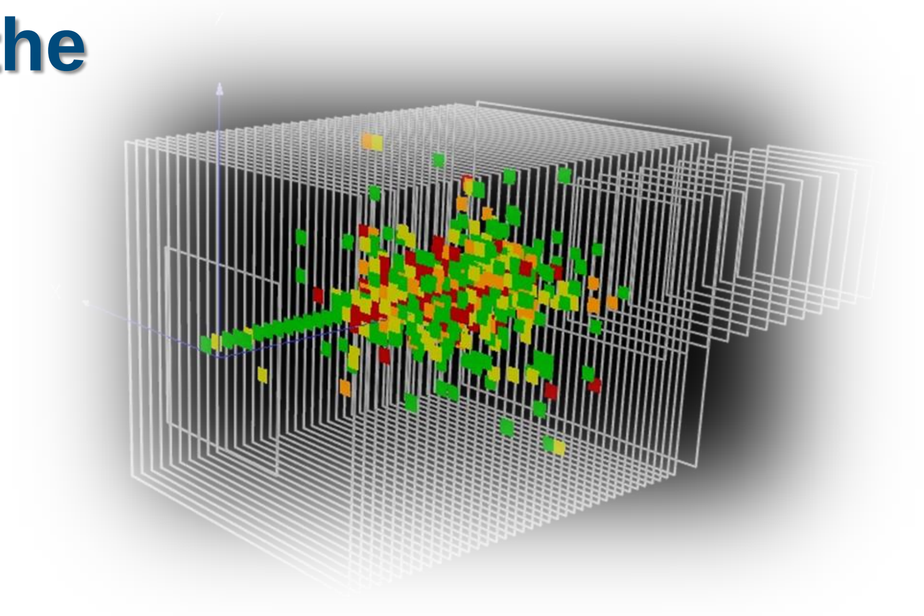
Analysis of shower shapes recorded with the CALICE-AHCAL in 2018 Test Beam Data



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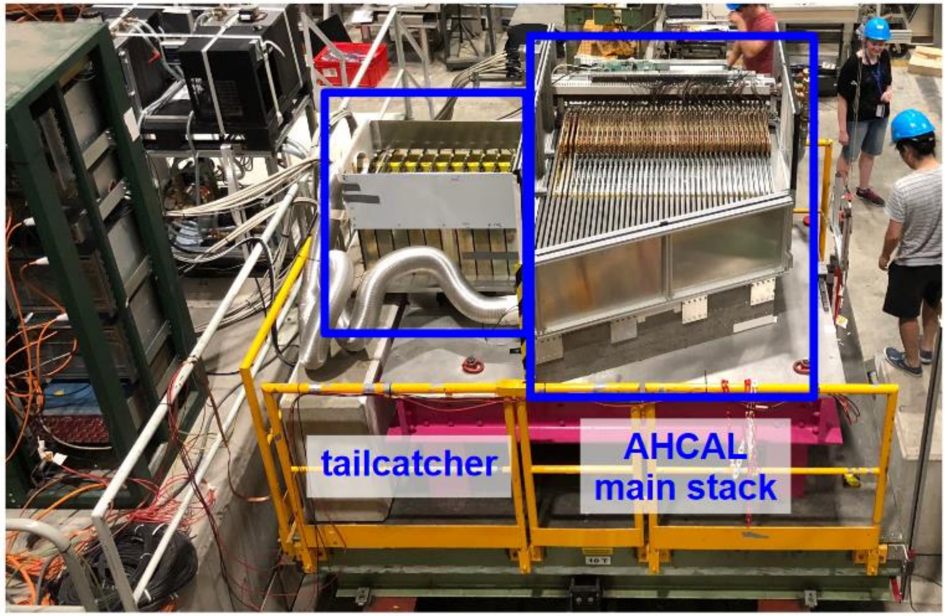
Virtual DPG – Spring meeting
Dortmund, 18.03.2021

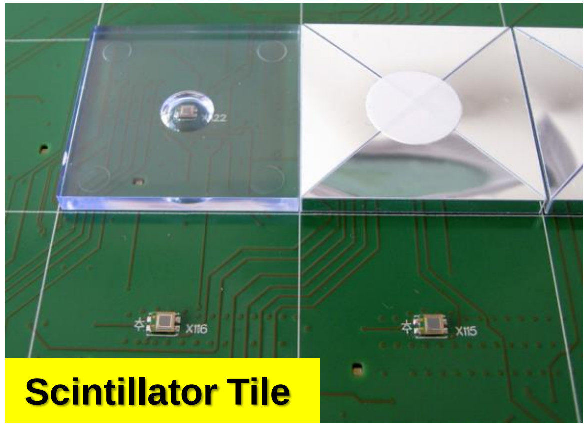
CALICE-AHCAL: a novelty in calorimetry

- Ideal detector for Particle Flow
- 5D imaging calorimeter: spatial + energy & time

