Studies of Average Shower Shapes with 2018 Testbeam Data

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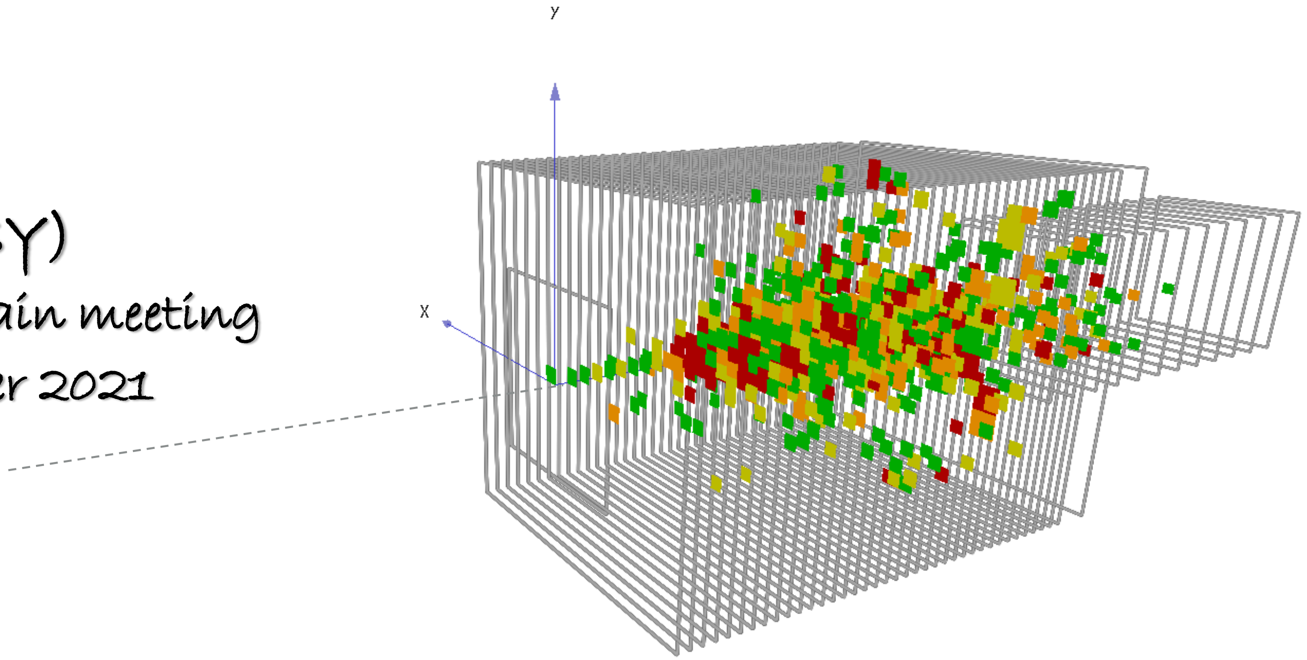
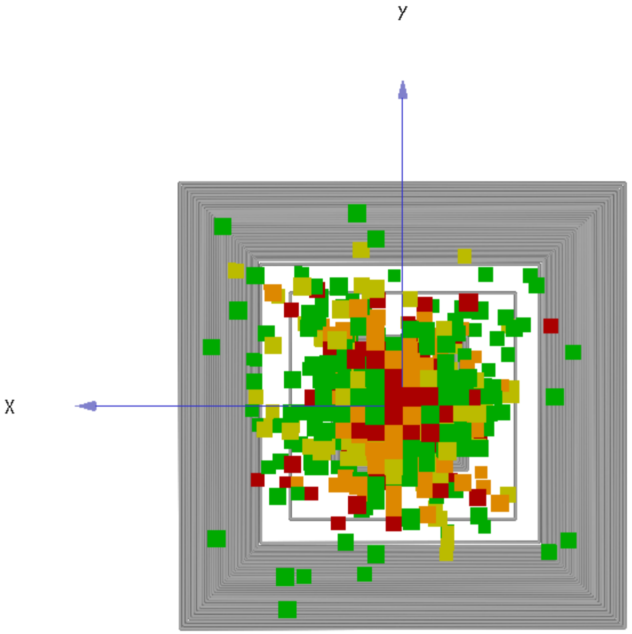
CALICE AHCAL main meeting

DESY, 08th December 2021





HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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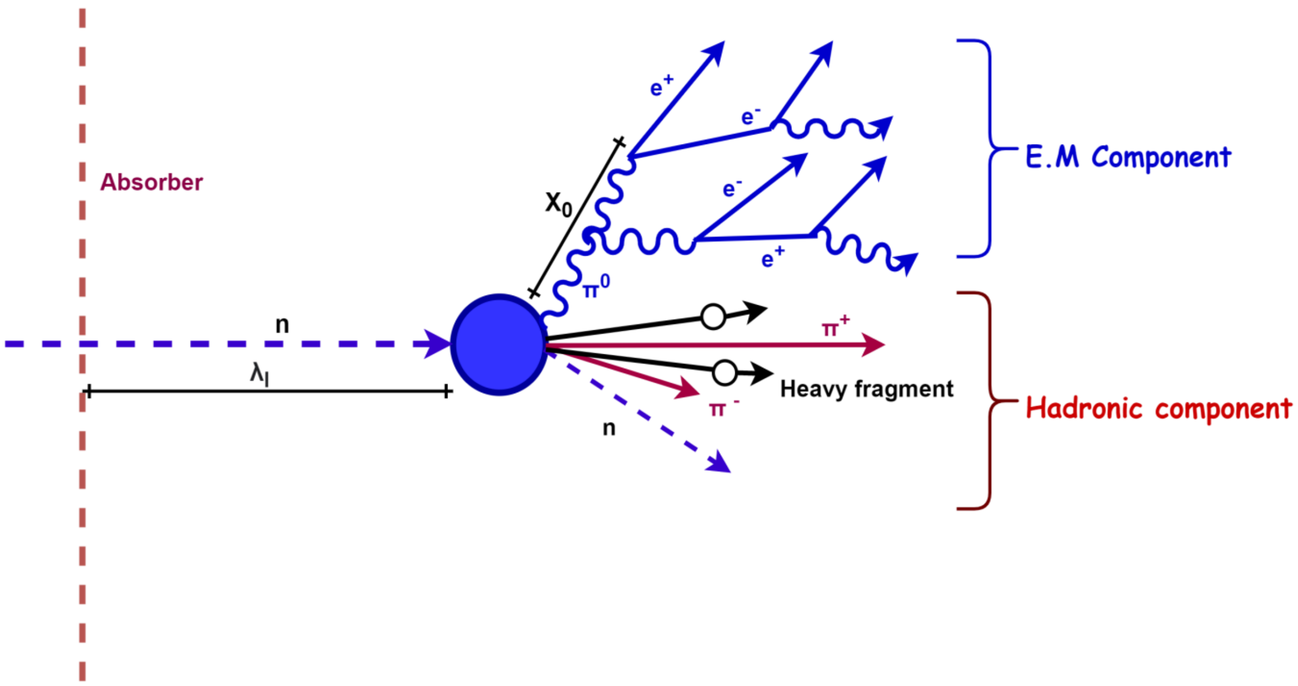
How does a hadronic shower look like?

Sketch of hadronic shower

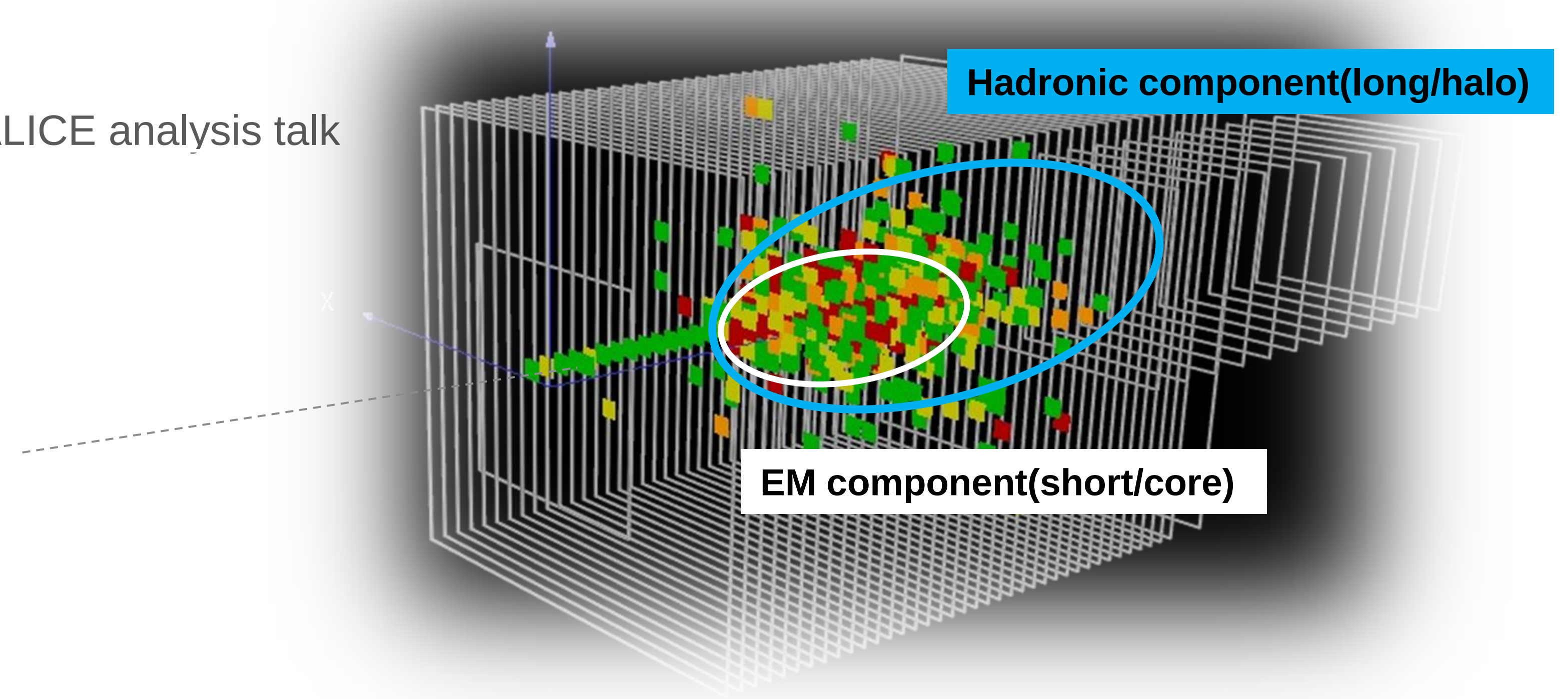


- Consists mainly charged and neutral pions
- Large component of secondary particles in hadron cascades are π^0
    - Initiating electromagnetic sub-cascades in a hadron shower
    - which represent ~ 1/3 of total energy produced in each inelastic collision
- Hadronic showers have a complex structure 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 model the shape of an average hadronic shower**
  - **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”**

This talk is partly an extension of the CALICE analysis talk



Samples and Selection

Samples

- Data for electrons & 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-technique 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)

e^+	
Energy (GeV)	Run No.
10	61293
20	61296
30	61213
40	61212
50	61214
60	61211
70	61215
80	61210
90	61216
100	61217

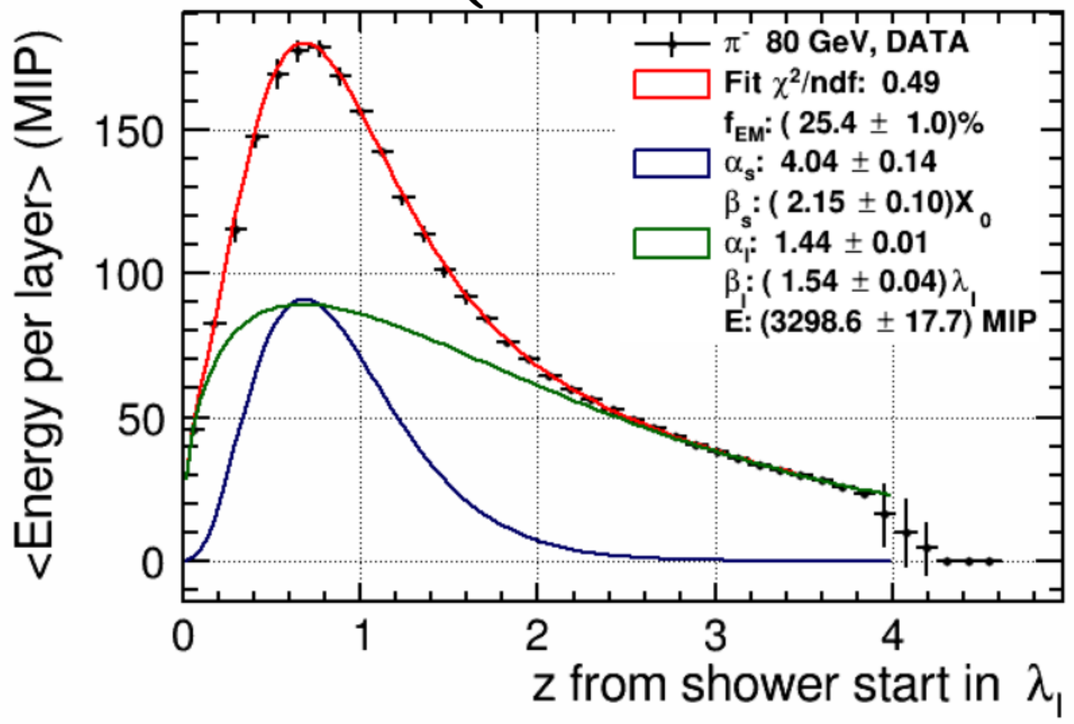
π^-	
Energy (GeV)	Run No.
10	61265
20	61273
30	61384
40	61275
60	61262
80	61279
120	61287
160	61222
200	61201

Longitudinal Parametrization

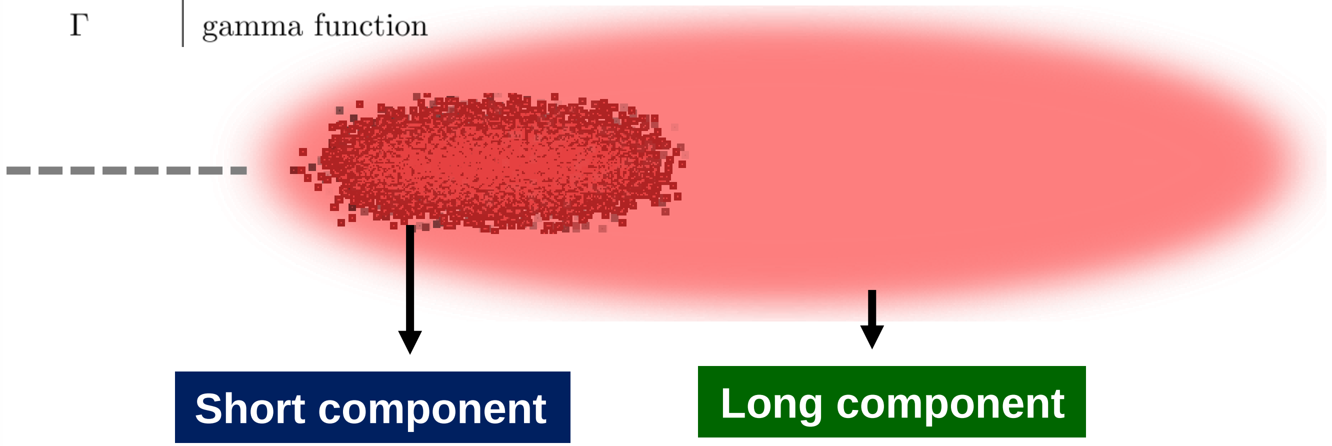
- **Longitudinal profile** is the mean energy deposited per layer from the shower start
- Parametrised with a sum of two Gamma-functions

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

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



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

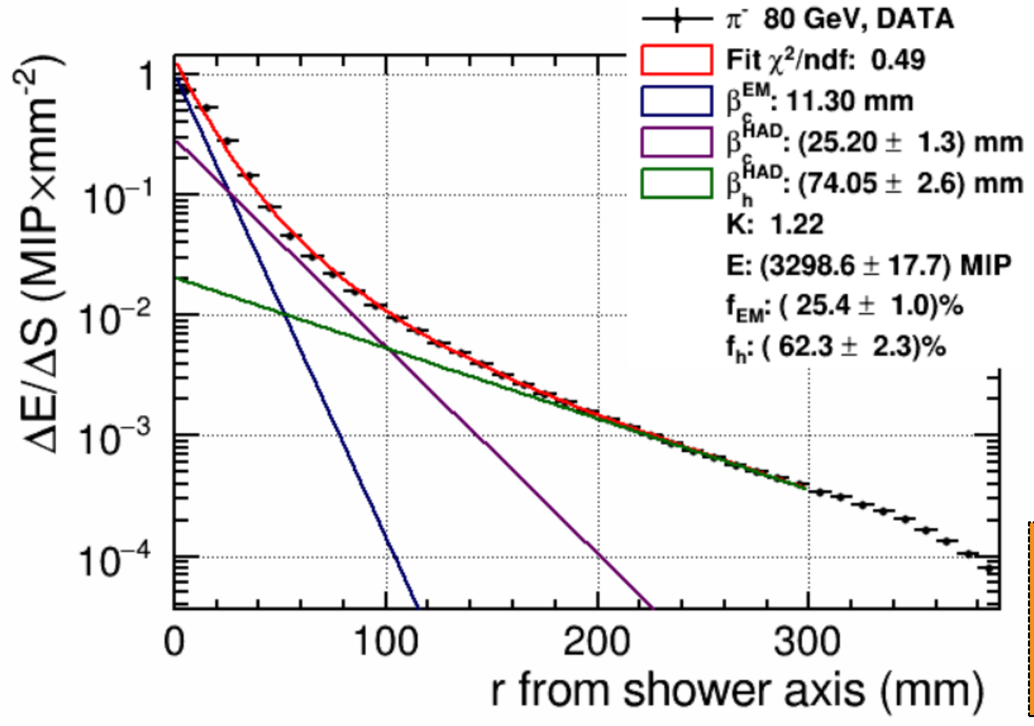


Radial Parametrization

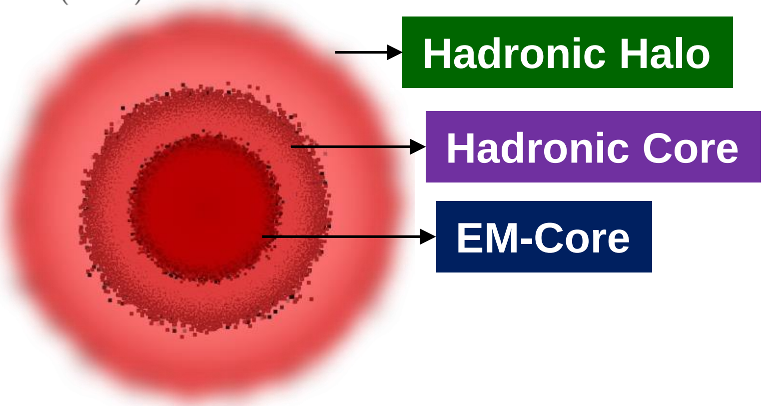
- **Radial profile** is the distribution of the energy density as a function of the radial distance to the shower axis

- Parametrized with the sum of three exponential distribution

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

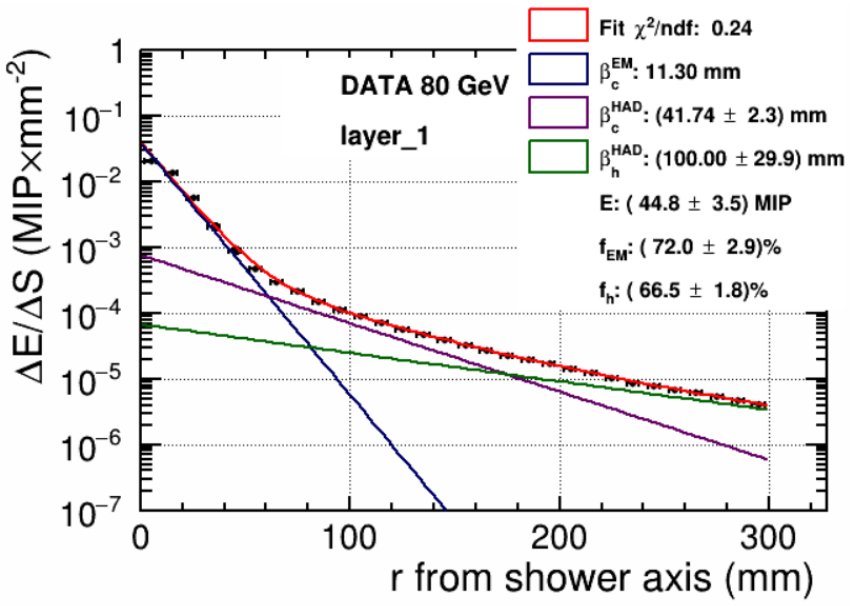


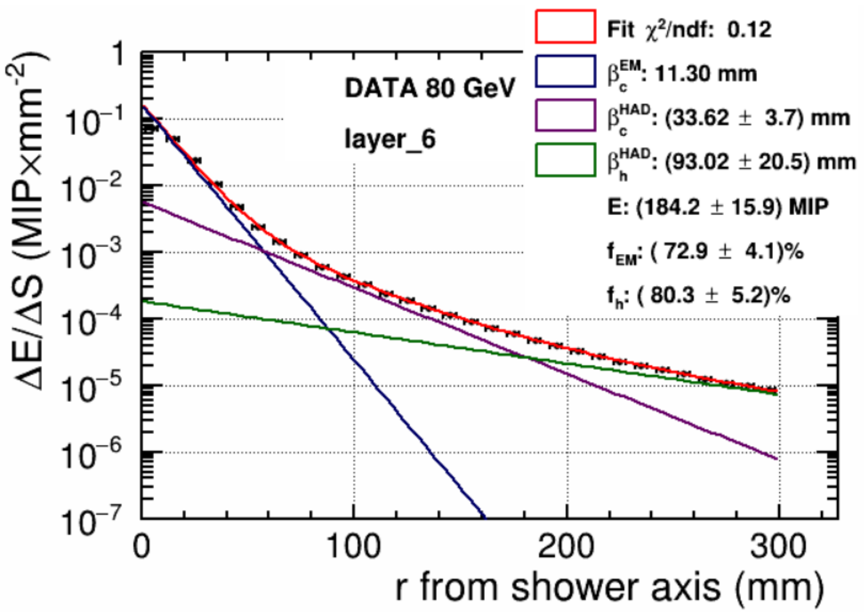
parameter	meaning
r	radial distance from shower axis (mm)
ΔS	2πrΔr, area of the ring of width Δr (mm^2)
E	mean visible energy (MIP)
K	leakage fraction
f	EM-fraction
β_c^{EM}	EM-core (mm)
f	halo-fraction
$\beta_c^{HAD}, \beta_h^{HAD}$	hadronic core and halo (mm)

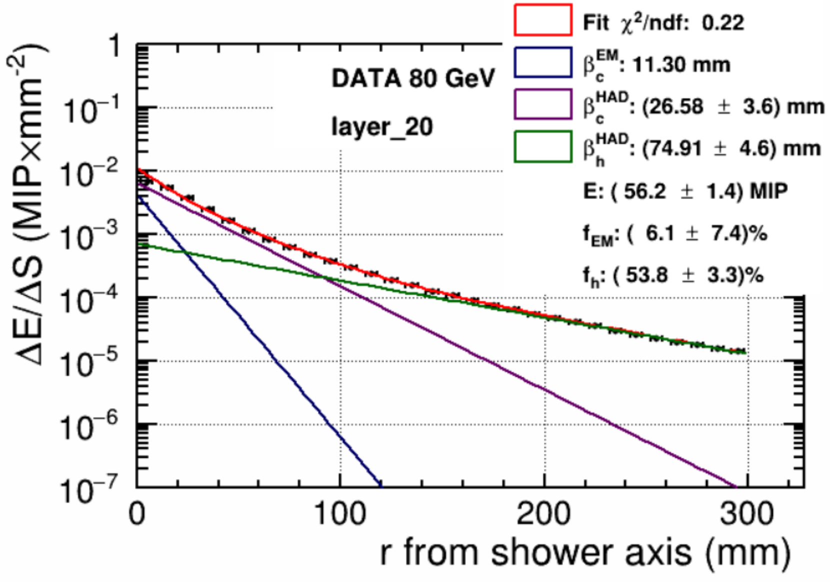


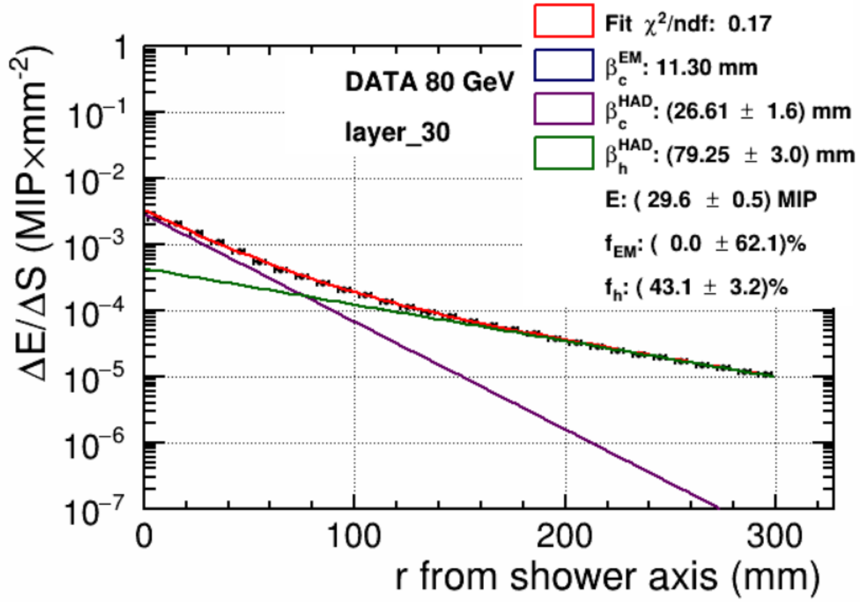
- With these parametrisations, we get **consistent EM fraction and total energy** from the two projections of the shower
- Let's see how the radial profile changes along the shower!

Radial shapes layer-wise

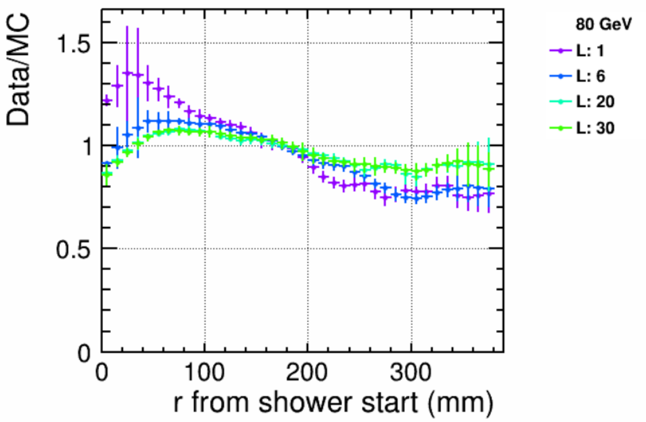








- Radial shapes layer-wise are obtained for layers beyond shower start
  - First layer
  - Layer at shower max.
  - Intermediate layer
  - Nearly last layer
- Allows to check the dependence of the radial parameters on the layer number

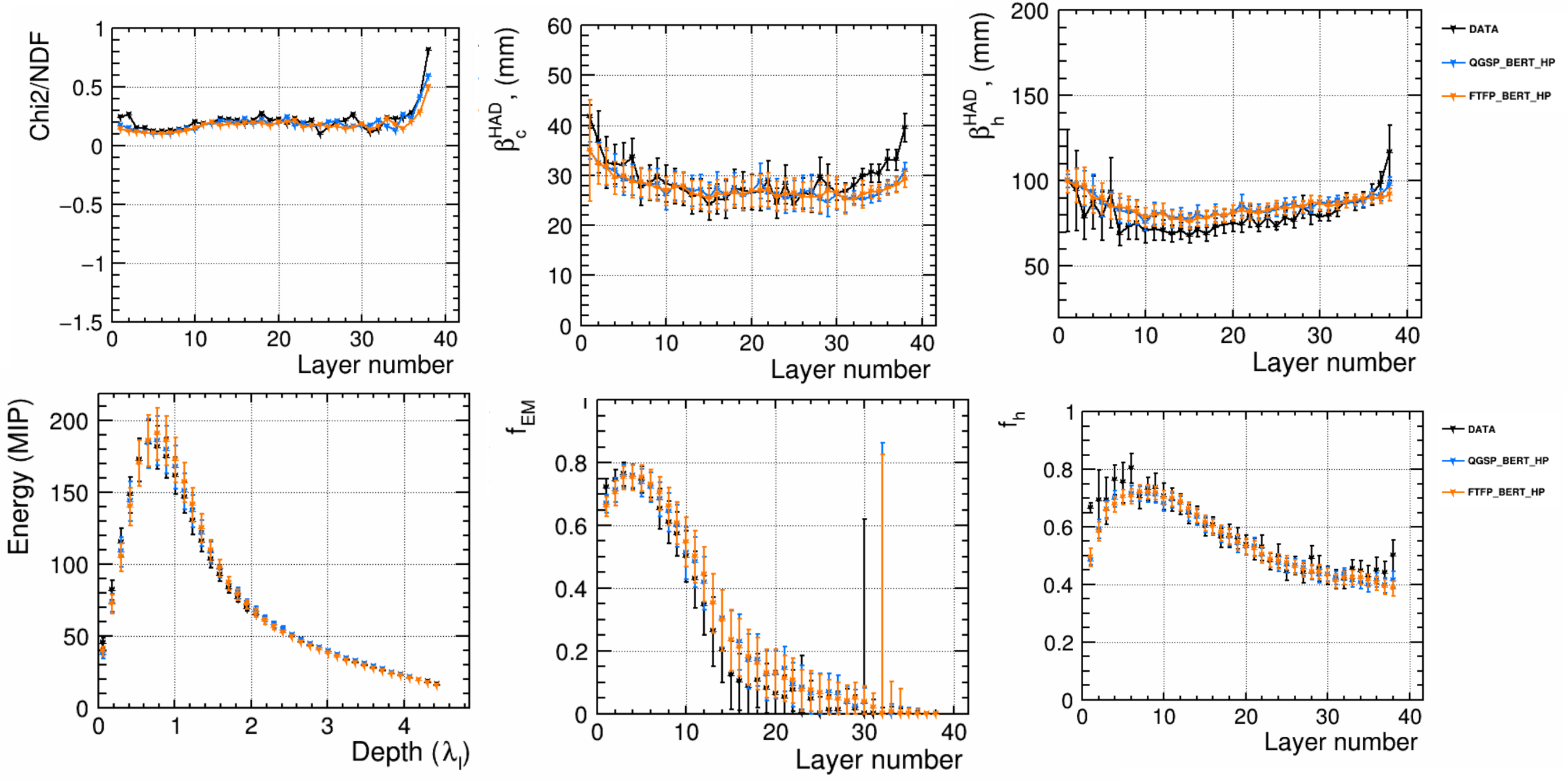


- Agreement between Data and MC is within ~20% for layers beyond 1

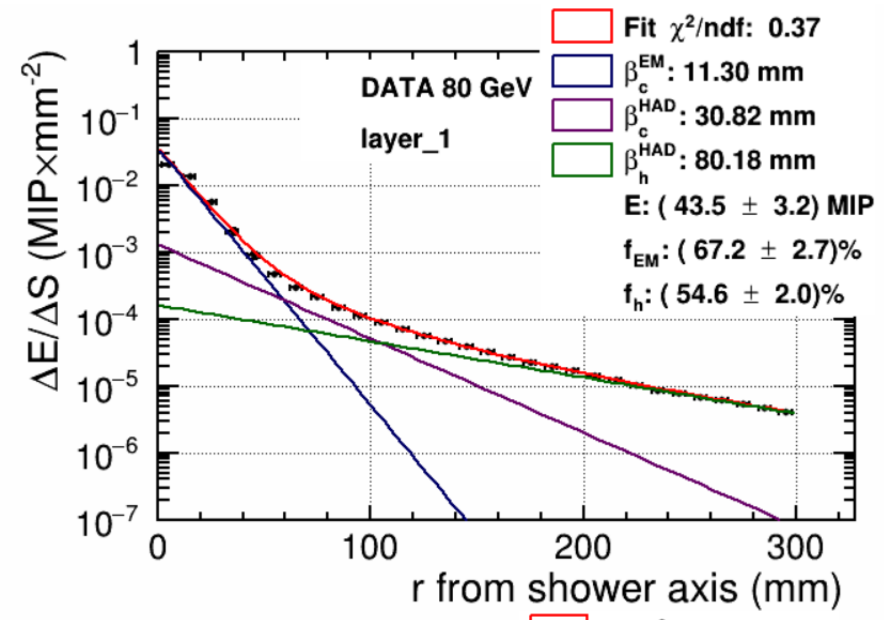
Parameters

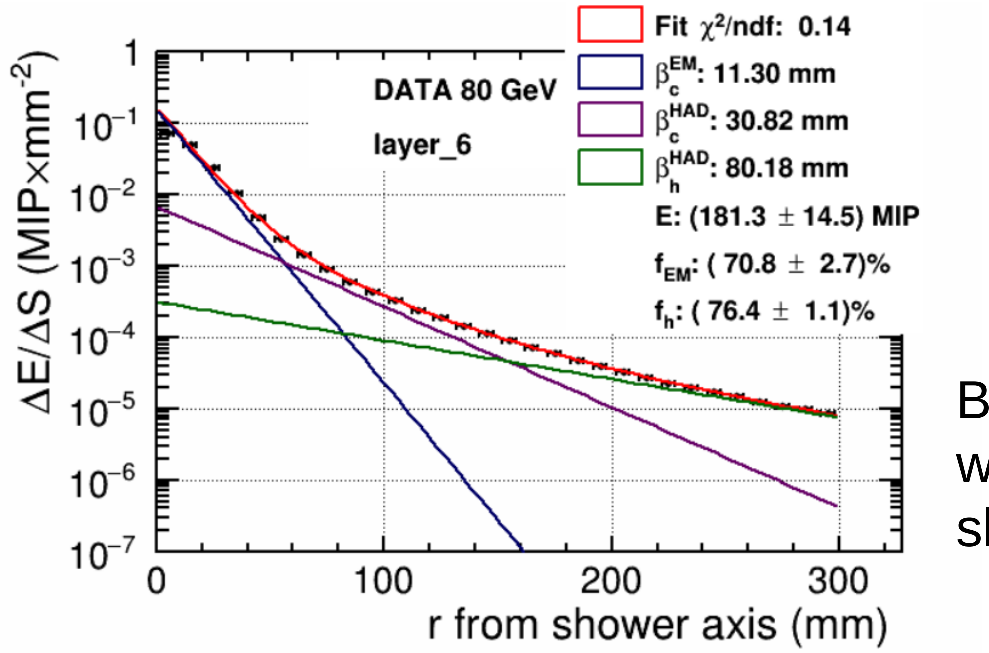
80 GeV Data

- The beta's show very little dependence through the layers
- Let's fix the beta's based on the values from simultaneous fits of longitudinal and radial shapes

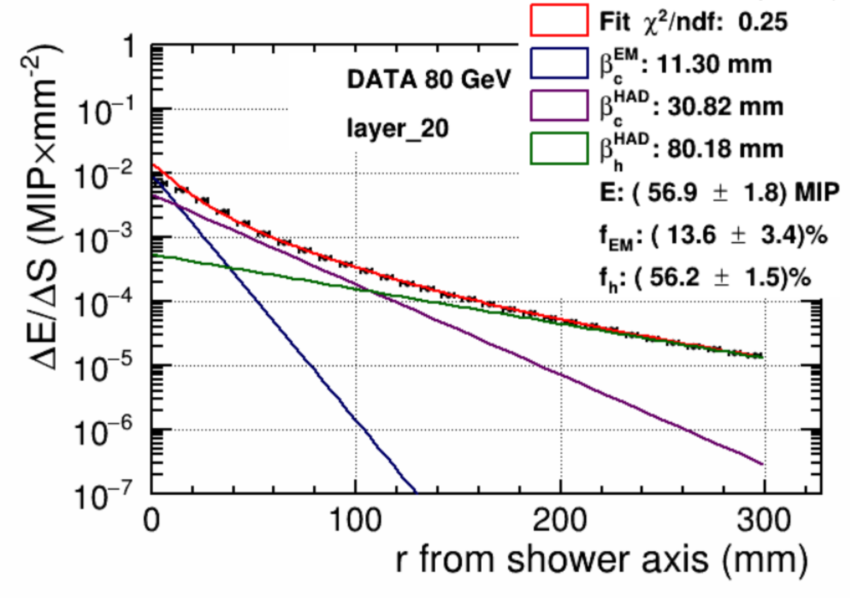


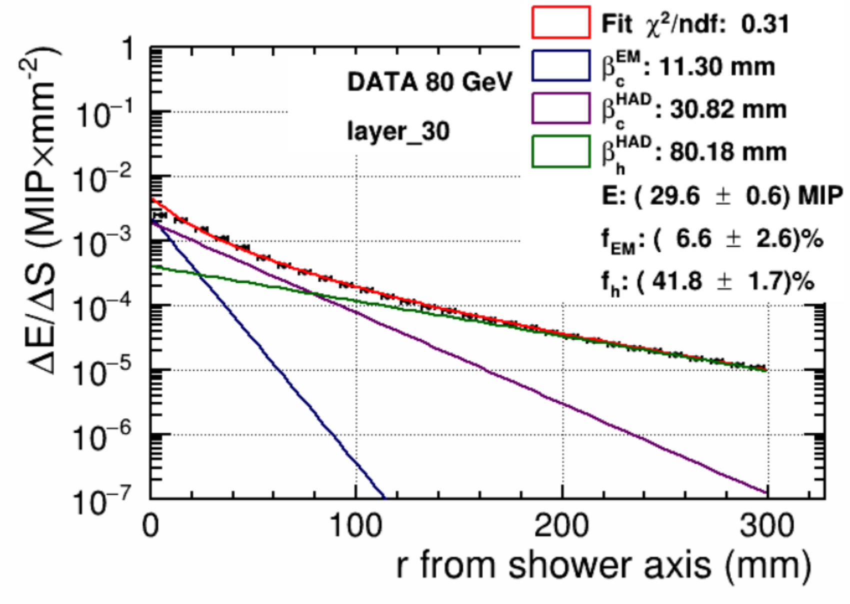
Radial shapes layer-wise

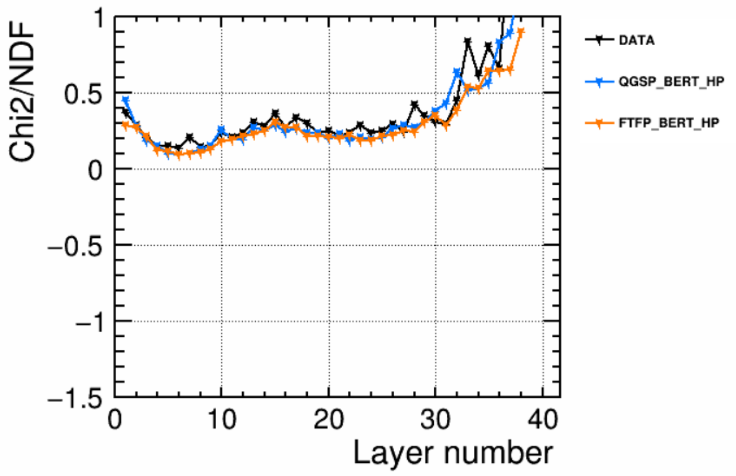




Behaviour of radial shapes well explained using fixed slopes

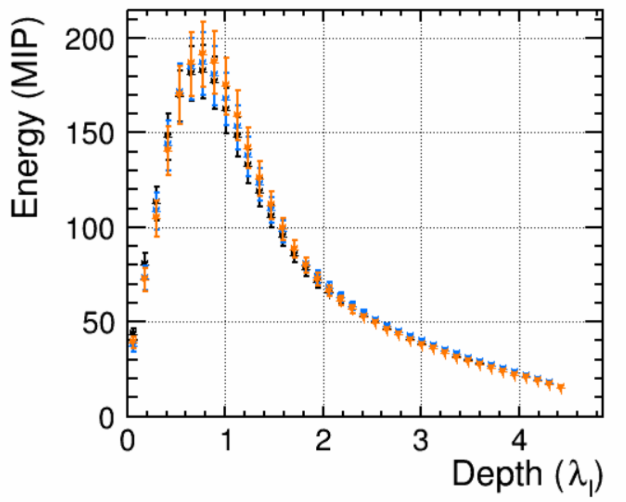


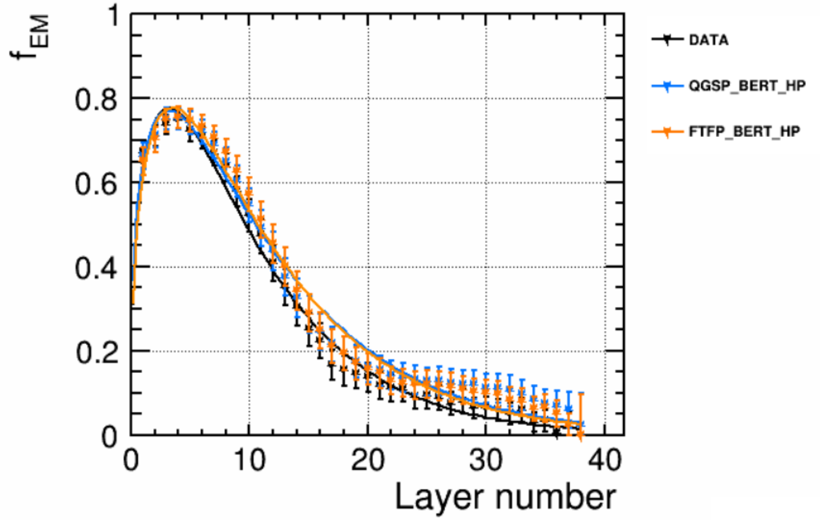


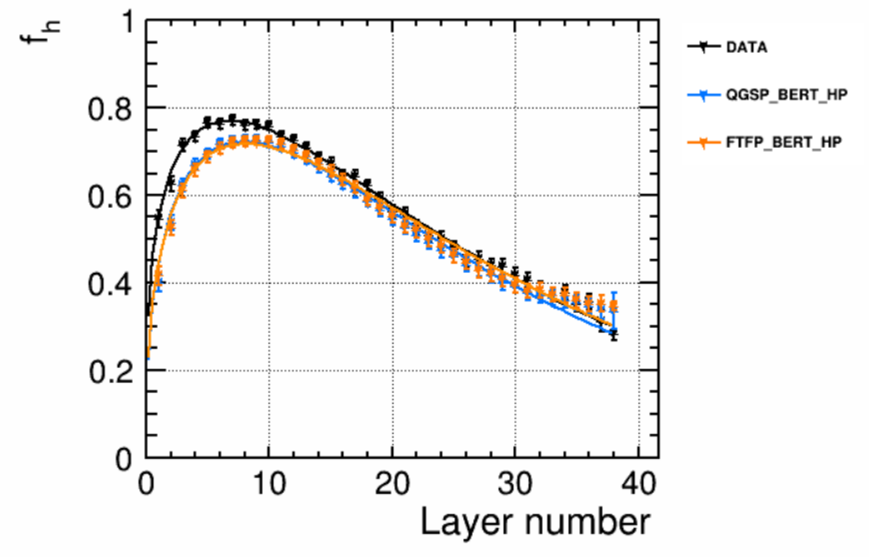


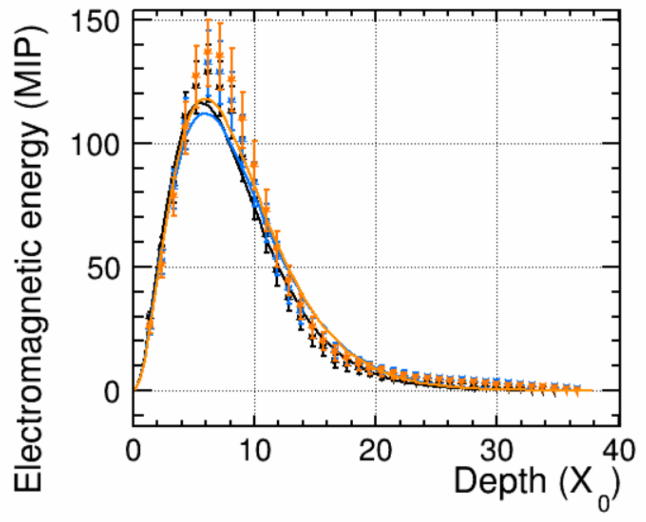
Parameters

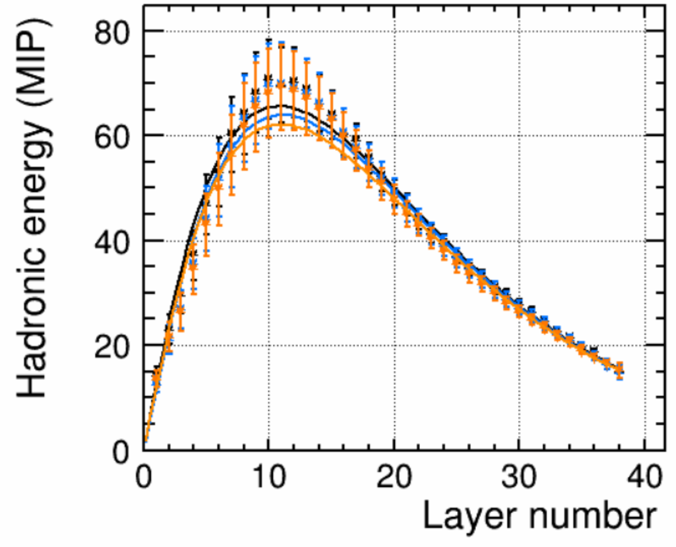
80 GeV Data











- Assumption in longitudinal fit that the short part is related to EM and long part to Hadronic,
  - Then split into electromagnetic and hadronic part energy then these individually should agree with one Gamma function.

$$\Delta E(z) = E \cdot \left\{ \frac{1}{\Gamma(\alpha)} \cdot \left(\frac{Z}{\beta}\right)^{\alpha-1} \cdot \frac{e^{\frac{-Z}{\beta}}}{\beta} \right\}$$

- The energies (EM & Hadronic) and fraction’s are described by a single Gamma function

Comparison of EM core of hadron shower to electrons

comparison of the longitudinal shape

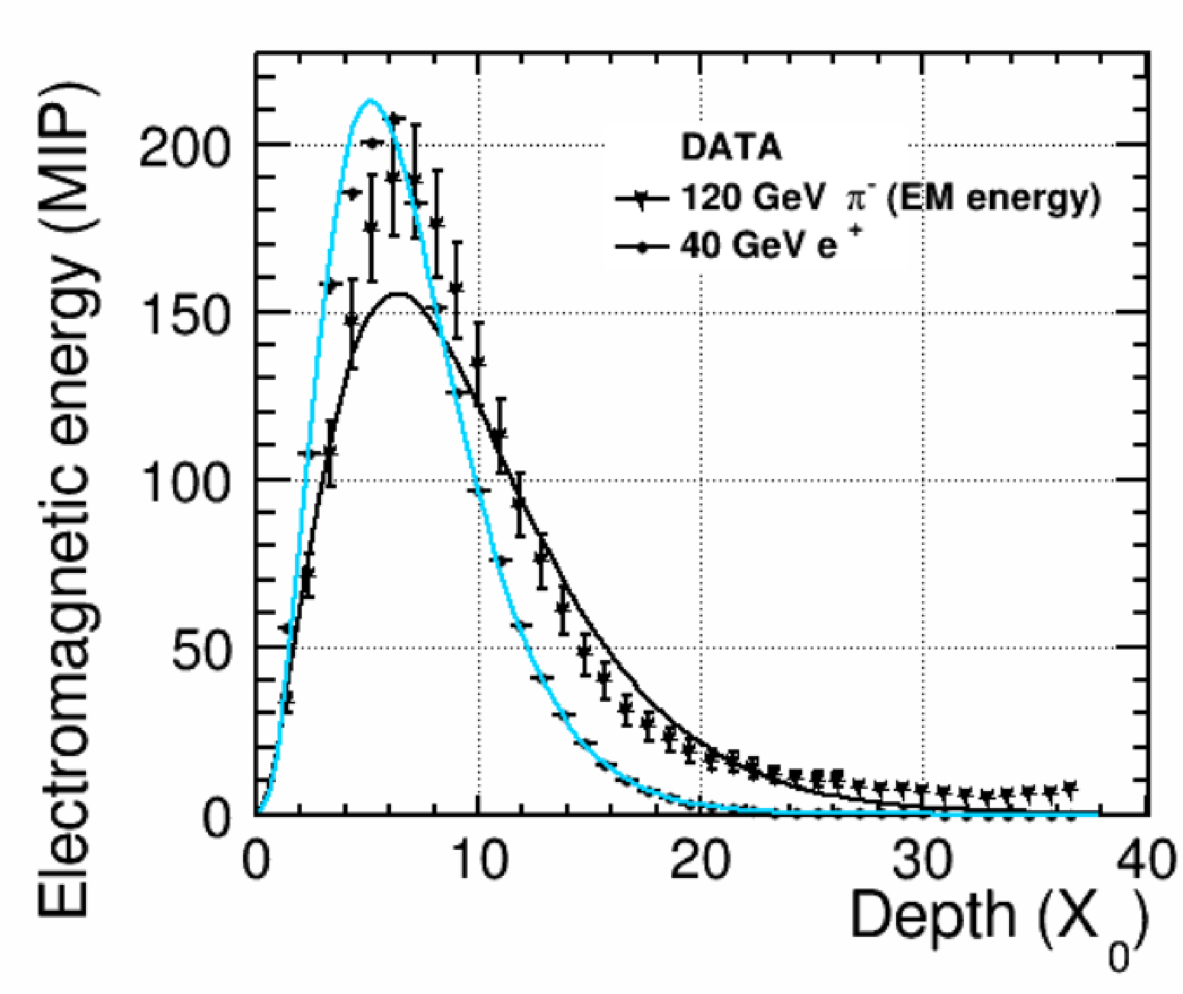
Is our hypothesis of simplified picture of a hadronic shower correct?

