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

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CALICE Analysis Meeting

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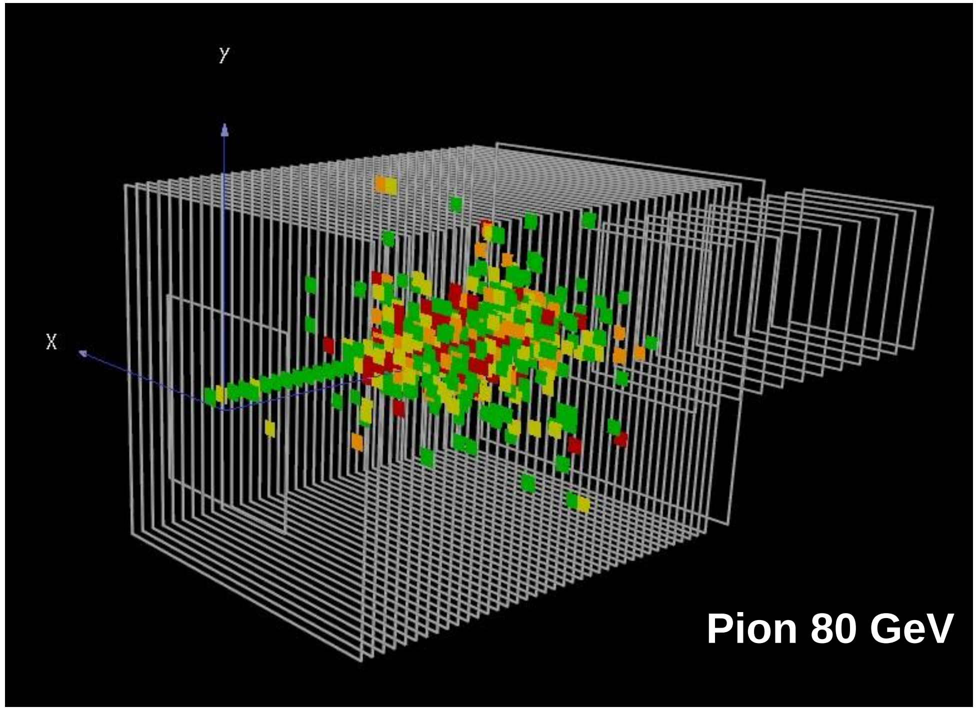


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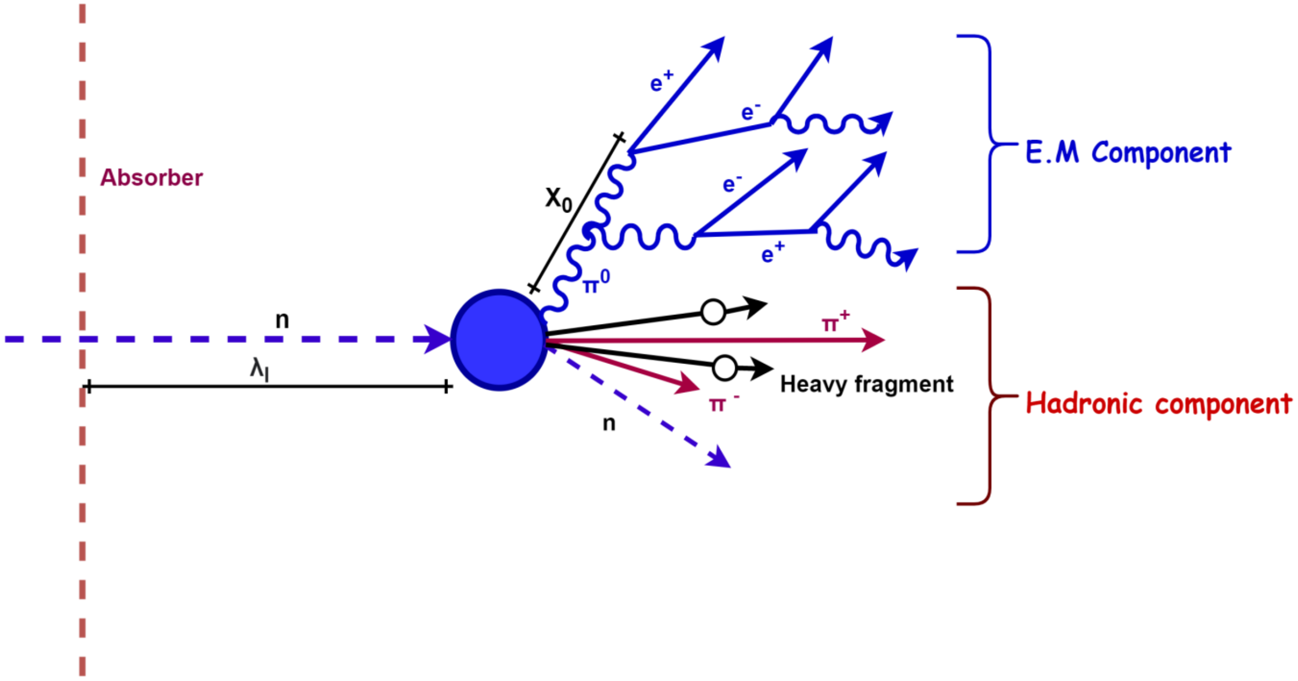
# How does a hadronic shower look like?

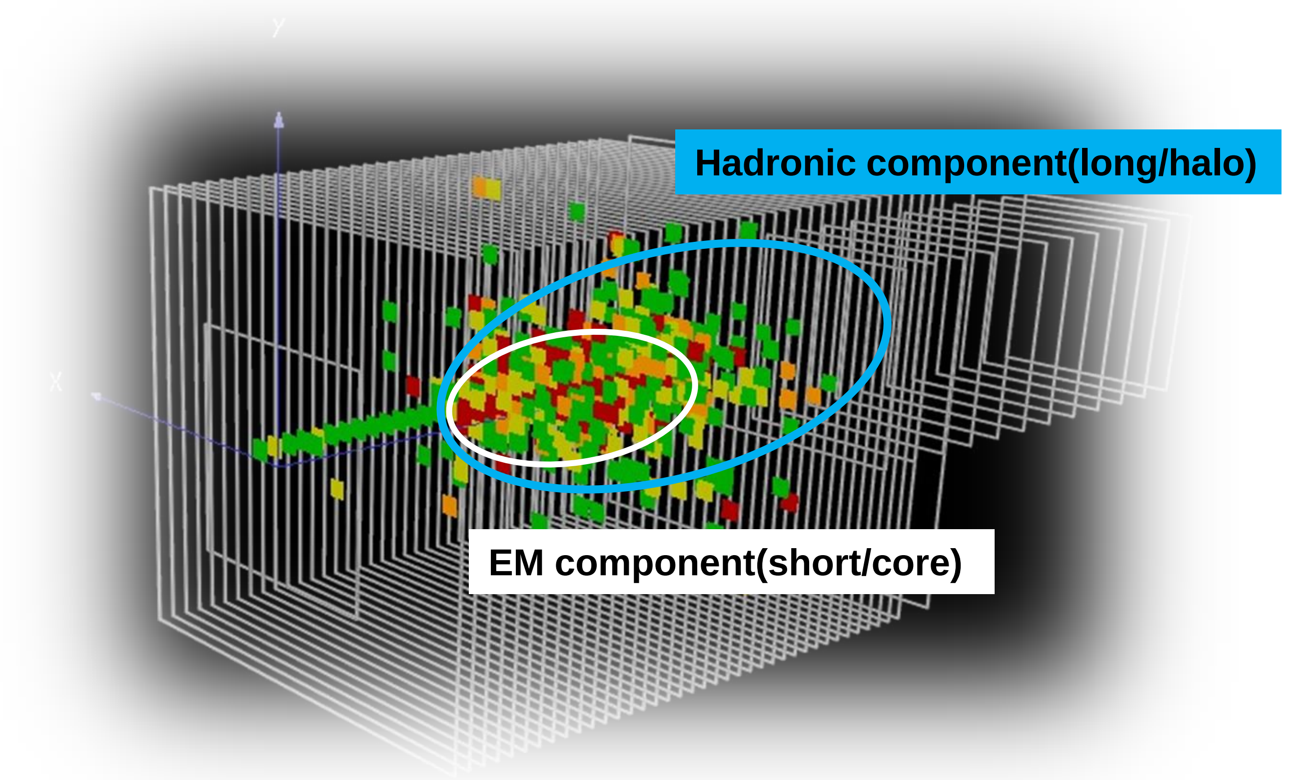
**Sketch of hadronic shower**




- Mainly charged and neutral pions
- Large component of secondary particles in hadron cascades are $\pi^0$
  - Initiating electromagnetic sub-cascades in a hadron shower
  - which represent ~ 1/3 of total energy produced in each inelastic collision
- 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** and to get an estimate of **"average electromagnetic fraction"**



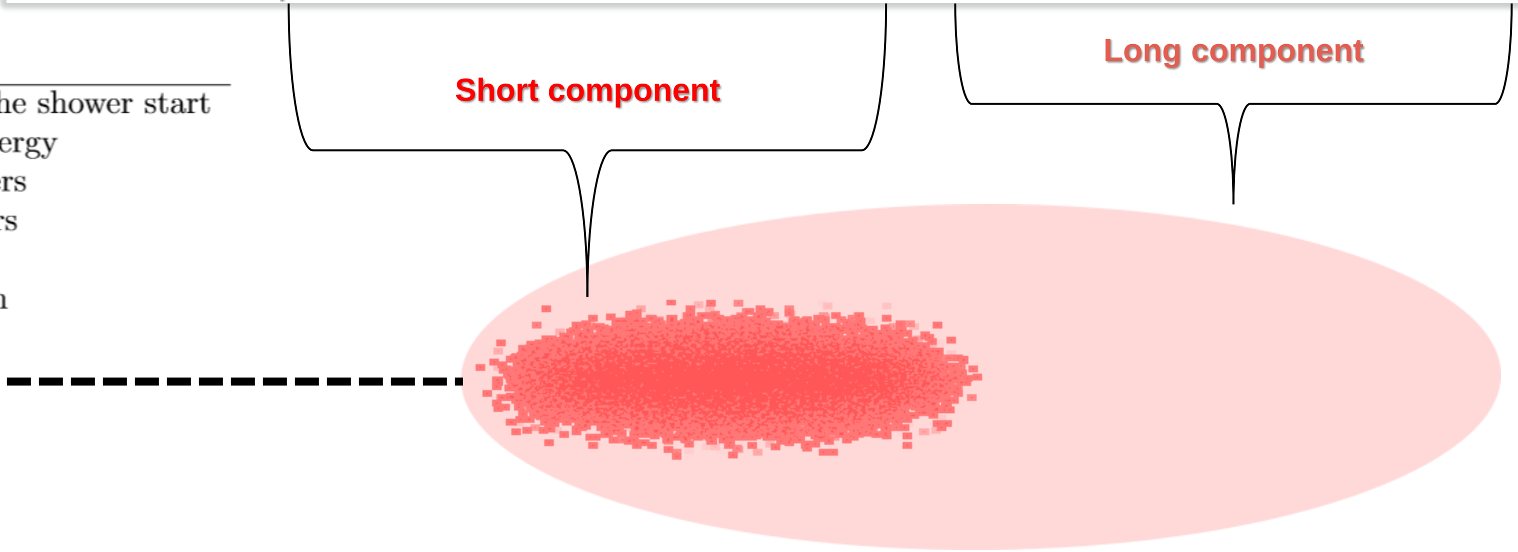
# Parametrization

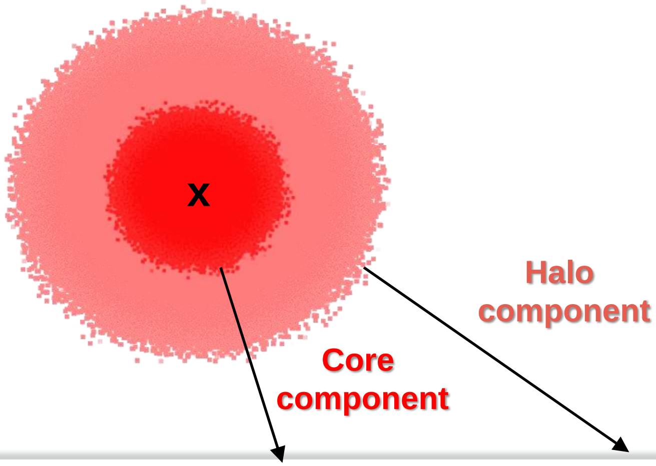
https://arxiv.org/pdf/1602.08578.pdf

**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 |
| $\alpha_s, \beta_s$ | shape parameters |
| $\alpha_l, \beta_l$ | slope parameters |
| f | short fraction |
| $\Gamma$ | 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 |
| $\beta_c, \beta_h$ | slope parameters |
| f | core fraction |

# Samples and Selection

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

**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

**Selection**

- Applied PID using BDT for hadrons to remove beam contamination
- First physical AHCAL layer is excluded due to uncertainties in shower start identification

**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 of  2.0 mm to require the impact point to not be in between the two slabs
- Selected events in MC are within the statistics available in data, due to the acceptance area of trigger scintillator and wire chamber (~10 x 10 $cm^2$)

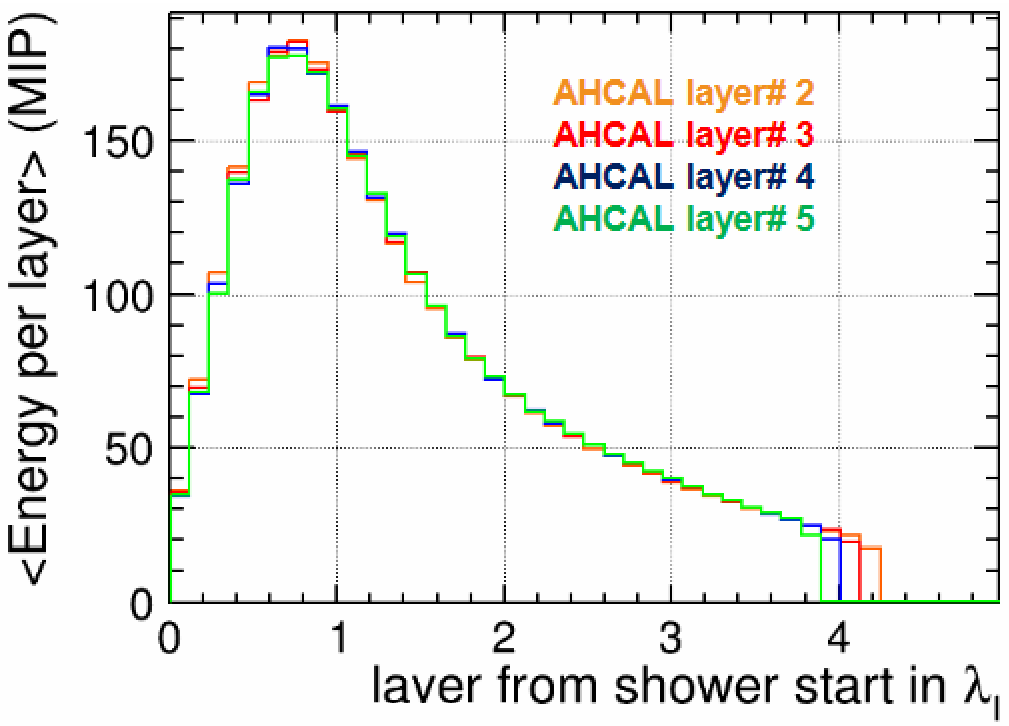
# Systematic Uncertainties

**Longitudinal: layer-to-layer variations**

Significant contribution comes from layer-to-layer variations

- Uncertainties in SiPM response function

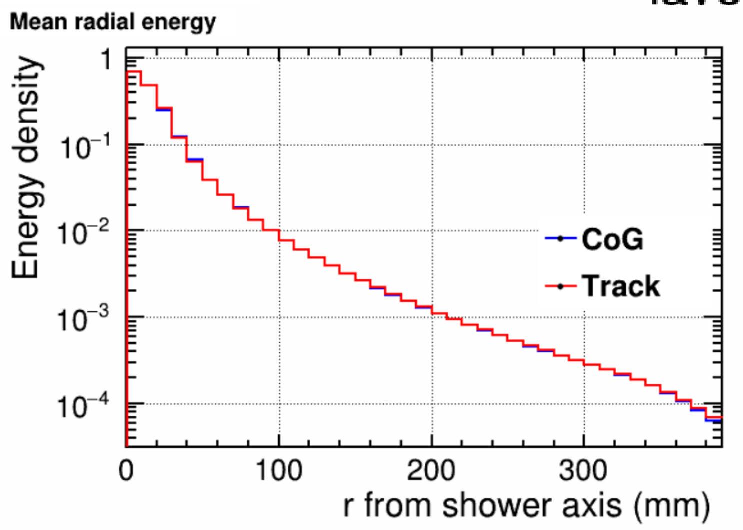
Averaging the contribution from different physical layers minimizes the layer-to-layer variation

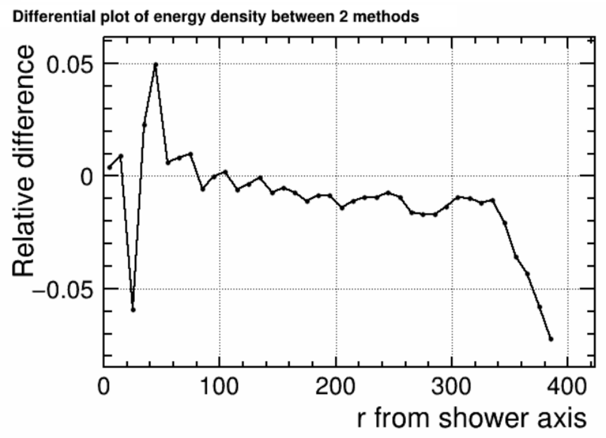



**Radial: Identification of shower axis**

The uncertainty is related to the difference between the two methods of shower-axis reconstruction

