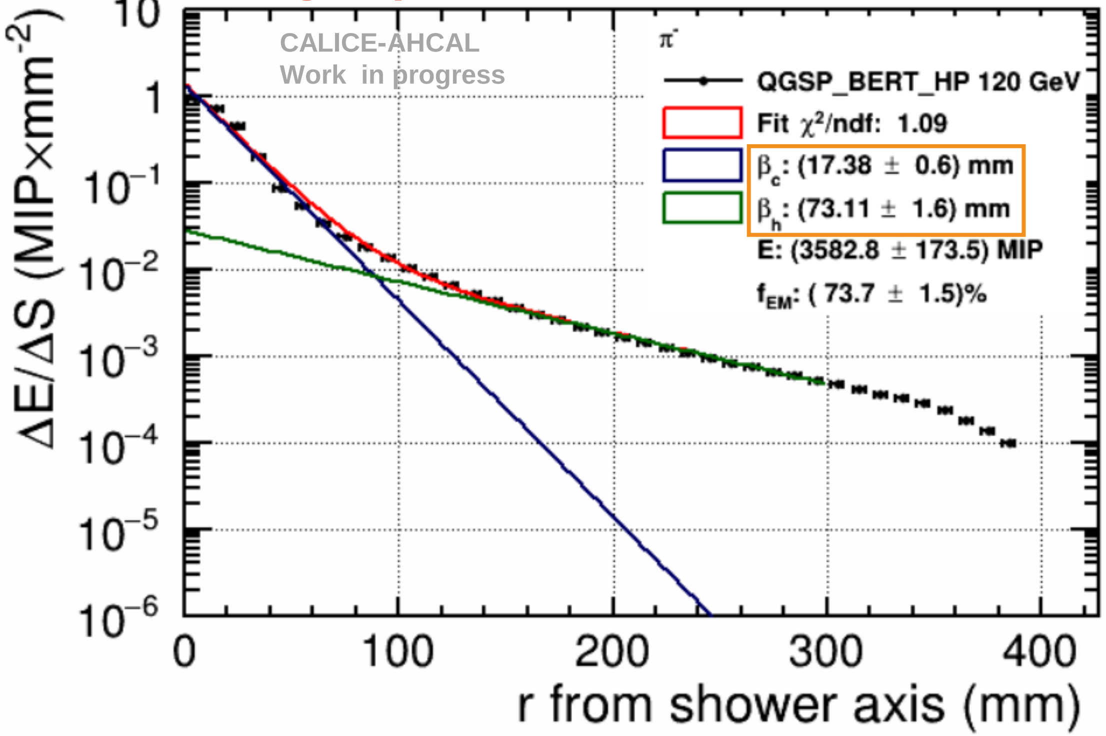
Parameter f_{EM}

- Fraction of hadron energy deposited via EM processes
- The f_{EM} is sum of several single EM showers and on average, the number of EM sub-showers scales with energy
- f_{EM} value is comparable to previous results and the obtained value increases at a faster rate until 30 GeV and thereafter remains nearly constant
- **Different “f_{EM}” from longitudinal and radial fits means that the initial interpretation that the short component and the core component both agree with the EM component of the shower is too simple**
- **Need a better fit model, one cross check is the comparison of the fit parameters to the ones from EM showers**

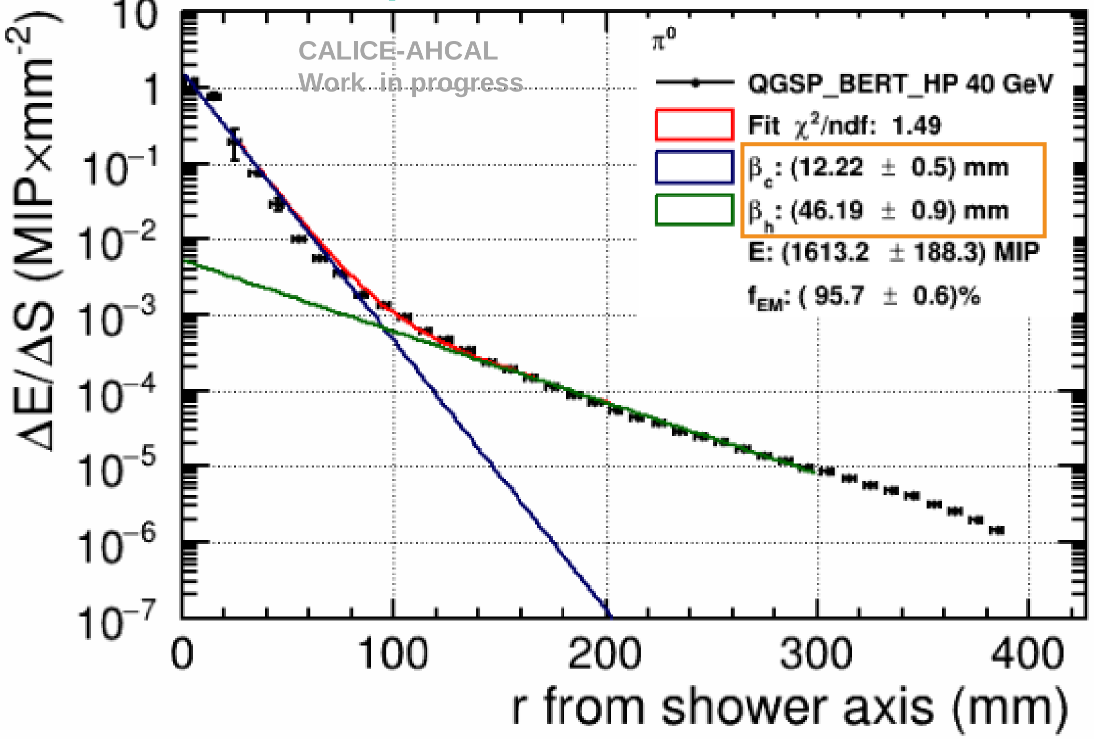
Comparison of core component to EM showers

40 GeV pi0's are simulated using QGSP_BERT_HP physics list, very close the AHCAL detector.
The fit parameter β_c is compared between 120 GeV π^- and 40 GeV π^0

Charged pion



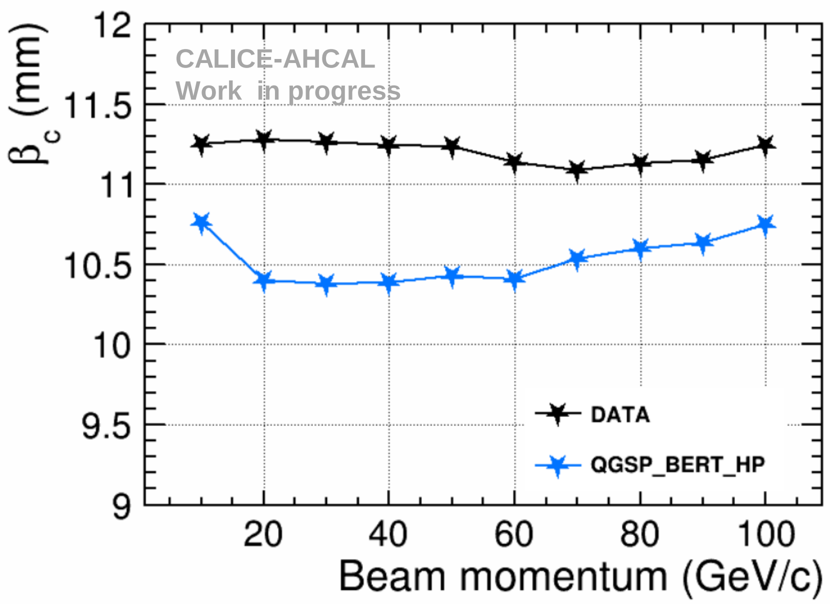
Neutral pion

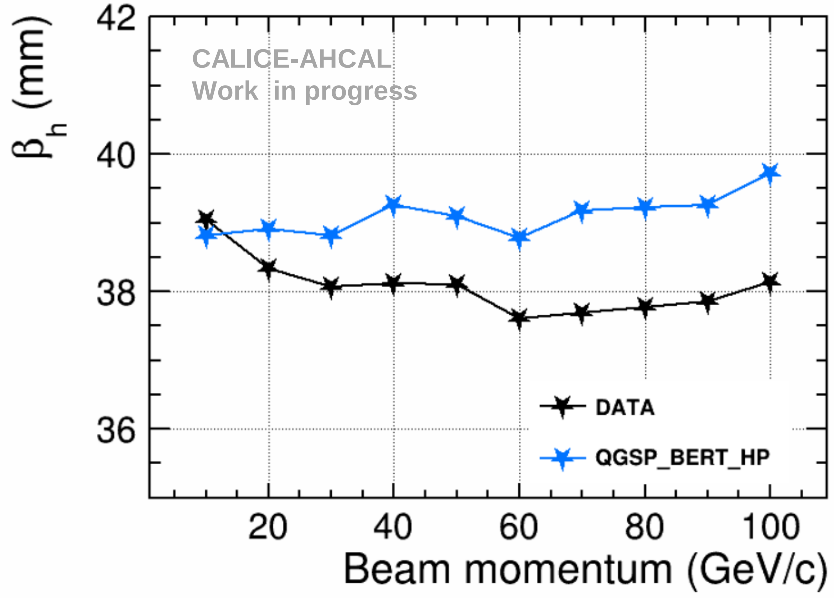


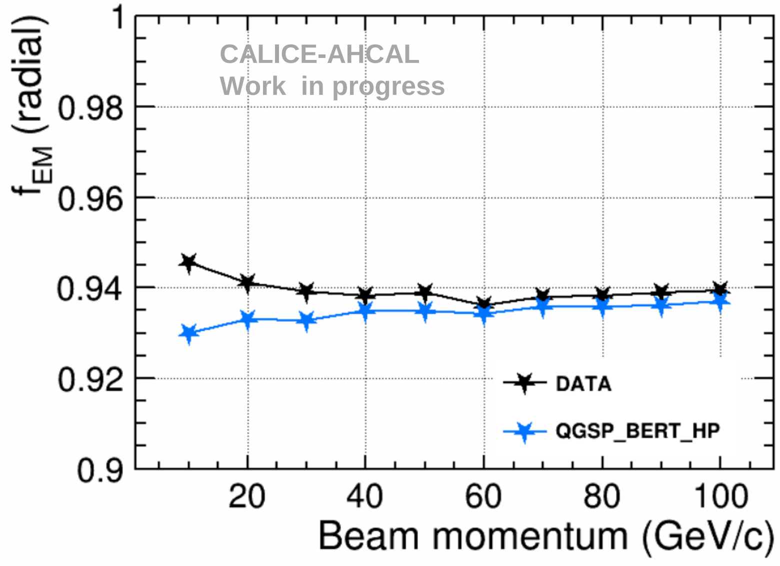
- **None of the beta's in the charged pion agrees with the beta's for the neutral pion**
- There are clearly two components seen in EM showers
- Need an additional 3rd component in the radial fit
  - Fit stability : Too many free parameters, need to fix some parameters