- A simple Gamma function does not fully describe the data

$$\Delta E(z) = E \cdot \left\{ \frac{1}{\Gamma(\alpha)} \cdot \left(\frac{Z}{\beta}\right)^{\alpha-1} \cdot \frac{e^{\frac{-Z}{\beta}}}{\beta} \right\}$$

- The depth of the maximum looks fairly similar for electrons and pions

- But, longer tails in pions
  - EM energy is deposited by later shower generations, and is deeper in the calorimeter

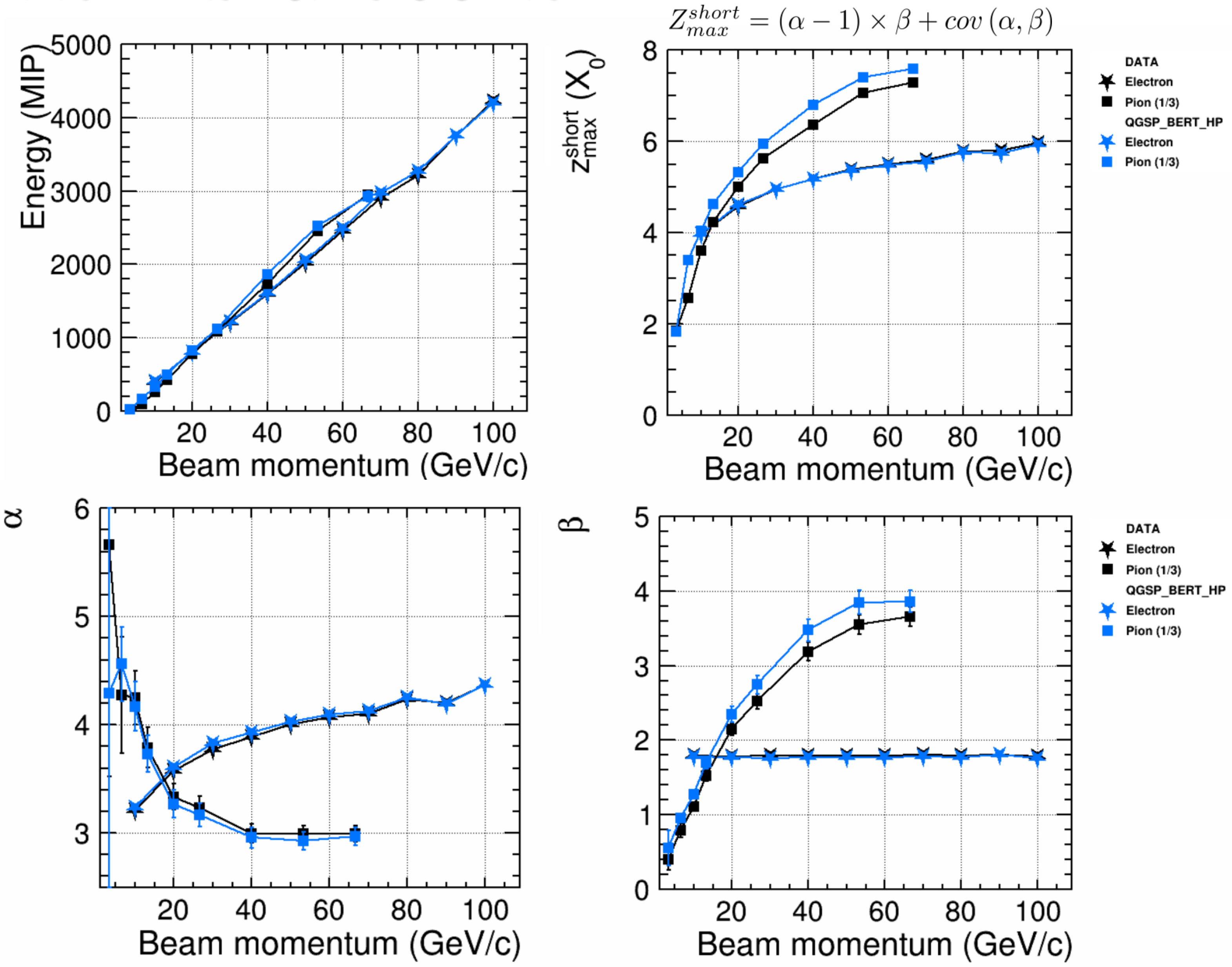


Comparison of EM core of hadron shower to electrons

fit parameters

To study the energy dependence, available pion energies are plotted to 1/3 of its corresponding energy

- **The parameters obtained from the EM-part of the pion showers do not fully agree in shape to the purely electron showers**
  - **limitations of our simple assumption**



3D Fits

We have seen that the layer-wise fits work with the same betas for all layers.
Try this fit with layer-independent hadronic beta’s

Parametrization

- Three terms, each individually written as:
  - **EM core** with one z dependent function and with exp. in r
  - **Hadronic** with two parts: core and halo with z times function of r
  - It is the sum of two which are factorized in r and z

EM Core **Hadronic**

$$\frac{\Delta E}{\Delta A}(r,z) = \frac{1}{2\pi}\left\{\frac{E_{EM}}{\Gamma(\alpha_s)}\cdot\left(\frac{z}{\beta_s}\right)^{\alpha_s-1}\cdot\frac{e^{\frac{-z}{\beta_s}}}{\beta_s}\cdot\frac{e^{\frac{-r}{\beta_c^{EM}}}}{(\beta_c^{EM})^2}+\frac{E_{HAD}}{\Gamma(\alpha_l)}\cdot\left(\frac{z}{\beta_l}\right)^{\alpha_l-1}\cdot\frac{e^{\frac{-z}{\beta_l}}}{\beta_l}\right.$$

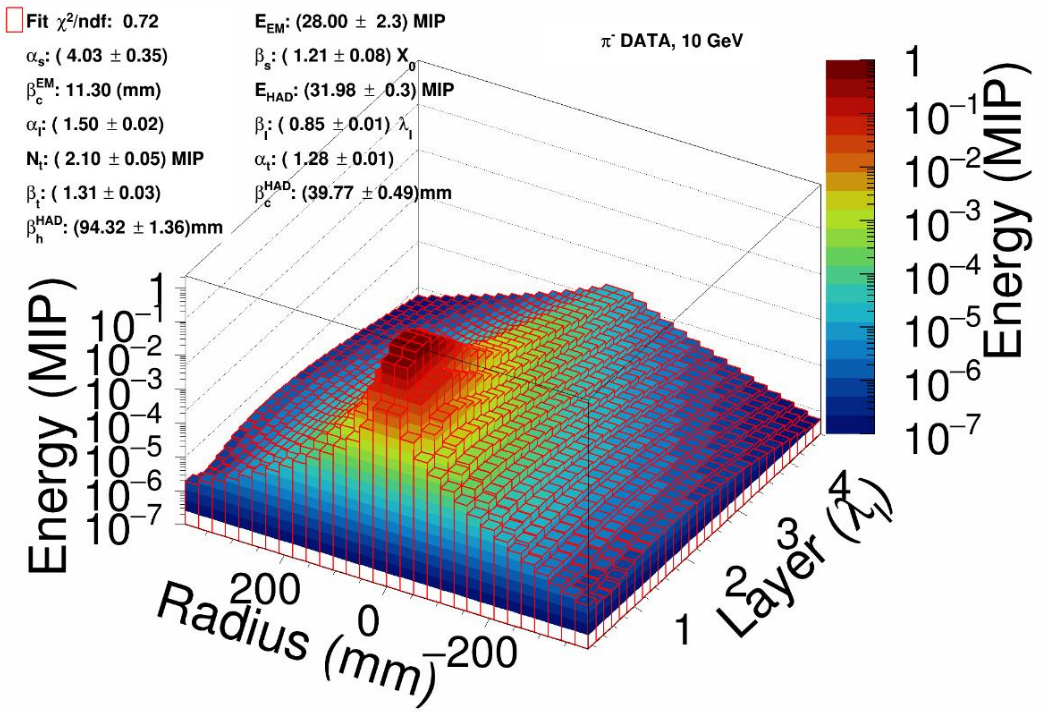
$$\left.\left(\frac{N_t}{\Gamma(\alpha_t)}\cdot\left(\frac{z}{\beta_t}\right)^{\alpha_t-1}\cdot\frac{e^{\frac{-z}{\beta_t}}}{\beta_t}\cdot\frac{e^{\frac{-r}{\beta_c^{HAD}}}}{(\beta_c^{HAD})^2}+\left(1-\left(\frac{N_t}{\Gamma(\alpha_t)}\cdot\left(\frac{z}{\beta_t}\right)^{\alpha_t-1}\cdot\frac{e^{\frac{-z}{\beta_t}}}{\beta_t}\right)\right)\cdot\frac{e^{\frac{-r}{\beta_h^{HAD}}}}{(\beta_h^{HAD})^2}\right)\right\}$$

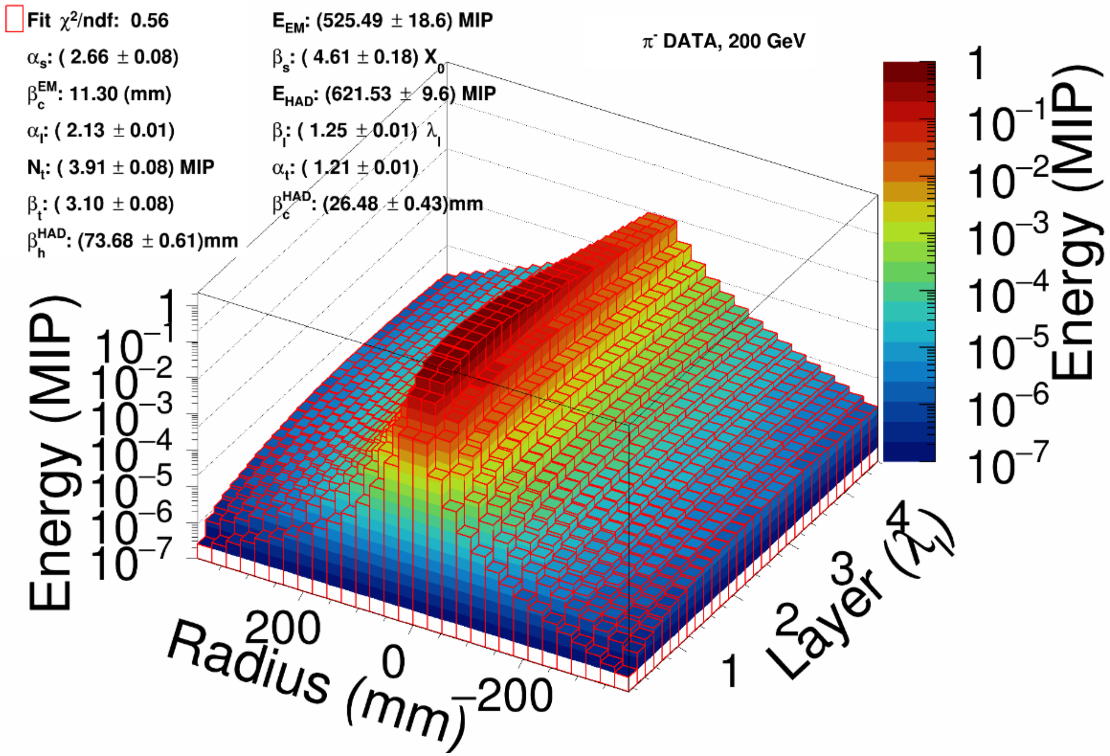
Total 12 parameters that allow determining the 3D shape of a hadronic shower

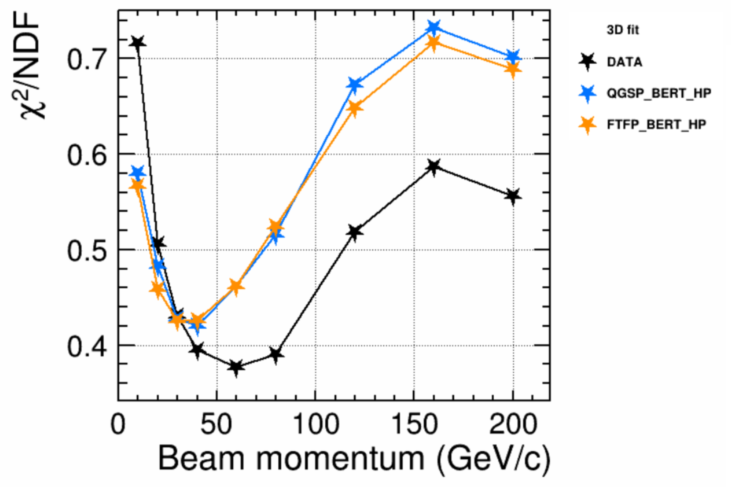
- 3 radial slopes
- Normalisations for each:
  - The energy of the electromagnetic core,
  - The energy of the hadronic component,
  - The halo fraction of the hadronic component
- parameters from 3 gamma function

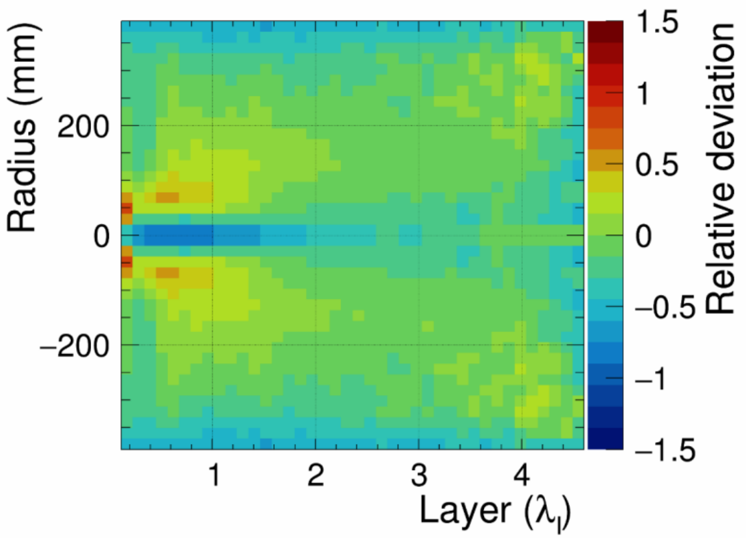
Can this parametrization describe the longitudinal and radial evolution of pion showers?

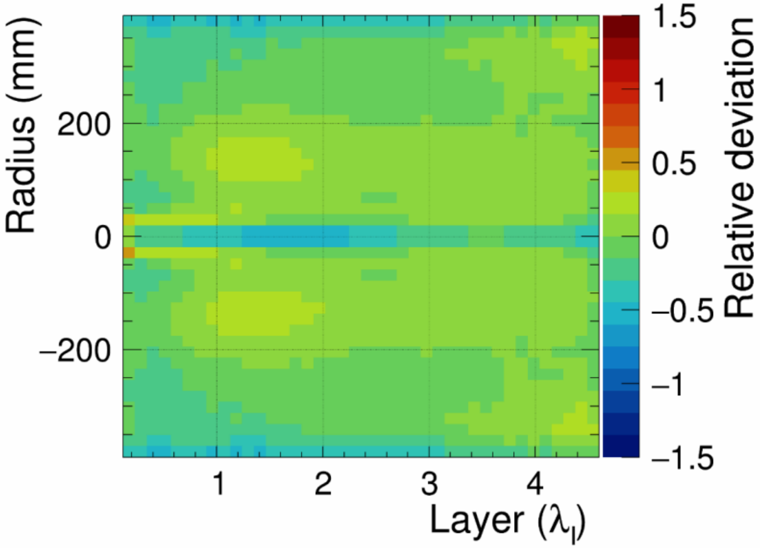
3D modelling of hadronic showers









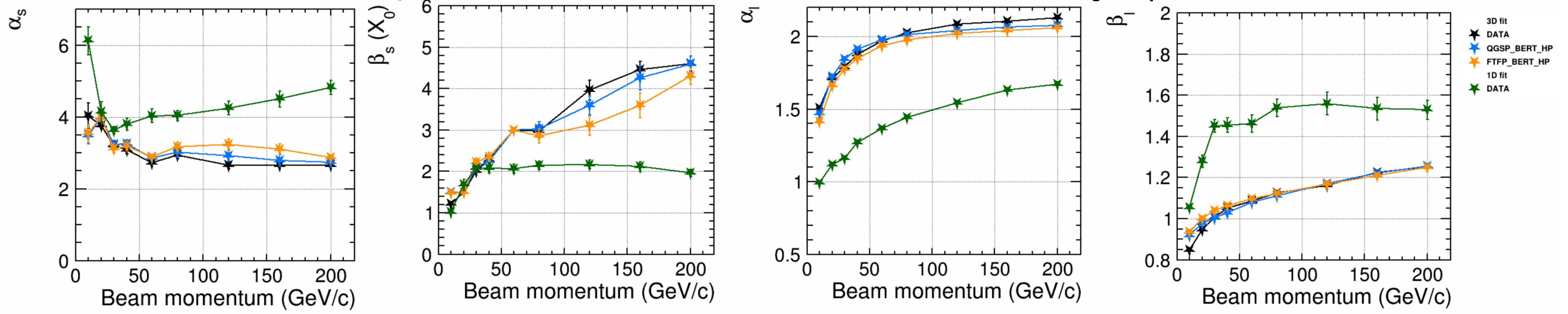


Parameters

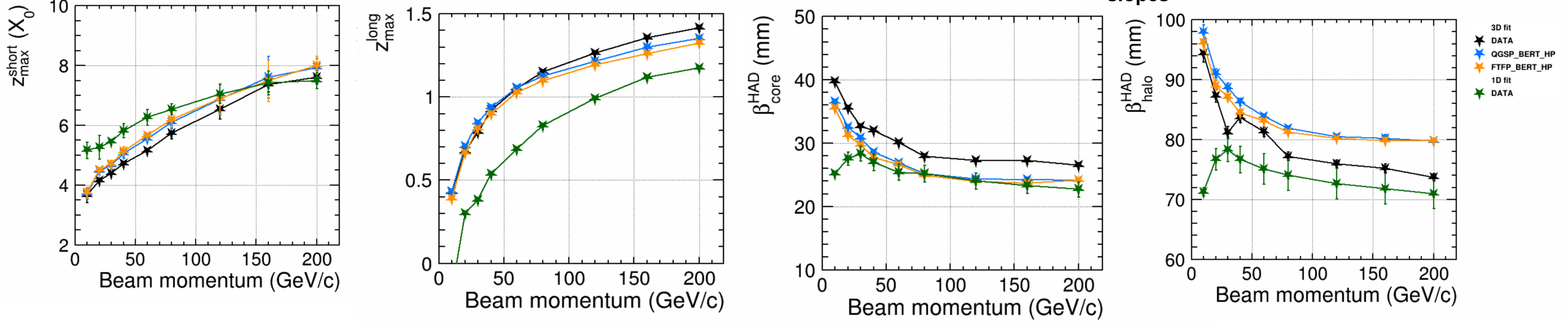
… in comparison to 1D fits

- We gain some additional information in the 3D fit which was not present in the 1D fit, and that is why the parameters change slightly
- With this parametrization all energies are be described well

short component **long component**



maximum **slopes**



To learn the shower structure

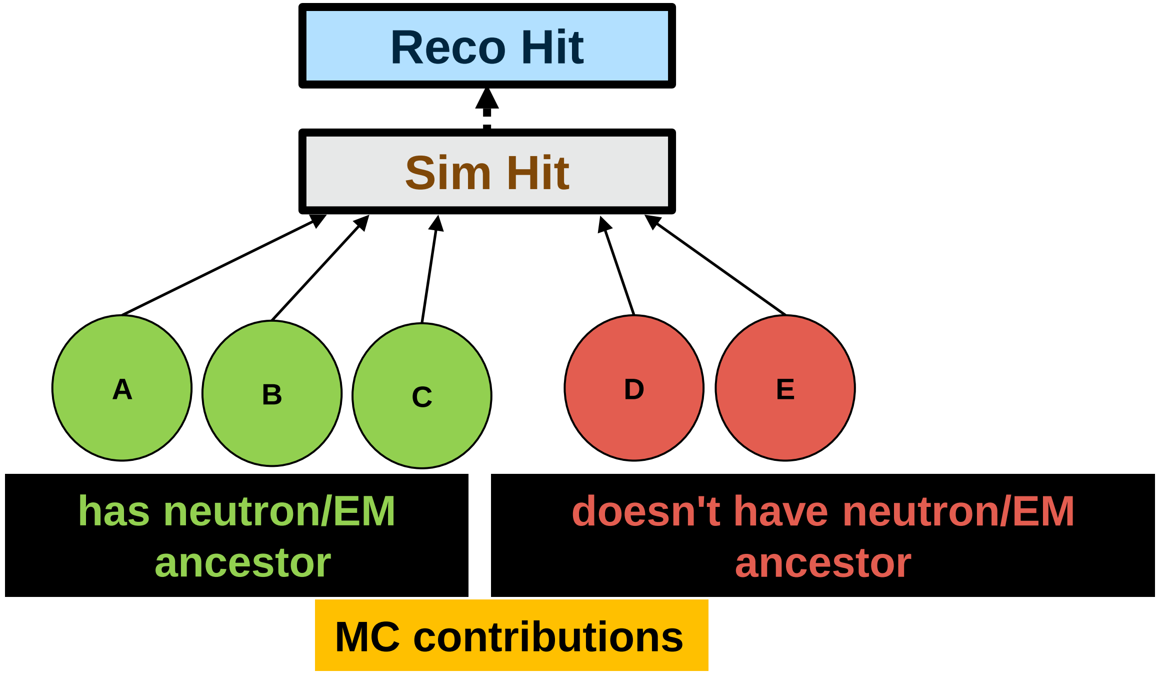
- In data, we can see only indirectly if / how well the short or core component fits to an EM shower, but in simulation we can actually check it by **looking into the history of the particle shower!**
- The assumption that the **core/short component** is related to purely **EM-shower (eta or pi0’s)** and the **halo/long component** is connected to hadrons (**neutrons**)

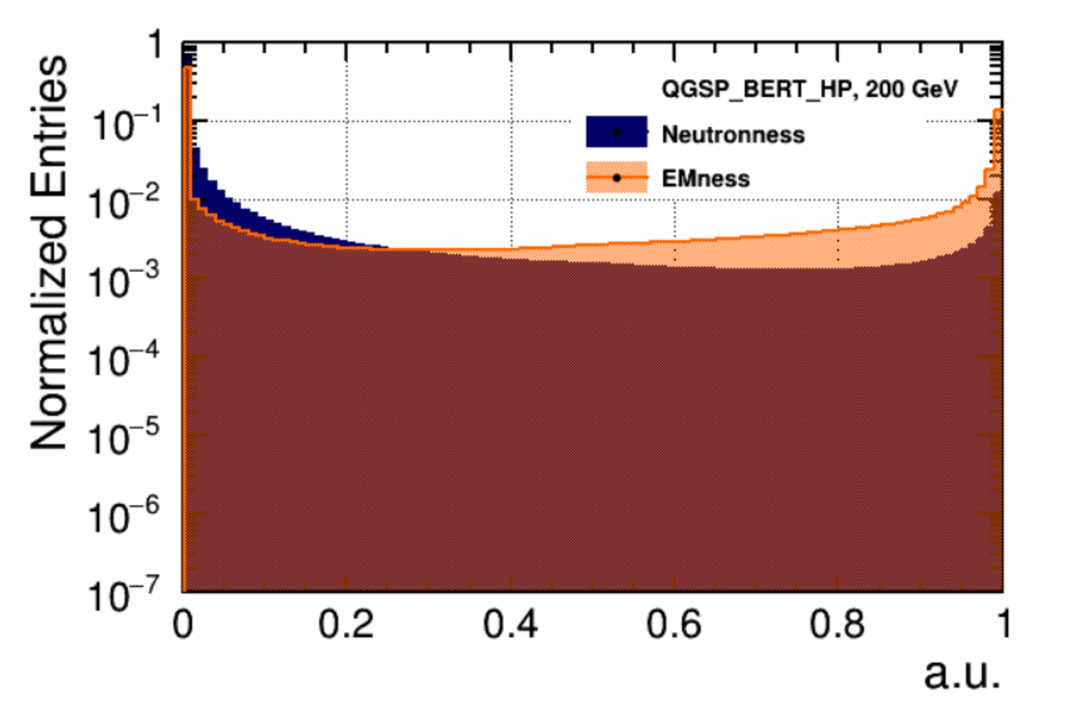
Neutronness and EM-ness

- **Neutronness/Emness** is defined as the energy-weighted contributions of MC particles with a **neutron or EM (eta or pi'0s) ancestor** compared to all contributions to the Sim hit

$$Neutronness\ or\ EMness(hit) = \frac{\sum_{contribution:Neutron\ \ or\ \ EM Ancestors} Energy(contribution)}{\sum_{contribution} Energy(contribution)}$$

- Define neutronness or EM-ness an energy weighted quantity to call a hit "from a neutron or EM particle respectively"

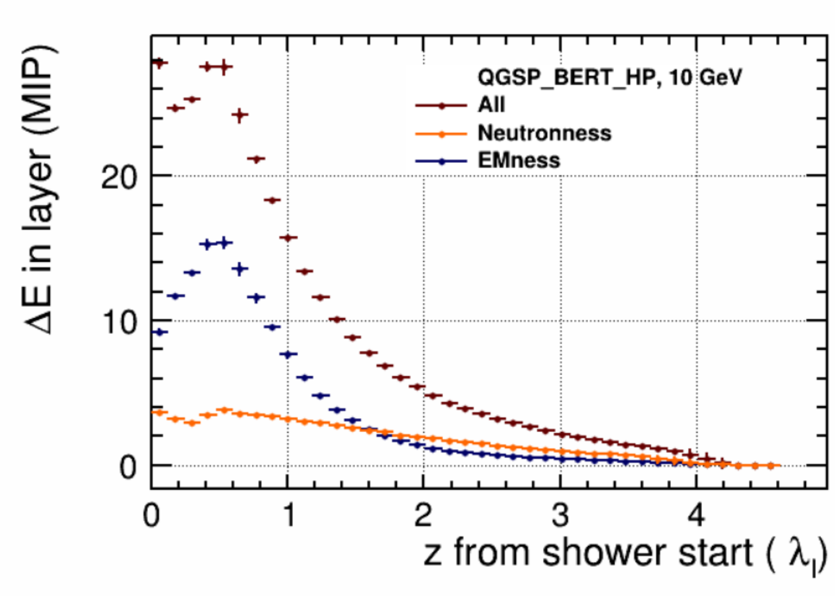


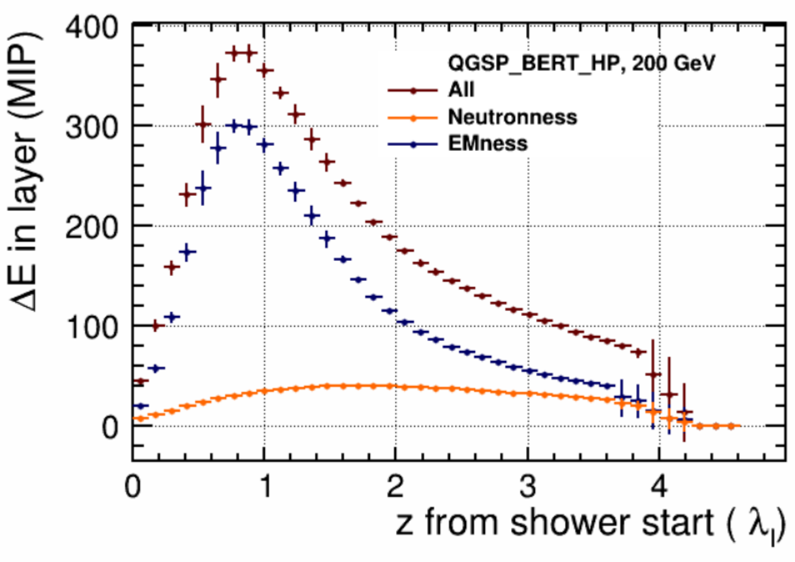


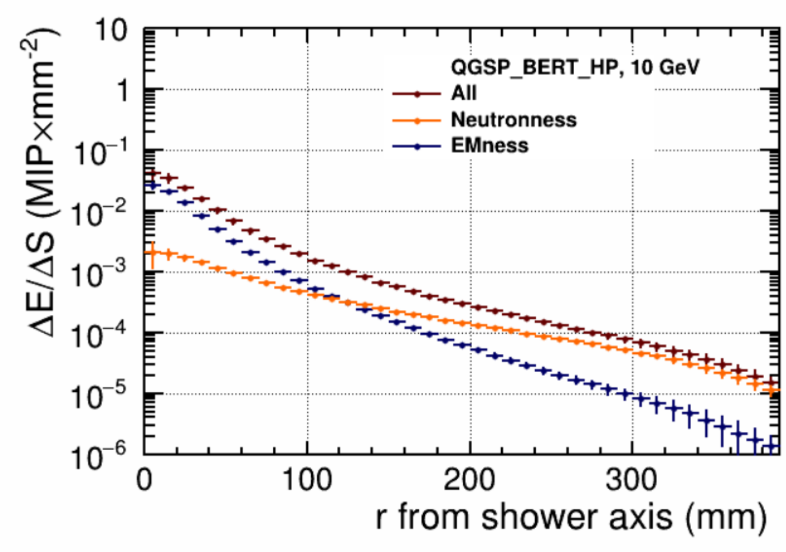
Longitudinal and Radial shapes

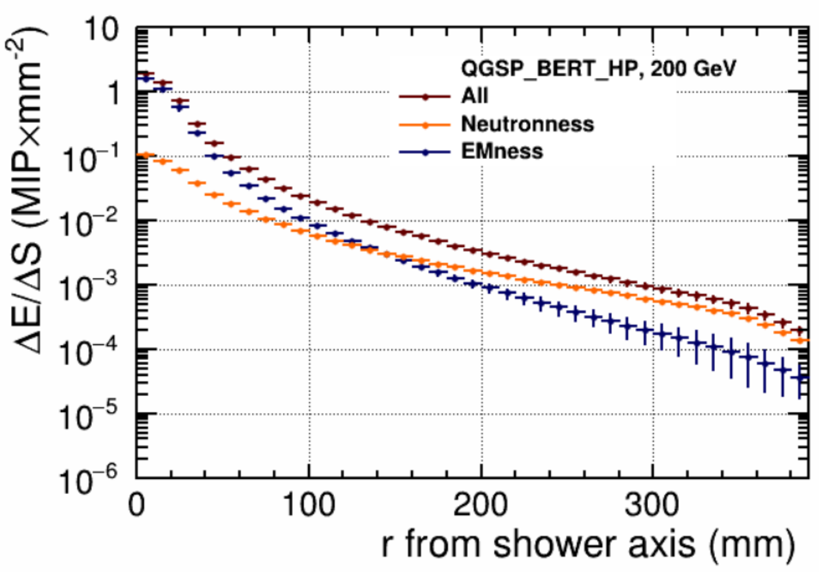
Neutronness = Energy(hit) * Neutronness(hit)
Emness = Energy(hit) * EMness(hit)

- From the radial profile it is clear that the neutrons persist in the entire calorimeter region, mainly dominated in the outermost parts. Whereas, this behaviour is partially suppressed in longitudinal profiles.
- The core of the shower is clearly dominated by the electromagnetic part of the hadronic shower.
- At larger radii, the probability that the hit contributed by other particles is minimum as compared to smaller radii, due to lots of hadronic activity.



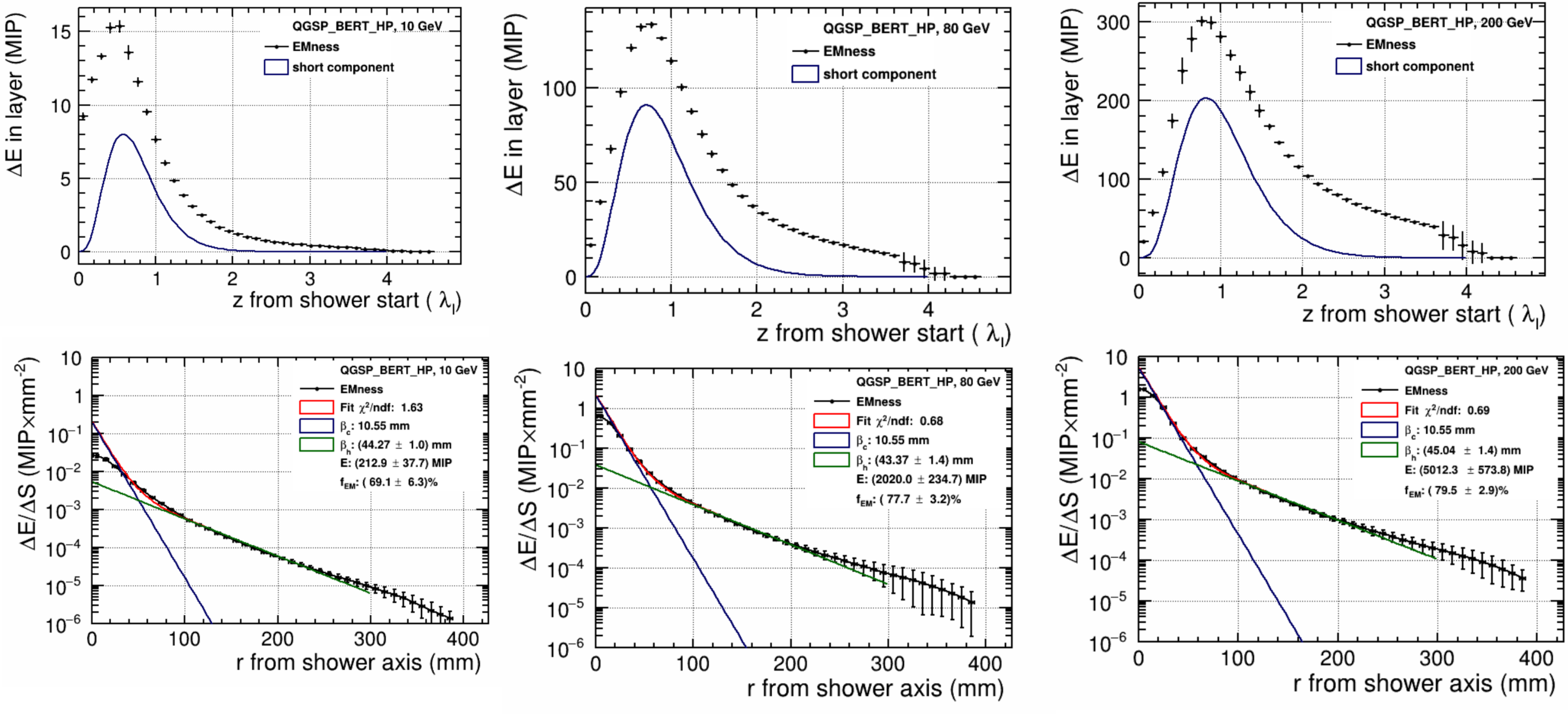






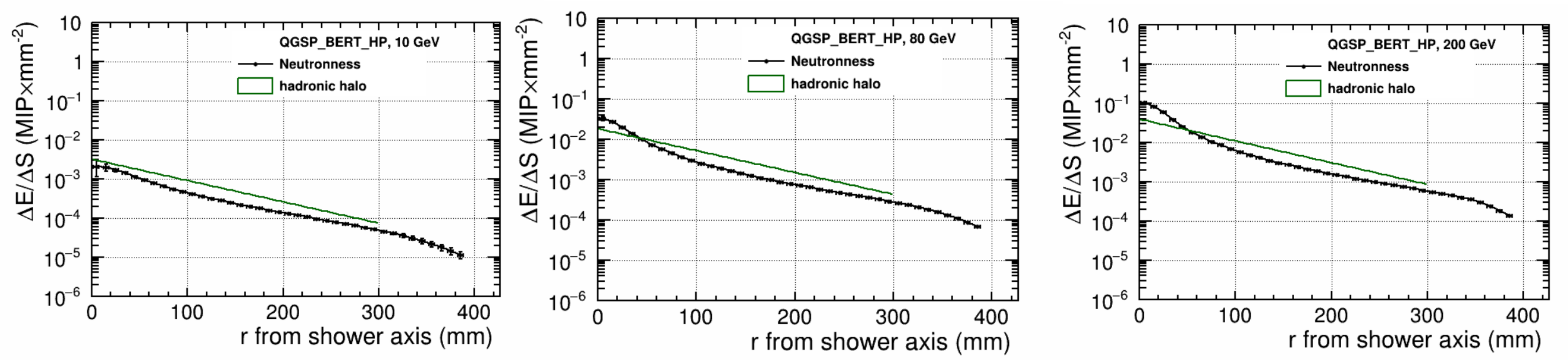
EM-ness

- The function with short component is drawn for the longitudinal profile to describe the EM part of shower
- For the radial the function is fitted with two exponential distribution with core component fixed due to its independent behaviour w.r.t energy



Neutron-ness

The function with hadronic halo component is drawn for the radial profile to describe the halo part of the shower



- We do see the radial slope of the halo distribution and the neutron component. But clearly, the normalization is not correct
- Also, for the EM part of the shower, the shapes are similar but the normalization is wrong and also we see that by fixing the EM-slopes we do not really get very good description of the shower
- **We clearly see that our explanation is too simple**

Summary

- **CALICE-AHCAL 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 three components** gaining additional information
  - A model that relies on 12 energy dependent parameters which describe an average hadronic shower
- The assumption of **hadronic shower is found to be a simplistic picture**
  - As the EM part of pion shower is similar, but longer and deeper than electron shower

Potential applications of the model!

- In **PFA algorithms**, to determine what is the probability that a hit belongs to some particle shower or not
  - Currently, shower shapes in PFA makes use of one Gamma function for the description of longitudinal profile
- Deliver an easy analytical parametrization of hadronic shower for **fast simulation**, e.g Gflash
- The main code will be documented on Git to reach wider calorimeter physics community

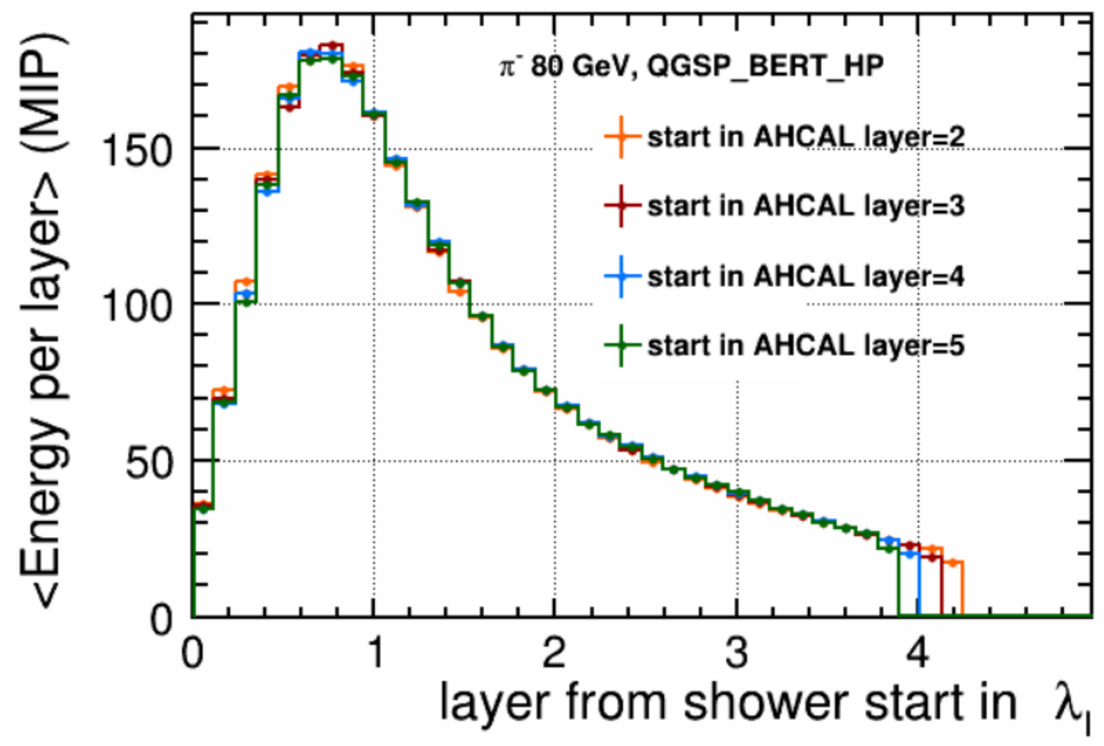
THANK YOU FOR YOUR ATTENTION!

Spares

Systematic Uncertainties

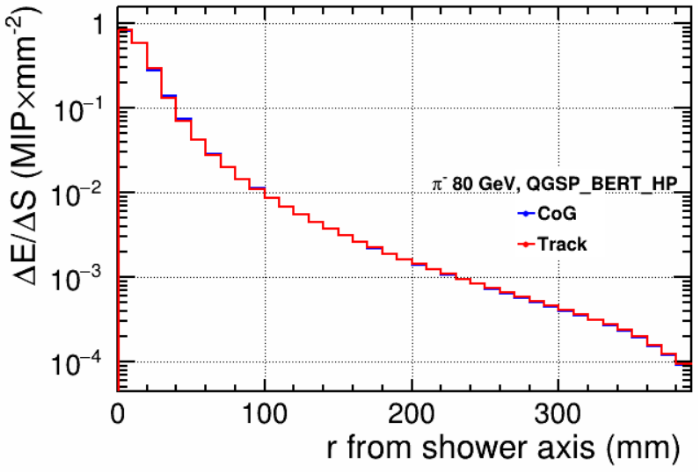
Longitudinal: layer-to-layer variations

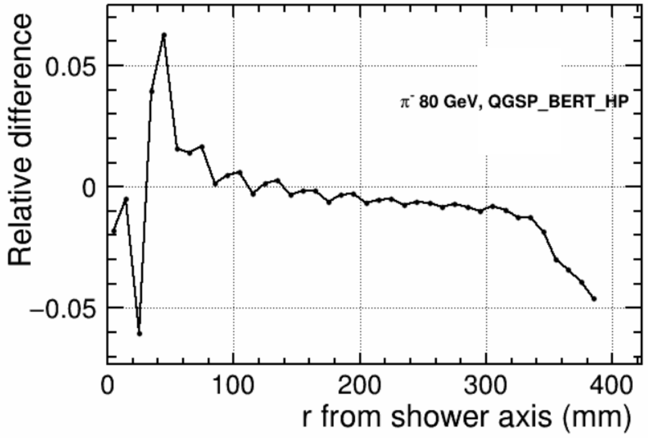
- Significant contribution comes from layer-to-layer variations
  - Uncertainties in SiPM response function
- Averaging the contribution from different physical layers minimizes the layer-to-layer variation



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



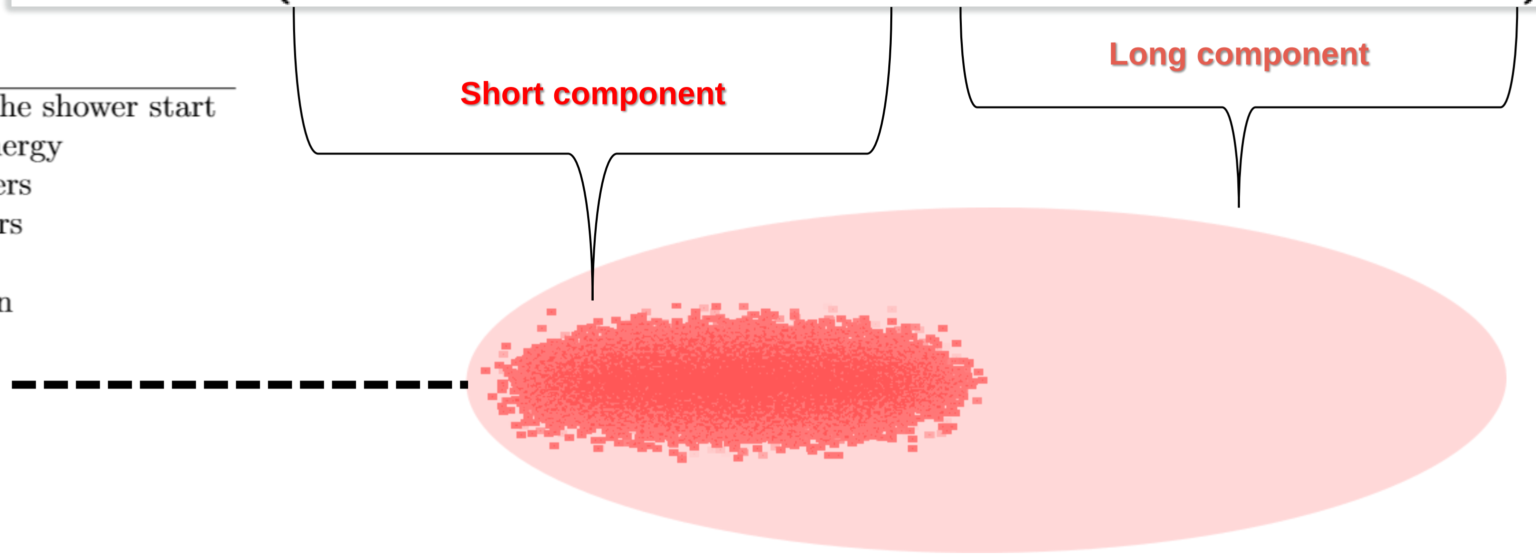


Parametrization

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	
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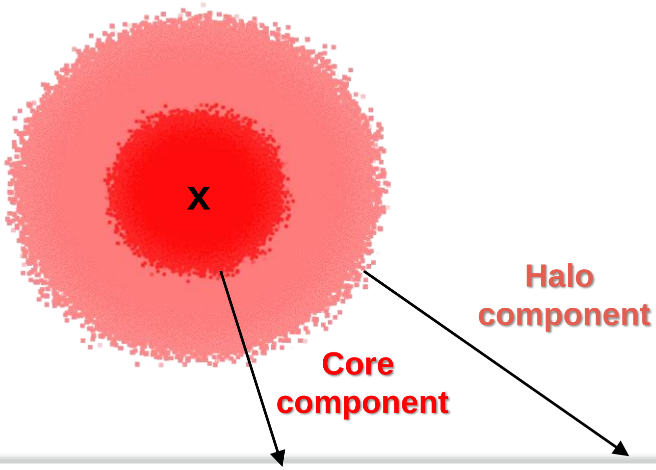
E	mean visible energy
α_s, β_s	shape parameters
α_l, β_l	slope parameters
f	short fraction
Γ	gamma function



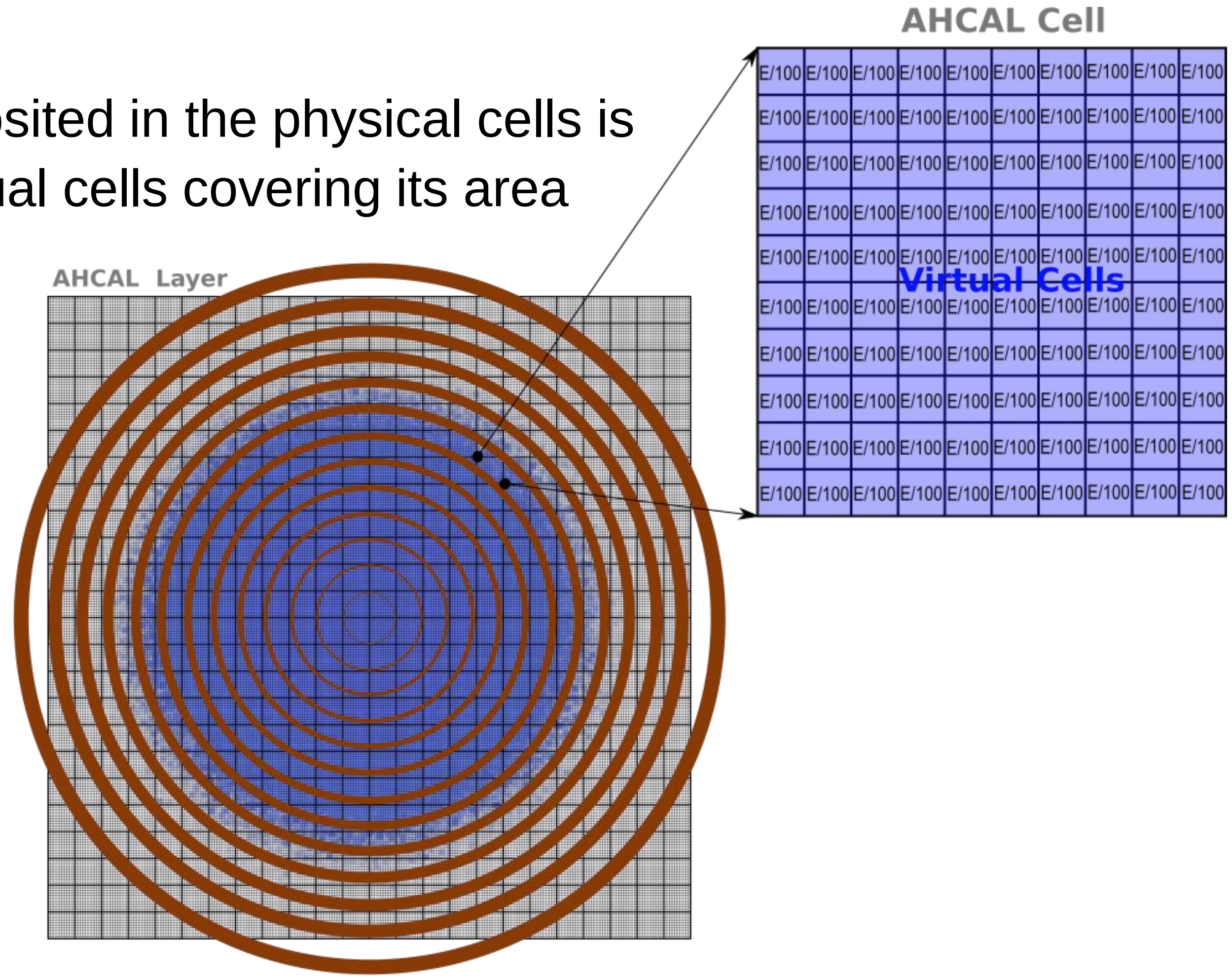
Radial profile is the distribution of the energy density as a function of the radial distance to the shower axis

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

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

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



Shower origin

Comparison of visible energy and number of hits with MIP-like deposition

- Calculate visible energy, E_i and number of hits, N_i, in i-th layer
- Average visible energy E_i within a sliding window of m layers up to k-th layer:

$$M_k = \sum_{j=0}^{m-1} E_{k-j}/m$$

- Calculate sum of averaged visible energy and number of hits in two successive layers

  $M_k + M_{k+1}$

  $N_k + N_{k+1}$

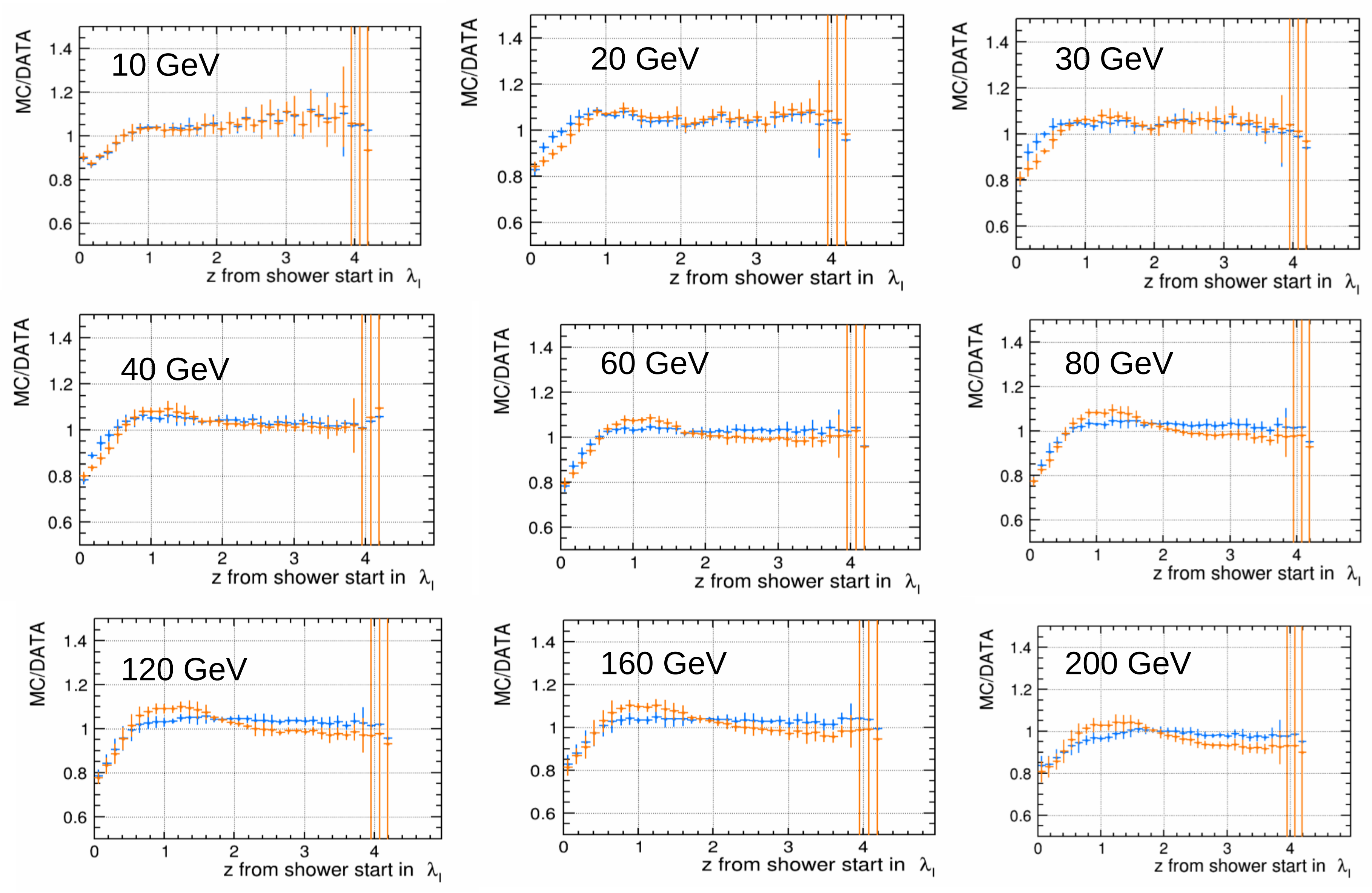
- Identify shower start if both values are above their thresholds
- Thresholds are beam energy dependent and tuned using simulations

