Performance of CMS HGCAL+AHCAL prototype to charged pions in beam test experiment

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Outline

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- ➔ Beam test experimental setup
- ➔ Event reconstruction
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- ➔ Depth of first hadronic interaction for pions
- ➔ Energy reconstruction of hadronic showers
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- ➔ Longitudinal and transverse shower profiles of pions
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Introduction

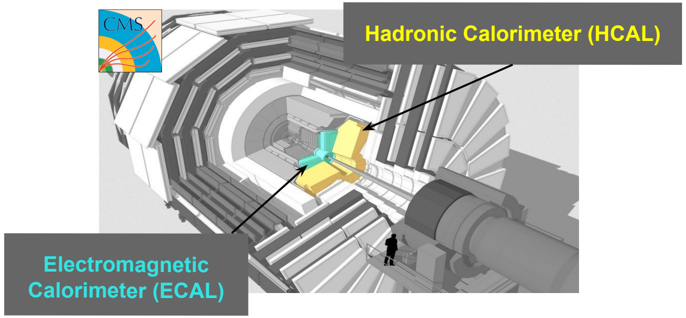
- To cope with the harsh environment of high-luminosity LHC (HL-LHC) run (from ~2027), the CMS collaboration will upgrade current endcap calorimeters with a highly granular calorimeter (HGCAL).

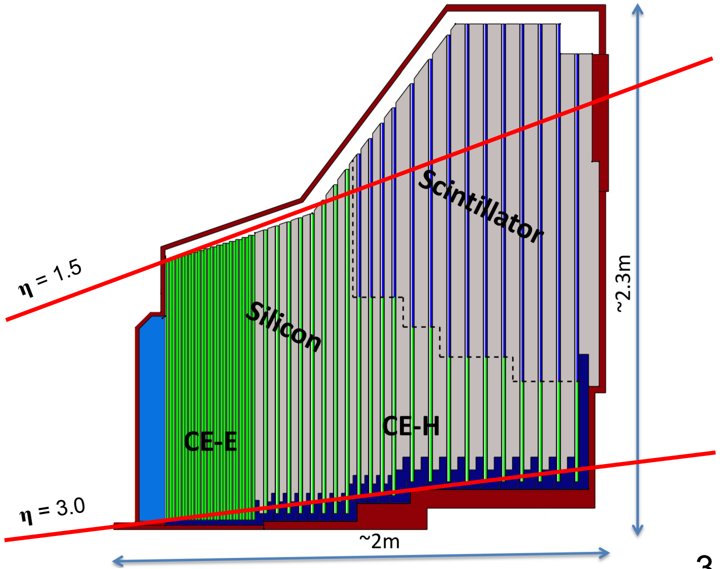
Active Elements:

- Electromagnetic part of HGCAL:
  - **CE-E** : Si sensors as active layers, Cu/CuW/Pb absorber
  - **28 layers, 25 X_0** and **~ 1.3 λ_{int}**
- Hadronic part of HGCAL:
  - **CE-H** : Si & **scintillator** as active layers, steel absorbers
  - **22 layers, ~ 8.5 λ_{int}**

➔ A prototype of Si-based CE-E and CE-H were built and tested along with CALICE AHCAL prototype, in the beam test experiments at H2 beamline, SPS CERN in October 2018.

➔ In this talk, I will present preliminary results for the performance of HGCAL+AHCAL combined prototype to hadronic showers.



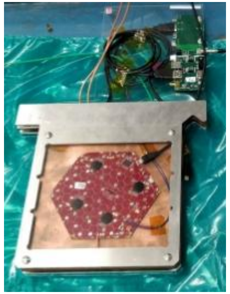


Longitudinal cross-sectional view

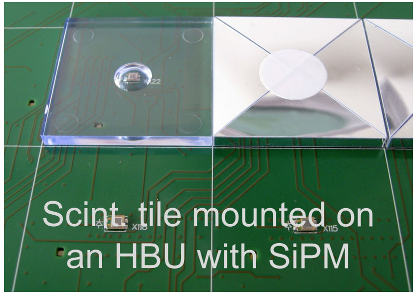
Beam test setup in experiment & simulation

Beam test setup in October 2018

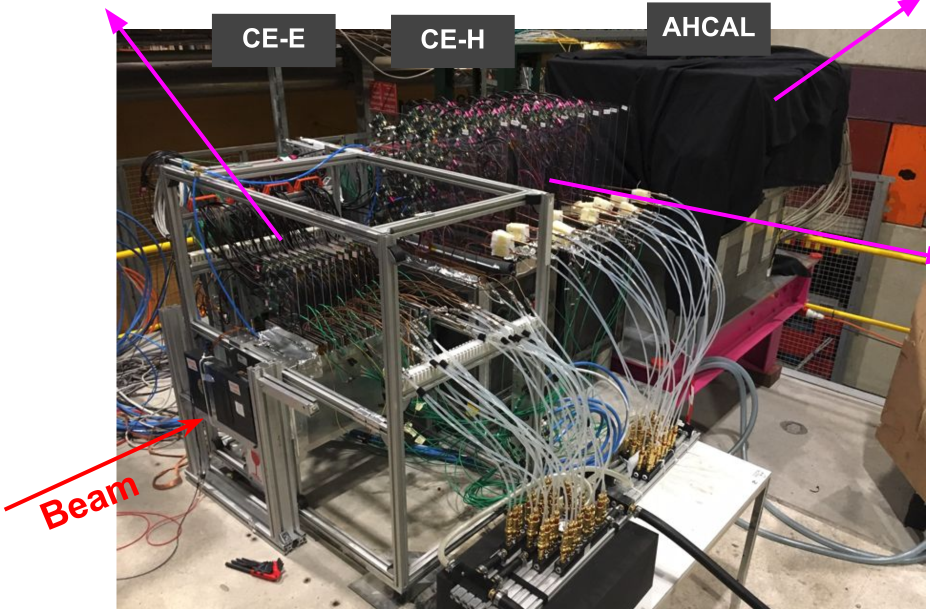
See [link] for more details

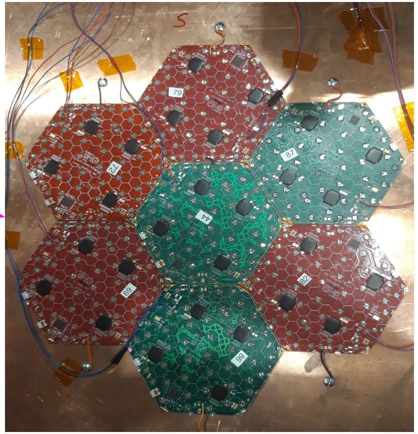


EM section: CE-E prototype
- Hanging file structure
- 28 sampling layer
- 14 double sided mini-cassettes
- **Pb/Cu/CuW absorber**
- **~ 28 X_0, 1.4 λ_{int}**



Had section: CALICE AHCAL prototype
- Scintillator-on-SiPM
- 39 sampling layers
- **Steel absorber**
- **~ 4.4 λ_{int}**





Had section: CE-H prototype
- Hanging file structure
- 12 sampling layers
- Modules arranged in daisy structure
- **Steel absorber**
- **~ 3.4 λ_{int}**

Si HGCAL protype: 94 sensor modules, ~12K channels
Scint AHCAL prototype ~22K channels

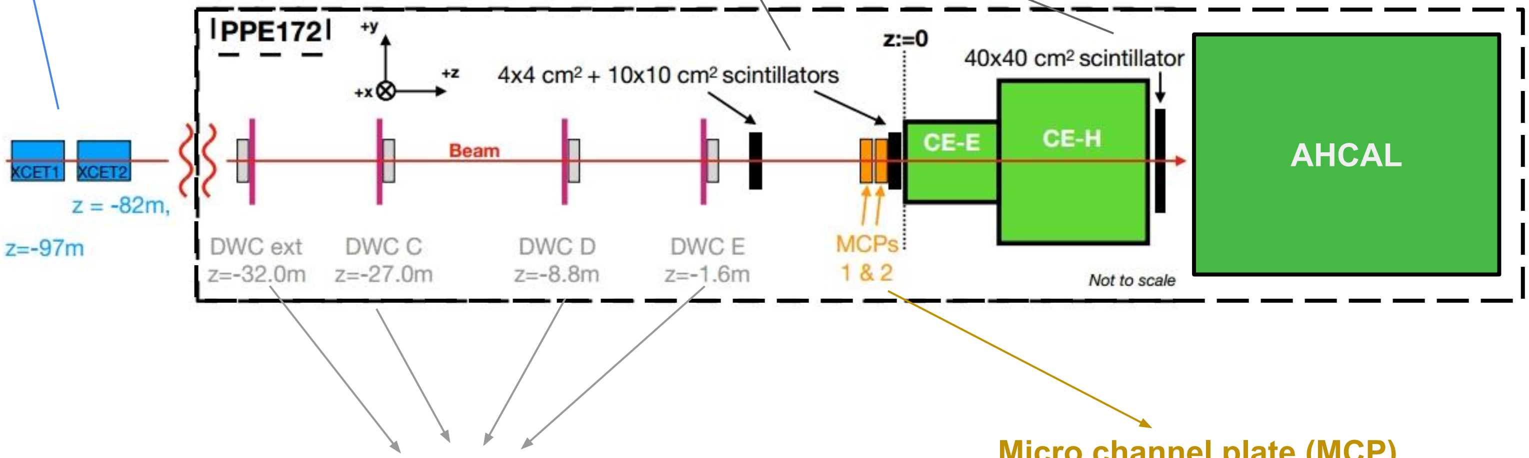
The setup was exposed to $\boldsymbol{e^+}$, $\boldsymbol{\pi^-}$ beam of energies ranging from 20 to 300 GeV and 200 GeV $\boldsymbol{\mu^-}$ beams.

Beamline detectors

Apart from HGCAL and AHCAL detector prototype, various detectors were deployed upstream the experimental setup to help in data taking operation & data analysis.

Cherenkov (XCET)
- For particle identification
- very low efficiency (<1%)
- Not used in any analysis

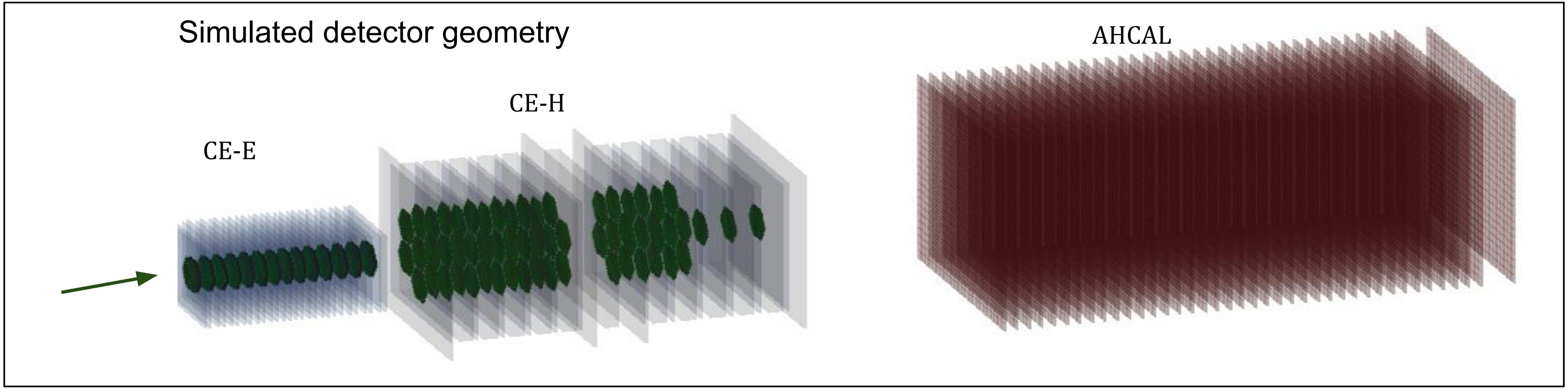
Scintillators
- To generate triggers for data taking
- Coincidence and veto triggering



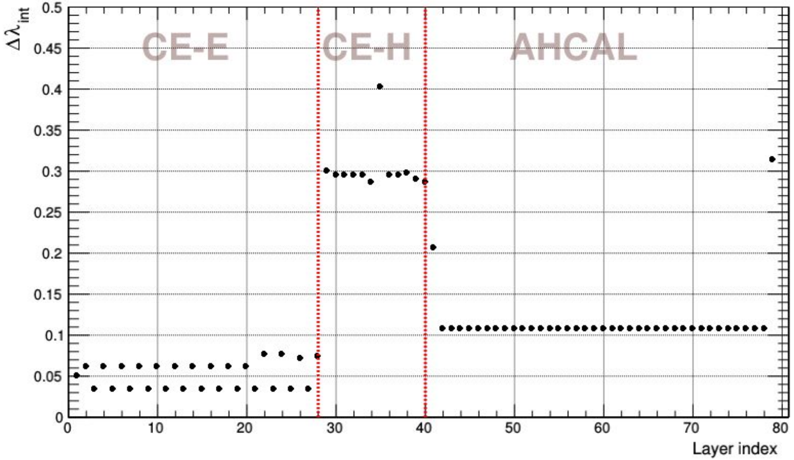
Delay wire chambers (DWC)
- For track reconstruction.

Micro channel plate (MCP)
- For timing reference.

Detector set up in GEANT4 simulation



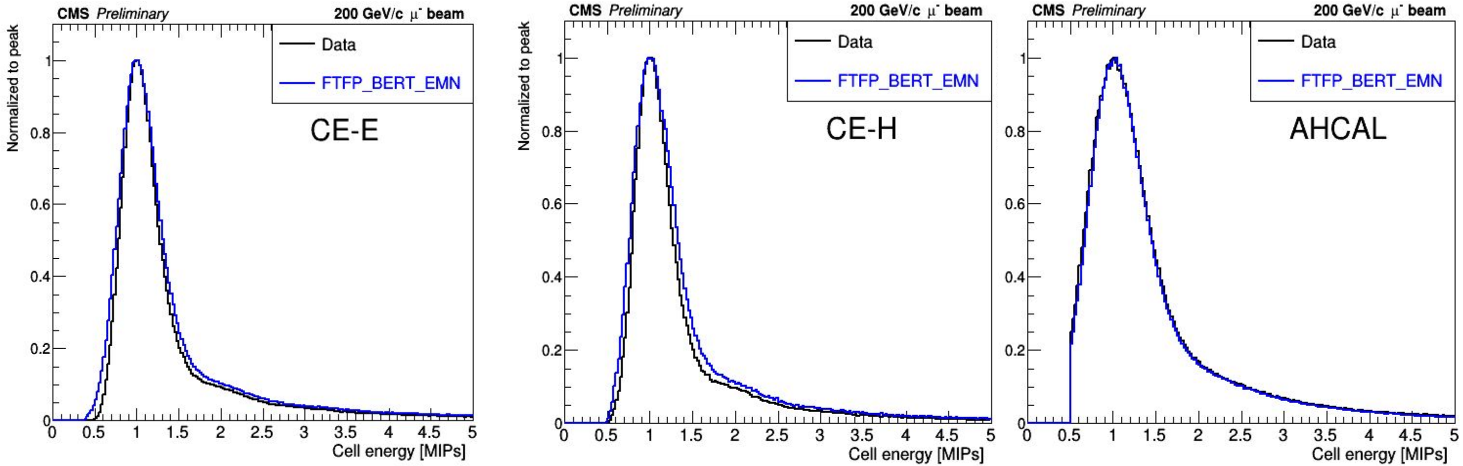
- Different sampling fractions CE-E, CE-H and AHCAL :
  - CE-E: 1.4 λ_{int} & $\Delta\lambda_{int}$~ 0.05 λ_{int}
  - CE-H: 3.4 λ_{in} & $\Delta\lambda_{int}$~ 0.3 λ_{int}
  - AHCAL: 4.4 λ_{in} & $\Delta\lambda_{int}$ ~ 0.1 λ_{int}
- The H2 beamline elements (quadrupoles, dipoles, collimators, other detectors) are simulated using G4Beamline package.
- ***π***$^-$ energies: 20, 50, 80, 100, 120, 200, 250, 300 GeV



Event reconstruction in data & simulation

Data-MC comparison at MIP level

- The starting point for pion analysis is the **energy reconstructed in terms of number of MIPs** using ***muons*** both in data and simulation.
  - More details about gain linearization & channel-to-channel calibration in data can be found in construction & commissioning paper: [2021 JINST 16 T04002](#).
- In CE-E & CE-H simulation, detailed electronics noise has not been simulated. Therefore, the MIP signal is smeared by a width of 1/6th of a MIP to account for electronics noise.
- AHCAL - reconstructed data (in terms of number of MIPs) & full simulation framework are provided by the CALICE collaboration.



Muon signal is reasonably well produced by simulation in all compartments

- The MIP signal peaks at 1 in both data and MC muon samples.
- There are minor differences in width in CE-E & CE-H which could be improved with realistic digitization.

Physics performance to hadronic showers

Data cleaning

- A set of cleaning cuts are applied to remove undesired events such as beam contamination, out-of-acceptance particle incidence etc.

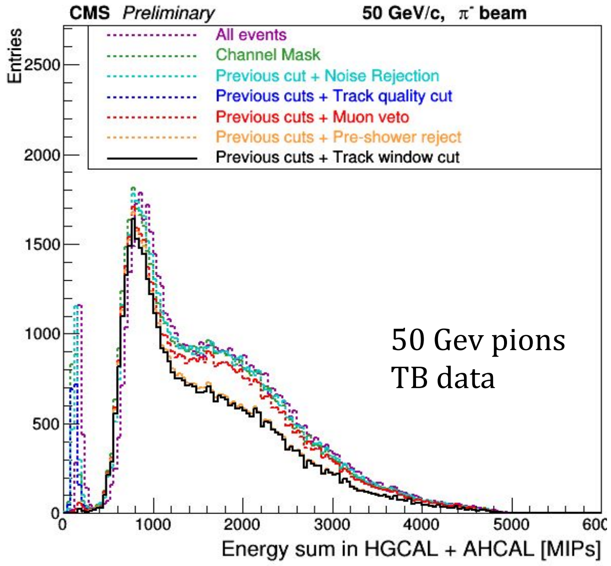
Applied per channel

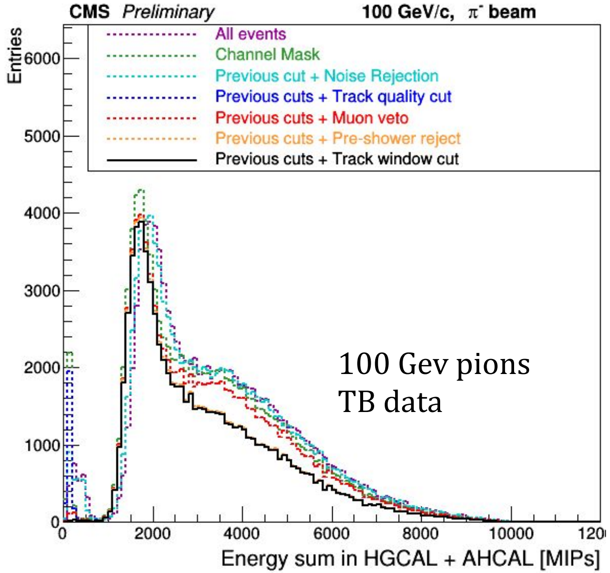
- **Channel masking:** Mask channel with H/W issues.
- **Noise rejection:** 3σ and 4σ noise rejection HG ADCs CE-E and CE-H prototype, respectively.

Applied per event

- **Track quality cut:** At least 3 hits out of 4 DWCs & χ^2/ndf of reco track < 10
- **Muon veto:** To reject muon contamination.
- **Track-window cut:** Reject events where incident particle out-of-acceptance i.e. it is way off-center.
- **Pre-showering pion rejection:** Rejects early showering pions (layer <=2).

