# Performance study with Sc-ECAL prototype and ILD simulation study

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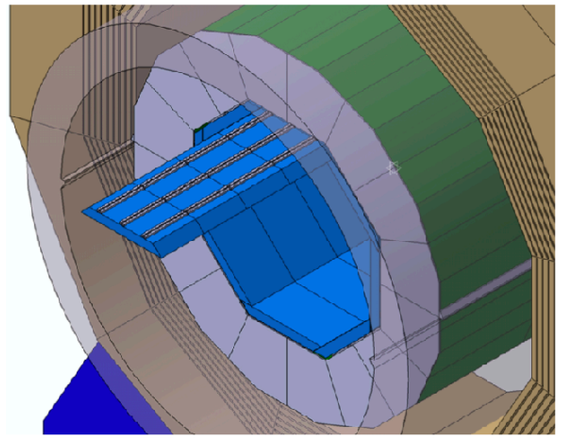
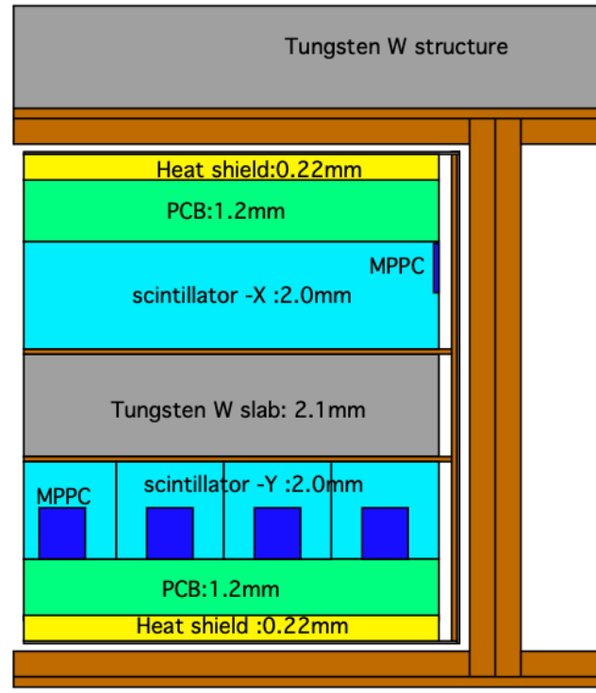
# Scintillator ECAL (Sc-ECAL)

- 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 ($10^8$ → $10^7$)
  - ➡ Low cost
  - Retaining performance compared to real 5 × 5 $mm^2$ segmentation at the Silicon ECAL
  - High granularity required for PFA (Particle Flow Algorithm)

ECAL in ILD

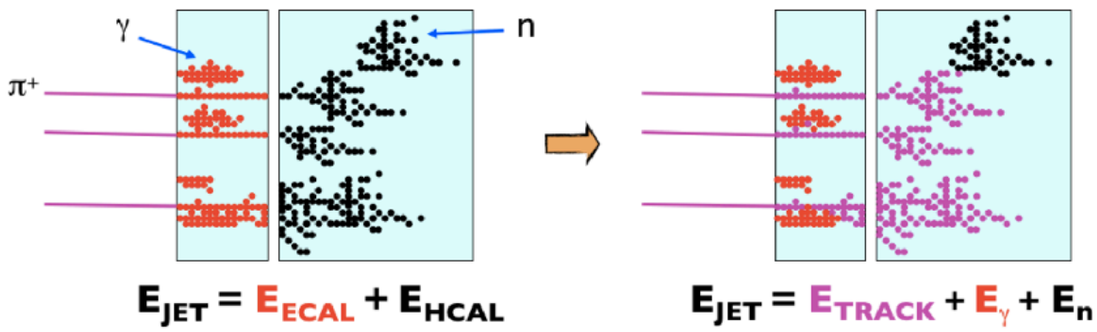


Structure of Sc-ECAL




- PFA (Particle Flow Algorithm)
  - Each particle is detected by the best suited detectors.
  - Improved jet energy resolution

Image of PFA

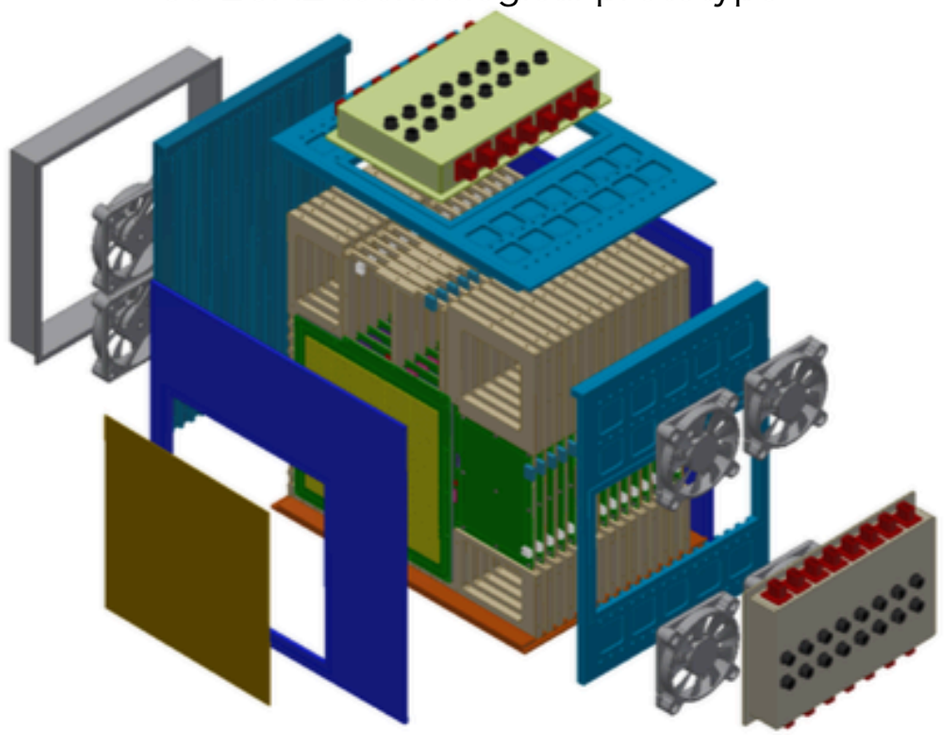


1. Performance study with Sc-ECAL prototype
2. ILD simulation study

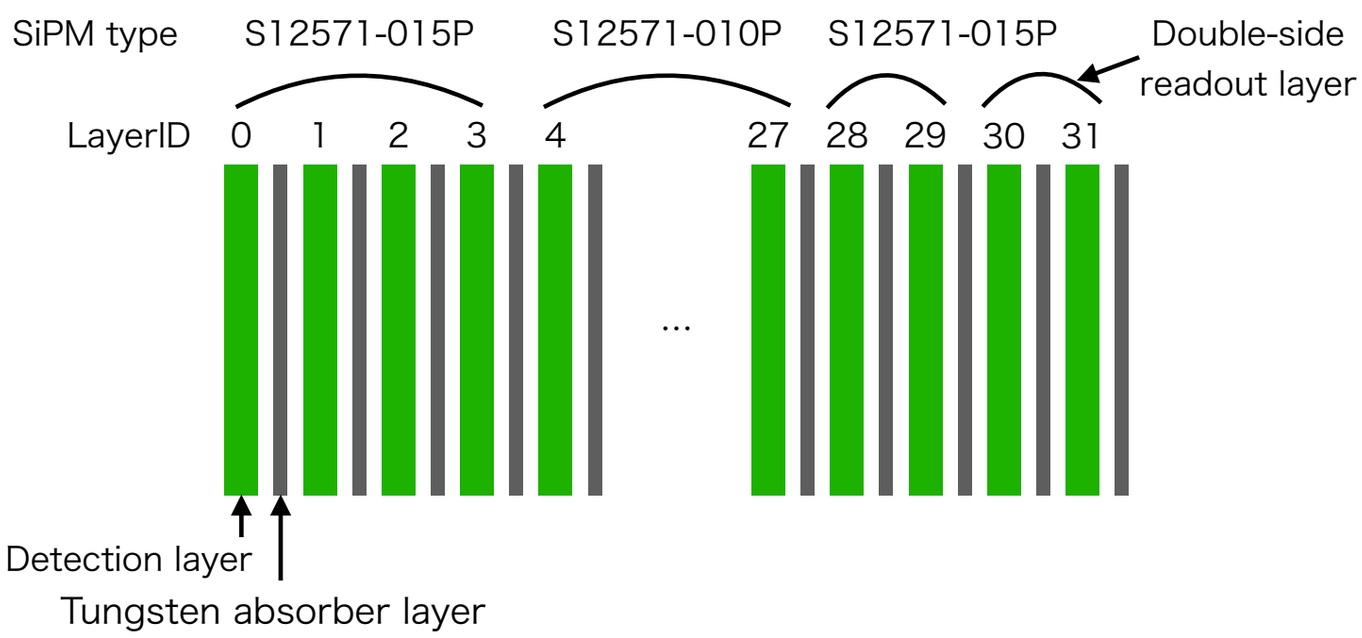
# Large technological prototype

- 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 × 45 × 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

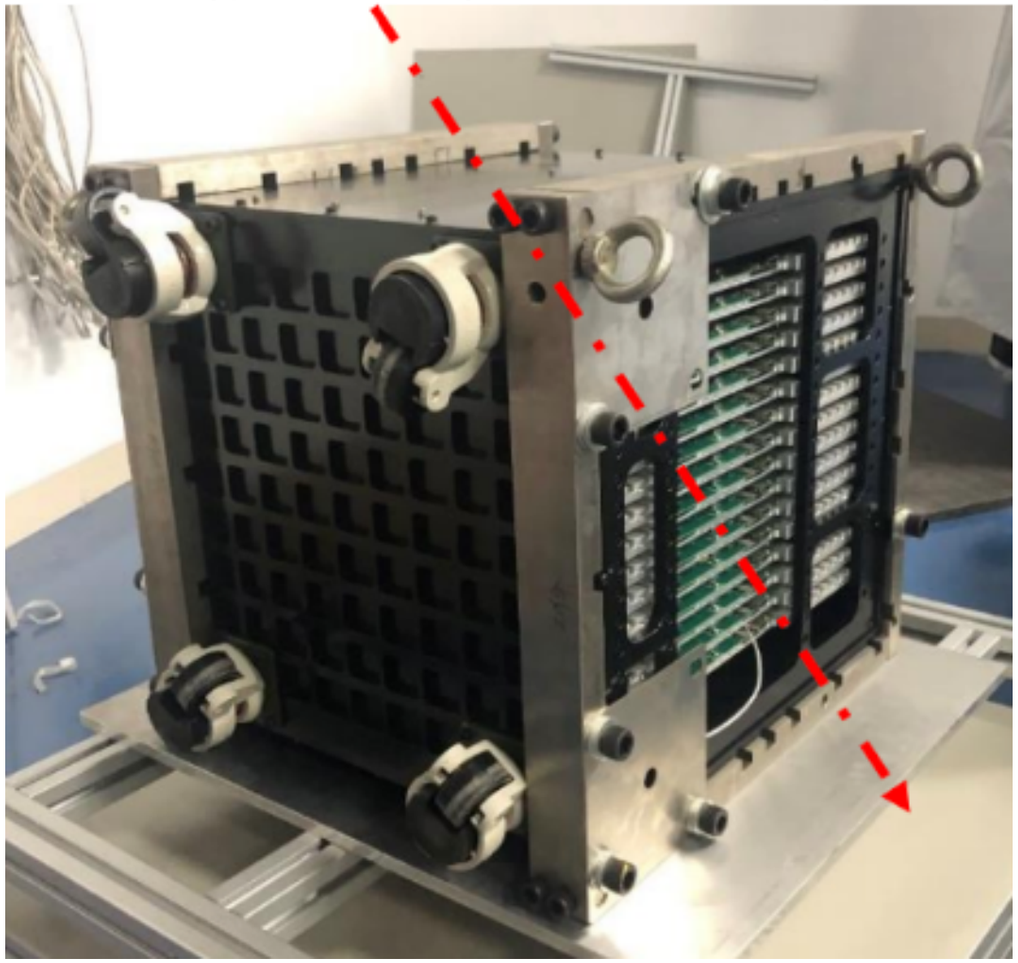
Uncorrected signal (ADC counts)
↓
Number of photoelectrons

Corrected signal

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

Saturation correction　Uncorrected signal　Number of p.e.
↓
Number of MIPs

Prototype rotated by 90° for cosmic-ray test



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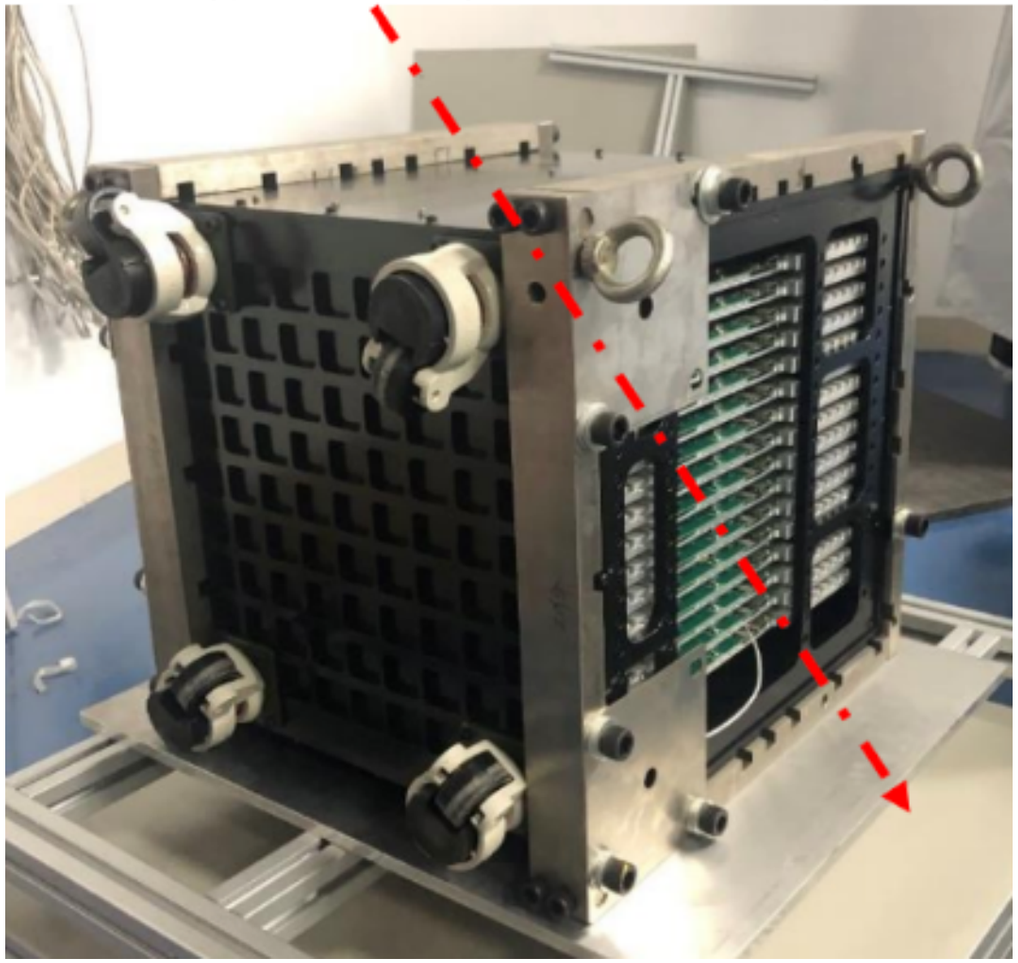
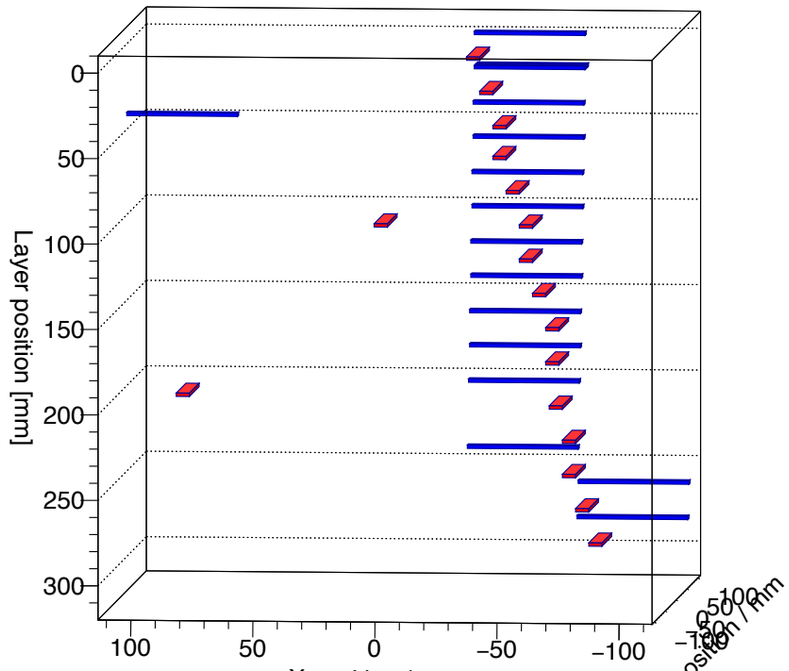


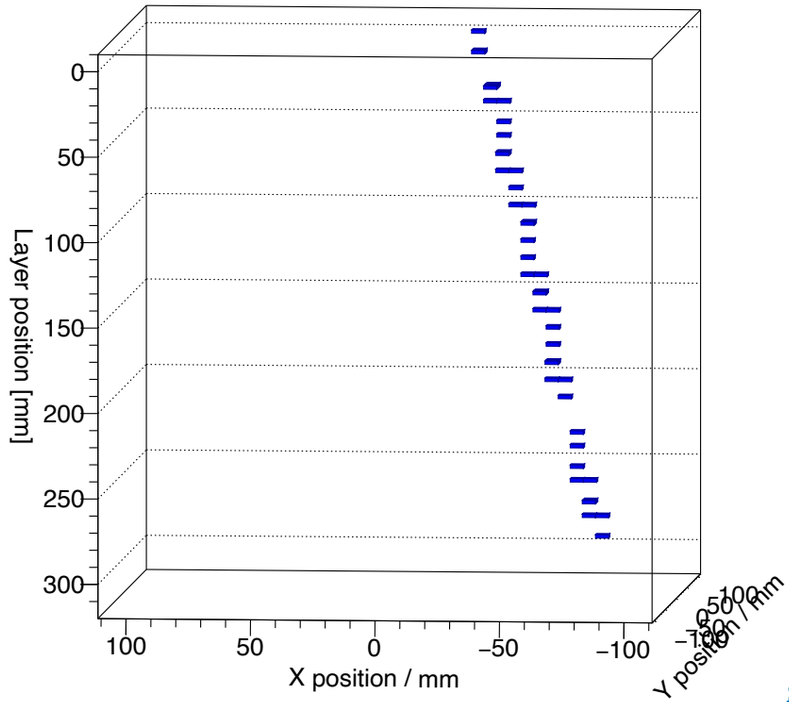
# Reconstruction for straight track

- 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

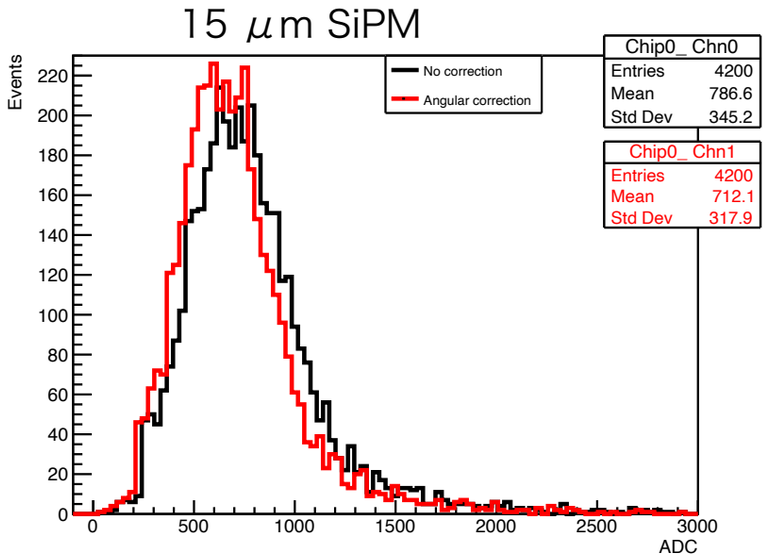



CR event display after reconstruction

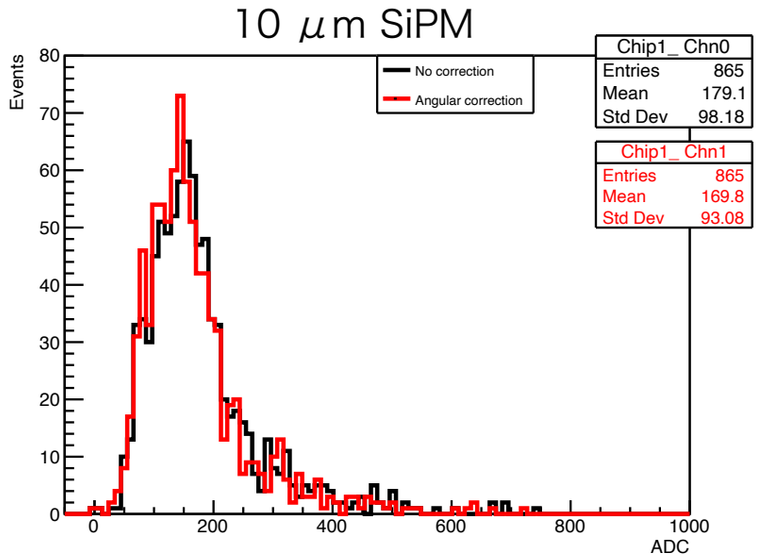



Signal ADC distribution for MIP response

15 $\mu$m SiPM




10 $\mu$m SiPM



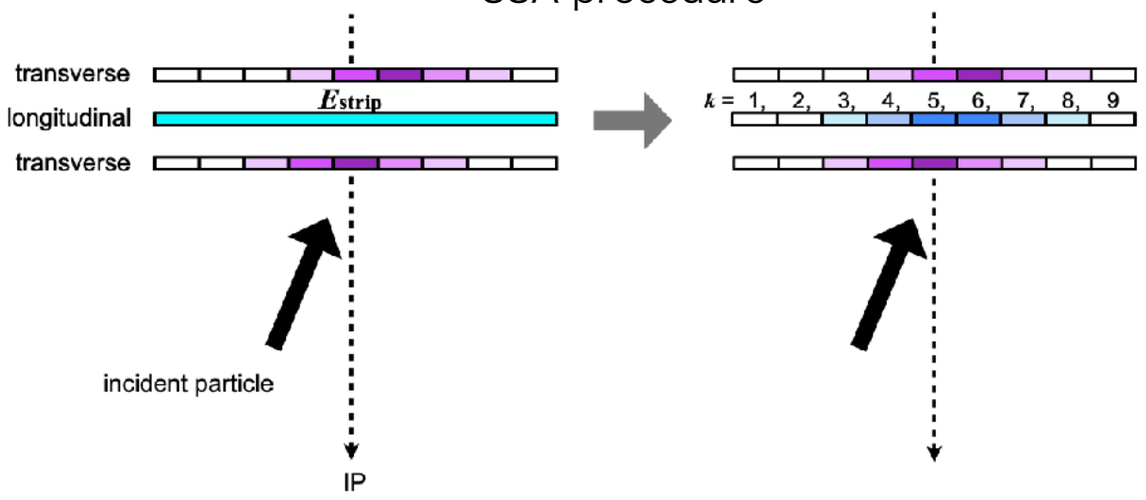
# SSA & clustering

- 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:

    $E_k = E_{strip} \frac{w_k}{\Sigma_j w_j}$

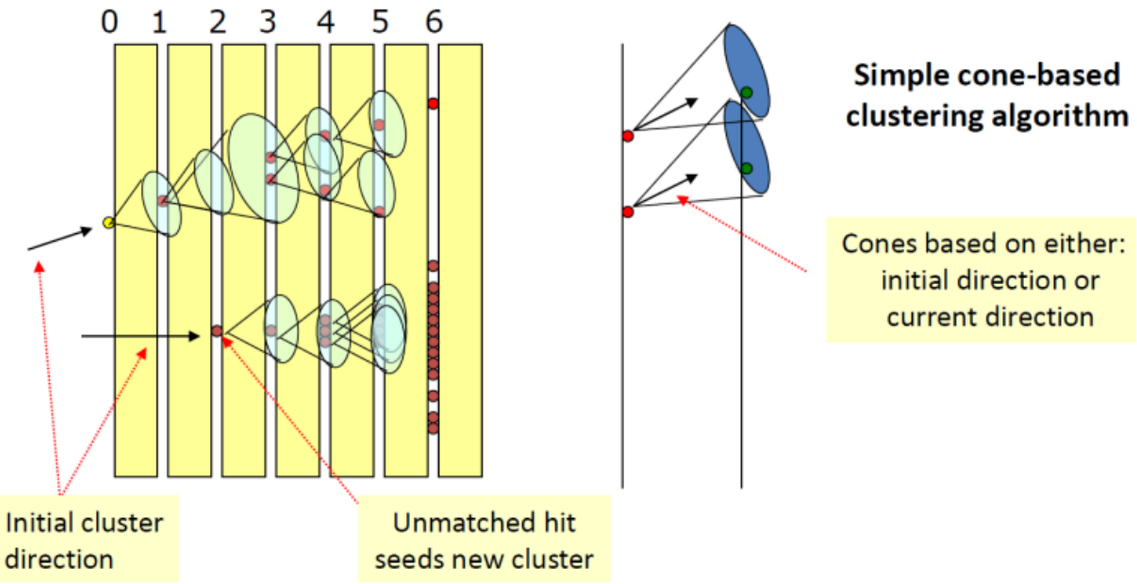
SSA procedure




- SSA applies all layers and strips and realize the 5 × 5 mm$^2$ cell segmentation

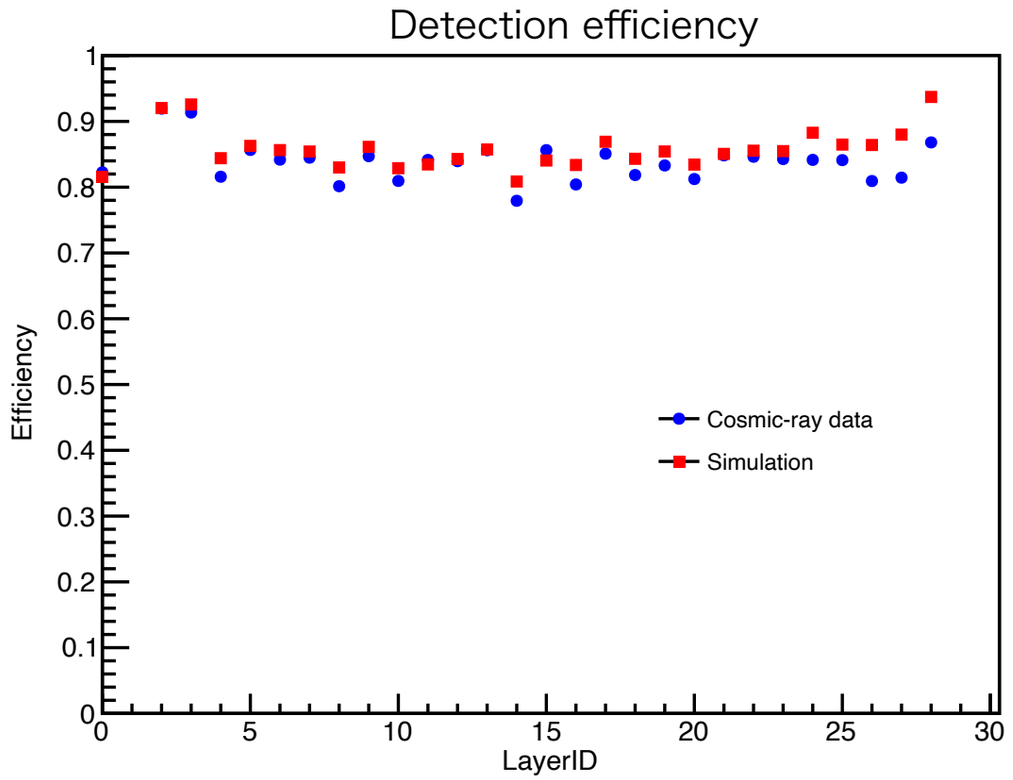
- Simple cone-based clustering algorithm implemented
  - Cone clustering with no angle
  - Linear fit
  - Cone clustering with injection angle
- Noise cut & search for shower-like events

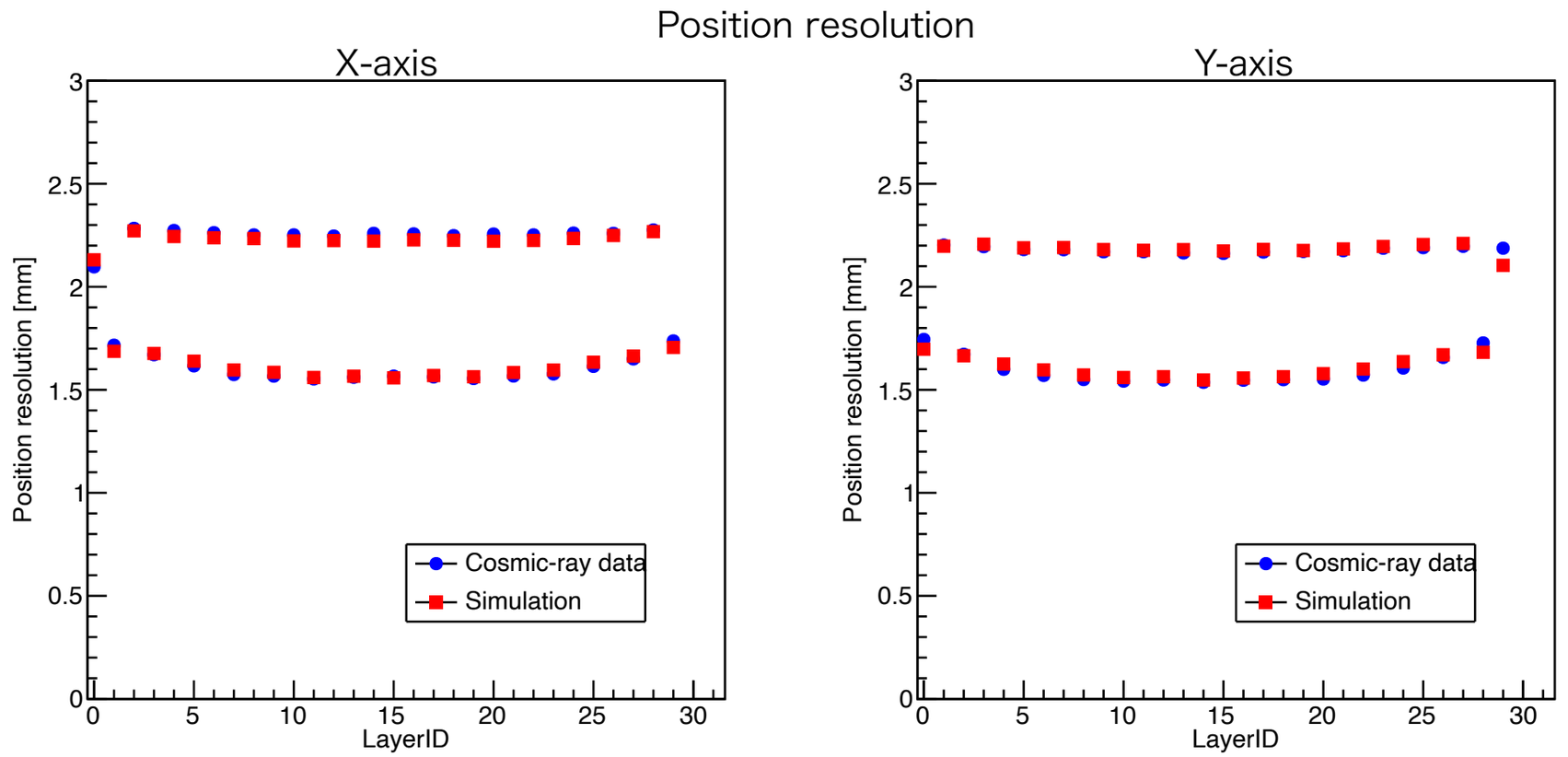
Cone clustering



# Performance evaluation using straight track

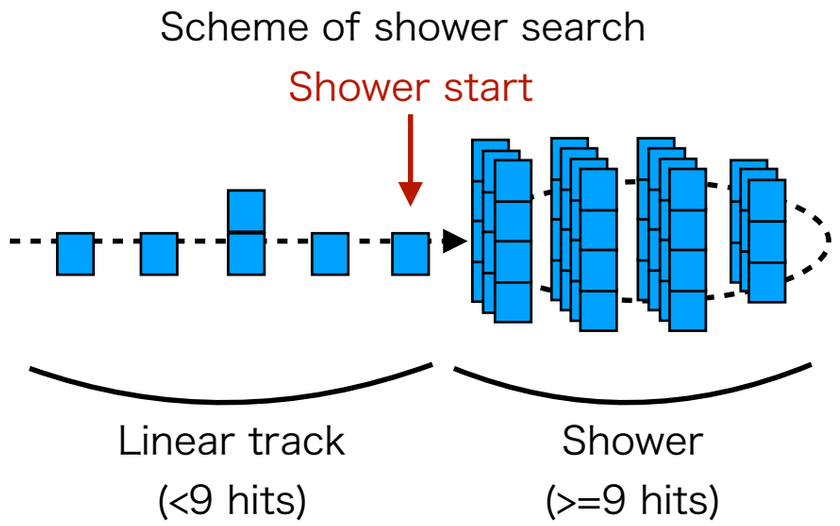
- **~84% detection efficiency achieved for all layers**
  - Ratio of events that have hits in a layer to all events
  - Agree with the Monte Carlo simulation
- **Good position resolution achieved for all layers**
  - 1.5–1.7 mm at short-side (5 mm) direction
    - Corresponds to ~5 mm uniform dist.
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



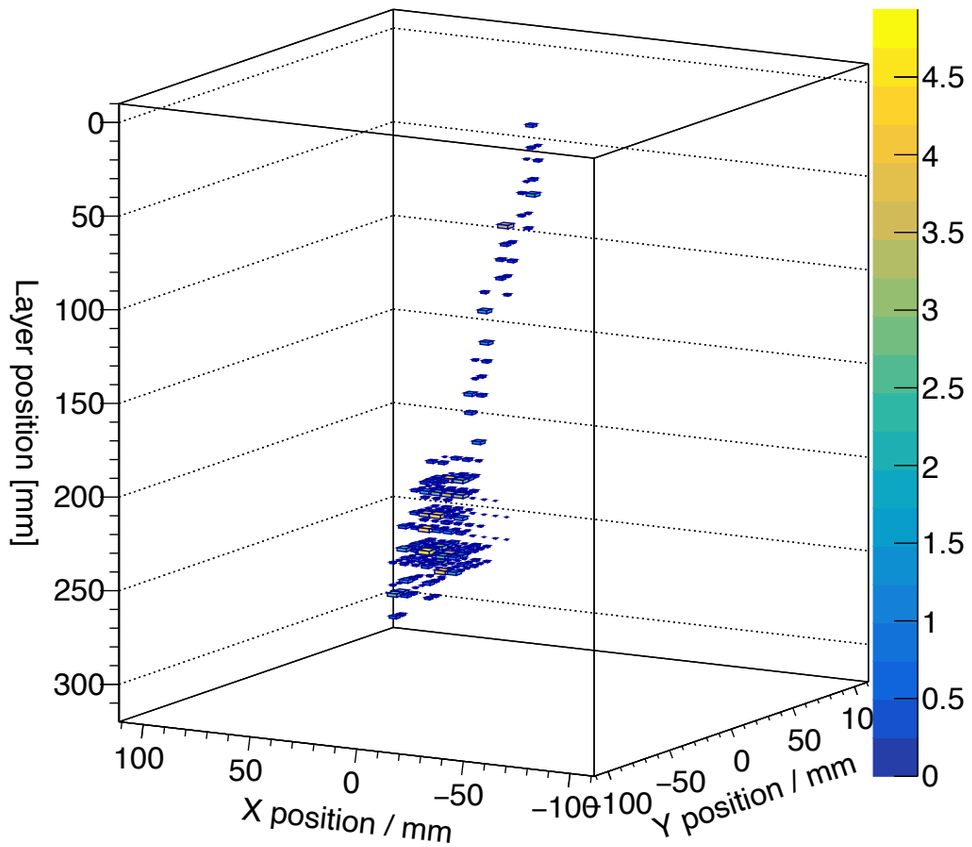



# Reconstruction for CR shower

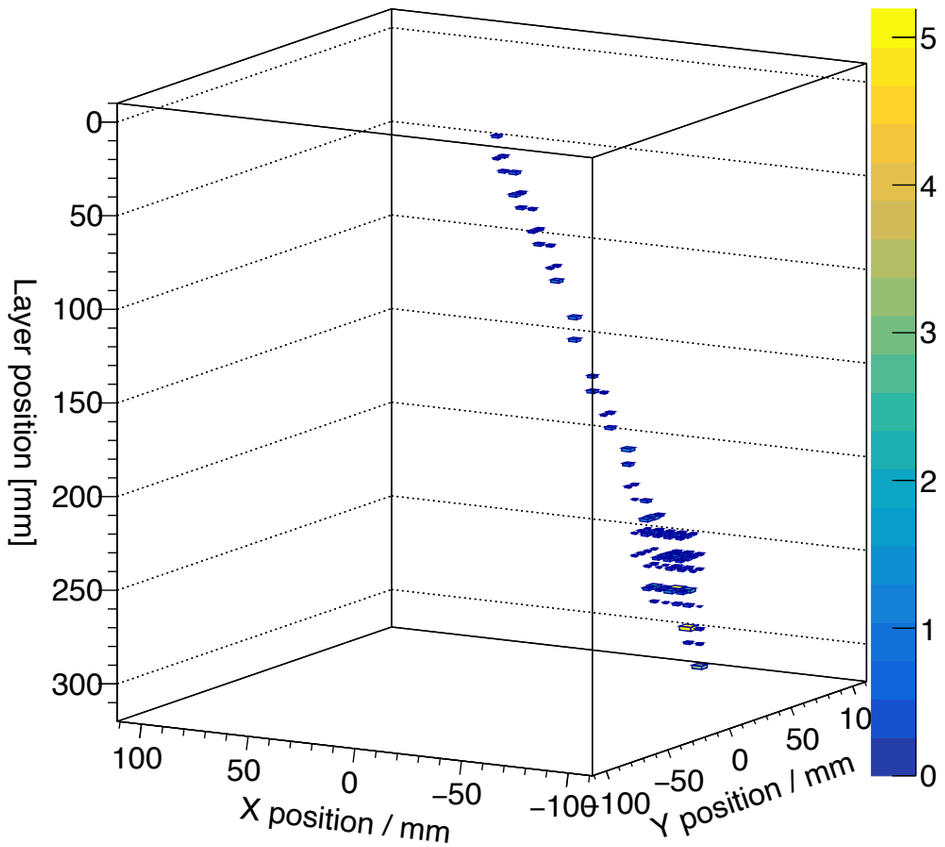
- Performance of Sc-ECAL for electromagnetic showers is evaluated using cosmic-ray showers
  - Instead of test beam experiment
- Shower events is searched for:
  - Calibration: ADC counts converts to # of MIPs
  - SSA & clustering
  - Shower search
    - Many hits in three consecutive layers




