Performance evaluation of the Sc-ECAL technological prototype

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CALICE Analysis Meeting, 17/Feb./2022

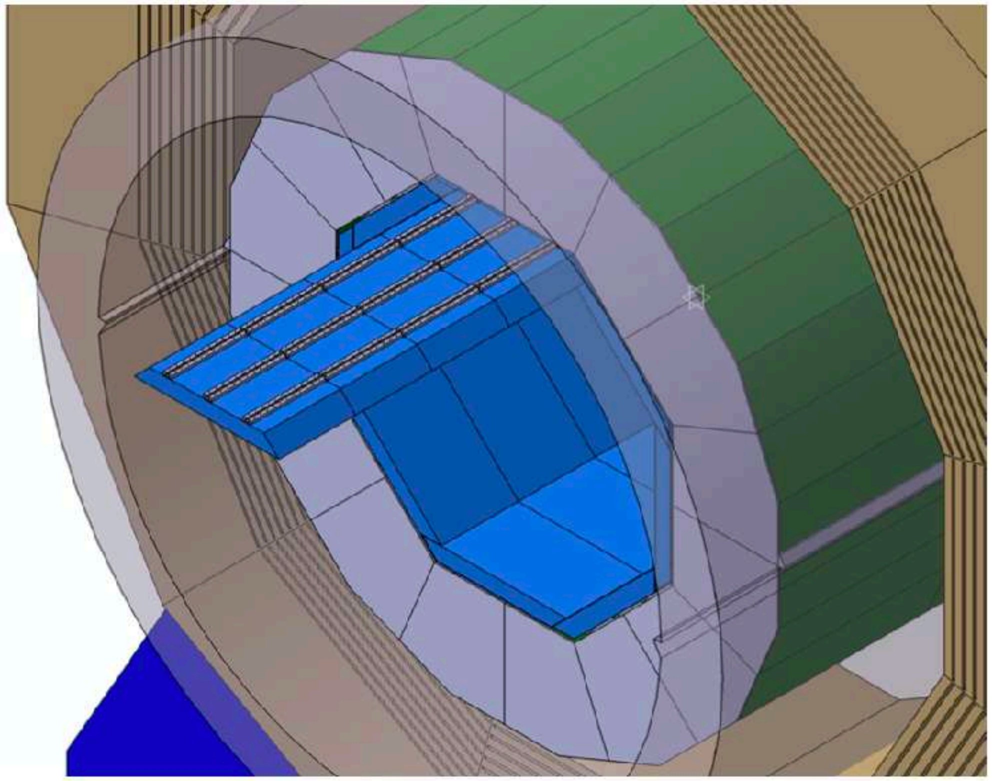
Contents

Scintillator ECAL (Sc-ECAL)

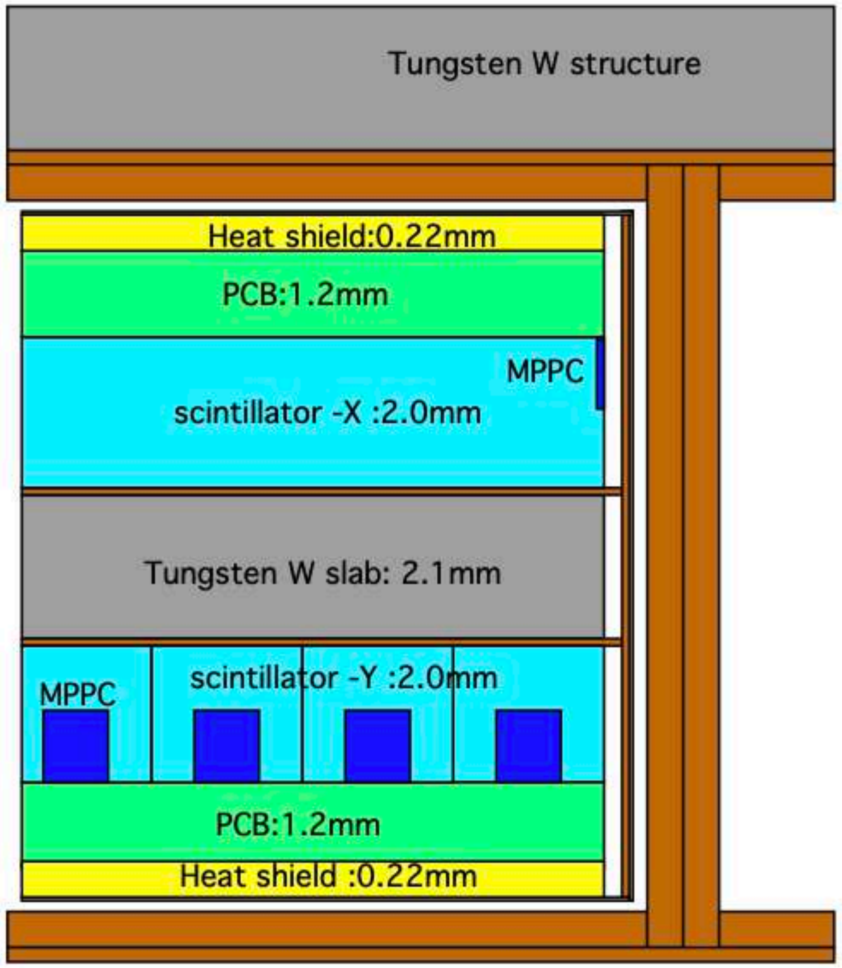
- Smapling calorimeter
  - 30 layers of absorber and detection layers
- Based on scintillator strips readout by Silicon PhotoMultiplier (SiPM)
- Virtual segmentation: 5×5 mm^2 with strips in x-y configuration
  - Number of readout channels significantly reduced ($10^8 \rightarrow 10^7$)
  - ➡ Low cost
  - Retaining performance compared to real 5×5 mm^2 segmentation at the Silicon ECAL

- Physics prototype
  - Concept of the Sc-ECAL was validated
  - Some difference from current configuration
    - Large cell size of 10×10 mm^2
    - Complex strip design with strip and WLS fiber
    - Fully integrated electronics not used

ECAL in ILD



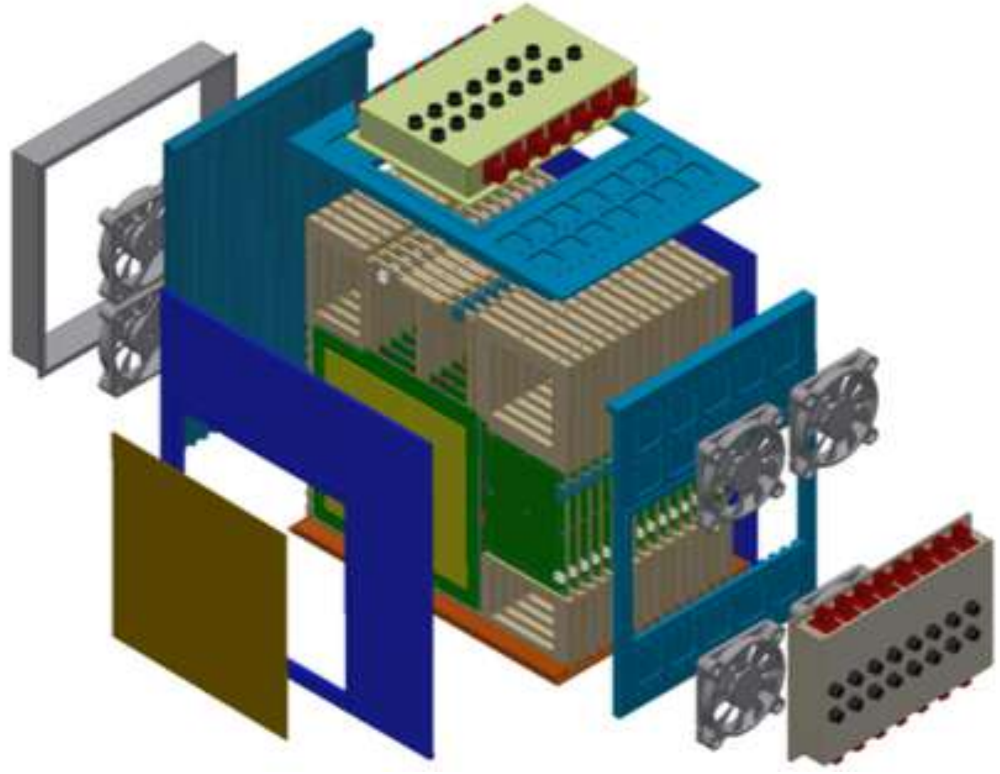
Structure of Sc-ECAL



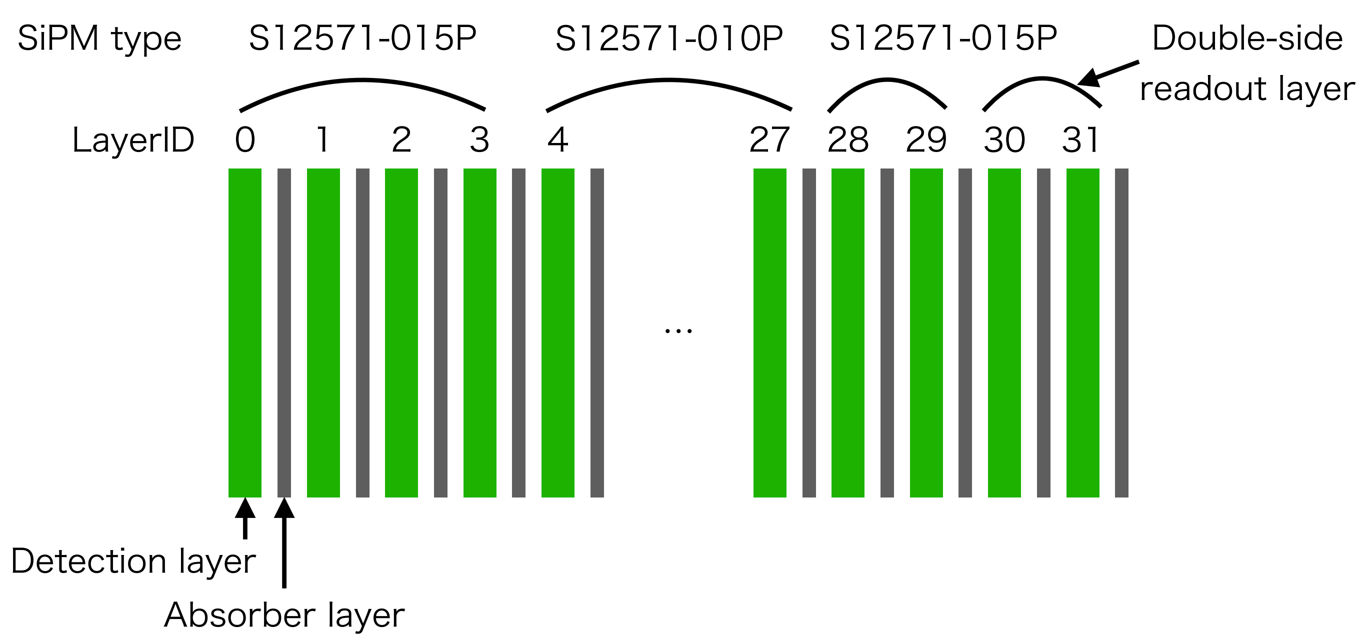
Large technological prototype

- Large technological prototype for Sc-ECAL has been constructed as a joint effort by R&D groups for ILC-ILD and CEPC-ECAL
  - Use the same technology as foreseen in the full scale detector
    - $5 \times 45 \times 2\ mm^3$ scintillator strip, bottom-center readout, fully integrated electronics
  - Evaluate the performance of the Sc-ECAL using full 30 layers

Sc-ECAL technological prototype



Layout of detection layers



Completed technological prototype

Commissioning

- Commissioning tests for calibration and performance evaluation
  - Calibration is performed to correct signal ADC counts to number of MIPs
- LED tests for 1 month
  - Single photoelectron gain calibration
    - Convert ADC counts to number of photoelectrons
  - Inter-calibration
    - Charge injection of electronics between high gain and low gain to meet wide dynamic range
  - Cross-talk and after-pulse calibration
    - CTAP probability is used for saturation correction
- Cosmic-ray tests for 3 months
  - Pedestal calibration
  - MIP calibration
    - Response to minimum ionized particle is used for energy scale
  - Performance evaluation
- Test beam experiments
  - Canceled due to COVID-19 pandemic

Uncorrected signal (ADC counts) ↓ Number of photoelectrons

Corrected signal

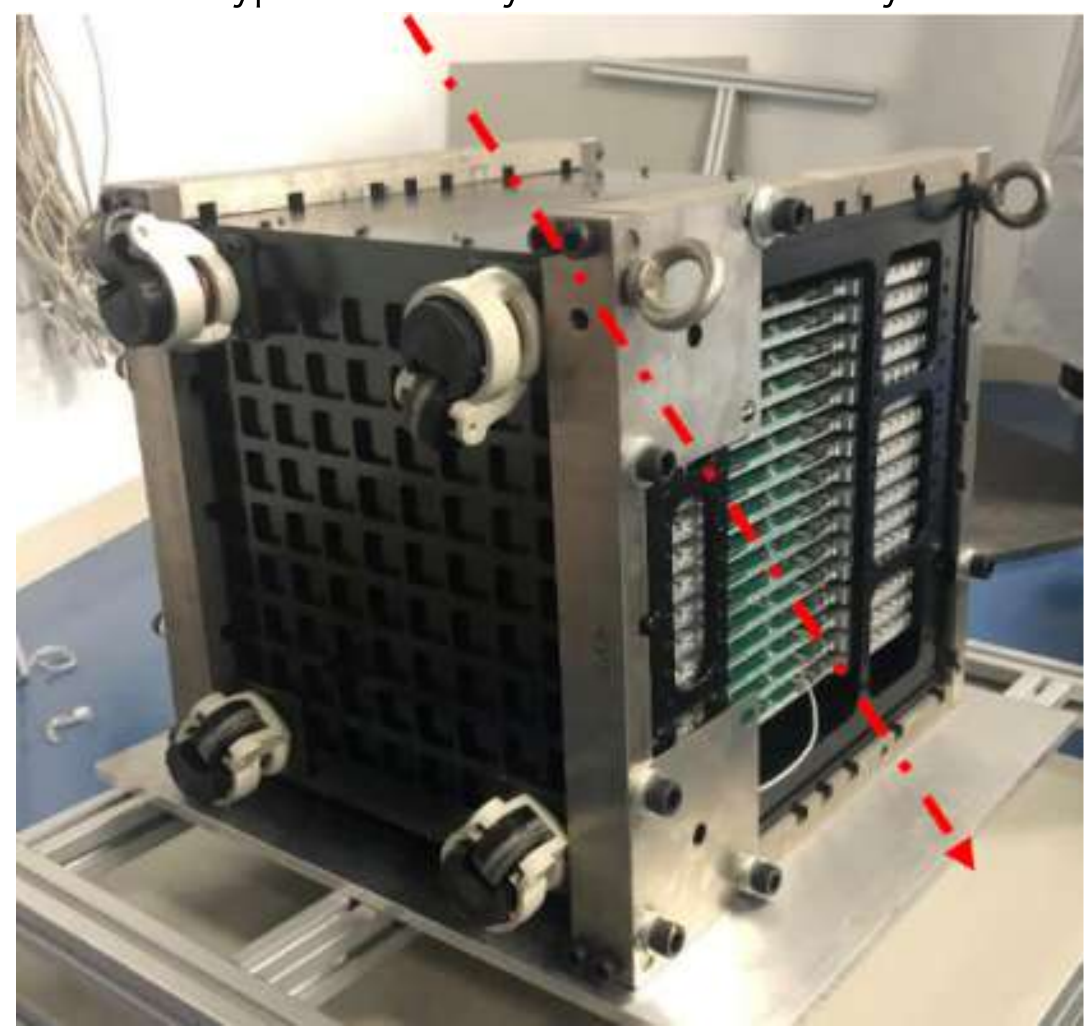
$$A_i^{corr}[\mathrm{MIP}] = F^{-1}_{P_{CTAP}}\left((A_i[\mathrm{ADC}](T) - c^{pedestal})\frac{c_i^{inter}}{c_i^{gain}(T)}\right)\frac{c_i^{gain}(T)}{c_i^{inter}c_i^{MIP}(T)}$$

Uncorrected signal

Saturation correction

Number of p.e. ↓ Number of MIPs

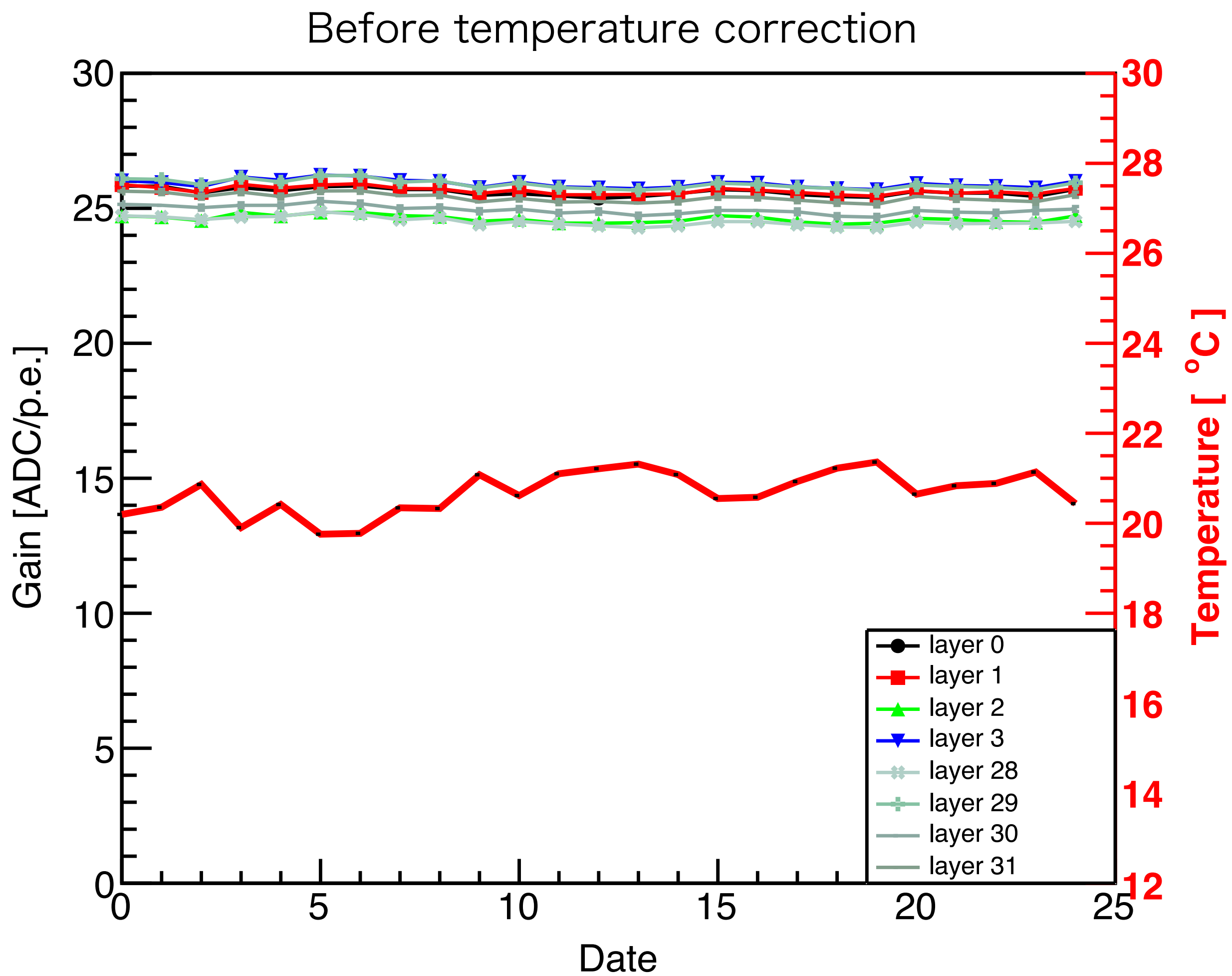
Prototype rotated by 90° for cosmic-ray test

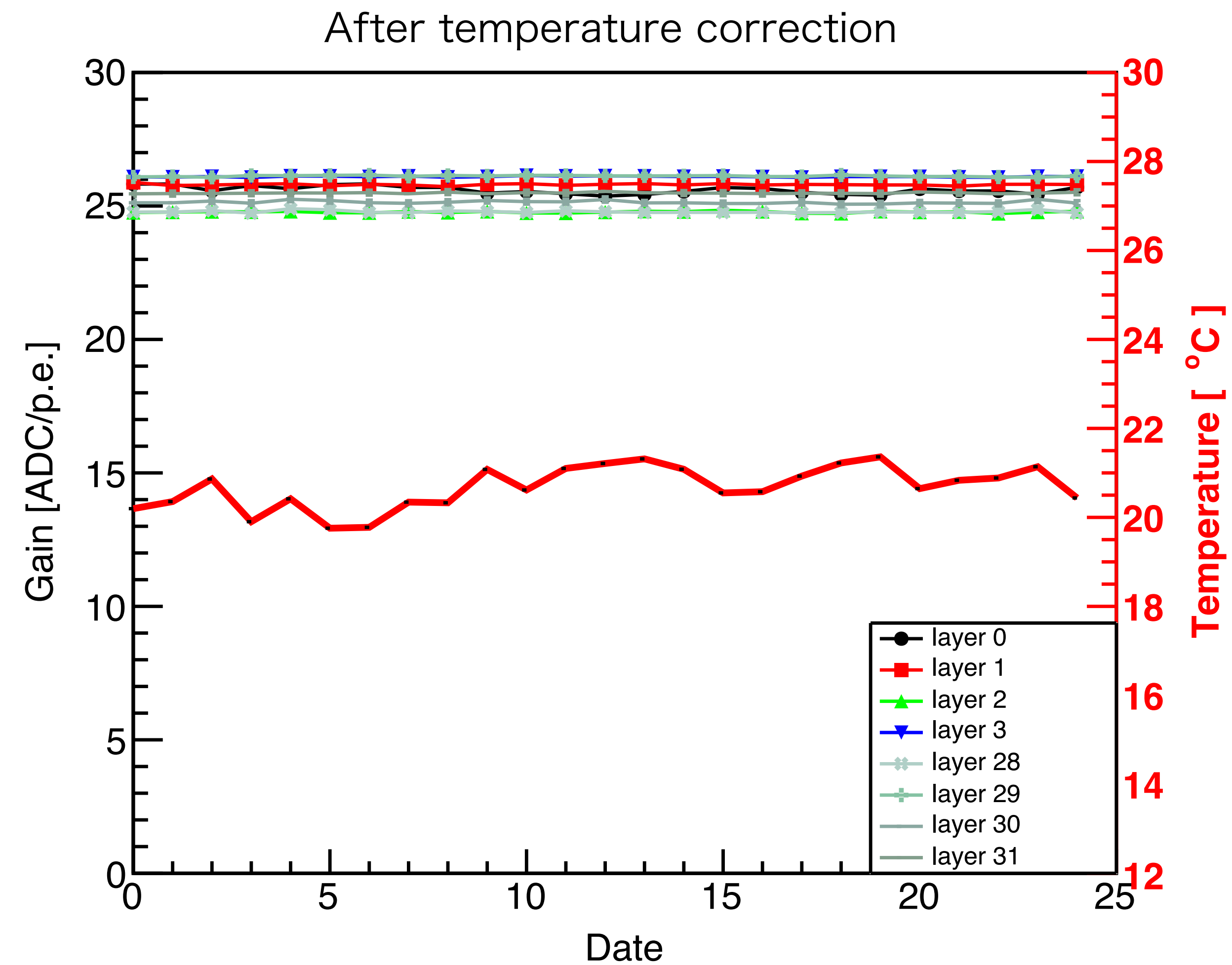


Stability

- **Gain is quite stable during one month LED run**
  - Weak correlation with the temperature variation
  - Further improved by temperature correction
- Inter-calibration, CTAP, and pedestal stability is quite stable when averaged over all channels
  - Improvement of LED system is needed to reduce the error
- Sc-ECAL can be calibrated well and operated stably

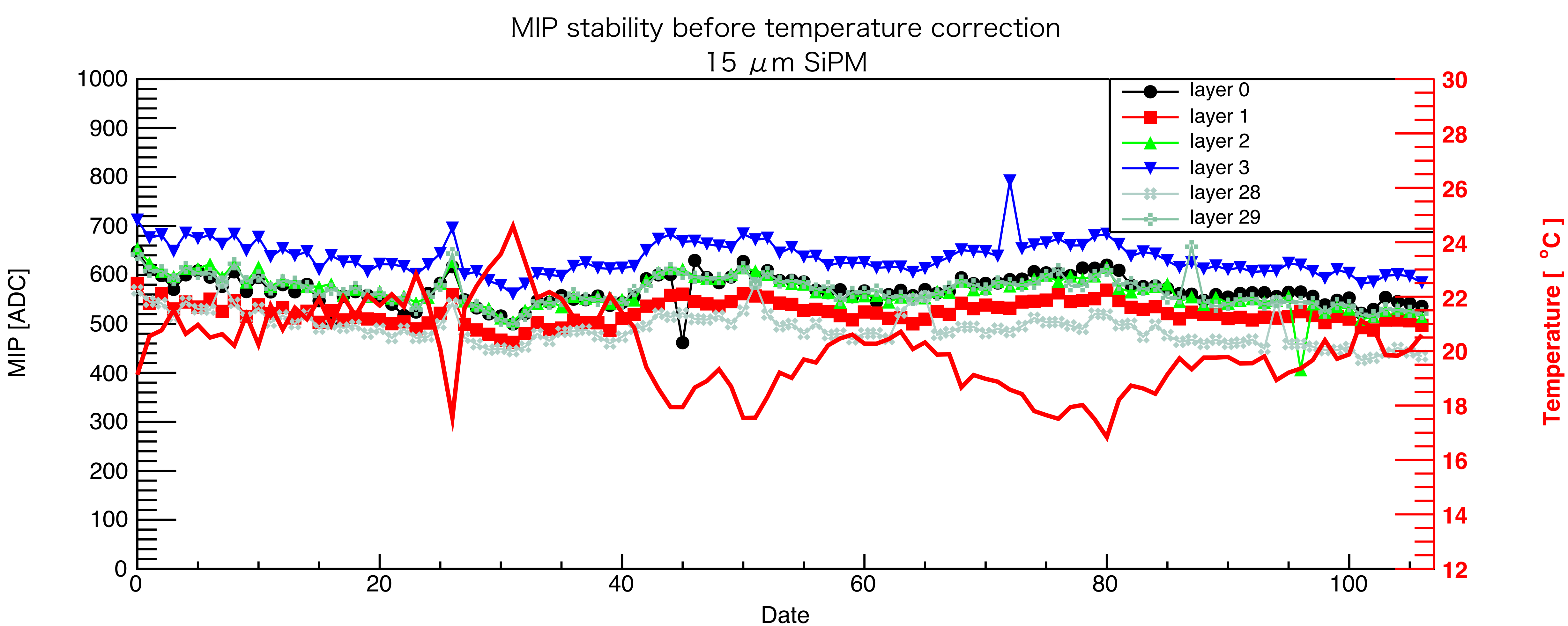
Gain stability with 15 μm SiPM





Stability

- **MIP response is almost stable during three month CR run**
  - Correlation with the temperature variation
  - Further improved by temperature correction
- 5–13% decrease over 3 months depending on layer
  - The reason is under investigation
    - Instability of electronics or SiPM
    - Aging of scintillation light emission
  - Possible approach is frequent MIP calibration and voltage adjustment of SiPMs



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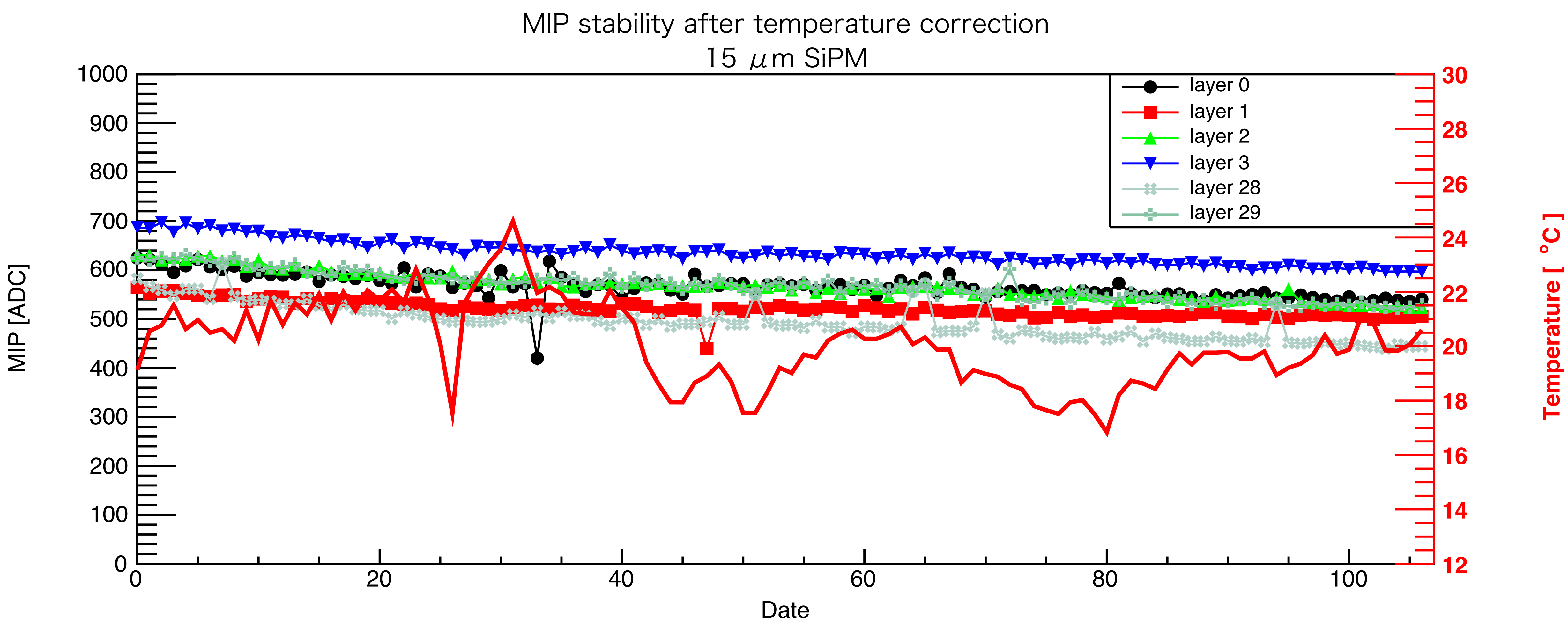
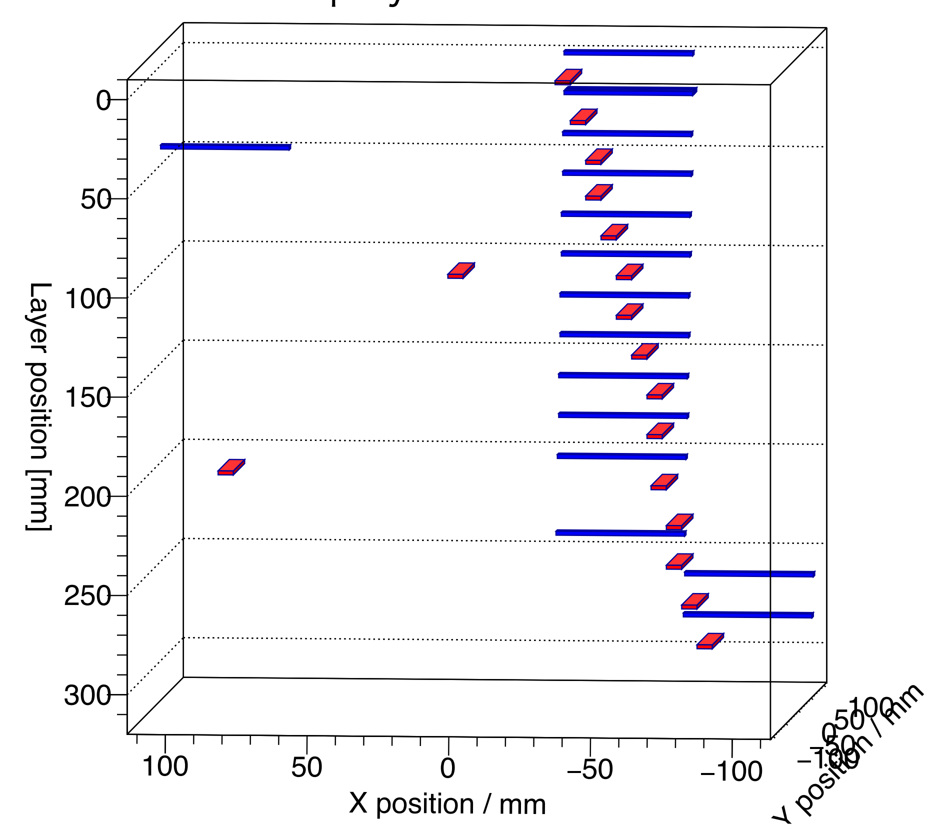