- The effect of each cleaning cut is shown in following two plots for total energy sum (CE-E+CE-H+AHCAL) in data..





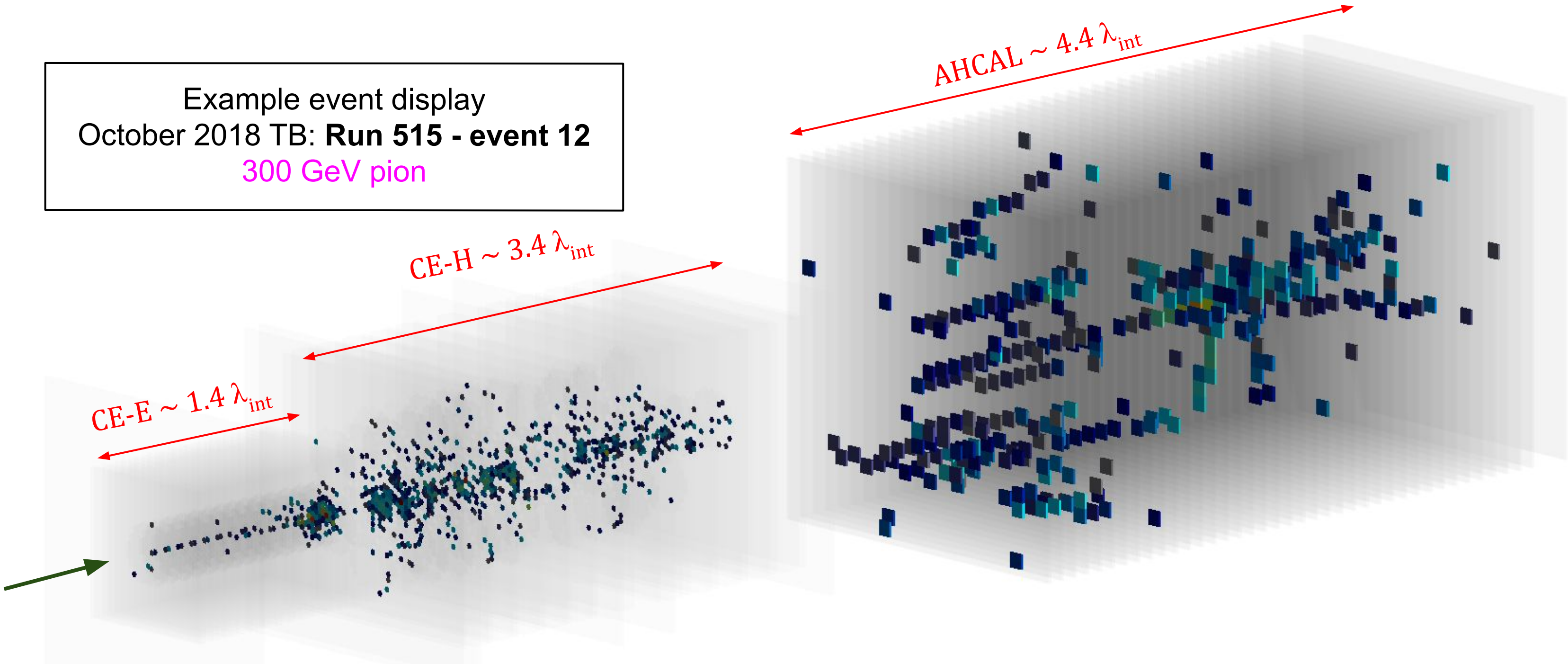
The cleaning cuts are applied on both data and simulation for consistency.

Depth of first hadronic interaction

(Shower start finder algorithm)

High granularity of CE-E and CE-H prototype allows us to develop an algorithm to identify the location of first hadronic interaction of pion where it initiates showering.

Example event display
October 2018 TB: **Run 515 - event 12**
300 GeV pion



Extraction of true first hadronic interaction

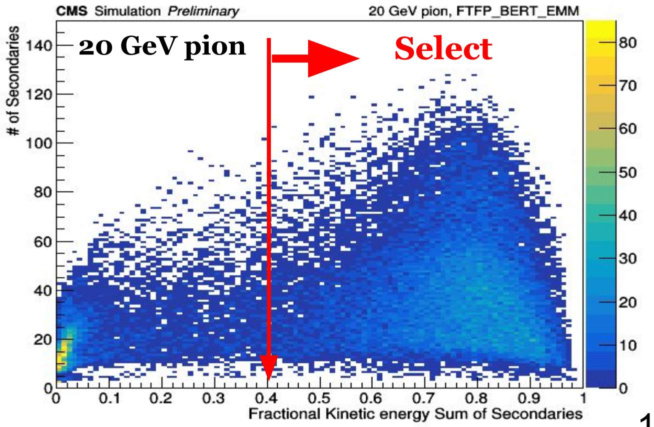
- The information of first hadronic interaction is extracted from Geant4 simulation package.

- The first hadronic interaction provided by truth information from simulation contains both "hard" hadronic interaction (where shower is initiated) as well as "soft" interaction (where shower is not initiated).

- For the optimization of this algorithm to be used in reconstructed data, we would like to select a sample of events where first hadronic interaction is a hard interaction.
  - In soft interactions, both number of secondaries and total fraction of energy carried by them is small.
  - We use these variables to select events with "hard" hadronic interaction.

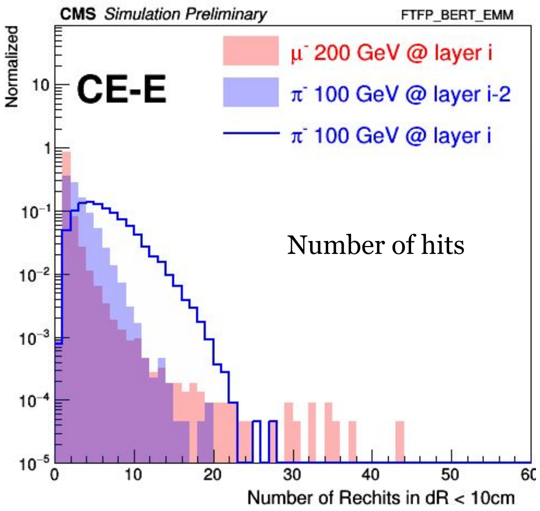
- Plot shows correlation plot of "Fractional kinetic energy carried by secondaries" vs "number of secondary particles" for 20 GeV pion.

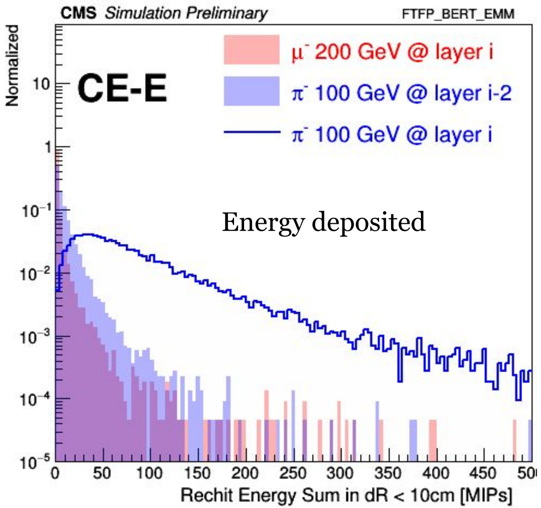
- **We select the events with total fractional energy carried by secondaries is more than 40% for the optimization of shower start finder algorithm.**

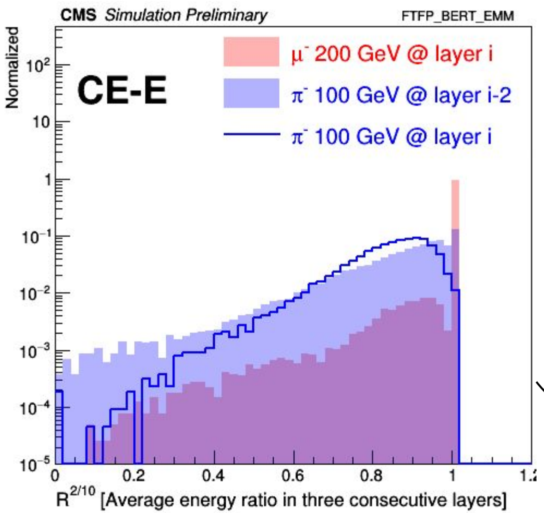


Algorithm optimization

- To identify the shower start location, we optimize the algorithm using number of hits, energy deposition and lateral shower spread.
- We use muons as a reference for differentiating against showering pions to optimize the thresholds on these observables.







Algorithm

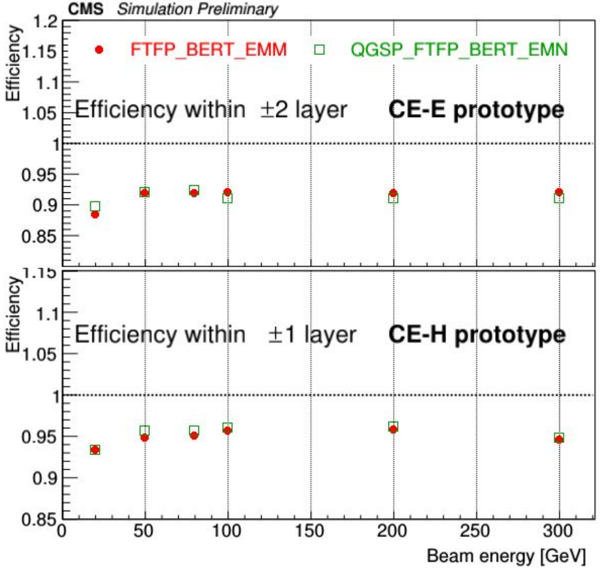
1. Compute $Nrechit^{10cm}\_i$, En^{10cm}_i and $R^{2/10}\_avg\_i$ at layer i
2. If ($Nrechit^{10cm}\_i > 3$ && $En^{10cm}\_i > E\_thres$ && $R^{2/10}\_avg\_i < 0.96$) ⇒ Shower started at layer i and Exit
3. If (i == End_of_HGCAL_layers) ⇒ Shower start not found and Exit, Else ⇒ Go to Next layer and repeat.

Lateral energy ratio

$$R\_avg^{i}_{(2/10)} = \frac{\sum_{j=i}^{i+2} En^{j}_{2cm}}{\sum_{j=i}^{i+2} En^{j}_{10cm}}$$

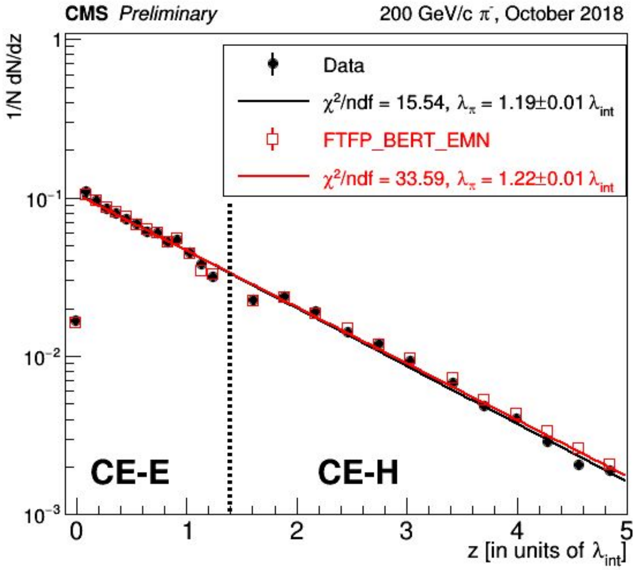
Efficiency of shower start finder algorithm

- The performance of the algorithm is assessed in terms of **efficiency** defined as **the fraction of events for which the predicted layer falls within ±n layers of GEANT4-true shower start layer.**
- Efficiency is compared for different GEANT4 physics lists.



- The algorithm shows consistent efficiency across all beam energies:
  - The efficiency is ≧ 90% & 95% for ±2 layers for CE-E and for ±1 layer CE-H prototype, respectively.

- When employed in beam test data it shows exponentially falling behaviour, as expected.
- Very well agreement with simulation.



Event categorization:

`If (Shower-start-layer <= 28)` := Showering in CE-E

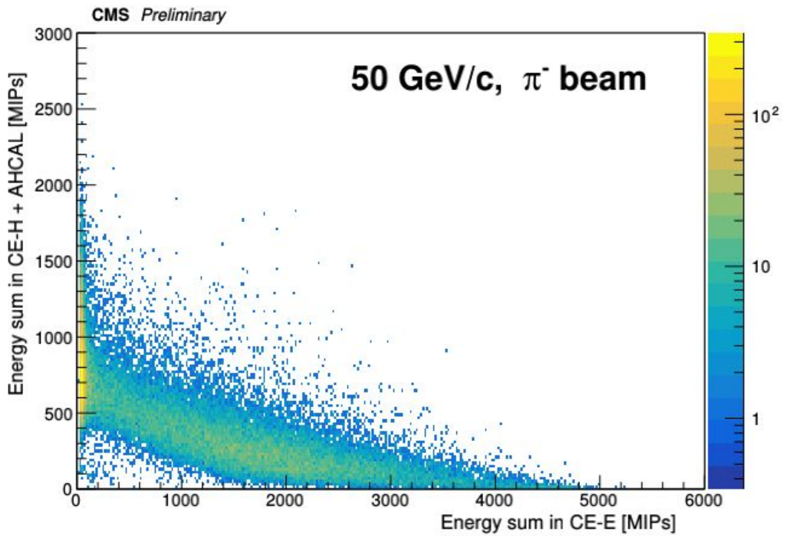
`Else If (Shower-start-layer > 28)` := MIPs in CE-E

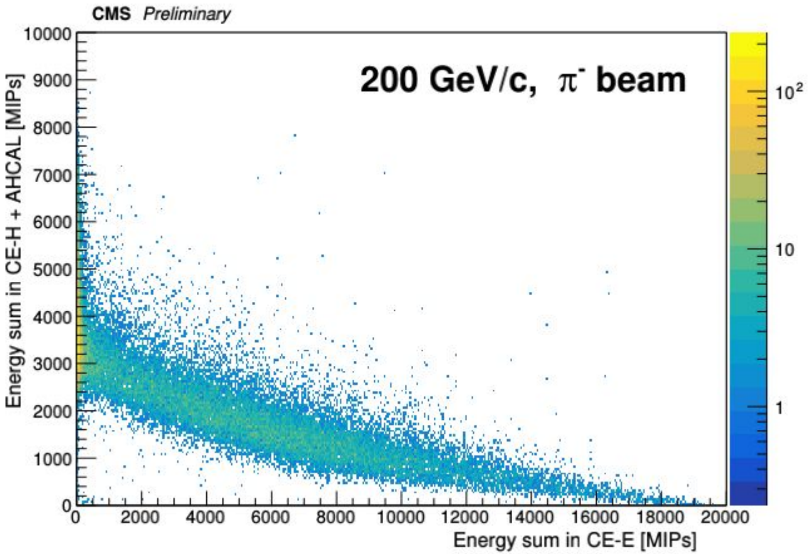
`Else`: Reject events

Energy reconstruction of pions

Energy reconstruction of pions

- Energy deposited by pion showers, is shared between the electromagnetic and hadronic sections.
  - CE-E is 1.4 $\boldsymbol{\lambda}_{int}$ & >70% pions start showering in CE-E.





- We use two methods to combine energies measured in terms of MIPs in different detectors.
  - In the first method, we use only calorimeter based calibration i.e. use 50 GeV e^+ to set MIP-to-GeV energy scale for CE-E and 50 GeV pions to set MIP-to-GeV energy scale for CE-H & AHCAL.
  - In the second method, we optimize the total energy measurement using a χ^2 minimization based method (to compensate for the non-linear response of the calorimeter).

MIP-to-GeV conversion factors

Pion shower energy reconstruction:

Showering in CE-E:

$E^{measured}$ [in GeV] $= \alpha^{fix} * E^{CE\text{-}E}_{[MIPs]} + \beta^{fix} * (E^{CE\text{-}H}_{[MIPs]} + \gamma^{fix} * E^{AHCAL}_{[MIPs]})$

MIPs in CE-E:

$E^{measured}$ [in GeV] $= \beta^{fix} * (E^{CE\text{-}H}_{[MIPs]} + \gamma^{fix} * E^{AHCAL}_{[MIPs]})$

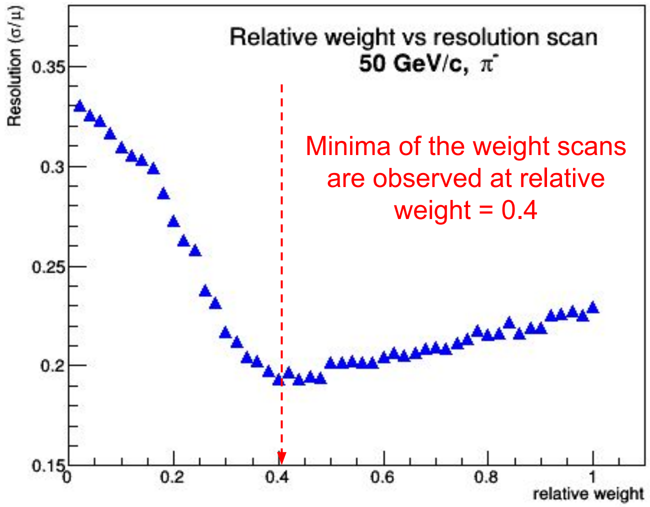
For CE-E:
α^{fix} = **10.6 MeV/MIP** using 50 GeV e^+

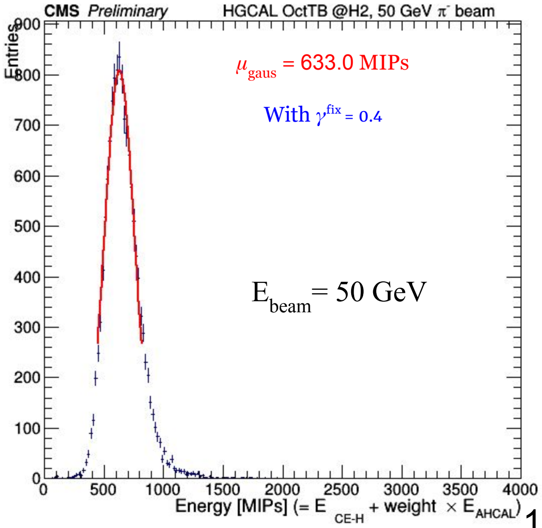
For CE-H + AHCAL:
β^{fix}= **78.9 MeV/MIP** using 50 GeV π^-

γ^{fix} = *relative_weight* between CE-H & AHCAL = **0.4**

To find energy scale CE-H+AHCAL, we use 50 GeV pions which are MIPs in CE-E.

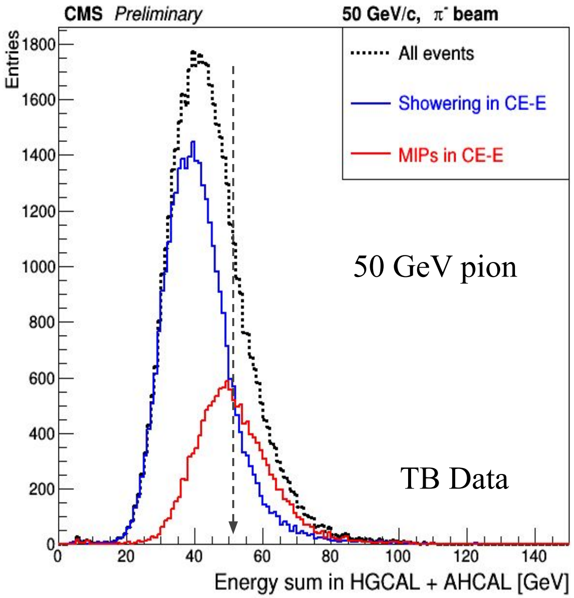
- Since the sampling fraction of CE-H and AHCAL are different therefore it is important to introduce a relative weight factor.
  - Relative weight between CE-H & AHCAL (γ^{fix}) is obtained by minimizing resolution (scan over different values of weight).
- After fixing this γ^{fix}, find overall MIP-to-GeV (β^{fix}) for CE-H+AHCAL.