CR data

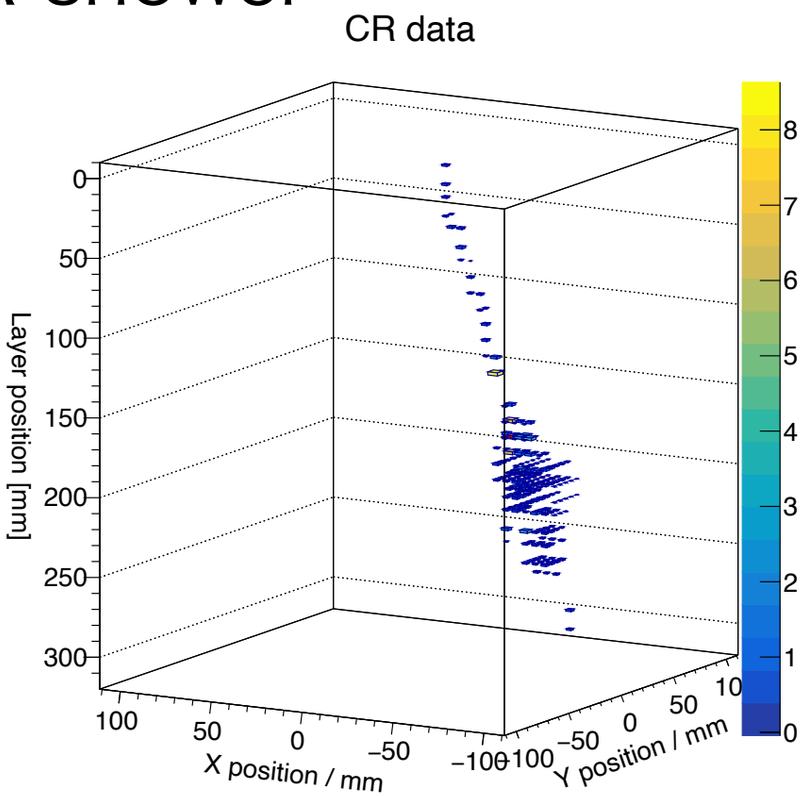


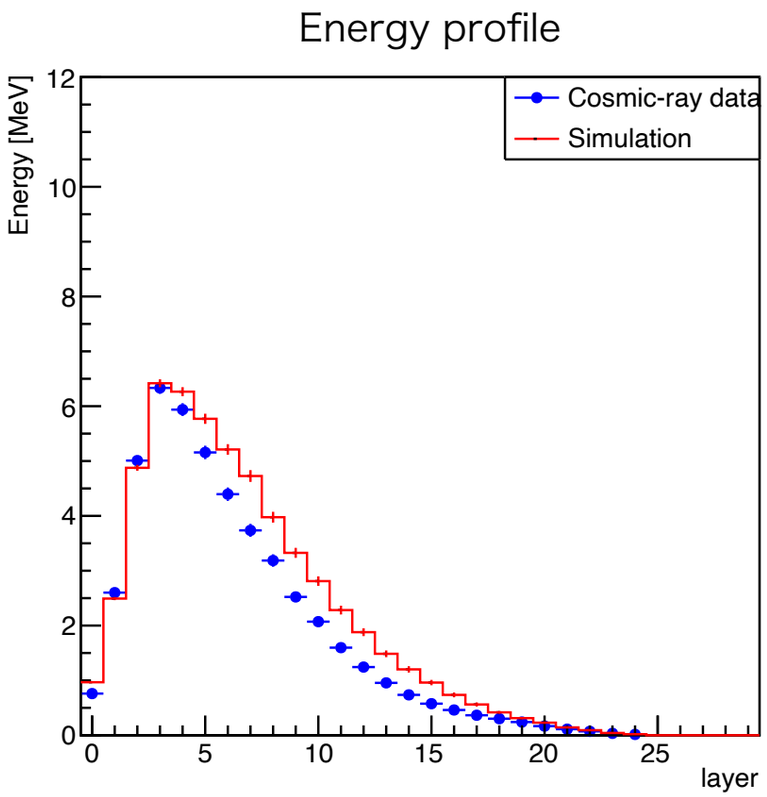

Simulation

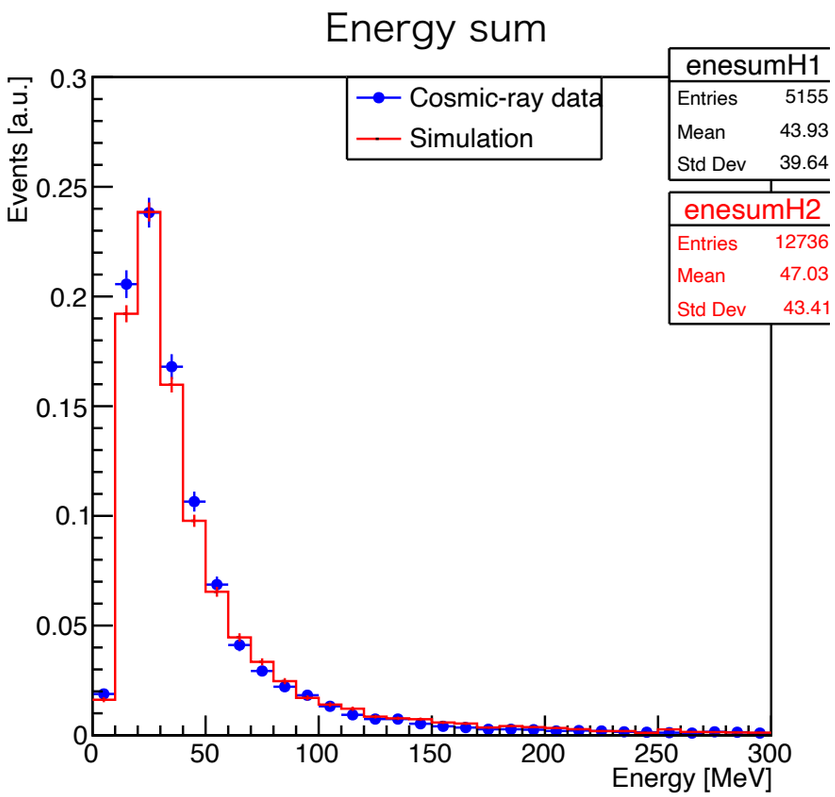


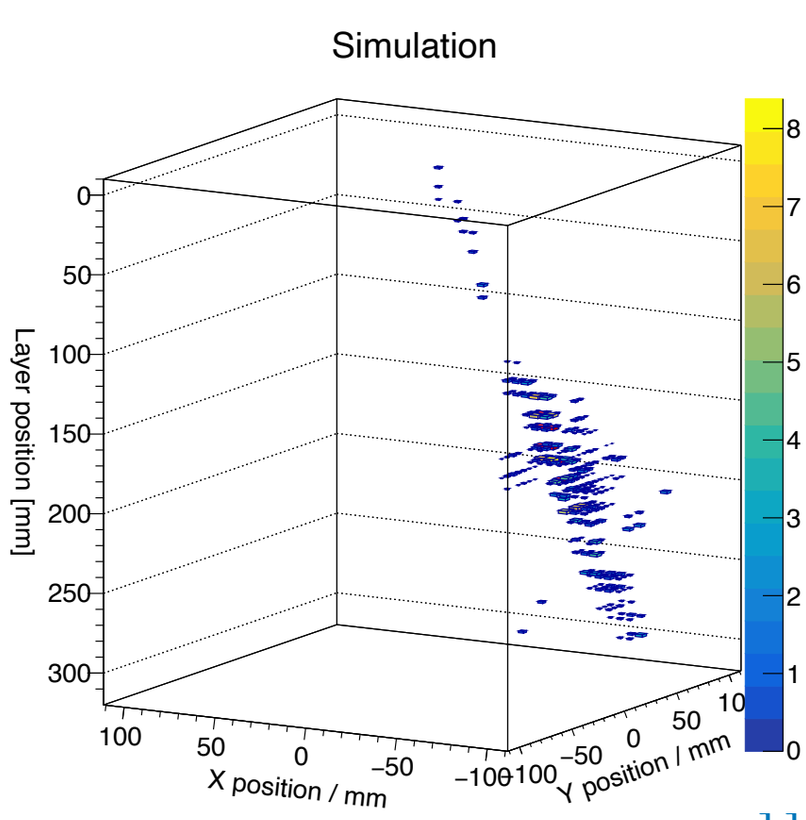
# Performance evaluation using CR shower

- 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



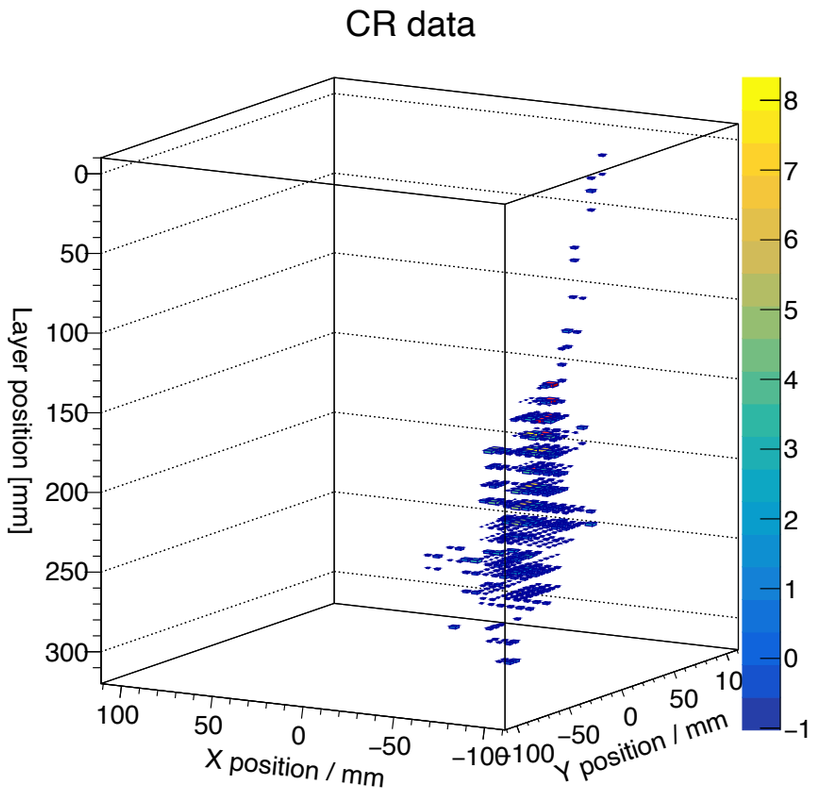



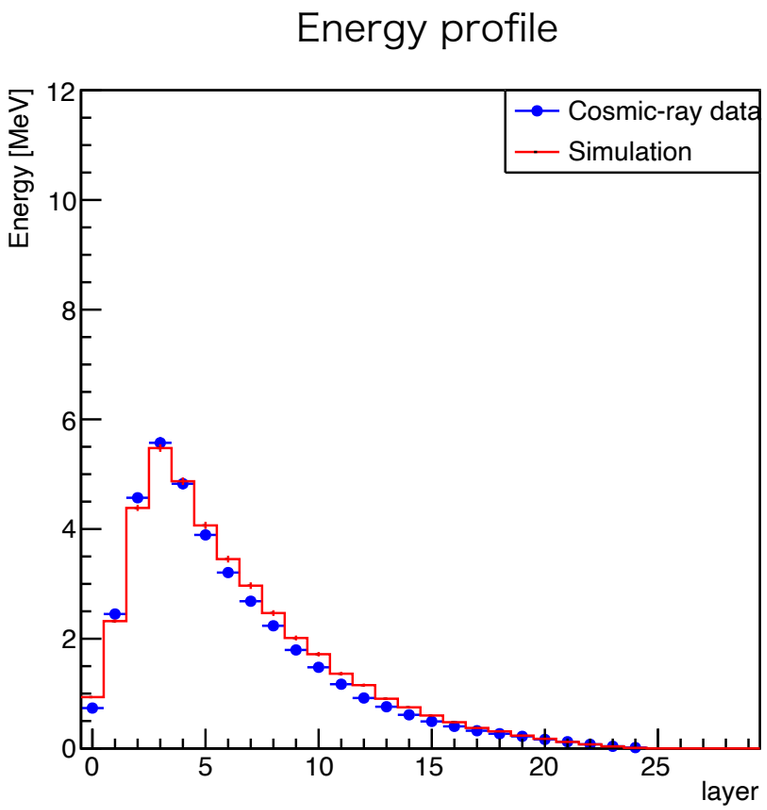



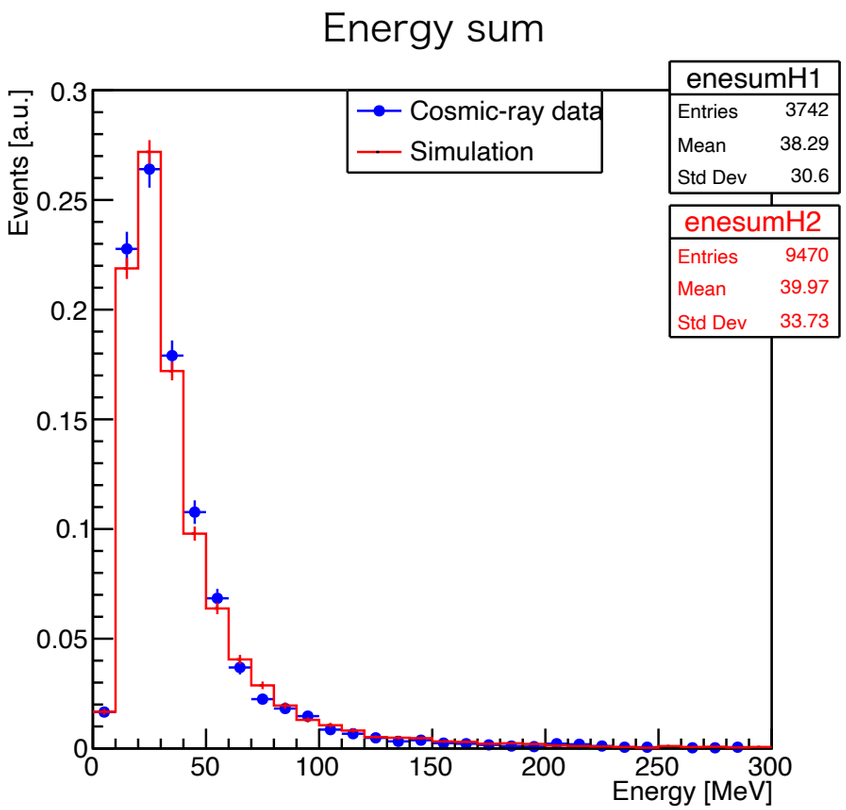



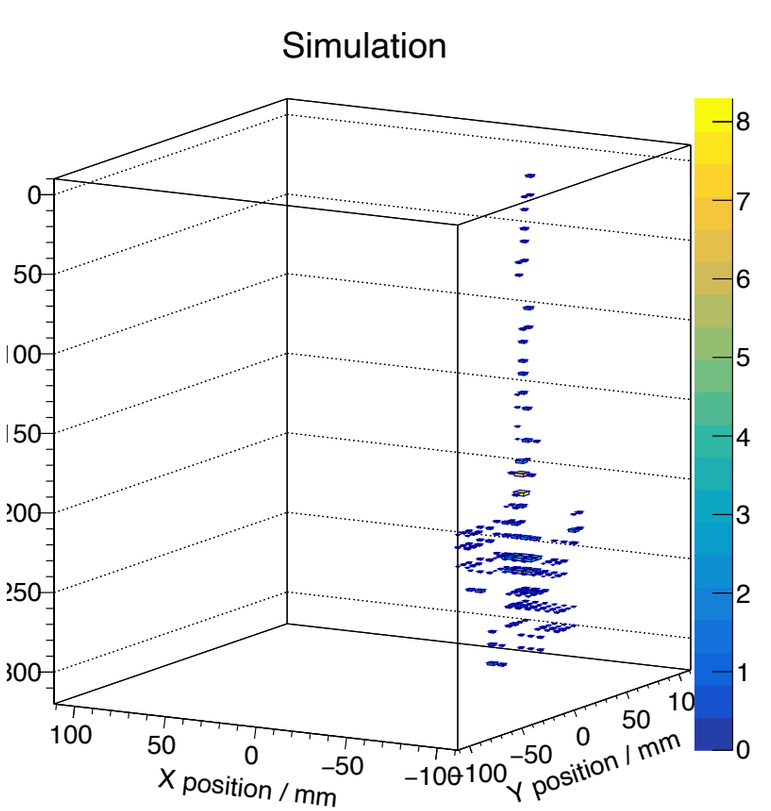
# Fully contained shower

- 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



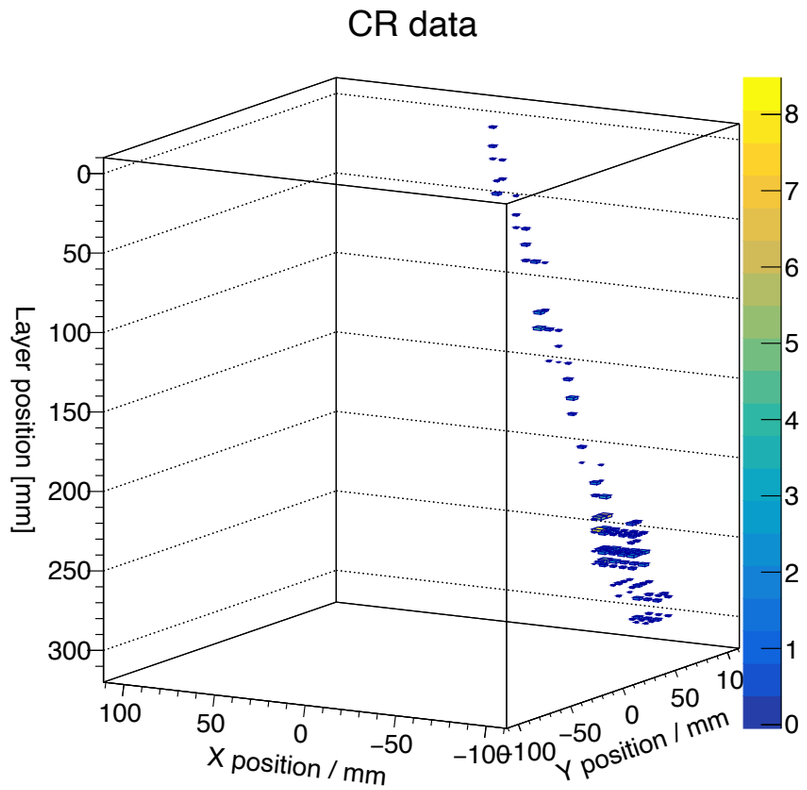



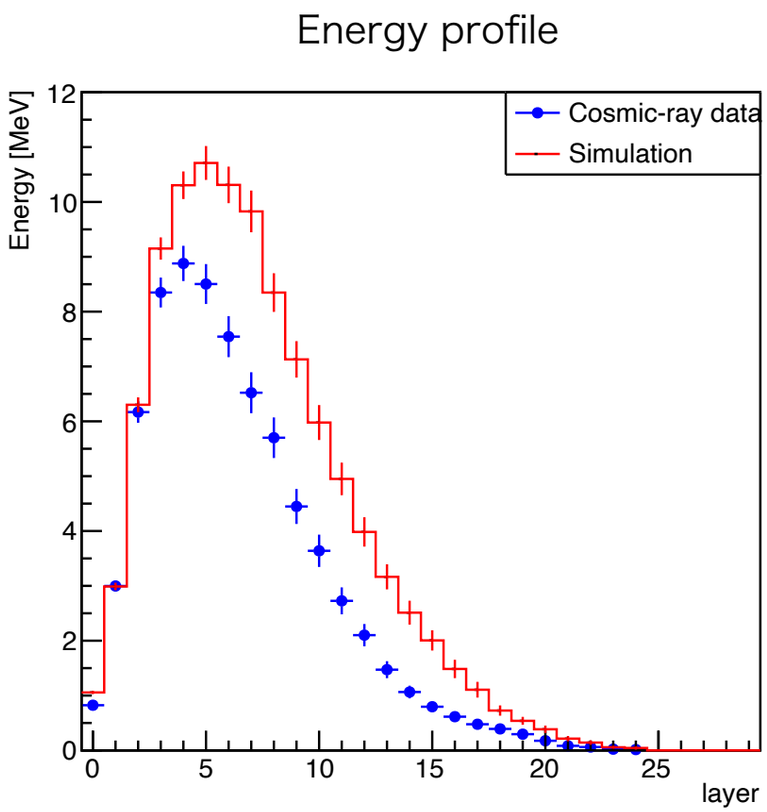



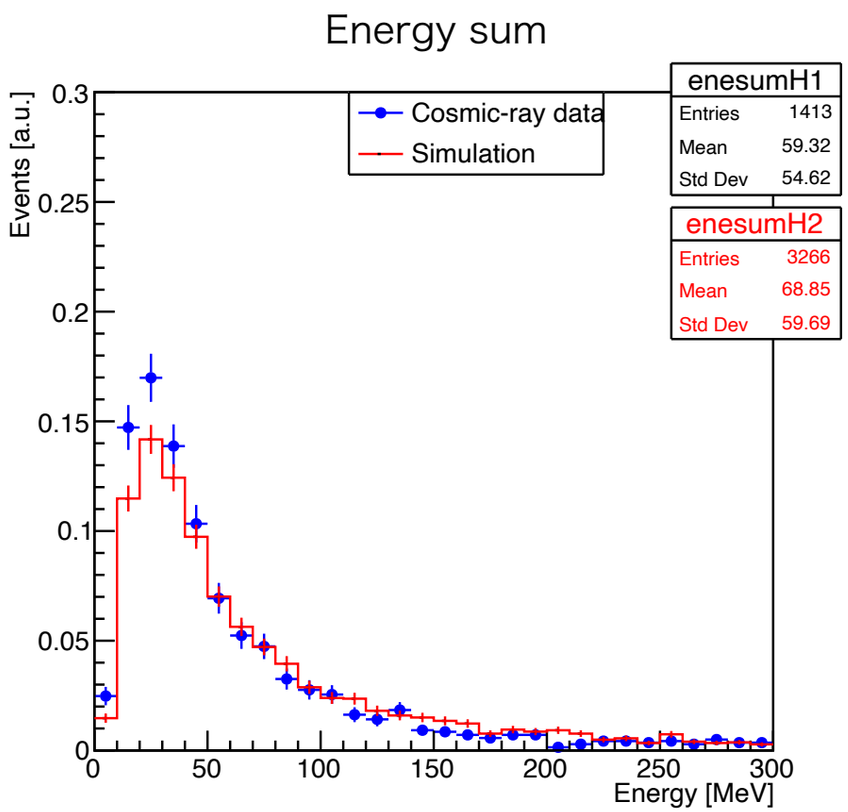



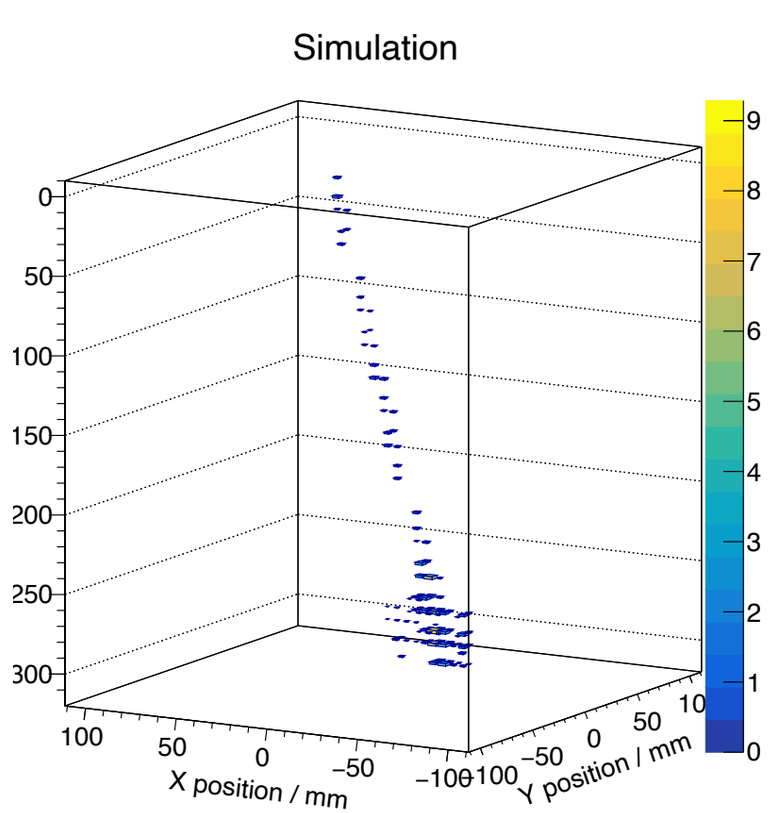
# Shower escape

- Shower comparison b/w data and simulation is performed for shower escape
- **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



