Development of Electromagnetic Calorimeter of Zero Degree Calorimeter

ePIC ZDC workshop@ 20251016

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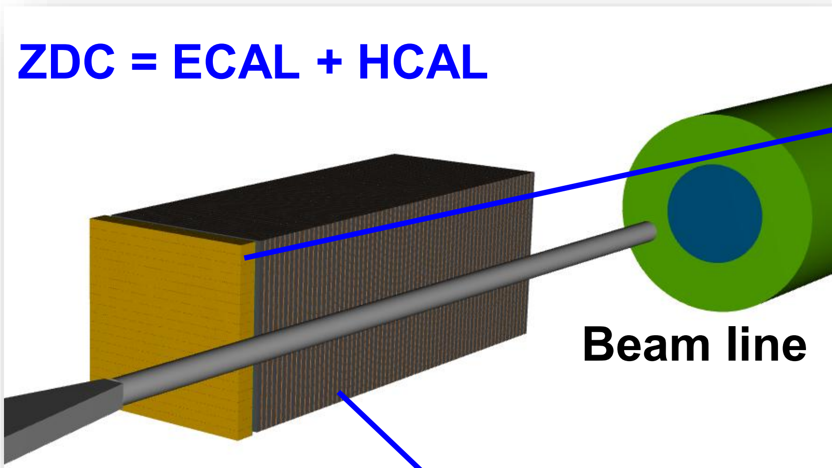
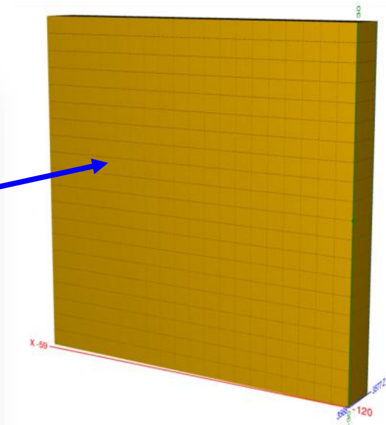
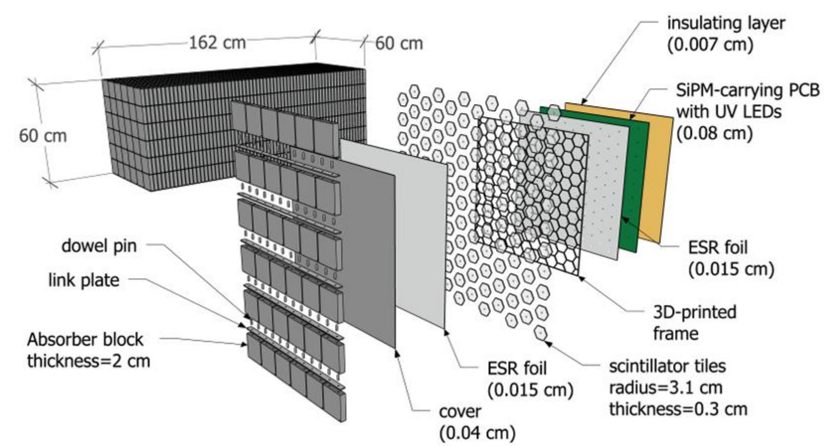
ZDC in ePIC Official MC





ECal

1. **LYSO Crysal**
2. 20*20 cells
3. 3cm*3cm*7cm / cell
4. 60cm*60cm
5. **7cm ~ 6.5X0 in Z**



- **ZDC requirement :**
  - 35-50% energy resolution and 2 mrad angular resolution for HCAL (up to 300GeV neutron).
  - 2-5% energy resolution and 1-2 cm position resolution for ECAL (up to 40GeV gamma).

- **We have developed ZDC ECAL prototypes as similar design in MC with smaller size.**

HCAL : sampling calorimeter

1. **1 layer = steel + scintillator tile + SiPM**
2. 64 layers, 8 slice/layer
3. 65cm in X, 60cm in Y, 163cm in Z