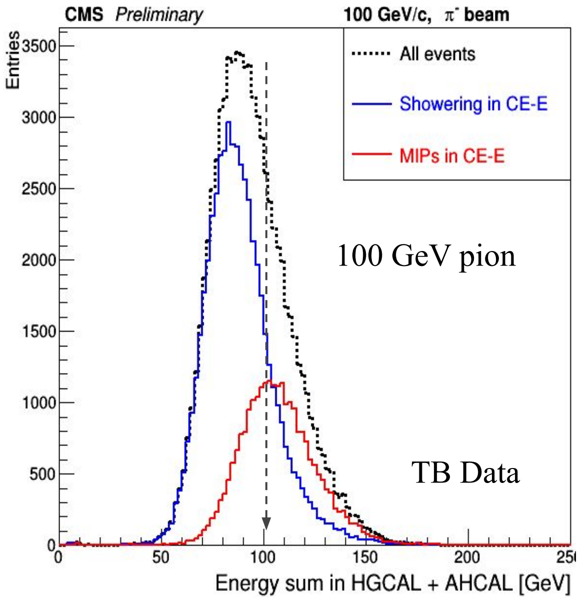




Pion energy distributions - method 1 [fixed weights]

- Using these weights, we obtain energy distribution for pions of all beam energies.
- Following two plots show energy distribution for pions MIPs & showering in CE-E as well as inclusively for 50 & 100 GeV pions.

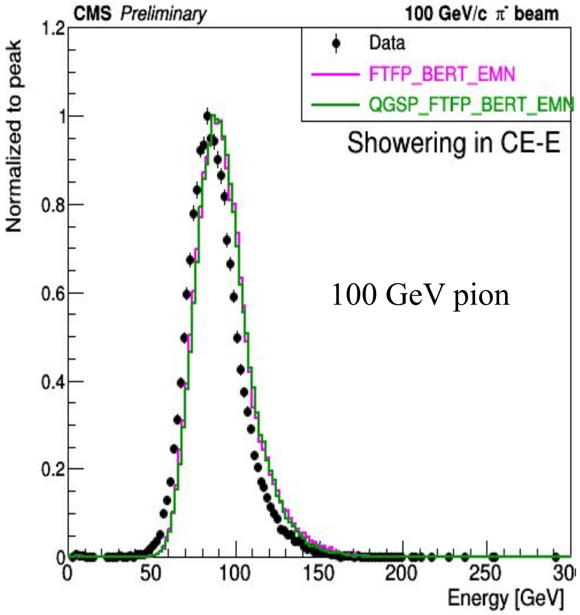


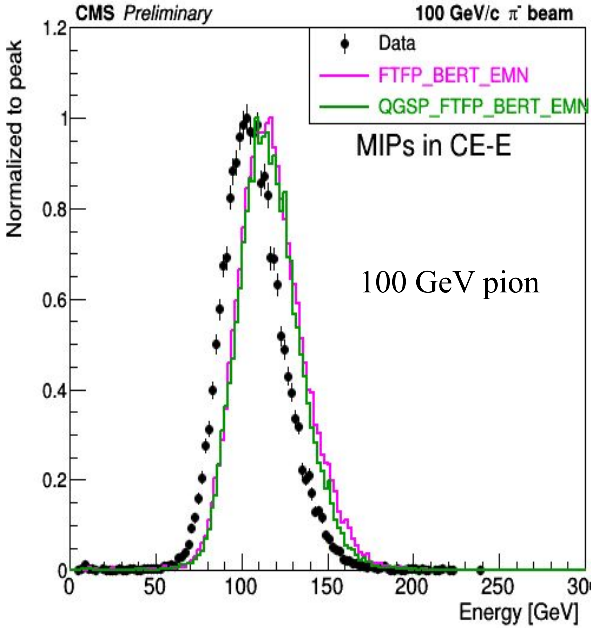


- Distribution for pions that start showering in CE-E peaks at a lower energy:
  - Because it uses CE-E energy, which is calibrated using EM shower and e/h > 1 for CE-E.

Distributions comparison in data & MC

- **Using the same α^{fix} , β^{fix}, γ^{fix} obtained from the data**, we compare energies measured in simulation with that in data.
- Plots show comparison between data and simulation for 100 GeV pions that start showering and that are MIPs in CE-E.



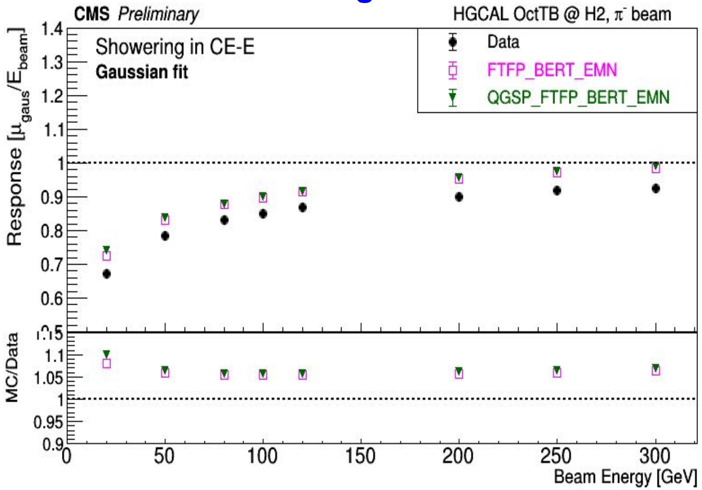


- The energy distribution shape is reproduced well by simulation.
- However, simulation distribution is shifted towards higher response.
  - We check this for other energies in terms of response by fitting a Gaussian function around the core of the energy distribution.

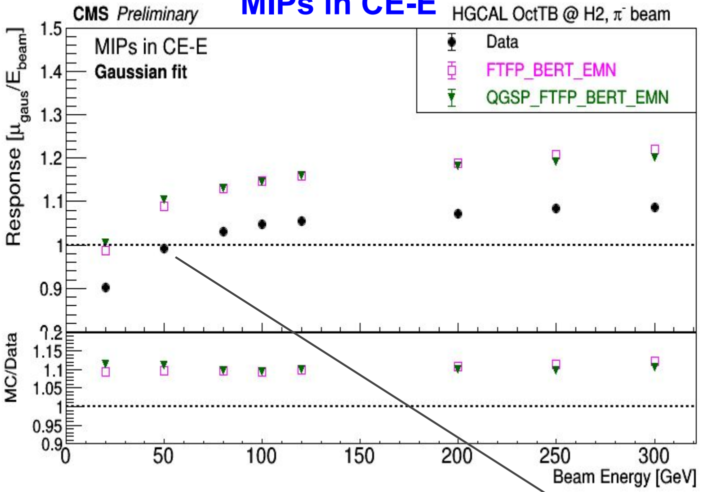
Energy response [fixed weights]

- Energy response (μ_{gaus}/E_{beam}) for data and simulation as a function of beam energy for pions that start showering in CE-E and MIPs in CE-E.

Showering in CE-E



MIPs in CE-E



By construction, energy response lies at 1 for 50 GeV pions that are MIPs in CE-E.

- Comments:
  - The detector response is non-linear as a function of beam energy:
    - Such non-linearity is expected for a non-compensating calorimeter.
  - Energy response for simulation is higher than data for all energies.
    - To match the energy scale, simulation energy in CE-E **(by 3.5%)** and in CE-H+AHCAL **(by 9.5%)** is globally scaled down.

Optimization of energy reconstruction of pions
Method-2

χ^2 optimization of weights

- The energy response can be linearized by obtaining energy-dependent weights using chi2-minimization.

- For pions showering in CE-E (EH pions):
  - E^{corr} [in GeV] = $\alpha_1(E_{beam})$ * $E^{CE\text{-}E}_{fix}$ + $\beta_1(E_{beam})$ * $E^{CE\text{-}H}_{fix}$ + $\gamma_1(E_{beam})$ * E^{AH}_{fix}

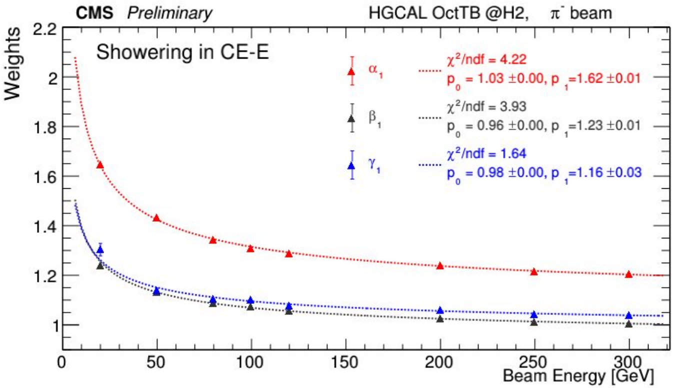
- For pions MIPs in CE-E (H pions):
  - E^{corr} [in GeV] = $\beta_2(E_{beam})$* $E^{CE\text{-}H}_{fix}$ + $\gamma_2(E_{beam})$ * E^{AH}_{fix} + 0.4 GeV

- Construct and minimize $\chi2$ analytically to obtain the weights.
  - CE-E/CE-H/AHCAL energy is already set to GeV with fixed weights.
  - σ(E) is the uncertainty in the measured energy obtained with fixed-weights.
  - 0.4 GeV offset corresponds to MIP track energy deposit in CE-E.

$$\chi^2 = \sum_{pions} \frac{(E_{beam} - E^{EH}_{corr})^2}{\sigma^2(E)}$$

$$\frac{\sigma^{EH}(E)}{E} = \frac{139\%}{\sqrt{E}} + 8.4$$

$$\frac{\sigma^{H}(E)}{E} = \frac{125\%}{\sqrt{E}} + 8.9$$

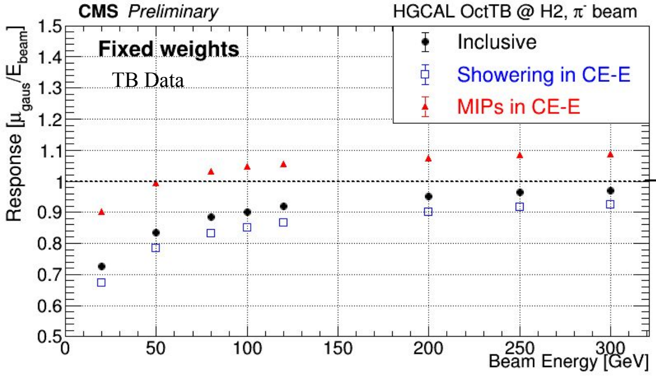


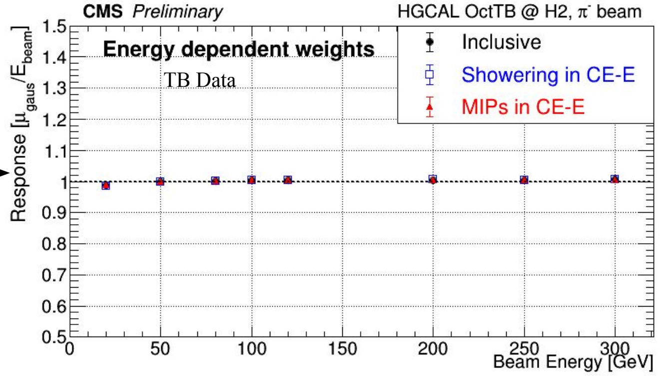
- **The weights are determined using TB data** and are applied on both data and simulation.

- In the real experiment, track momenta is taken as a reference to extract energy-dependent weights.
  - For neutral hadrons or beyond tracker coverage, calorimeter energy measured using fixed weights (method-1) is taken as a reference.
  - We fit the weights with a polynomial function, and evaluate the weights from the fitted function.

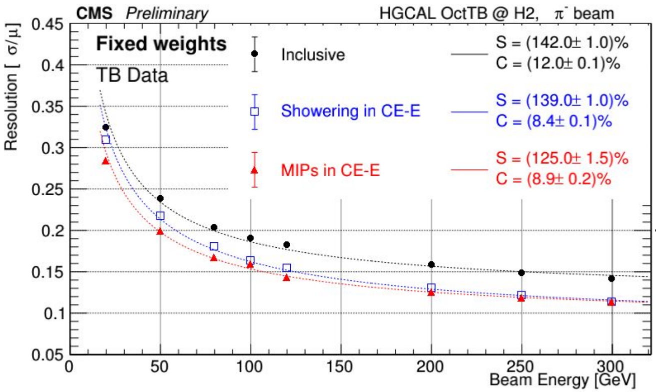
Optimized energy reconstruction

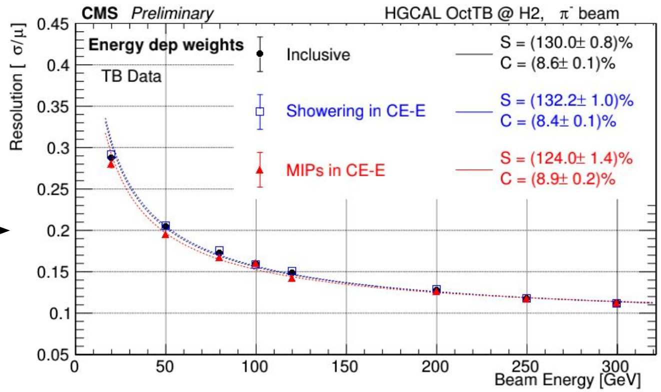
Energy response becomes linear application of E-dep weights.





- ~6% improvement at lower energies for pions showering in CE-E.
- Almost no change for MIPs in CE-E.
- Resolution for all categories becomes almost equal.

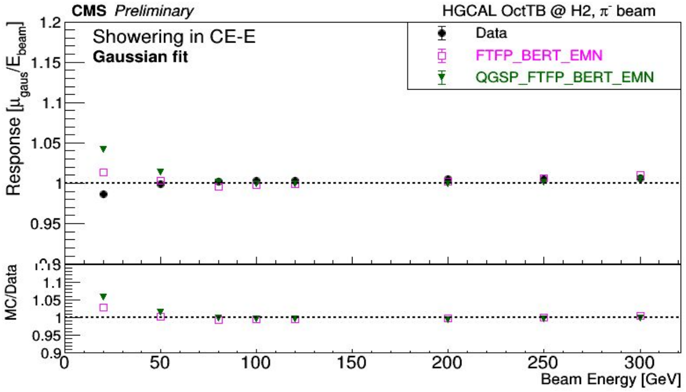


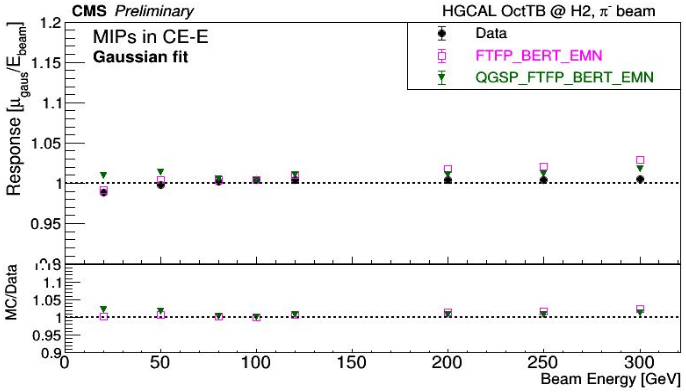


Similar improvement is observed in MC as well (see backup).

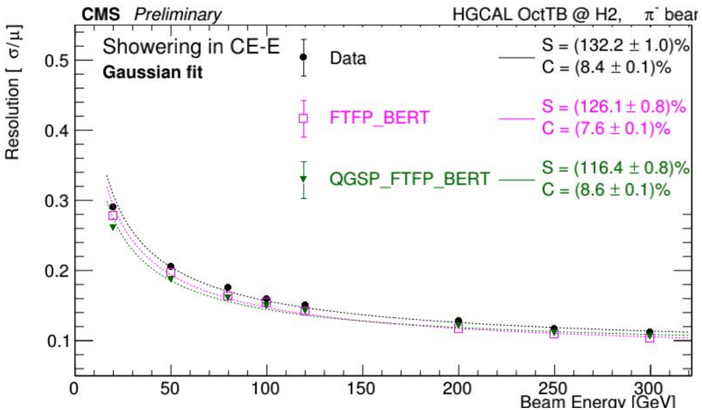
Response and resolution data-MC comparison

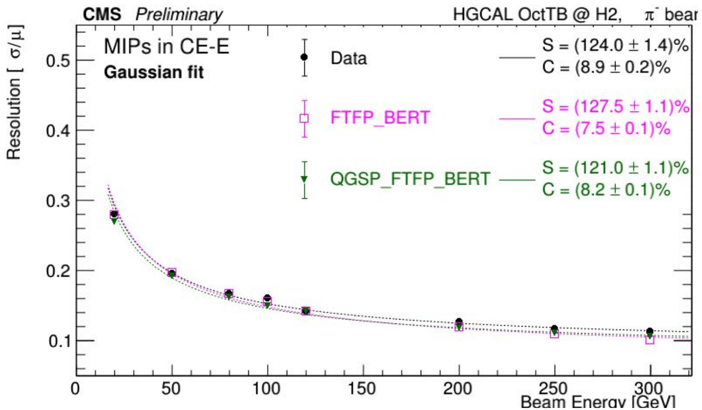
- Response and resolution is compared between data and simulation with both physics lists after applying optimized weights as shown below. (**Energy rescaling is applied on MC to match data.**)





Response: Agreement within ~5% between data and MC.





Resolution

- **Showering in CE-E:** Better agreement at higher energies & slight difference at lower energies. Overall agreement 1- 10% at low energies .

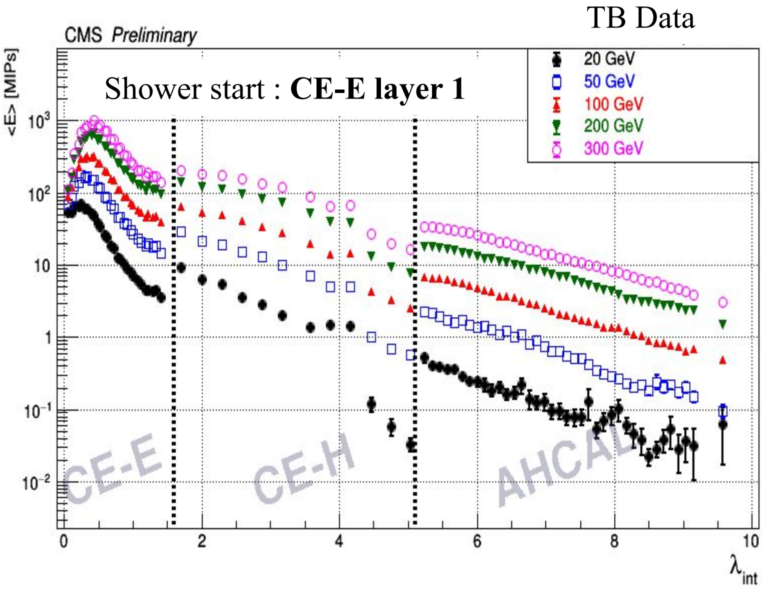
- **MIPs in CE-E:** Better agreement at higher energies & slight difference at lower energies. Overall agreement within 10%.