Description of EM Showers

- As no large differences in beta’s and core fraction are observed for all electron energies, use this to fix the EM core
- By keeping energy as free parameter and fixing the beta’s and core fraction to average values, provides a reasonable description of electron showers







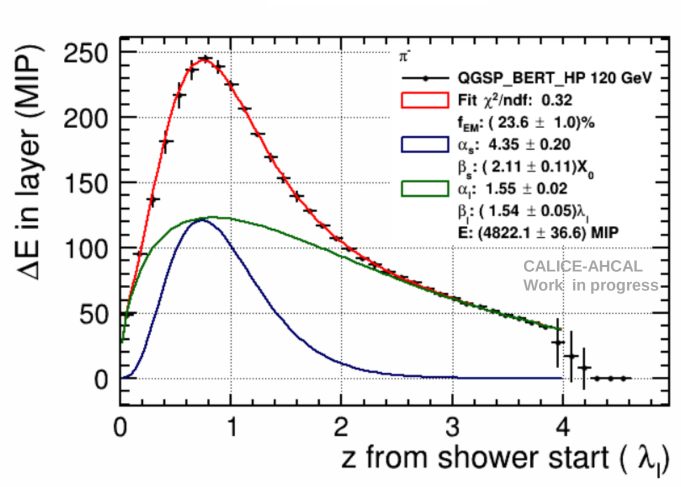
Effective Radial Parametrization

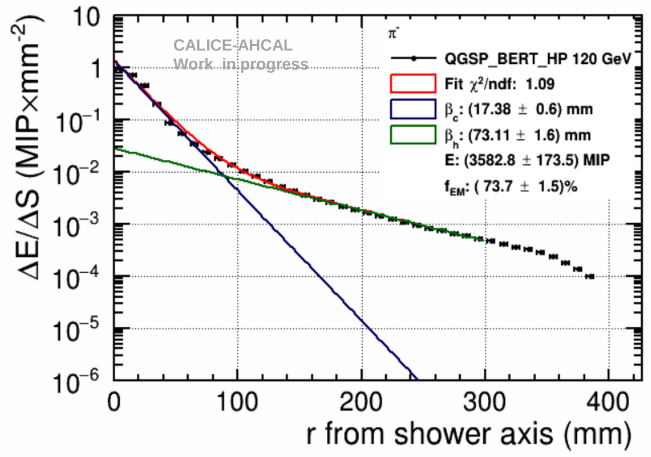
$$\frac{\Delta E}{\Delta S}(r) = \frac{E}{2\pi}\cdot\left\{ f\cdot K\cdot\frac{e^{\frac{-r}{\beta_c^{EM}}}}{(\beta_c^{EM})^2} + (1-f\cdot K)\left(f_h\cdot\frac{e^{\frac{-r}{\beta_c^{HAD}}}}{(\beta_c^{HAD})^2} + (1-f_h)\cdot\frac{e^{\frac{-r}{\beta_h^{HAD}}}}{(\beta_h^{HAD})^2}\right)\right\}$$

$$\Downarrow$$

$$\mathrm{K} = \frac{E_\infty}{E_{vis}}$$

- The short/core part, is well contained in both longitudinal as well as radial
- We can assume that the integral under this short/core part is the same in both radial and longitudinal
- The hadronic/tail part in longitudinal profile is larger because it does extrapolation (which means the f_{EM} is smaller)
- But, a correction is needed for the integral under the long component (longitudinal plot)
- Use the radial one, and instead of directly the f_{EM}, an effective f_{EM} is used, and this is corrected exactly for the tail in the longitudinal profile with a K factor
- The K factor is extracted from the longitudinal fit

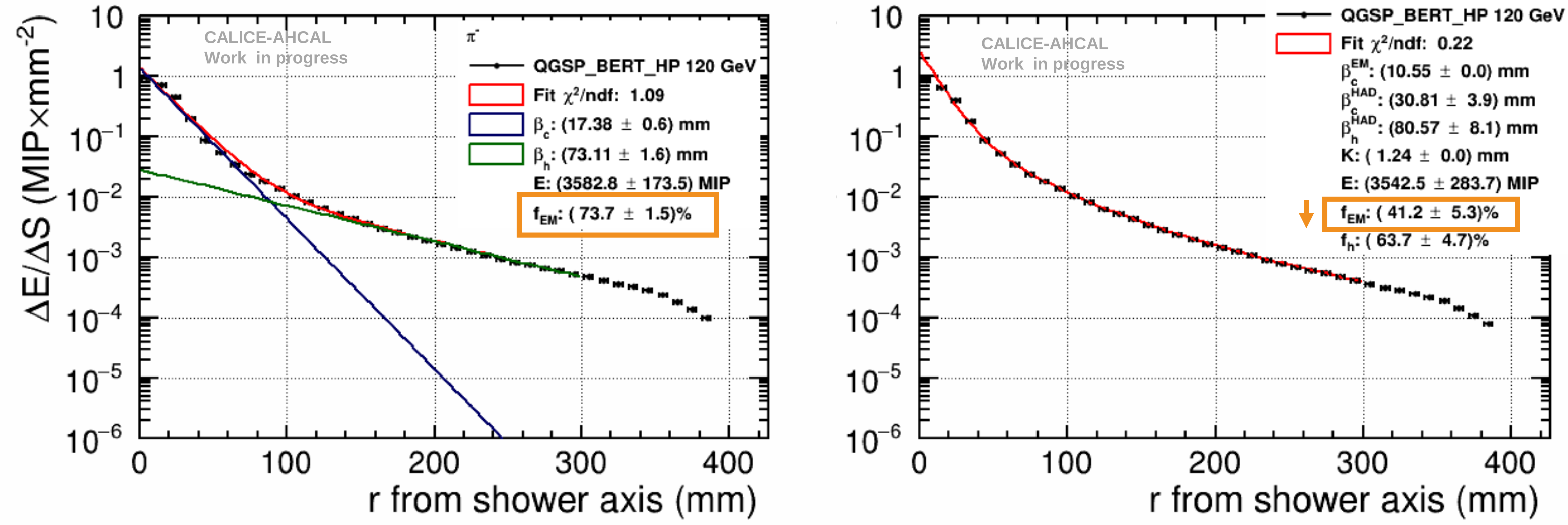




Effective Radial Parametrization

f_{EM} value is close to an expected value, but has a large uncertainty

$$\frac{\Delta E}{\Delta S}(r) = \frac{E}{2\pi}\cdot\left\{ f\cdot K\cdot \frac{e^{\frac{-r}{\beta_c^{EM}}}}{(\beta_c^{EM})^2} + (1-f\cdot K)\left(f_h\cdot\frac{e^{\frac{-r}{\beta_c^{HAD}}}}{(\beta_c^{HAD})^2} + (1-f_h)\cdot\frac{e^{\frac{-r}{\beta_h^{HAD}}}}{(\beta_h^{HAD})^2}\right)\right\}$$



Need to use both pion and electron showers in the whole energy range to find a consistent description (and interpretation) of the shower structure for pions

Summary & Outlook

- **Hadronic showers shapes** are well described by the sum of two contributions: sum of gamma distributions for longitudinal and sum of exponential distributions for radial development
- The behaviour & reproducibility of spatial parameters both for longitudinal and radial profiles agree around 25% to physics prototype measurements
- **Good agreement between data and GEANT4** physics lists ~10% at all energies
- The ratio of response between pion-induced and electron-induced shower (**h/e signal ratio**) obtained from the longitudinal profile is found to be between 0.8 and 0.95
  - The values of h/e predicted by simulations are in agreement with data within 5%
- An effective radial parametrization is used to describe pion shower structure
  - This leads to decrease in $\mathbf{f_{EM}}$**:** Information extracted from EM showers

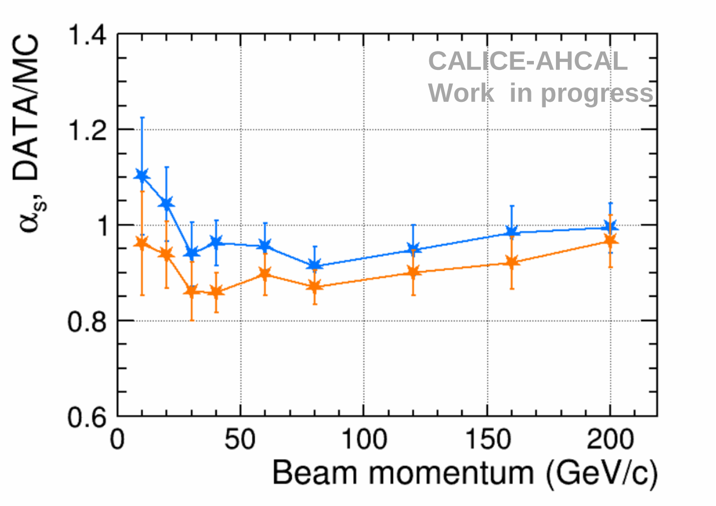
- Obtain the true electromagnetic fraction in hadron shower (MC particle study)
- Next steps will be in the direction of **3D shower modelling**