- Event centre of gravity
- Identification of incoming track

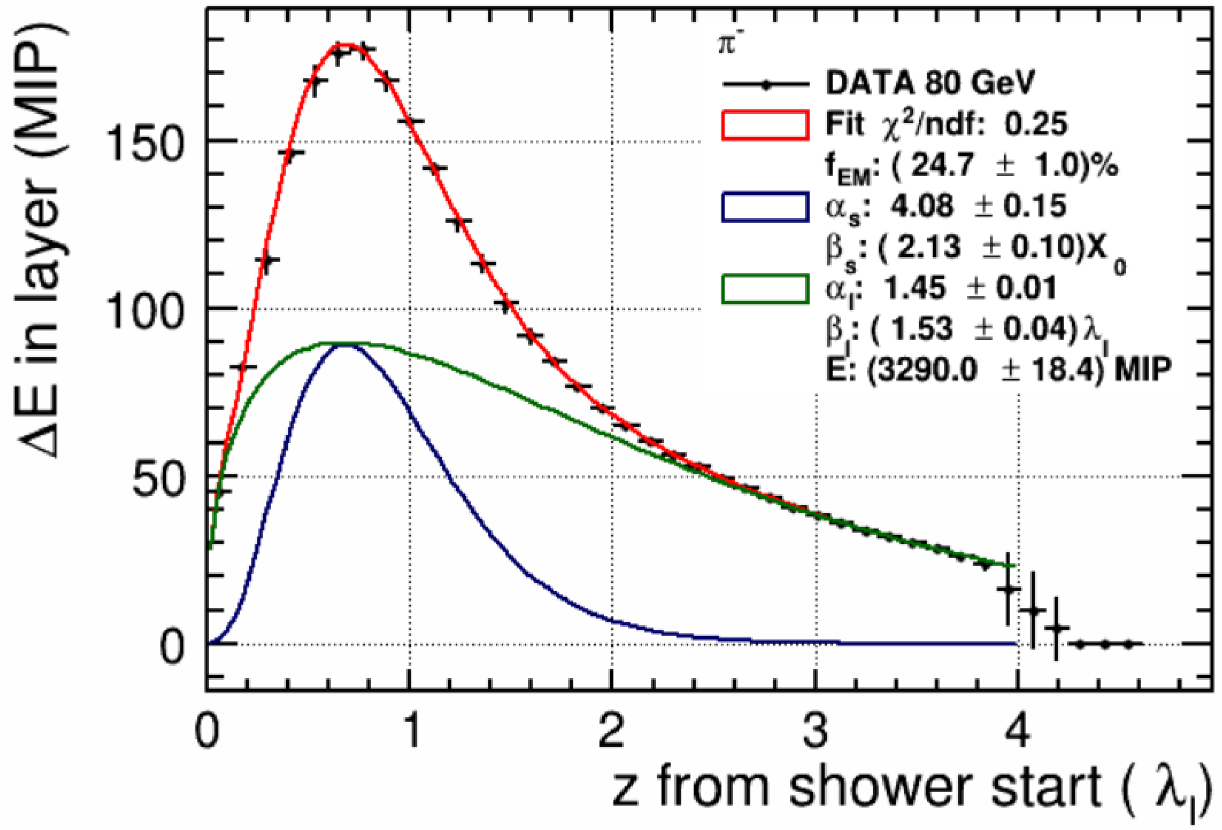


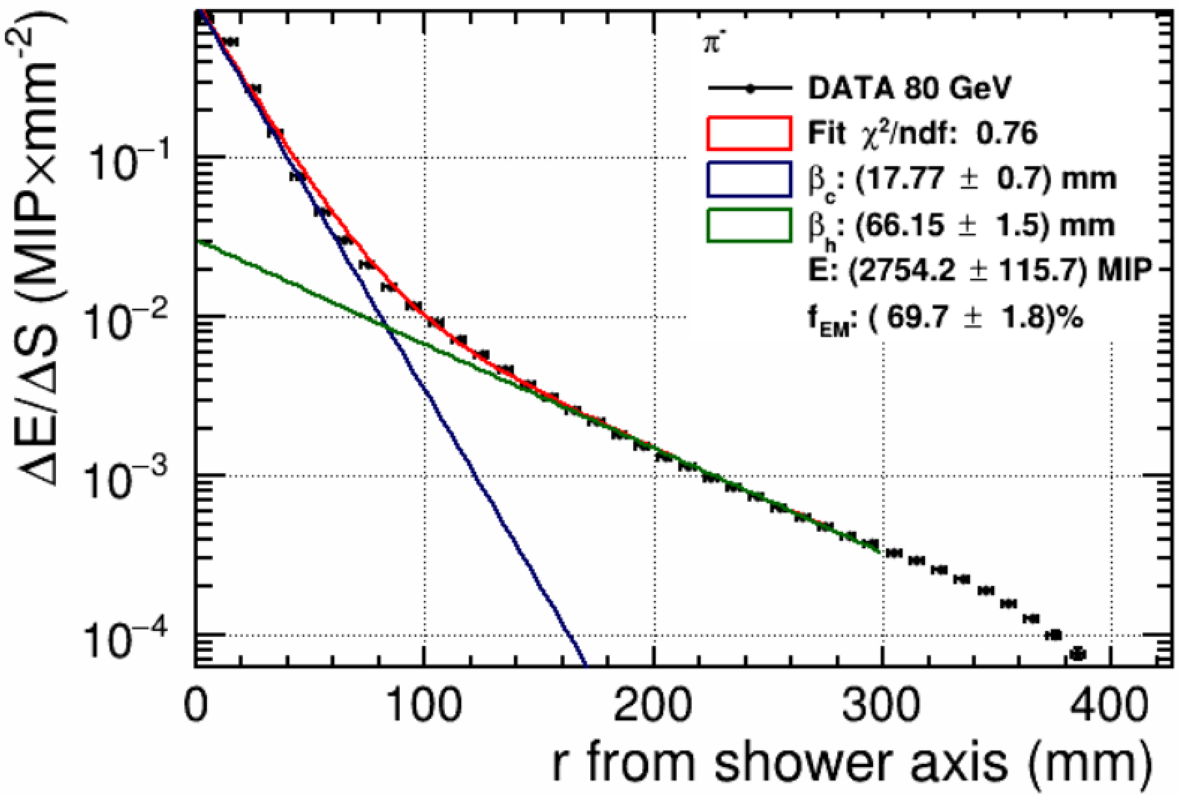



# Shower Shapes

## Using original parametrization

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



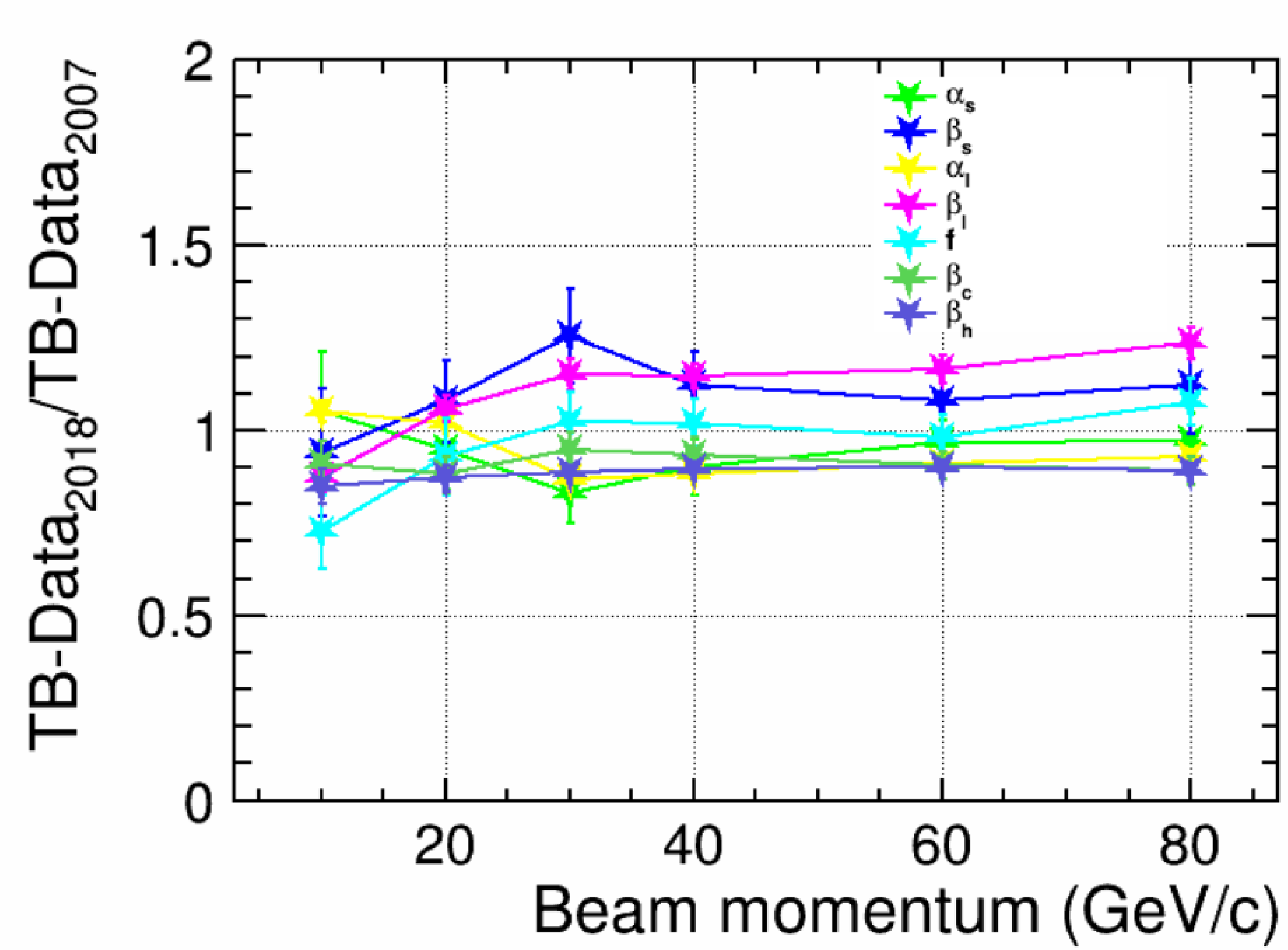



# Reproducibility

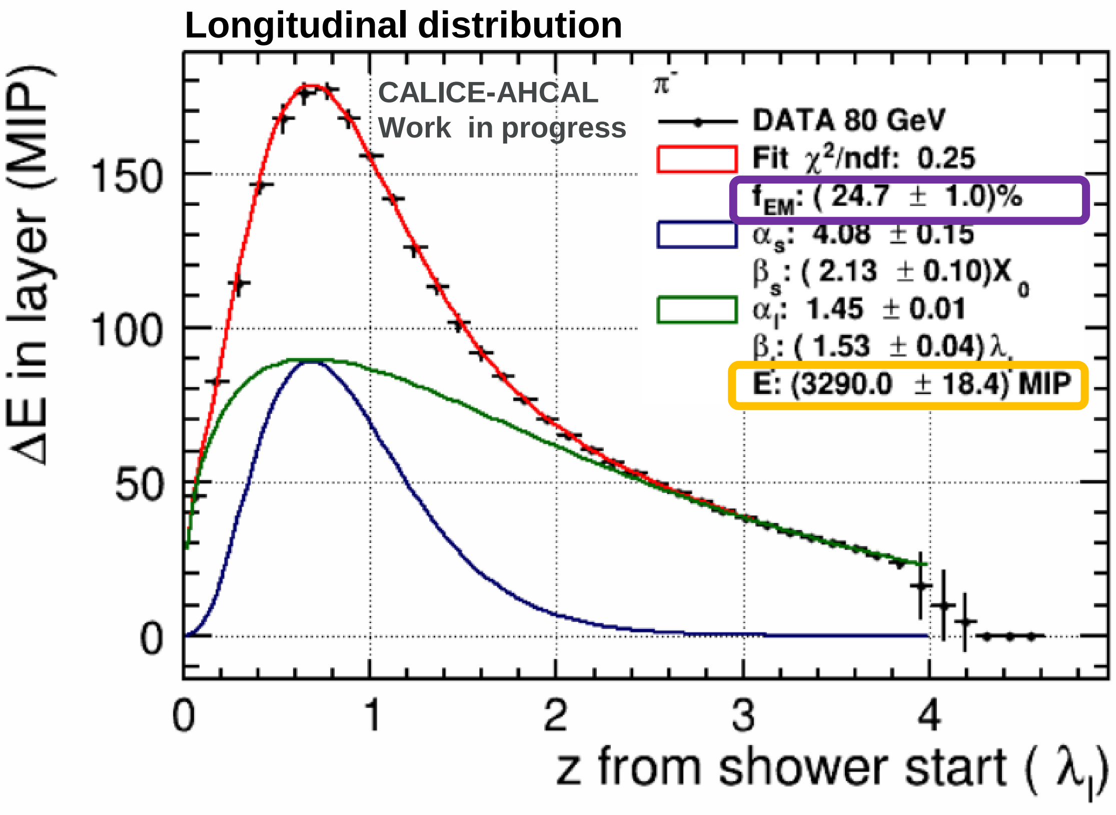
## Do we get the same parameters?

| | PP (2007) | EPT (2018) |
|---|---|---|
| Total active layers | 38 | 38 |
| Absorber thickness | 21.0 mm | 17.2 mm |
| Cell-size | varying | homogeneous ($3\times3cm^2$) |
| Total depth | $\sim 5.3\lambda_I$ ($\sim 0.14\ \lambda_I$/layer) | $\sim 4.2\ \lambda_I$ ($\sim 0.11\ \lambda_I$/layer) |

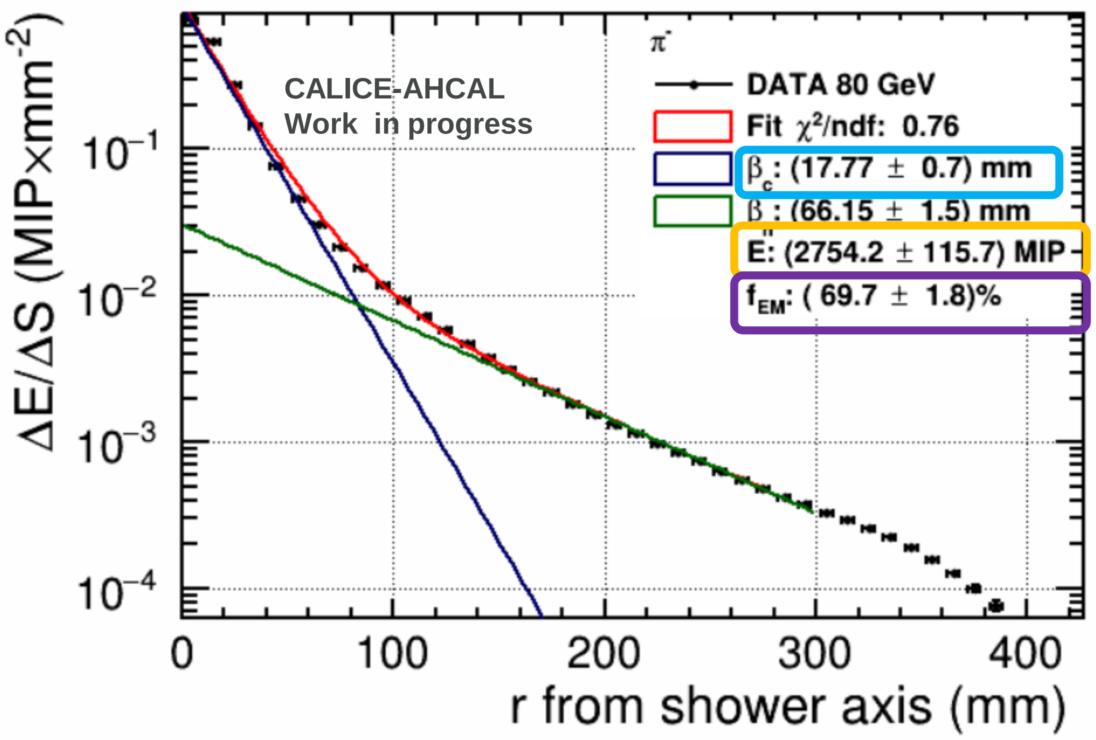
Comparison of fit parameters extracted, shows a good agreement of Data between TB-2018 and TB-2007 within ~20%



# What were the problems?

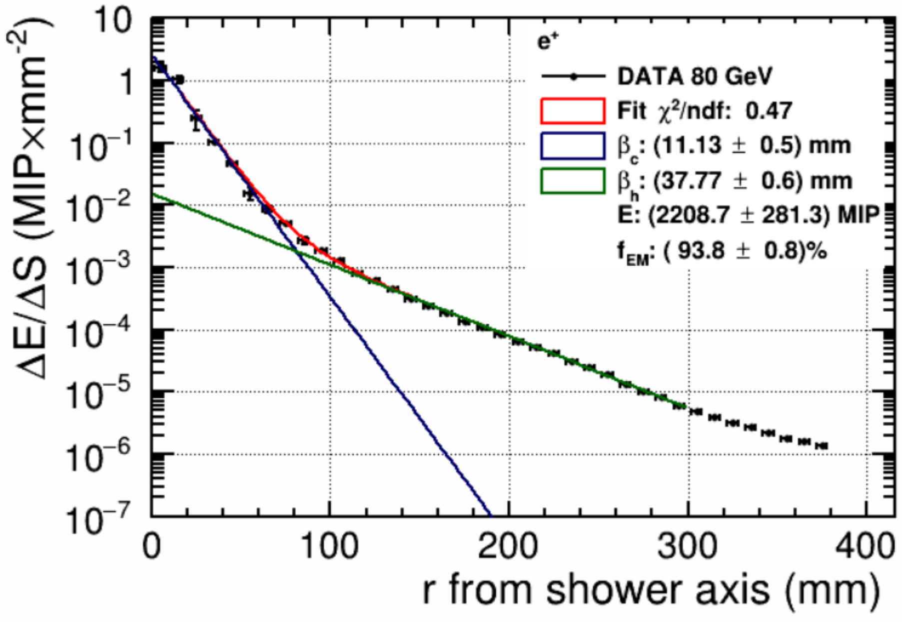


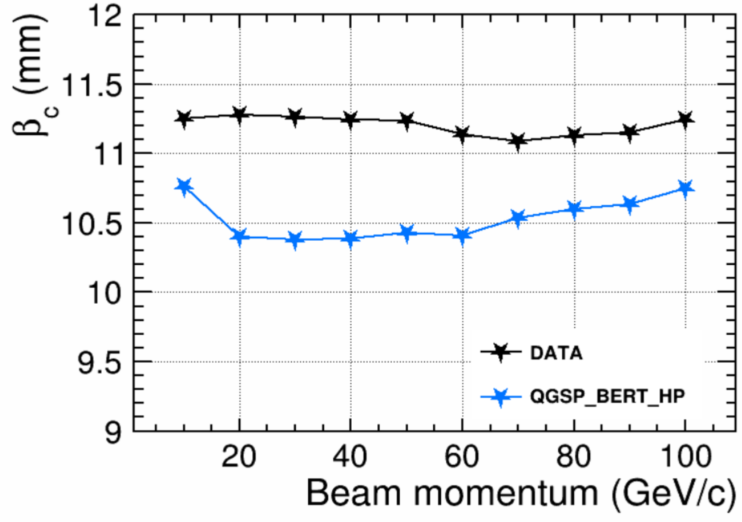

- The **energies** do not agree with each other
- With the understanding that the core is related to EM-shower
  - The **fraction's** do not agree
  - For **beta core** the value that it fits does not agree with EM shower

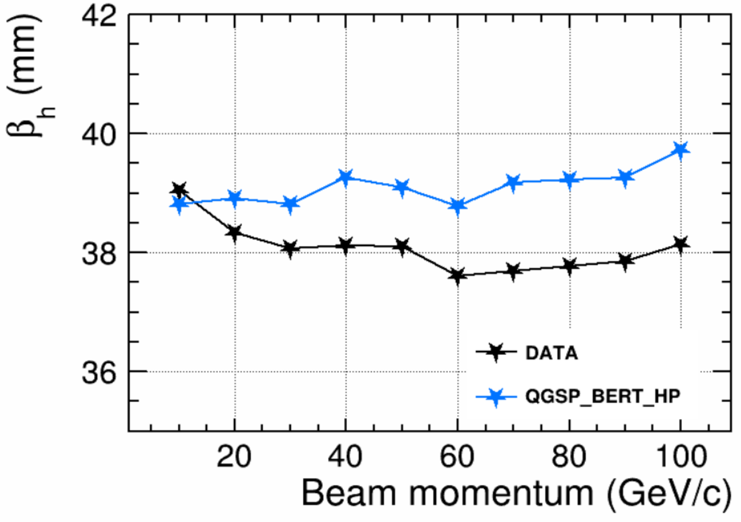


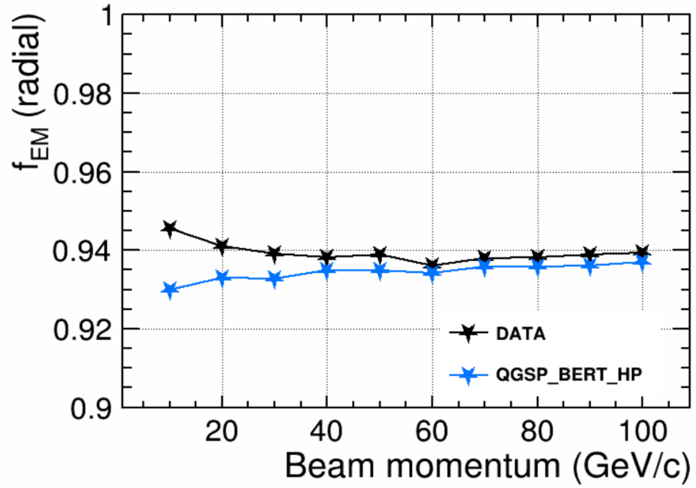
# Beta's from EM

- Two components needed to describe EM shower
- No large differences in beta's and core fraction are observed for all electron energies
- Beta core obtained from radial fits to EM-shower do not agree with beta core obtained from pion-showers
- Need three components for radial fits in pions and fixing the beta core from EM-showers to avoid too much degree of freedom to fit three components



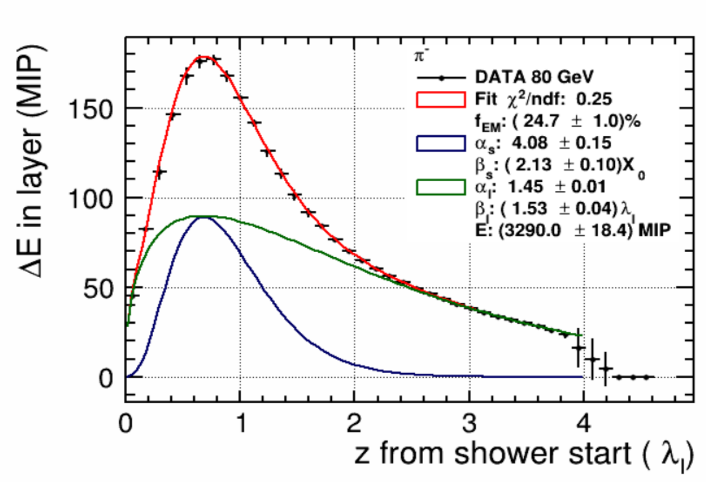



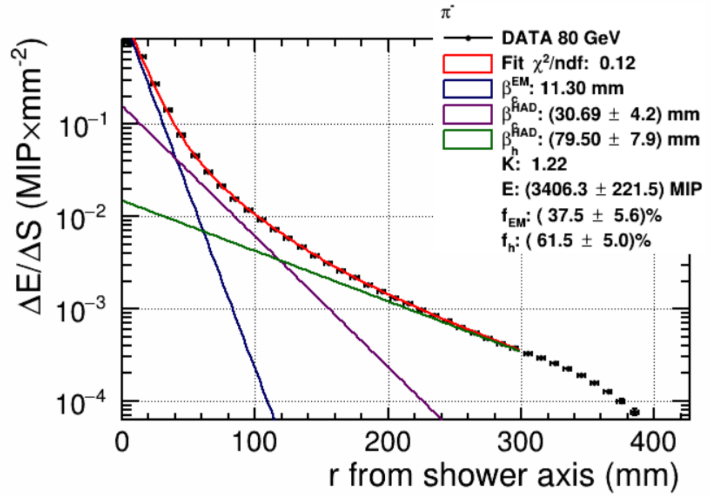
# Understanding the total energy

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

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

- The core/short 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



# Does it now look reasonable?

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

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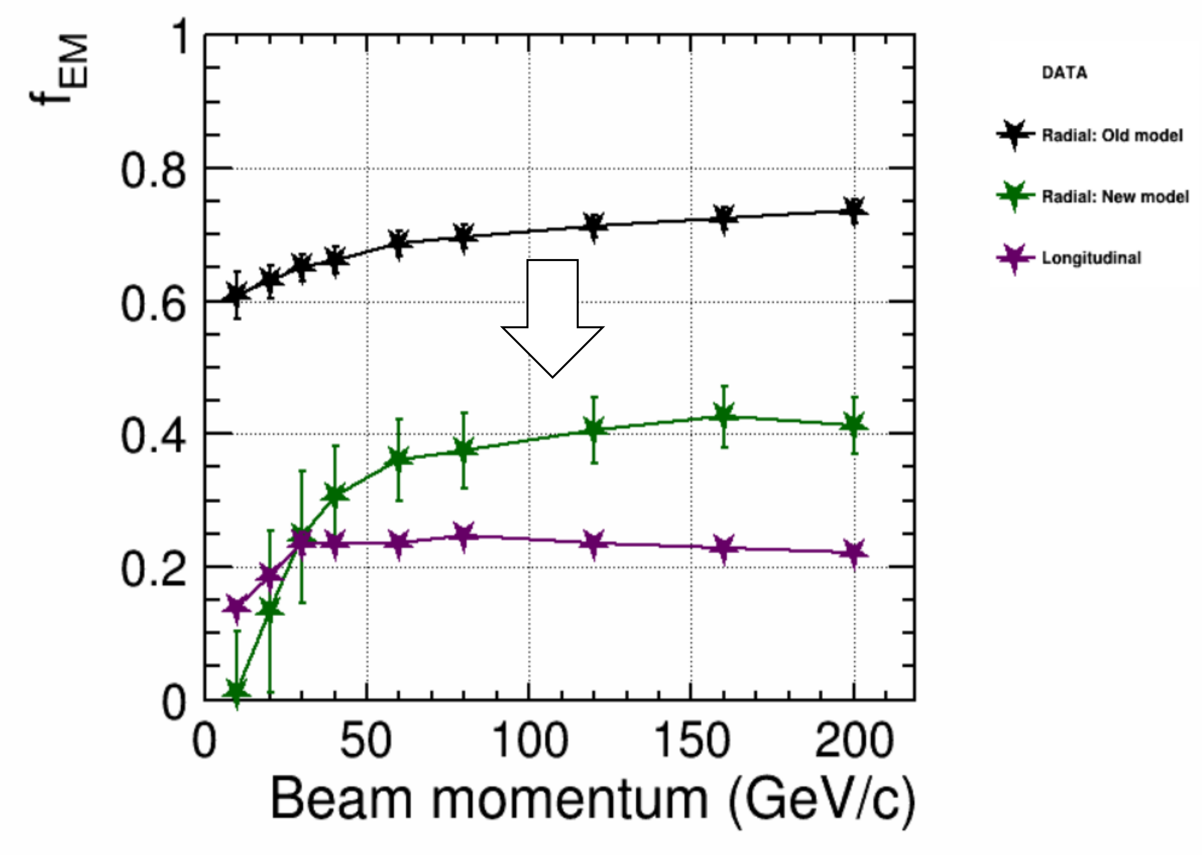
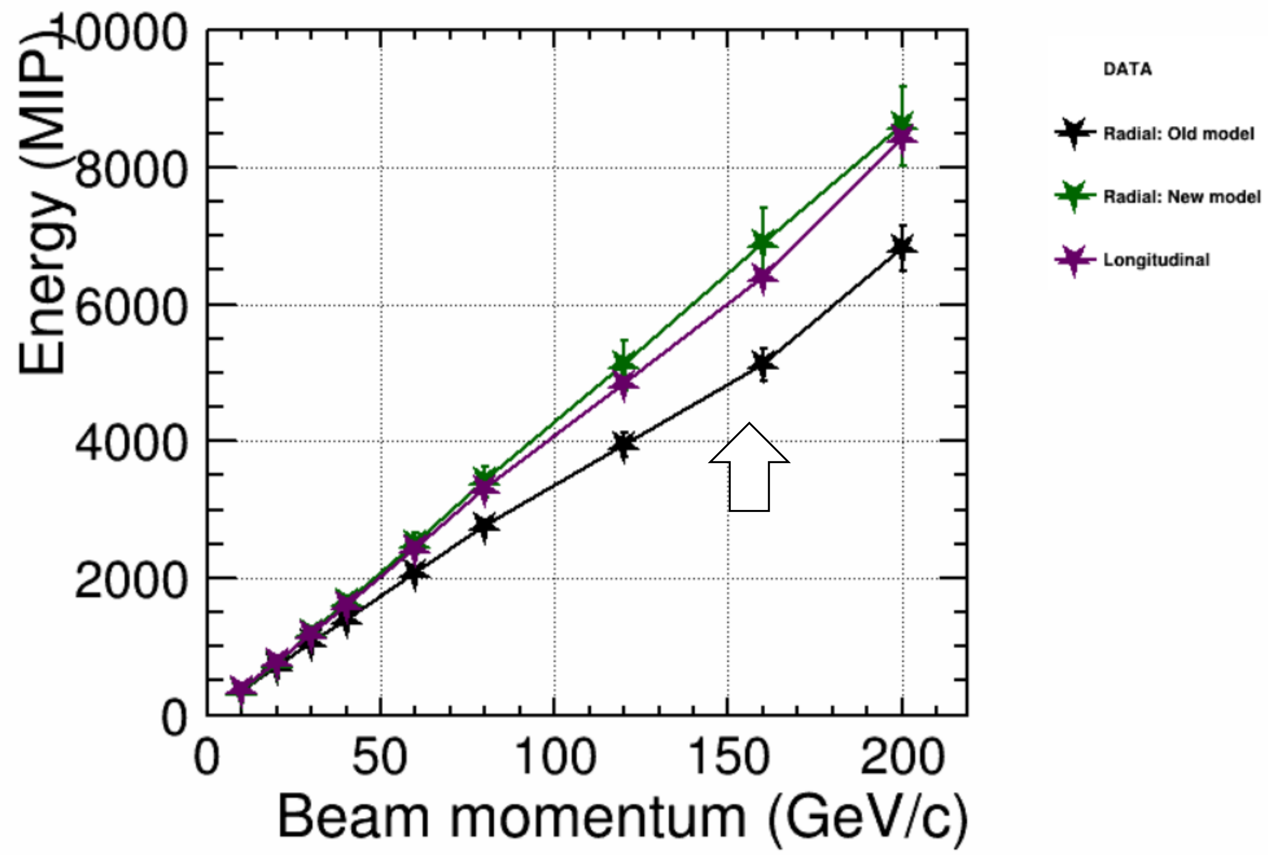
Between the two models for radial
- >45% effect in the fraction
- ~ 20 - 25% effect in the total energy