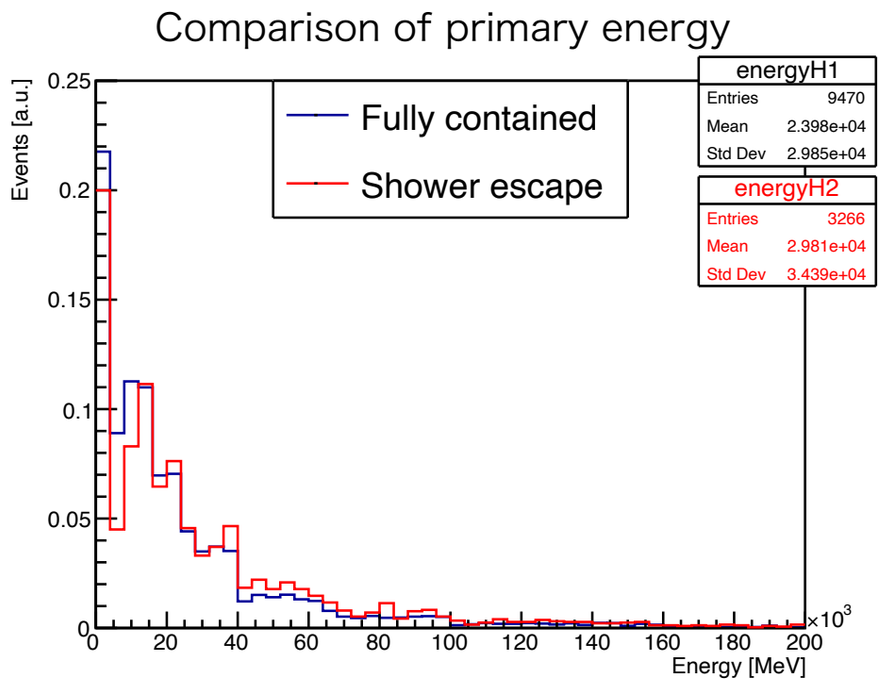



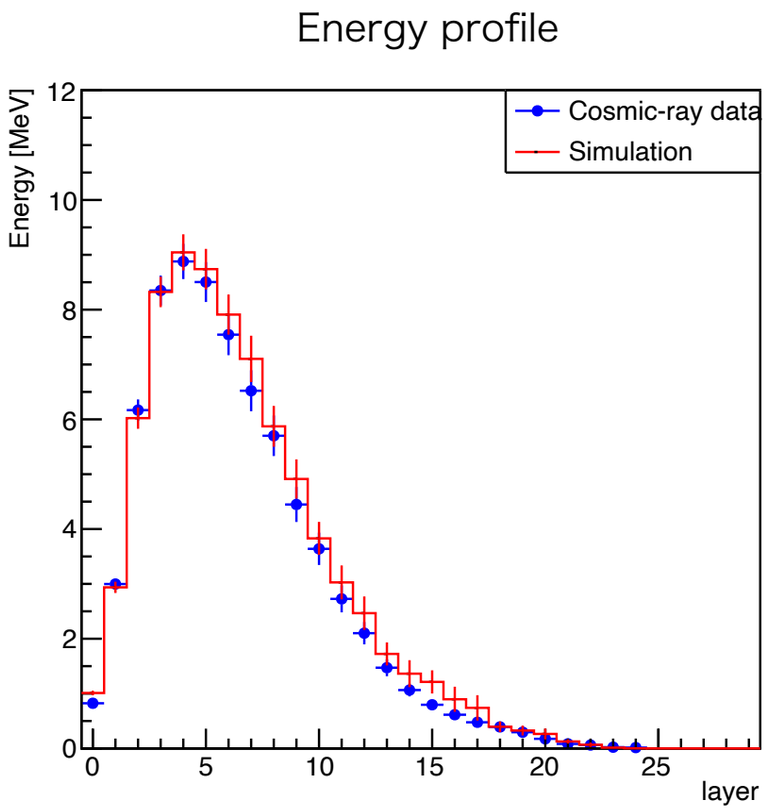



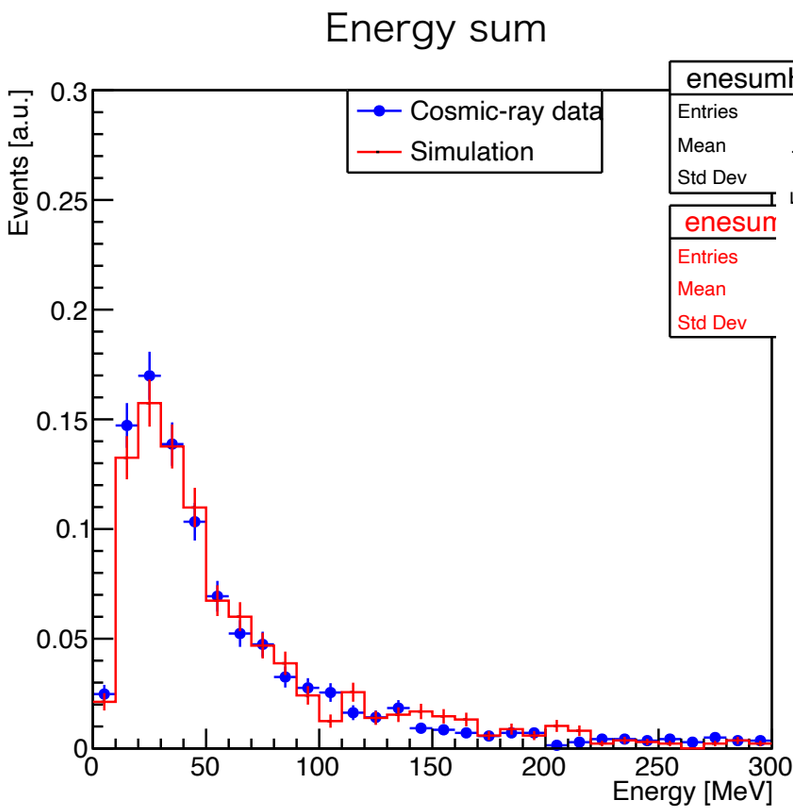



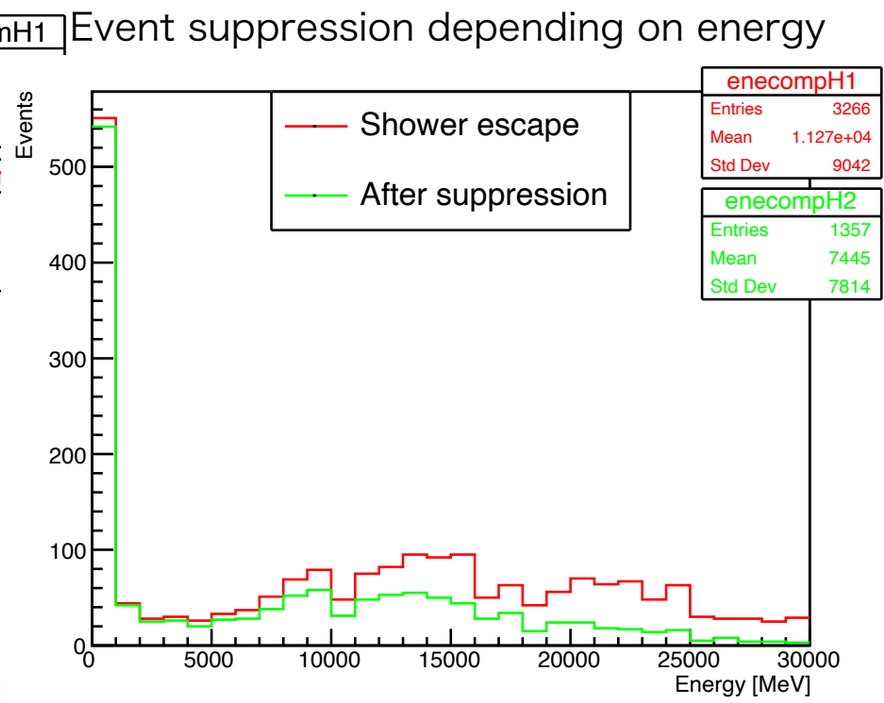
# Comparison with primary energy

- 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



# Summary - Sc-ECAL prototype study

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

- Performance evaluation
  - ~84 % detection efficiency was achieved
  - Good position resolution was achieved (1.5-1.7 mm for short-side direction, ~2.3 mm for long-side direction of strip)
    - Achieve granularity requirement for PFA
  - Shower events can be detected as expected at the simulation
    - Slight deviation data and simulation at high energy events observed

- Prospects
  - Performance tests in beam
    - Stand-alone beam test of Sc-ECAL at IHEP
    - Combined beam test of Sc-ECAL and CEPC-AHCAL at CERN

1. Performance study with Sc-ECAL prototype
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# Sc-EACL study using ILD simulation

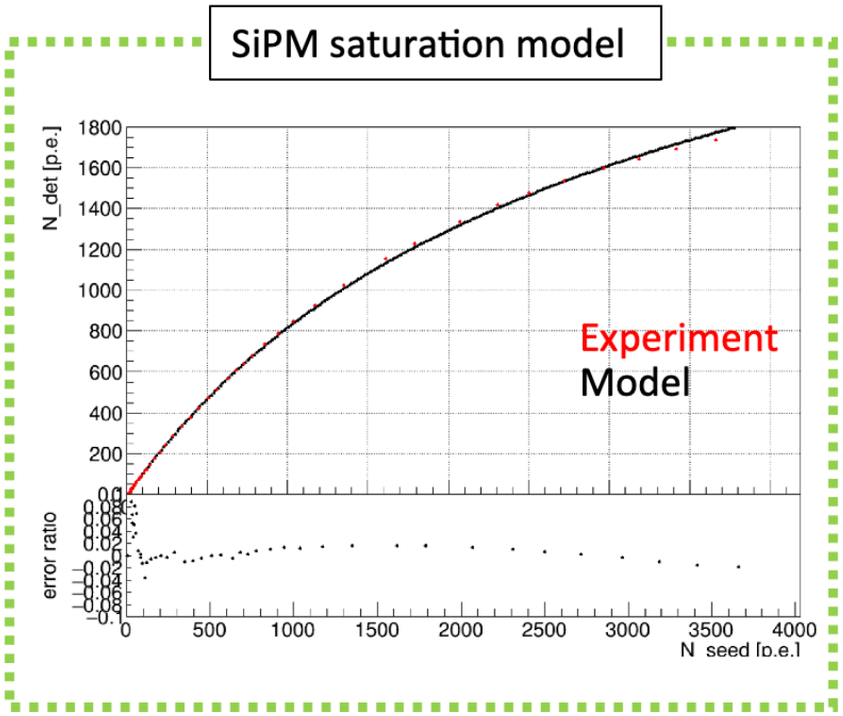
- Simulation study for Sc-ECAL to evaluate performance of ILD
  - Based on Sc-ECAL data obtained from large technological prototype test

- ILD model simulation
  - Simulation tool : iLCSoft
  - Detector geometry : ILD_l5_o3_v2 (Both ECAL and HCAL are based on plastic scintillator)

- Linearity check of reconstructed photon energy & Jet Energy Resolution (JER) evaluation
  - Sc-ECAL performance simulation with realistic effects of strip and SiPM
    - SiPM saturation model for several MPPC candidates
    - Position dependence of light yield on 45 mm strip

# Implemented SiPM saturation model

- New SiPM saturation models have been implemented instead of default model
  - These models were obtained from measurement data
  - Simulation parameters assuming 4 types of MPPC (Talk of T. Murata)




- Parameters for implemented MPPC models

S12571-010P (pixel size = 10 um, # of pixel = 10,000, p.e. per MIP = 7)
S12571-015P (pixel size = 15 um, # of pixel = 4,489, p.e. per MIP = 18)
} Obtained from measurement

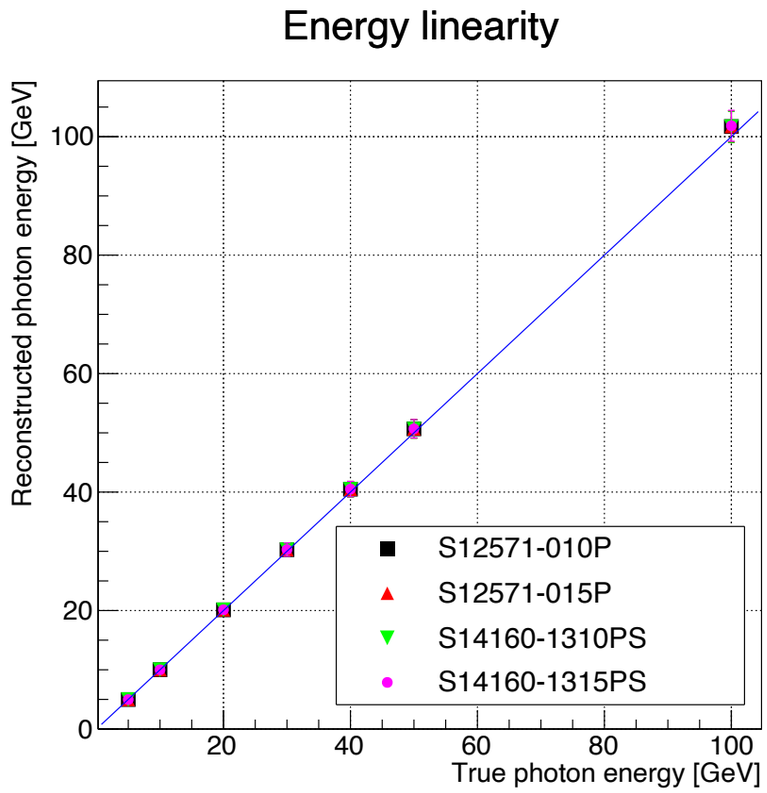
S14160-1310PS (pixel size = 10 um, # of pixel = 16,675, p.e. per MIP = 21)
S14160-1315PS (pixel size = 15 um, # of pixel = 7,296, p.e. per MIP = 38)
} Estimated from S14160 datasheet

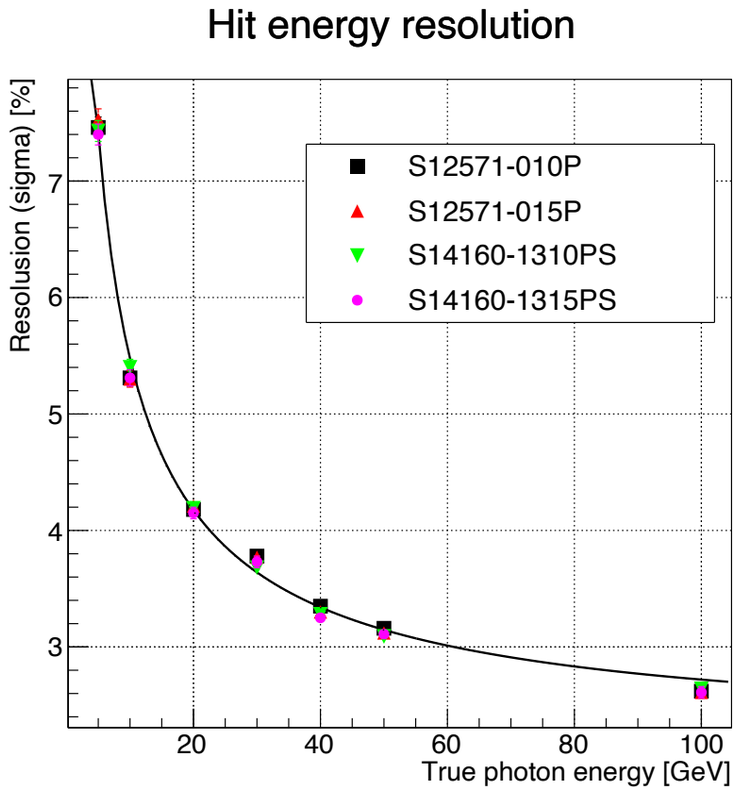
# Sc-ECAL performance simulation

- Hit position dependence of light yield is not included in this test
  - Only SiPM saturation effect is included
- Checking energy response of Sc-ECAL for each MPPC model
  - Reconstructed energy is almost linear to true energy
  - Checked for {5, 10, 20, 30, 40, 50,100} GeV MC gamma
- Energy resolution of Sc-ECAL was also tested
  - Fit : $(\frac{\sigma_E}{E})^2 = (\frac{a}{\sqrt{E}})^2 + (b)^2$

| | a | b |
|---|---|---|
| parameters | 16.0 | 2.0 |

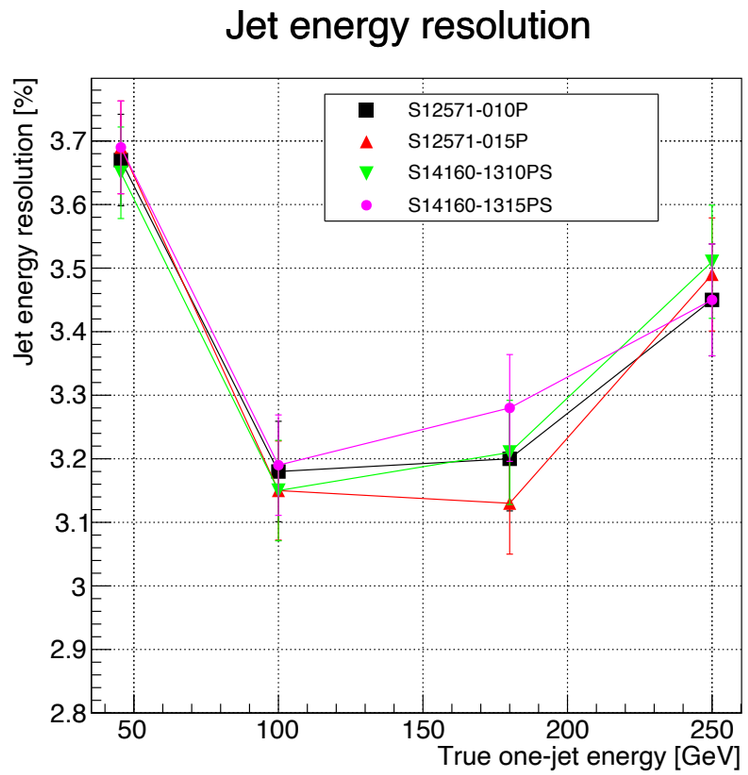
  - Resolution ~ 16 %
  - SiPM saturation does not affect energy linearity and resolution of Sc-ECAL