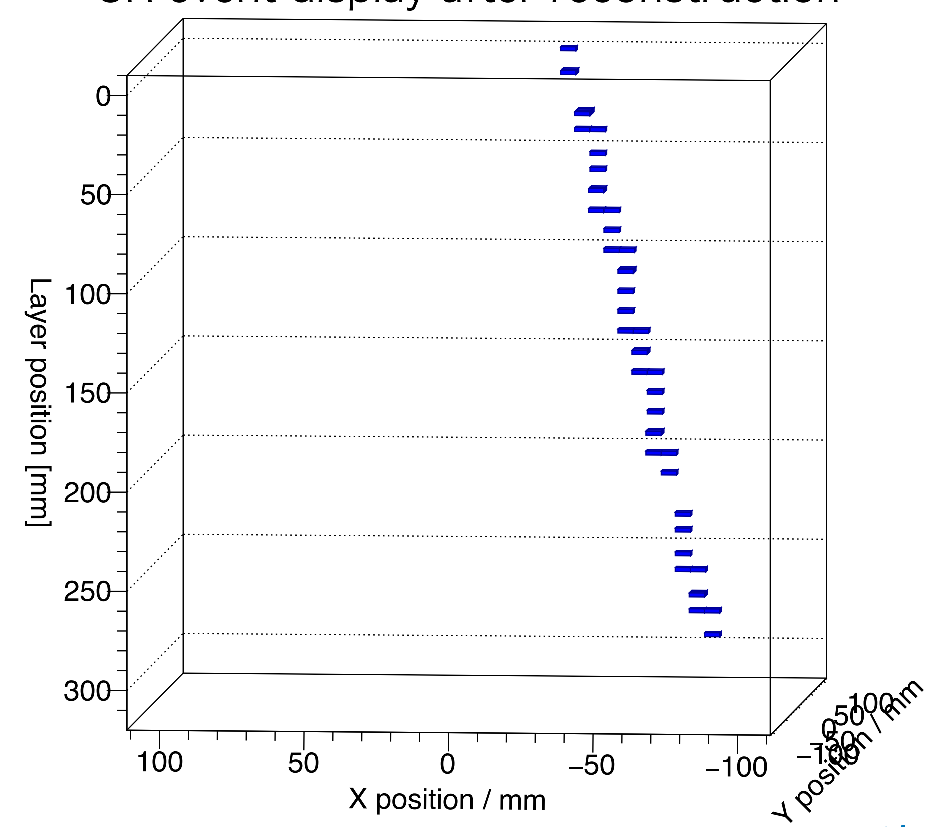
Reconstruction for straight track

- Straight track of cosmic-ray is reconstructed:
  - Preselection: cut for noise events
  - Strip Splitting Algorithm (SSA)
  - Cone clustering
  - Track fit: linear fit for the straight track
- **5 × 5 mm² segmentation and clustering are applied, and cosmic-ray straight track can be obtained**
- Angular correction for the ADC distribution is applied to each hit
  - Injection with an angle (larger energy deposit)
    → Perpendicular injection (energy deposit in 2 mm)

CR event display before reconstruction

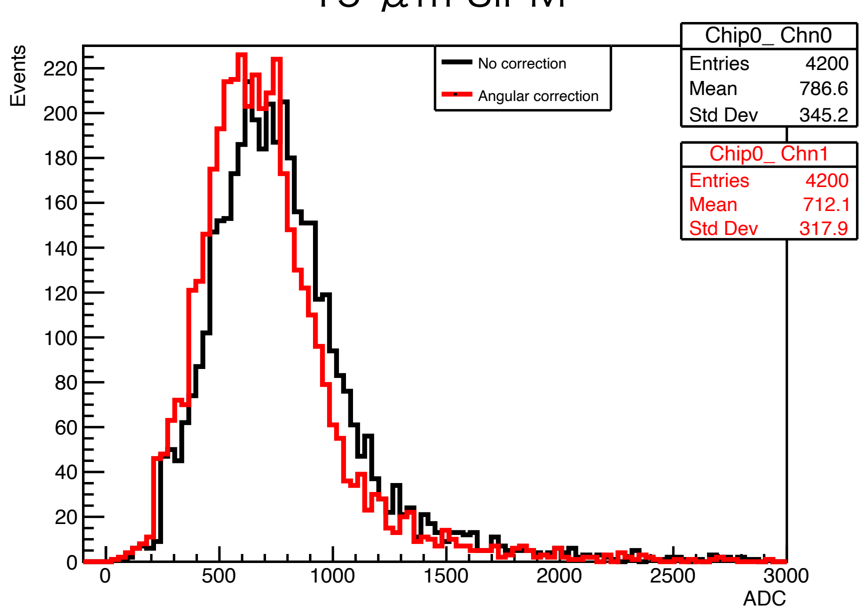


CR event display after reconstruction

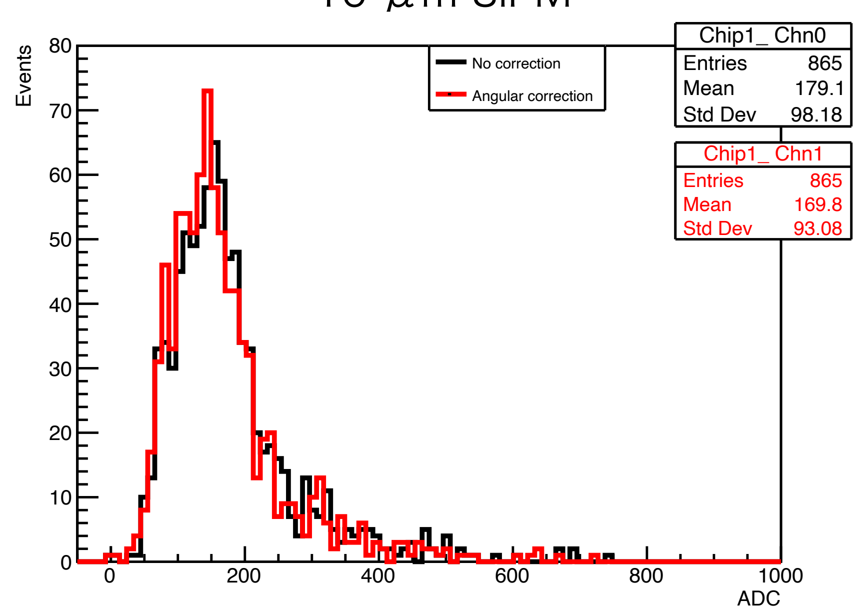


Signal ADC distribution for MIP response

15 μm SiPM



10 μm SiPM



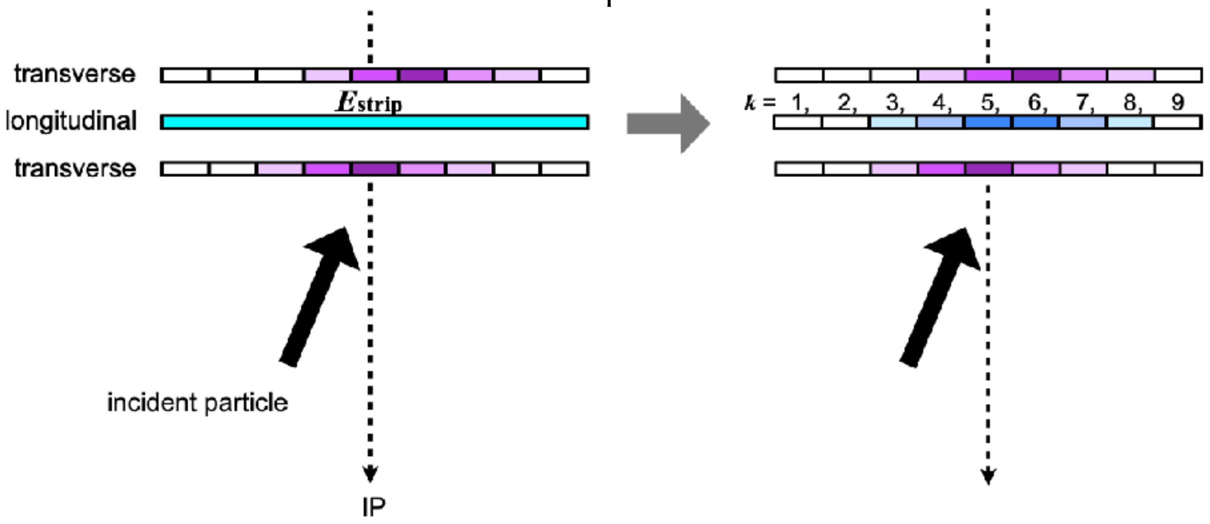
SSA & clustering

- 45 mm strip is split by 9 cells (5mm) using the hit and energy of upper and lower layers
  - Weighting factor w_k for k-th virtual cell:

    $w_k = \Sigma_i E_i$
  - Energy deposit in k-th virtual cell:

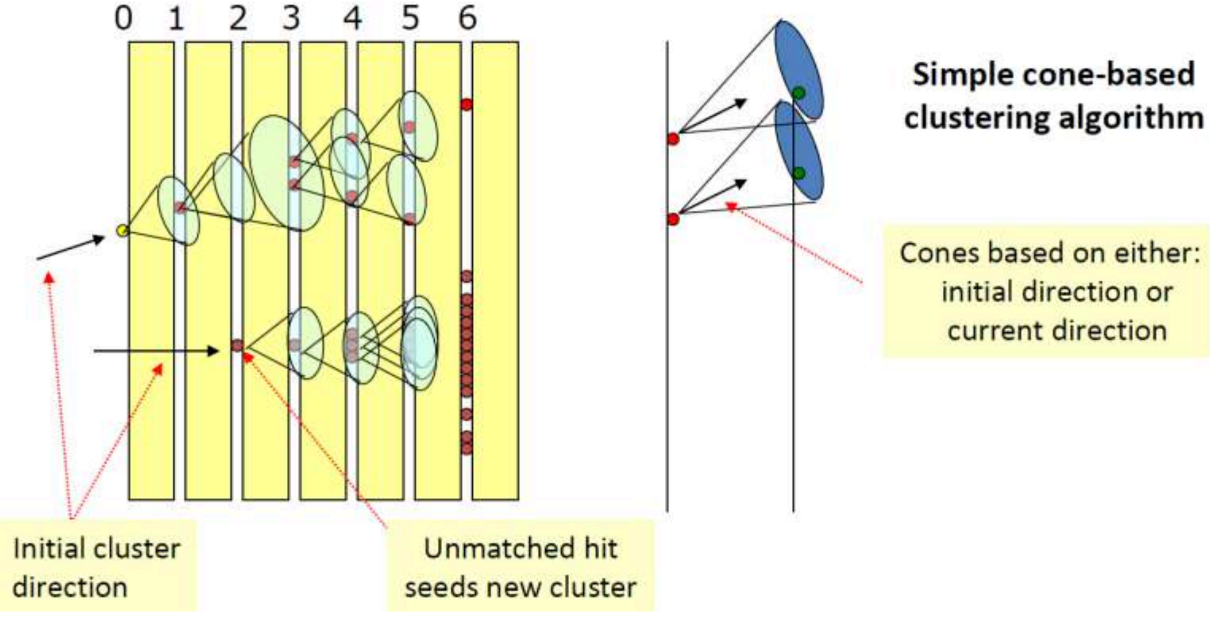
    $E_k = E_{strip} \frac{w_k}{\Sigma_j w_j}$
- SSA applies all layers and strips and realize the 5 × 5 mm^2 cell segmentation

SSA procedure



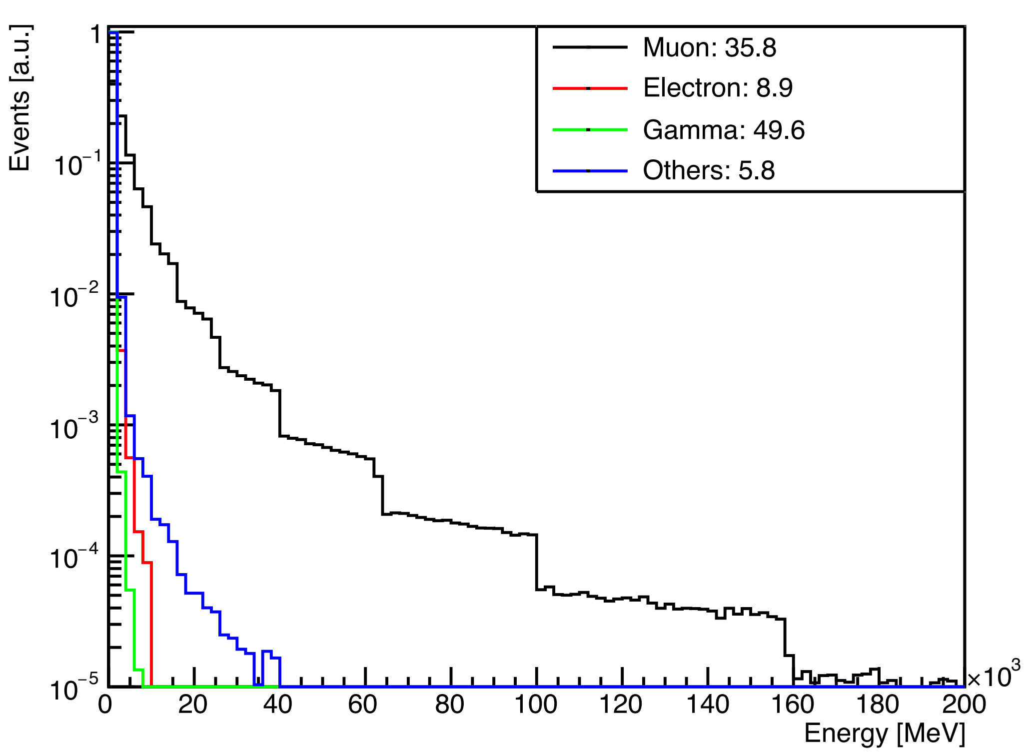
- Simple cone-based clustering algorithm implemented
  - Cone clustering with no angle
  - Linear fit
  - Cone clustering with injection angle
- Noise cut & search for shower-like events

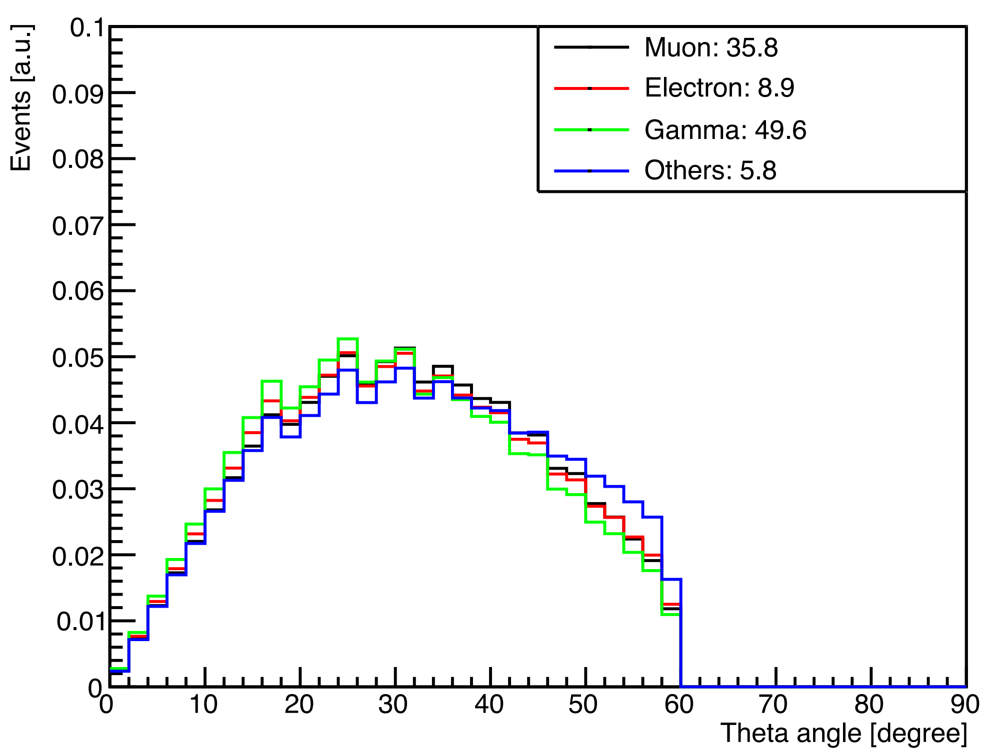
Cone clustering



Monte Carlo simulation

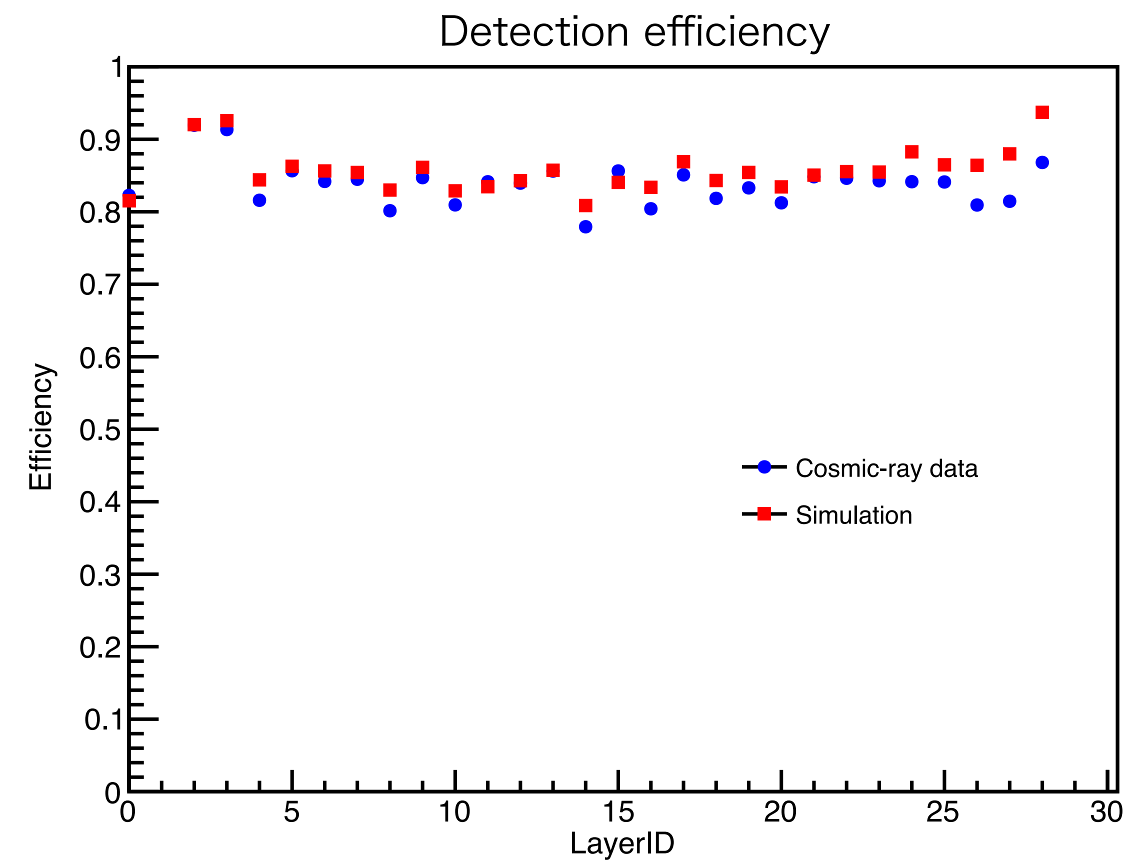
- CR test is simulated using Geant4 to compare with CR data
  - 30 layers of absorbers, detection layers, readout PCBs
  - Aligned in the same way as technological prototype
  - Building material corresponding to the situation with 15 floors above the prototype
- Cosmic-ray shower library (CRY)
  - Wide energy range: 1 MeV — 100 TeV
  - Several particle types: muon, electron, gamma, hadron
- Channel characteristics obtained in the calibration are applied to each channel
  - MIP response, threshold

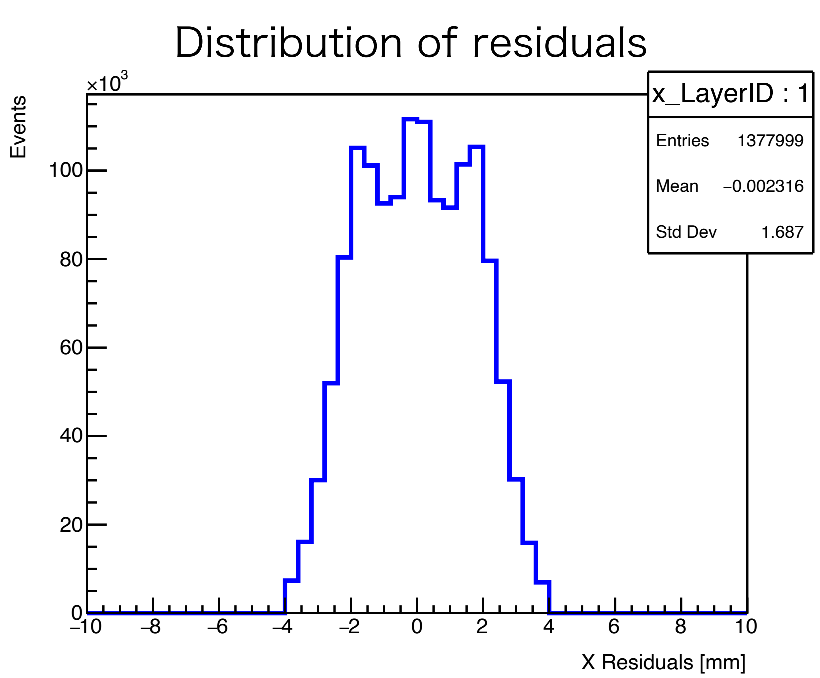


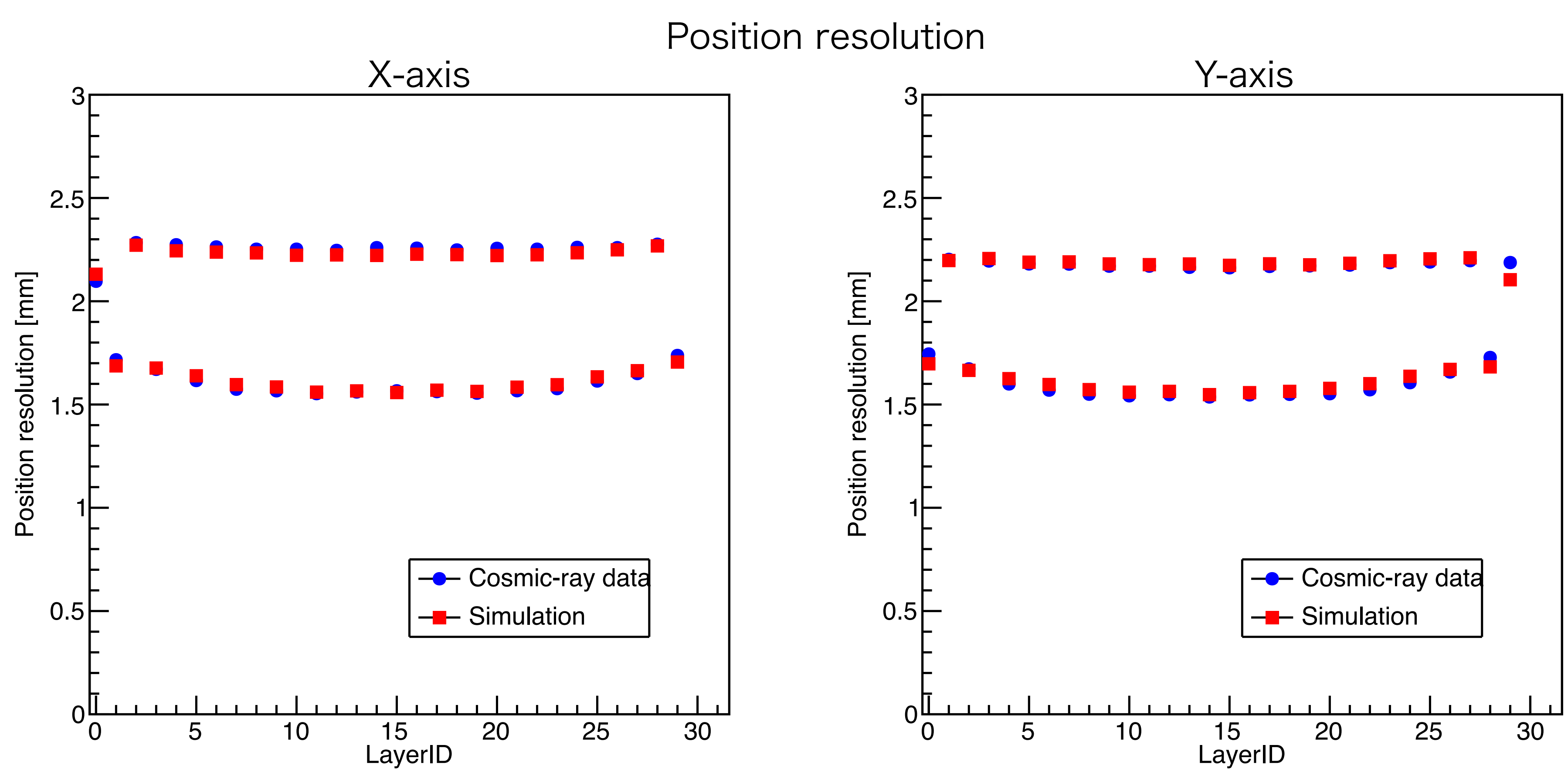


Performance evaluation using straight track

- **~84% detection efficiency achieved for all layers**
  - Ratio of events that have hits in a layer to all events
  - Agree with the Monte Carlo simulation
- **Good position resolution achieved for all layers**
  - RMS of residuals (distance between intersection of reconstructed track and SSA hit)
  - 1.5–1.7 mm at short-side (5 mm) direction
    - Corresponds to ~5 mm uniform dist.
  - A bit worse at long-side (45 mm) direction due to the SSA
  - Achieve granularity requirement for PFA ECAL

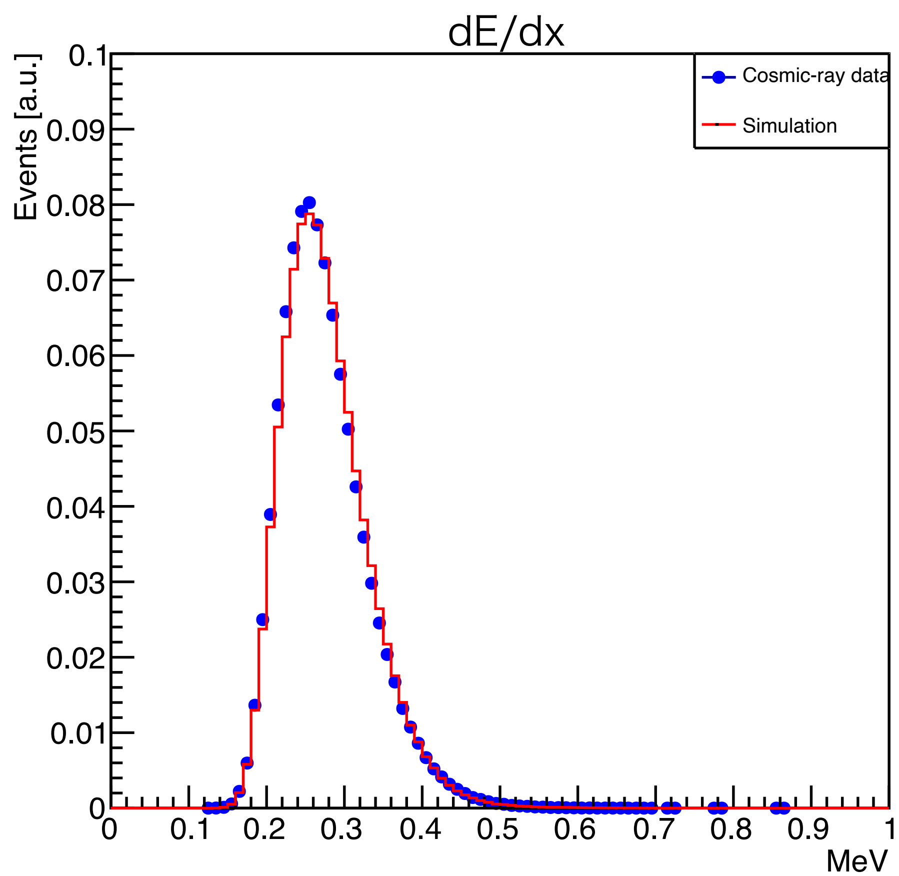


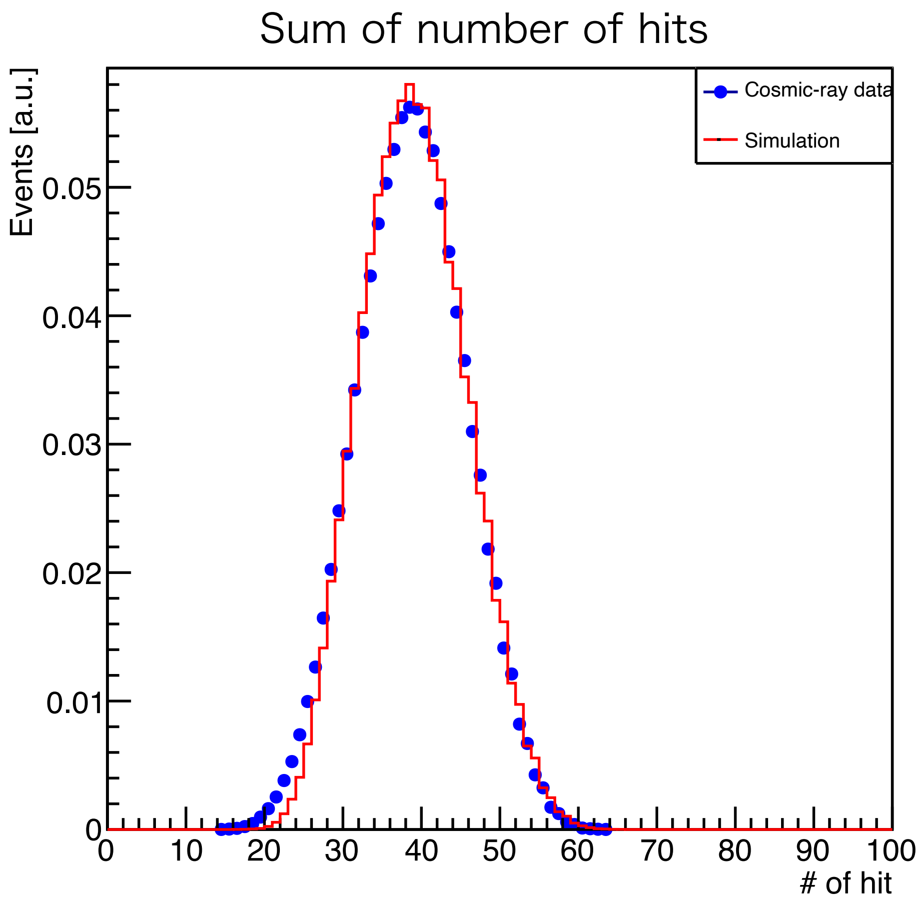


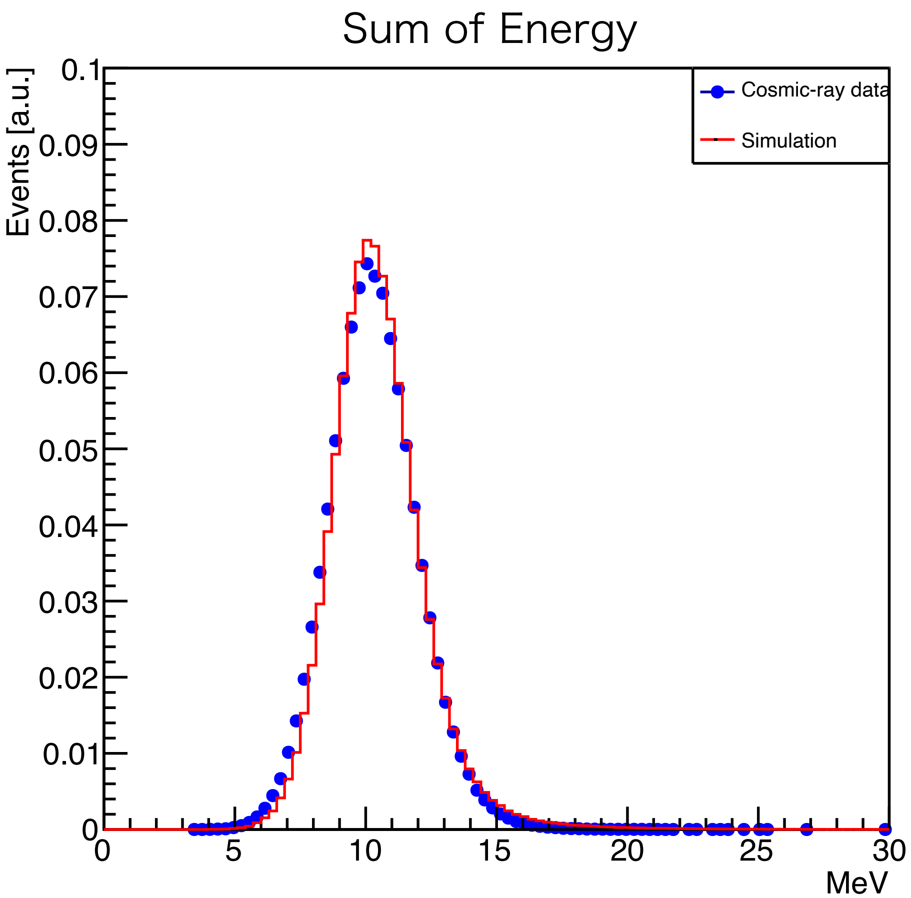


Performance evaluation using straight track

- Sum of number of hits and energy
  - Data and simulation matches well
- Average energy deposit in a single cell
  - Total energy / total hits
  - Data and simulation matches well