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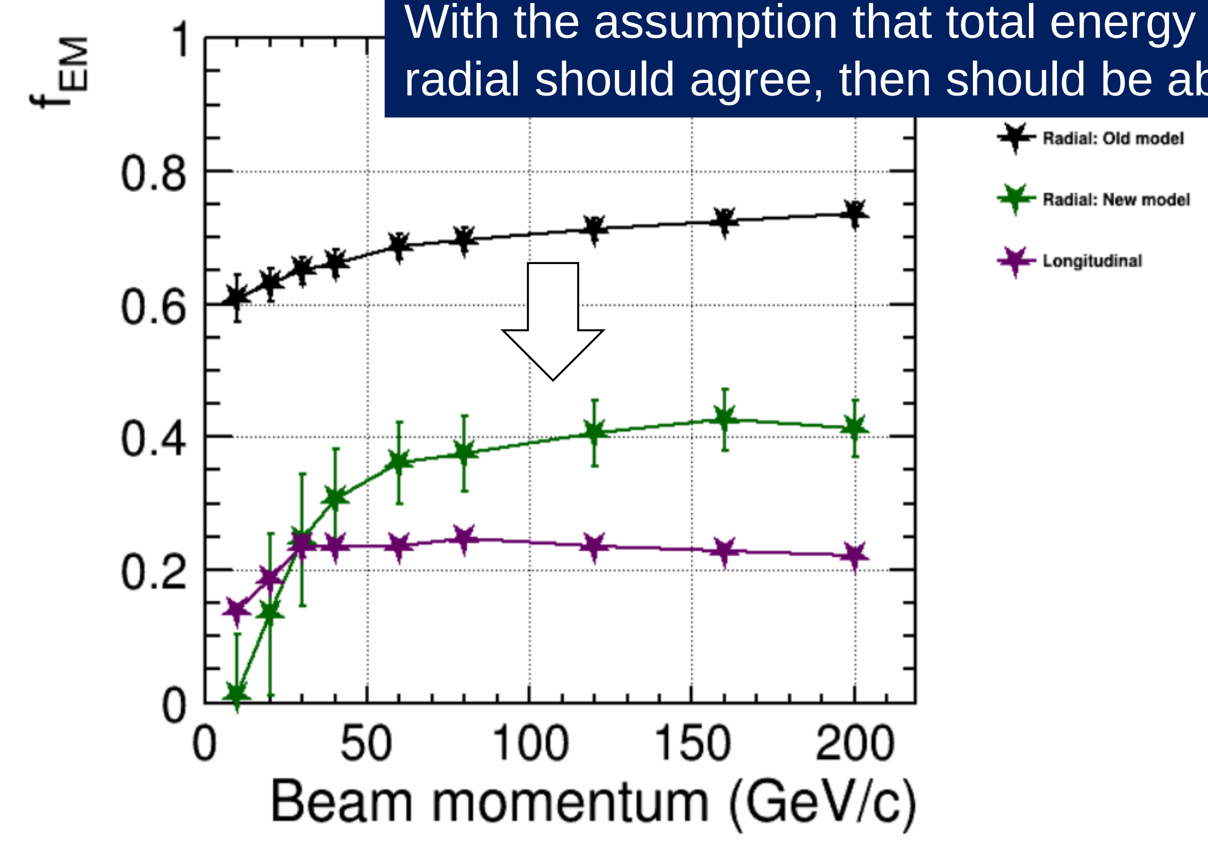
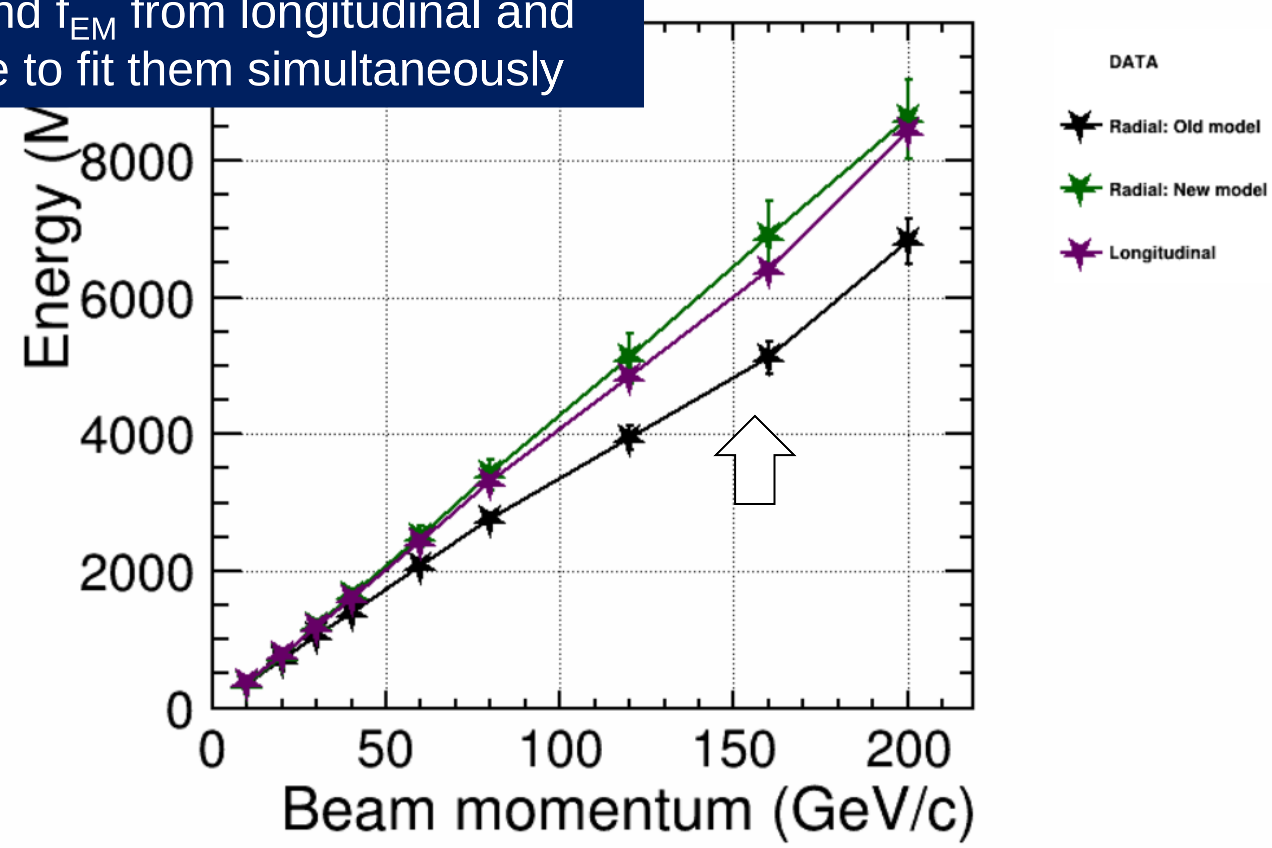
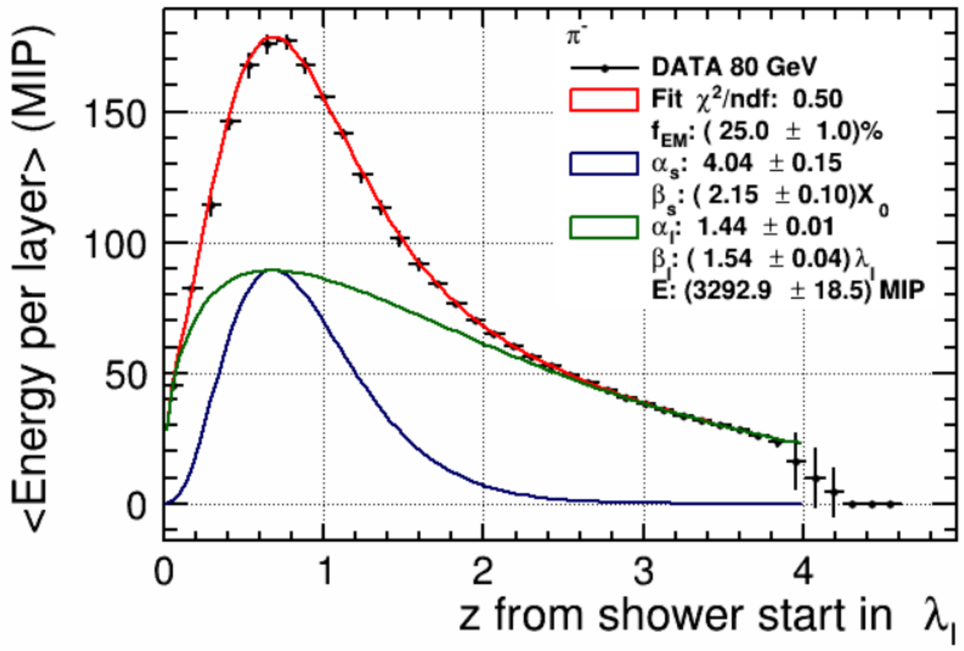
With the assumption that total energy and $f_{EM}$ from longitudinal and radial should agree, then should be able to fit them simultaneously

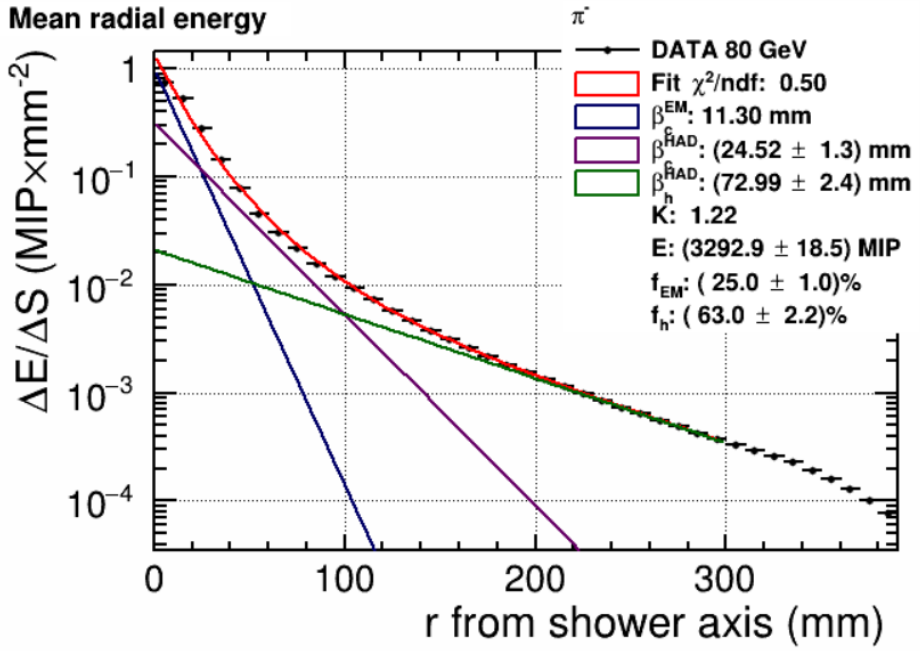


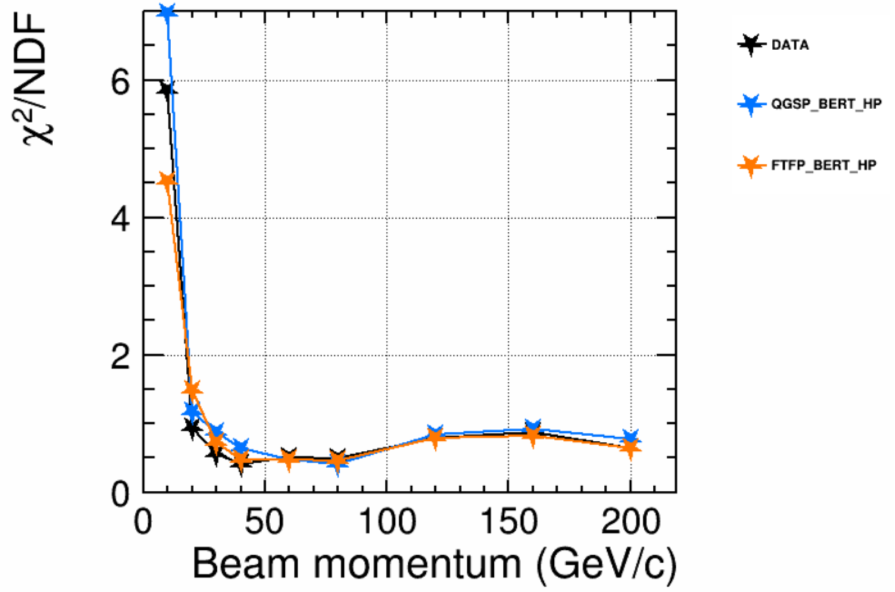



# Simultaneous fitting

## Sharing $f_{EM}$ & energy parameter

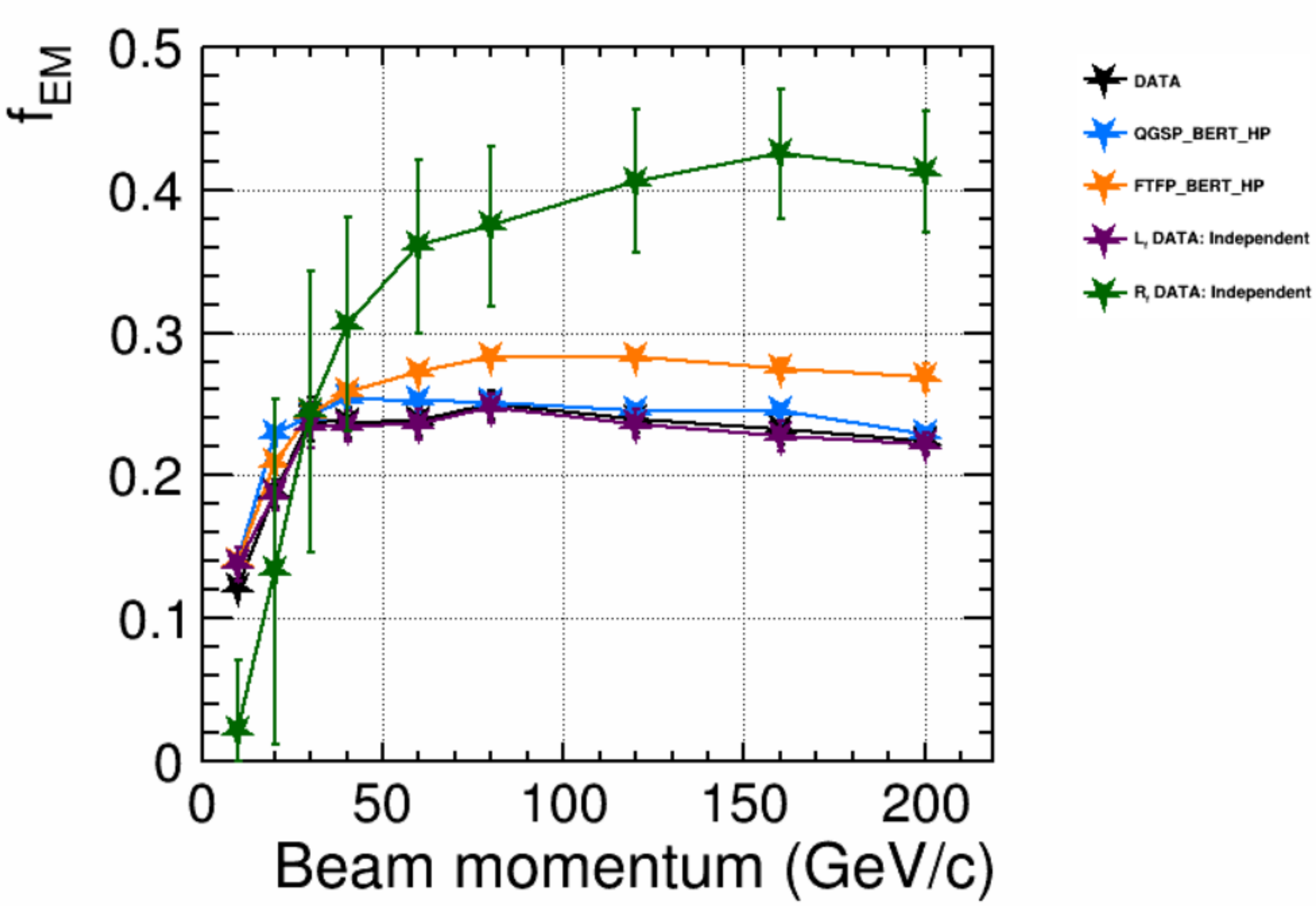


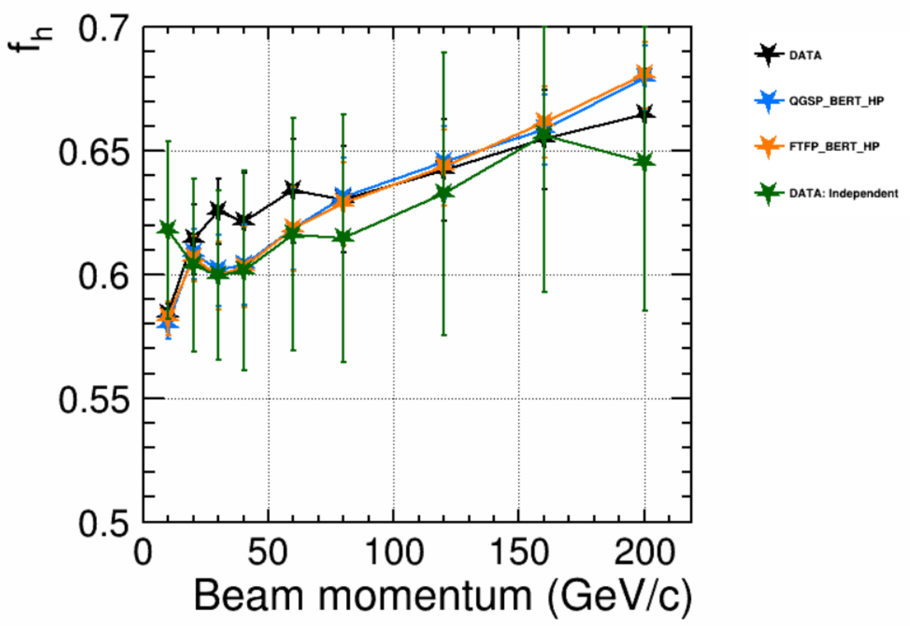




- A simultaneous fitting is performed with sharing $f_{EM}$ and energy parameter
- This fitting allows to obtain an average $f_{EM}$
- All energies above 10 GeV show a good CHI2/NDF

# Average "EM-fraction" and Halo- fraction

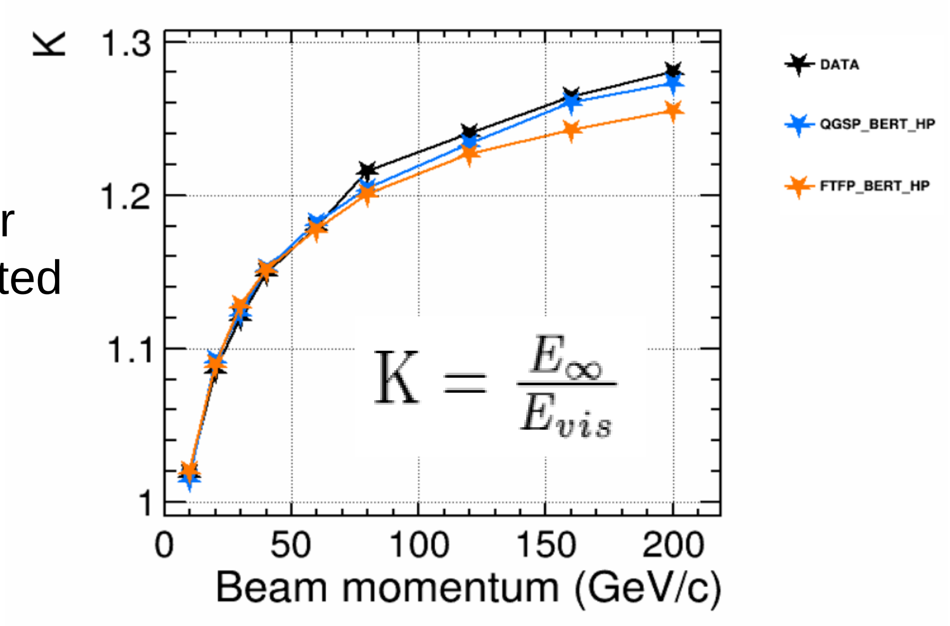


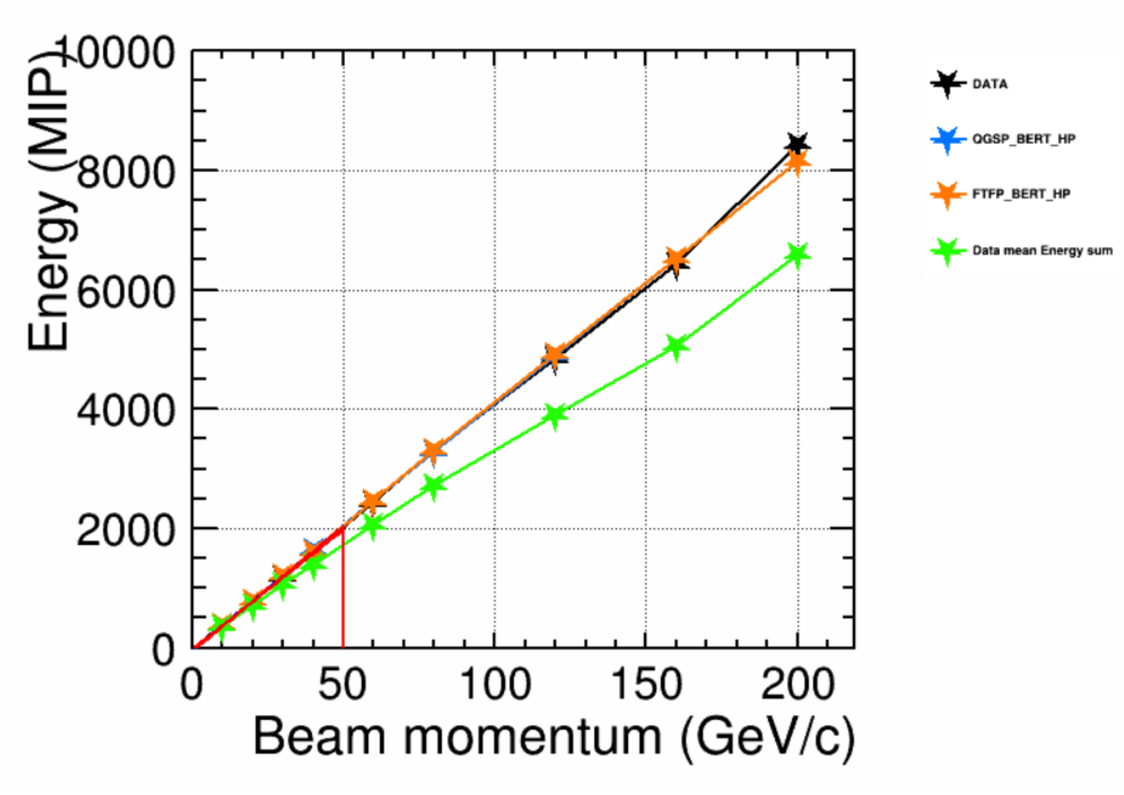

- The average $f_{EM}$ obtained from simultaneous fitting is mainly pulled by the longitudinal parameter compared to the one obtained from independent fits
- The acquired $f_{EM}$ value is found to be around 10-30%
- The halo fraction remains to be less dependent

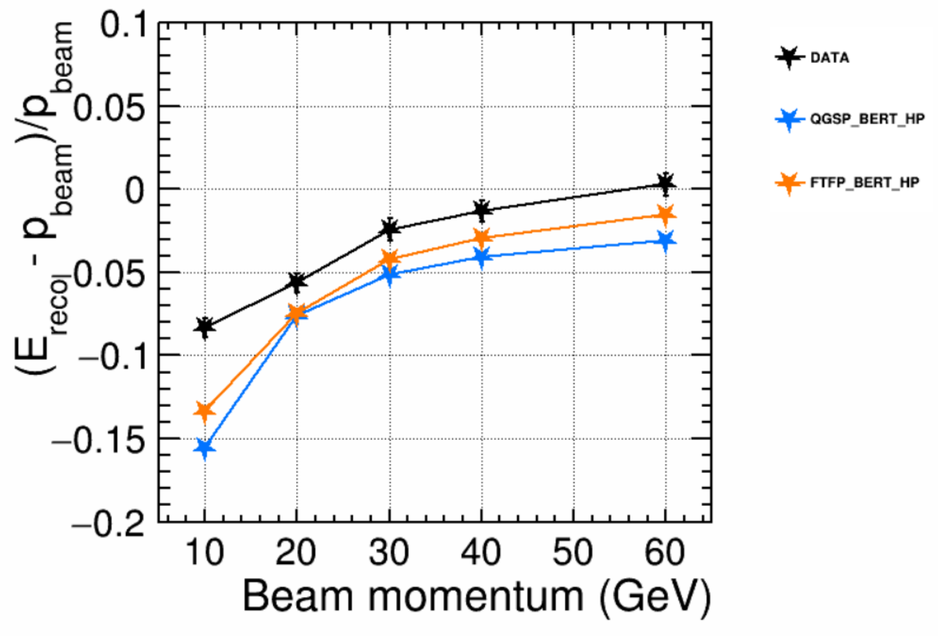


# Energy and leakage term 'K'

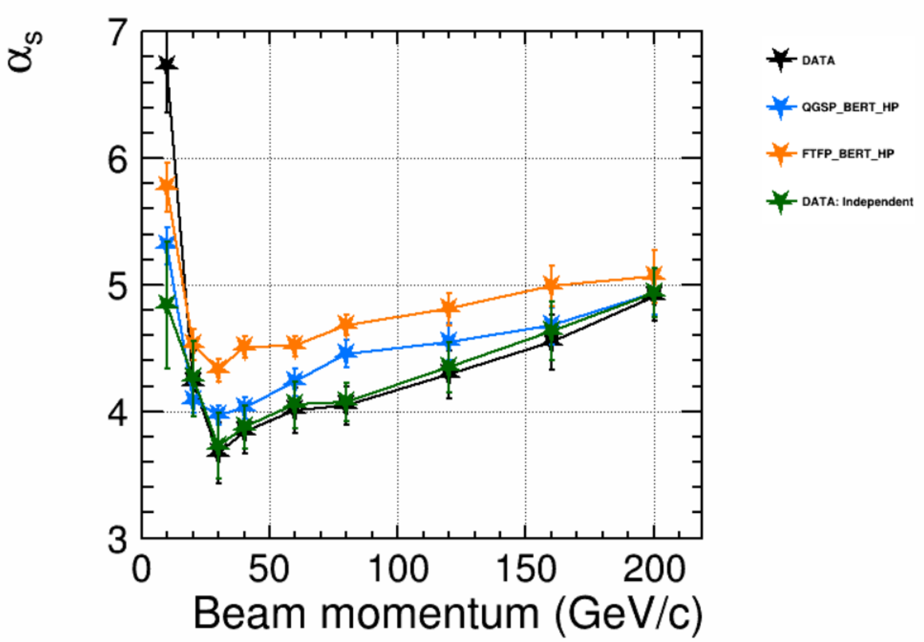
- About 20% leakage already at 100 GeV
- A linear fit is performed in the energy range [0, 50] GeV
- $E_{reco}$ [GeV] is obtained from the ratio of energy parameter from simultaneous fitting and the slope parameter extracted from the linearity fit
- Deviation from linearity is within ~15%