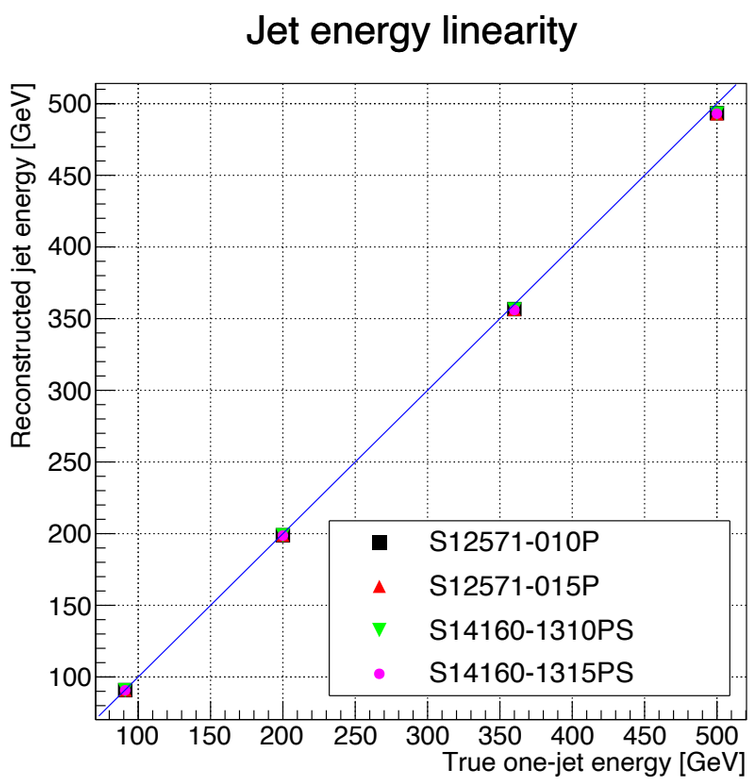



# Evaluation of jet energy resolution

- JER was tested for 4 MPPC models
  - Use {91, 200, 360, 500} GeV di-jet events
  - No big difference
  - 3.1-3.7 % JER was achieved for all models
    - Almost consistent to previous simulation results
  - Variation at 360 GeV is under investigation

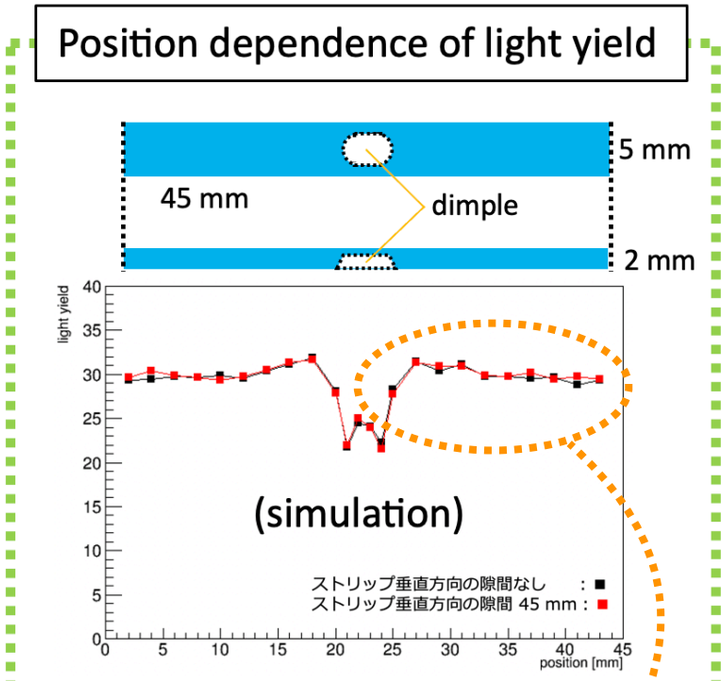



- Linearity of jet energy response was checked
  - There is no difference between 4 models
  - Saturation does not affect energy linearity

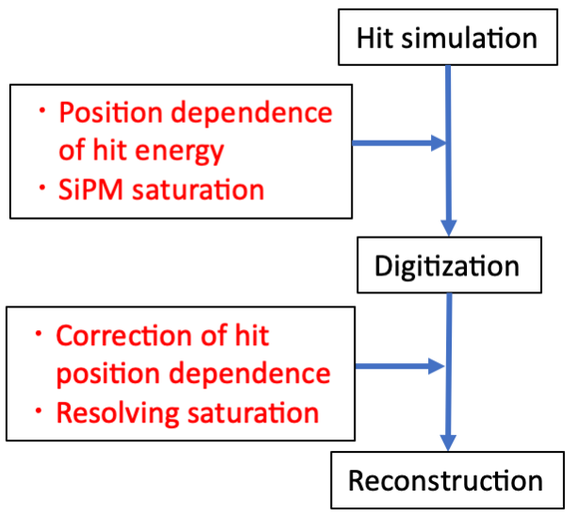


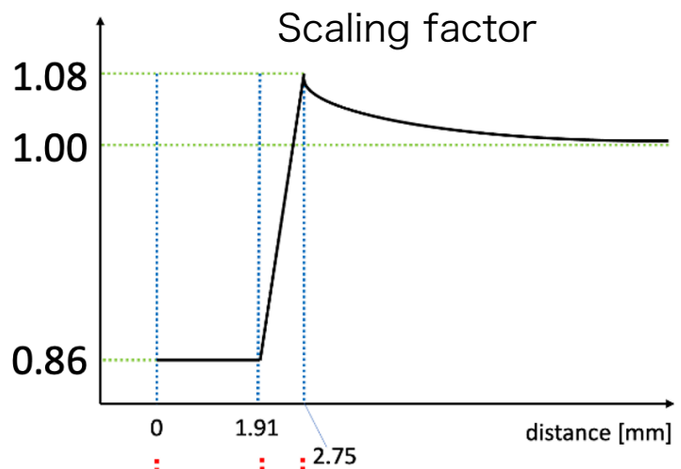
# Implemented realistic effects of strip

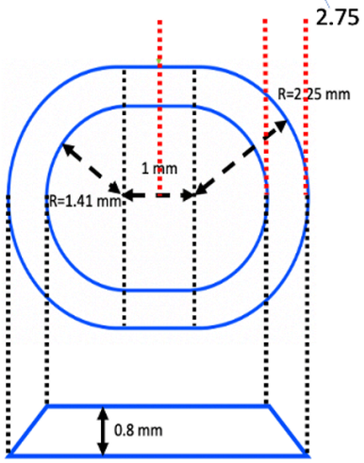
- Light yield response of strip & SiPM unit
  - Measured light yield is not uniform due to the dimple on strip
- In simulation, scaling energy deposit of hit at digitization to reproduce this position dependence
  - Only S12571-010P case was tested
  - Scaling factor is obtained from Geant4 optical simulation

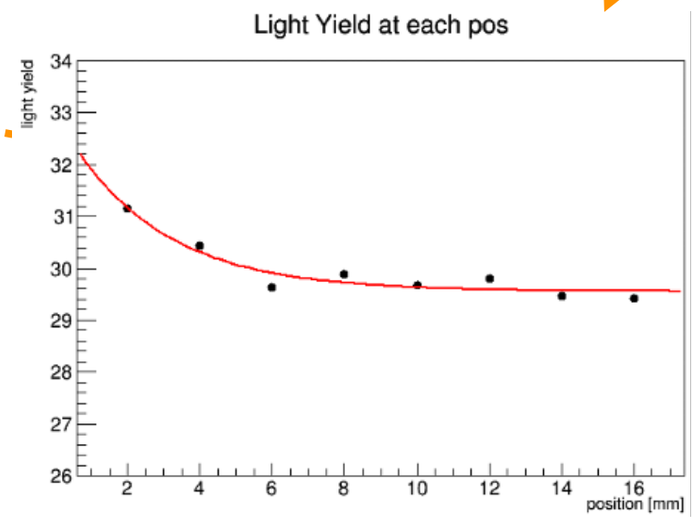


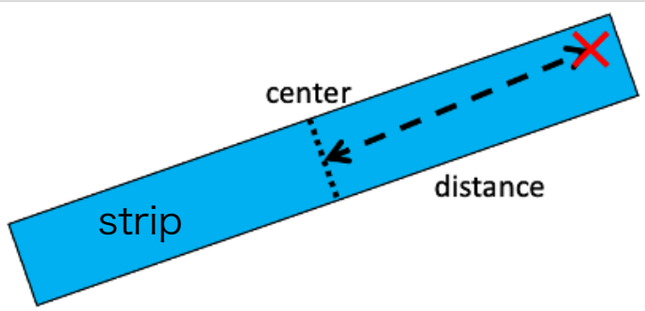

- Simulation flows



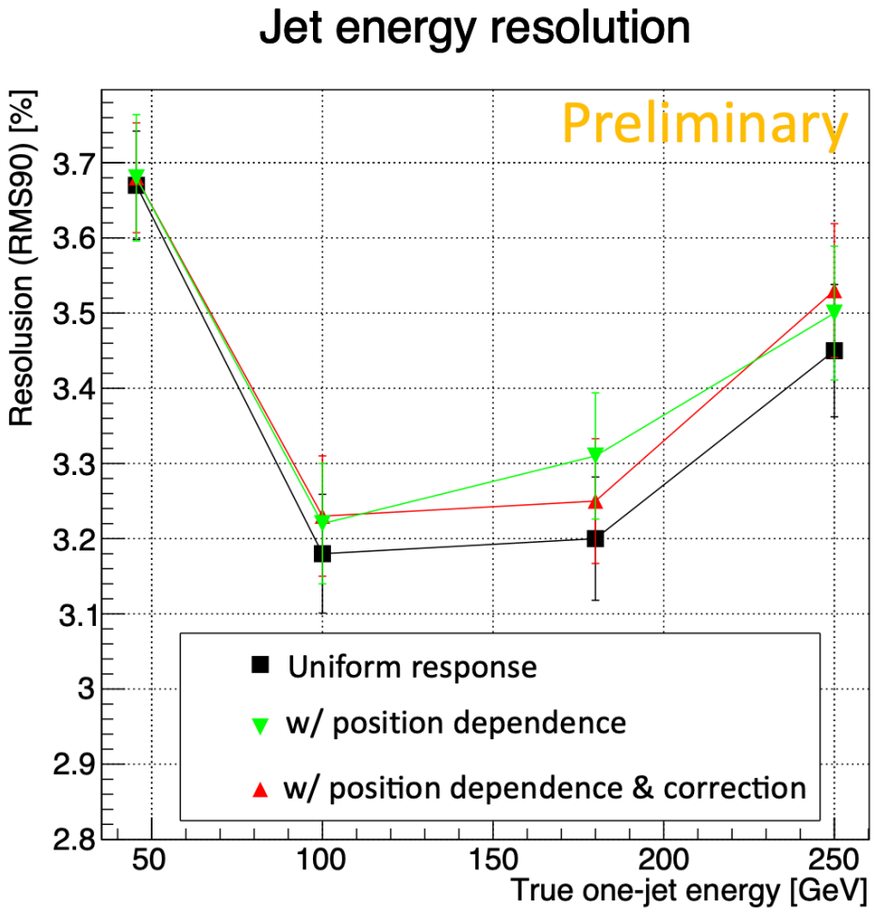



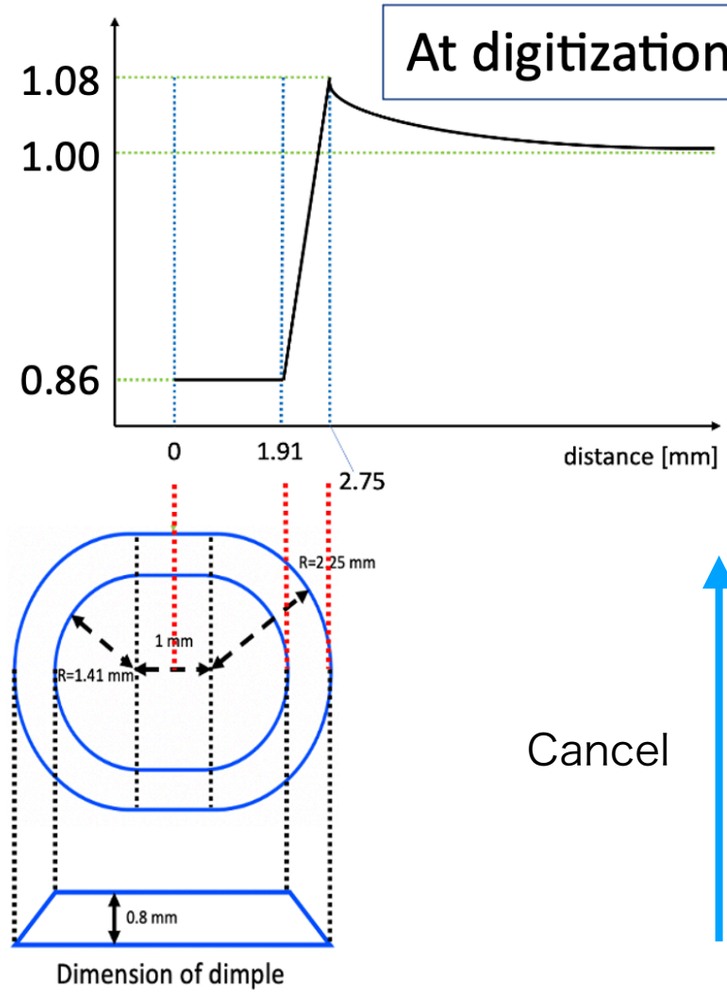



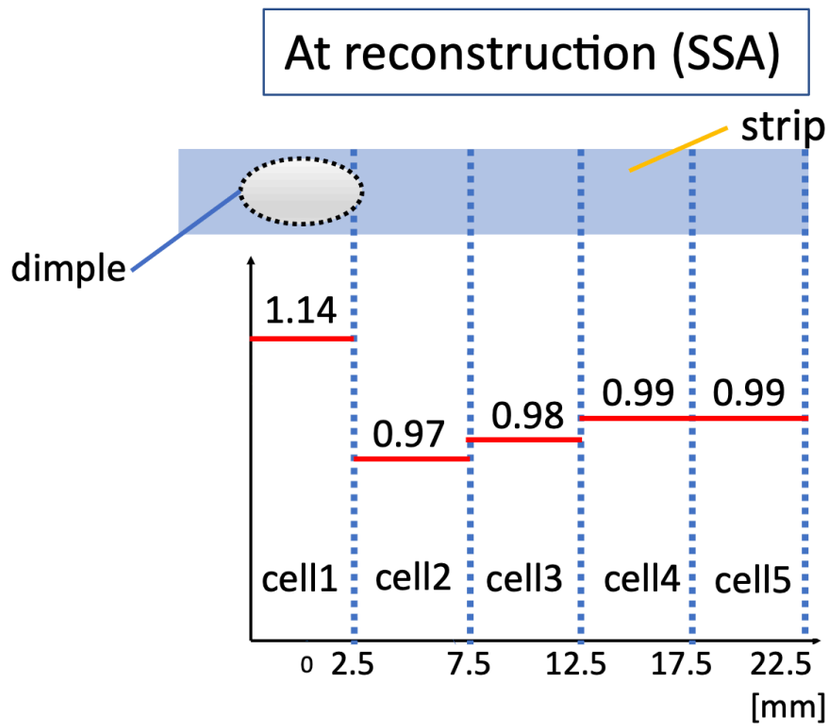



# Evaluation of jet energy resolution

- JER test for S12571-010P including the saturation model and hit position dependence of light yield on strip
  - JER is slightly worsened at all energy region due to non-uniformity of strip response
- Implement correction for this non-uniformity at SSA to see whether JER is recovered
  - No obvious recovery of JER observed
  - Need to find other correction method



# Summary - ILD simulation study

- ILD simulation study for Sc-ECAL is ongoing
  - To evaluate the ILD performance with more realistic conditions for strip and SiPM at Sc-ECAL
  - Simulation parameters were decided according to large technological prototype test

- Performance evaluation
  - No big difference between 4 MPPC saturation models
  - Saturation does not affect energy linearity and resolution
  - JER is slightly deteriorated by position dependence of strip response
  - Correction for the position dependence using reconstructed position
    - No obvious recovery, need to find other correction method

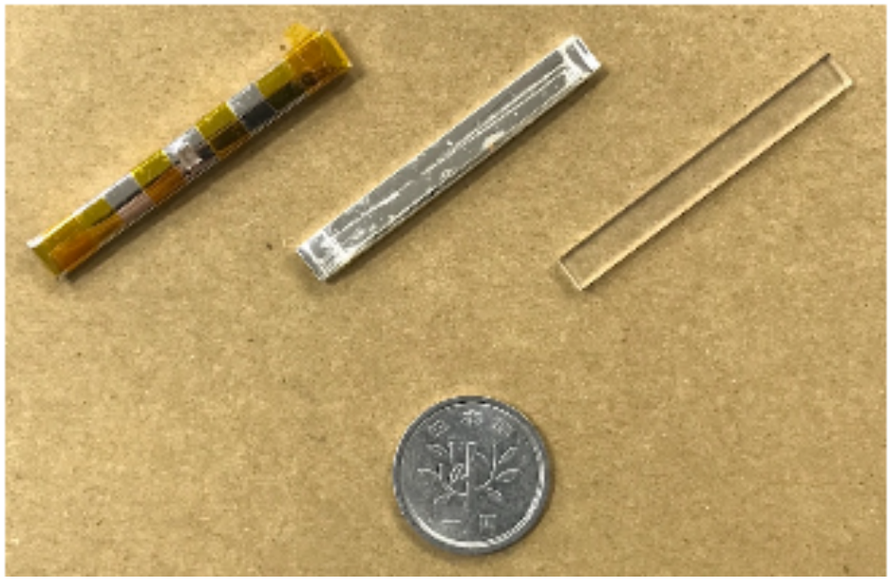
- Prospects
  - Add more realistic strip conditions (effect of misalignment between strip and SiPM etc.)
  - Implement double SiPM readout to simulation

# Backup

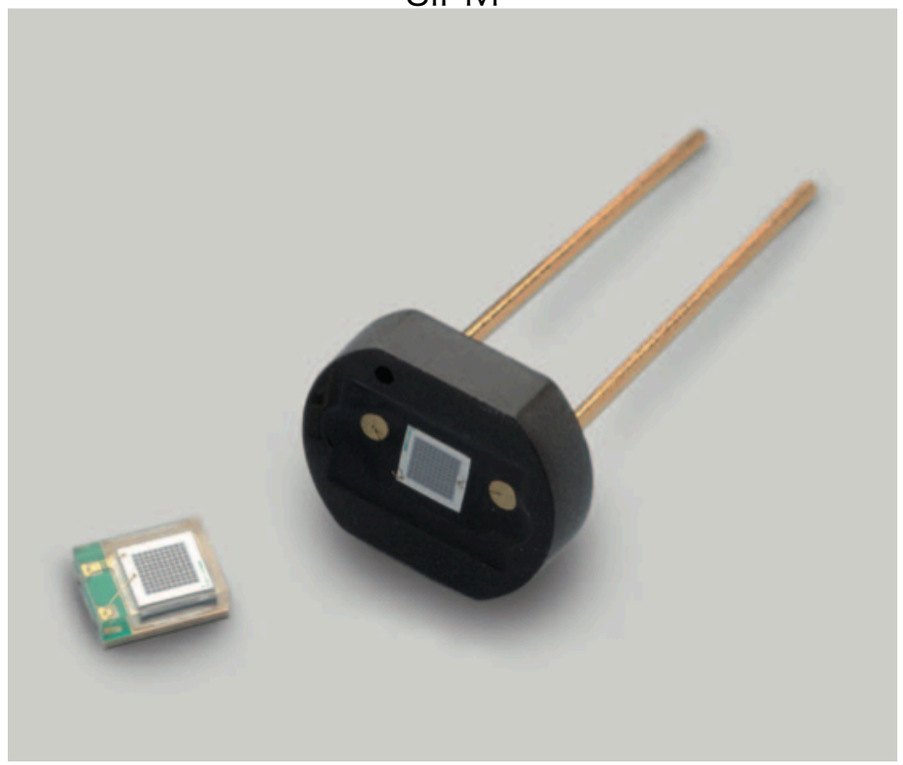
# Scintillator strip & Silicon PhotoMultiplier (SiPM)

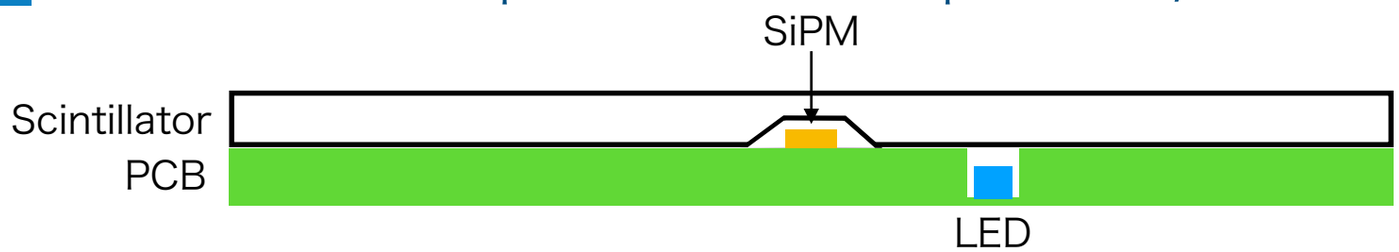
- 5 × 45 × 2 $mm^3$ strip made by BC-408
  - PVT-based plastic scintillator by cast moulding
    - Wrapped in ESR film
  - PS-based scintillator by injection moulding under development
    - Injection moulding is suitable for large scale production
- Bottom-center SiPM coupling is adopted
- Multi-Pixel Photon Counter (MPPC)
  - Surface-mount type with an active area of 1.0 mm × 1.0 mm and 10/15 $\mu$m pixel pitch
    - S12571-010P/-015P
  - Small-pixel SiPM with the trench structure developed
  - Detailed performance comparison b/w SiPM types