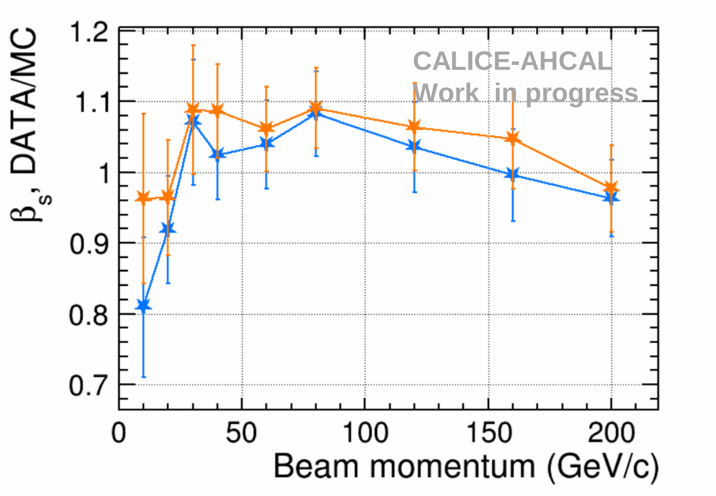
SPARES

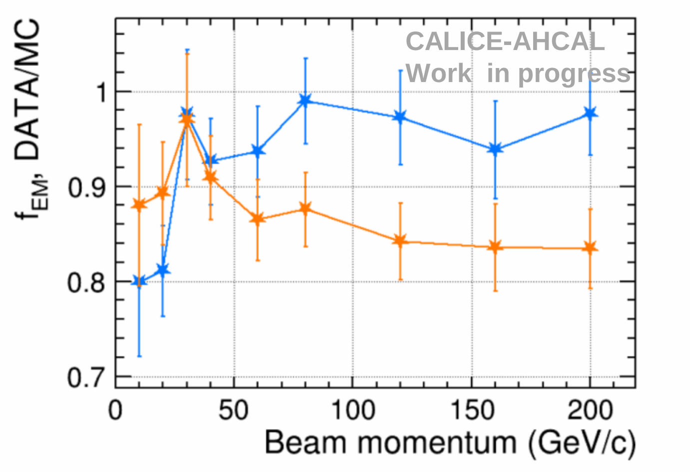
Ratio of longitudinal parameters

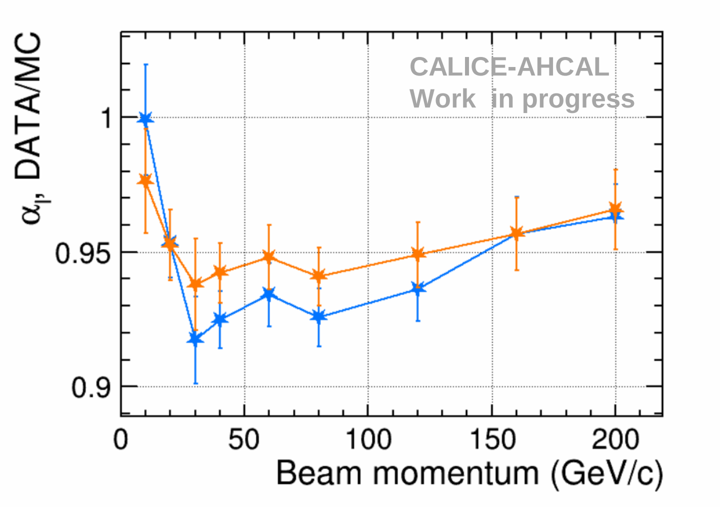
Data/MC

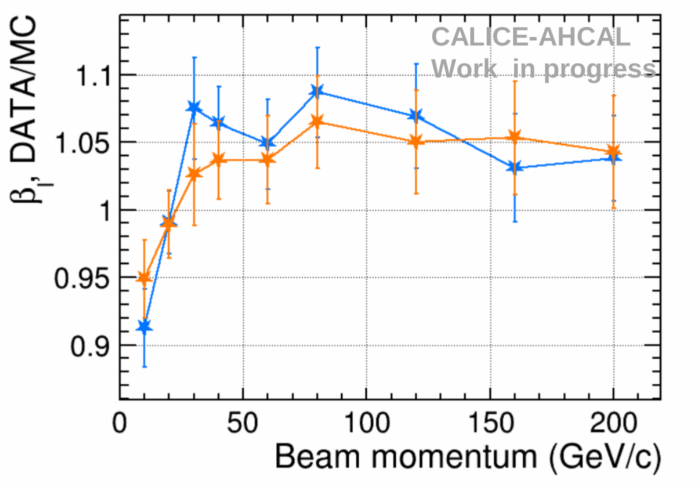
QGSP_BERT_HP
FTFP_BERT_HP

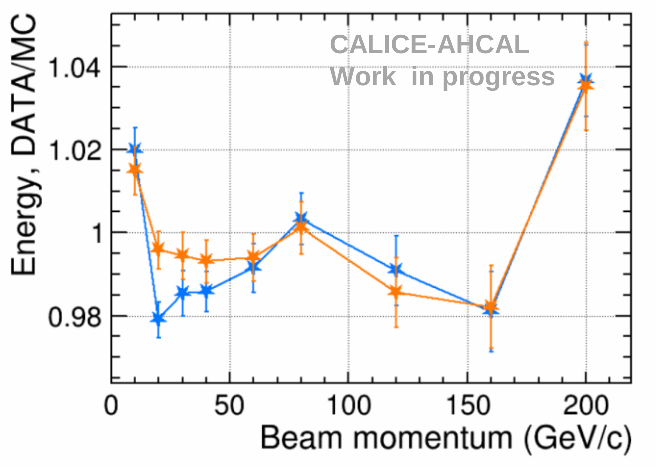








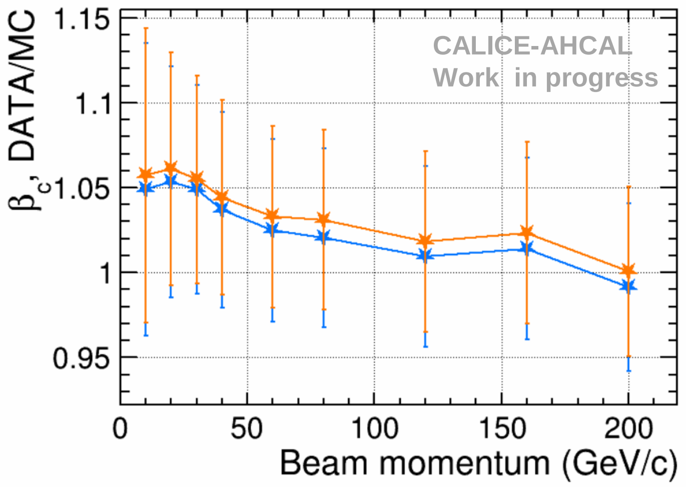


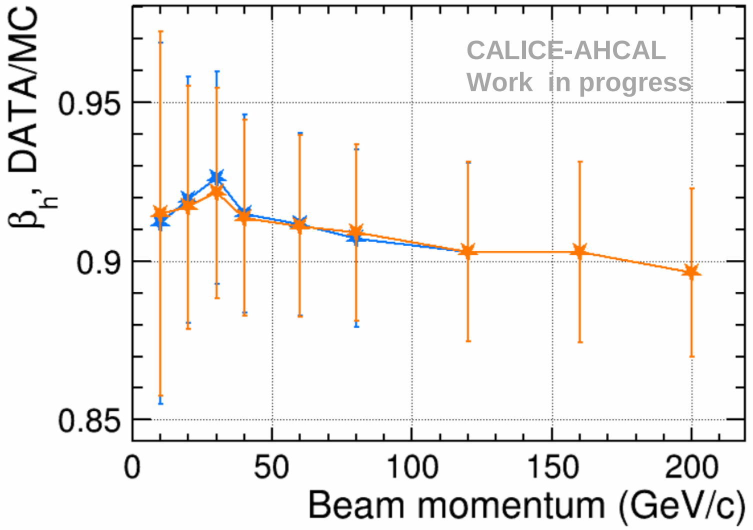


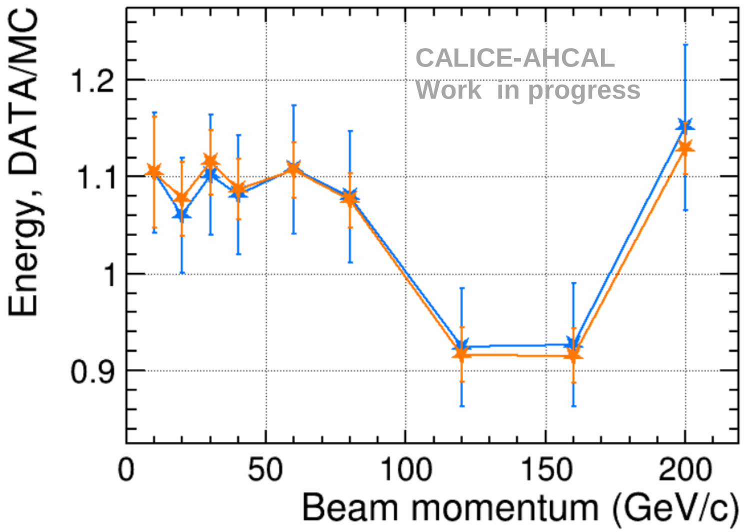