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



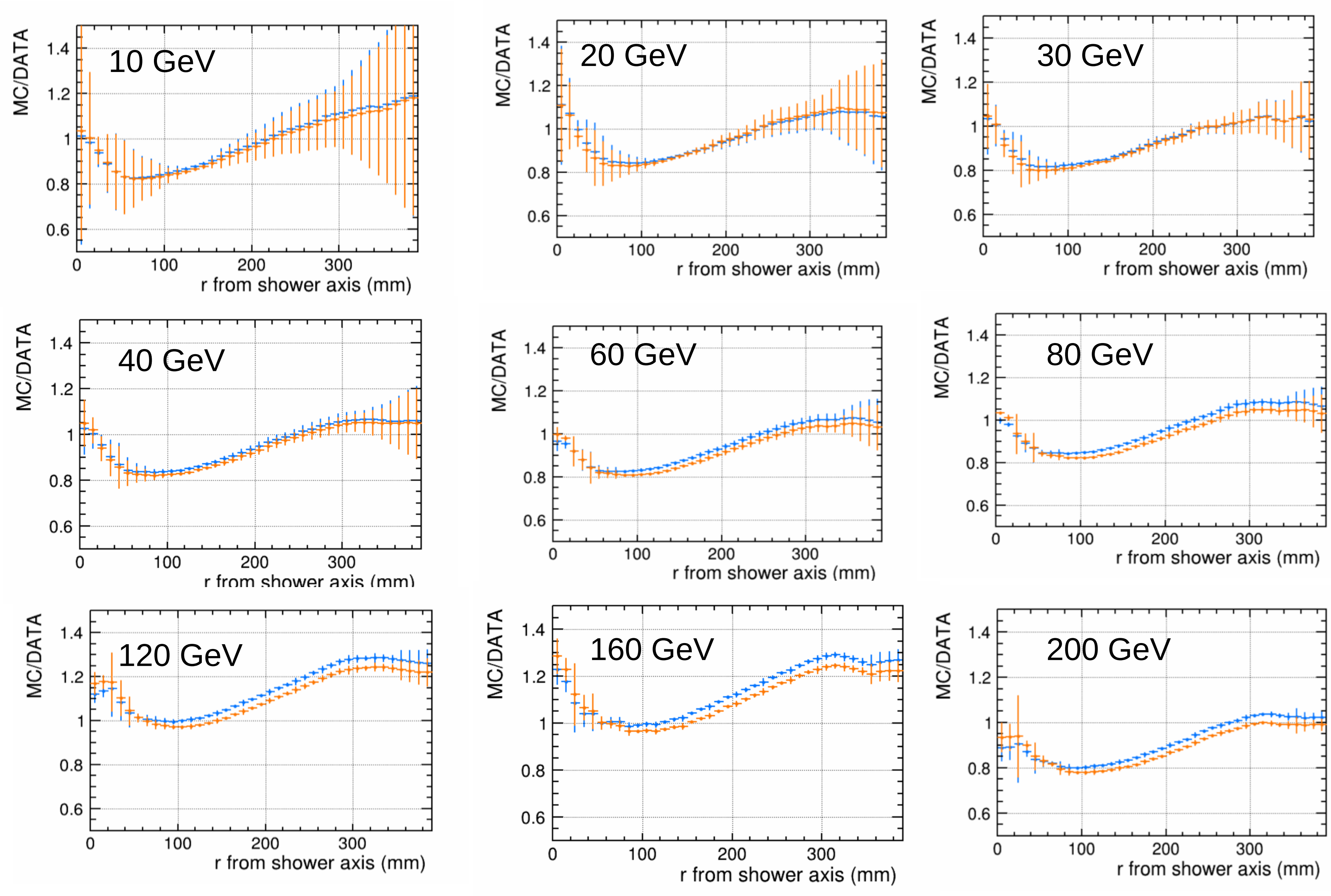
Comparison between Data & MC

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

Longitudinal Parameters

"short" parameters

Parameter α_s

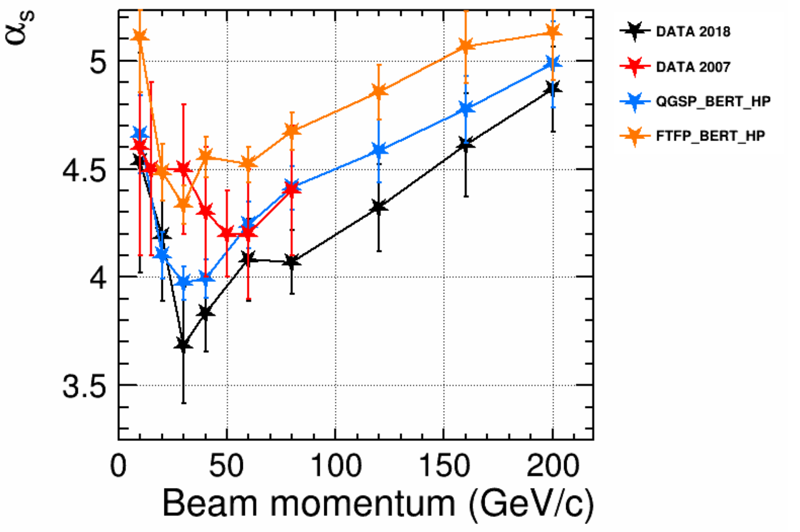
- Decreases with energy until 30GeV and shows opposite behaviour from 80 GeV which is also predicted by both the simulations

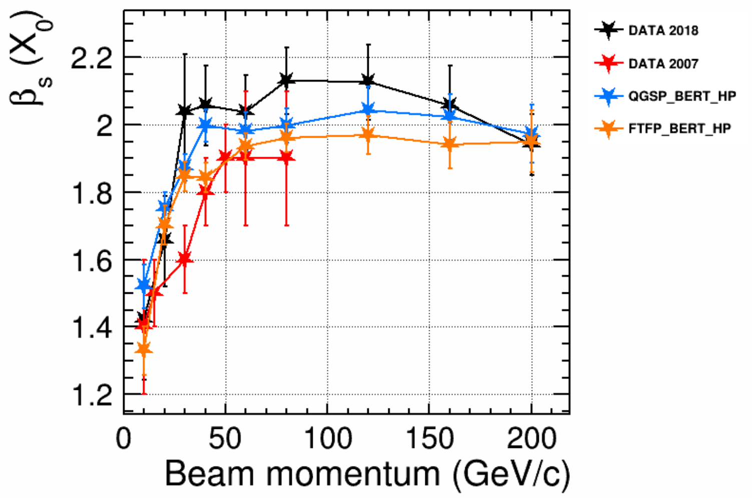
- Both physics list show an agreement to data within ~5 to ~10%

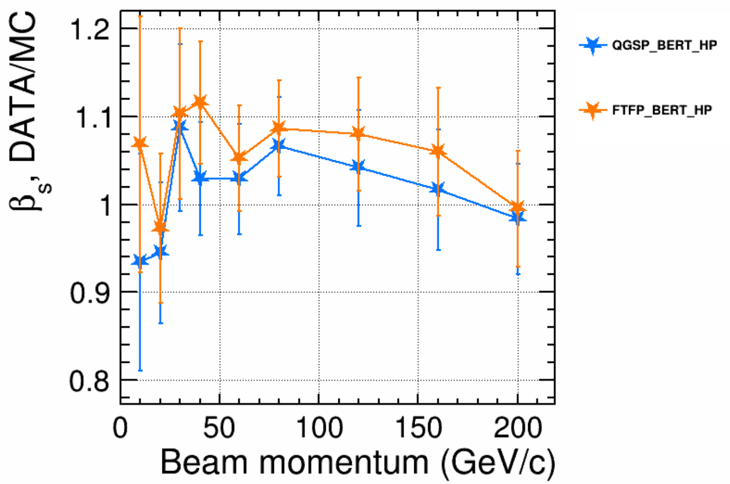
Parameter β_s

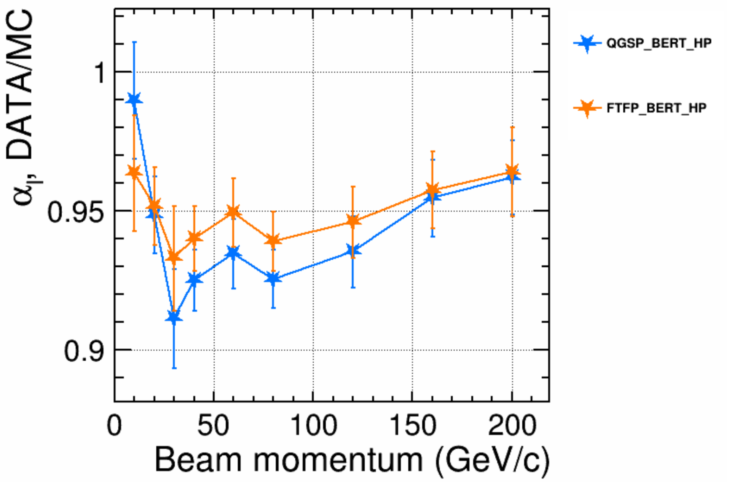
- Almost energy independent above 30 GeV also predicted by both physics lists

There exists a very high correlation between α_s and β_s



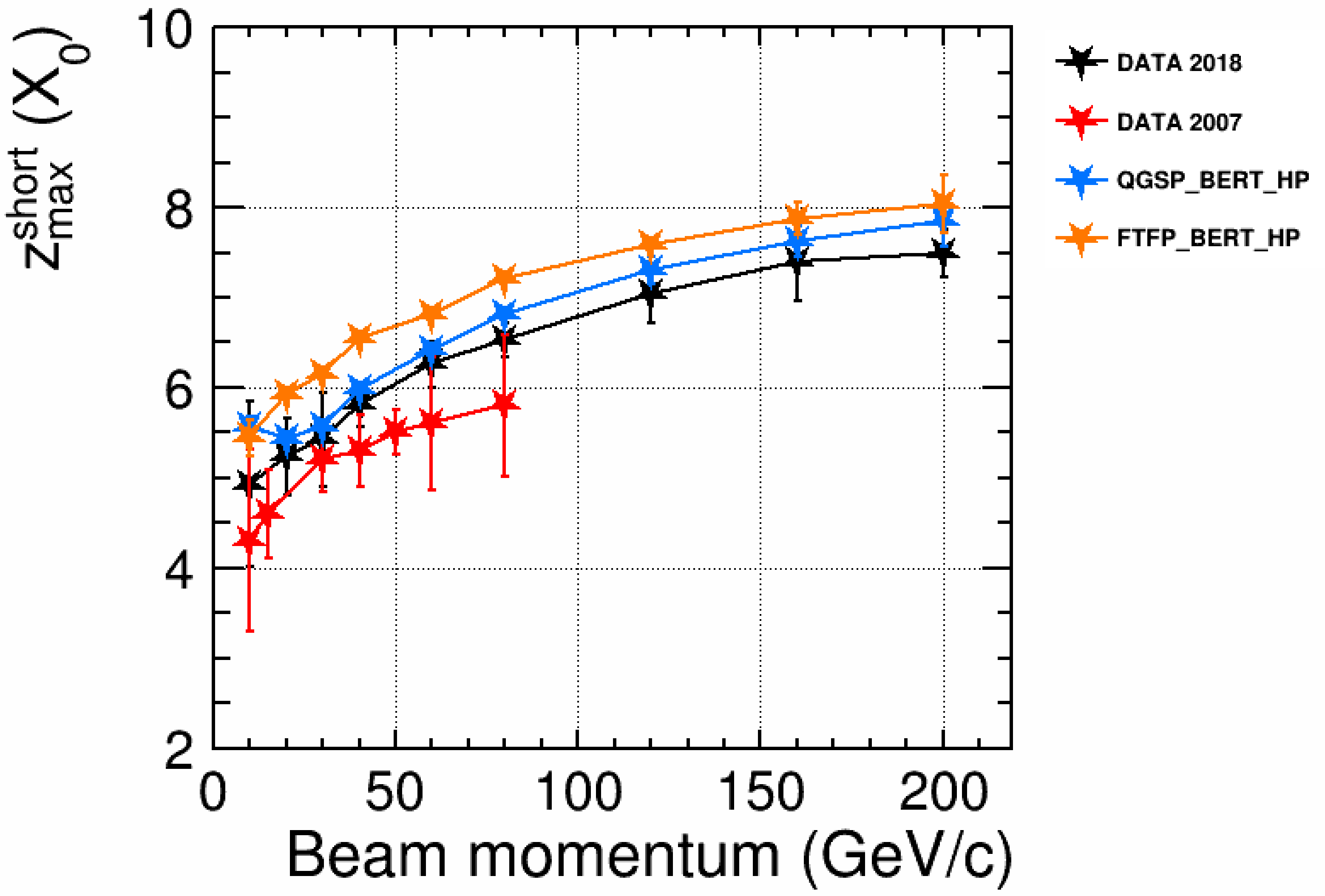






Maximum Position of the “short” Component

- 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

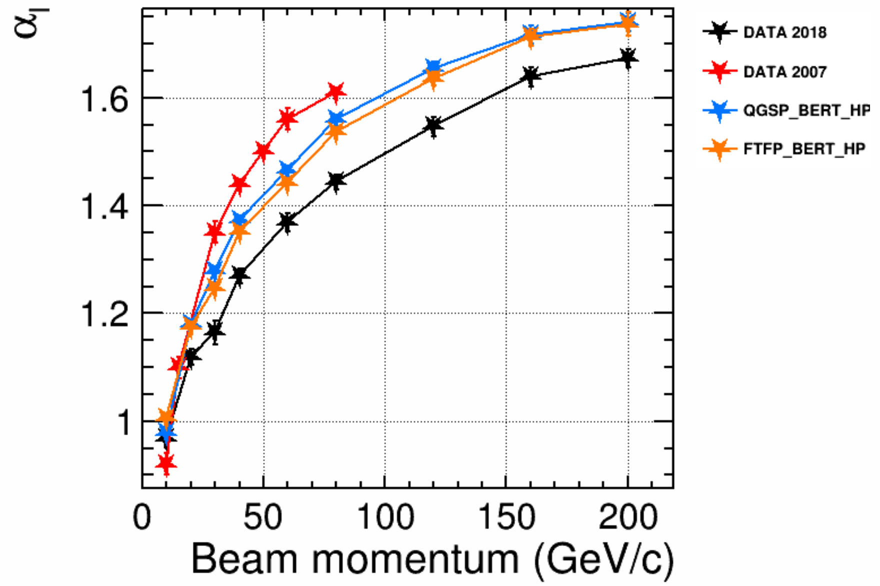


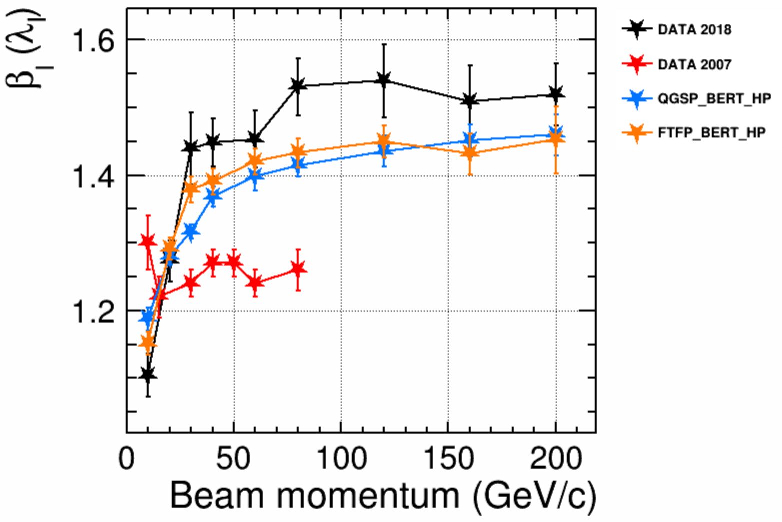
Longitudinal Parameters

"Long" parameters

Parameter α_l

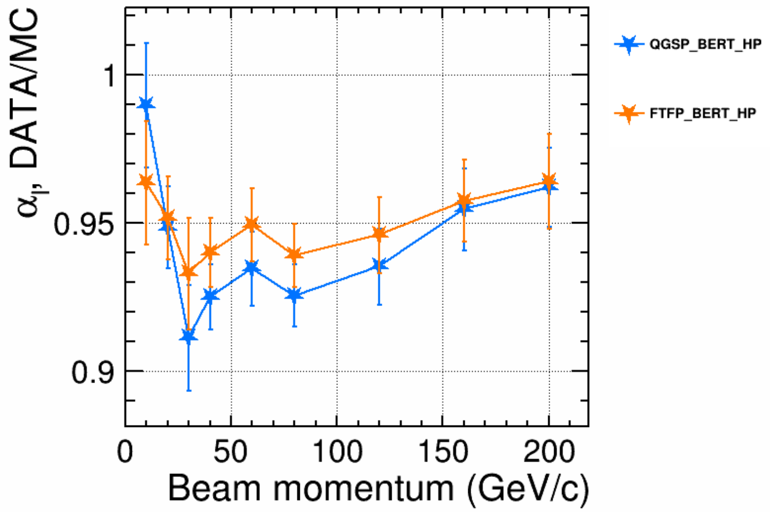
- Shows logarithmic rise in energy
- Both physics list show similar behaviour and the results are comparable

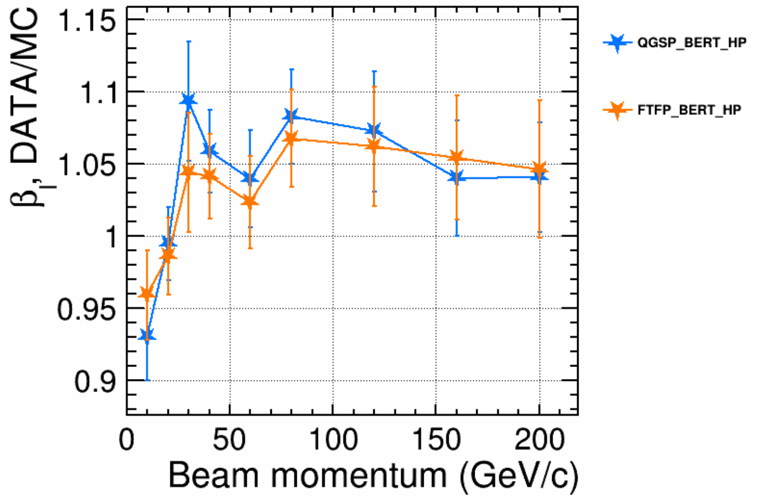




Parameter β_l

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



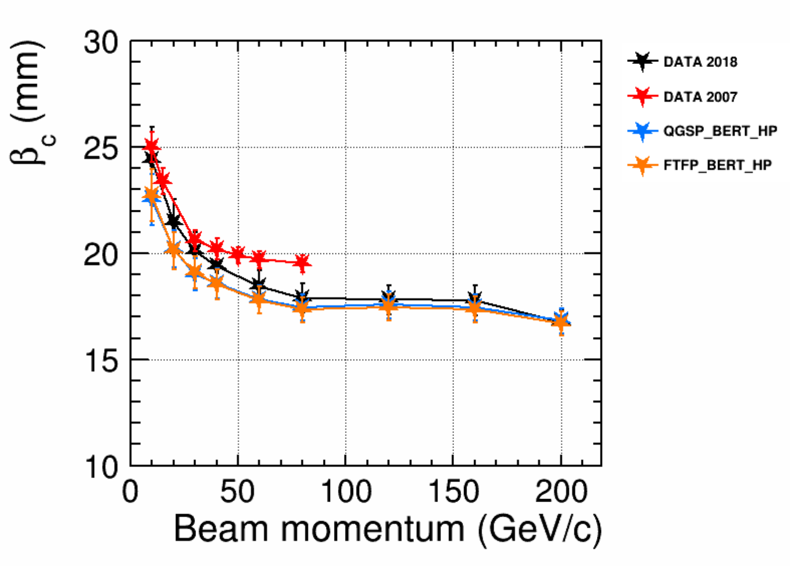


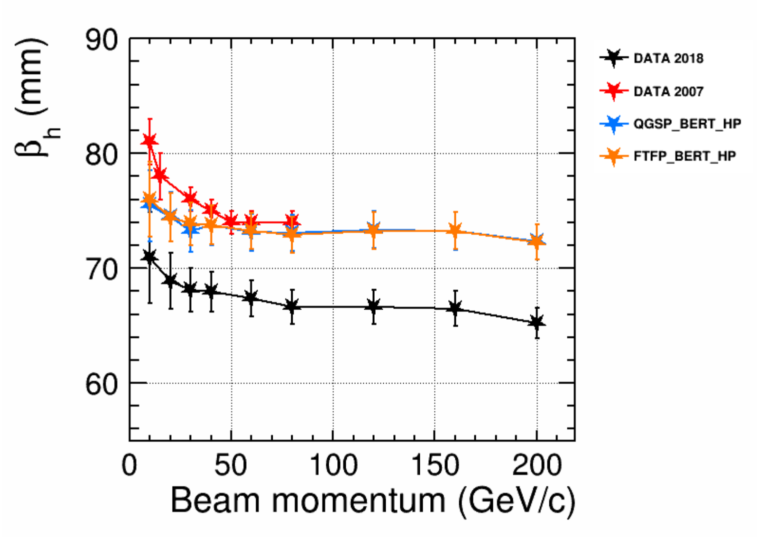
Radial Parameters

Core & Halo

Parameter β_c

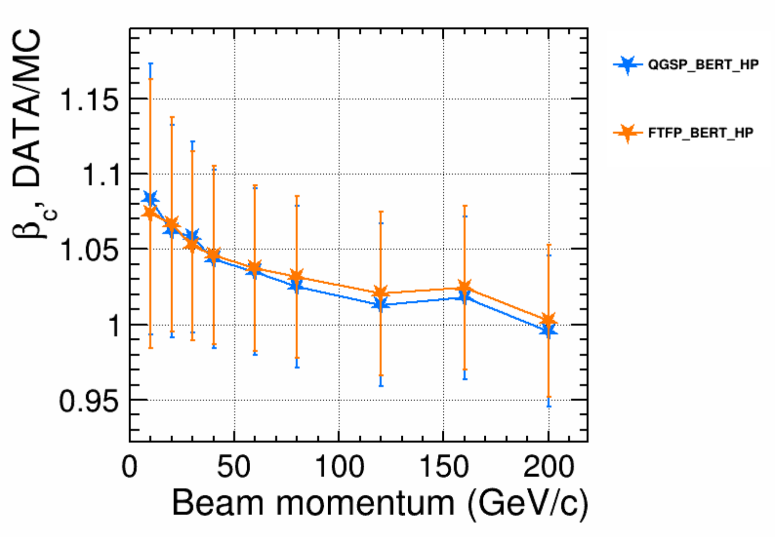
- Decrease at a faster rate at low energies compared to the energies above 30 GeV, this behaviour being well reproduced by simulations
- No energy dependence above 30 GeV

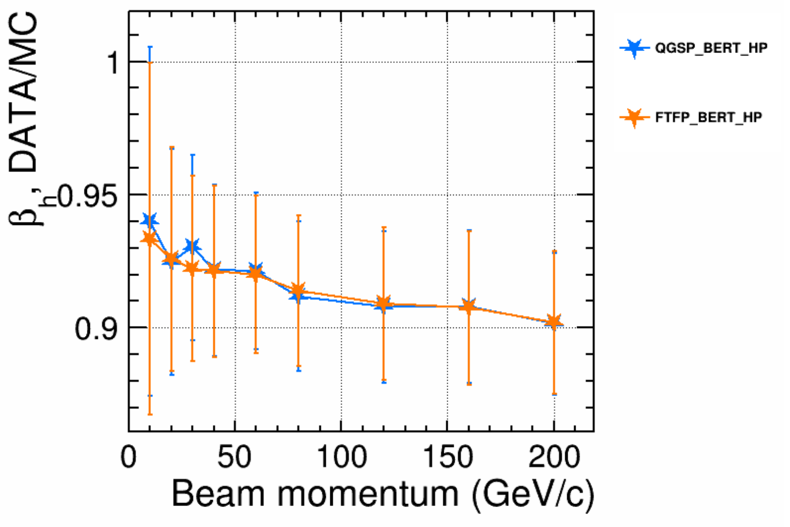




Parameter β_h

- 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





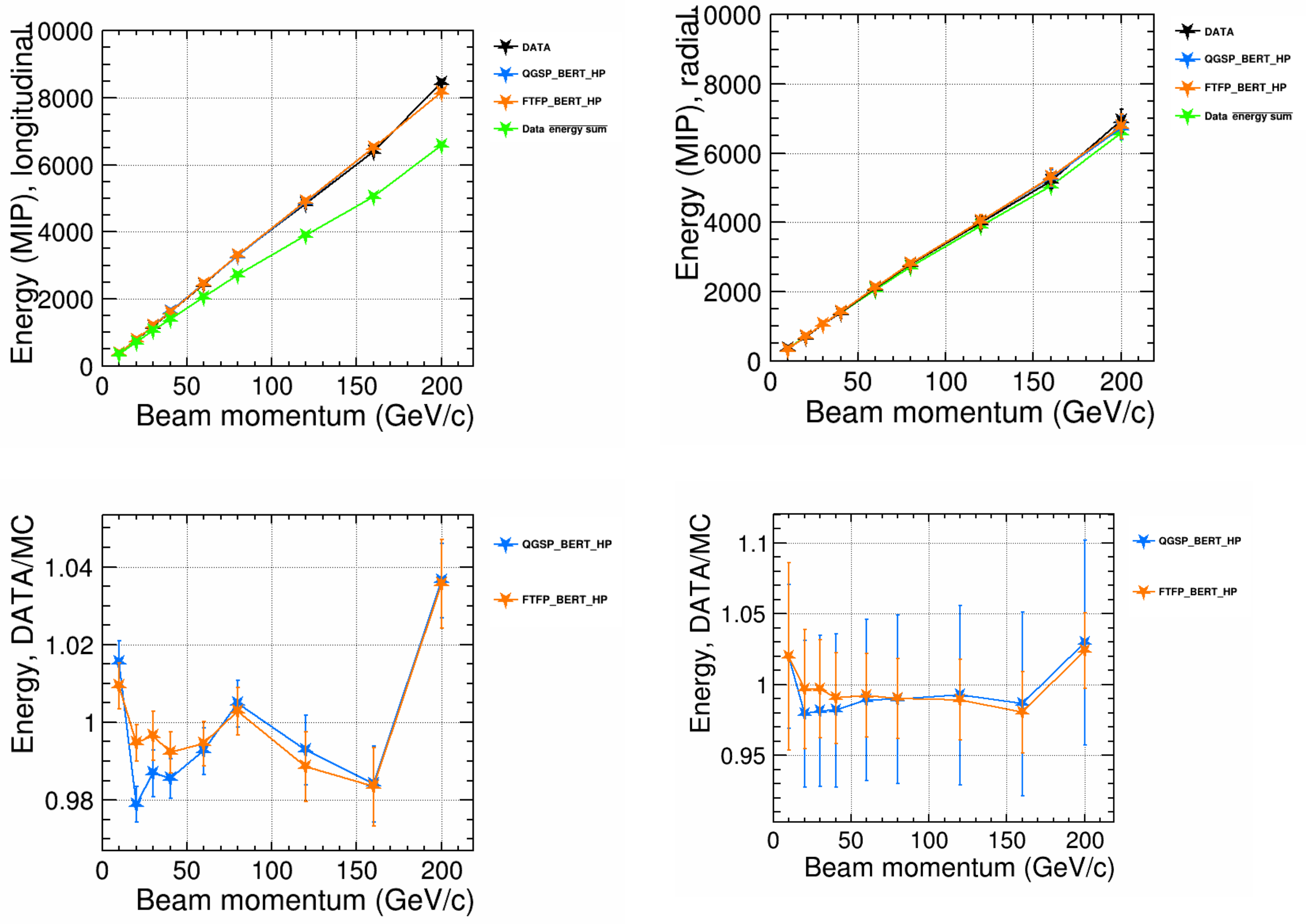
Energy- Scaling Parameter

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

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

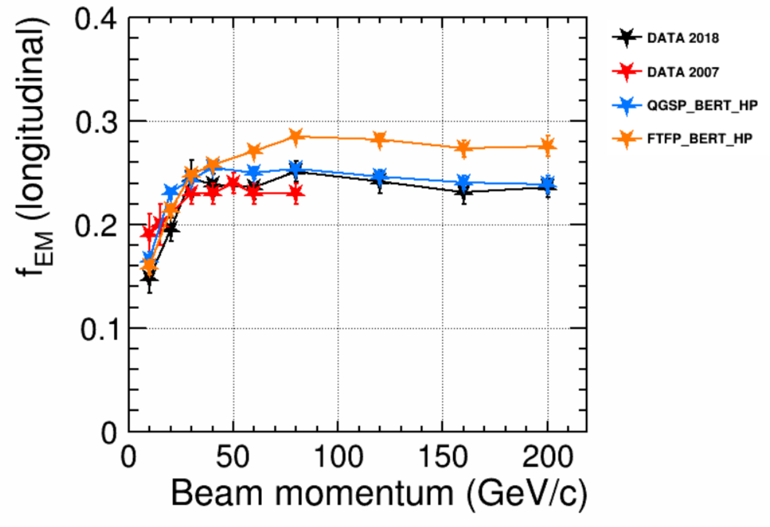
- Also, the radial showers are well contained unlike the longitudinal showers

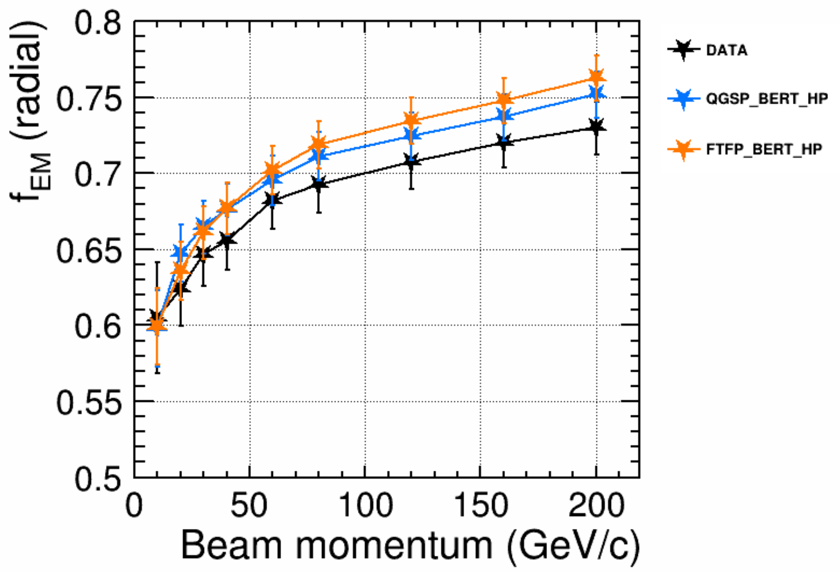


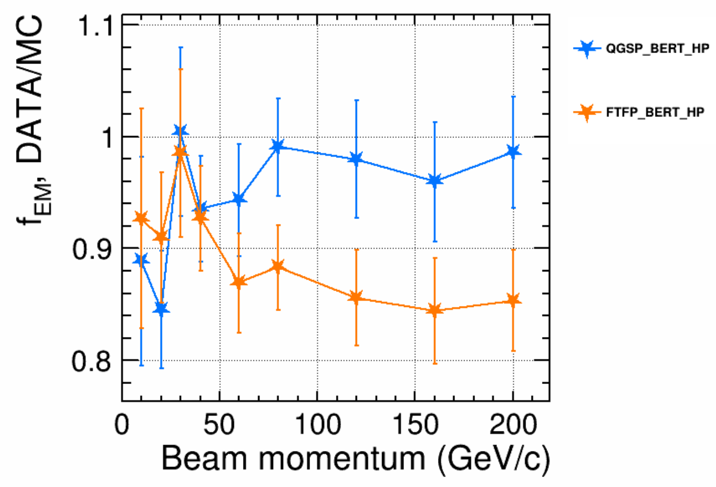
Fraction of short/core component: “Average EM fraction”

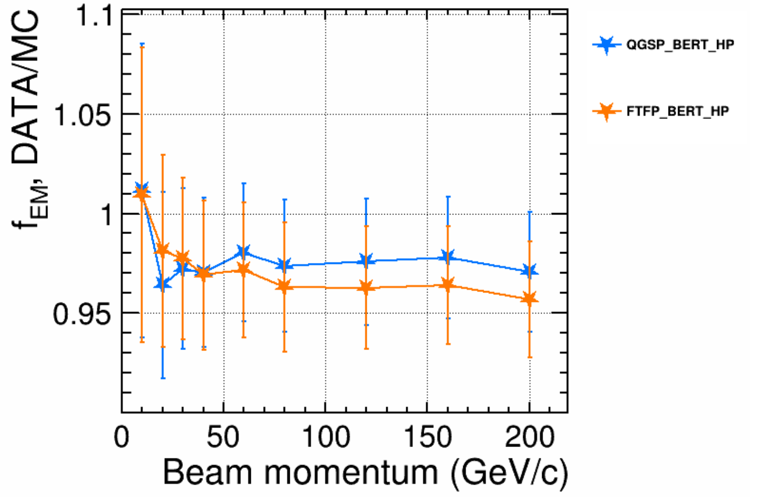
Parameter f_{EM}

- 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

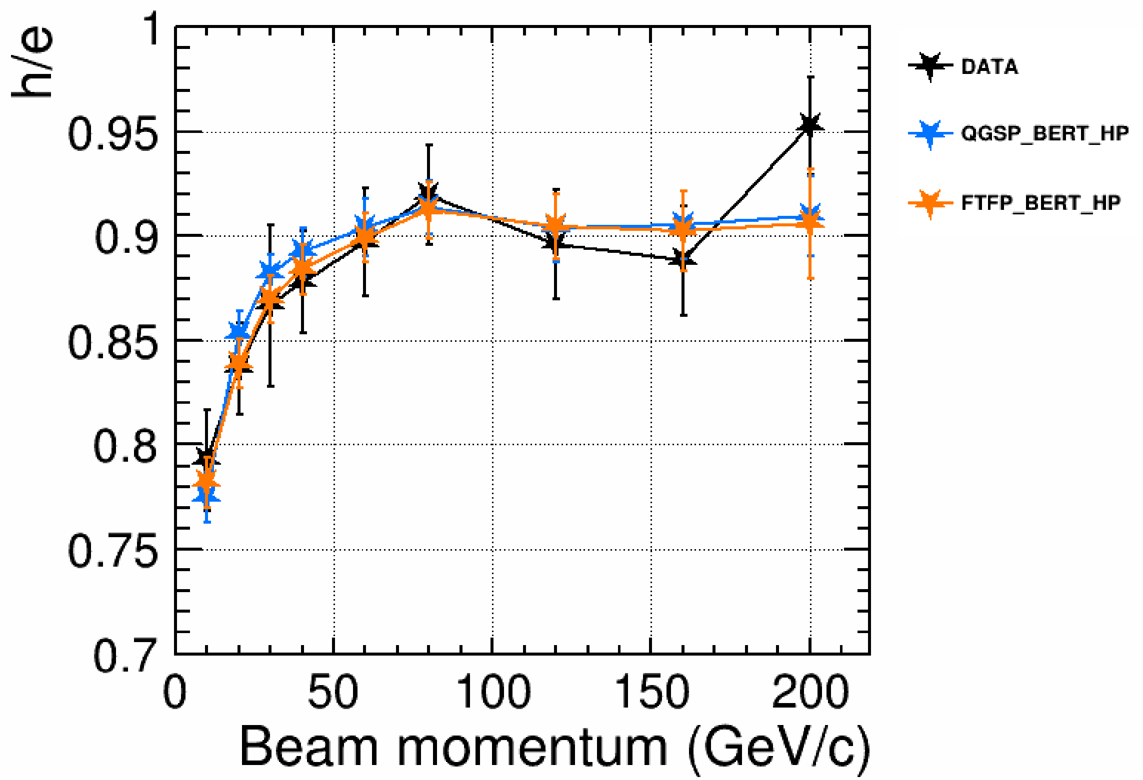
The ratio of responses to the non-electromagnetic and electromagnetic components of a hadron-induced shower

- 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

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

Electromagnetic calibration constant 0.02278 GeV/MIP

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

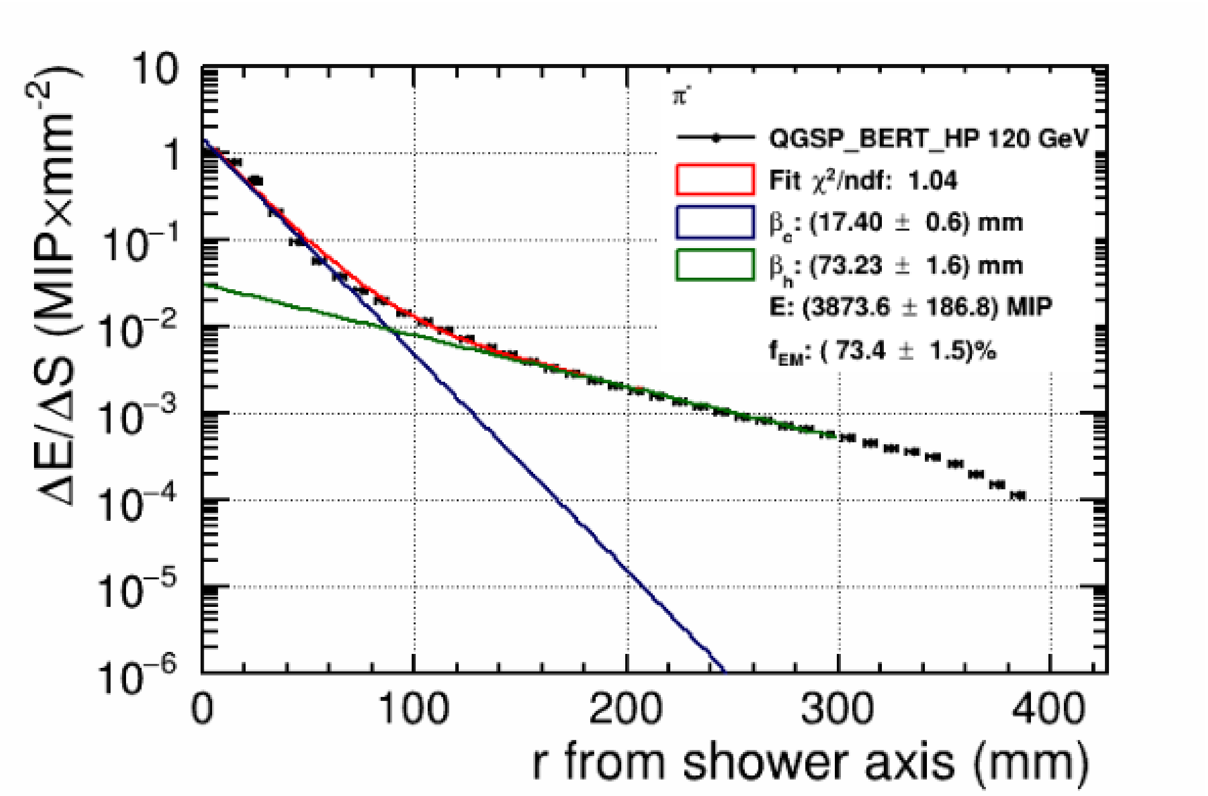


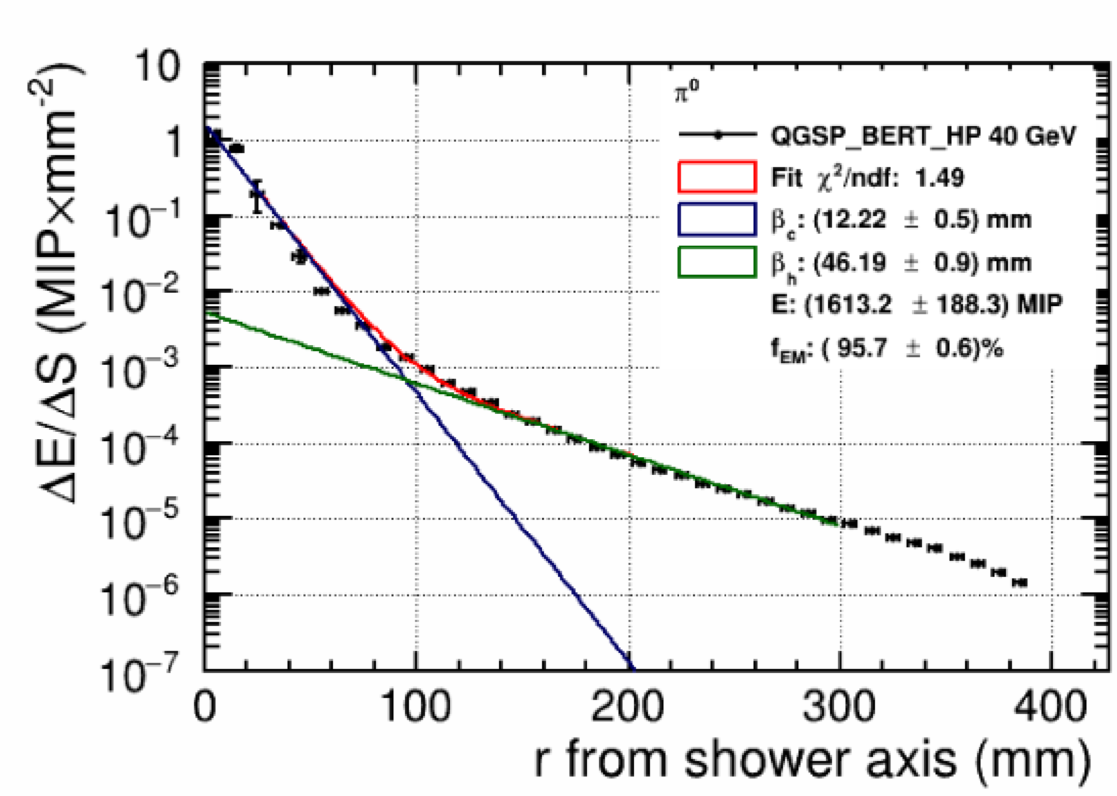
- h/e signal ratio is energy independent at higher energies as expected
- The values of h/e predicted by simulations are in agreement with data within 5%

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 β_c is compared between 120 GeV π^- and 40 GeV π^0



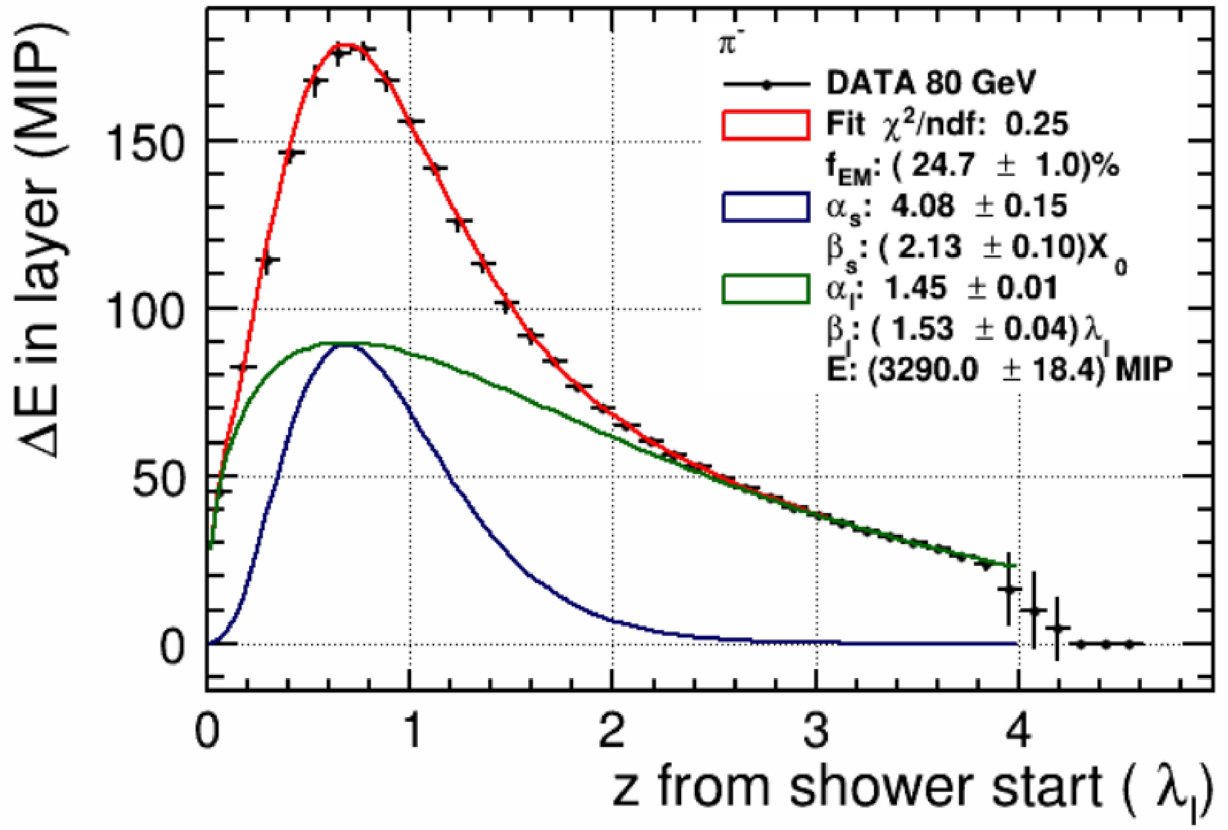


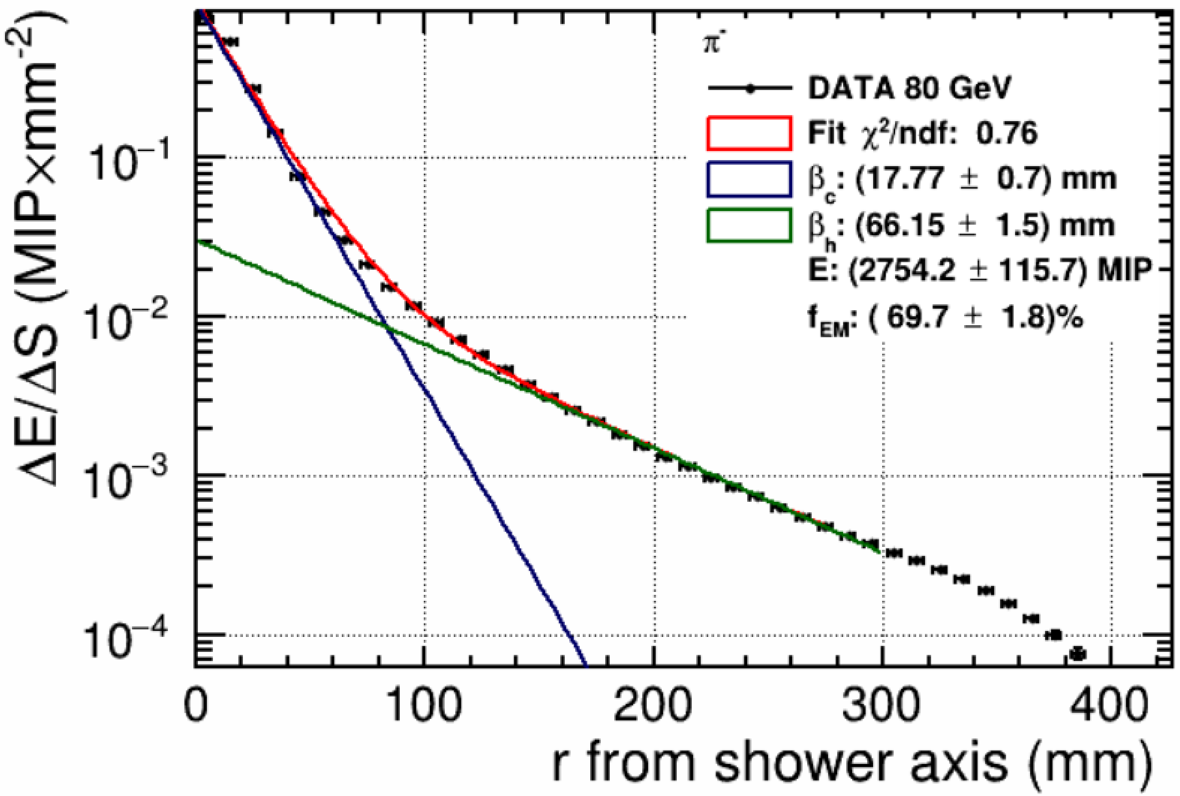
- There are clearly two components seen in EM showers
- The discrepancy in the electromagnetic fraction in radial and longitudinal fits, and the discrepancy between the fit values for pi0's and the core component in the pions, could possibly be interconnected!

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



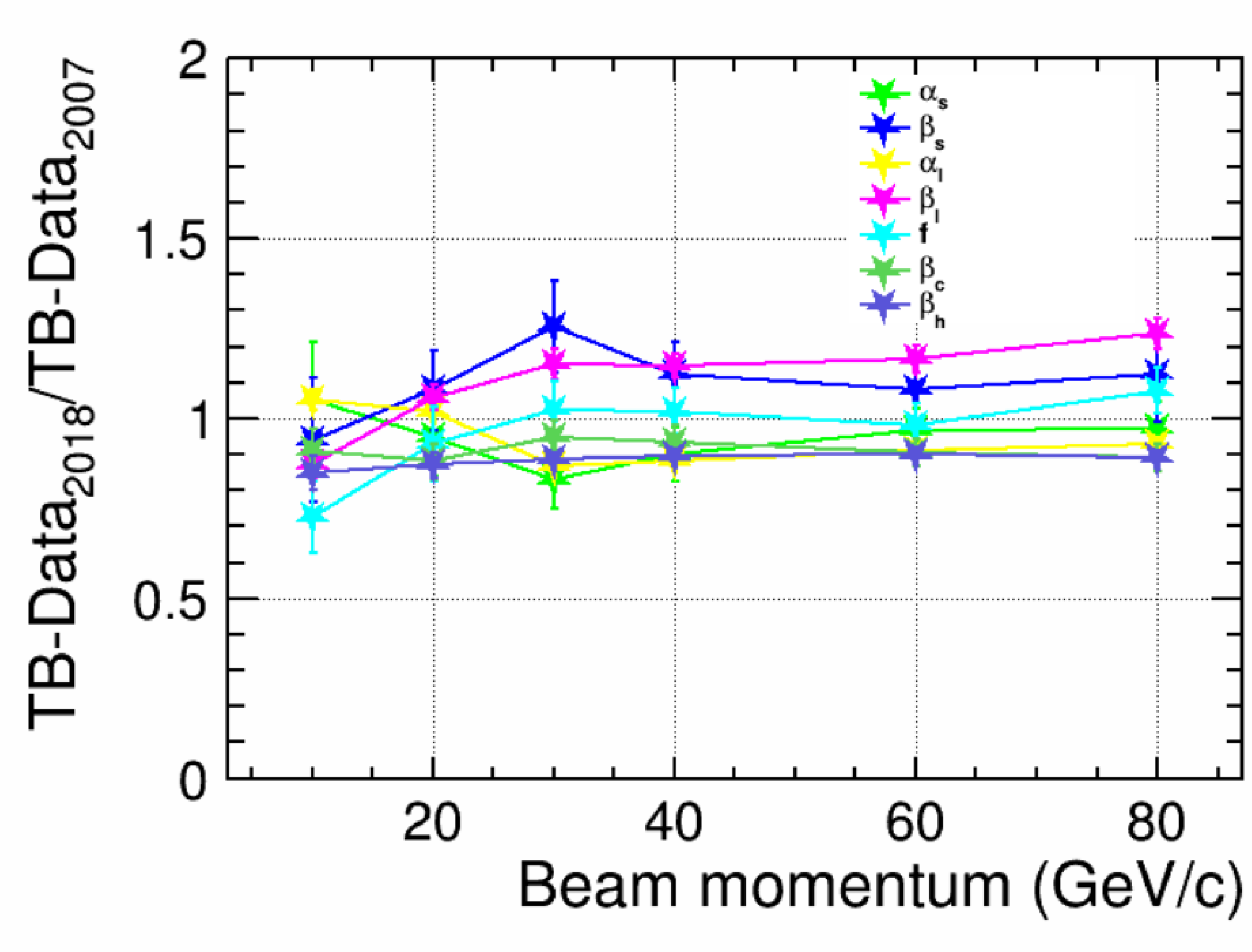


Reproducibility

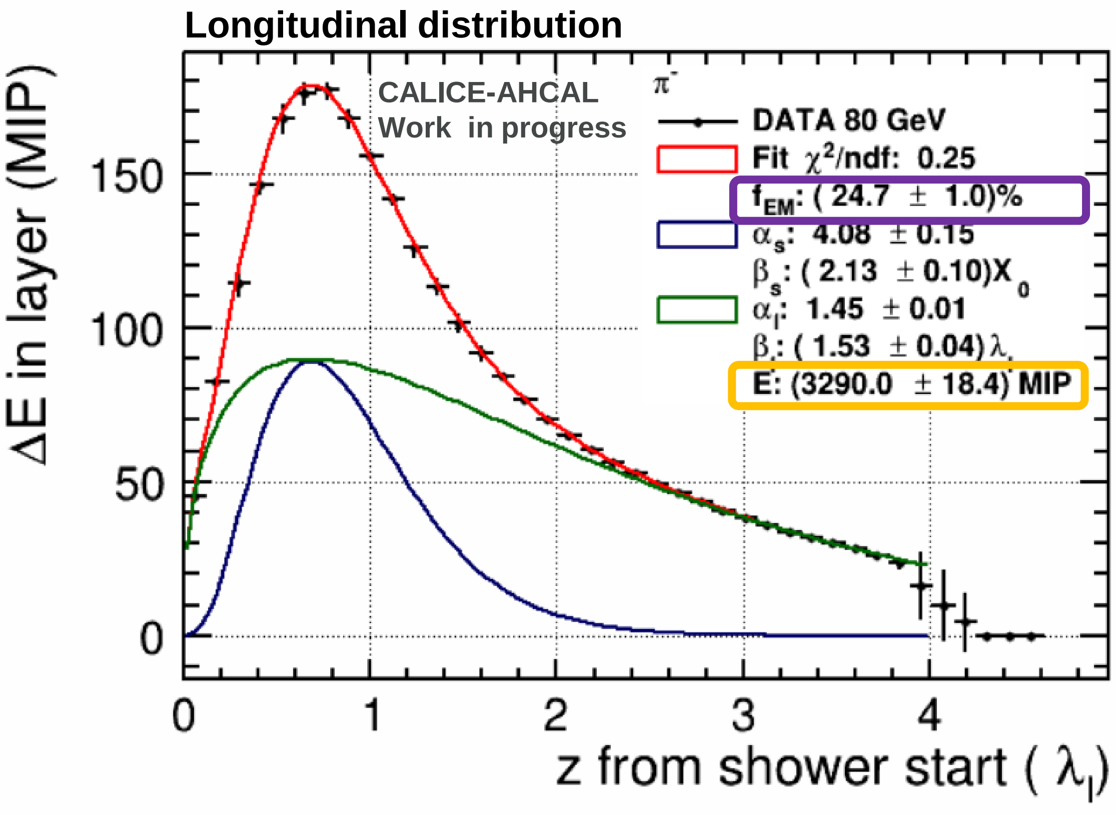
Do we get the same parameters?