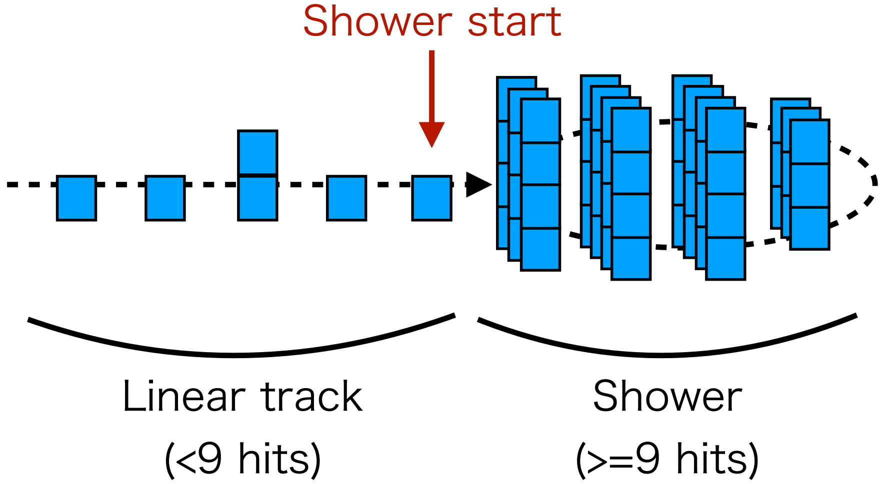




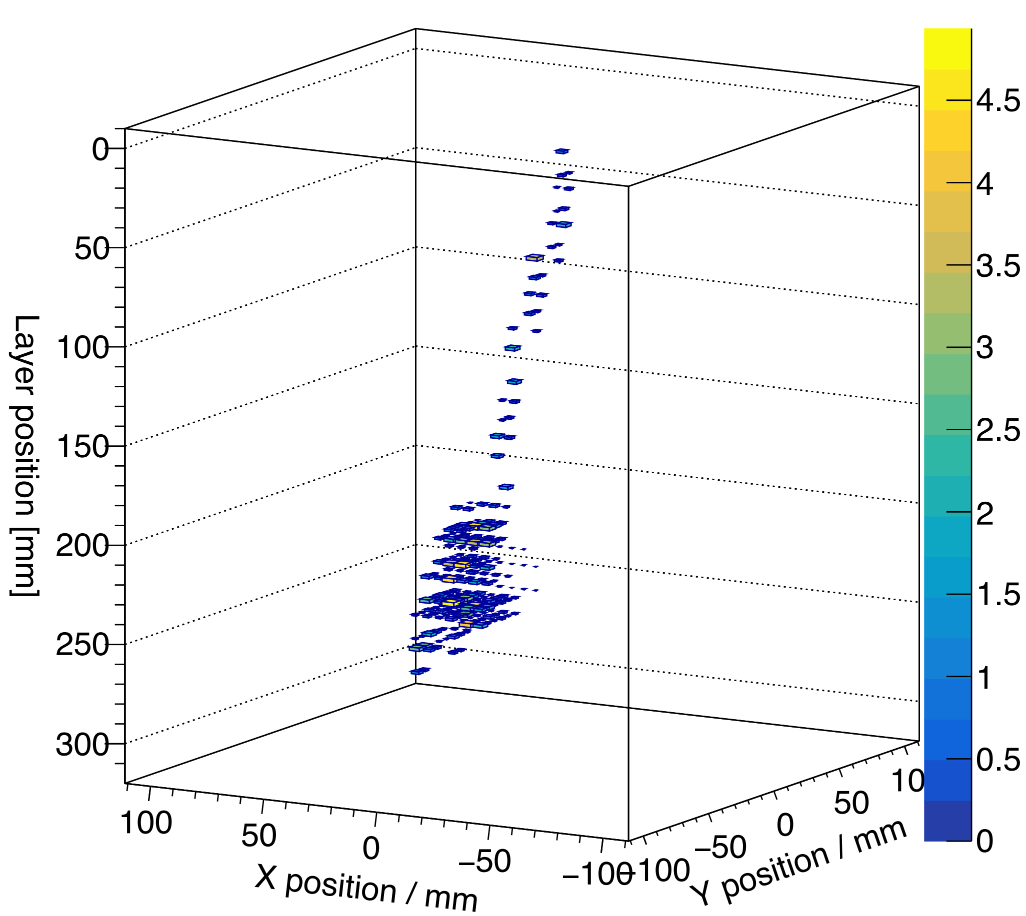
Reconstruction for CR shower

- Performance of Sc-ECAL for electromagnetic showers is evaluated using cosmic-ray showers
  - Instead of test beam experiment
- Shower events is searched for:
  - Calibration: ADC counts converts to # of MIPs
  - SSA & clustering
  - Shower search
    - Many hits in three consecutive layers

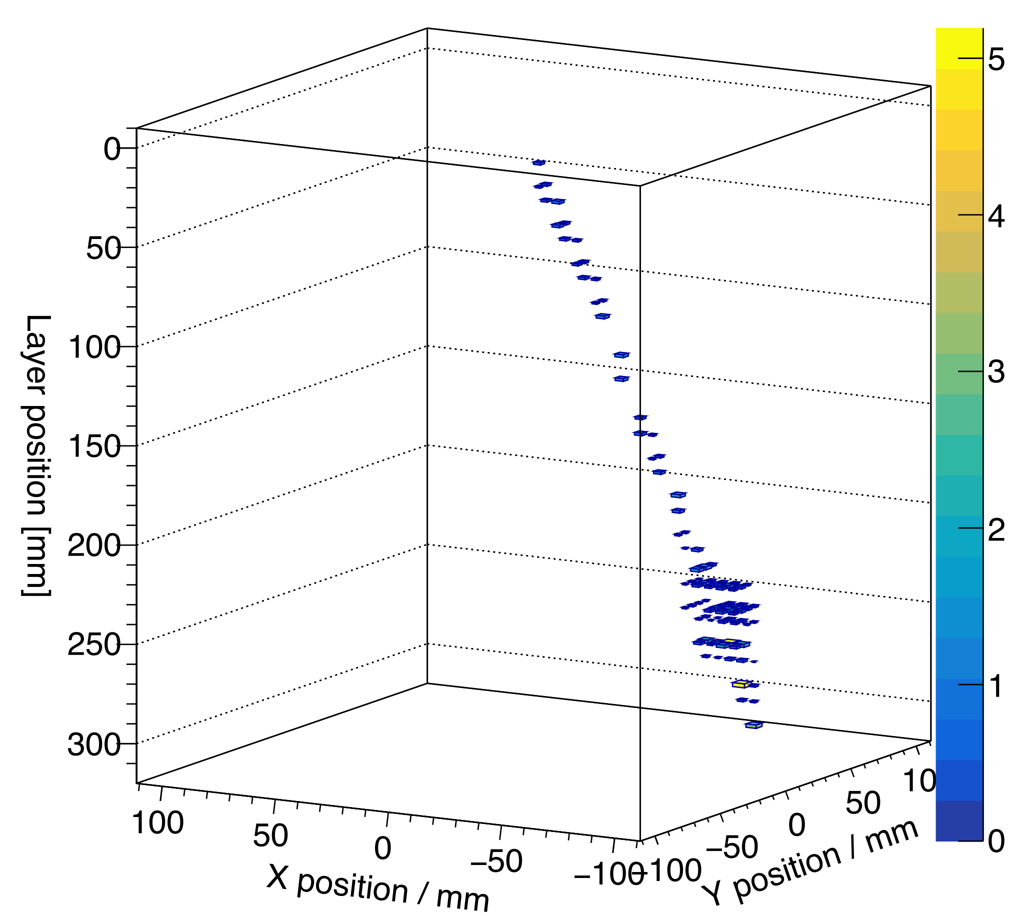
Scheme of shower search



CR data

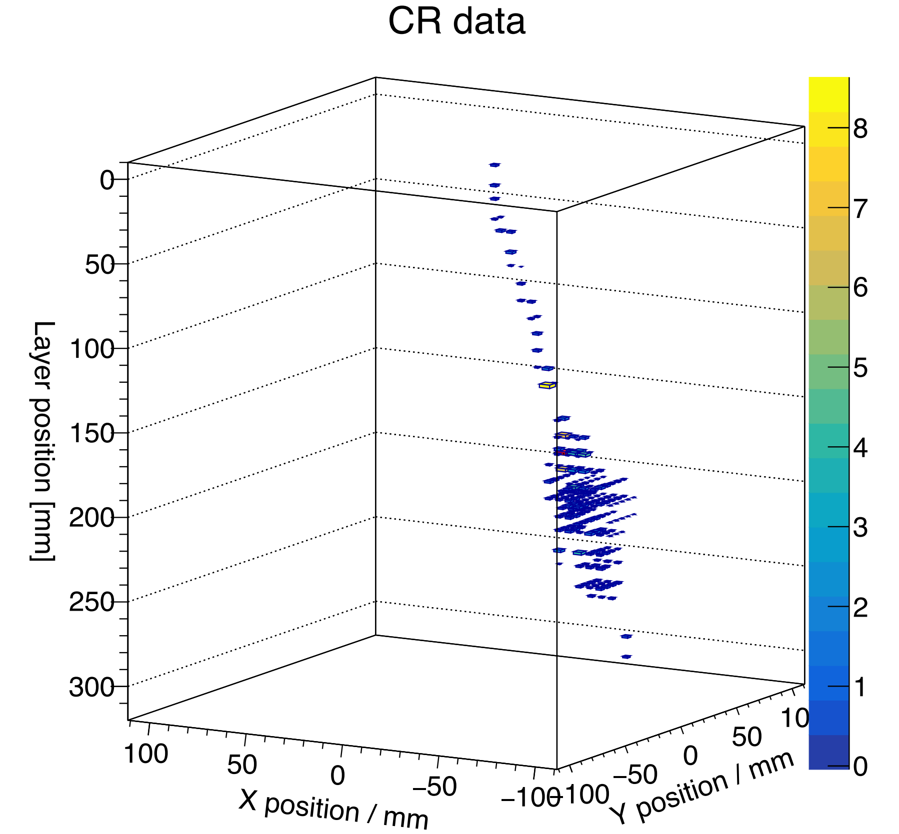


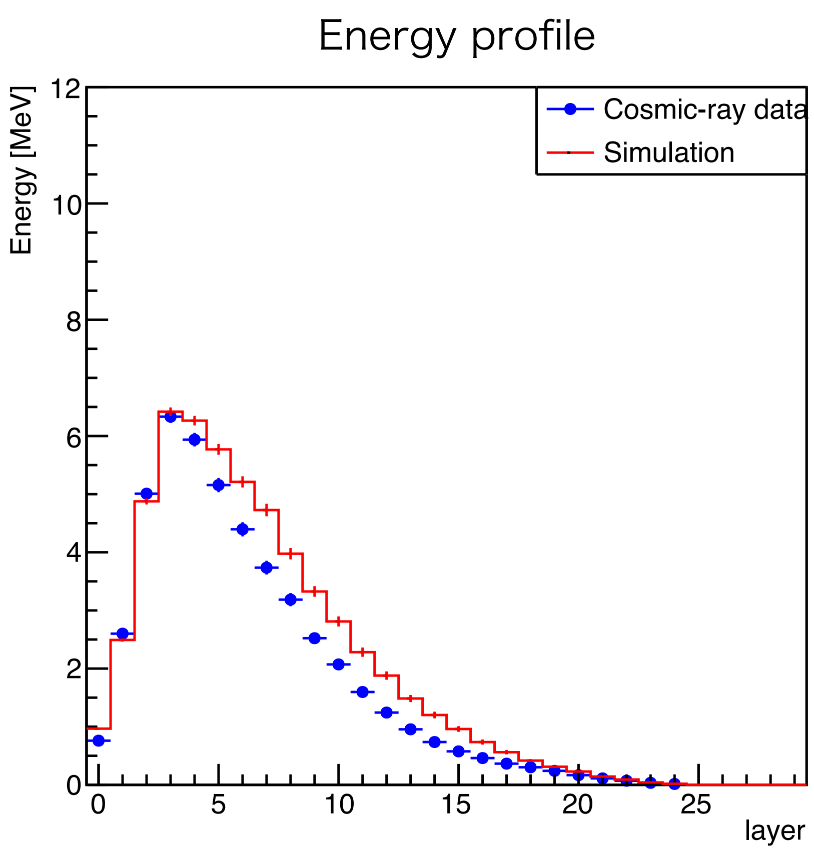
Simulation

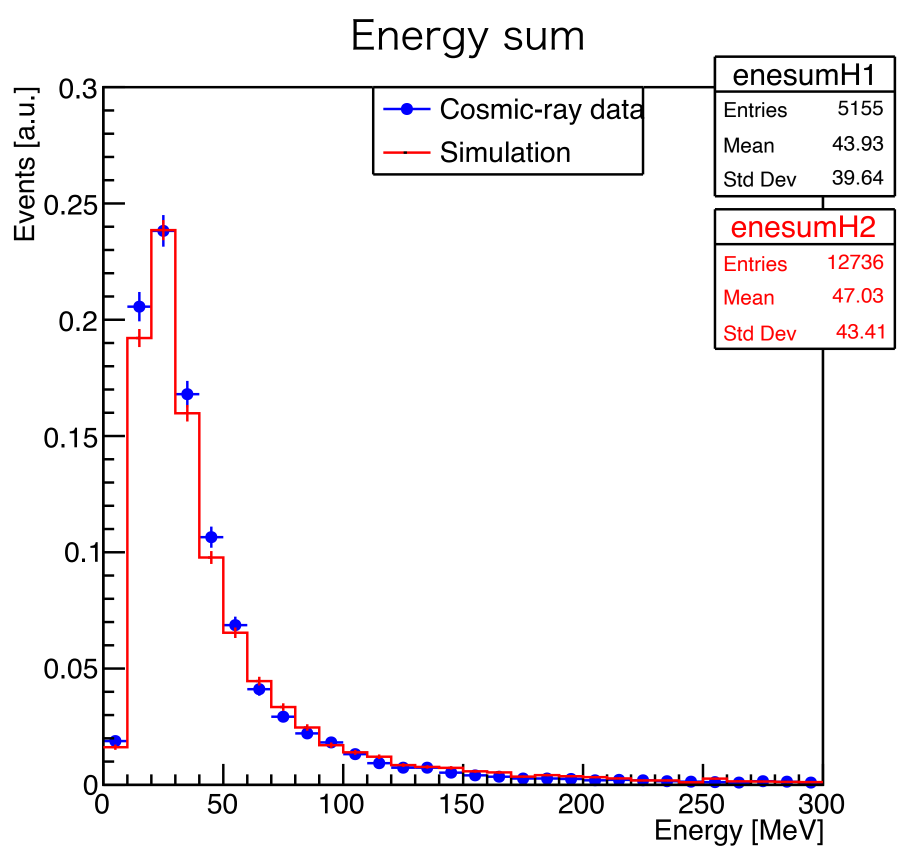


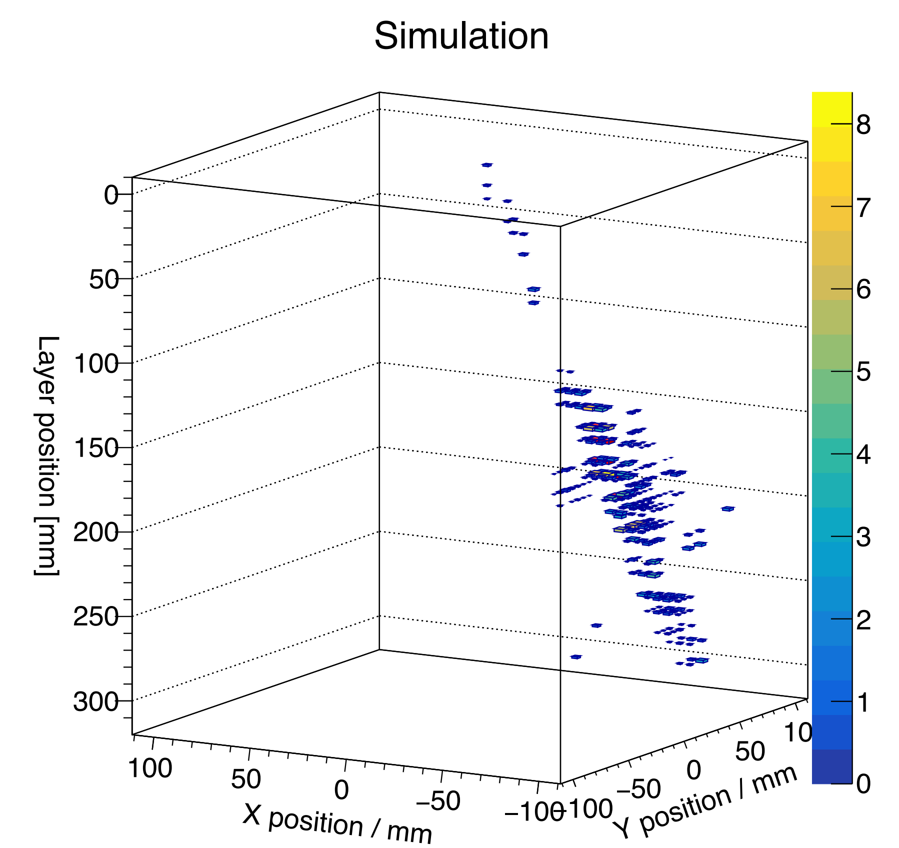
Performance evaluation using CR shower

- Performance for EM showers evaluated by comparing the shower properties with data and simulation
- **Data and simulation matches reasonably well**
  - Slight deviation observed
  - Simulation has less low-energy events compared to data
- Comparison using the events with fully contained shower and with shower escape









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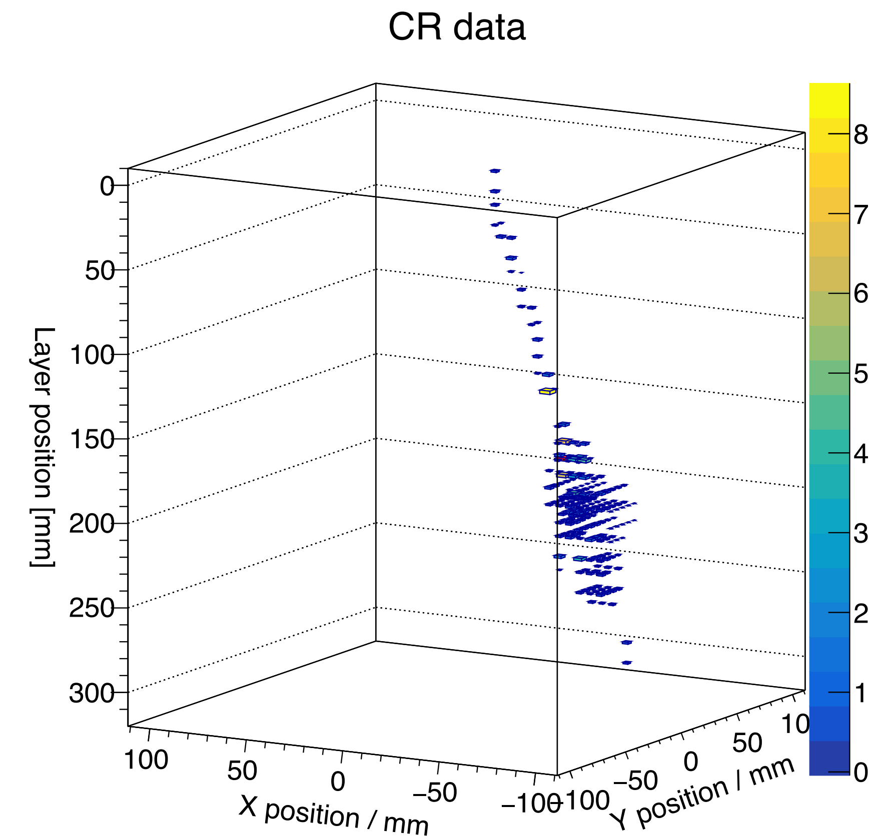

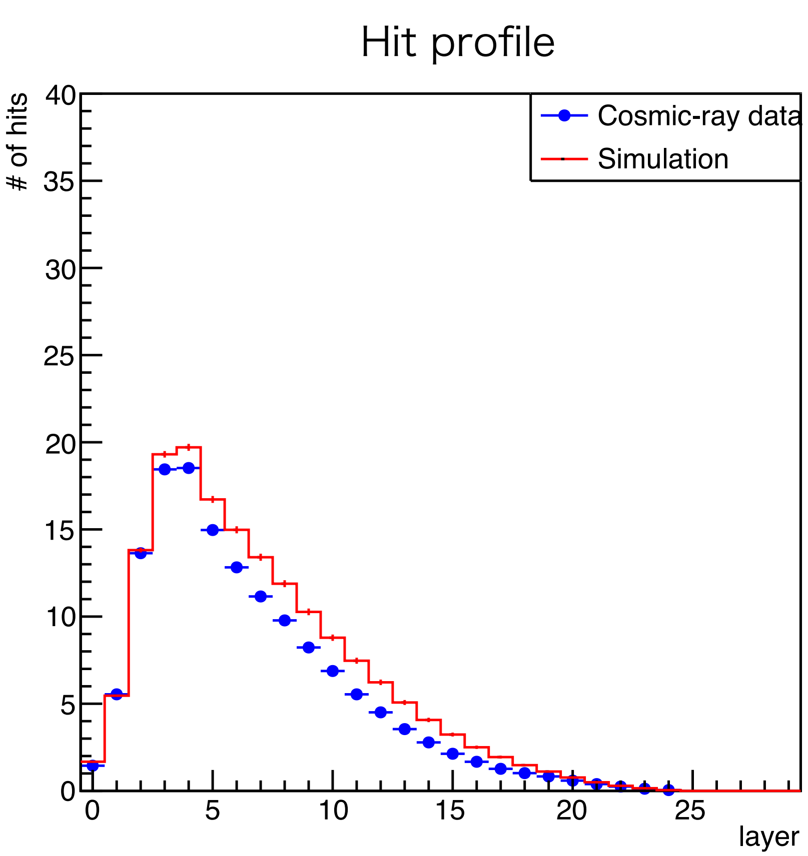

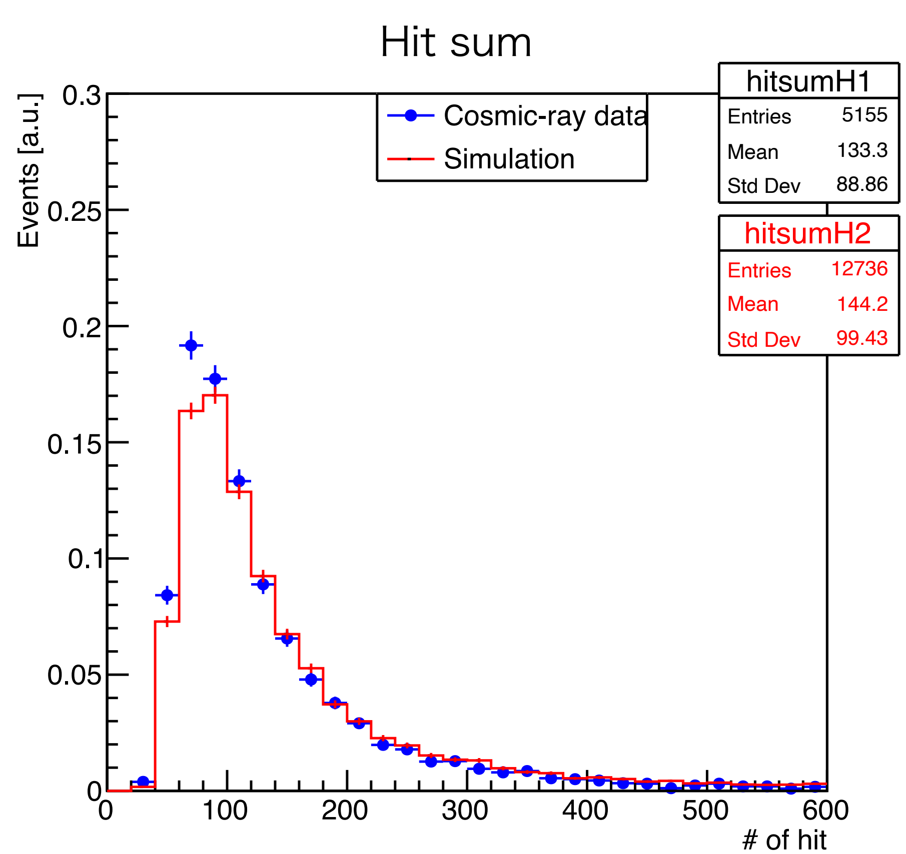

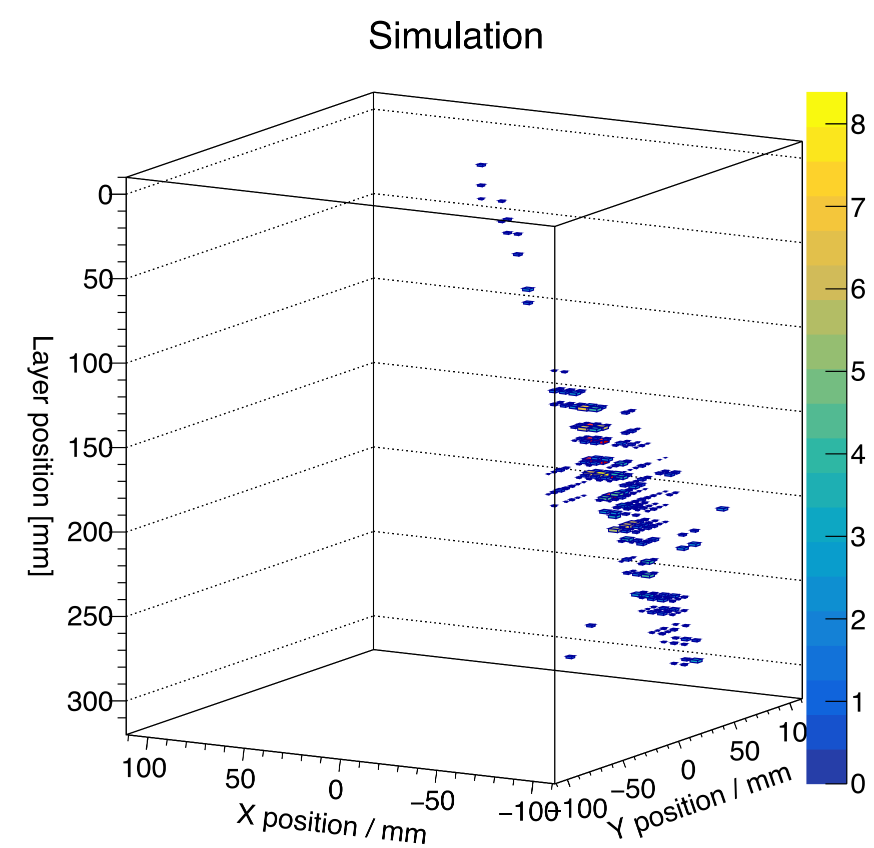

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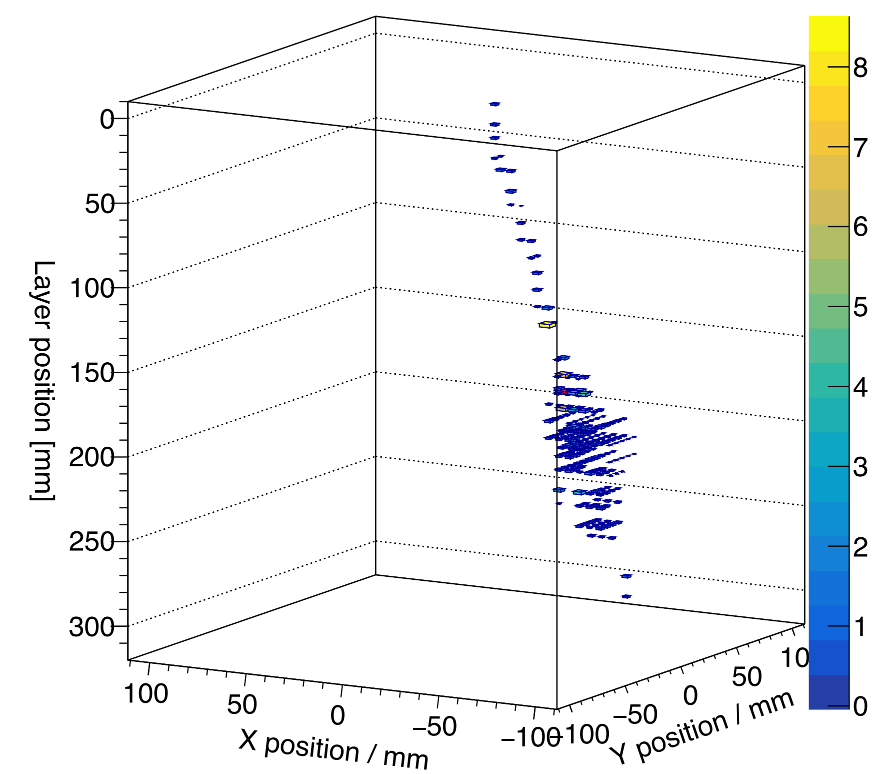
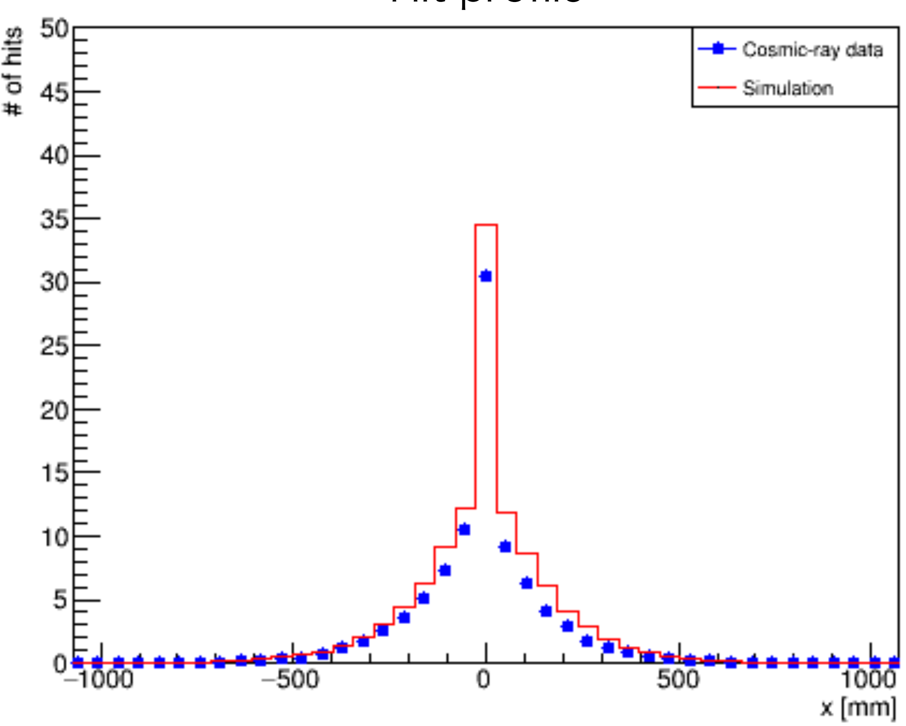
CR data

