Development of Highly Granular Scintillator Strip Electromagnetic Calorimeter

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CPAD Instrumentation Frontier Workshop2021, 18 Mar. 2021

LOI for Snowmass 2021

- LOI on highly granular Sc-ECAL for Snowmass 2021

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Abstract

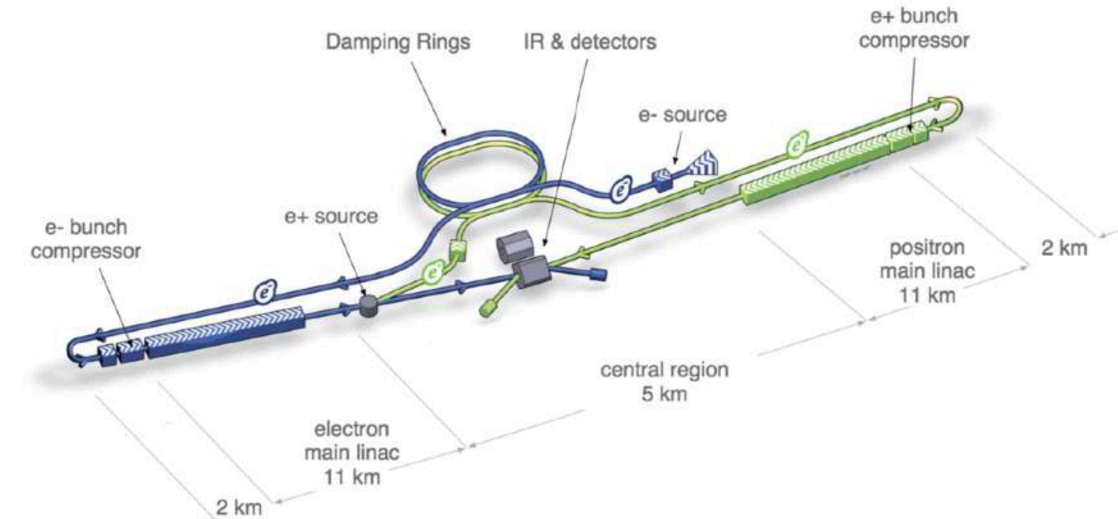
Highly granular electromagnetic calorimeter based on scintillator strip with SiPM readout (Sc-ECAL) is under development in the framework of the CALICE collaboration for future electron-positron colliders such as ILC and CEPC. After the validation of the concept with the physics prototype, a technological prototype with full layers is being constructed to demonstrate the performance of Sc-ECAL with more realistic technical implementation. The status and prospects of the R&D of Sc-ECAL are briefly described.

Contents

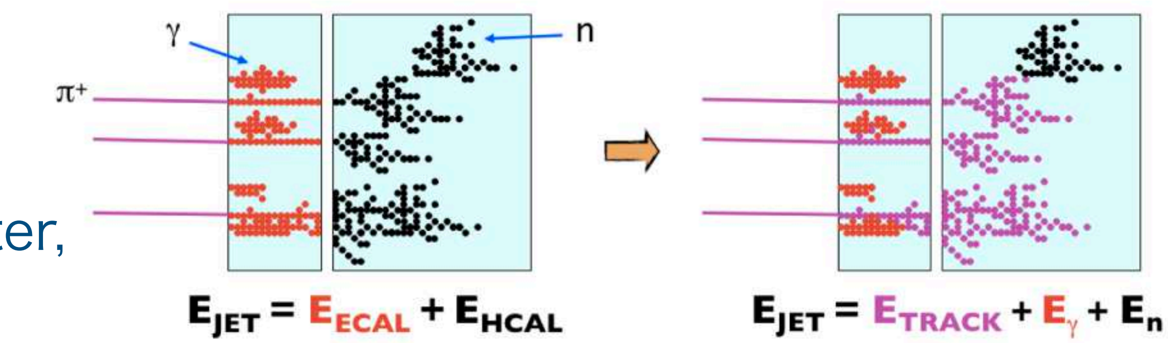
Contents

International linear Collider (ILC)

- <u>Future high energy frontier machine</u>
    - Electron-positron linear collider
    - Ecm : 250-500 GeV (extendable to 1 TeV)
- Precise measurements in low background environment



- International Large Detector (ILD)
    - vertex detector, central tracker, EM calorimeter, hadron caloriemeter, and muon tracker.

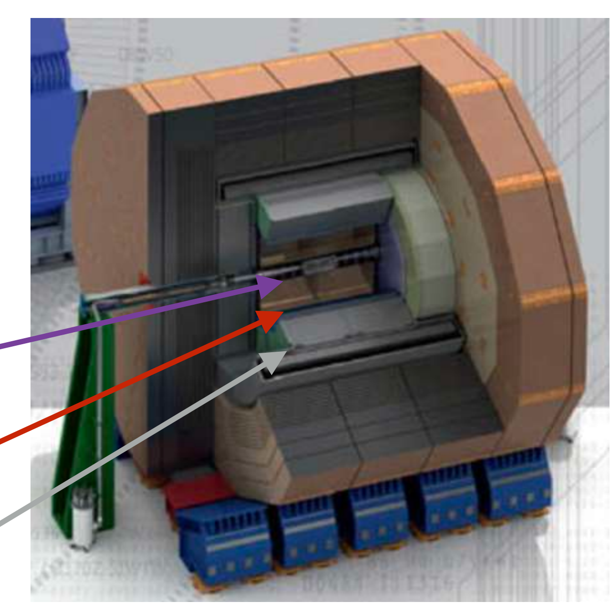


- Particle Flow Algorithm (PFA)
    - Each particle is detected by the best suited detectors.
    - Improved jet energy resolution
- **In order to realize the PFA, high granularity calorimeter is required.**

Charged particle → inner tracker

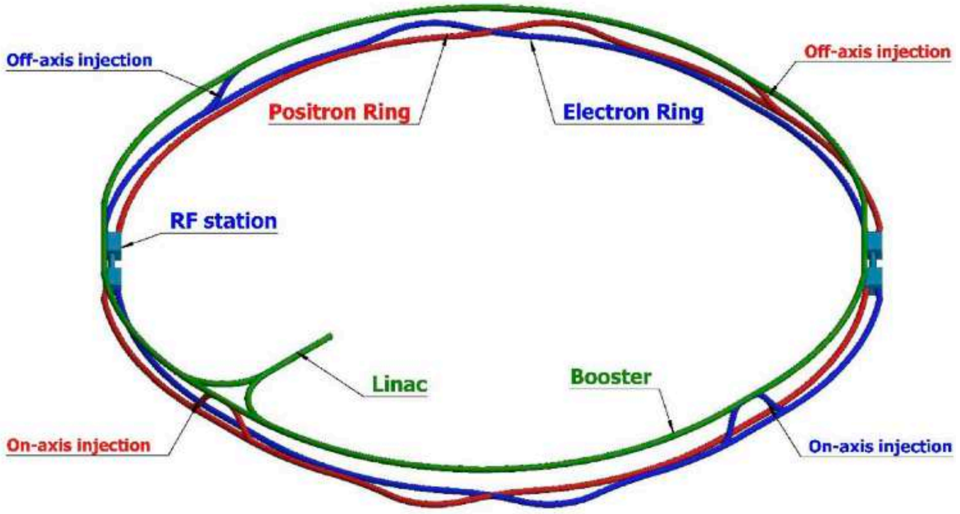
Gamma → ECAL

Neutral hadron → HCAL

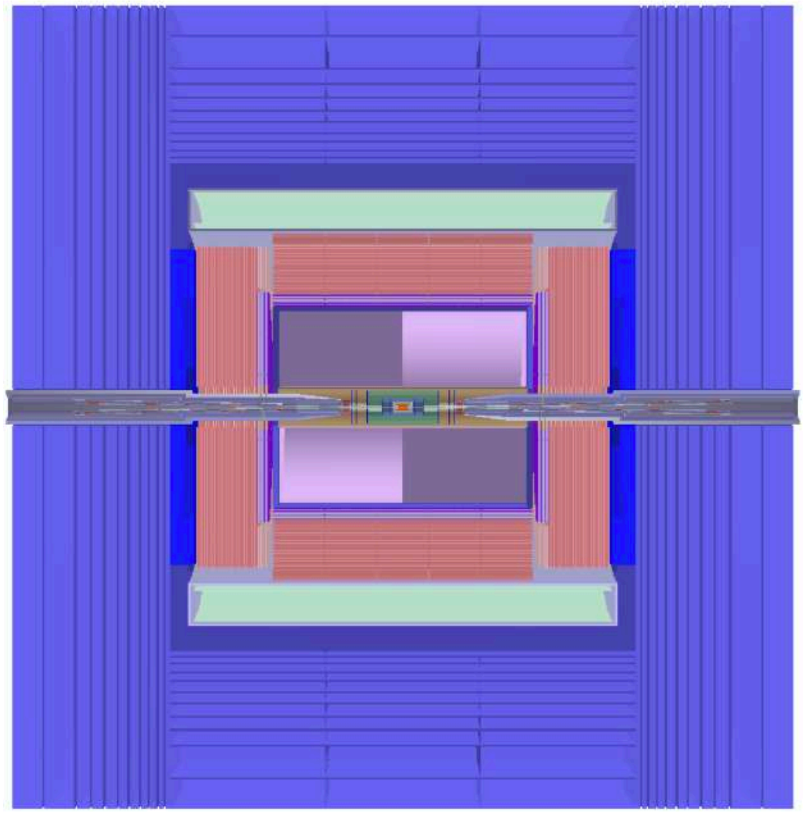


Circular Electron Positron Collider (CEPC)

- Higgs factory
  - Electron positron circular collider
  - Ecm : 240 GeV
  - Precise measurement of the Higgs (and Z) boson
- Discovery machine for BSM new physics
  - Upgradable to pp collision with Ecm : 50-100 TeV



- Detectors
  - Baseline concept is similar to ILD
    - Tracker, TPC, ECAL, HCAL, muon detector
  - Adopt PFA for reconstruction algorithm



Performance requirements

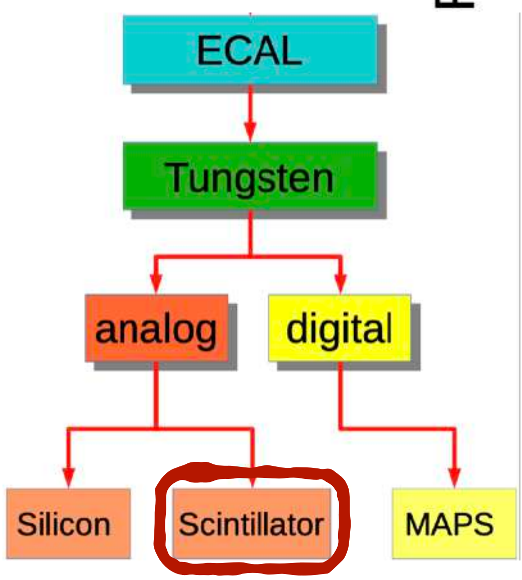
ILC

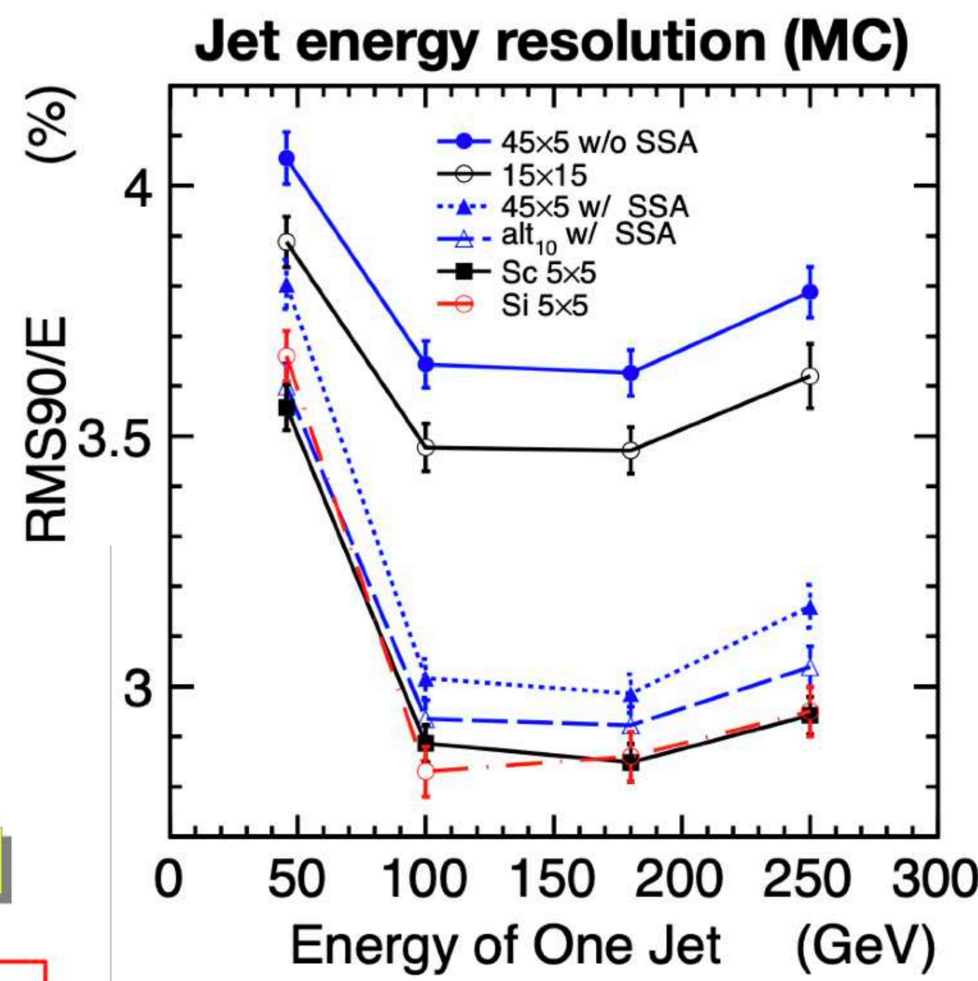
Zhh $Zh \to q\bar{q}b\bar{b}$ $Zh \to ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs coupling Higgs mass $B(h \to WW^*)$ $\sigma(e^+e^- \to \nu\bar{\nu}W^+W^-)$	Tracker and Calorimeter	Jet Energy Resolution $\Delta E/E$	3% to 4%

