BTTB9

10/02/2021

Electromagnetic performance of CMS HGCAL in beam tests

Matteo Bonanomi

(LLR, Ecole Polytechnique, CNRS)

On behalf of the HGCAL Beam Tests group

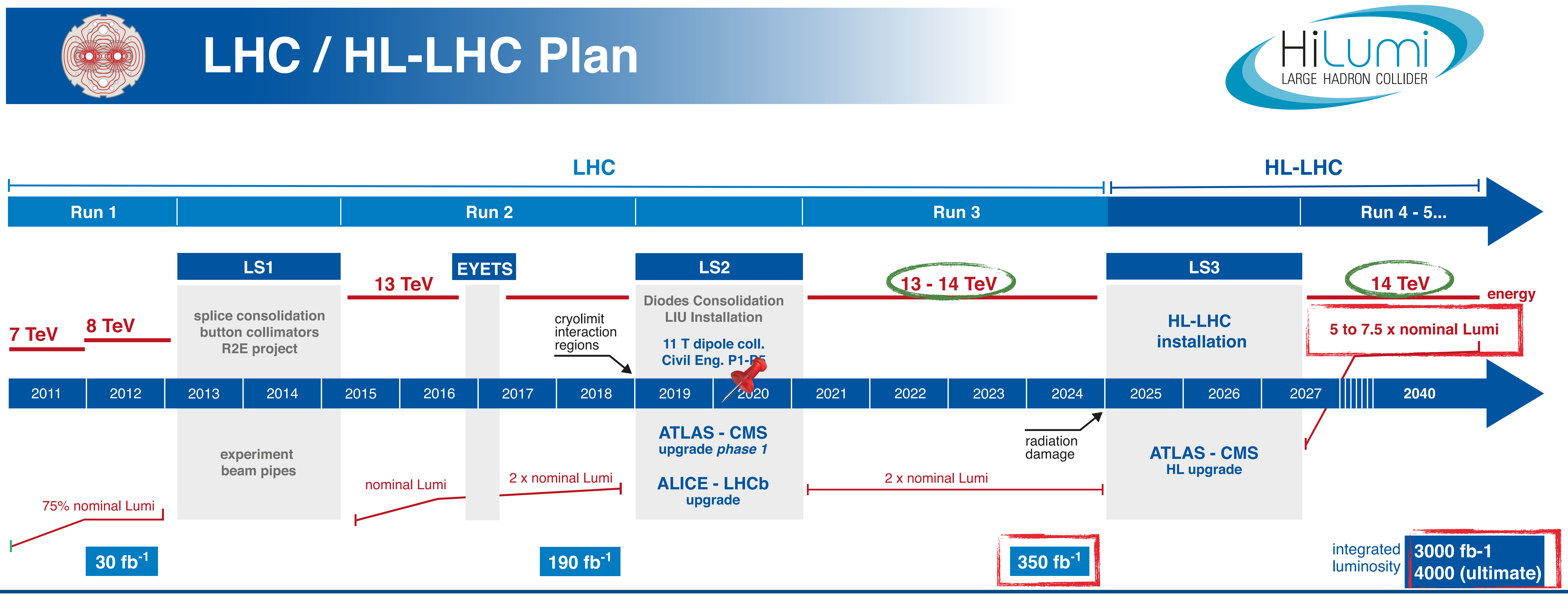
The High-Luminosity LHC

- In 2027 CERN is intended to start the **H**igh-**L**uminosity **LHC** program:

- **HL-LHC** will integrate **5** (10) **times the instantaneous** (integrated) **luminosity** of LHC:

  - 🆙 **High pile-up rate**: evts/bunch-crossing from ~70 in LHC to O(140/200) in HL-LHC!

  - ☢️ **Unprecedented radiation levels**: doses up to 2 MGy and fluences up to 10^{16} n_{eq}/cm^2



The High-Luminosity LHC

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- **HL-LHC** will integrate **5** (10) **times the instantaneous** (integrated) **luminosity** of LHC:
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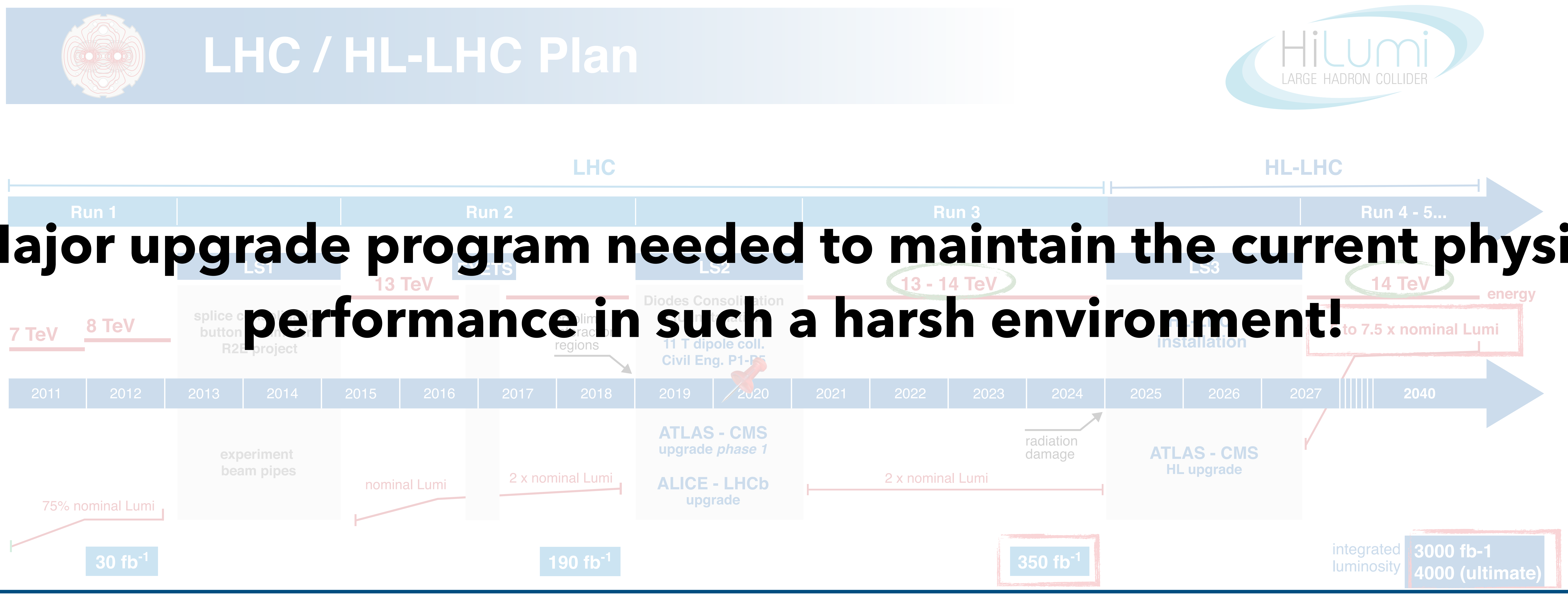


Major upgrade program needed to maintain the current physics performance in such a harsh environment!

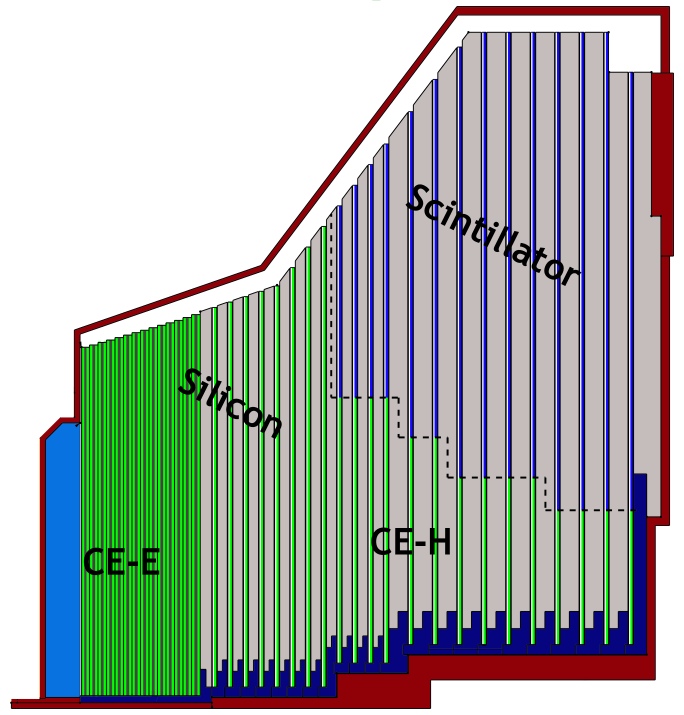
The CMS Upgrades for HL-LHC

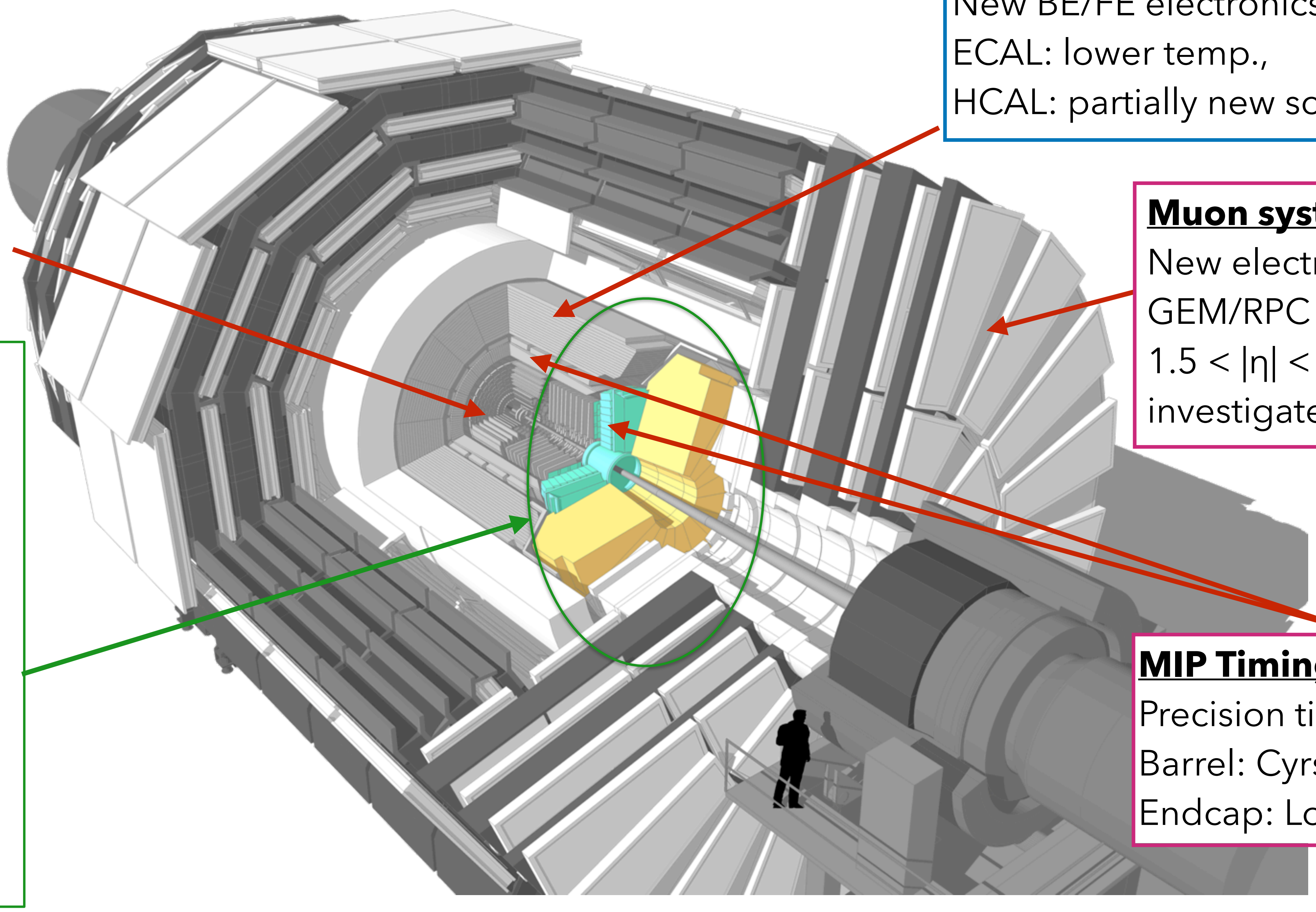
TriDAS system:
L1 trigger primitives @40 MHz
PF selection, 750 kHz output
HLT output @7.5 kHz

Tracker:
Radiation tolerant,
high granularity,
less materials, tracks in
hardware trigger (L1),
coverage up to |η| = 3.8

Barrel Calorimeter:
New BE/FE electronics,
ECAL: lower temp.,
HCAL: partially new scintillator

HGCAL:
Coverage 1.5 < |η| < 3.0





Muon system:
New electronics
GEM/RPC coverage in
1.5 < |η| < 2.4,
investigate muon tagging at higher η

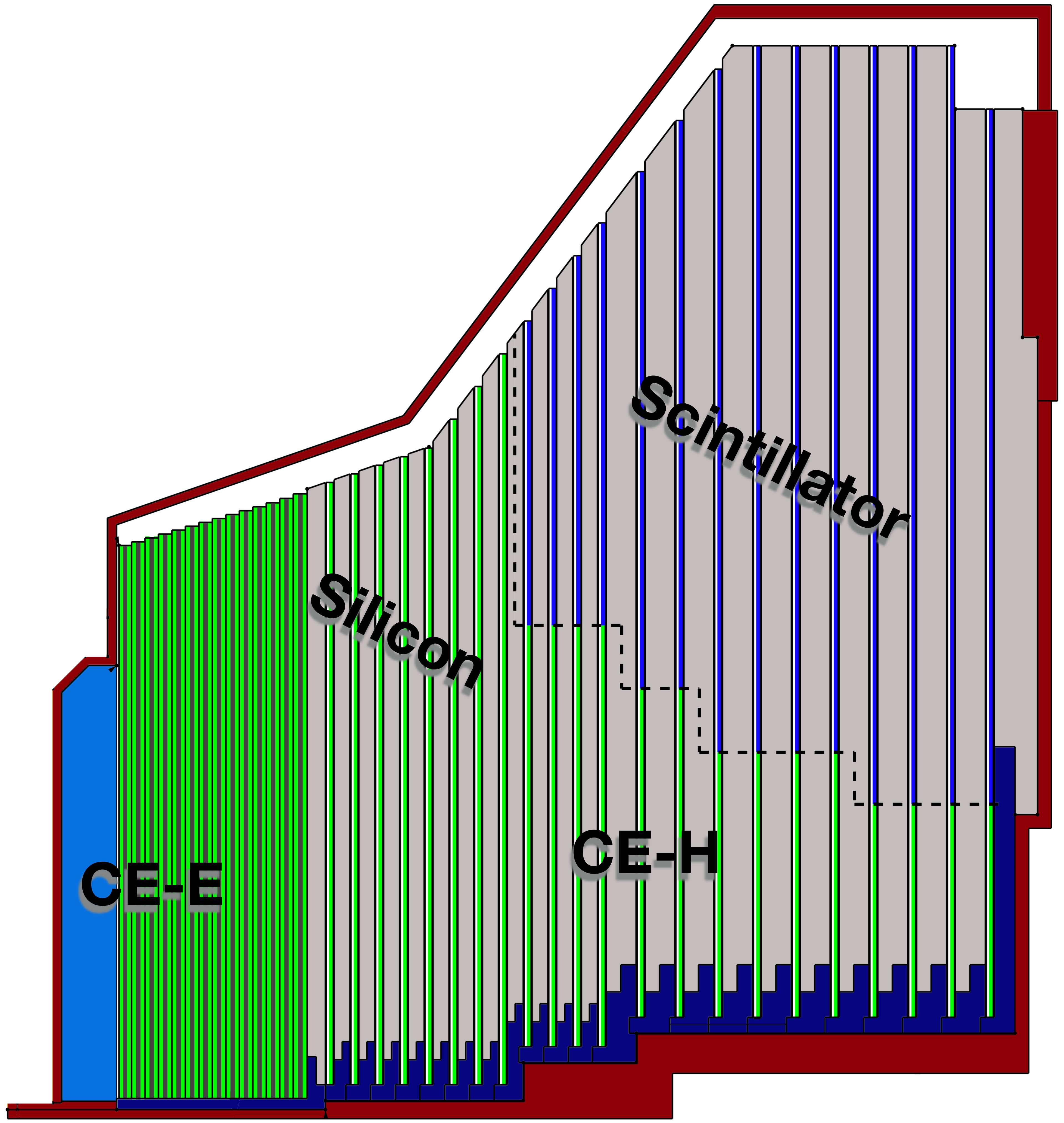
MIP Timing Detector:
Precision timing for PU mitigation
Barrel: Cyrstals+SiPM
Endcap: Low gain avalanche diodes

🆙 **High granularity and precise timing to mitigate pile-up**

☢️ **Radiation hard detector material to cope with large dose**

HGCAL: a novelty in calorimetry

- New **endcap calorimeter** of CMS:
  - Need to replace **ECAL** crystals and **HCAL** scintillators as they were **designed for 500 fb^{-1}**
- **High precision energy measurements**:
  - Missing energy/precision resolution;
- **Ideal** detector **for Particle Flow**;
- Fully utilise **timing*** (real novelty in calorimetry!);
- **5D** (*imaging*) **calorimeter**:
  - Energy, time, x, y, z

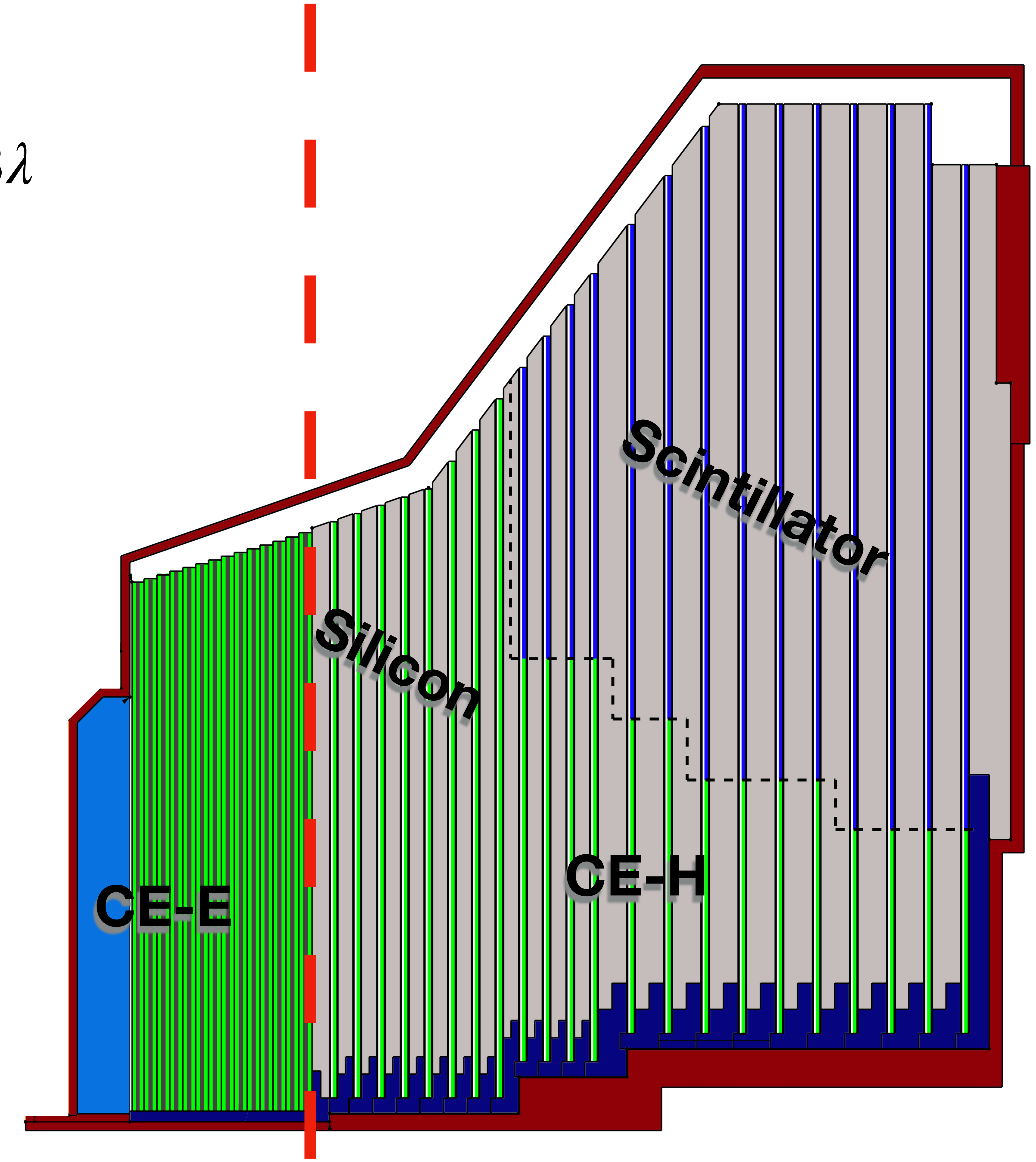


*** See Rohith talk for results on timing performance in TB**

HGCAL in numbers

Sampling calorimeter consisting of:

- 28 layers **Si-based** EM compartment (CE-E), ~25X_0 and ~1.3λ
- 22 layers hadronic compartment (CE-H):
  Si-based + Scintillator tiles, ~8.5λ



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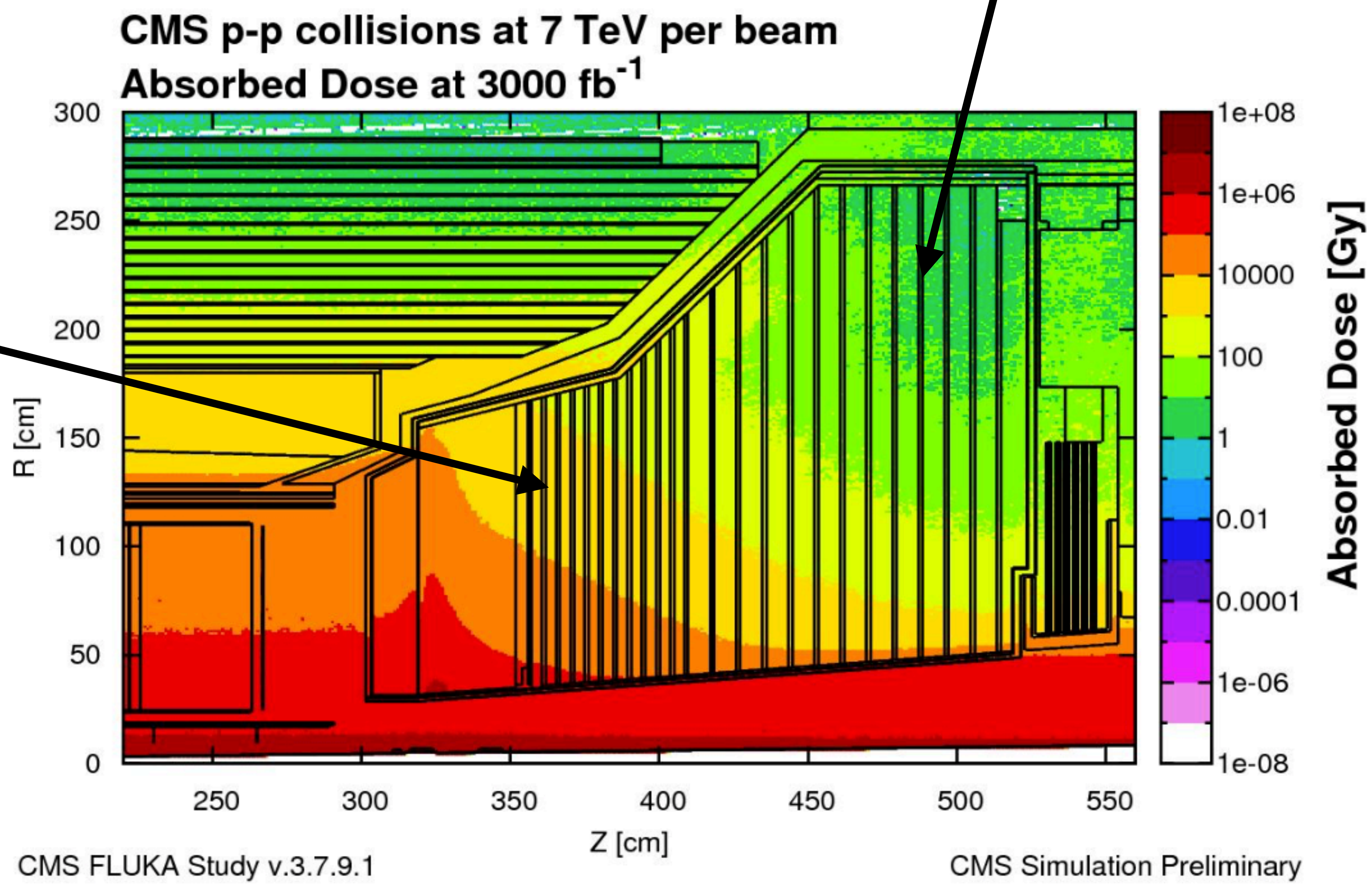
SiPM tiles*

Si is radiation hard!



*** See Malinda talk for results with SiPM tiles**

HGCAL in numbers

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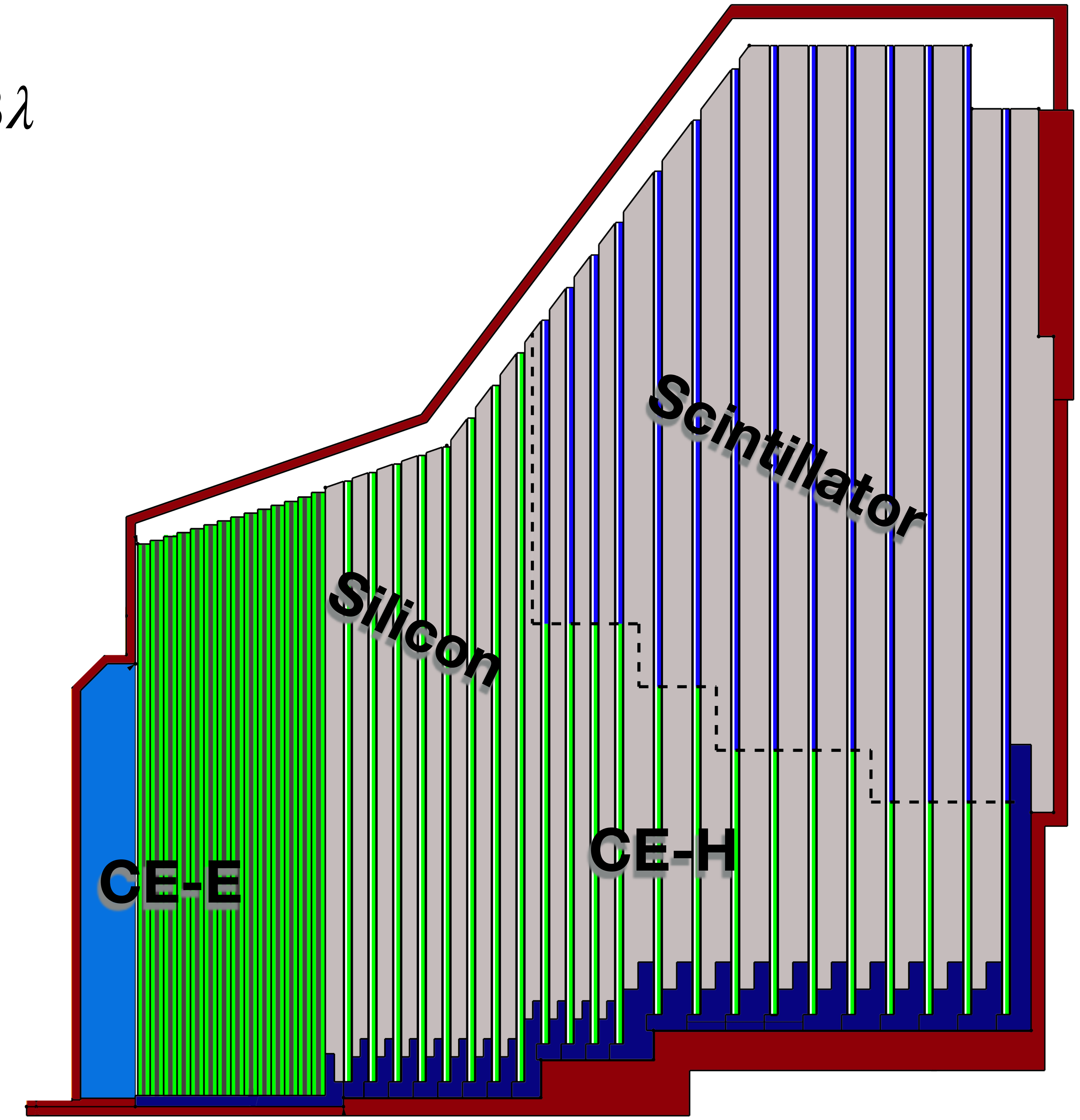
- 28 layers **Si-based** EM compartment (CE-E), ~25X_0 and ~1.3λ
- 22 layers hadronic compartment (CE-H):
  Si-based + Scintillator tiles, ~8.5λ

- Coverage: $1.5 < |\eta| < 3.0$
- **~620 m² Si** sensors in ~30k channels;
- **6M Si channels** of 0.5/1 cm² cell size;
- **~400 m²** of **scintillators** in 4k boards;
- ~240k scintillators channels, 4-30 cm² cell size;

Operating temperature: -35 °C

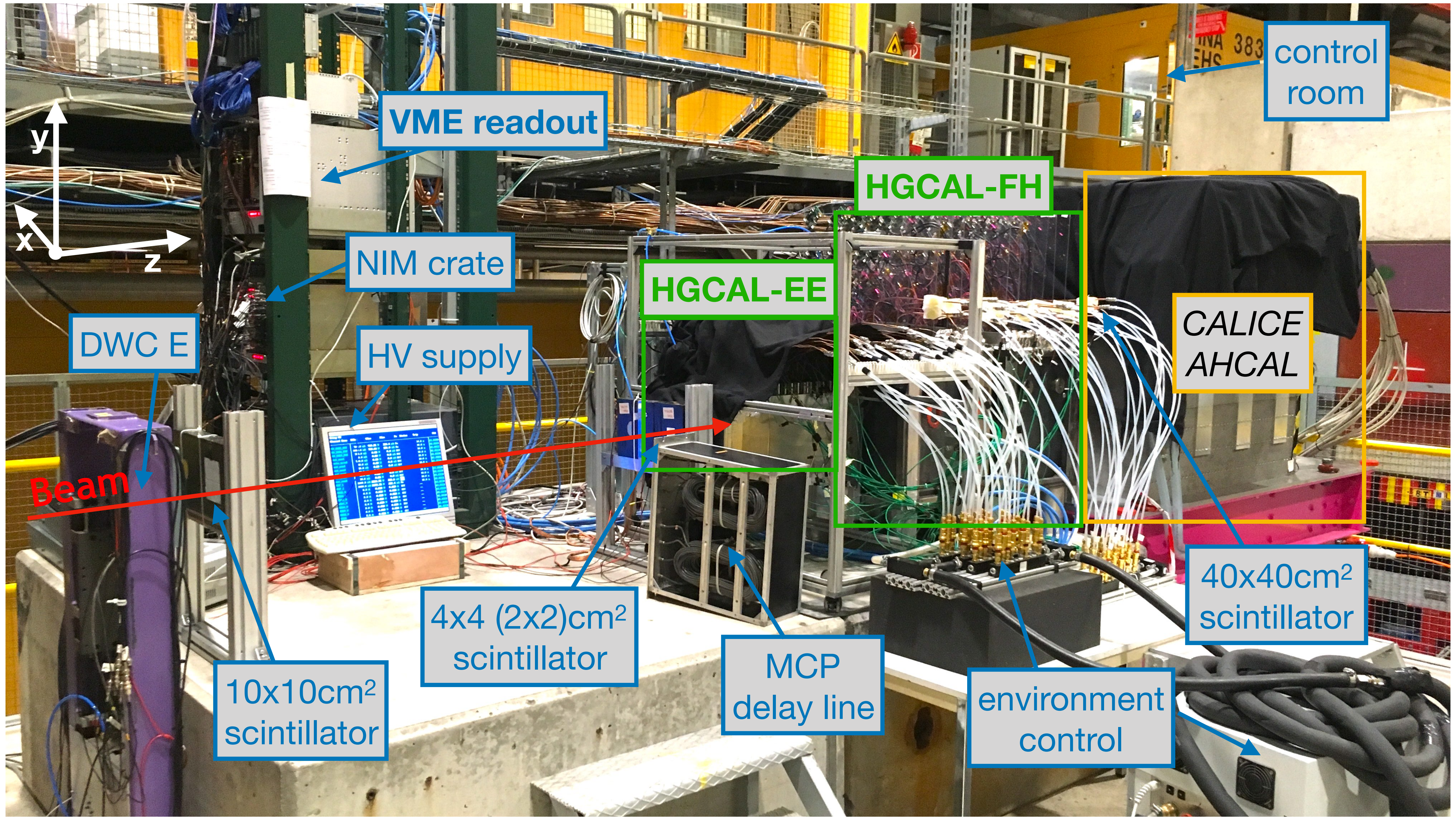


BEAM TESTS

October 2018: beam test @CERN-SPS

Validation of the **detector design** and assessment of **HGCAL performance**

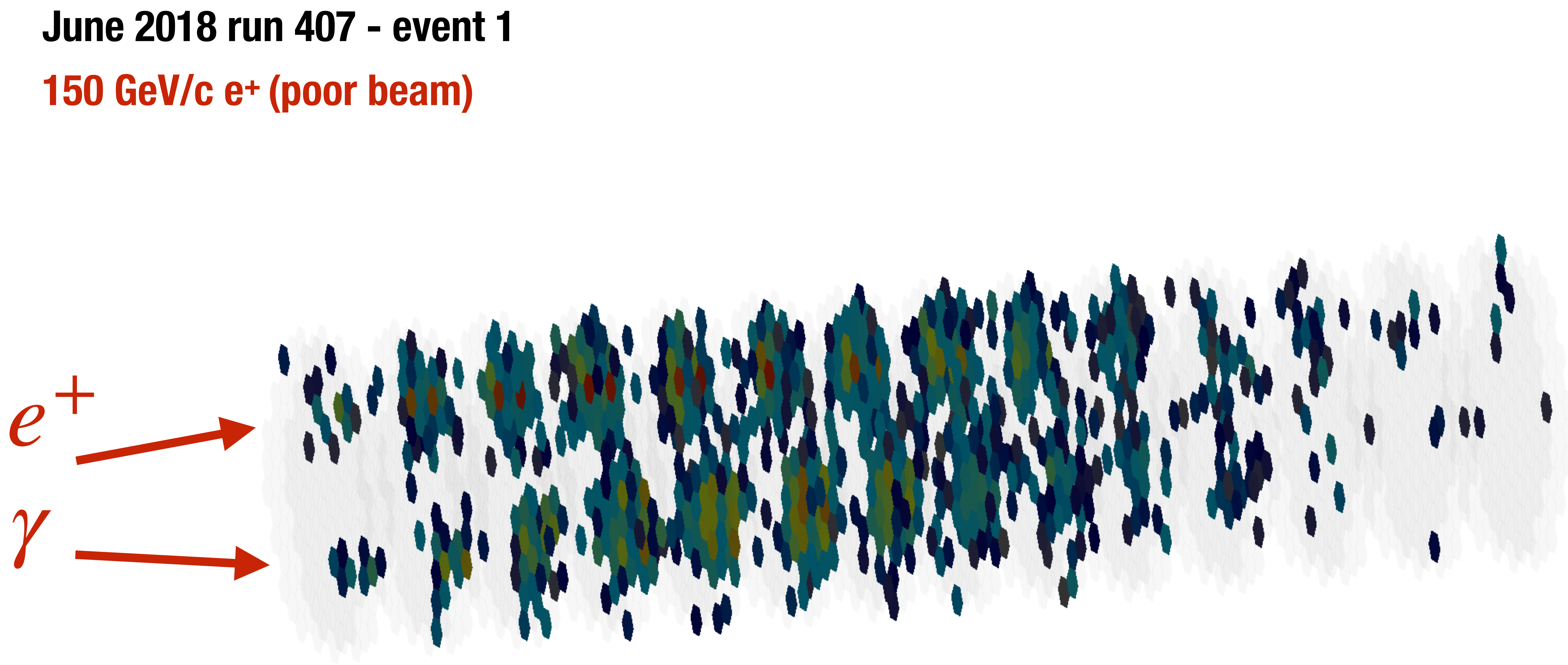
- **First large scale prototype**
  - 28 layers CE-E
  - 12 layers CE-H
  - 39 layers CALICE AHCAL
- **Calibration with MIPs** and showers;
- **Physics performance** : e^+ and π^- over a wide energy range (20-300 GeV);
- **Timing performance** from TOA.