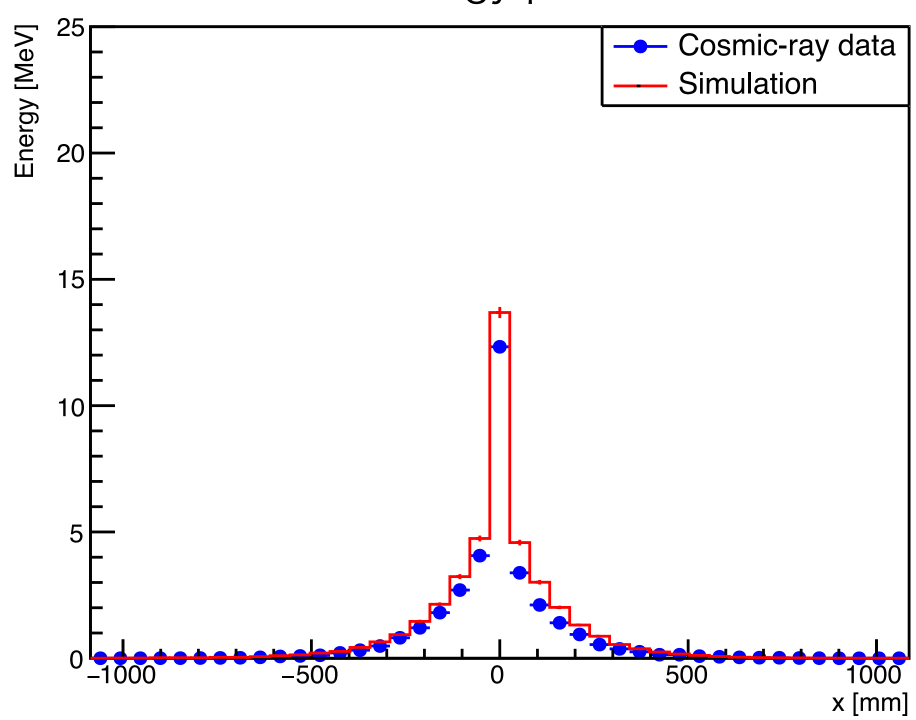


Transverse profile

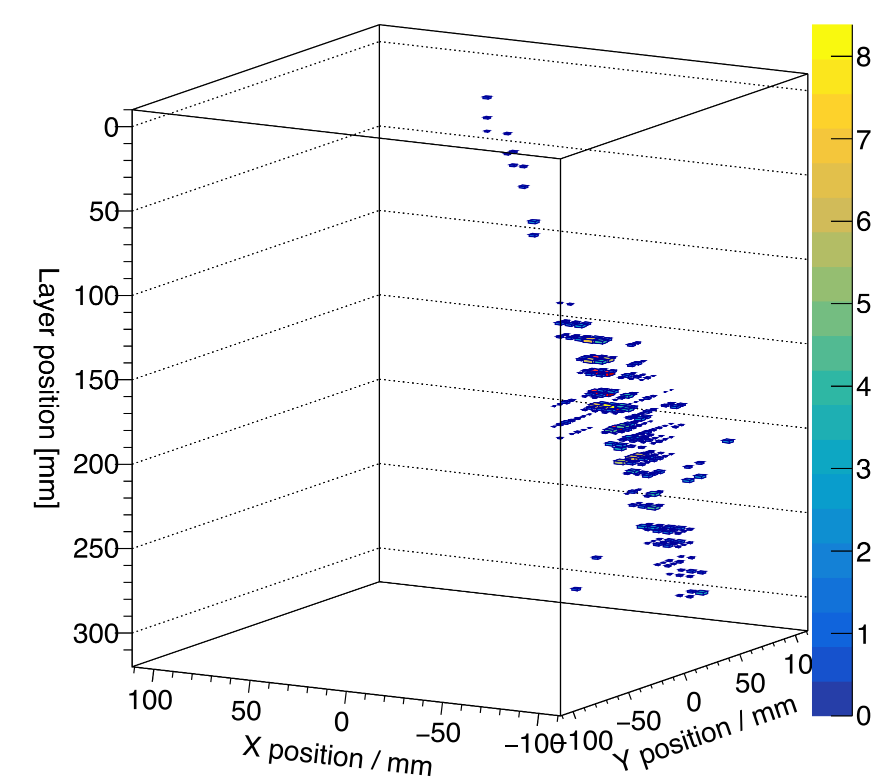
Hit profile



Energy profile

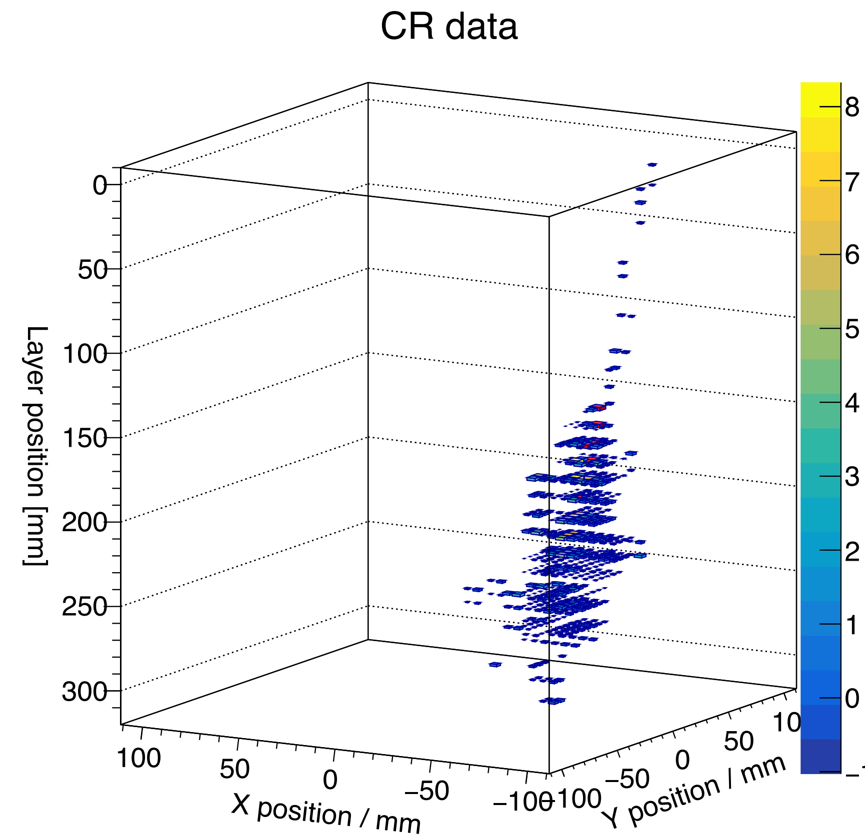


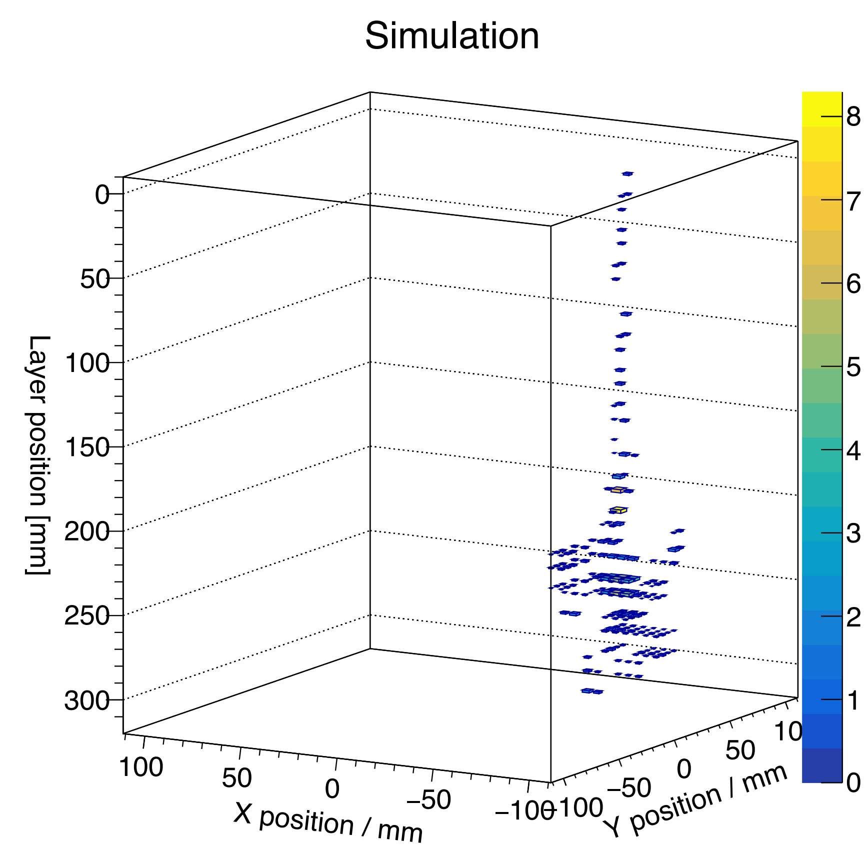
Simulation

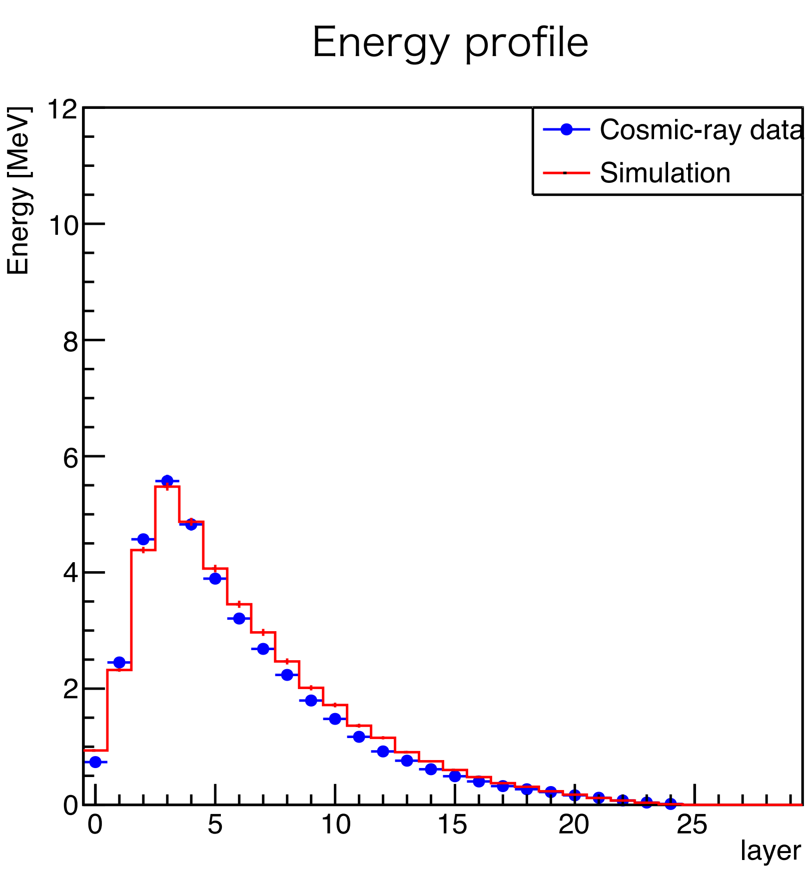


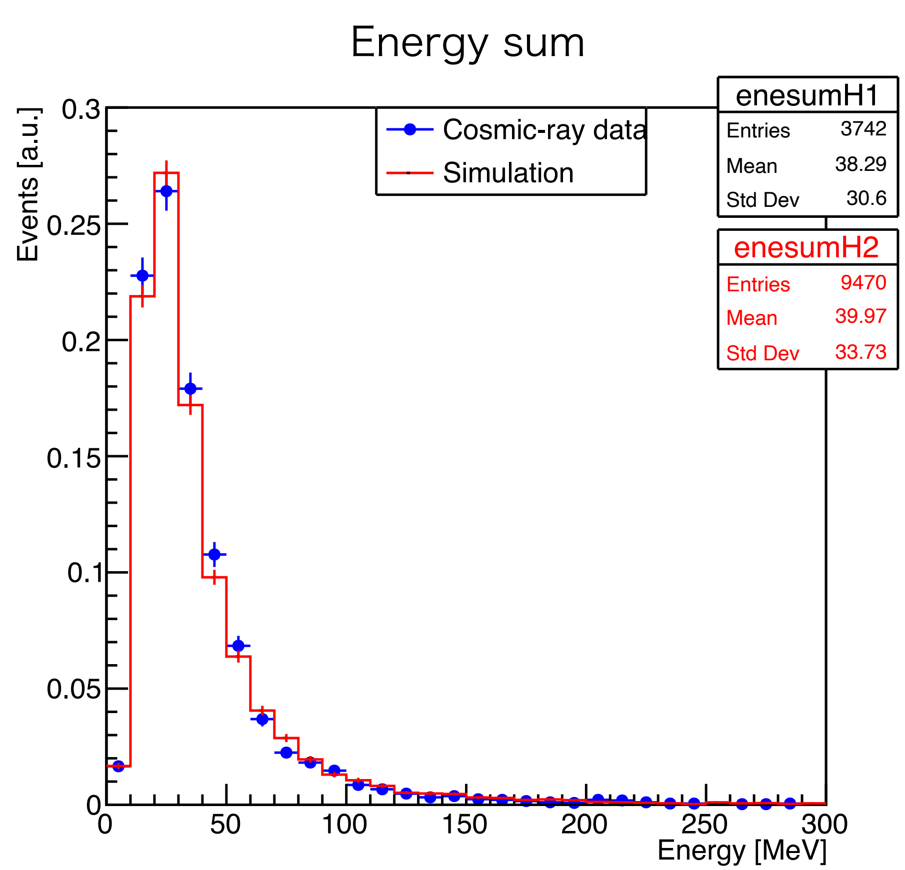
Fully contained shower

- Shower comparison b/w data and simulation is performed for fully contained showers
- **Data and simulation matches better**
- Simulation reproduces the behavior of the prototype very well for the fully contained showers









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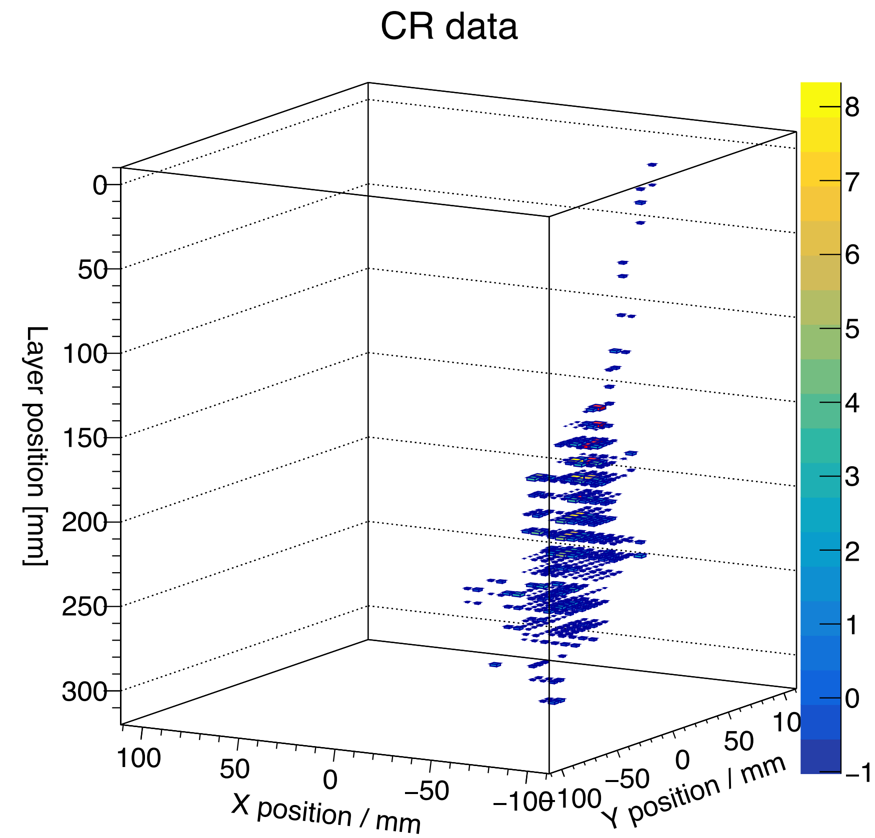

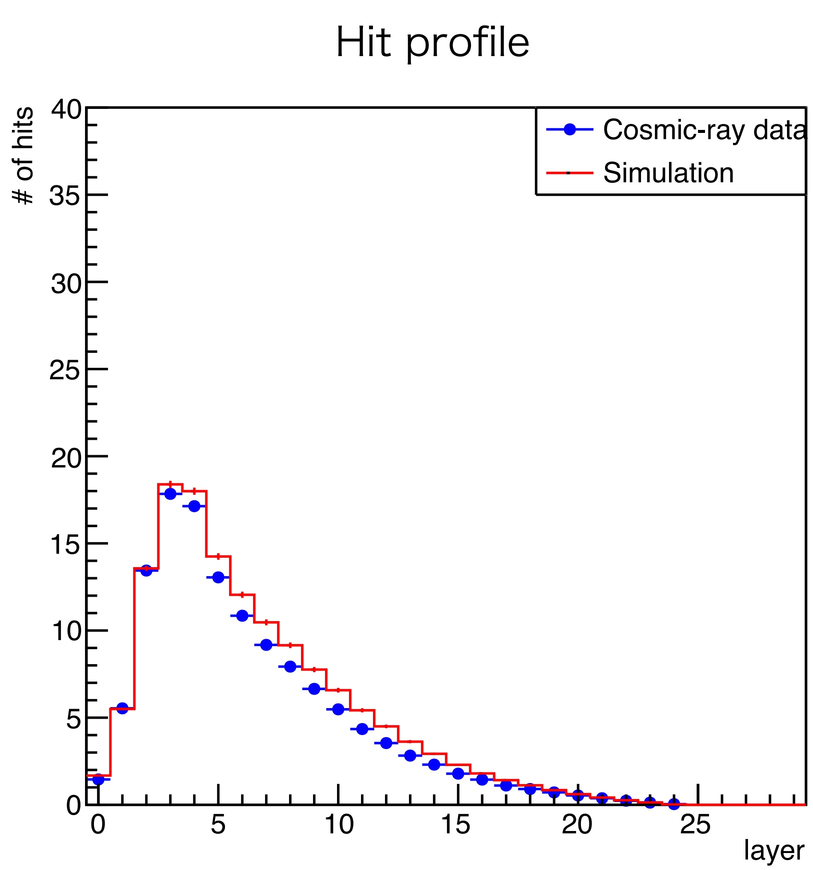

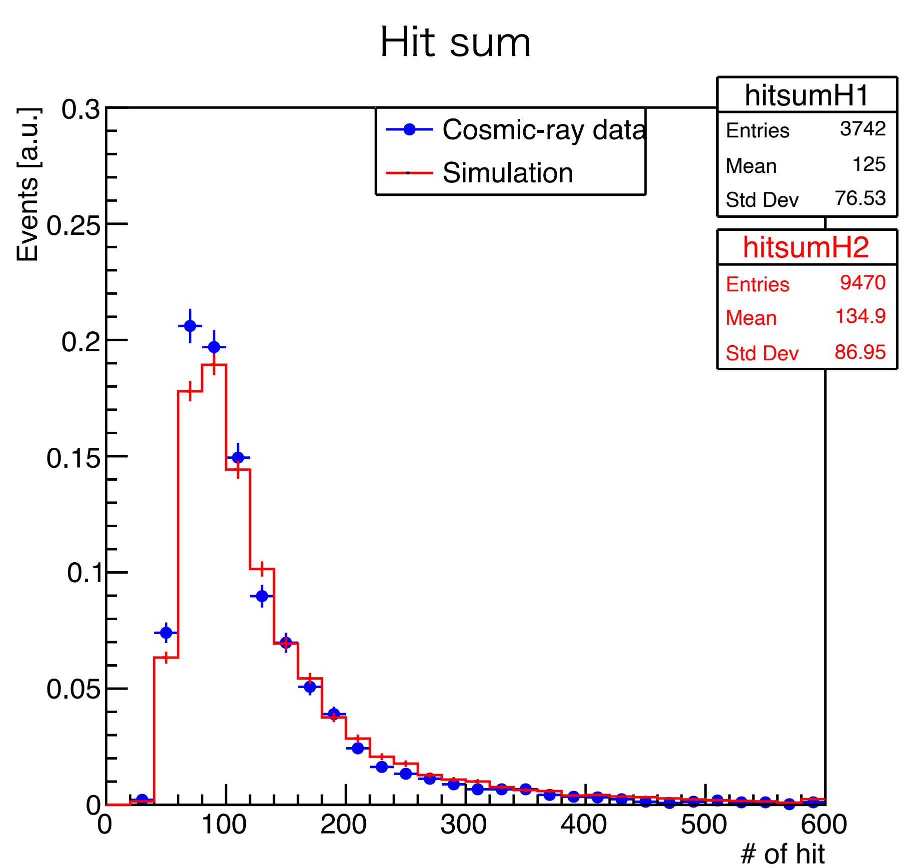

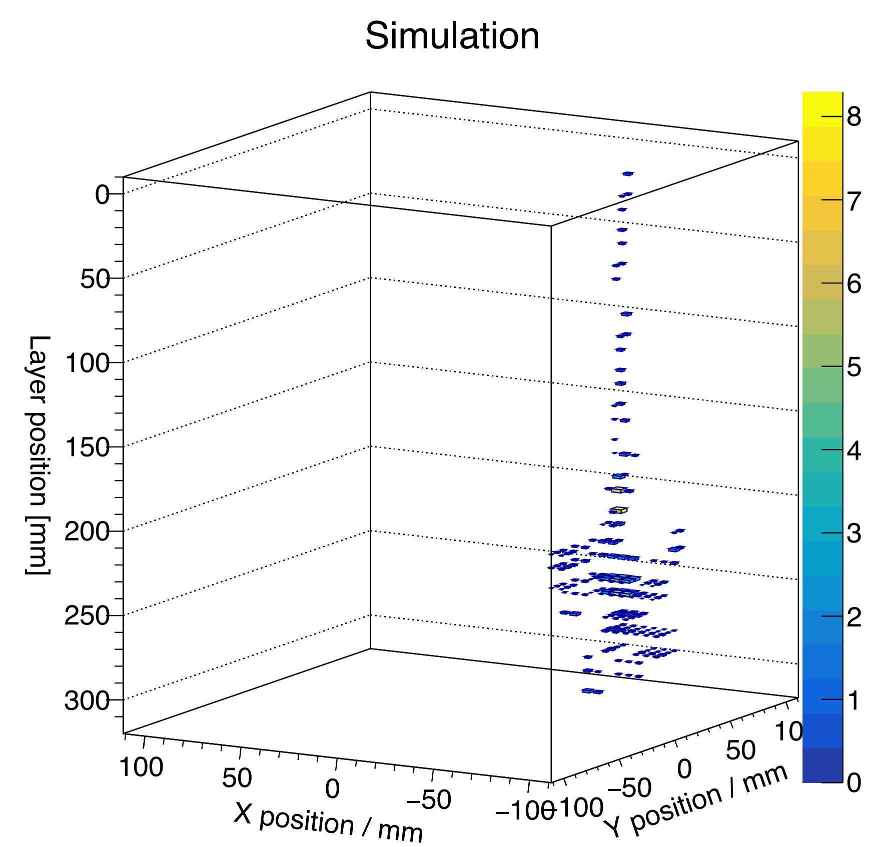

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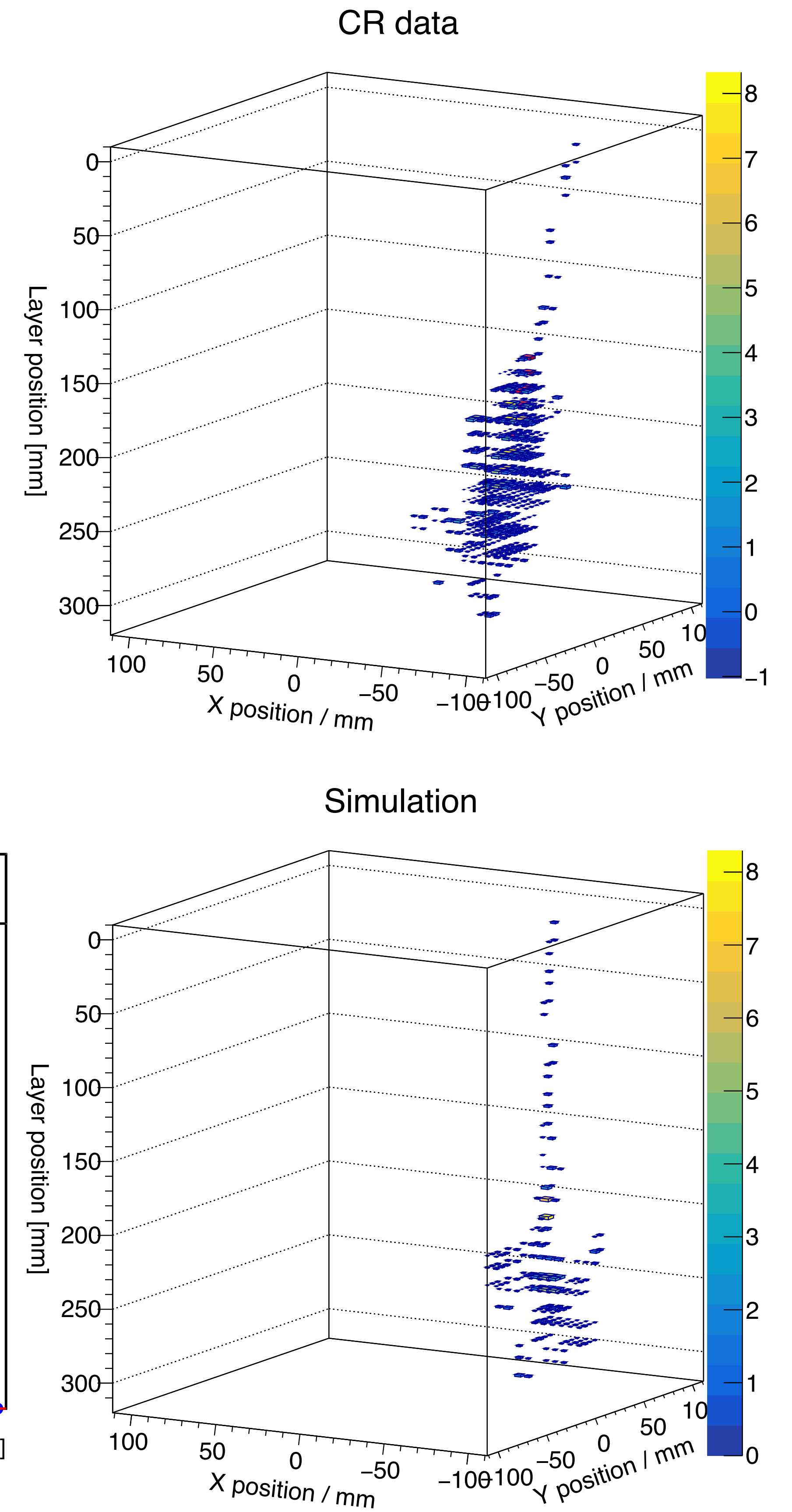
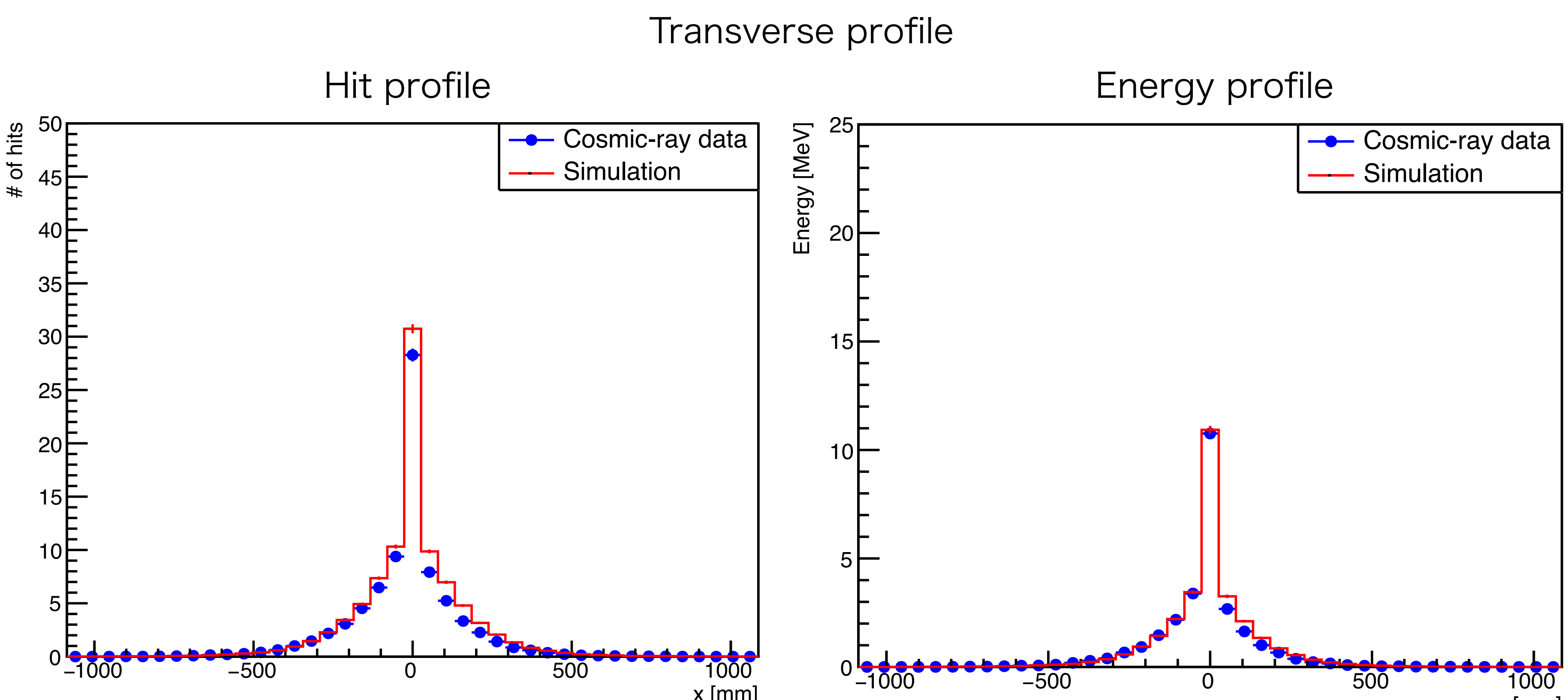
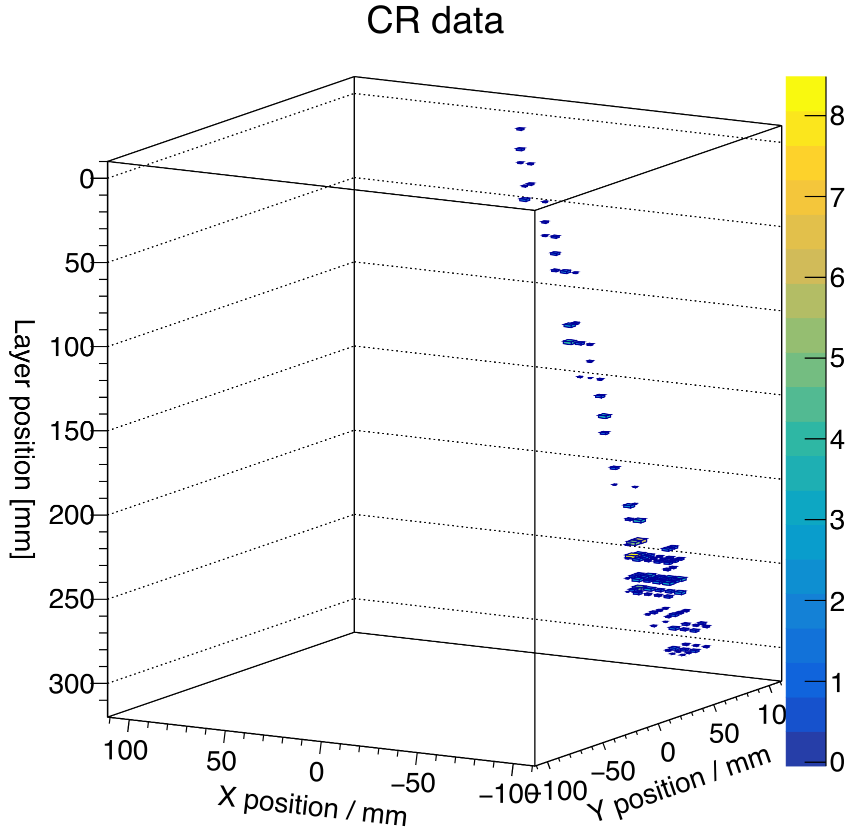
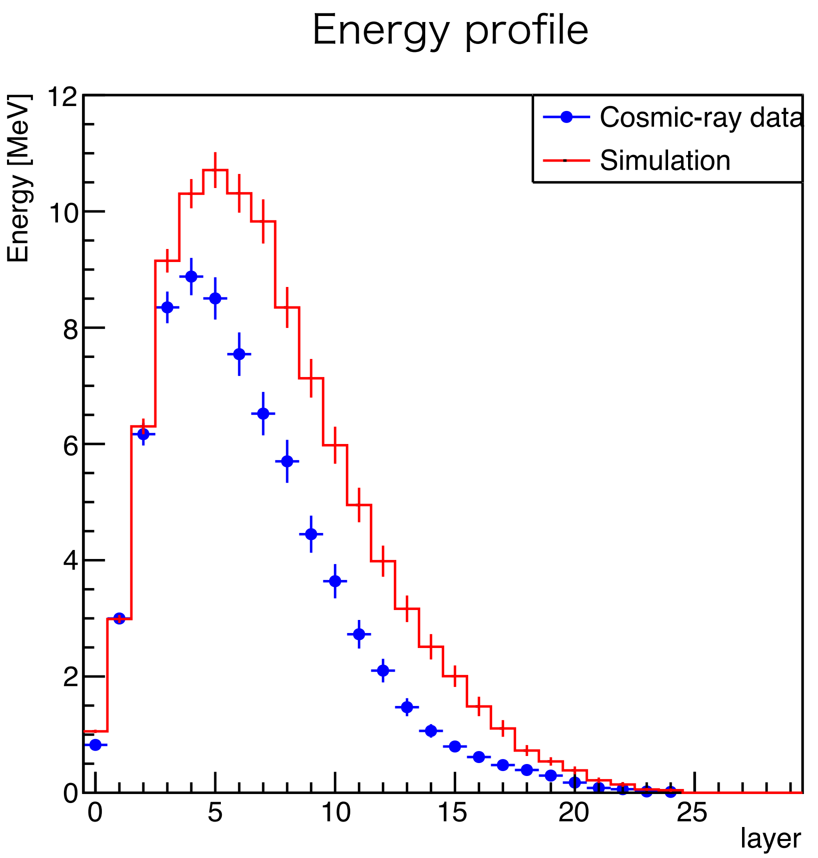