CEPC

$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV

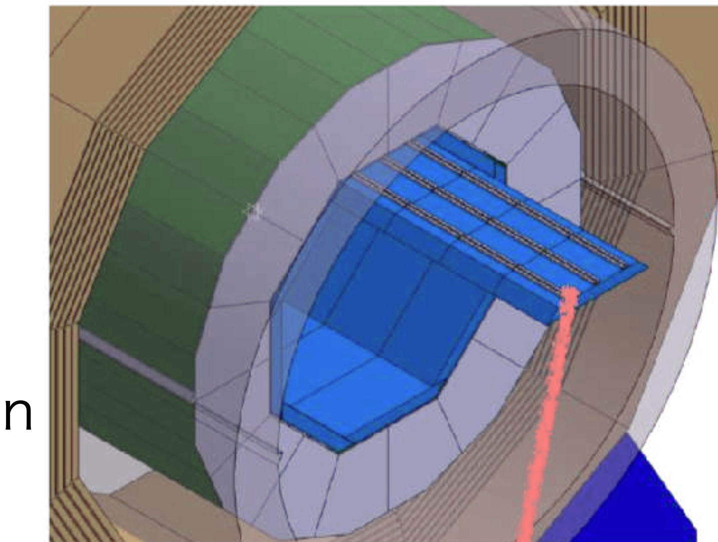
- Jet energy resolution
  - σ_E/E ~ 3% to 4%
  - Combined with tracker, ECAL and HCAL
- MC simulation
  - 2 options for PFA analog ECAL
    - Silicon
    - Scintillator ←**Topic of this talk**
  - Good resolution achieved at both options

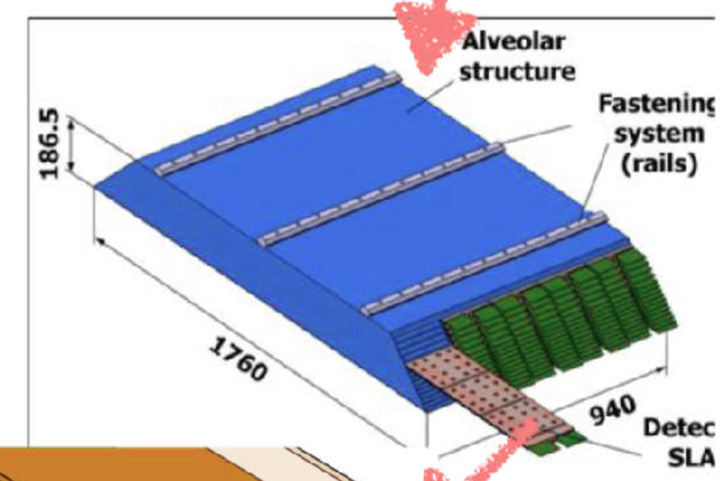


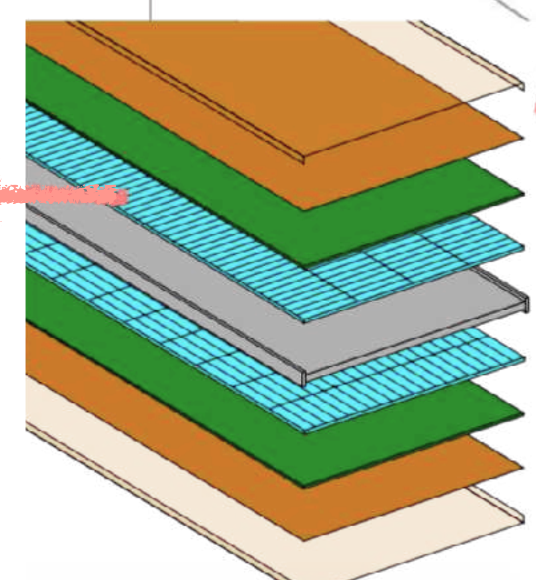


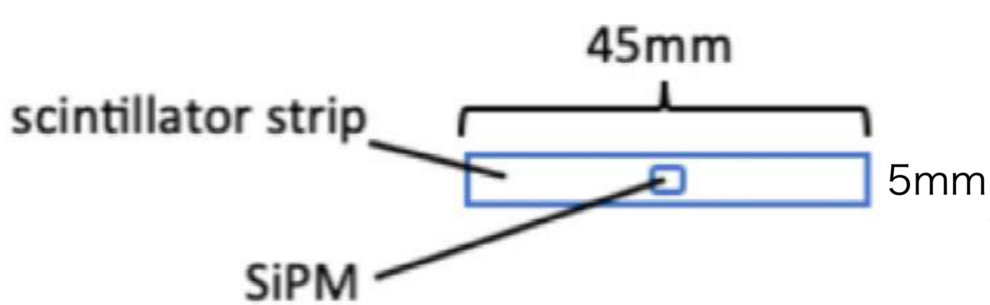
Sc-ECAL

- Scintillator Electromagnetic CALorimeter (Sc-ECAL)
  - Technology option of EM calorimeter for ILC and CEPC
- Based on scintillator strips readout by Silicon PhotoMultiplier (SiPM)
  - $5 \times 45 \times 2$ mm^3 scintillator strip
- Virtual segmentation : 5×5 mm^2 with strips in x-y configuration
  - # readout channels significantly reduced ($10^8 \rightarrow 10^7$) →Low cost
  - Retaining performance comparable to real 5×5 mm^2 segmentation
- Timing resolution < 1 ns





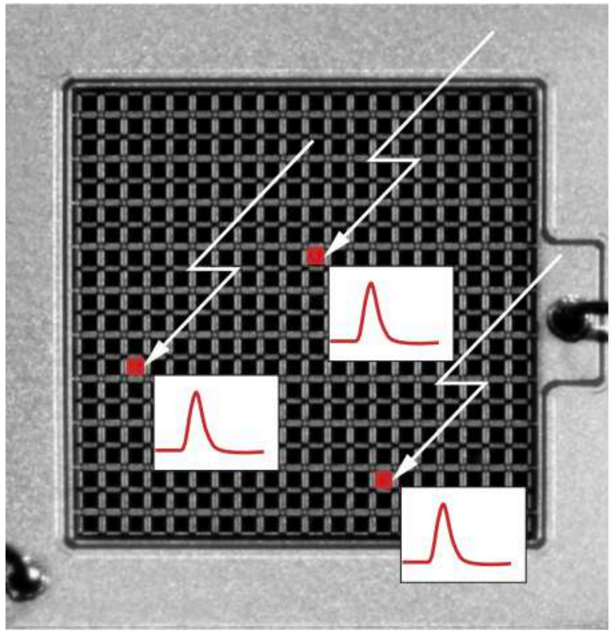




Contents

Small-pixel SiPM

- Silicon PhotoMultiplier (SiPM)
  - Made up of multiple APD pixels operated in Geiger mode
  - Excellent photon-counting capability

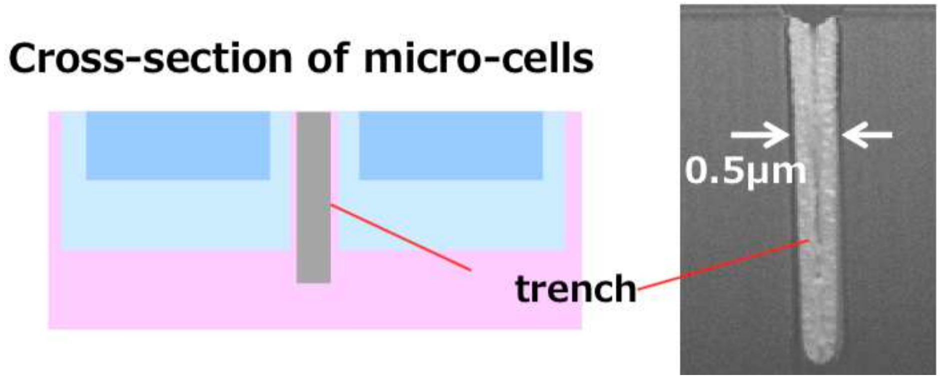


Hamamatsu Photonics K.K.,

- Requirement of small-pixel SiPM for large dynamic range
- Comparative study b/w 10 μm-pixel and 15 μm-pixel SiPM
  - Developed detection layers with both types

Model number	S12571-010P	S12571-015P	S14160-1315PS
Photosensitive area	1 mm^2	1 mm^2	1.3 mm^2
Pixel size	10 μm	15 μm	15 μm
Number of pixels	10000	4489	7296
PDE	10%	25%	32%
Gain	1.35×10^5	2.3×10^5	3.6×10^5
Crosstalk Probability	~5%	~15%	Less than 1%
Fill factor	33%	53%	49%

- New small-pixel SiPM with trench
  - Low crosstalk
  - Low operation voltage
  - No reduction of fill factor
- 2 detection layers with new SiPM tested



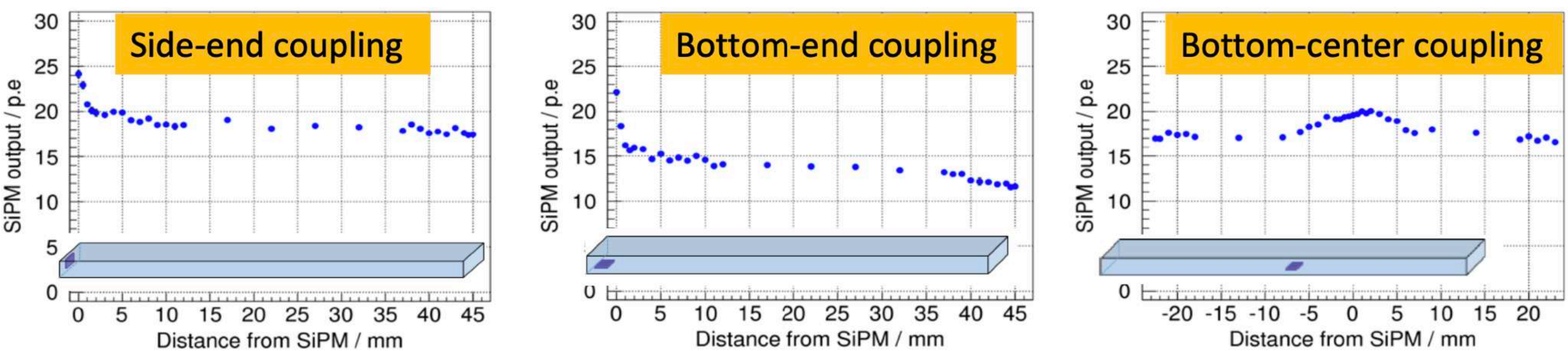
Crosstalk : IR photons from avalanche in fired pixel can trigger adjacent pixels

Trench : Separation between adjacent pixels in order to reduce crosstalk

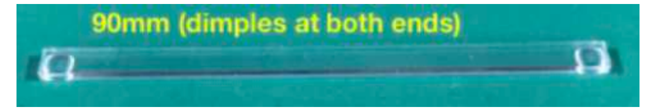
SiPM Coupling optimization

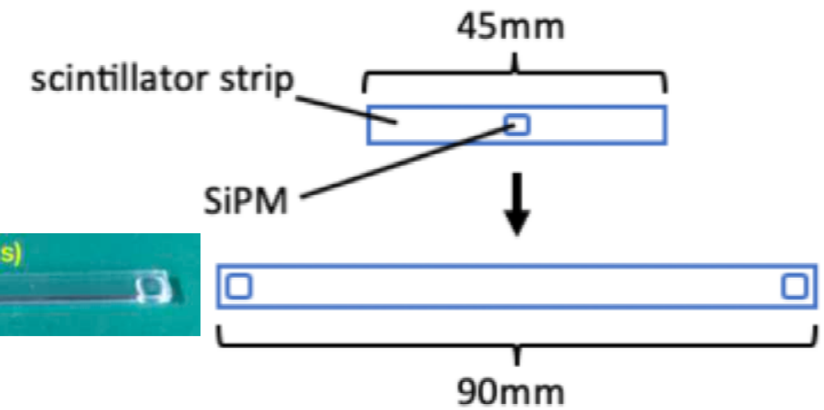
- Three coupling models investigated
  - side-end, bottom-end and bottom-center
- Uniformity of light yield along the strip is important to the ECAL energy resolution
- **Bottom-center coupling gives the best uniformity with additional advantages:**
  - Avoiding the dead area between scintillators introducing by SiPMs
  - Simplifying sensitive layer assembly
  - Allowing for large-size SiPM
- Adopt bottom-center coupling as default design of detection layer

・Commercial PVT scintillator
・MPPC S12571-010P

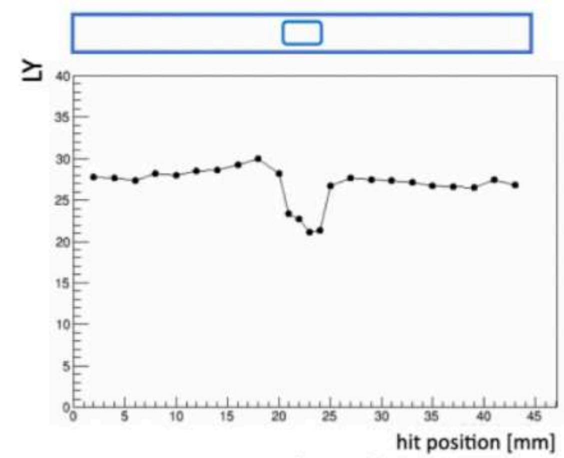


Double SiPM readout

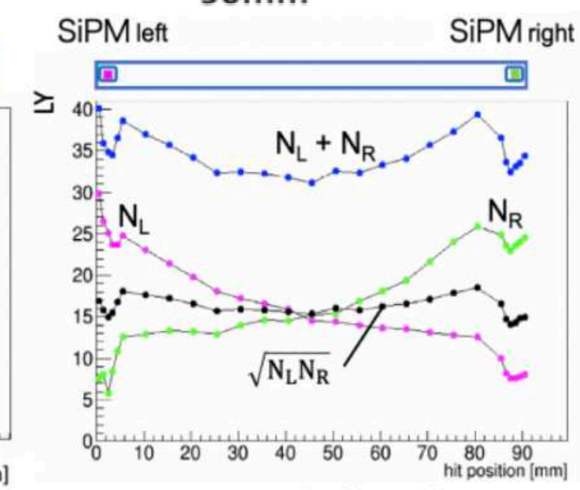




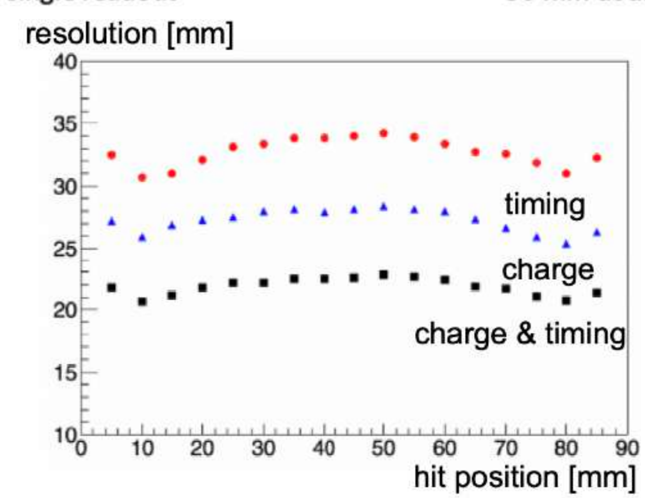
- **Readout by 2 SiPMs at strip ends**
- Twice longer strip (L=90mm) to keep the number of SiPMs
- Possible advantages
  - Eliminating noise by taking coincidence
  - Higher light yield by summing 2 SiPM readouts
  - Even lower light yield for each SiPMs (→less saturation)
  - Position reconstruction by charge and/or timing difference between two readouts (→ reduce ghost hits)
- Performance
  - Higher light yield (~37 p.e.) than single readout (~20 p.e.) by summing 2 SiPM readouts
  - Hit position reconstruction with 20 mm resolution
  - Noise reduction achieved by taking coincidence
- Two detection layers with double readout tested