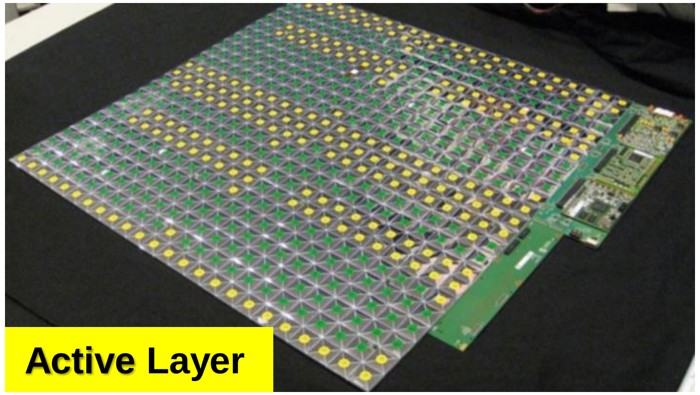


AHCAL in numbers:

- **39 active layers** alternating with steel absorber (1.72 cm) structure of ~4λ depth
- Each active layer is equipped with 576 channels with scintillator tile size of **3*3*0.3cm³**, individual readout by silicon photomultipliers
- **~22,000 channels** in total



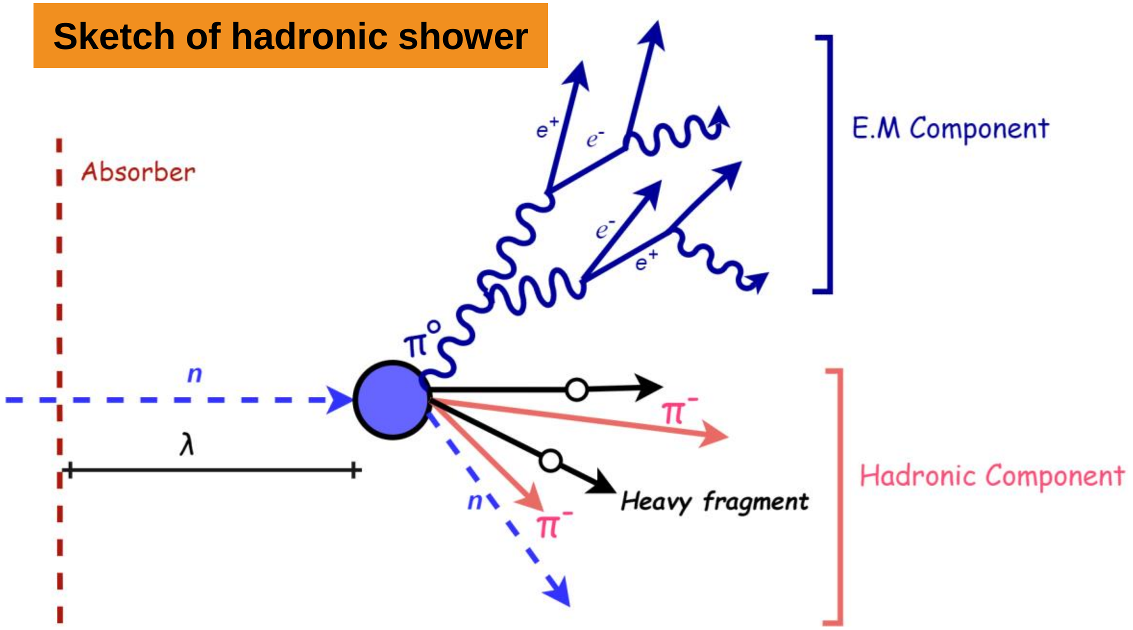
Scintillator Tile



Active Layer

Hadronic Showers

Sketch of hadronic shower



- The production of secondary particles in a **hadronic cascade** is mainly caused by inelastic hadronic processes. **Mainly charged and neutral pions**, but, with lower multiplicities, also kaons, nucleons and other hadrons are produced