O(10⁶) events collected!

Electrons performance in CE-E

Fine longitudinal and transverse granularities: **HGCAL is an *imaging* calorimeter**



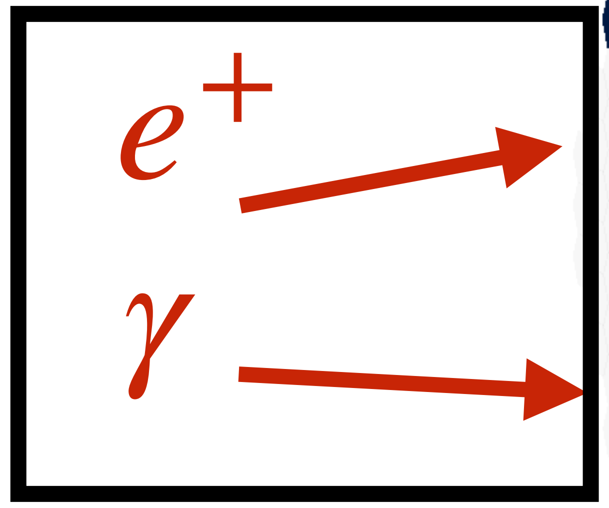
Electrons performance in CE-E

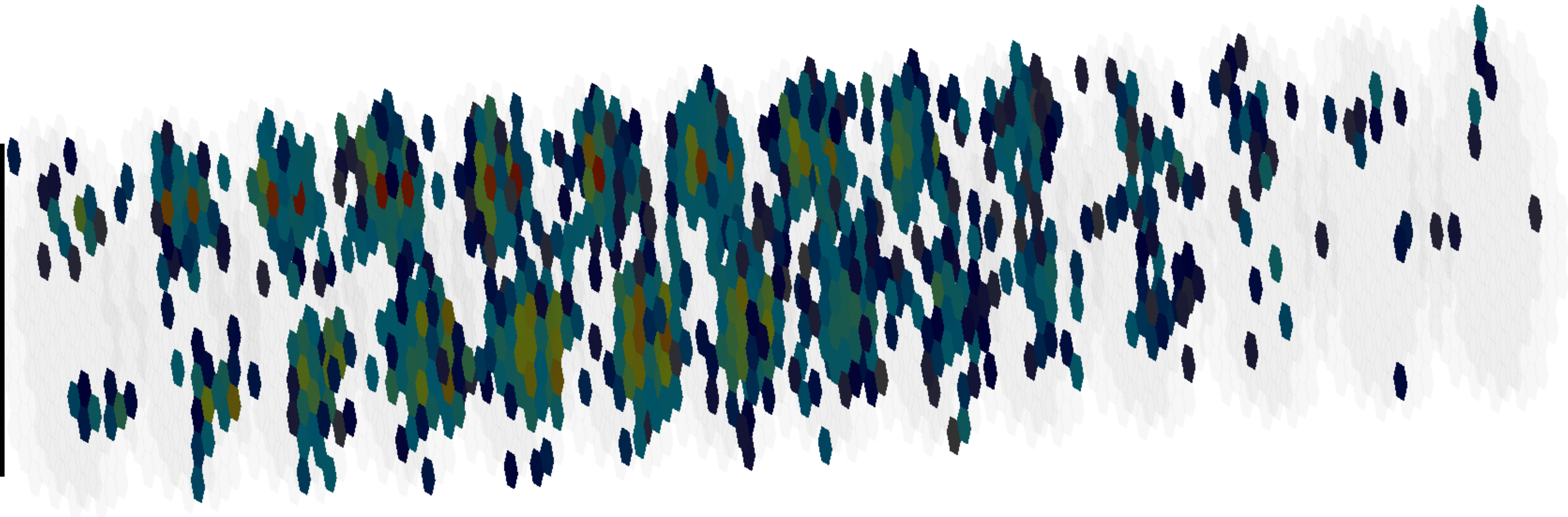
Fine longitudinal and transverse granularities: **HGCAL is an *imaging* calorimeter**

June 2018 run 407 - event 1

150 GeV/c e+ (poor beam)

Particle ID
&
Energy reco





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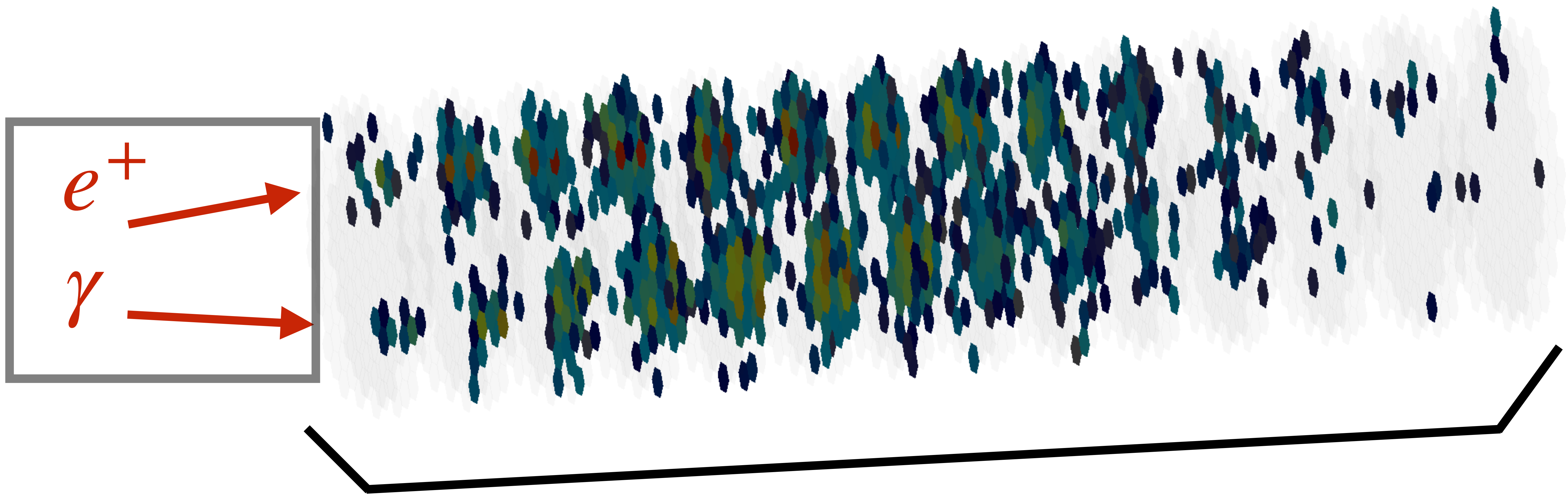

Longitudinal shower shapes

Electrons performance in CE-E

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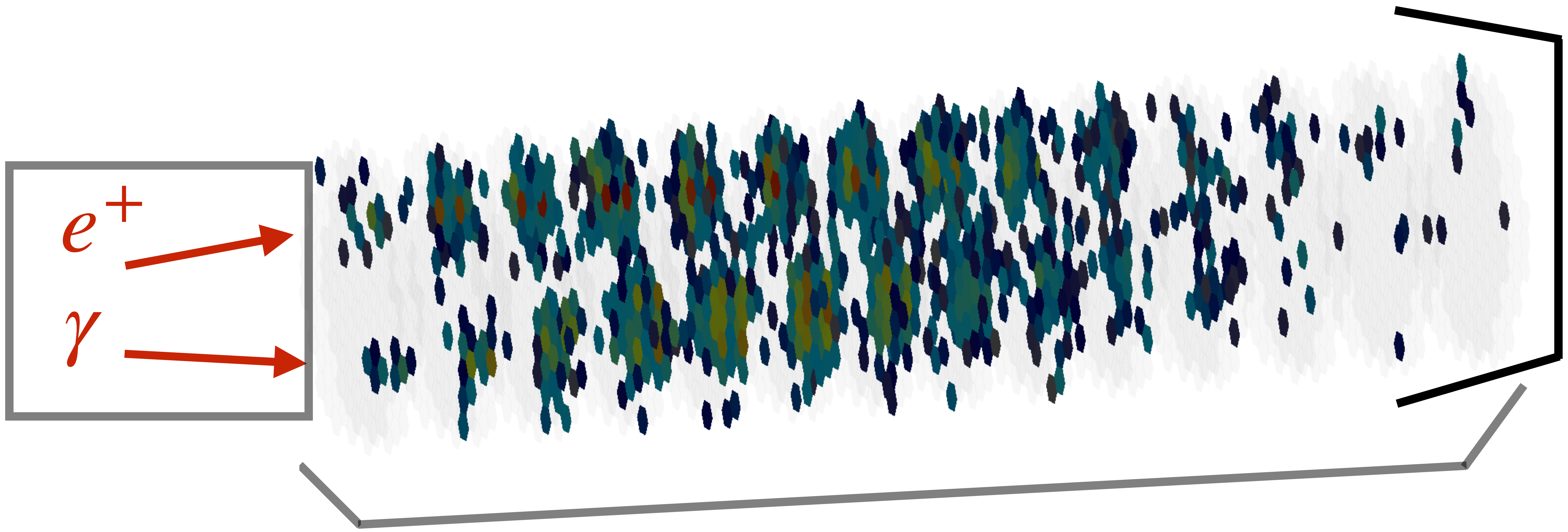

Transverse shower shapes

Longitudinal shower shapes

Electrons performance in CE-E

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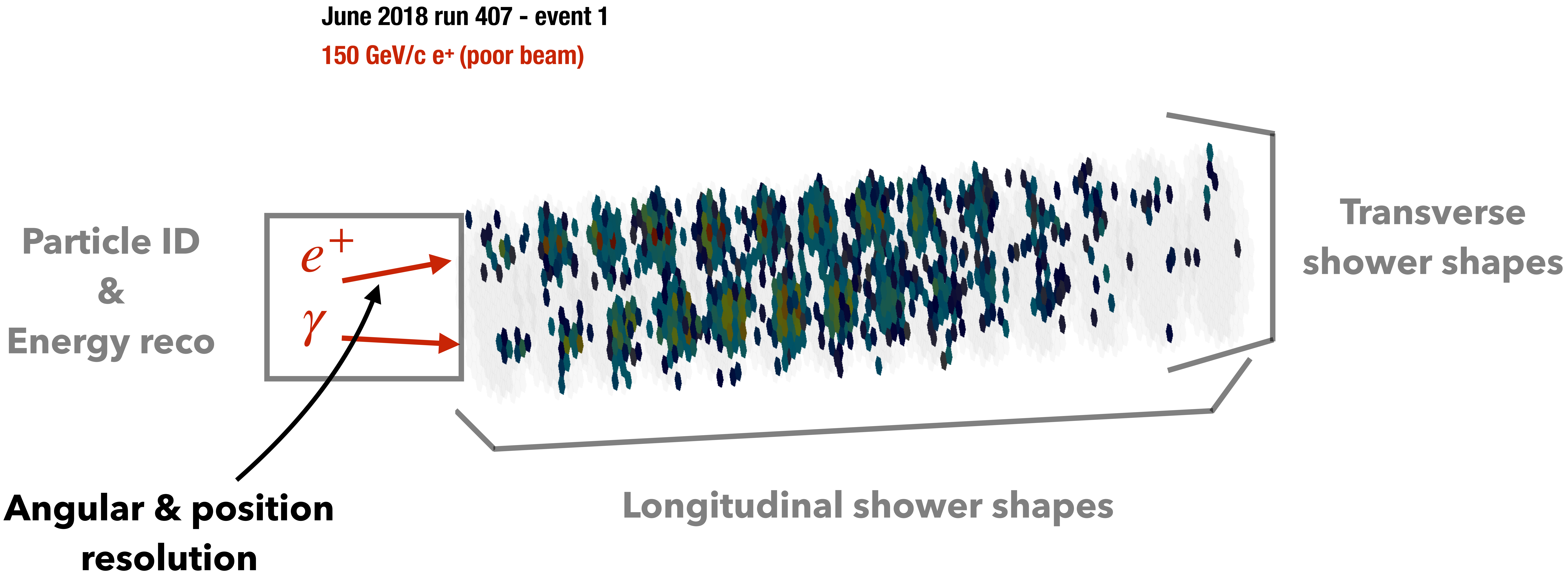

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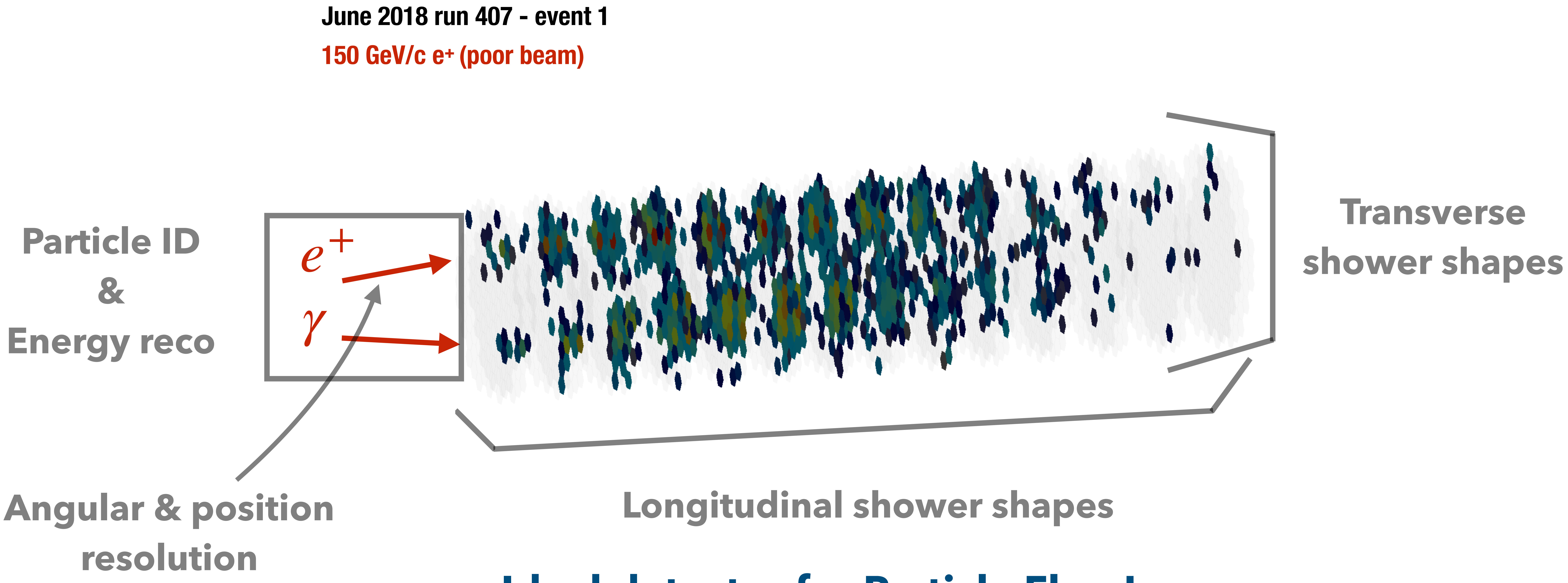
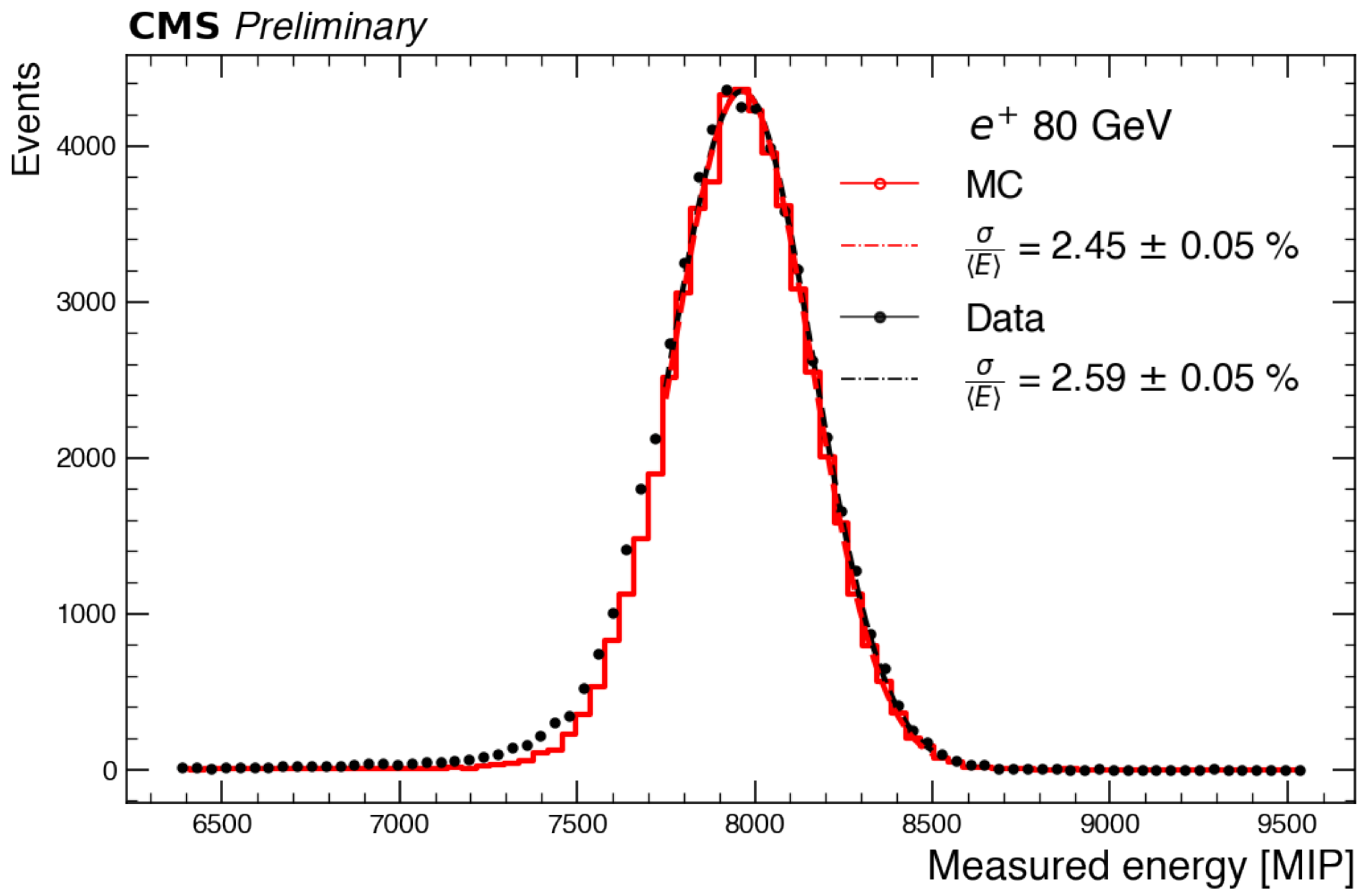


Ideal detector for Particle Flow!

Electrons energy reconstruction

- **Different reconstructions** studied: **MIP** calibration, **dE/dx weights**, sampling fraction method (**SF**);
- **Energy distribution:** unclustered **energy sum** of the deposit **in all Si-pads**;
- **Gaussian fit** around the core region **to determine the energy resolution $\sigma_E/\langle E\rangle$**
- **Good Data/MC agreement** throughout the full energy range;

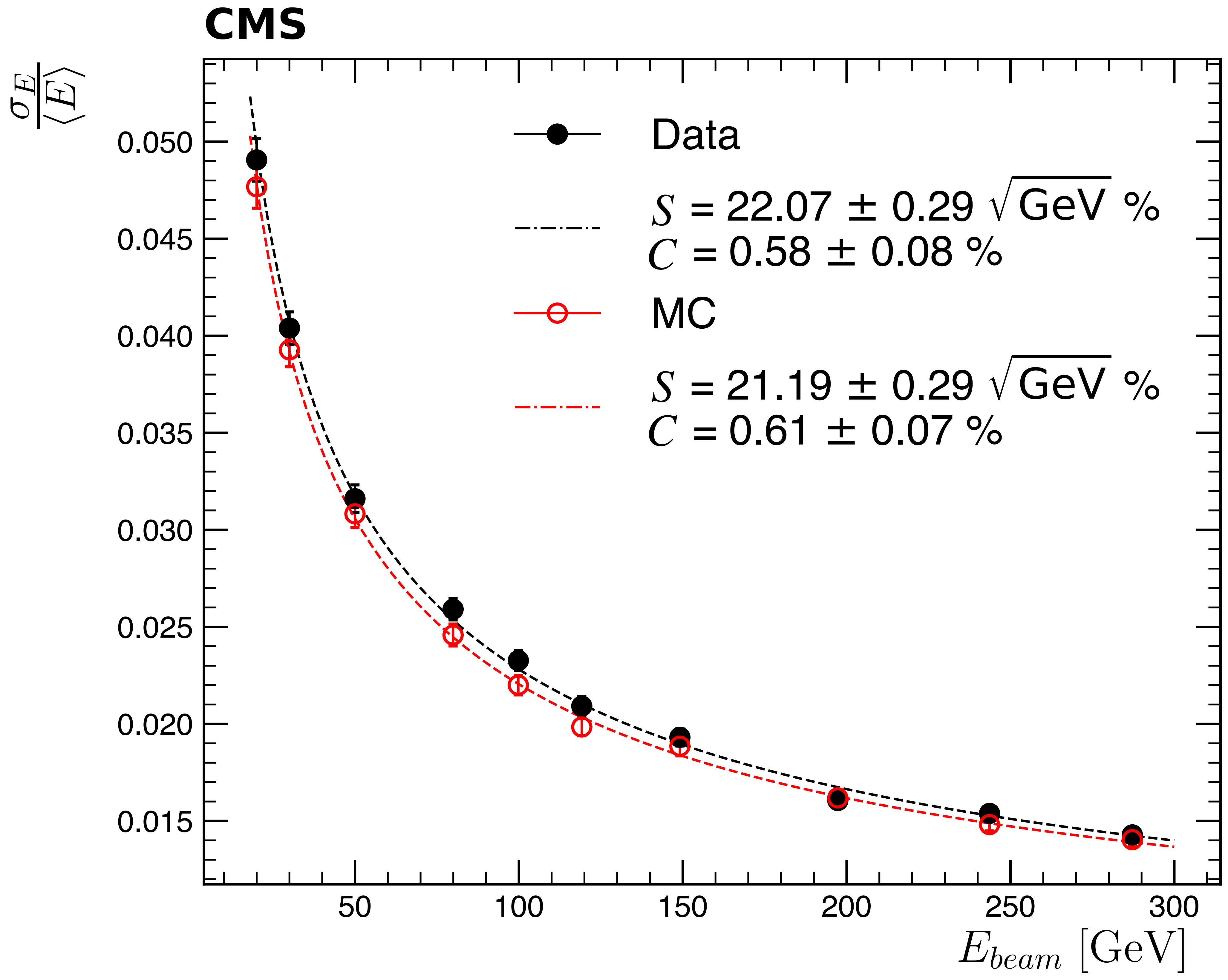


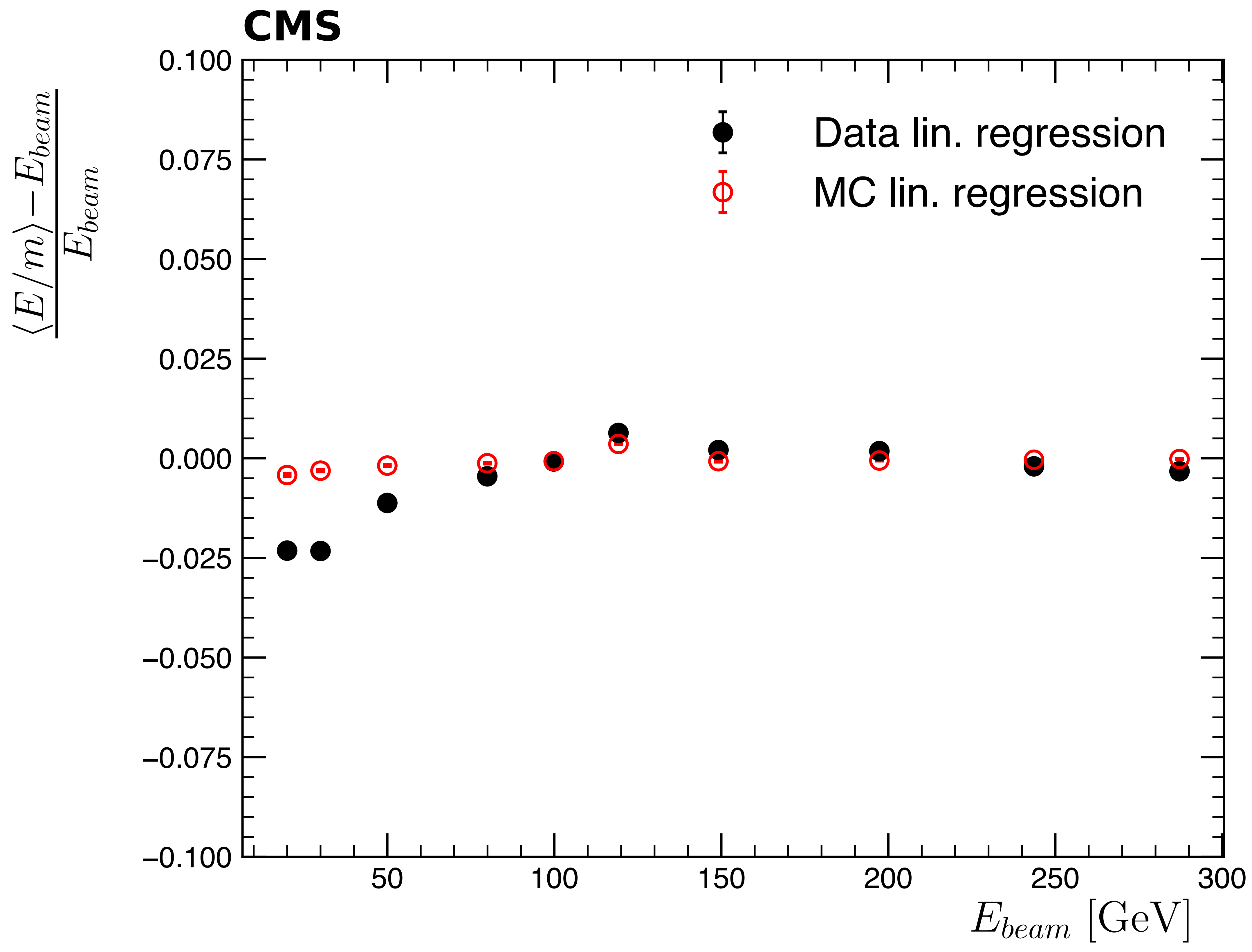
Energy resolution and linearity

Good Data/MC agreement across the entire energy range

Small non-linearity O(2%) at low energies, but optimal linearity for E>50 GeV

Values in agreement with TDR expectation!



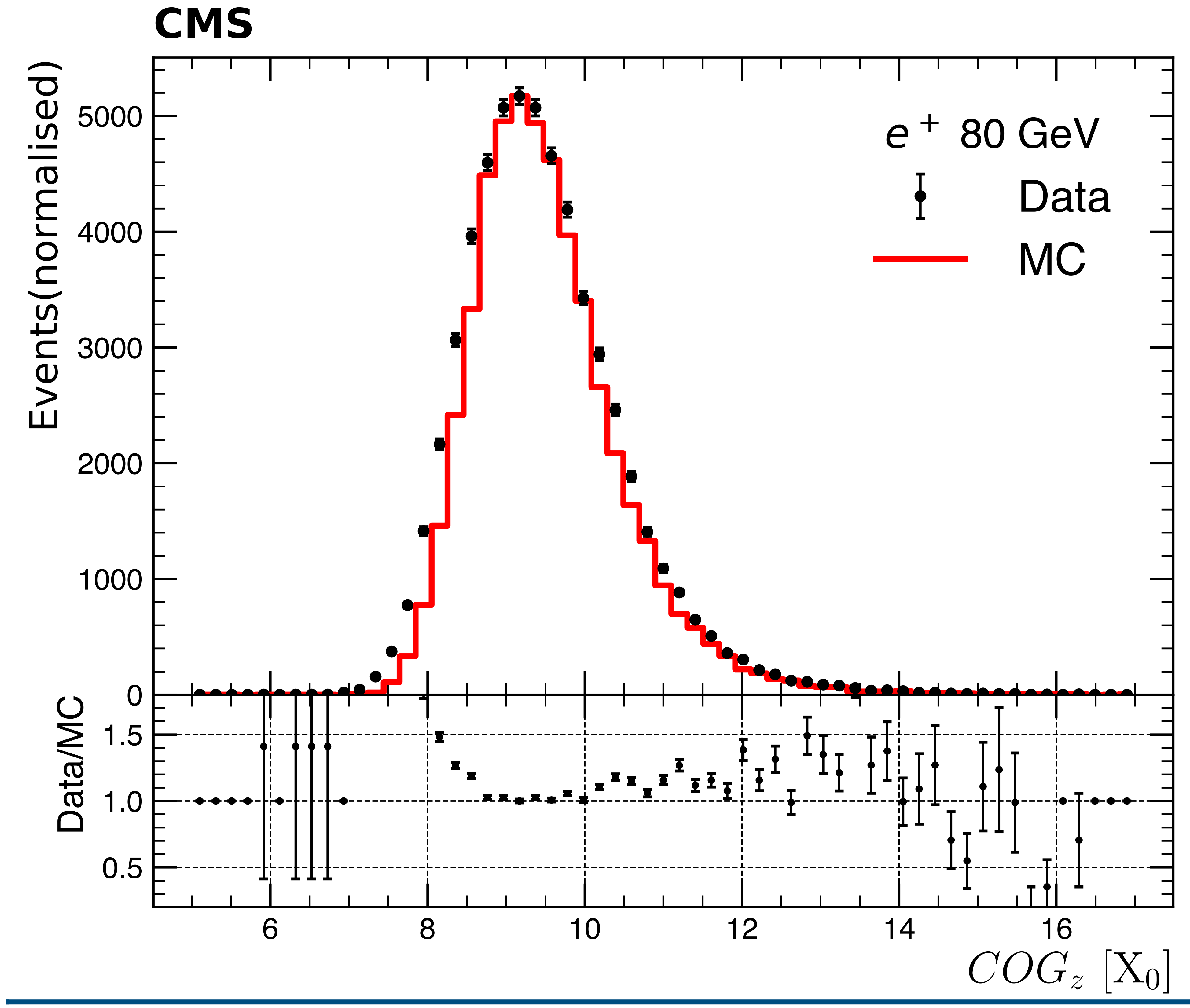


Longitudinal center of gravity

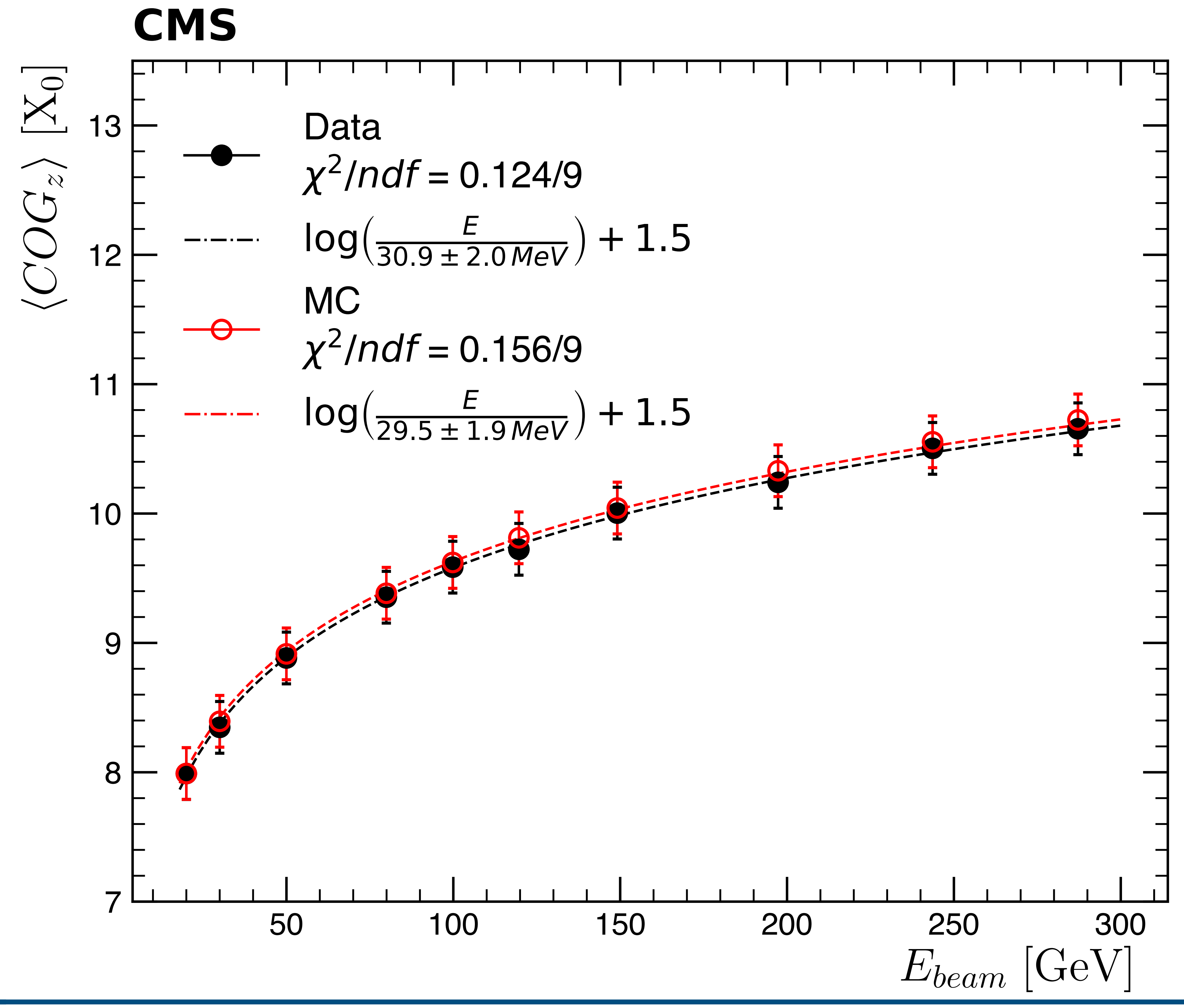
Assessment of longitudinal shower evolution studying **center of gravity:**

$$COG_z = \frac{\sum_{i=1}^{28} E_i^{Si} \cdot z_i[X_0]}{\sum_{i=1}^{28} E_i^{Si}}$$