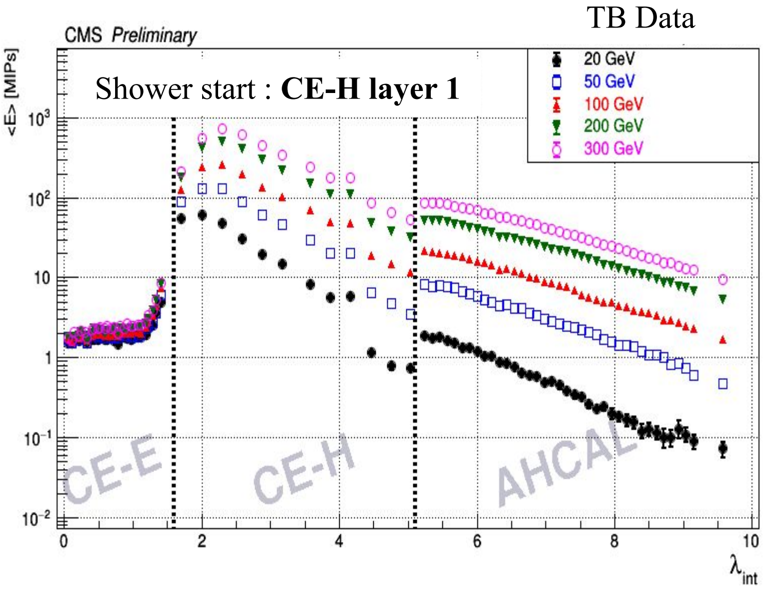
Shower shapes

Longitudinal shower Shapes

Longitudinal shower development

- The longitudinal shower shapes for is studied in terms of **mean energy deposited** (in MIPs) as a function of calorimeter depth (λ_{int}) as shown in following two plots.

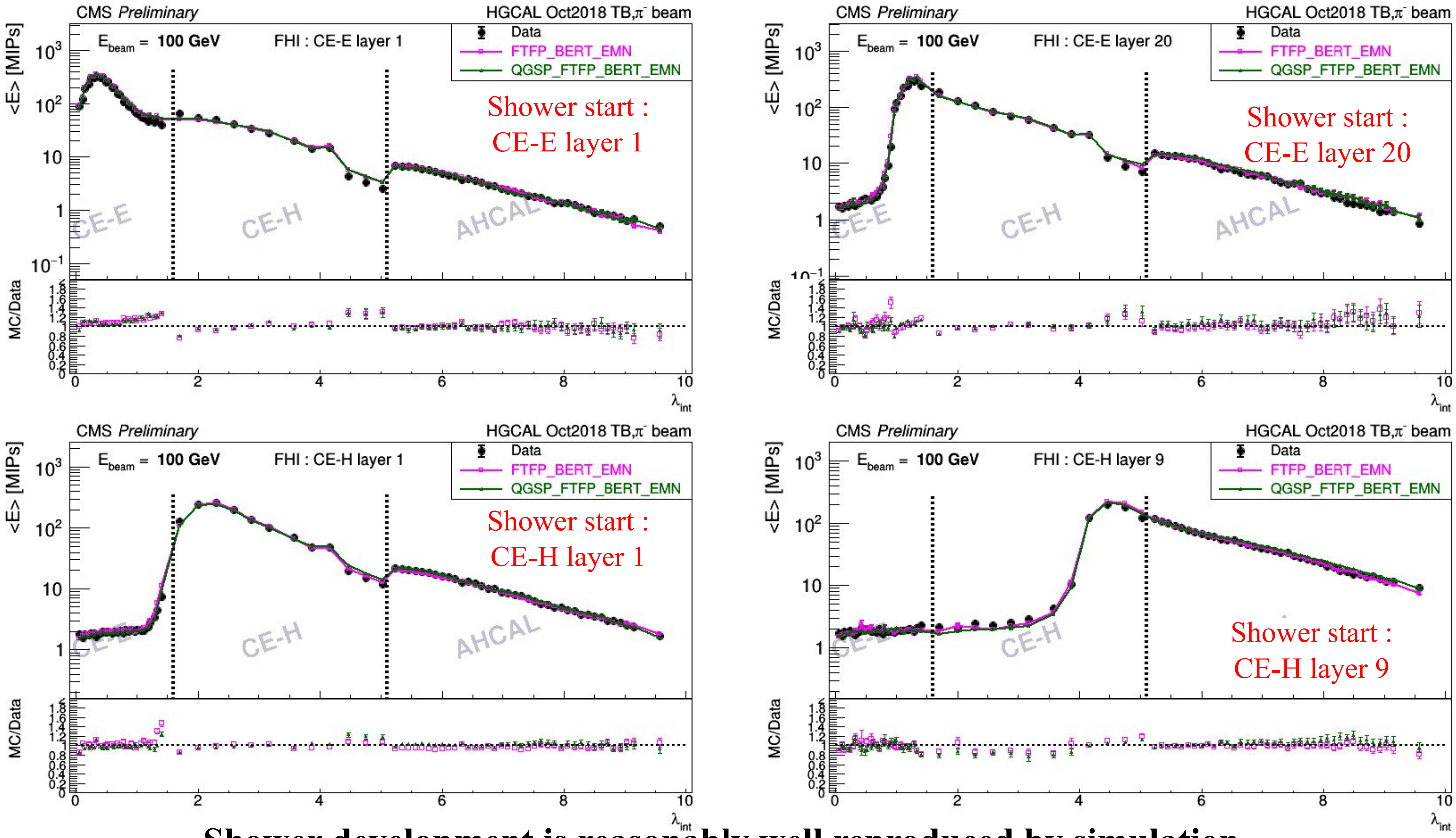




- For higher beam energy, the peak shifts slightly towards right.
- Last three points in CE-H show dip: Due to 1 module per layer.
- The shower peaks rather early (< 0.5 λ_{int}) in CE-E for early showering pions.
  - Our studies with Geant4 truth-level information shows that this peak corresponds to EM component (π^0) of hadronic shower.

Longitudinal shower shapes (Data-MC comparison)

Mean energy deposited (in MIPs) as a function of calorimeter depth (λ_{int}) for **100 GeV pions**.



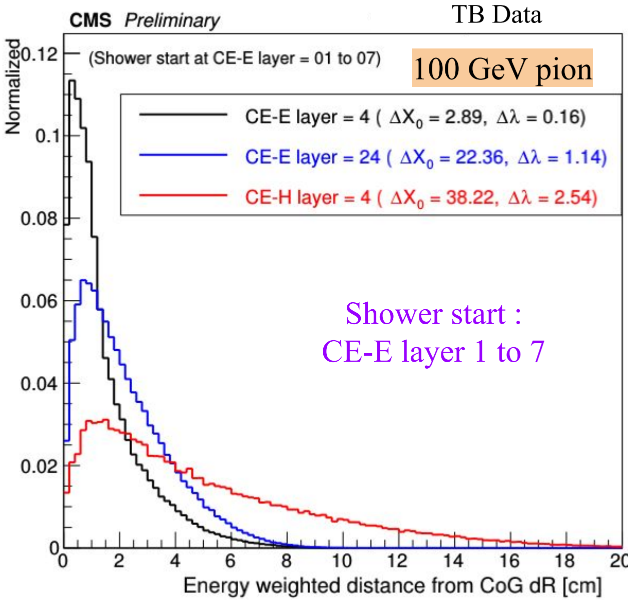
Shower development is reasonably well reproduced by simulation.

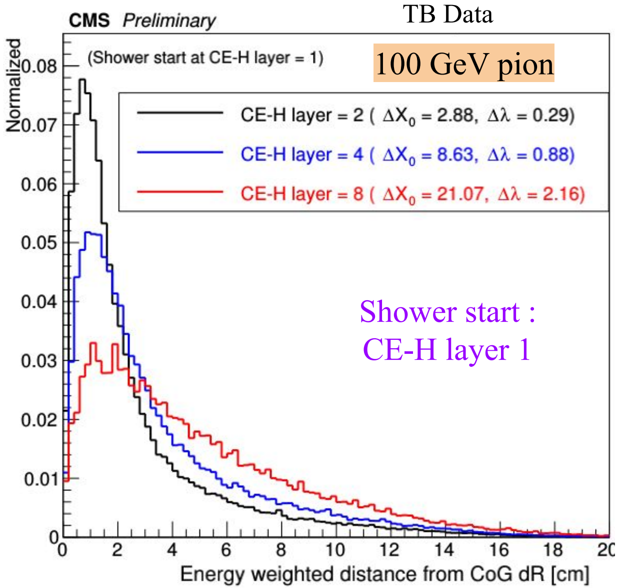
Shower shapes

Transverse shower shapes

Transverse shower shapes

- Transverse shower shapes are studied in terms of **energy weighted distance ($dR^{weighted}$)** from the center of gravity at layers downstream of shower start location.
- Following two plots show $dR^{weighted}$ distribution at layers downstream of shower start location.

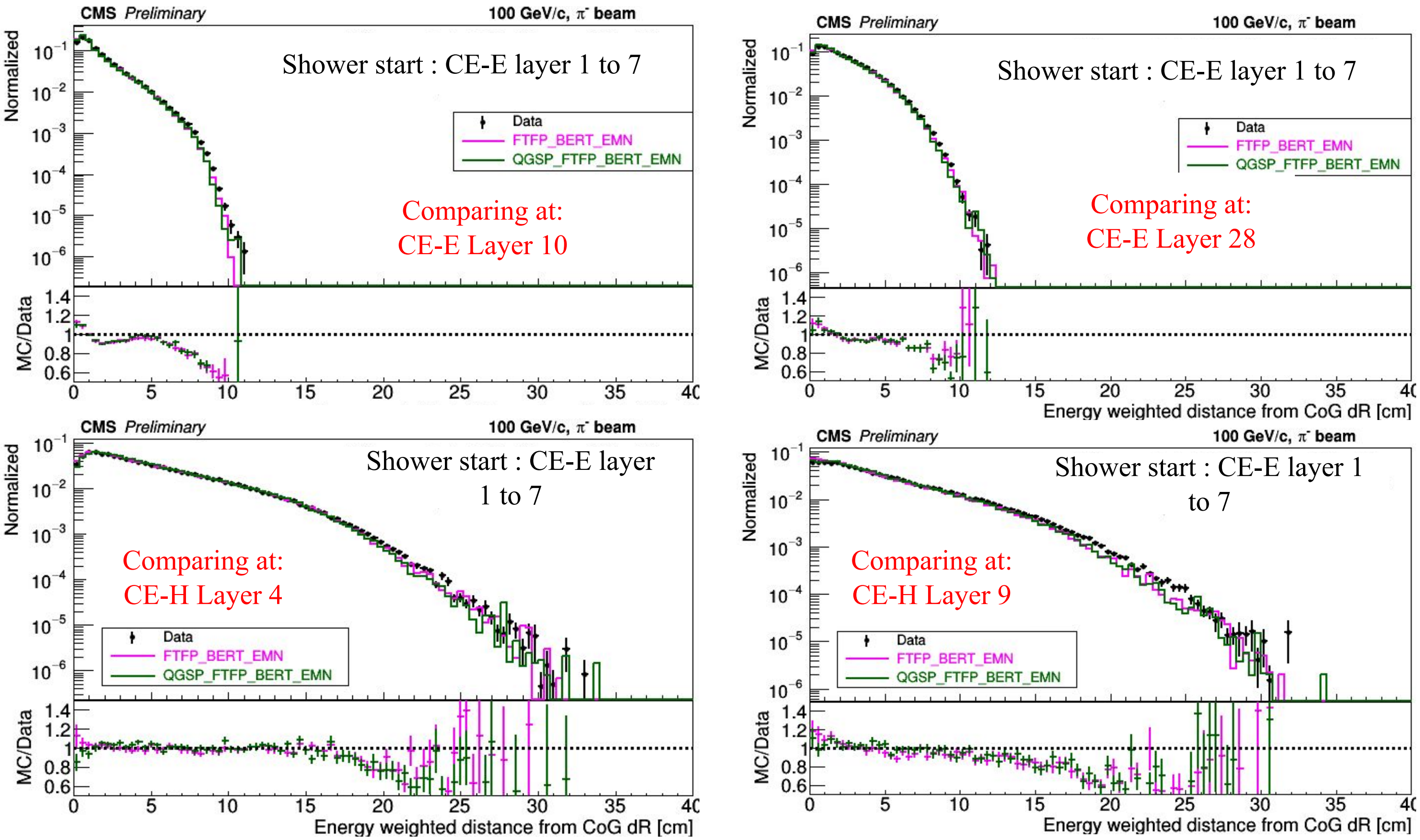




- **Comments:**
  - Transverse distribution for the initial layers of SS shows a very narrow spread.
  - Lateral spread in later layers is considerably larger.
- The narrow spread in energy weighted distance distribution for early layers, seems to be consistent with EM core of the hadronic shower with a hadronic halo.
  - We are making further checks on this front.

Data MC comparison for transverse shower shapes

Transverse shower shape comparison for **100 GeV/c** pions at different downstream layers of shower start.



Early layers in the shower development shows slight disagreement.

Data-MC agreement is reasonably well at later stage of shower development.

Summary

- The beam test experiments were conducted using HGCAL & AHCAL prototype at H2 SPS, CERN during October 2018.
  - Two papers concerning DAQ (2021 JINST 16 T04001) and construction & commissioning (2021 JINST 16 T04002) of HGCAL prototype has been published in JINST.
  - Another paper concerning performance of HGCAL prototype to EM showers using e^{+} beam test data, is under review with the CMS editorial board.

- The results for pion beam test data with combined HGCAL+AHCAL prototype, are being finalized.

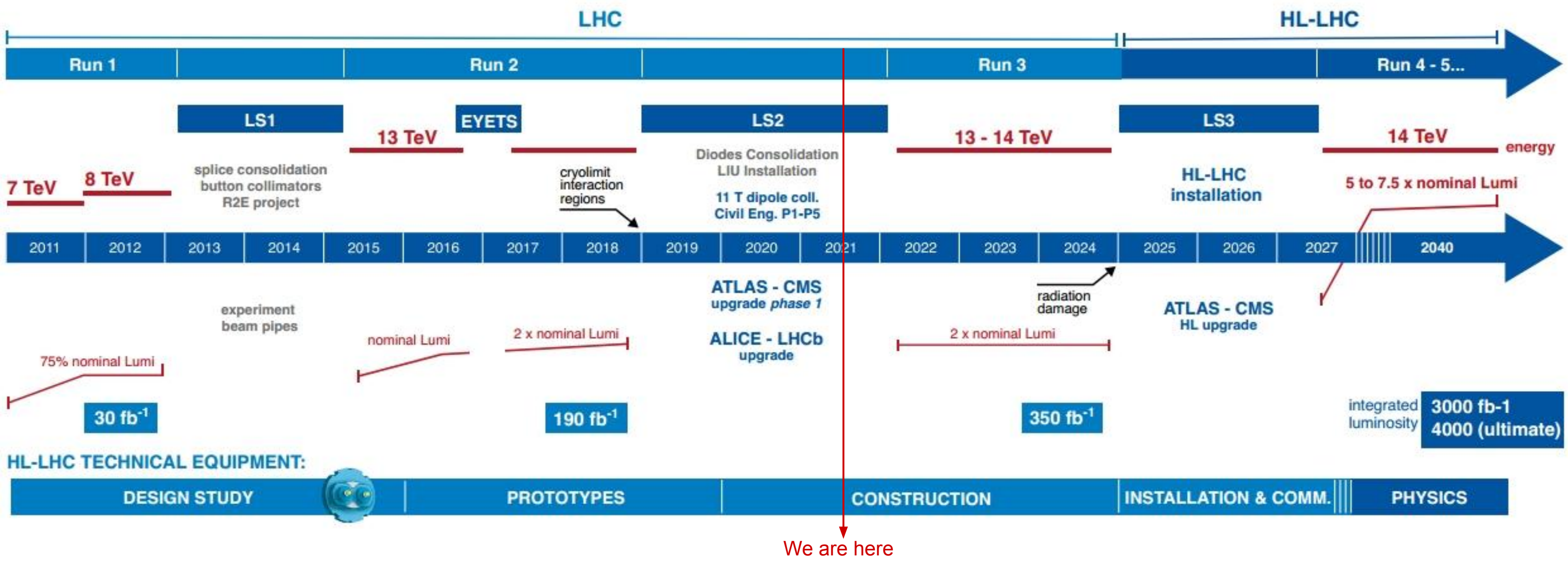
- This is going to be the first performance results for HGCAL prototype using pion beam test data.

- We are preparing a manuscript for the pion analysis paper to submitted to CMS editorial board.

Thank you.

Backup slides

High Luminosity Large Hadron Collider (HL-LHC)



HL-LHC run is expected to start around 2027.
HL-LHC will deliver 10x more integrated luminosity than LHC over 10 years of operation.

Advantages

More Statistics for:

- Higgs and other SM precision measurements
- Searches for Beyond SM physics

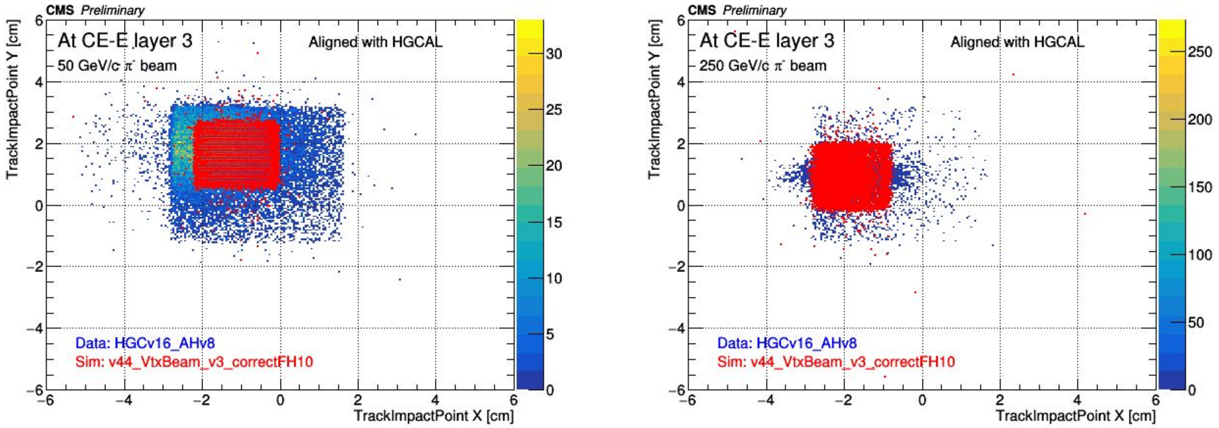
Challenges

- Very high radiation dose
- High pile-up condition
    - <PU> ~ 140 - 200 per bunch collision

Pion dataset in data & simulation

- π^- data : 20, 50, 80, 100, 120, 200, 250, 300 GeV pions
  - ~70-120k events in data and ~100k events in simulation
- μ^- beams - 200 GeV in data and simulation, ~100k events

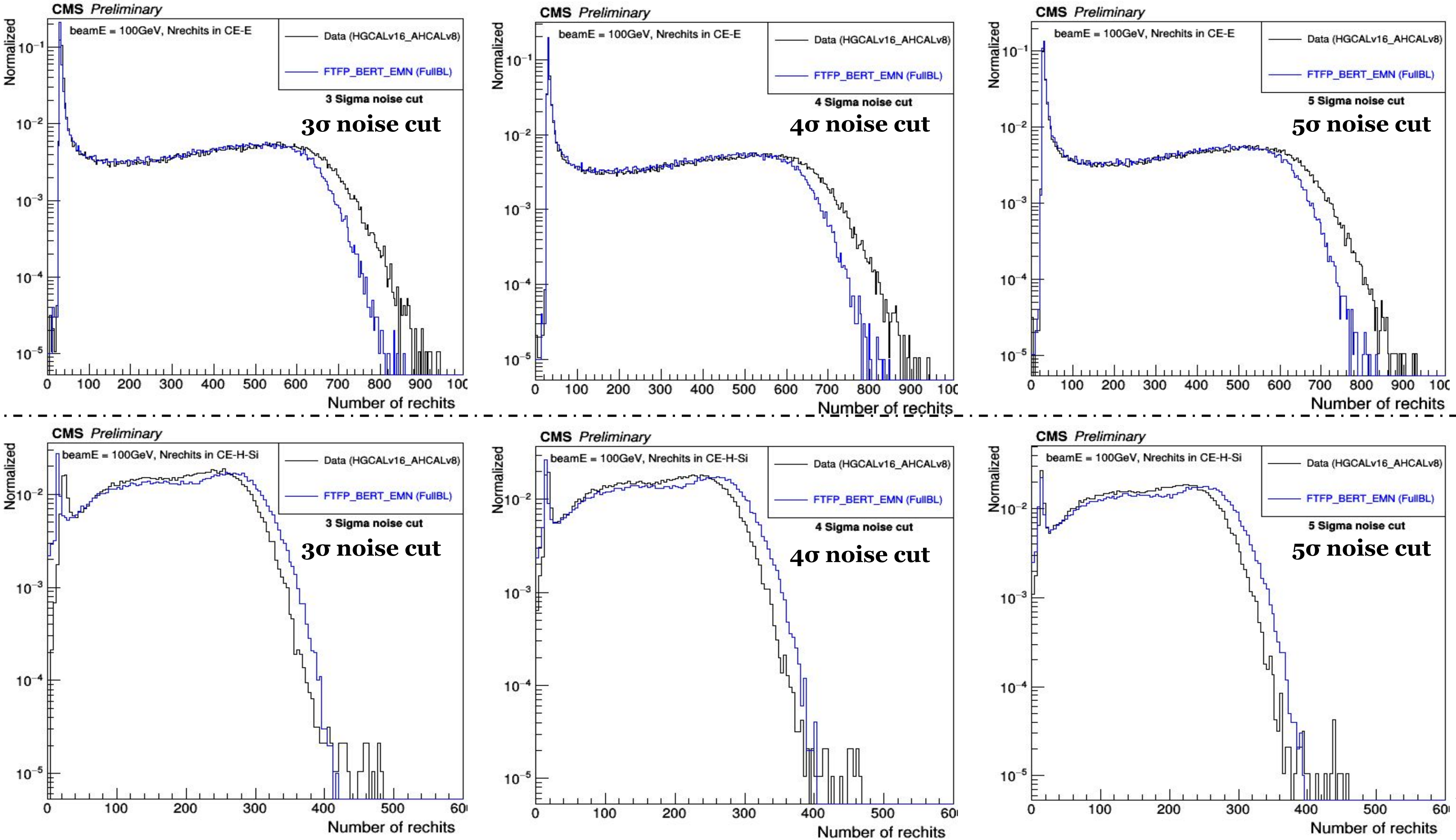
- Data: tracks reconstructed using DWC are extrapolated to find impact point in various active layers
- Sim: the particles are extrapolated using production vertex and DWC coordinates.