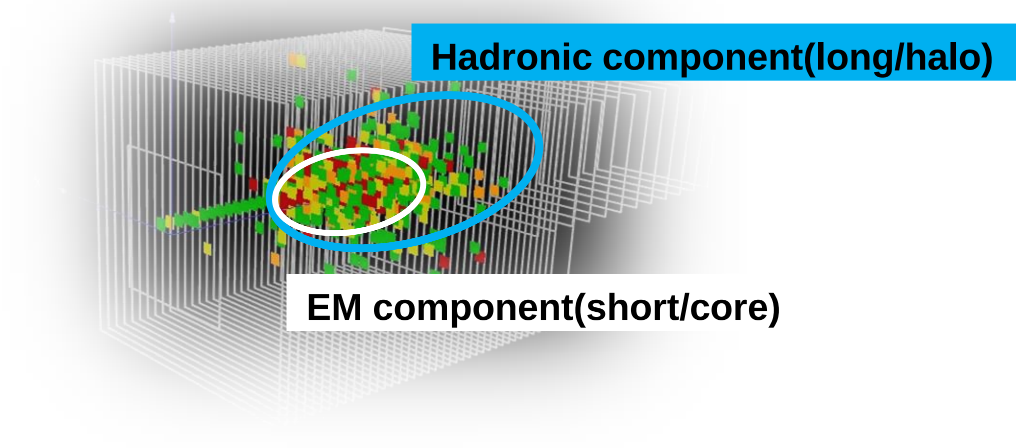
- **Large component** of secondary particles in hadron cascades are π^0 which represent ~ 1/3 of the pions produced in each inelastic collision. Thereby initiating **electromagnetic subcascades** in a hadron shower

- For **EM component** the relevant scale is X_0, while for the truly **hadronic component** the scale is λ_I

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

Motivation

- A complete understanding of the shower shapes is essential for several reasons:
    - To **recognize and distinguish** between two types of particles one can use the distinctive shower shape of electromagnetically and hadronically interacting particles
    - Secondly, the knowledge of the profiles enables to **understand the energy overlap** of showers initiated by particles that are closely spaced apart, which provides a key factor for PFA efficiency
- Shower shapes can be investigated with excellent accuracy, due to fine segmentation of the calorimeter
- The goal is to identify the core/short part of the shower with an **EM component**, and the long/halo part with the “truly” **hadronic component**



- Exploitation of shower shapes allows an estimation of **h/e signal ratio.** The ratio of response between pion-induced and electron-induced showers, determines the origin of non-linearity

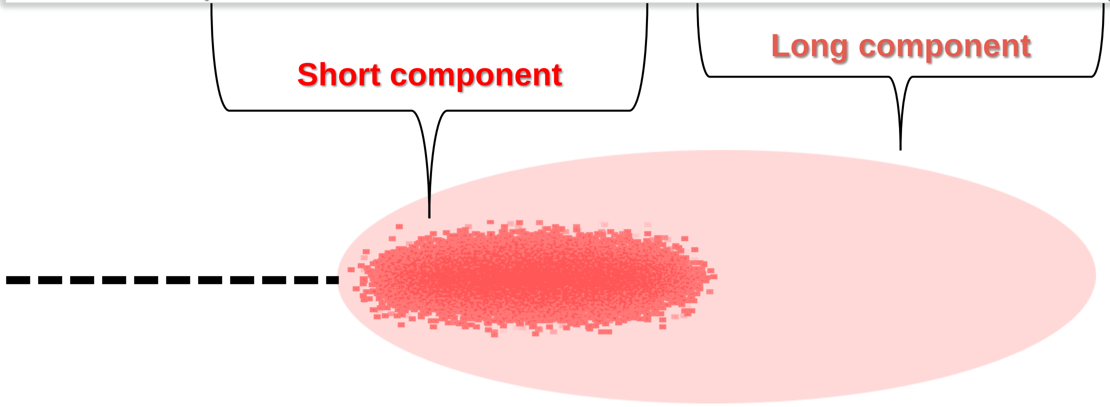
Parametrization

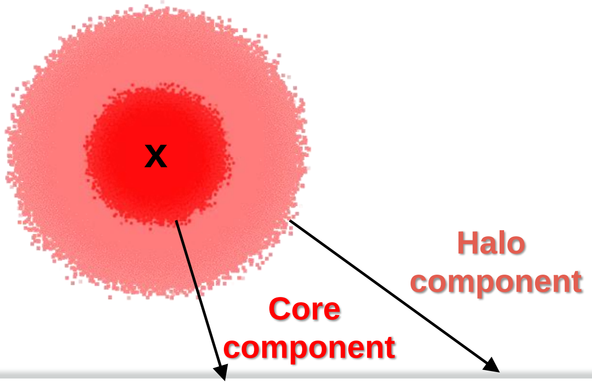
Longitudinal profile is the mean energy deposited per layer from the shower start

- Parametrized using the sum of two Gamma-functions, describing the shower development