Validation of dependence on the beam energy and measurement of CE-E critical energy



Average COG_z from reconstructed distribution



Shower shapes: longitudinal profiles

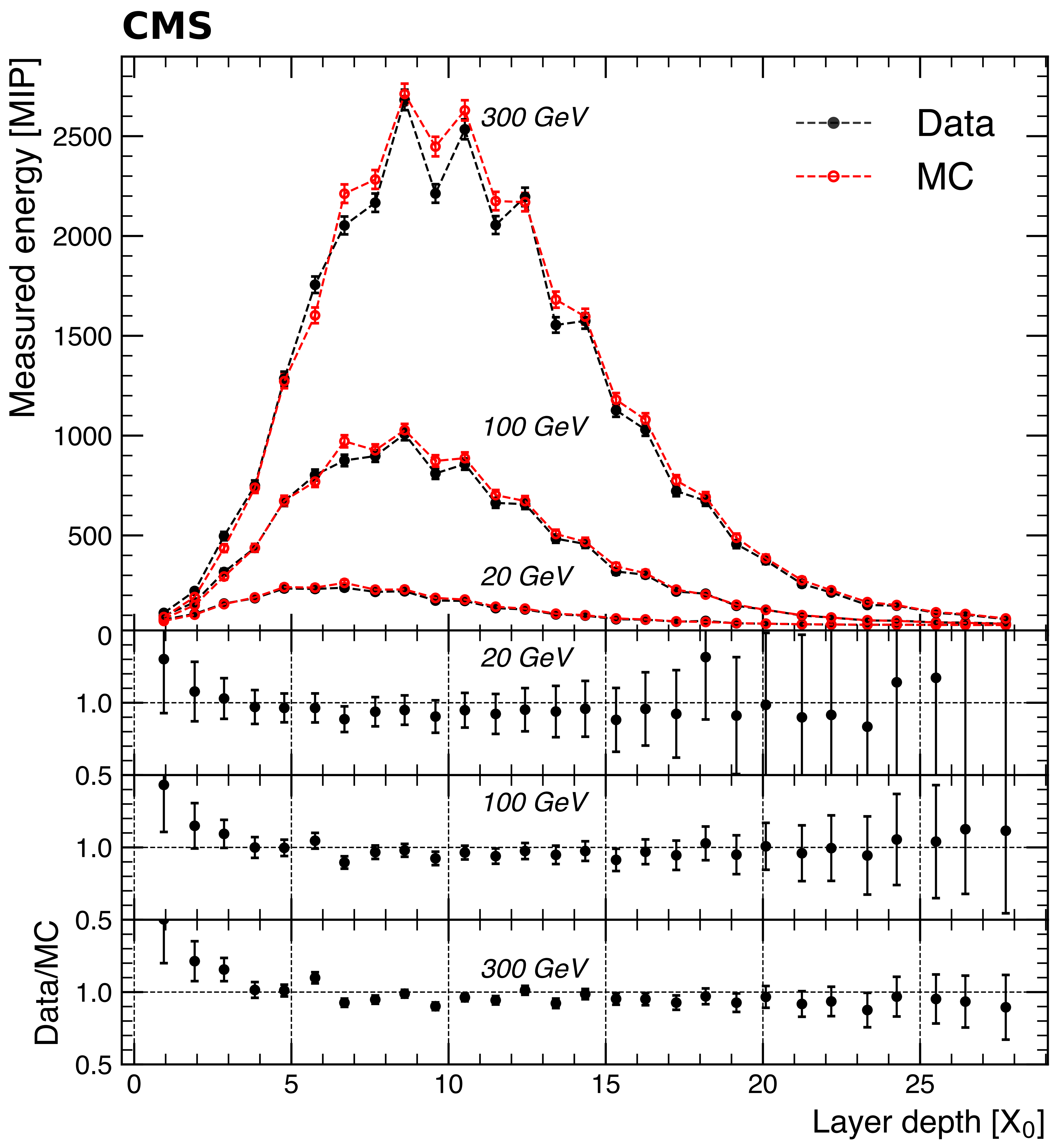
Longo's parametrisation:

$$\left\langle \frac{dE(t)}{dt} \right\rangle = E_0 \frac{(\beta t)^{\alpha-1}\beta \exp(-\beta t)}{\Gamma(\alpha)},$$

Longitudinal center of gravity and shower maximum:

$$\langle COG_z \rangle = \frac{\alpha}{\beta}, \quad t_{\text{max}} = \frac{\alpha - 1}{\beta}$$

- Validation of $\langle COG_z \rangle$, $t_{\text{max}} \propto \ln\left(E/E_C\right)$
- **Measurement of** the CE-E **critical energy**
- Sampling calorimeter: reconstruction of the longitudinal profiles

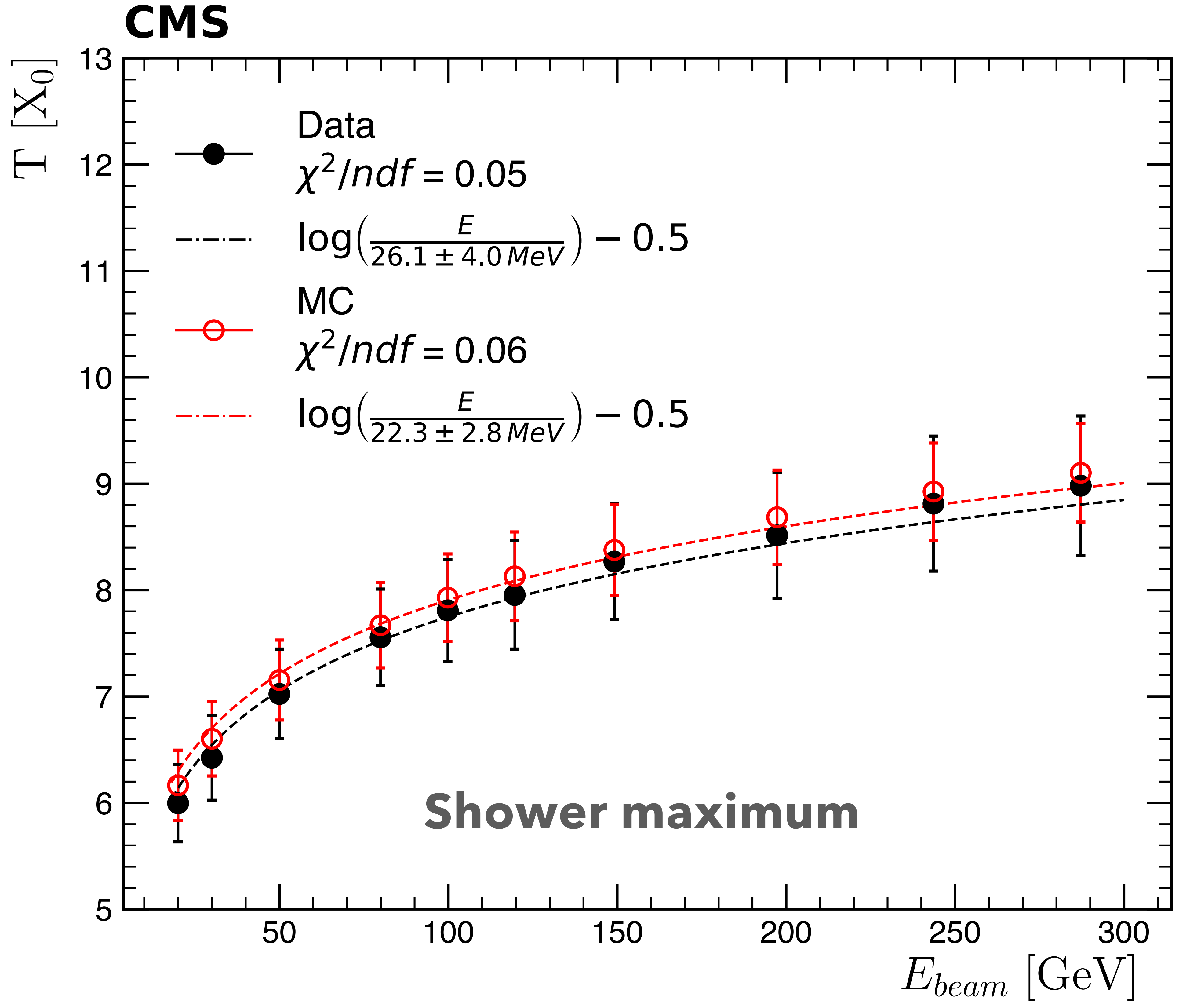


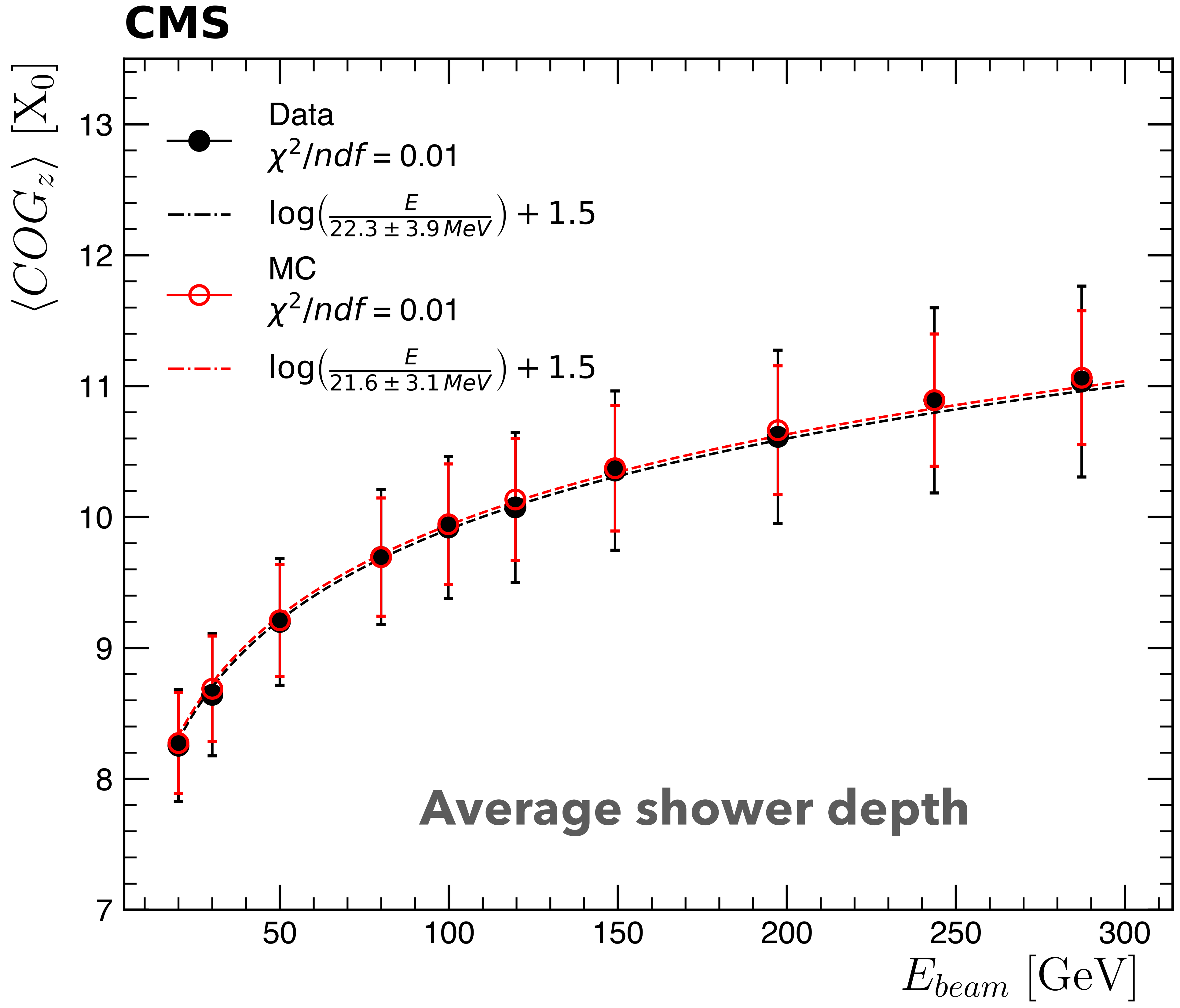
From the fit to CE-E critical energy

Measurement of the CE-E Critical Energy from T and $\langle COG_z \rangle$ vs E_{beam}

Complete reconstruction of longitudinal showers profile

Good Data/MC agreement over a wide energy range



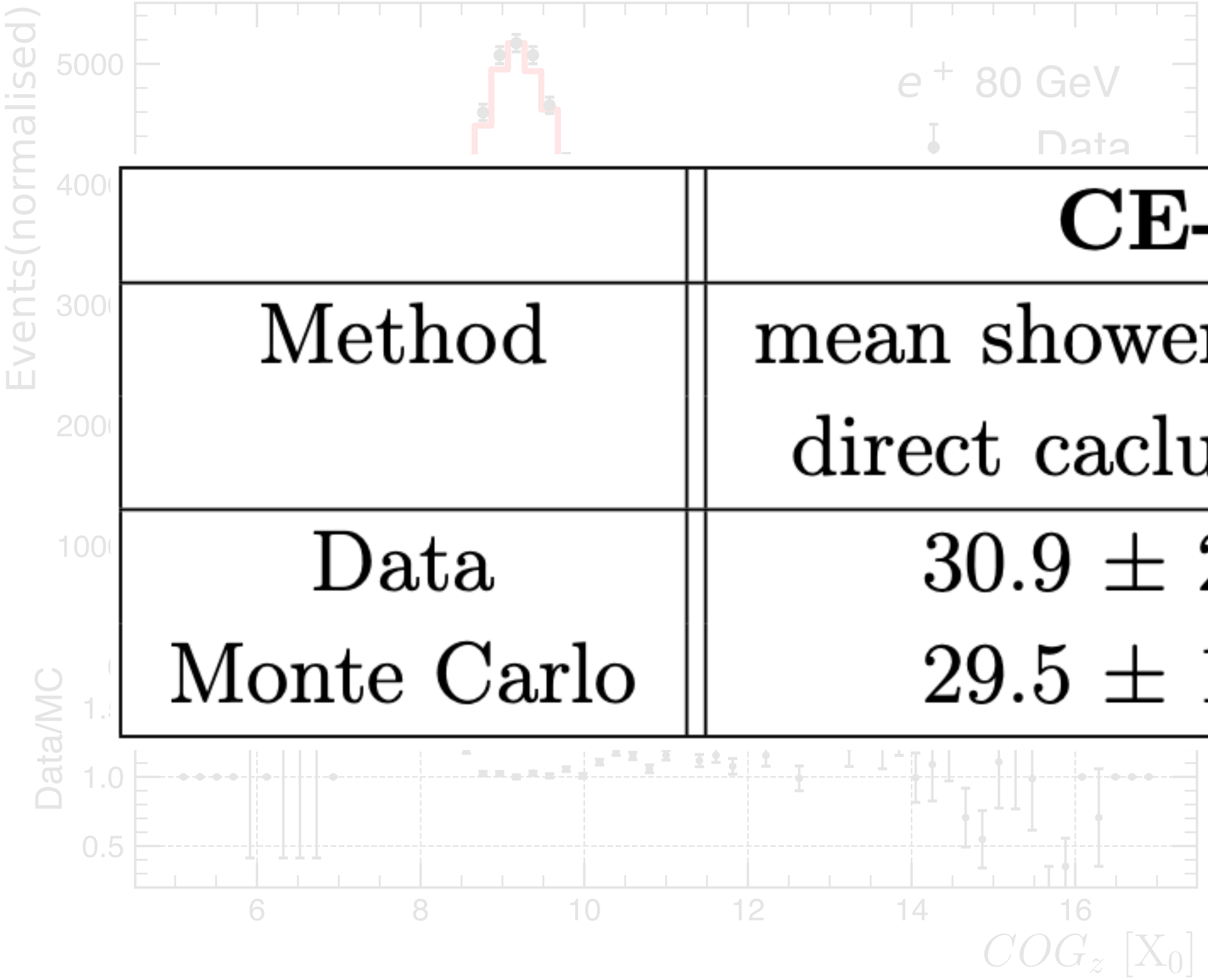


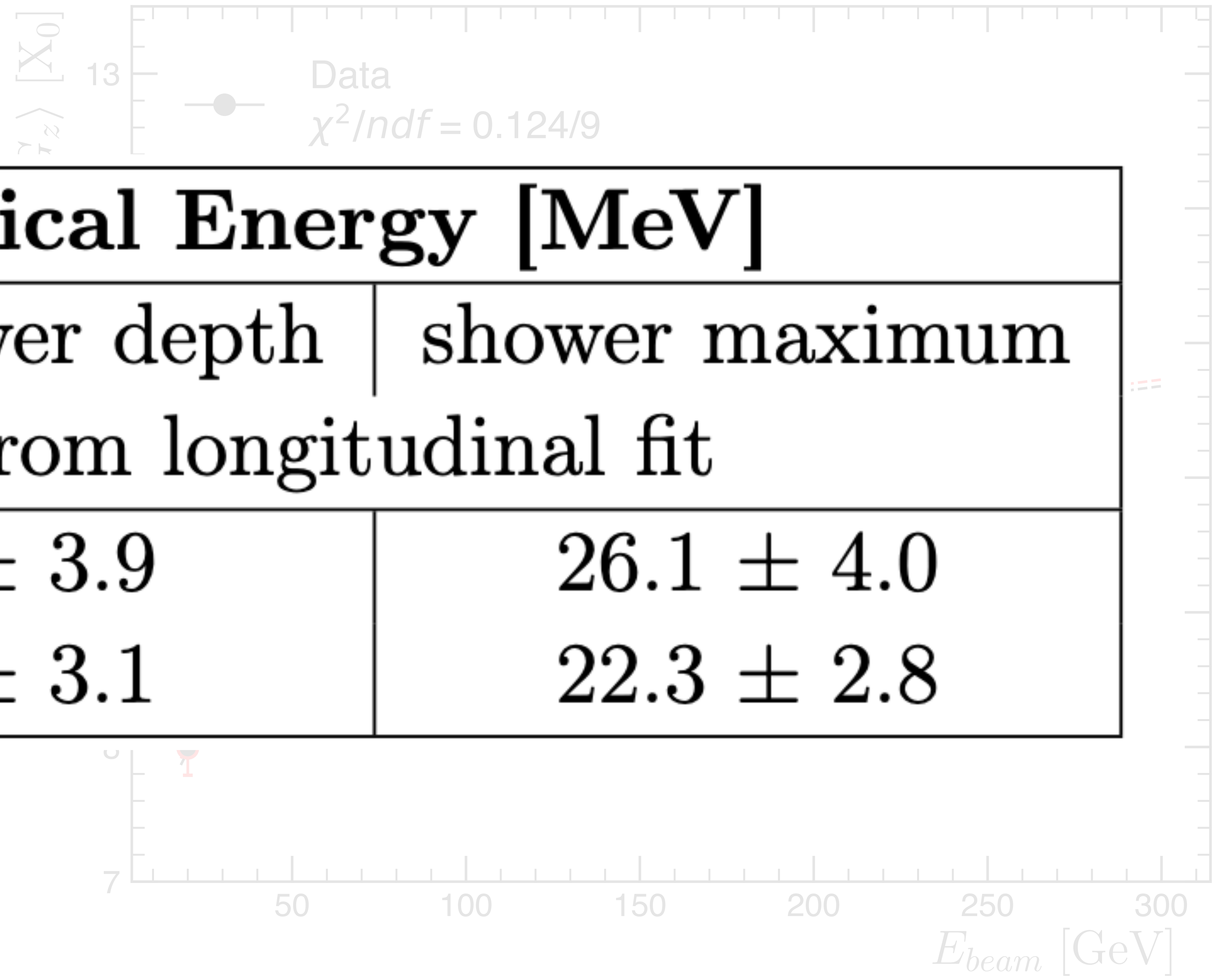
CE-E critical energy in a nutshell

Three complementary measurements of CE-E Critical Energy (E_C)

Overall qualitative agreement within 2σ

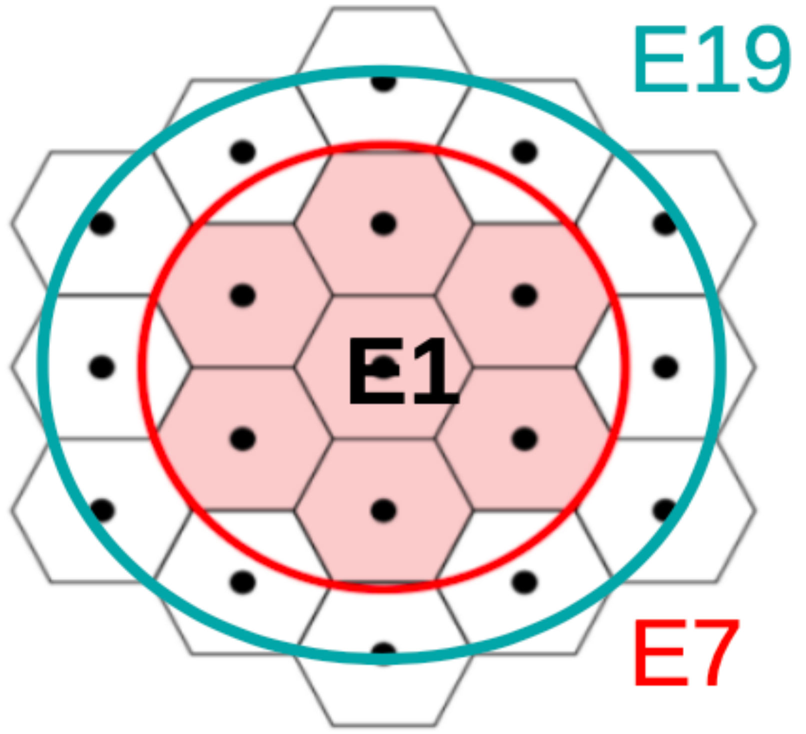
E_C from longitudinal fit lower than E_C from $\langle COG_z \rangle$ definition, being the latter more precise





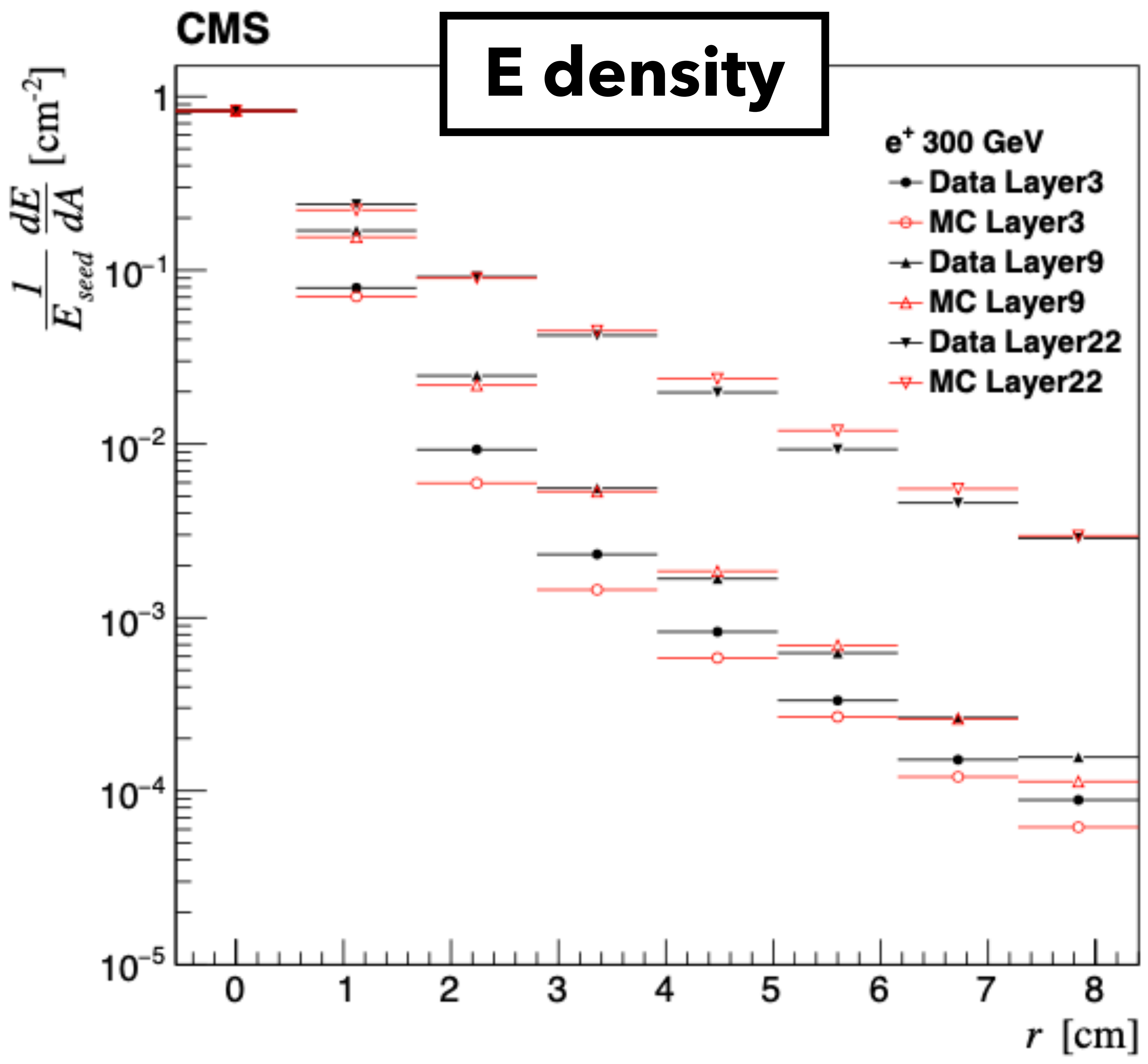
	CE-E Prototype Critical Energy [MeV]		
Method	mean shower depth direct caclulation	mean shower depth from longitudinal fit	shower maximum from longitudinal fit
Data	30.9 ± 2.0	22.3 ± 3.9	26.1 ± 4.0
Monte Carlo	29.5 ± 1.9	21.6 ± 3.1	22.3 ± 2.8

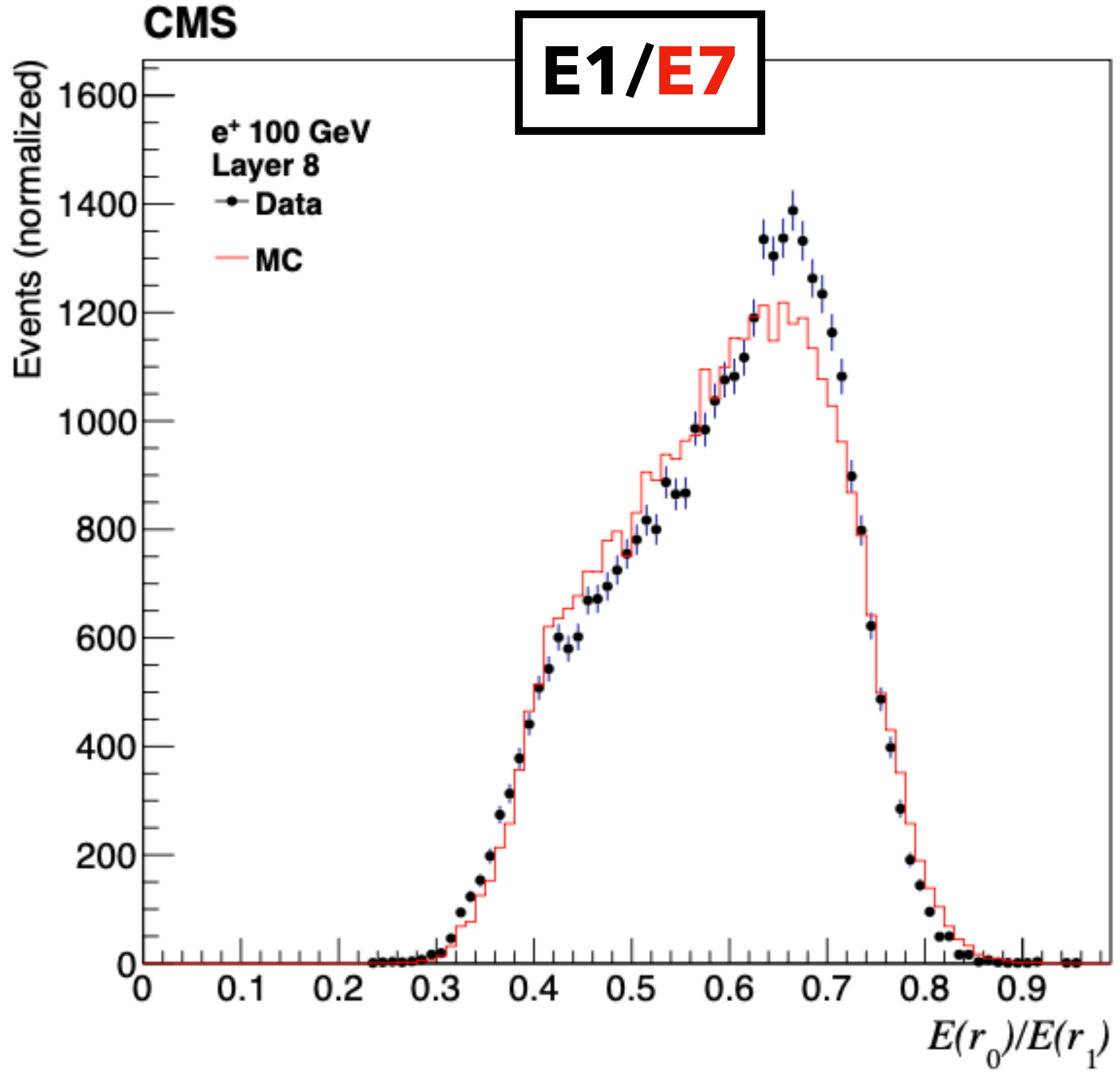
Transversal shower shapes

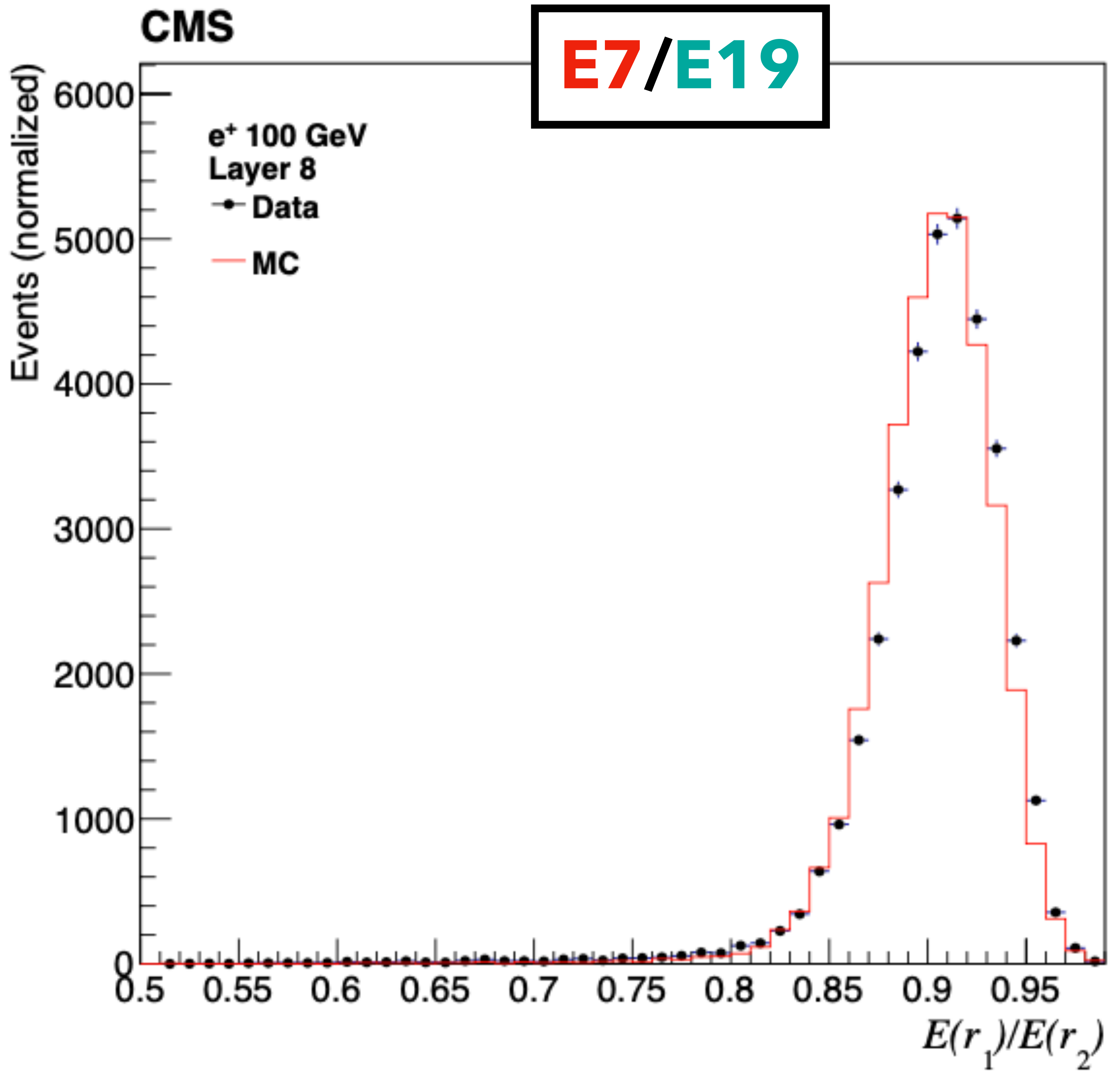


Transverse shower **containment** assessed looking at:

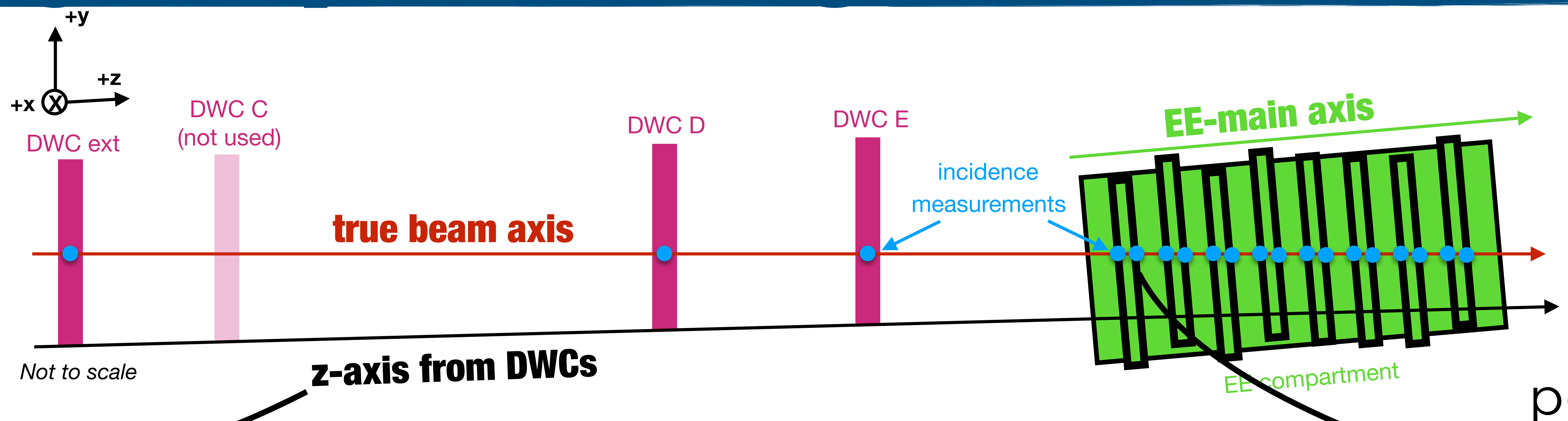
- **Layer energy density w.r.t central pad** (*seed*)
- **Ratio** between **central pad and one (two) ring(s) around it**