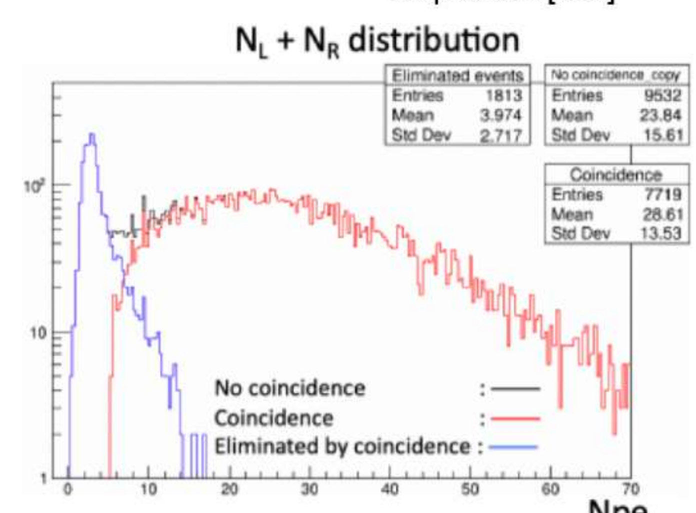


45 mm single readout



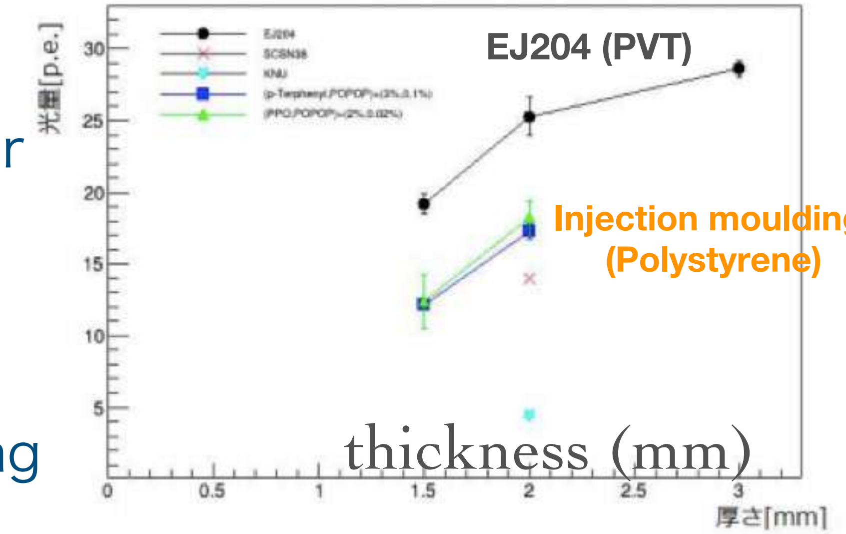
90 mm double readout





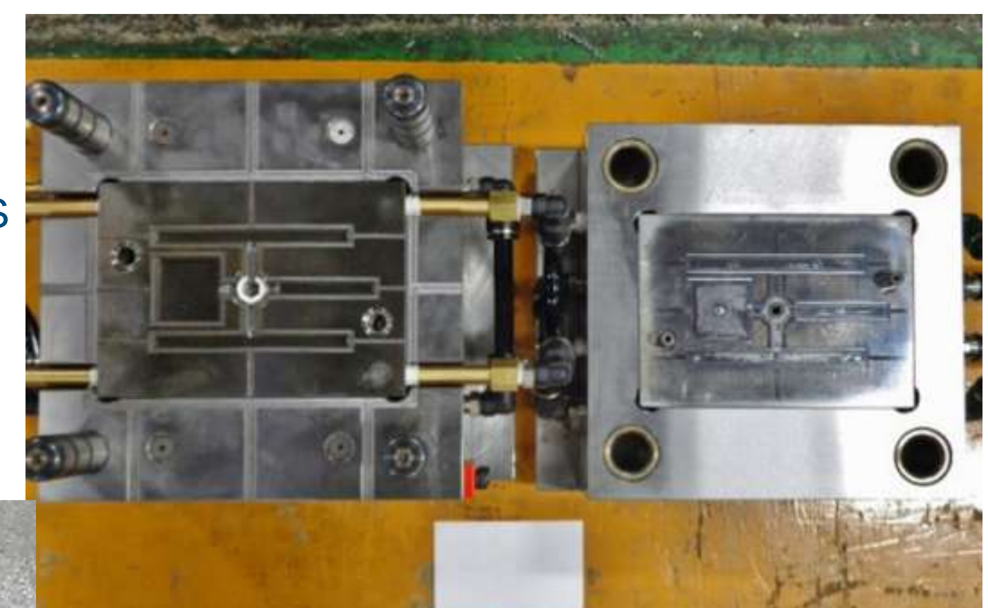
Scintillator material

- Polystyrene-based scintillator produced by injection moulding
  - Suitable for large-scale production
  - Lower light yield compared to commercial PVT scintillator



- Performance
  - Production of large 2mm-thick plate by injection moulding → machining (strip shape + cavity)
  - Light yield by injection moulding is lower by ~20% compared to PVT
    - Still sufficient light yield

Dedicated mould for Sc-CAL

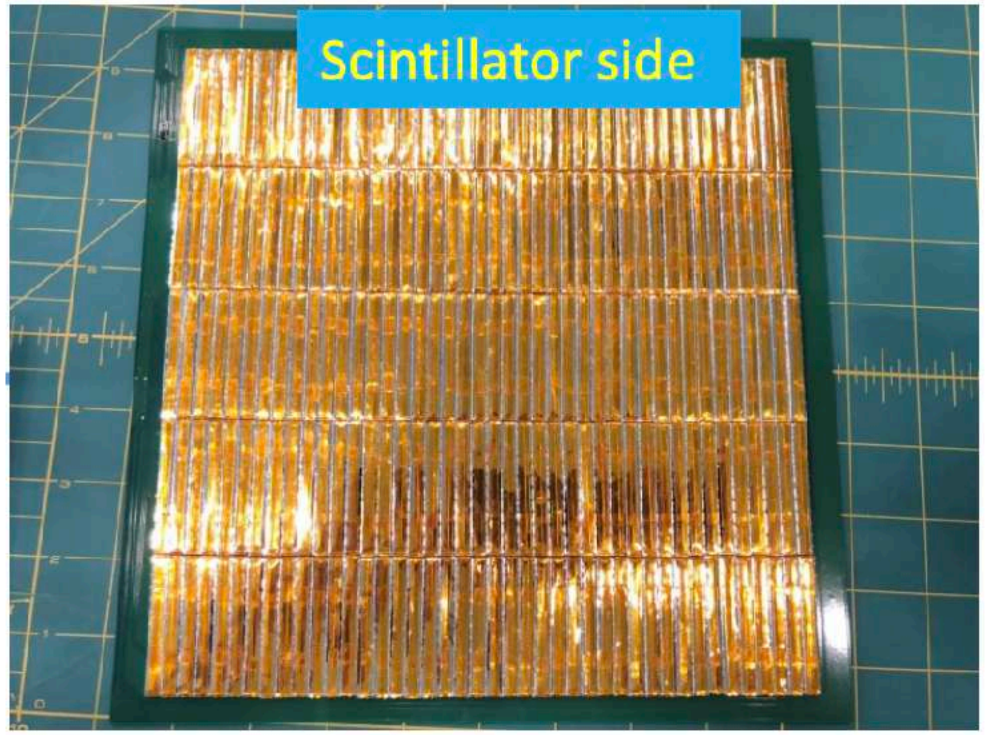


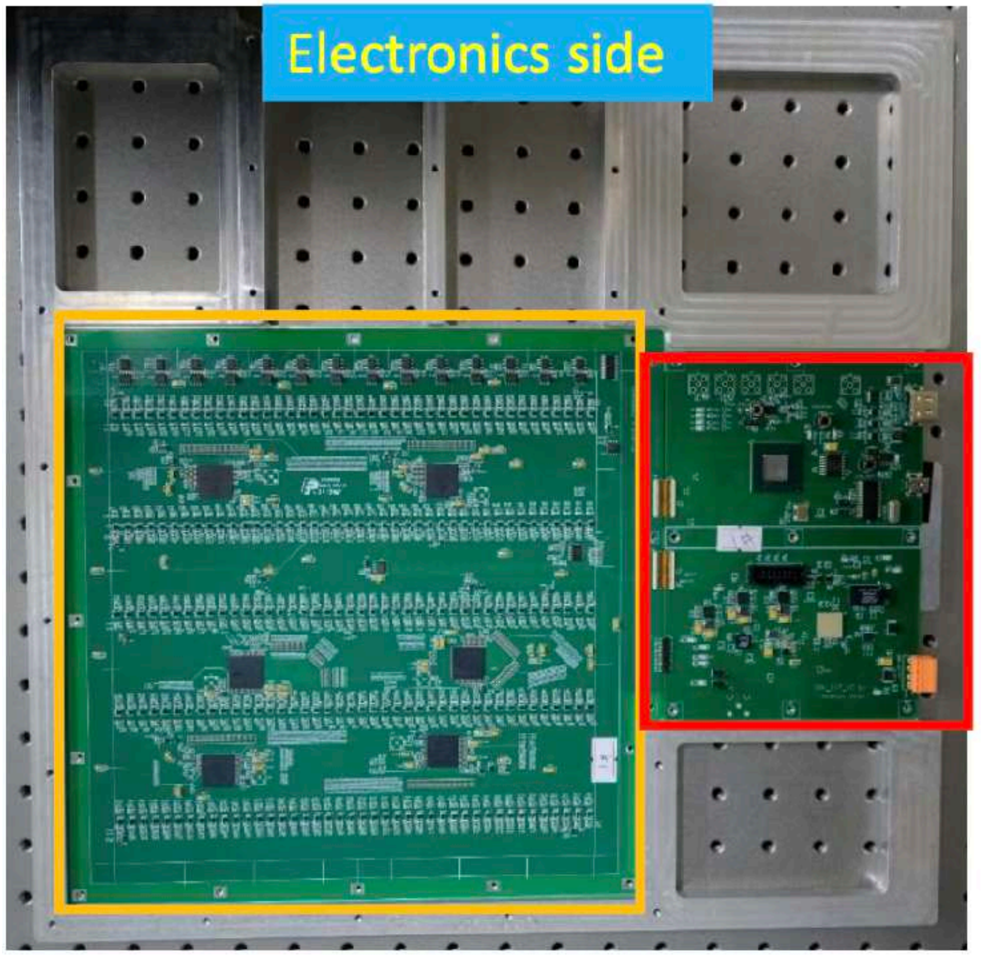
- Test production using dedicated mould
  - Dedicated mould with strips/tiles in different shapes
  - Light yield test in preparation

ECAL Base Unit (EBU)

- Fully integrated electronics for high granularity
  - 210 channels readout with 6 × ASIC (SPIROC2E) chips divided into 5 rows and 42 columns
  - Using S12571-010P (10μm-pixel) / S12571-015P (15μm-pixel) SiPMs
  - Electronics calibration and SiPM operation voltage adjustment realized
  - LED calibration and temperature monitoring circuits
  - Total layer: 6 mm / layer

- Scintillator strips were wrapped with ESR film and assembled on EBU boards by Shanghai Institute of Ceramic