- Near the shower axis is “short” component, closely related to the electromagnetic content of the shower and in the shower tail (“long” component), is closely related to the pure hadronic activity

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





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

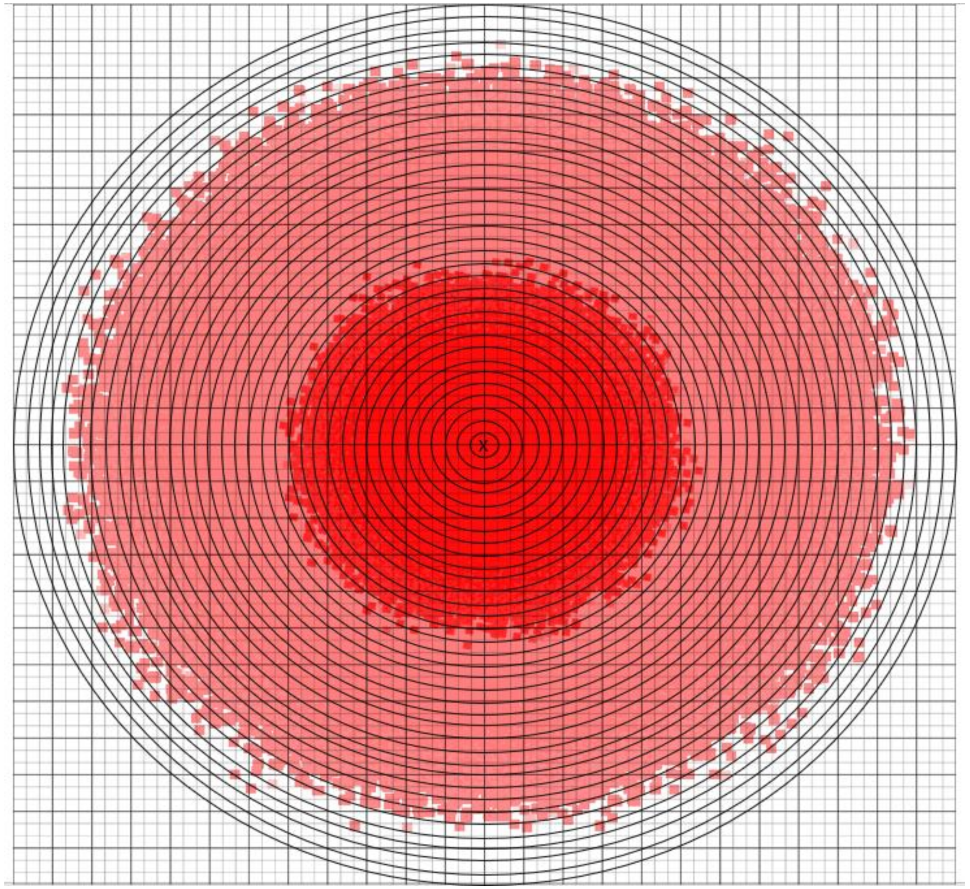
Radial profile is the distribution of the energy density as a function of the radial distance to the shower axis

- Parametrised with the sum of “core”, β_c component close to the shower axis and a “halo”, β_h component distant from the shower axis

- ΔE is the energy density, and $\Delta S = 2\pi r \Delta r$ is the area of a ring of width Δr at a distance r from the shower axis