Ratio of radial parameters

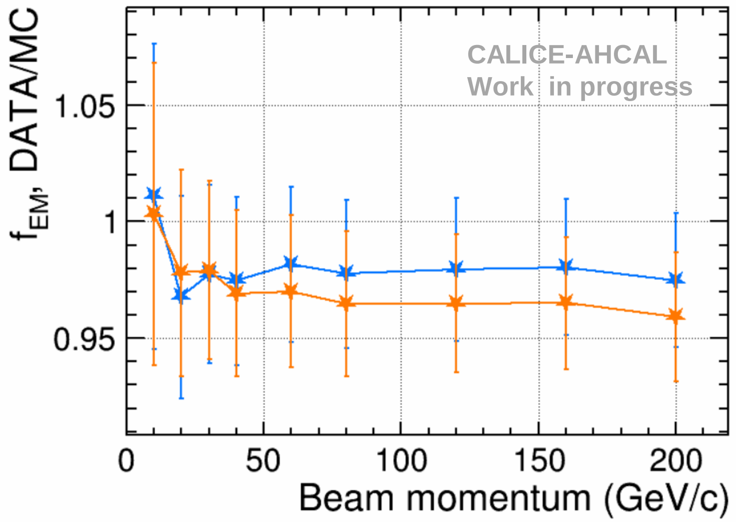
Data/MC

QGSP_BERT_HP
FTFP_BERT_HP

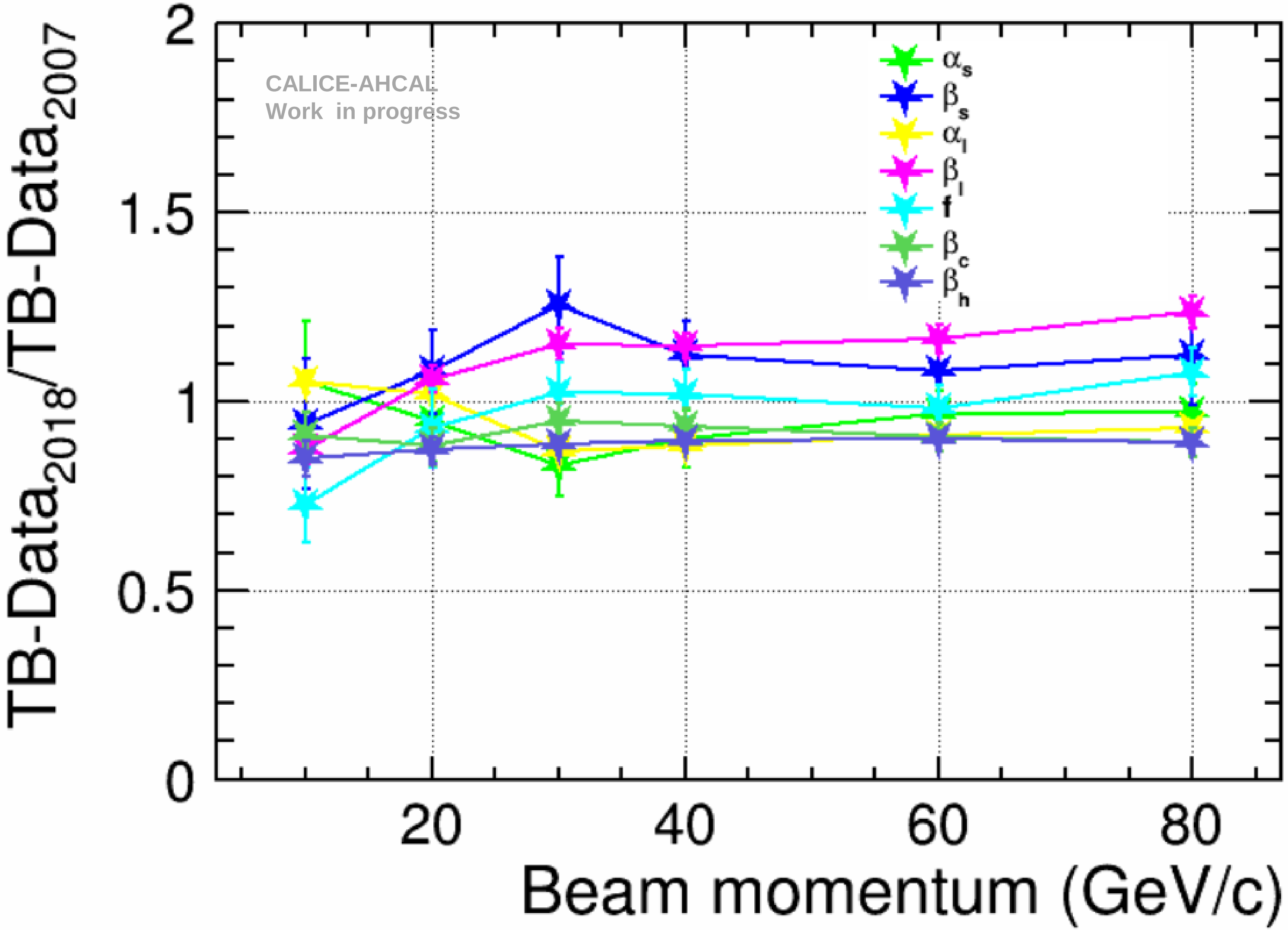








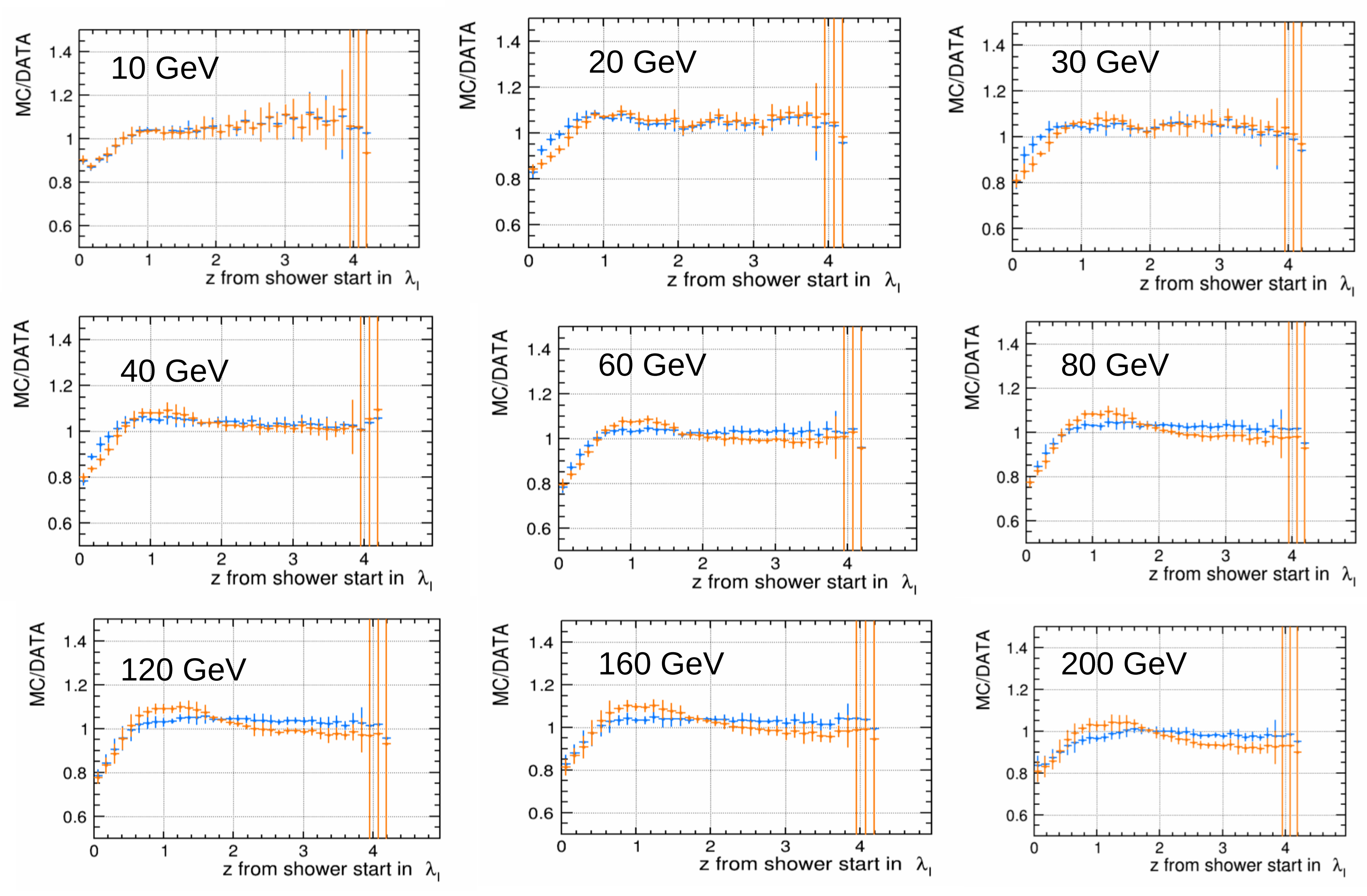
Reproducibility



Comparison between Data & MC

Longitudinal profiles

QGSP_BERT_HP
FTFP_BERT_HP



- The energy deposition predicted by simulation around the shower maximum is lower compared to data