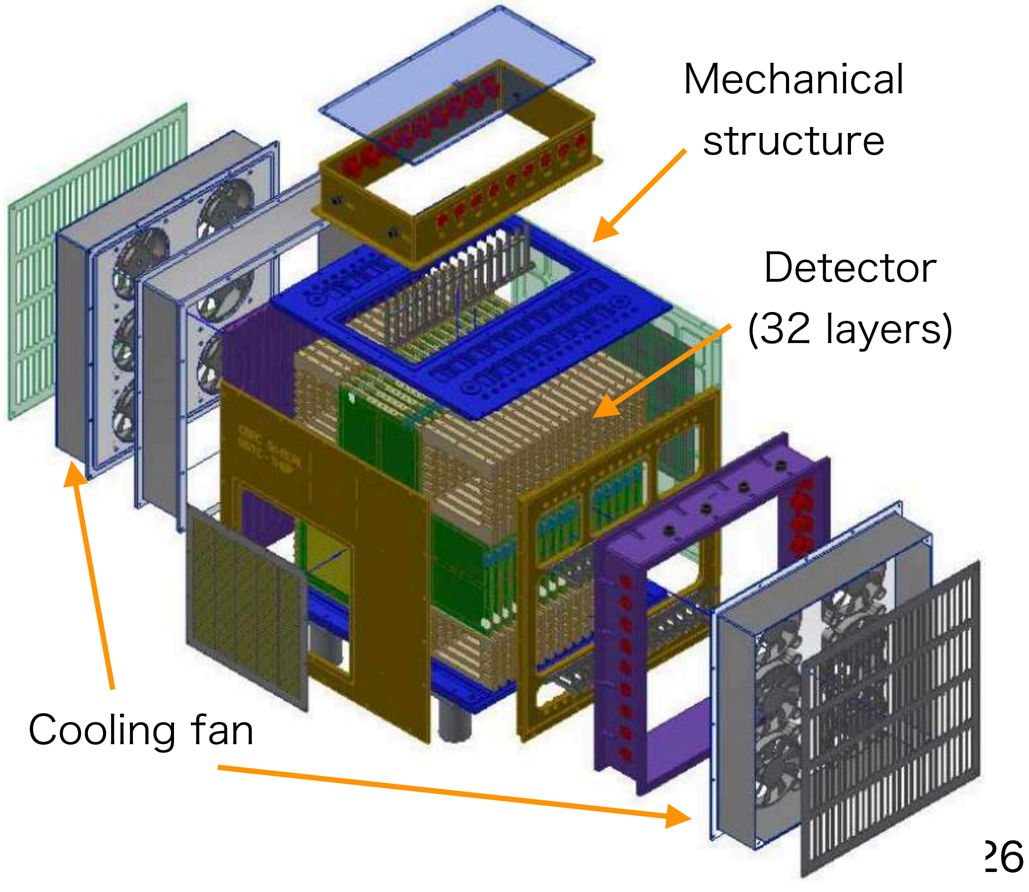


Contents

Technological prototype

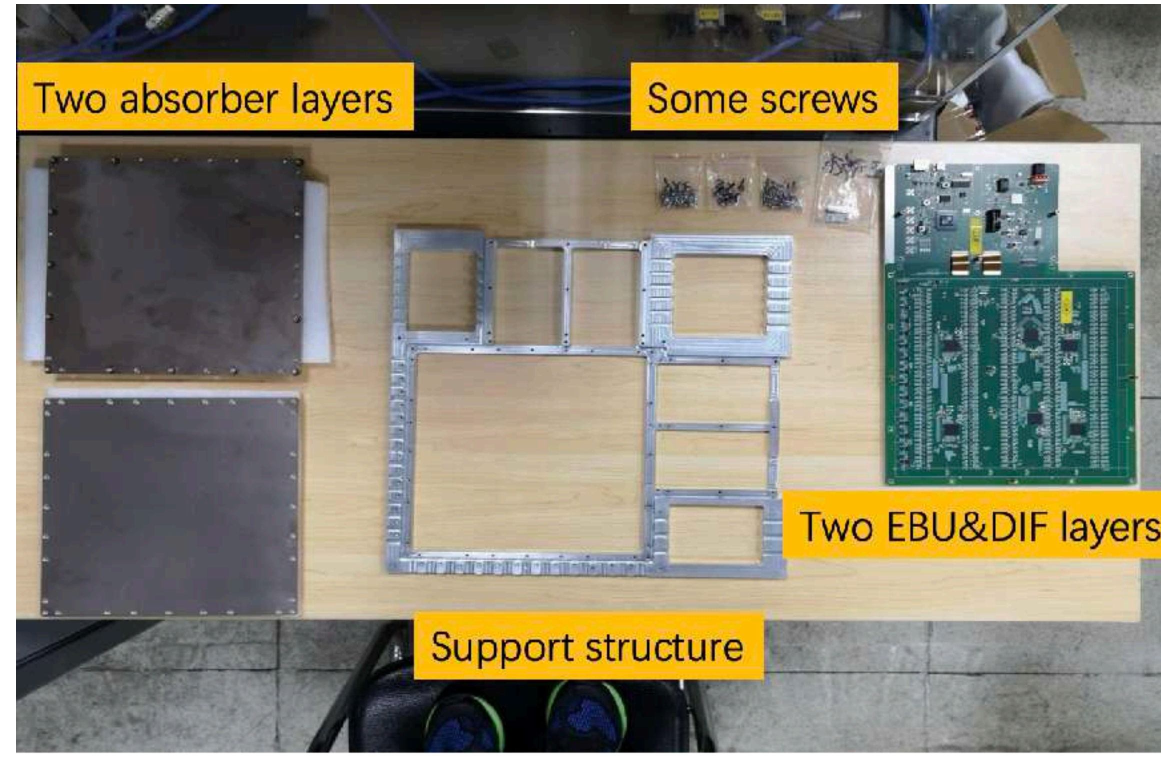
- **Technological prototype for Sc-ECAL has been constructed as a joint effort by R&D groups for ILC-ILD and CEPC-ECAL**
  - Use the same technology as foreseen in the full scale detector
  - Evaluate the performance using full layers (32 layers)
- Two detection layers with double SiPM readout have been installed in the prototype
- Two additional layers with new type of SiPM are also tested

- Test beam in DESY
  - Originally scheduled in Aug. 2020, but postponed to Mar. 2021, which was again canceled due to COVID-19
  - Hoping to have it later this year

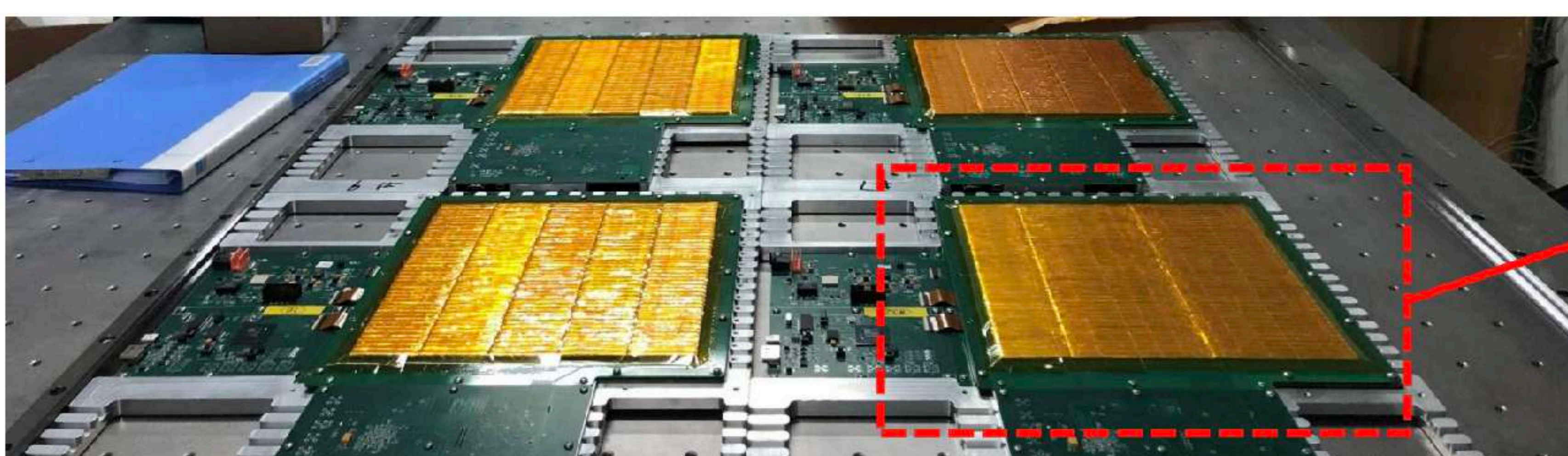


Assembly & mounting

- 16 super-modules (32 EBUs) completed
- One super-module consists of two sets of EBU and absorber layer
  - 2 EBUs in x-y configuration
  - Absorber layer: 3.2 mm, 15%-85% Cu-W



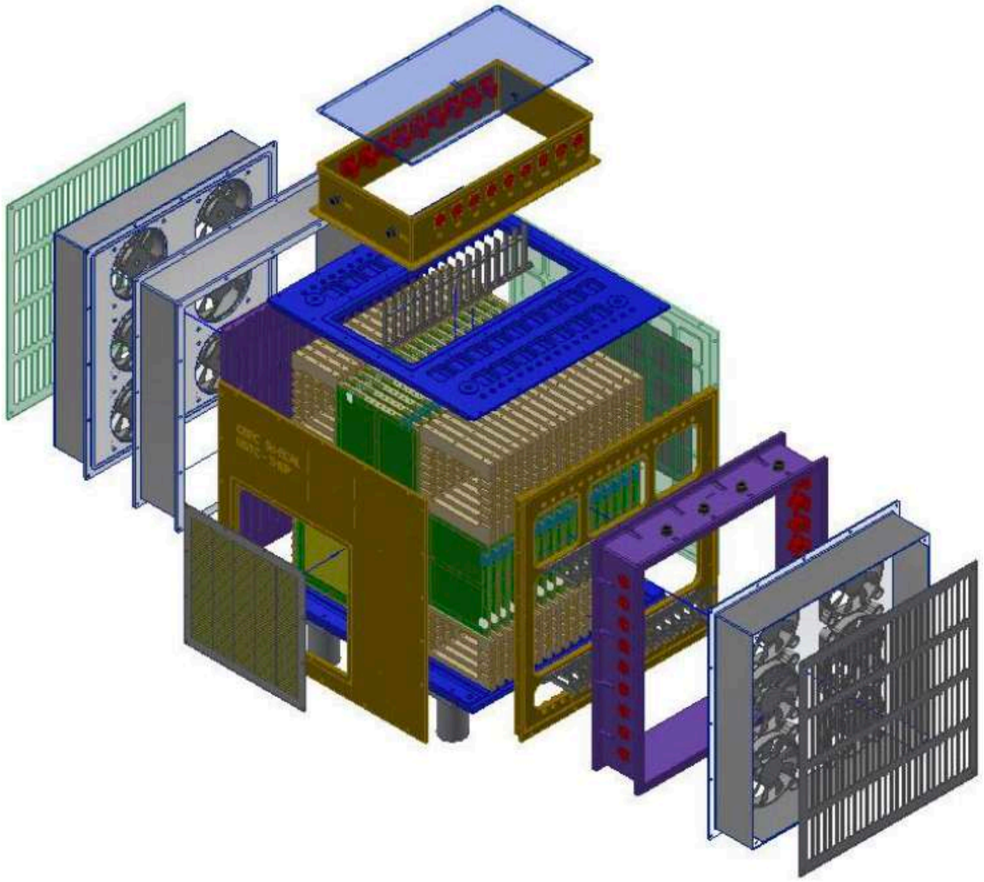
Super-module	#module (EBU)	SiPM	Strip length	Strip material (process)
Single-readout 1	12 (24)	S12571-010P	45 mm	PVT (casting)
Single-readout 2	3 (6)	S12571-015P	45 mm	PVT (casting)
Double-readout	1 (2)	S12571-015P	90 mm	PS (injection moulding)
Shinshu	1 (2)	S14160-1315PS	45 mm	PVT (casting)

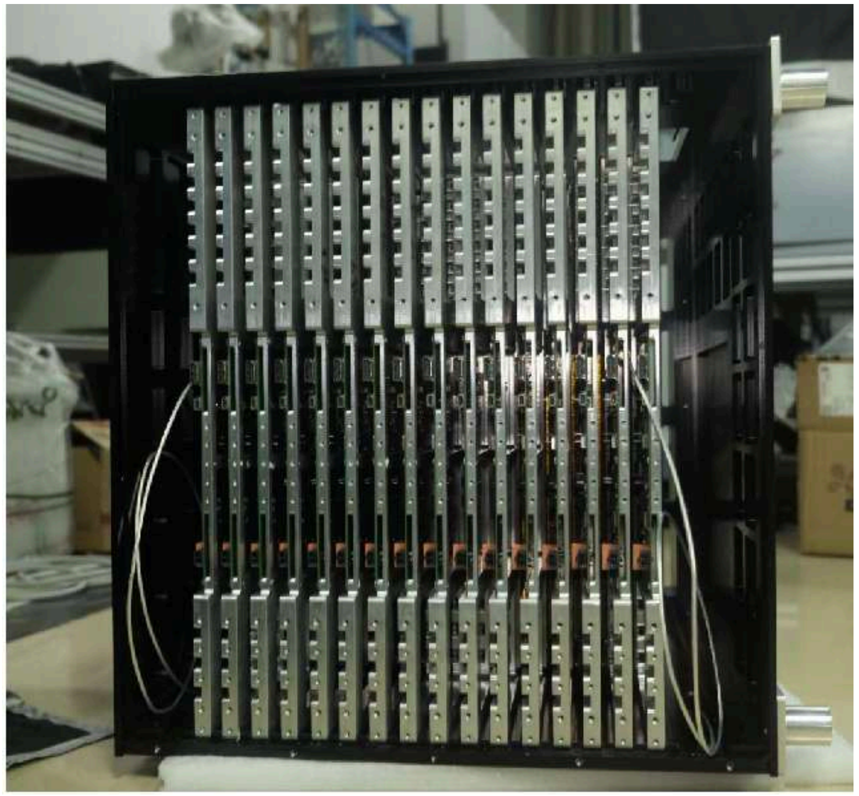


Double-side readout layer

Mechanical structure

- The mechanical structure with 17 slots for super-modules
- **Assembly of full Sc-ECAL prototype finished**