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 shapes
Results

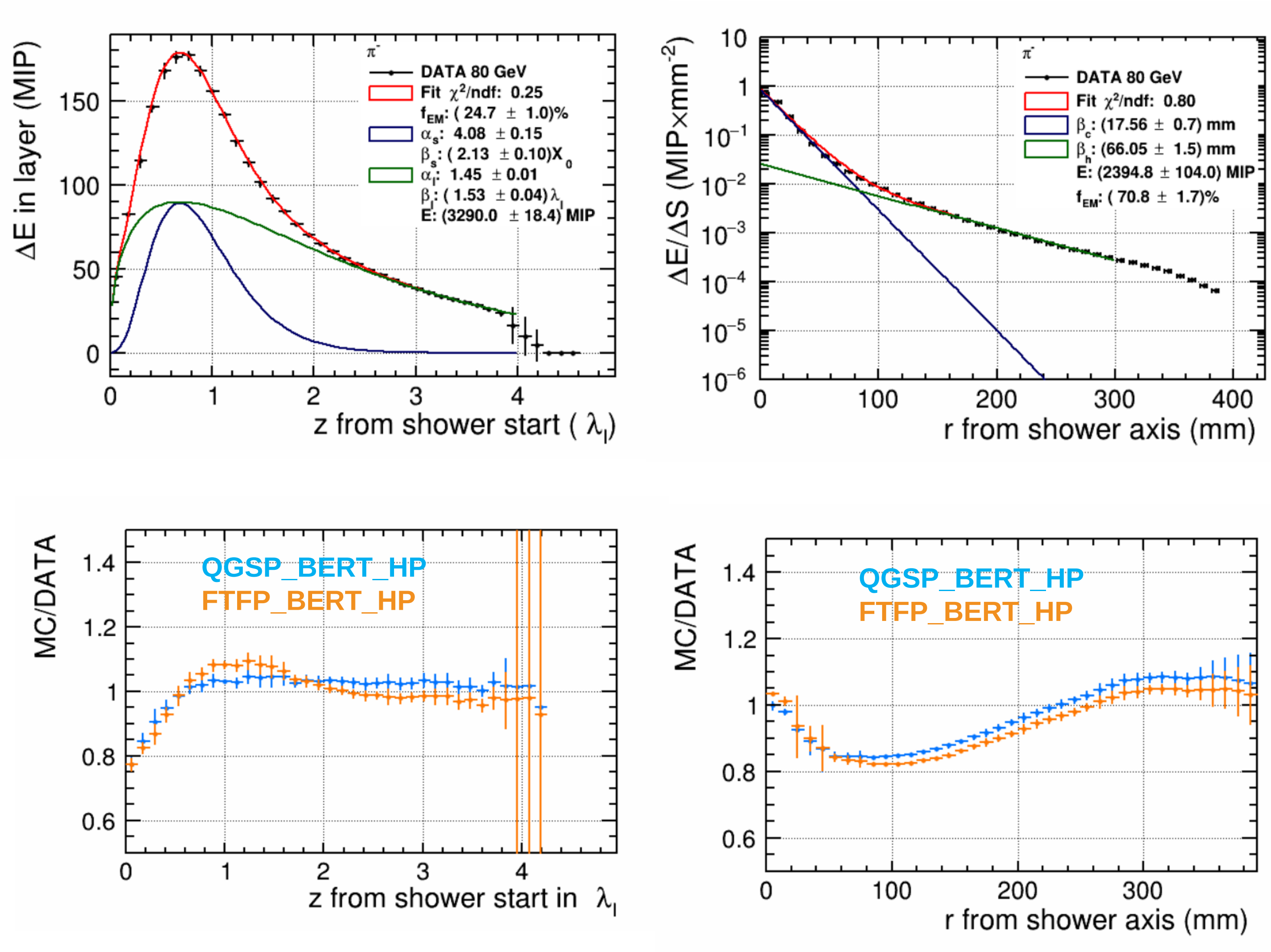
- The longitudinal fit range corresponds to a depth of $4\lambda_I$ from the shower start and for radial up to a width of 300 mm with a step size of 10 mm

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

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

  - The central core of the pion shower is seen to have a 17.56 mm scale length while the large r region scales with 66.0 mm. The latter presumably is composed mainly of low energy neutrons released in the shower development process that have rather large scattering lengths

The parametrisation with the two-component function allows to roughly separate the contributions from the **electromagnetic** and **hadronic** components within a shower