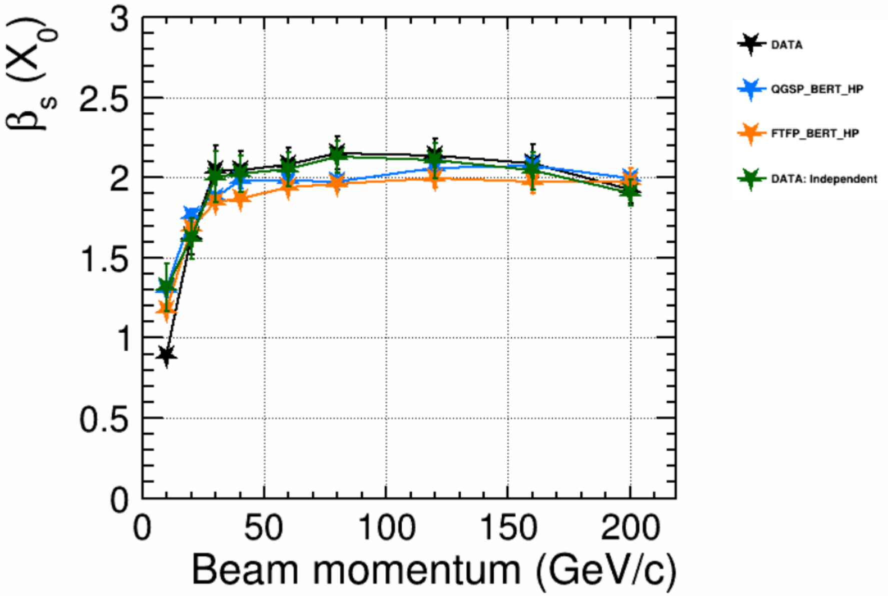


# Short and long parameters

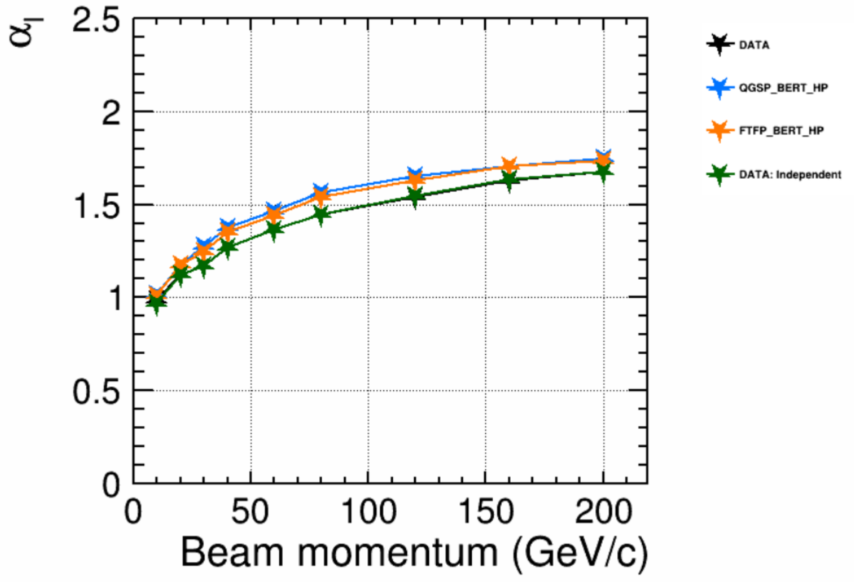


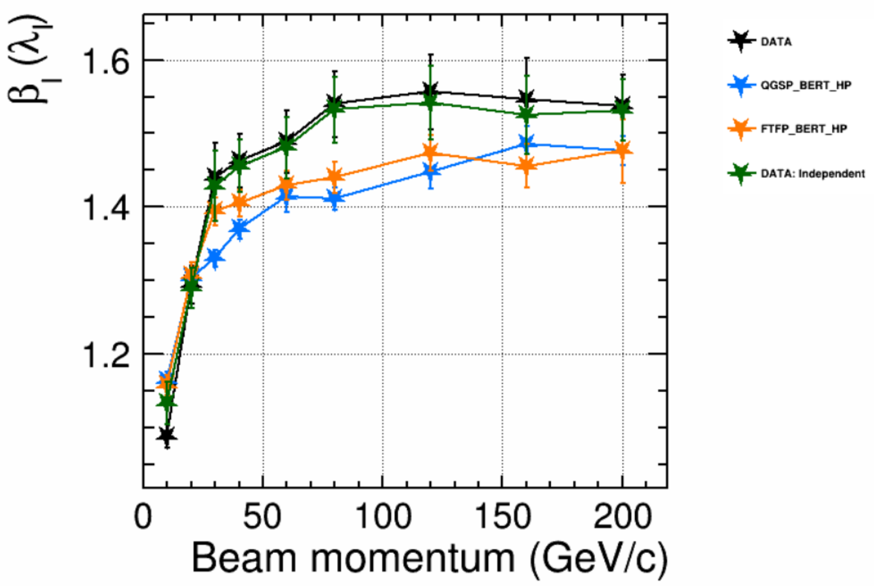



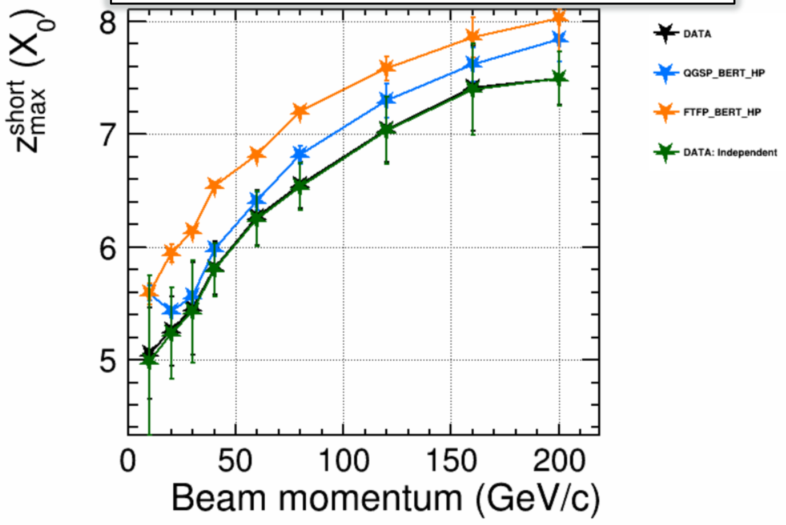

No significant difference is observed in the short and long parameter compared to data points from **independent fits**

The **maximum of the short component** agrees very close to the data points from independent fits

$$Z_{\max}^{short} = (\alpha_s - 1) \times \beta_s + cov(\alpha_s, \beta_s)$$

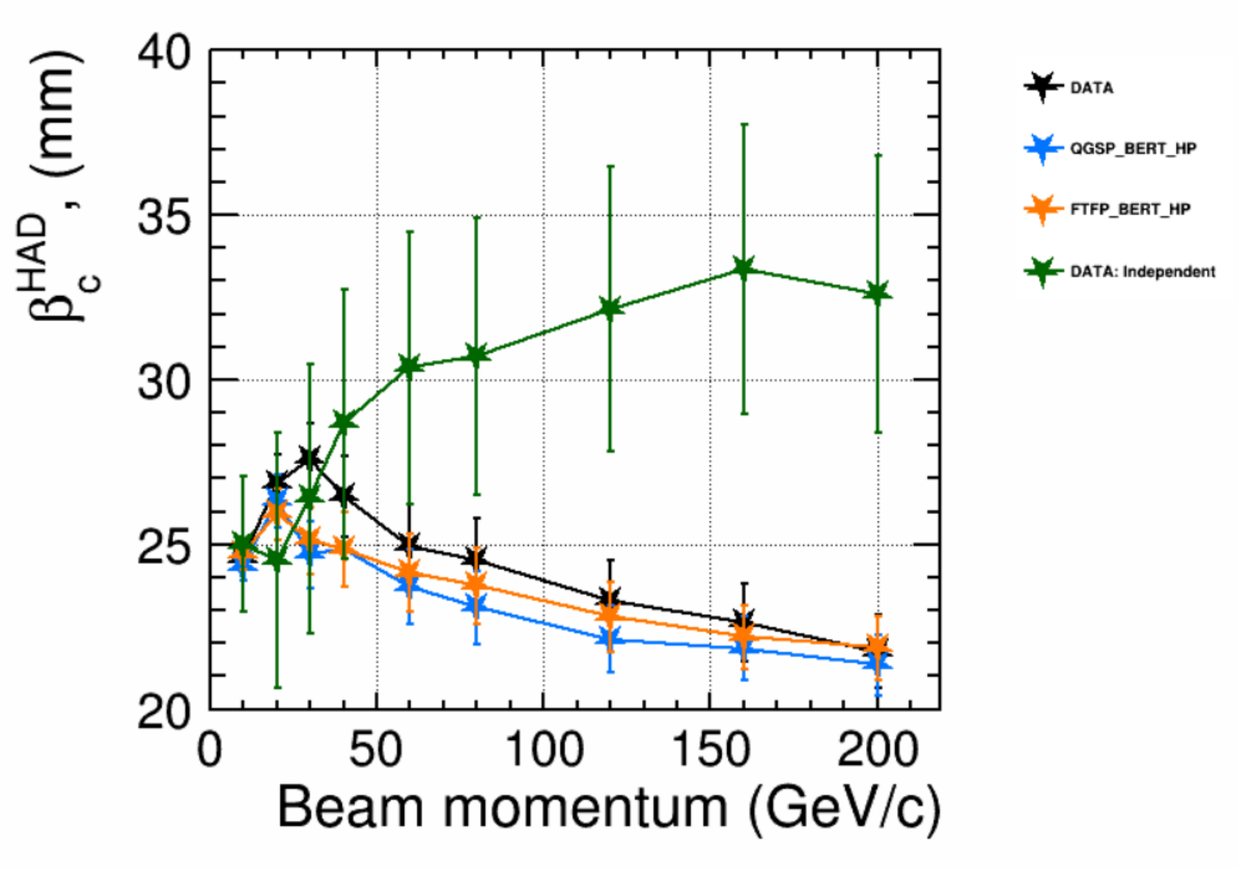


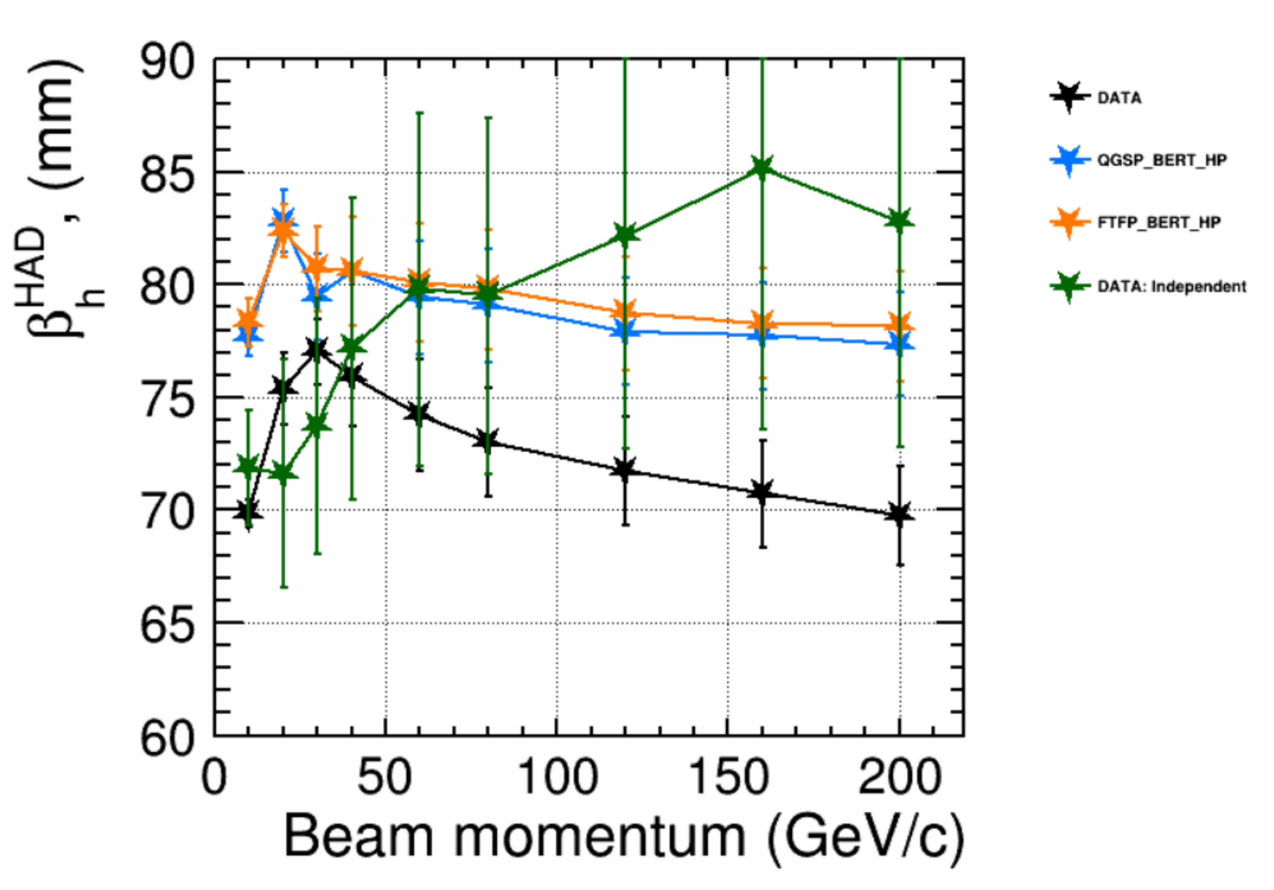



# Core and Halo

Both core and halo parameters are pulled down to a smaller value with simultaneous fits

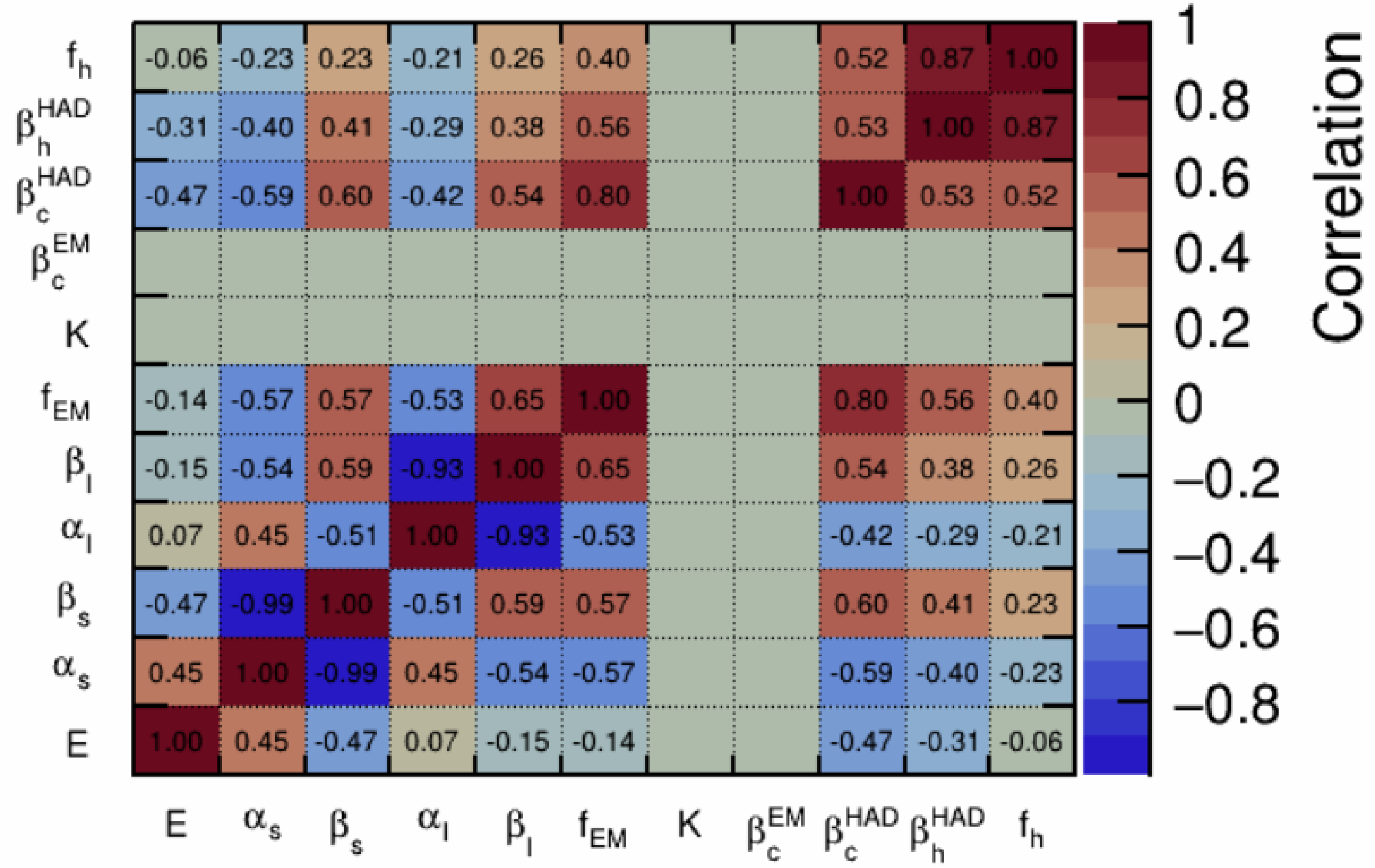


# Correlation of parameter

## 80 GeV

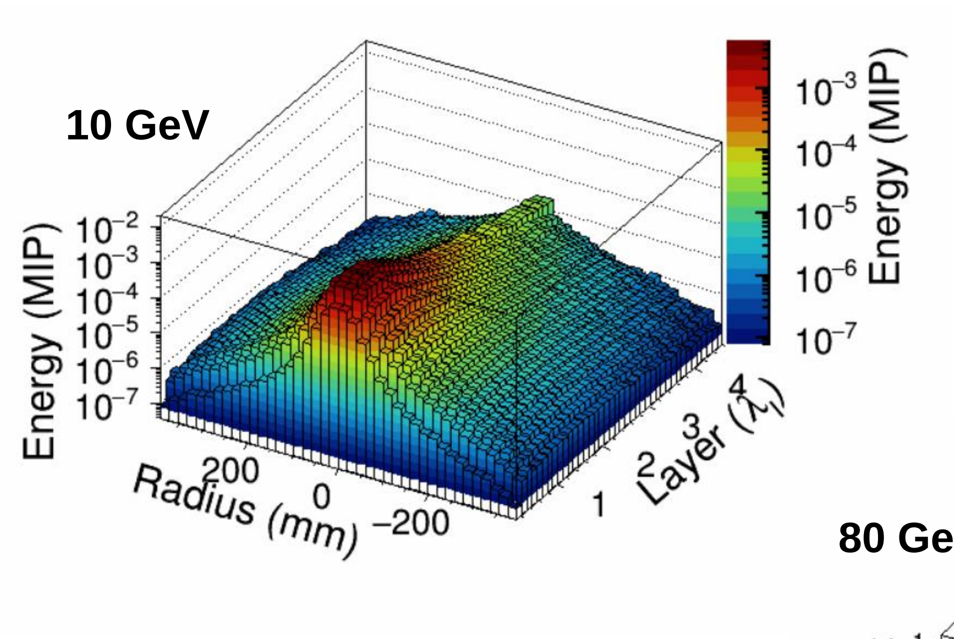
- The alpha's and beta's have anti-correlation
- The radial beta's are highly correlated and have a positive correlation!