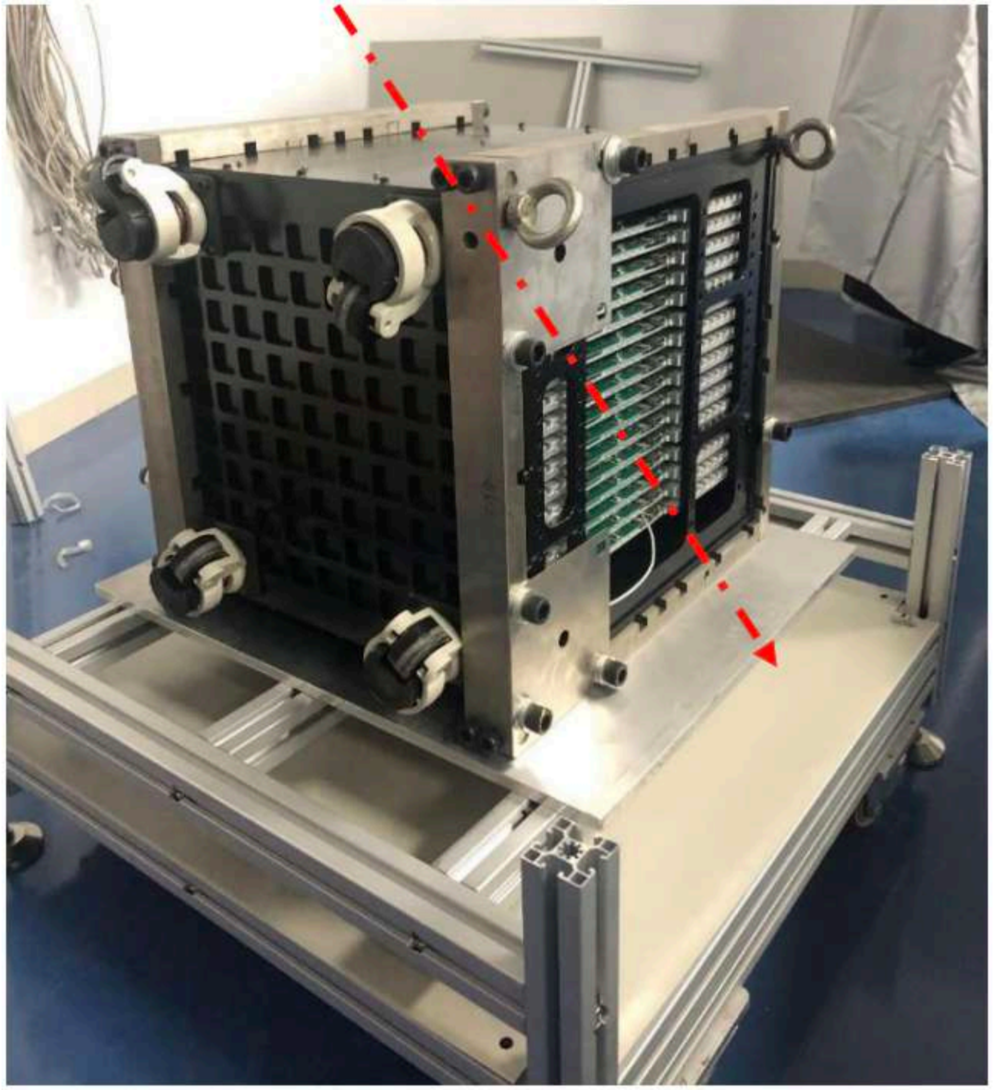


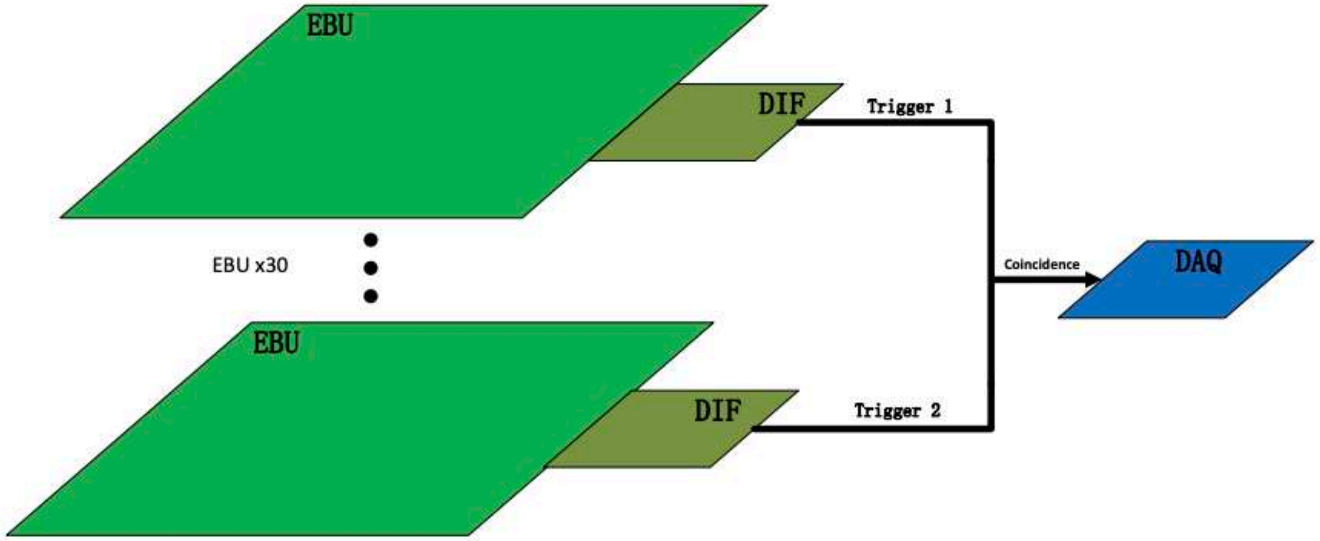


Cosmic-ray test

- Purpose
  - Perfomance evaluation
    - Track finding
    - Efficiency & position resolution
  - Cell-to-cell MIP calibration

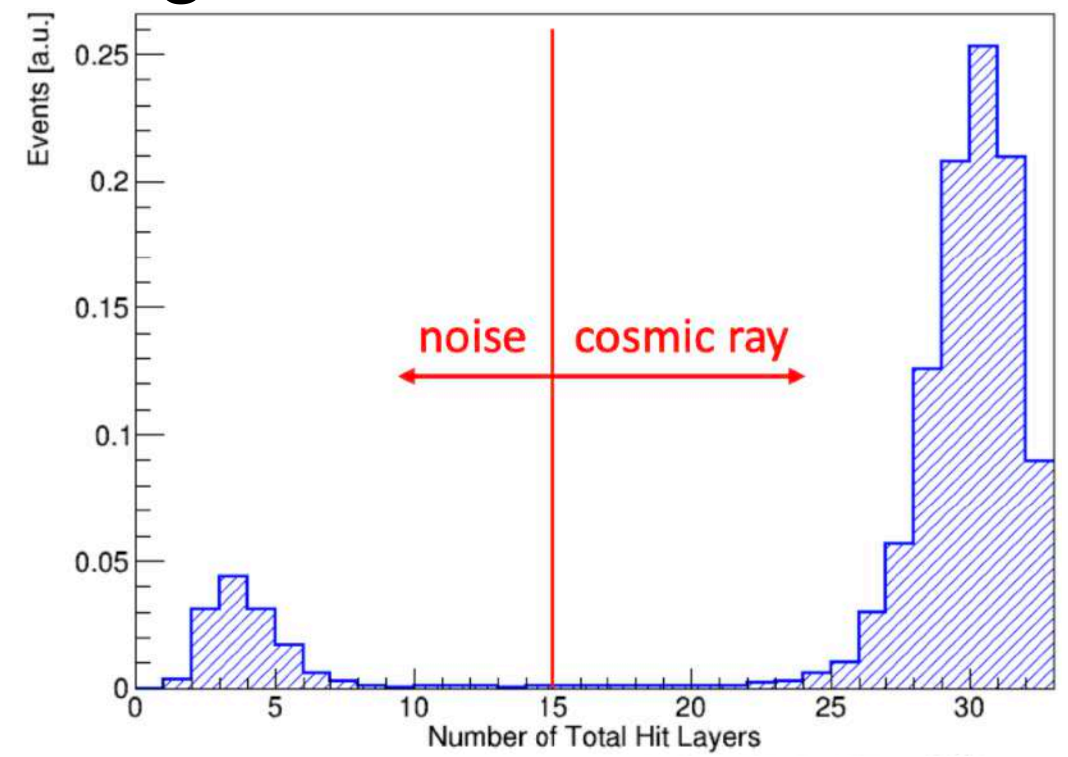
- Longterm test in 1.5 month
  - Coincidence trigger of top and bottom layers
  - Event rate: ~16 events per minute
  - Collect ~2000 events at each channel



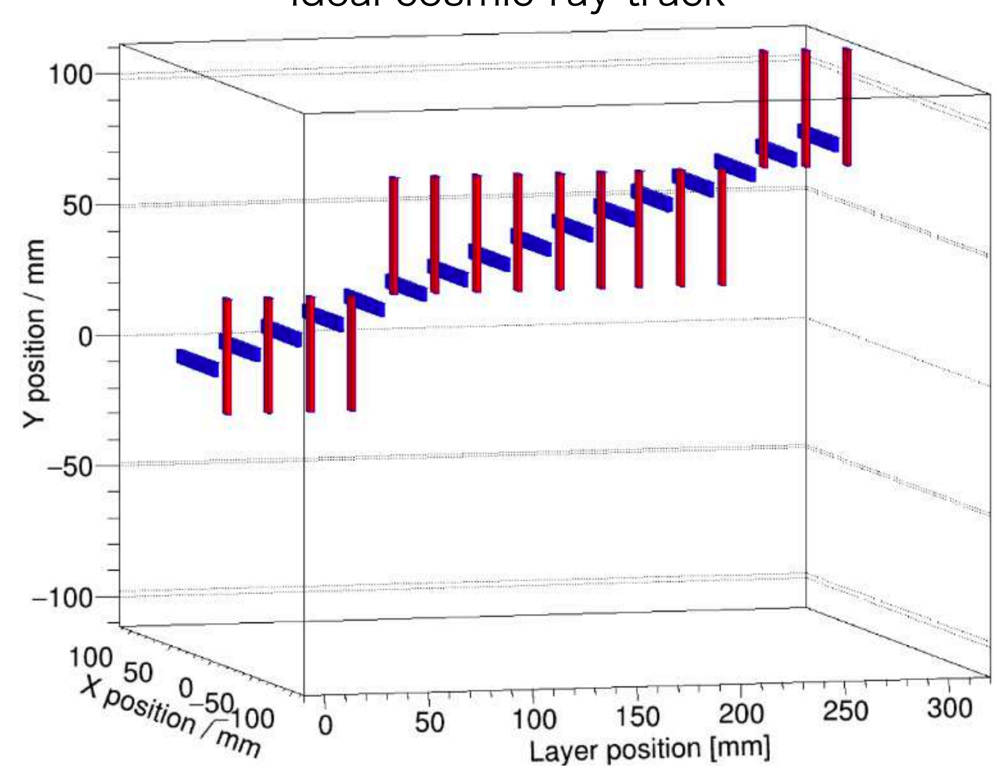


Track finding and fitting

- Some preselections are needed
  - Get rid of noise
  - Find the precise hit track
- A preliminary algorithm performed



Ideal cosmic-ray track

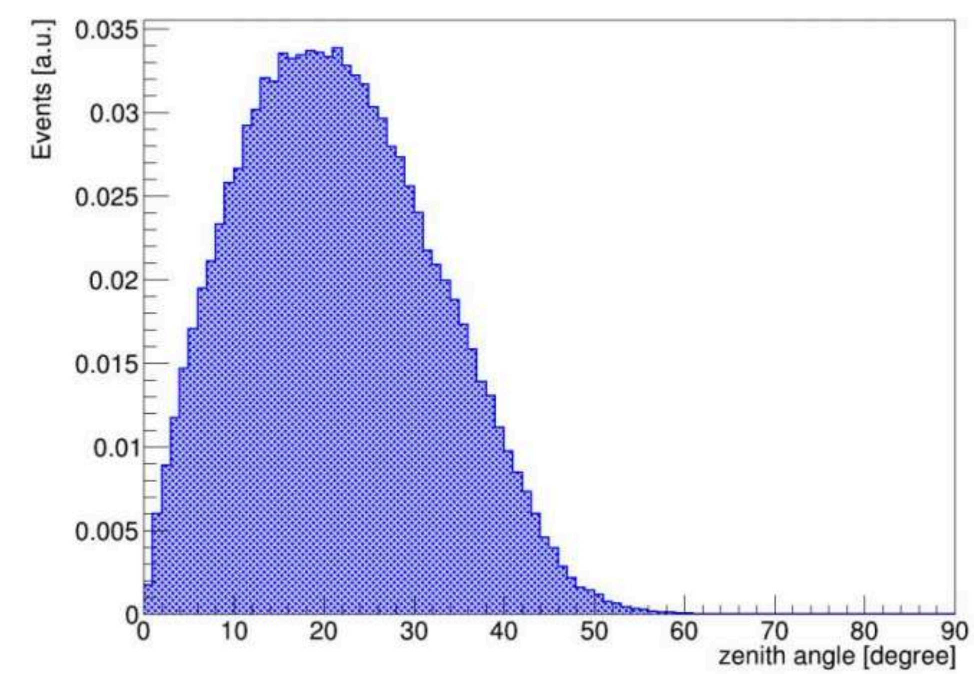


	Cut	Efficiency
preSelections	$TotalHitLayer \geq 22$	92%
	$TotalHitStrips \leq 64$	99.6%
	$ADC \geq 5\sigma$	99%
Iteration Fitting	All hits	
	$\lvert Pos_{x/y} - tracking\rvert \leq (47.5, 5, 7.5)$	
Track Selections	$\lvert Intercept_{x/y}\rvert \leq 114$ $\lvert\varphi_{x/y}\rvert \leq 0.7$	98.2%
	$\sigma^2_{x/y} \leq 9.6$	98.3%
	$TotalHitLayer_{x/y} > 6$	99.8%
Alignment	$Pos_{x/y} - track\ fitting$	

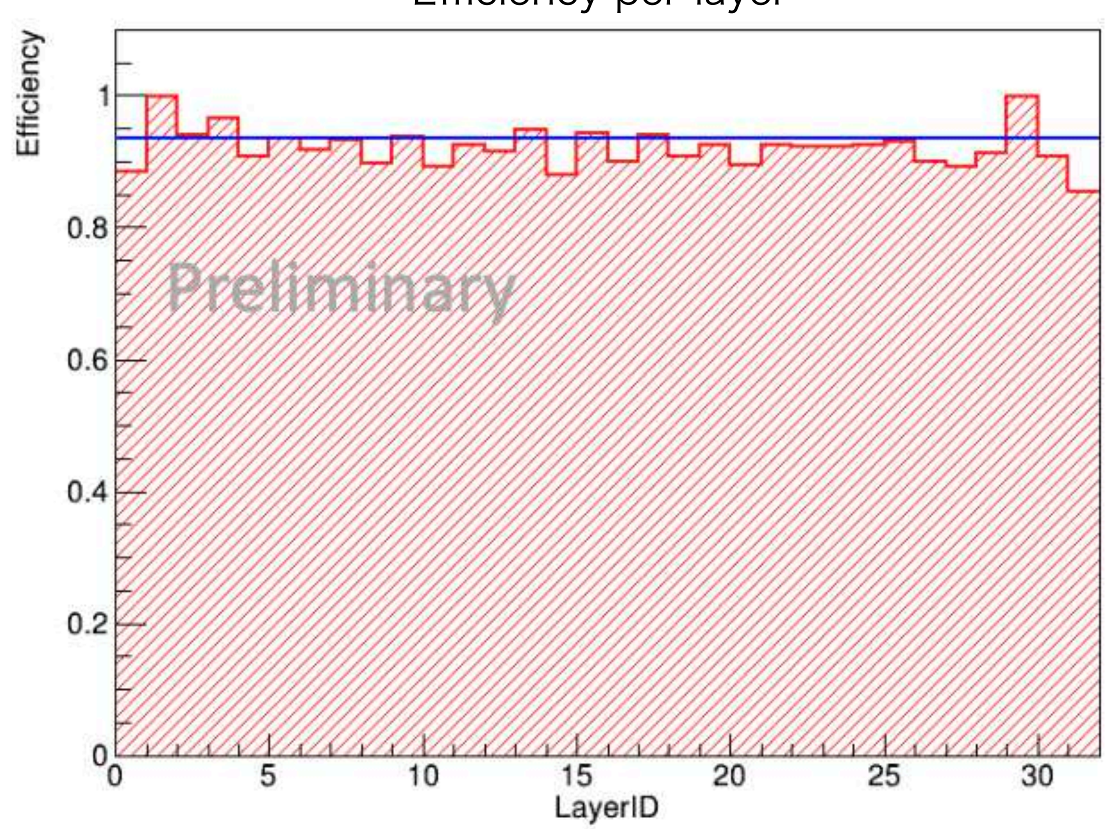
Performance

- Efficiency achieves 95% for all layers
  - Layer 1 & 29 are trigger
  - Affected by MIP threshold
- Position resolution: ~2 mm
  - Difference b/w hit position and fit track for a given layer
  - Achieve the requirement for Sc-ECAL