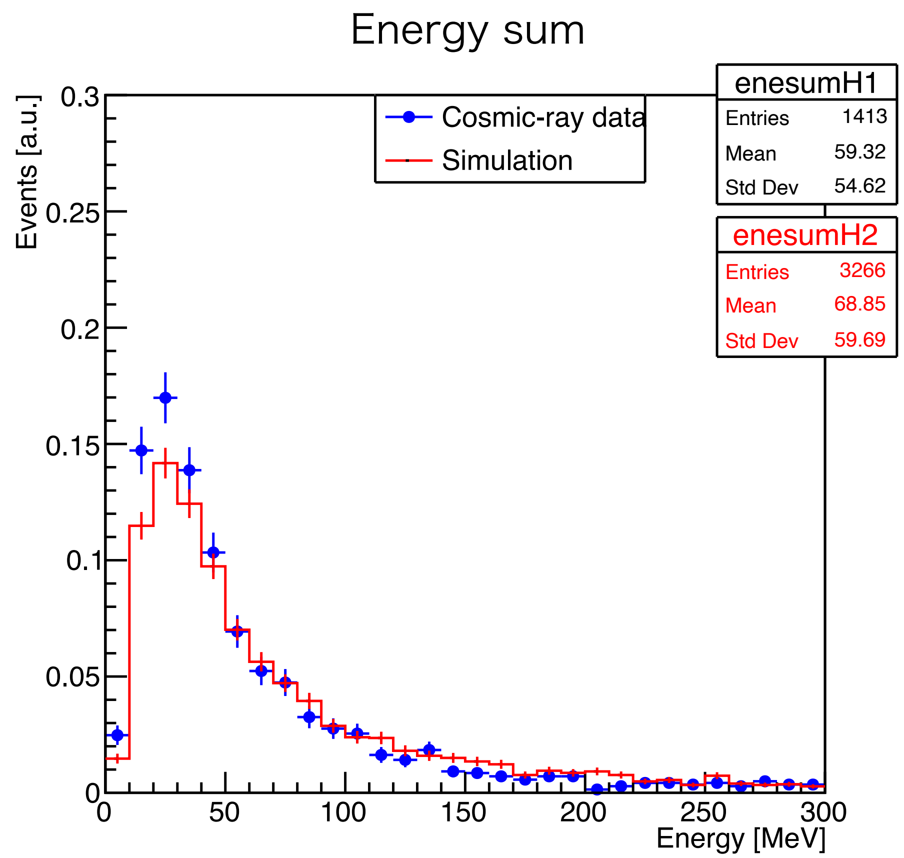


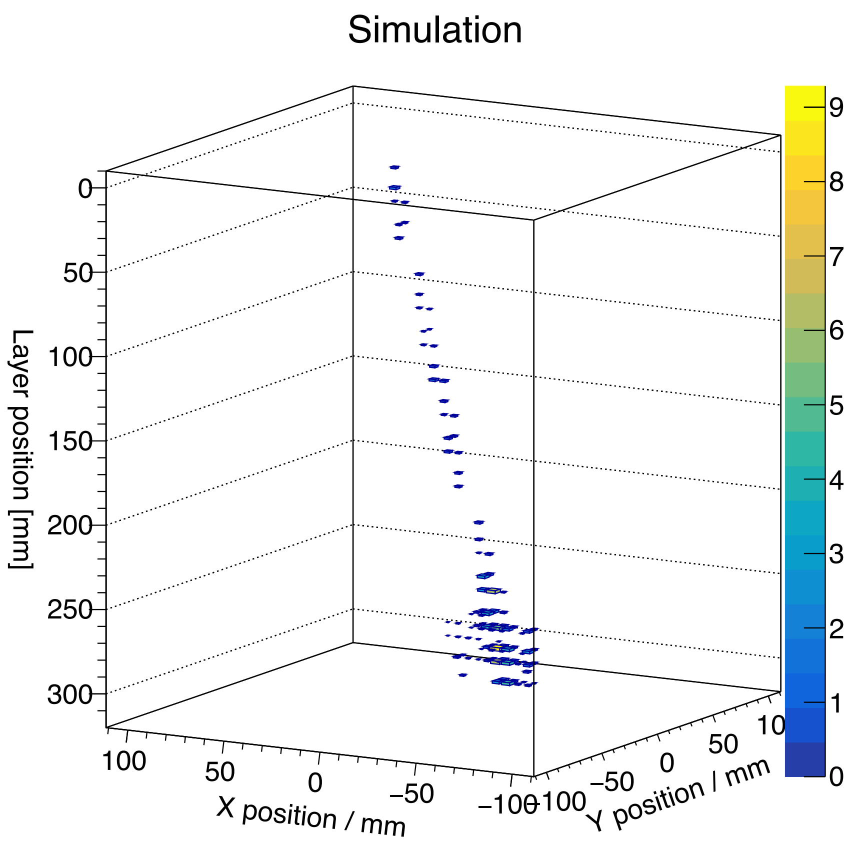
Shower escape

- <u>Shower comparison b/w data and simulation is performed for shower escape</u>
- **Larger deviation b/w data and simulation observed**
  - Simulation has less low-energy events compared to the data
- Comparison with the primary energy in the simulation is performed
  - To understand the deviation in more detail









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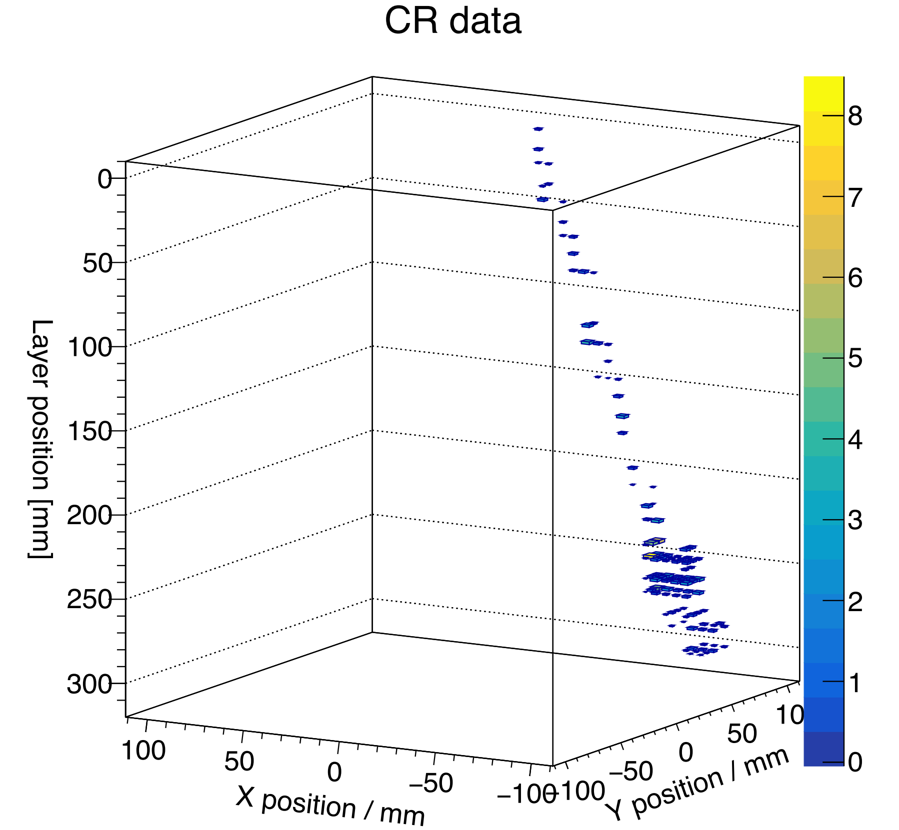

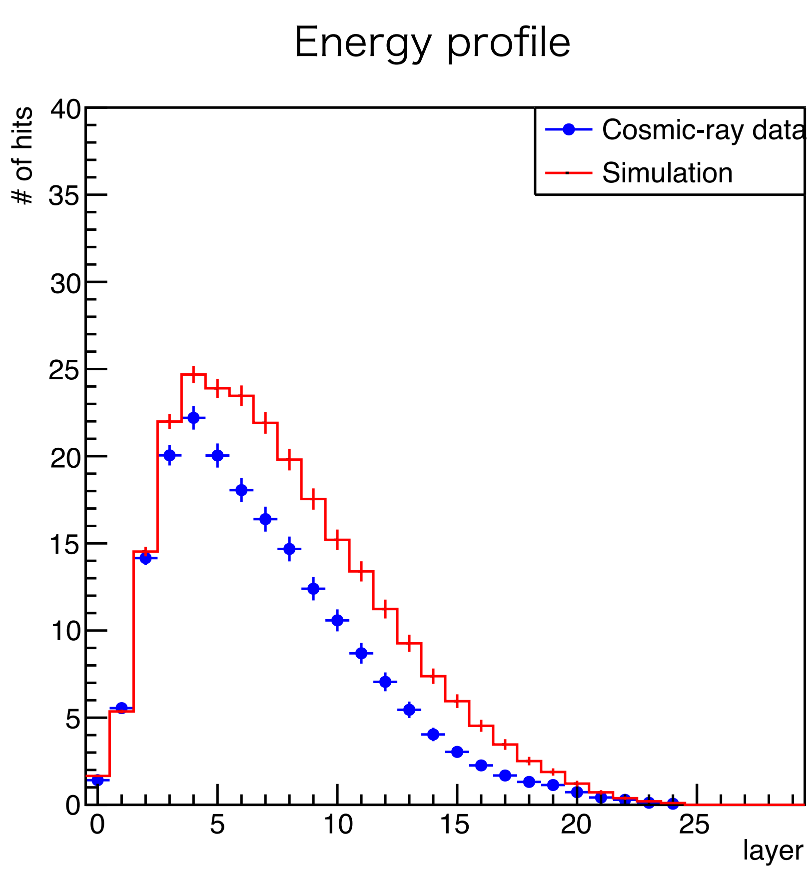

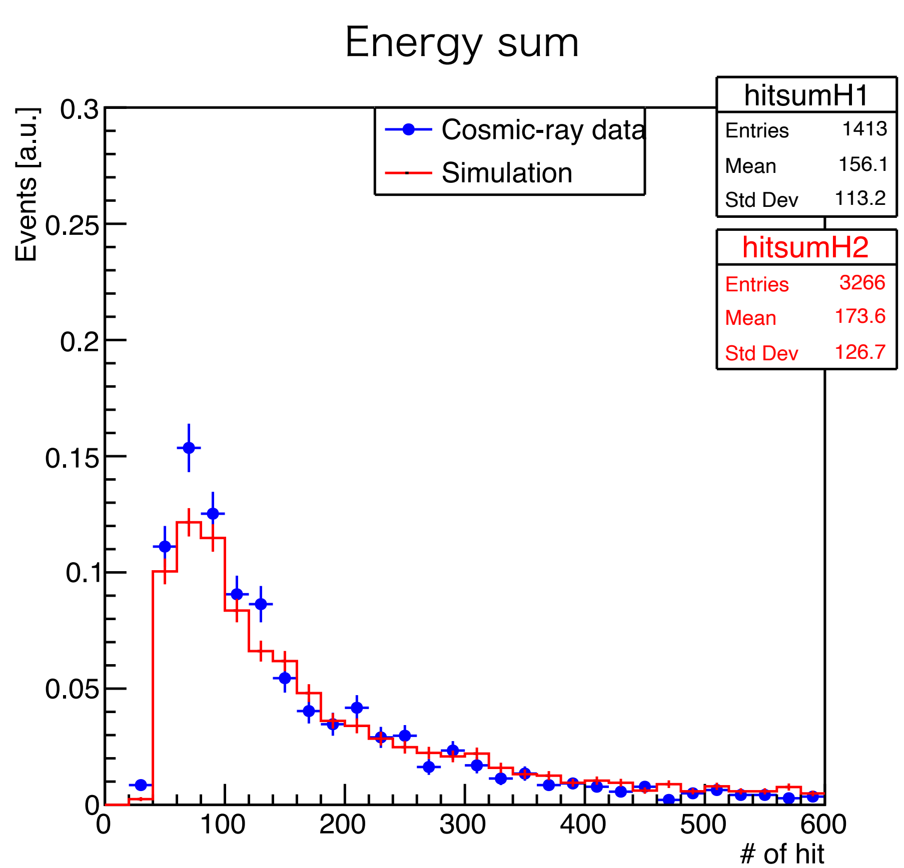

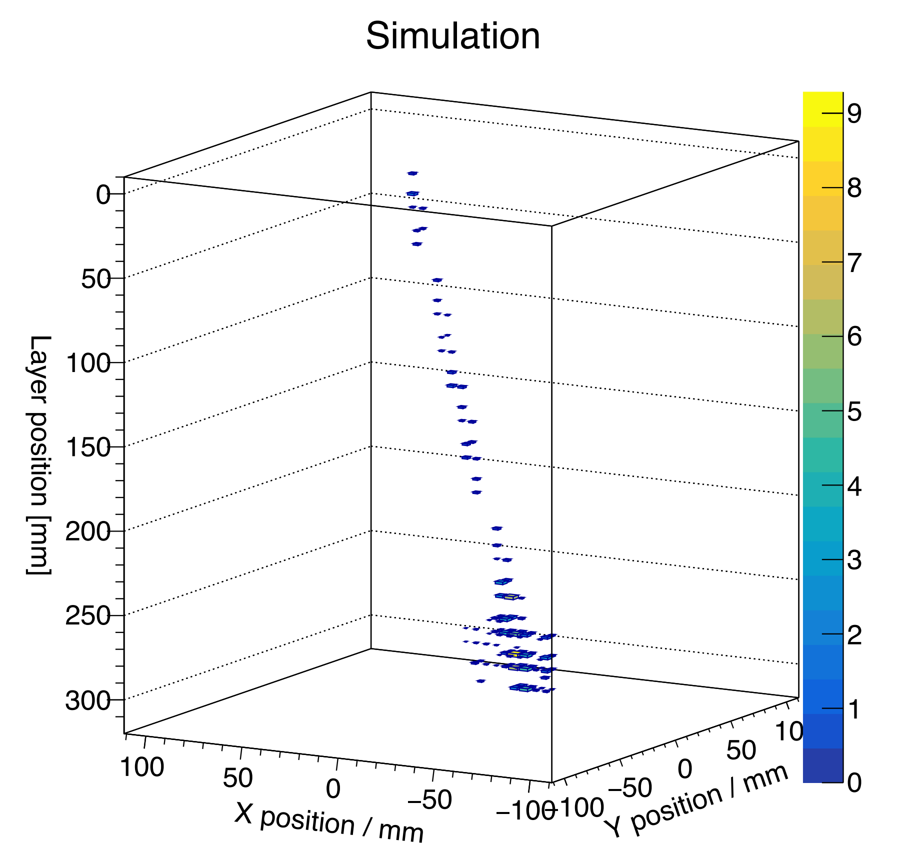

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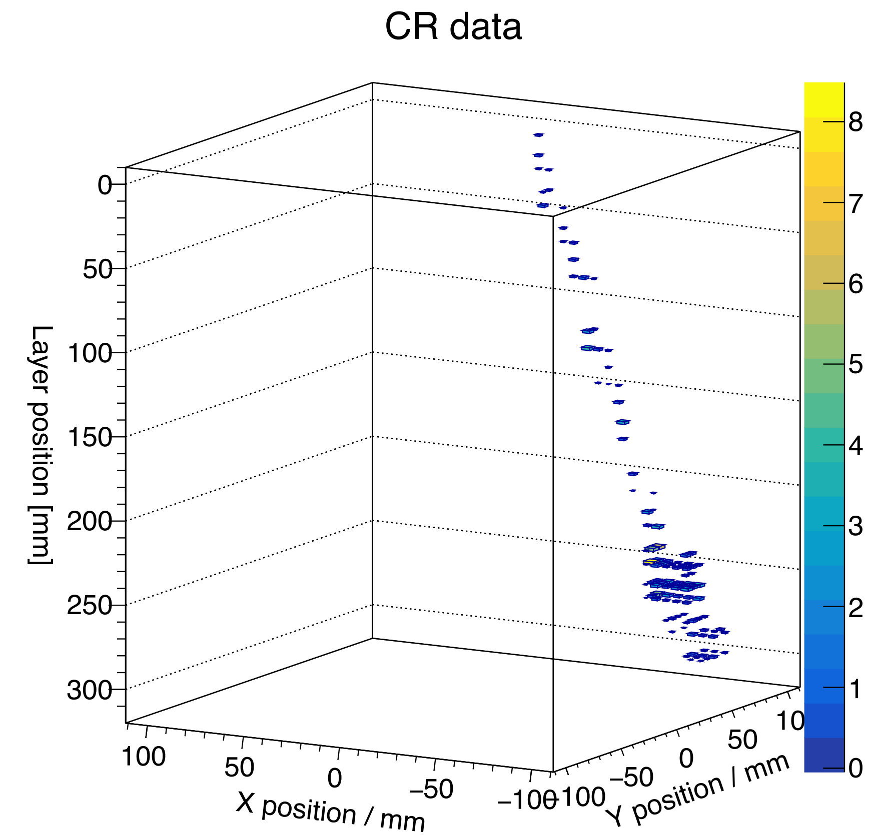
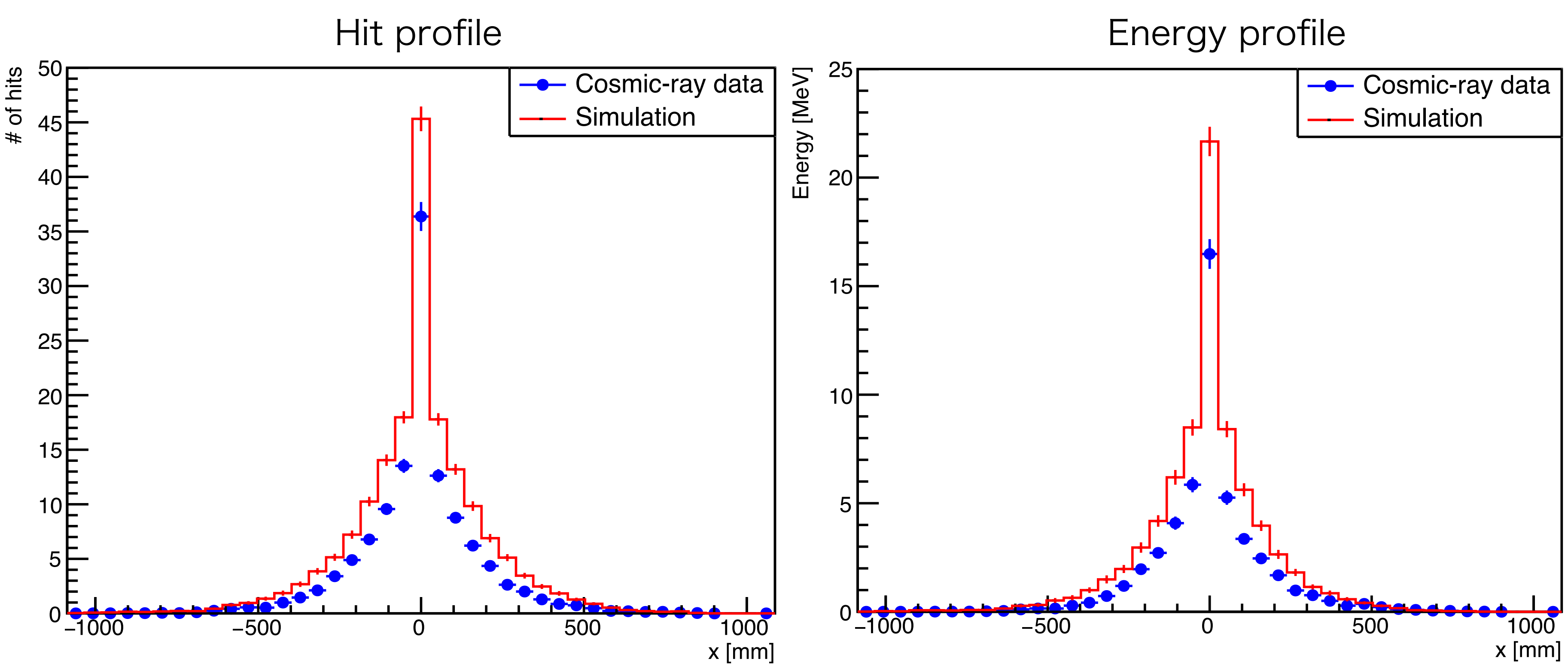
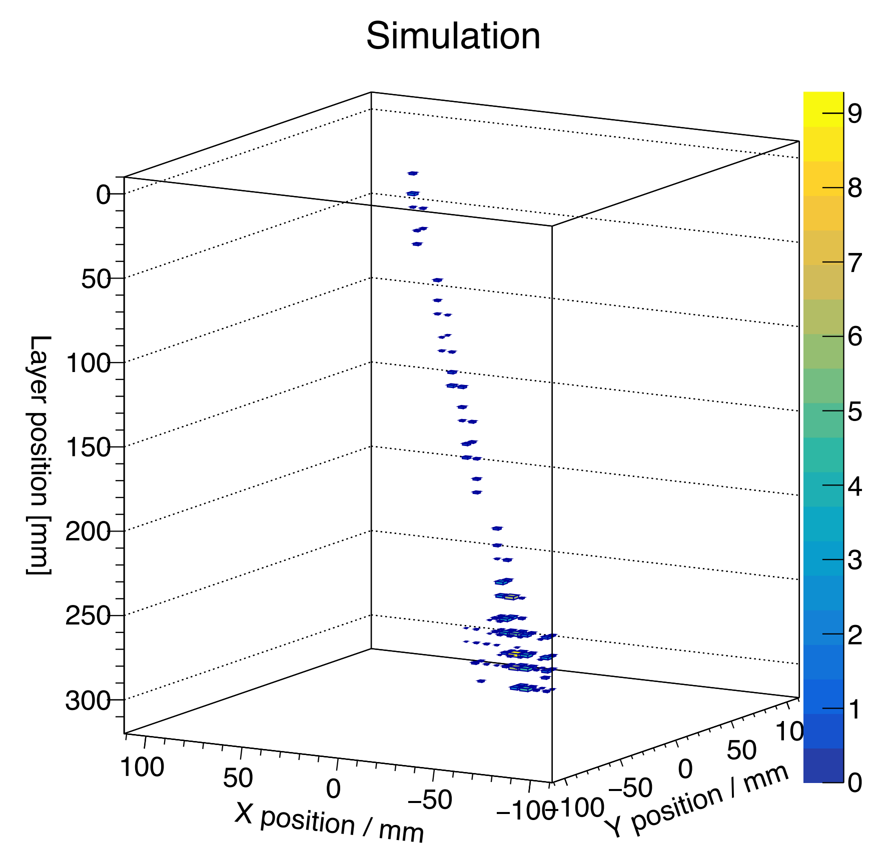
  - Simulation has less low-energy events compared to the data
- Comparison with the primary energy in the simulation is performed
  - To understand the deviation in more detail



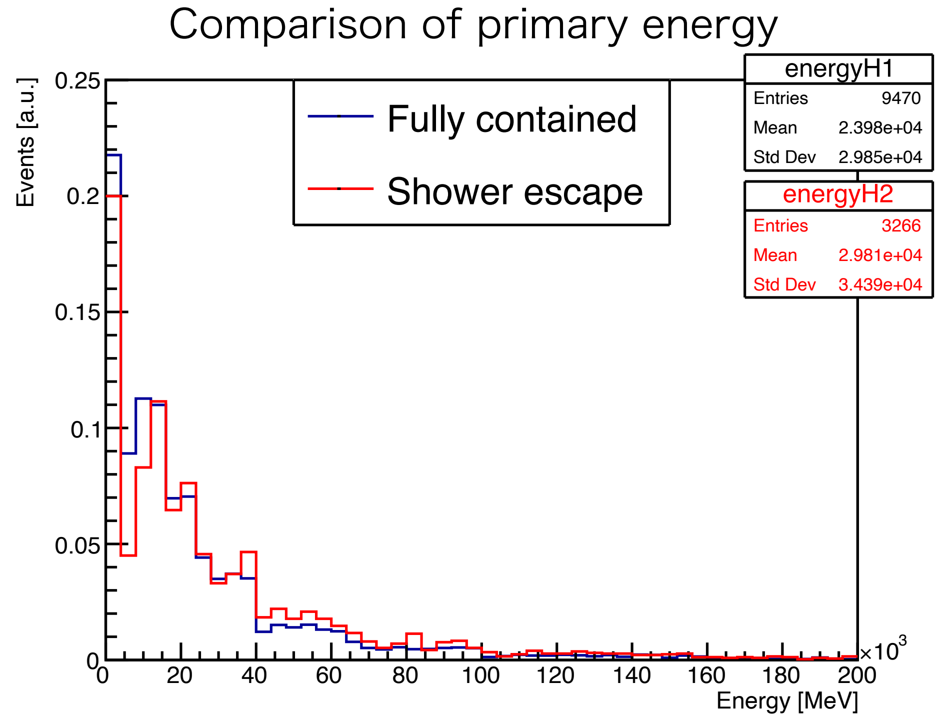
Transverse profile

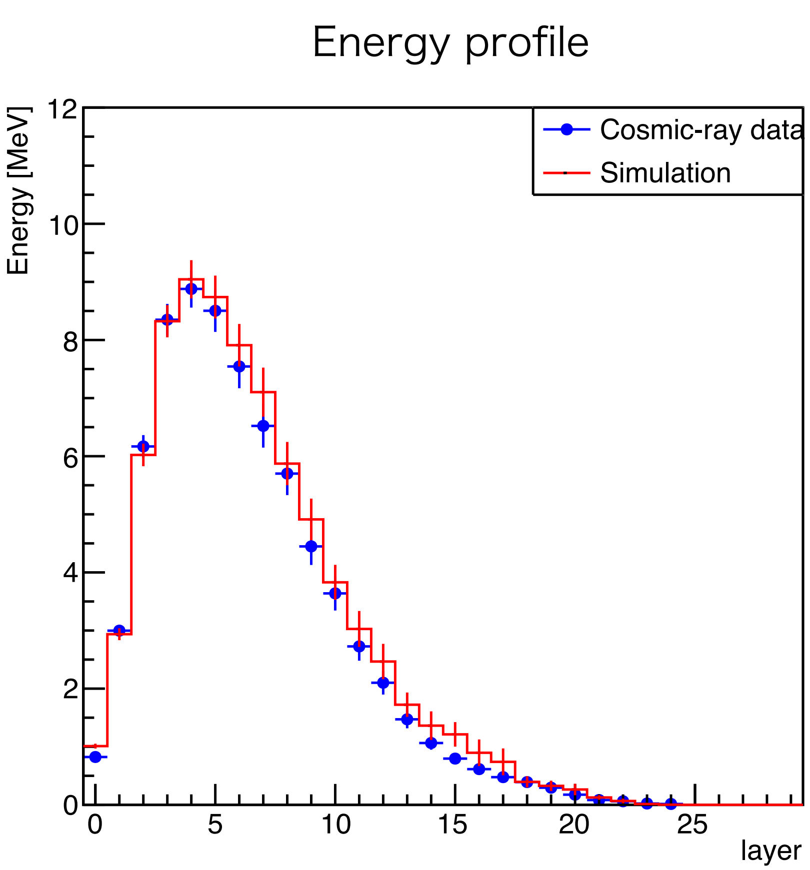


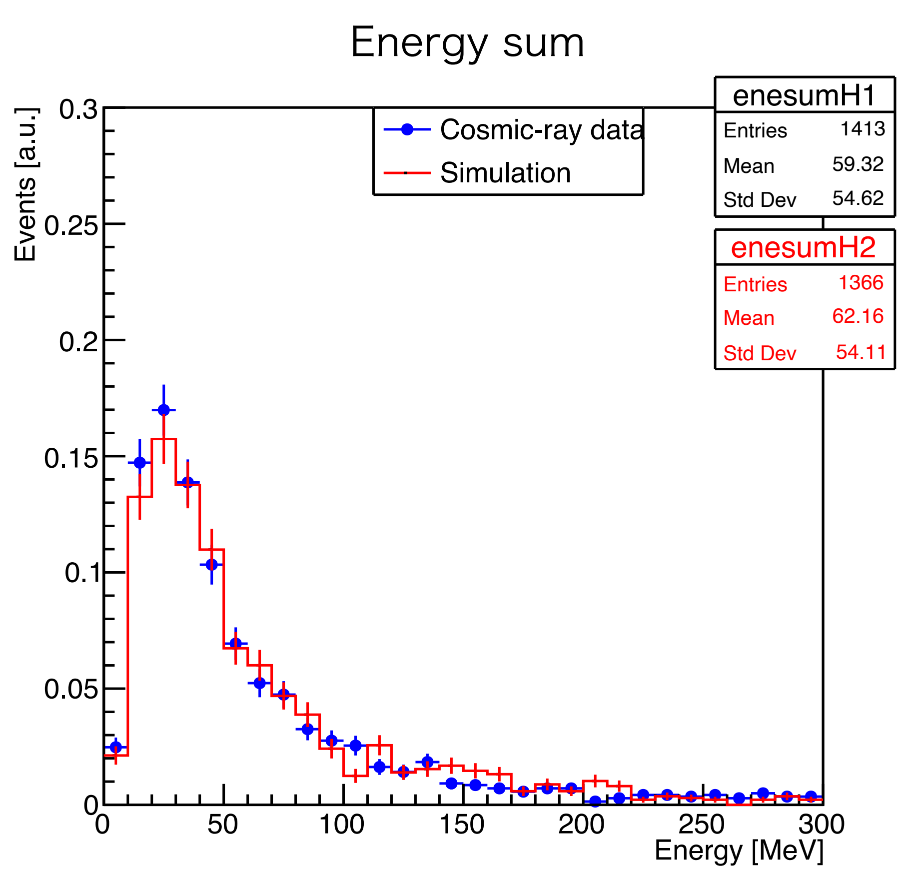


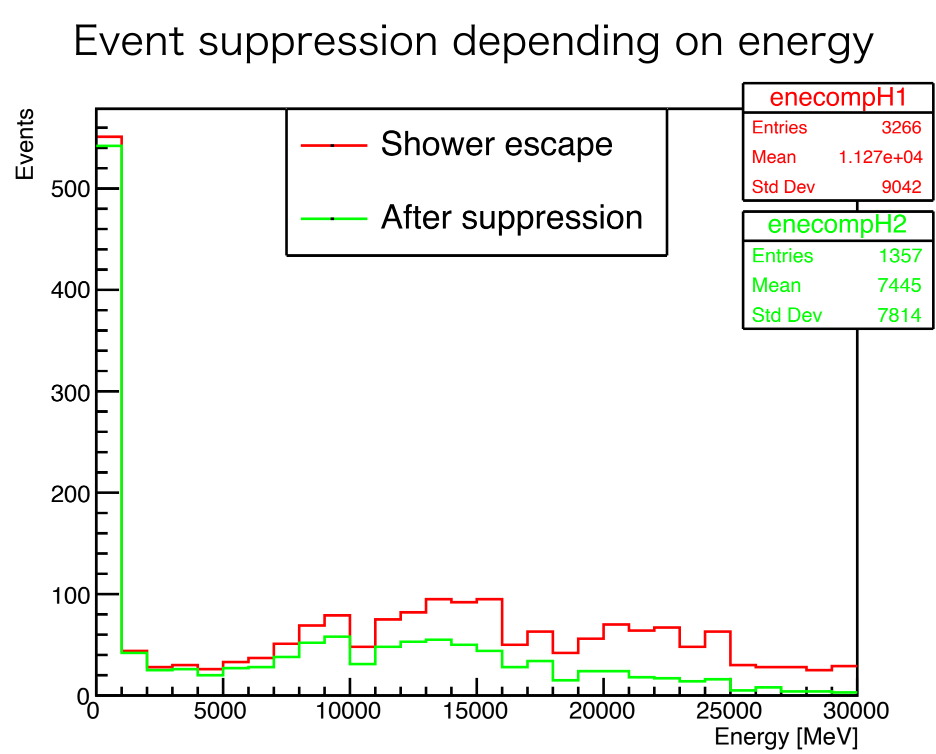
Comparison with primary energy

- Shower escape events are suppressed linearly depending on the primary energy
    - Shower escape events have more high-energy events
- **Data and simulation matches much better**
    - Observed deviation b/w data and simulation is likely due to a problem of the energy distribution in the high energy region in the simulation