	PP (2007)	EPT (2018)
Total active layers	38	38
Absorber thickness	21.0 mm	17.2 mm
Cell-size	varying	homogeneous ($3\times3\text{cm}^2$)
Total depth	$\sim 5.3\lambda_I$ ($\sim 0.14\ \lambda_I$/layer)	$\sim 4.2\ \lambda_I$ ($\sim 0.11\ \lambda_I$/layer)

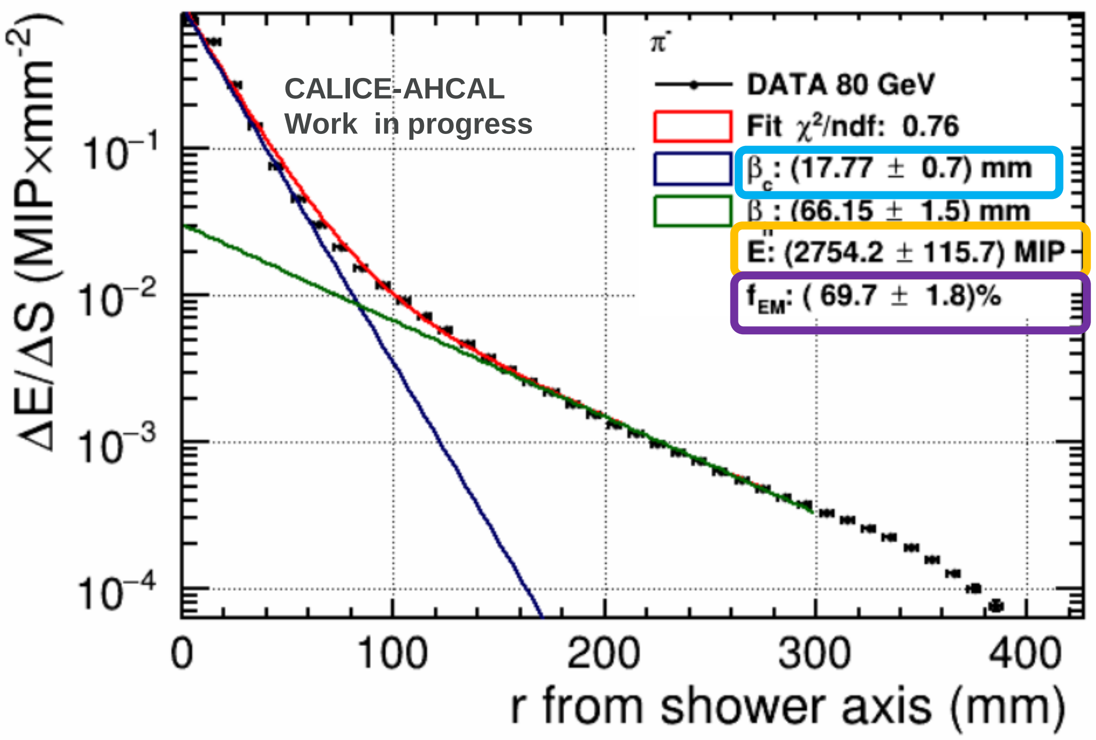
- Comparison of fit parameters extracted, shows a good agreement of Data between TB-2018 and
  TB-2007 within ~20%



What were the problems?

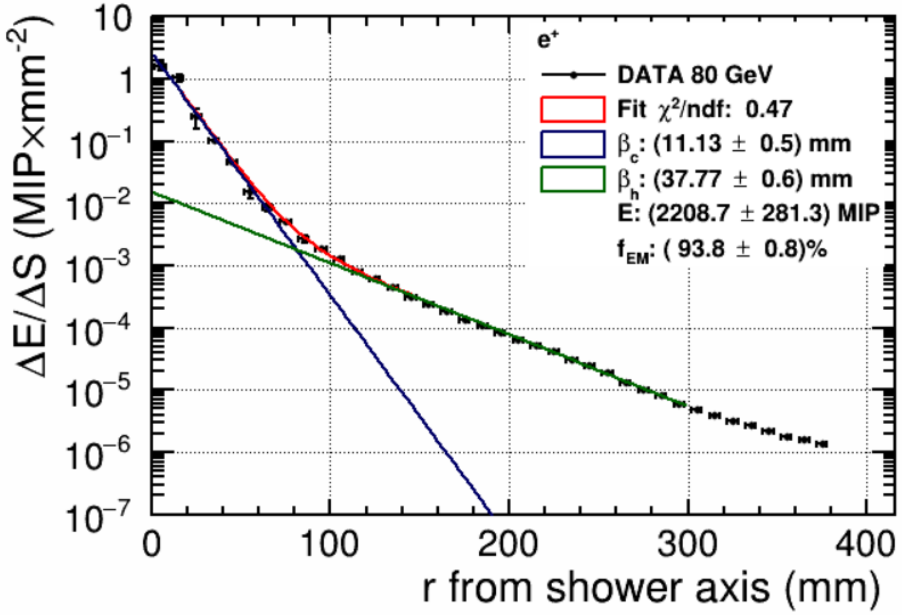


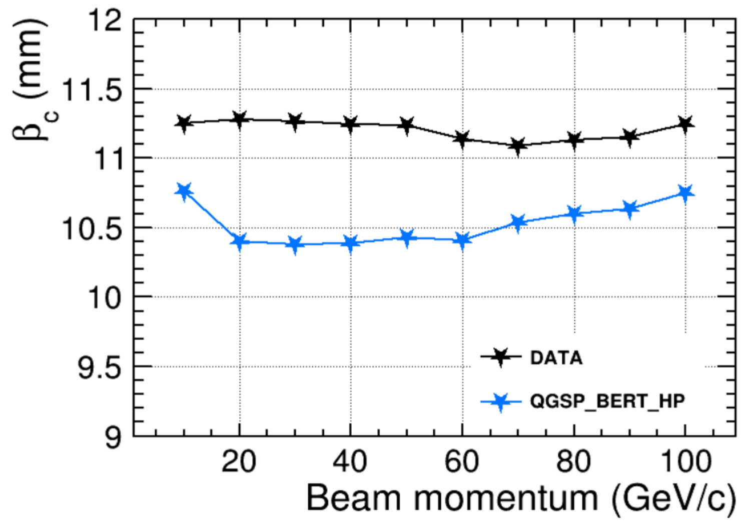
- The **energies** do not agree with each other
- With the understanding that the core is related to EM-shower
  - The **fraction's** do not agree
  - For **beta core** the value that it fits does not agree with EM shower

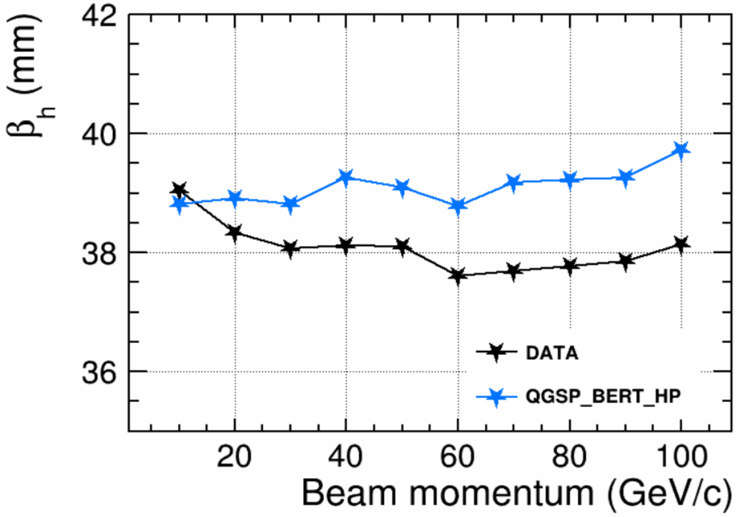


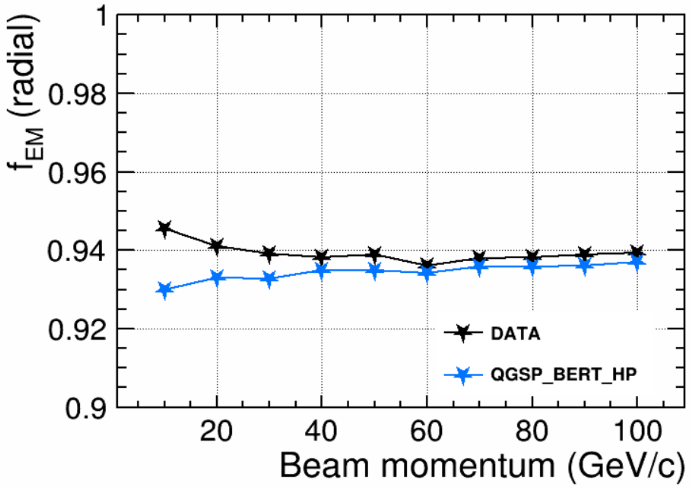
Beta's from EM

- 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







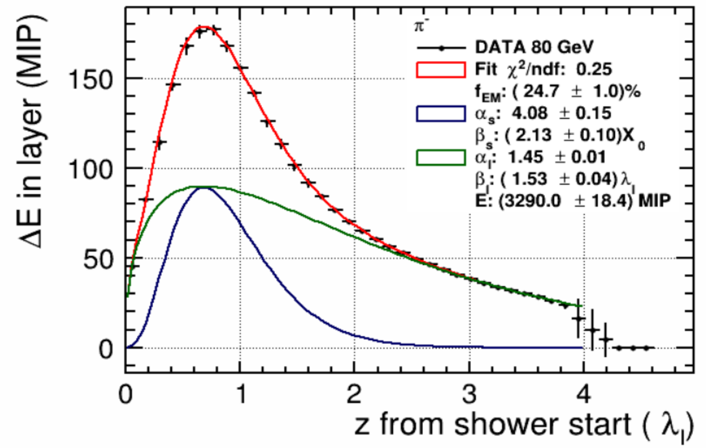


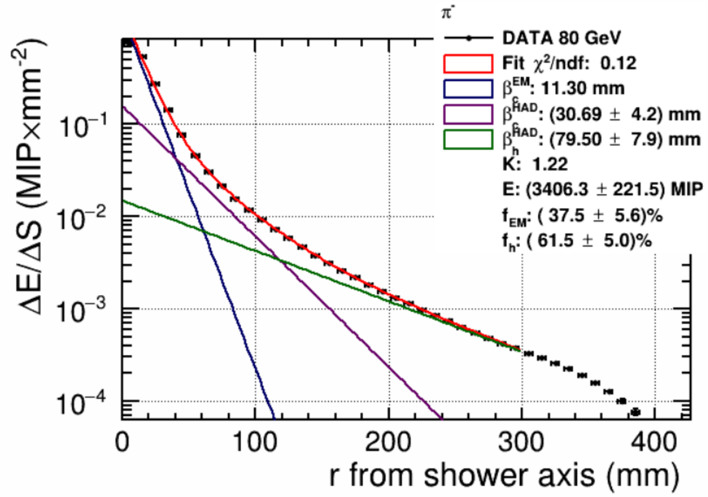
Understanding the total energy

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

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

- 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



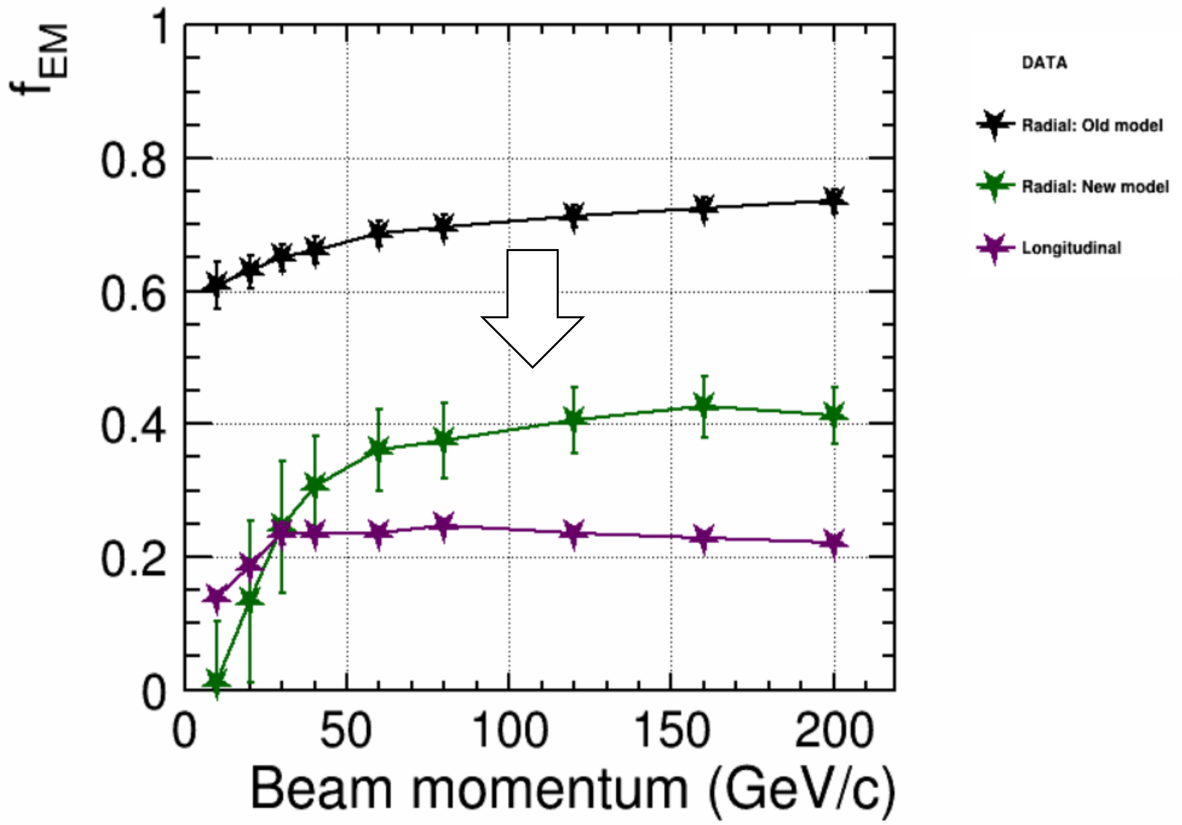


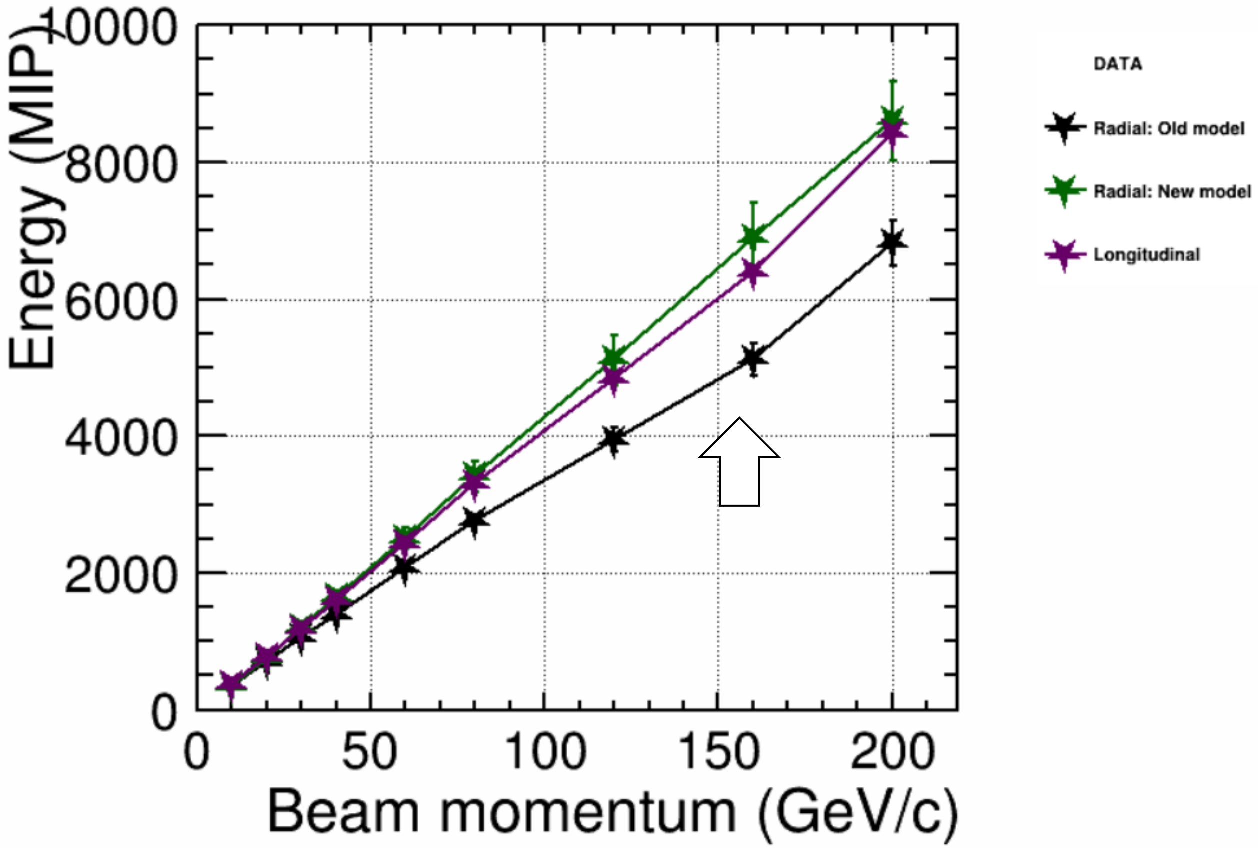
Does it now look reasonable?

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

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

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





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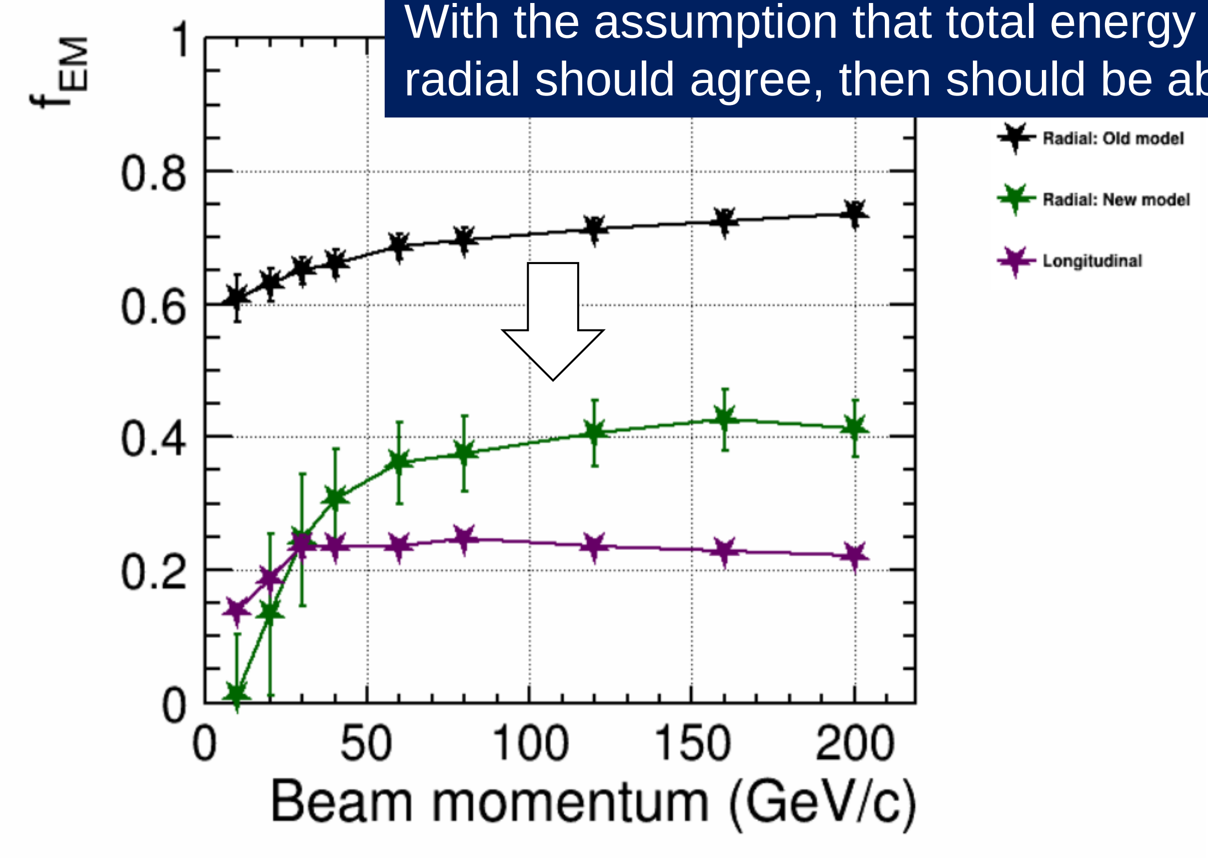
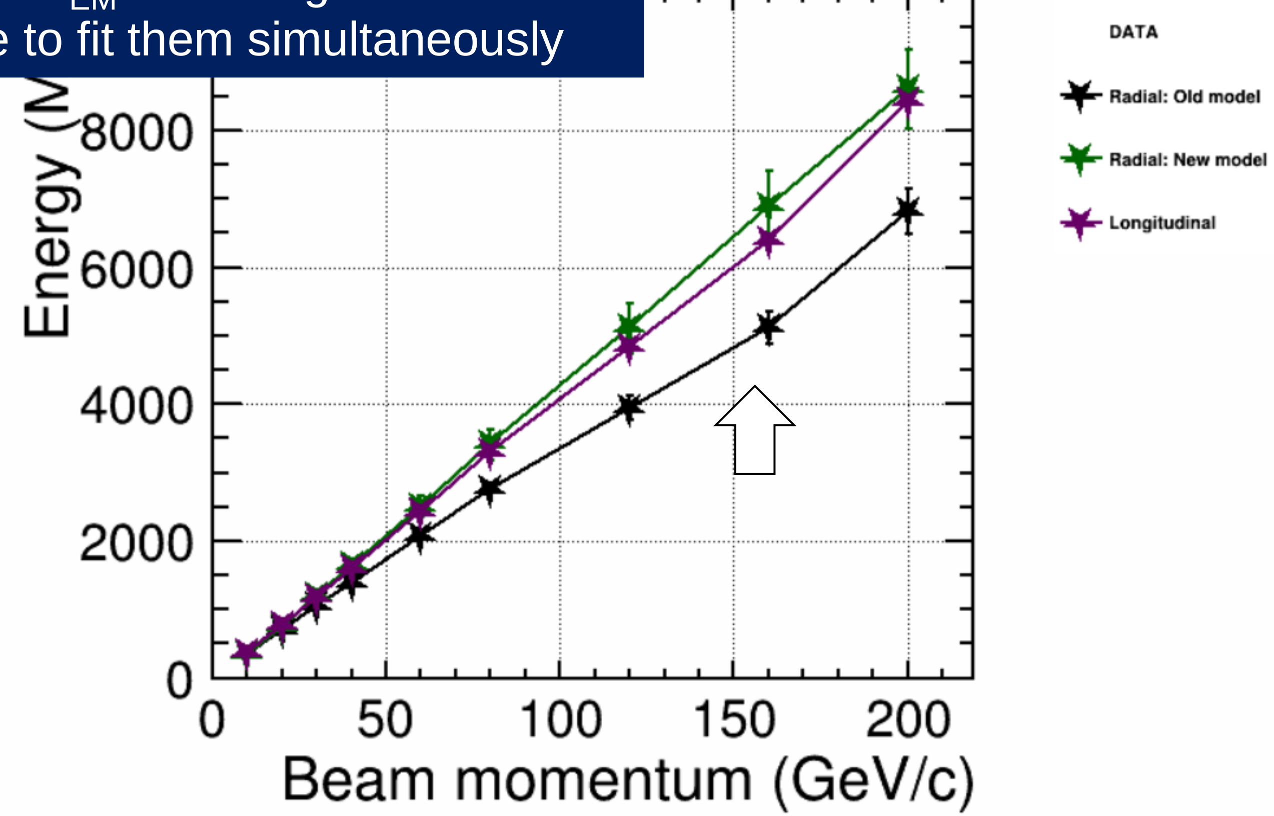
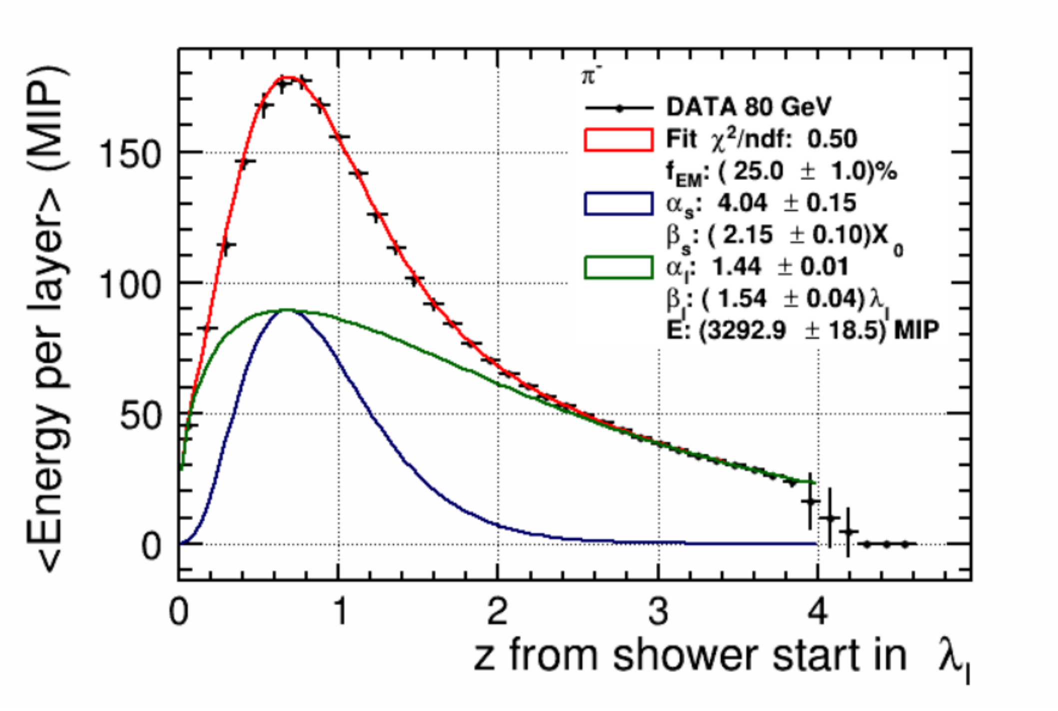
With the assumption that total energy and f_{EM} from longitudinal and radial should agree, then should be able to fit them simultaneously

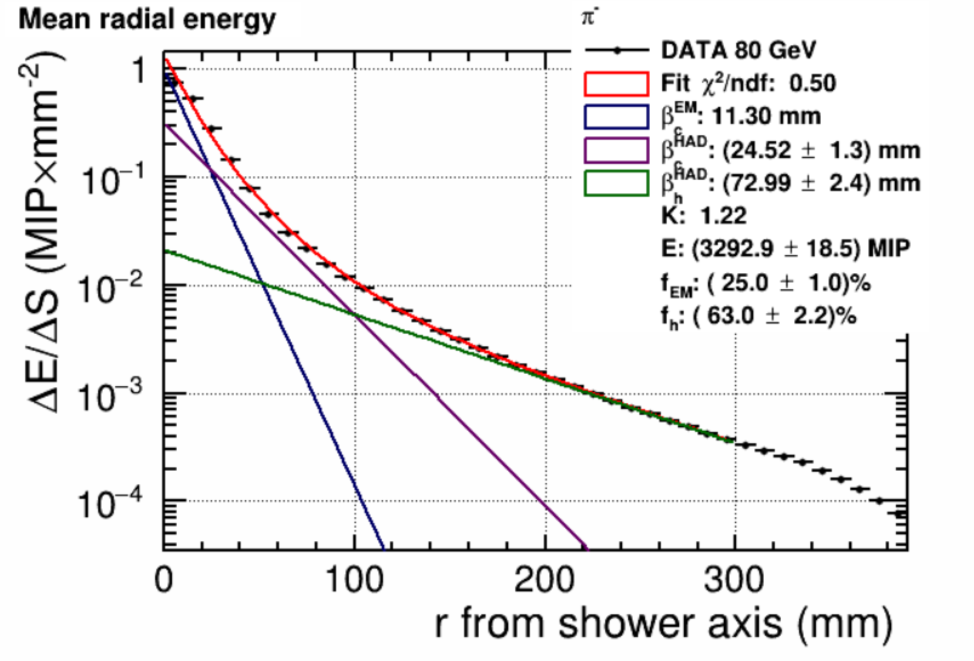


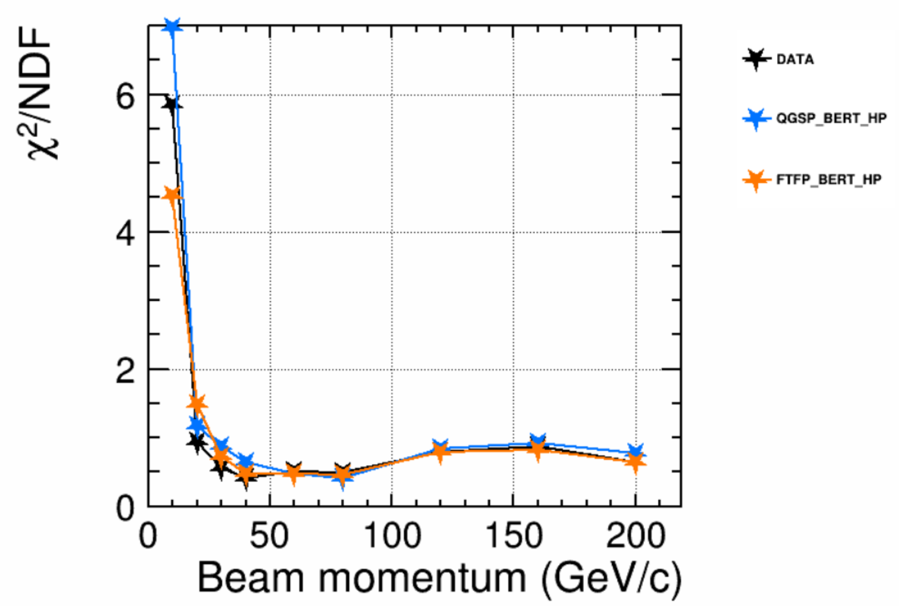


Simultaneous fitting

Sharing f_{EM} & energy parameter

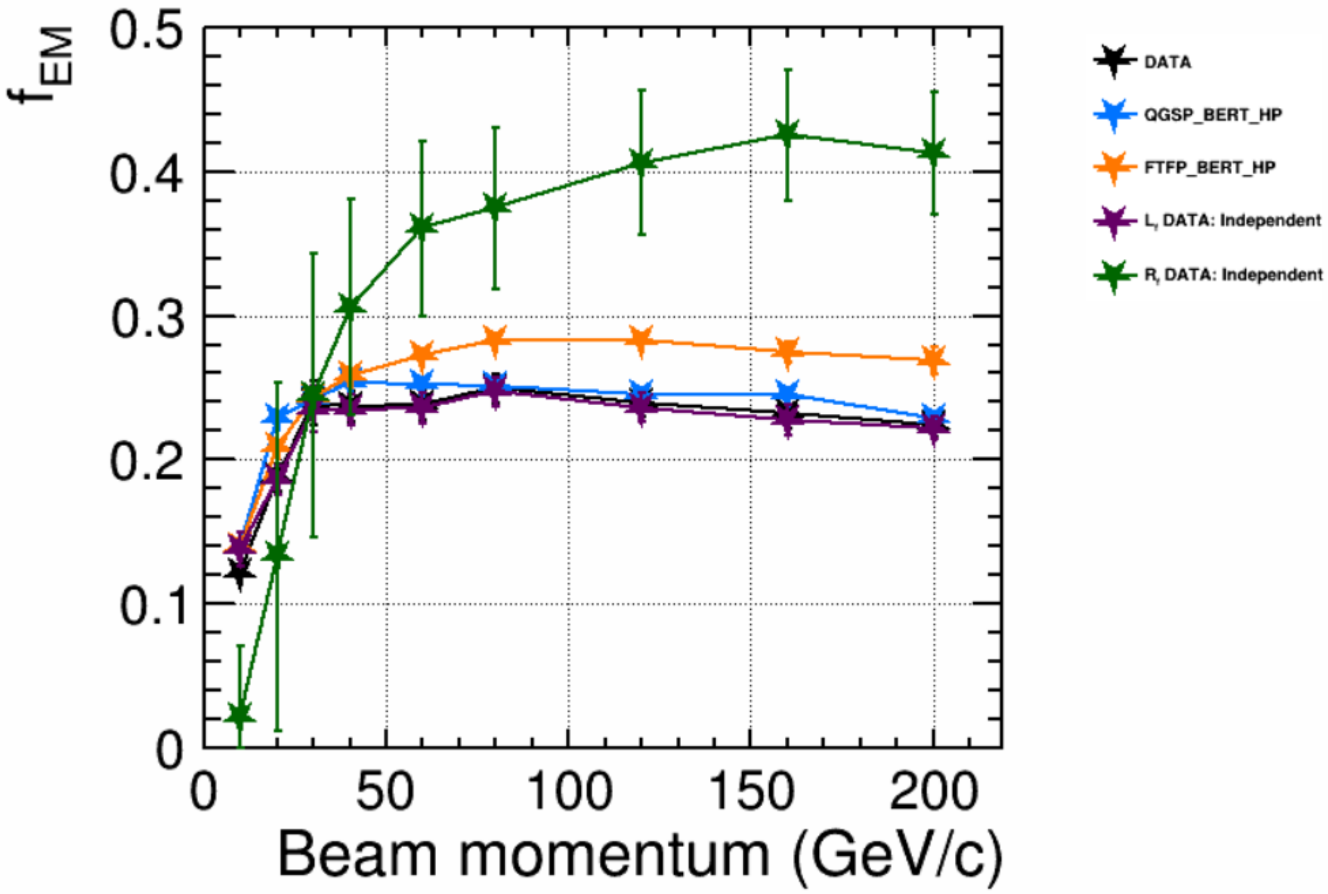




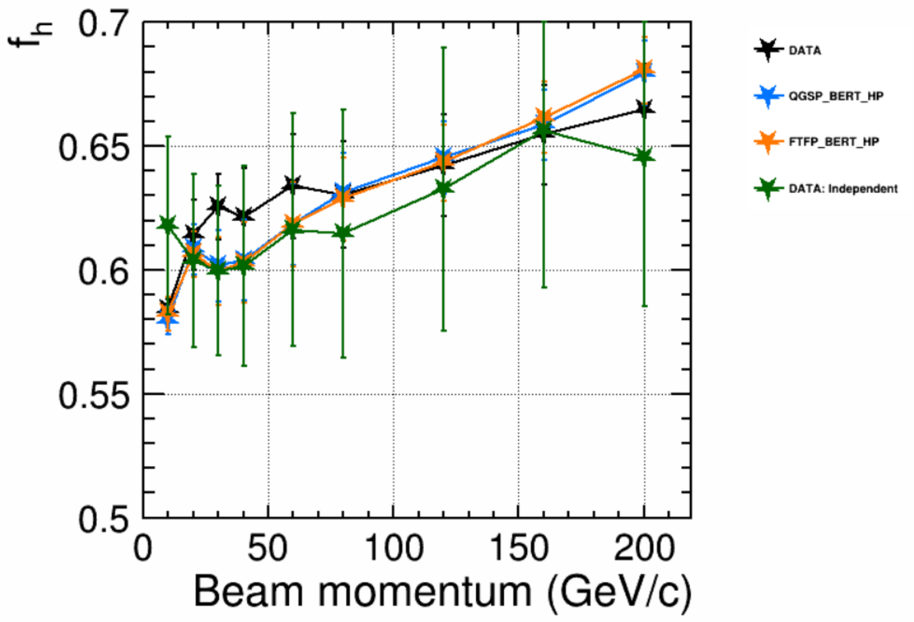


- A simultaneous fitting is performed with sharing f_{EM} and energy parameter
- This fitting allows to obtain an average f_{EM}
- All energies above 10 GeV show a good CHI2/NDF

Average "EM-fraction" and Halo- fraction

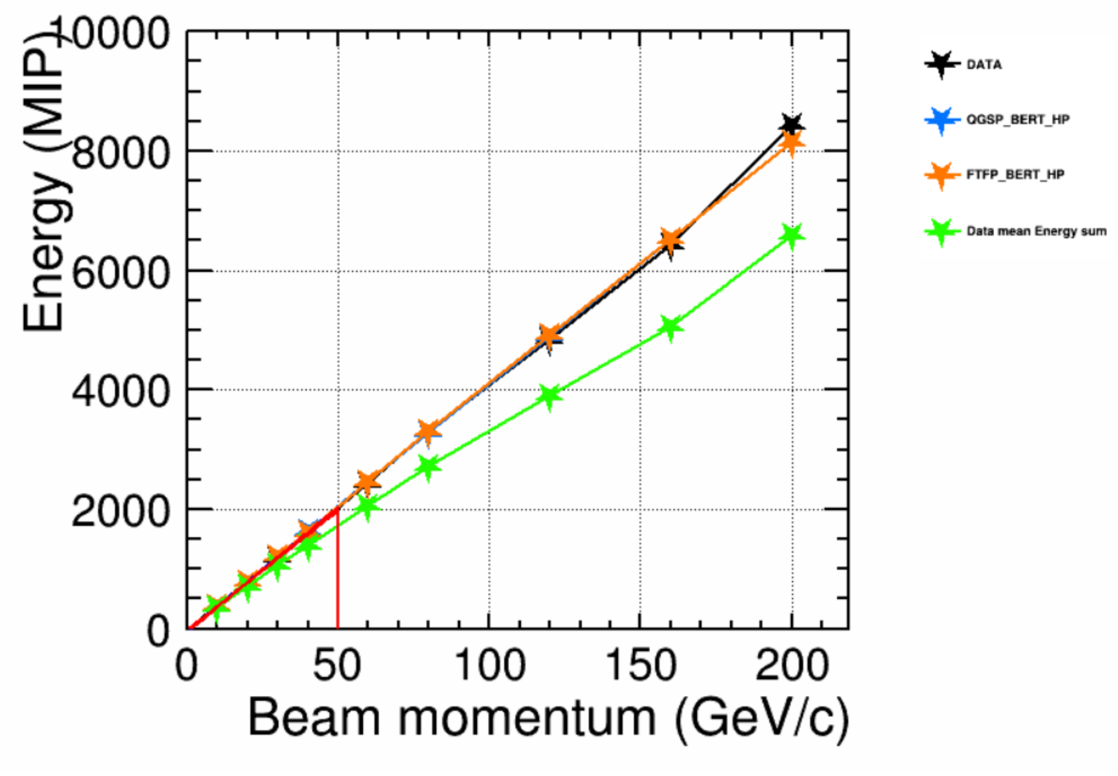


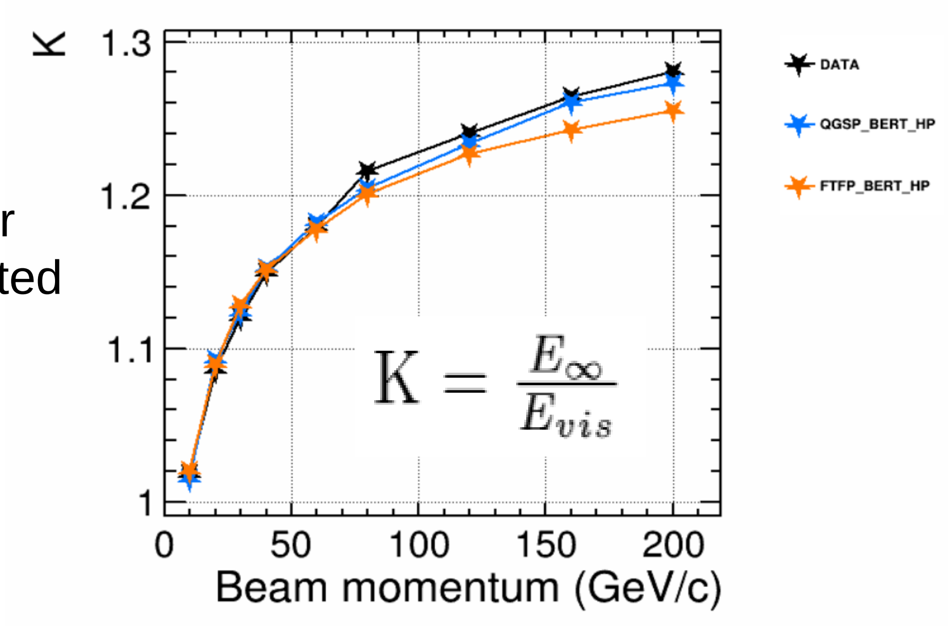
- The average f_{EM} obtained from simultaneous fitting is mainly pulled by the longitudinal parameter compared to the one obtained from independent fits
- The acquired f_{EM} value is found to be around 10-30%
- The halo fraction remains to be less dependent

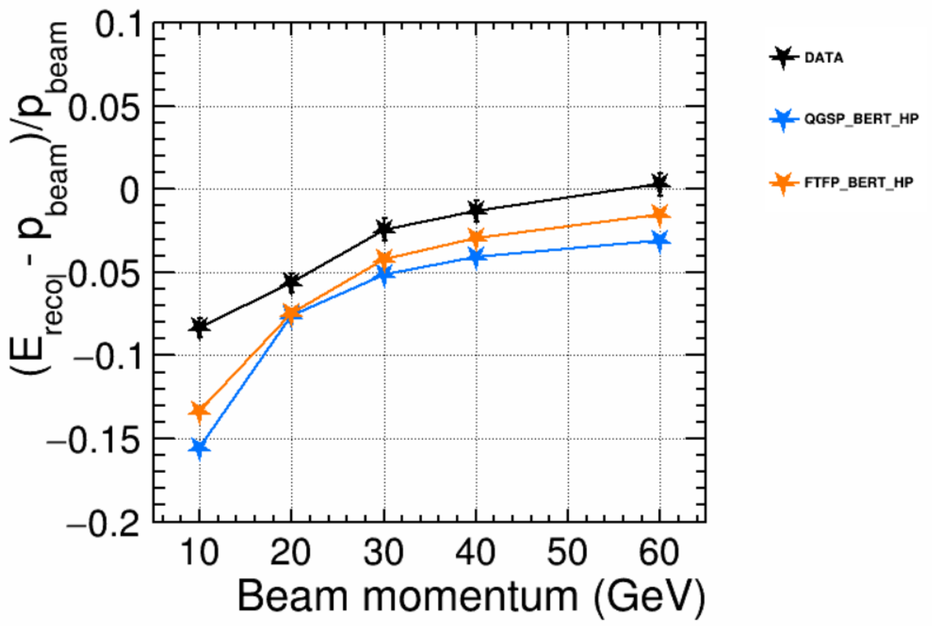


Energy and leakage term 'K'

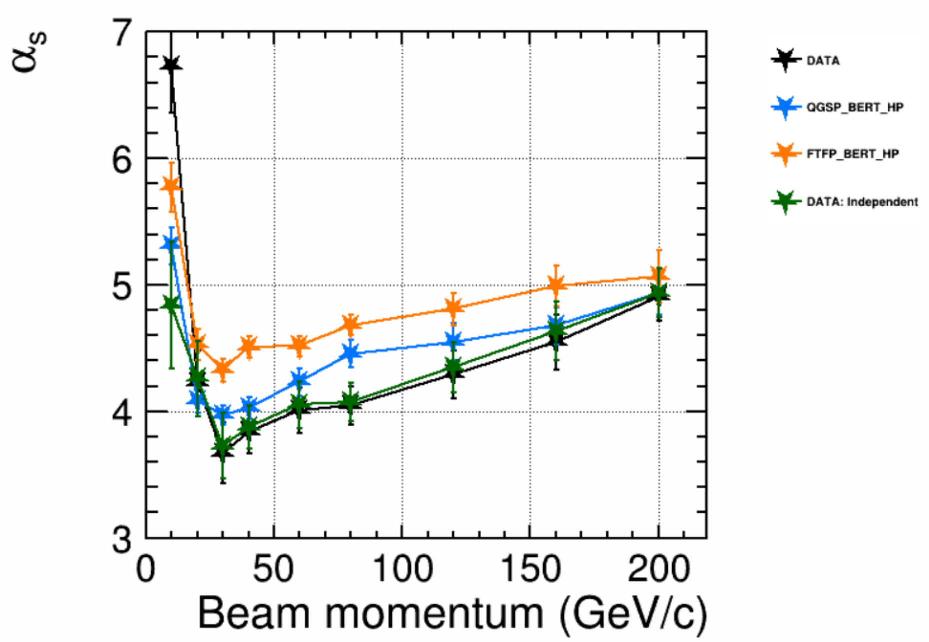
- About 20% leakage already at 100 GeV
- A linear fit is performed in the energy range [0, 50] GeV
- E_{reco} [GeV] is obtained from the ratio of energy parameter from simultaneous fitting and the slope parameter extracted from the linearity fit
- Deviation from linearity is within ~15%

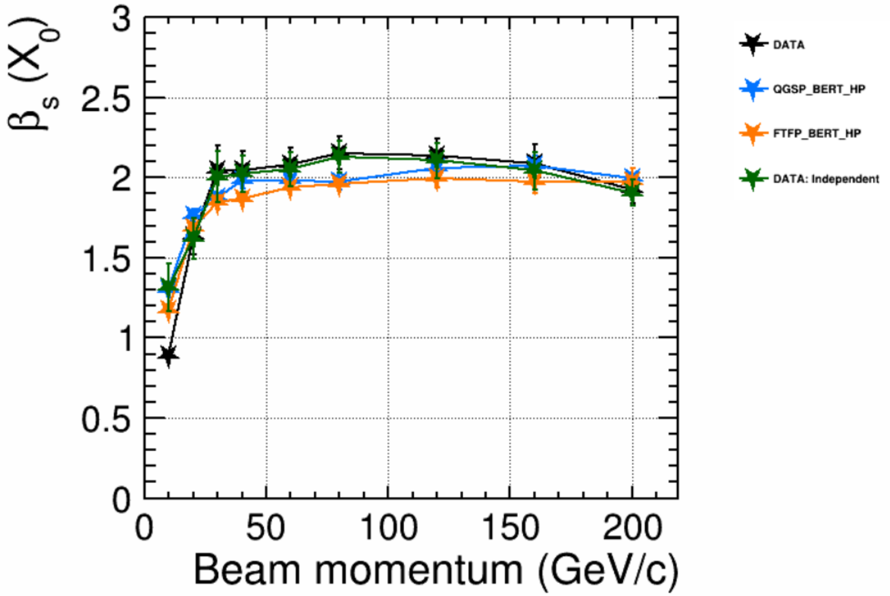






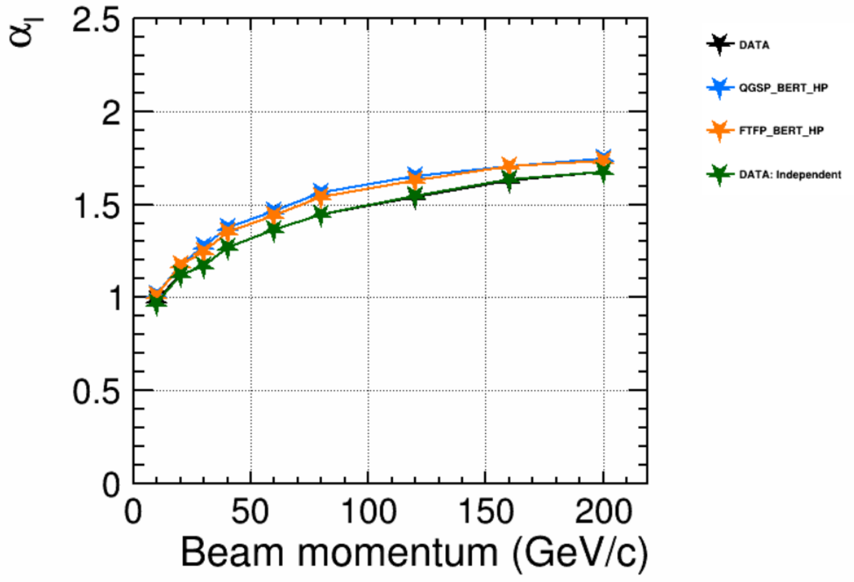
Short and long parameters

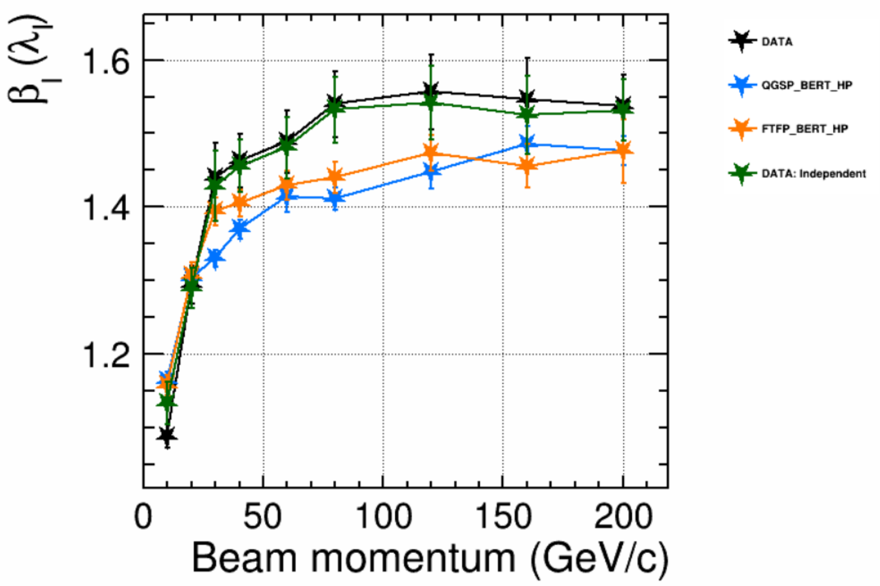




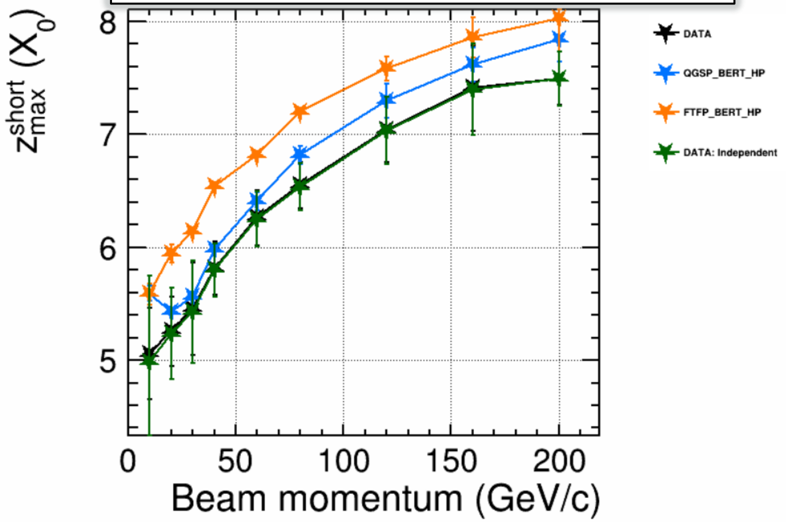
No significant difference is observed in the short and long parameter compared to data points from **independent fits**