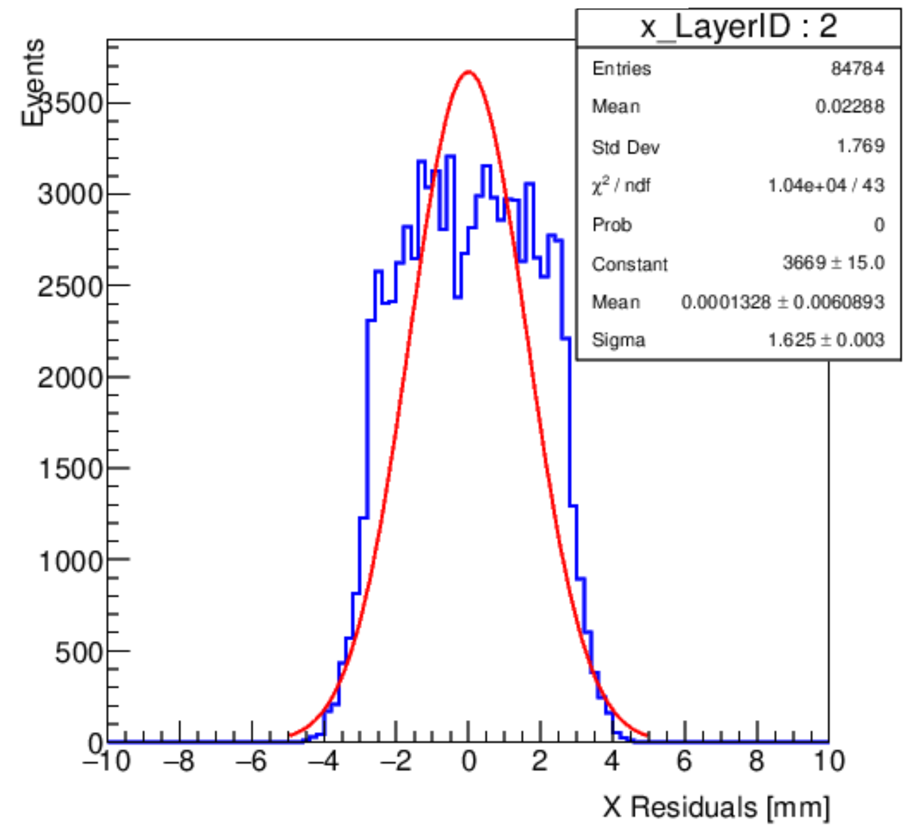
Zenith angle of injection particle



Efficiency per layer

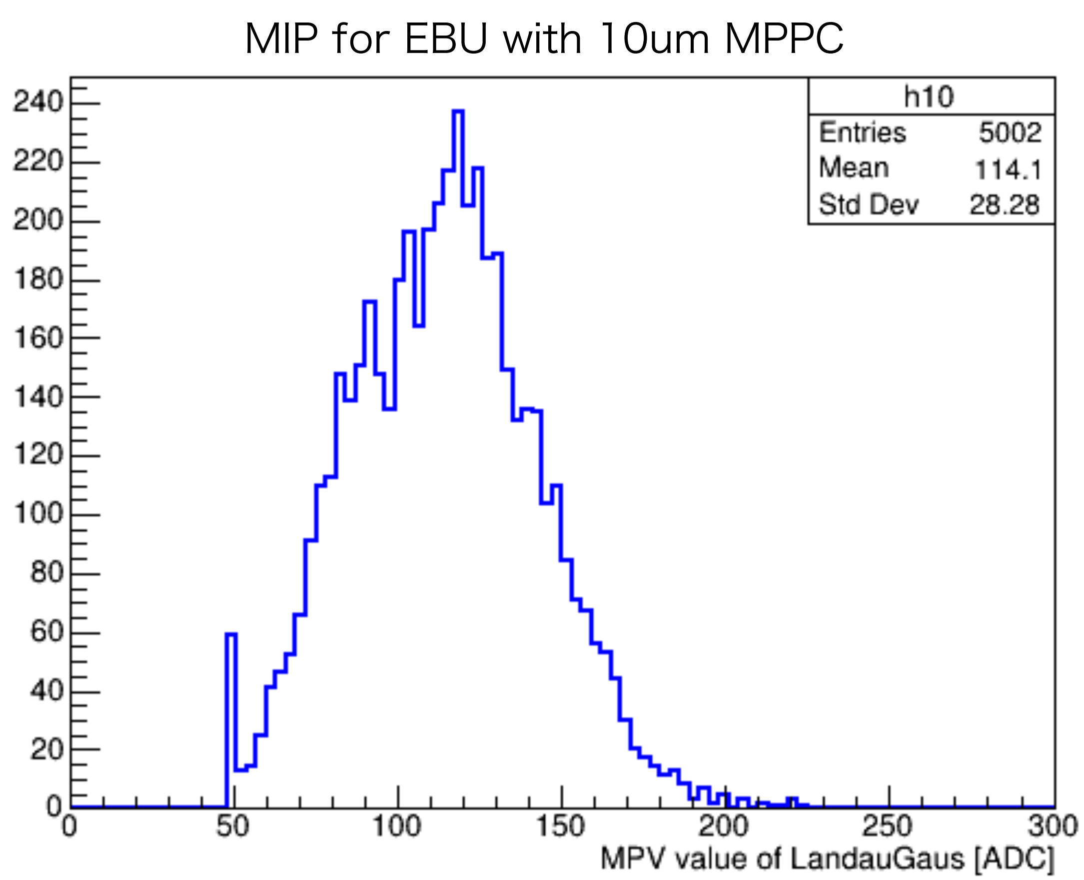


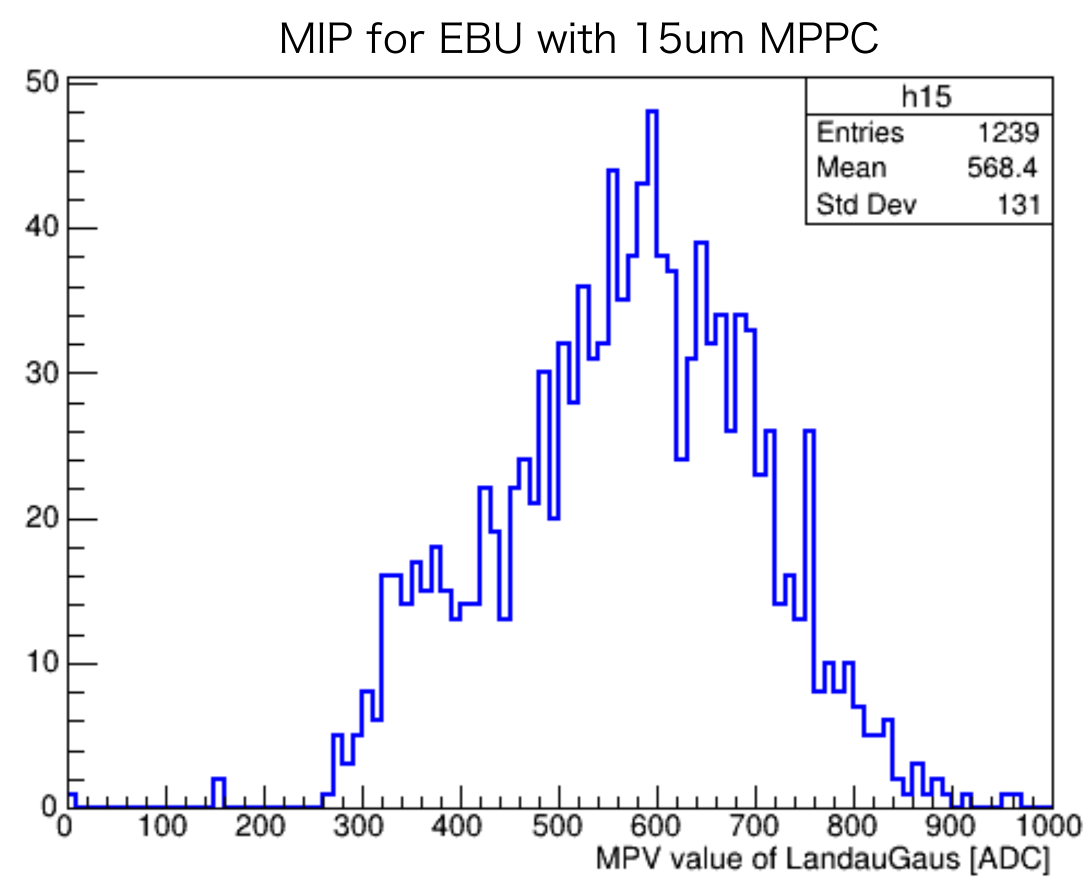
Position difference



MIP calibration

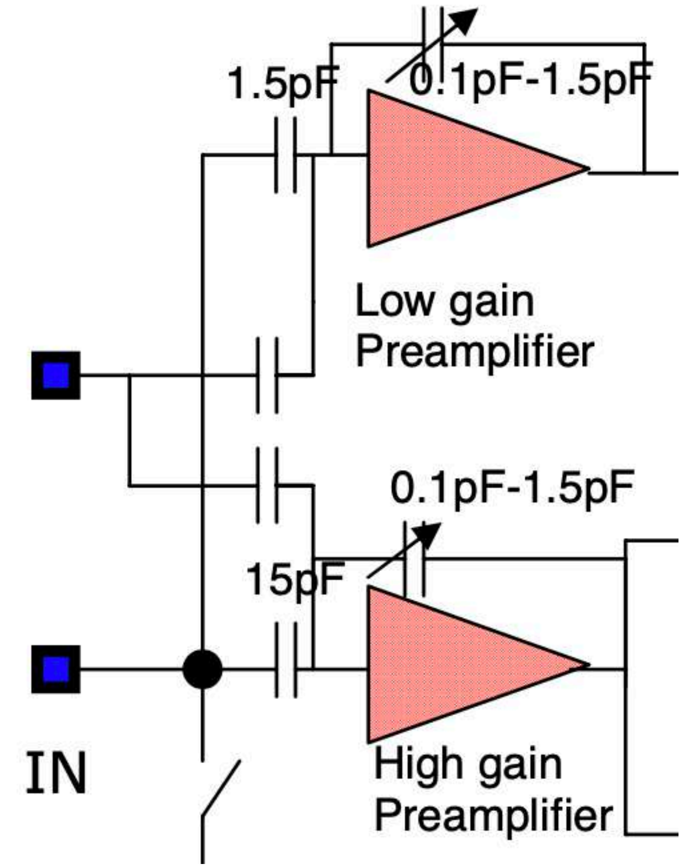
- Preliminary Cell-to-cell MIP calibration succeeded
  - After the angle and gain correction
- MIP values widely spread
  - MIP value is different channel to channel and chip to chip
- Dead channels ~1%
  - 66 / 6720



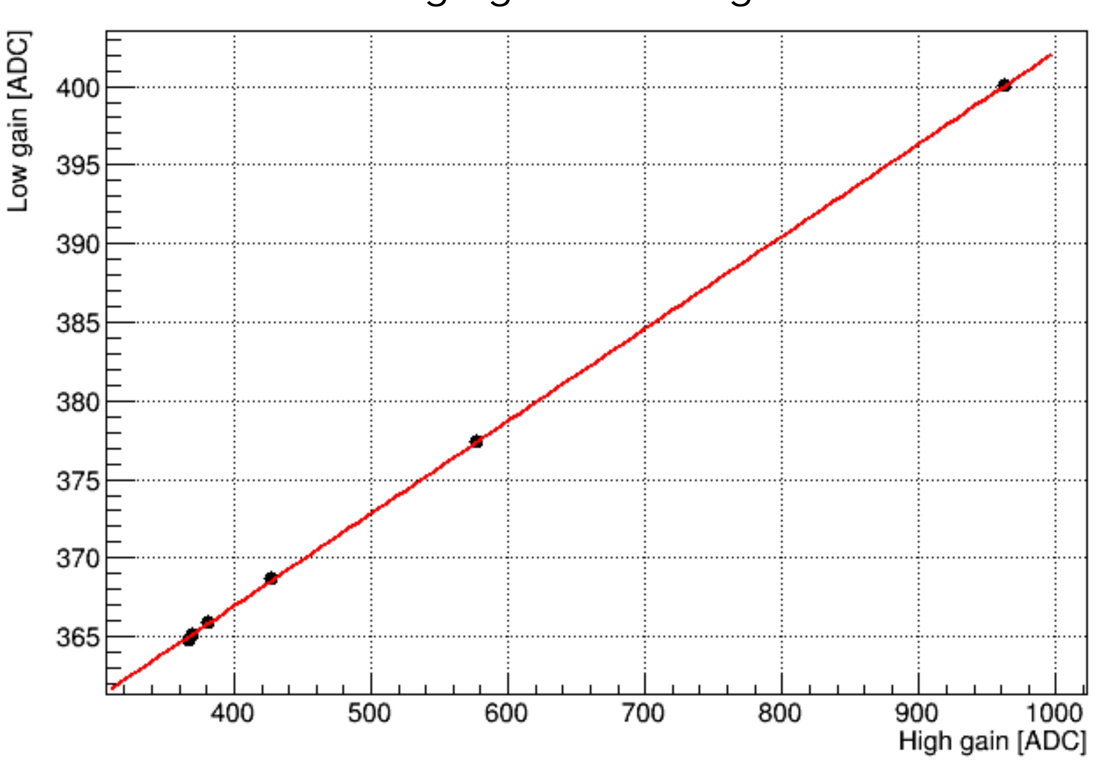


LED calibration (Inter-calibration)

- LED calibration
  - Inter-calibration of low gain and high gain for electronics
  - Gain calibration of SiPMs (going to study)
- SPIROC2E has high gain and low gain preamplifier
  - Record both data



- Inter-calibration factor obtained by the gradient of the relation
  - Check ADC counts of high gain and low gain, and these relation
    - Turn on LED at different voltages