Scintillator strip



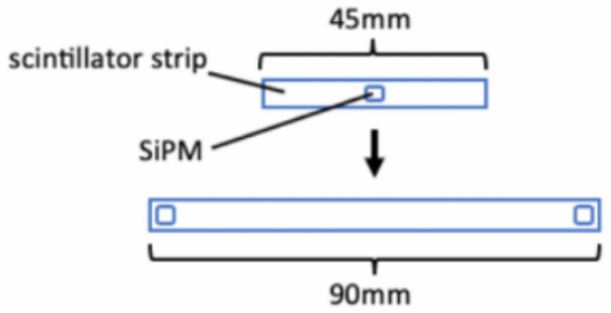
SiPM






Scintillator strip coupled to SiPM (and LED)

# Double SiPM readout

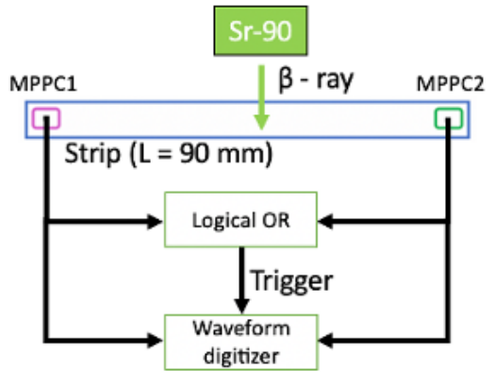


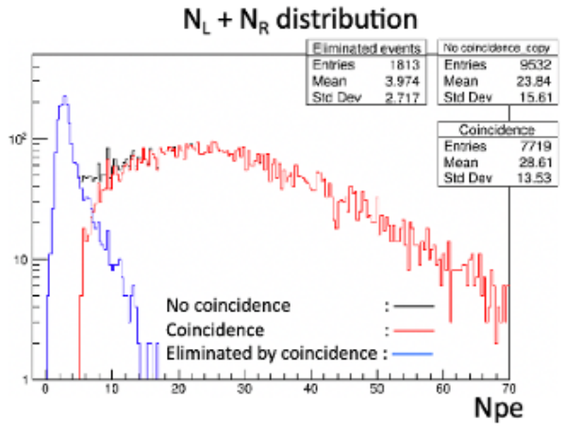


- Possible advantages
  - Eliminating noise by taking coincidence between two SiPM readouts
  - Hit position on a strip can be reconstructed with ~20 mm resolution
    ➡ Possibility of solving ghost hit
  - Higher light yield than single readout by summing two SiPM readouts
- Further studies on performance for double SiPM readout are in progress

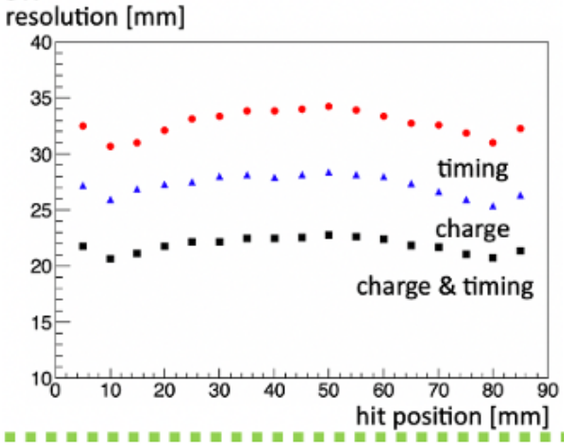
# Measured performance

## Noise suppression by coincidence

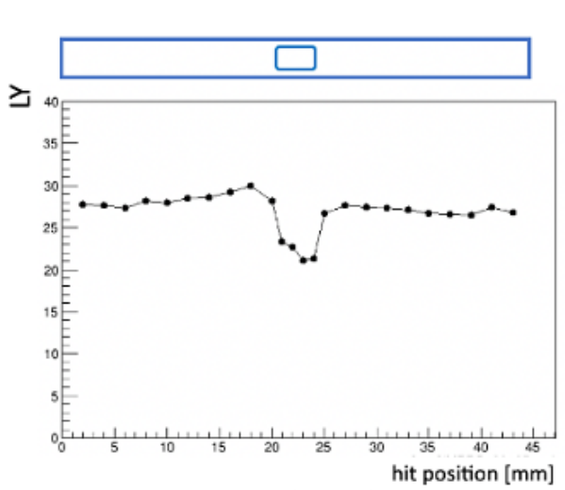


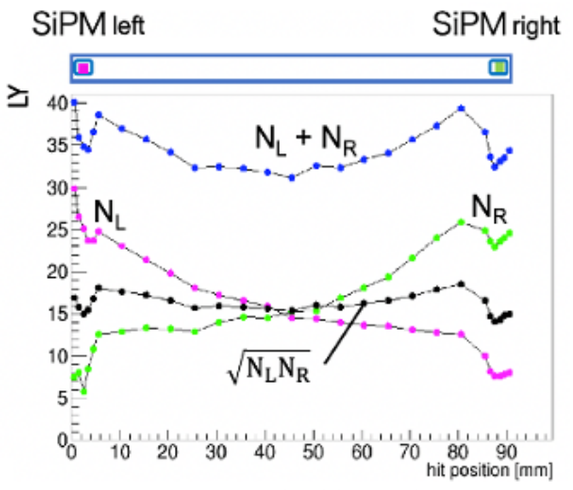




## Position resolution




## Light yield

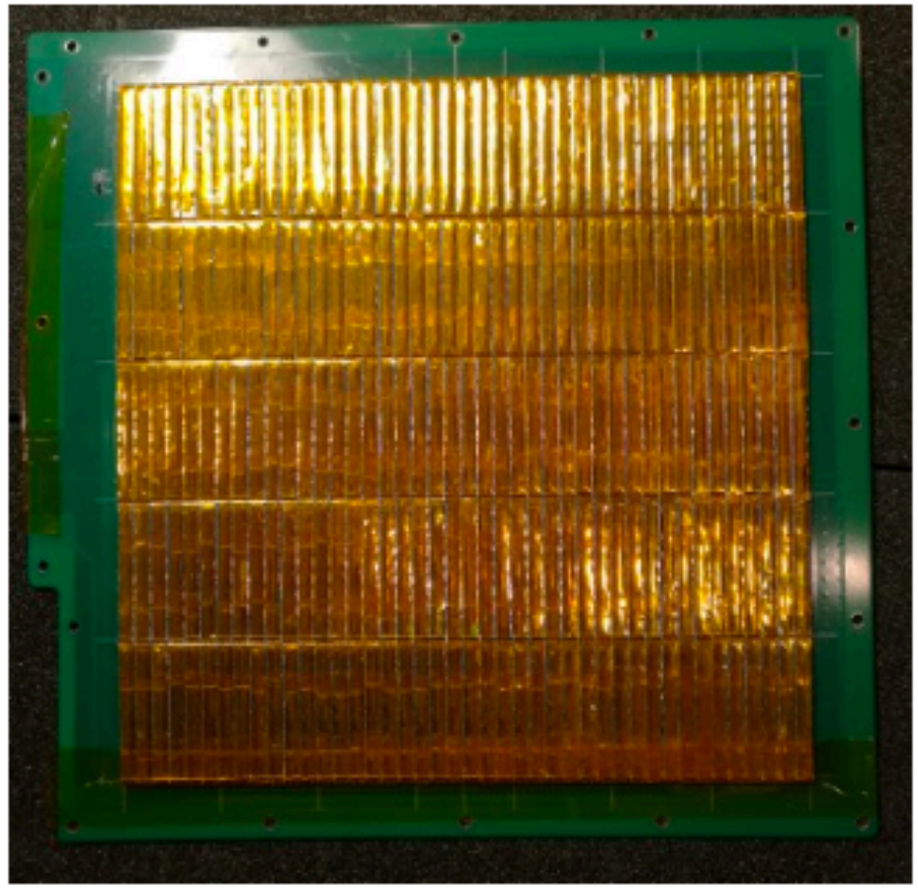


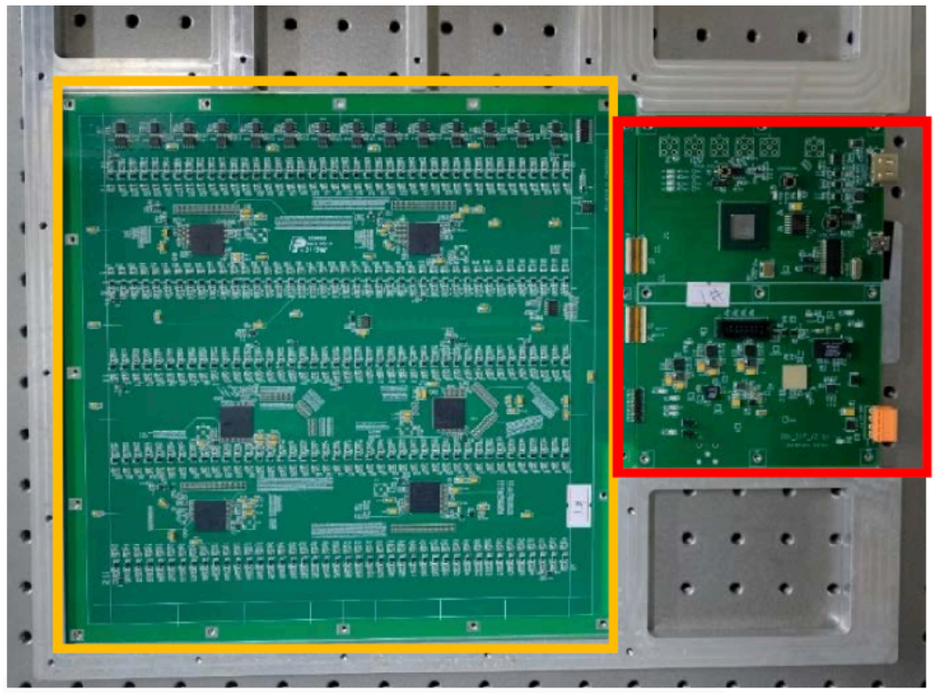
# ECAL Base Unit (EBU)

- 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

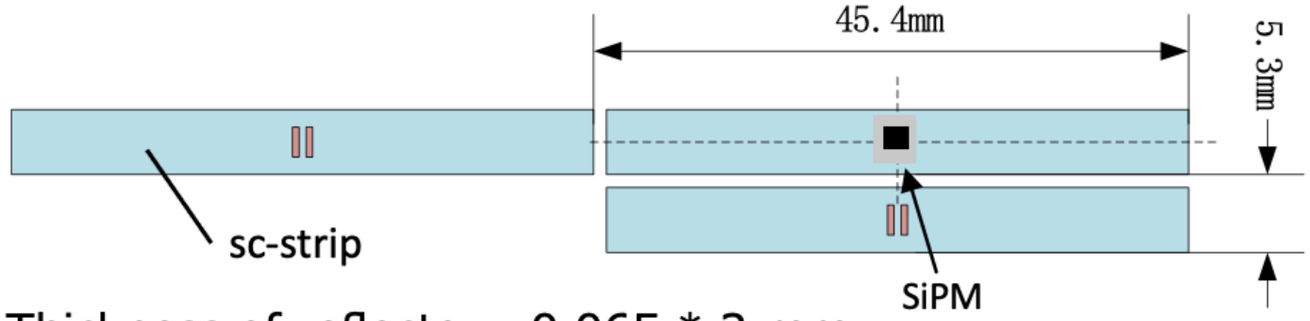


Electronics side of EBU



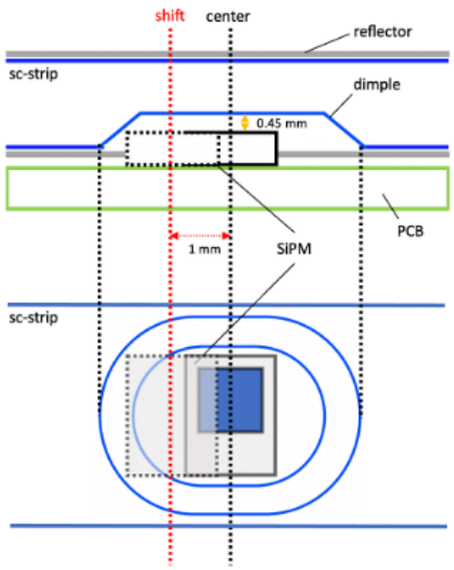
# Possible SiPM-strip misalignment on EBU

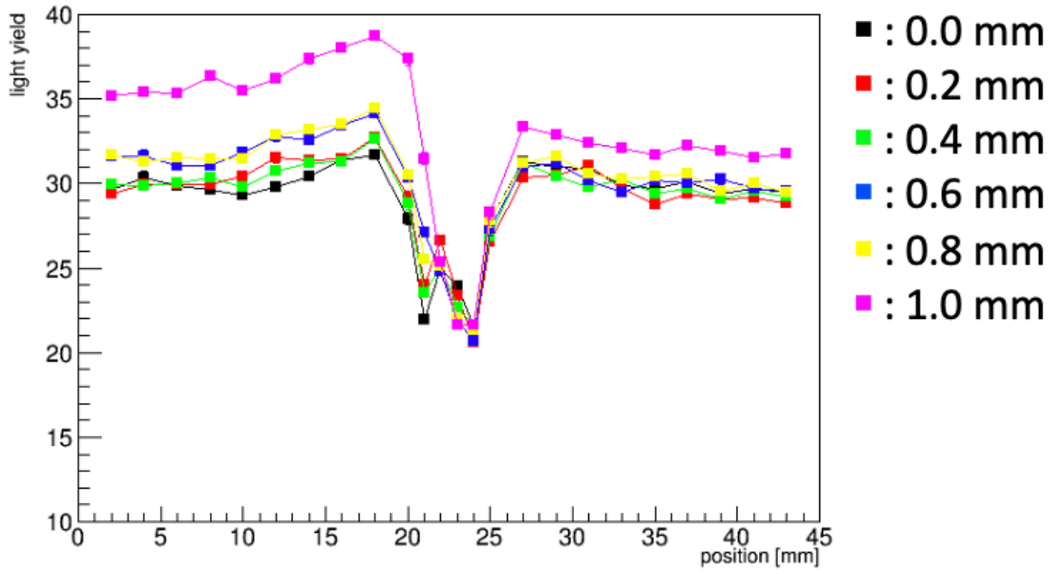
- Layout of strips on readout board (ECAL Base Unit, EBU)



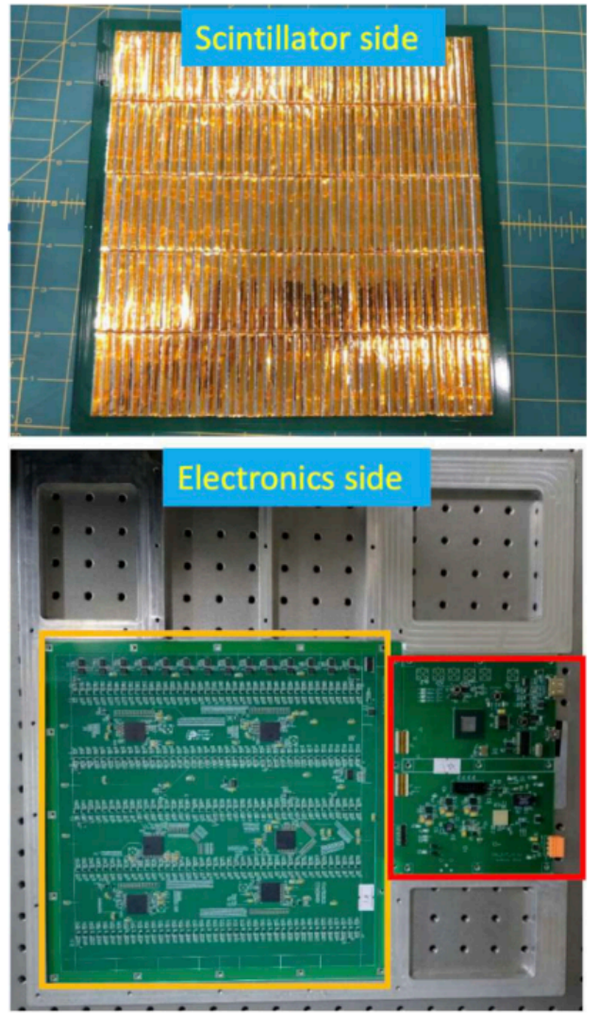

Thickness of reflector : 0.065 * 2 mm
Thickness of Kapton tape : 0.05 * 2 mm

- The effect of strip-SiPM misalignment on the light yield distribution has been investigated by both simulation and measurement

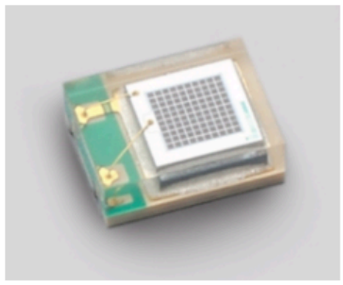



- Uniformity of light yield is affected only when the misalignment is as large as 1 mm




ECAL Base Unit (EBU)

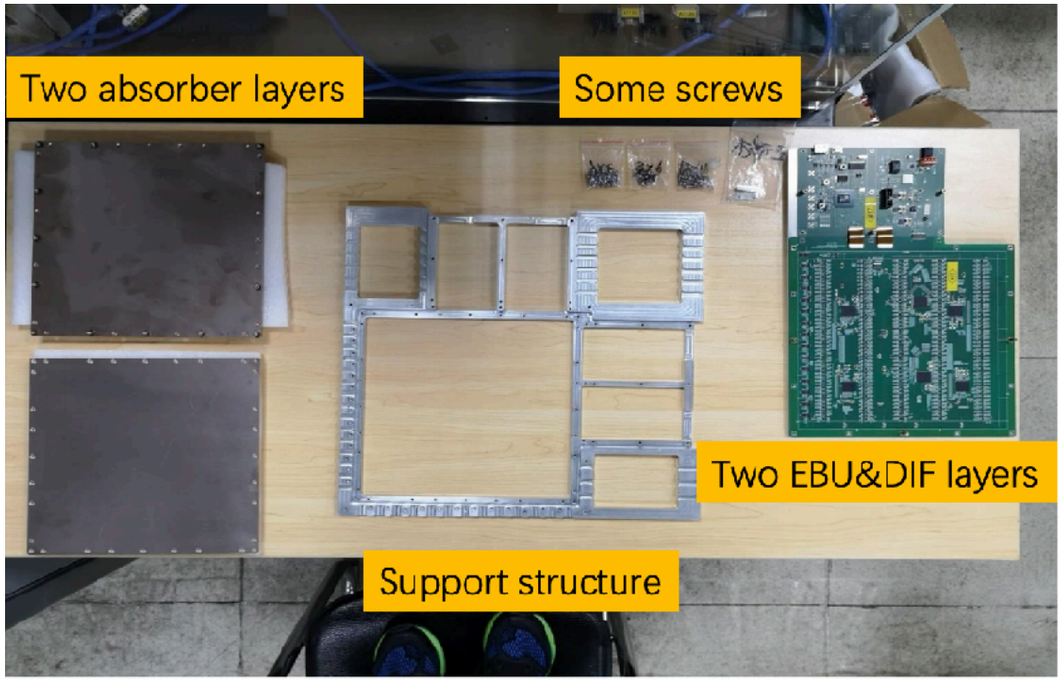


MPPC : S12571-015P
(1 x 1 mm$^2$ 15µm-pixel)
hit position[mm]