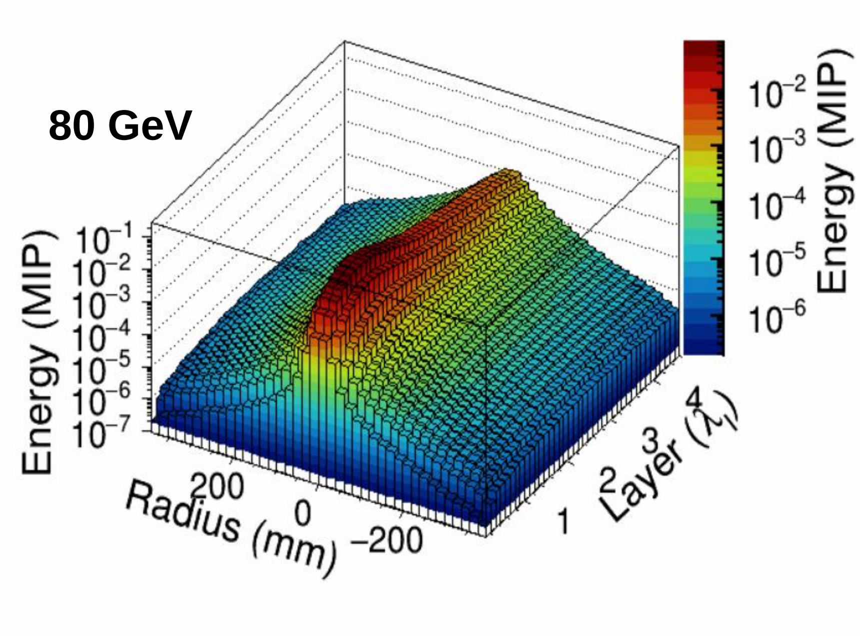


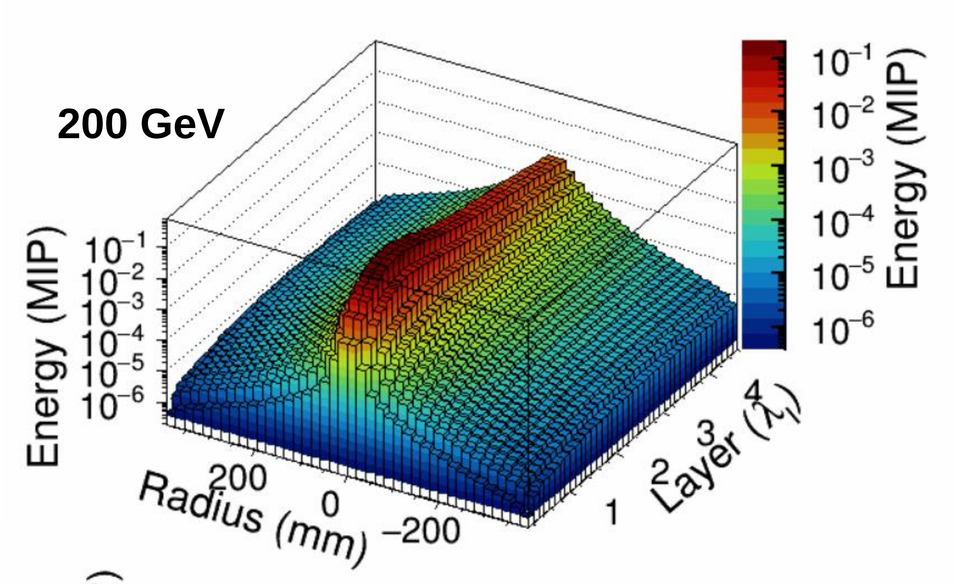
# Outlook

## 3D shower shapes

**Work in progress**, to fit 3D model to such shower shapes

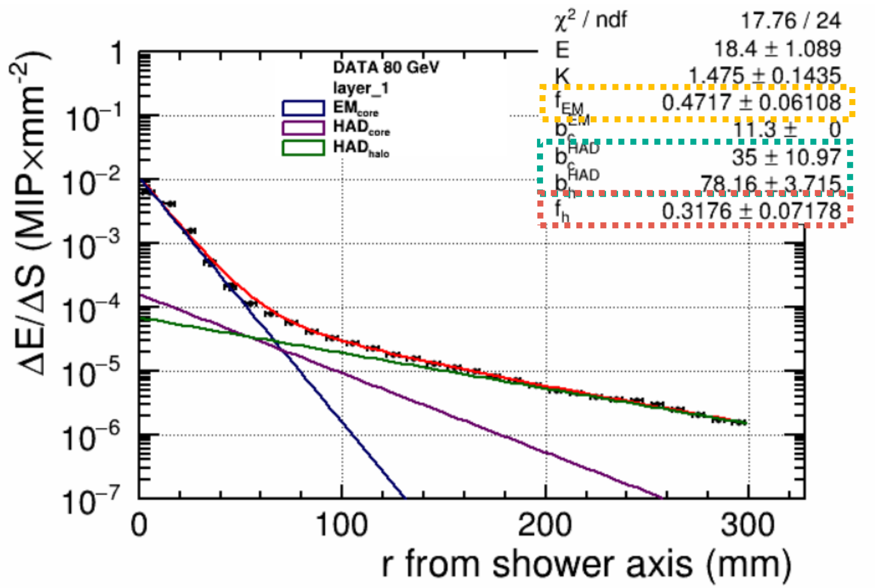


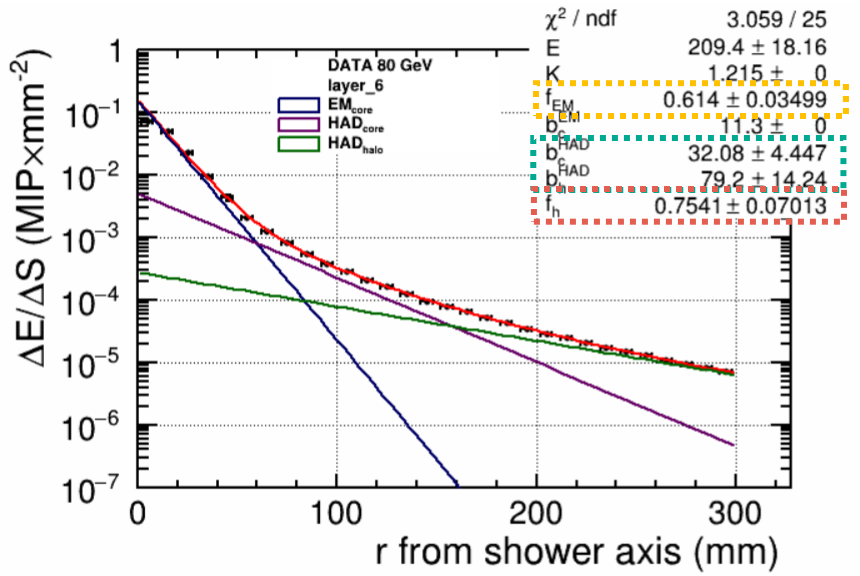



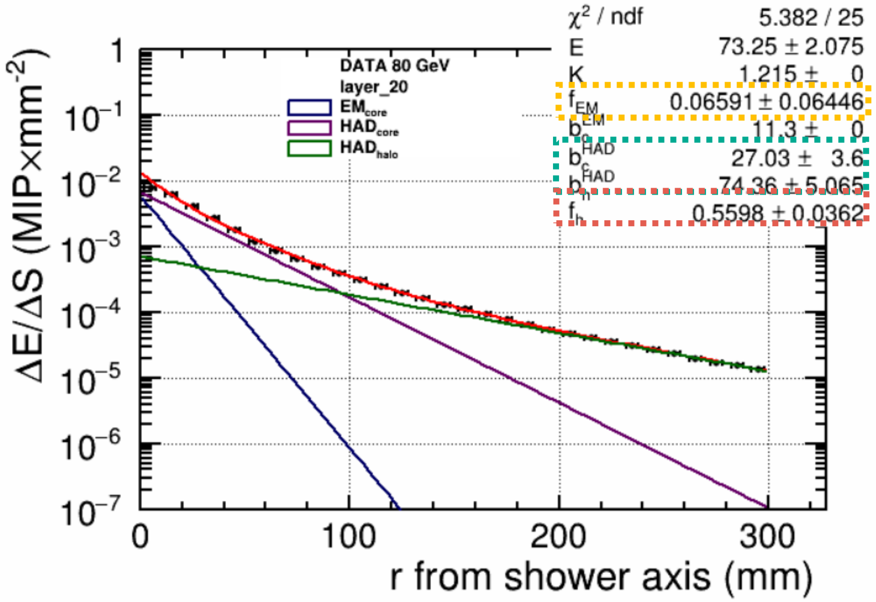



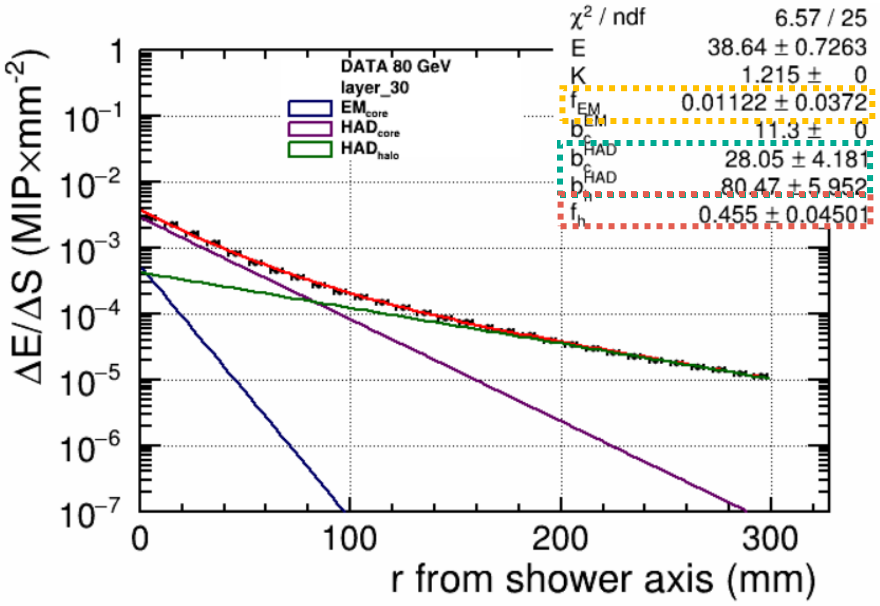
# Outlook

## Radial shapes layer-wise

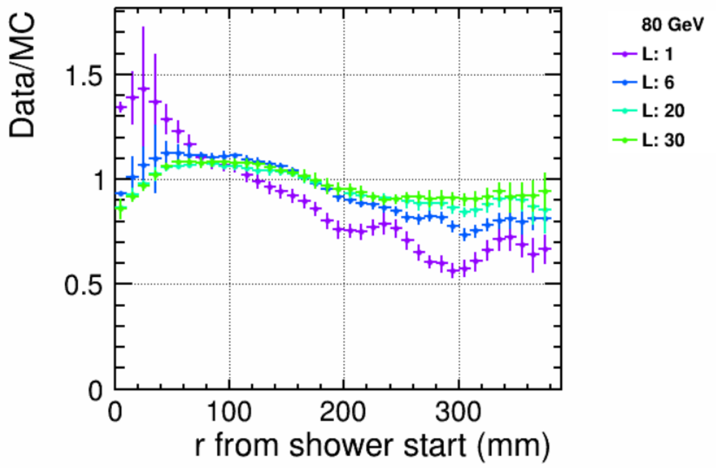


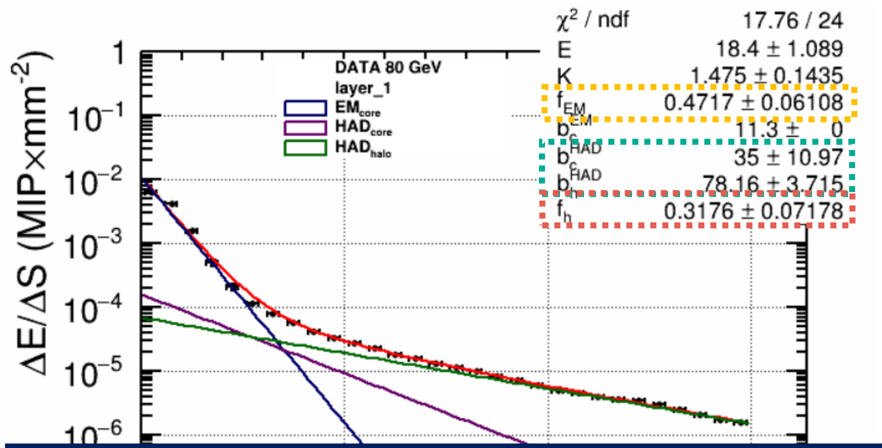

- Radial shapes layer-wise are obtained for layers beyond shower start
  - First layer
  - Layer at shower max.
  - Intermediate layer
  - Nearly last layer
- Allows to check the dependence of the radial parameters on the layer number

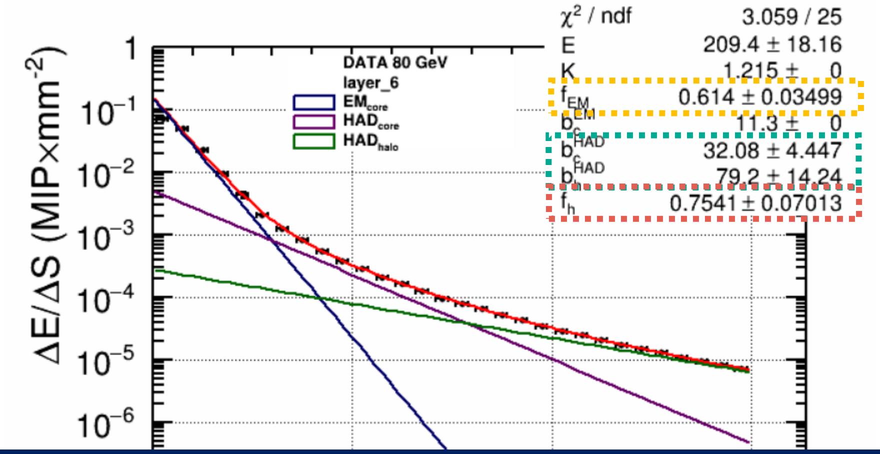



- Agreement between Data and MC is within ~20% for layer beyond 1

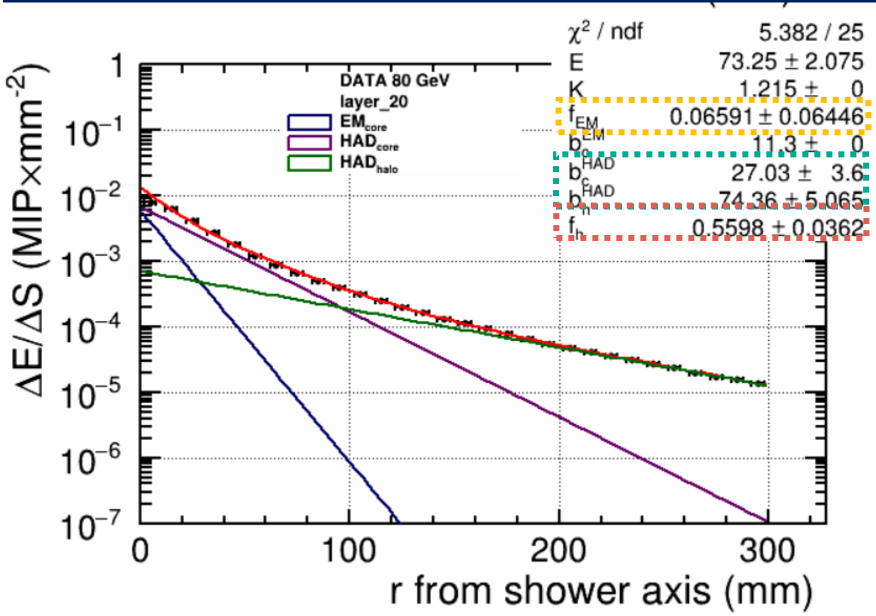
# Outlook

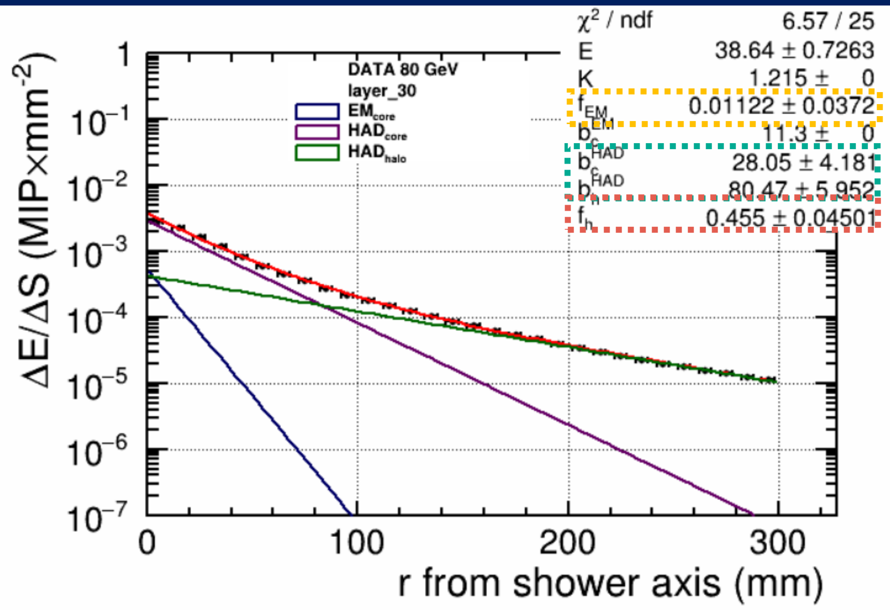
## Radial shapes layer-wise



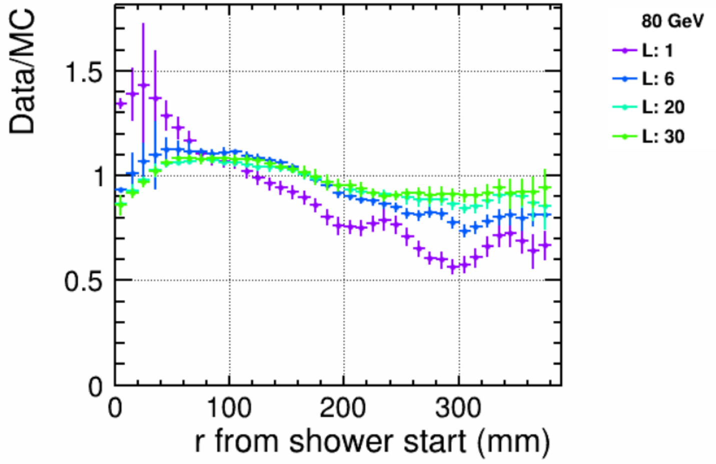




If the beta's stay the same and the fraction changes. Then all layers could be fitted with the same radial slopes, which would simplify the 3D fit function




- Radial shapes layer-wise are obtained for layers beyond shower start
  - First layer
  - Layer at shower max.
  - Intermediate layer
  - Nearly last layer
- Allows to check the dependence of the radial parameters on the layer number




- Agreement between Data and MC is within ~20% for layer beyond 1

# Summary

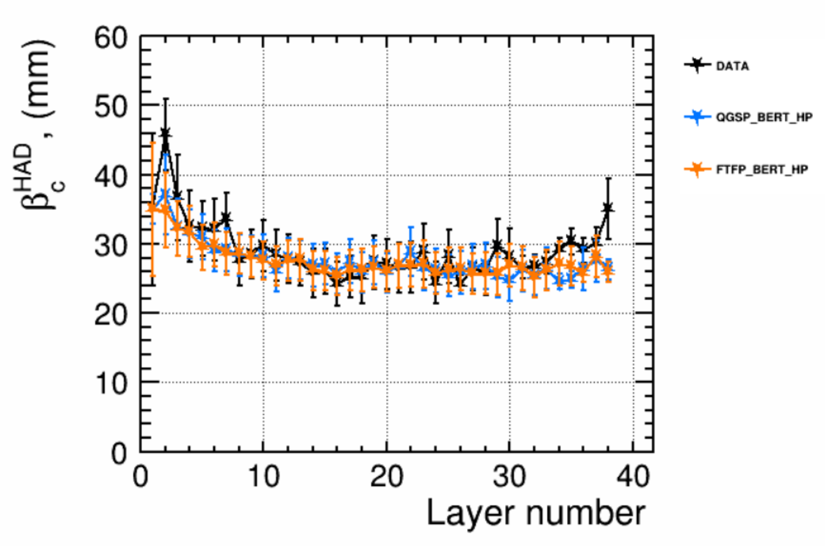
- **Analog Hadron Calorimeter** is an imaging calorimeter and is granular enough to fully exploit the characteristics of particle showers
- **Hadronic showers shapes** are well described by the sum of two contributions: sum of gamma distributions for longitudinal and sum of exponential distributions for radial development
- An **effective radial parametrization** is performed to have an agreement with energy and fraction from longitudinal profile
- A **simultaneous fit** is performed to obtain an average electromagnetic fraction using both the longitudinal and radial distributions
    - Provides reasonable Chi2/NDF
    - The obtained average **electromagnetic fraction** is between 10 to 30 % for all available energies

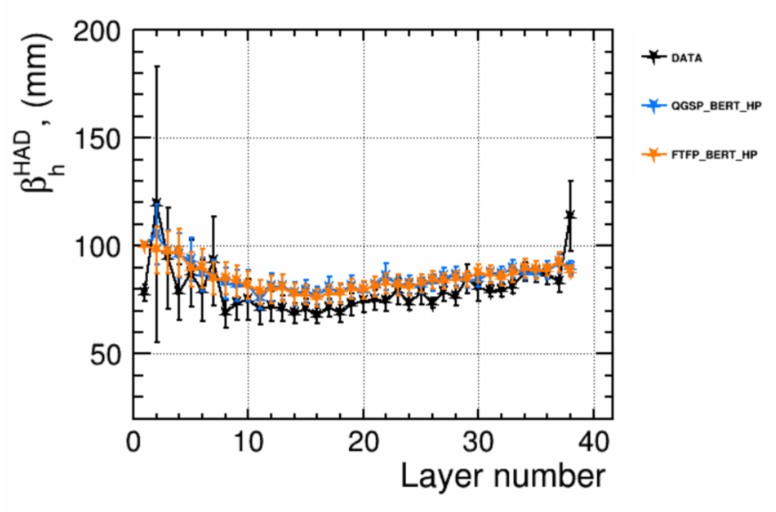
THANK YOU FOR YOUR ATTENTION!