- The tail of the shower is well reproduced by simulation at all energies

- In general, FTFP_BERT_HP show more variations within energies

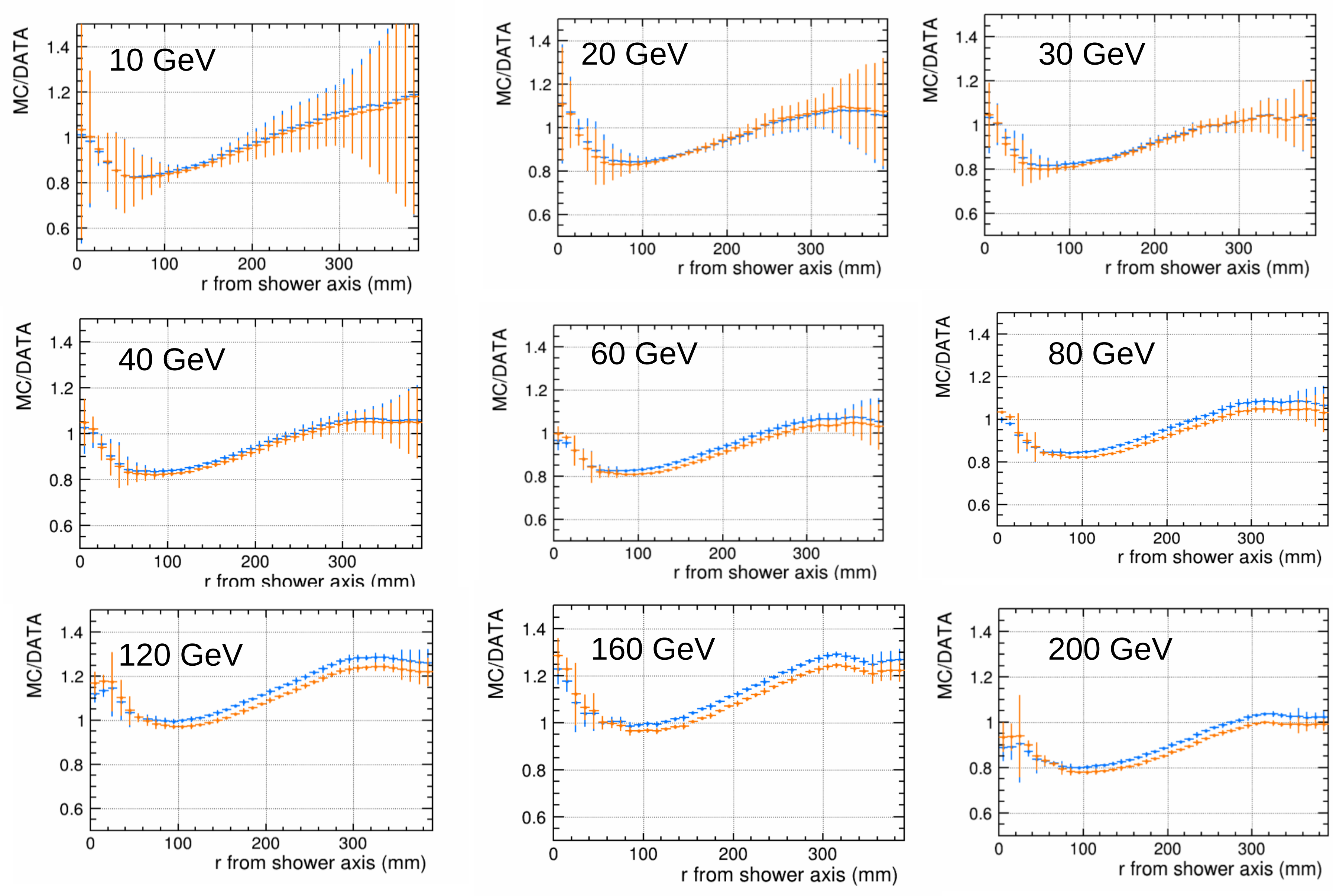
Comparison between Data & MC

Radial profiles

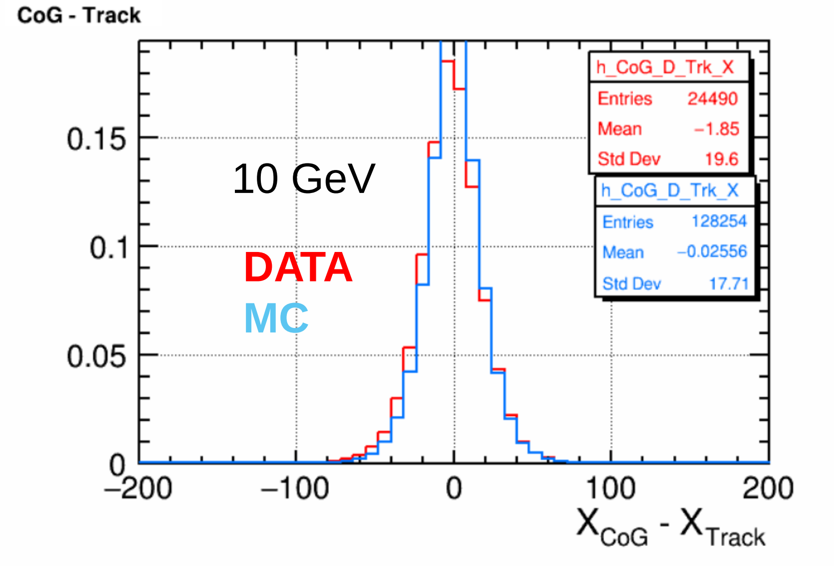
QGSP_BERT_HP
FTFP_BERT_HP

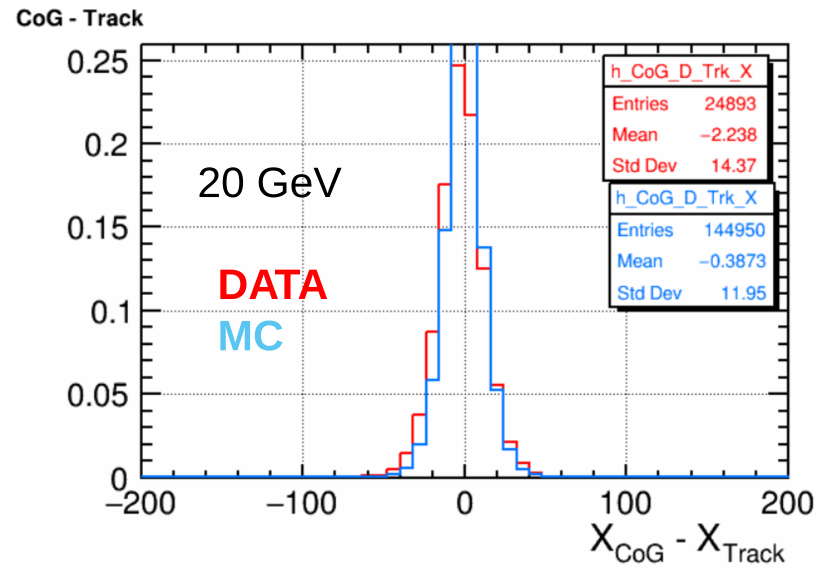
- The agreement of energy deposition between data and MC near the shower core is within 20%, with larger difference at lower energies and better at higher energies

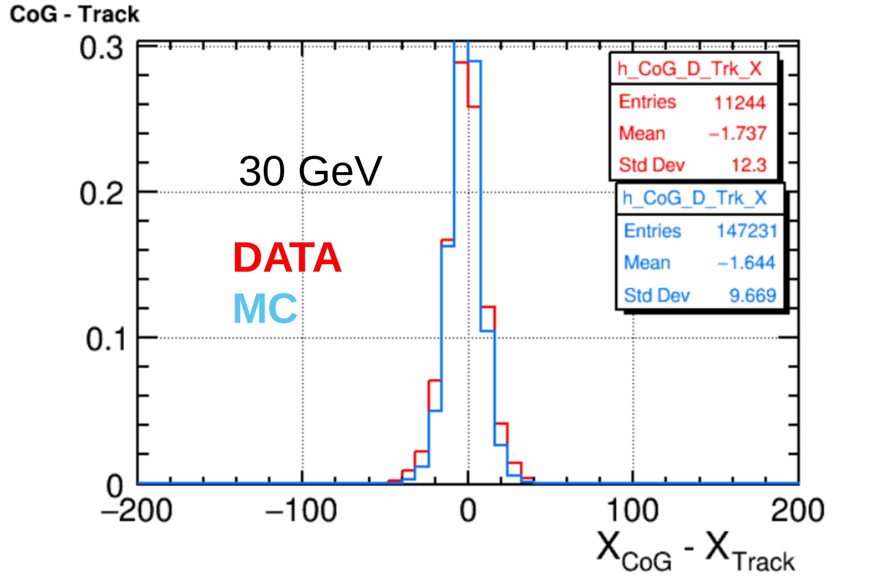
- For deposition far from shower axis the simulation is over-estimated at all energies with larger discrepancy of MC to data and the QGSP_BERT_HP in general obtains higher values

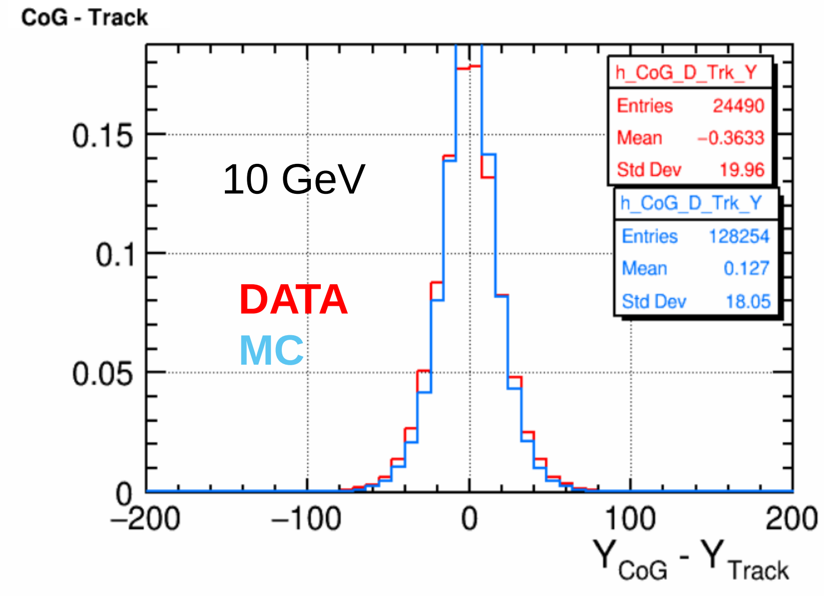


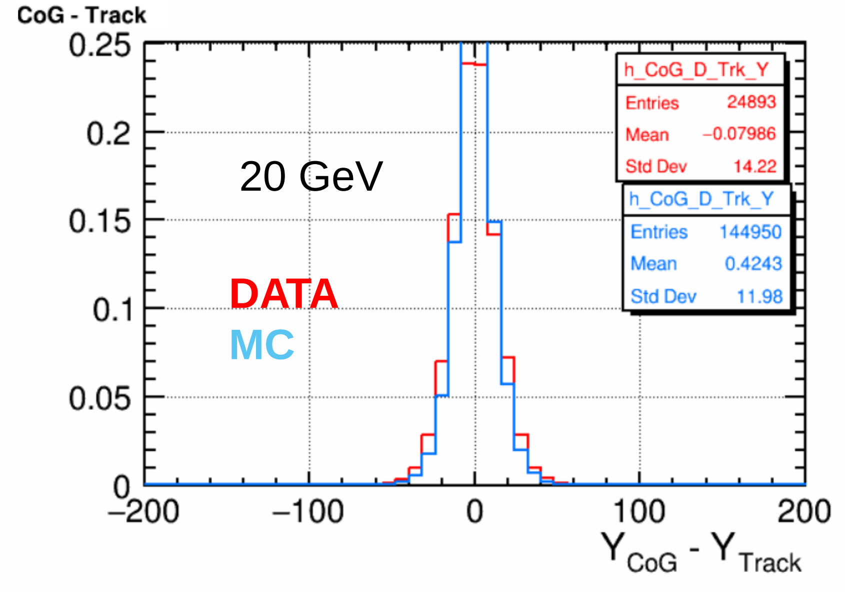
Track to event Centre of gravity comparison