100 GeV pion **Number of reconstructed hits** with varying noise-threshold

CE-E

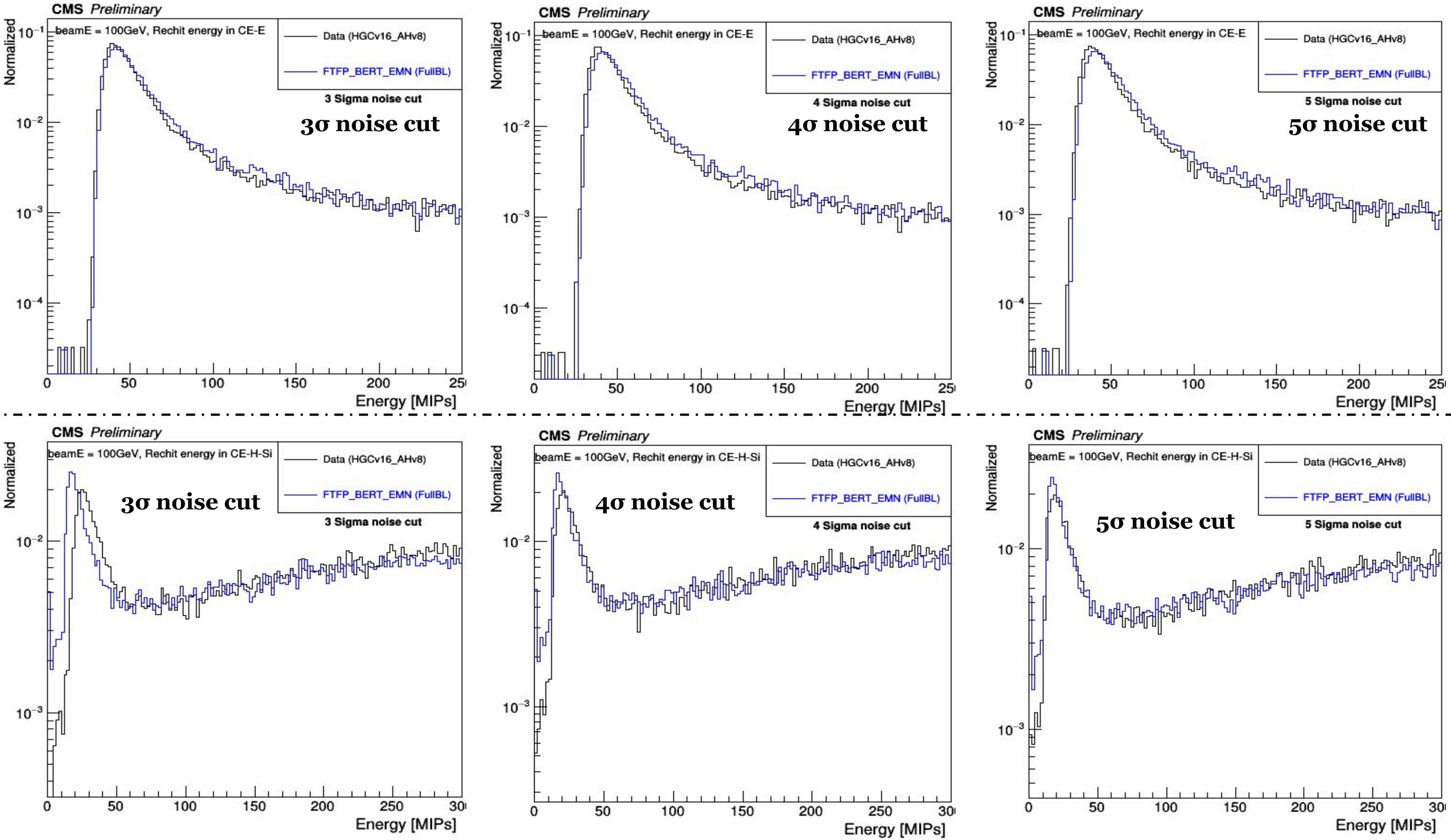
CE-H-Si



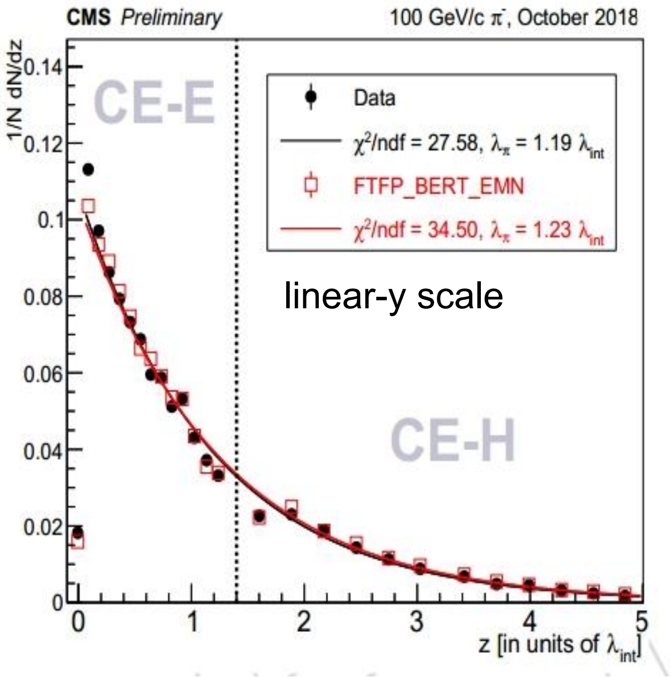
100 GeV pion **Reconstructed energy** near MIP with varying noise-threshold

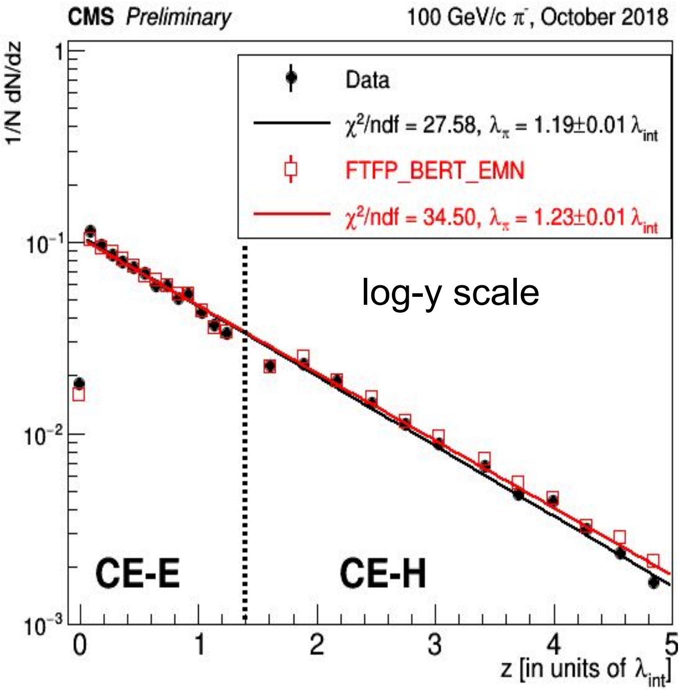
CE-E

CE-H-Si



Shower start finder algorithm

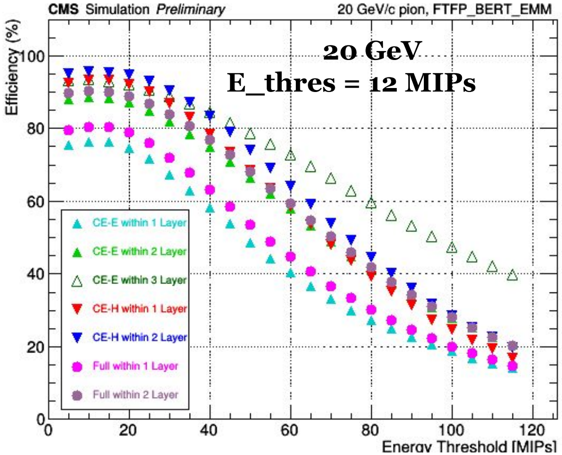


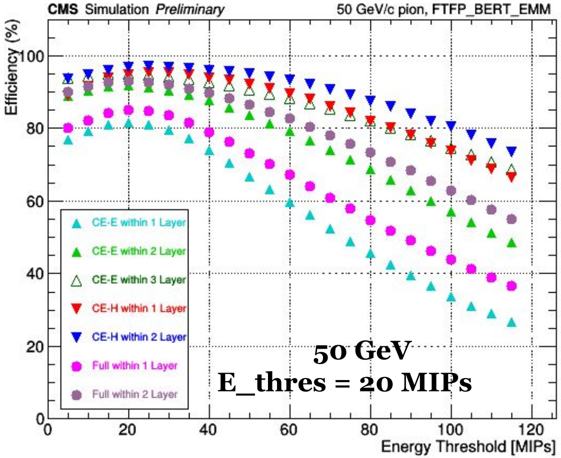


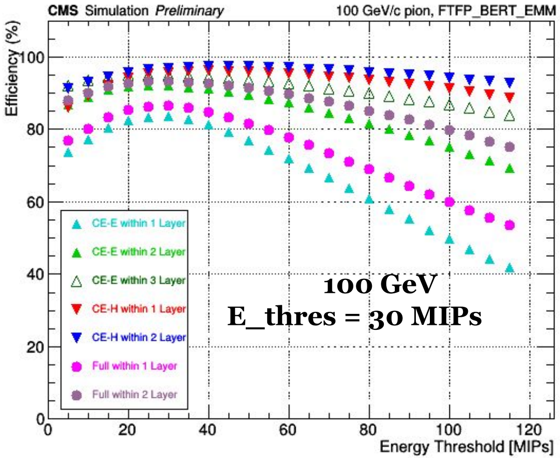
- Total cross section (σ_{tot}) for **pp** in fixed target experiment at 100 GeV is 38 mb.
- Total cross section (σ_{tot}) for **πp** in fixed target experiment at 100 GeV is 24 mb.

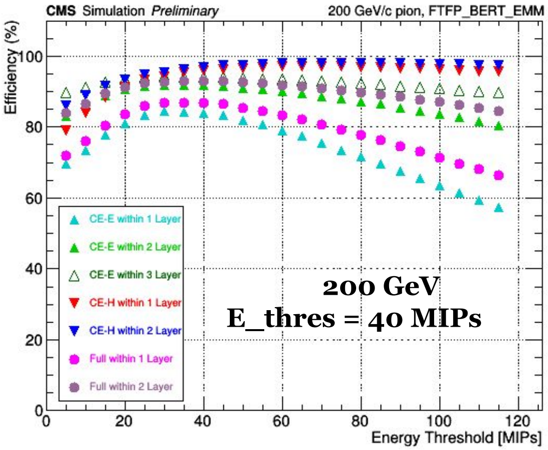
$$\lambda_{int} = \frac{A}{N_A \sigma_{tot}}$$

E_thres scan values for different energies



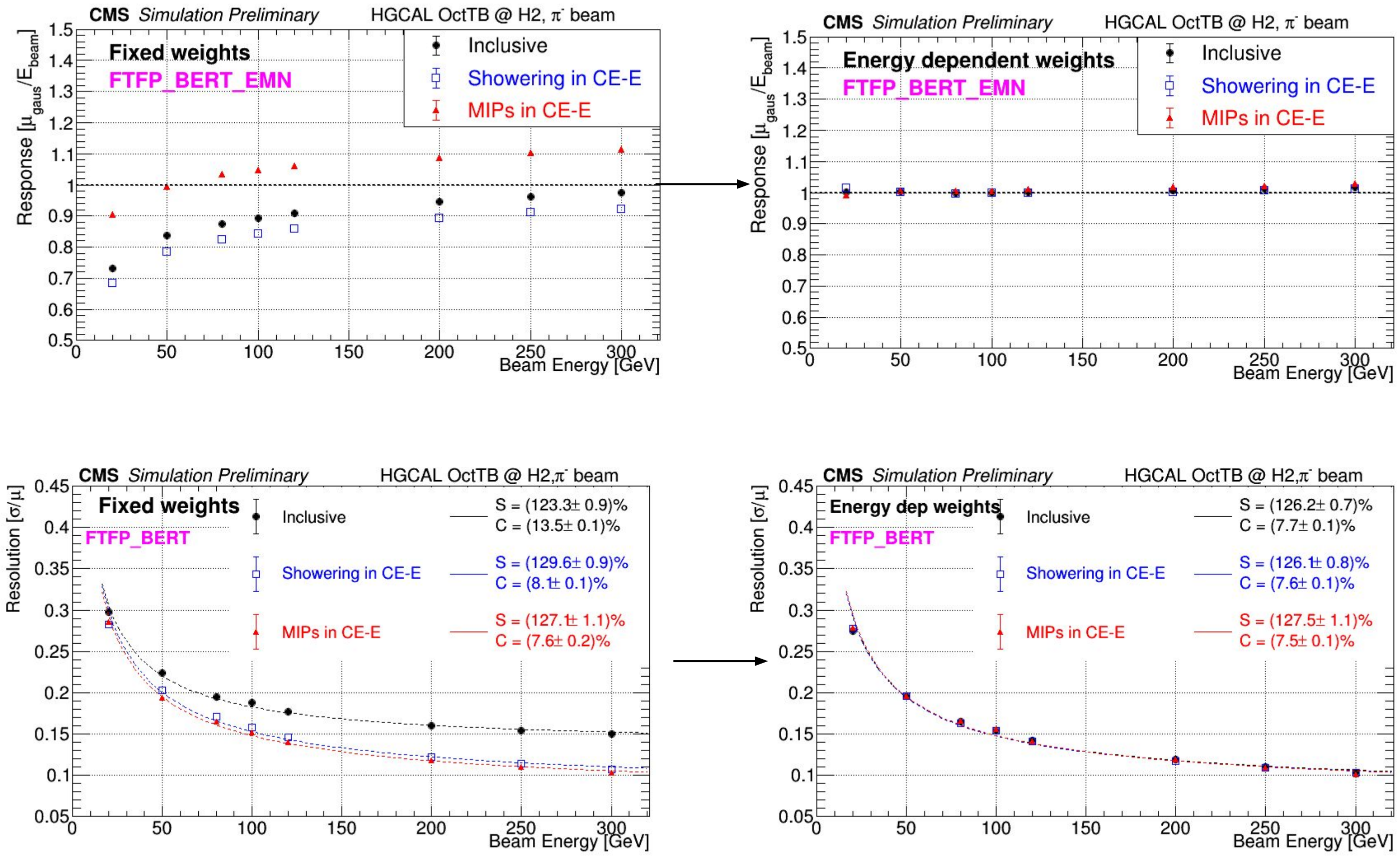




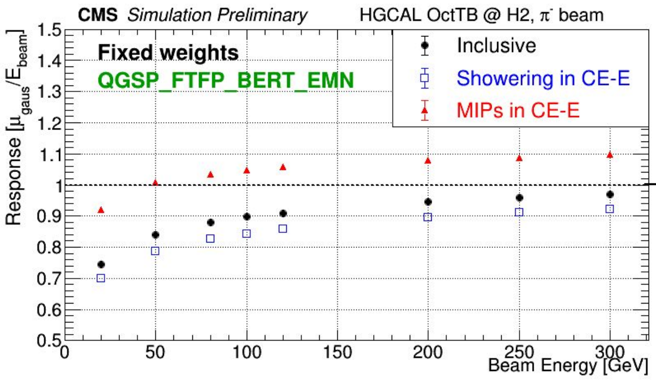


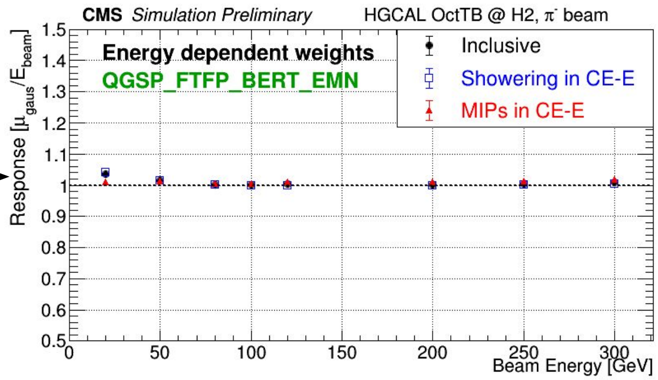
Beam energy [GeV]	E_threshold [MIPs]
20	12
50	20
80	25
100	30
120	30
200	40
250	40
300	40

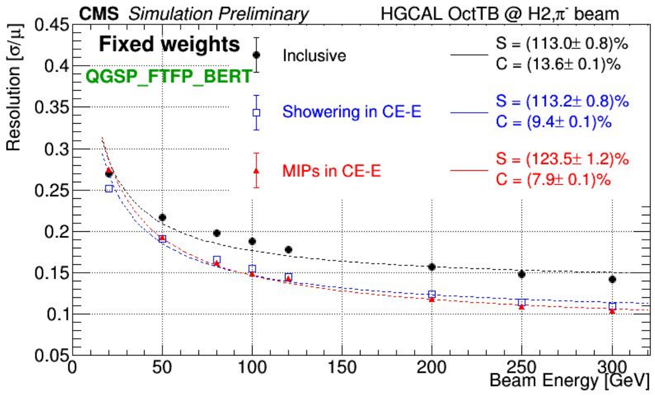
Optimized energy reconstruction (Effect in simulation)