Single layer pointing resolution

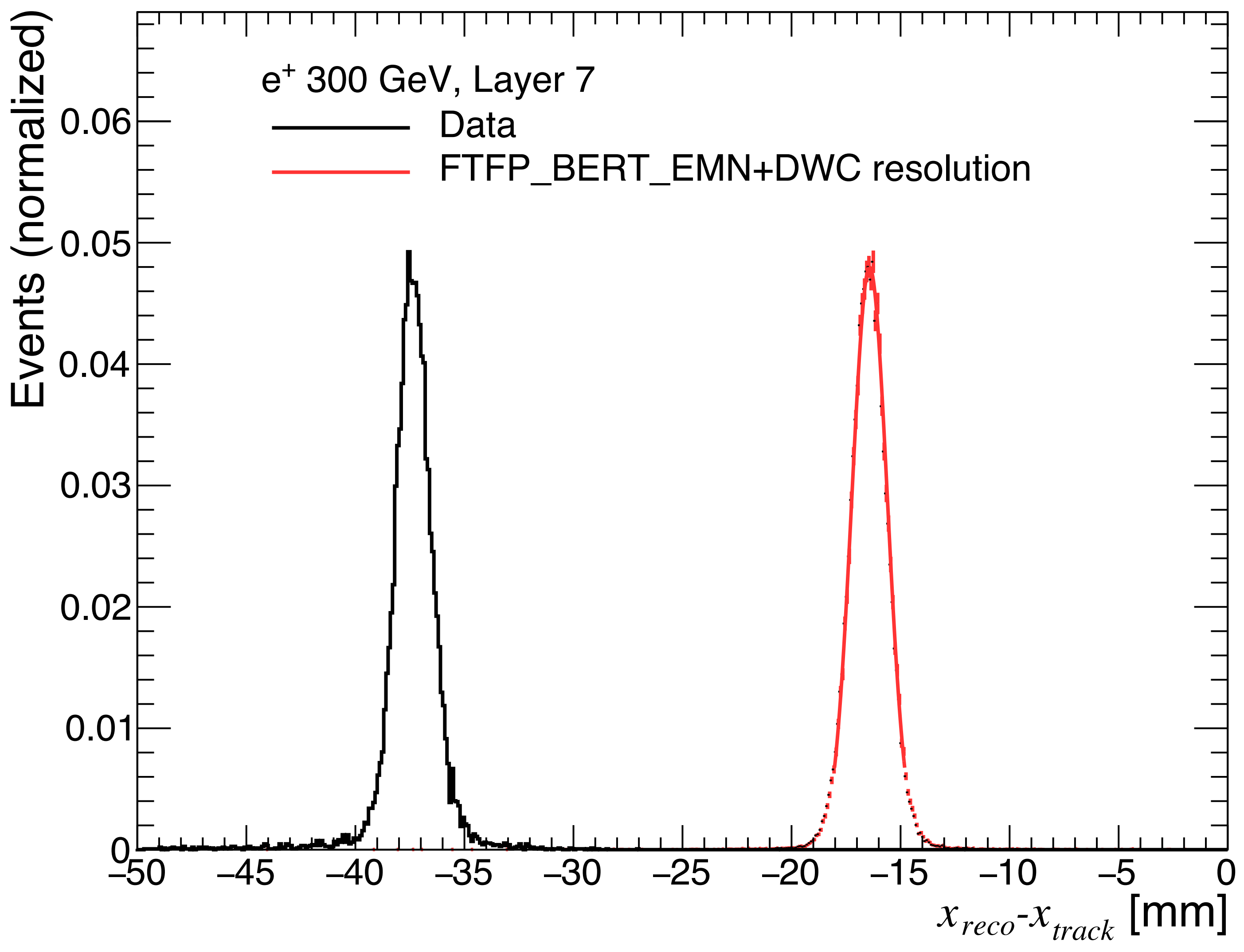


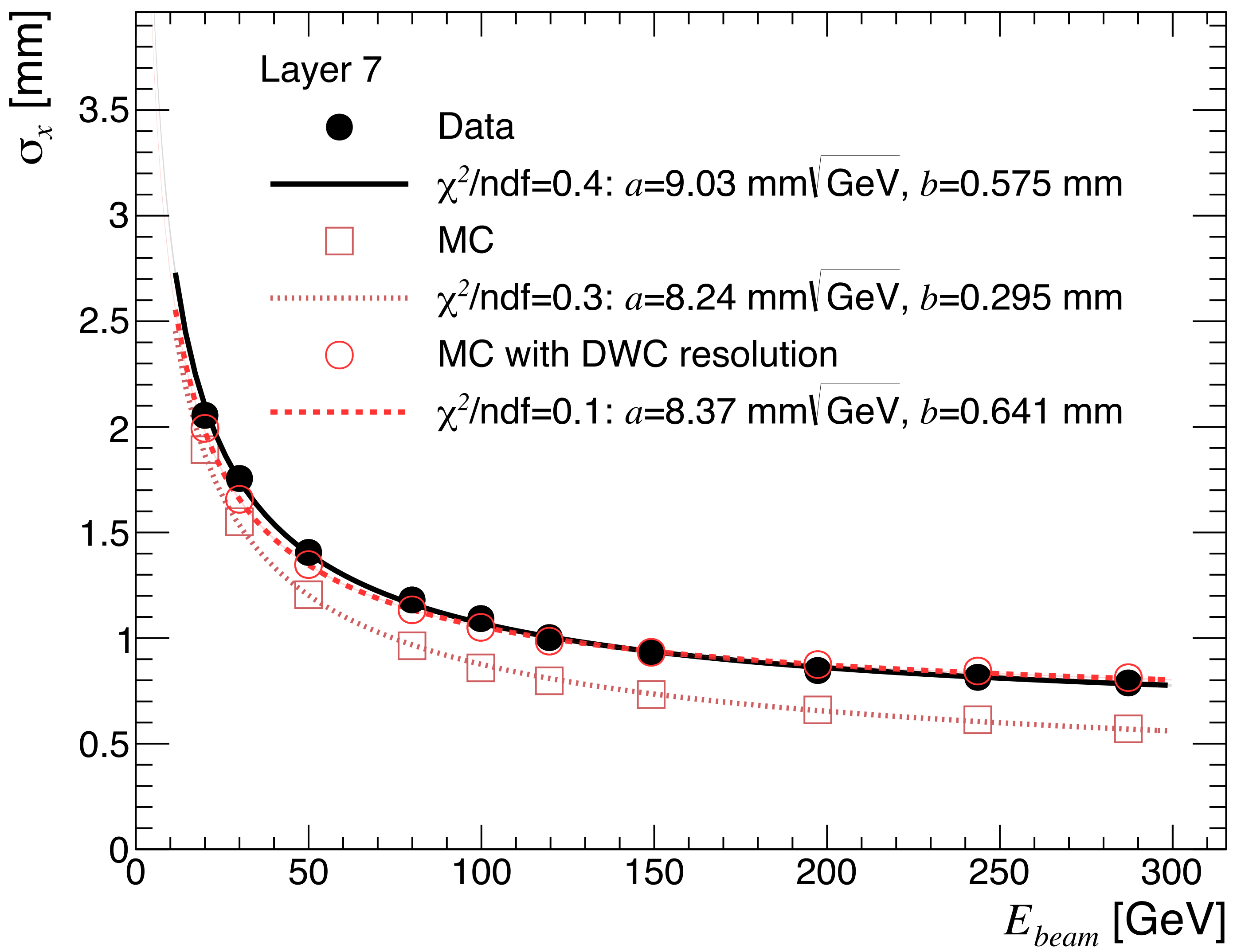
DWCs used to infer impact points in HGCAL layers

Log-E weighted reconstructed position on each layer

$$\vec{x}_{\text{reco}} := \frac{\sum_{i \in M} \omega(E_i) \cdot \vec{x}_i}{\sum_{i \in M} \omega(E_i)}$$

Pointing resolution from gauss fit of residuals





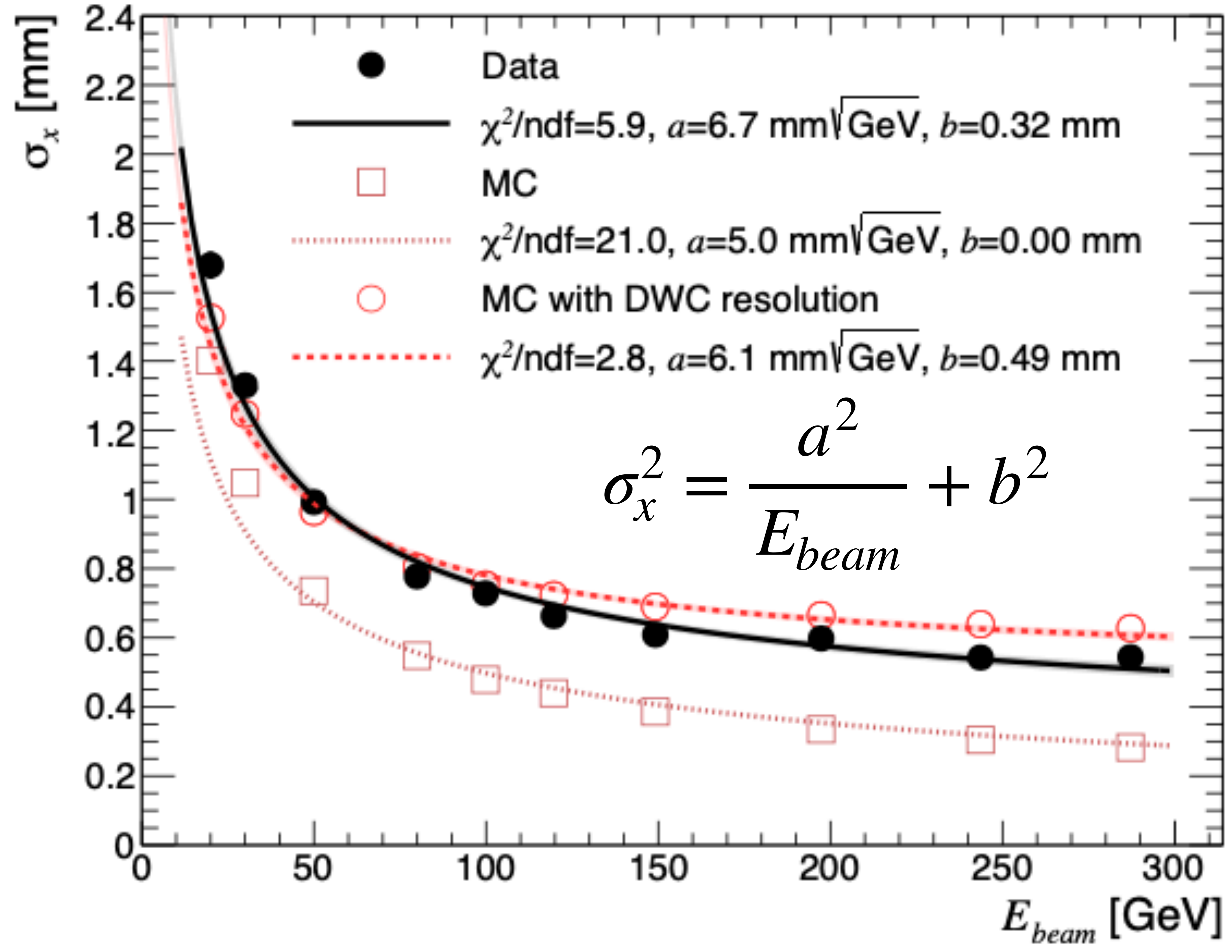
Position & angular resolution

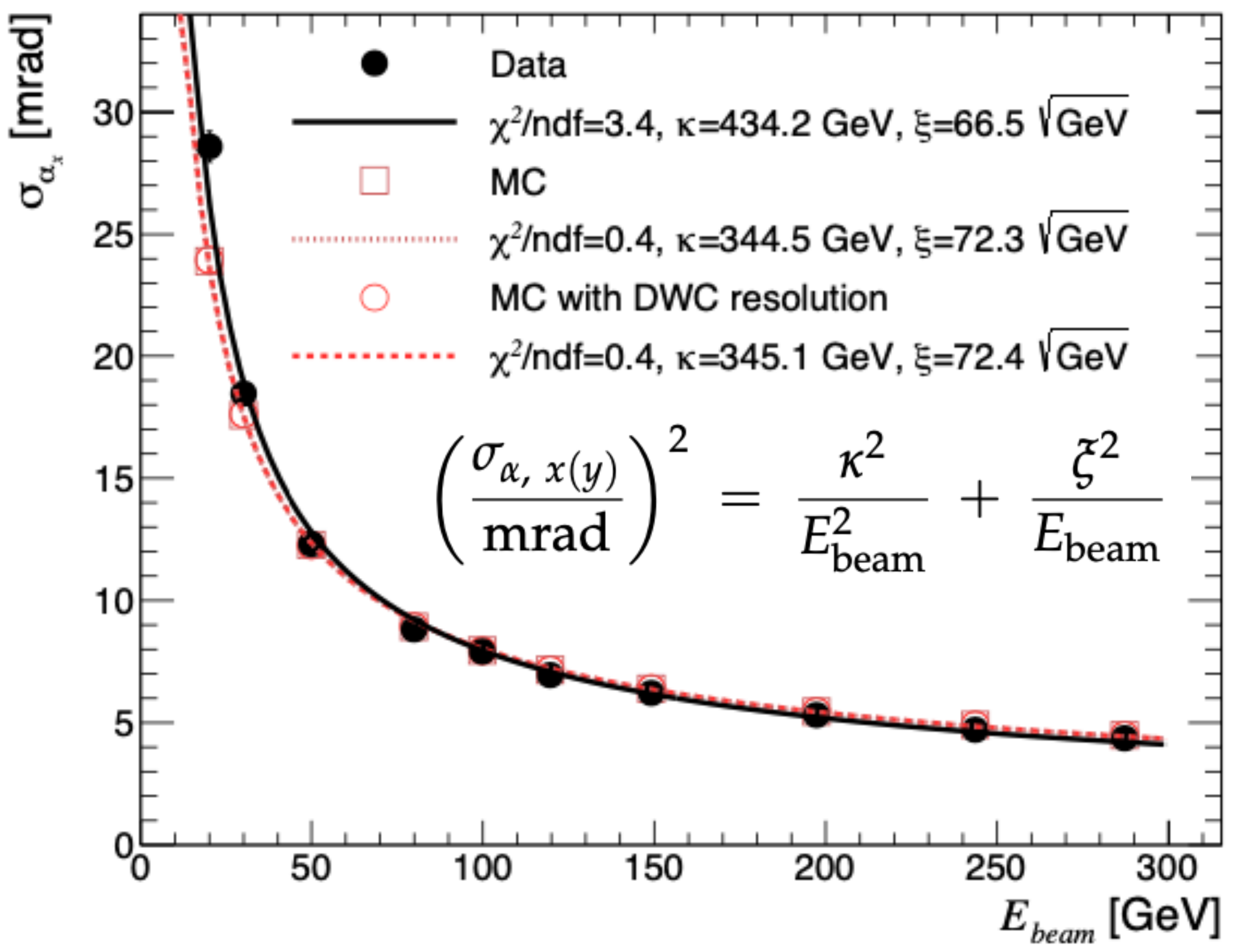
CE-E prototype with 28 layers: shower axis reconstruction

Straight line fit on single layer positions for layers with 1% to 95% energy deposit

DWC and HGCAL systems alignment → **residuals** as a **function** of **longitudinal center of gravity**

Pointing and **angular resolutions of the HGCAL CE-E prototype**





Conclusions

The **HGCAL** will **replace CMS endcap** calorimeters for **HL-LHC programme**

28-layer CE-E HGCAL prototype studied in beam tests:

- **Validation of dedicated GEANT4 simulation** shows good agreement
- **Energy resolution**: $S \simeq 22\,\%$, and $C \simeq 0.6\,\%$ **in agreement with TDR expectation**
- Complete shower characterisation: **longitudinal** and **transverse** shower **shapes**
- ***Imaging calorimeter:*** reconstruction of **shower axis**
- **Position** and **angular resolutions** at the level of 0.3 mm and 5 mrad

Validation of the HGCAL design and complete characterisation of electromagnetic showers!

CMS High Granularity Calorimeter Prototype at CERN
Timing Analysis

Test Beams 2018

Rohith Saradhy
(University of Minnesota)
On behalf of the HGCAL Beam Tests group

10th February, 2021

Motivation Recap

- High Granularity Calorimeter will replace CMS End-Caps as part of the HL-LHC upgrade
- Two of the many challenges that HL-LHC poses are:
  - Higher Levels of Pileup
  - Higher Dose of Radiation
- HGCAL prototype was designed keeping these constraints in mind, and the prototypes was tested at various beam facilities over the past few year.
- Si detectors are radiation tolerant compared to the Lead Tungstate Crystals currently used, these are used in the CE-E and CE-H-Si parts of the HGCAL (placed in high radiation zones) to provide radiation tolerance.
- One of the goals of the 2018 Test Beam was to characterize the timing of the HGCAL Prototype.
  - The 2018 HGCAL prototype uses SKIROC2_CMS ASIC with a precision as low as 50ps
  - The final version with HGCROC ASIC will have a precision of ≥ 20ps (for Si)
- These tests were essential to validate the Monte Carlo simulation of the prototype and readout.
  - The same Monte Carlo will be used in the design of the final version of the detector and readout

October 2018 Test Beam Configuration

Delay Wire Chamber

Threshold Cherenkov Counter

CALICE - AHCAL

e, ***μ***, ***hadrons* upto 300 GeV**

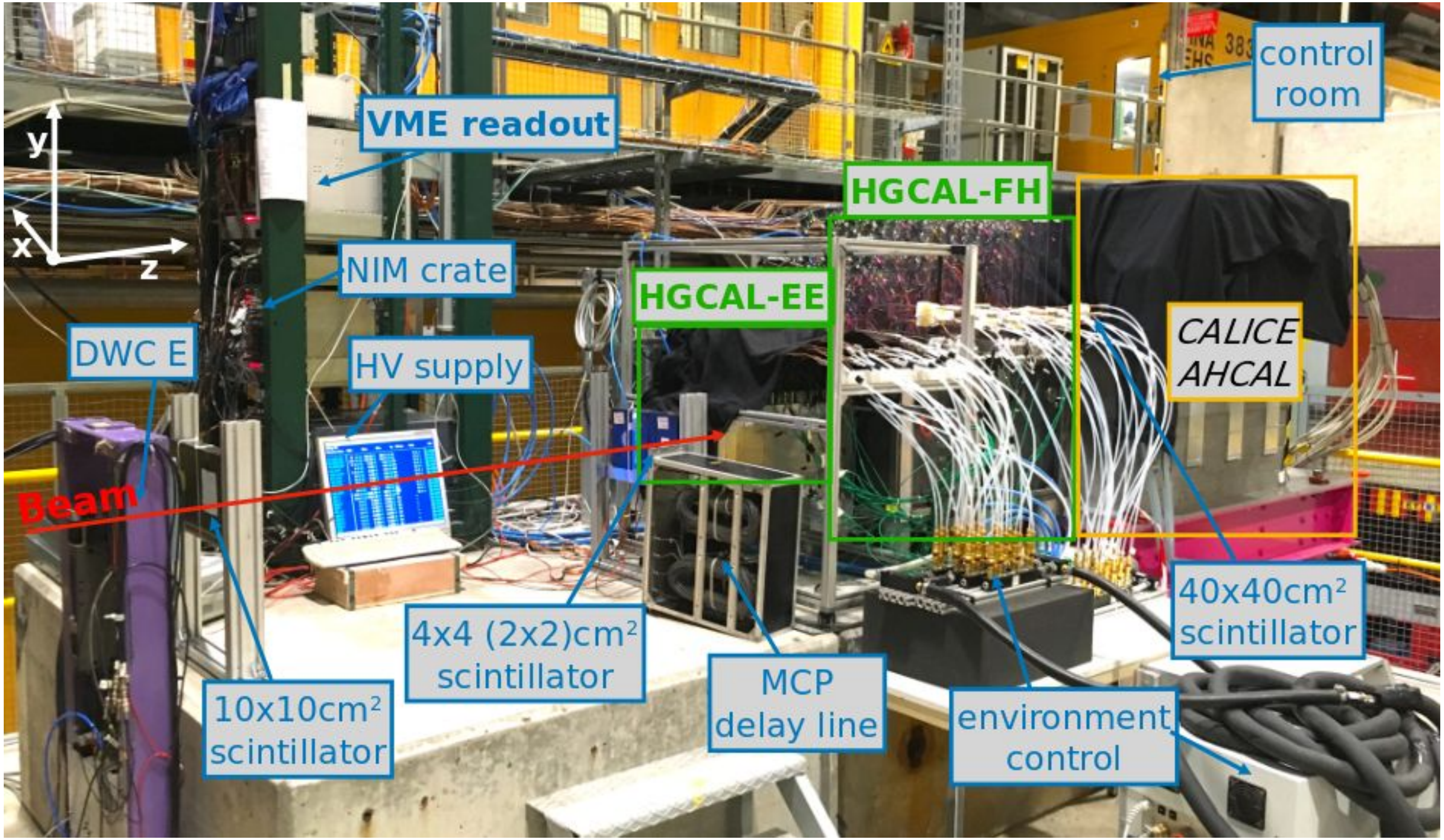
Trigger:

2x Scintillators in front of CE-E

1x Veto Behind CE-H-Si

Two MCP Detectors (Micro Channel Plate)

- ➔ Used as a reference time-stamp
- ➔ In-front of CE-E
- ➔ Orthogonal to the beam

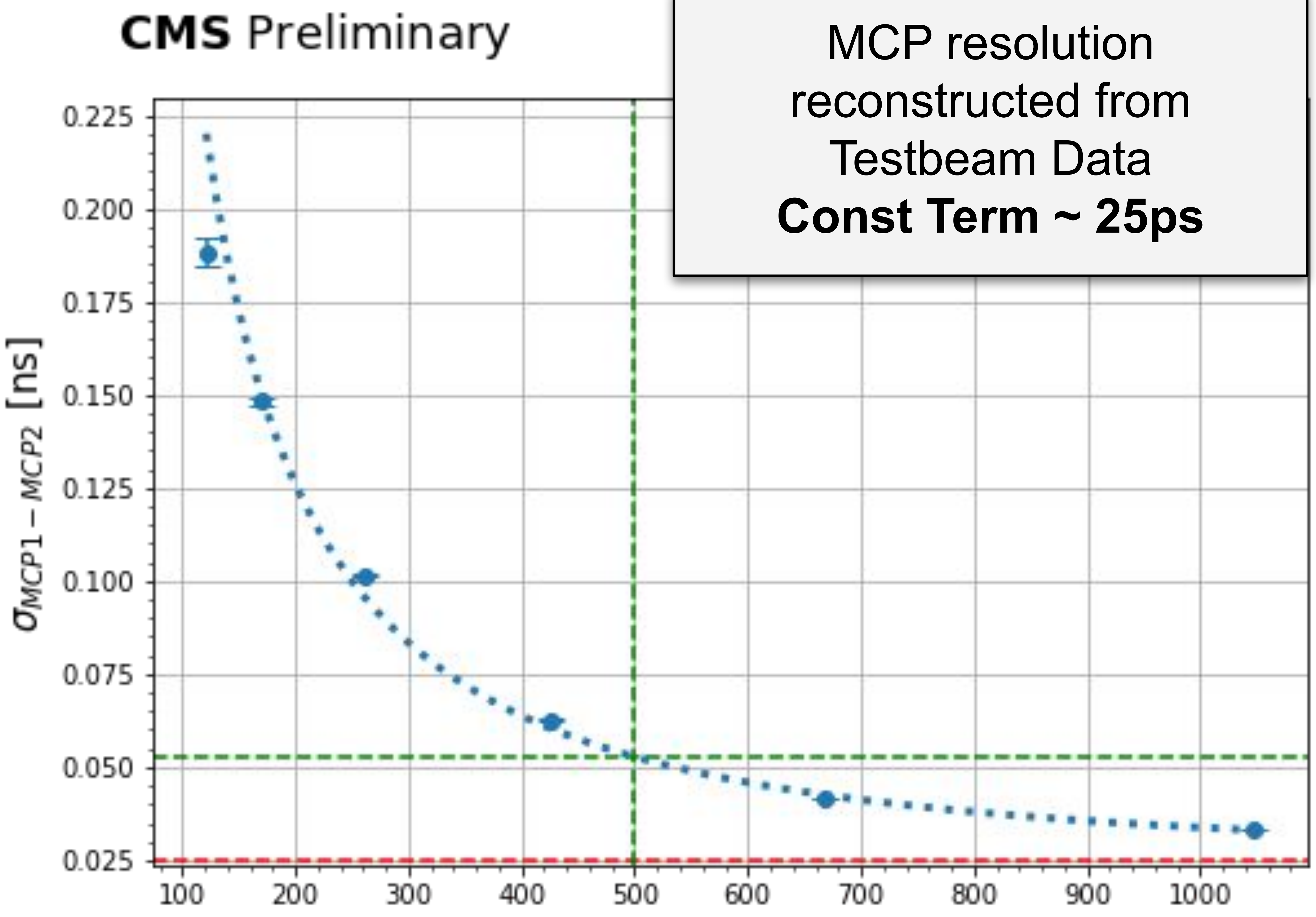


MCP Characteristics

➔ 2x MCP Detectors
- Operated in PMT-MCP mode
- Provides high-precision timing, used as a time-reference
- For ease of calibration and characterisation

Assuming identical performance between the two MCPs:

➔ **Time Resolution (single MCP) ~18 ps**



MCP resolution reconstructed from Testbeam Data
Const Term ~ 25ps

Avg. MCP Amplitude [ADC Count]

Note
Green dotted lines represents combined resolution of MCP at 500 MCP Ampl

Available Timing Information

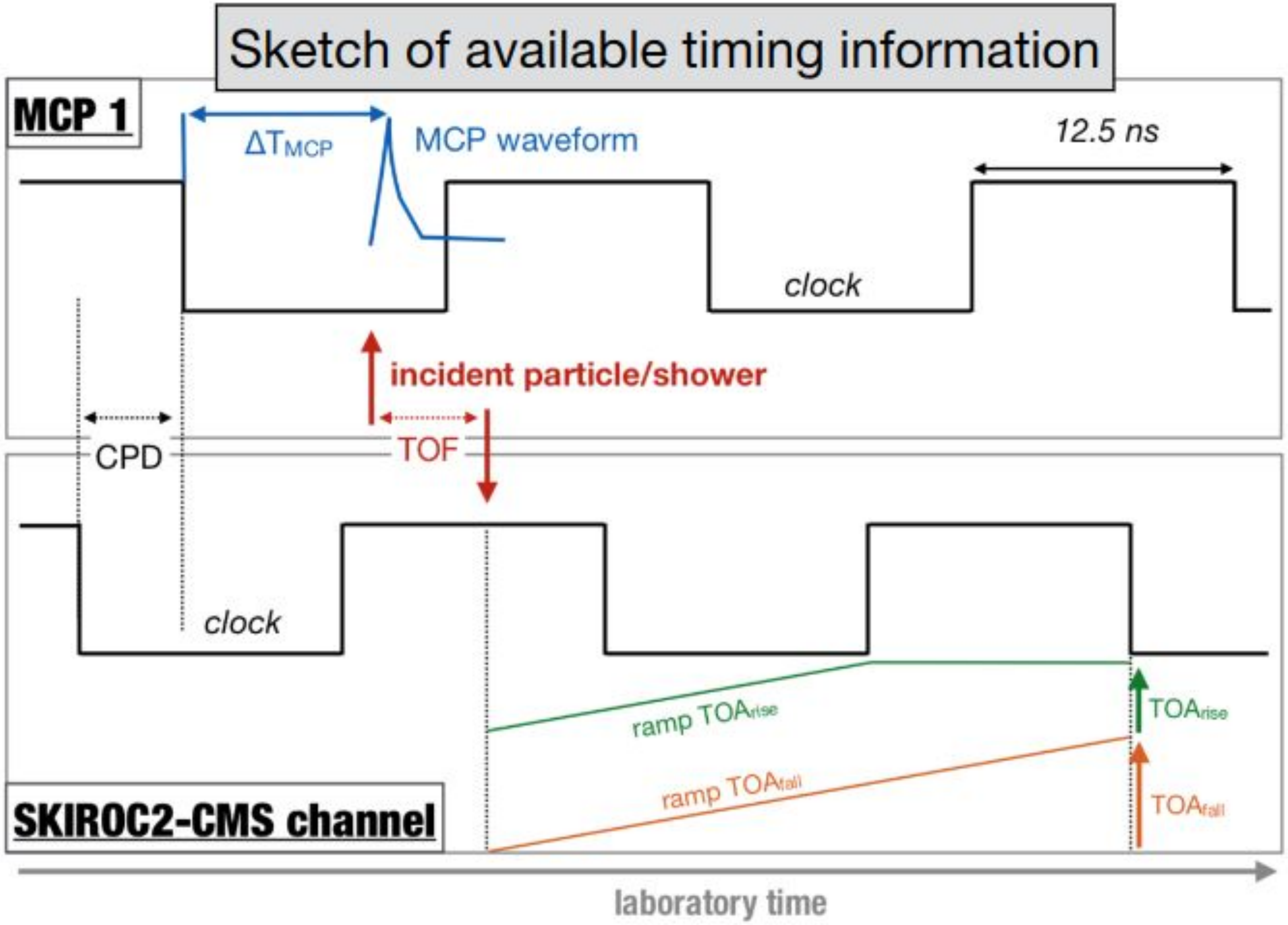
MCP Time Stamp:

- ➔ Time recorded with respect to the falling edge of the global clock
- ➔ Tighter cuts on MCP amplitudes were used for better timing performance

Time-of-Arrival (TOA) Time Stamp:

- ➔ TOA circuit starts a voltage ramp when threshold of ~10MIPs is exceeded
- ➔ Stops the timing circuit at Rising/Falling edge of the global clock
  - ◆ This corresponds to TOA-Rise / TOA-Fall

MCP was used as a reference to calibrate TOA and calculate the Time of Flight

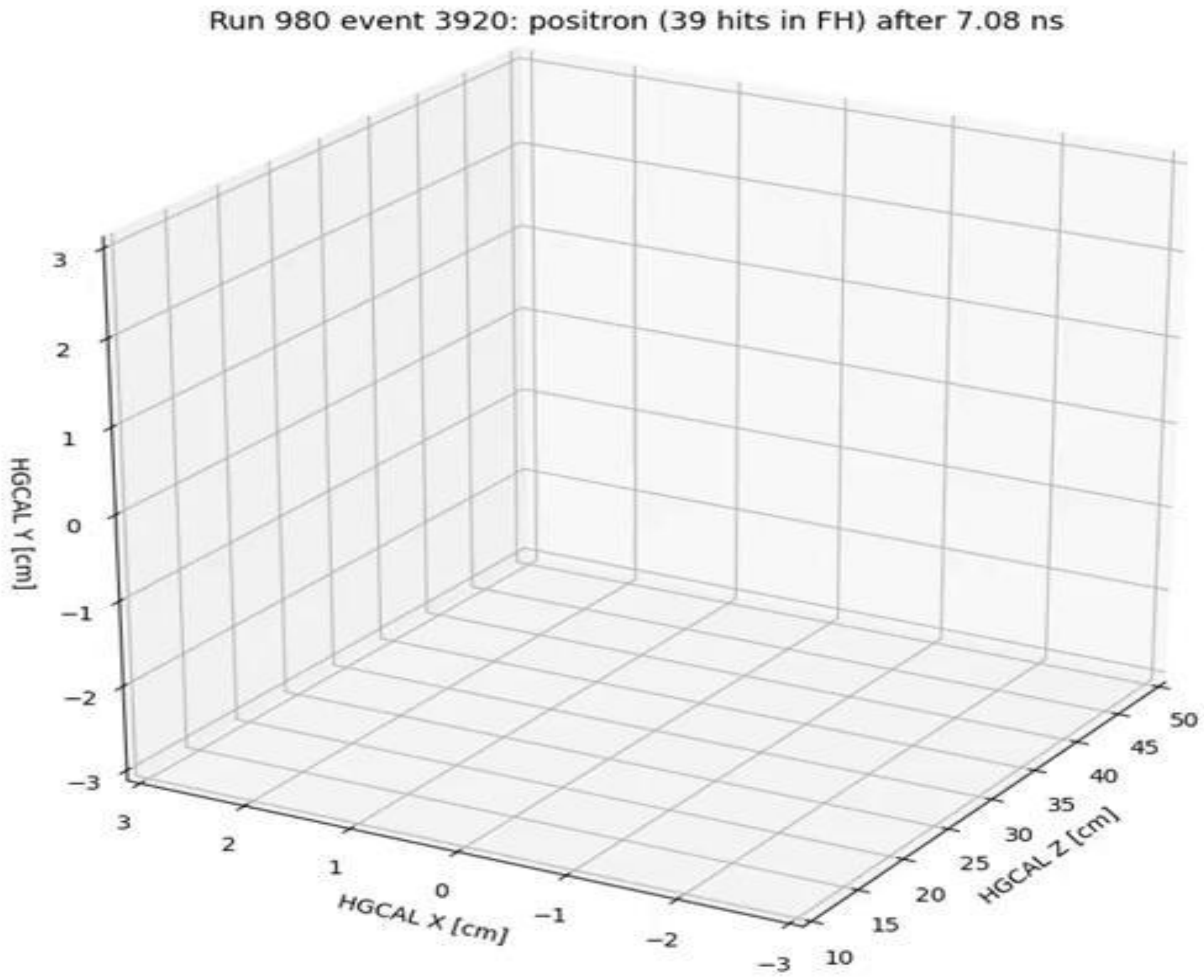


Electron Shower

Animation of a single event focussing on timing:

- ➔ Hits > 50 MIPs considered
- ➔ Size of the point correlates to amount of energy deposited
- ➔ Colour encodes hit timestamp w.r.t current frame

We observe the shower depositing energy in the central cells and the cells immediately around it in most of the layers



Timing Calibration

Linearisation:

- ➔ Non-Linearity caused by ramp saturation
- ➔ Two independent calibration techniques were implemented
  1. TOA data-driven method exploiting the asynchronous nature of the beam particles.
  2. TOA calibration using the full MCP time-stamp