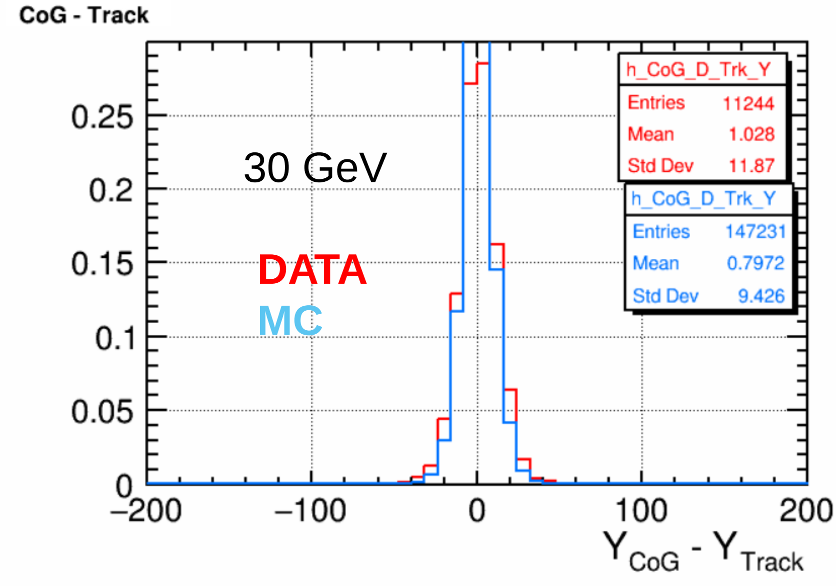




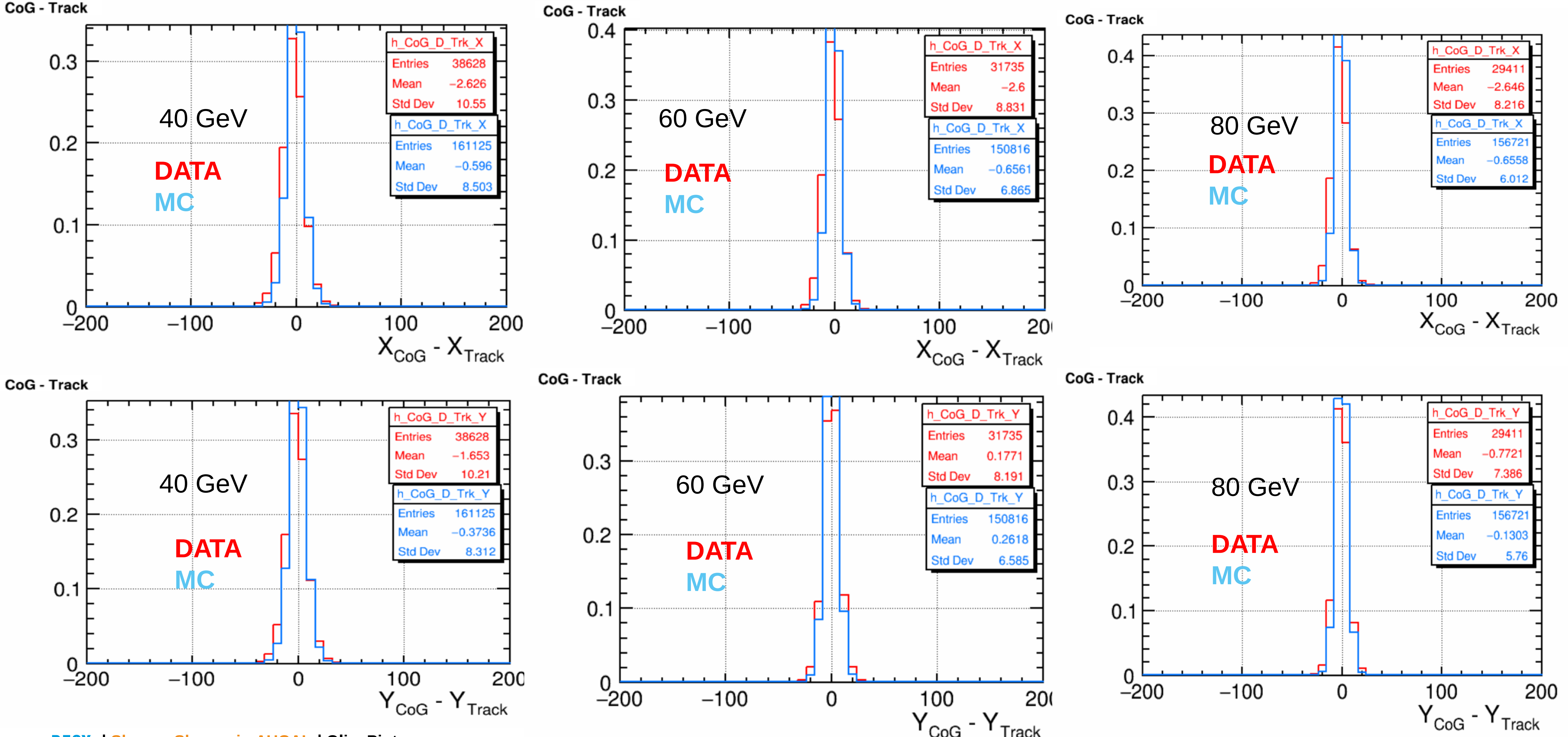




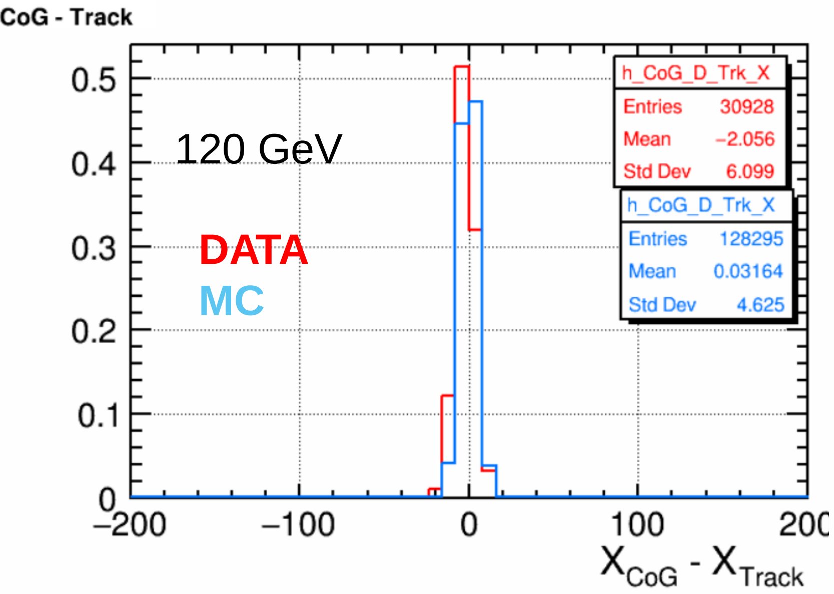


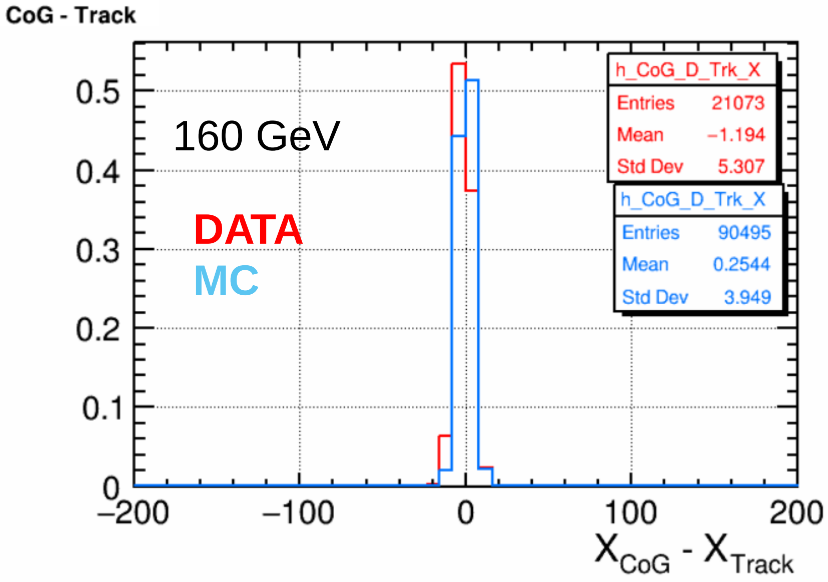


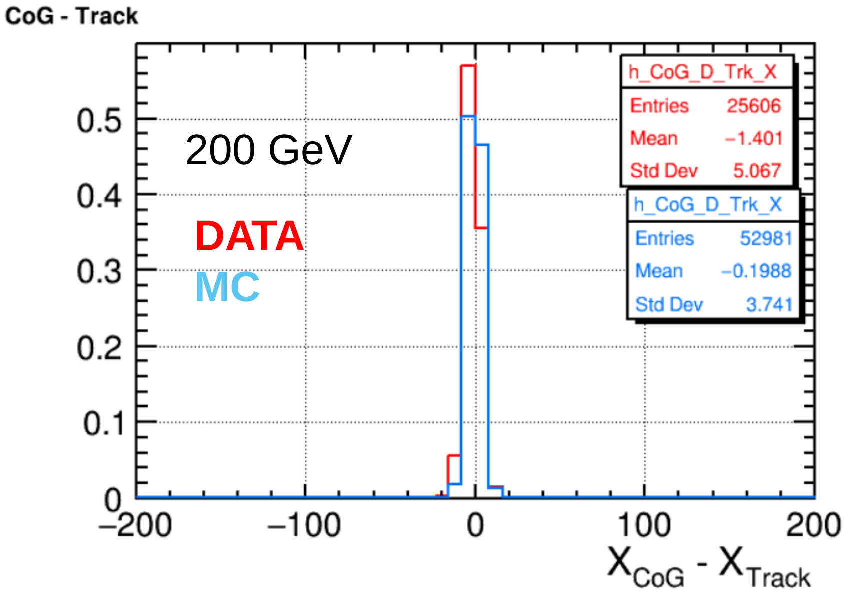
Track to event Centre of gravity comparison