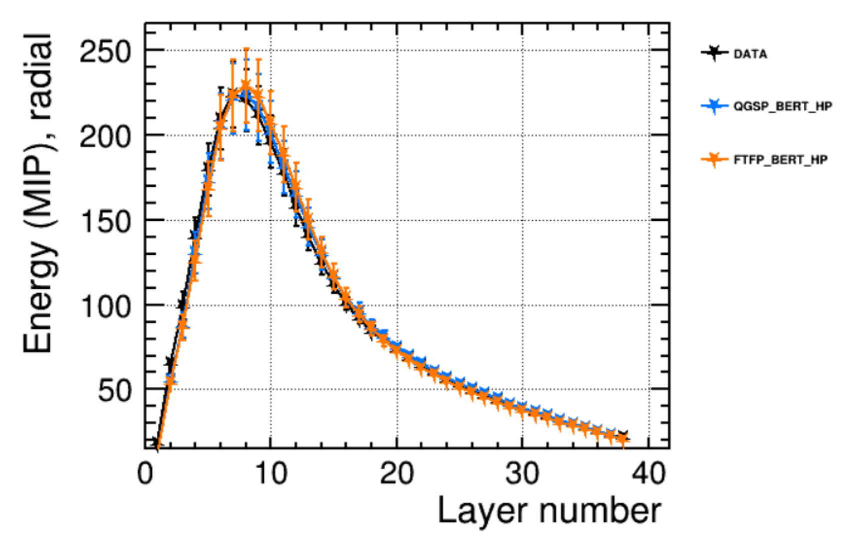
# Spares

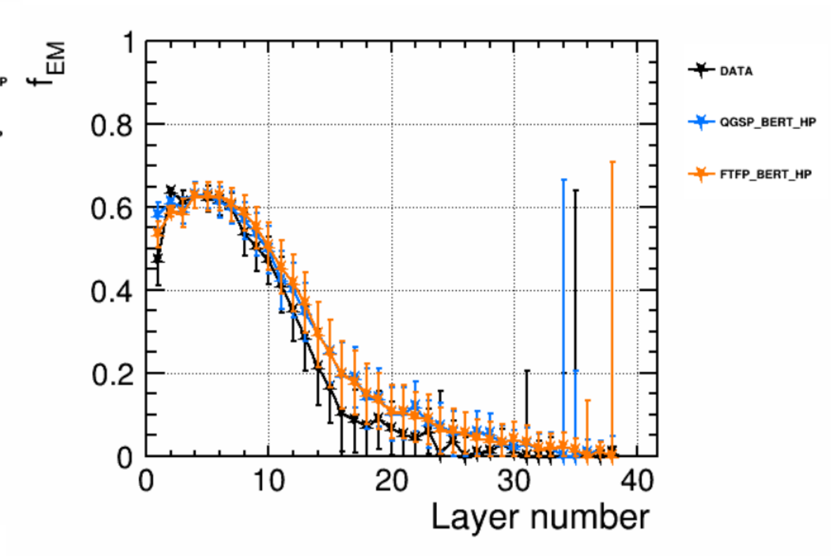
# Radial Parameter's layer-wise

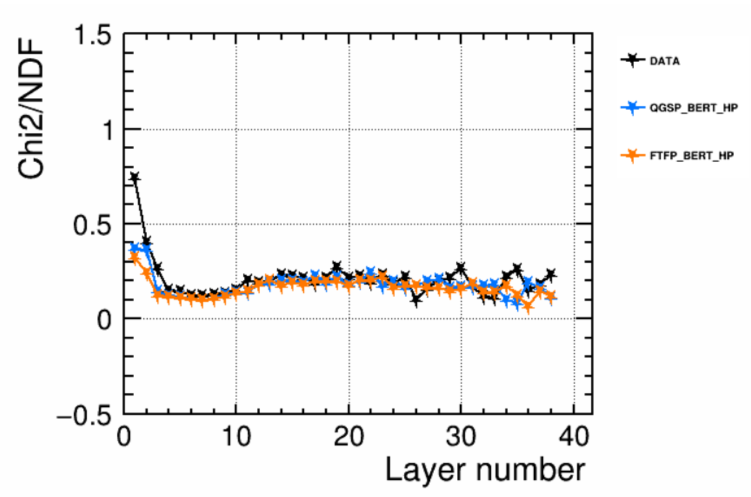
## 80 GeV



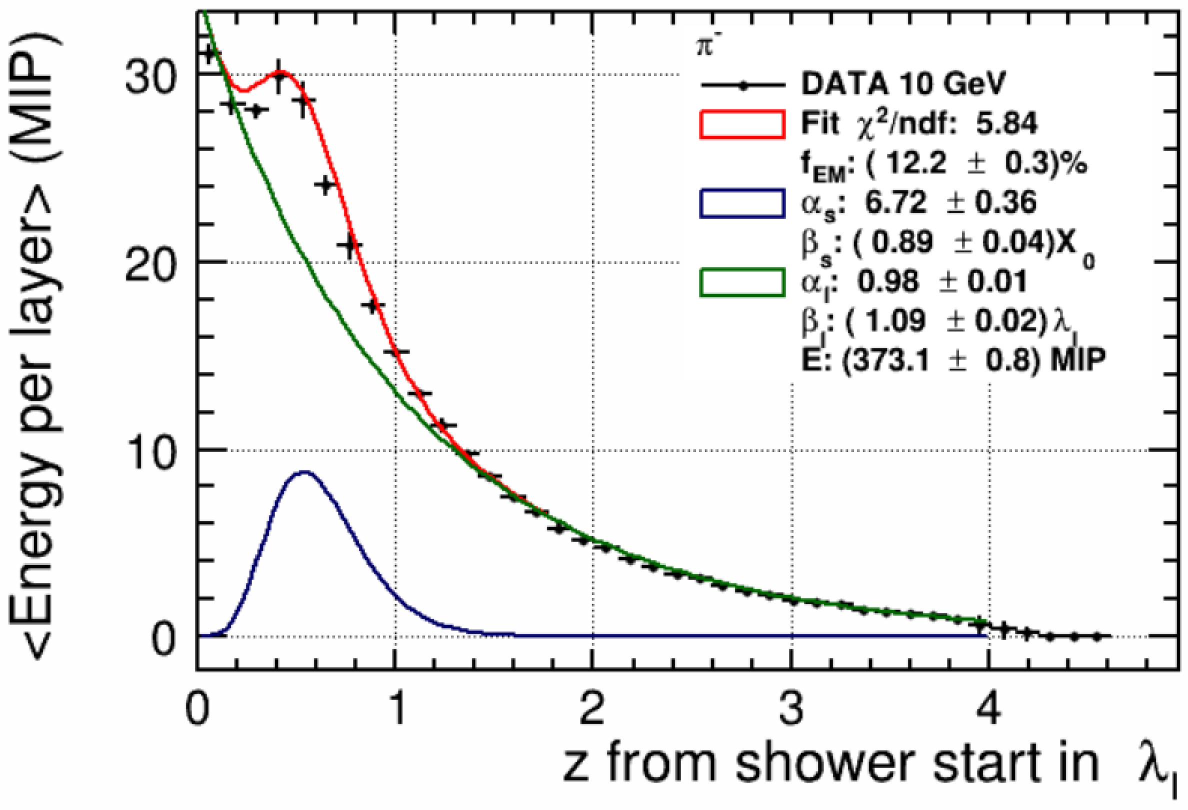



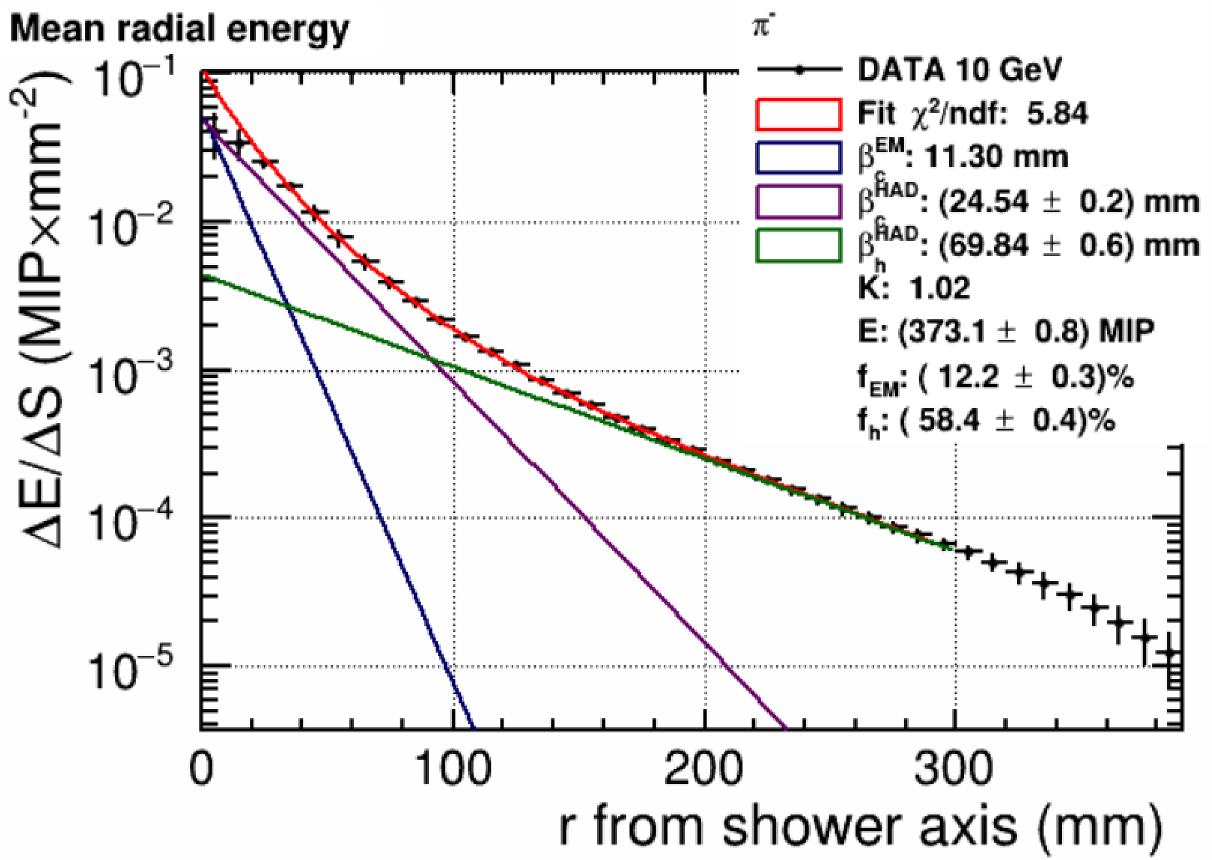



# Simultaneous Fit



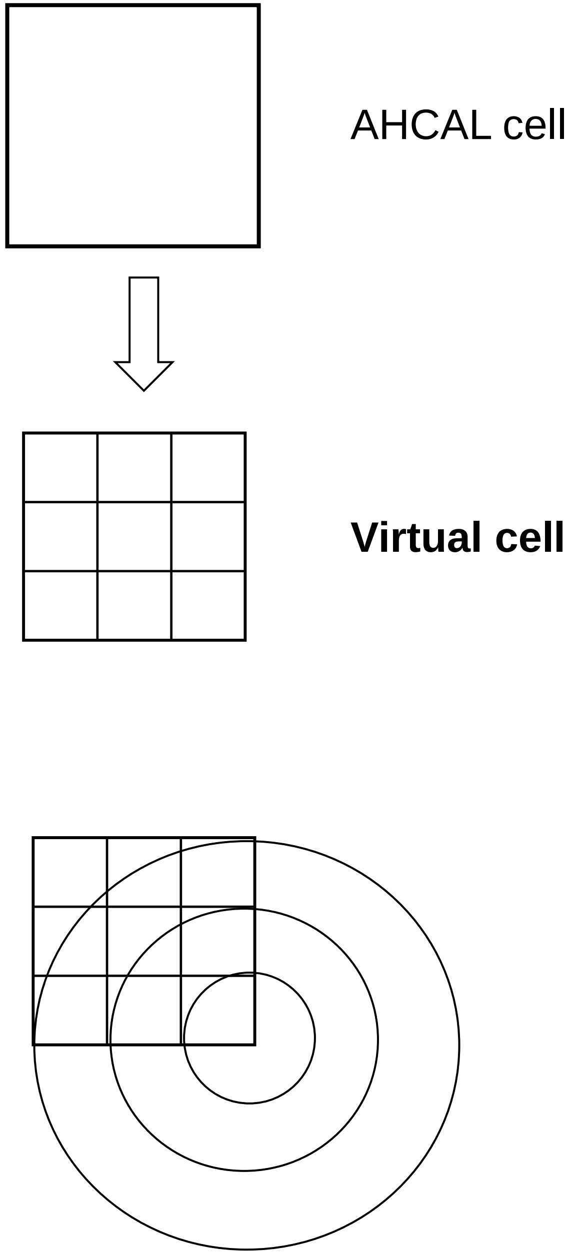



# Virtual Cells

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

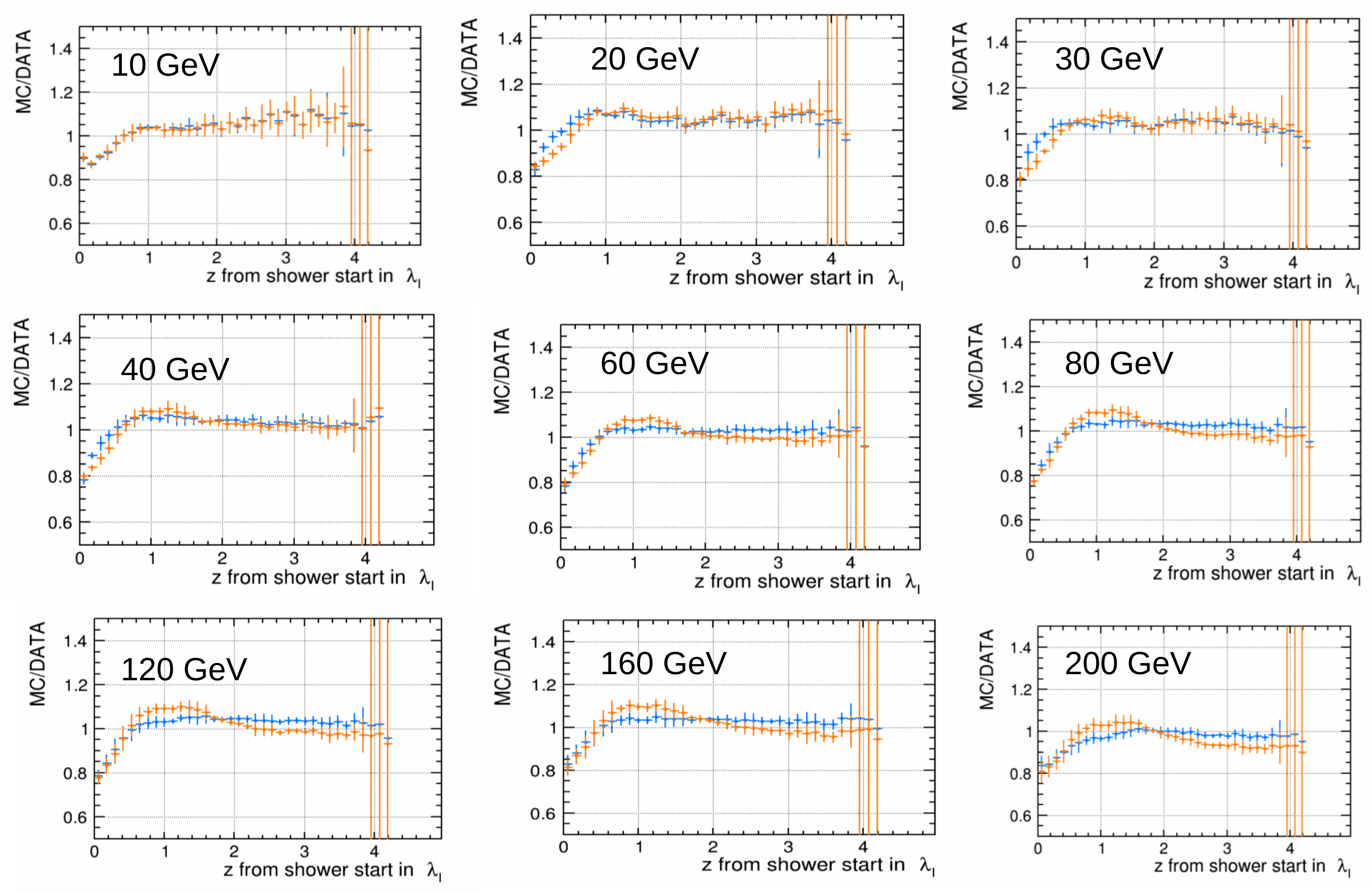


# Comparison between Data & MC

## 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



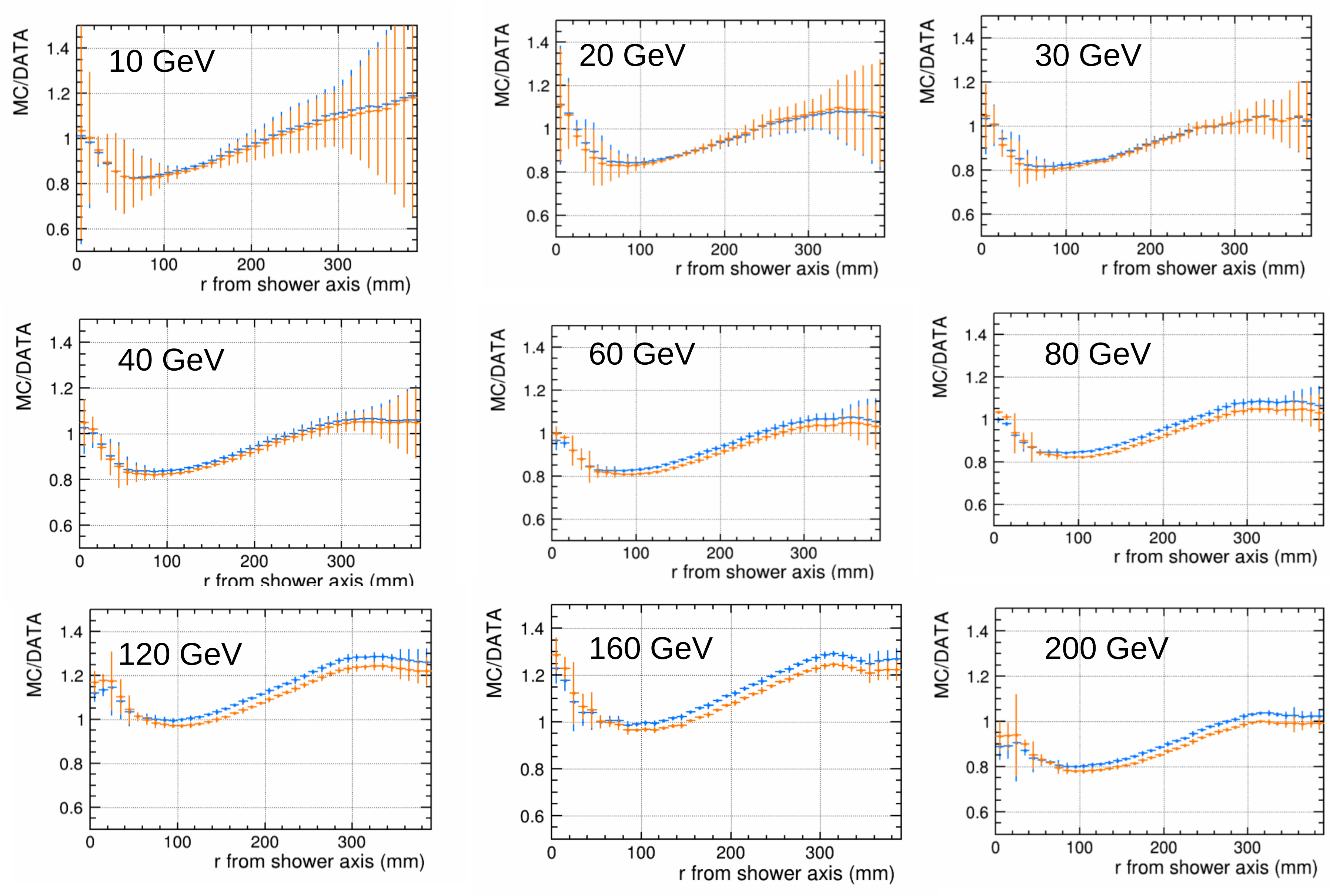
# Comparison between Data & MC

## 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



# ENERGY DEPENDANCE OF SHOWER PROFILE PARAMETERS

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

# Longitudinal Parameters

## “short” parameters

### Parameter $\alpha_s$

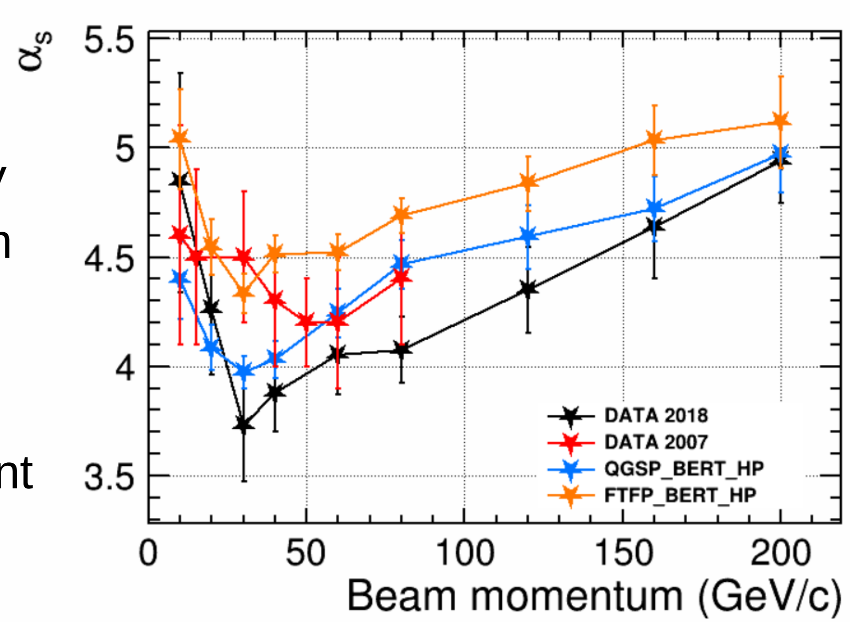
- Decreases with energy until 30GeV and shows opposite behaviour from 80 GeV which is also predicted by both the simulations

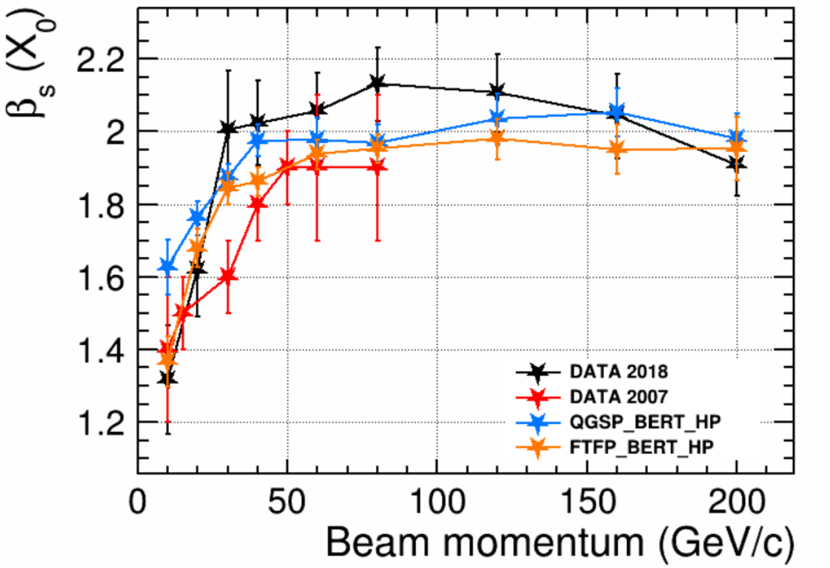
- Both physics list show an agreement to data within ~5 to ~10%

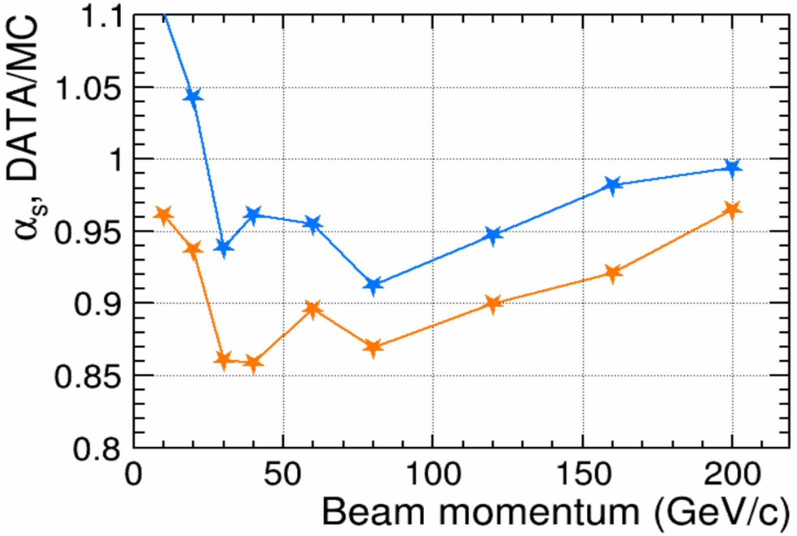
### Parameter $\beta_s$

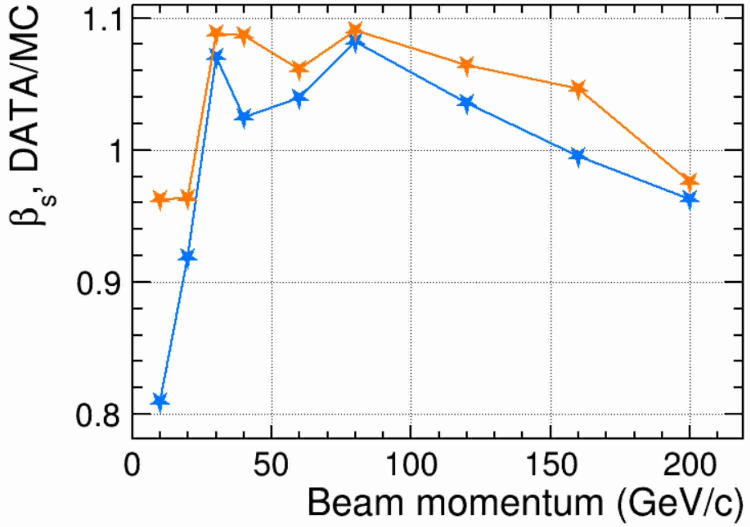
- Almost energy independent above 30 GeV also predicted by both physics lists

**There exists a very high correlation between $\alpha_s$and $\beta_s$**



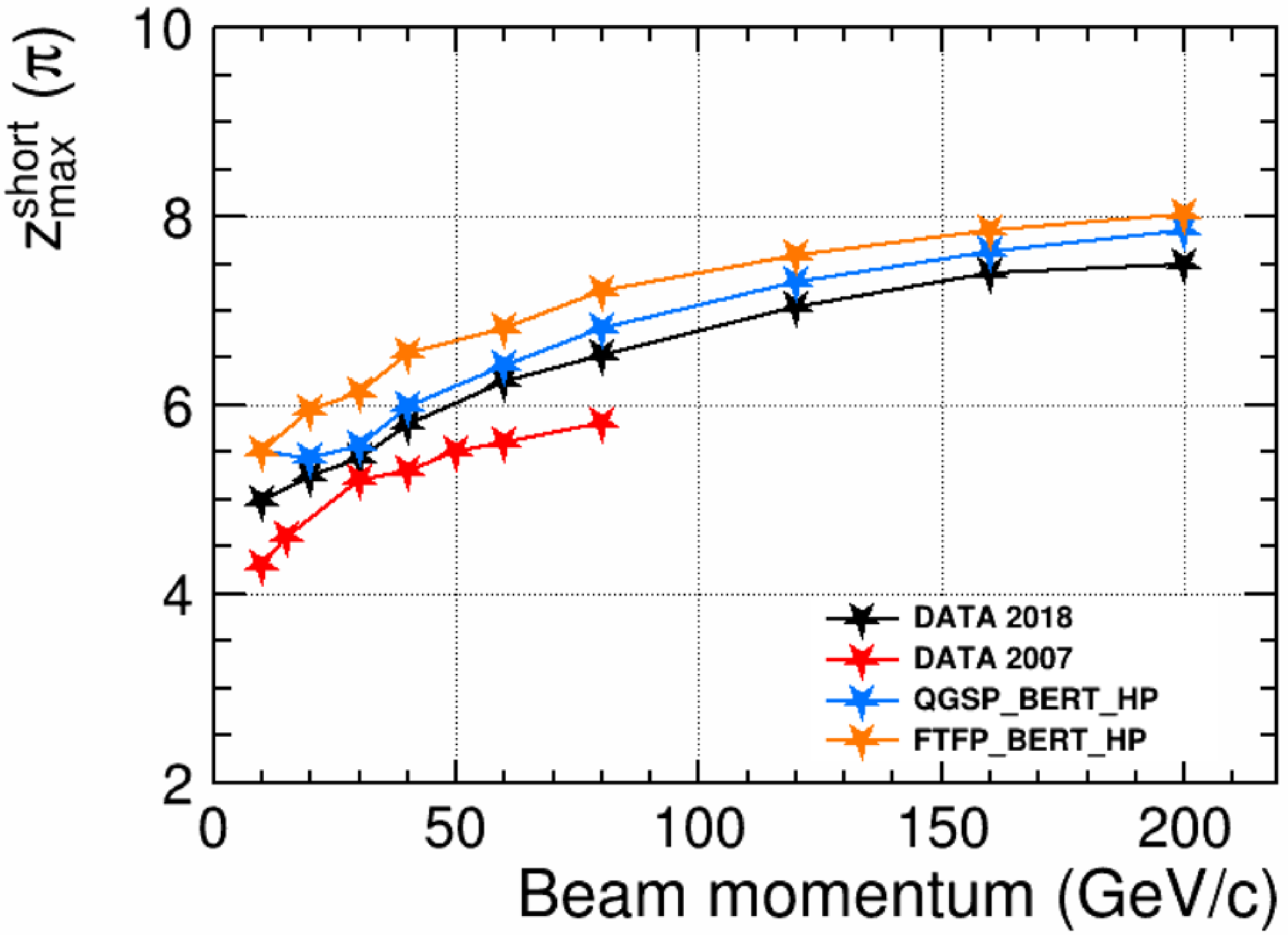



# Maximum Position of the "short" Component

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

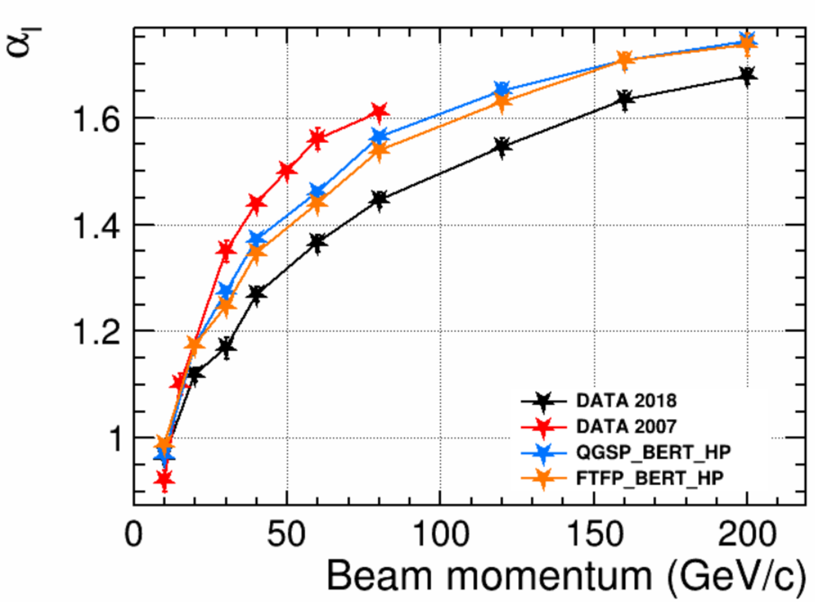


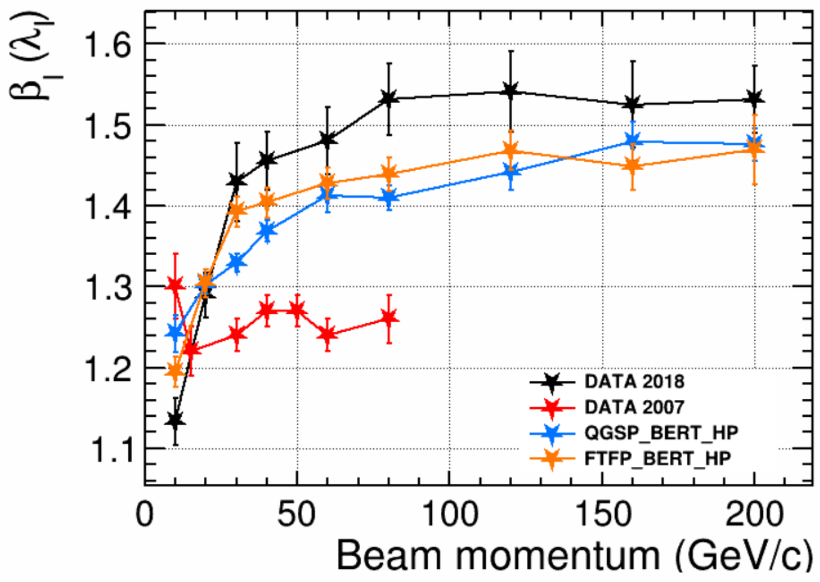
# Longitudinal Parameters

## “Long” parameters

### Parameter $\alpha_l$

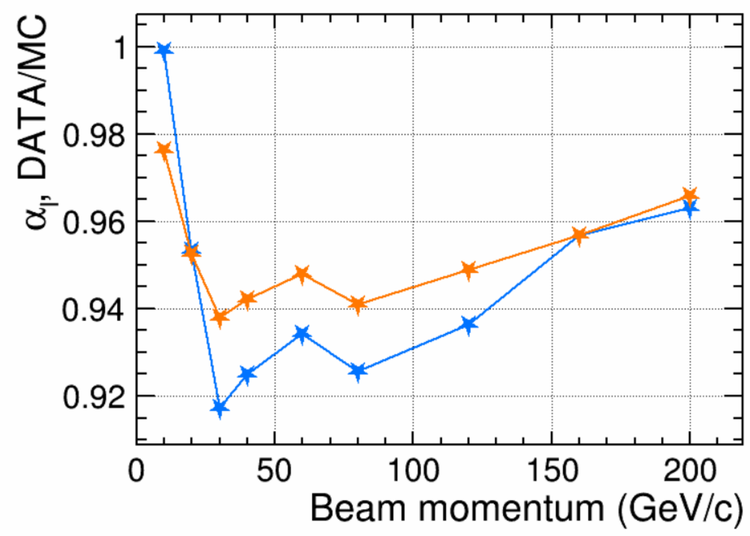
- Shows logarithmic rise in energy
- Both physics list show similar behaviour and the results are comparable