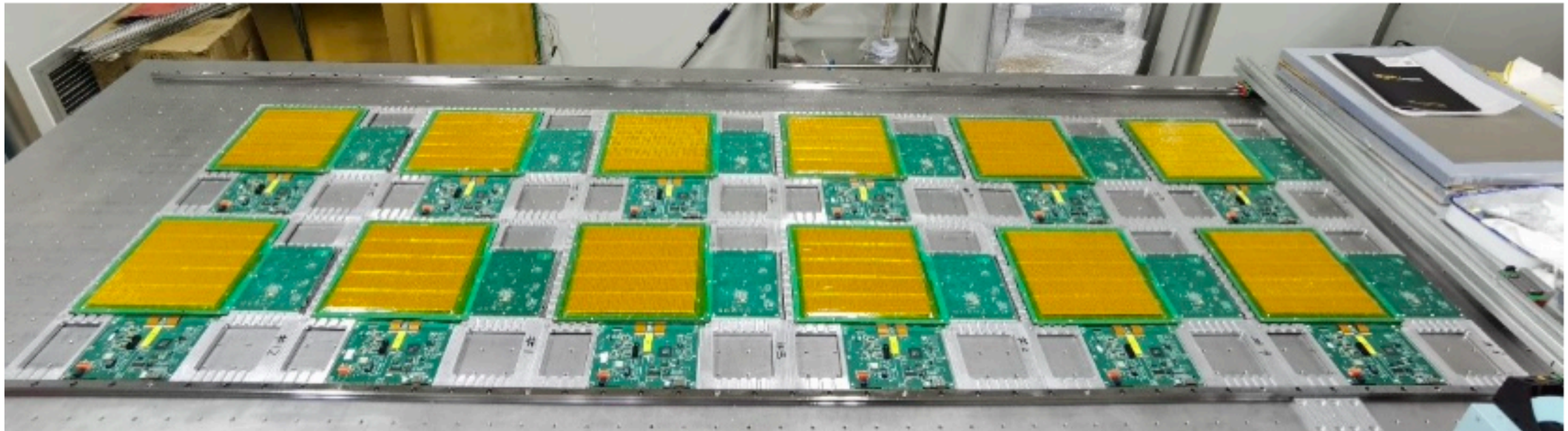
# Construction

- 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

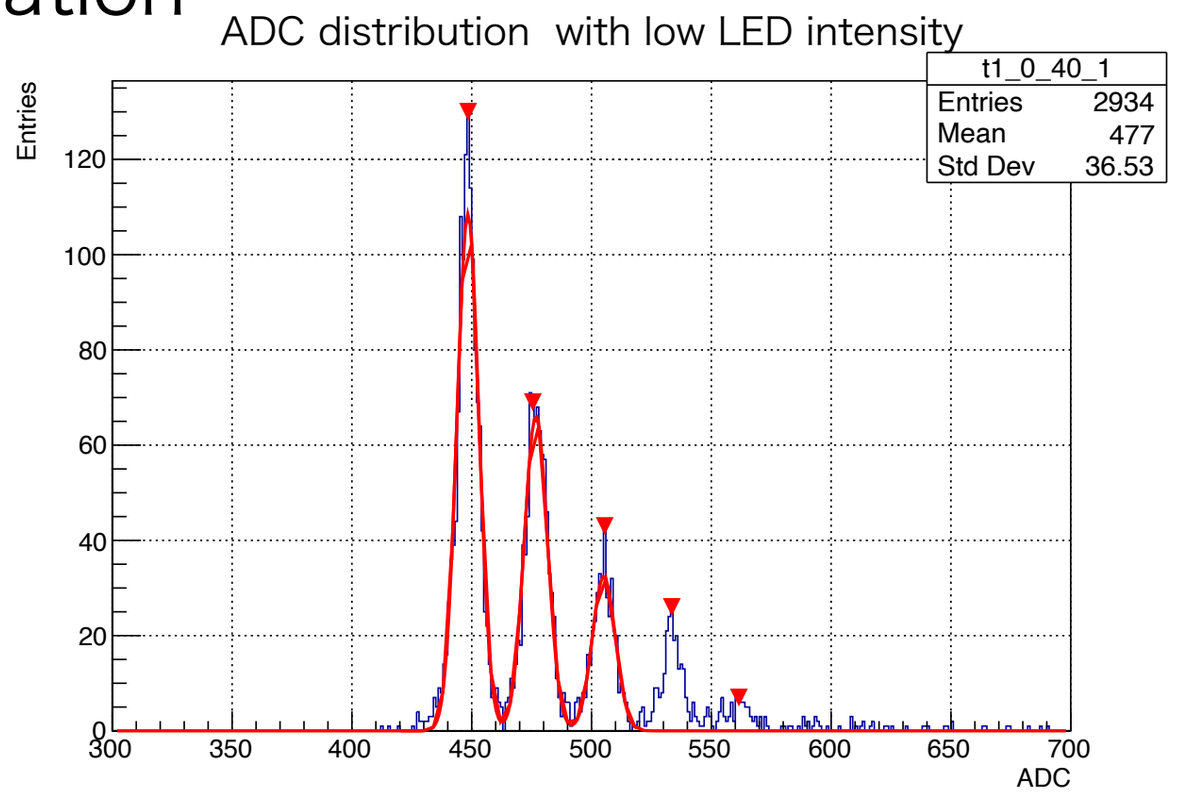


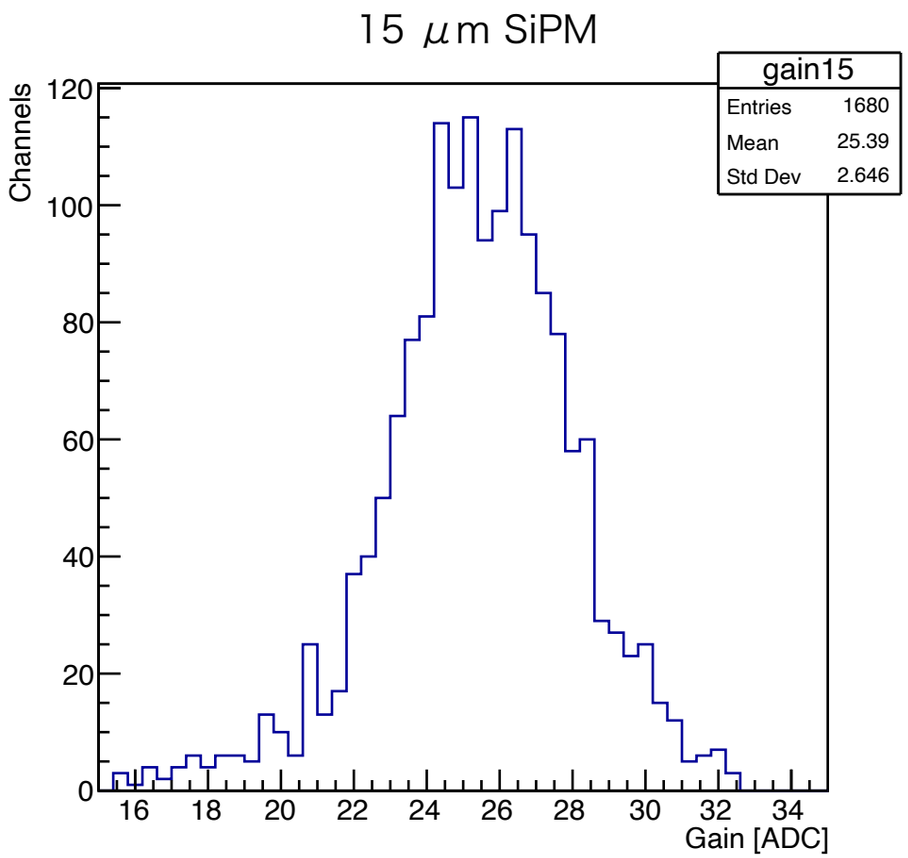

| Super-module | #module (EBU) | SiPM | Strip length | Strip material (process) |
|---|---|---|---|---|
| Single-readout 1 | 12 (24) | S12571-010P | 45 mm | PVT (casting) |
| Single-readout 2 | 3 (6) | S12571-015P | 45 mm | PVT (casting) |
| Double-readout | 1 (2) | S12571-015P | 90 mm | PS (injection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

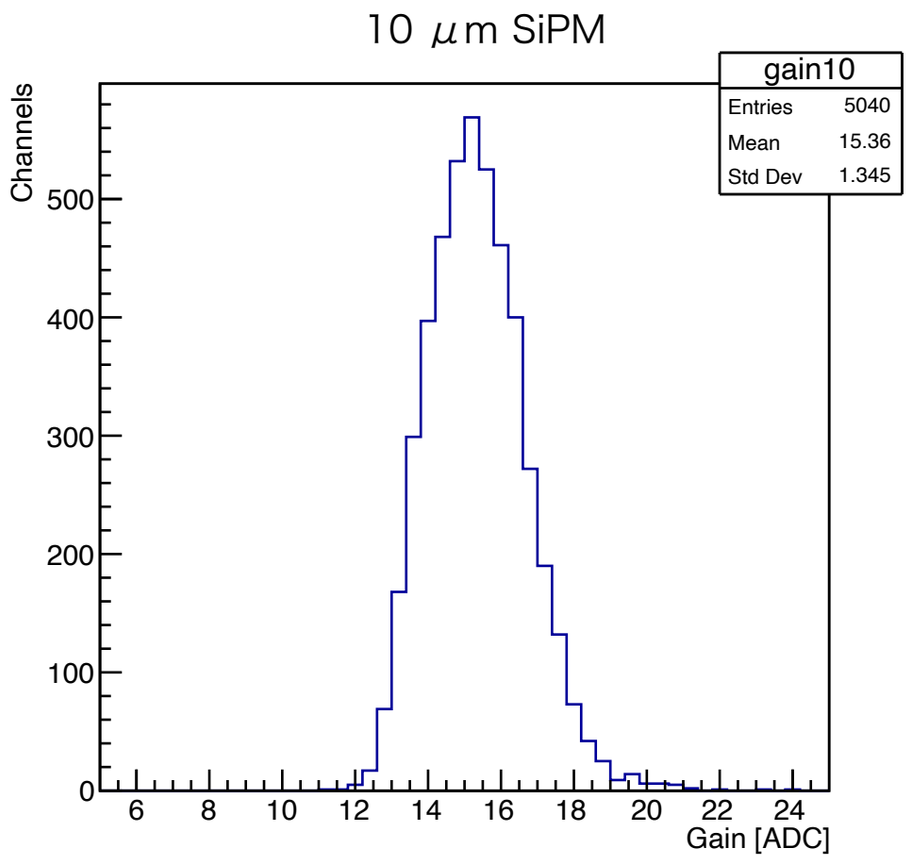


# Gain calibration

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

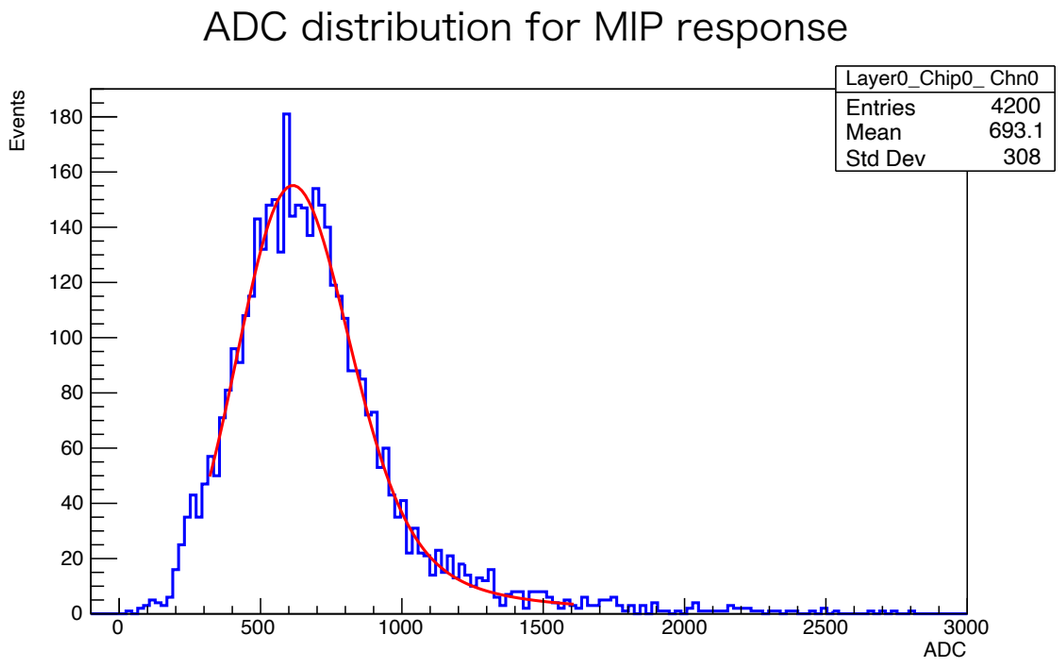


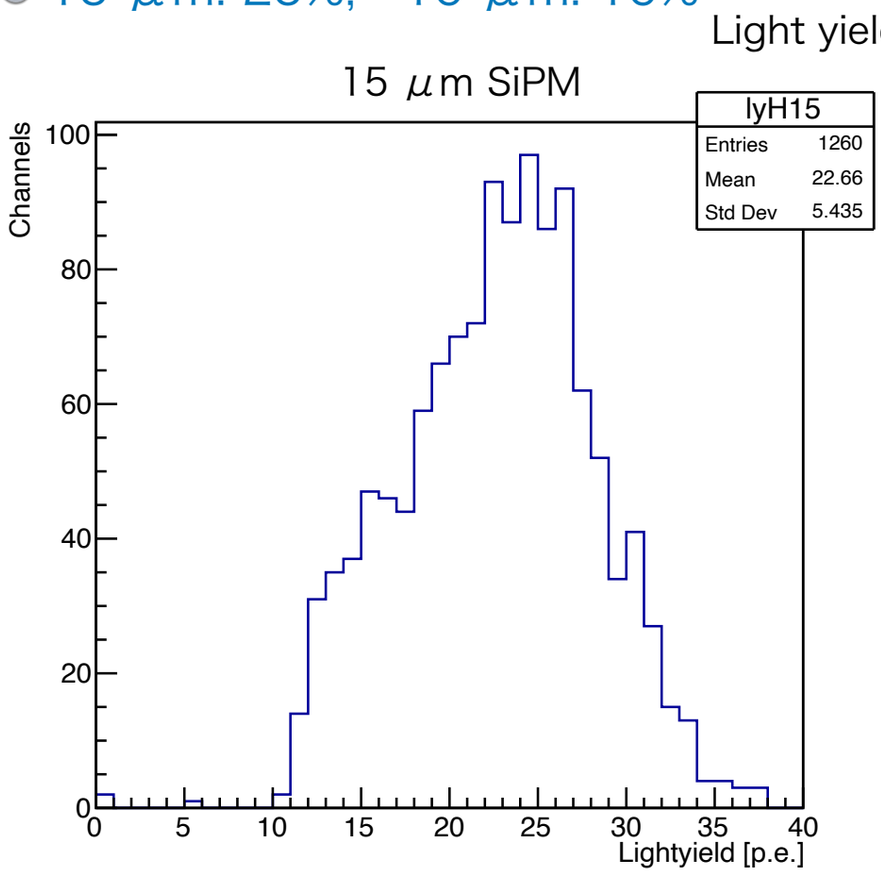



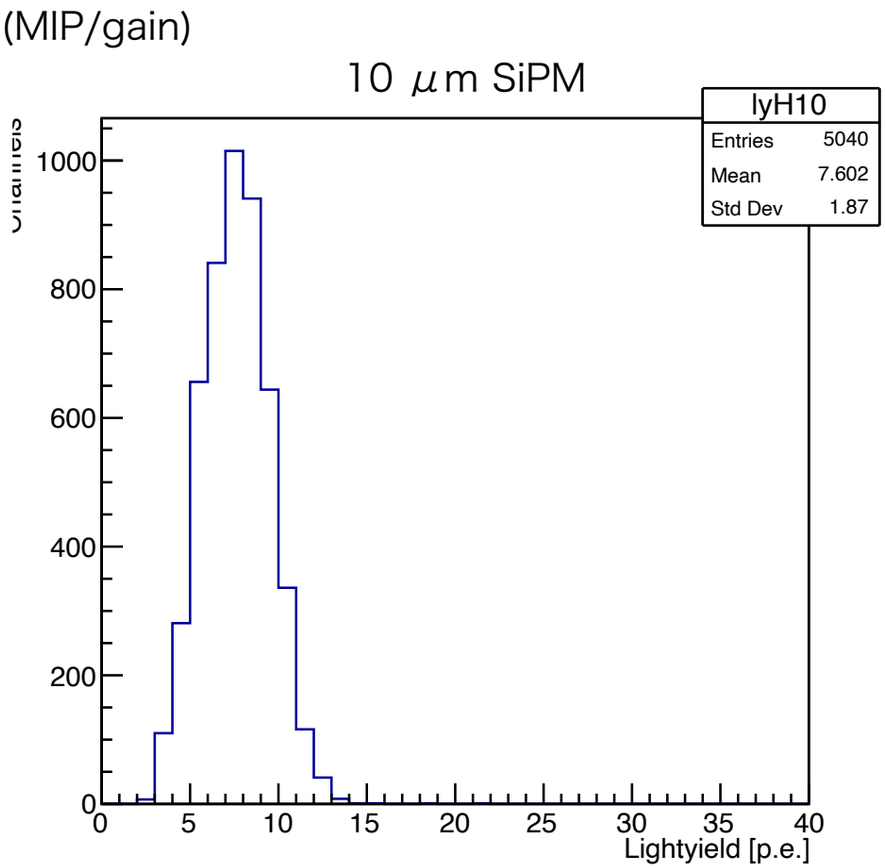



# MIP calibration

- 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 $\mu$m SiPM: 22.6 p.e. (18 p.e. w/o CTAP)
    - 10 $\mu$m SiPM: 7.6 p.e. (7 p.e. w/o CTAP)
  - Consistent with PDE difference
    - 15 $\mu$m: 25%, 10 $\mu$m: 10%