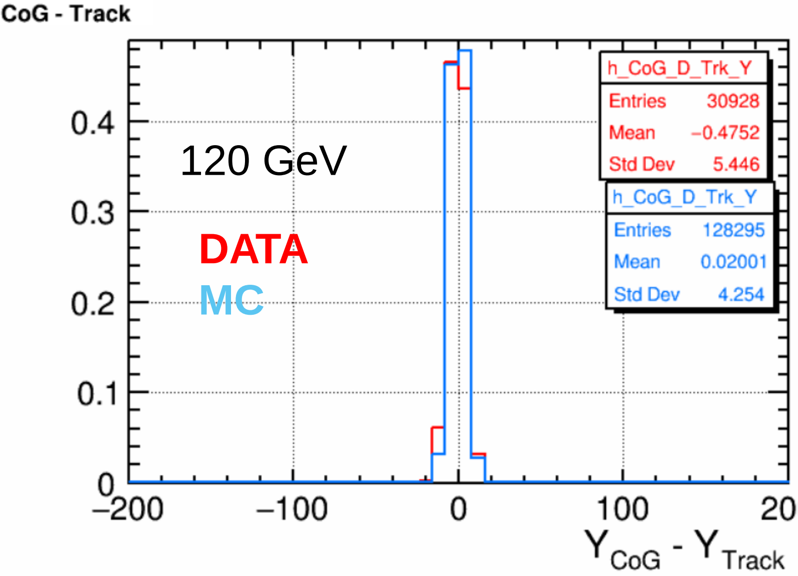


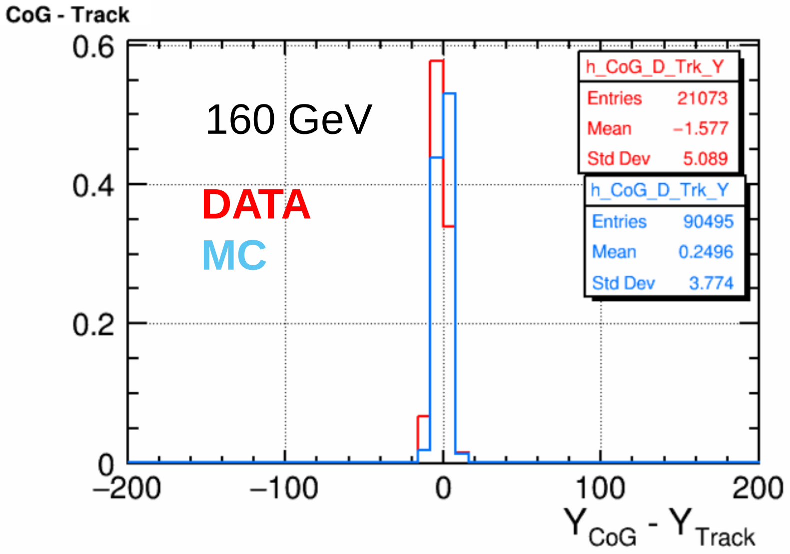
Track to event Centre of gravity comparison

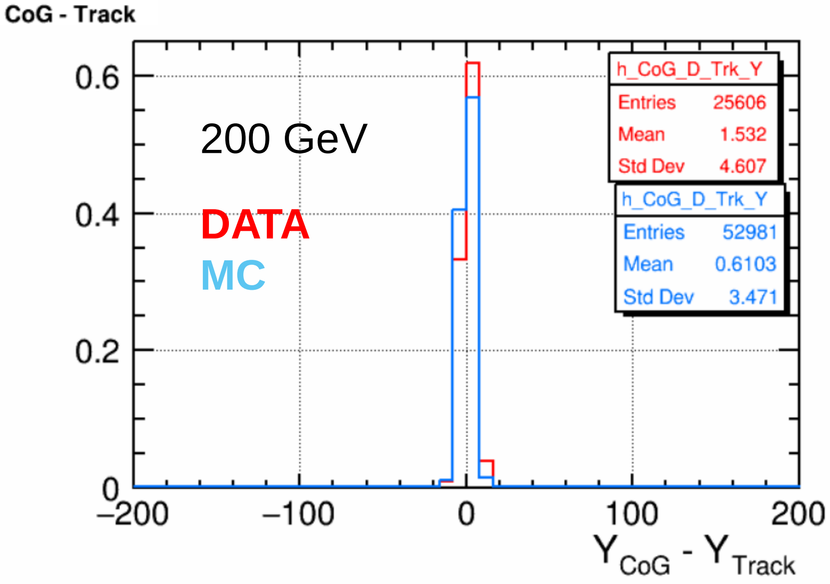












h/e signal ratio

h/e in first approx. is to be flat, **physics view point**

- The secondary **particle spectrum and inelastic cross section** in the cascade are relatively independent of the energy

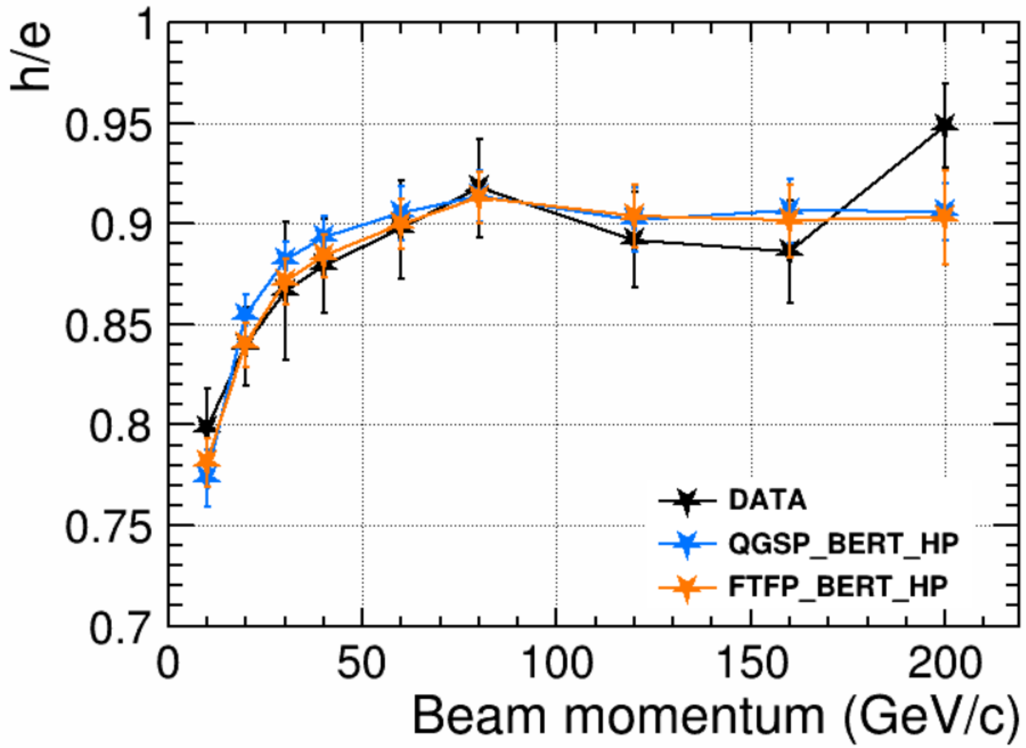
Possible interpretation of the shape at low energies

- With the little memory of the incident hadron, the **fraction of invisible energy** that is detected in calo. is more less the same for all energies
  - A possible interpretation is that the invisible energy is higher at low beam energy

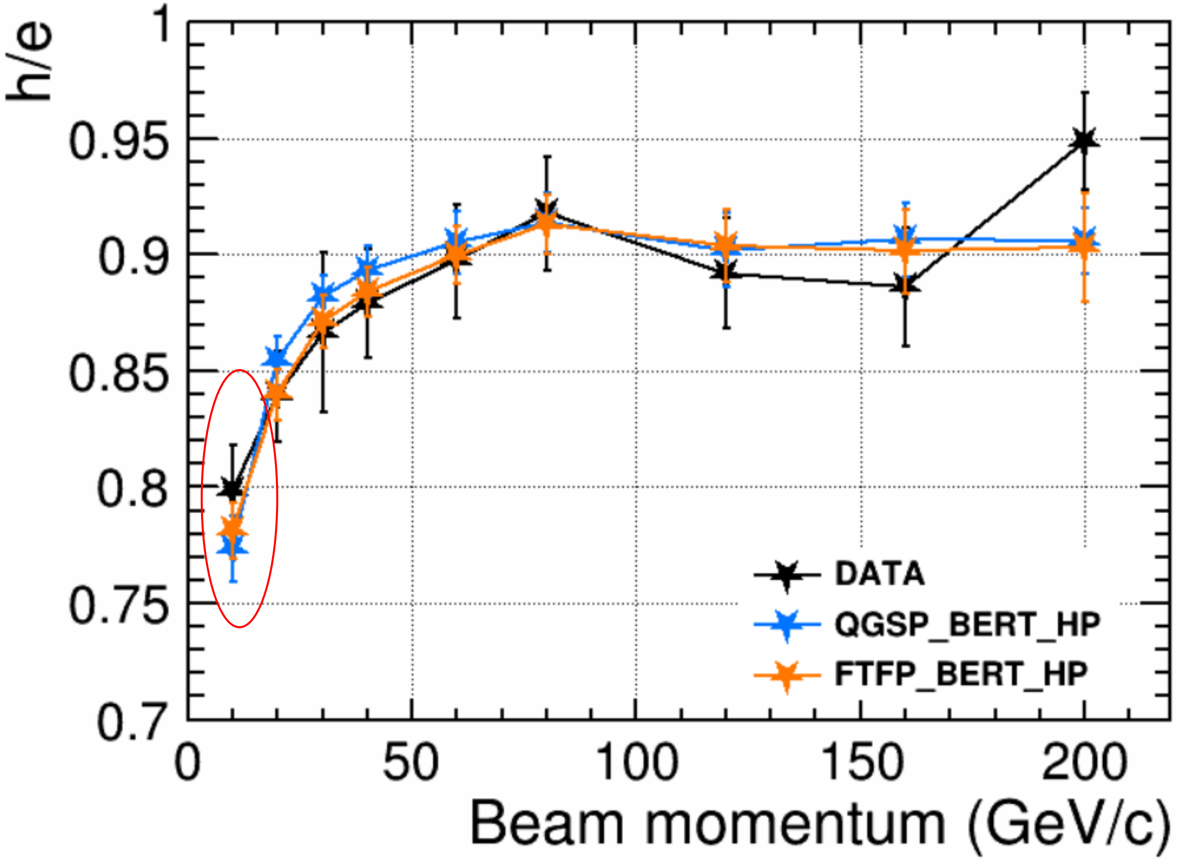
Possibly my fits are not described well below 50 GeV!