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



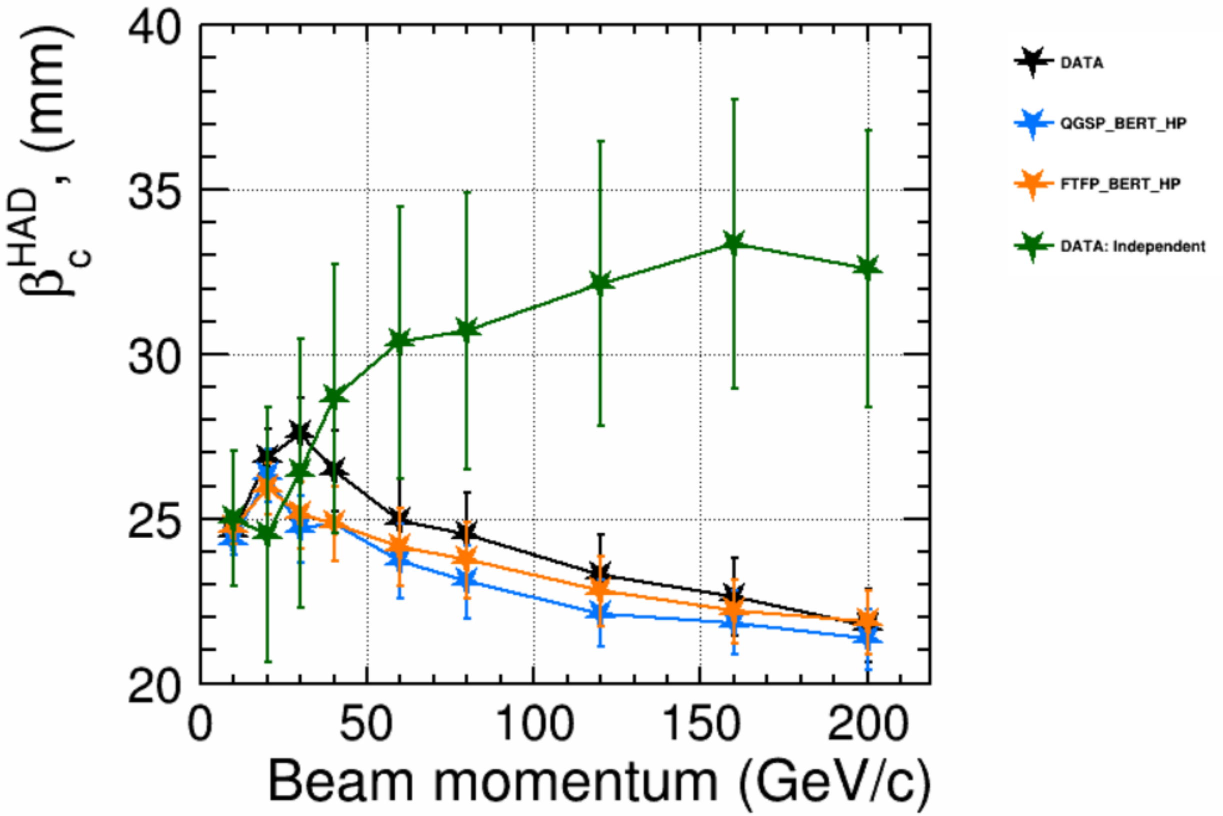


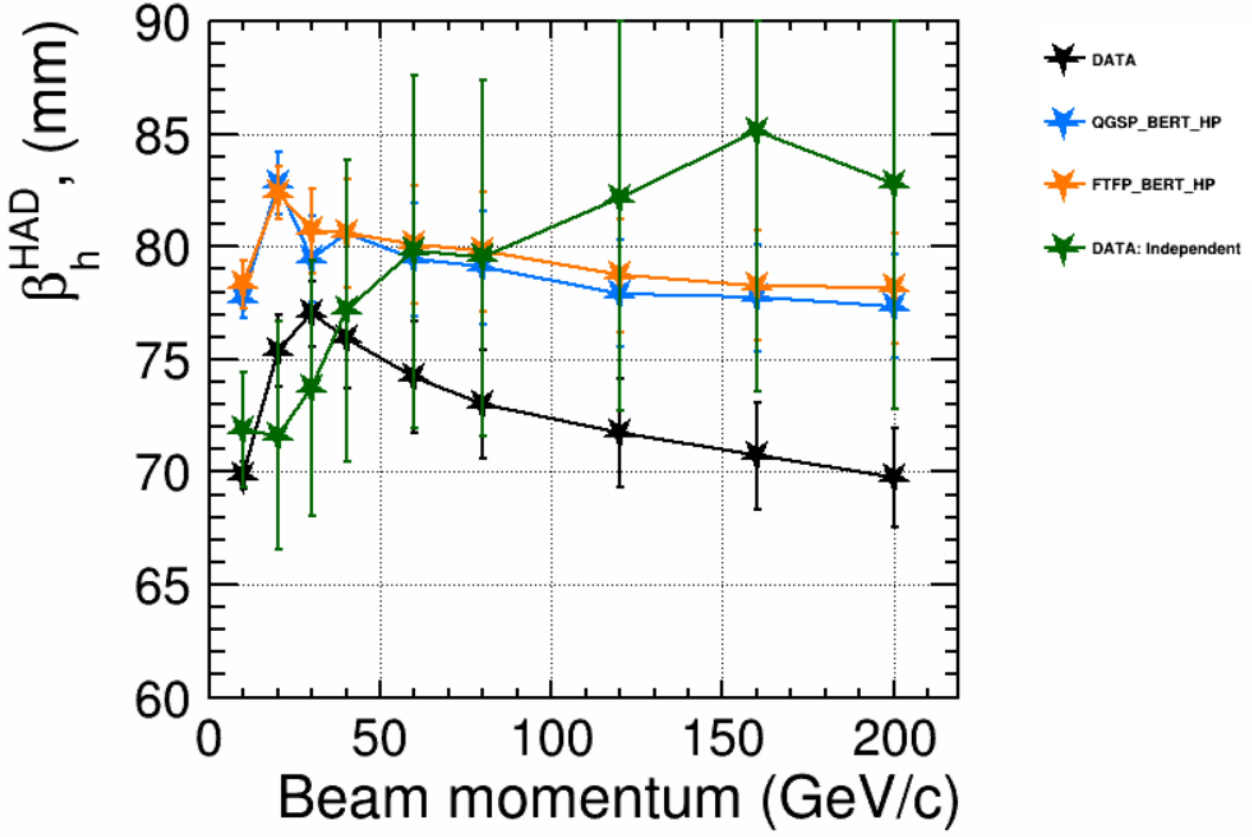
$$Z^{short}_{\max} = (\alpha_s - 1) \times \beta_s + cov\,(\alpha_s, \beta_s)$$



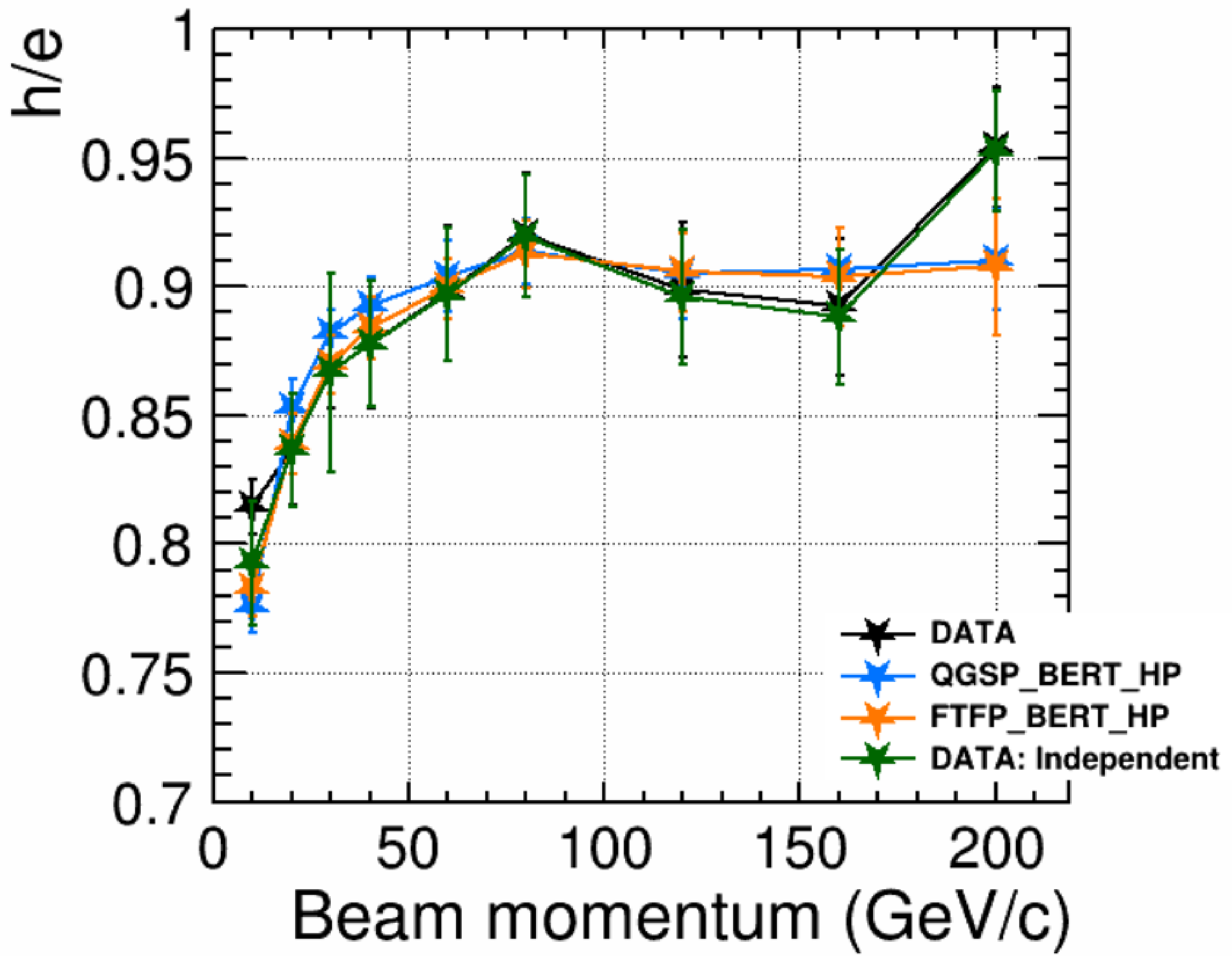
Core and Halo

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





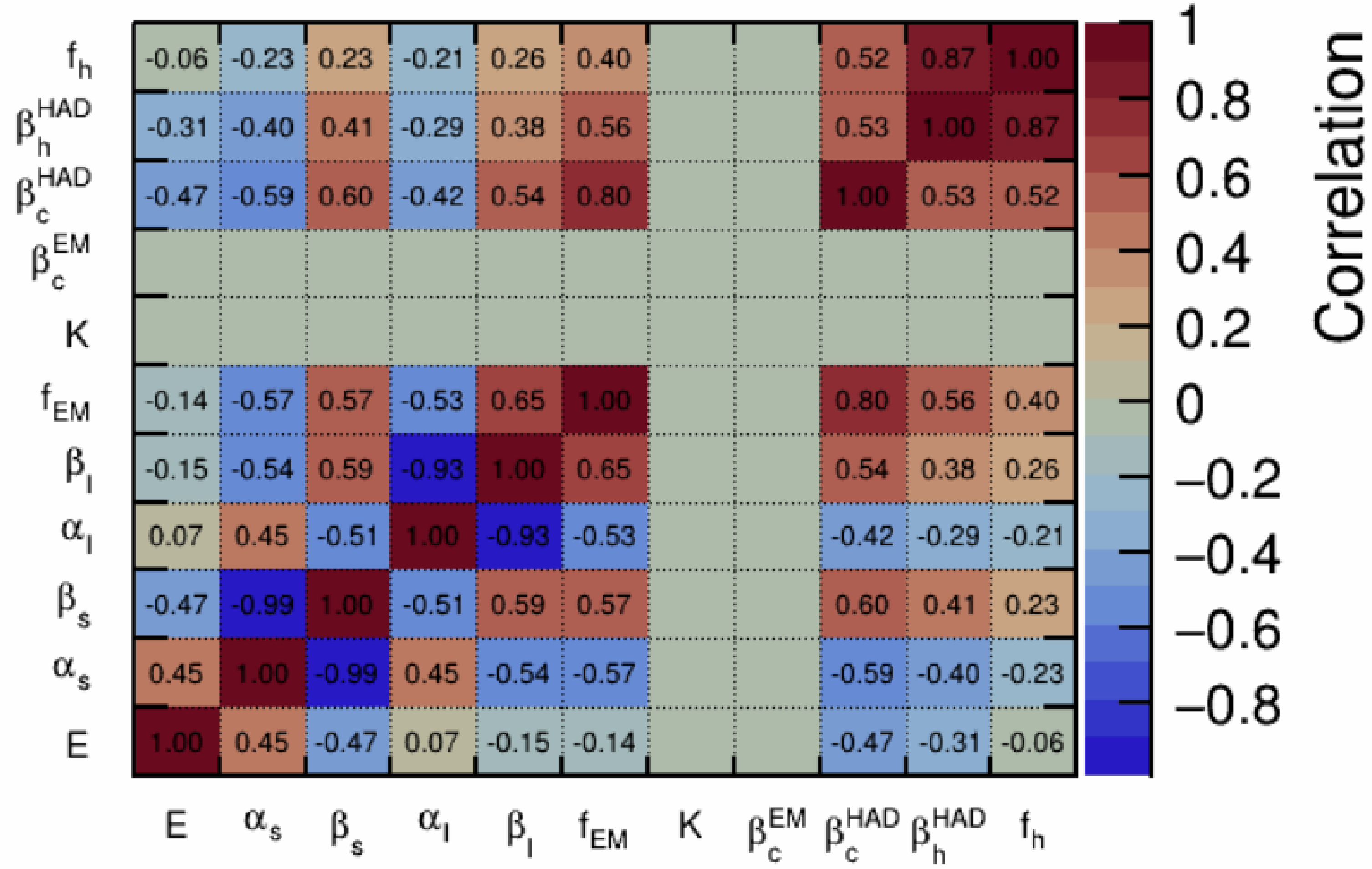
h/e signal ratio



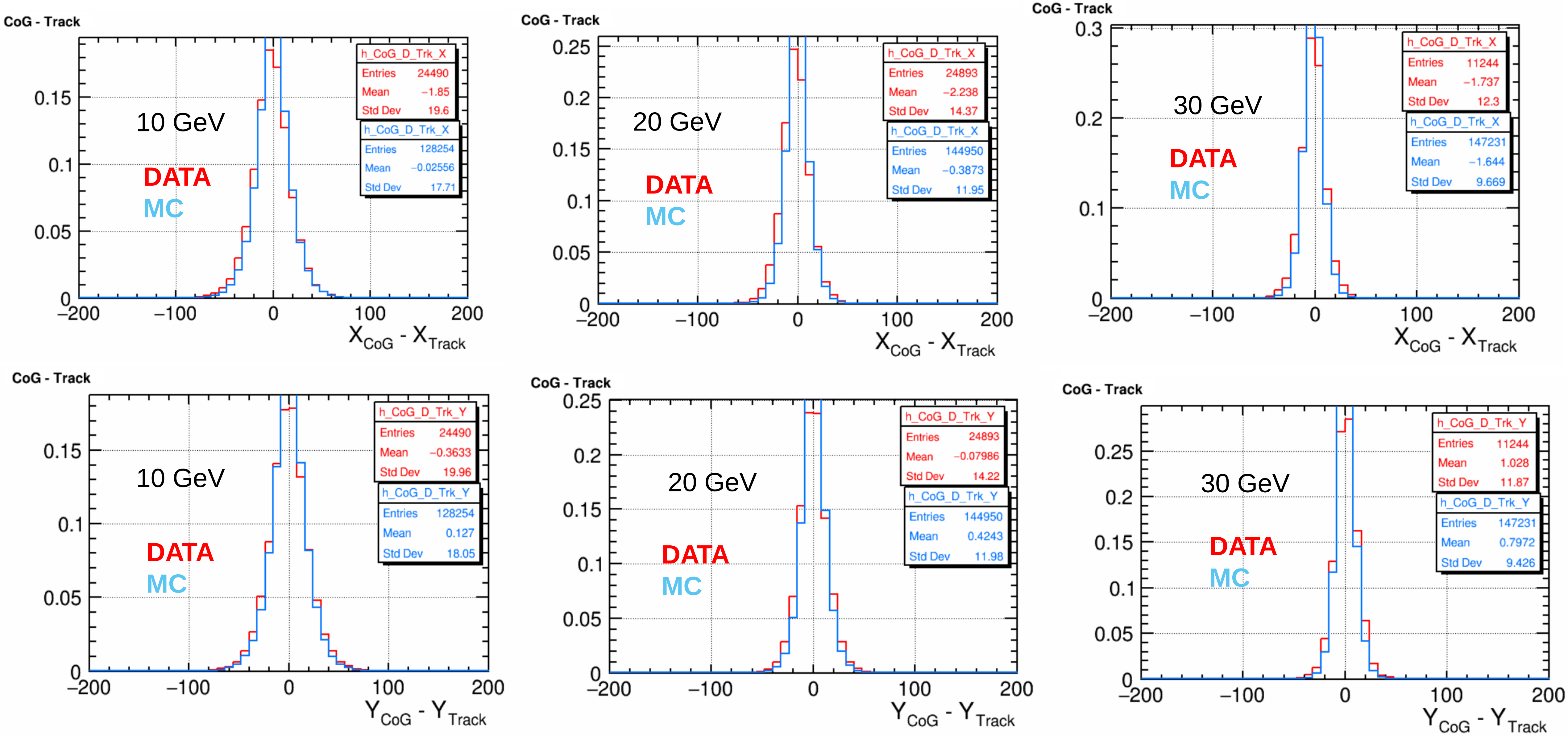
Correlation of parameter

80 GeV

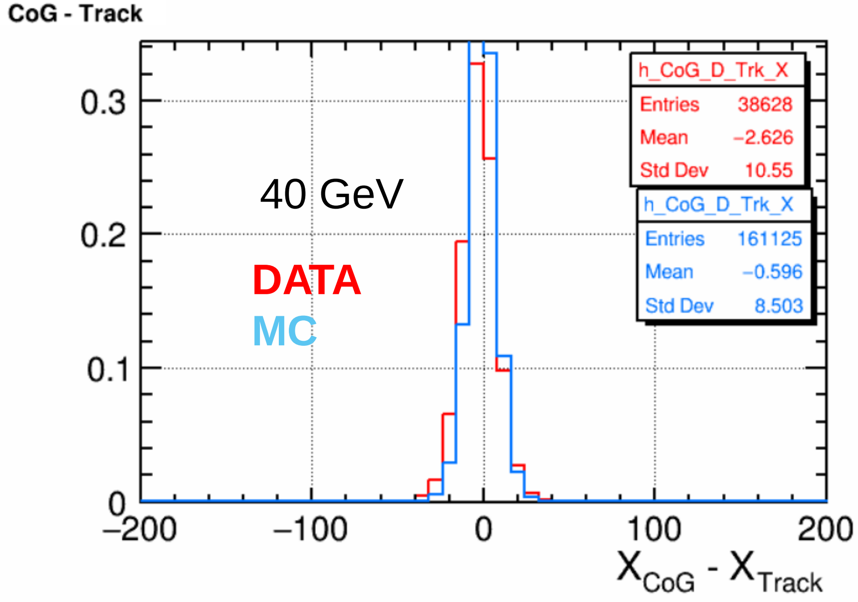
- The alpha’s and beta’s have anti-correlation
- The radial beta's are highly correlated and have a positive correlation!

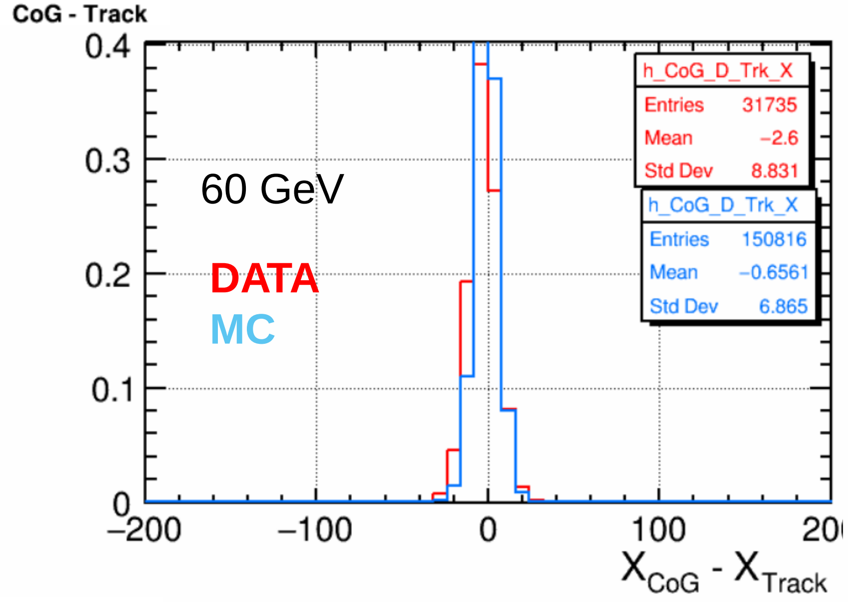


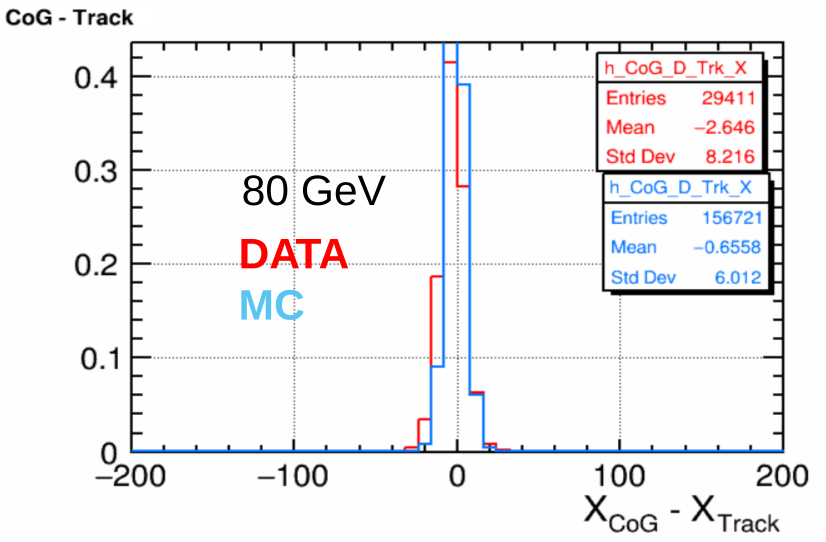
Track to COG (event) Comparison

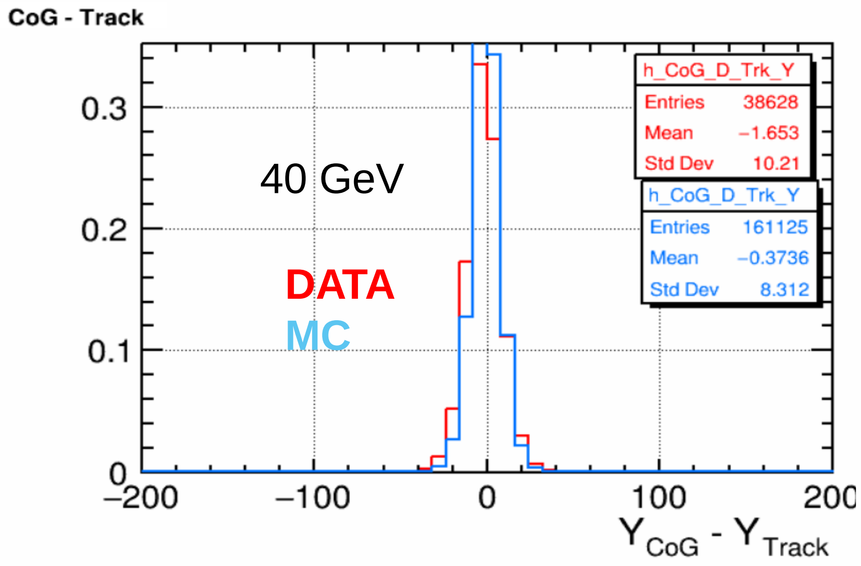


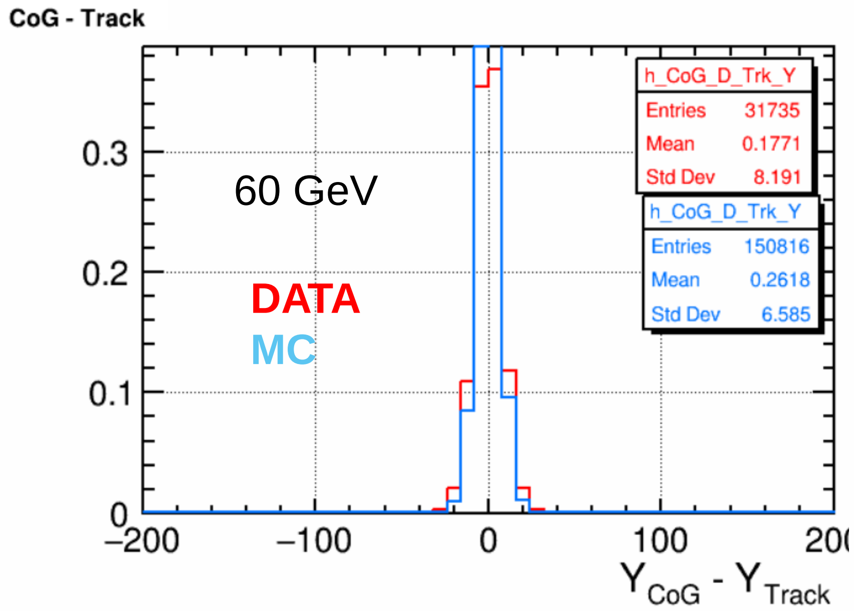
Track to CoG (event) comparison

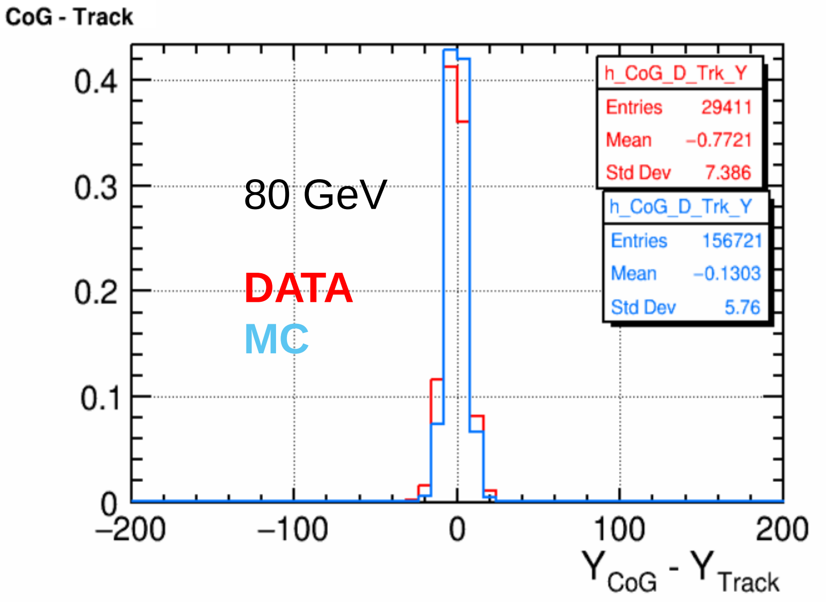




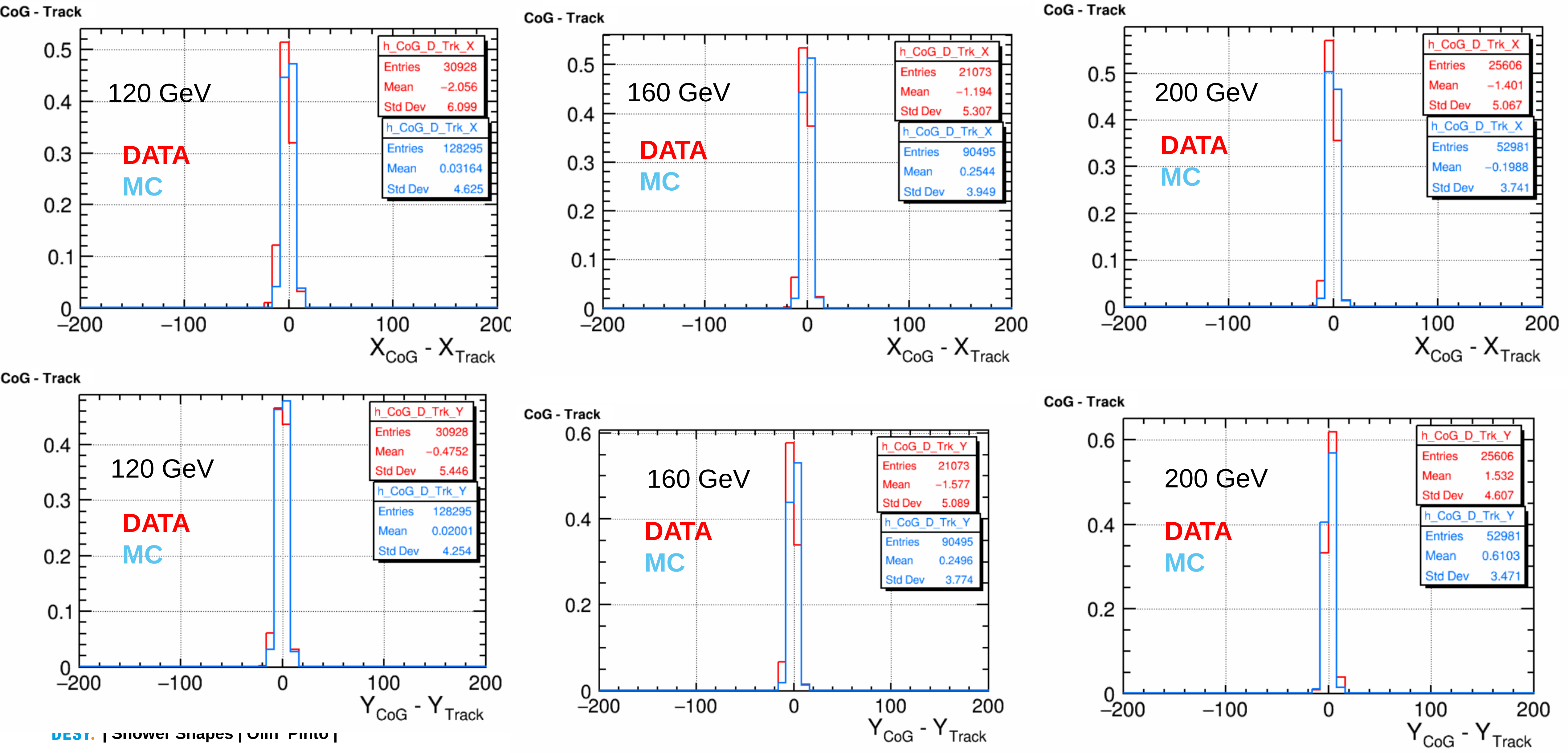








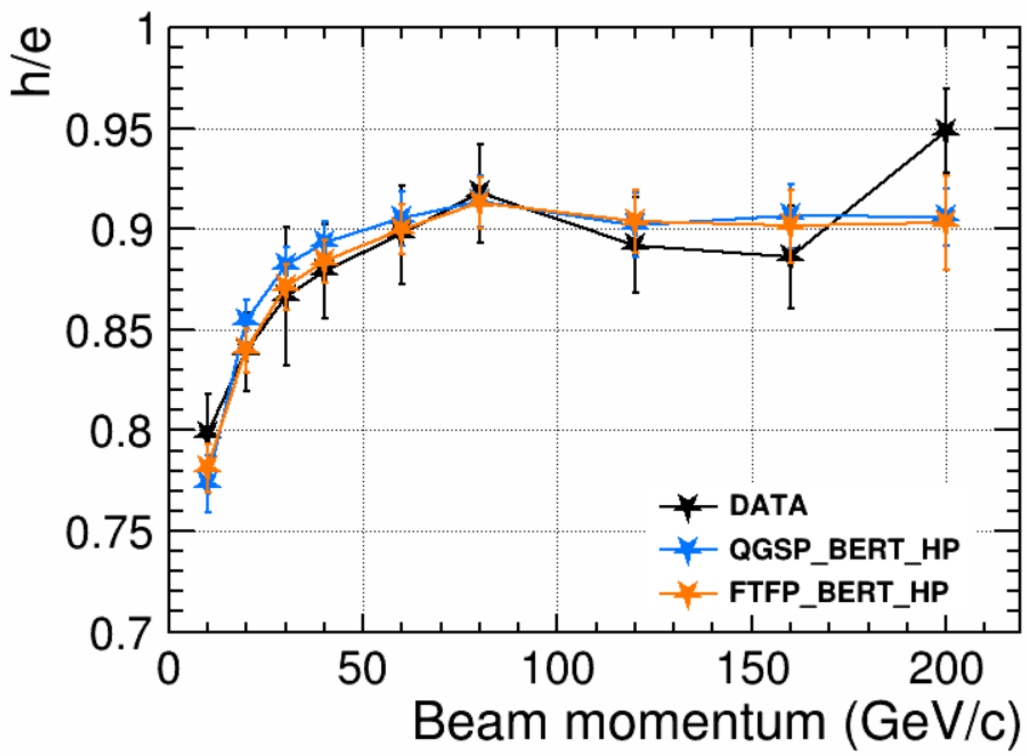
Track to COG (event) Comparison



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>

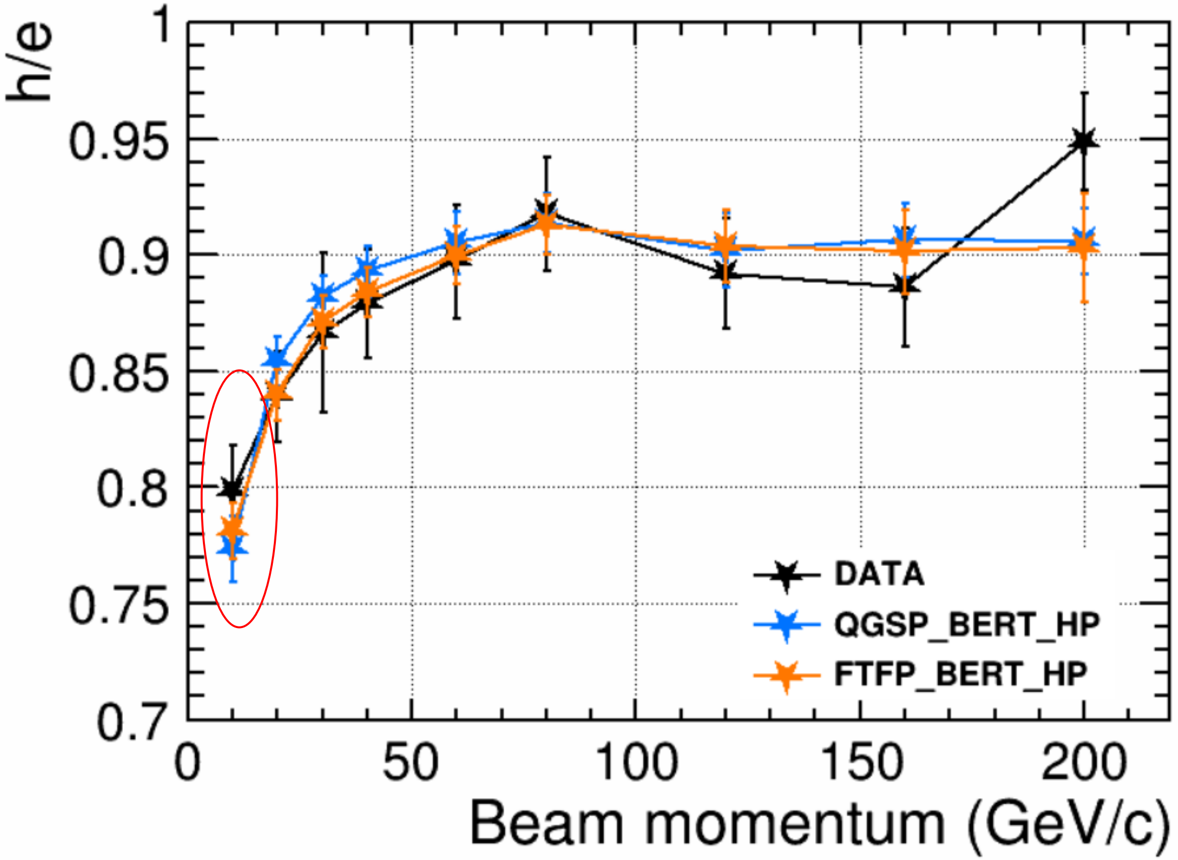
- With the little memory of the incident hadron, the **fraction of invisible energy** that is detected in calo. is more less the same for all energies
  - A possible interpretation is that the invisible energy is higher at low beam energy

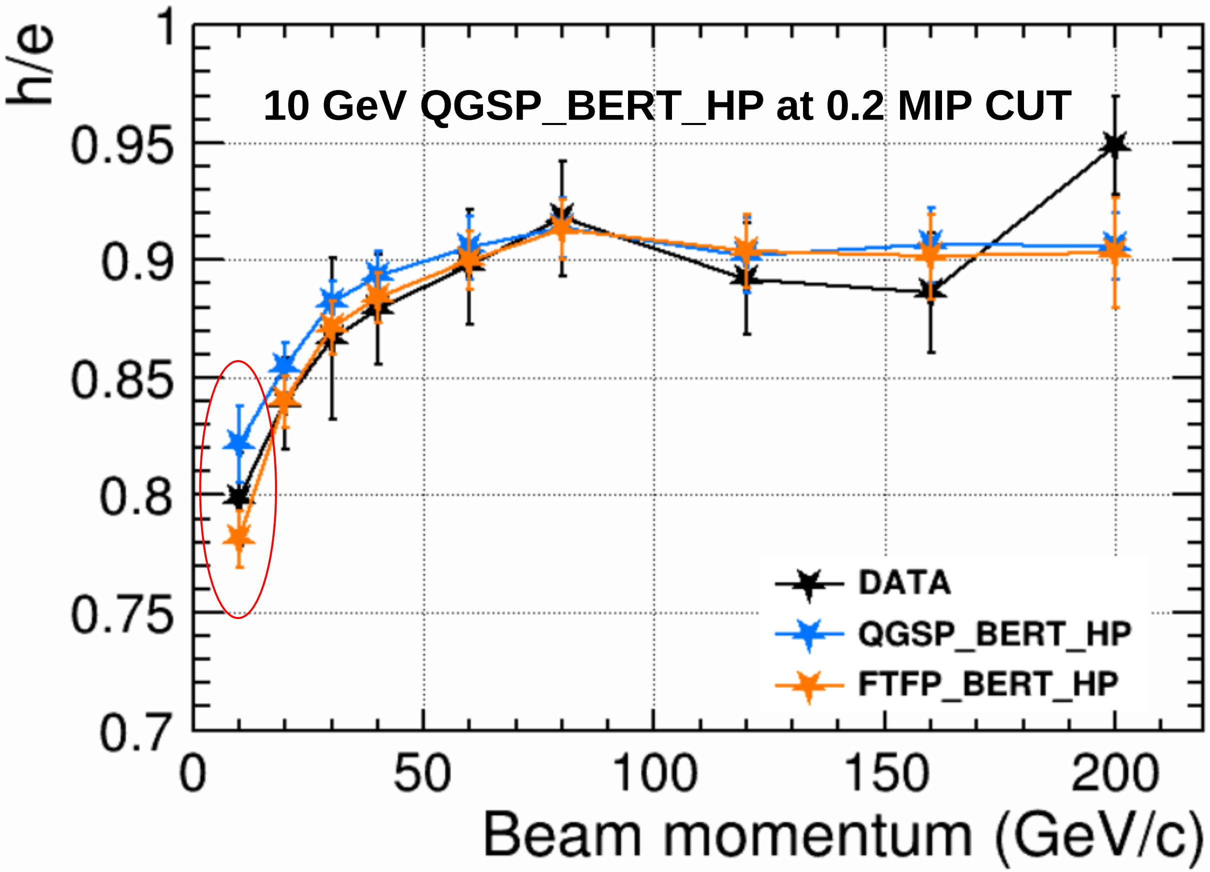
Possibly my fits are not described well below 50 GeV!

Detector effects:

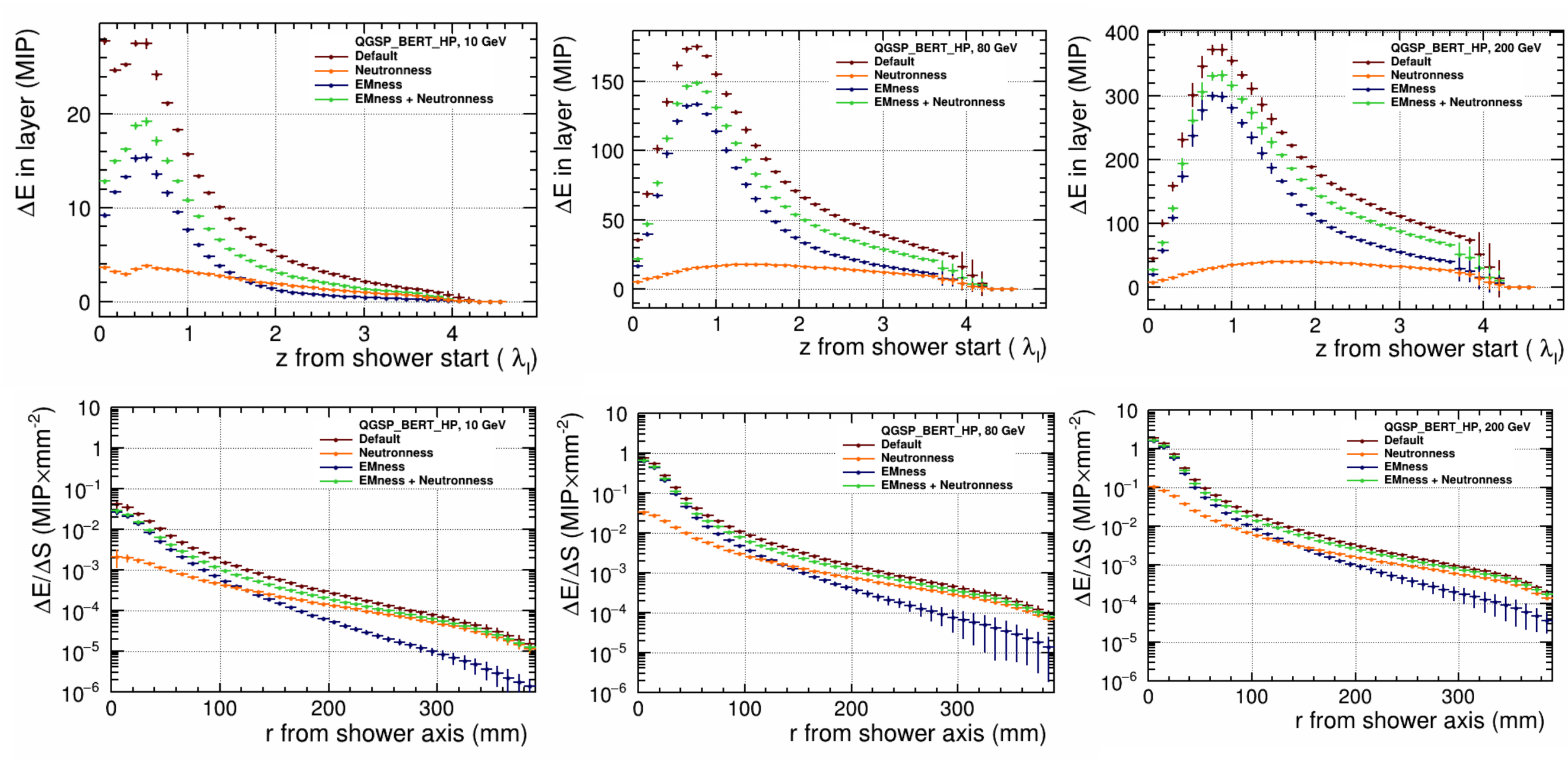
- With a cut at 0.5 MIP, might be that the fraction of hits that is below half a MIP is bigger at low beam energies
  - With 0.5 MIP at 1 x 1 cm^2 we could lose significant fraction of hits

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



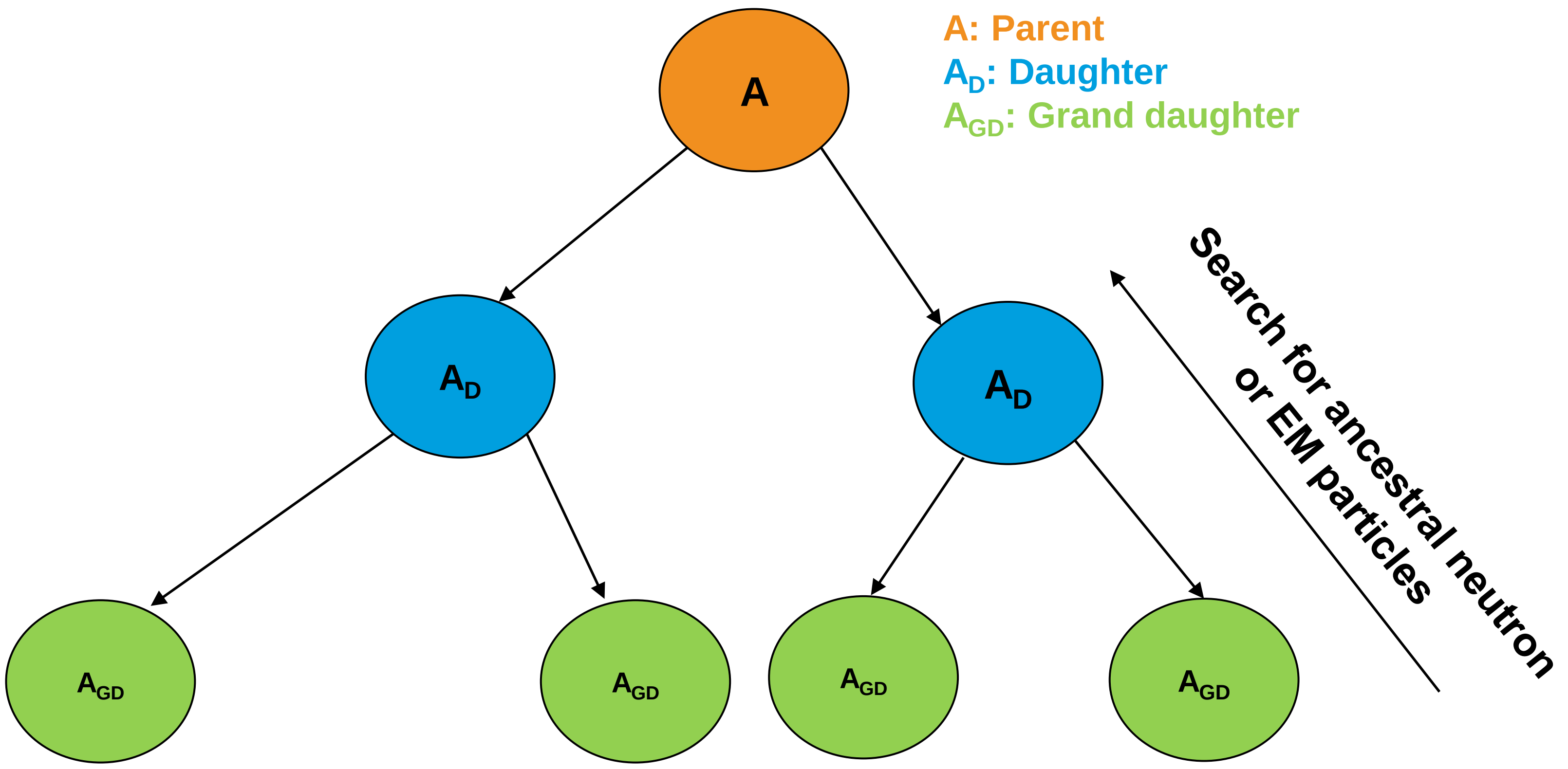


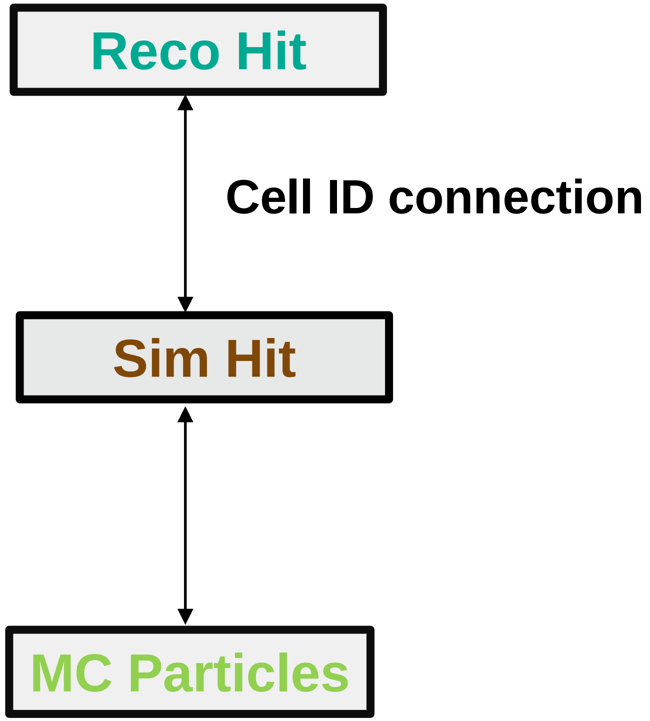
Longitudinal and Radial shapes



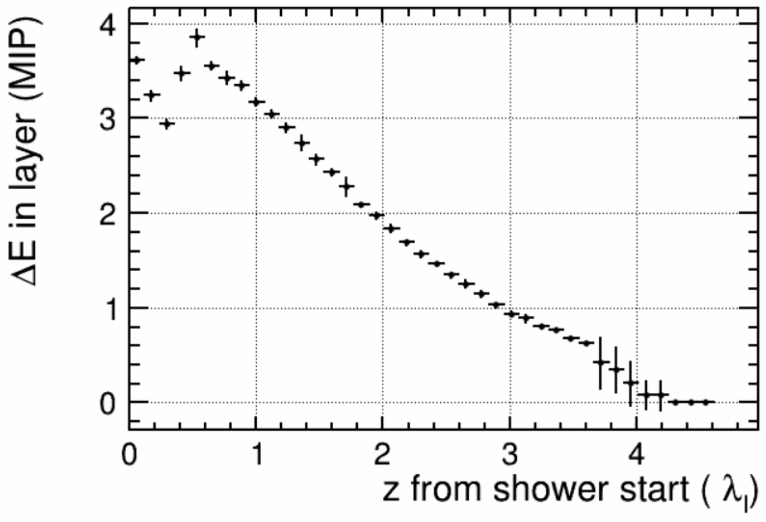
Introduction: MC particle study

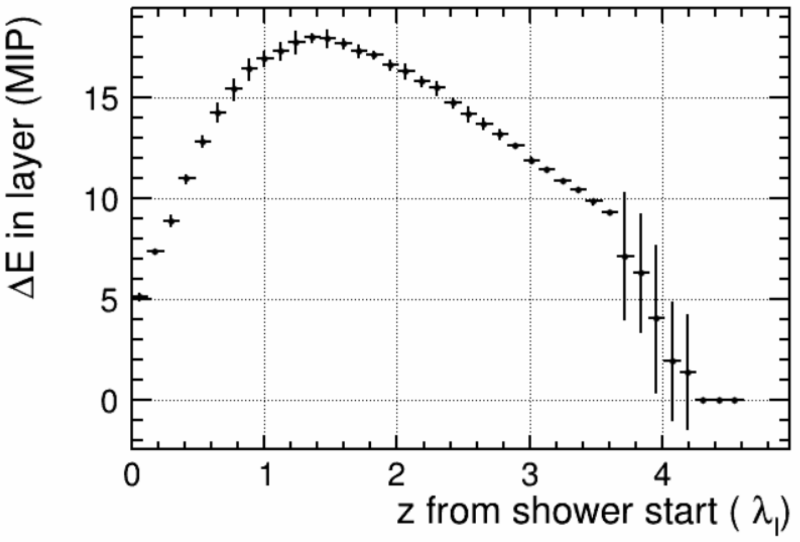
- To extract the properties of the MC particles (energy, momentum, PDG and time stamps)
- A relation between the **Reco Hit** and the **Sim Hit** is built which gives all the **MC particles** contributing to that hit