Contents

Summary and Prospects

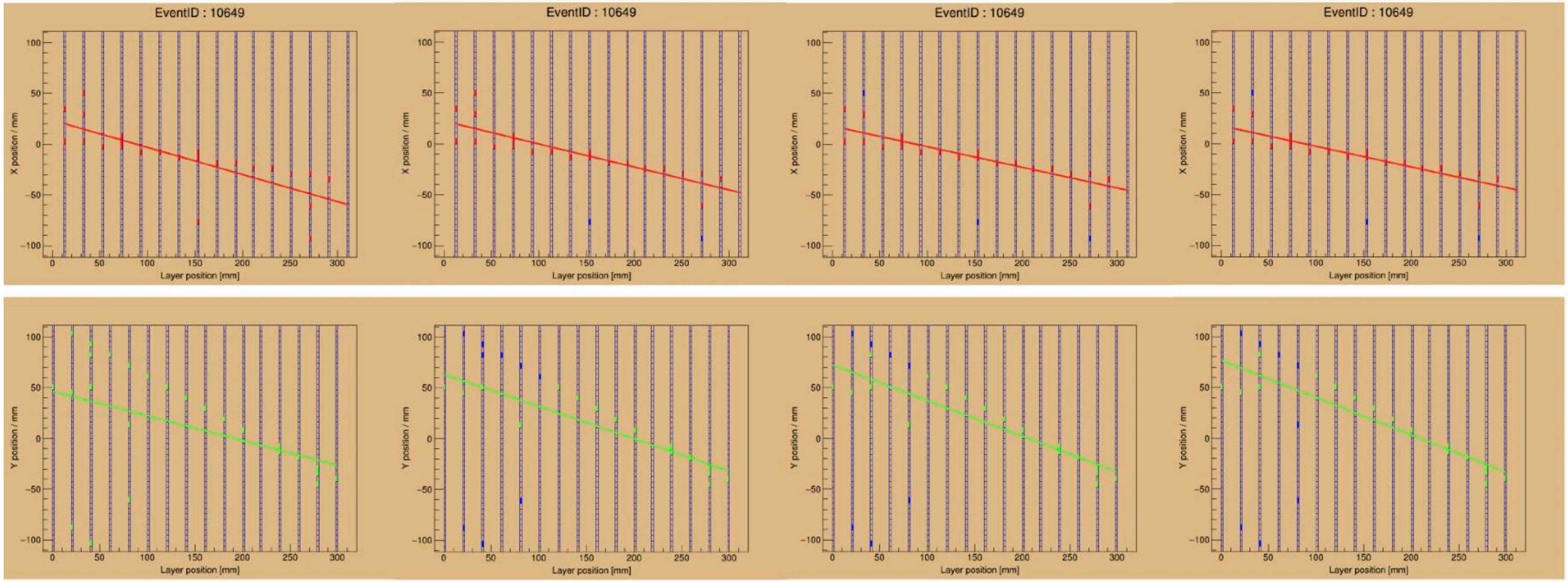
- Scintillator ECAL
  - In order to realize PFA and high jet energy resolution, high granular calorimeter is required
  - Virtual segmentation : 5 × 5 mm^2 with scintillator strips in x-y configuration
- R&D status
  - Small-pixel SiPM developed for large dynamic range
  - Bottom-center SiPM coupling gives the best performance
  - Double SiPM readout tested, and detection layer developed
  - Polystyrene-based scintillator produced by injection moulding has good light yield and capability for large-scale production
  - Fully integrated electronics developed
- Sc-ECAL technological prototype
  - Full 32 layers and mechanical structure constructed
  - High efficiency and 2 mm position resolution achieved
  - Cell-to-cell MIP calibration implemented
  - LED calibration such as inter-calibration is on going

Prospects

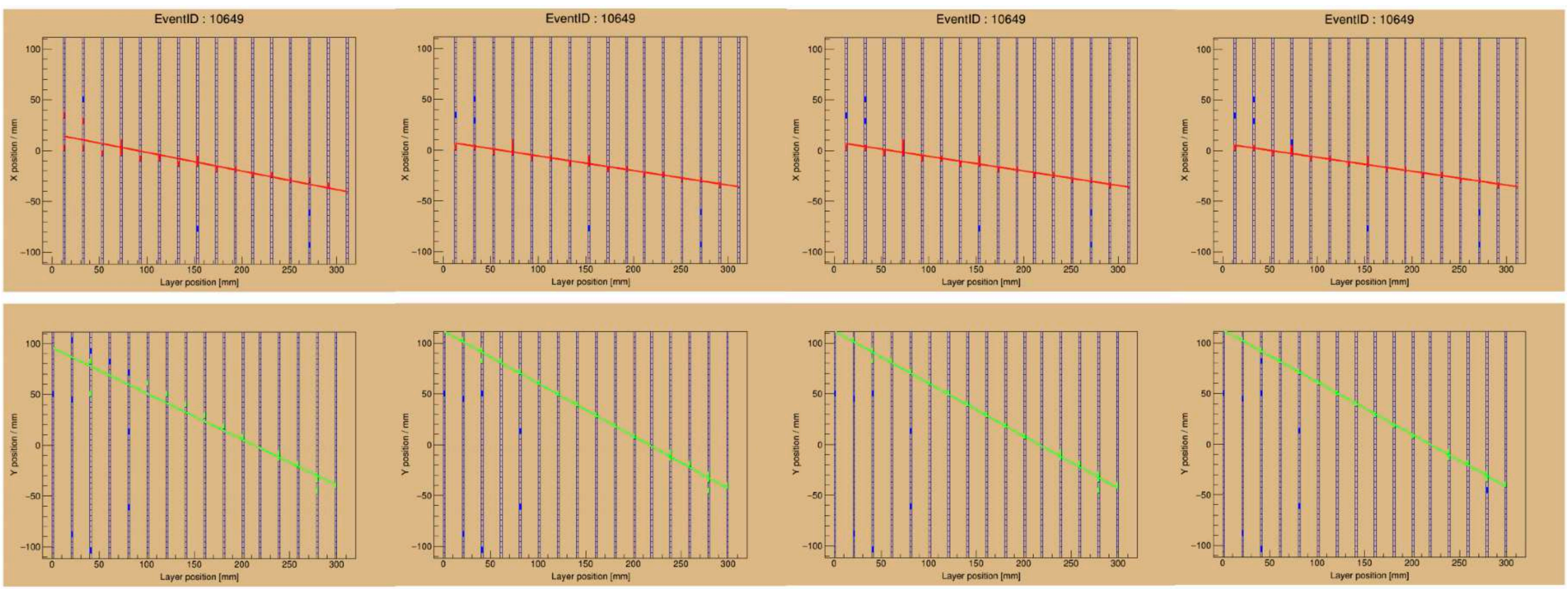
- Test beam experiments
  - Test beam using electron beam at DESY in 2021
  - Combined test beam experiments together with other CALICE calorimeter prototype
    - such as AHCAL
- Remaining
  - Detector assembly system for large-scale production
  - Test of power pulsing operation of integrated electronics for ILC Sc-ECAL
  - Optimization of cooling system of integrated electronics for CEPC Sc-ECAL
    - Continuous operation required for CEPC

Backup

Iterative fitting

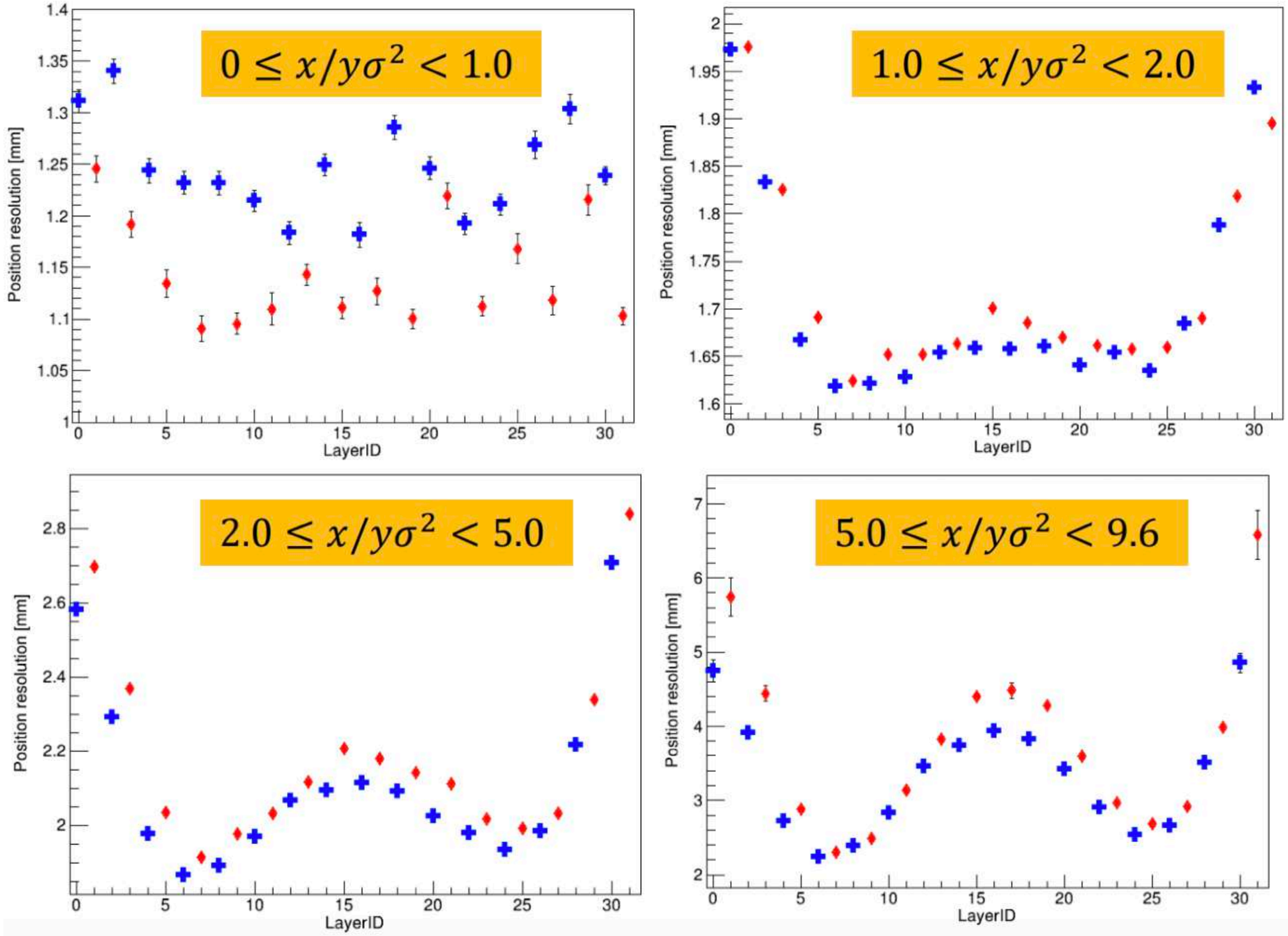


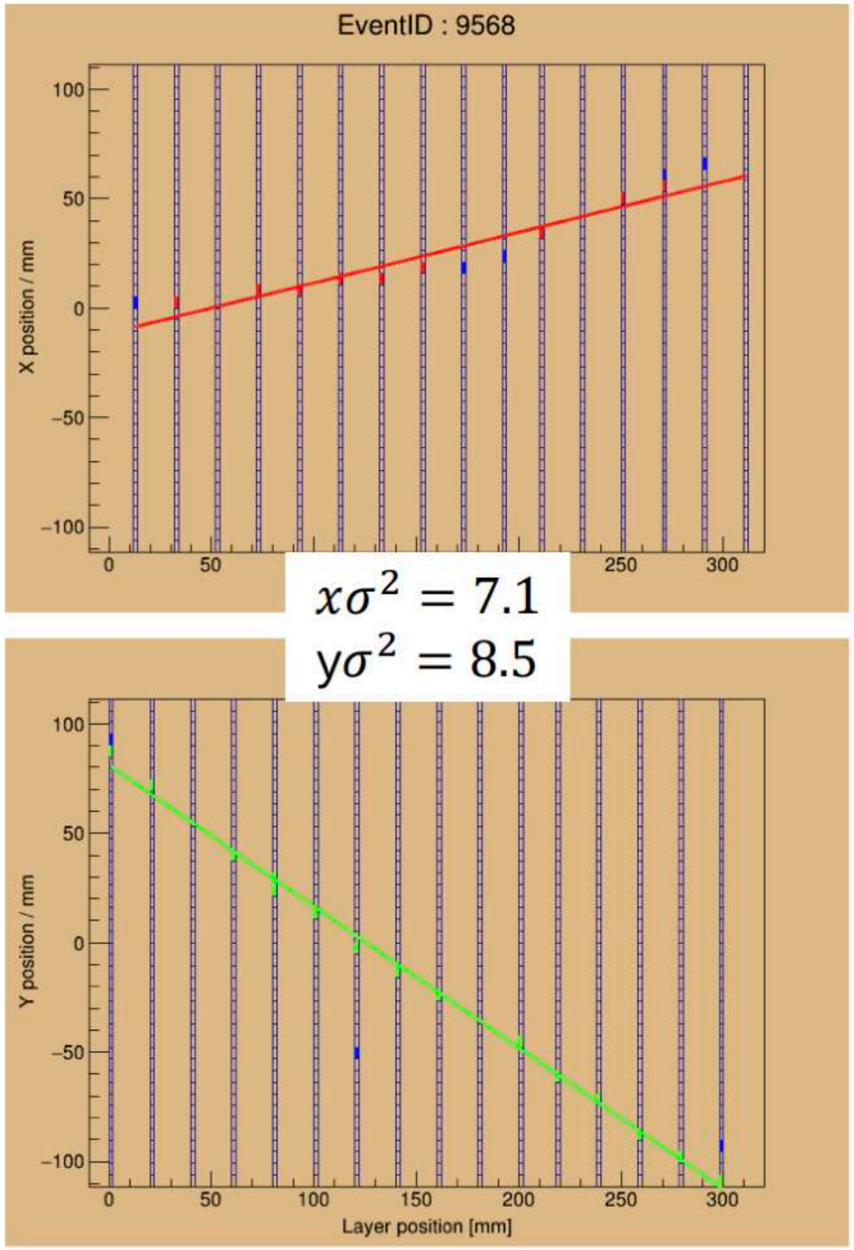
all hits $|x/y - tracking| \leq 37.5$ $|x/y - tracking| \leq 32.5$ $|x/y - tracking| \leq 27.5$



$|x/y - tracking| \leq 22.5$ $|x/y - tracking| \leq 17.5$ $|x/y - tracking| \leq 12.5$ $|x/y - tracking| \leq 7.5$