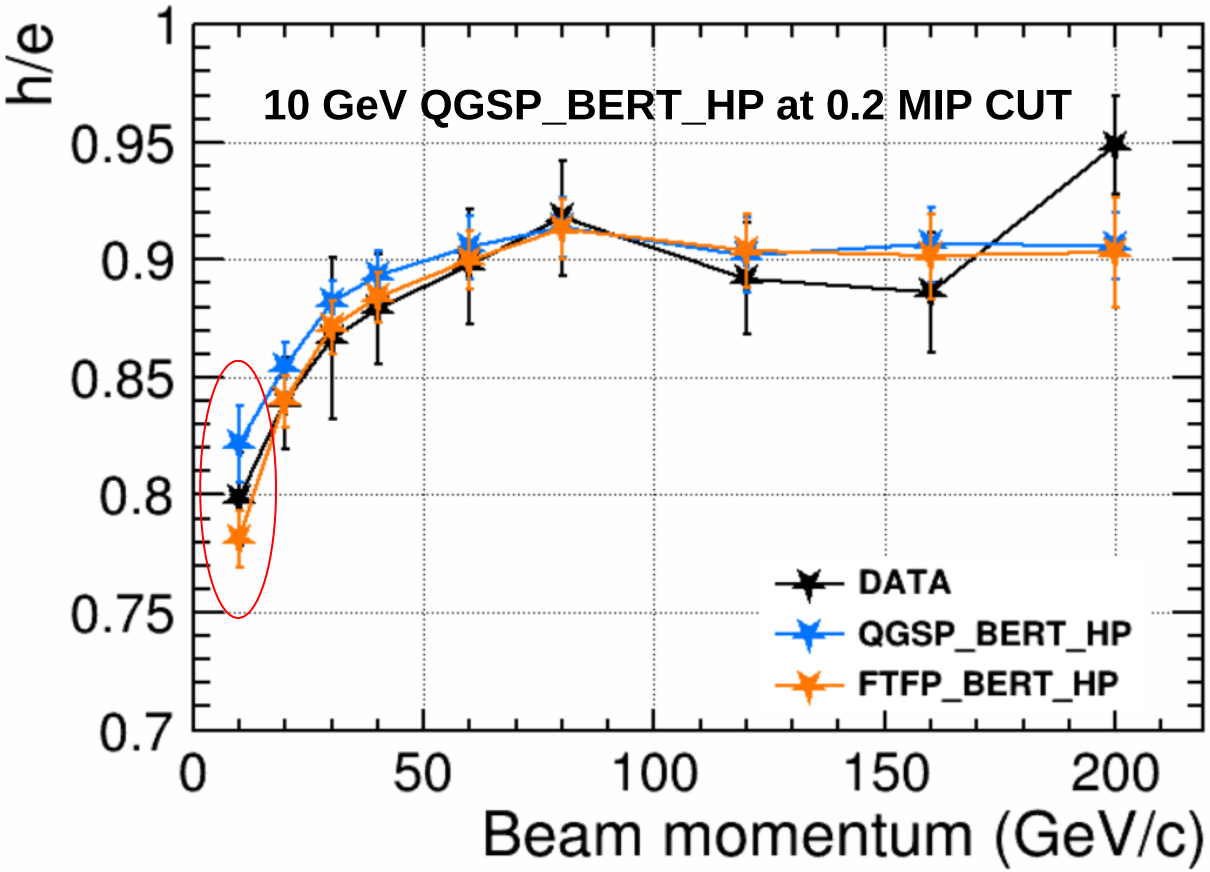
Detector effects:

- With a cut at 0.5 MIP, might be that the fraction of hits that is below half a MIP is bigger at low beam energies
  - With 0.5 MIP at 1 x 1 cm^2 we could lose significant fraction of hits



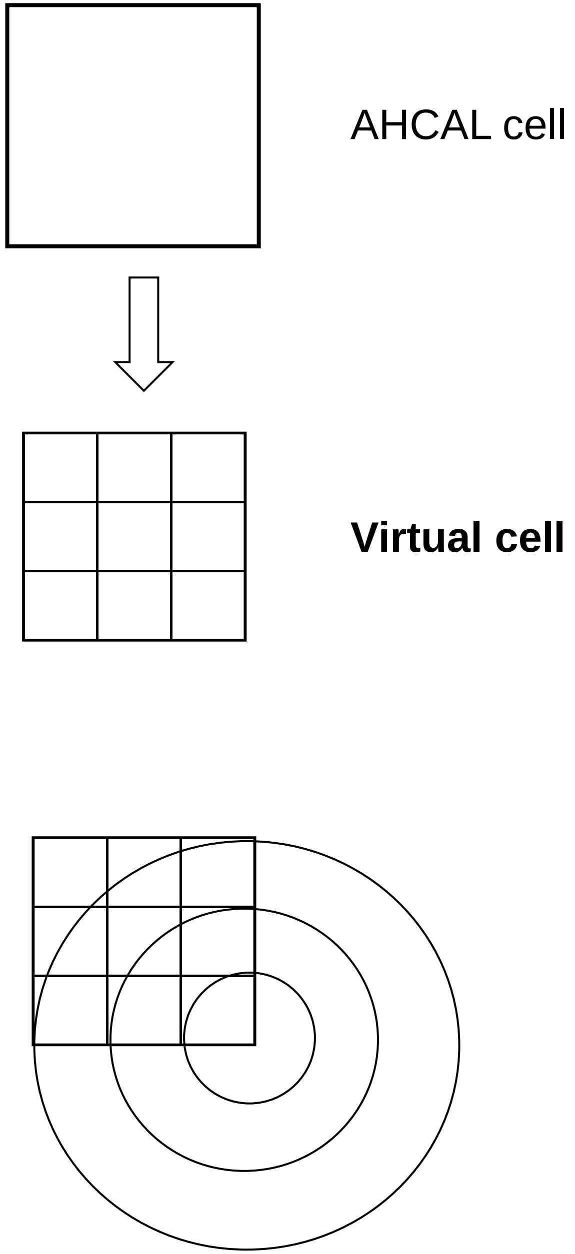
Is there is an affect for 10GeV MC (QGSP_BERT_HP) with a cut at 0.2 MIP?





Virtual Cells

- To analyse the radial shower profile, finer width is chosen
- All physical AHCAL cells (30×30 mm^2) are subdivided into virtual cells of 10×10 mm^2
- In this method, the energy deposited in the physical cells is equally distributed over the virtual cells covering its area

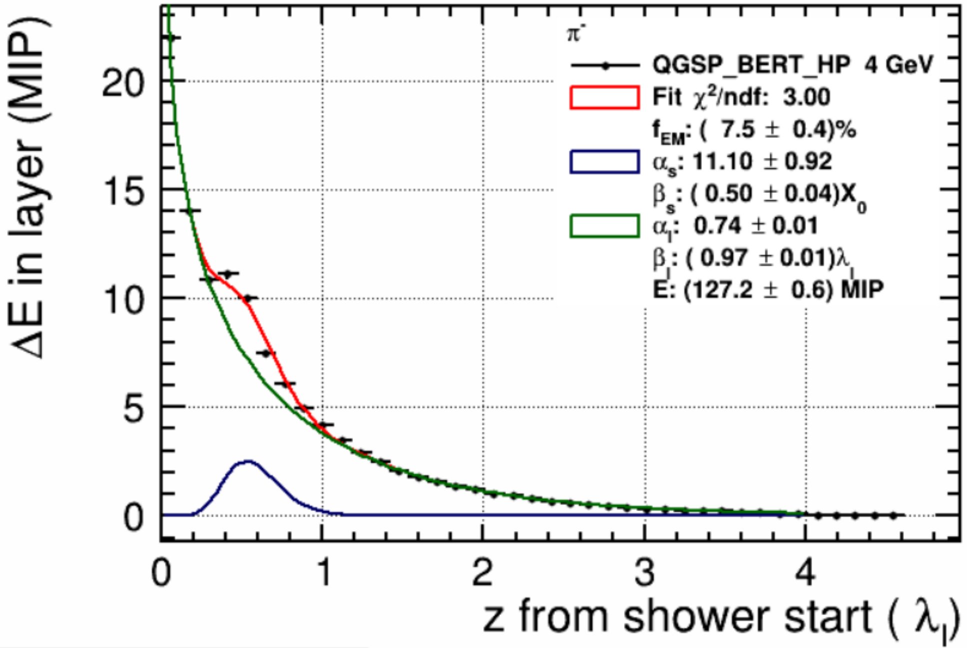


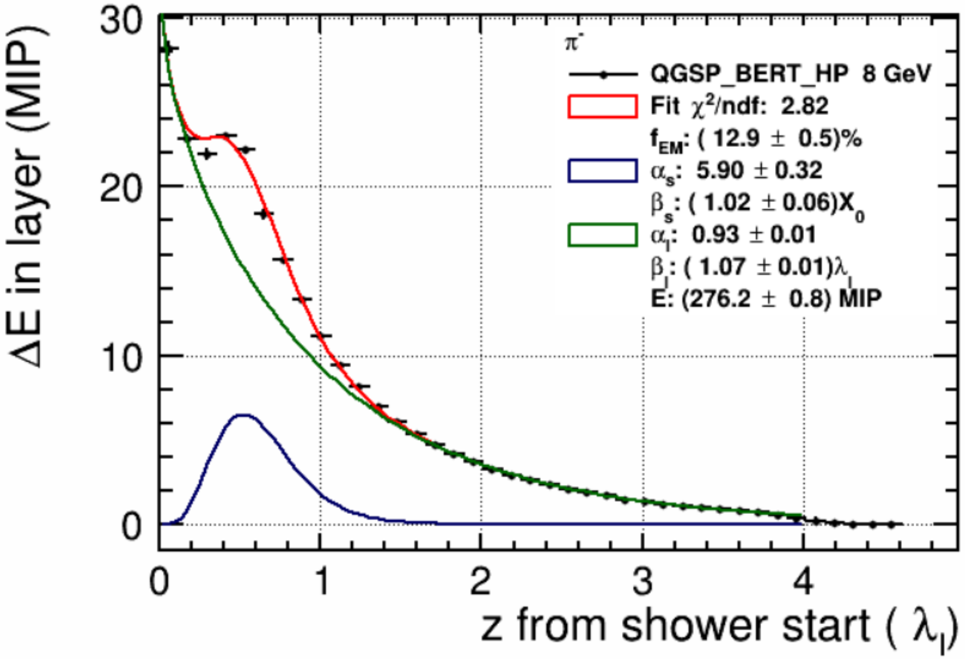
Low Energy Pions

Limitations

The longitudinal parameterization actually requires two separate sets of parameters based on the incident particle energy:

- low-energy particles, 2 GeV< E < 10 GeV
- high-energy particles, 10 GeV< E < 200 GeV





More shower shapes …