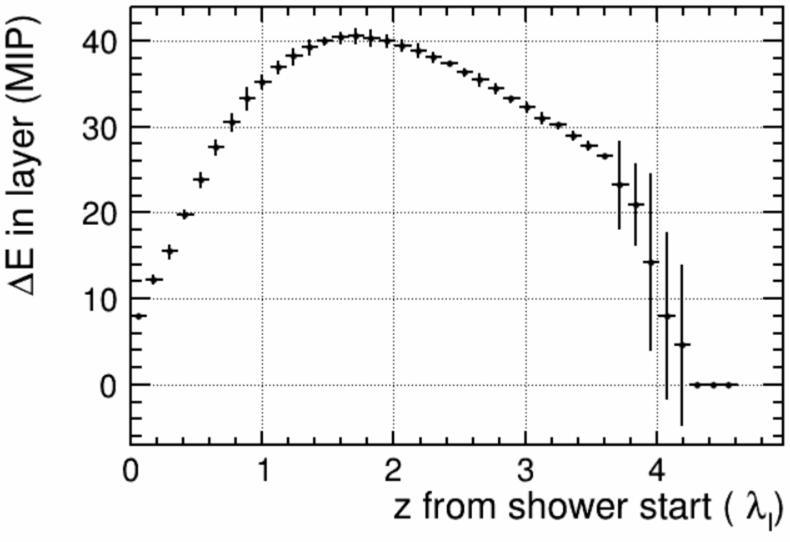




Neutron-ness





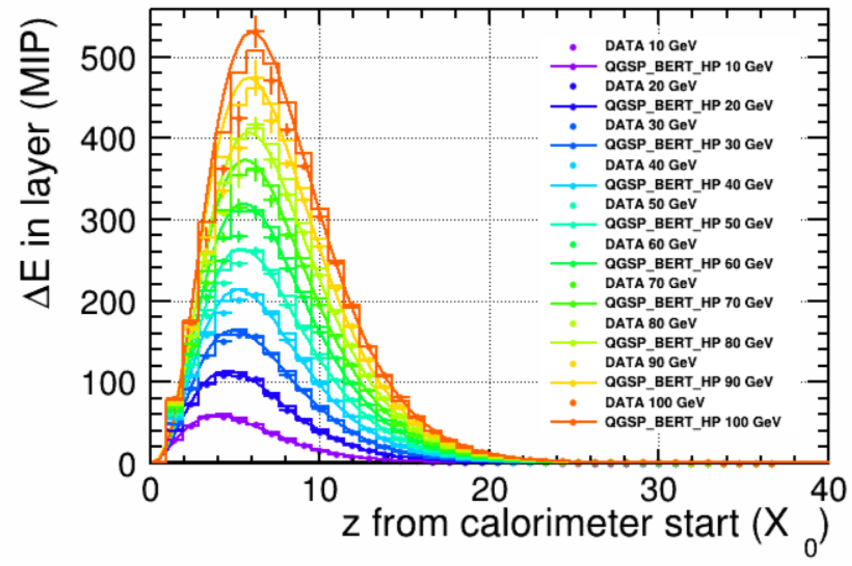


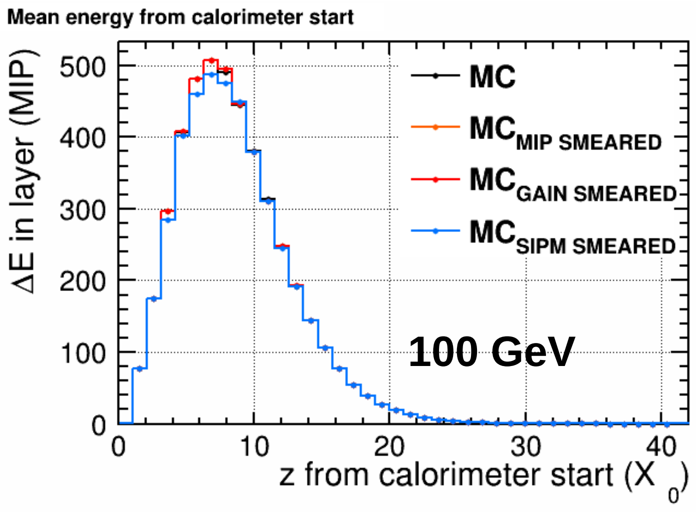
MORE SHOWER SHAPES …

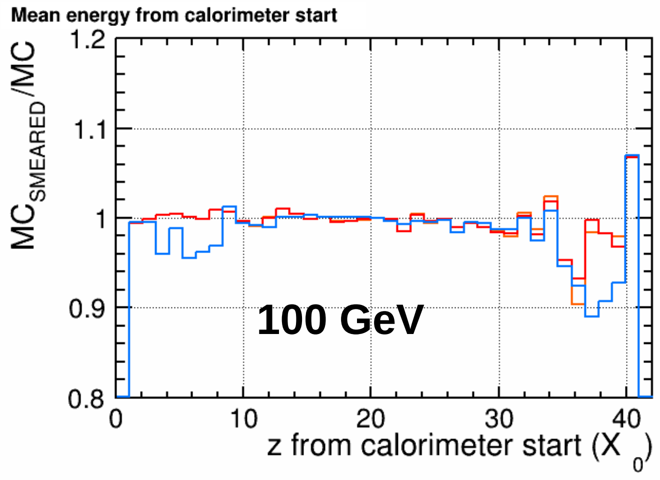
Electron Shapes

Electron longitudinal shapes

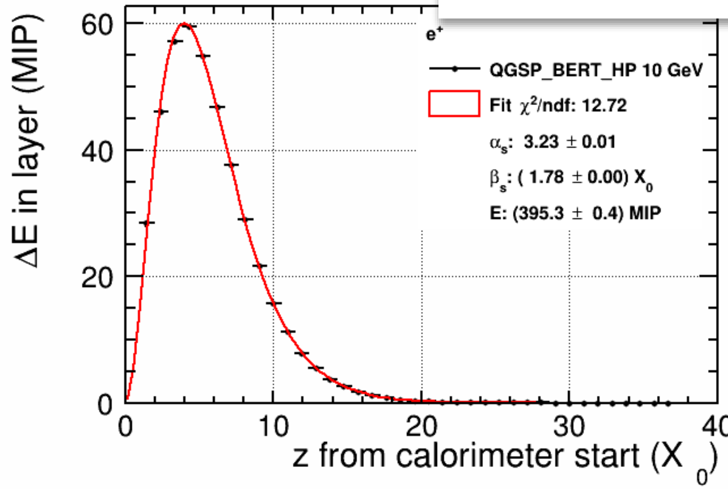
- **Systematics uncertainty are obtained by smearing the calibration constants (MIP, Gain & SiPM)**
- **The uncertainties are estimated for all energy ranges from 10 to 100 GeV**

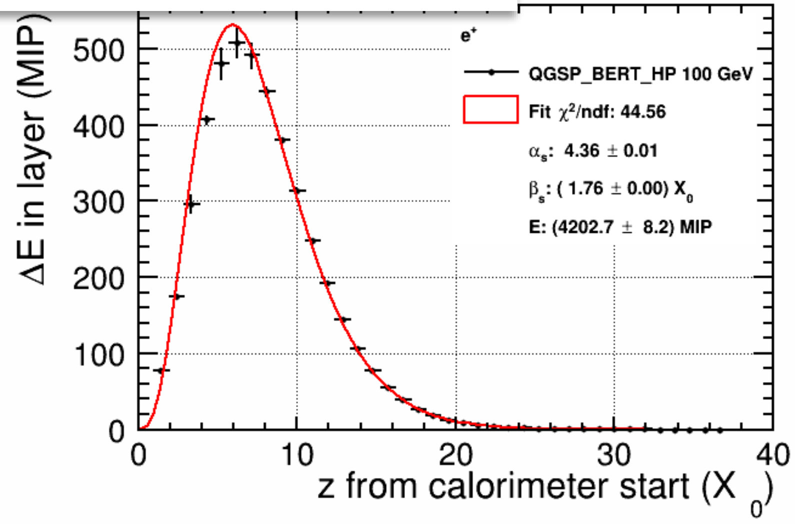


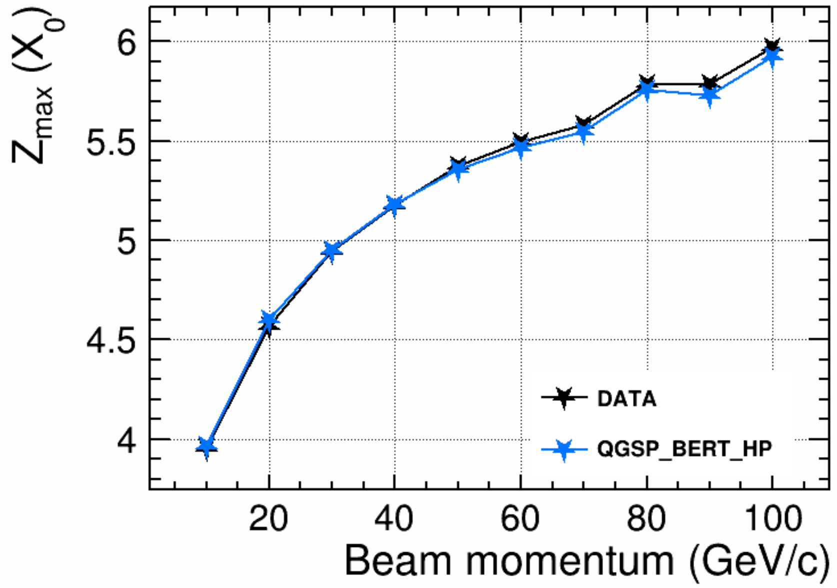




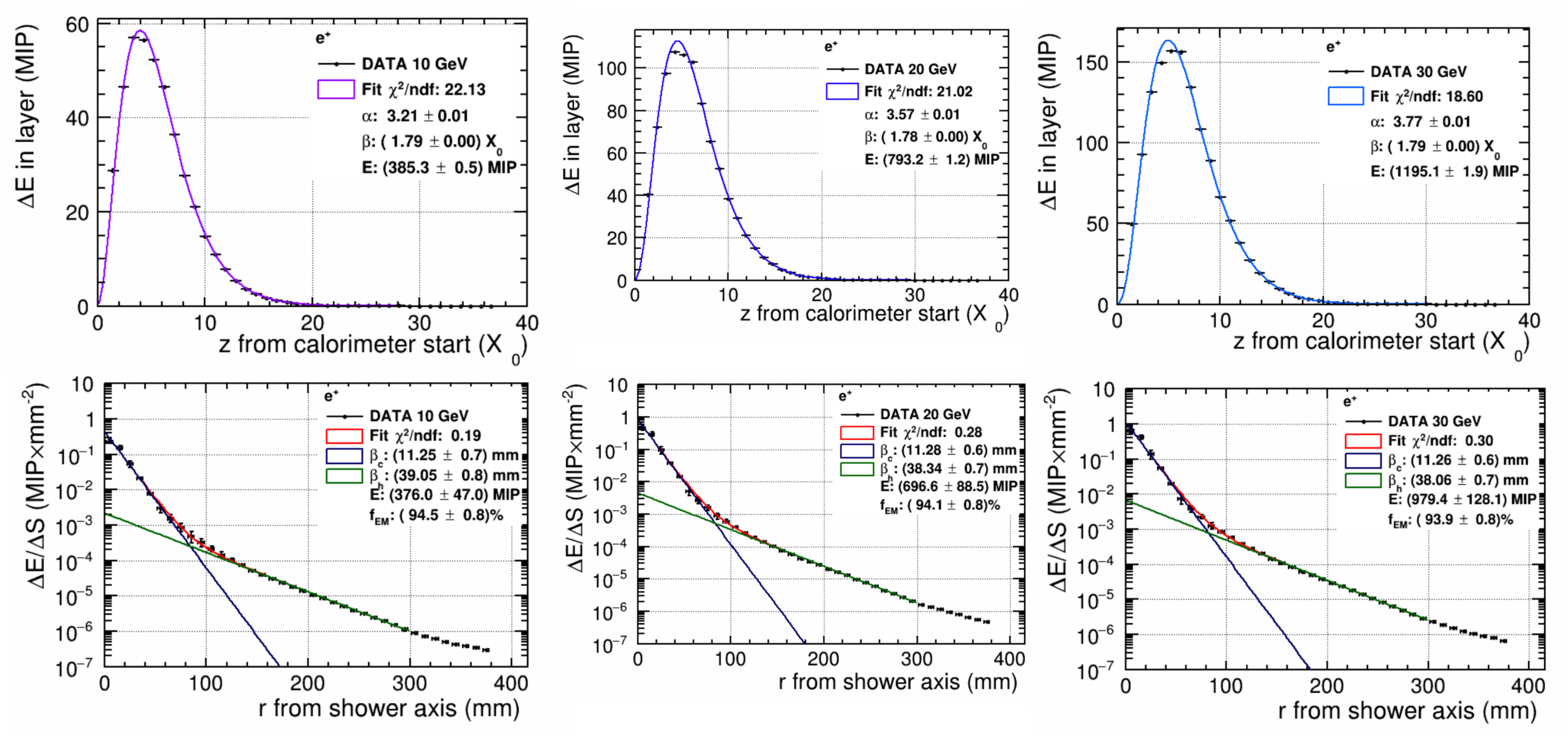
$$\Delta E(z) = E \cdot \left\{ \frac{1}{\Gamma(\alpha_s)} \cdot \left(\frac{Z[X_0]}{\beta_s} \right)^{\alpha_s - 1} \cdot \frac{e^{\frac{-z[X_0]}{\beta_s}}}{\beta_s} \right\}$$



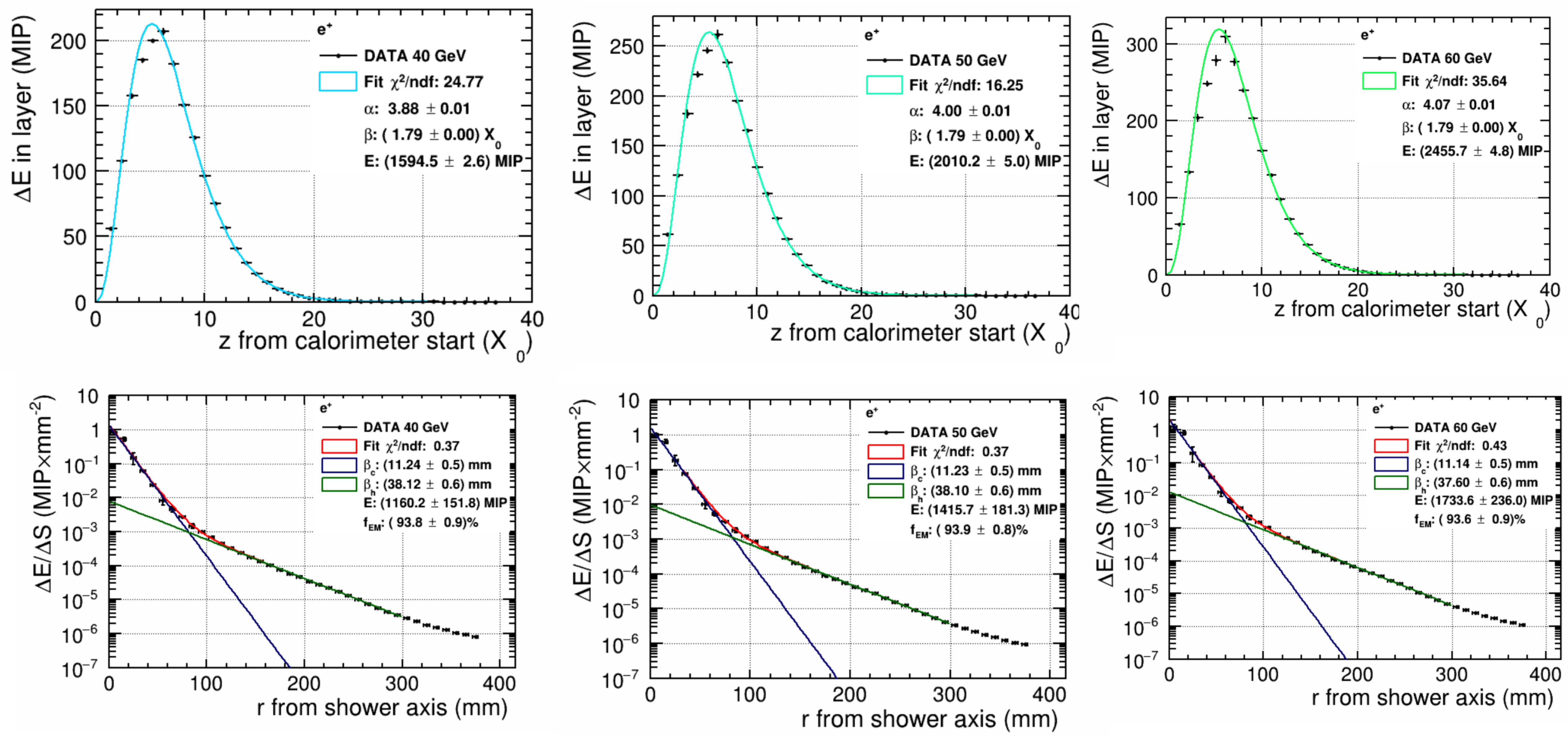




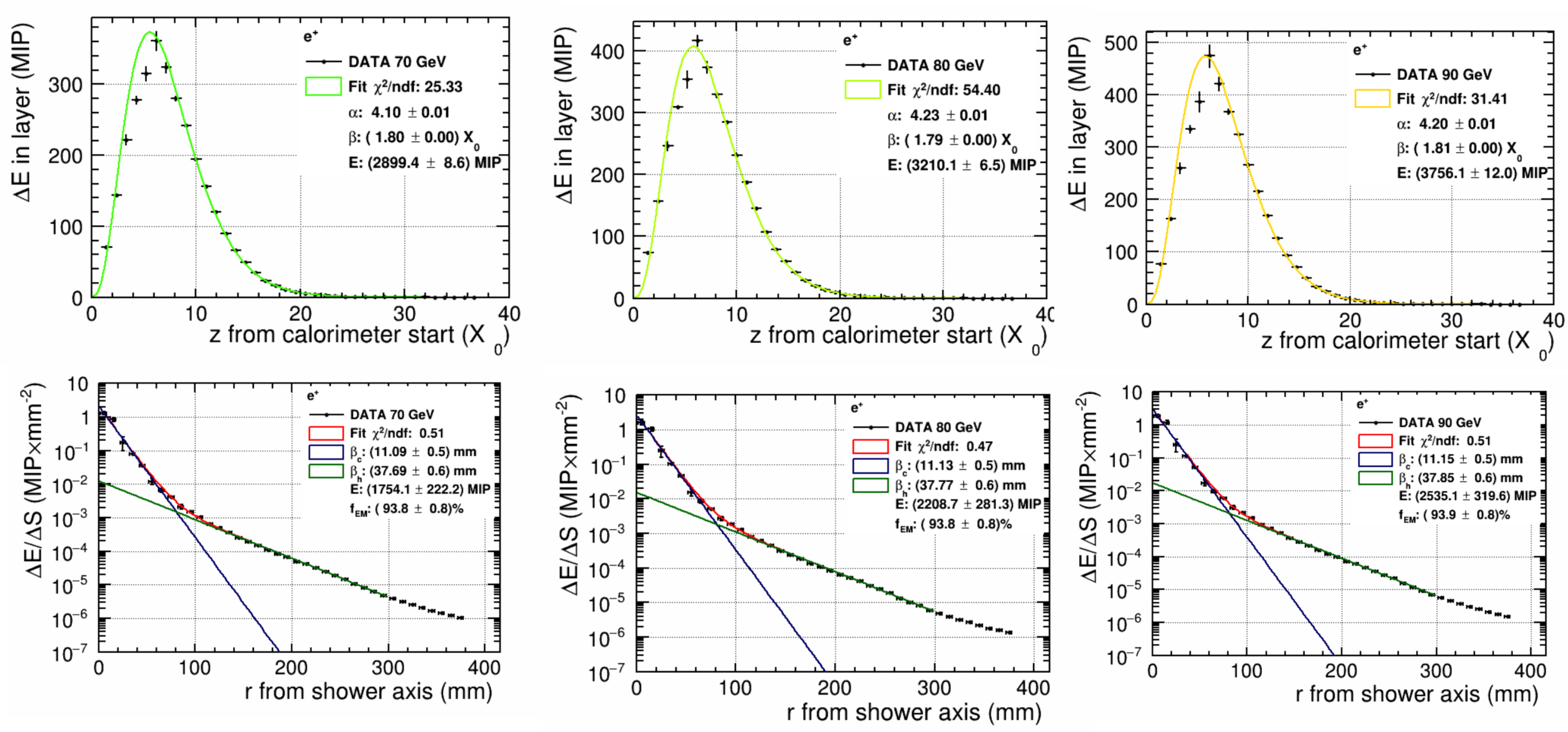
Electron Shapes



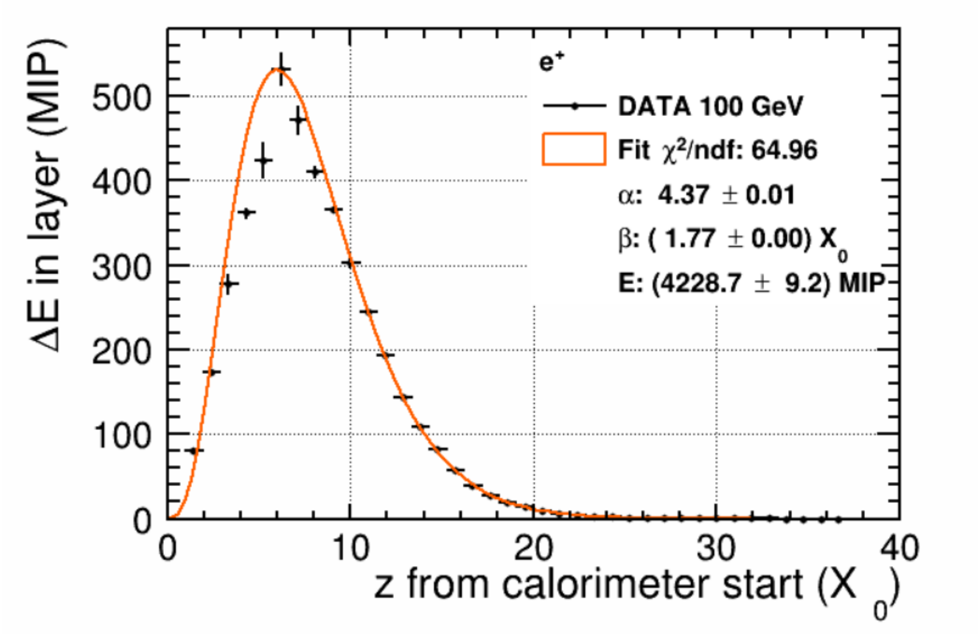
Electron Shapes

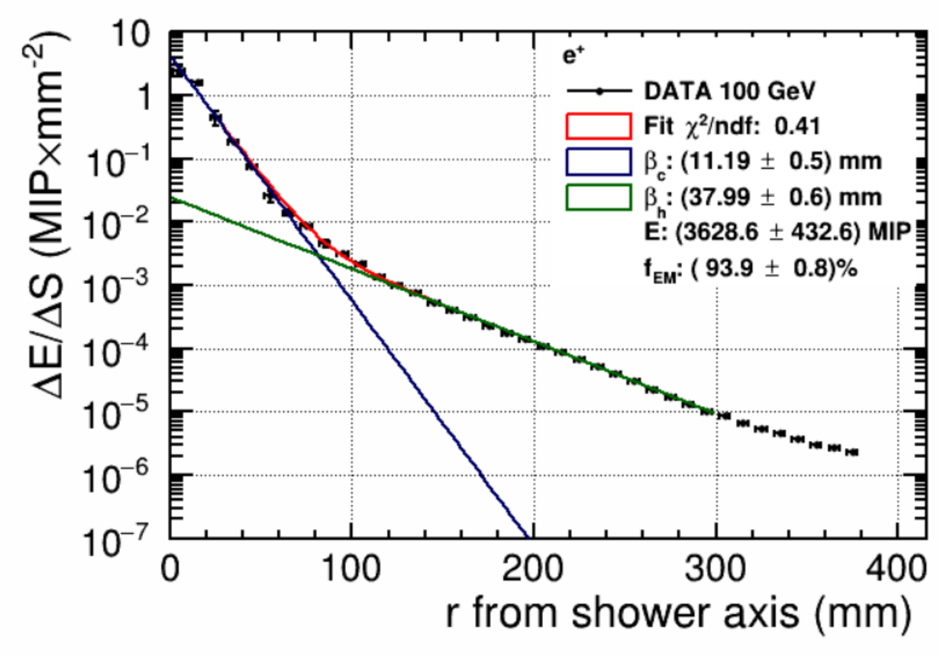


Electron Shapes

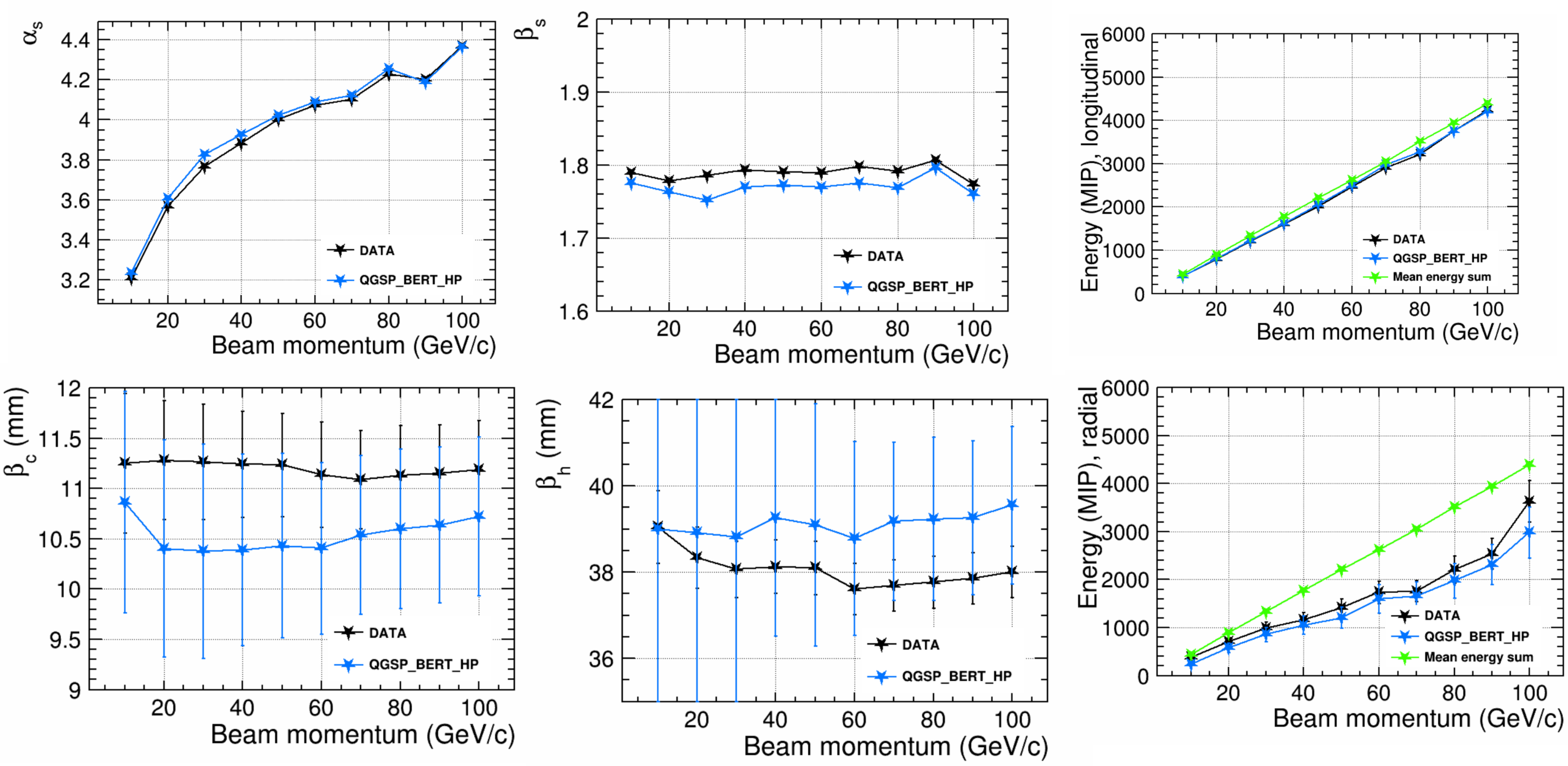


Electron Shapes





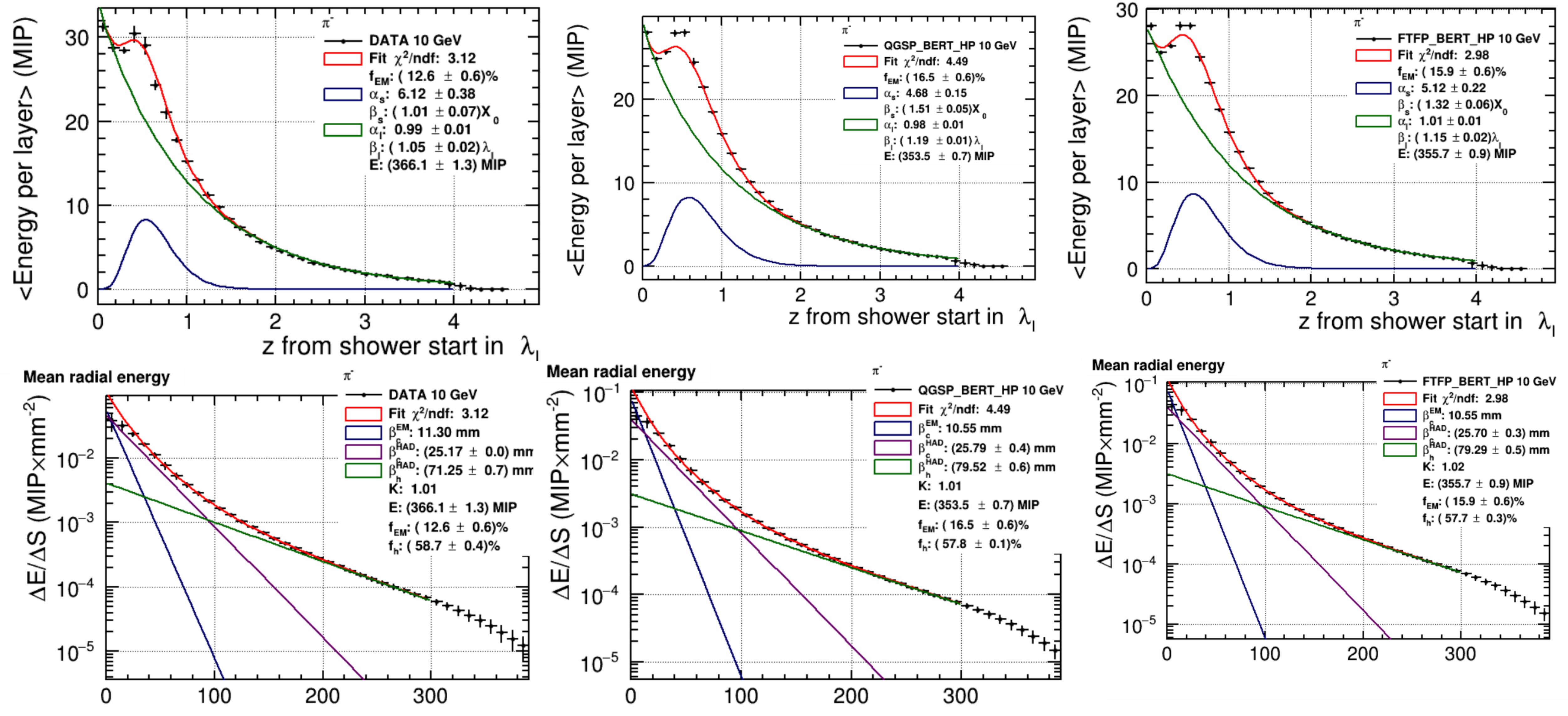
Parameters



α_s
β_s
Energy (MIP), longitudinal
β_c (mm)
β_h (mm)
Energy (MIP), radial
Beam momentum (GeV/c)
DATA
QGSP_BERT_HP
Mean energy sum

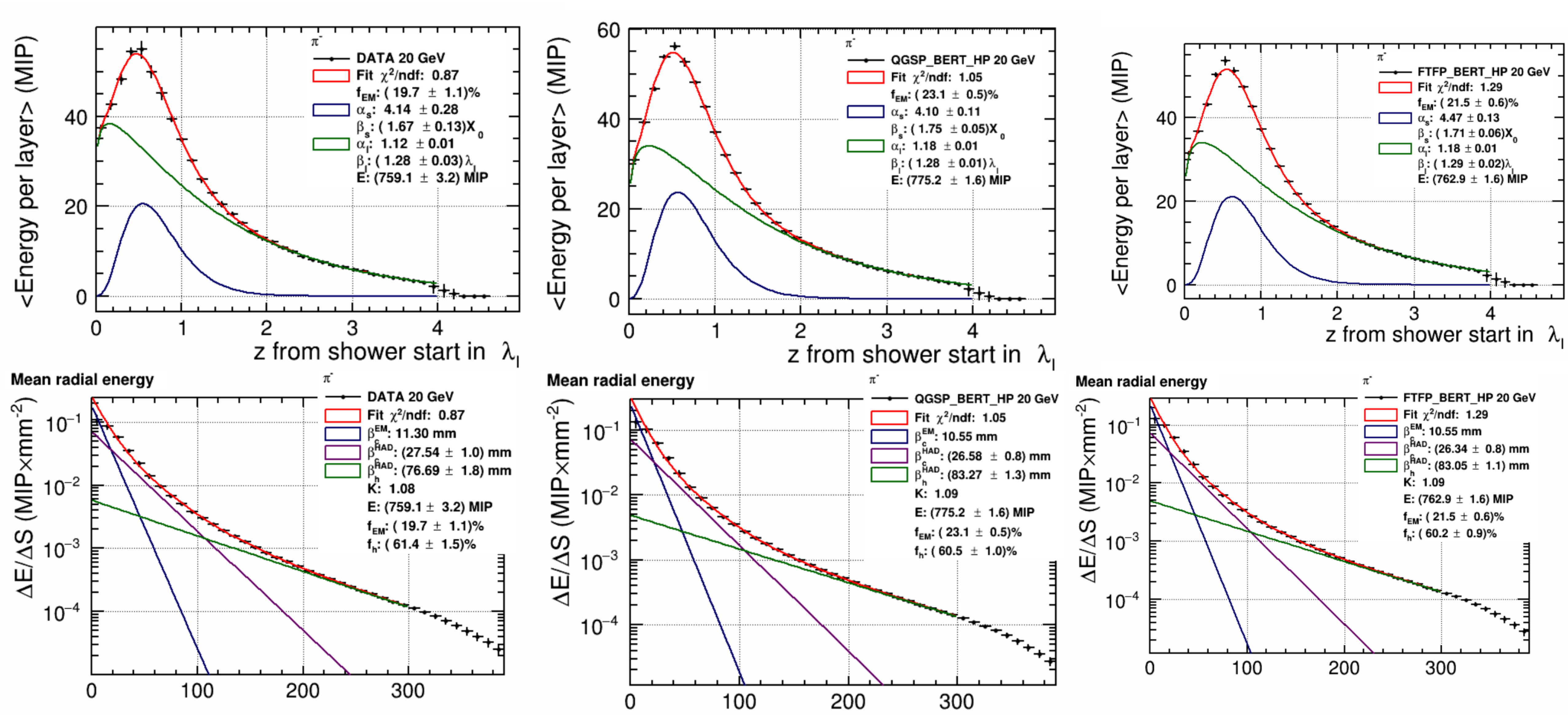
Simultaneous fits: Pions

10 GeV



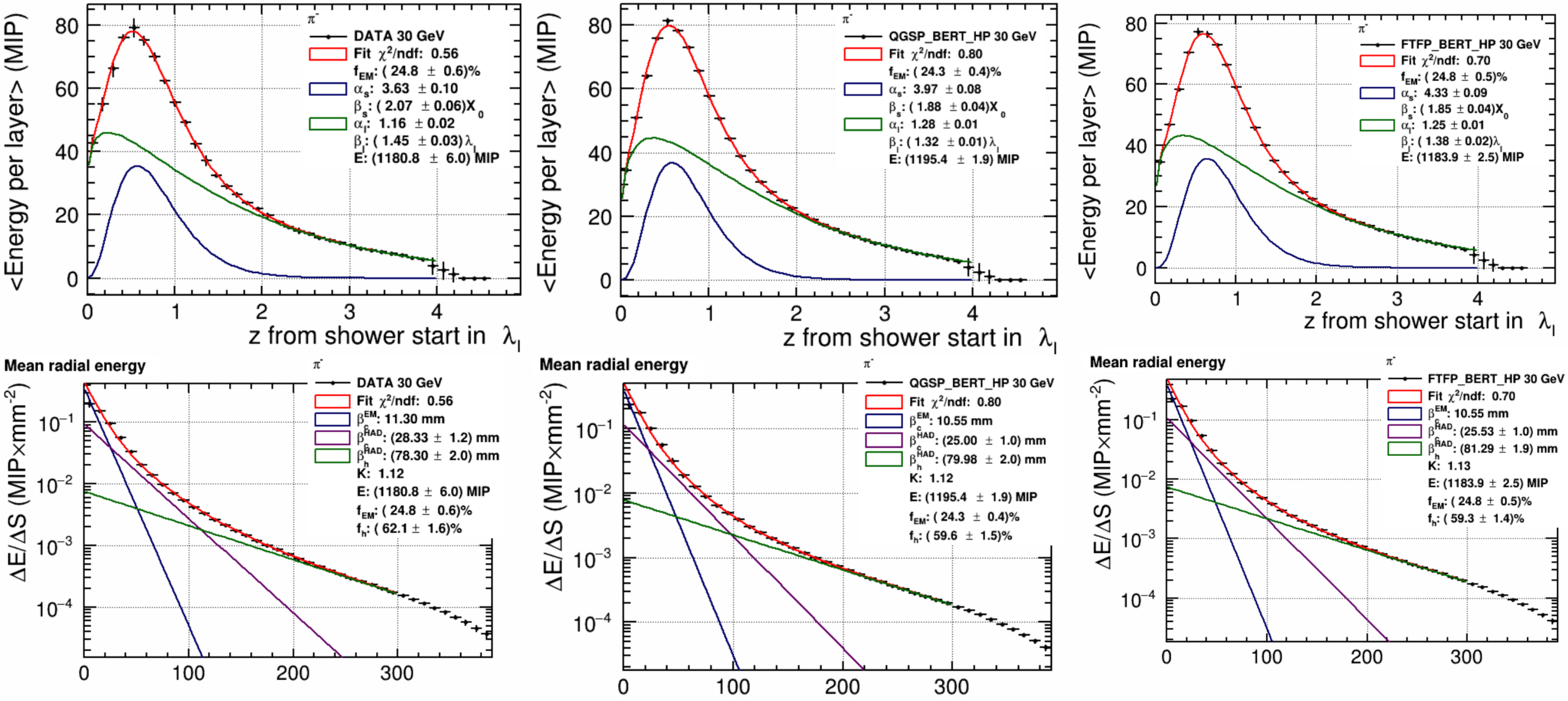
π-
DATA 10 GeV
Fit χ2/ndf: 3.12
fEM: (12.6 ± 0.6)%
αs: 6.12 ± 0.38
βs: (1.01 ± 0.07)X0
αl: 0.99 ± 0.01
βl: (1.05 ± 0.02) λl
E: (366.1 ± 1.3) MIP
<Energy per layer> (MIP)
z from shower start in λI
QGSP_BERT_HP 10 GeV
Fit χ2/ndf: 4.49
fEM: (16.5 ± 0.6)%
αs: 4.68 ± 0.15
βs: (1.51 ± 0.05)X0
αl: 0.98 ± 0.01
βl: (1.19 ± 0.01) λl
E: (353.5 ± 0.7) MIP
FTFP_BERT_HP 10 GeV
Fit χ2/ndf: 2.98
fEM: (15.9 ± 0.6)%
αs: 5.12 ± 0.22
βs: (1.32 ± 0.06)X0
αl: 1.01 ± 0.01
βl: (1.15 ± 0.02)λl
E: (355.7 ± 0.9) MIP
Mean radial energy
ΔE/ΔS (MIP×mm-2)
DATA 10 GeV
Fit χ2/ndf: 3.12
βcEM: 11.30 mm
βcHAD: (25.17 ± 0.0) mm
βhHAD: (71.25 ± 0.7) mm
K: 1.01
E: (366.1 ± 1.3) MIP
fEM: (12.6 ± 0.6)%
fh: (58.7 ± 0.4)%
QGSP_BERT_HP 10 GeV
Fit χ2/ndf: 4.49
βcEM: 10.55 mm
βcHAD: (25.79 ± 0.4) mm
βhHAD: (79.52 ± 0.6) mm
K: 1.01
E: (353.5 ± 0.7) MIP
fEM: (16.5 ± 0.6)%
fh: (57.8 ± 0.1)%
FTFP_BERT_HP 10 GeV
Fit χ2/ndf: 2.98
βcEM: 10.55 mm
βcHAD: (25.70 ± 0.3) mm
βhHAD: (79.29 ± 0.5) mm
K: 1.02
E: (355.7 ± 0.9) MIP
fEM: (15.9 ± 0.6)%
fh: (57.7 ± 0.3)%

20 GeV

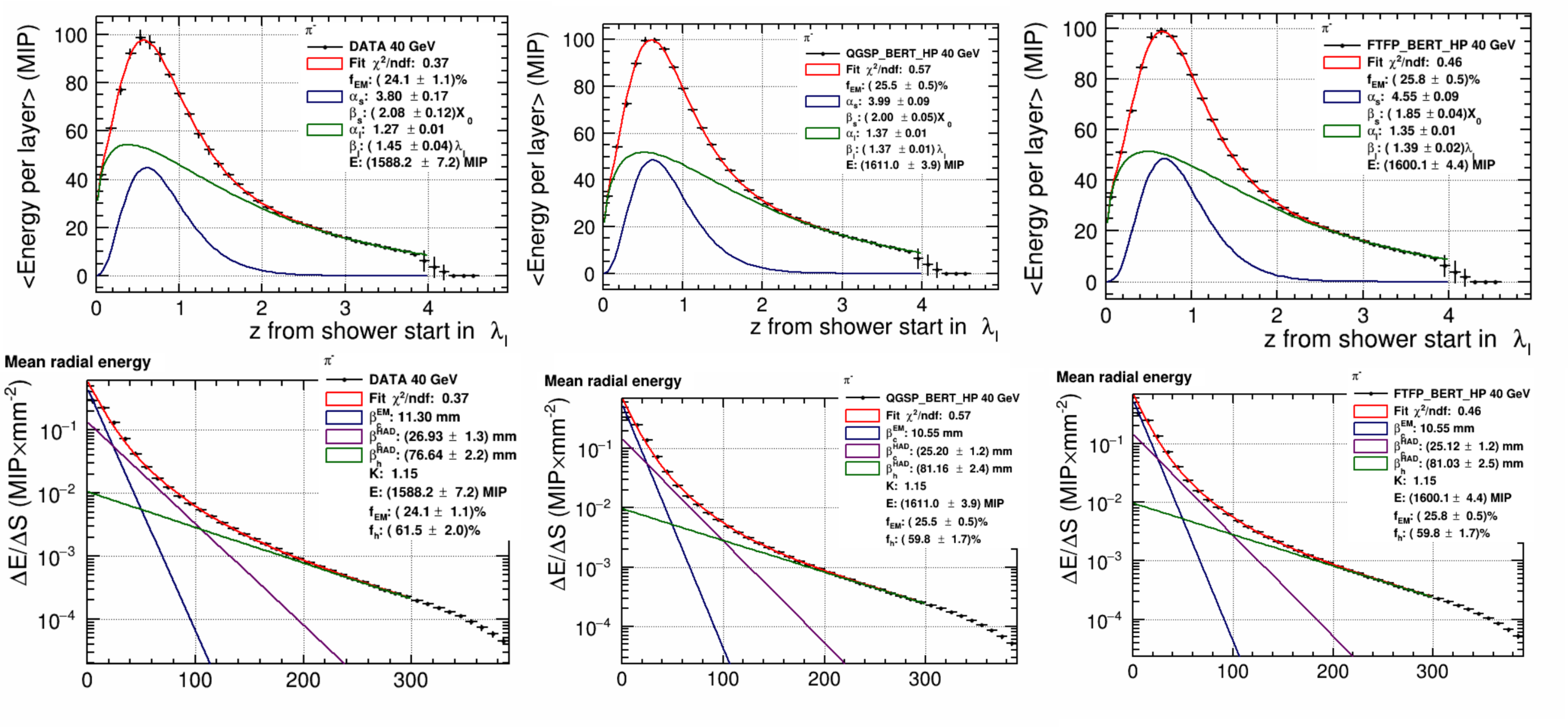


<Energy per layer> (MIP)
z from shower start in λI
π-
DATA 20 GeV
Fit χ2/ndf: 0.87
fEM: (19.7 ± 1.1)%
αs: 4.14 ± 0.28
βs: (1.67 ± 0.13)X0
αl: 1.12 ± 0.01
βl: (1.28 ± 0.03) λI
E: (759.1 ± 3.2) MIP
QGSP_BERT_HP 20 GeV
Fit χ2/ndf: 1.05
fEM: (23.1 ± 0.5)%
αs: 4.10 ± 0.11
βs: (1.75 ± 0.05)X0
αl: 1.18 ± 0.01
βl: (1.28 ± 0.01) λI
E: (775.2 ± 1.6) MIP
FTFP_BERT_HP 20 GeV
Fit χ2/ndf: 1.29
fEM: (21.5 ± 0.6)%
αs: 4.47 ± 0.13
βs: (1.71 ± 0.06)X0
αl: 1.18 ± 0.01
βl: (1.29 ± 0.02)λI
E: (762.9 ± 1.6) MIP
Mean radial energy
ΔE/ΔS (MIP×mm-2)
DATA 20 GeV
Fit χ2/ndf: 0.87
βcEM: 11.30 mm
βcHAD: (27.54 ± 1.0) mm
βhHAD: (76.69 ± 1.8) mm
K: 1.08
E: (759.1 ± 3.2) MIP
fEM: (19.7 ± 1.1)%
fh: (61.4 ± 1.5)%
QGSP_BERT_HP 20 GeV
Fit χ2/ndf: 1.05
βcEM: 10.55 mm
βcHAD: (26.58 ± 0.8) mm
βhHAD: (83.27 ± 1.3) mm
K: 1.09
E: (775.2 ± 1.6) MIP
fEM: (23.1 ± 0.5)%
fh: (60.5 ± 1.0)%
FTFP_BERT_HP 20 GeV
Fit χ2/ndf: 1.29
βcEM: 10.55 mm
βcHAD: (26.34 ± 0.8) mm
βhHAD: (83.05 ± 1.1) mm
K: 1.09
E: (762.9 ± 1.6) MIP
fEM: (21.5 ± 0.6)%
fh: (60.2 ± 0.9)%

30 GeV

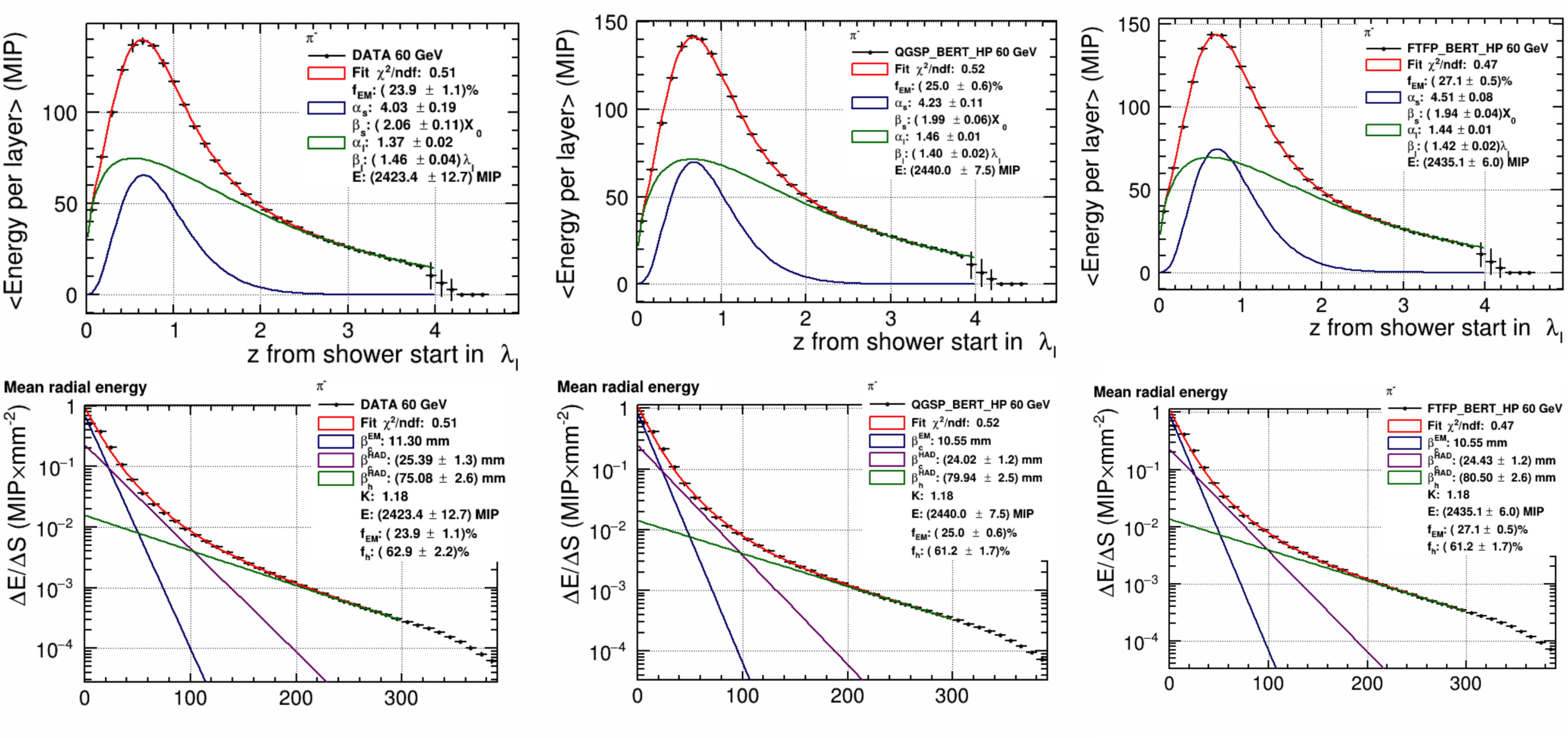

π-
DATA 30 GeV
Fit χ2/ndf: 0.56
fEM: (24.8 ± 0.6)%
αs: 3.63 ± 0.10
βs: (2.07 ± 0.06)X0
αl: 1.16 ± 0.02
βl: (1.45 ± 0.03) λl
E: (1180.8 ± 6.0) MIP
<Energy per layer> (MIP)
z from shower start in λI
QGSP_BERT_HP 30 GeV
Fit χ2/ndf: 0.80
fEM: (24.3 ± 0.4)%
αs: 3.97 ± 0.08
βs: (1.88 ± 0.04)X0
αl: 1.28 ± 0.01
βl: (1.32 ± 0.01) λl
E: (1195.4 ± 1.9) MIP
FTFP_BERT_HP 30 GeV
Fit χ2/ndf: 0.70
fEM: (24.8 ± 0.5)%
αs: 4.33 ± 0.09
βs: (1.85 ± 0.04)X0
αl: 1.25 ± 0.01
βl: (1.38 ± 0.02)λl
E: (1183.9 ± 2.5) MIP
Mean radial energy
ΔE/ΔS (MIP×mm-2)
DATA 30 GeV
Fit χ2/ndf: 0.56
βcEM: 11.30 mm
βcHAD: (28.33 ± 1.2) mm
βhHAD: (78.30 ± 2.0) mm
K: 1.12
E: (1180.8 ± 6.0) MIP
fEM: (24.8 ± 0.6)%
fh: (62.1 ± 1.6)%
QGSP_BERT_HP 30 GeV
Fit χ2/ndf: 0.80
βcEM: 10.55 mm
βcHAD: (25.00 ± 1.0) mm
βhHAD: (79.98 ± 2.0) mm
K: 1.12
E: (1195.4 ± 1.9) MIP
fEM: (24.3 ± 0.4)%
fh: (59.6 ± 1.5)%
FTFP_BERT_HP 30 GeV
Fit χ2/ndf: 0.70
βcEM: 10.55 mm
βcHAD: (25.53 ± 1.0) mm
βhHAD: (81.29 ± 1.9) mm
K: 1.13
E: (1183.9 ± 2.5) MIP
fEM: (24.8 ± 0.5)%
fh: (59.3 ± 1.4)%