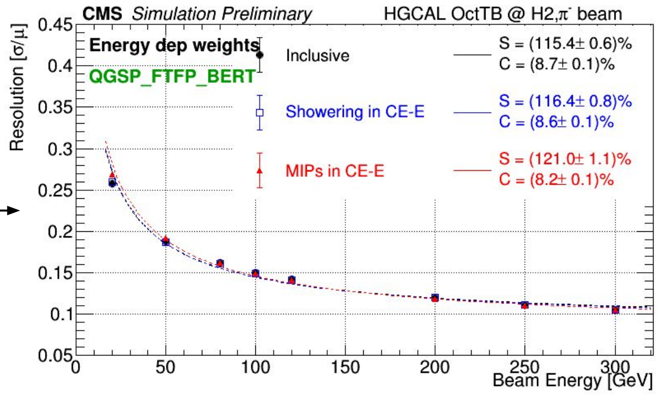


Optimized energy reconstruction (Effect in simulation)



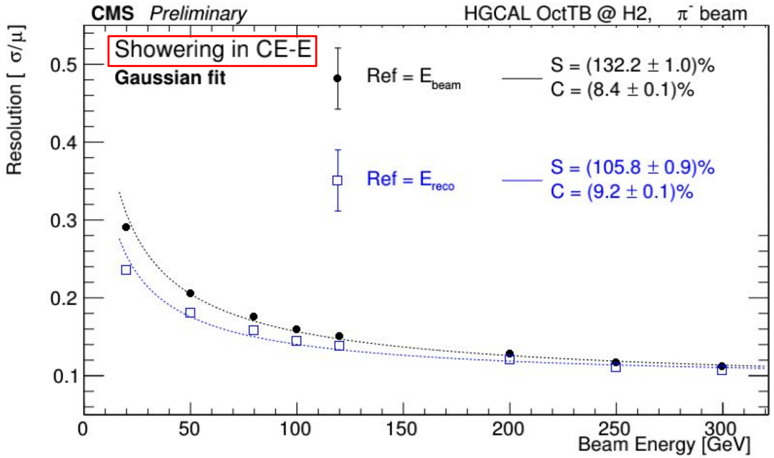


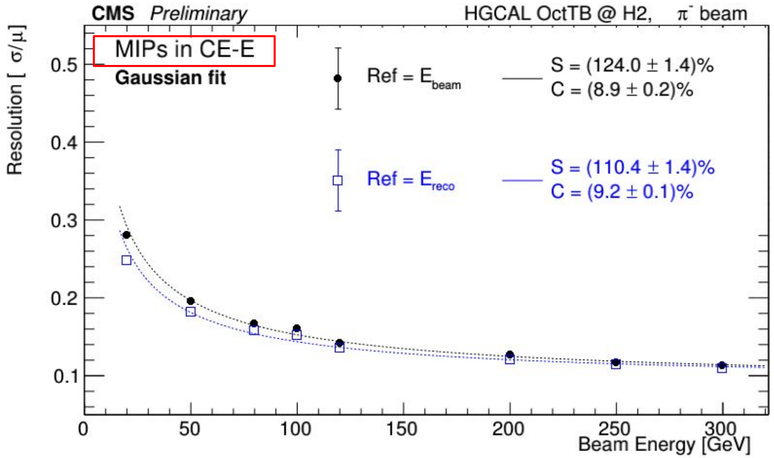




Optimized energy reconstruction

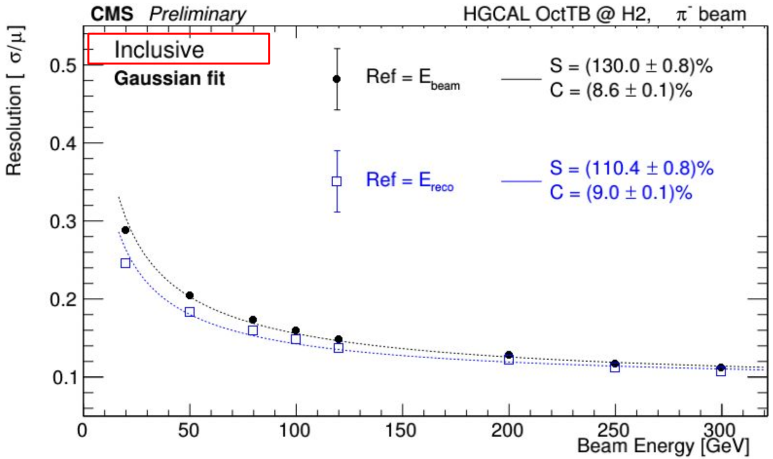
Using beam energy and measured energy (w/ fixed weights) as reference





- Plots show energy resolution in TB data for different event categories, using optimized weights when
  - E_{beam} : used as reference to pick up weights
  - $E_{measured}^{fixed\text{-}weights}$: used as reference to pick up weights

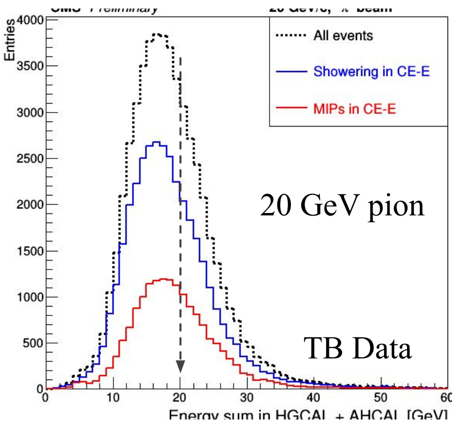
- We see good performance with E_{reco} when used as reference.
- We are making further checks to ensure that performance with E_{reco} as ref. is consistent at lower energies as well.

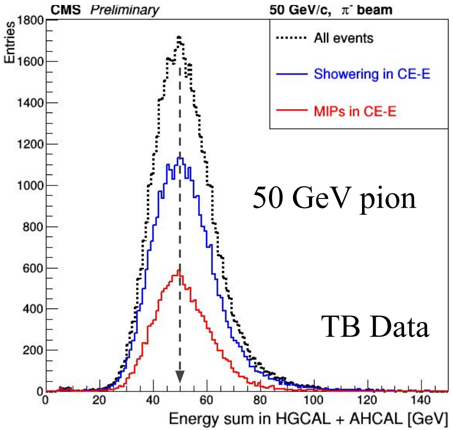


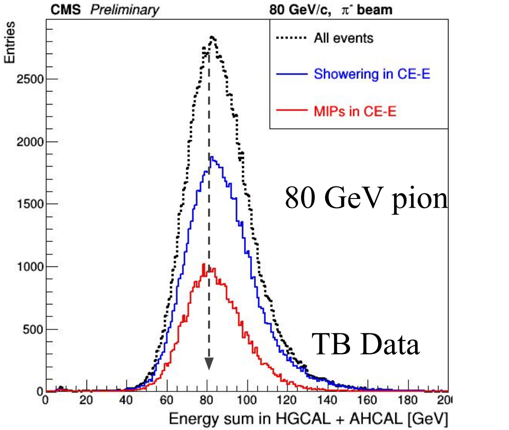
Energy distributions for different event categories

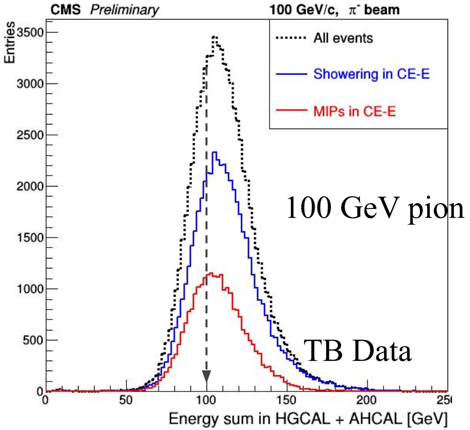
With fudge factor on pions that start showering in CE-E to make response 1 for 50 GeV pions

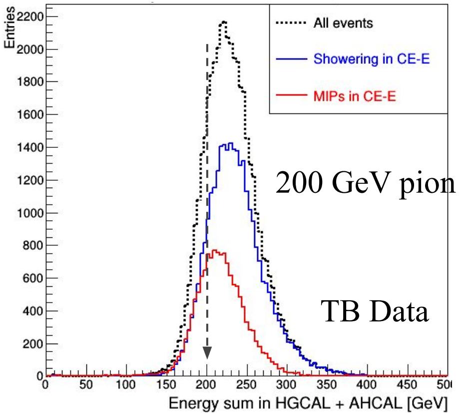
TB data: **With fix weights**

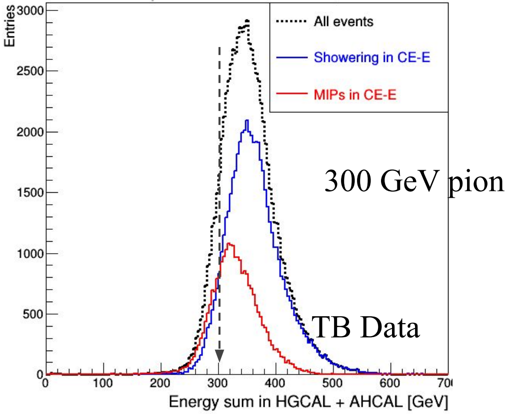




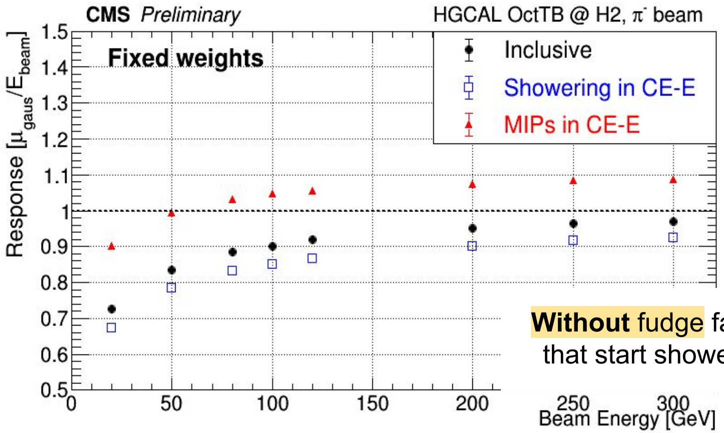


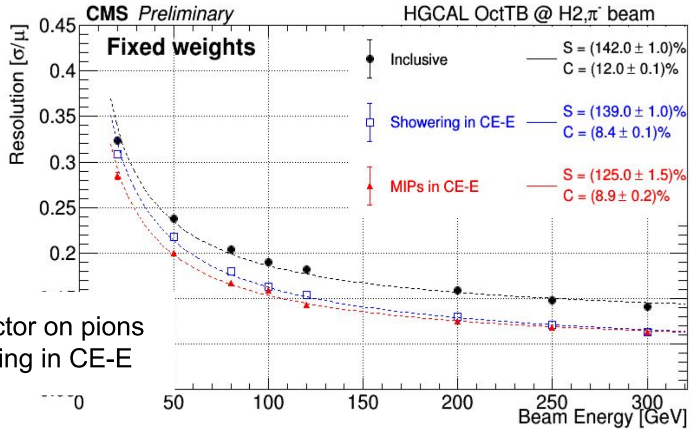






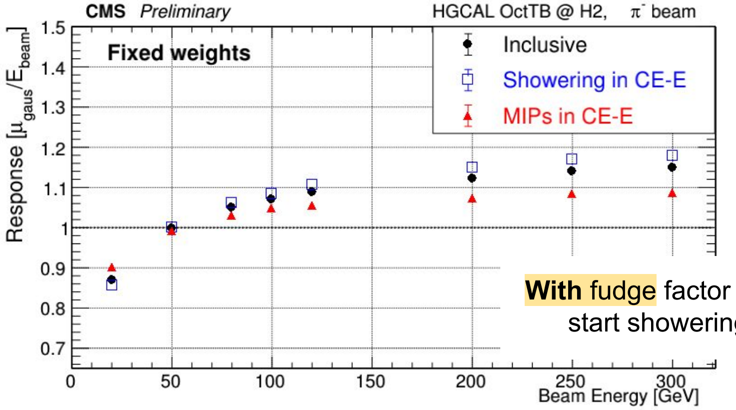
Energy response [fixed weights]

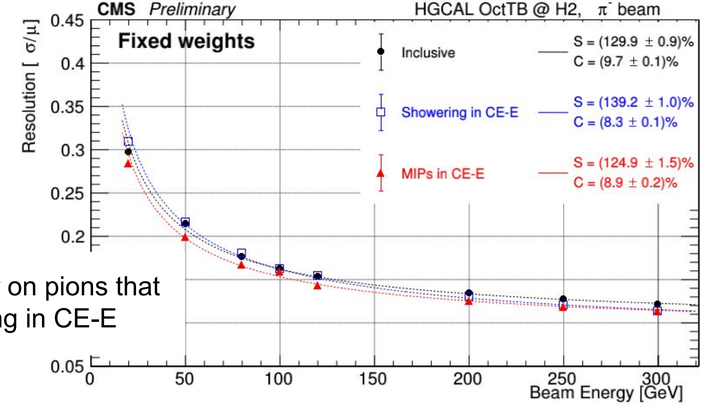




Without fudge factor on pions that start showering in CE-E

With fudge factor applied on pions that start showering in CE-E, the resolution improves slightly for inclusive events but the linearity doesn't get fixed.

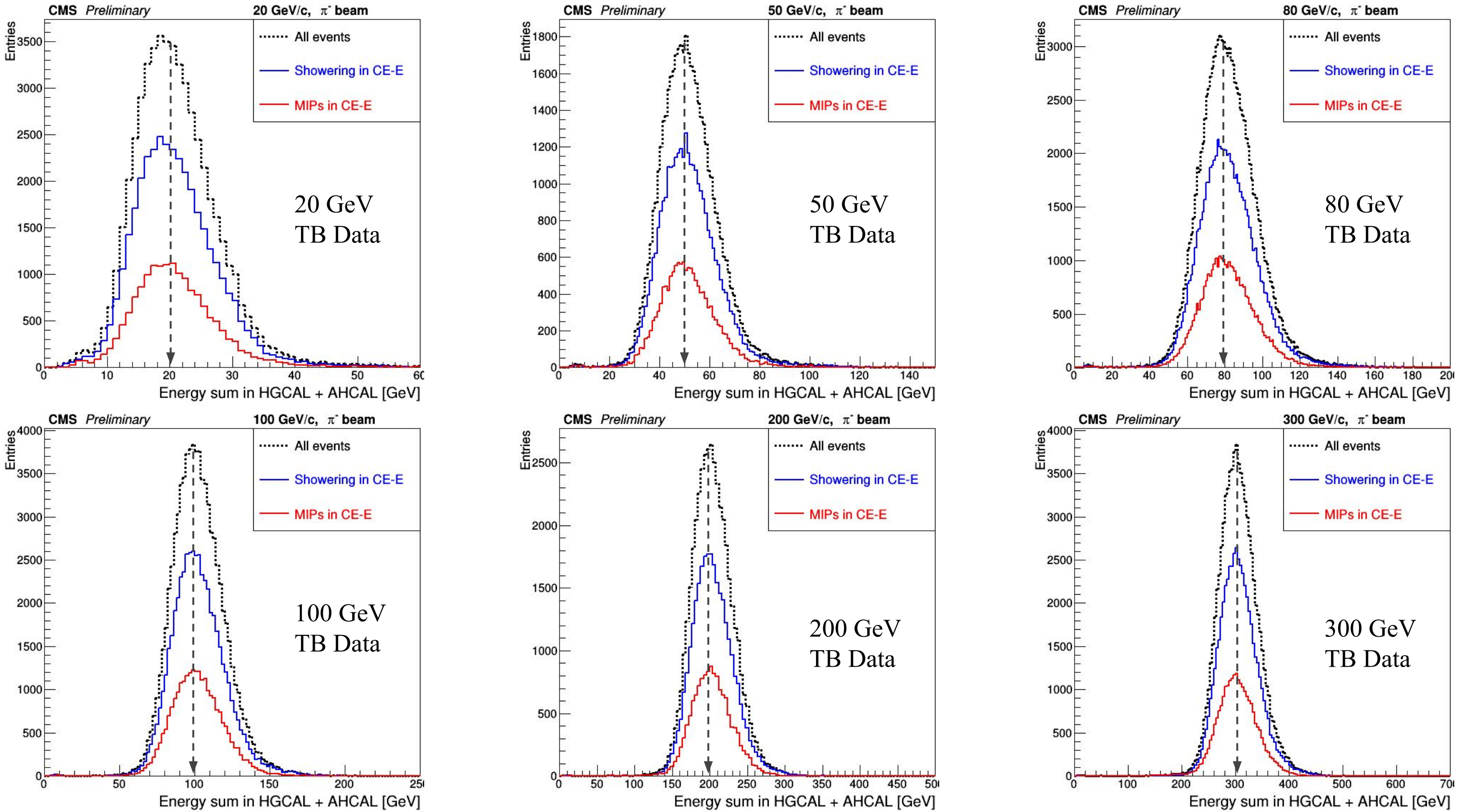




With fudge factor on pions that start showering in CE-E

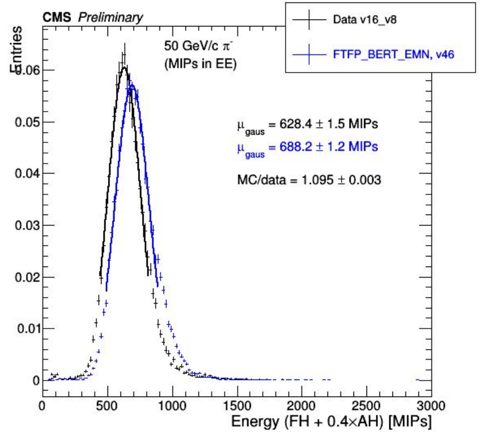
Optimized energy reconstruction

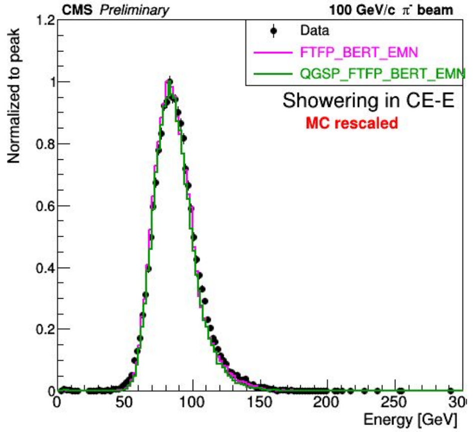
Chi2-optimized energy dependent weights bring the mean of energy distribution to beam energy for all event categories.

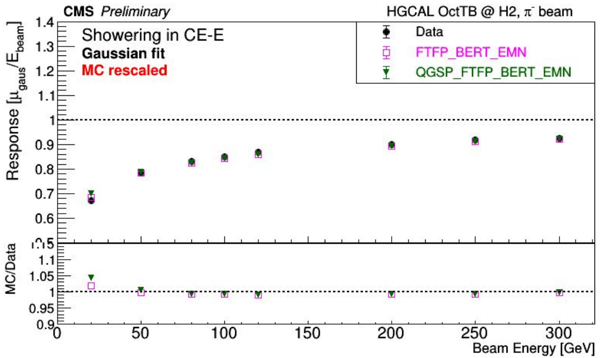


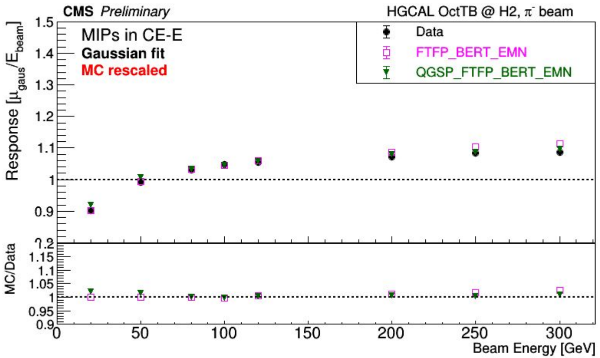
Energy scale matching between MC and data

- To match the energy scale of simulation with data, we apply a scaling factor for each detector prototype.
- The energy scale for CE-E is set by positron analysis studies : 3.5%
- To find the scaling factor for CE-H and AHCAL, we use events where pions are MIPs in CE-E.
- The scale difference is observed to be ~ 9.5% between data and MC.
    - CE-E energy in MC is scaled down by 3.5%
    - CE-H & AHCAL energy is scaled down by 9.5%.
- After the application of scaling factors, energy scale of simulation matched with data within a few percent.