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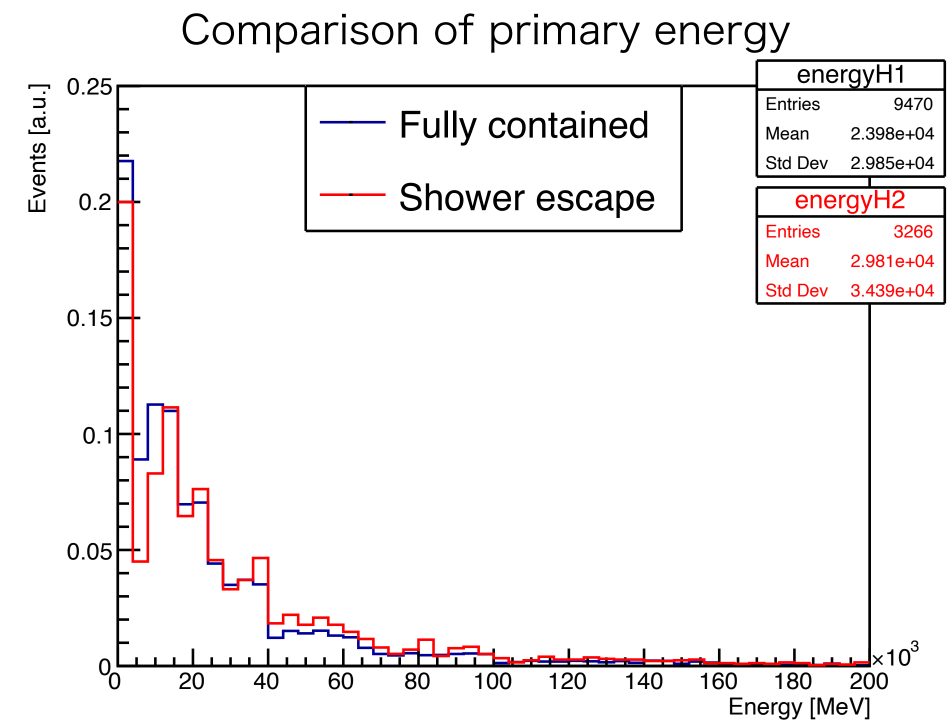

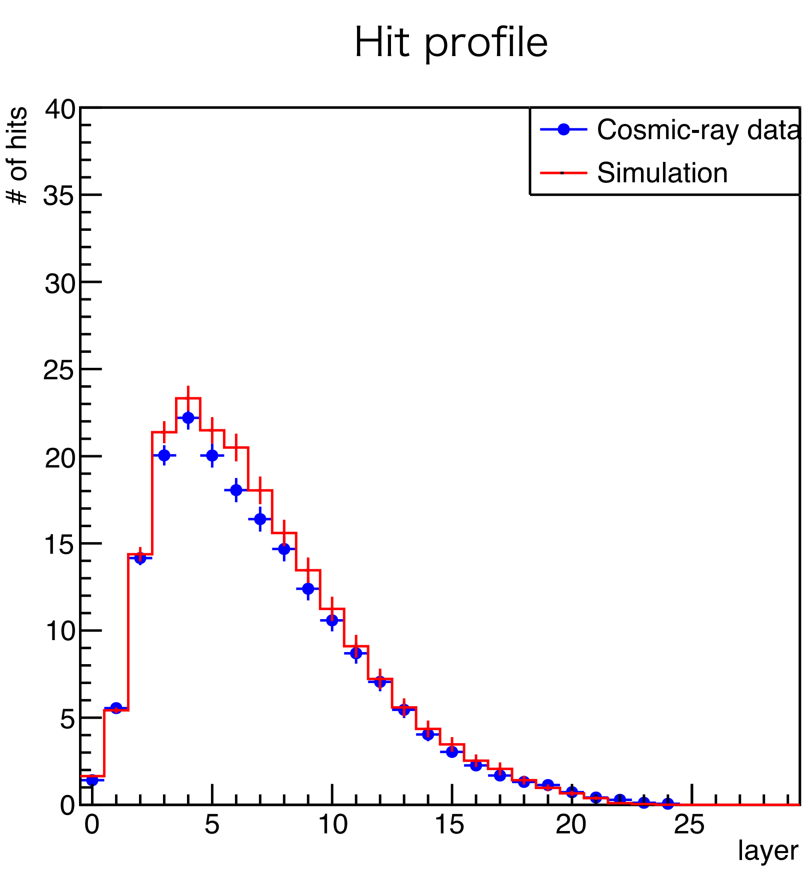

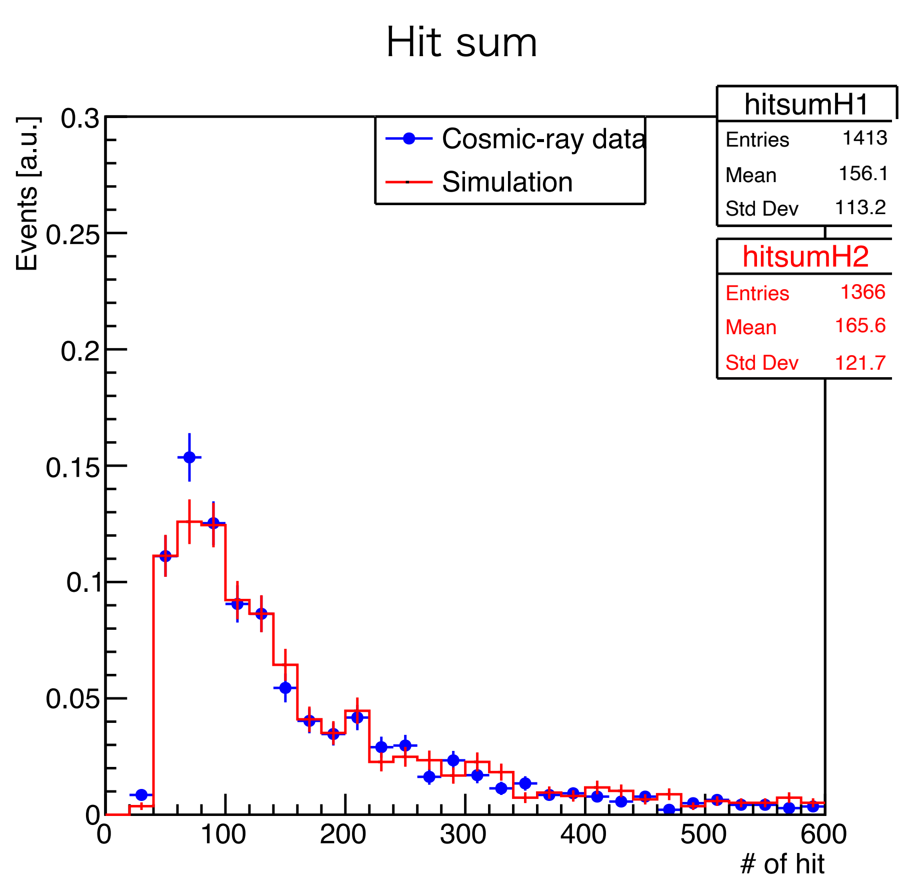

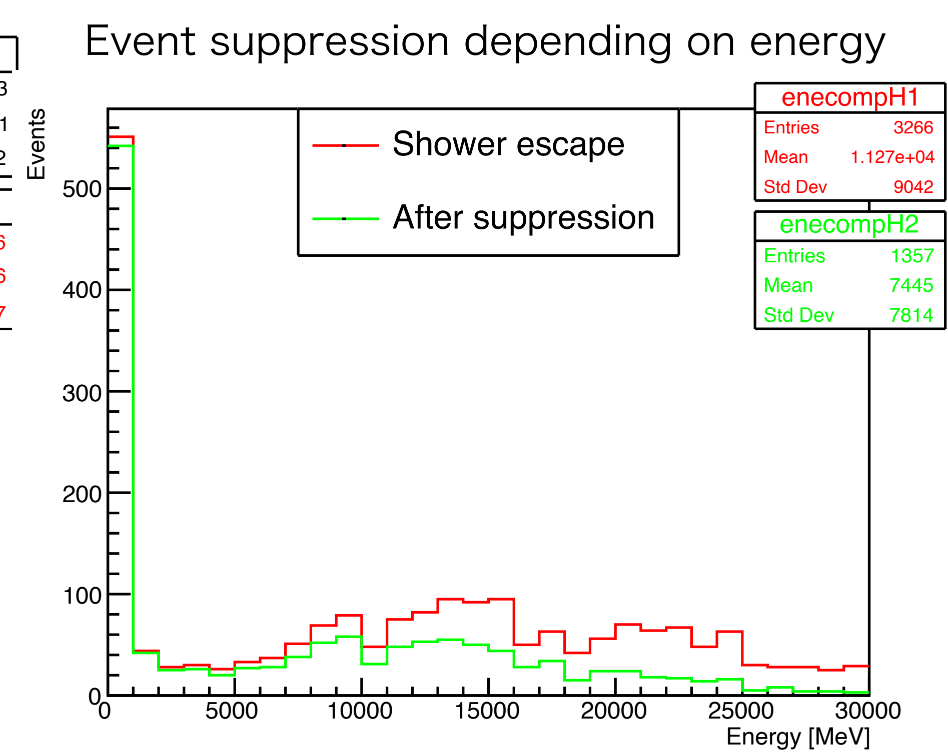

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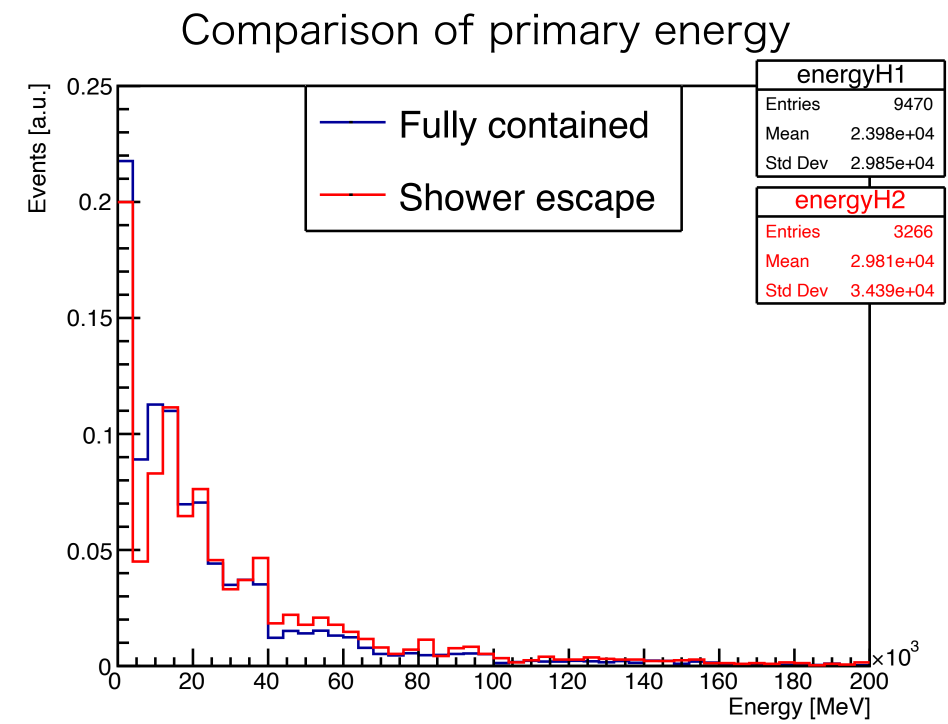
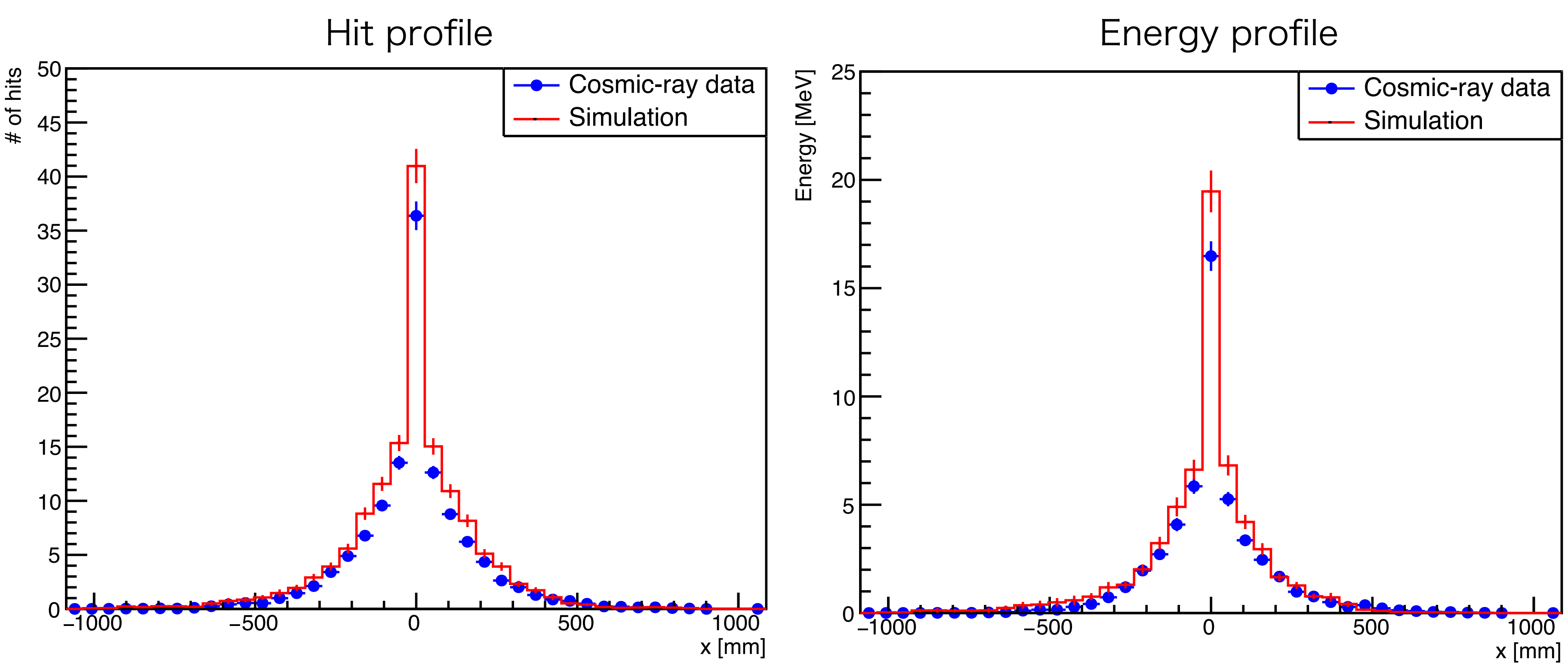
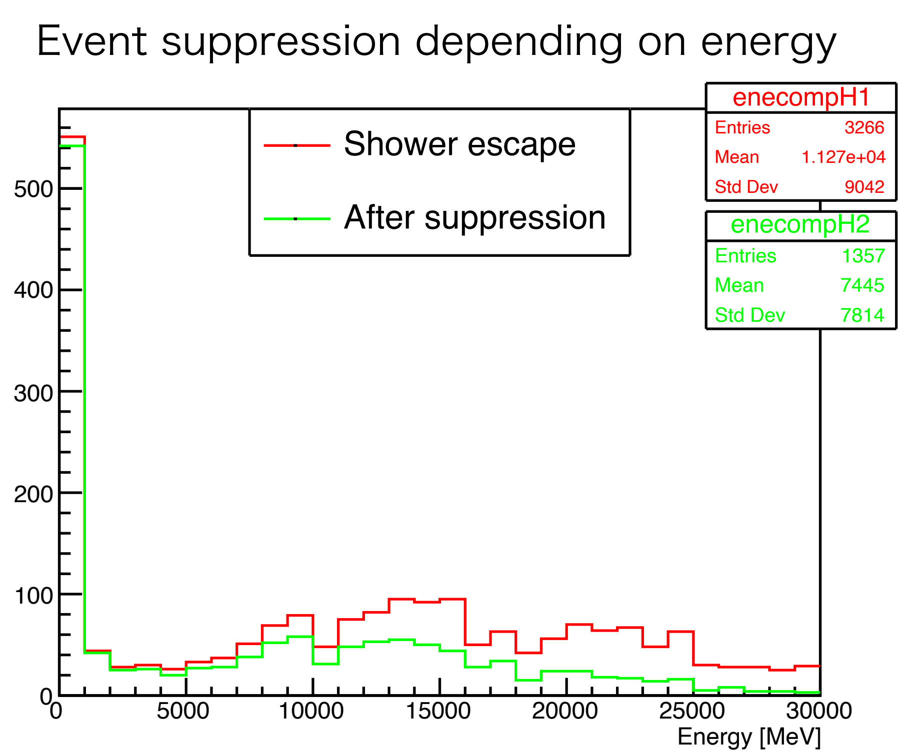


Transverse profile





Summary

- Scintillator electromagnetic calorimeter (Sc-ECAL)
  - Large technological prototype has been constructed
  - Cosmic-ray run and LED run for commissioning

- Performance evaluation
  - Good stability
  - Sufficient efficiency, position resolution
  - Shower events can be detected as expected at the simulation

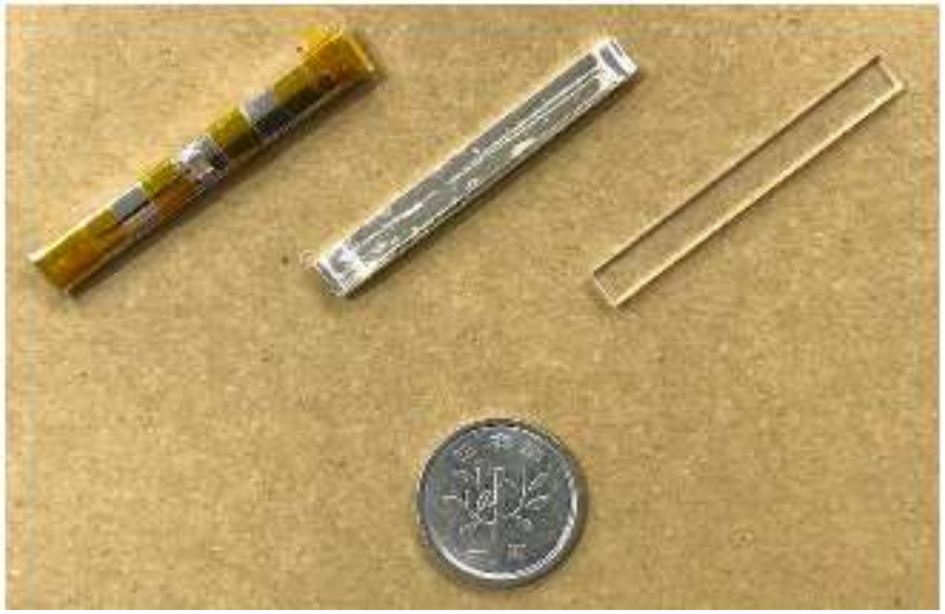
Backup

Scintillator strip & Silicon PhotoMultiplier (SiPM)

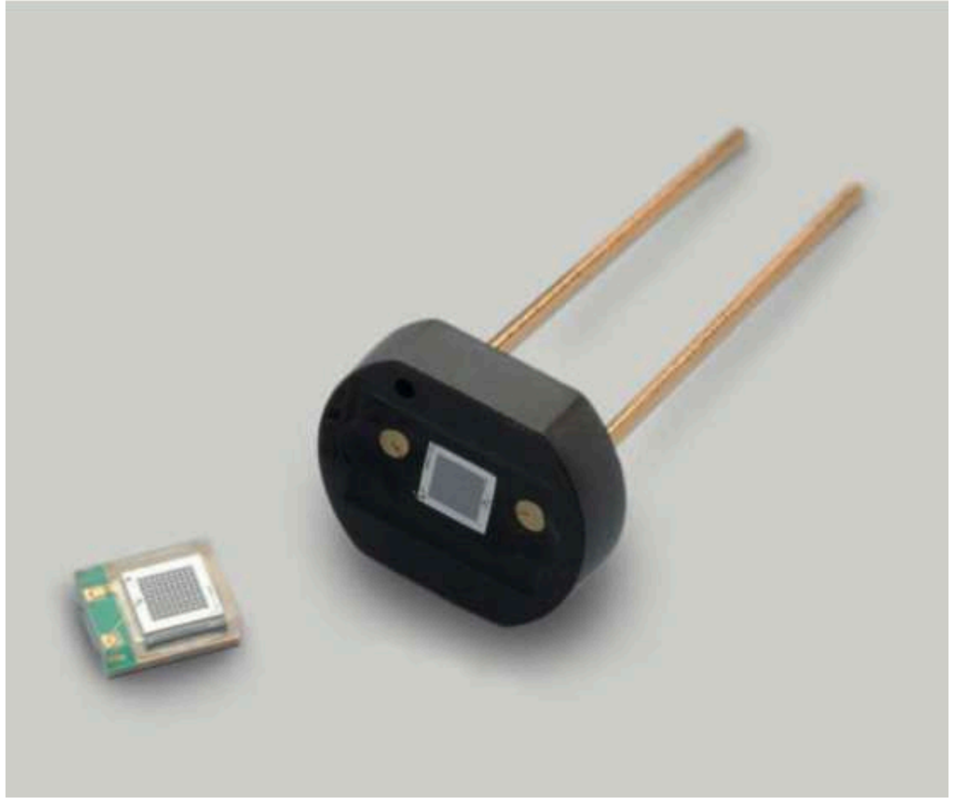
- 5 × 45 × 2 mm³ strip made by BC-408
  - PVT-based plastic scintillator by cast moulding
    - Wrapped in ESR film
  - PS-based scintillator by injection moulding under development
    - Injection moulding is suitable for large scale production
- Bottom-center SiPM coupling is adopted

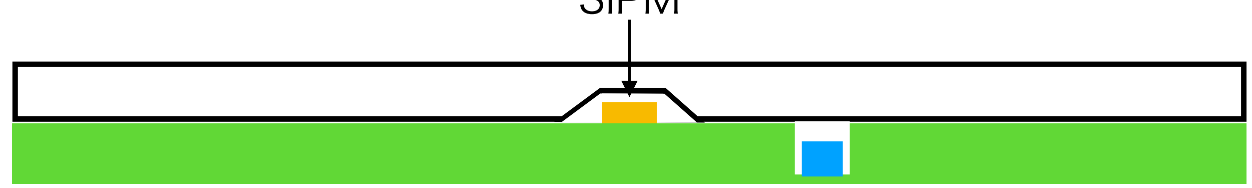
- Multi-Pixel Photon Counter (MPPC)
  - Surface-mount type with an active area of 1.0 mm × 1.0 mm and 10/15 μm pixel pitch
    - S12571-010P/-015P
  - Small-pixel SiPM with the trench structure developed
  - Detailed performance comparison b/w SiPM types not yet done

Scintillator strip



SiPM



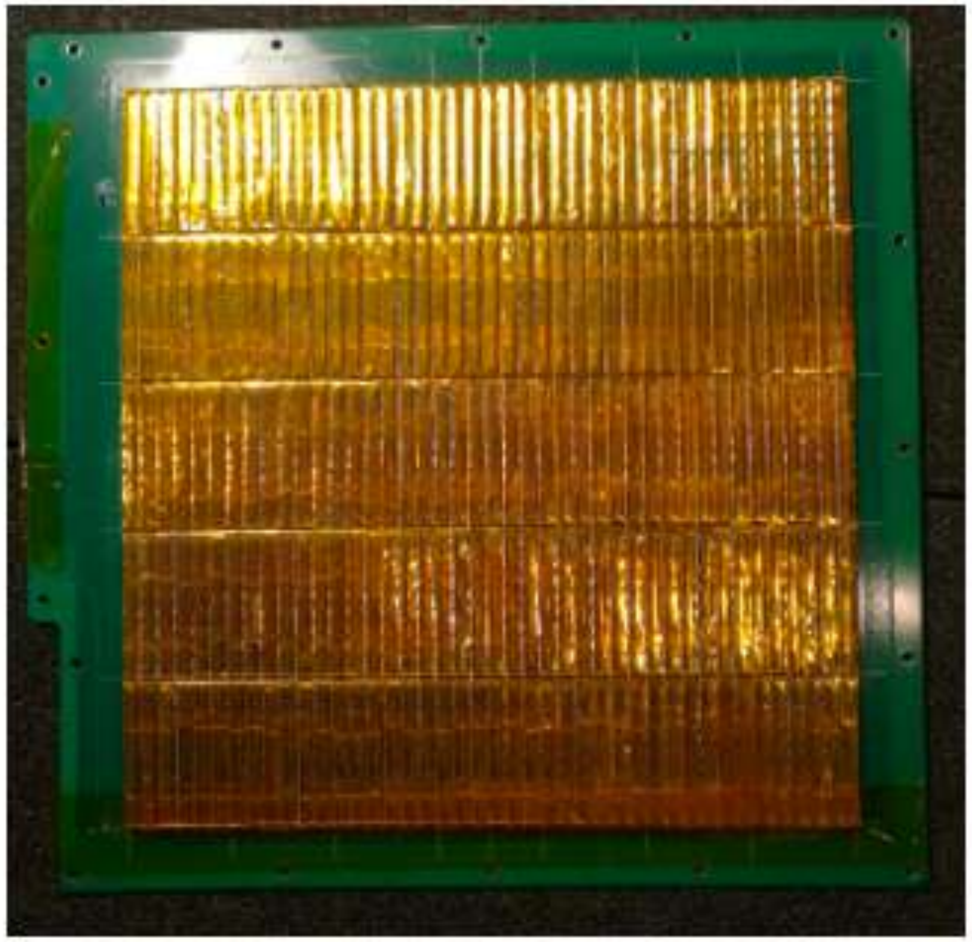


Scintillator strip coupled to SiPM (and LED)

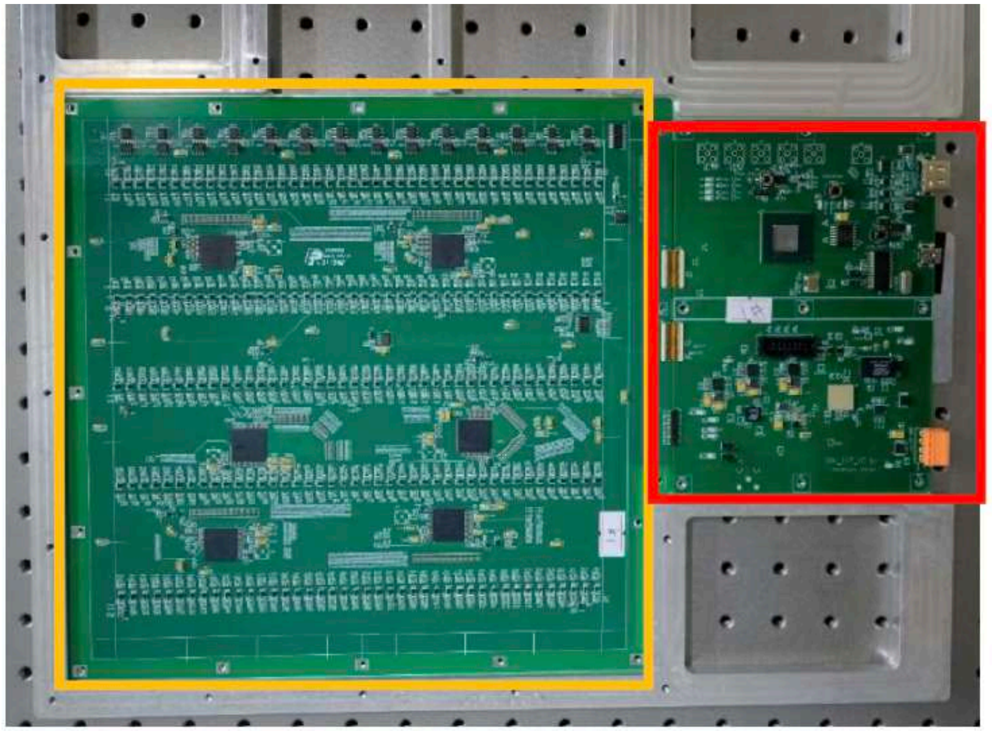
ECAL Base Unit (EBU)