40 GeV

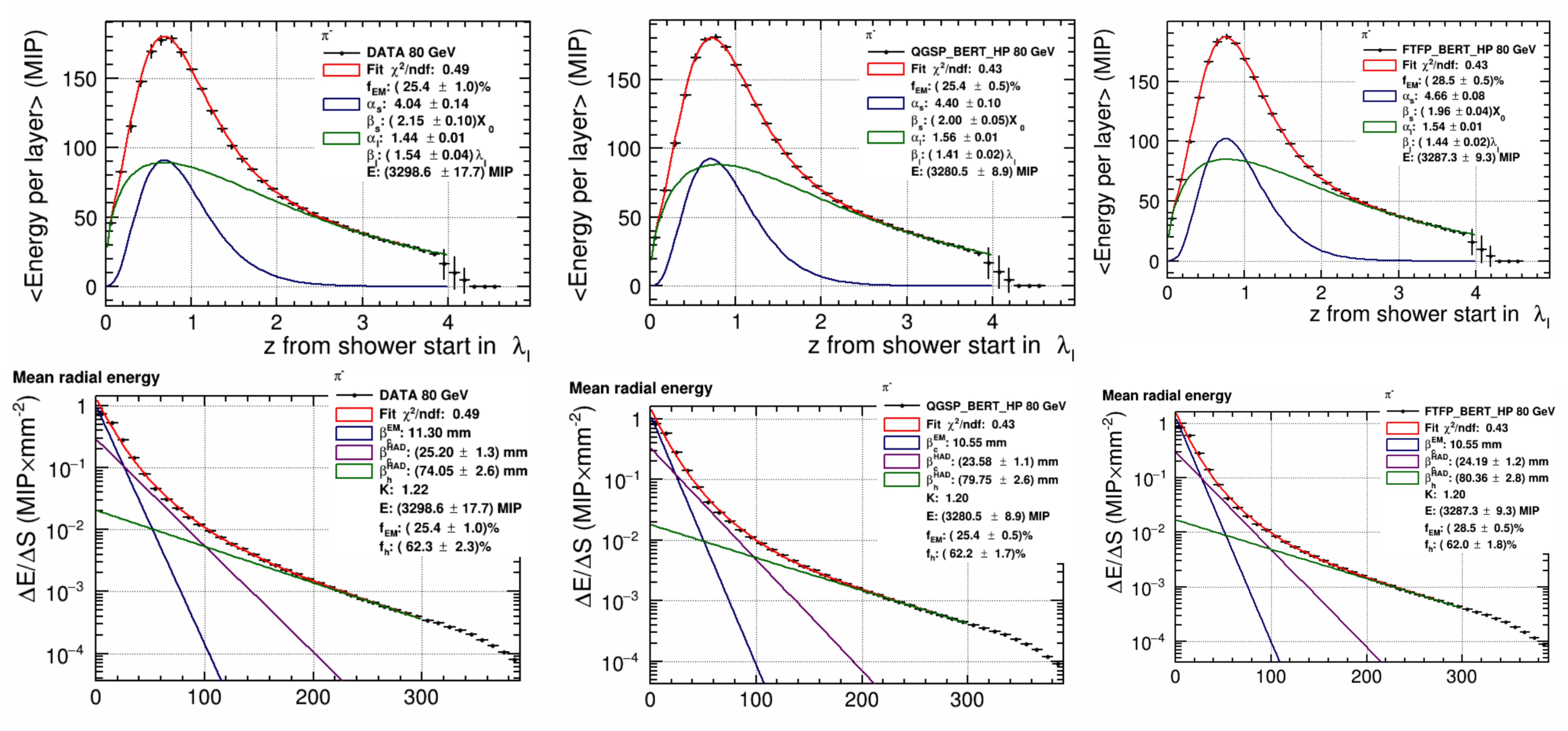


<Energy per layer> (MIP)
z from shower start in λ_I
π^-
DATA 40 GeV
Fit χ^2/ndf: 0.37
f_{EM}: (24.1 ± 1.1)%
α_s: 3.80 ± 0.17
β_s: (2.08 ± 0.12)X_0
α_l: 1.27 ± 0.01
β_l: (1.45 ± 0.04) λ_I
E: (1588.2 ± 7.2) MIP
QGSP_BERT_HP 40 GeV
Fit χ^2/ndf: 0.57
f_{EM}: (25.5 ± 0.5)%
α_s: 3.99 ± 0.09
β_s: (2.00 ± 0.05)X_0
α_l: 1.37 ± 0.01
β_l: (1.37 ± 0.01) λ_I
E: (1611.0 ± 3.9) MIP
FTFP_BERT_HP 40 GeV
Fit χ^2/ndf: 0.46
f_{EM}: (25.8 ± 0.5)%
α_s: 4.55 ± 0.09
β_s: (1.85 ± 0.04)X_0
α_l: 1.35 ± 0.01
β_l: (1.39 ± 0.02)λ_I
E: (1600.1 ± 4.4) MIP
Mean radial energy
$\Delta E/\Delta S$ (MIP×mm^{-2})
DATA 40 GeV
Fit χ^2/ndf: 0.37
β_c^{EM}: 11.30 mm
β_c^{HAD}: (26.93 ± 1.3) mm
β_h^{HAD}: (76.64 ± 2.2) mm
K: 1.15
E: (1588.2 ± 7.2) MIP
f_{EM}: (24.1 ± 1.1)%
f_h: (61.5 ± 2.0)%
QGSP_BERT_HP 40 GeV
Fit χ^2/ndf: 0.57
β_c^{EM}: 10.55 mm
β_c^{HAD}: (25.20 ± 1.2) mm
β_h^{HAD}: (81.16 ± 2.4) mm
K: 1.15
E: (1611.0 ± 3.9) MIP
f_{EM}: (25.5 ± 0.5)%
f_h: (59.8 ± 1.7)%
FTFP_BERT_HP 40 GeV
Fit χ^2/ndf: 0.46
β_c^{EM}: 10.55 mm
β_c^{HAD}: (25.12 ± 1.2) mm
β_h^{HAD}: (81.03 ± 2.5) mm
K: 1.15
E: (1600.1 ± 4.4) MIP
f_{EM}: (25.8 ± 0.5)%
f_h: (59.8 ± 1.7)%

60 GeV

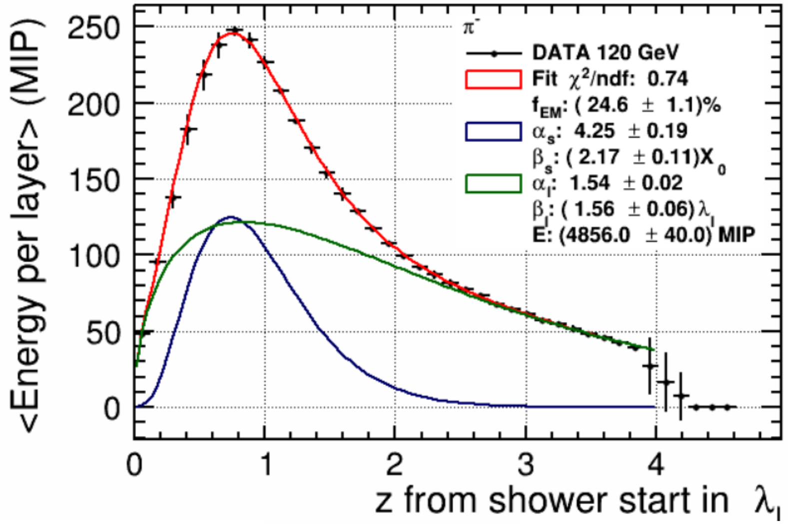

π-
DATA 60 GeV
Fit χ2/ndf: 0.51
fEM: (23.9 ± 1.1)%
αs: 4.03 ± 0.19
βs: (2.06 ± 0.11)X0
αl: 1.37 ± 0.02
βl: (1.46 ± 0.04) λI
E: (2423.4 ± 12.7) MIP
<Energy per layer> (MIP)
z from shower start in λI
π-
QGSP_BERT_HP 60 GeV
Fit χ2/ndf: 0.52
fEM: (25.0 ± 0.6)%
αs: 4.23 ± 0.11
βs: (1.99 ± 0.06)X0
αl: 1.46 ± 0.01
βl: (1.40 ± 0.02) λI
E: (2440.0 ± 7.5) MIP
<Energy per layer> (MIP)
z from shower start in λI
π-
FTFP_BERT_HP 60 GeV
Fit χ2/ndf: 0.47
fEM: (27.1 ± 0.5)%
αs: 4.51 ± 0.08
βs: (1.94 ± 0.04)X0
αl: 1.44 ± 0.01
βl: (1.42 ± 0.02)λI
E: (2435.1 ± 6.0) MIP
<Energy per layer> (MIP)
z from shower start in λI
Mean radial energy
π-
DATA 60 GeV
Fit χ2/ndf: 0.51
βcEM: 11.30 mm
βcHAD: (25.39 ± 1.3) mm
βhHAD: (75.08 ± 2.6) mm
K: 1.18
E: (2423.4 ± 12.7) MIP
fEM: (23.9 ± 1.1)%
fh: (62.9 ± 2.2)%
ΔE/ΔS (MIP×mm-2)
Mean radial energy
π-
QGSP_BERT_HP 60 GeV
Fit χ2/ndf: 0.52
βcEM: 10.55 mm
βcHAD: (24.02 ± 1.2) mm
βhHAD: (79.94 ± 2.5) mm
K: 1.18
E: (2440.0 ± 7.5) MIP
fEM: (25.0 ± 0.6)%
fh: (61.2 ± 1.7)%
ΔE/ΔS (MIP×mm-2)
Mean radial energy
π-
FTFP_BERT_HP 60 GeV
Fit χ2/ndf: 0.47
βcEM: 10.55 mm
βcHAD: (24.43 ± 1.2) mm
βhHAD: (80.50 ± 2.6) mm
K: 1.18
E: (2435.1 ± 6.0) MIP
fEM: (27.1 ± 0.5)%
fh: (61.2 ± 1.7)%
ΔE/ΔS (MIP×mm-2)

80 GeV

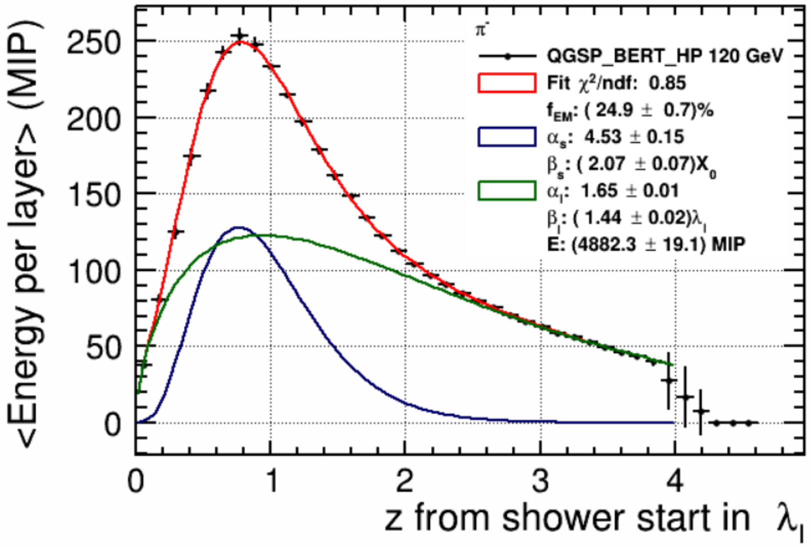


DATA 80 GeV
Fit χ^2/ndf: 0.49
f_{EM}: (25.4 ± 1.0)%
α_s: 4.04 ± 0.14
β_s: (2.15 ± 0.10)X_0
α_l: 1.44 ± 0.01
β_l: (1.54 ± 0.04) λ_I
E: (3298.6 ± 17.7) MIP
QGSP_BERT_HP 80 GeV
Fit χ^2/ndf: 0.43
f_{EM}: (25.4 ± 0.5)%
α_s: 4.40 ± 0.10
β_s: (2.00 ± 0.05)X_0
α_l: 1.56 ± 0.01
β_l: (1.41 ± 0.02) λ_I
E: (3280.5 ± 8.9) MIP
FTFP_BERT_HP 80 GeV
Fit χ^2/ndf: 0.43
f_{EM}: (28.5 ± 0.5)%
α_s: 4.66 ± 0.08
β_s: (1.96 ± 0.04)X_0
α_l: 1.54 ± 0.01
β_l: (1.44 ± 0.02)λ_I
E: (3287.3 ± 9.3) MIP
<Energy per layer> (MIP)
z from shower start in λ_I
Mean radial energy
DATA 80 GeV
Fit χ^2/ndf: 0.49
β^{EM}: 11.30 mm
β_c^{HAD}: (25.20 ± 1.3) mm
β_h^{HAD}: (74.05 ± 2.6) mm
K: 1.22
E: (3298.6 ± 17.7) MIP
f_{EM}: (25.4 ± 1.0)%
f_h: (62.3 ± 2.3)%
QGSP_BERT_HP 80 GeV
Fit χ^2/ndf: 0.43
β_c^{EM}: 10.55 mm
β_c^{HAD}: (23.58 ± 1.1) mm
β_h^{HAD}: (79.75 ± 2.6) mm
K: 1.20
E: (3280.5 ± 8.9) MIP
f_{EM}: (25.4 ± 0.5)%
f_h: (62.2 ± 1.7)%
FTFP_BERT_HP 80 GeV
Fit χ^2/ndf: 0.43
β^{EM}: 10.55 mm
β_c^{HAD}: (24.19 ± 1.2) mm
β_h^{HAD}: (80.36 ± 2.8) mm
K: 1.20
E: (3287.3 ± 9.3) MIP
f_{EM}: (28.5 ± 0.5)%
f_h: (62.0 ± 1.8)%
$\Delta E/\Delta S$ (MIP×mm^{-2})

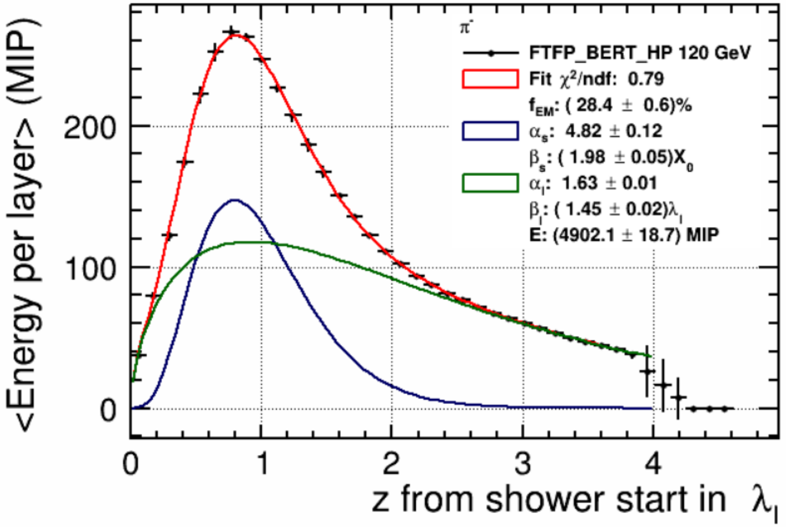
120 GeV



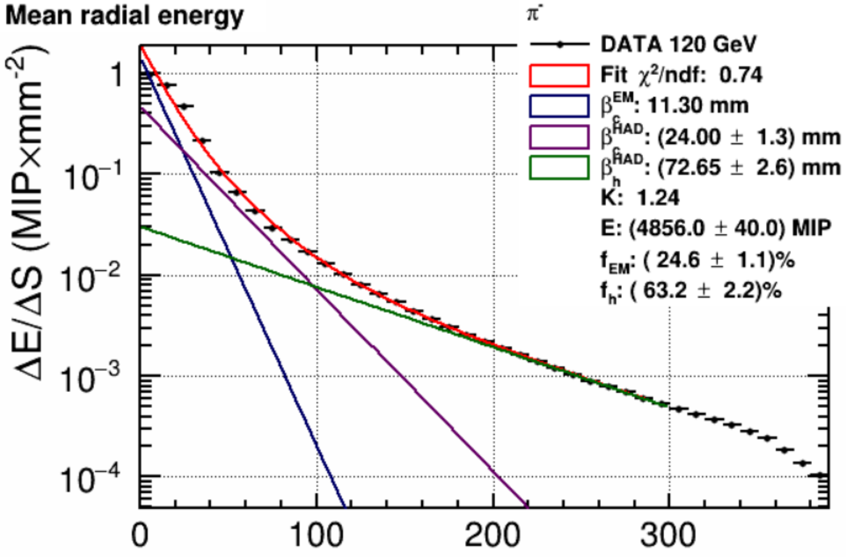
π^-
DATA 120 GeV
Fit χ^2/ndf: 0.74
f_{EM}: (24.6 ± 1.1)%
α_s: 4.25 ± 0.19
β_s: (2.17 ± 0.11)X_0
α_l: 1.54 ± 0.02
β_l: (1.56 ± 0.06) λ_I
E: (4856.0 ± 40.0) MIP
<Energy per layer> (MIP)
z from shower start in λ_I



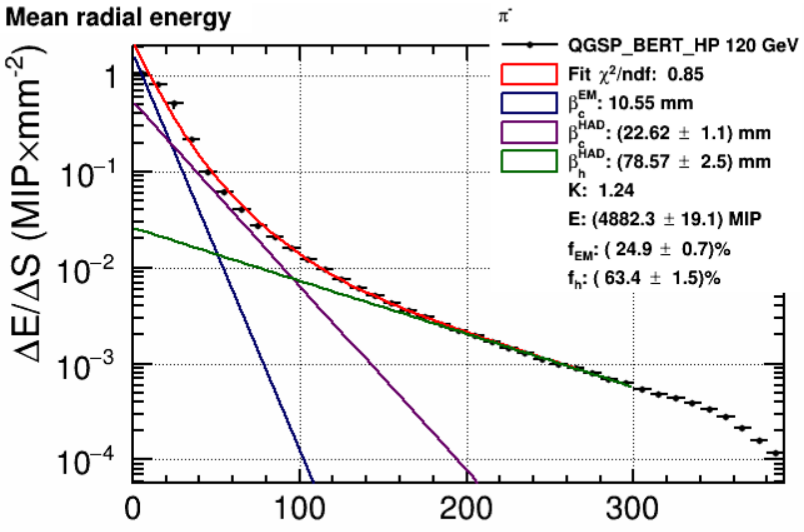
π^-
QGSP_BERT_HP 120 GeV
Fit χ^2/ndf: 0.85
f_{EM}: (24.9 ± 0.7)%
α_s: 4.53 ± 0.15
β_s: (2.07 ± 0.07)X_0
α_l: 1.65 ± 0.01
β_l: (1.44 ± 0.02)λ_I
E: (4882.3 ± 19.1) MIP
<Energy per layer> (MIP)
z from shower start in λ_I



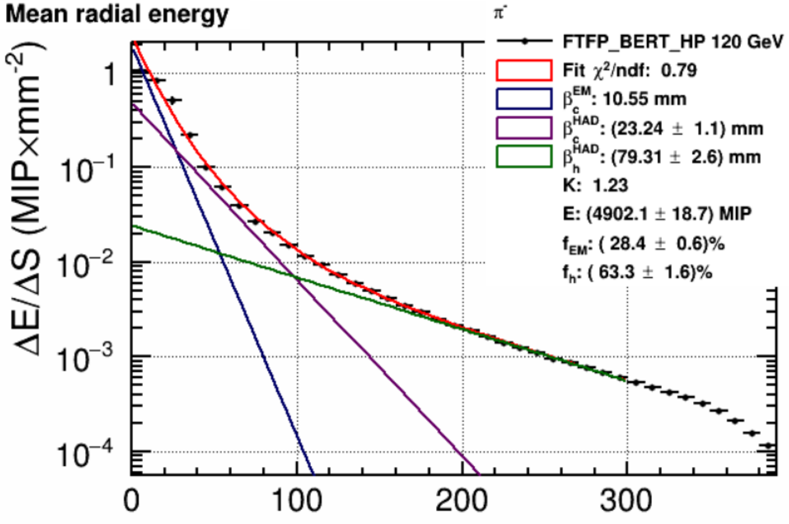
π^-
FTFP_BERT_HP 120 GeV
Fit χ^2/ndf: 0.79
f_{EM}: (28.4 ± 0.6)%
α_s: 4.82 ± 0.12
β_s: (1.98 ± 0.05)X_0
α_l: 1.63 ± 0.01
β_l: (1.45 ± 0.02)λ_I
E: (4902.1 ± 18.7) MIP
<Energy per layer> (MIP)
z from shower start in λ_I



Mean radial energy
π^-
DATA 120 GeV
Fit χ^2/ndf: 0.74
β_c^{EM}: 11.30 mm
β_c^{HAD}: (24.00 ± 1.3) mm
β_h^{HAD}: (72.65 ± 2.6) mm
K: 1.24
E: (4856.0 ± 40.0) MIP
f_{EM}: (24.6 ± 1.1)%
f_h: (63.2 ± 2.2)%
$\Delta E/\Delta S$ (MIP×mm^{-2})

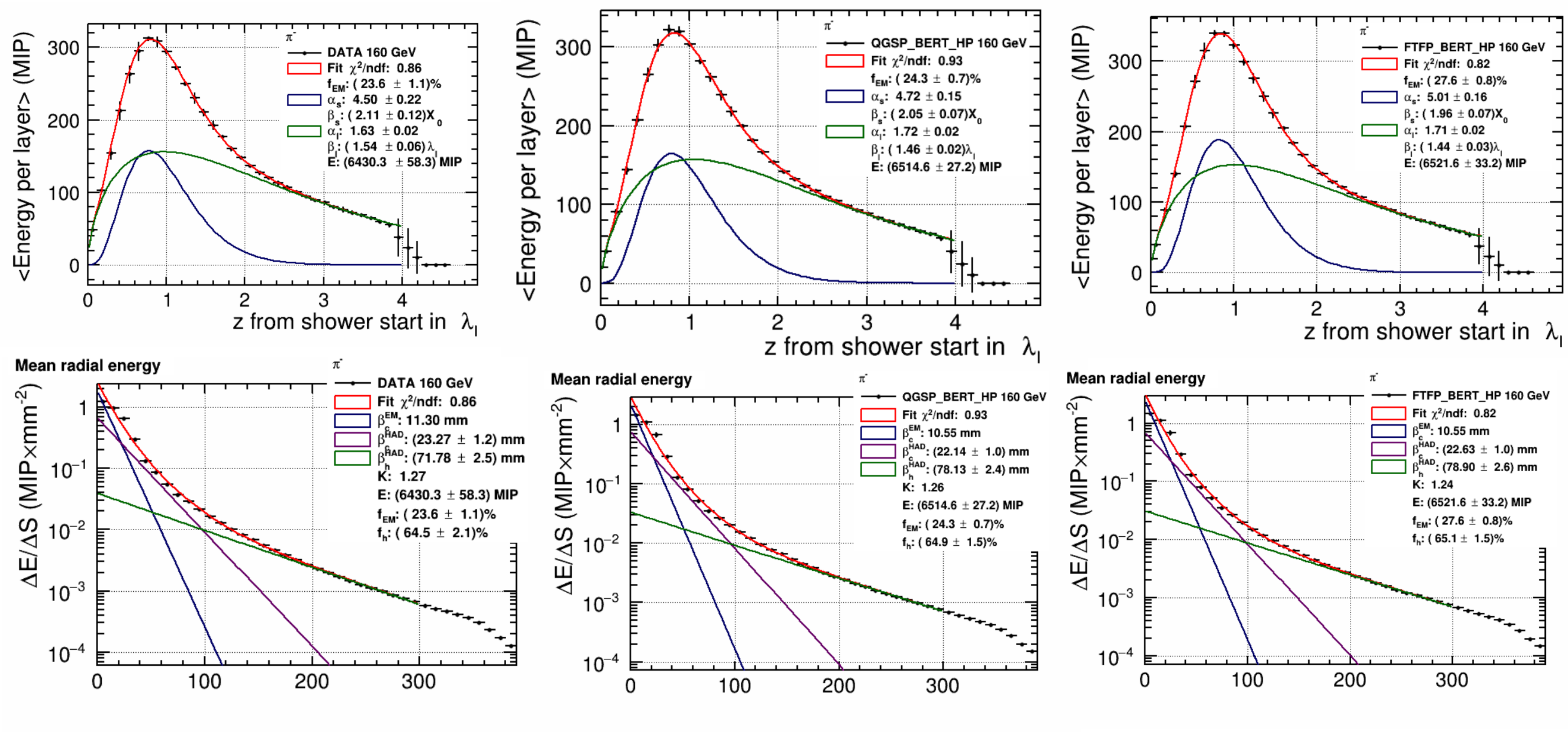


Mean radial energy
π^-
QGSP_BERT_HP 120 GeV
Fit χ^2/ndf: 0.85
β_c^{EM}: 10.55 mm
β_c^{HAD}: (22.62 ± 1.1) mm
β_h^{HAD}: (78.57 ± 2.5) mm
K: 1.24
E: (4882.3 ± 19.1) MIP
f_{EM}: (24.9 ± 0.7)%
f_h: (63.4 ± 1.5)%
$\Delta E/\Delta S$ (MIP×mm^{-2})



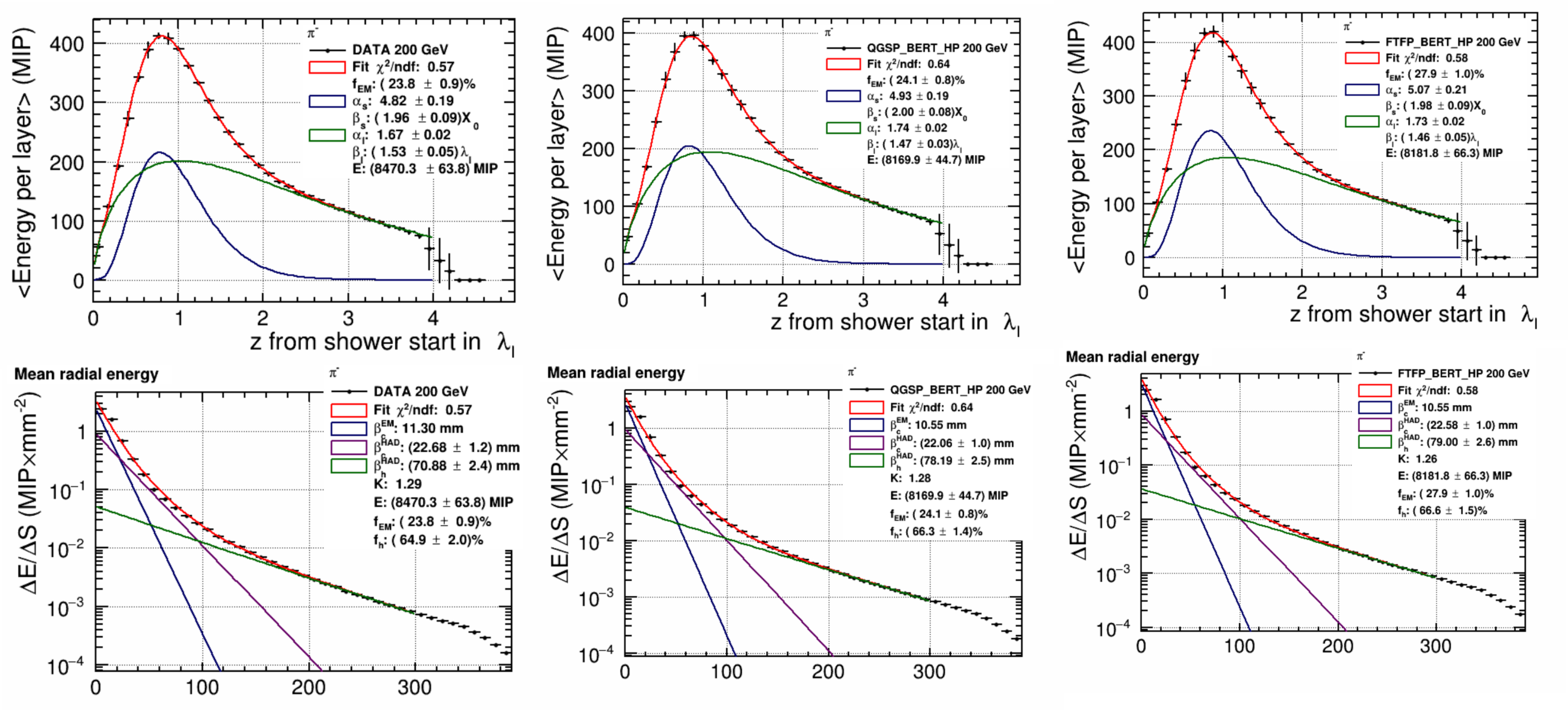
Mean radial energy
π^-
FTFP_BERT_HP 120 GeV
Fit χ^2/ndf: 0.79
β_c^{EM}: 10.55 mm
β_c^{HAD}: (23.24 ± 1.1) mm
β_h^{HAD}: (79.31 ± 2.6) mm
K: 1.23
E: (4902.1 ± 18.7) MIP
f_{EM}: (28.4 ± 0.6)%
f_h: (63.3 ± 1.6)%
$\Delta E/\Delta S$ (MIP×mm^{-2})

160 GeV



π⁻
DATA 160 GeV
Fit χ²/ndf: 0.86
f_EM: (23.6 ± 1.1)%
α_s: 4.50 ± 0.22
β_s: (2.11 ± 0.12)X_0
α_l: 1.63 ± 0.02
β_l: (1.54 ± 0.06)λ_I
E: (6430.3 ± 58.3) MIP
<Energy per layer> (MIP)
z from shower start in λ_I
QGSP_BERT_HP 160 GeV
Fit χ²/ndf: 0.93
f_EM: (24.3 ± 0.7)%
α_s: 4.72 ± 0.15
β_s: (2.05 ± 0.07)X_0
α_l: 1.72 ± 0.02
β_l: (1.46 ± 0.02)λ_I
E: (6514.6 ± 27.2) MIP
FTFP_BERT_HP 160 GeV
Fit χ²/ndf: 0.82
f_EM: (27.6 ± 0.8)%
α_s: 5.01 ± 0.16
β_s: (1.96 ± 0.07)X_0
α_l: 1.71 ± 0.02
β_l: (1.44 ± 0.03)λ_I
E: (6521.6 ± 33.2) MIP
Mean radial energy
DATA 160 GeV
Fit χ²/ndf: 0.86
β_c^EM: 11.30 mm
β_c^HAD: (23.27 ± 1.2) mm
β_h^HAD: (71.78 ± 2.5) mm
K: 1.27
E: (6430.3 ± 58.3) MIP
f_EM: (23.6 ± 1.1)%
f_h: (64.5 ± 2.1)%
ΔE/ΔS (MIP×mm⁻²)
Mean radial energy
QGSP_BERT_HP 160 GeV
Fit χ²/ndf: 0.93
β_c^EM: 10.55 mm
β_c^HAD: (22.14 ± 1.0) mm
β_h^HAD: (78.13 ± 2.4) mm
K: 1.26
E: (6514.6 ± 27.2) MIP
f_EM: (24.3 ± 0.7)%
f_h: (64.9 ± 1.5)%
Mean radial energy
FTFP_BERT_HP 160 GeV
Fit χ²/ndf: 0.82
β_c^EM: 10.55 mm
β_c^HAD: (22.63 ± 1.0) mm
β_h^HAD: (78.90 ± 2.6) mm
K: 1.24
E: (6521.6 ± 33.2) MIP
f_EM: (27.6 ± 0.8)%
f_h: (65.1 ± 1.5)%

200 GeV

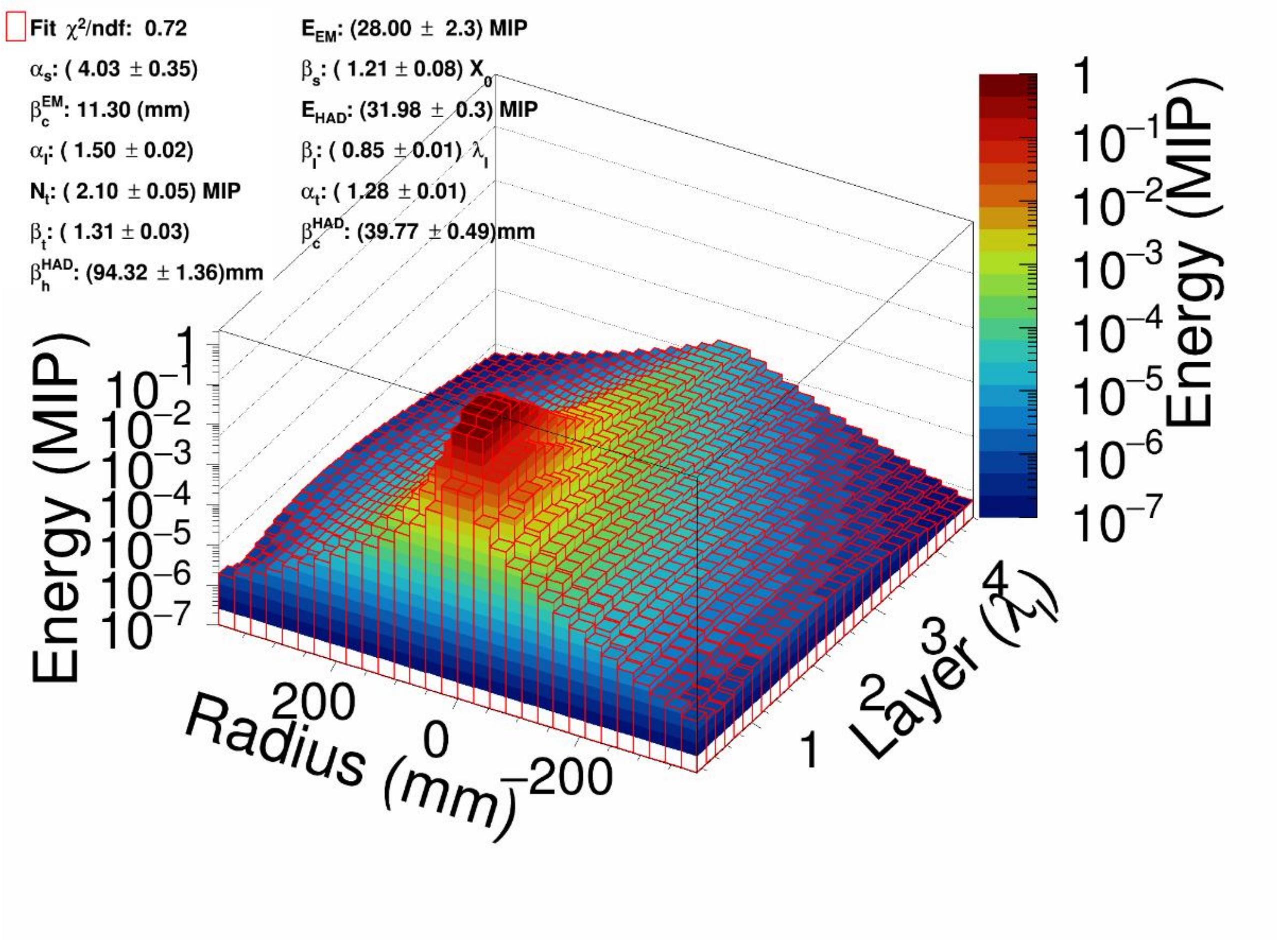


DATA 200 GeV
Fit χ²/ndf: 0.57
f_EM: (23.8 ± 0.9)%
α_s: 4.82 ± 0.19
β_s: (1.96 ± 0.09)X_0
α_l: 1.67 ± 0.02
β_l: (1.53 ± 0.05) λ_l
E: (8470.3 ± 63.8) MIP
<Energy per layer> (MIP)
z from shower start in λ_I
QGSP_BERT_HP 200 GeV
Fit χ²/ndf: 0.64
f_EM: (24.1 ± 0.8)%
α_s: 4.93 ± 0.19
β_s: (2.00 ± 0.08)X_0
α_l: 1.74 ± 0.02
β_l: (1.47 ± 0.03)λ_l
E: (8169.9 ± 44.7) MIP
FTFP_BERT_HP 200 GeV
Fit χ²/ndf: 0.58
f_EM: (27.9 ± 1.0)%
α_s: 5.07 ± 0.21
β_s: (1.98 ± 0.09)X_0
α_l: 1.73 ± 0.02
β_l: (1.46 ± 0.05)λ_l
E: (8181.8 ± 66.3) MIP
Mean radial energy
ΔE/ΔS (MIP×mm⁻²)
DATA 200 GeV
Fit χ²/ndf: 0.57
β_c^EM: 11.30 mm
β_c^HAD: (22.68 ± 1.2) mm
β_h^HAD: (70.88 ± 2.4) mm
K: 1.29
E: (8470.3 ± 63.8) MIP
f_EM: (23.8 ± 0.9)%
f_h: (64.9 ± 2.0)%
QGSP_BERT_HP 200 GeV
Fit χ²/ndf: 0.64
β_c^EM: 10.55 mm
β_c^HAD: (22.06 ± 1.0) mm
β_h^HAD: (78.19 ± 2.5) mm
K: 1.28
E: (8169.9 ± 44.7) MIP
f_EM: (24.1 ± 0.8)%
f_h: (66.3 ± 1.4)%
FTFP_BERT_HP 200 GeV
Fit χ²/ndf: 0.58
β_c^EM: 10.55 mm
β_c^HAD: (22.58 ± 1.0) mm
β_h^HAD: (79.00 ± 2.6) mm
K: 1.26
E: (8181.8 ± 66.3) MIP
f_EM: (27.9 ± 1.0)%
f_h: (66.6 ± 1.5)%

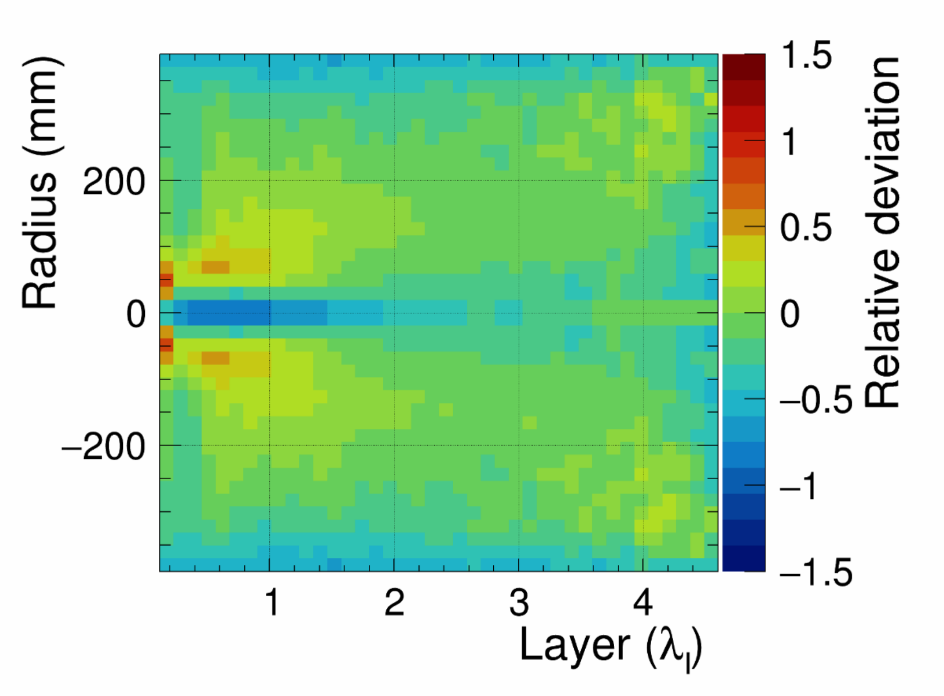
3-Dimensional fits: Pions

10 GeV

DATA



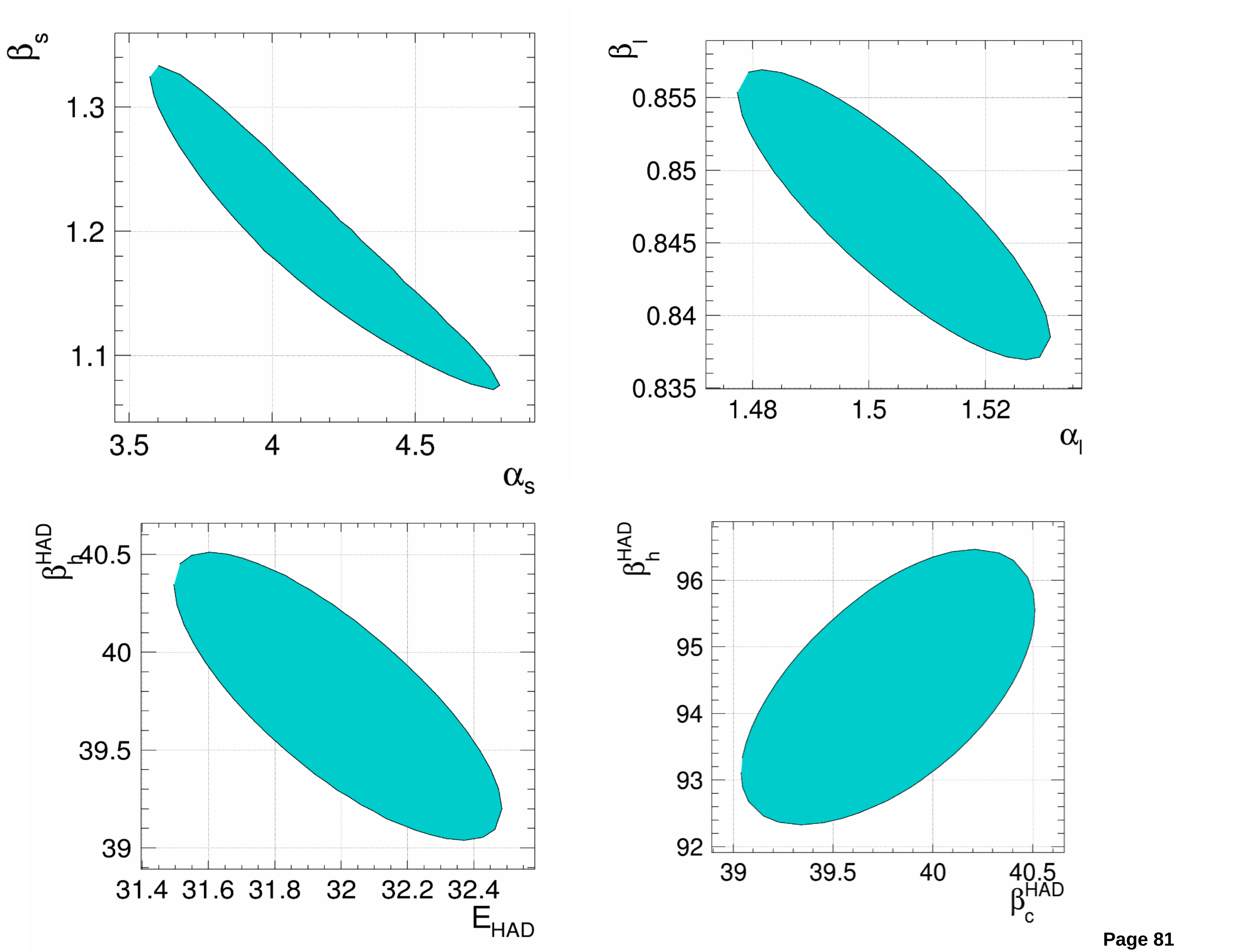
Fit χ²/ndf: 0.72
αs: (4.03 ± 0.35)
βc EM: 11.30 (mm)
αl: (1.50 ± 0.02)
Nt: (2.10 ± 0.05) MIP
βt: (1.31 ± 0.03)
βh HAD: (94.32 ± 1.36)mm
E EM: (28.00 ± 2.3) MIP
βs: (1.21 ± 0.08) X0
E HAD: (31.98 ± 0.3) MIP
βl: (0.85 ± 0.01) λl
αt: (1.28 ± 0.01)
βc HAD: (39.77 ± 0.49)mm
Energy (MIP)
Radius (mm)
Layer (λl)



Radius (mm)
Layer (λl)
Relative deviation

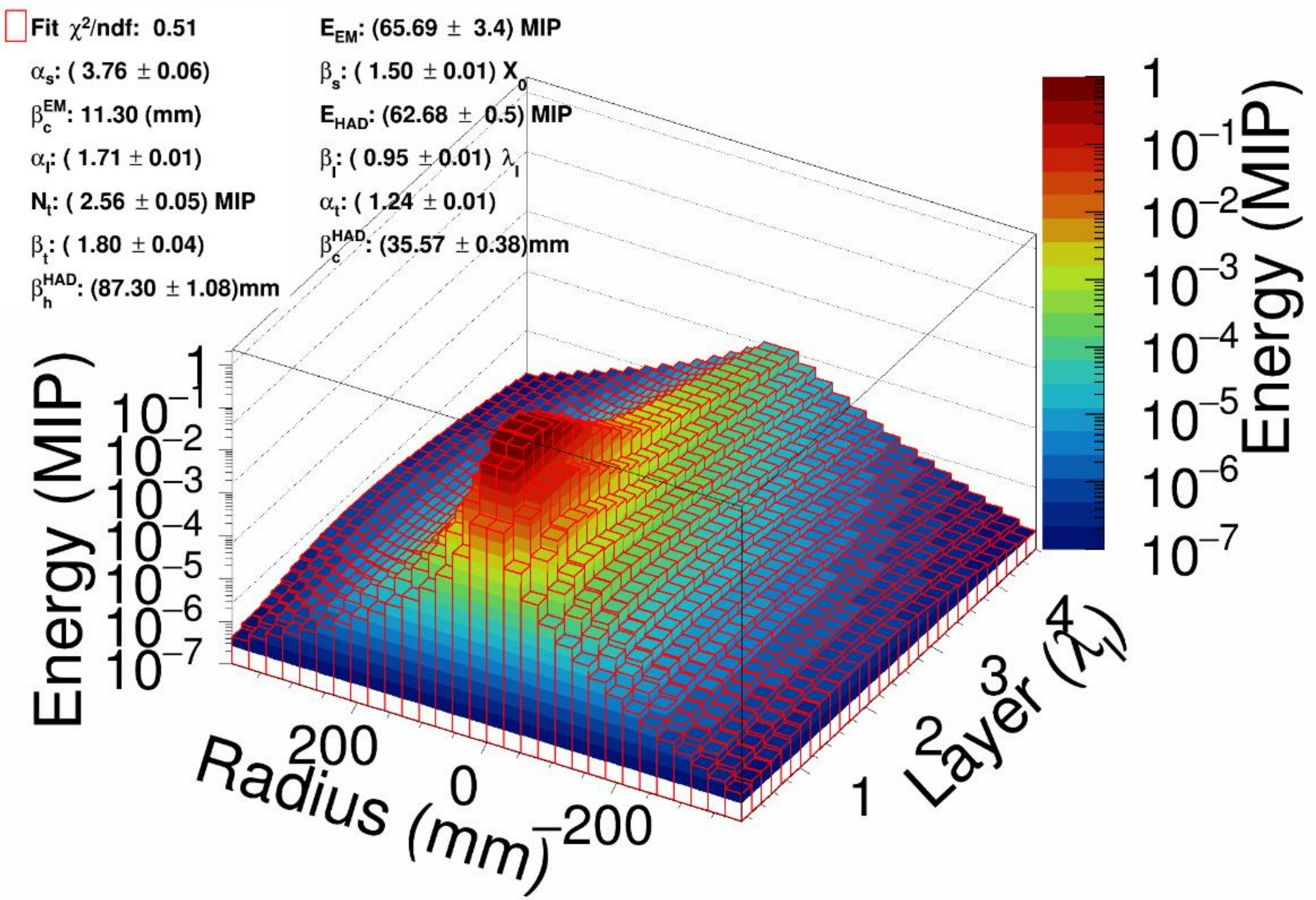
Contour plots

Data 10 GeV

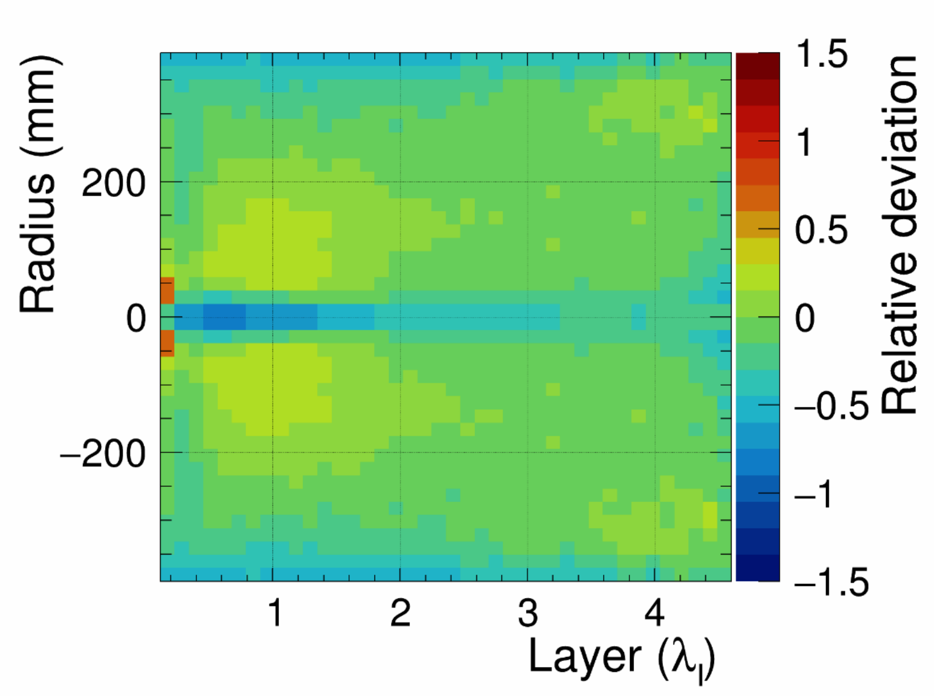


20 GeV

DATA



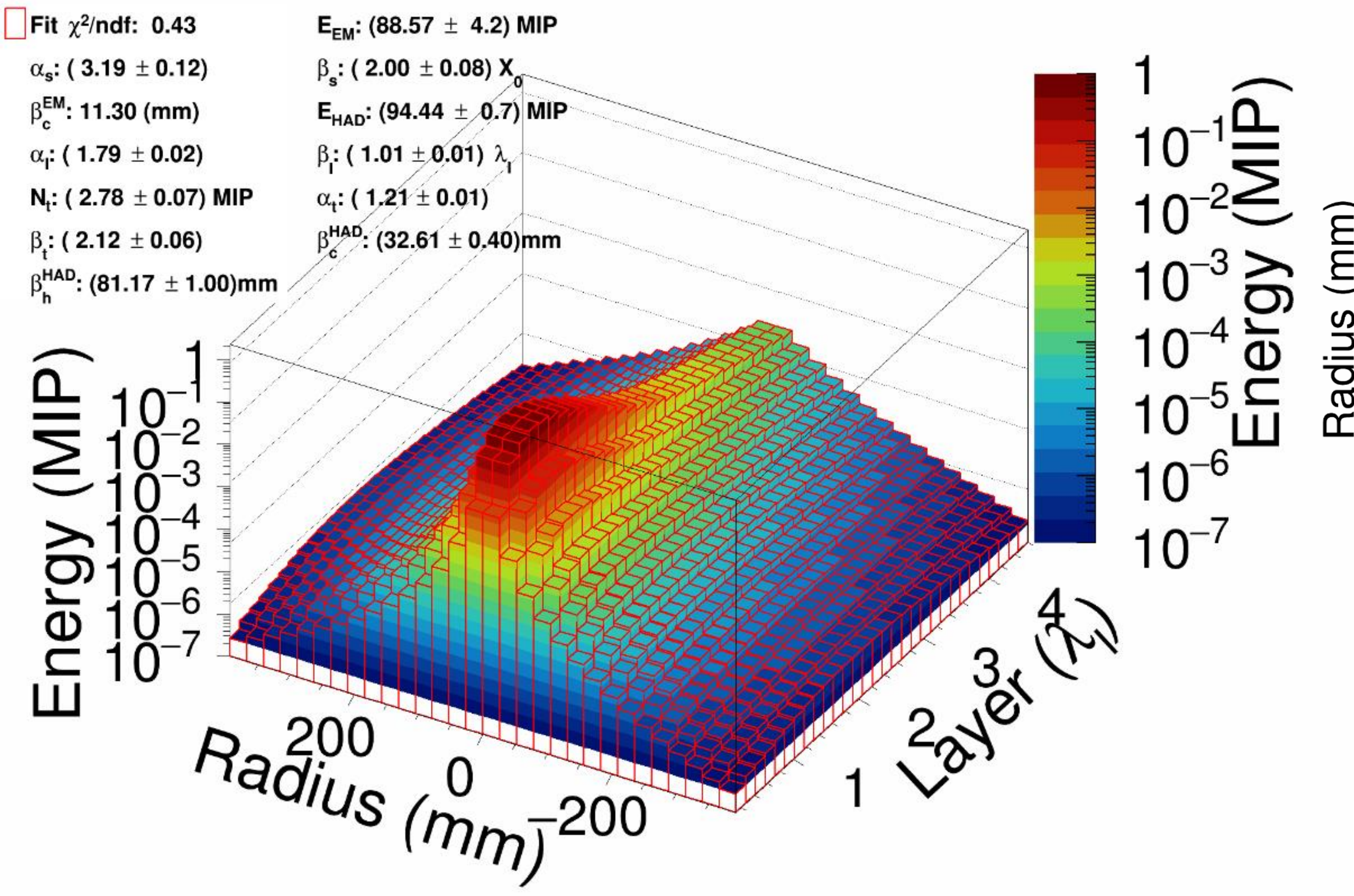
Fit χ²/ndf: 0.51
α_s: (3.76 ± 0.06)
β_c^EM: 11.30 (mm)
α_l: (1.71 ± 0.01)
N_t: (2.56 ± 0.05) MIP
β_t: (1.80 ± 0.04)
β_h^HAD: (87.30 ± 1.08)mm
E_EM: (65.69 ± 3.4) MIP
β_s: (1.50 ± 0.01) X_0
E_HAD: (62.68 ± 0.5) MIP
β_l: (0.95 ± 0.01) λ_I
α_t: (1.24 ± 0.01)
β_c^HAD: (35.57 ± 0.38)mm
Energy (MIP)
Radius (mm)
Layer (λ_I)



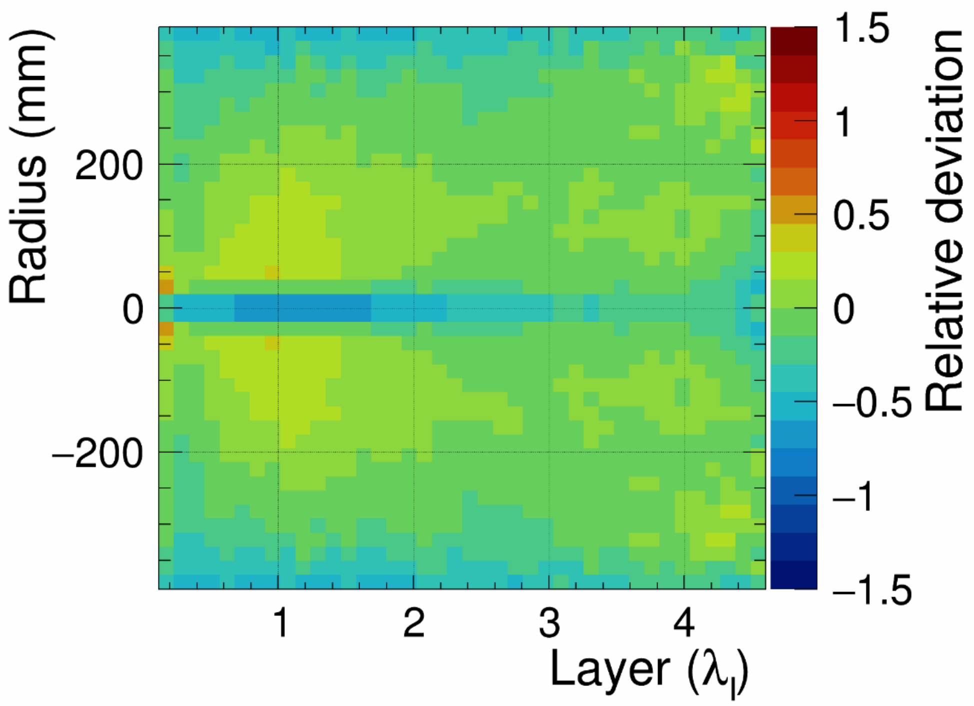
Radius (mm)
Layer (λ_I)
Relative deviation