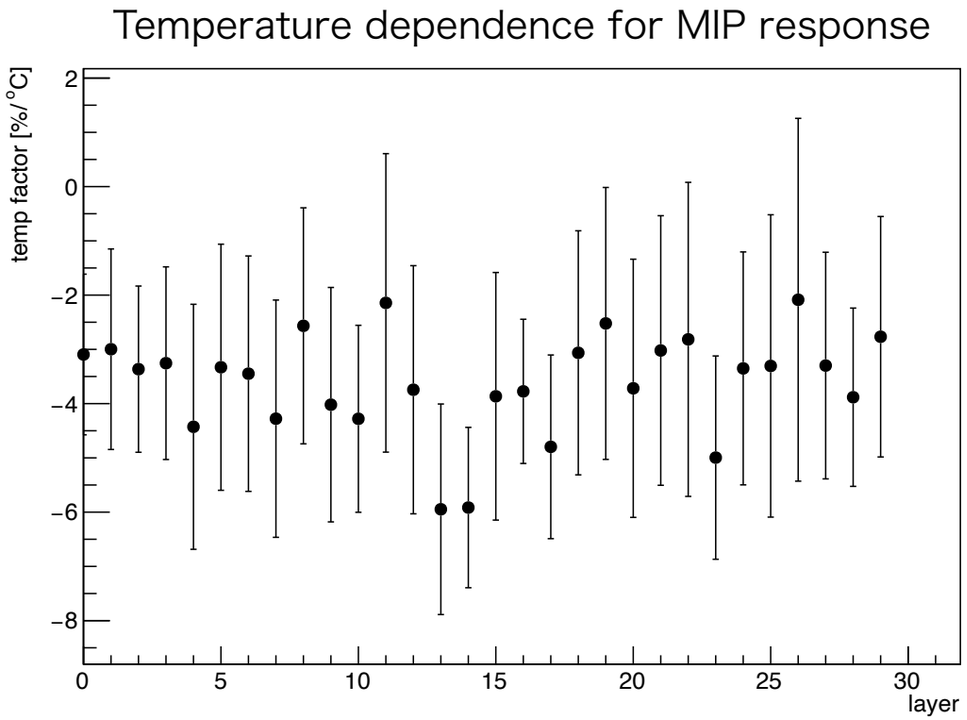


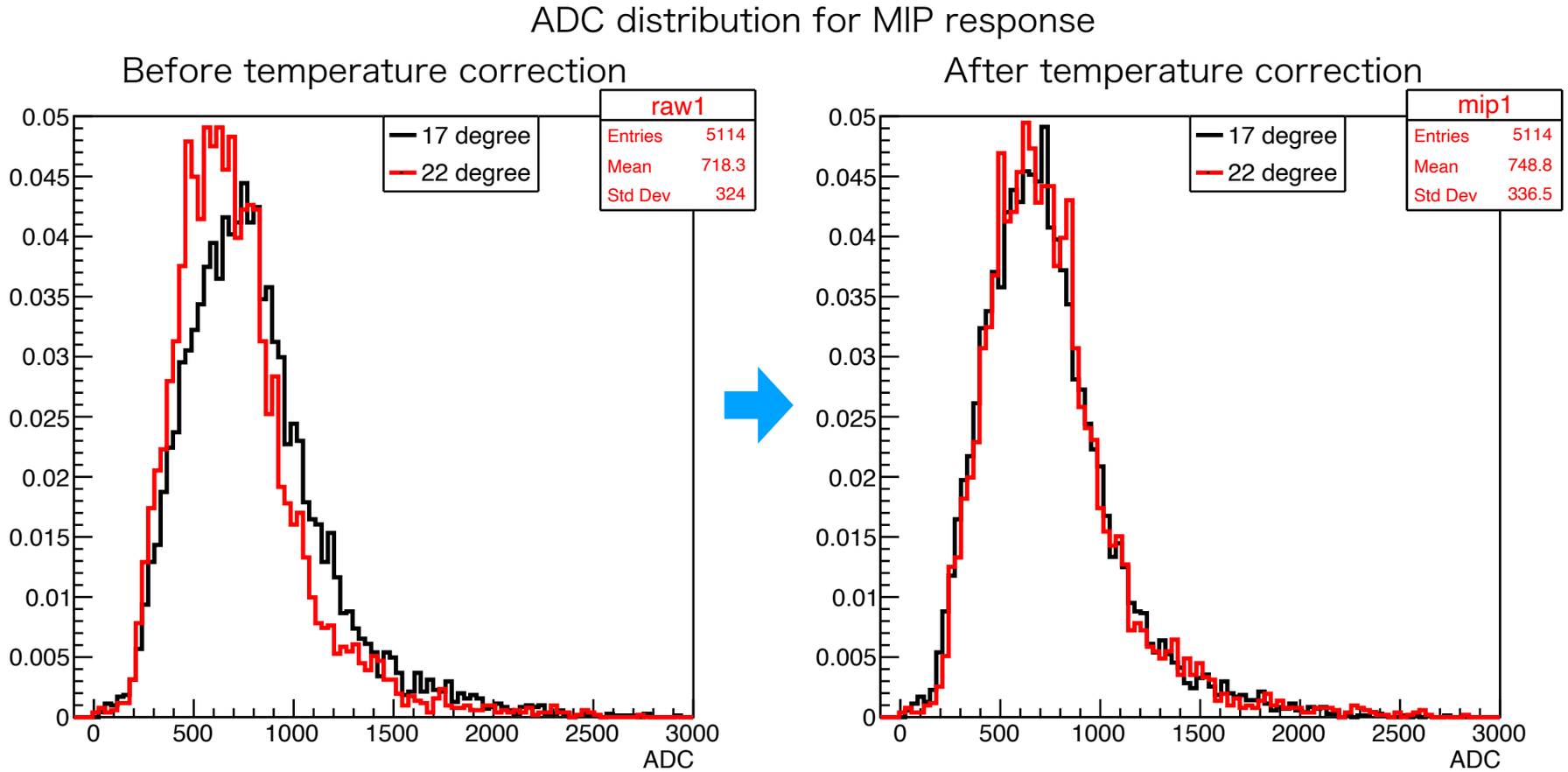



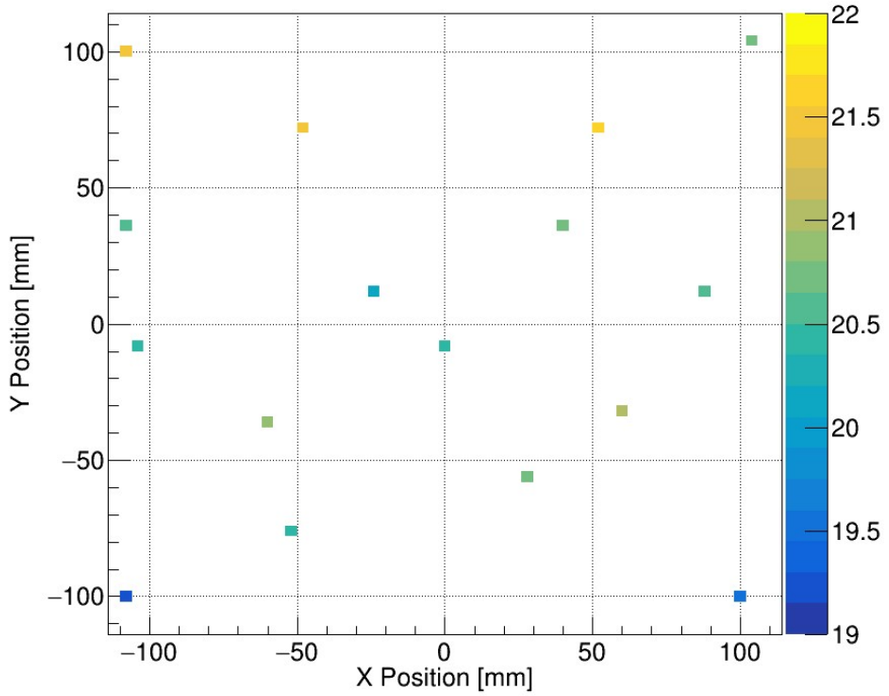
# Temperature correction

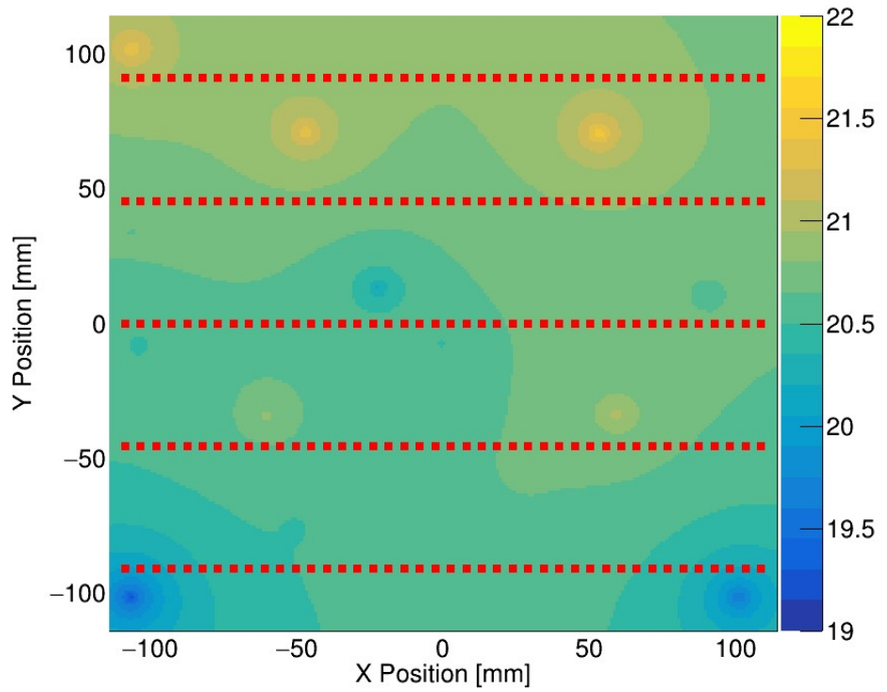
- Temperature is monitored during LED tests and cosmic-ray tests
- Temperature dependence on MIP response and gain obtained
  - 15 $\mu$m SiPM: -3.23%/℃
  - 10 $\mu$m SiPM: -3.70%/℃
- Temperature correction is applied at each hit
  - ADC distributions with large temperature difference match well after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

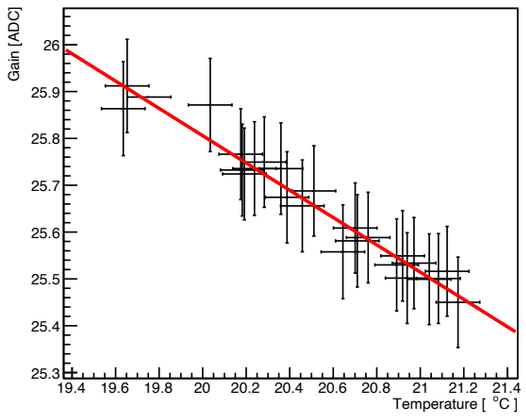


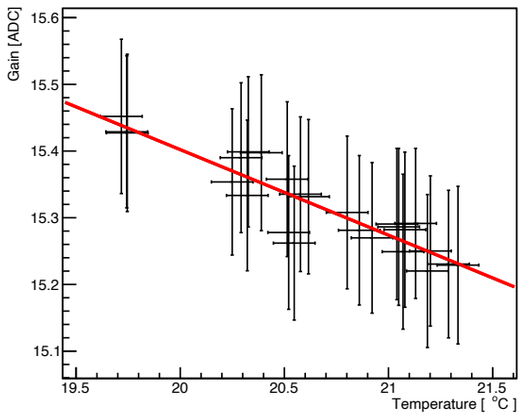



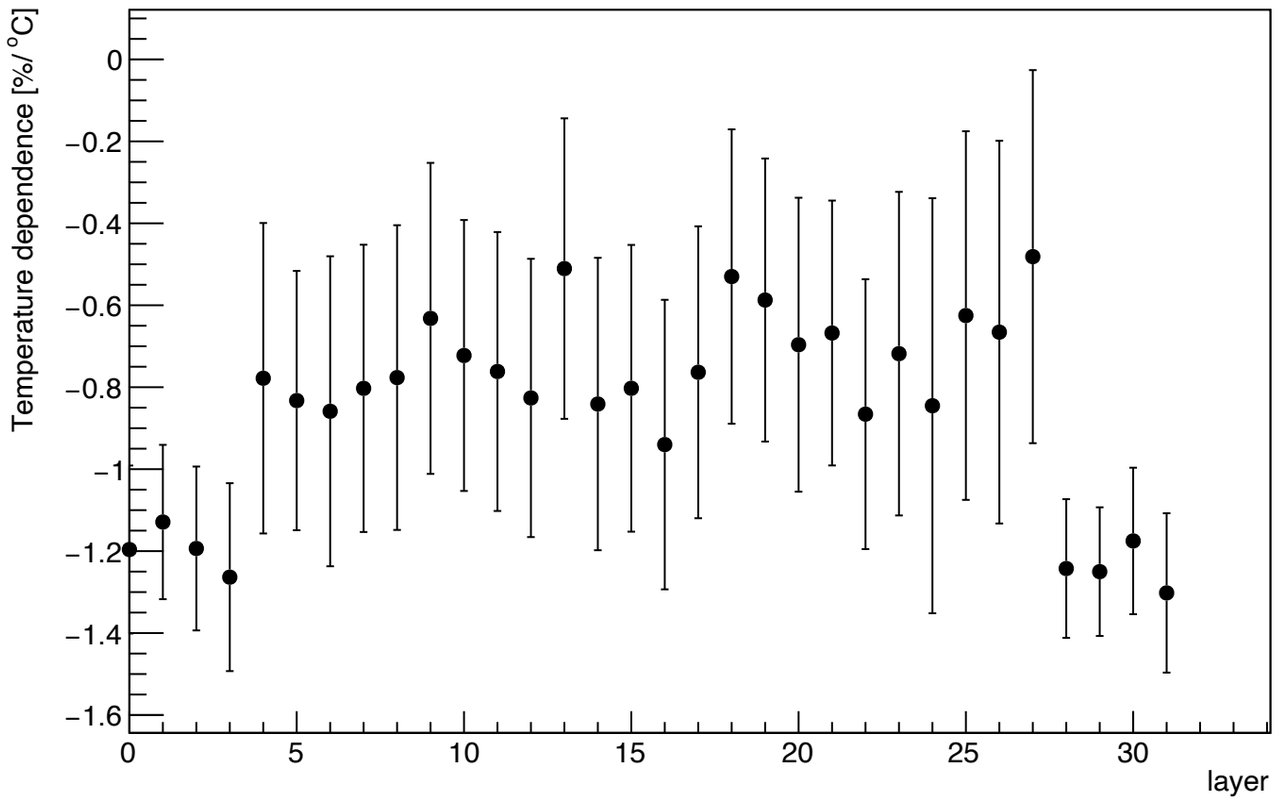
# Temp reco & gain



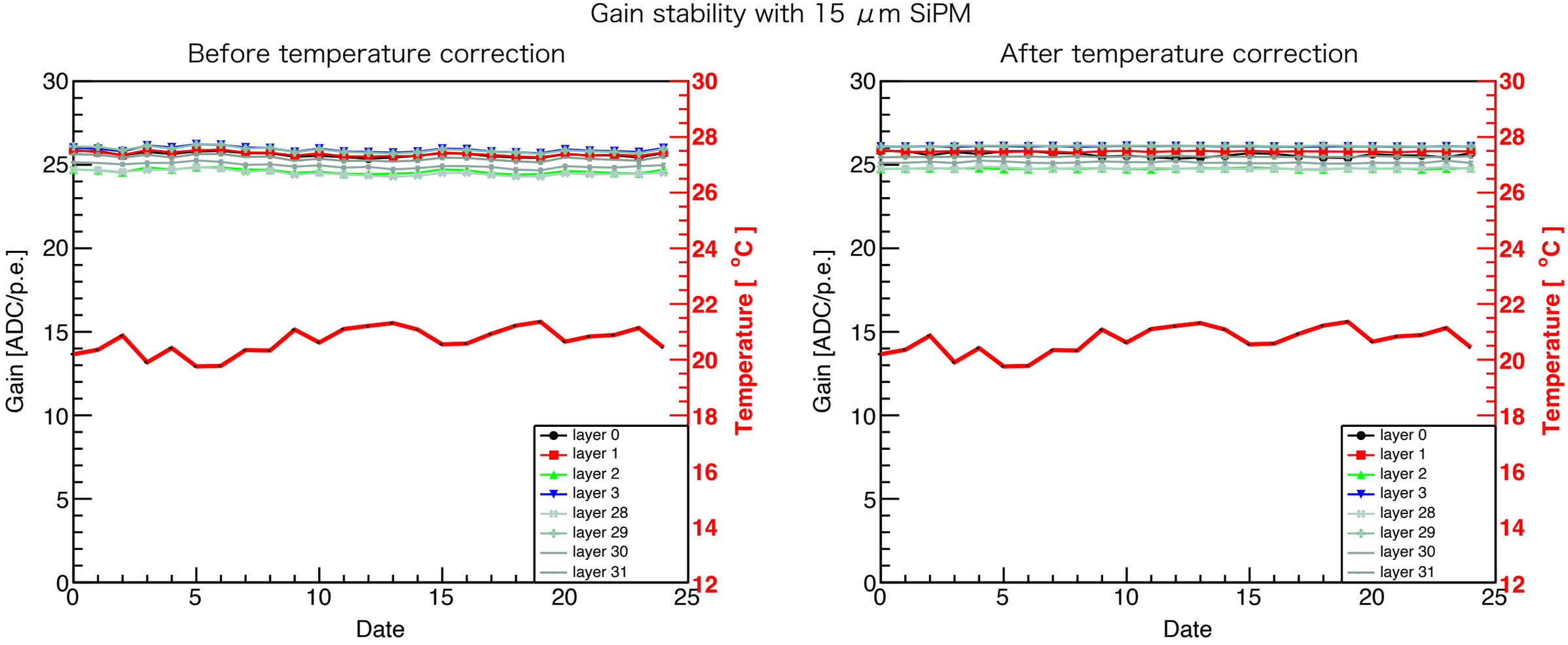



# Stability

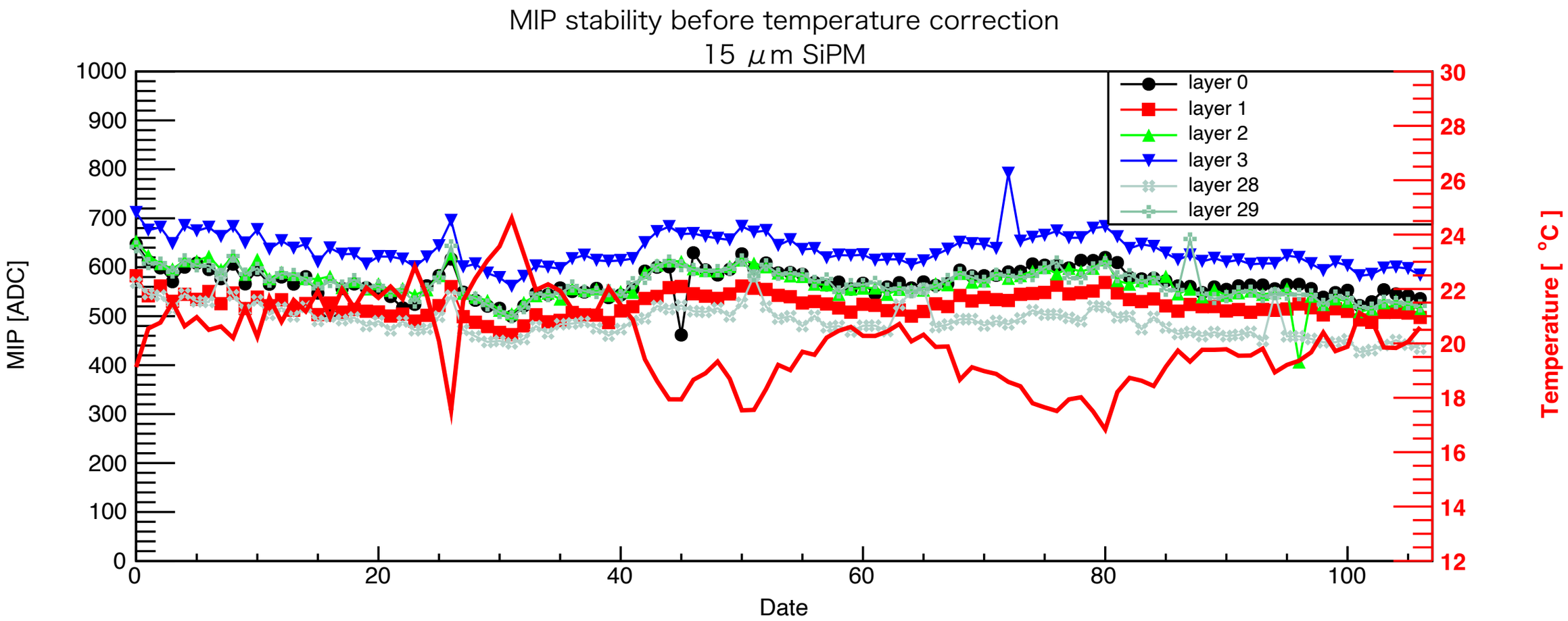
- **Gain is quite stable during one month LED run**
  - Weak correlation with the temperature variation
  - Further improved by temperature correction
- Inter-calibration, CTAP, and pedestal are quite stable when averaged over all channels
  - Improvement of LED system is needed to reduce the error
-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

Gain stability with 15 $\mu$m 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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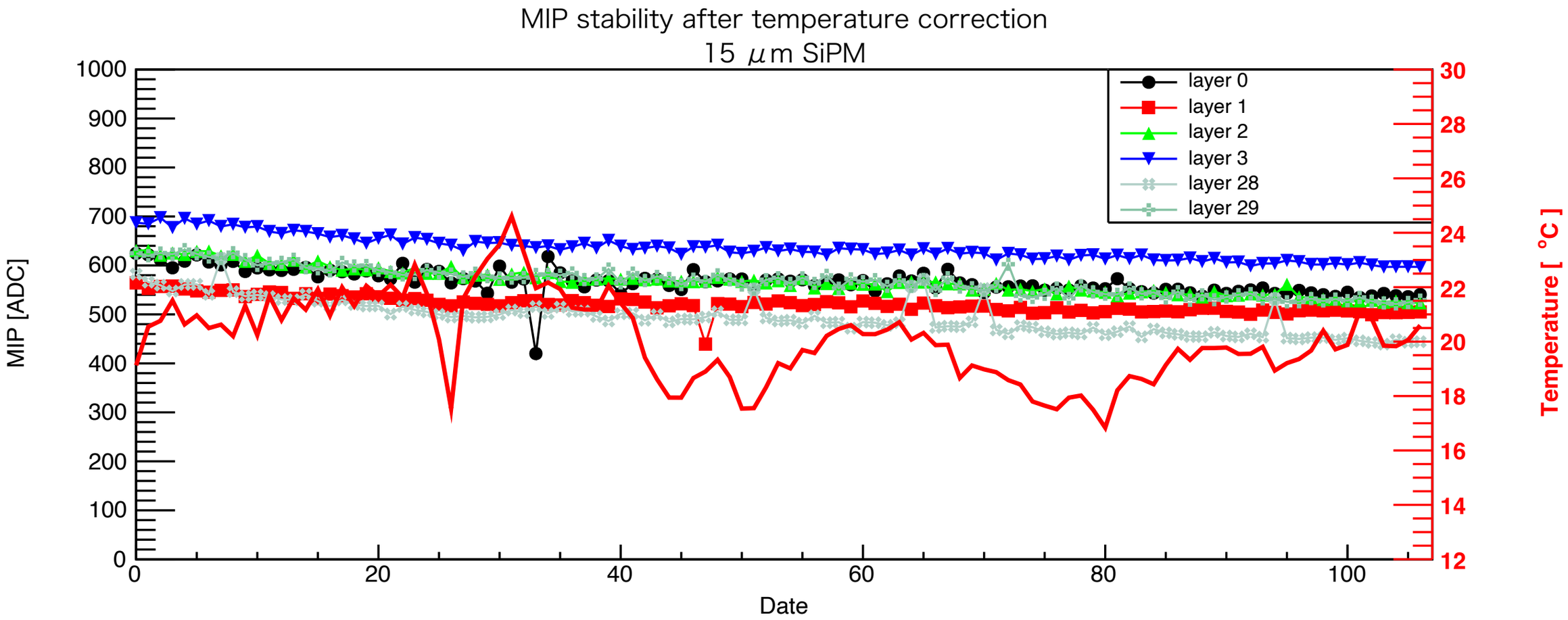

# Monte Carlo simulation

- 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