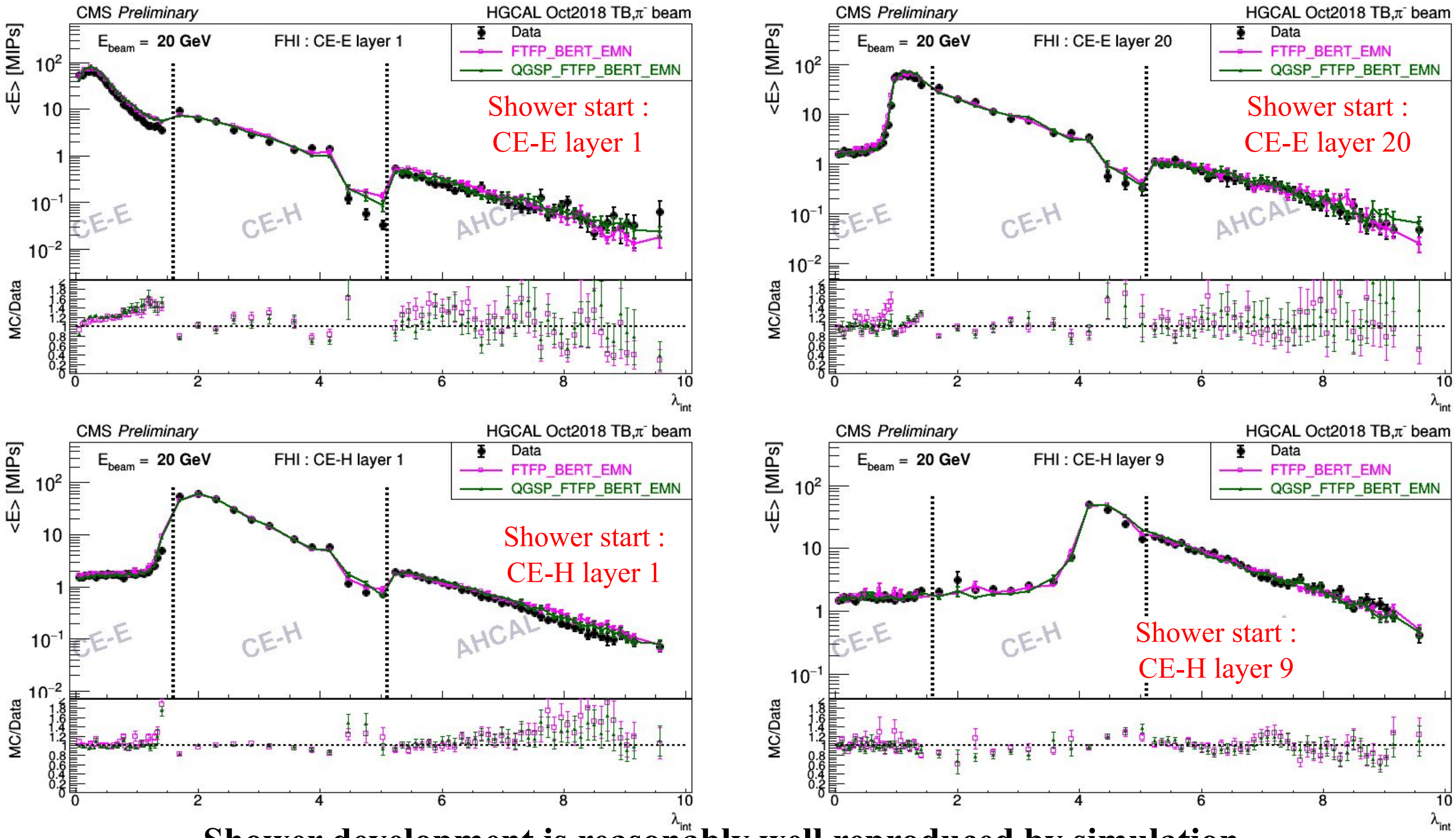






Longitudinal shower shapes (Data-MC comparison)

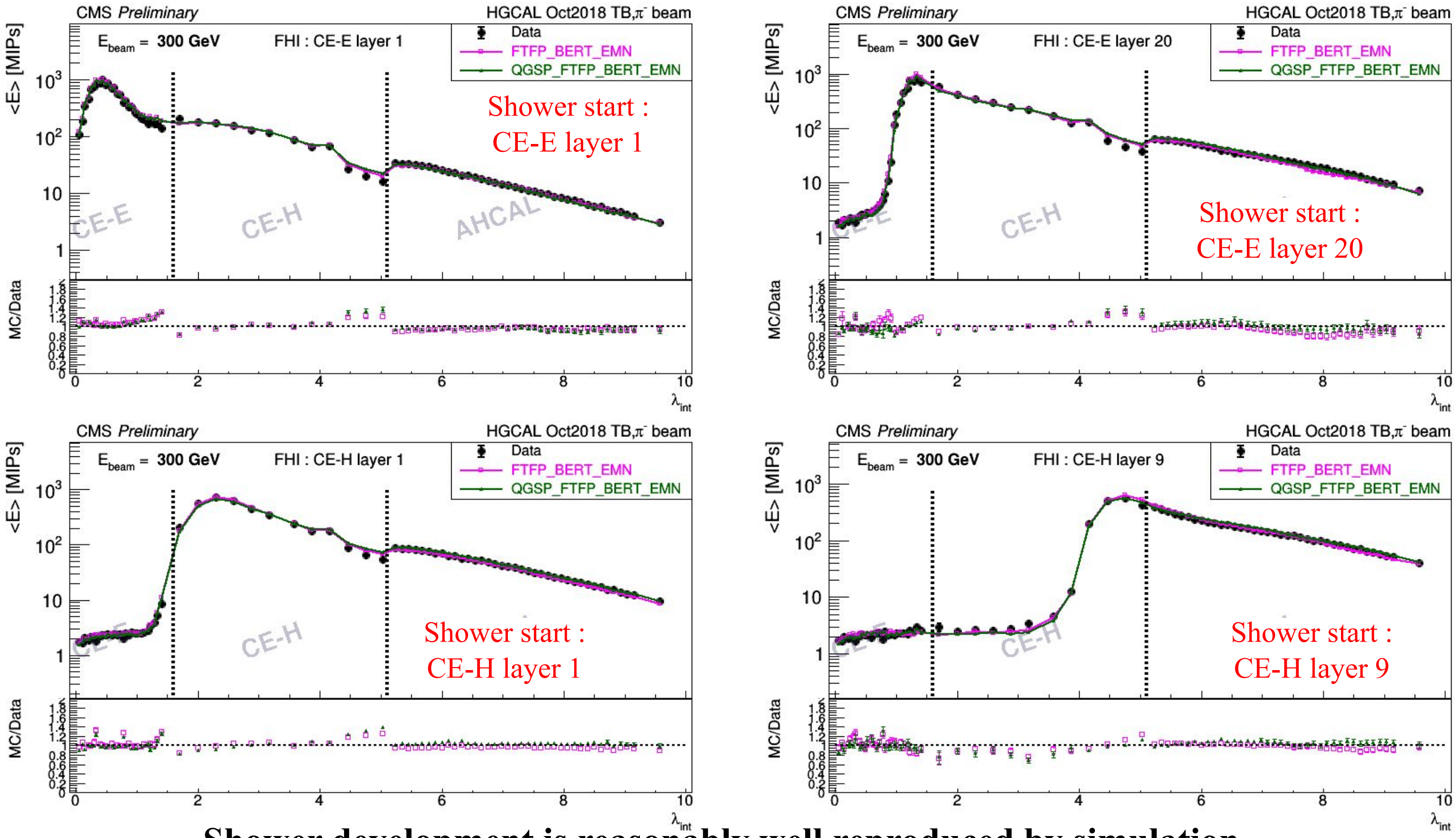
Mean energy deposited (in MIPs) as a function of calorimeter depth (λ_{int}) for **20 GeV pions**.



Shower development is reasonably well reproduced by simulation.

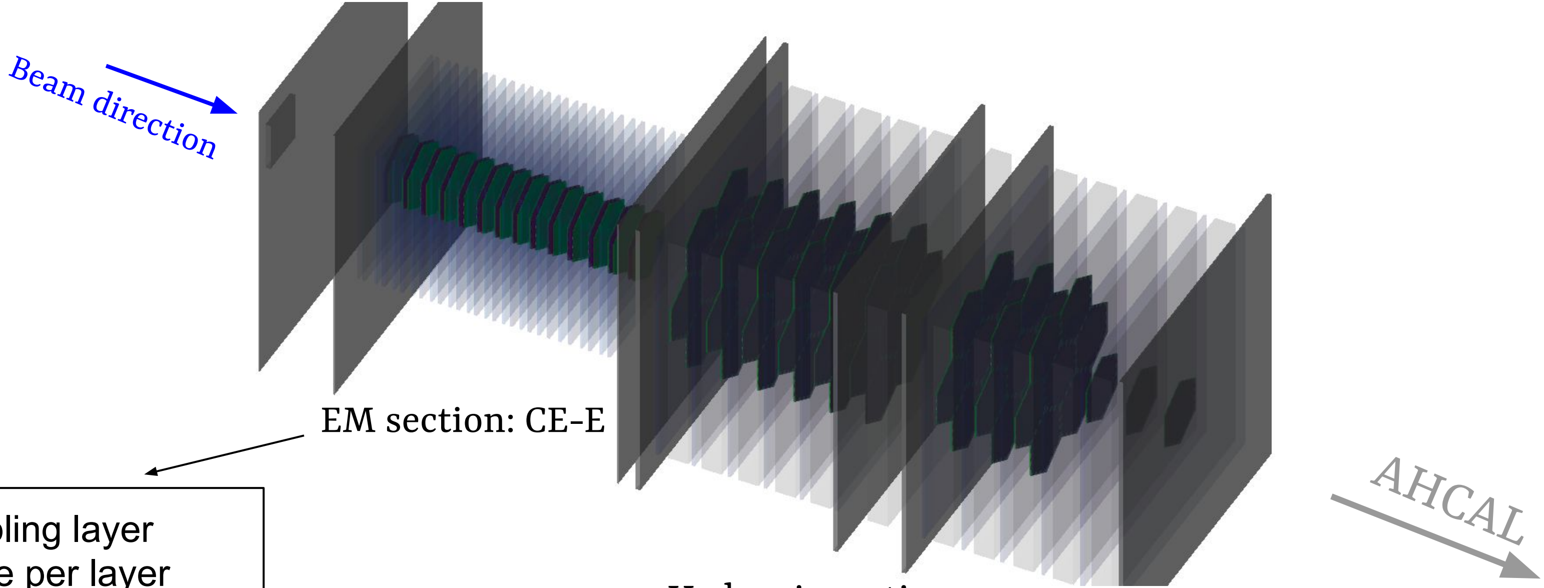
Longitudinal shower shapes (Data-MC comparison)

Mean energy deposited (in MIPs) as a function of calorimeter depth (λ_{int}) for **300 GeV pions**.



Shower development is reasonably well reproduced by simulation.

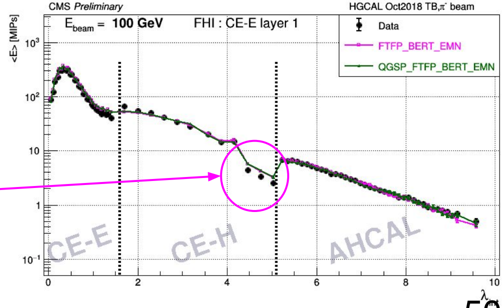
Beam test setup: Detector prototype



- 28 sampling layer
- 1 module per layer
- **Pb/Cu/CuW absorber**
- **~ 26 X_0, 1.4 λ_{int}**

Hadronic section:
CE-H

- 12 sampling layer
- 7 modules per layer in first 9 layers
- 1 module per layer in last 3 layers
- **Steel absorber**
- **~ 3.4 λ_{int}**

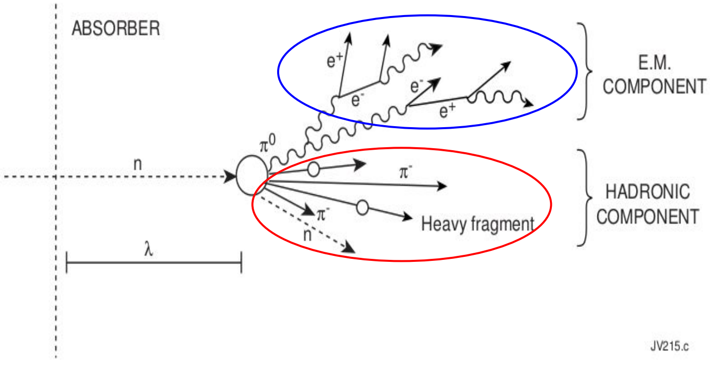


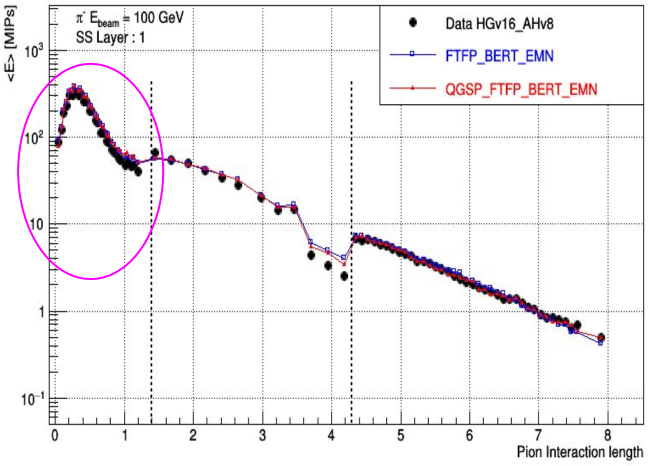
Nature of hadronic showers

- It has two components:
  - EM component: from π^0 → instantly decays to two γ
  - Hadronic component

- For same incident energy of pion and electron:
  - EM shower has more secondary particles as compared to hadronic shower.
  - In our setup, we have:
    - 100 GeV e^+ → approx. 10000 MIPs in CE-E
    - 100 GeV π^- → approx. 1500 MIPs in CE-H

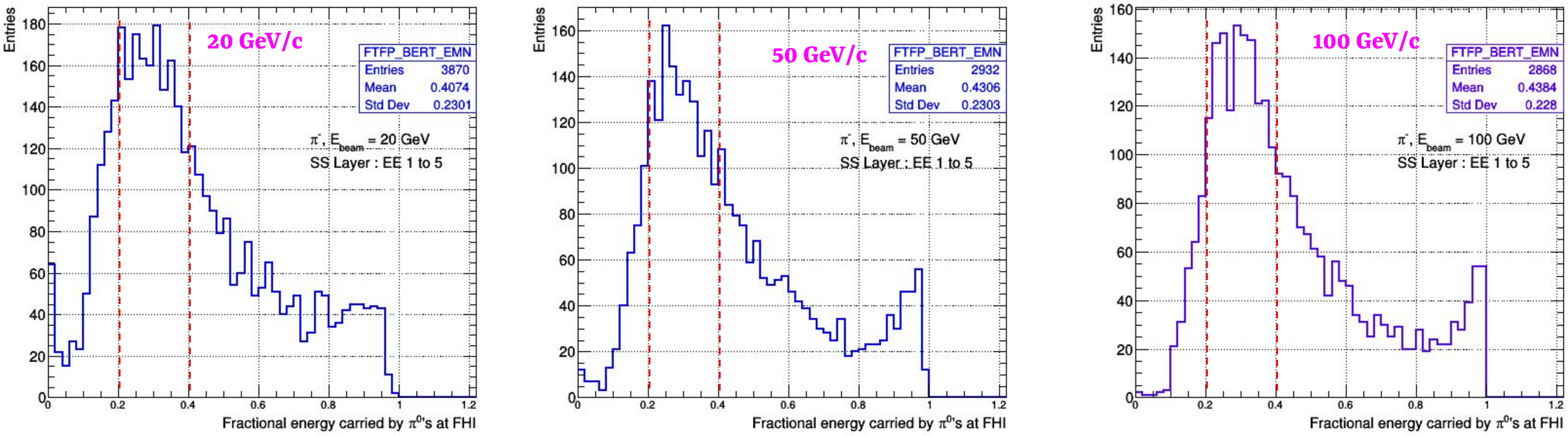
- Taking above two points into consideration along with the fact that ~26 X_0 of Pb is enough to contain almost all of EM shower.
  - Are we probing into EM component of pion shower in CE-E compartment?
  - To check this, we make use truth information of secondary particles, generated at first hadronic interaction (similar to shower start finder algorithm optimization).





Number of neutral pions at first hadronic interaction

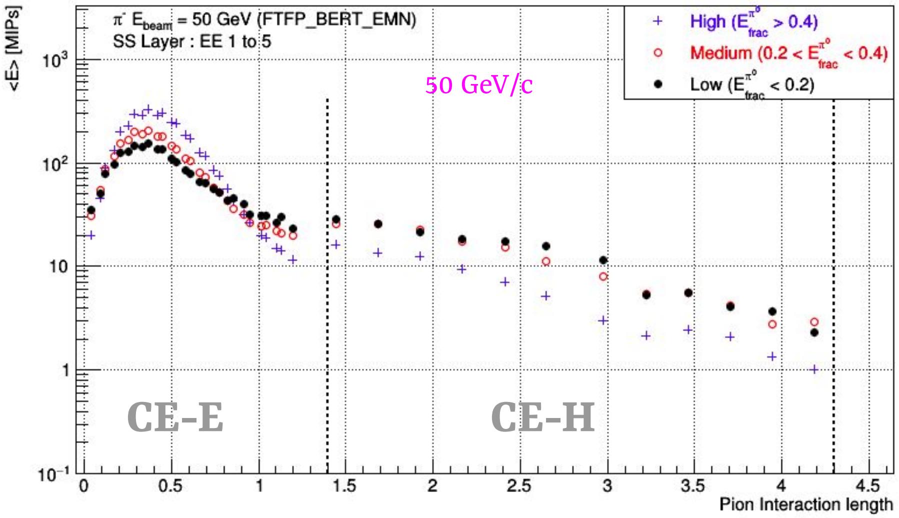
- Using the same handle, we plot the distribution of fractional energies carried by π^0's produced at the first interaction.
  - No cut is applied on π^0 energies.
  - Neutral pions produced at the first interaction has been considered in this study.
  - Neutral pions are produced at later interactions also, especially for higher incident energies.