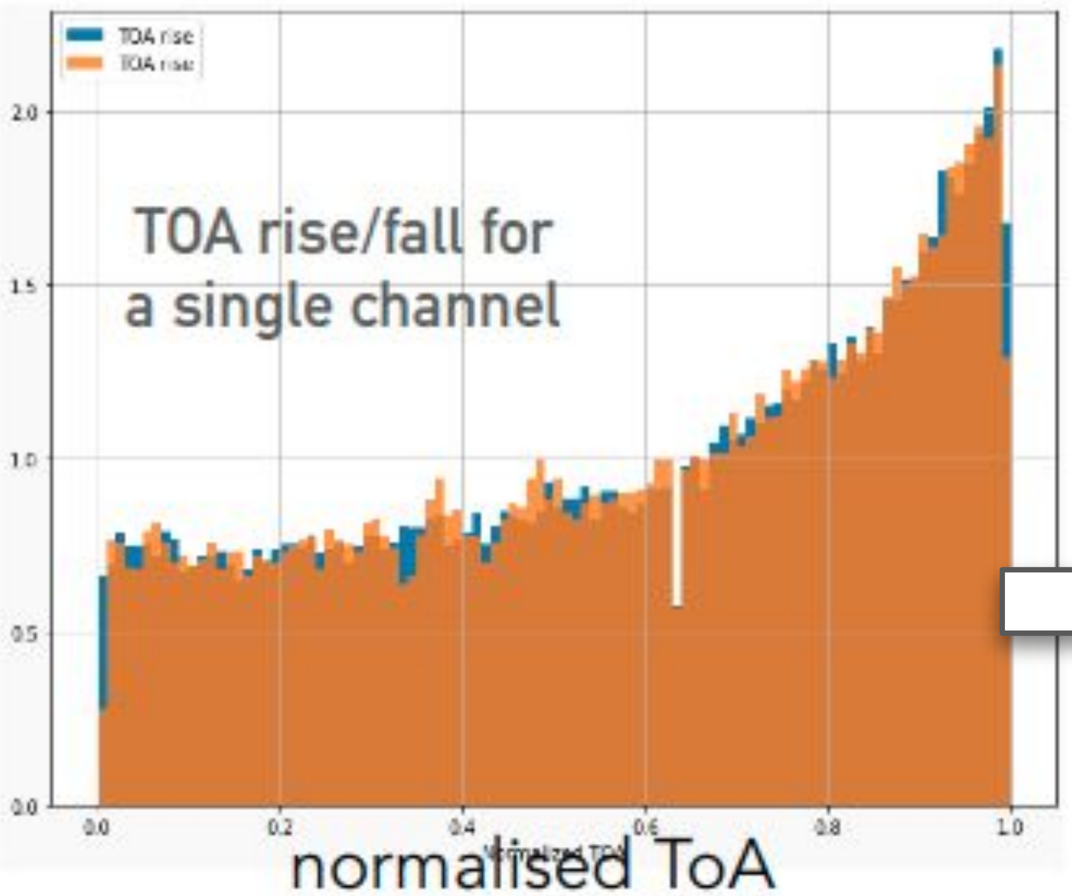
Consistent results were derived from both techniques

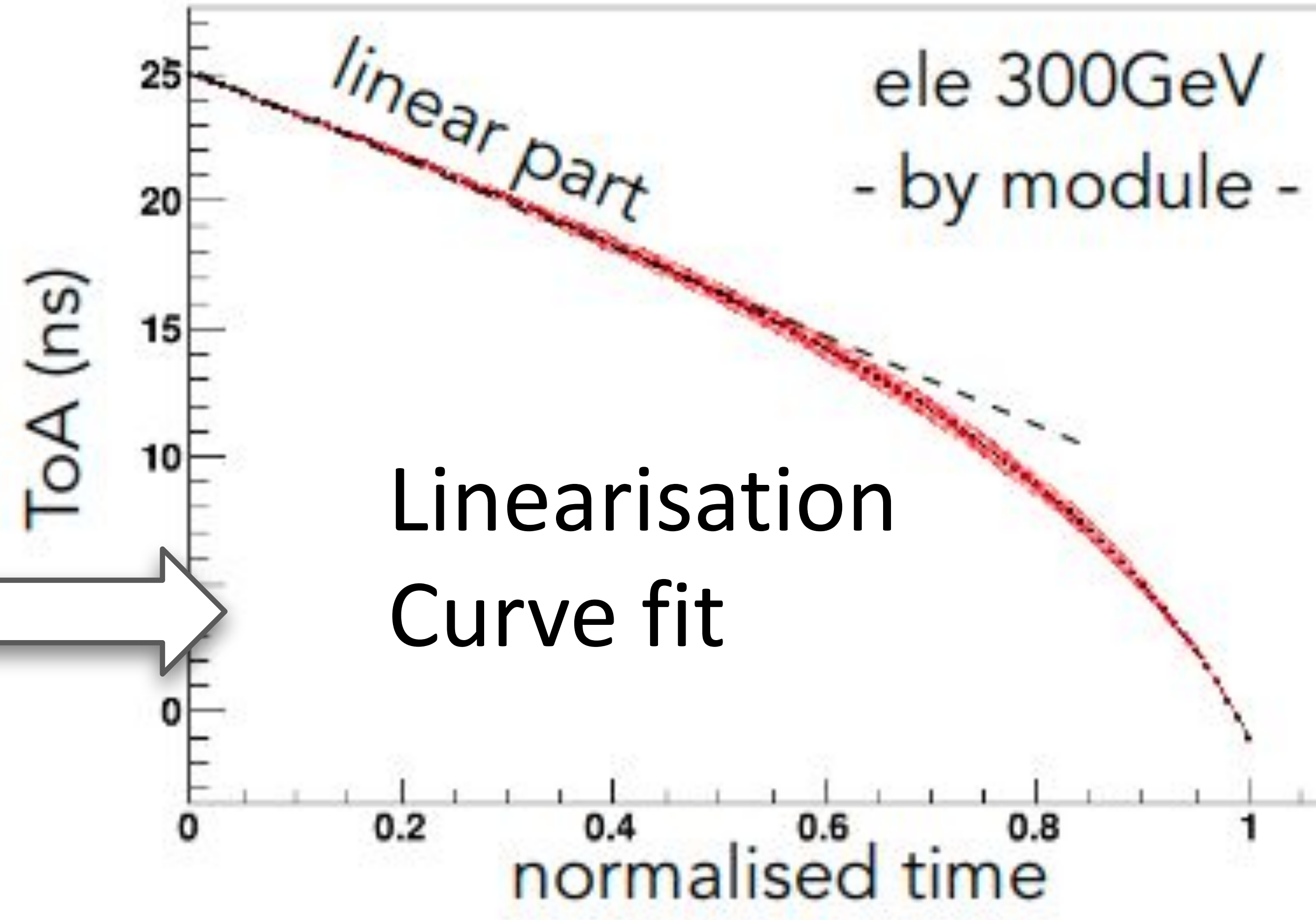
Calibration

- ➔ Reasonably stable over
  - ◆ Beam Energies
  - ◆ Rise and Fall
- ➔ Calibration applied on the smallest level of granularity (per channel)

METHOD 1

Cumulative TOA is linearised with a parametric equation





Linearisation:

Fit using a parametric equation and corrected by inverting it

$$[0] * x + 25 + [1] * (\frac{1}{x - 1.25} + 0.8)$$

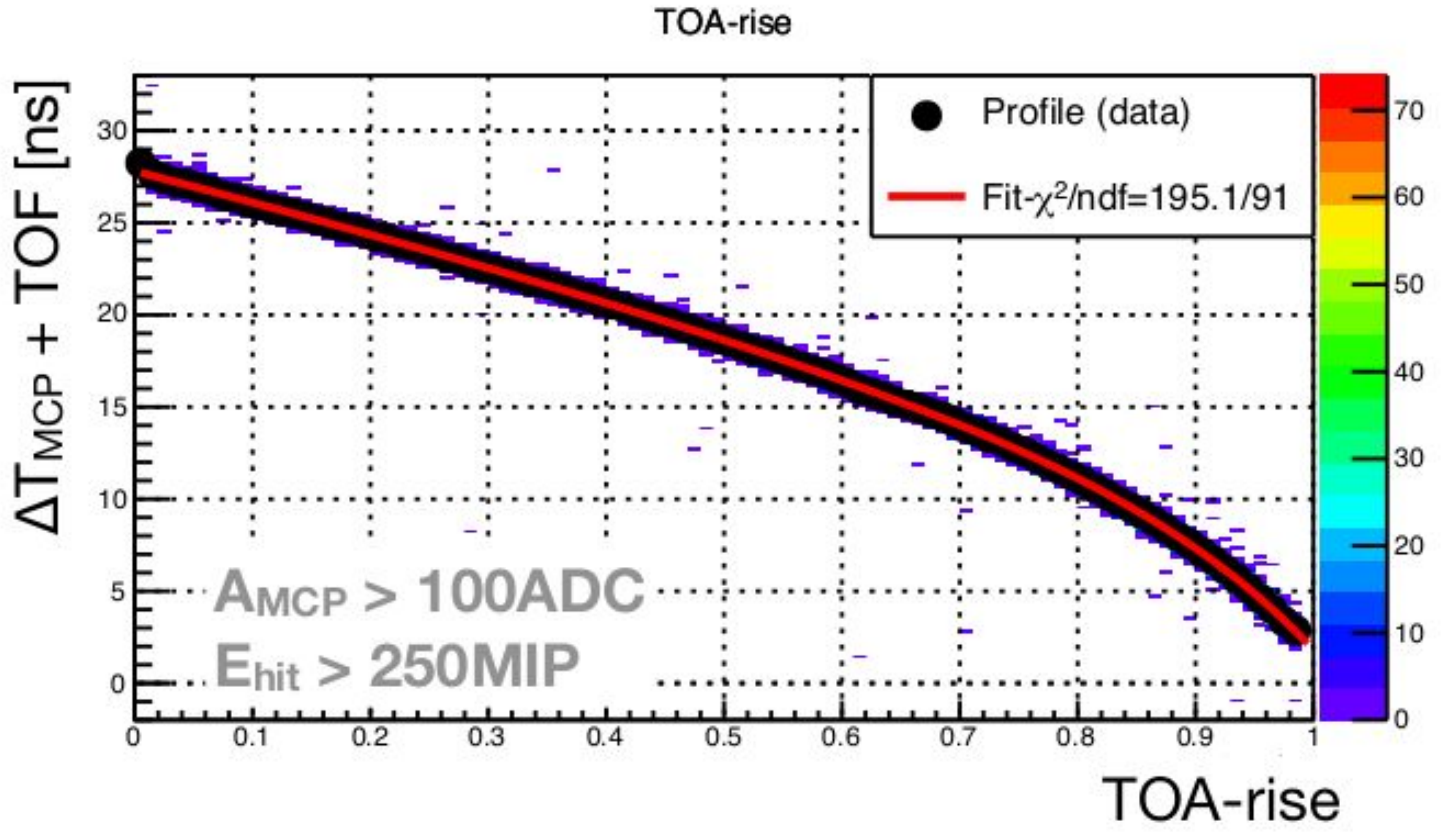
METHOD 2

Normalized TOA is plotted against MCP time-stamp and linearised

Linearisation:

Fit using a parametric equation and corrected by inverting it

$$f_{\mathrm{TOA}}(x) := a_{\mathrm{TOA}} \cdot x + b_{\mathrm{TOA}} + \frac{c_{\mathrm{TOA}}}{x - d_{\mathrm{TOA}}}$$

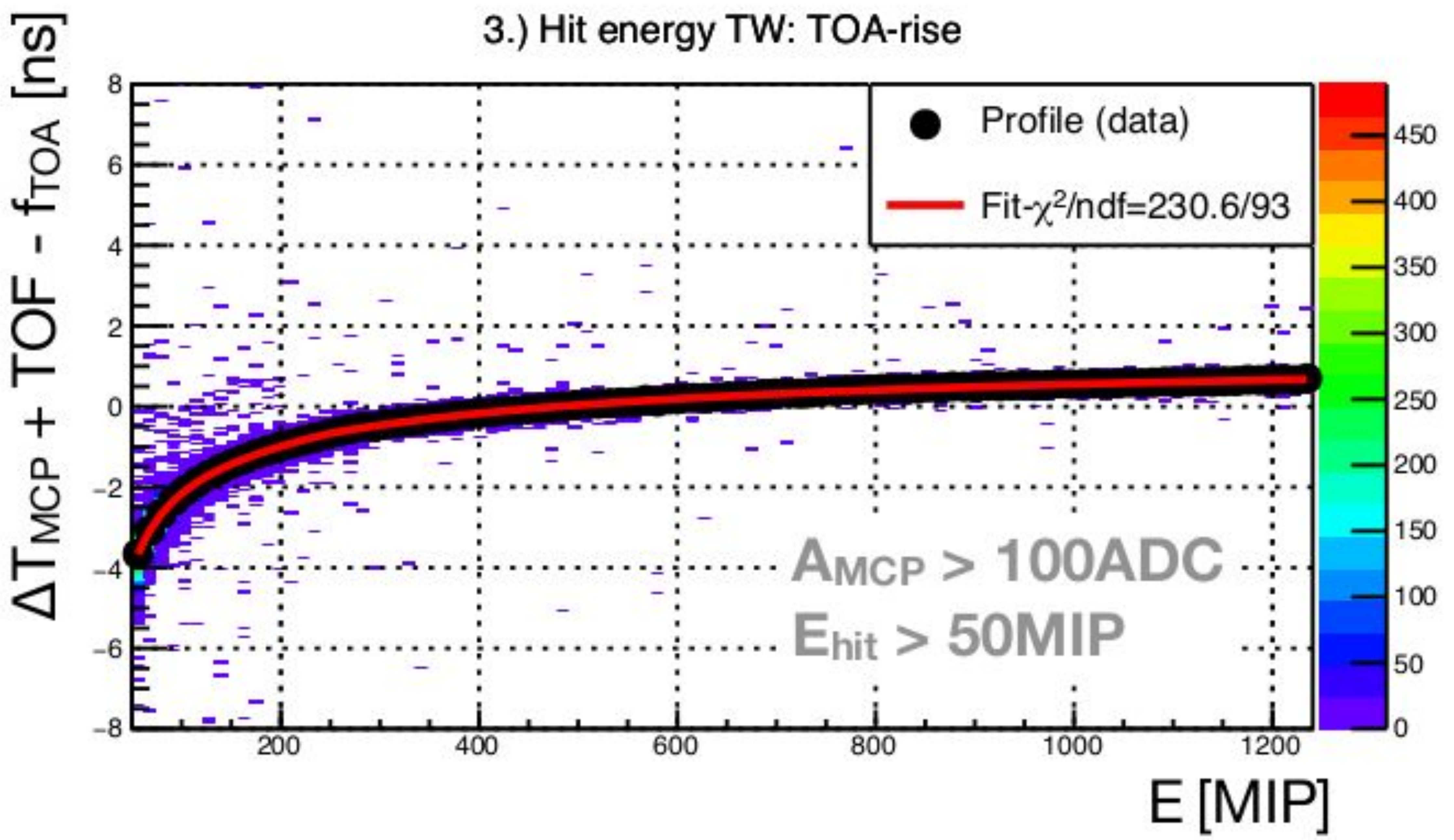


Timing Calibration

Time Walk:

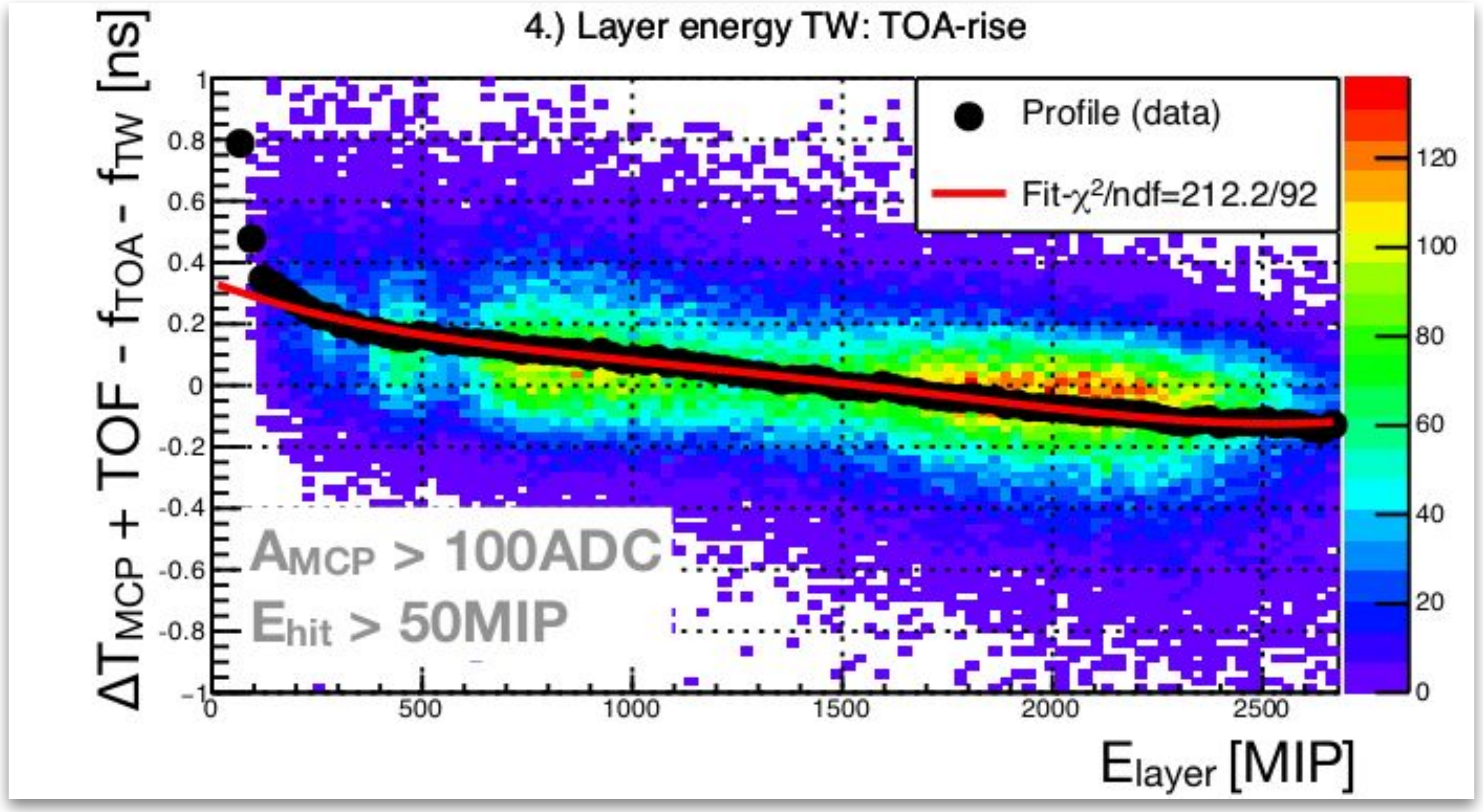
- ➔ Phenomenon where the time-stamp depends on the energy deposited in the detector
- ➔ Corrected by inverting Time Walk parametric equation

$$f_{\mathrm{TW}}(E) := a_{\mathrm{TW}} \cdot E + b_{\mathrm{TW}} + \frac{c_{\mathrm{TW}}}{E - d_{\mathrm{TW}}}$$



Correction for Baseline Shift:

- ➔ It was observed that there was a systematic shift in timing of the channel with respect to the energy deposited in the layer
- ➔ This was corrected using the parametric form below



$$f_{\hat{B}}(E_{\mathrm{module}}) = a_{\mathrm{B}} + b_{\mathrm{B}} \cdot E_{\mathrm{module}} + c_{\mathrm{B}} \cdot E^2_{\mathrm{module}} + d_{\mathrm{B}} \cdot E^3_{\mathrm{module}} + e_{\mathrm{B}} \cdot E^4_{\mathrm{module}}$$

Single Si Channel Resolution (MCP reference)

METHOD 1

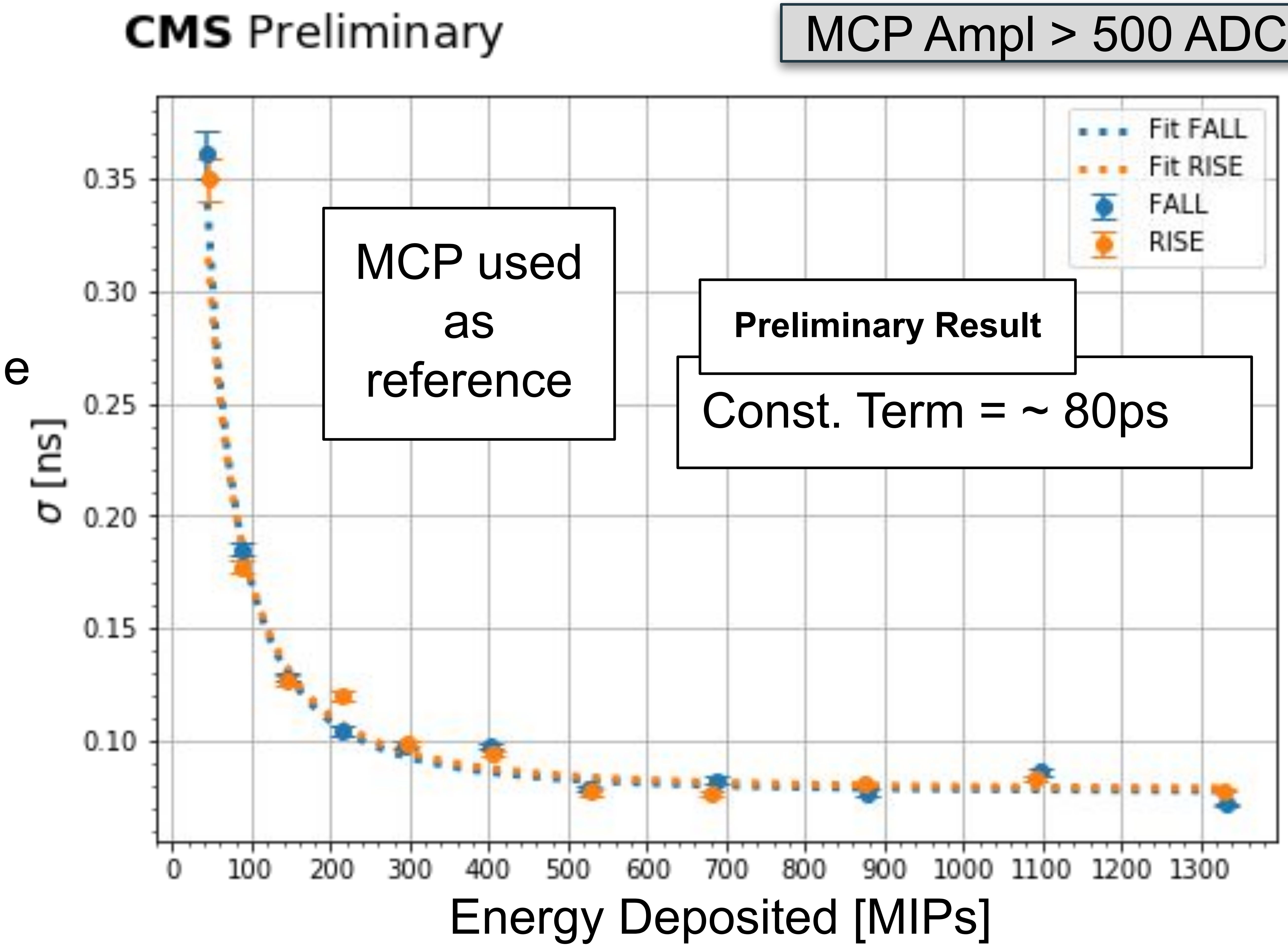
Layer 8 Single Cell, 300 GeV Electrons

Single Channel Resolution:

- ➔ 300 GeV Electrons
- ➔ Binned in energy deposited in the channel fit against a gaussian distribution
- ➔ Consistent results between fall and rise TOA

MCP Resolution is estimated to be between 18-35ps

MCP Ampl > 500 ADC



MCP used as reference

Preliminary Result

Const. Term = ~ 80ps

$$\text{RISE} = \sqrt{\left(\frac{A}{E-B}\right)^2 + C^2}$$

A = 16.473±0.49
B = -8.972±2.742
C = 0.078±0.0
χ^2_ν = 20.312

$$\text{FALL} = \sqrt{\left(\frac{A}{E-B}\right)^2 + C^2}$$

A = 15.609±0.448
B = -3.309±2.487
C = 0.077±0.001
χ^2_ν = 20.605

Note: Result includes the time resolution of the MCP

Timing characterization of the full shower

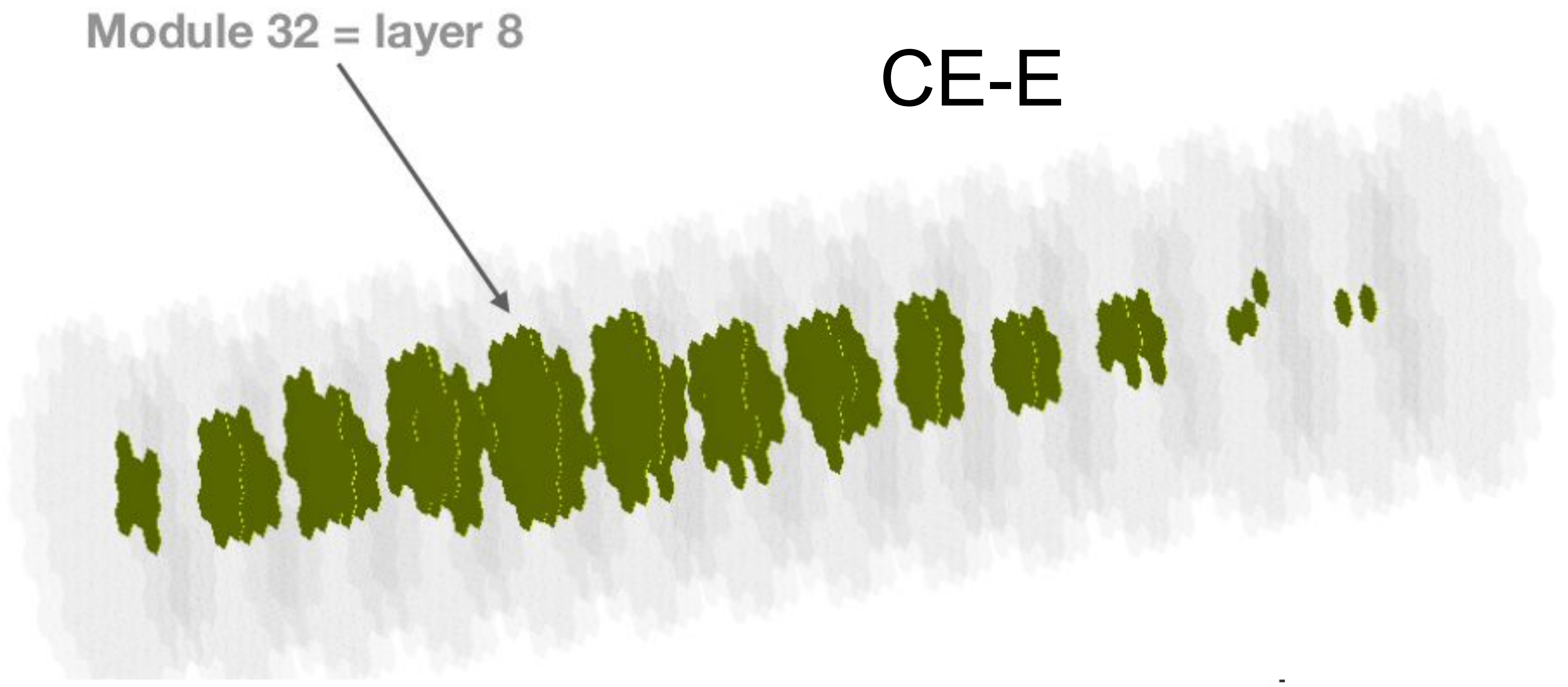
METHOD 2

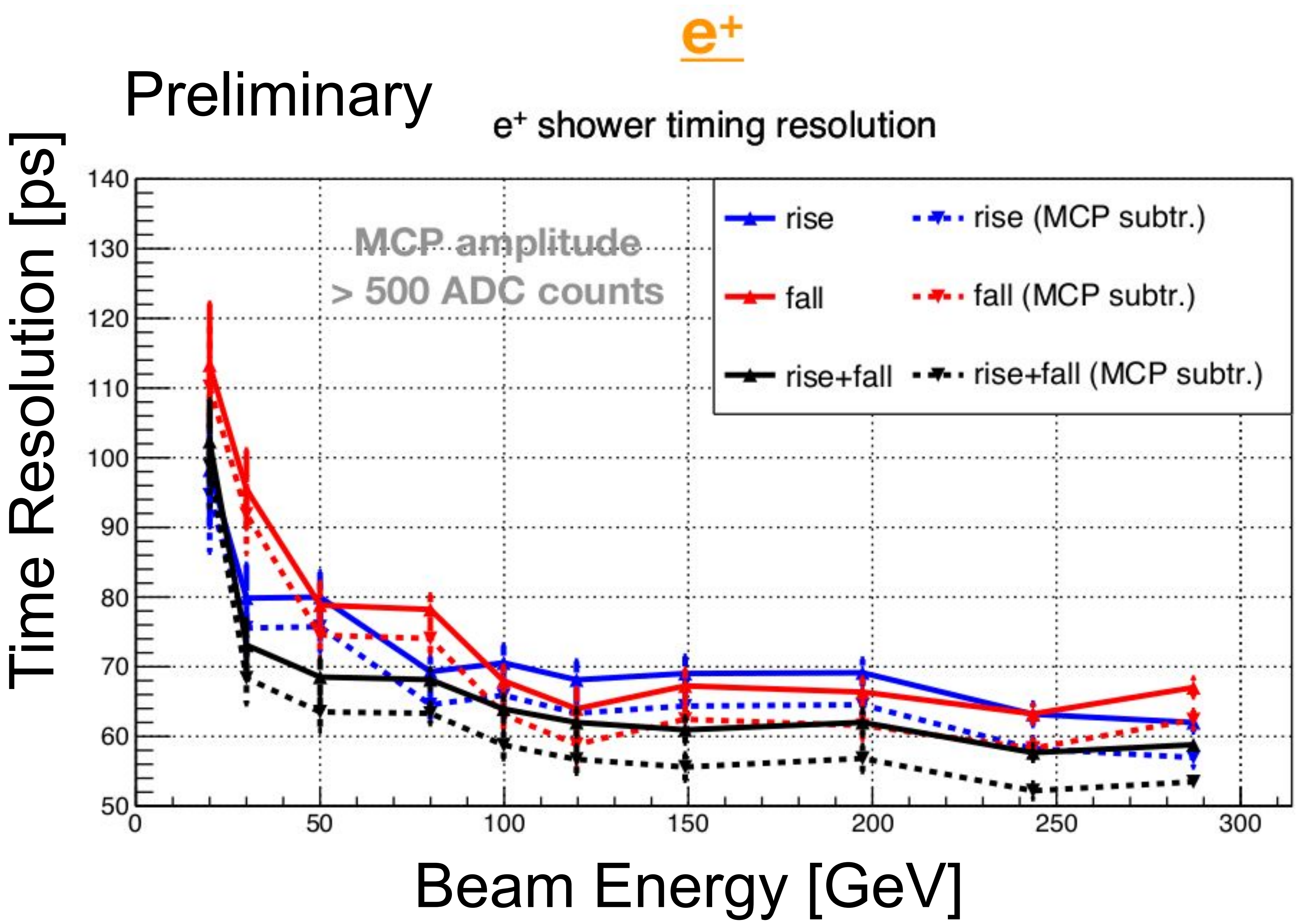
Hits with > 50 MIPs contributions were selected

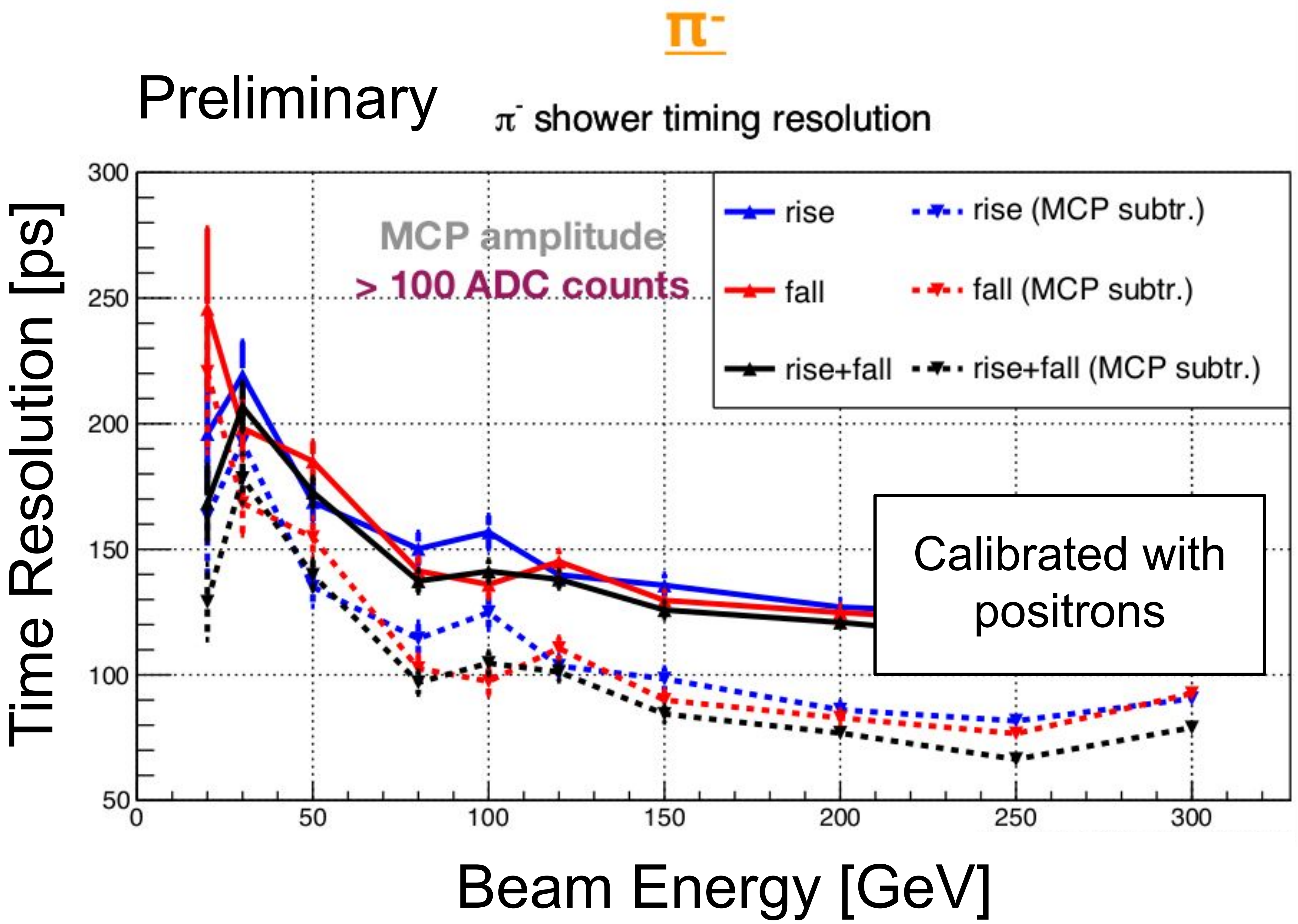
Observations:

$$T_{\text{shower}} = \frac{\Sigma_i^{E_i \geq 50\text{ MIP}} E_i \cdot (T_i - TOF_i)}{\Sigma_i^{E_i \geq 50\text{ MIP}} E_i}$$