30 GeV

DATA



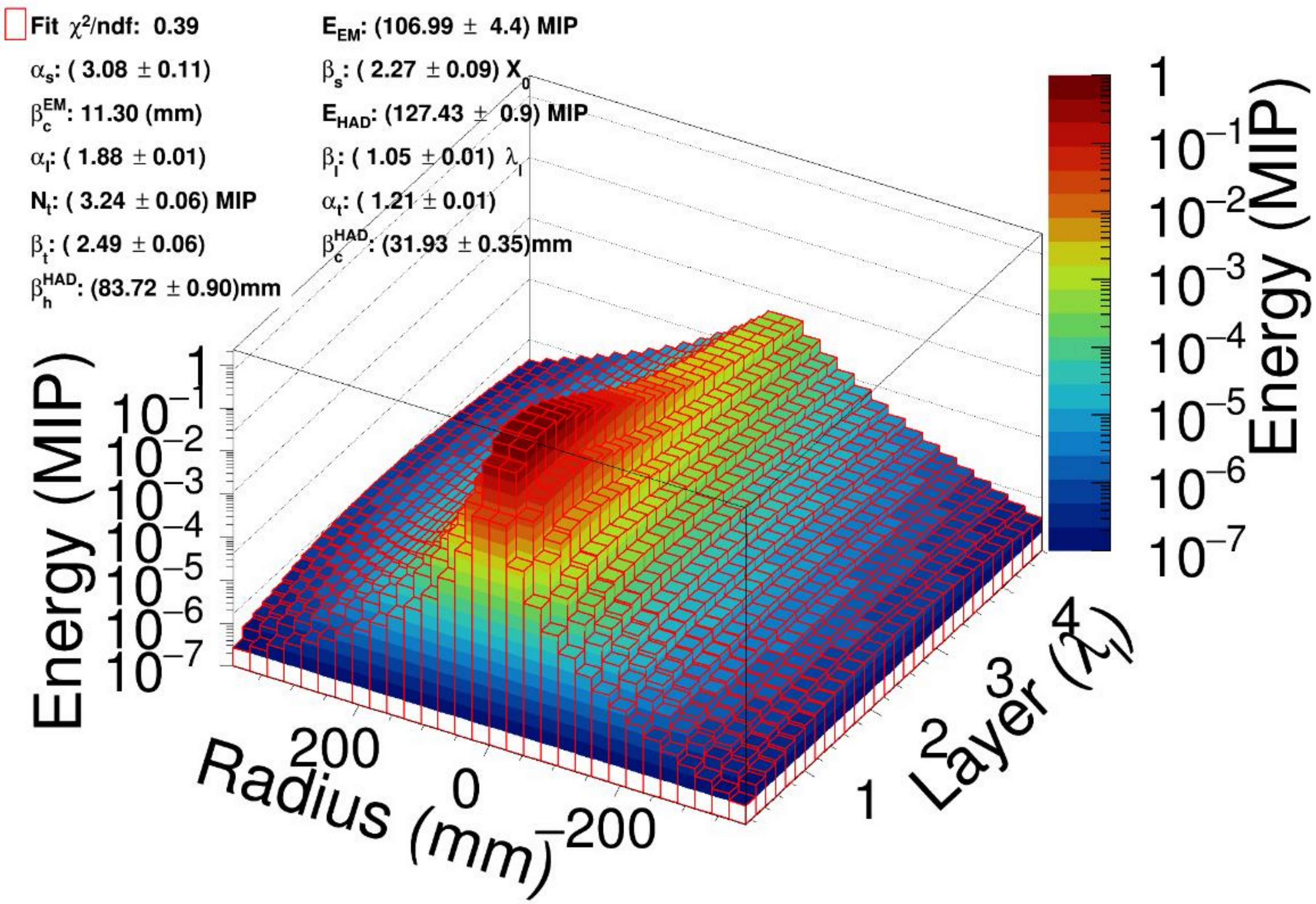
Fit χ²/ndf: 0.43
αs: (3.19 ± 0.12)
βc EM: 11.30 (mm)
αl: (1.79 ± 0.02)
Nt: (2.78 ± 0.07) MIP
βt: (2.12 ± 0.06)
βh HAD: (81.17 ± 1.00)mm
EEM: (88.57 ± 4.2) MIP
βs: (2.00 ± 0.08) X0
EHAD: (94.44 ± 0.7) MIP
βl: (1.01 ± 0.01) λI
αt: (1.21 ± 0.01)
βc HAD: (32.61 ± 0.40)mm
Energy (MIP)
Radius (mm)
Layer (λI)



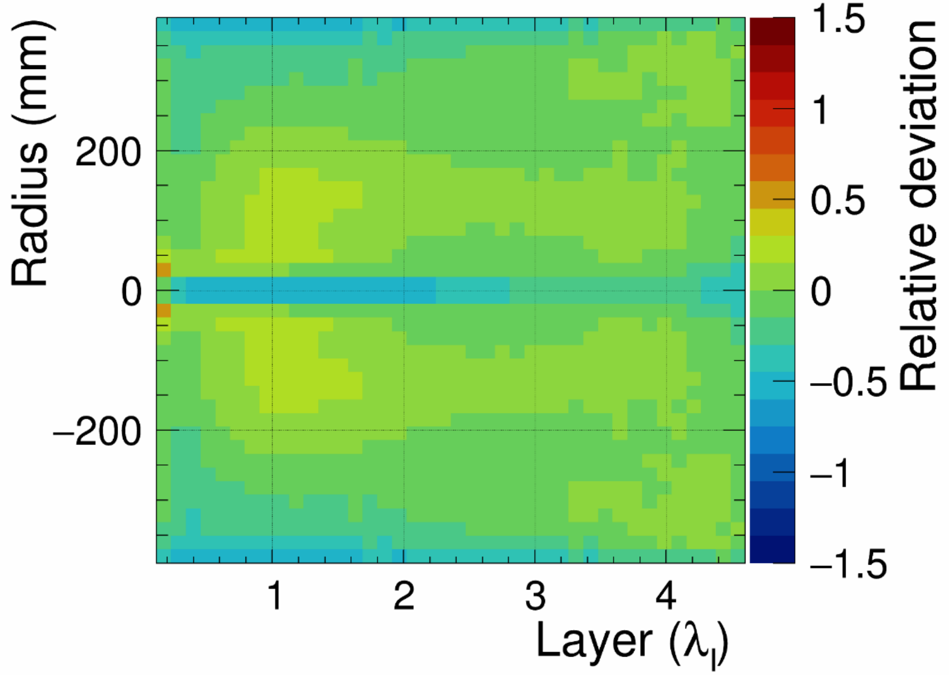
Radius (mm)
Layer (λI)
Relative deviation

40 GeV

DATA



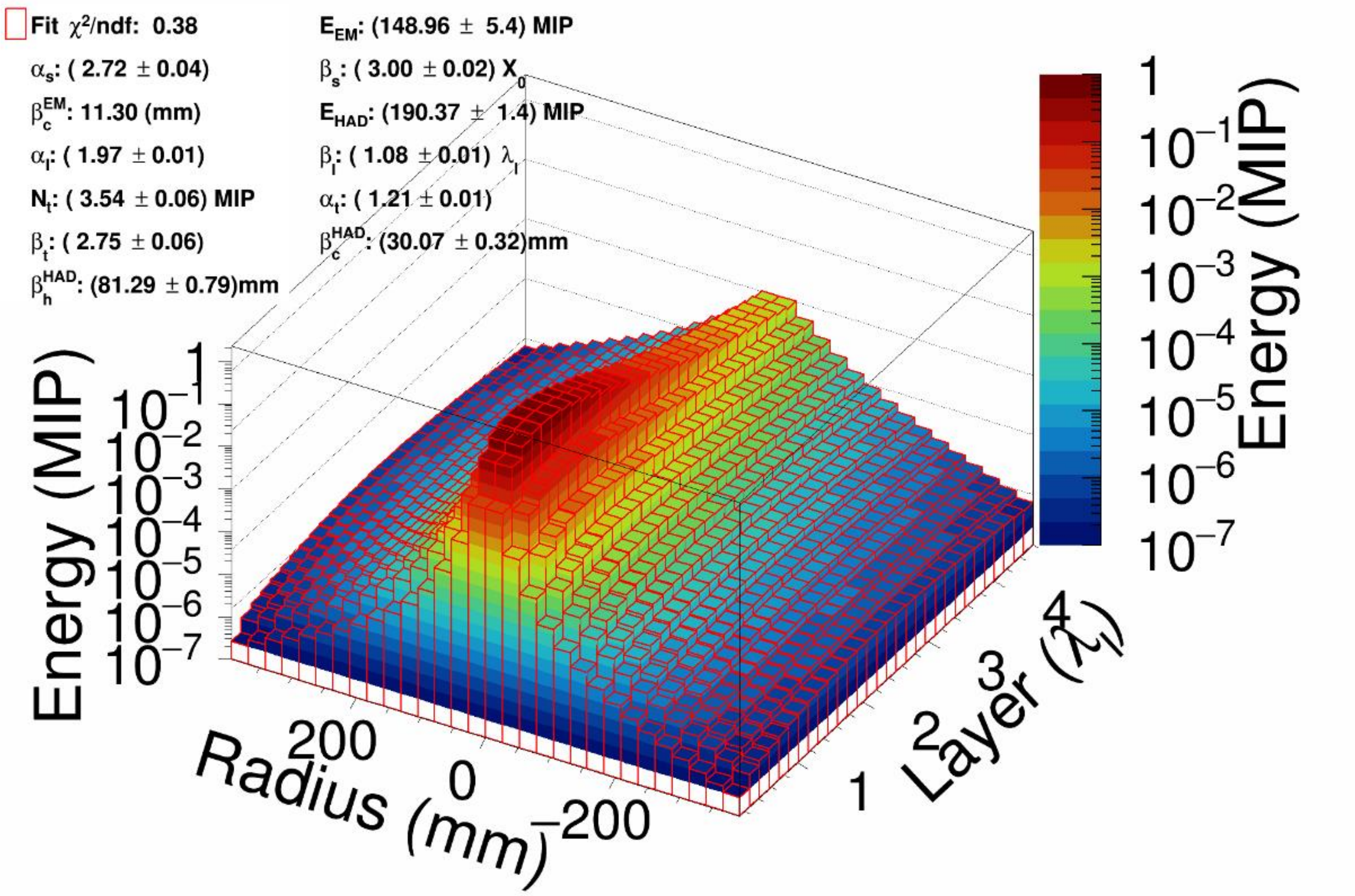
Fit χ^2/ndf: 0.39
E_{EM}: (106.99 ± 4.4) MIP
α_s: (3.08 ± 0.11)
β_s: (2.27 ± 0.09) X_0
β_c^{EM}: 11.30 (mm)
E_{HAD}: (127.43 ± 0.9) MIP
α_l: (1.88 ± 0.01)
β_l: (1.05 ± 0.01) λ_I
N_t: (3.24 ± 0.06) MIP
α_t: (1.21 ± 0.01)
β_t: (2.49 ± 0.06)
β_c^{HAD}: (31.93 ± 0.35)mm
β_h^{HAD}: (83.72 ± 0.90)mm
Energy (MIP)
Radius (mm)
Layer (λ_I)



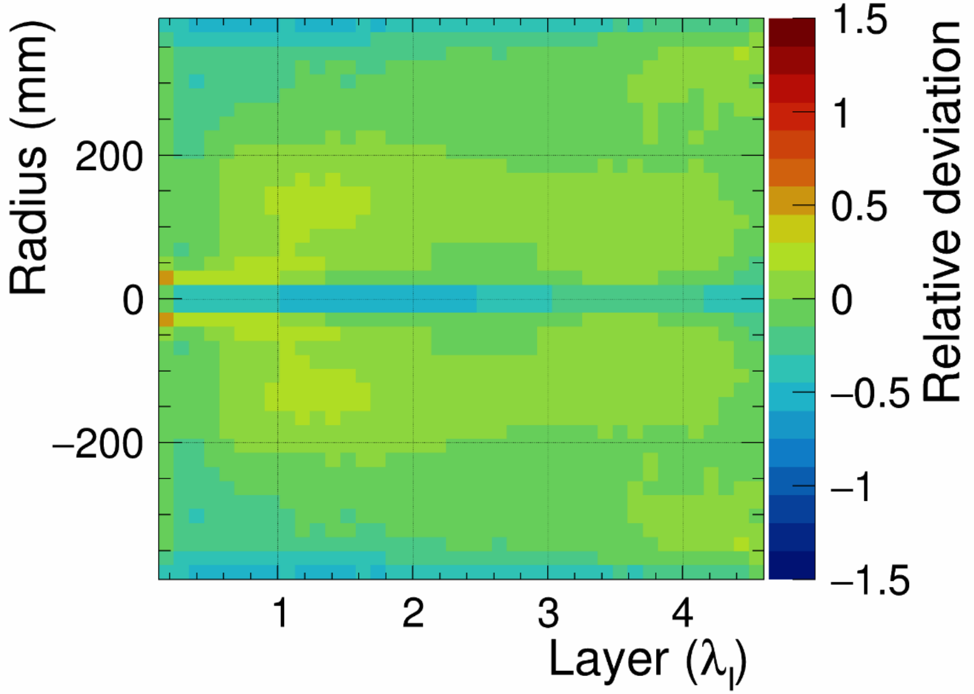
Radius (mm)
Layer (λ_I)
Relative deviation

60 GeV

DATA



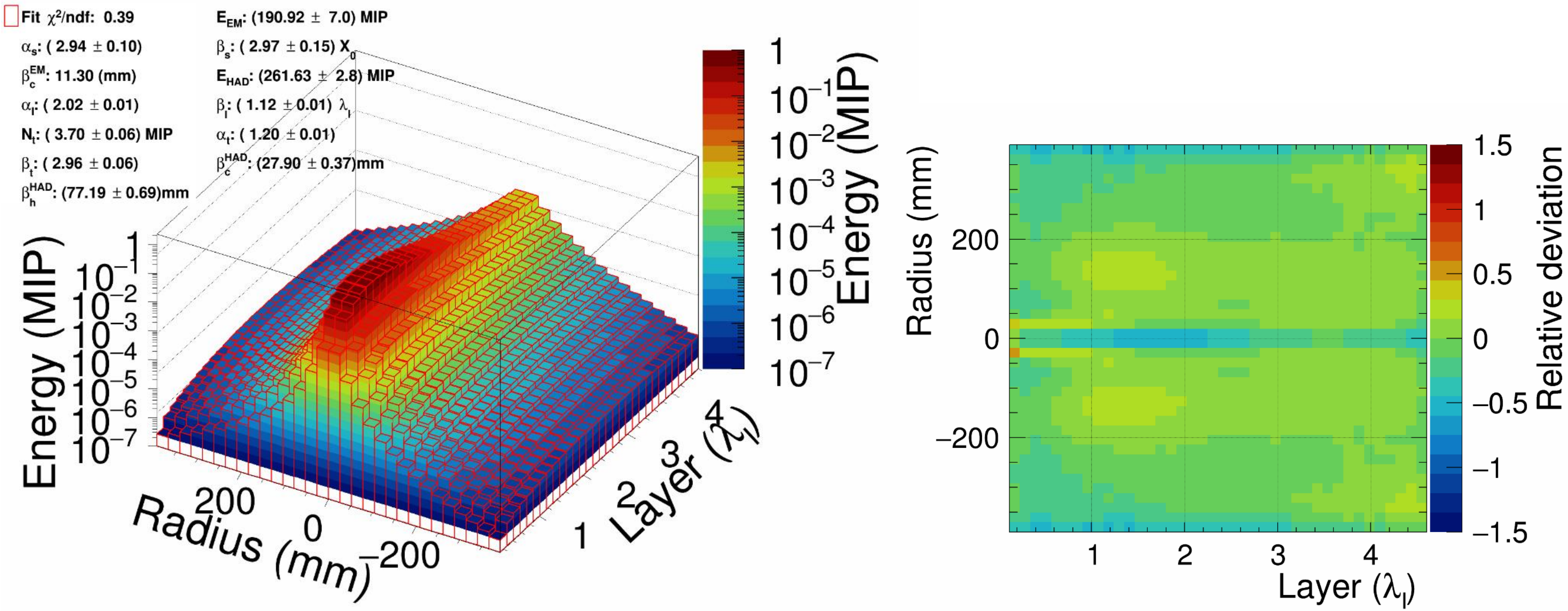
Fit χ^2/ndf: 0.38
α_s: (2.72 ± 0.04)
β_c^{EM}: 11.30 (mm)
α_l: (1.97 ± 0.01)
N_t: (3.54 ± 0.06) MIP
β_t: (2.75 ± 0.06)
β_h^{HAD}: (81.29 ± 0.79)mm
E_{EM}: (148.96 ± 5.4) MIP
β_s: (3.00 ± 0.02) X_0
E_{HAD}: (190.37 ± 1.4) MIP
β_l: (1.08 ± 0.01) λ_I
α_t: (1.21 ± 0.01)
β_c^{HAD}: (30.07 ± 0.32)mm
Energy (MIP)
Radius (mm)
Layer (λ_I)



Radius (mm)
Layer (λ_I)
Relative deviation

80 GeV

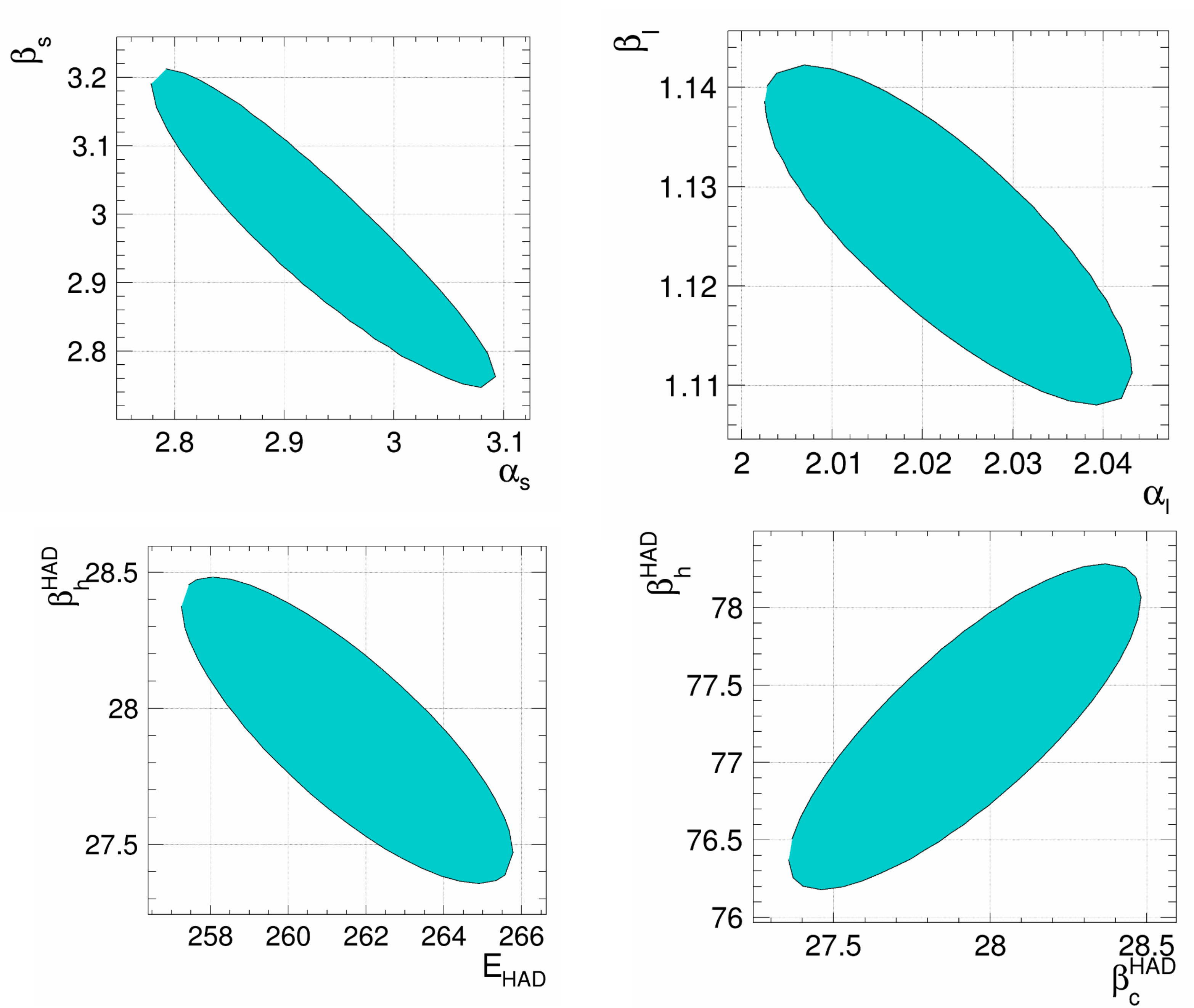
DATA



Fit χ²/ndf: 0.39
αs: (2.94 ± 0.10)
βc^EM: 11.30 (mm)
αl: (2.02 ± 0.01)
Nt: (3.70 ± 0.06) MIP
βt: (2.96 ± 0.06)
βh^HAD: (77.19 ± 0.69)mm
EEM: (190.92 ± 7.0) MIP
βs: (2.97 ± 0.15) X0
EHAD: (261.63 ± 2.8) MIP
βl: (1.12 ± 0.01) λI
αt: (1.20 ± 0.01)
βc^HAD: (27.90 ± 0.37)mm
Energy (MIP)
Radius (mm)
Layer (λI)
Relative deviation

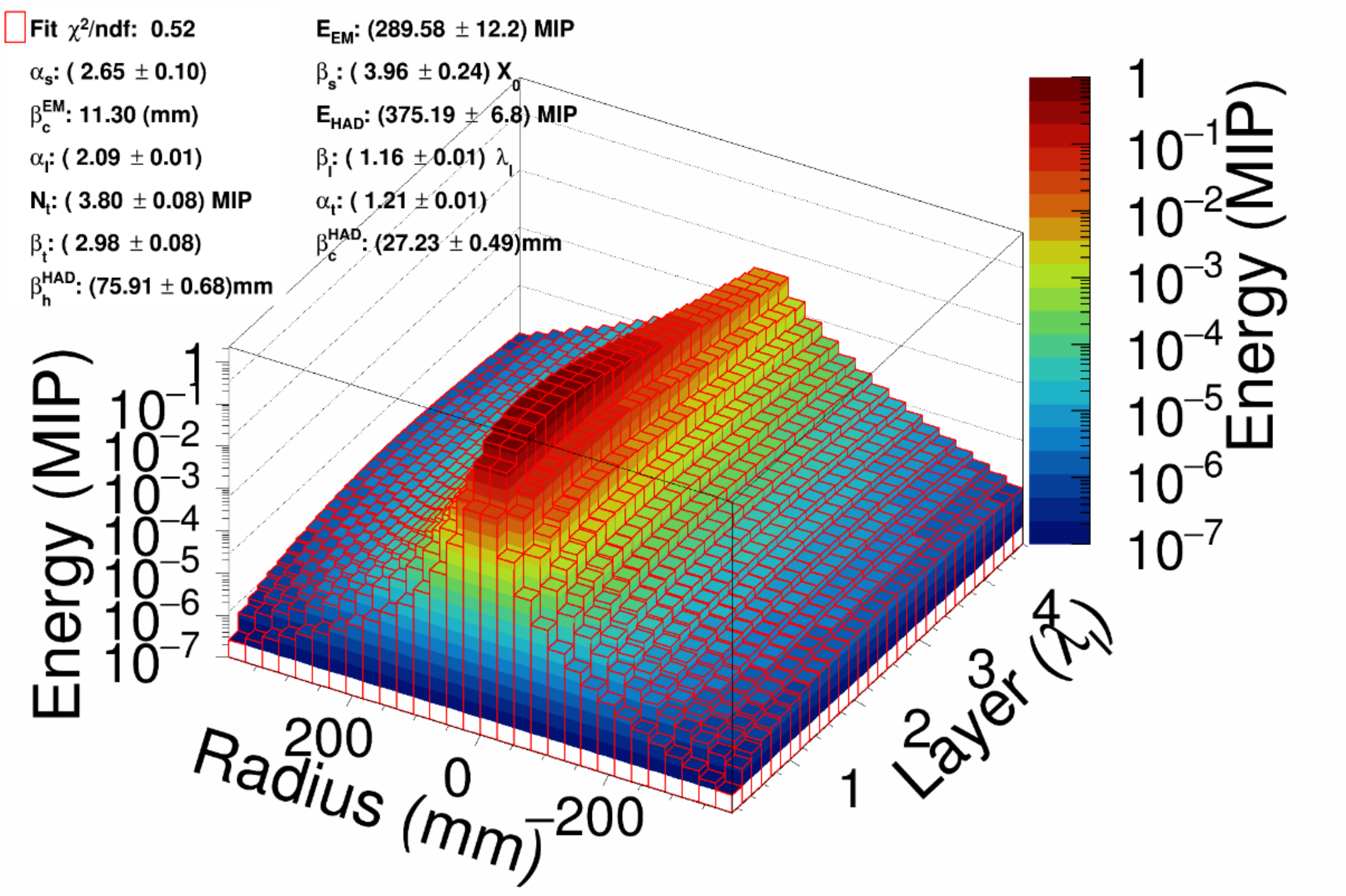
Contour plots

Data 80 GeV

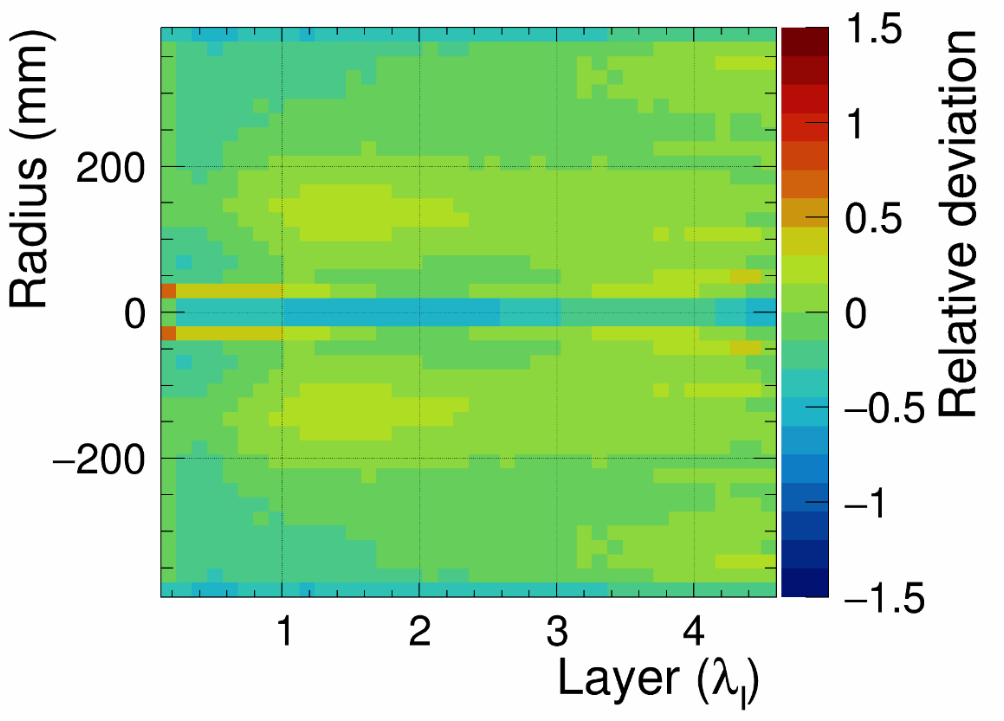


120 GeV

DATA



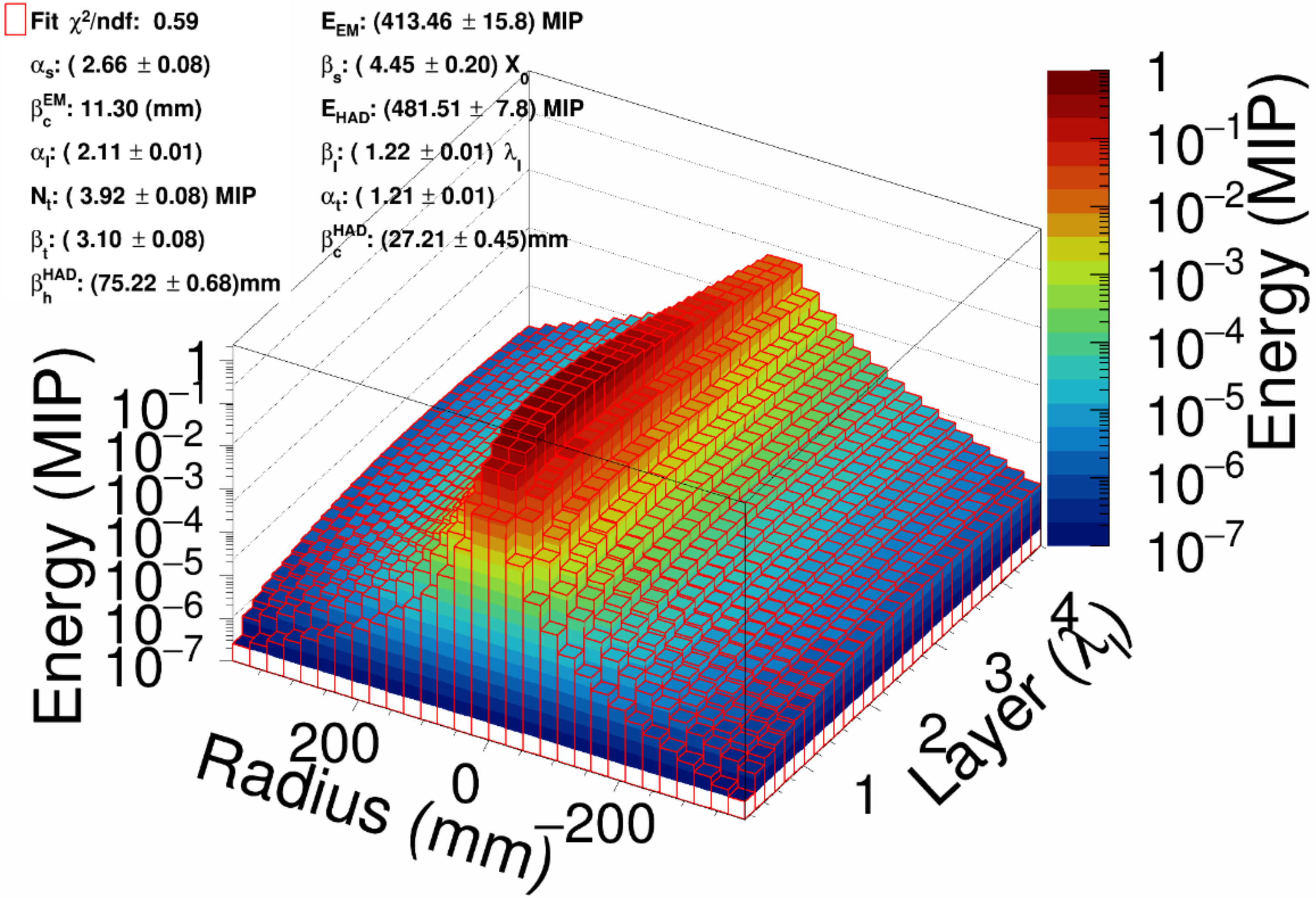
Fit χ^2/ndf: 0.52
α_s: (2.65 ± 0.10)
β_c^{EM}: 11.30 (mm)
α_l: (2.09 ± 0.01)
N_t: (3.80 ± 0.08) MIP
β_t: (2.98 ± 0.08)
β_h^{HAD}: (75.91 ± 0.68)mm
E_{EM}: (289.58 ± 12.2) MIP
β_s: (3.96 ± 0.24) X_0
E_{HAD}: (375.19 ± 6.8) MIP
β_l: (1.16 ± 0.01) λ_I
α_t: (1.21 ± 0.01)
β_c^{HAD}: (27.23 ± 0.49)mm
Energy (MIP)
Radius (mm)
Layer (λ_I)



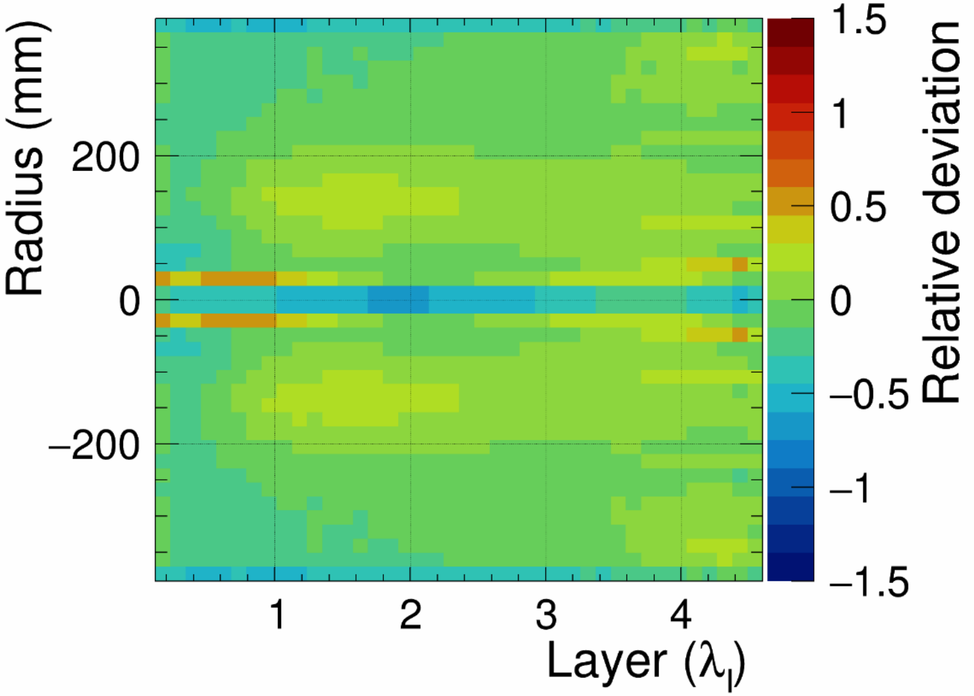
Radius (mm)
Layer (λ_I)
Relative deviation

160 GeV

DATA



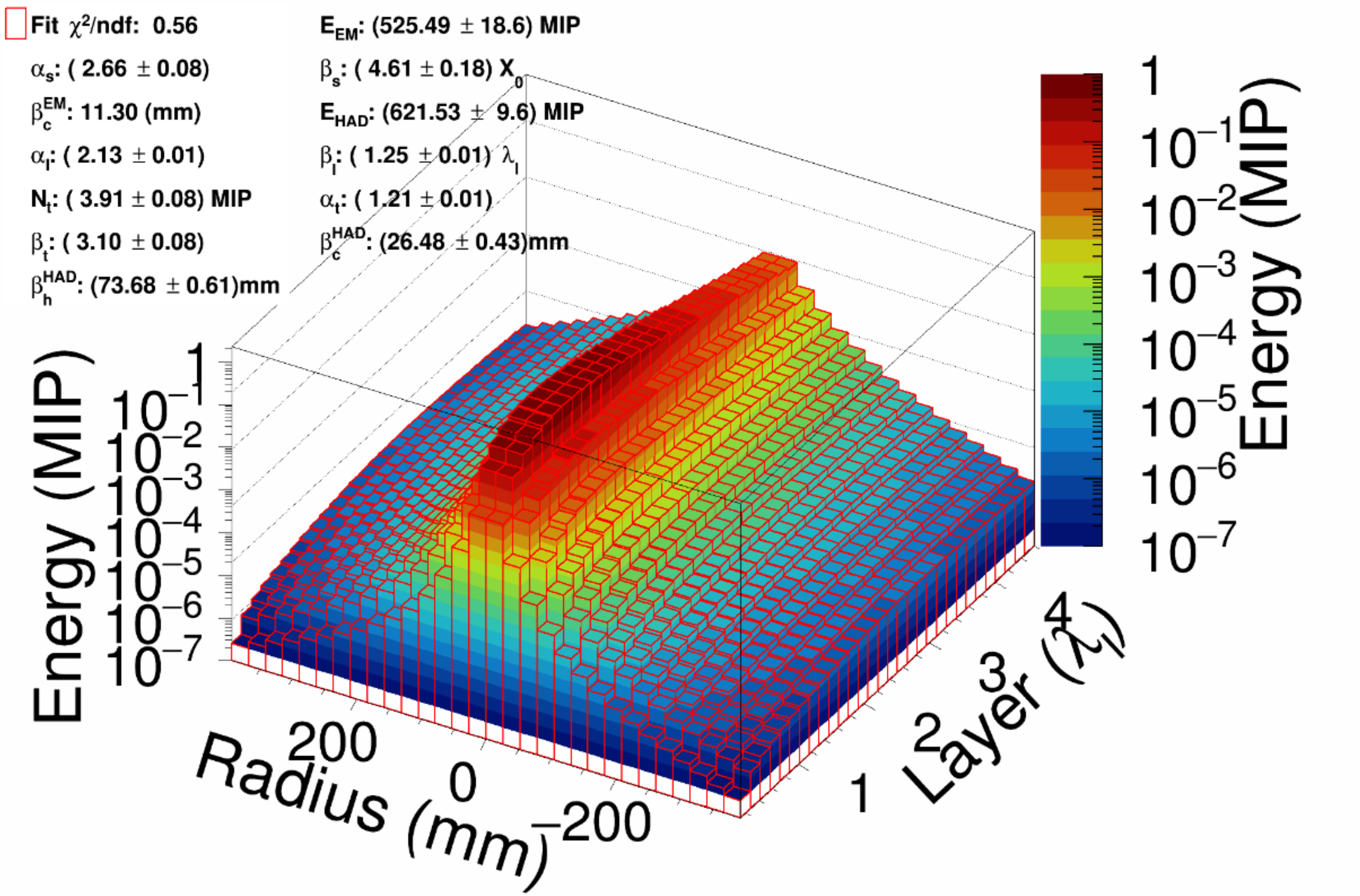
Fit χ^2/ndf: 0.59
E_{EM}: (413.46 ± 15.8) MIP
α_s: (2.66 ± 0.08)
β_s: (4.45 ± 0.20) X_0
β_c^{EM}: 11.30 (mm)
E_{HAD}: (481.51 ± 7.8) MIP
α_l: (2.11 ± 0.01)
β_l: (1.22 ± 0.01) λ_I
N_t: (3.92 ± 0.08) MIP
α_t: (1.21 ± 0.01)
β_t: (3.10 ± 0.08)
β_c^{HAD}: (27.21 ± 0.45)mm
β_h^{HAD}: (75.22 ± 0.68)mm
Energy (MIP)
Radius (mm)
Layer (λ_I)



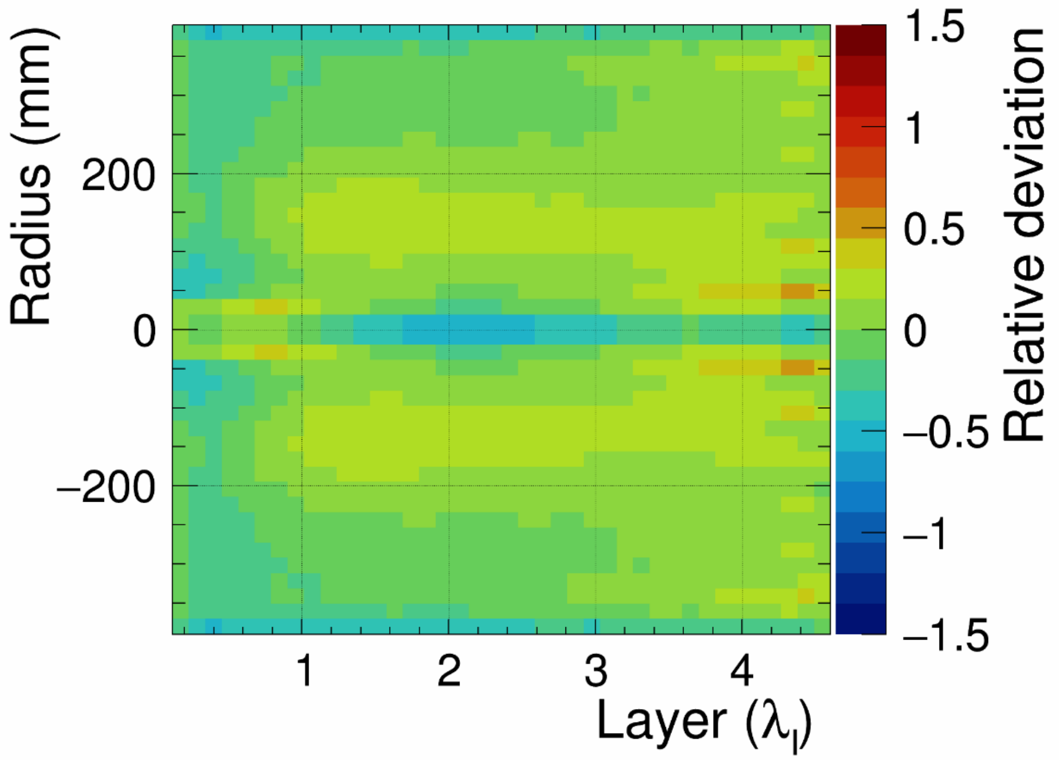
Radius (mm)
Layer (λ_I)
Relative deviation

200 GeV

DATA



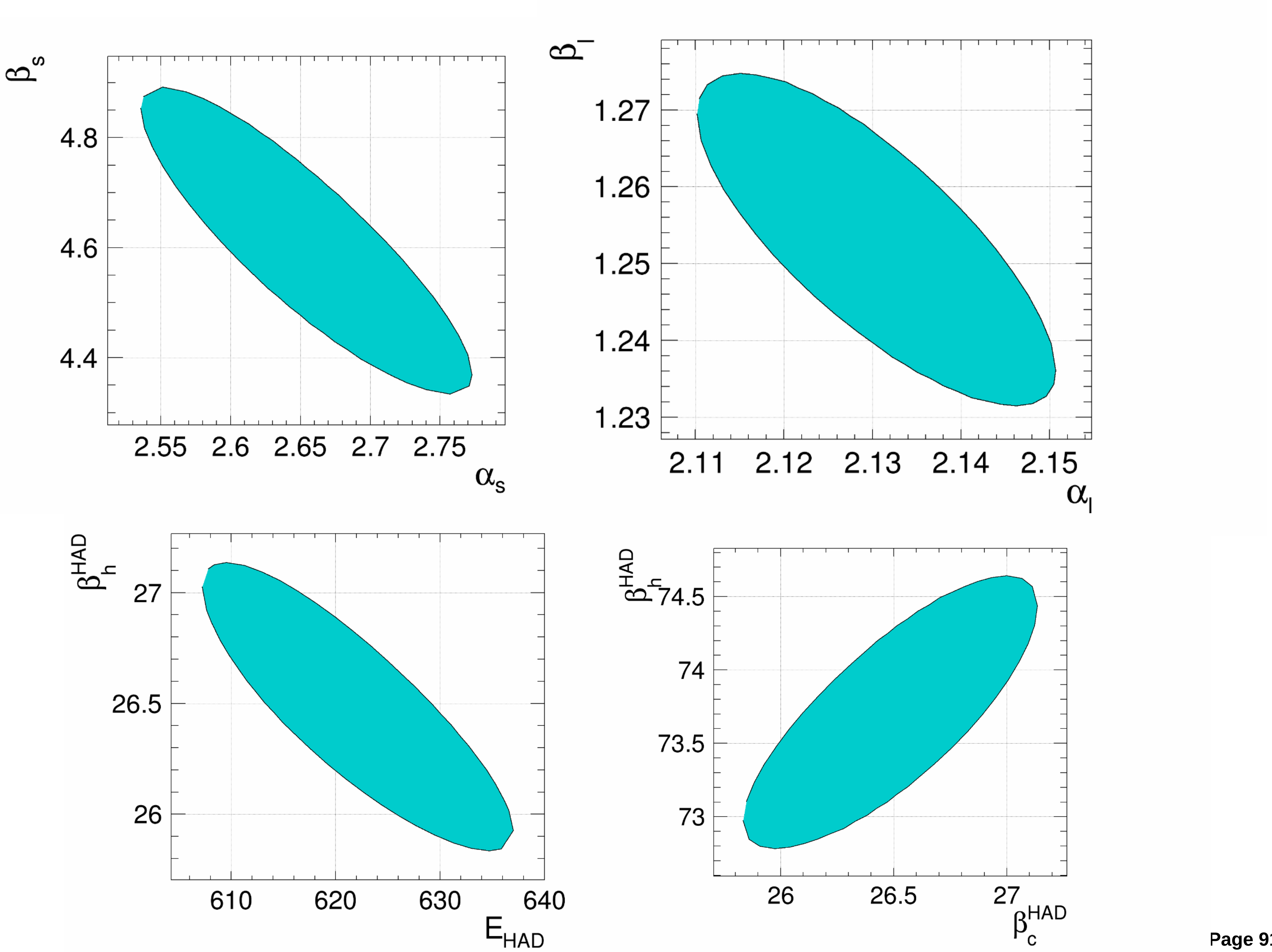
Fit χ^2/ndf: 0.56
α_s: (2.66 ± 0.08)
β_c^{EM}: 11.30 (mm)
α_l: (2.13 ± 0.01)
N_t: (3.91 ± 0.08) MIP
β_t: (3.10 ± 0.08)
β_h^{HAD}: (73.68 ± 0.61)mm
E_{EM}: (525.49 ± 18.6) MIP
β_s: (4.61 ± 0.18) X_0
E_{HAD}: (621.53 ± 9.6) MIP
β_l: (1.25 ± 0.01) λ_I
α_t: (1.21 ± 0.01)
β_c^{HAD}: (26.48 ± 0.43)mm
Energy (MIP)
Radius (mm)
Layer (λ_I)



Radius (mm)
Layer (λ_I)
Relative deviation

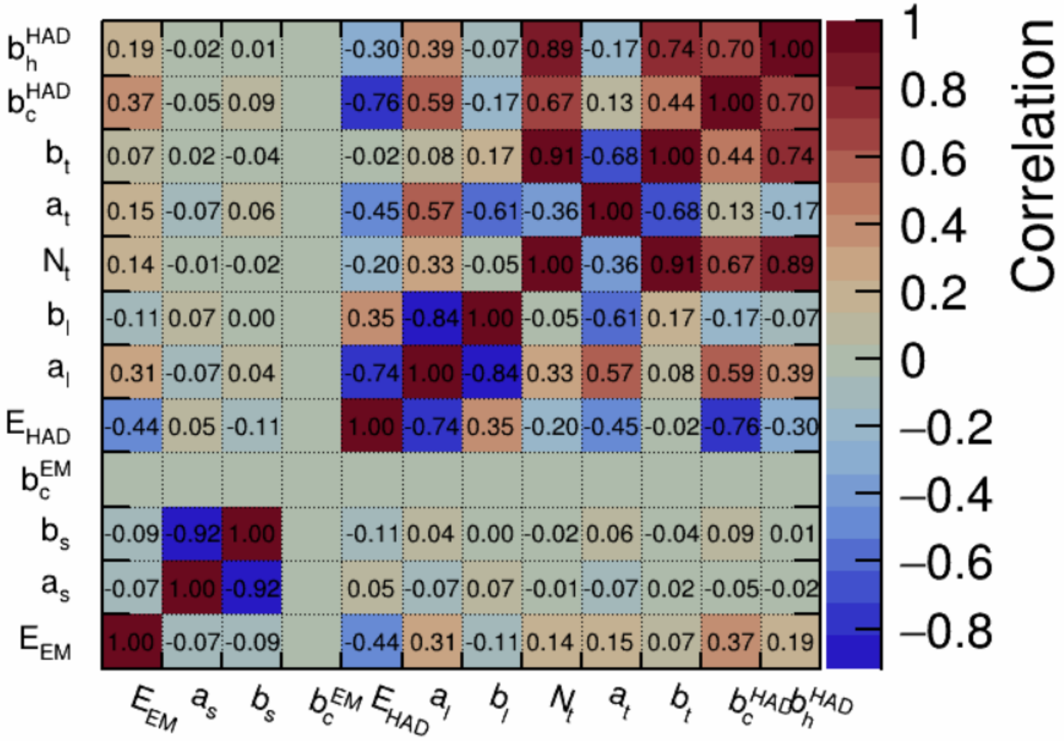
Contour plots

Data 200 GeV

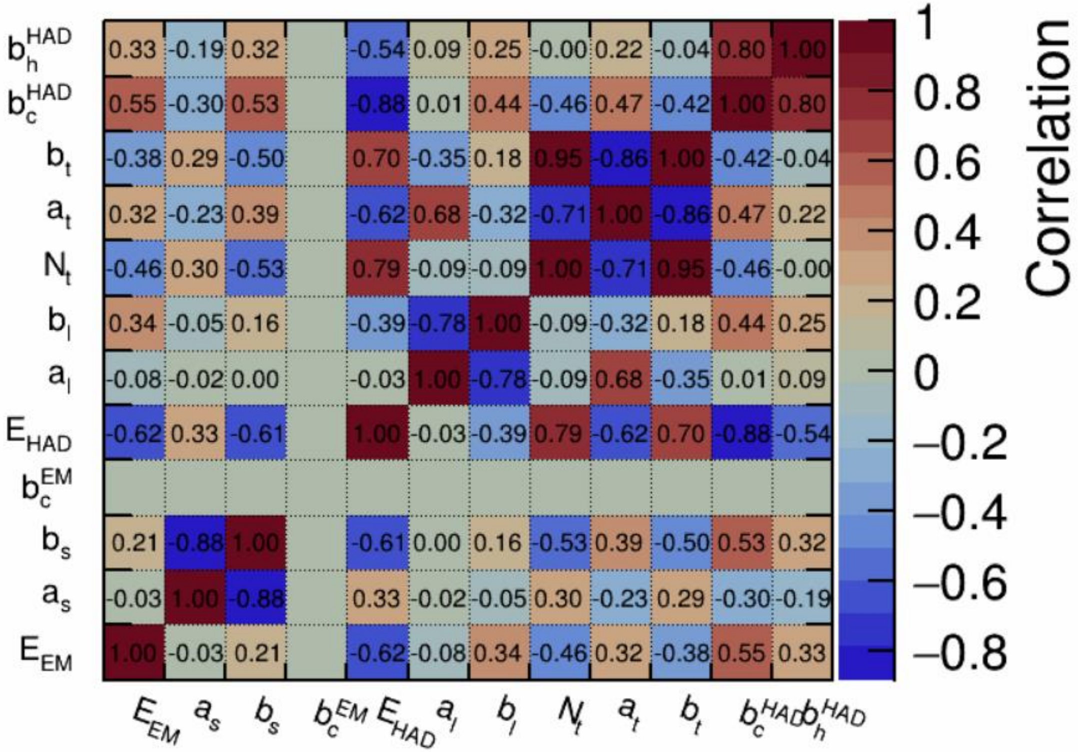


Correlation of parameters

Data
10 GeV



Data
200 GeV



- The alpha’s and beta’s have anti-correlation
- The hadronic beta's are highly correlated and have a positive correlation!
- There exists a correlation between the hadronic core and the hadronic energy

An application of hadronic model in Pandora PFA

```
// 2. Construct expected cluster profile
const double a(m_longProfileParameter0 + m_longProfileParameter1 * std::log(clusterEnergy / m_longProfileCriticalEnergy));
const double gammaA(std::exp(lgamma(a)));

float t(0.f);
FloatVector expectedProfile;
for (unsigned int iBin = 0; iBin < m_longProfileNBins; ++iBin)
{
    t += m_longProfileBinWidth;
    expectedProfile.push_back(static_cast<float>(clusterEnergy / 2. * std::pow(t / 2.f, static_cast<float>(a - 1.)) *
        std::exp(-t / 2.) * m_longProfileBinWidth / gammaA));
}

// 3. Compare the cluster profile with the expected profile
unsigned int binOffsetAtMinDifference(0);
float minProfileDifference(std::numeric_limits<float>::max());

for (unsigned int iBinOffset = 0; iBinOffset < profileEndBin; ++iBinOffset)
{
    float profileDifference(0.);

    for (unsigned int iBin = 0; iBin < profileEndBin; ++iBin)
    {
        if (iBin < iBinOffset)
        {
            profileDifference += profile[iBin];
        }
        else
        {
            profileDifference += std::fabs(expectedProfile[iBin - iBinOffset] - profile[iBin]);
        }
    }

    if (profileDifference < minProfileDifference)
    {
        minProfileDifference = profileDifference;
        binOffsetAtMinDifference = iBinOffset;
    }

    if (profileDifference - minProfileDifference > m_longProfileMaxDifference)
        break;
}

profileStart =  binOffsetAtMinDifference * m_longProfileBinWidth;
profileDiscrepancy = minProfileDifference / eCalEnergy;
```