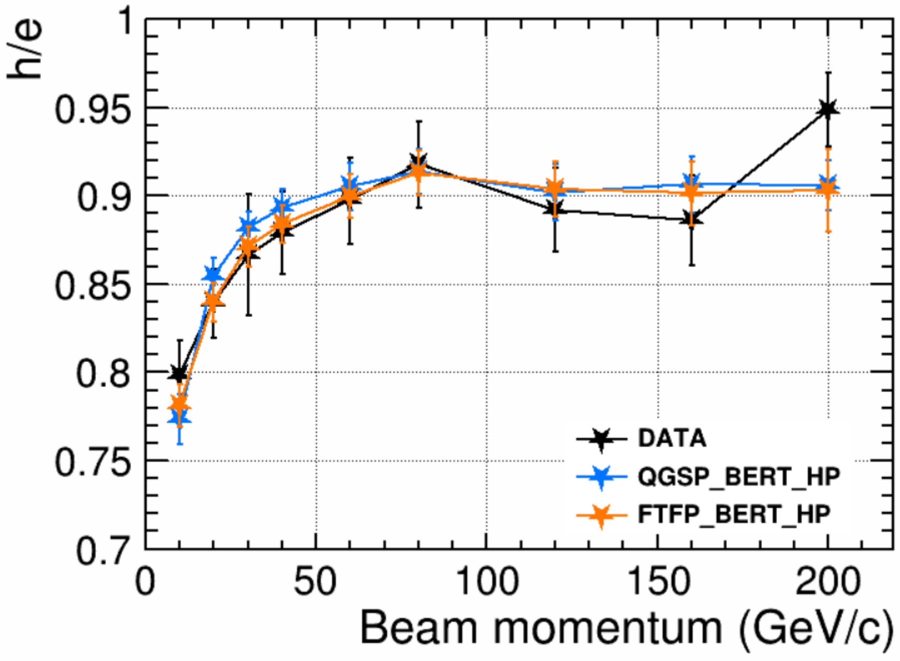


h/e signal ratio

- **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 profiles

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

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

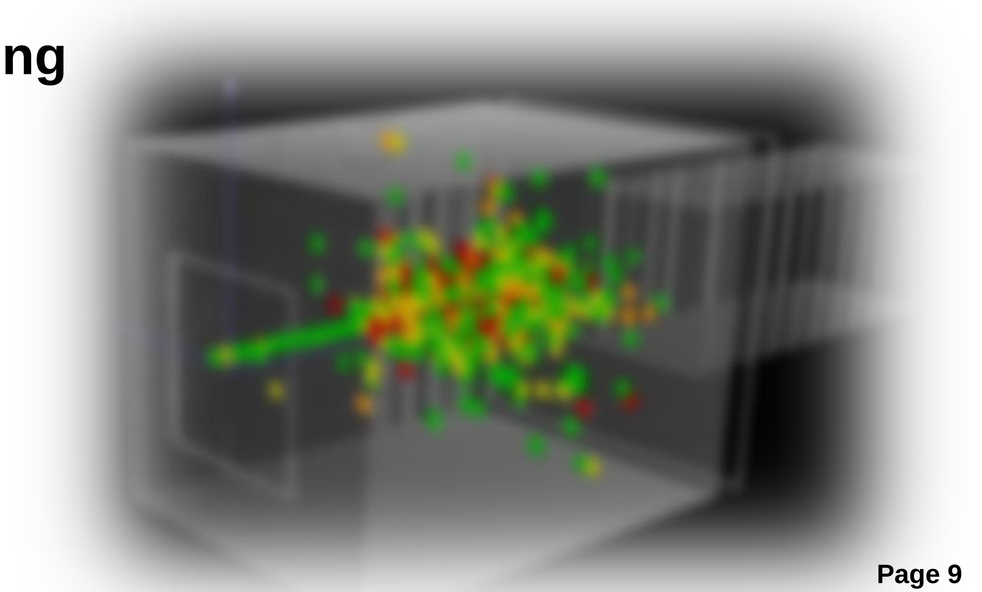


Electromagnetic calibration constant
0.02278 GeV/MIP

- 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%

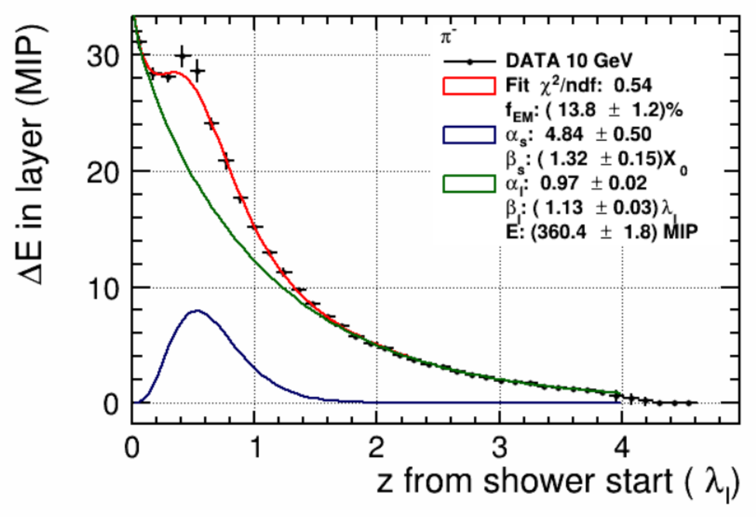
Summary & Outlook

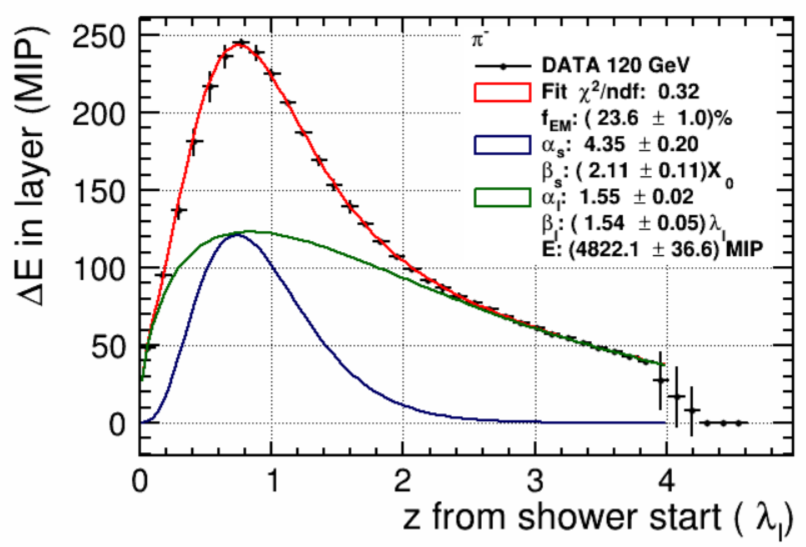
- **Analog Hadron Calorimeter** is an imaging calorimeter and is granular enough to fully exploit the characteristics of particle showers
- **Hadronic showers shapes** are well described by the sum of two contributions: sum of gamma distributions for longitudinal and sum of exponents for radial development
- The ratio of response between pion-induced and electron-induced shower (**h/e signal ratio**) obtained from the longitudinal profile is found to be between 0.8 and 0.95
- Next steps will be in the direction of **3D shower modelling**