- Fully integrated electronics for high granularity
  - 210 channels divided into 5 rows and 42 columns
  - Readout with 6 × ASIC (SPIROC2E)
    - ADC (High gain and low gain) & TDC
    - Voltage adjustment
    - Self-triggering & forced-triggering
  - Temperature monitoring system
    - 16 temperature sensors on EBU
  - Electronics scaling system
    - For the high gain and low gain inter-calibration
  - LED scaling system
    - For the SiPM calibration
- SiPMs are soldered on EBU, and scintillator strips wrapped with ESR films are assembled on EBU

Scintillator side of EBU



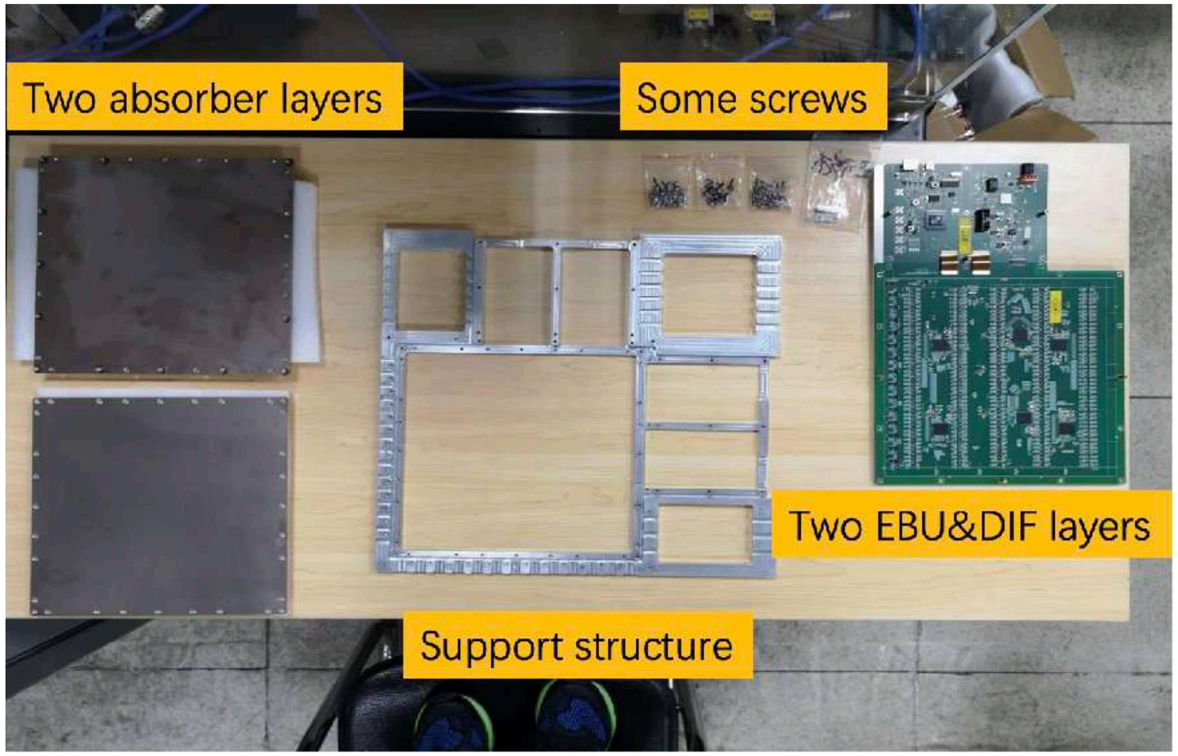
Electronics side of EBU



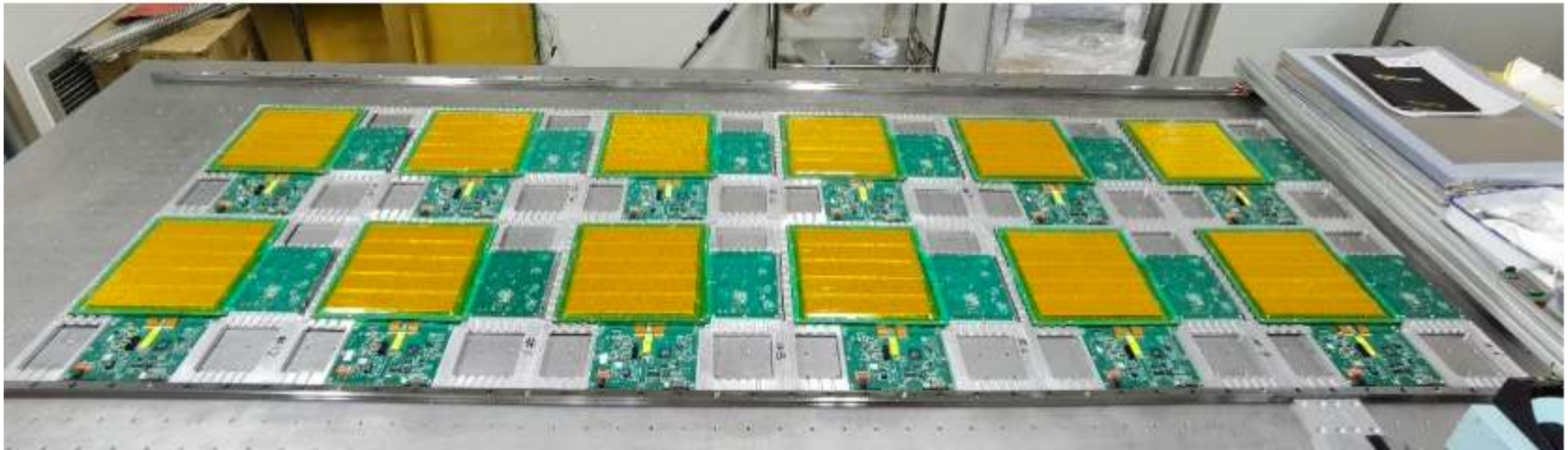
Construction

- One super-layer consists of two sets of EBUs and absorber layers
  - 2 EBUs in x-y configuration
  - Absorber: 3.2 mm, 15%-85% Cu-W
- 15 super-layers (30 EBUs) completed
  - 1 additional super-layer with double SiPM readout (Appendix)

Components of super-layer



Super-module	#module (EBU)	SiPM	Strip length	Strip material (process)
Single-readout 1	12 (24)	S12571-010P	45 mm	PVT (casting)
Single-readout 2	3 (6)	S12571-015P	45 mm	PVT (casting)
Double-readout	1 (2)	S12571-015P	90 mm	PS (injection moulding)



Mechanical structure

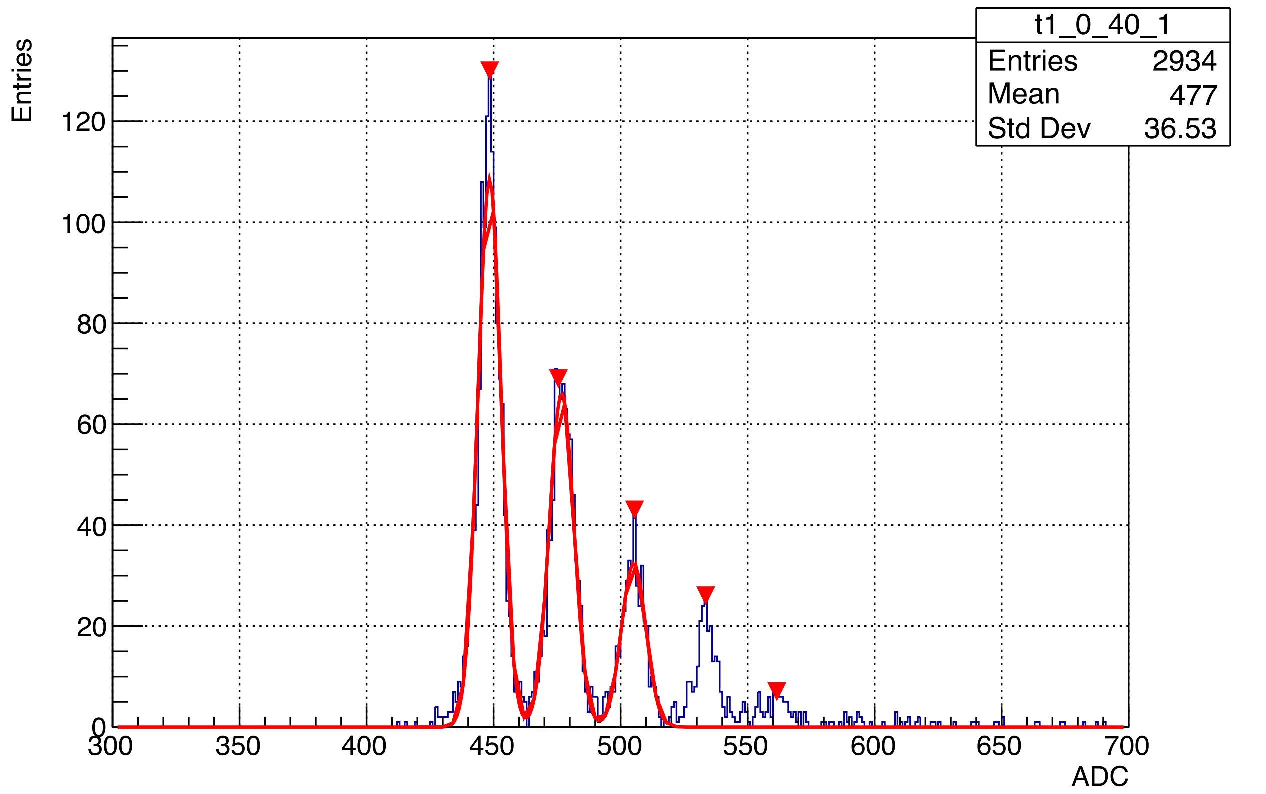
- The mechanical structure with 17 slots for super-layer
  - Super-layer can be individually assembled and disassembled

Completed technological prototype

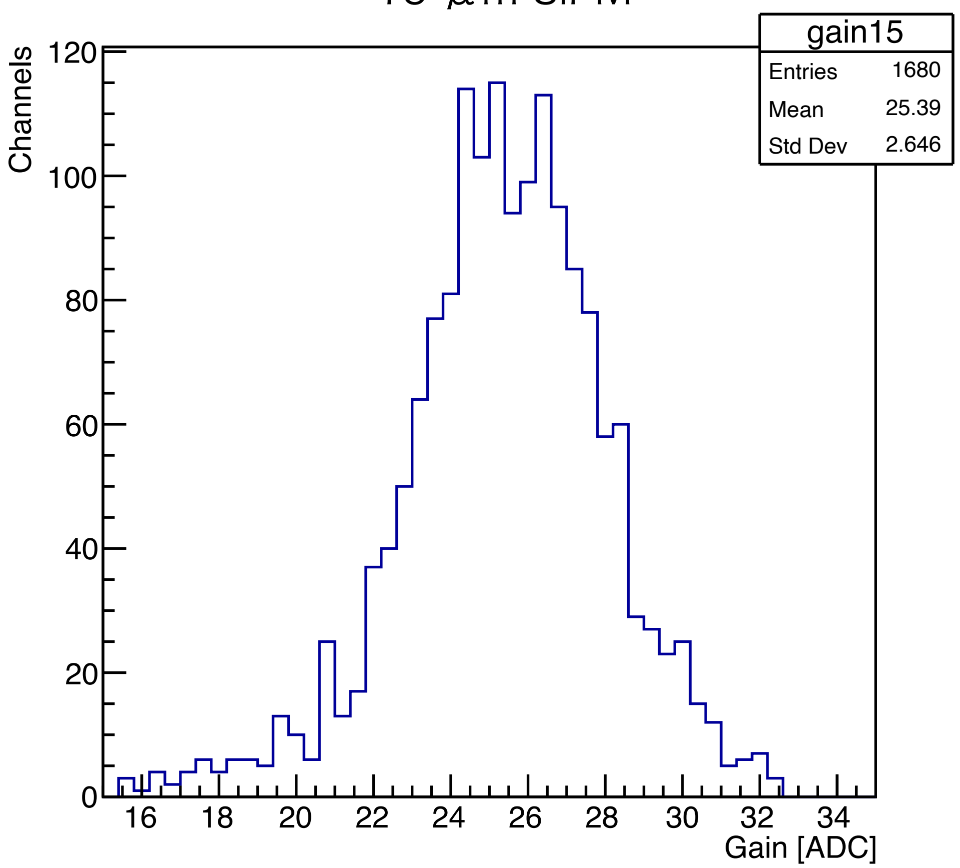
Gain calibration

- Gain obtained by the gap of peaks of 0,1,2 photons
- Per-channel calibration
  - 15 μm SiPM: 25.4 ADC
  - 10 μm SiPM: 15.36 ADC
  - Consistent with gain ratio at catalogue
    - Data: 25.4/15.36 = 1.65
    - Catalogue: 2.30/1.35 = 1.70

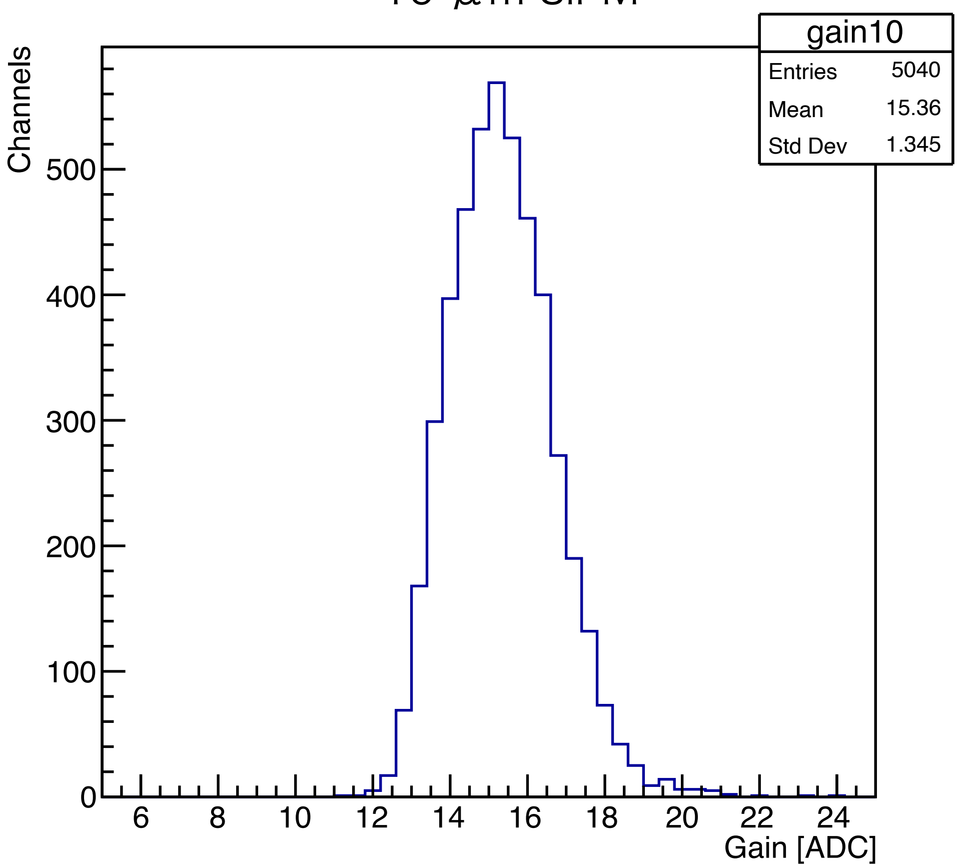
ADC distribution with low LED intensity



15 μm SiPM



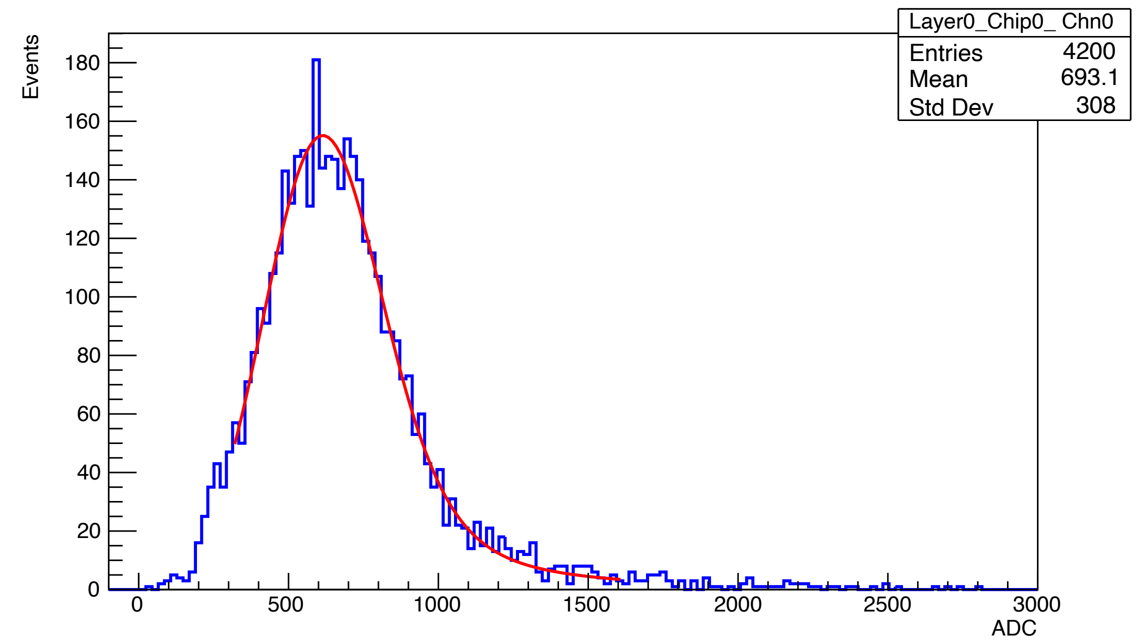
10 μm SiPM



MIP calibration

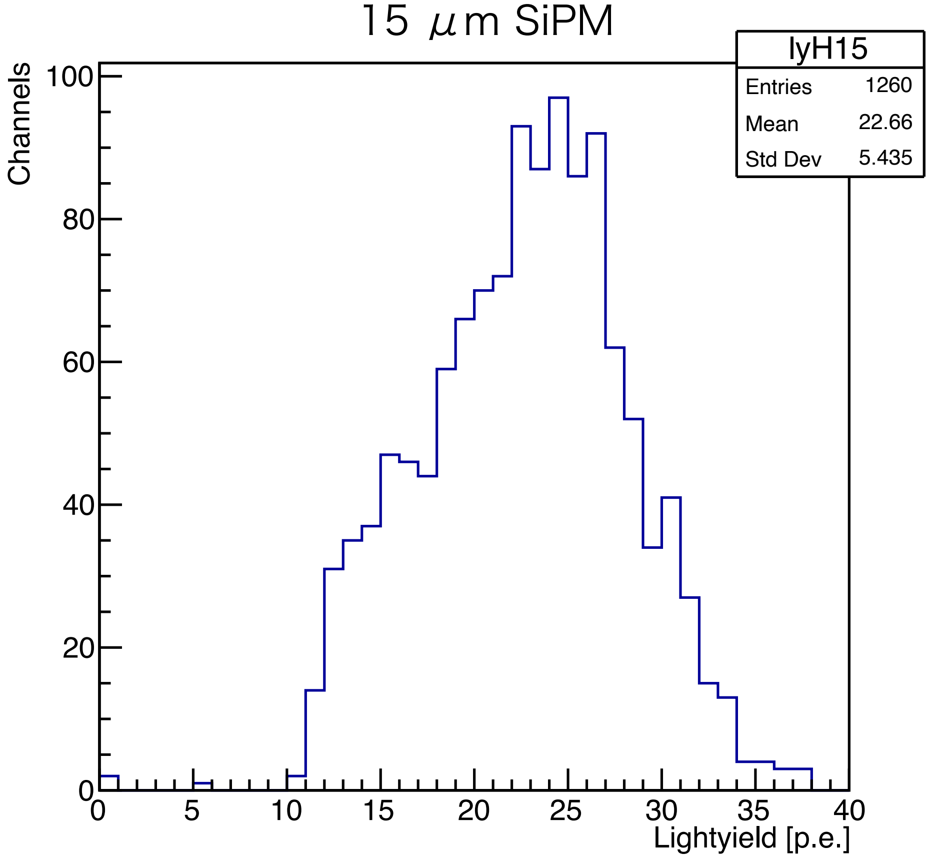
- MIP calibration factor obtained by Landau MPV of ADC distribution of cosmic-ray hits
  - Angular and temperature correction applied
- Landau distribution of MIP obtained for all channels
  - Light yield is also obtained
    - 15 μm SiPM: 22.6 p.e. (18 p.e. w/o CTAP)
    - 10 μm SiPM: 7.6 p.e. (7 p.e. w/o CTAP)
  - Consistent with PDE difference
    - 15 μm: 25%,　10 μm: 10%

ADC distribution for MIP response

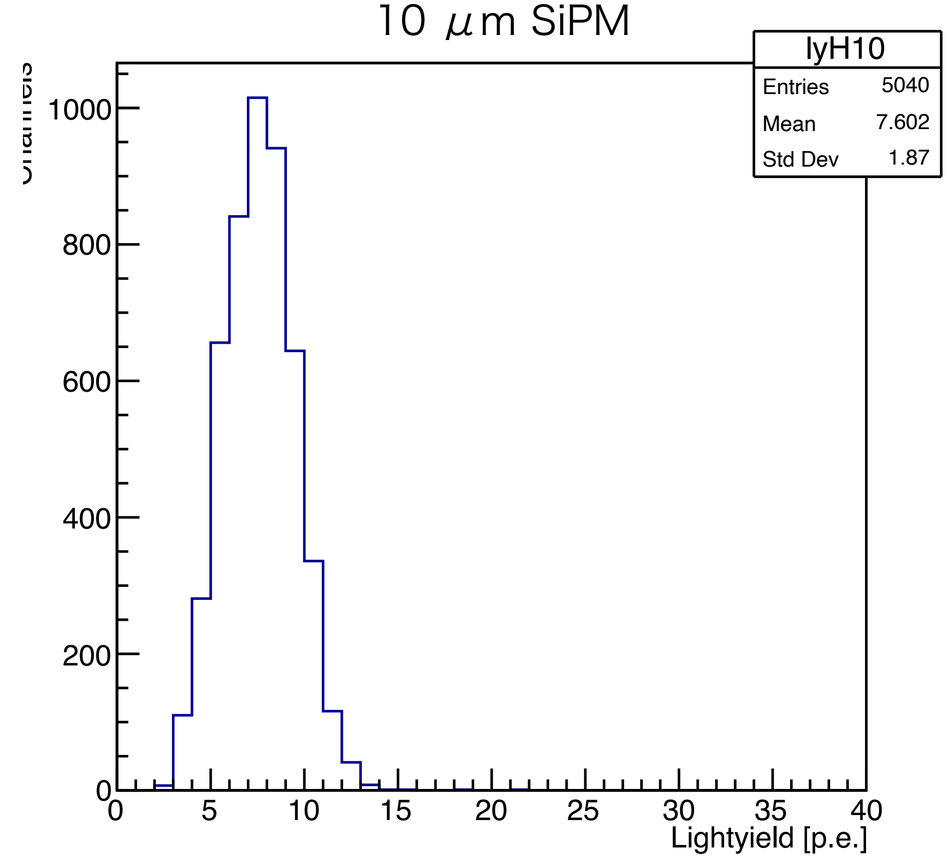


Light yield (MIP/gain)

15 μm SiPM



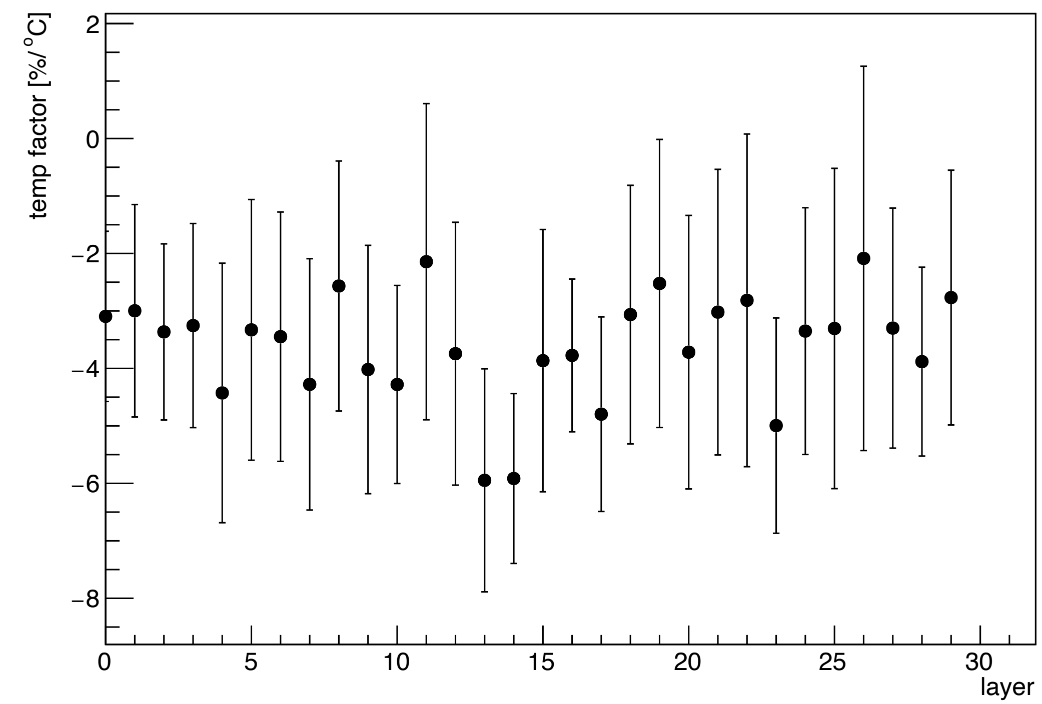
10 μm SiPM



Temperature correction

- Temperature is monitored during LED tests and cosmic-ray tests
- Temperature dependence on MIP response and gain obtained
  - 15 μm SiPM: -3.23%/°C
  - 10 μm SiPM: -3.70%/°C
- Temperature correction is applied at each hit
  - ADC distributions with large temperature difference match well after the correction