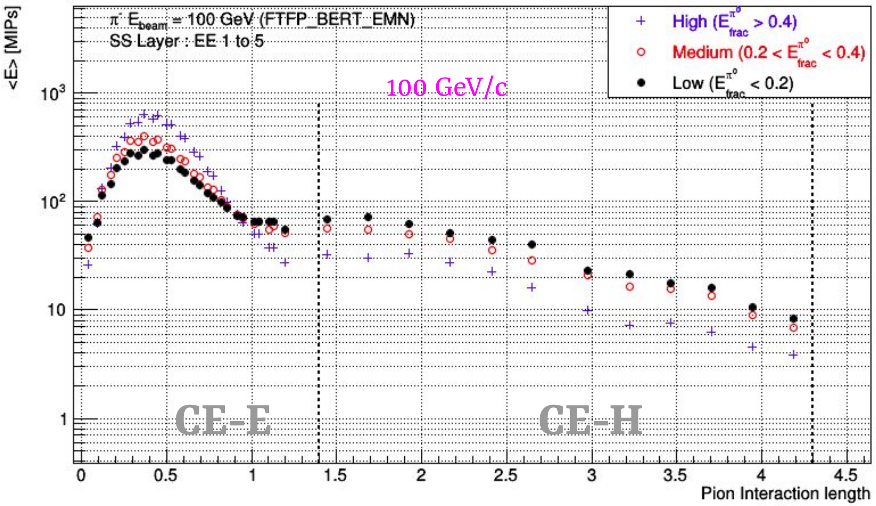


Plot the shower shapes again, but now divide them into separate categories.
(See next slide)

Shower shapes in different categories

- Following two plots show, longitudinal shower shapes for 50 GeV/c pion (left) and 100 GeV/c pions (right) in three different categories based on fraction energies carried by pi0's at the first hadronic interaction.
  - Inclusive in shower starting in first five layers.

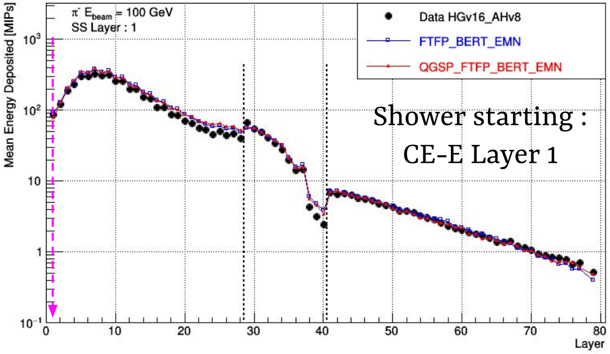


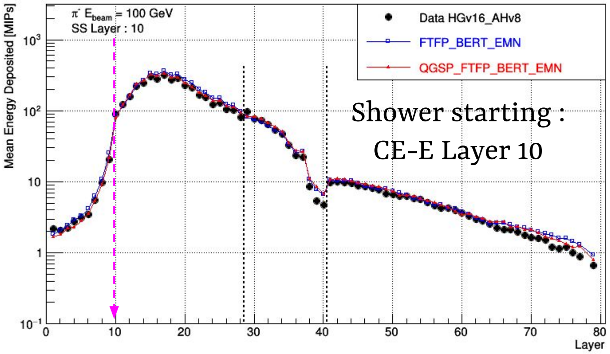


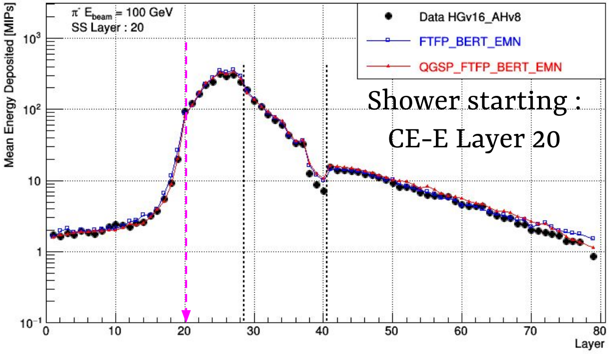
- Average energy deposited:
  - **Higher in CE-E and lower in CE-H when E_{frac} > 0.4 → higher EM fraction → mostly contained in CE-E**
  - **Lower in CE-E and higher in CE-H E_{frac} < 0.2 → higher had fraction → mostly contained in CE-H**

Shift of shower maximum

- Following plots show average energy deposited [MIPs] as a function of **“layer”** for three shower starting points for 100 GeV/c π^- beam.







- Shower maximum lies ~ 7 layers away from shower starting point.
- Shower maxima for 30-50 GeV positron lies at around 8-9.
- These studies indicates that the first peak that we see in the shower shapes is dominated by EM component of hadronic shower.
- We are able to probe the π^0 component with our fine longitudinal sampling of CE-E prototype !!

Variable used to study transverse shower shapes

- Variable: energy weighted distance from the center of gravity at ith layer.
  - Accentuates lateral spread according to energy deposited.

Center of Gravity at layer - i

$$x^i_{CG} = \frac{\sum_j x^i_j \times E^i_j}{\sum_j E^i_j} \; ; i \in [1, 40] \text{ and } j \in [\text{rechits at layer i}]$$

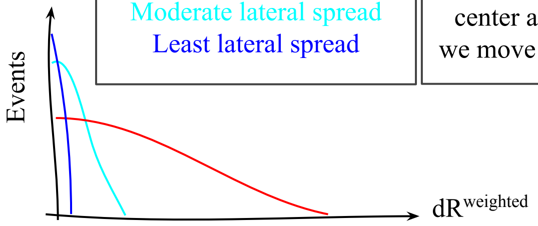
$$y^i_{CG} = \frac{\sum_j y^i_j \times E^i_j}{\sum_j E^i_j} \; ; i \in [1, 40] \text{ and } j \in [\text{rechits at layer i}]$$

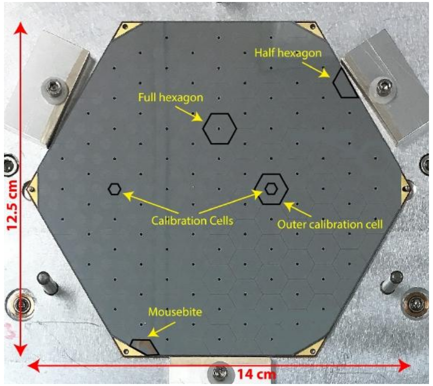
Energy weighted distance from CG of rechit - j

$$dR_j^{\text{weighted}} = \sqrt{(x_j - x_{CG})^2 + (y_j - y_{CG})^2} \times E_j$$

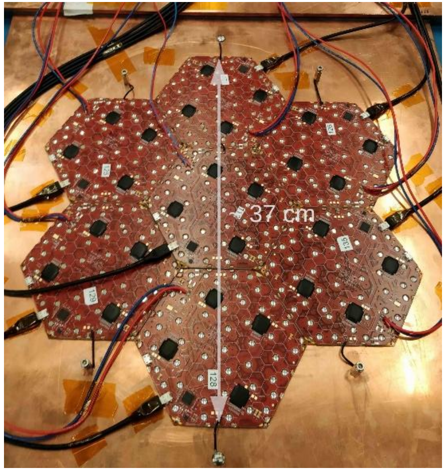
Larger lateral spread
Moderate lateral spread
Least lateral spread

Highest energy at the center and dies down as we move radially outward.





CE-E prototype layer

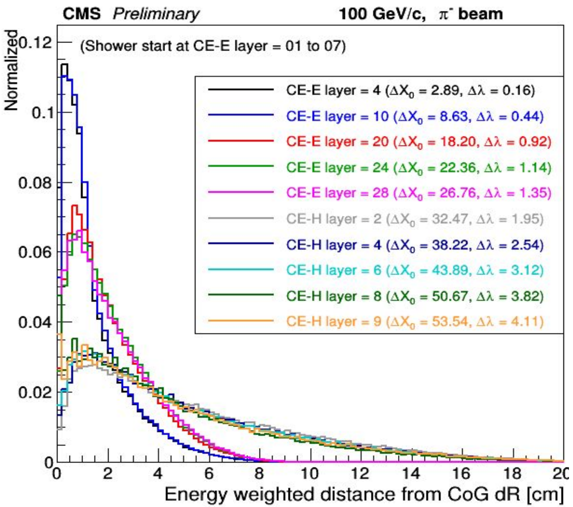


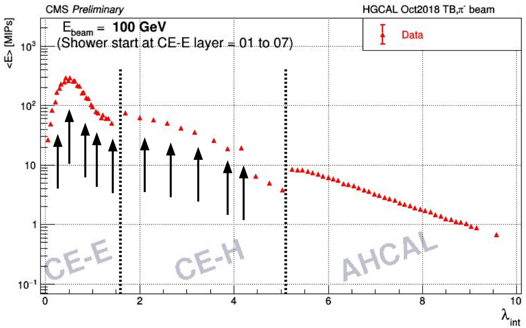
CE-H prototype layer

Point to remember:
CE-H prototype layer has considerably larger area than CE-E layer.

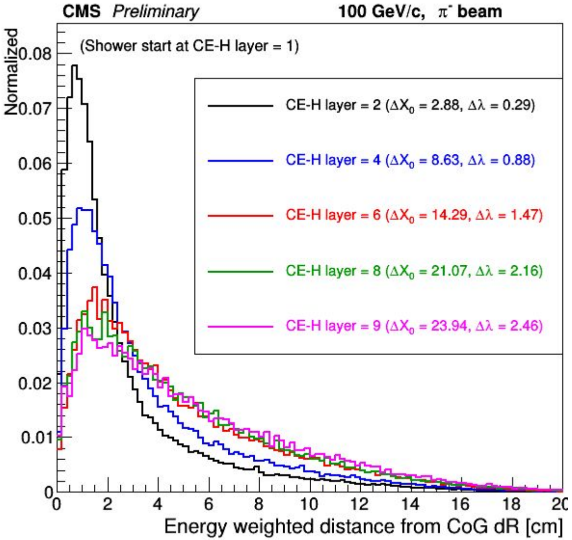
Transverse shower shapes at different depths (Contd…)

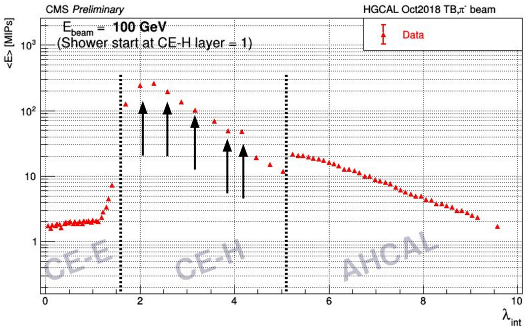
Shower start location: CE-E layer 1-7





Shower start location: CE-H layer 1





For shower starting in CE-H also, we observe narrower spread around the the peak.

Though the spread is larger as compared to SS in CE-E.

Possible reasons:

- More modules in CE-H.
- For similar $\mathbf{\Delta X_0}$ in CE-H, $\mathbf{\Delta\lambda}$ is ~2x as compared to CE-E → more space for hadronic component to spread in CE-H.

Longitudinal shower shapes (Data-MC comparison)

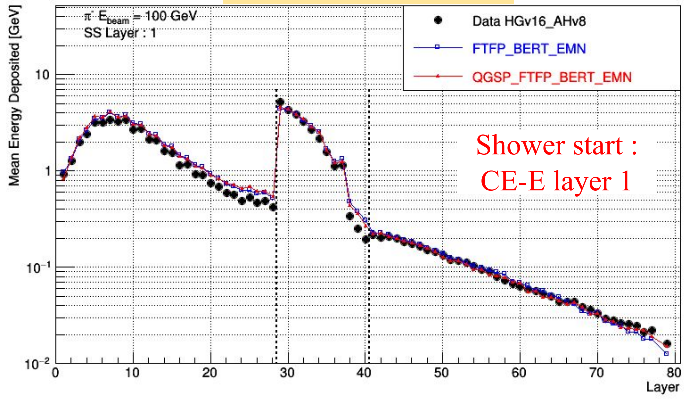
- The longitudinal shower shapes is plotted in terms of mean energy deposited **in GeV** as a function of calorimeter depth (λ_{int}) as shown in the plots for 300 GeV/c pions.
  - MIP-to-GeV conversion is done using optimized weights.

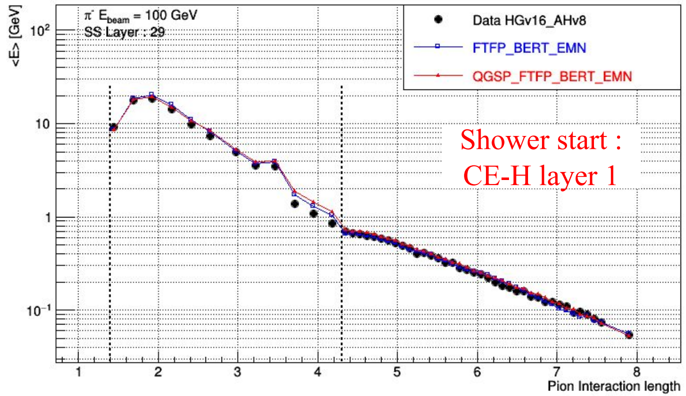
- We observe a sudden jump at the transition region between CE-E and CE-H prototype.

- This jump in mean energy deposited is because of the fact that MIP-to-GeV weights take absorber thicknesses into account.
  - In CE-E prototype, $\Delta\lambda_{in}$ ~ 0.05
  - In CE-H prototype, $\Delta\lambda_{in}$ ~ 0.3
  - Higher absorber thickness ⇒ Higher measured energy in terms of GeV

- Very good agreement between data and simulation.

Older simulation version

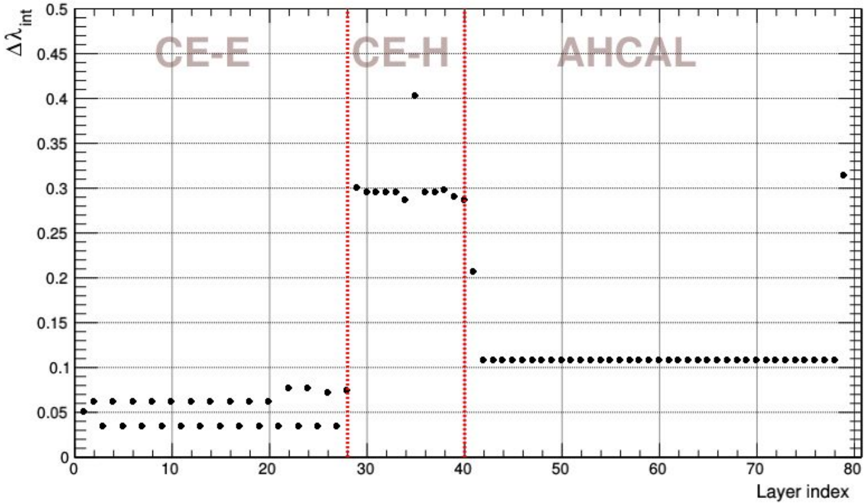




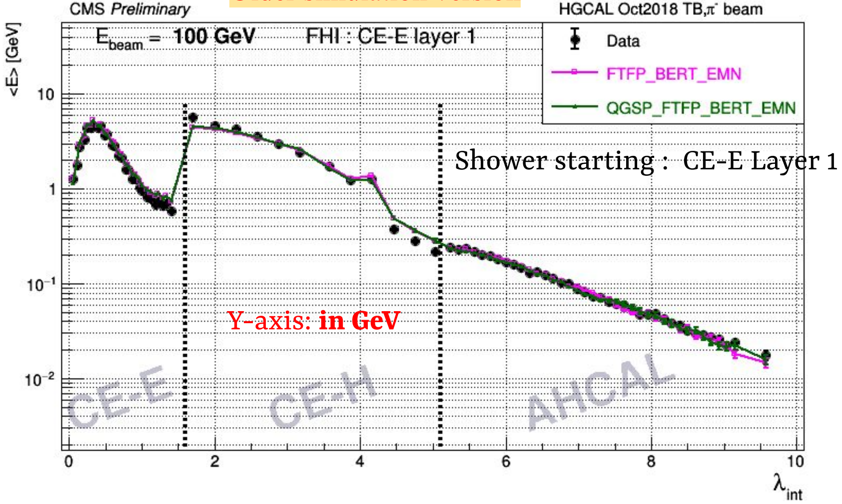
Plots will be updated with MIP energy shown in CE-E.

Jump at transition region

- In HGCAL detector prototype, absorber width between consecutive CE-H layers are larger than consecutive CE-E layers.
- Plot on the left shows, $\Delta\lambda_{int}$ between two consecutive layers (layer i & layer i-1).



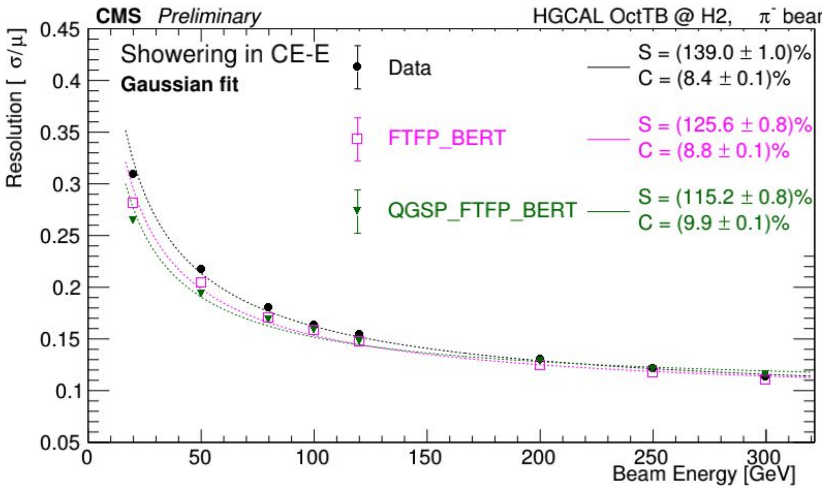
Older simulation version

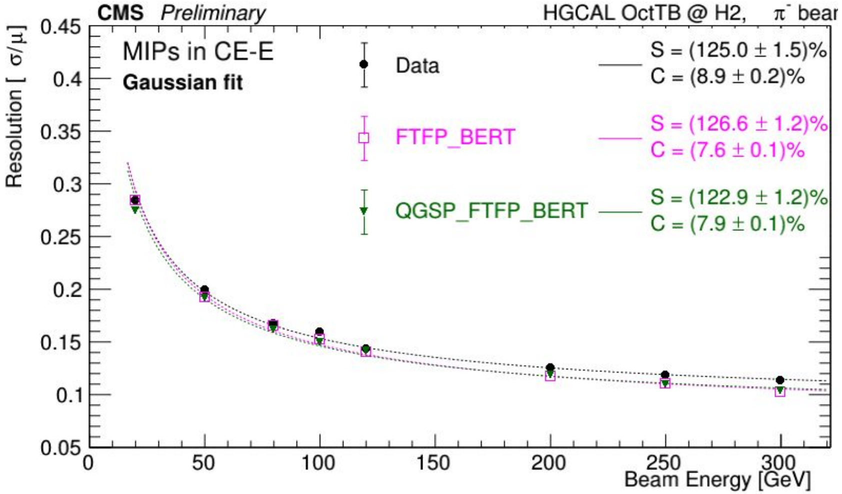


- We see a jump in at the transition region.
  - This jump is reflected in energy measured in GeV.
- The alternating high-low $\Delta\lambda_{int}$ is due to alternating absorber material in CE-E i.e. Pb & CuW that have different λ_{int}.
- One high point around CE-H layer 6 is because of extra material of steel box on which the active layers were placed.

Energy resolution [fixed weights]

- Following two plots show energy response for data and two simulation samples as a function of beam energy for pions that start showering in CE-E (left) and that are MIPs in CE-E (right).
- The response is defined as : σ_{gaus}/μ_{gaus}





- Comments:
  - For pions **showering in CE-E**: Data & MC shows good agreement at higher energies and shows slight difference at lower energies. Overall agreement ~1-15%,
  - For pions **MIPs in CE-E**: Data & MC shows agreement slight difference at higher energies but shows good agreement at at lower energies. Overall agreement within 10%.

Resolution fit function:

$$\left(\frac{\sigma}{E}\right) = \sqrt{\left(\frac{s}{E}\right)^2 + c^2}$$

s = Stochastic term

c = Constant term