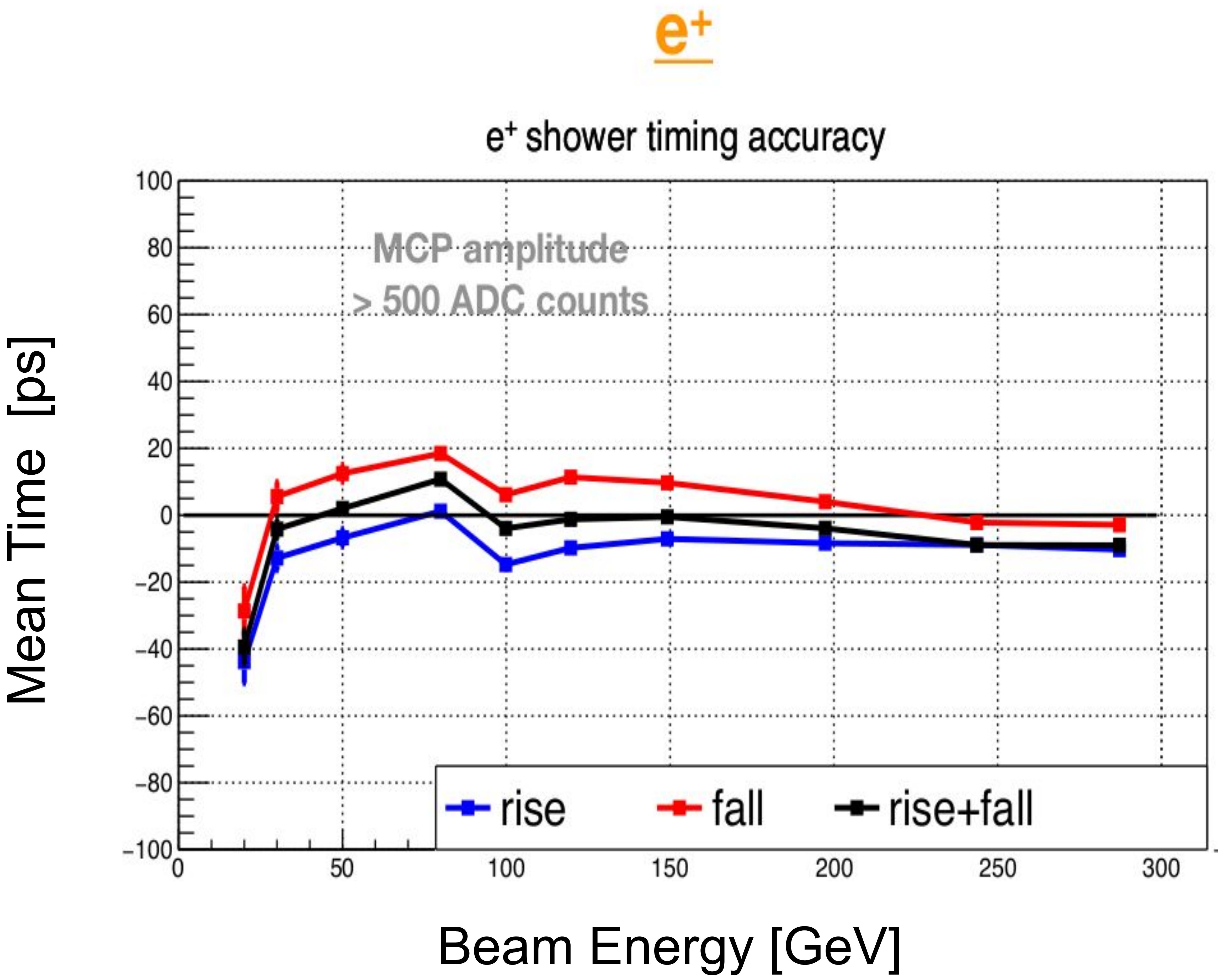
- ➔ Electrons in CE-E
  - ◆ Const. term ~ 60 ps
- ➔ Pions in CE-E
  - ◆ Const. term < 100ps

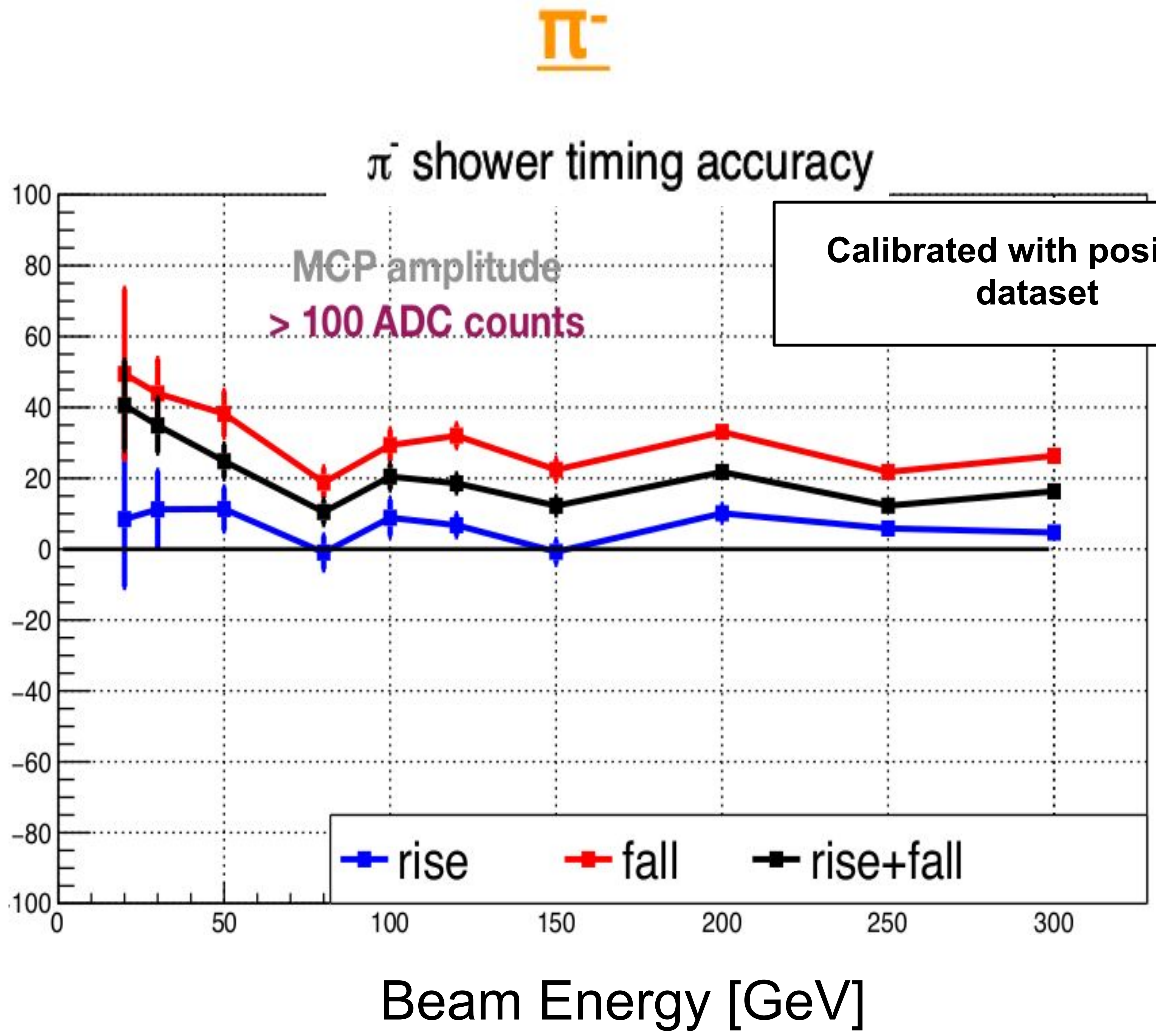






Stability of the shower timing with respect to beam energy





Calibrated with positrons dataset

Monte Carlo Simulation of HGCAL Prototype

Algorithm to measure time:

- ➔ Electron Beams (20-300 GeV)
- ➔ Selection Implicitly requires > 15MIPs (simulating voltage threshold)
- ➔ CE-E Channels Considered:
  - ◆ All Cells
  - ◆ 7-Cells (1 (max hit) + 6 (neighbour))
  - ◆ 19-Cells (1 + 18(neighbours))
- ➔ Shower timing is *truncated*
  - ◆ Keep only the hits from the smallest interval containing **68% the timing distribution**

We observe:

- ➔ Differences in 7-cell and 19-cell clusters
  - ◆ Hits are dispersed laterally
- ➔ At low beam energy, we expect bigger average times, if any, not smaller as seen in Fig 2 (7,9 cell cluster)

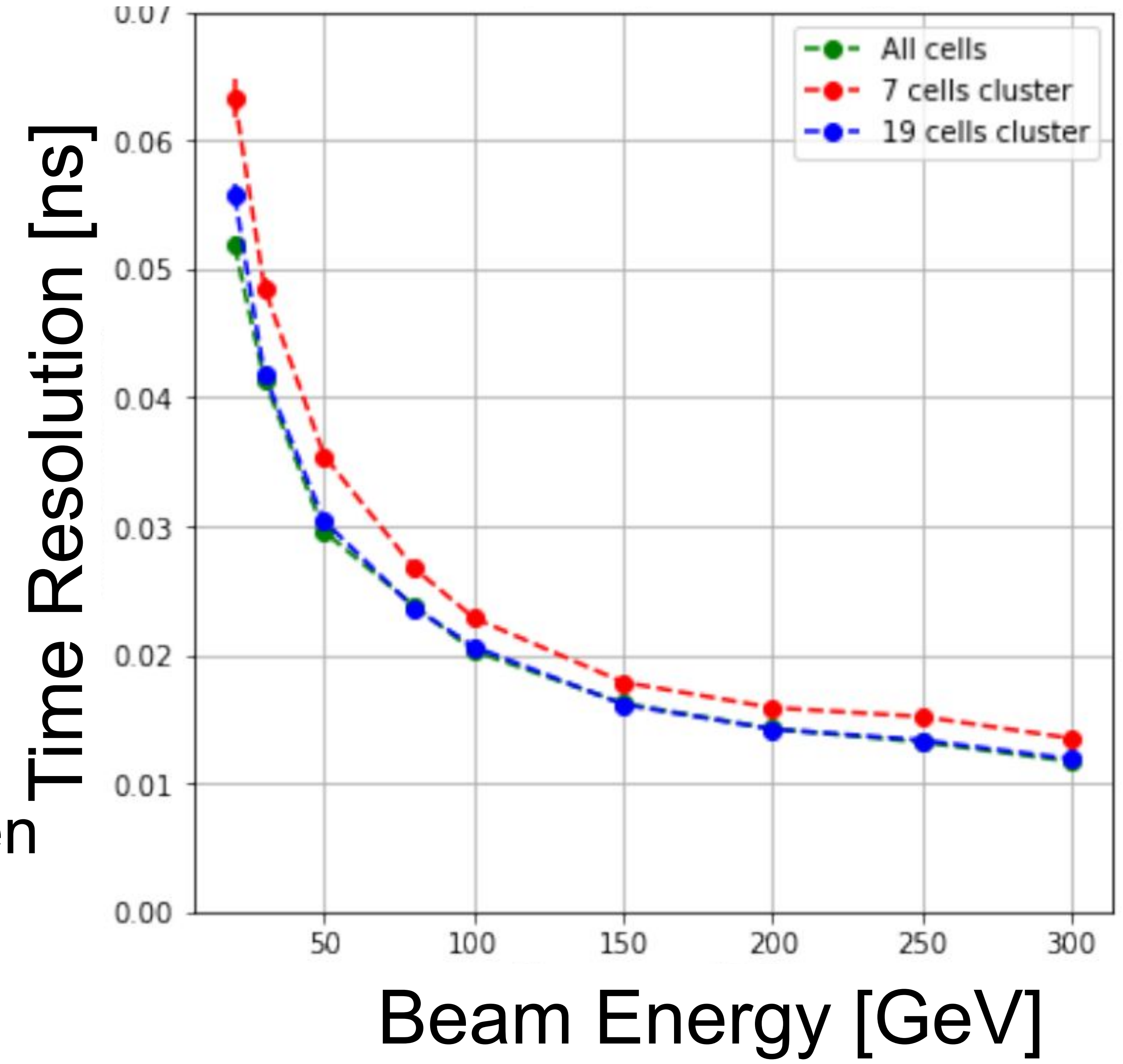
Time was smeared using parameters derived from data

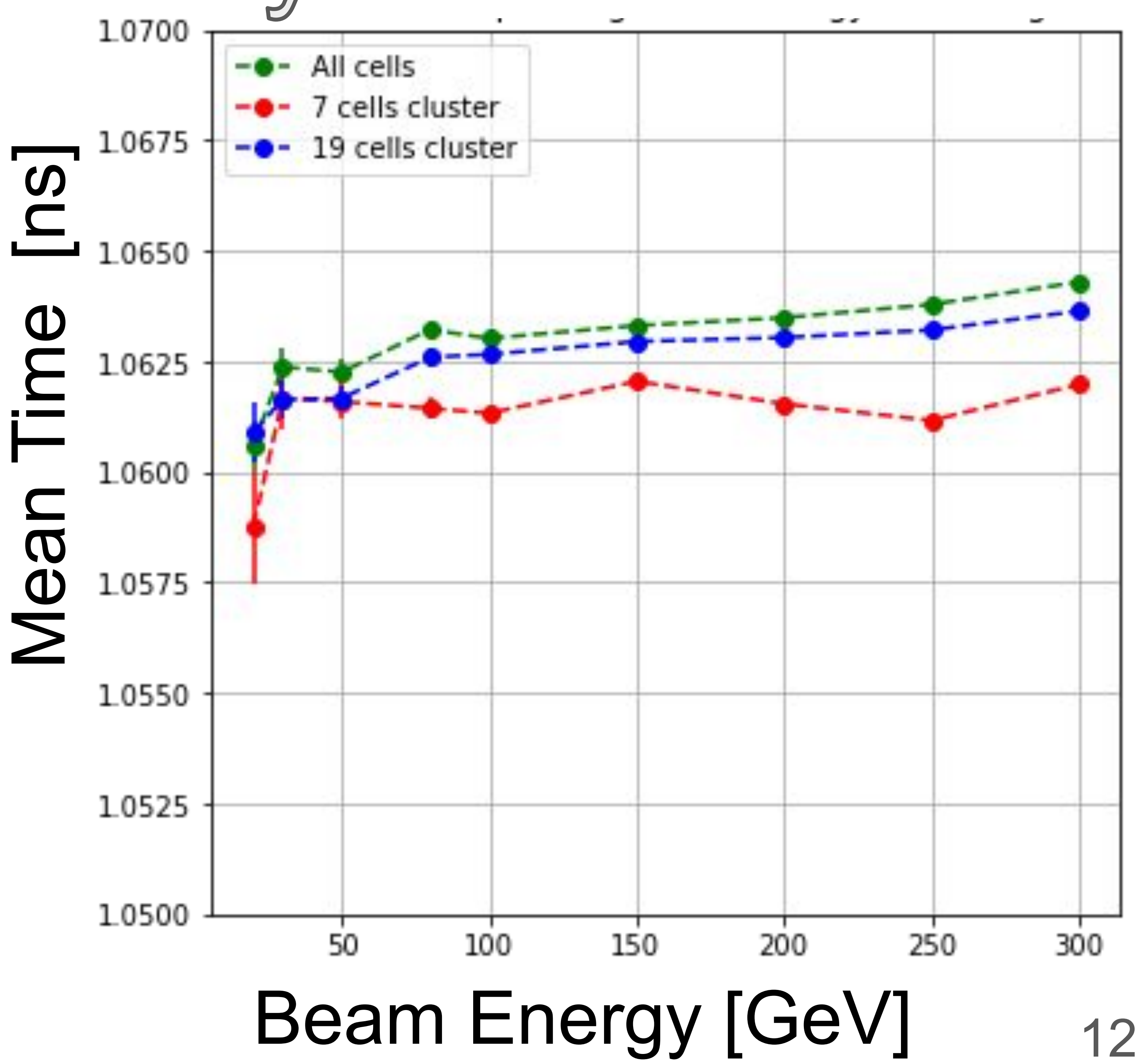
$$y = \frac{A}{Energy} \oplus C$$

Derived from Si-channel compared to another Si-channel test beam data

Const Term (C) = 50ps ; Stochastic Term (A) = 10 MIP.ns

Preliminary





Conclusion

HGCAL prototype was designed with radiation hardness and superior time-resolution in mind

Test Beam 2018:

- ➔ We observe a constant term of ~60ps for electrons and <100ps for pions in the CE-E
  - *Combined using simple energy weighting between channels*
  - *Expected to improve with resolution weighting and improved reconstruction algorithms*
  - ***Preliminary results appears to be consistent with specification of the SKIROC2_CMS ASIC***
- ➔ Timing studies were carried out on full statistics
- ➔ Geant4 Simulation yields insightful results
  - *Timing performance for electrons in the CE-E was studied*
  - *MC data was smeared using results derived from data*

Next Steps:

- ➔ Comparison of MC result to data
- ➔ Extending the study to CE-H-Si for Hadronic Showers

Backup of Timing Analysis

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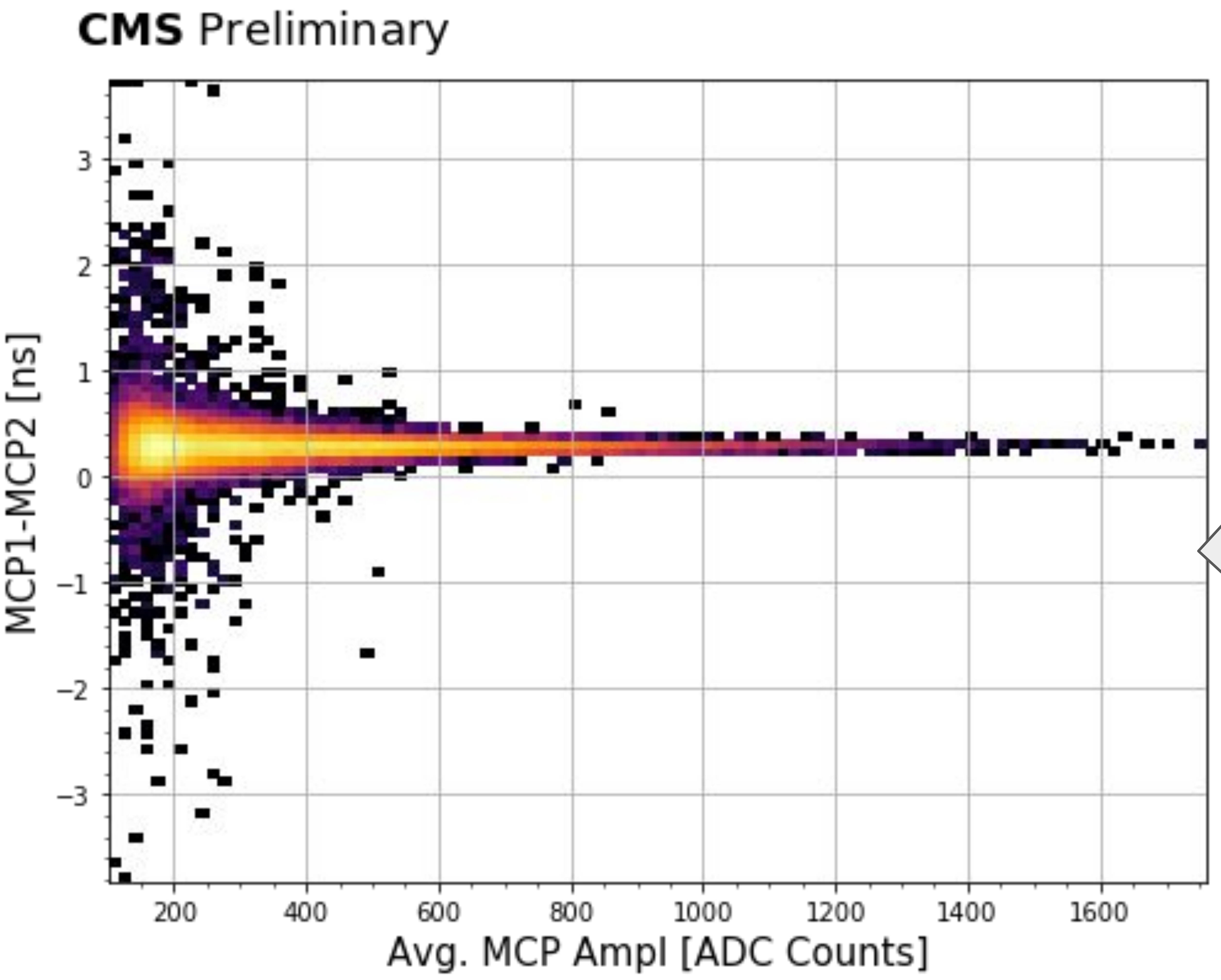
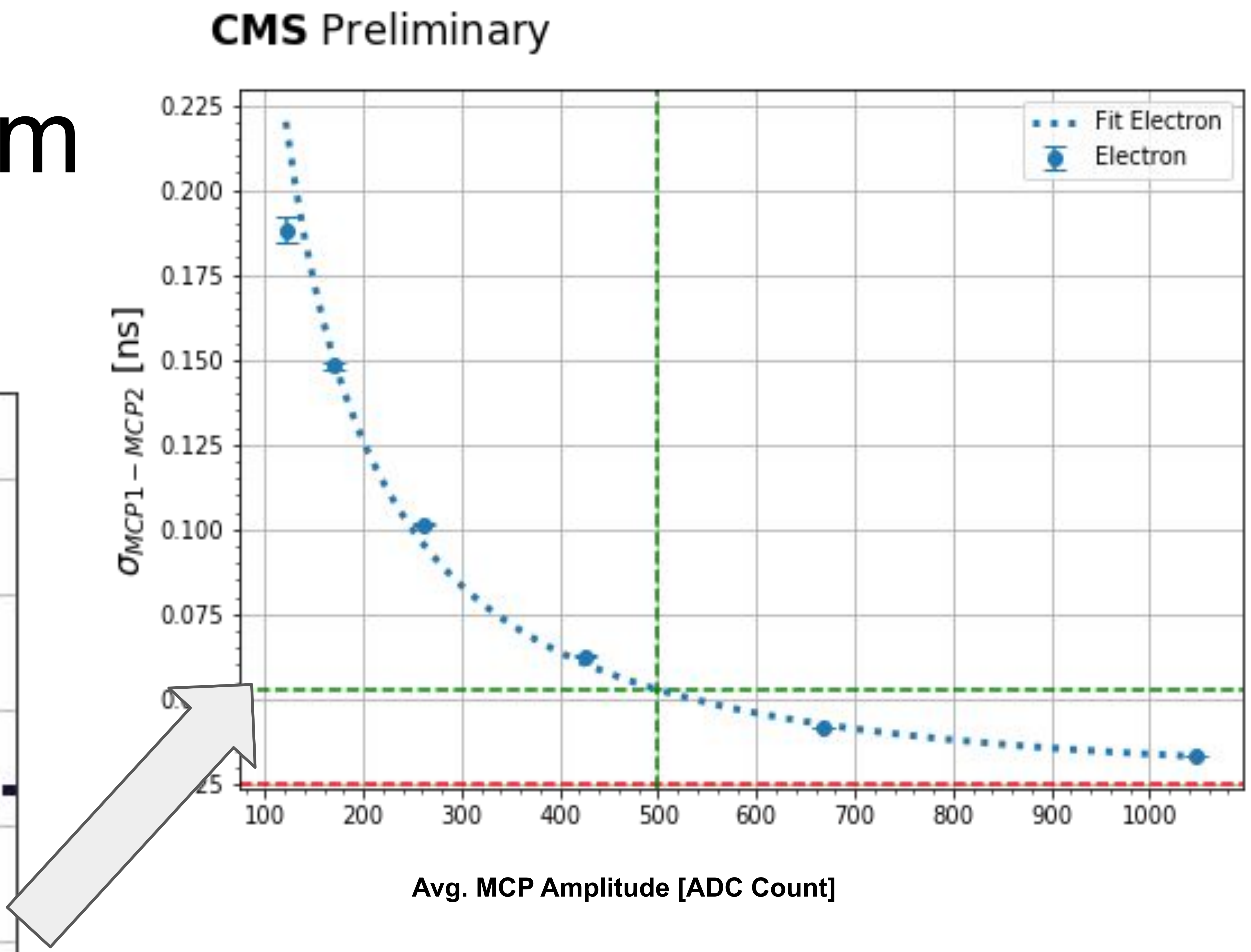
MCP Detector 2D Histogram





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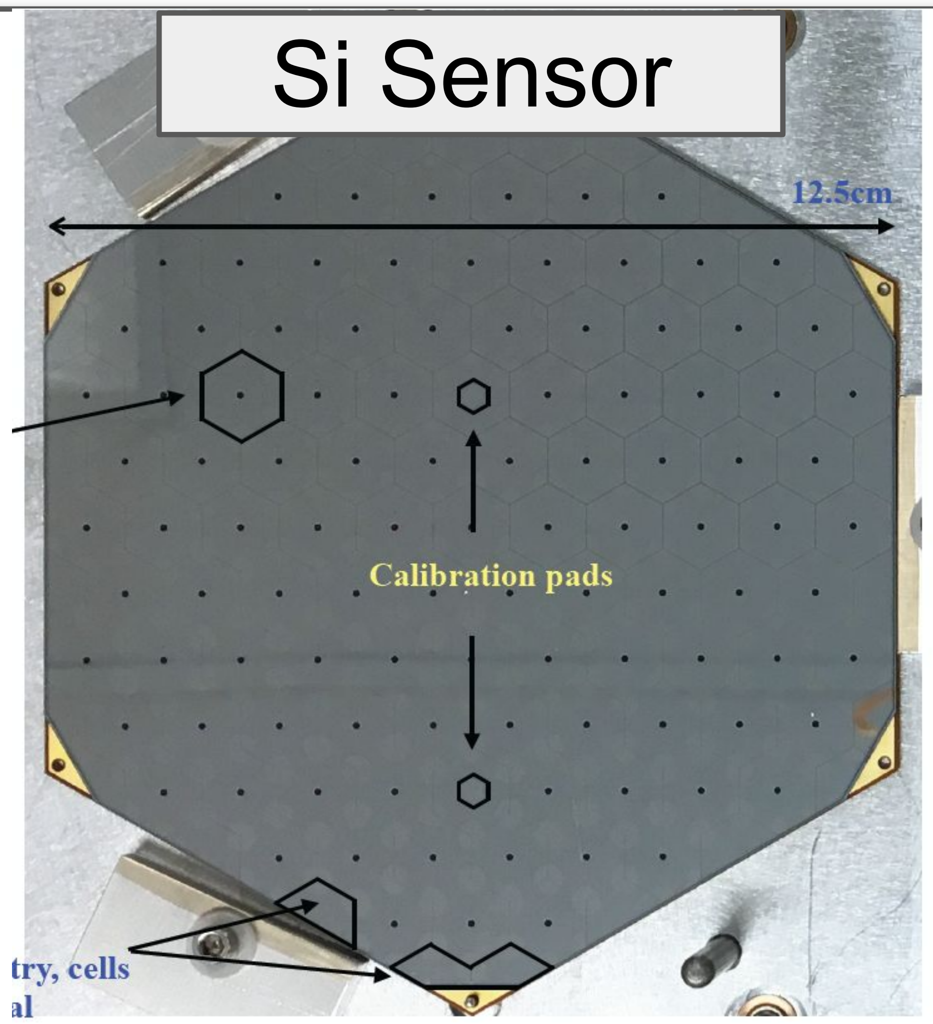
Ref: HGCal beam test DAQ:
➡Rajdeep M. Chatterjee