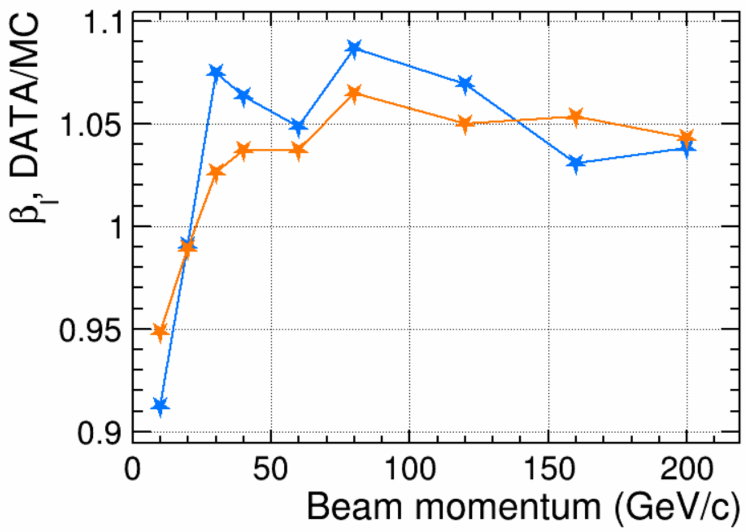



### Parameter $\beta_l$

- Almost energy independent above 80 GeV also predicted by the two physics list
- Two physics list are overestimated at 10 GeV by ~10%



# Radial Parameters

## Core & Halo

### Parameter $\beta_c$

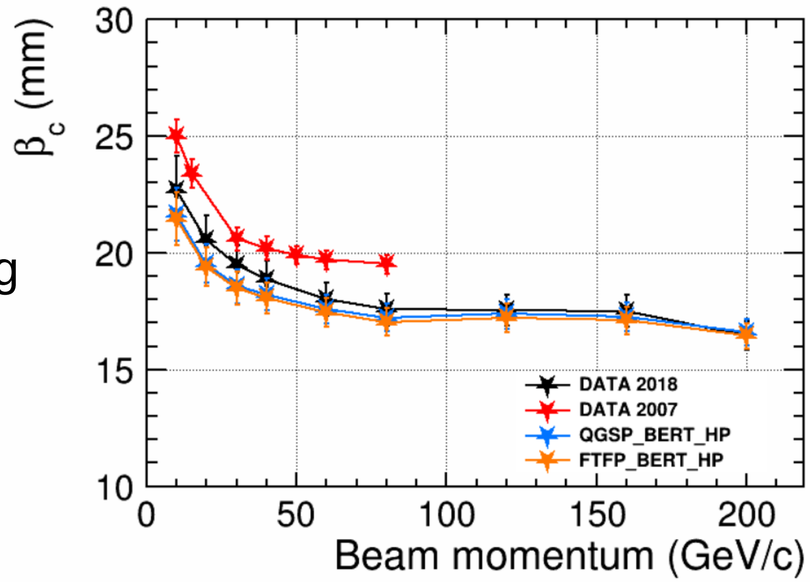
- Decrease at a faster rate at low energies compared to the energies above 30 GeV, this behaviour being well reproduced by simulations

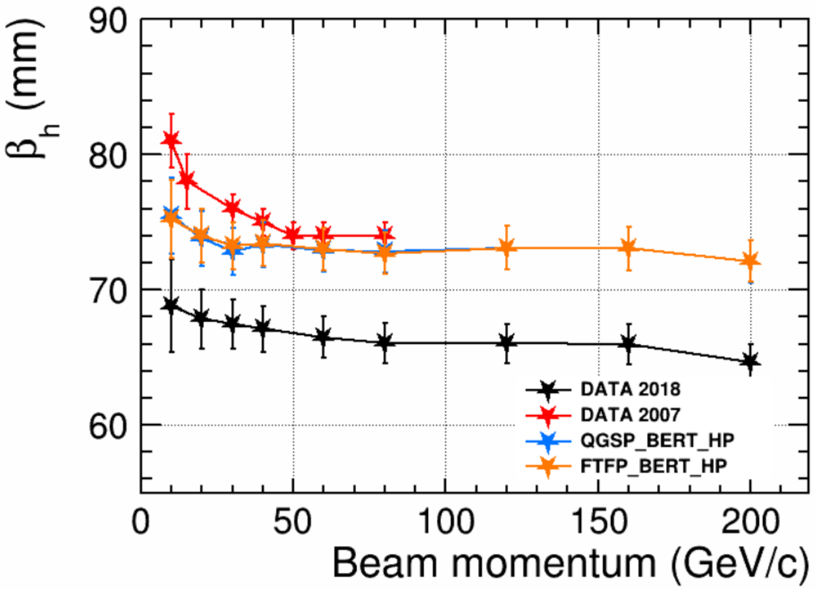
- No energy dependence above 30 GeV

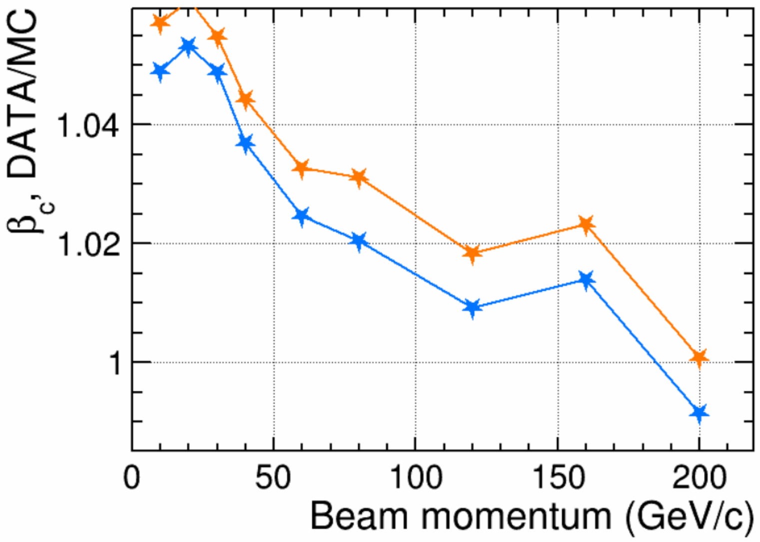
### Parameter $\beta_h$

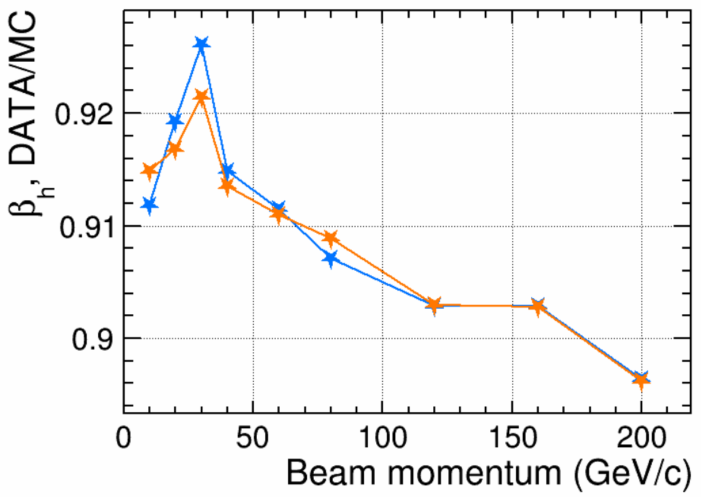
- Almost no energy dependence above 30 GeV also predicted by simulations

- In general, simulations obtains a larger halo component and the difference in the parameter increases with increasing energy



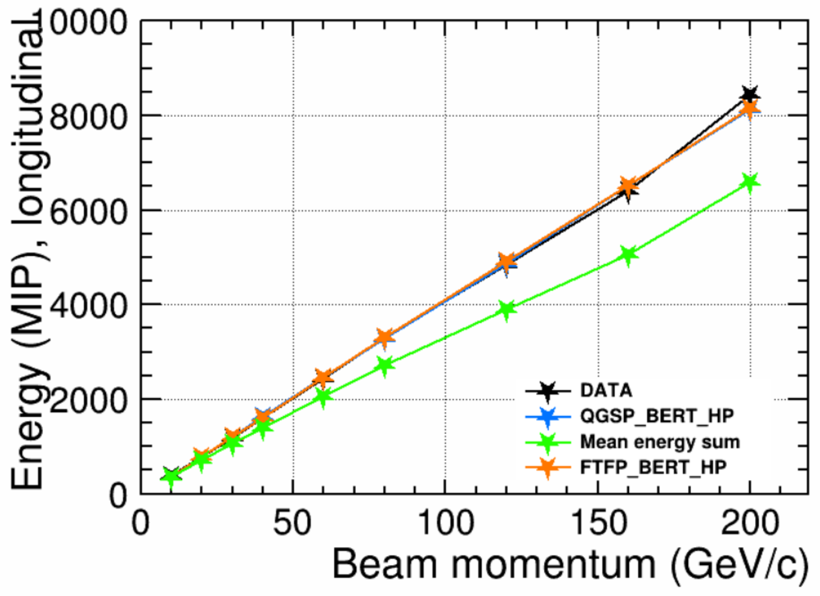
# Energy- Scaling Parameter

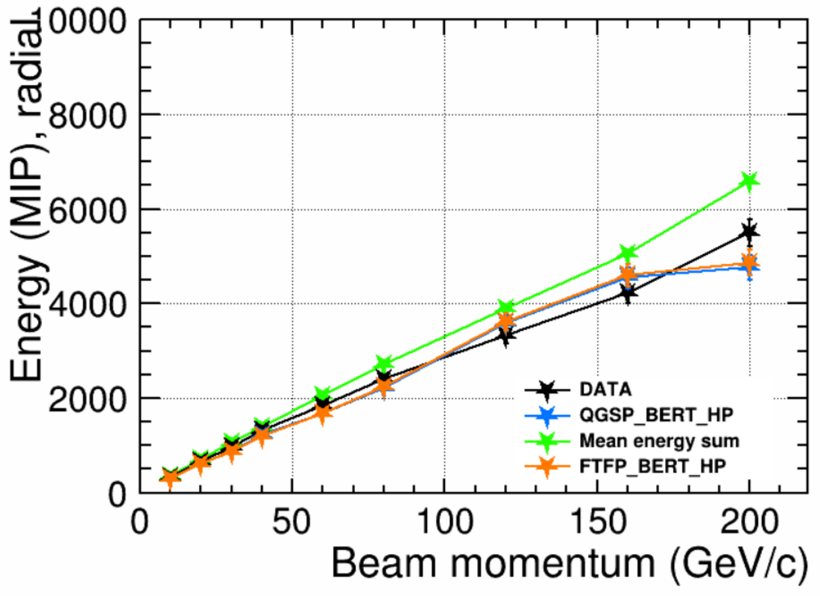
## Parameter E

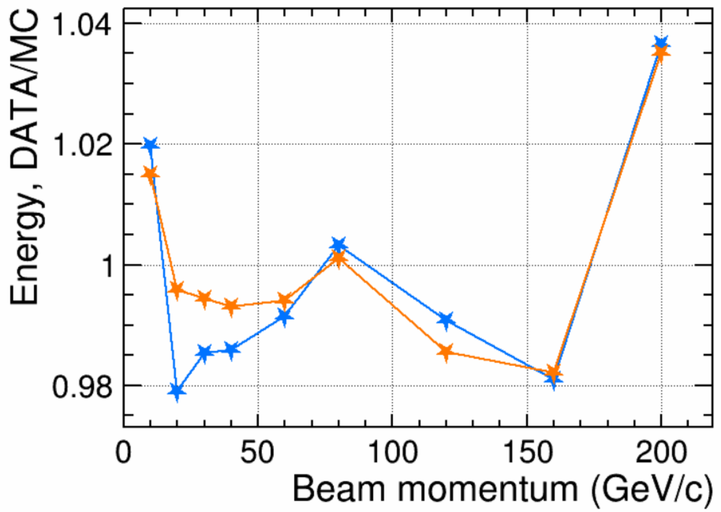
- This parameter is obtained from the longitudinal and radial fit function and is equal to the integral under the curves up to infinity as this corresponds to the mean visible energy in units of MIP

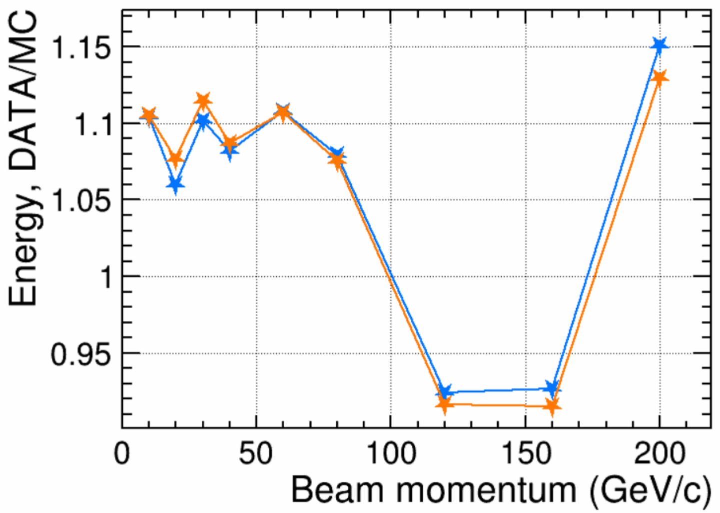
- The simulation predicts the showers produced in an ideal calorimeter with an infinite depth

- Also, the radial showers are well contained unlike the longitudinal showers



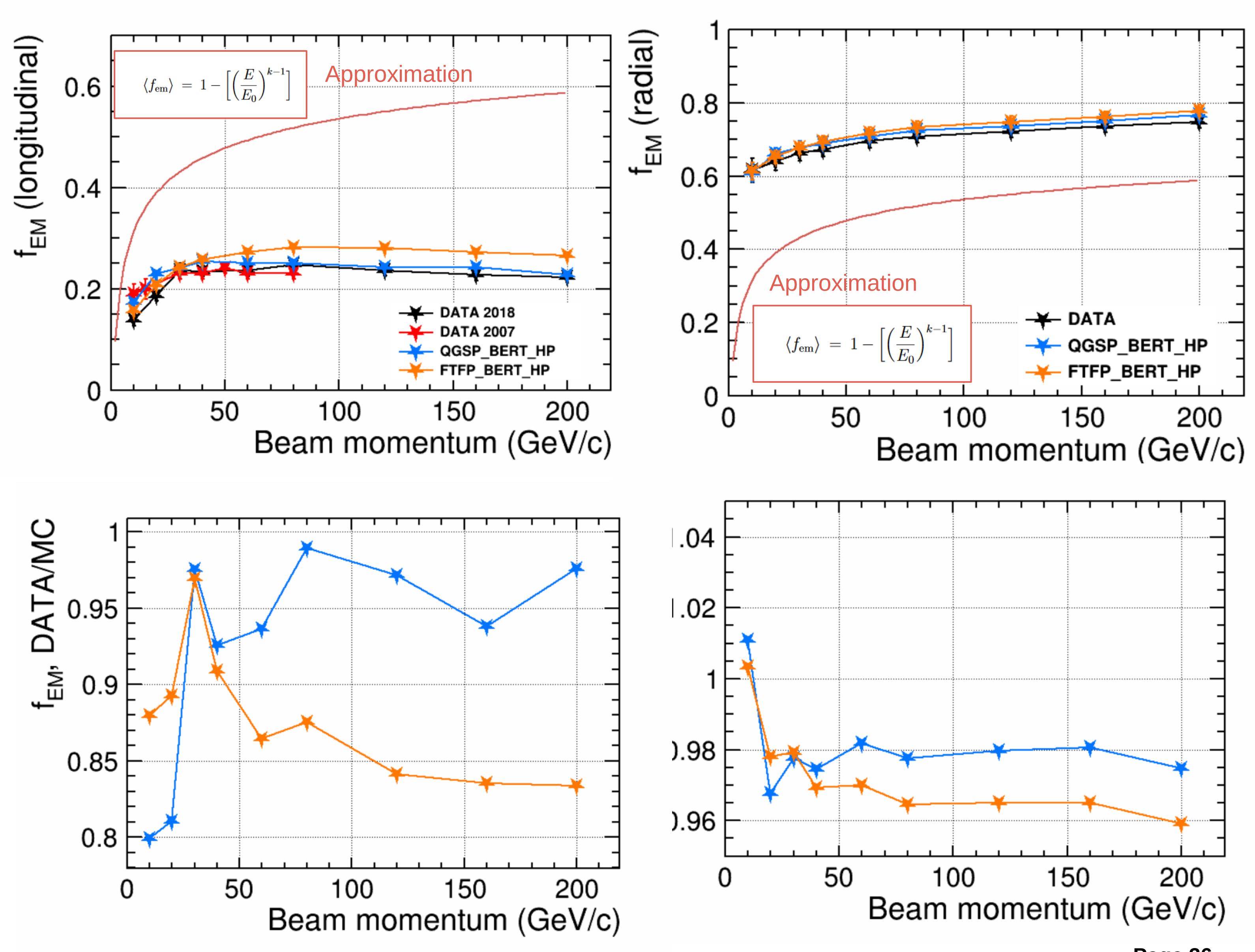



# Fraction of short/core component: "Average EM fraction"

## Parameter $f_{EM}$

- Fraction of hadron energy deposited via EM processes
- The $f_{EM}$ is sum of several single EM showers
- 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
- The fraction obtained from radial fits are overestimated. But the observed trend show a slow increase at higher energies



# h/e Signal Ratio

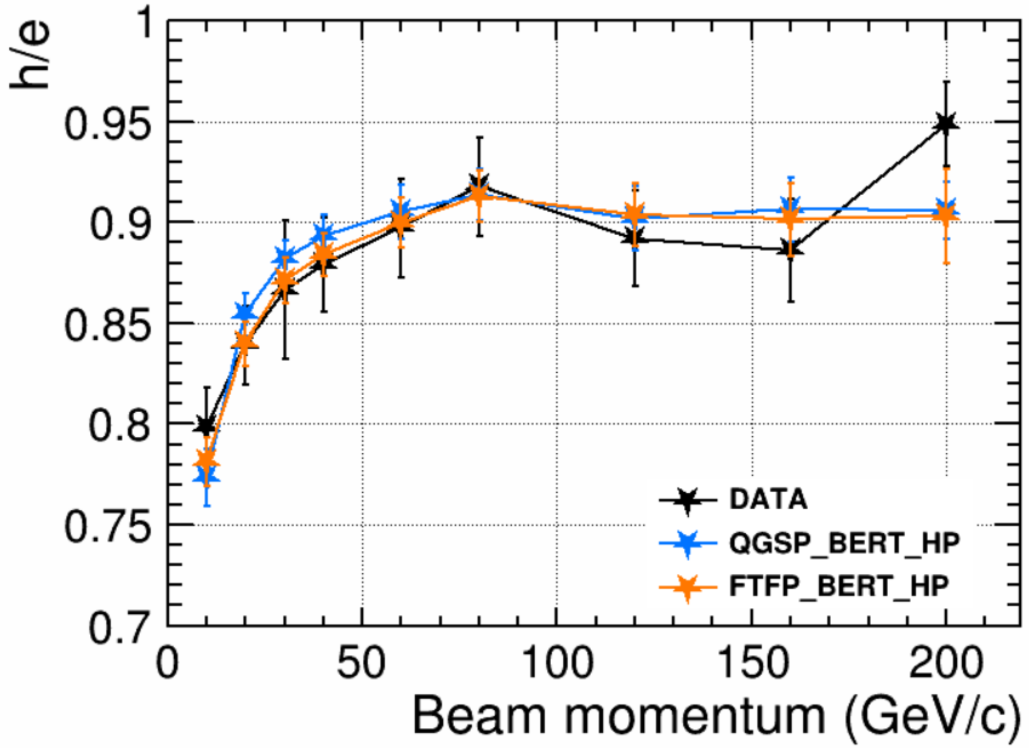
**The ratio of responses to the non-electromagnetic and electromagnetic components of a hadron-induced shower**