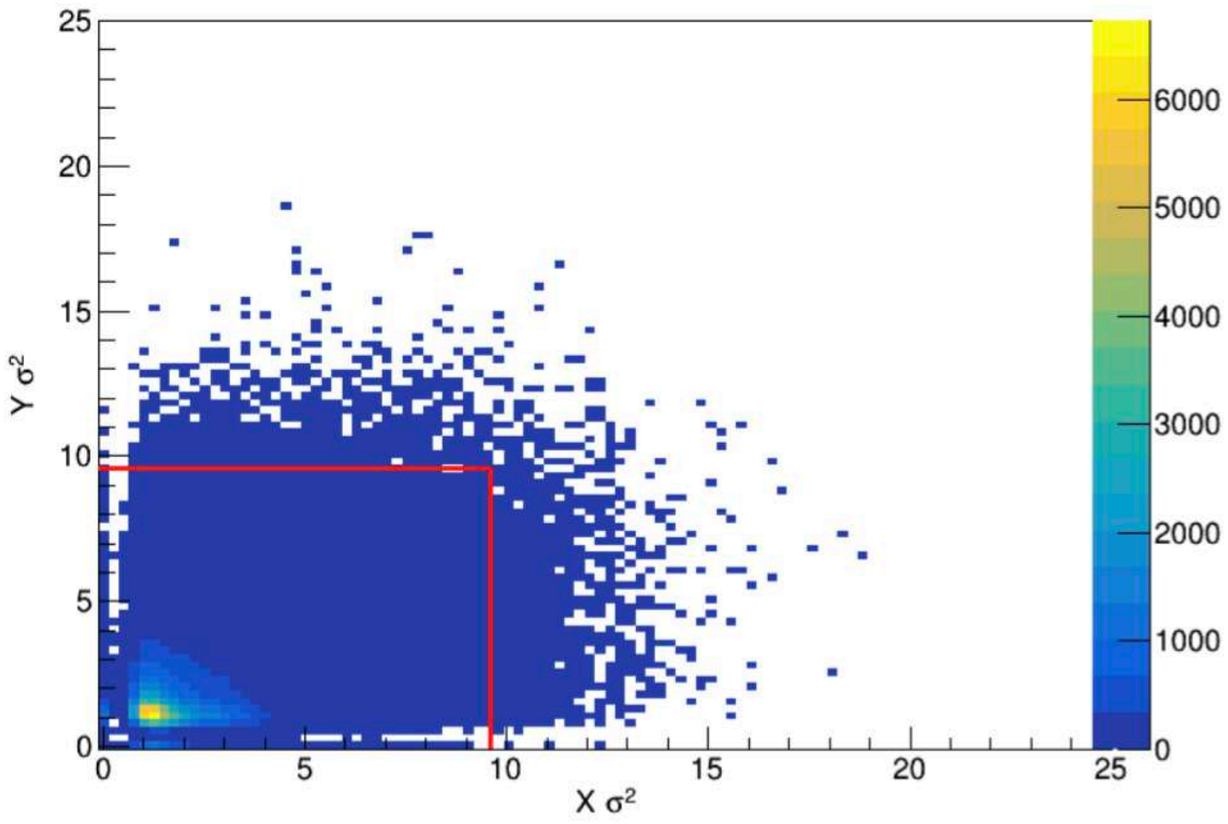
Large angle scattering





13

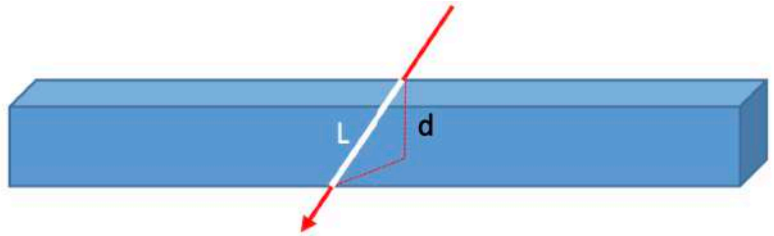
Residual Sum of Squares

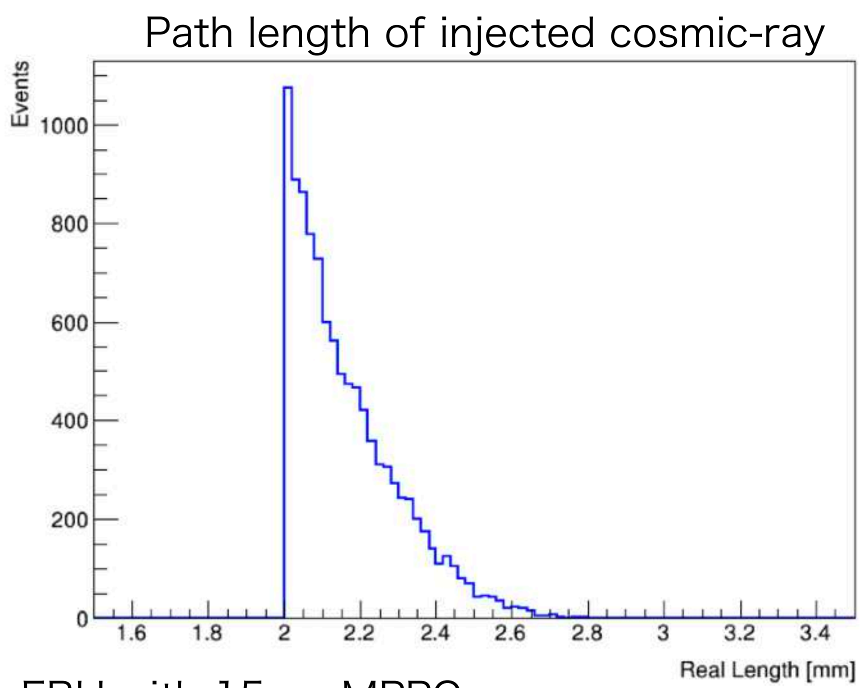


- Residual : $\hat{\varepsilon}_i = Y_i - \hat{Y}_i$
- Residual Sum of Squares : $RSS = \sum_{i=1}^{n} \hat{\varepsilon}_i^2$
- σ^2 unbiased estimation : $\hat{\sigma}^2 = \frac{1}{n-2} \sum_{i=1}^{n} \hat{\varepsilon}_i^2$

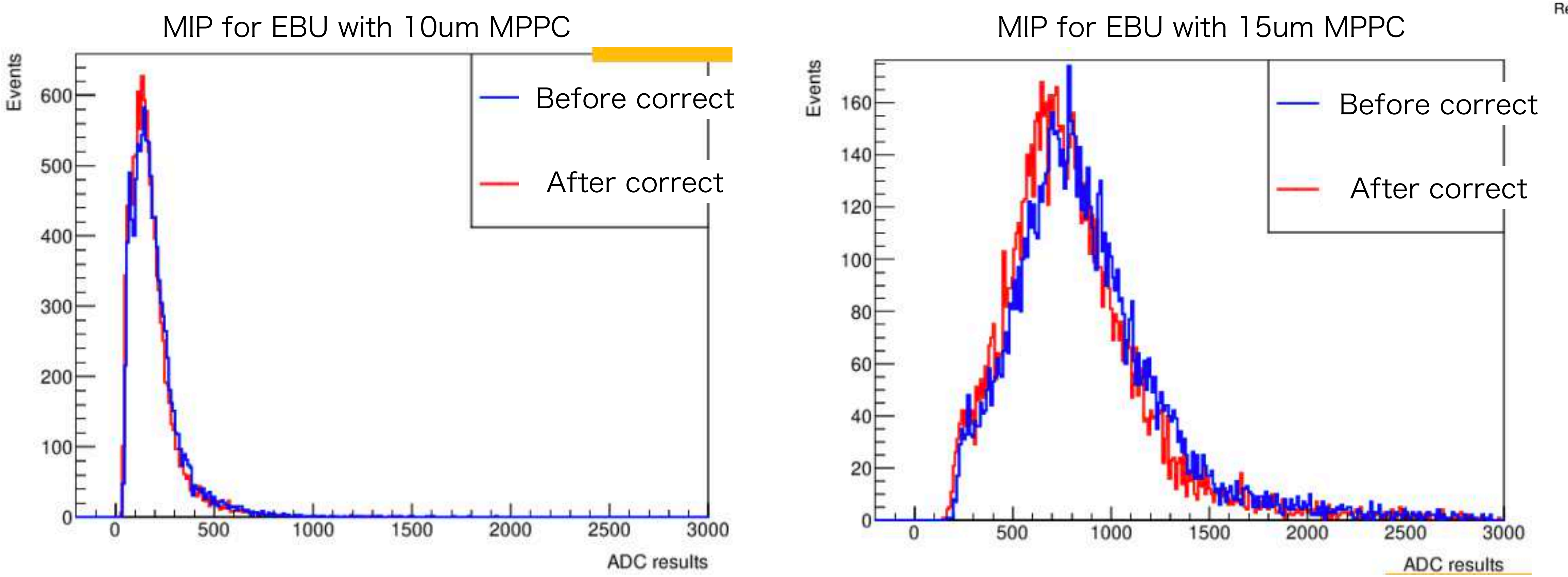
Angular correction for ADC

- ADC value should be corrected by the path length in the stri
  - If the path length is longer than 2 mm, the output ADC v



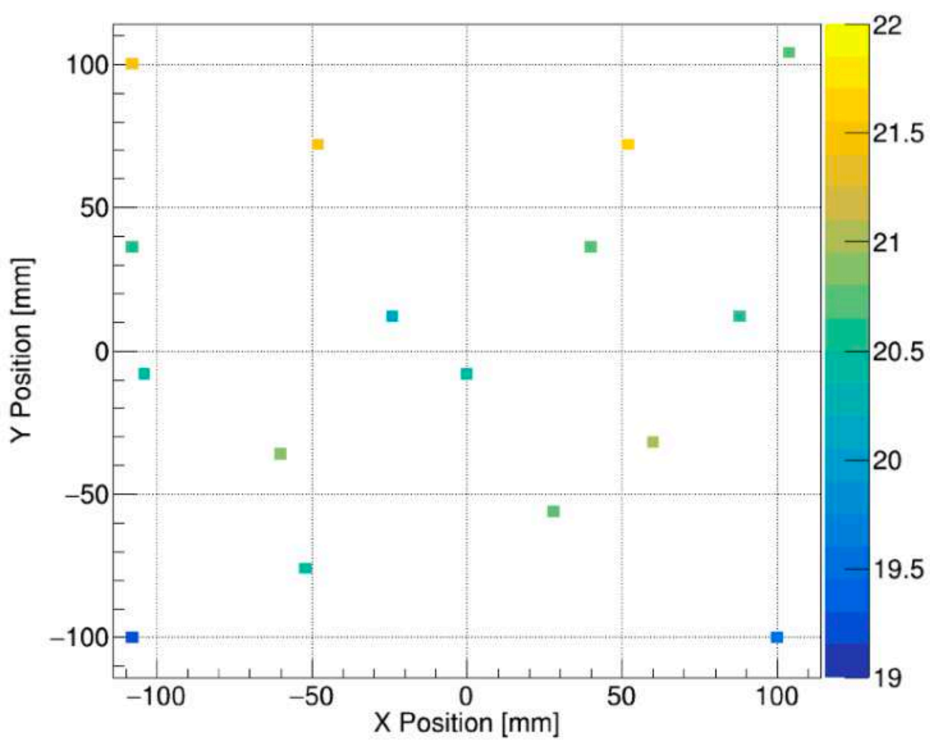


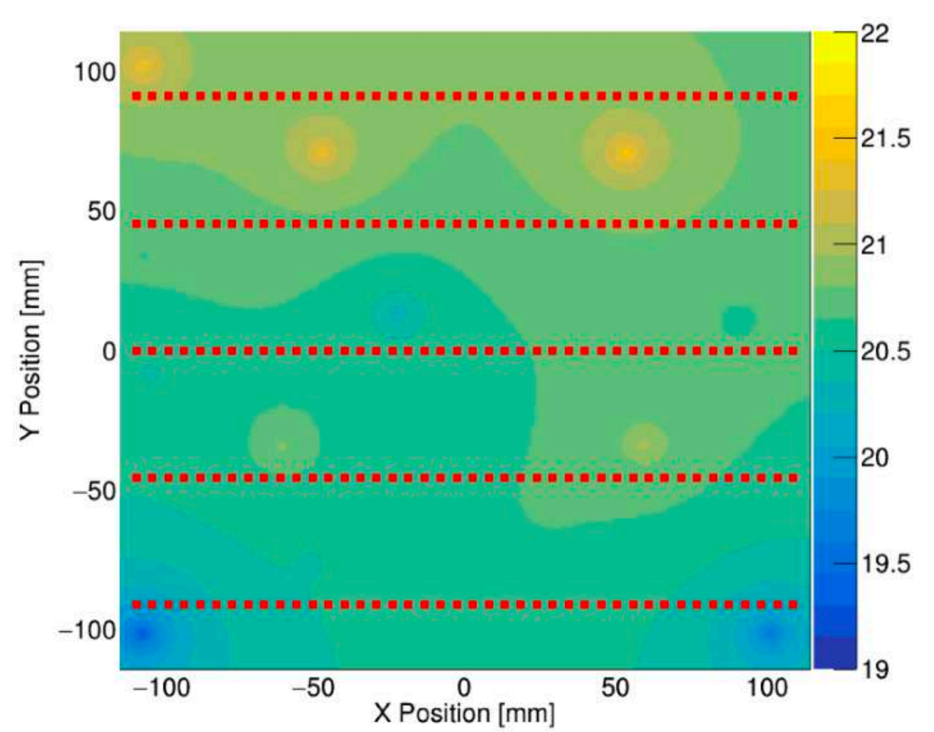
- Correction of incident angle is implemented



Temperature monitoring

- Each layers equipped 16 temperature sensors (0℃~85℃, ±0.1℃)
  - Temperature difference in one layer ~3℃
- Distribution on layer reconstructed by inverse distance weighted



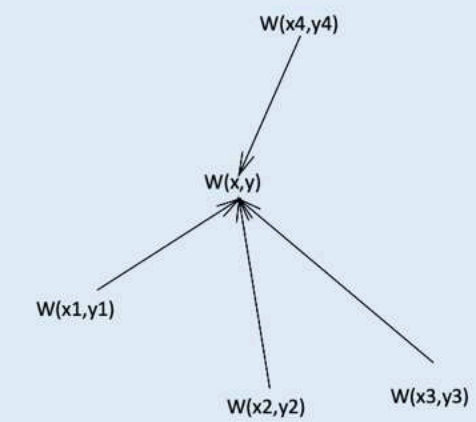


- **Inverse Distance Weighted**

$$W(x,y) = \sum_{i=1}^{n} Q_i W_i$$

$$Q_i = \frac{\frac{1}{L_i}}{\Sigma \frac{1}{L_i}}$$

(W: temperature, Q: weight, L: length)



Temperature and gain correction

- Temperature dependence of SiPM gain
  - -2%/℃
- Gain correction according to temperature is implemented
  - Setting 18 ℃ as reference temperature

Two period with large temperature difference