HGCAL Prototype Modules
Active Materials

Si Sensor



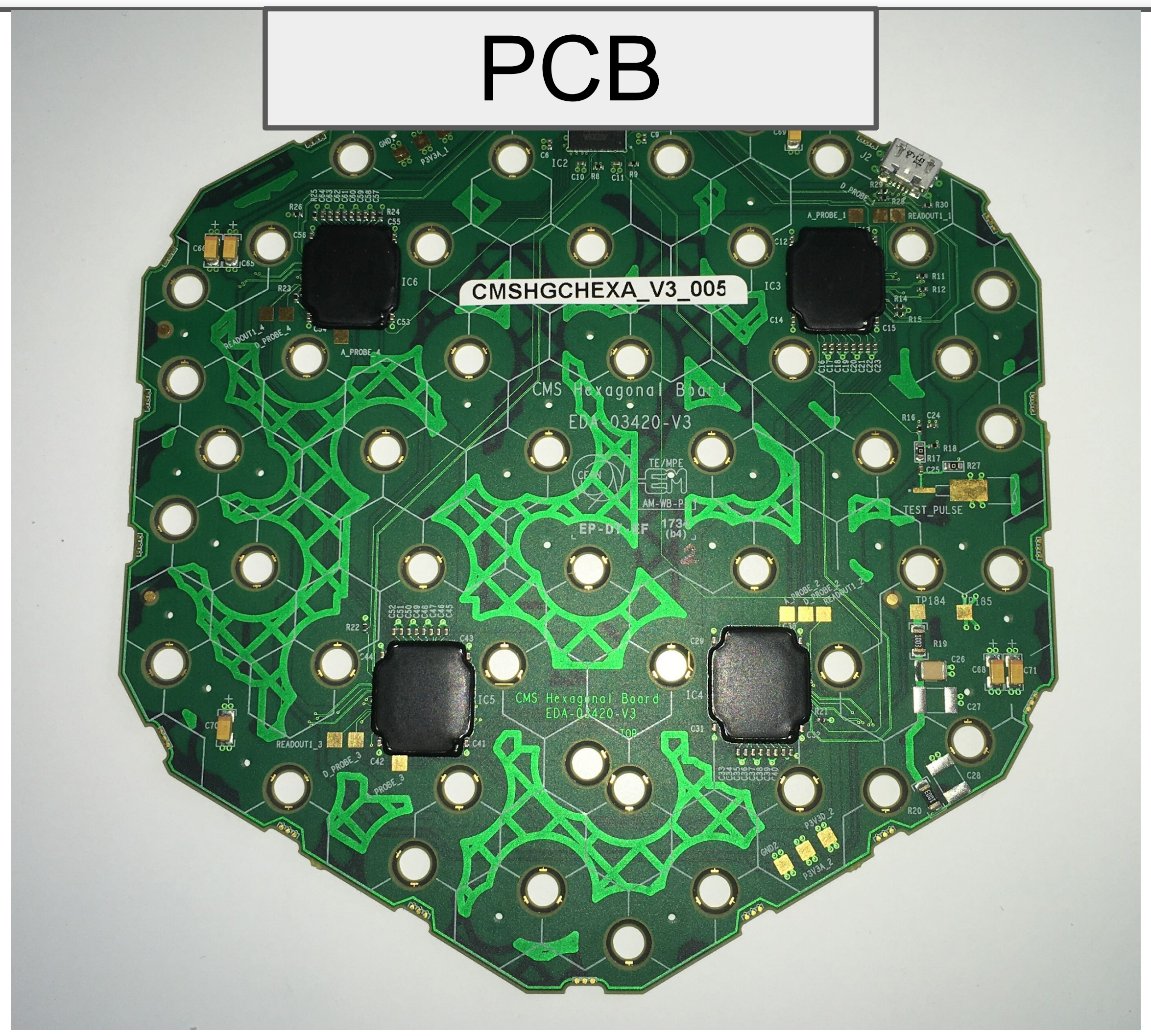
6" Si Sensors

n-type, 128 cells

1 cm^2 cell size

depletion: 200 & 300μm

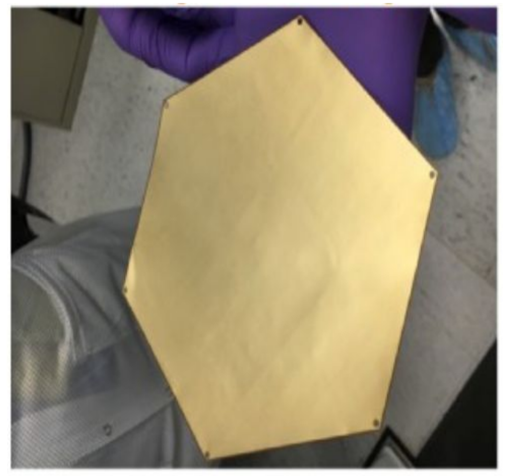
PCB



SKIROC2_CMS ASIC

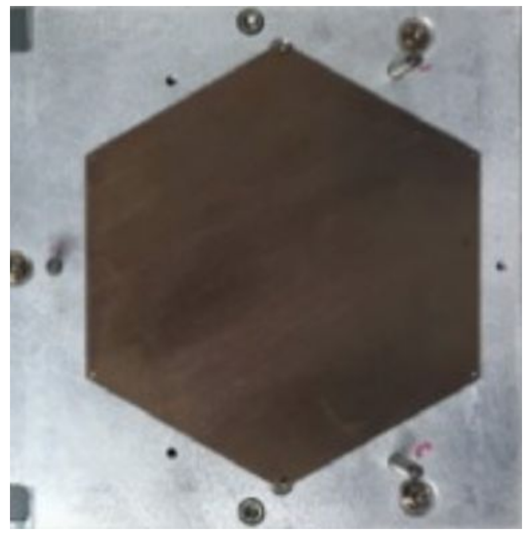
- 64 Ch., 4 Chips/Module

Developed for CALICE (SKIROC2) & adjusted for HGCAL



Kapton®

Gold Plated

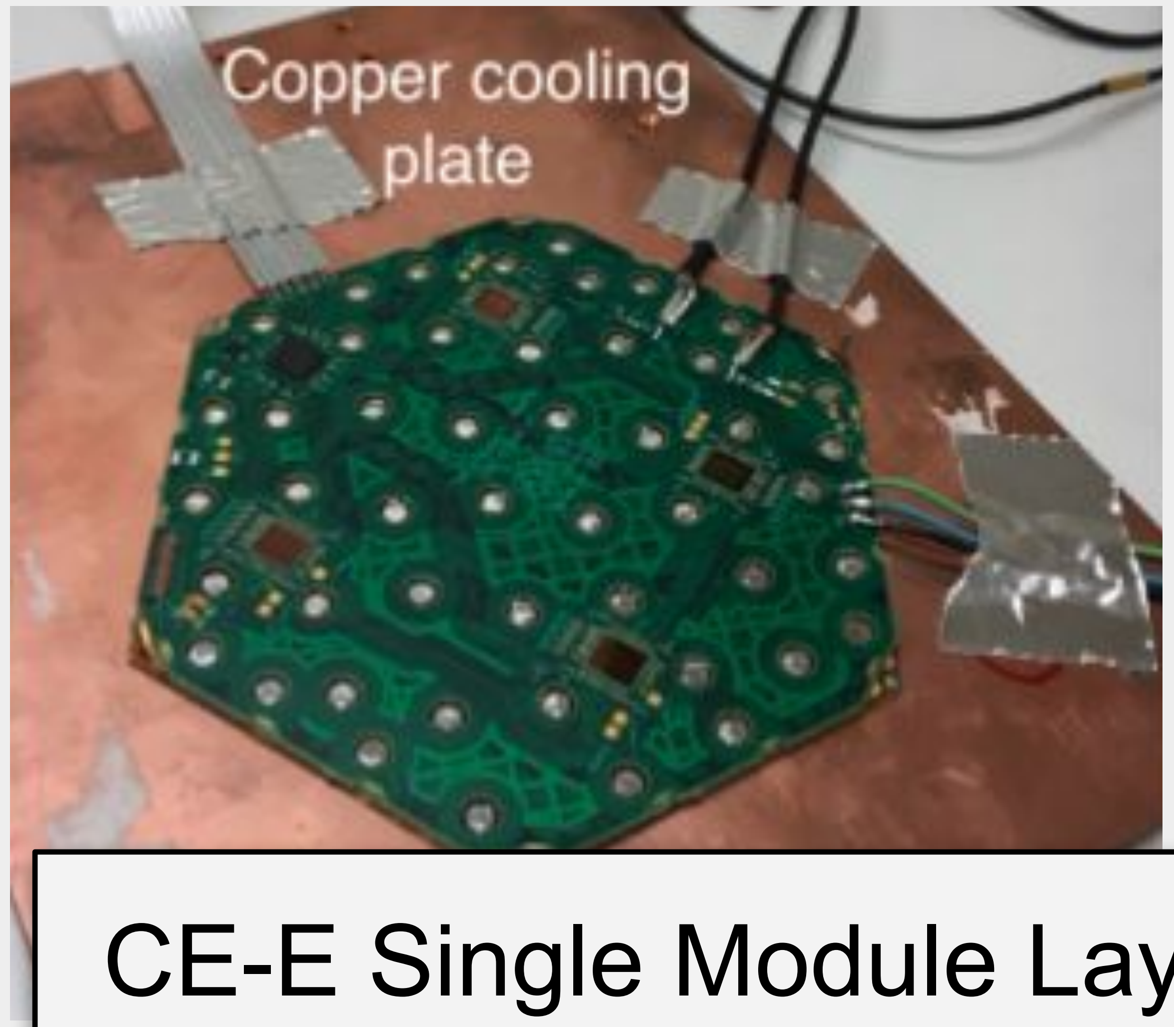


Baseplate

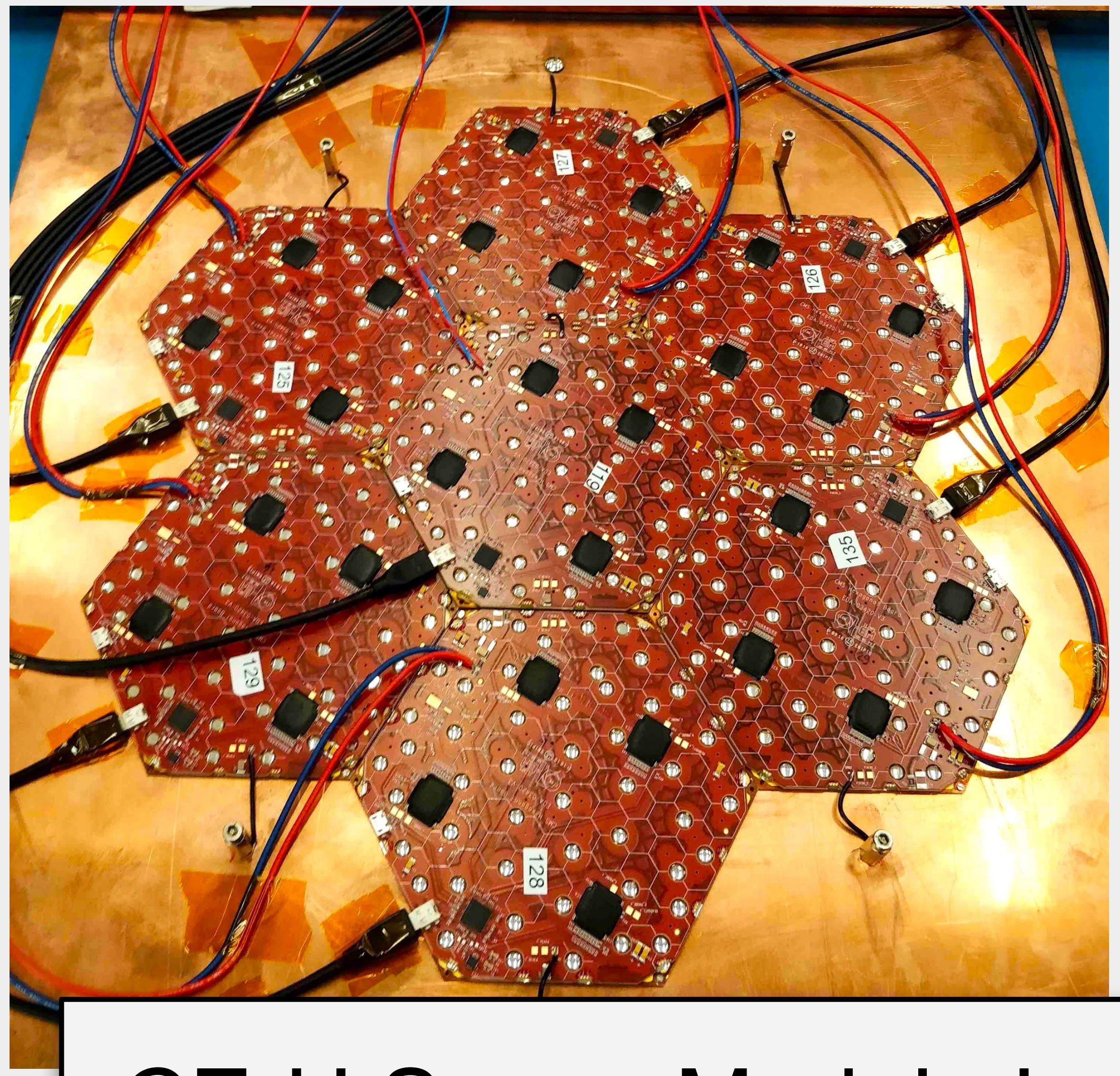
CuW

Cu

Wire-bonded and glued together



CE-E Single Module Layer



CE-H Seven Module Layer

Testbeam Configurations

PASSIVE MATERIAL

CE-E:
- **Pb, W, Cu**
- **5-6 mm thickness**

CE-H-Si:
- **Fe**
- **4 cm thickness**
- **O(1000Kg) weight**

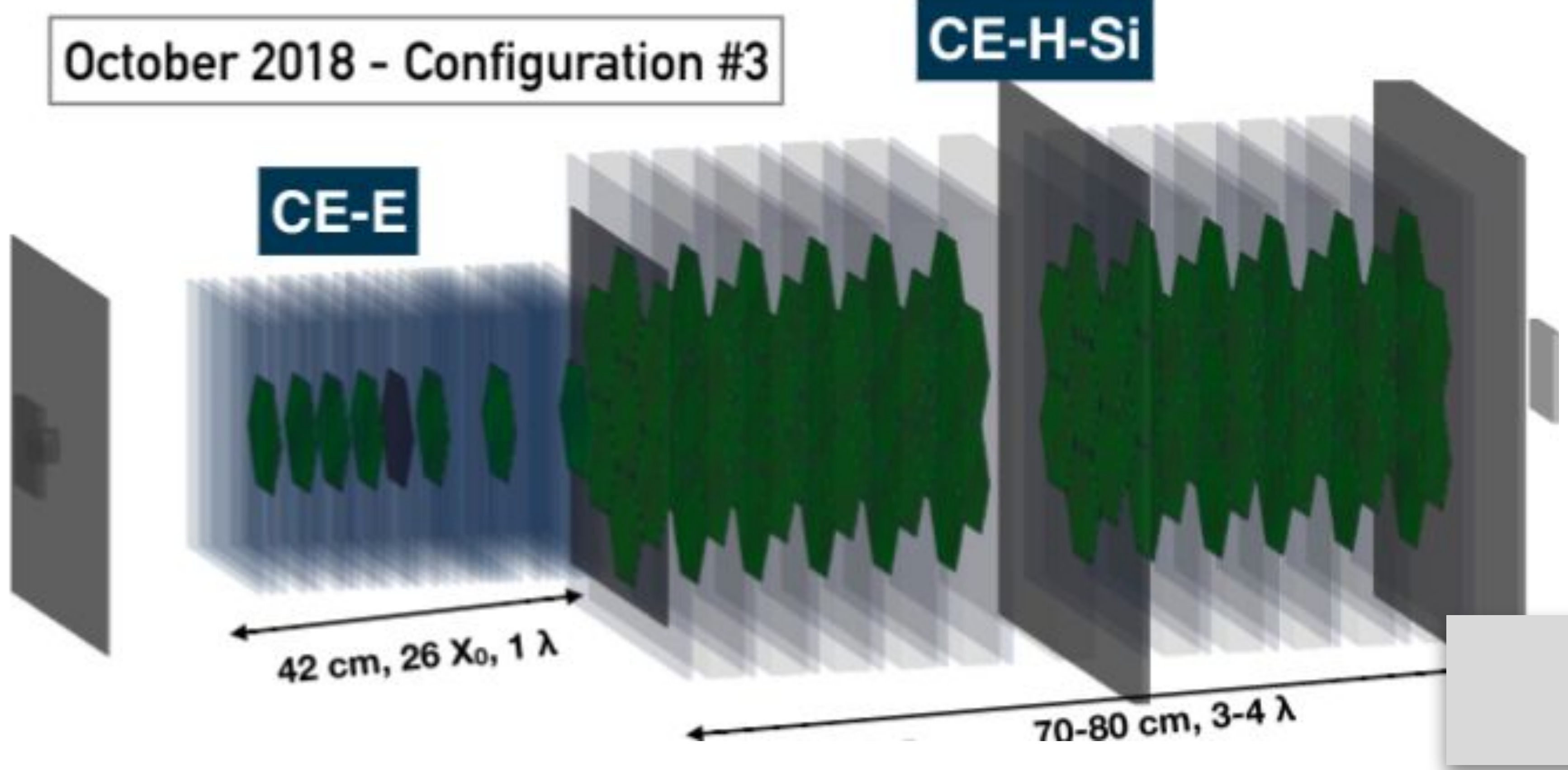


Fig 1

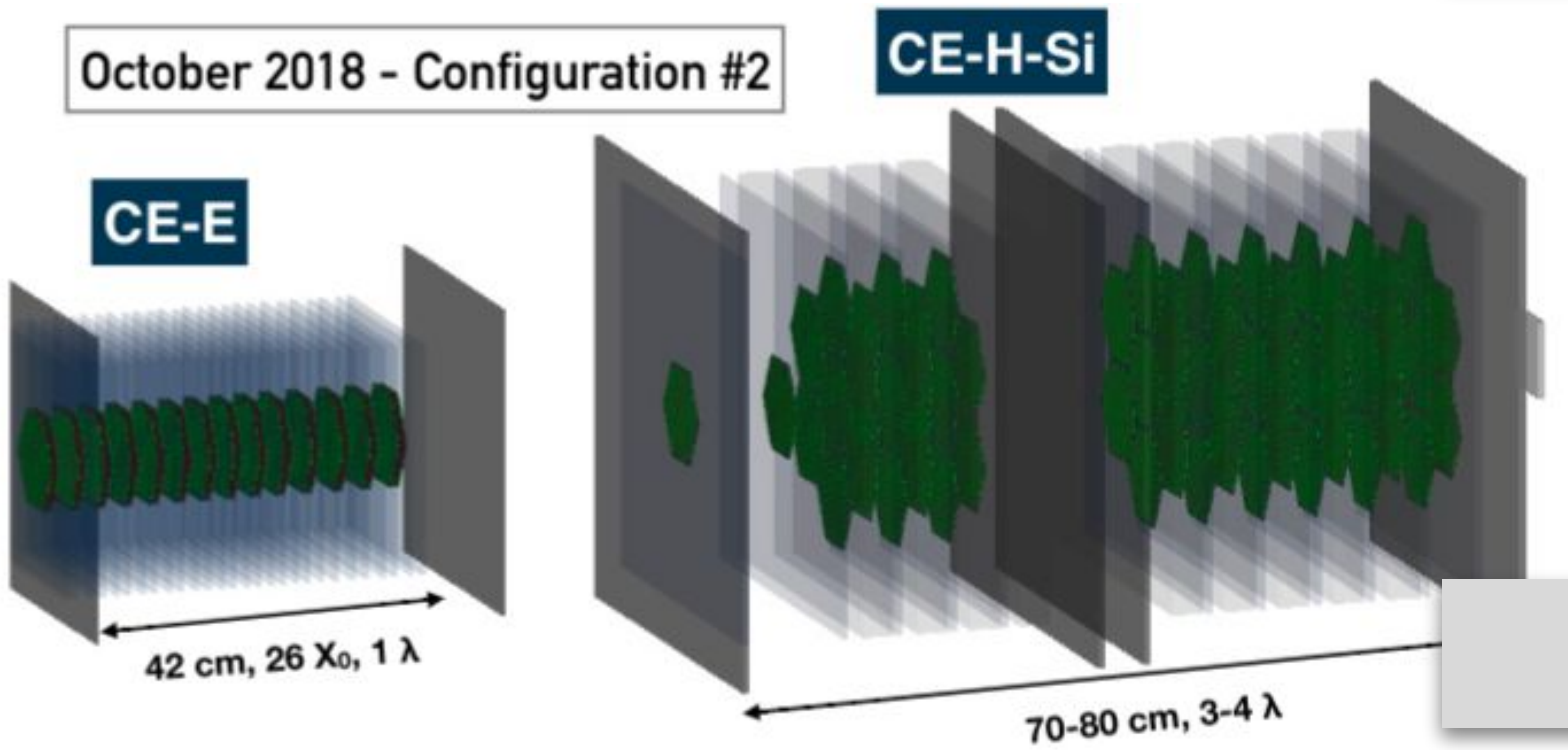


Fig 2

2016 — N Akchurin et al. 2018 JINST 13 P10023

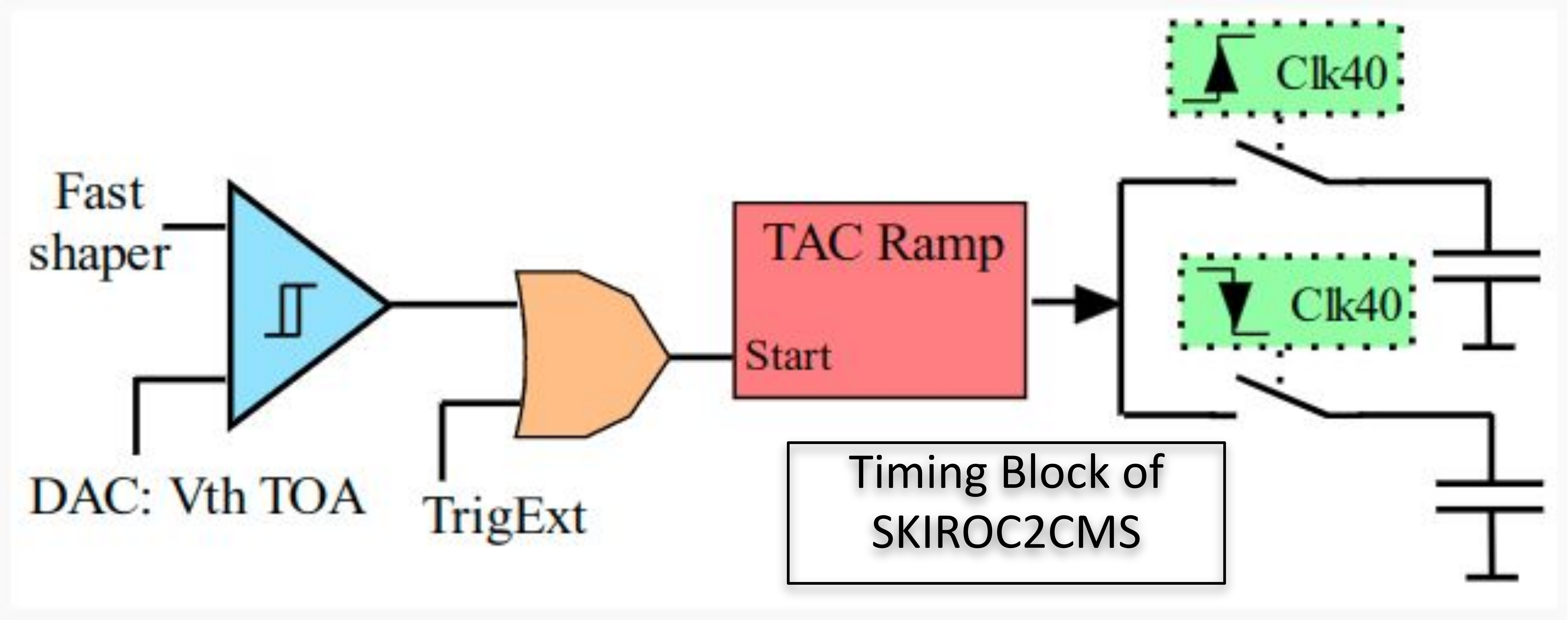
2017 — First Tests with SKIROC2-CMS ASIC

March 2018 — Tests @DESY: 3 Modules

June 2018 — Tests @SPS CERN: Full CE-E: 28 modules

October 2018 — Tests @SPS CERN: Full Prototype: 94 Modules

HGCAL Prototype Timing Circuit

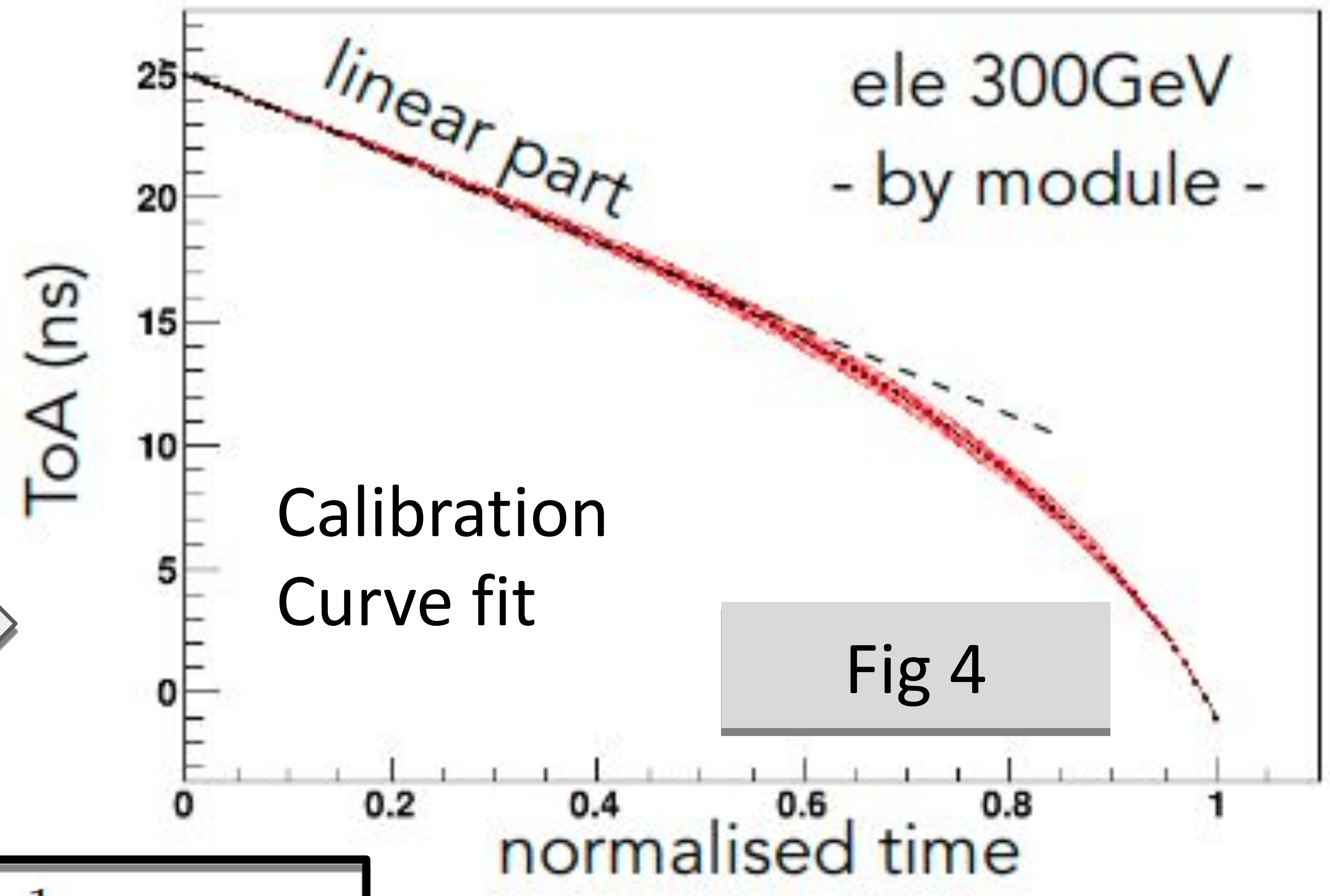


- SKIROC2_CMS Timing Circuit

Fast Shaper	Discriminator	Time to Amplitude Converter
5ns Shaping Time	Voltage threshold set to >15 MIPs equivalent	Clocks the signal w.r.t Rising and Falling Edge of the Clock

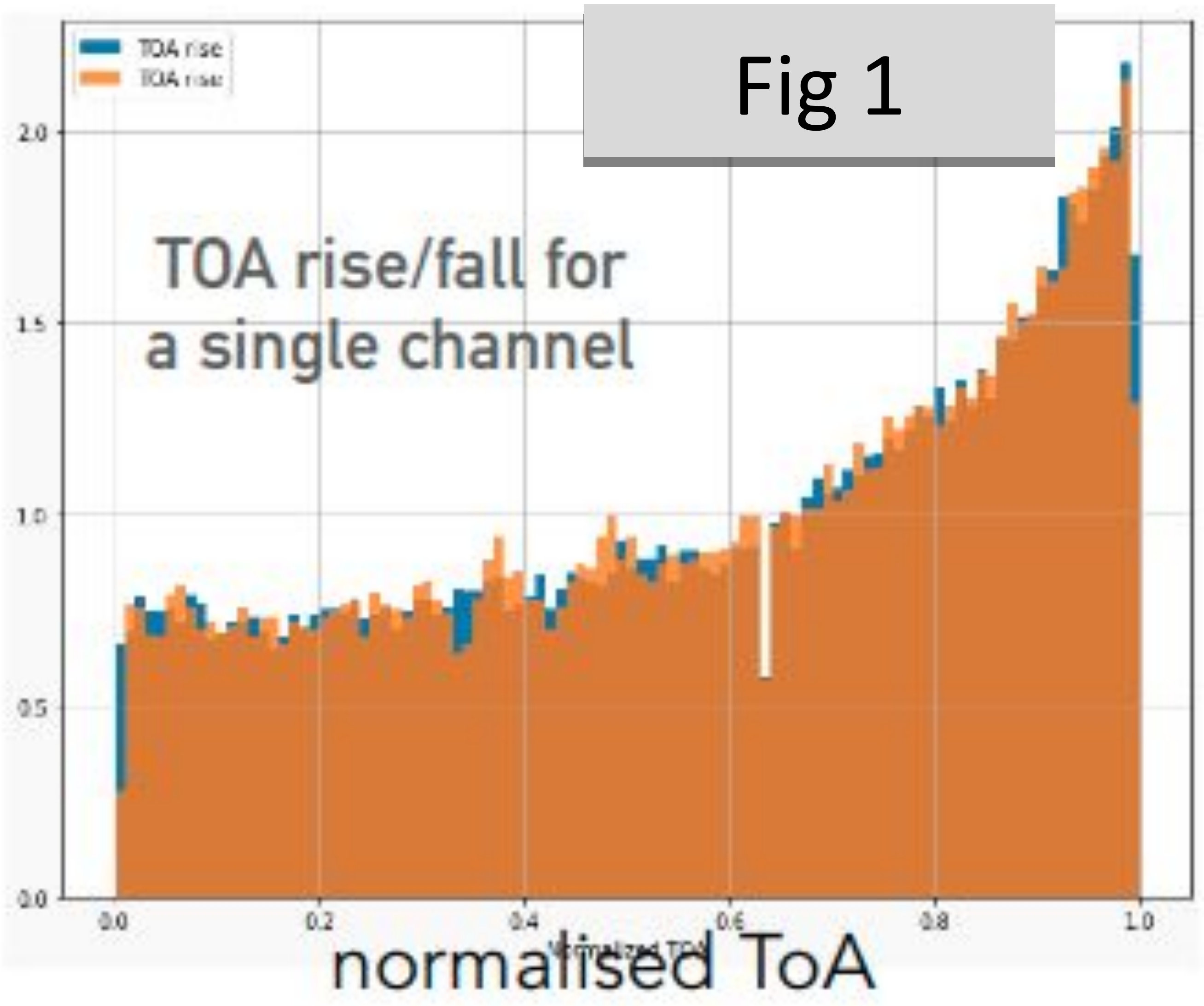
Calibration -- Linearisation

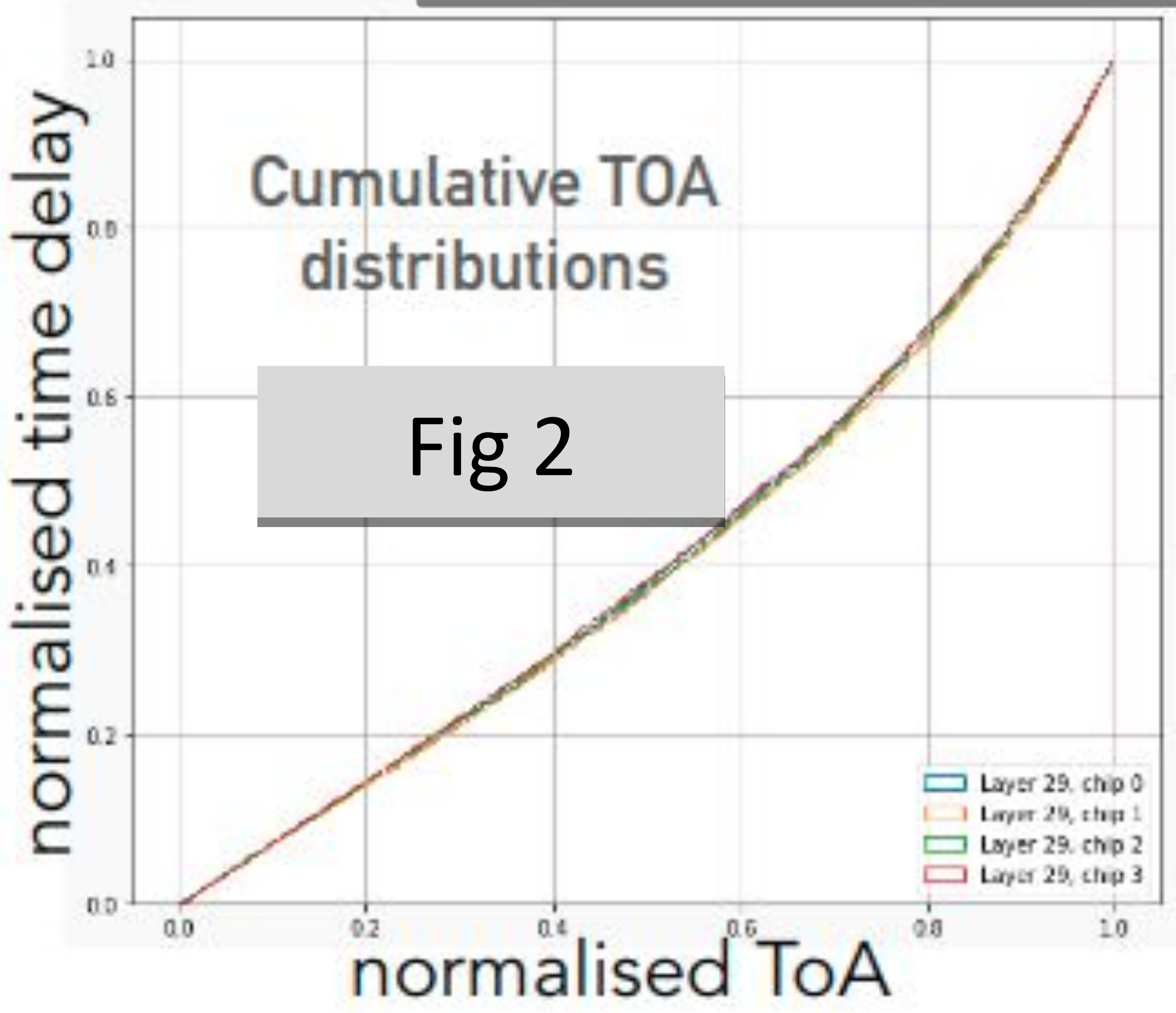
- The ramp saturation causes non-linearity in the TOA
- This was calibrated using a data driven method which exploits the asynchronous nature of the internal clock and the beam.
- Sampled with a uniformly distributed beam delay from which we derived the time calibration curves [more info]

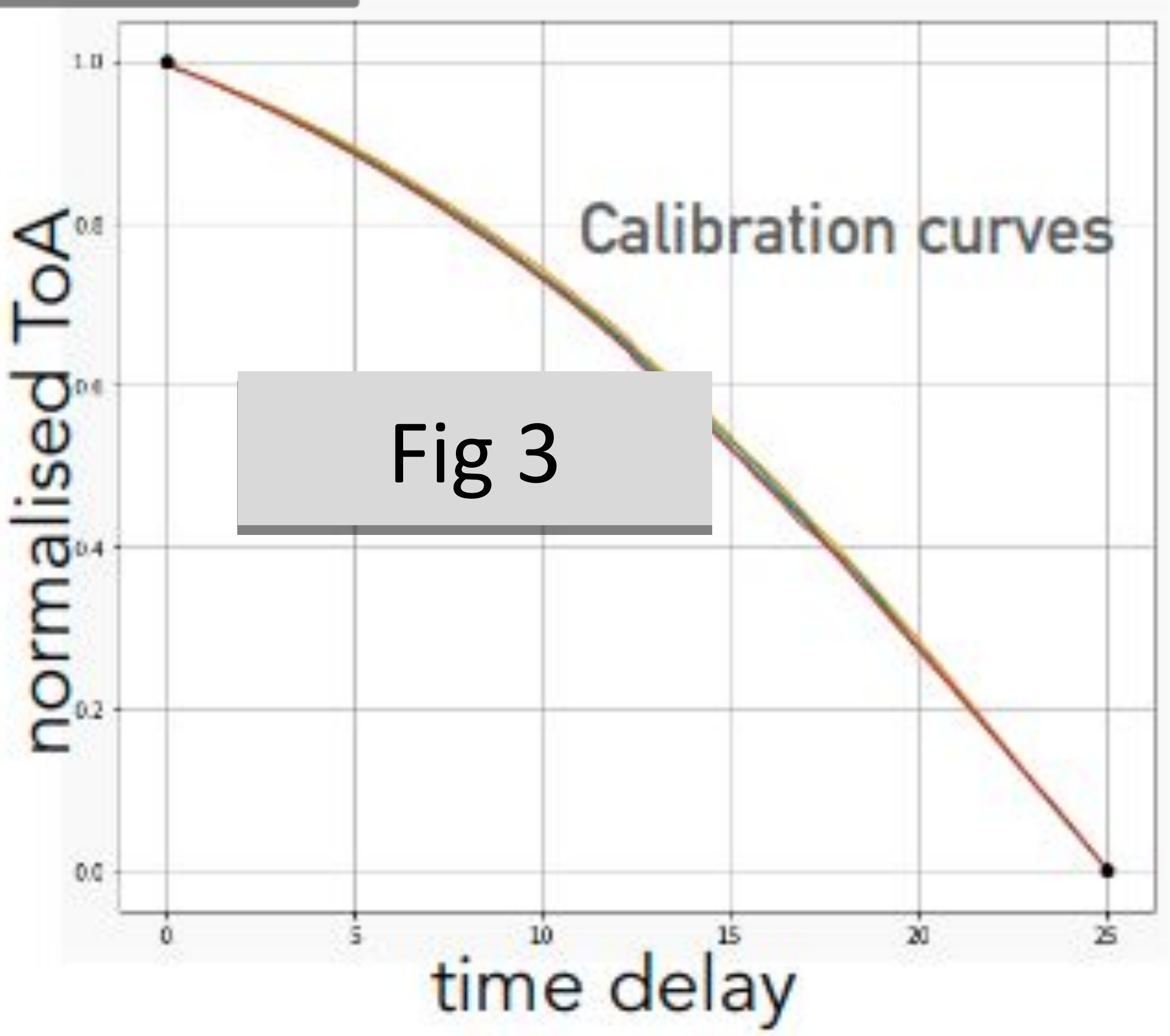


$$[0] * x + 25 + [1] * (\frac{1}{x - 1.25} + 0.8)$$

Equation 1: Fit curve for 300 GeV Electron







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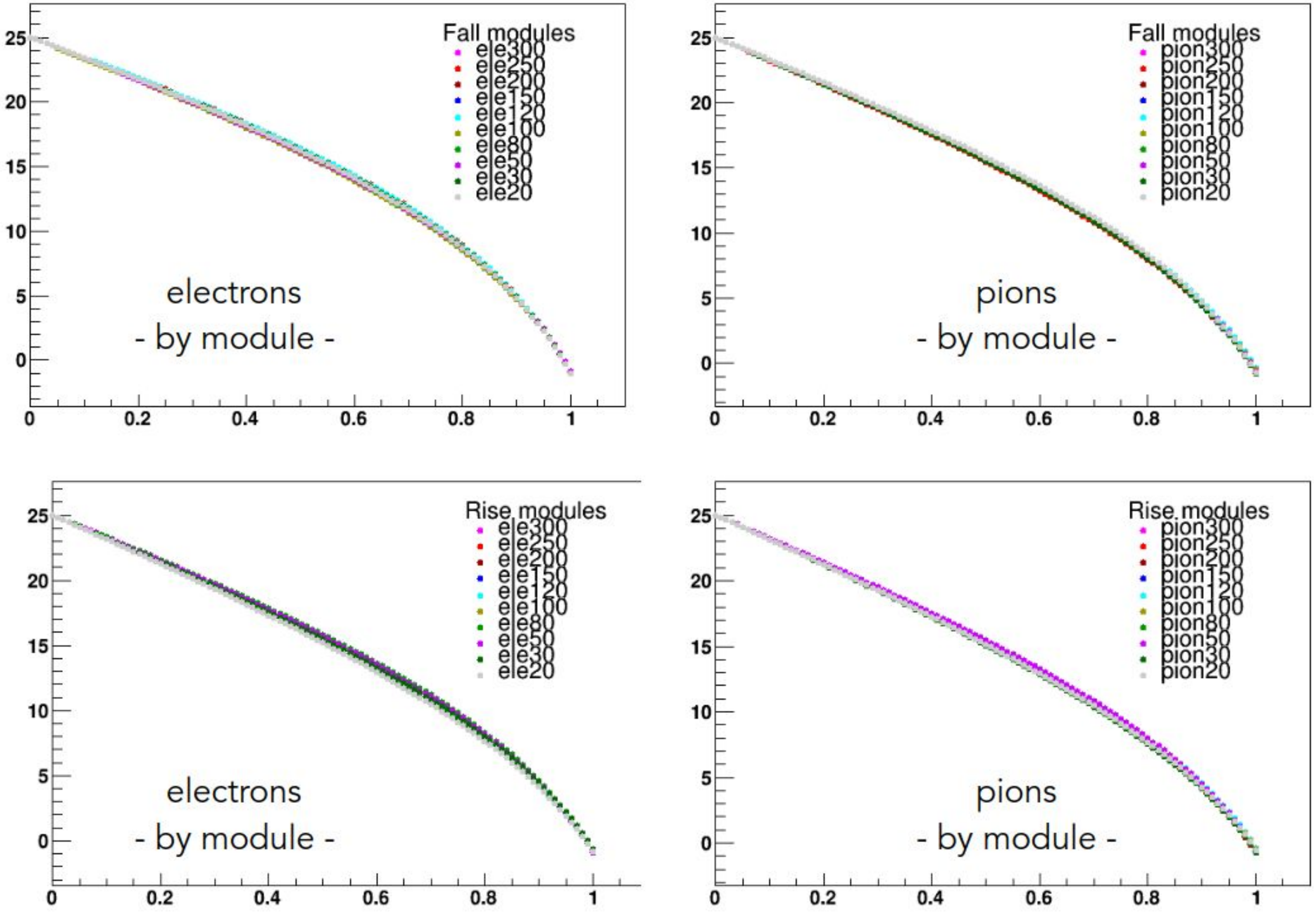
TOA Linearisation (Performance)