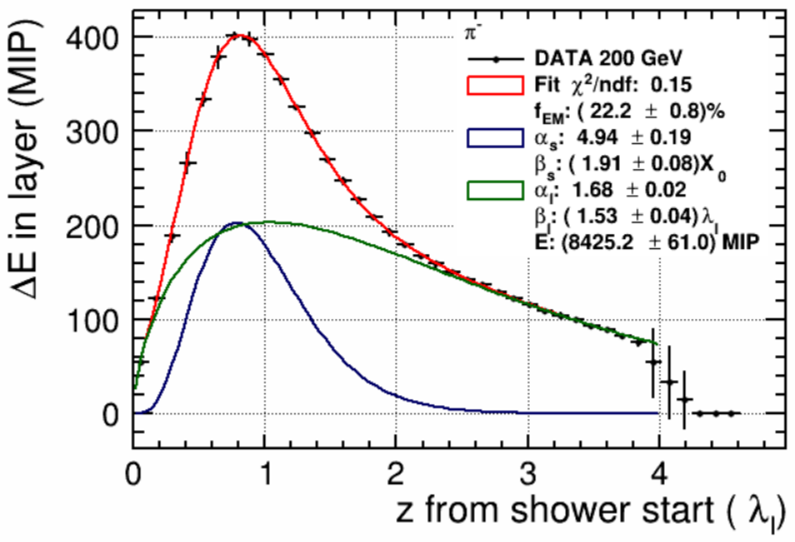


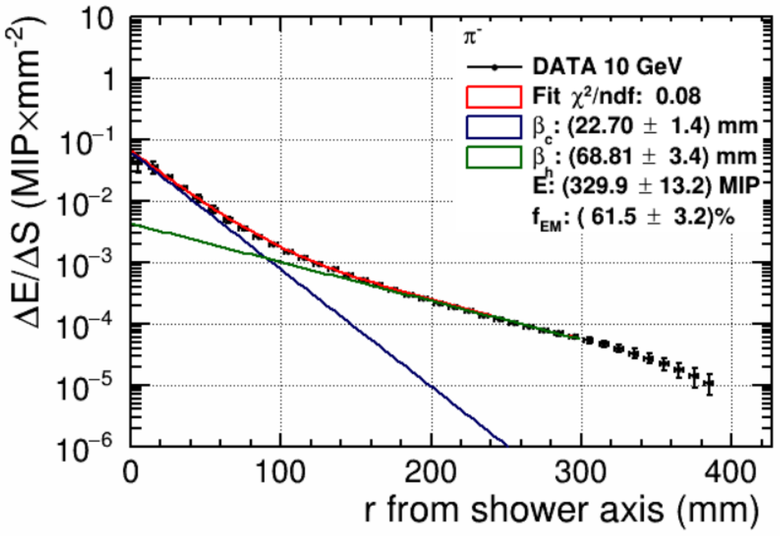
SPARES

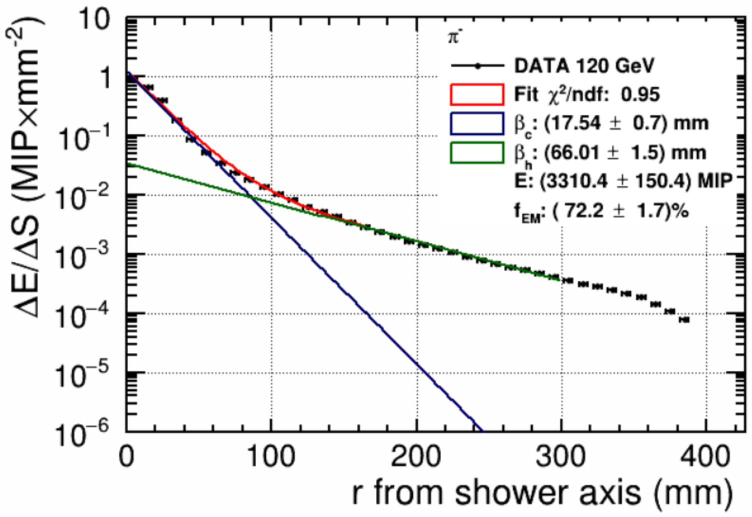
More Shower shapes ...

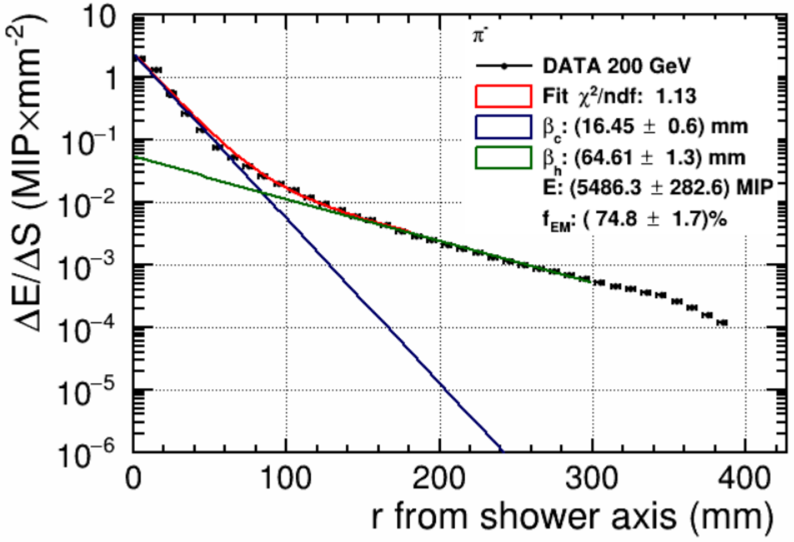








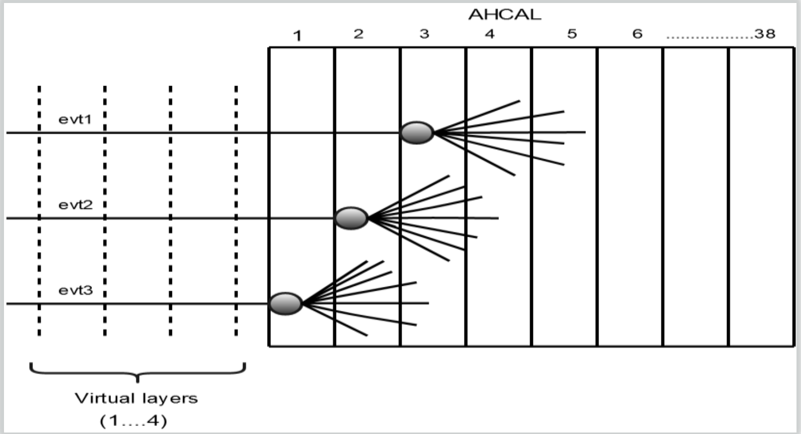




Shower start finder

Idea: comparison of visible energy, E_i in units of MIP and number of hits, N_i in i^{th} layer

With an average E_i of the visible signal in MIP in a moving window of six consecutive layers up to the i^{th} layer and the number of hits in the i^{th} layer N_i are analysed on a layer-by-layer basis, starting from the first AHCAL layer



- calculate sum of averaged visible energy in two successive layers

$$(E_i + E_{i+1}) > \left(6.0 + 0.1\frac{E_{\mathrm{beam}}}{\mathrm{GeV}}\right)\,\mathrm{MIP}$$

- calculate sum of number of hits in two successive layers

$$(N_i + N_{i+1}) > \left(3.77 + 1.44 \cdot \ln\left(\frac{E_{beam}}{\mathrm{GeV}}\right)\right)$$

- If the above conditions were satisfied, the i^{th} layer is considered to be the shower start layer otherwise the layer (i -1) is taken as the layer where the shower starts
- Thresholds and their energy dependence are adjusted using Geant4 simulation

Shower axis determination

80 GeV