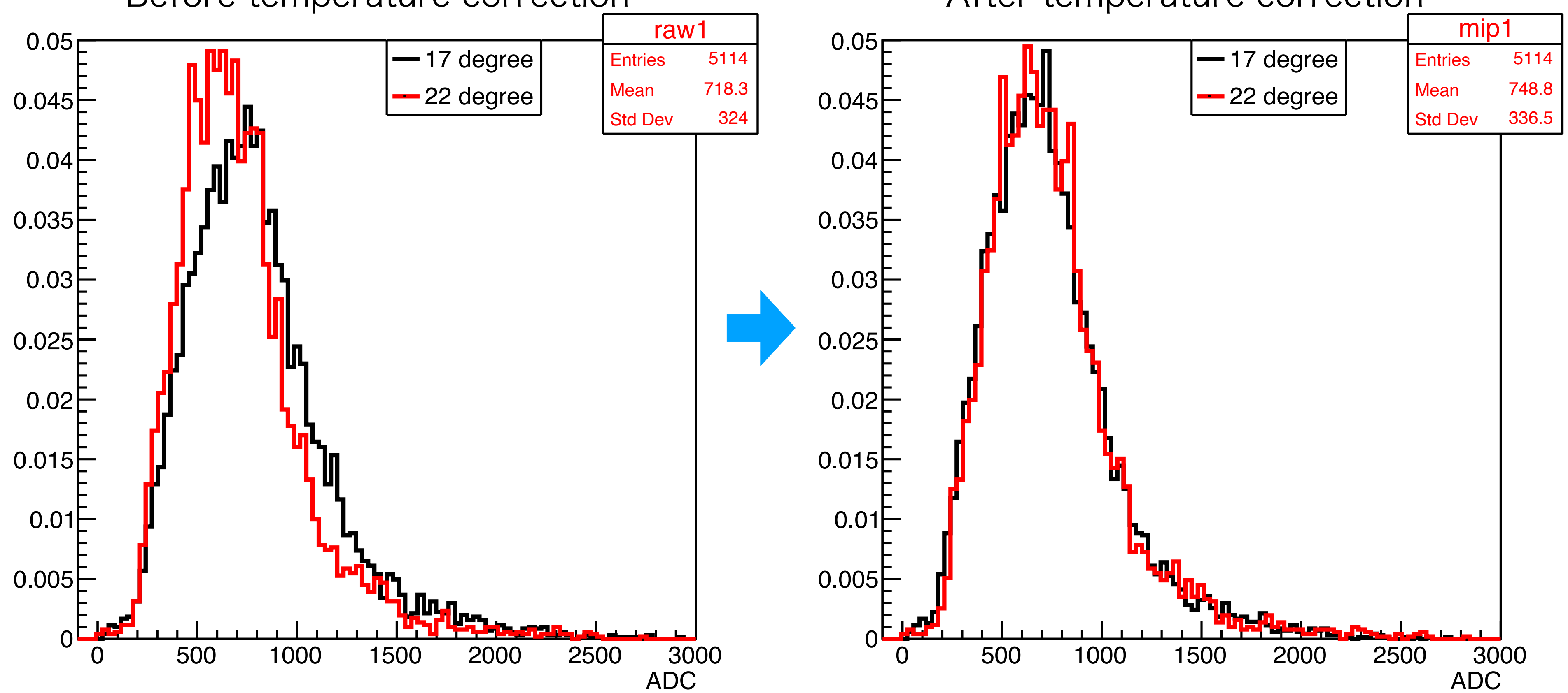
Temperature dependence for MIP response



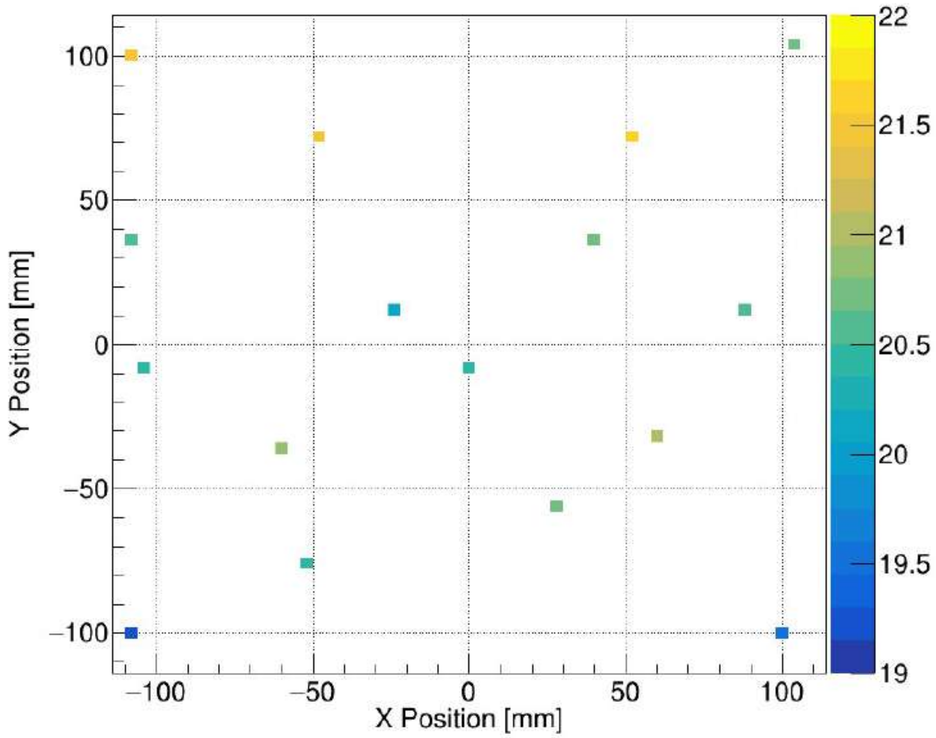
ADC distribution for MIP response

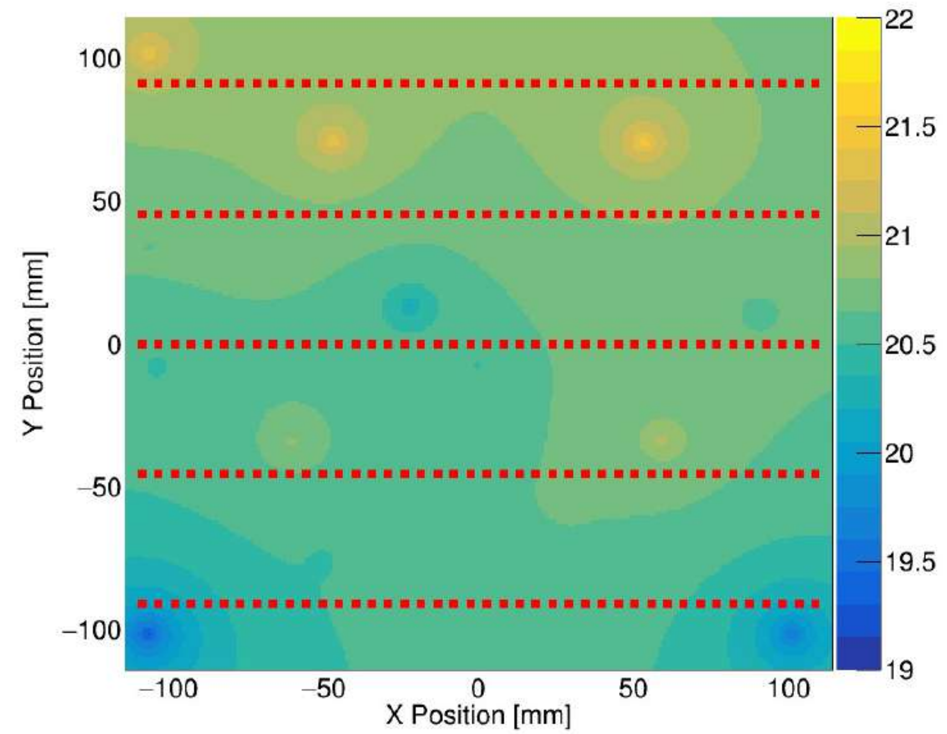
Before temperature correction

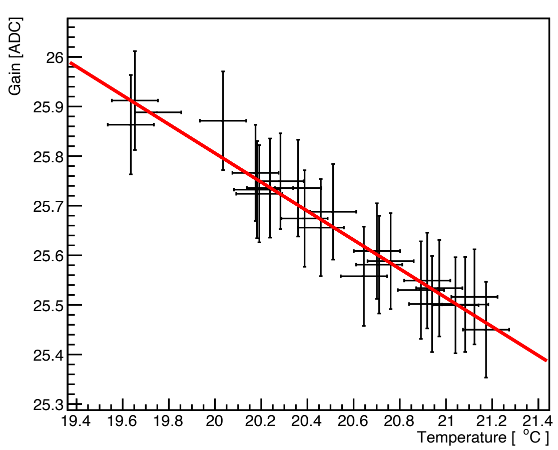
After temperature correction

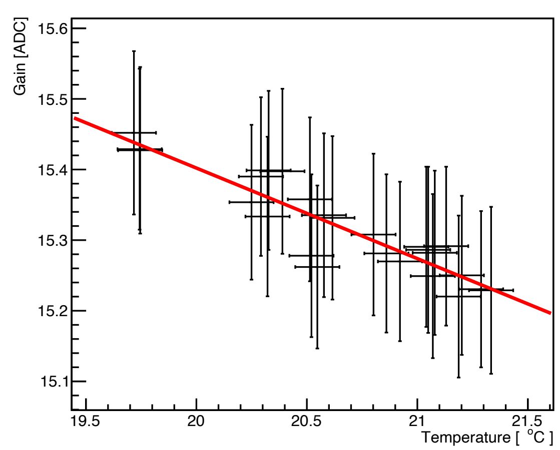


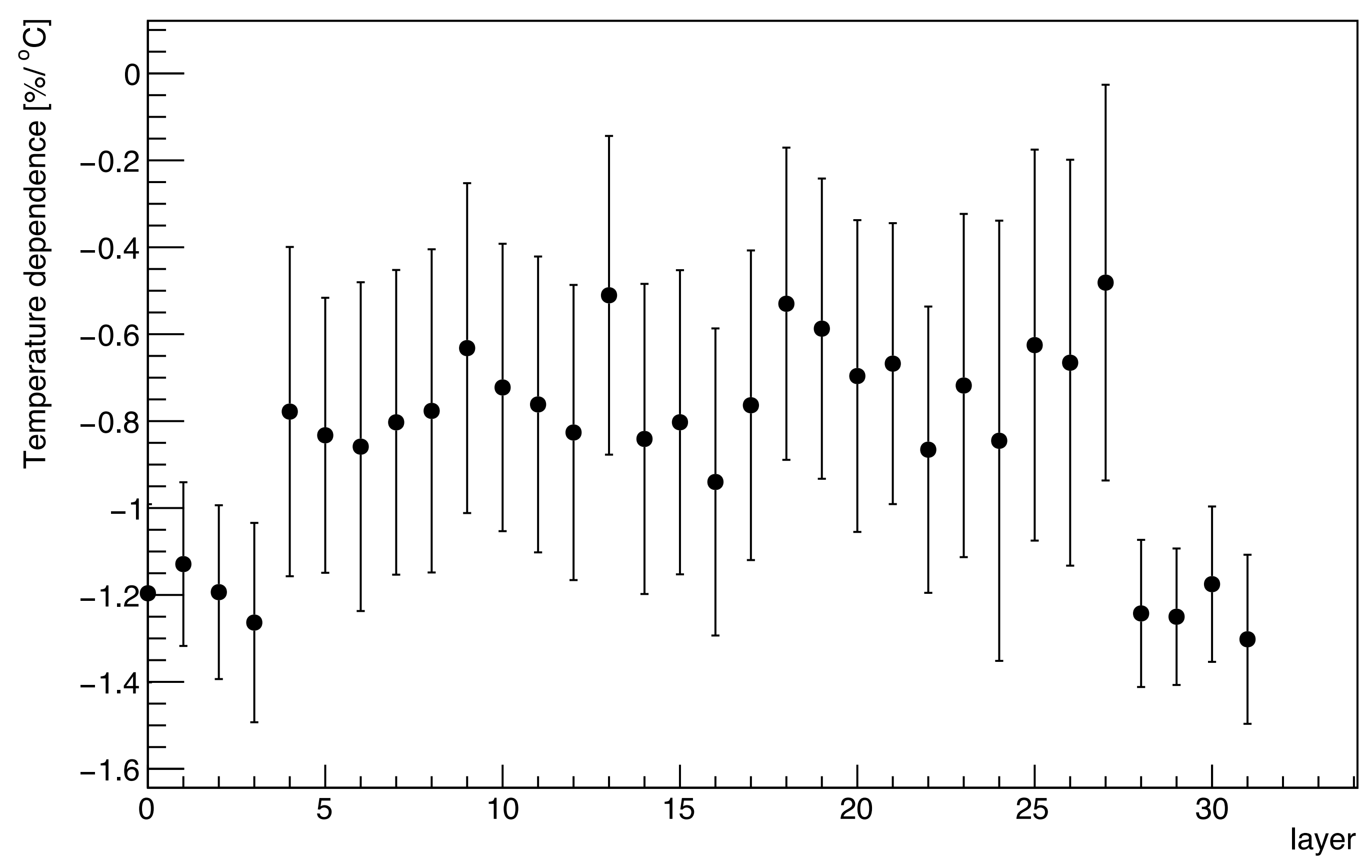
Temp reco & gain







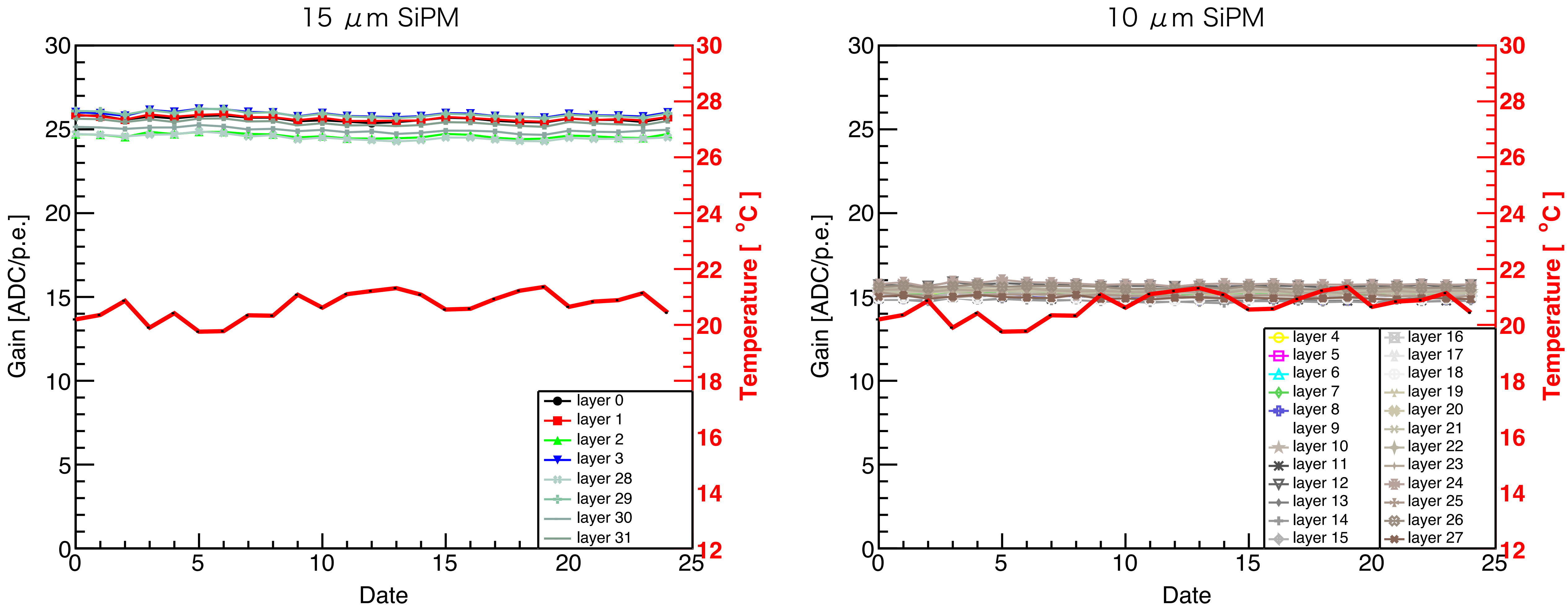




Stability

- **Gain is quite stable during one month LED run**
  - Weak correlation with the temperature variation
  - Further improved by temperature correction
- Inter-calibration, CTAP, and pedestal stability is quite stable when averaged over all channels
  - Improvement of LED system is needed to reduce the error
- Sc-ECAL can be calibrated well and operated stably

Gain stability before temperature correction



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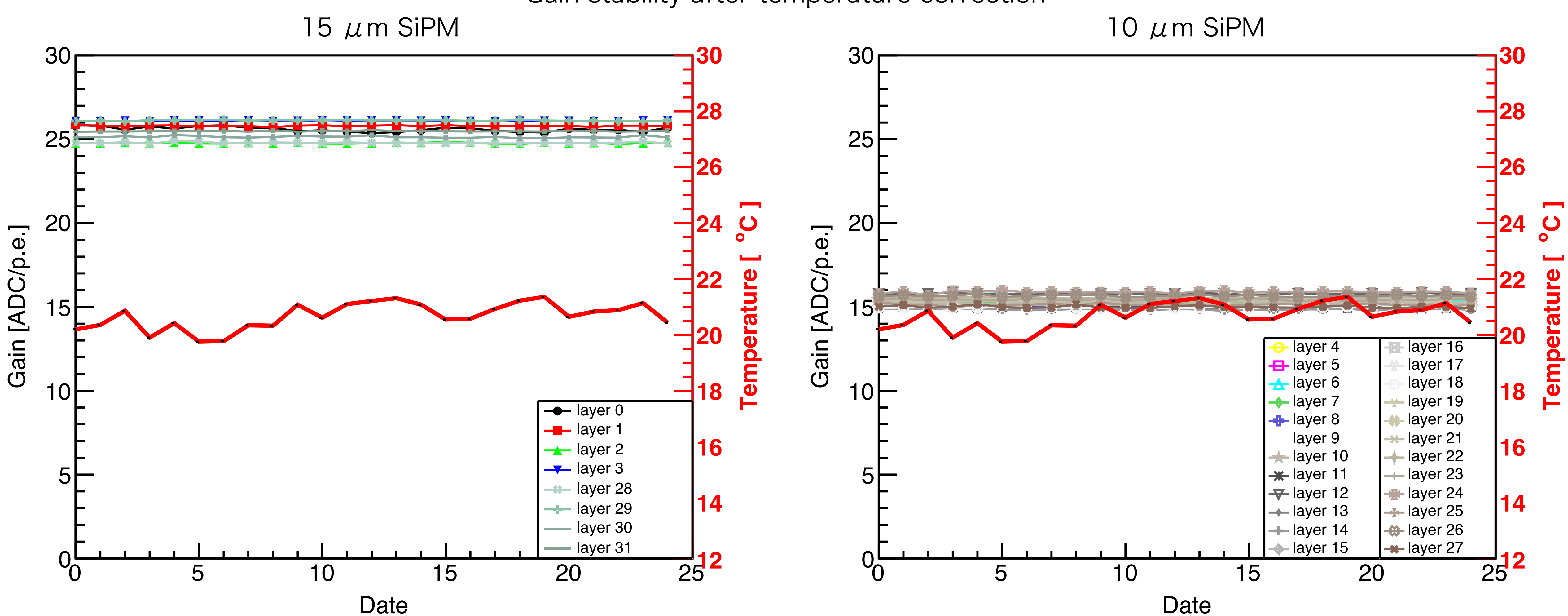
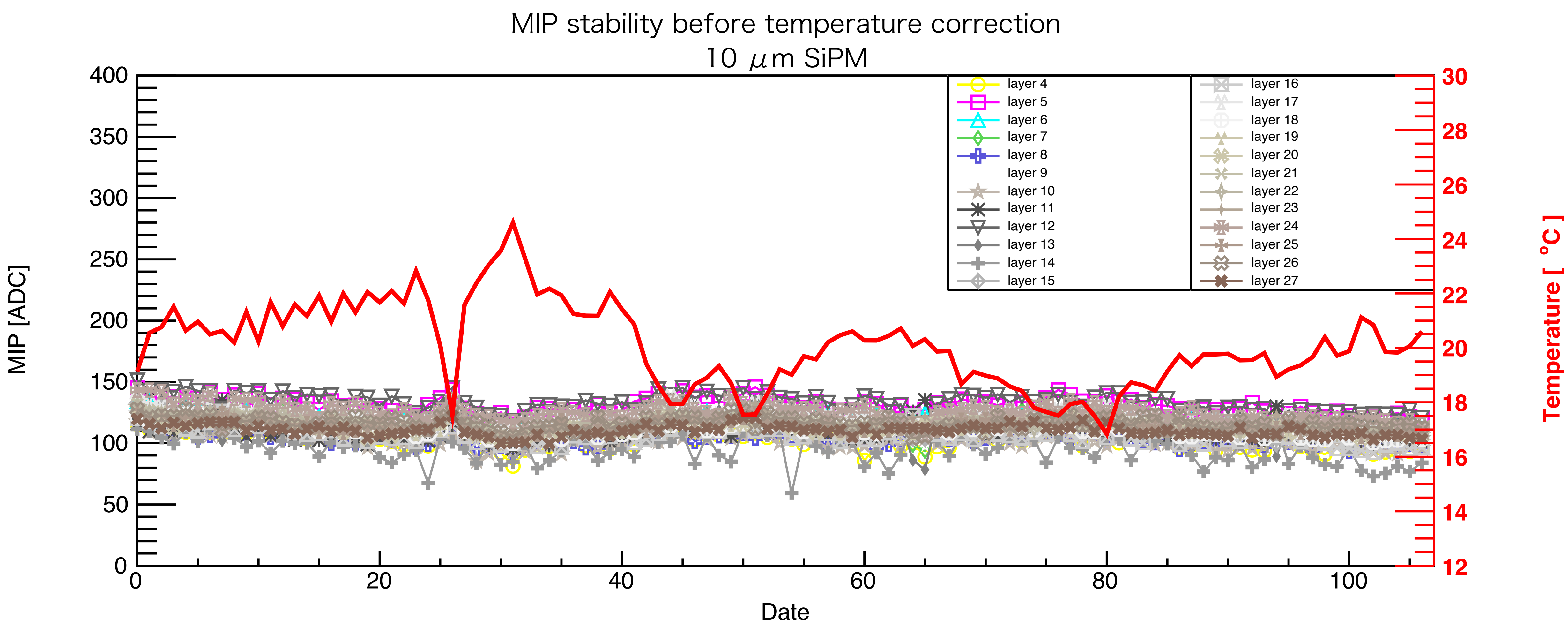


Stability

- **MIP response is almost stable during three month CR run**
  - Correlation with the temperature variation
  - Further improved by temperature correction
- 5–13% decrease over 3 months depending on layer
  - The reason is under investigation
    - Instability of electronics or SiPM
    - Aging of scintillation light emission
  - Possible approach is frequent MIP calibration and voltage adjustment of SiPMs



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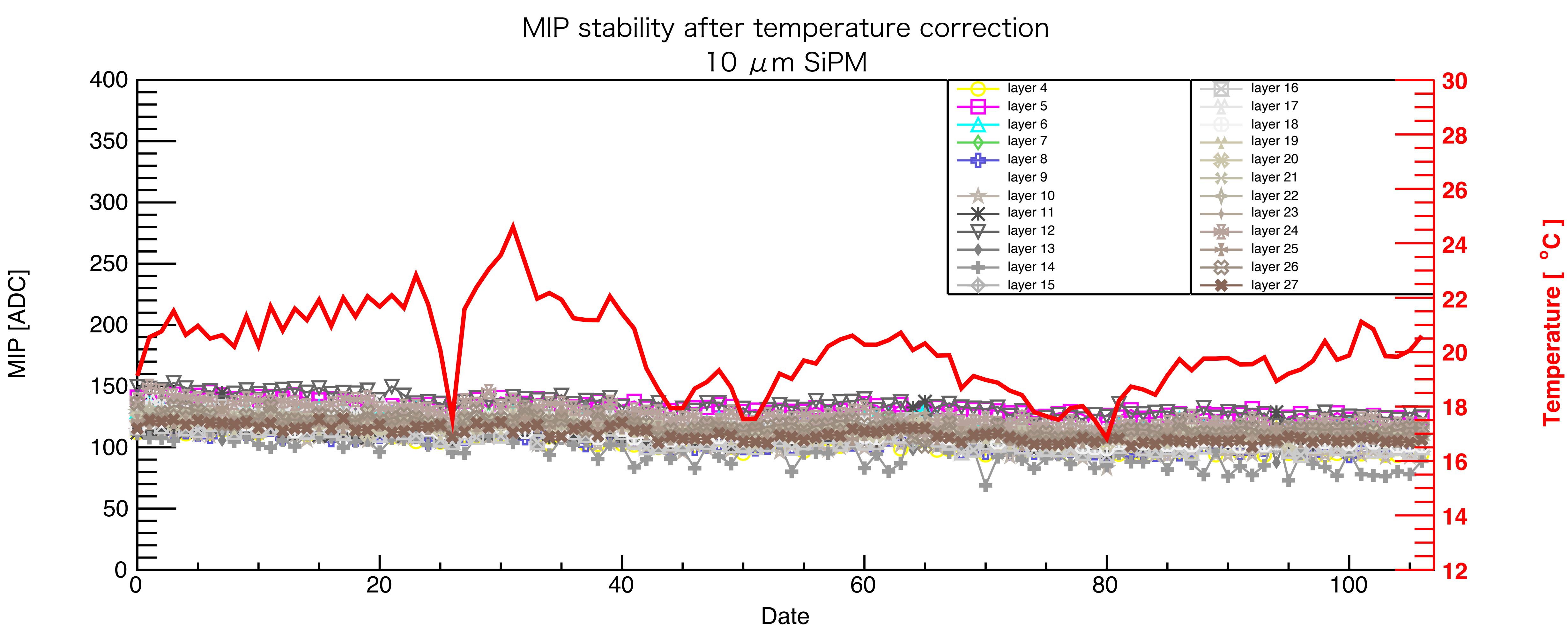
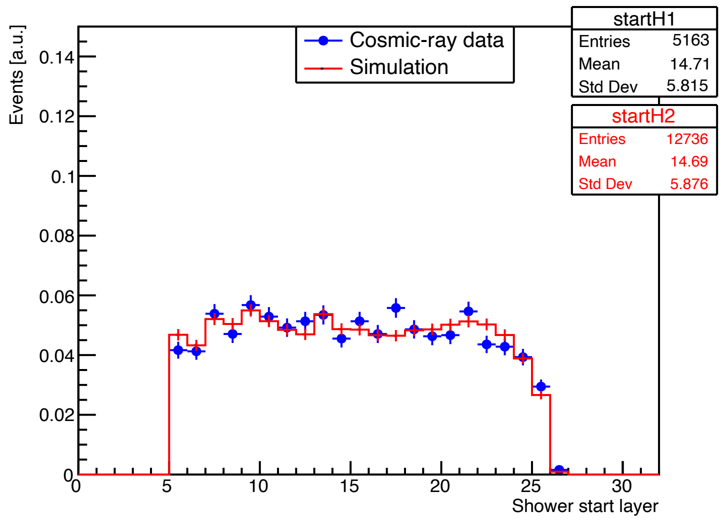
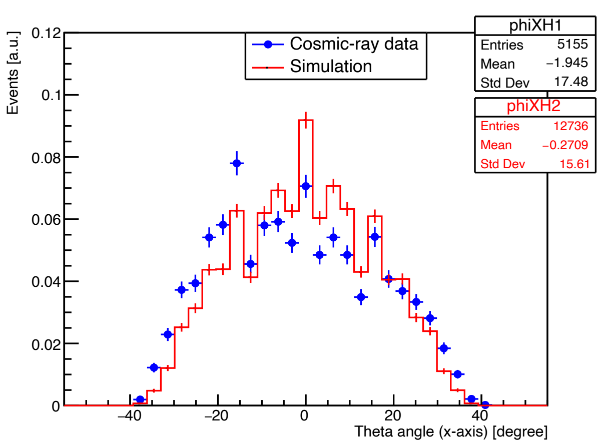
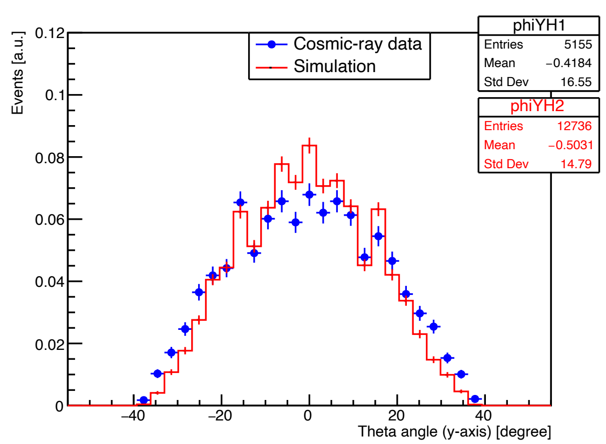


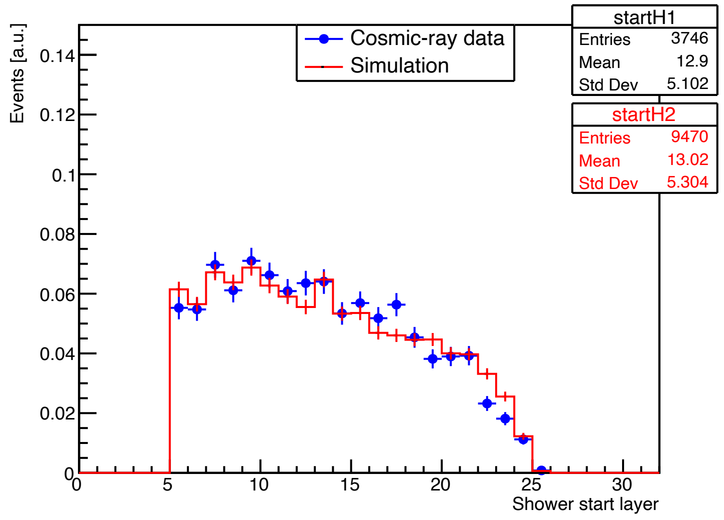
CR shower

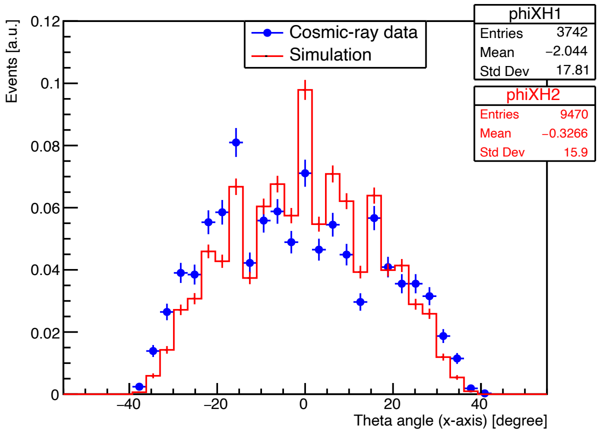

Events [a.u.]
Cosmic-ray data
Simulation
startH1
Entries 5163
Mean 14.71
Std Dev 5.815
startH2
Entries 12736
Mean 14.69
Std Dev 5.876
Shower start layer

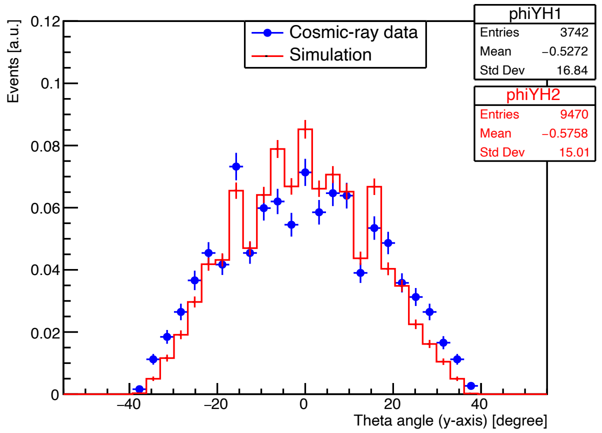

Events [a.u.]
Cosmic-ray data
Simulation
phiXH1
Entries 5155
Mean −1.945
Std Dev 17.48
phiXH2
Entries 12736
Mean −0.2709
Std Dev 15.61
Theta angle (x-axis) [degree]


Events [a.u.]
Cosmic-ray data
Simulation
phiYH1
Entries 5155
Mean −0.4184
Std Dev 16.55
phiYH2
Entries 12736
Mean −0.5031
Std Dev 14.79
Theta angle (y-axis) [degree]

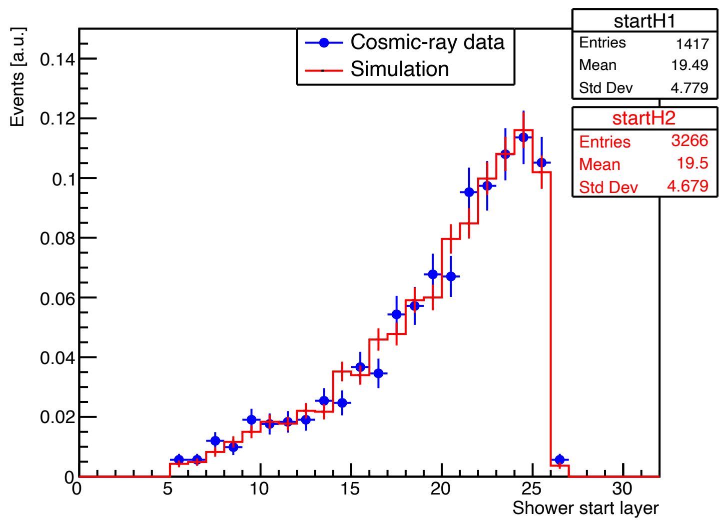
Fully contained

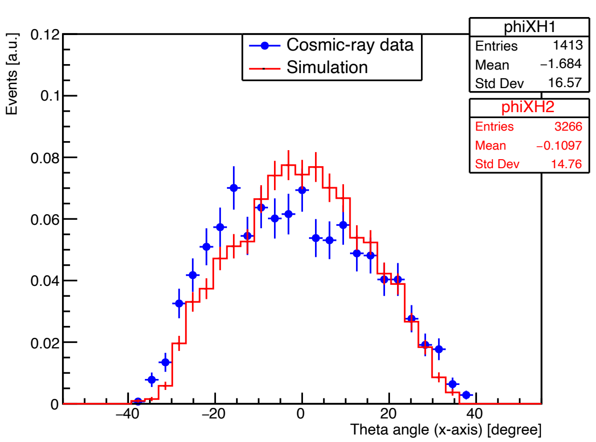


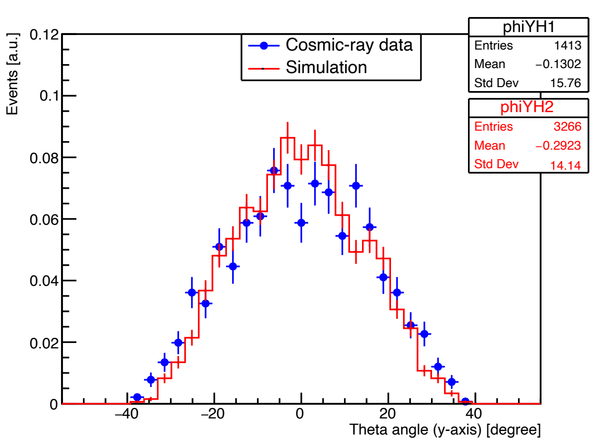




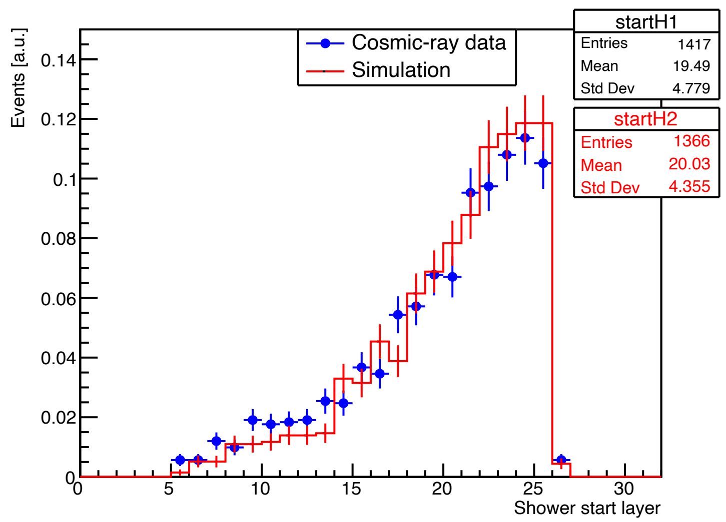
Shower escape

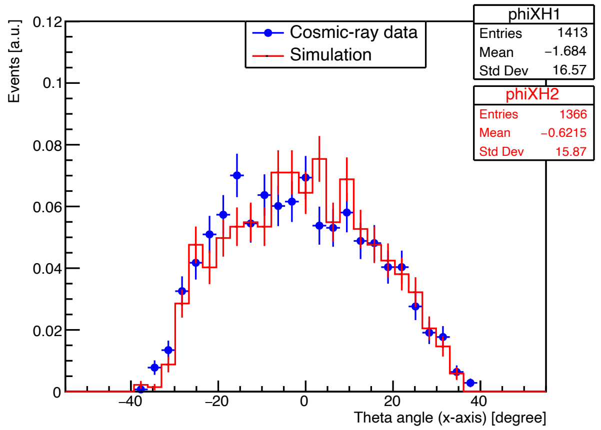


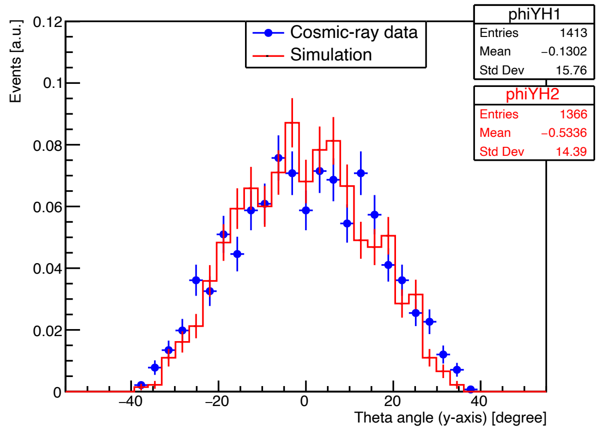




Low primary energy







Comparison with primary energy