- ➔ Reasonably stable over
  - Beam Energies
  - Rise and Fall
- ➔ Calibration applied on the smallest level of granularity (per channel)
  - If the channel channel doesn't have stats the following preference is applied

$$[0] * x + 25 + [1] * \left(\frac{1}{x - 1.25} + 0.8\right)$$

Equation 1: Shows the fit curve for 300 GeV Electron

Calibration -- Time Walk Correction

Layer 8 Single Cell, 300 GeV Electrons

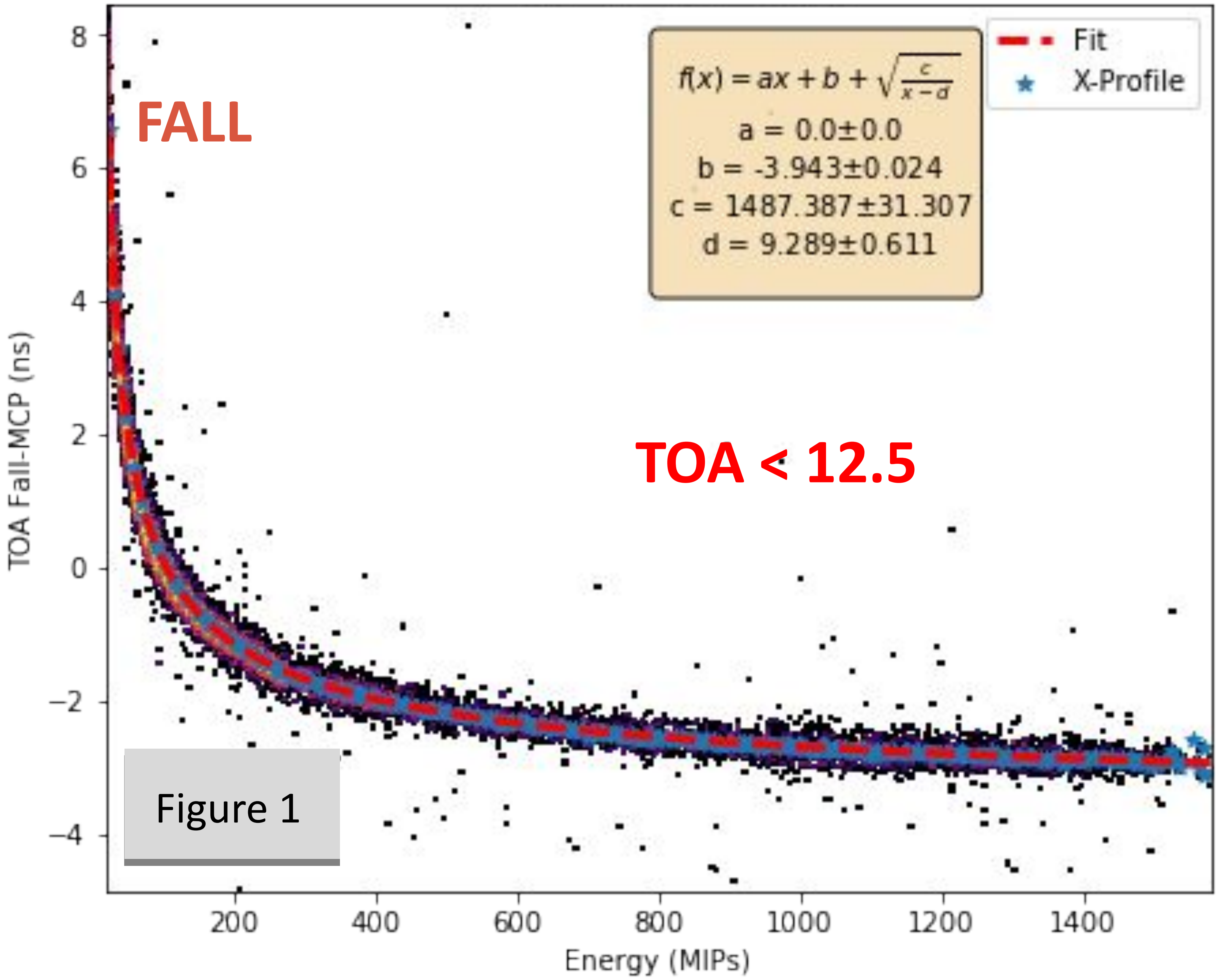


Figure 1

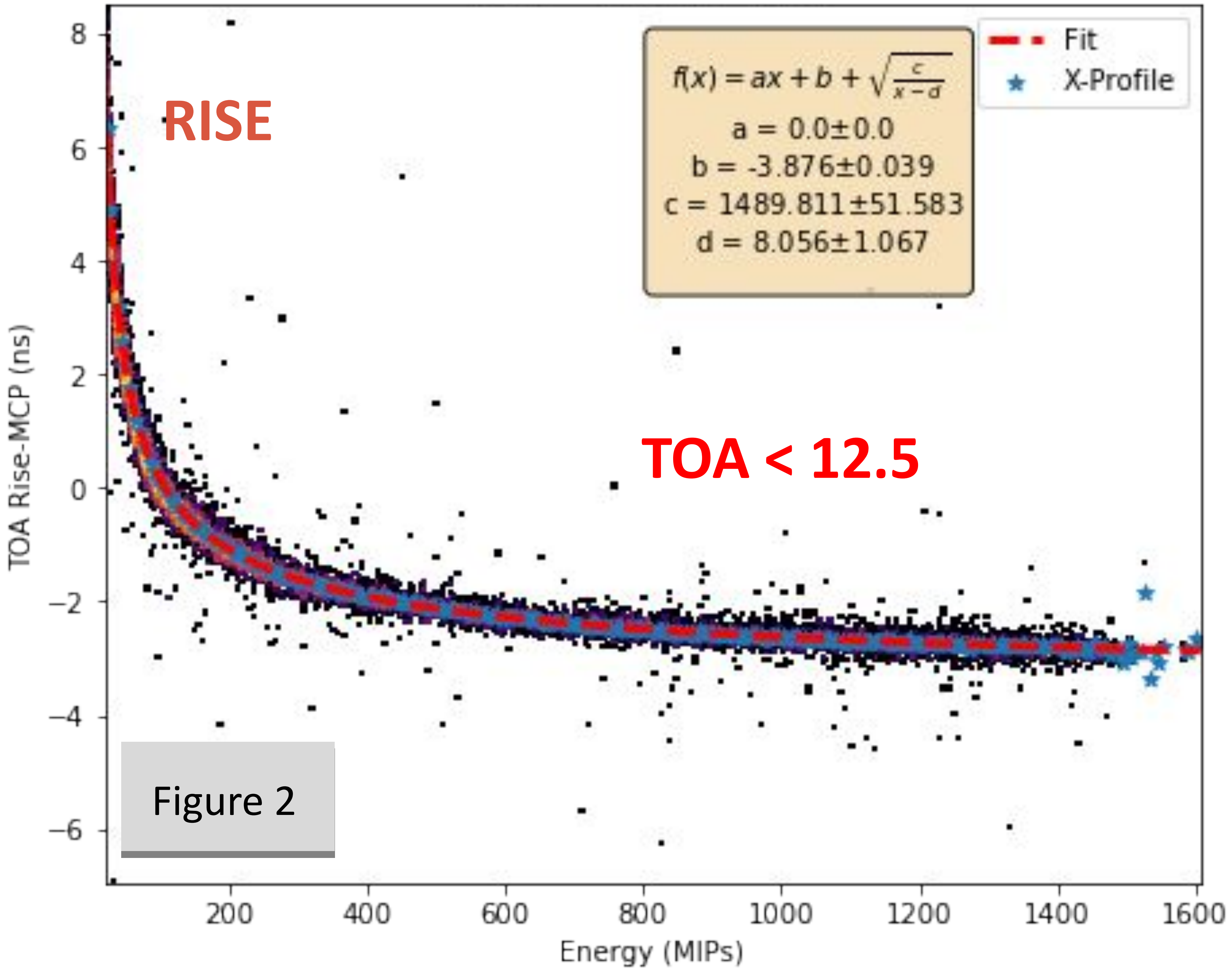


Figure 2

We apply a phase selection cut, TOA < 12.5ns , to remove residual non-linearity.
We fit the Time Walk Curve with f(x) (given in the figure), and correct for it by inverting the equation.

Fit parameters are consistent between Fall and Rise

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Timing Characterization using full MCP time-stamp

<u>Goals:</u>

- ➔ Reconstruction of MCP timestamp for calibration of the per-channel TOA-rise/fall
- ➔ Resolution + accuracy for single channels and channels combined

<u>Key differences to other studies:</u>

- ➔ Full usage of MCP timestamp
- ➔ No strict dependence on random beam incidence
- ➔ Per-channel time offsets, due to path lengths or TOF are not considered here

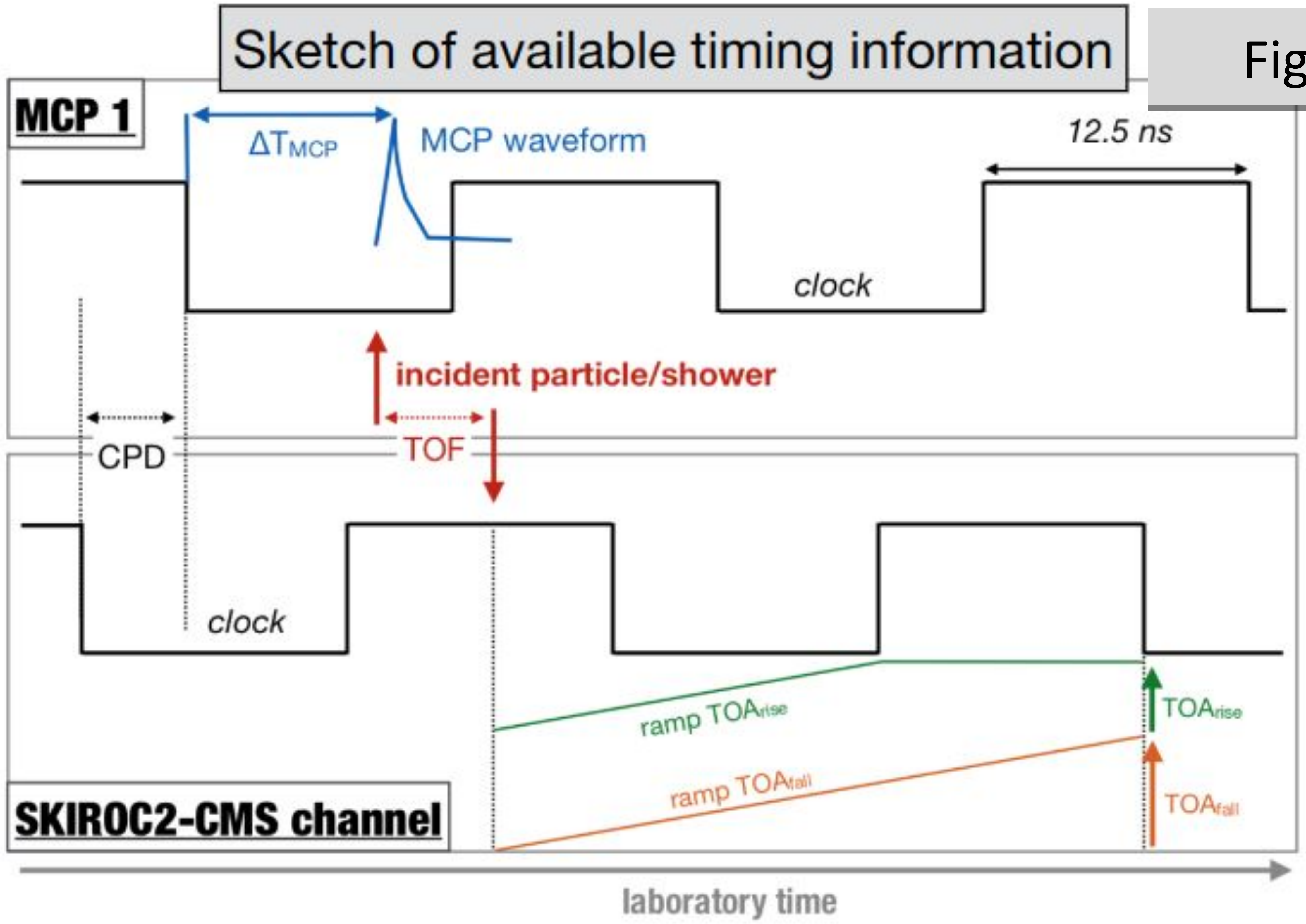


Fig 1

Calibrated hit-timestamp; hit energy timewalk; Signal trace lengths,

$$T = T(TOA,\, E,\, E_{\mathrm{module}}) = f_{\mathrm{TOA}}\left(\frac{TOA - TOA^{\mathrm{min}}}{TOA^{\mathrm{max}} - TOA^{\mathrm{min}}}\right) + f_{\mathrm{TW}}(E) + f_{\mathrm{B}}(E_{\mathrm{module}}) + \Delta l_0$$

TOA-non linearity; per-event baseline shift

Si-MCP: Single Channel Resolution

Layer 8 Single Cell, 300 GeV Electrons

CMS Preliminary

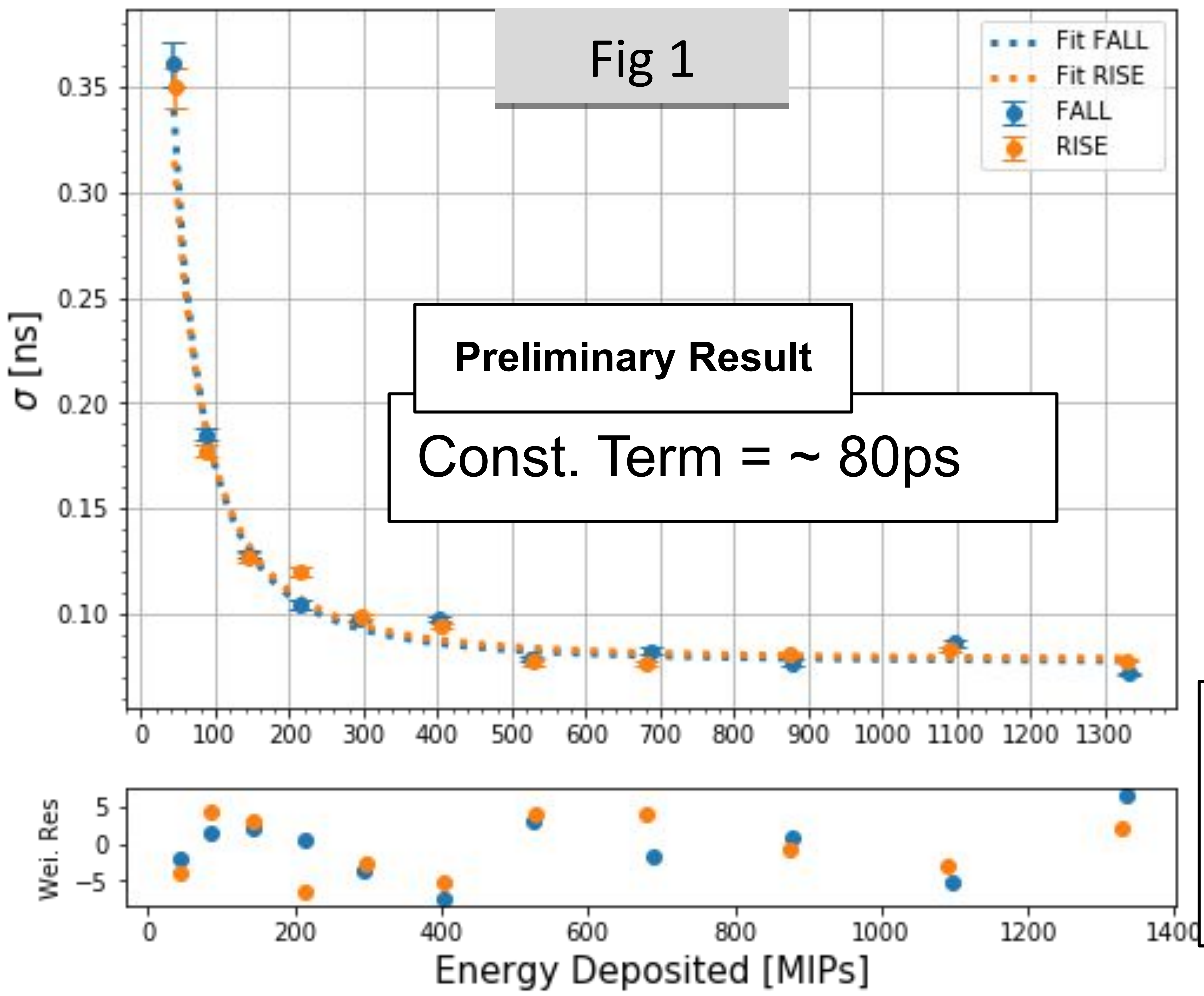
MCP Ampl > 500 ADC

Calibration Steps:

➔ Linearisation:
- Non-Linearity caused by ramp saturation
- Calibrated using a data driven method which exploits the asynchronous nature of the internal clock and the beam.

➔ Time Walk Correction:
- Phenomenon where the timing depends on the energy deposited in the detector
- Corrected by inverting Time Walk parametric equation

Single Channel Resolution:
- 300 GeV Electrons
- Binned in energy deposited in the channel fit against a gaussian distribution
- Consistent results between fall and rise TOA



$RISE = \sqrt{(\frac{A}{E-B})^2 + C^2}$

A = 16.473±0.49
B = -8.972±2.742
C = 0.078±0.0
χ^2_ν = 20.312

$FALL = \sqrt{(\frac{A}{E-B})^2 + C^2}$

A = 15.609±0.448
B = -3.309±2.487
C = 0.077±0.001
χ^2_ν = 20.605

MCP used as reference

Figure 1: Time-Resolution as a function of Energy Deposited

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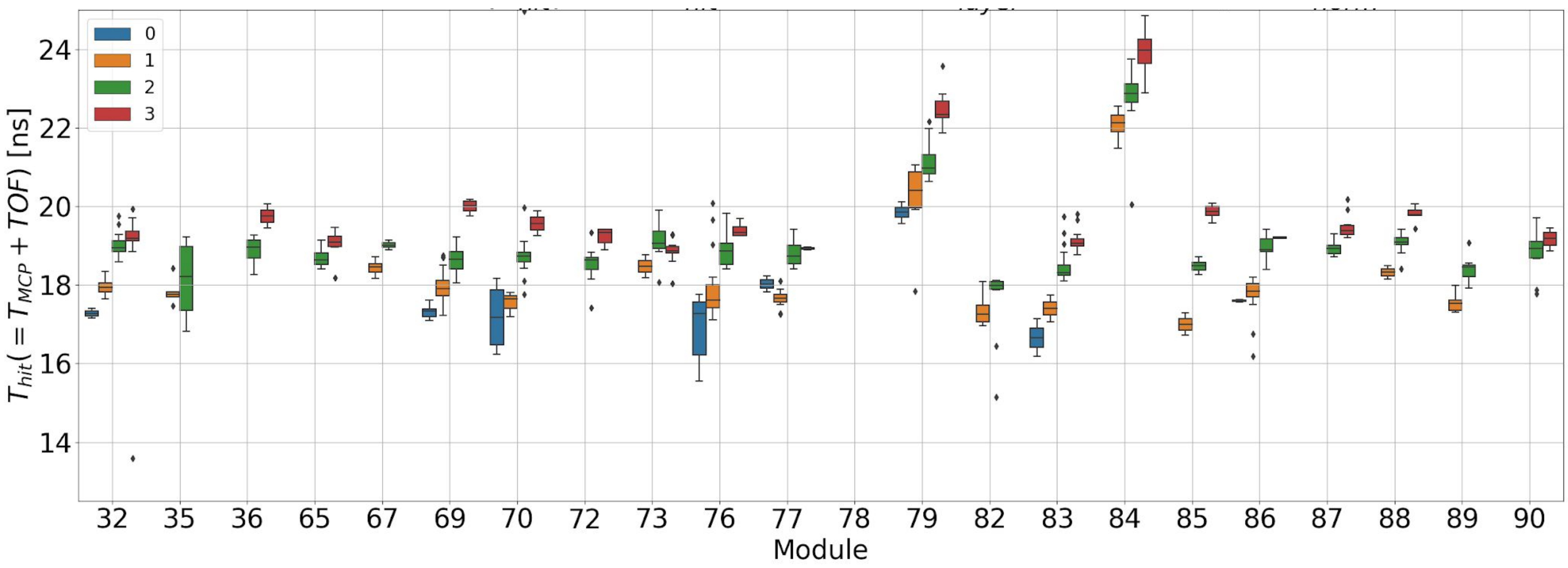
Mean, median, and spread of the calibrated hit time

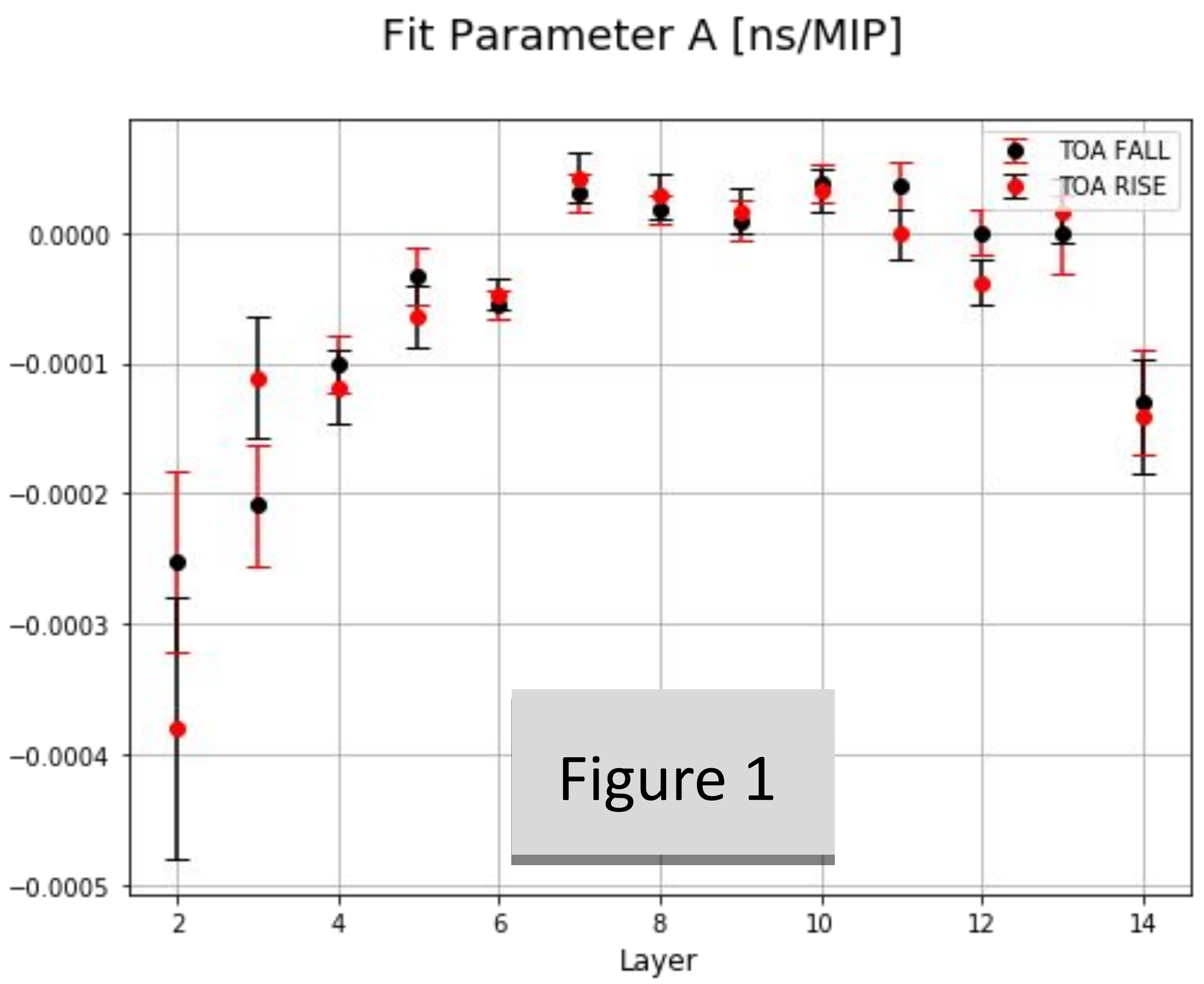


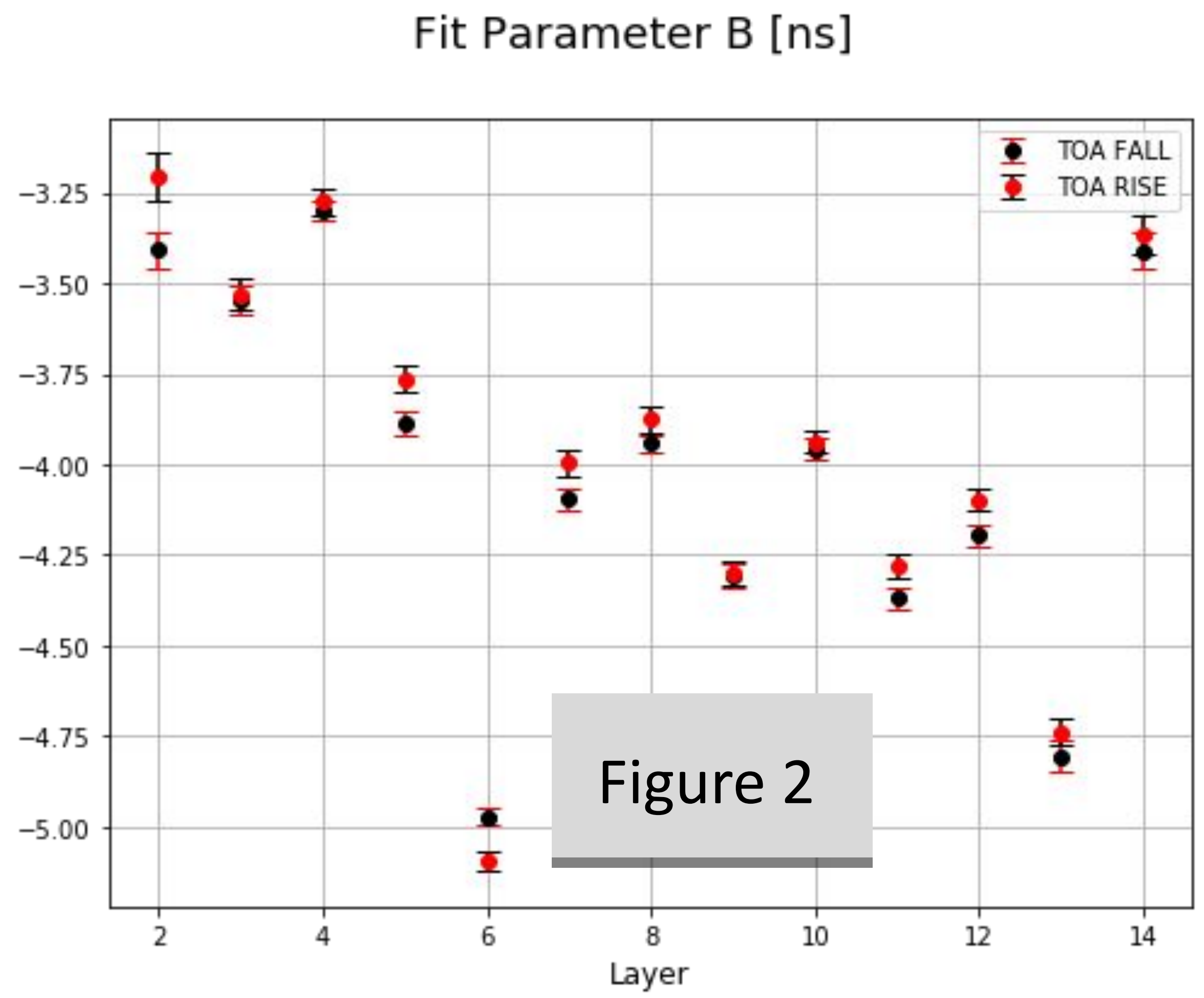
Shows the box plot of

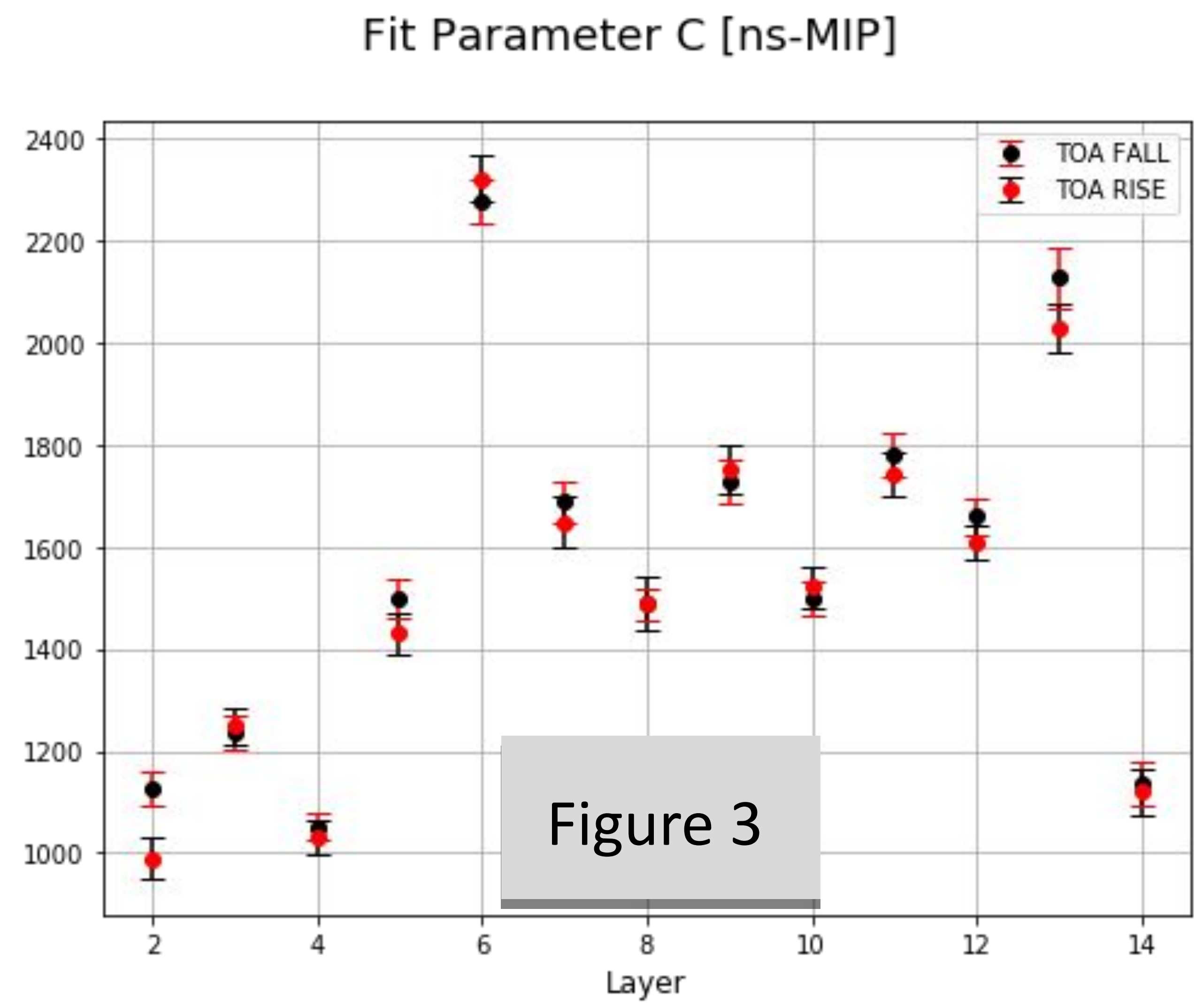
Calibrated Hit Time (T_{hit}):

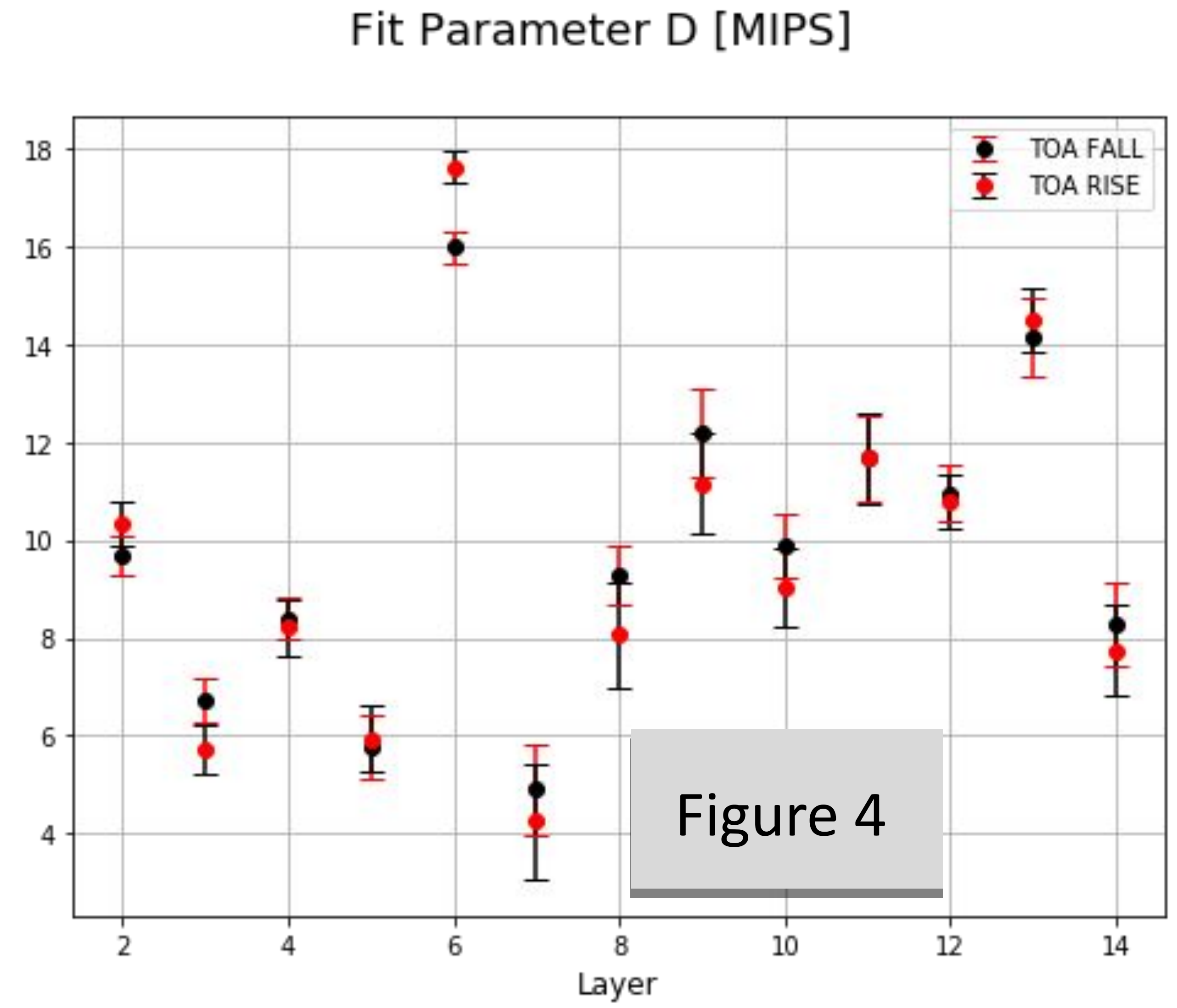
- E_{hit} = 500 MIPs
- E_{layer} = 600 MIPs

Stability Across Layers









$$y = A.x + B + \sqrt{\frac{C}{x - D}}$$

Consistent results between TOA Fall and TOA Rise

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Effects of Variation in Smearing