- 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

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

Electromagnetic calibration constant 0.02278 GeV/MIP

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

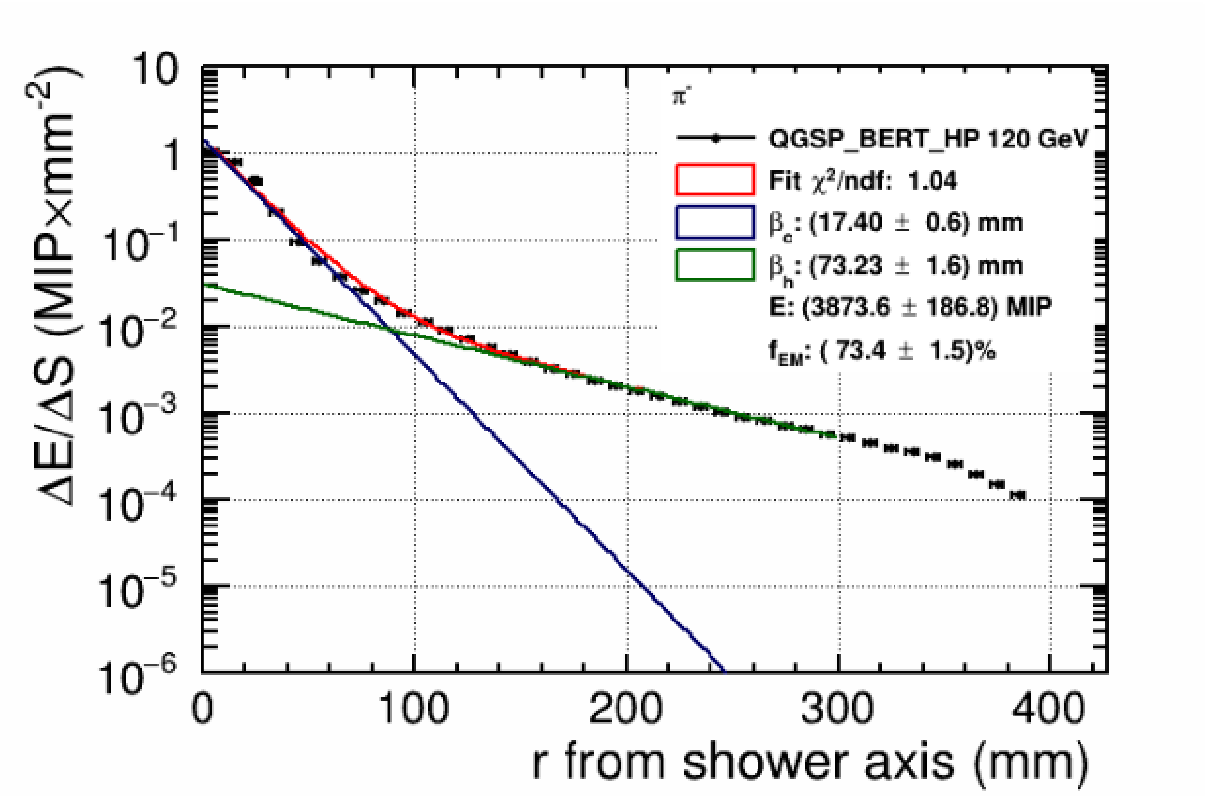


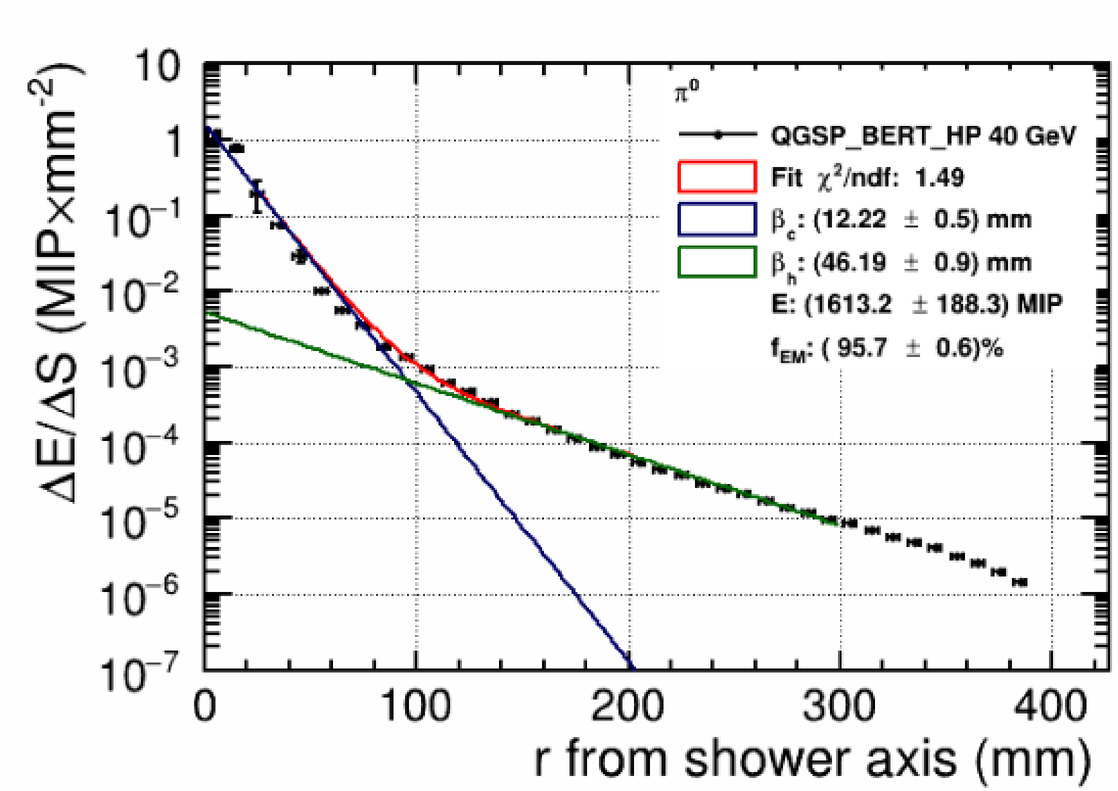

- h/e signal ratio is energy independent at higher energies as expected
- The values of h/e predicted by simulations are in agreement with data within 5%

# Comparison of core component to EM showers

## Outlook

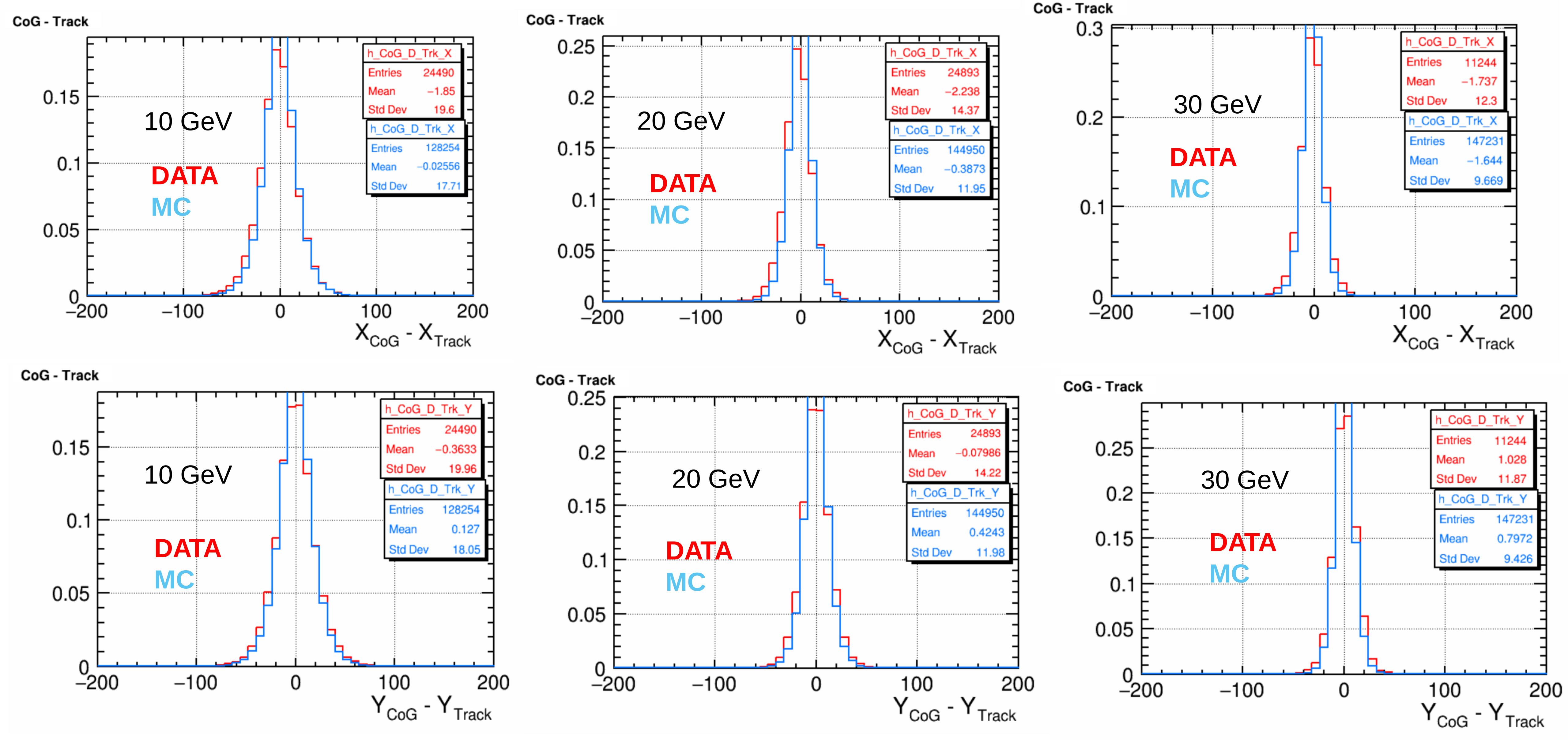
40 GeV pi0's are simulated using QGSP_BERT_HP physics list, very close the AHCAL detector. The fit parameter $\beta_c$ is compared between 120 GeV $\pi^-$ and 40 GeV $\pi^0$



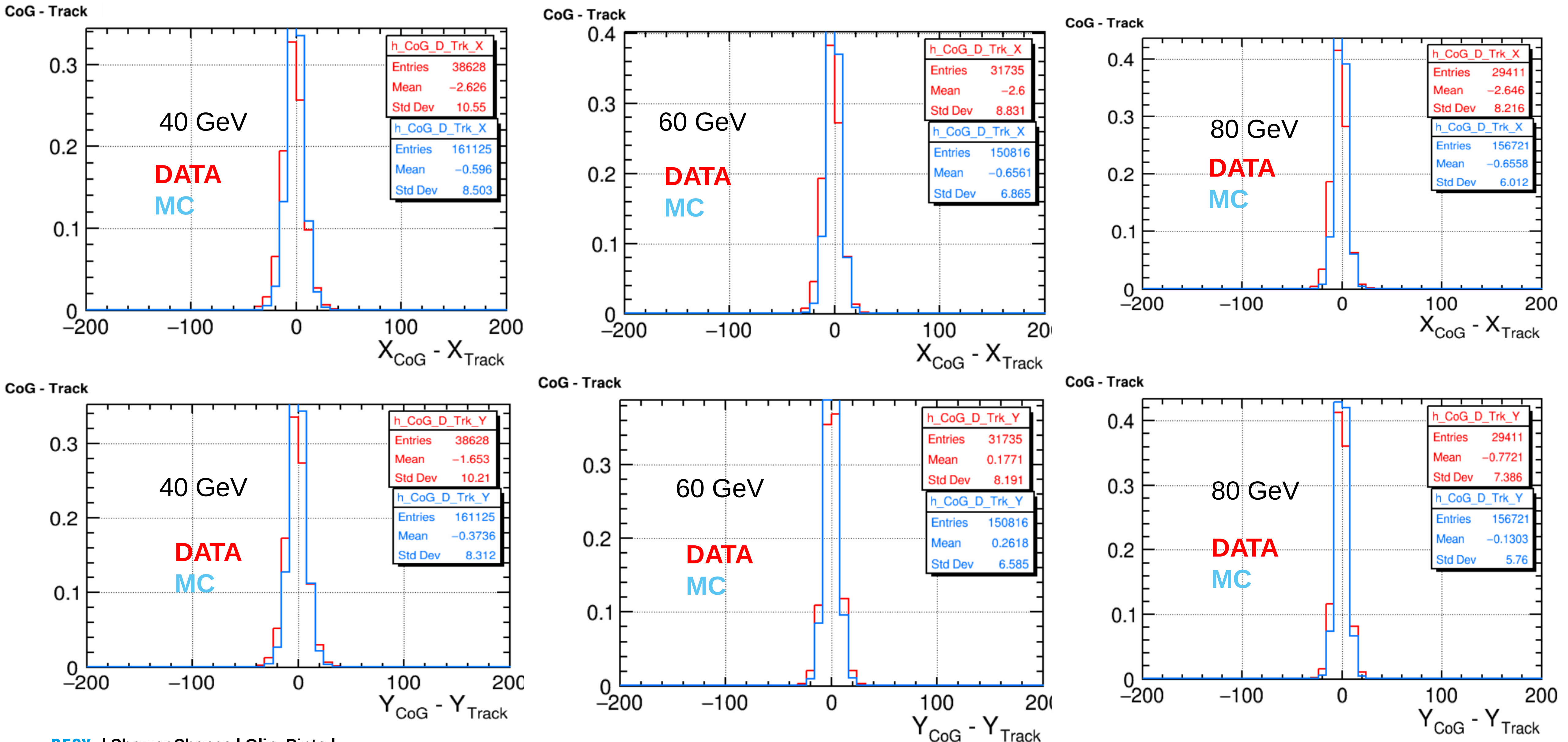




- There are clearly two components seen in EM showers
- The discrepancy in the electromagnetic fraction in radial and longitudinal fits, and the discrepancy between the fit values for pi0's and the core component in the pions, could possibly be interconnected!

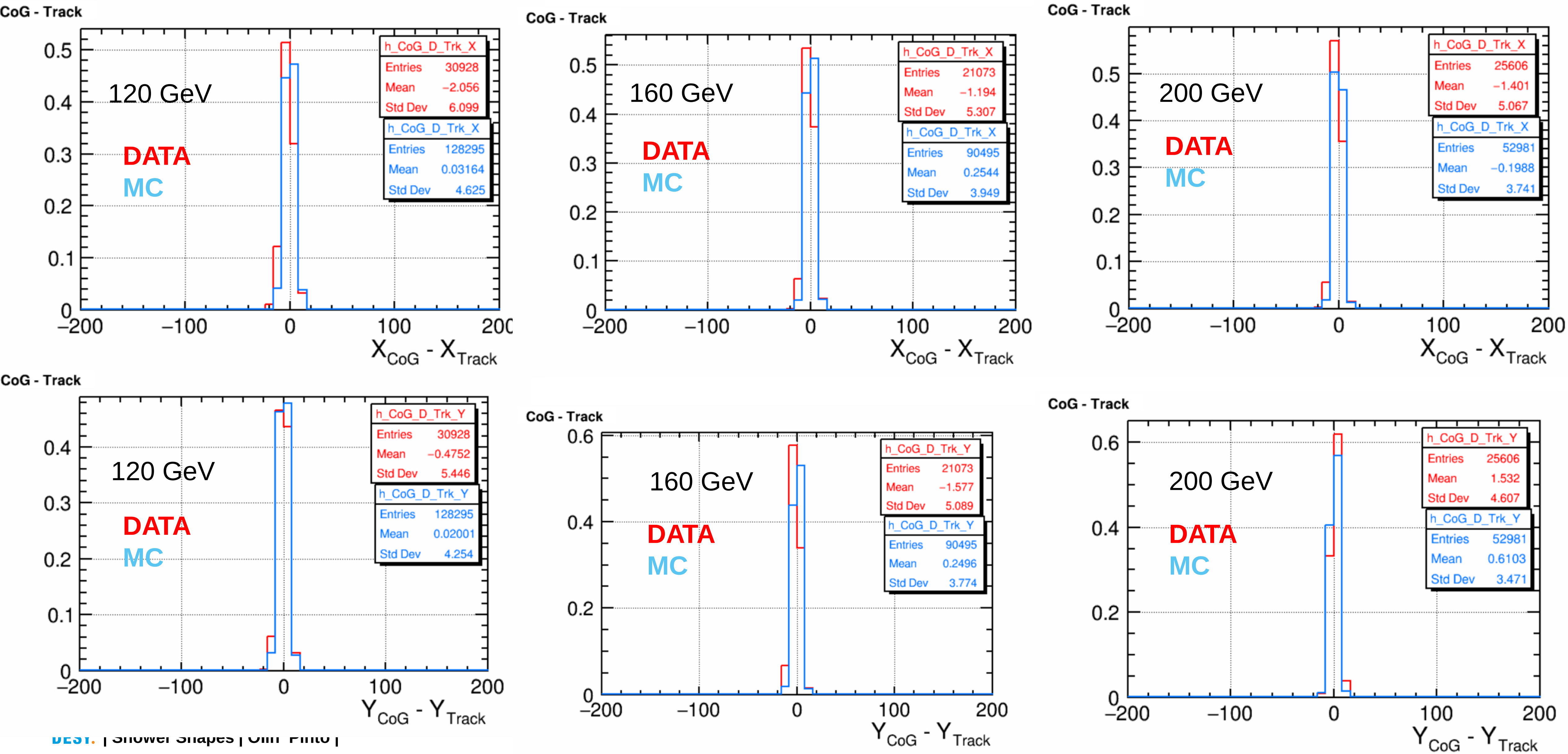
# Track to COG (event) Comparison



# Track to CoG (event) comparison



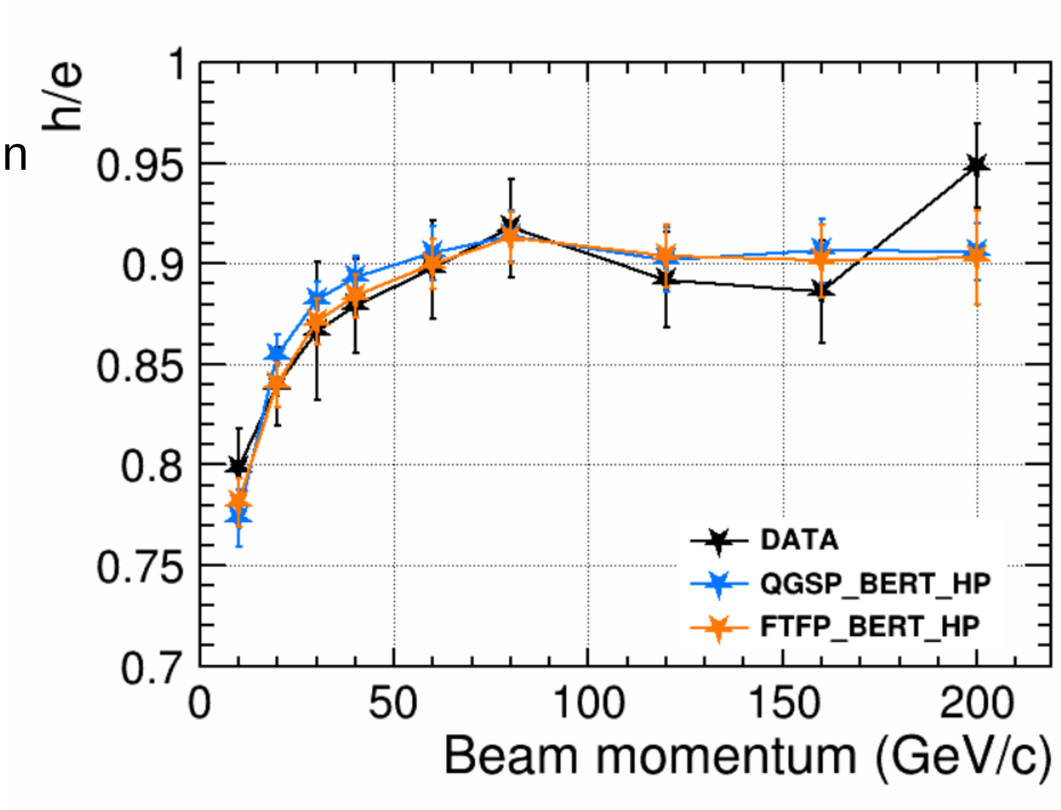
# Track to COG (event) Comparison



# 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




**<u>Possible interpretation of the shape at low energies</u>**

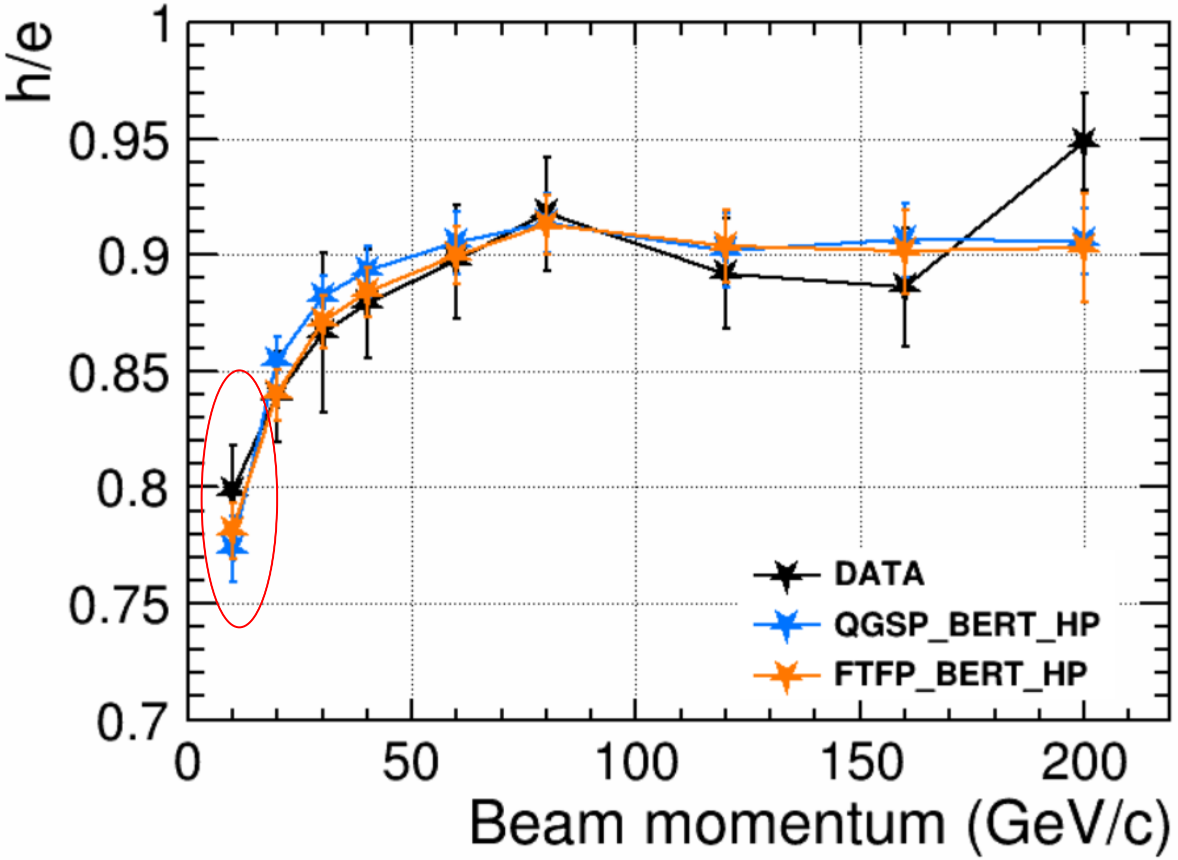
- With the little memory of the incident hadron, the **fraction of invisible energy** that is detected in calo. is more less the same for all energies
  - A possible interpretation is that the invisible energy is higher at low beam energy

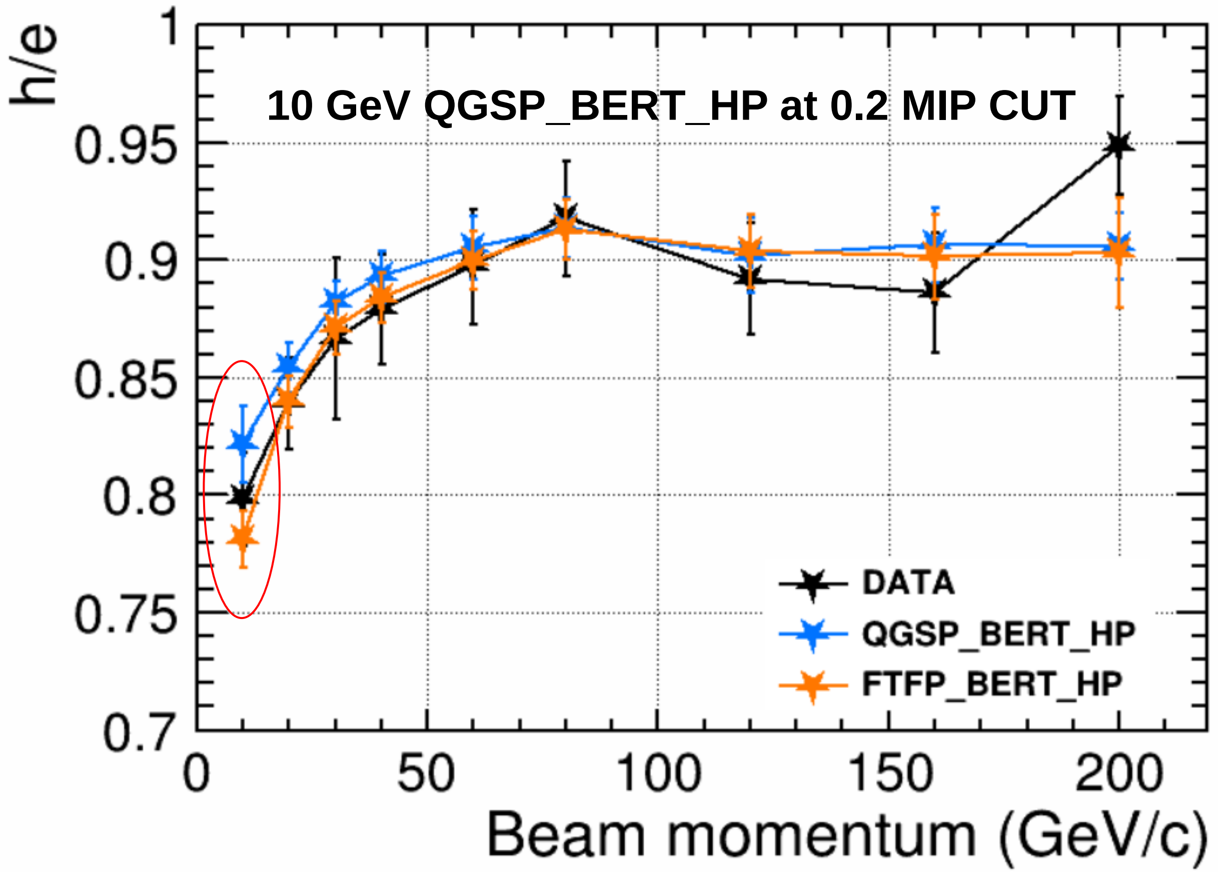
Possibly my fits are not described well below 50 GeV!

**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?



# More Shower Shapes to come…