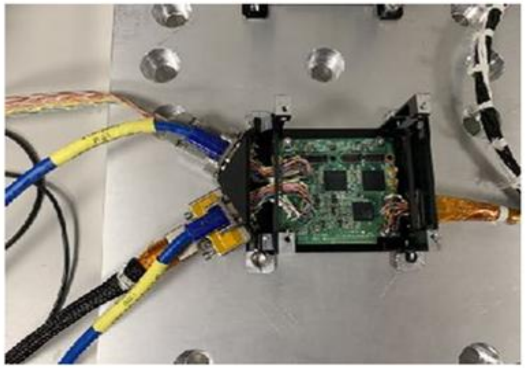
ZDC ECAL Prototypes

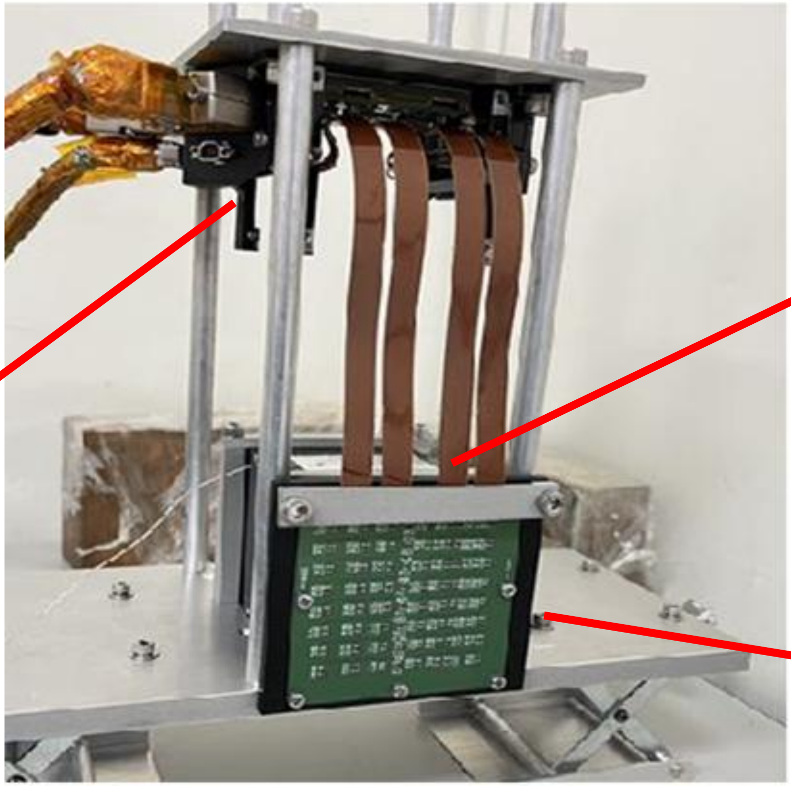
	Detector	Crystal				Sensor		DAQ
		name	Size of one cell	Length	Array	Type	sensor/crystal	
1st prototype 2023-2024	LYSO + SiPM	LYSO	0.7cm*0.7cm	**8.8cm (8X0)**	8x8	SiPM Onsemi MICROFC-60035	1	CITIROC
2nd prototype 2024-2025	LYSO + APD	LYSO	1cm*1cm	**6.6cm (6X0)**	8x8	APD C30739ECERH	1	CITIROC
	PbWO4 + SiPM	PbWO4	2cm*2cm	**5.3cm (6X0)**	6x6	SiPM Onsemi MICROFC-60035	2	CITIROC
3rd prototype 2025-2026 (developing)	LYSO + SiPM	LYSO	1cm*1cm	**6.6cm (6X0)**	8x8	SiPM Hamamatsu S14160-3015PS	4	**HGCROC**
	PbWO4 + SiPM	PbWO4	2cm*2cm	**5.3cm (6X0)**	6x6	SiPM Hamamatsu S14160-3015PS	16	**HGCROC**

In this presentation, we will discuss the **design and test beam analysis results of the 1st and the 2nd prototypes**. The **third prototype** is currently under development.

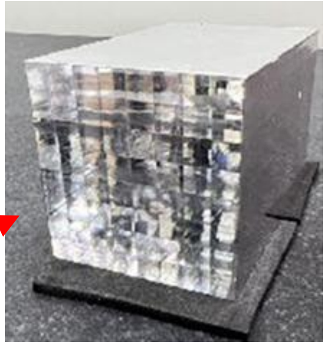
1^{st} Prototype of ZDC ECAL

CITIROC (160-400pC)

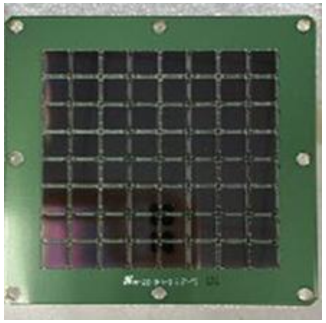




LYSO crystal (8x8 , 8X0, ESR)

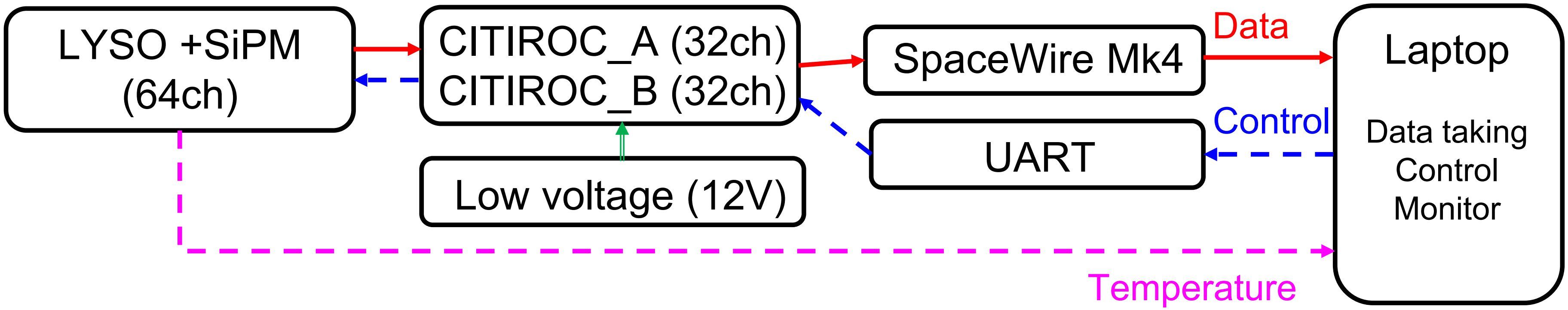


Onsemi SiPM



	Detector	Crystal				Sensor		DAQ
		name	**Size of one cell**	**Length**	**Array**	**Type**	**Sensor /crystal**	
1^{st} prototype 2023-2024	**LYSO + SiPM**	LYSO	0.7cm*0.7cm	**8cm (8X0)**	8x8	SiPM Onsemi MICROFC-60035	1	CITIROC

CITIROC DAQ



- **CITIROC** is a 32-channel front-end ASIC designed to readout silicon photo-multipliers.
- **Dynamic range up to 400pC**
- **Shaper**
- **Peak Sensenig ADC**

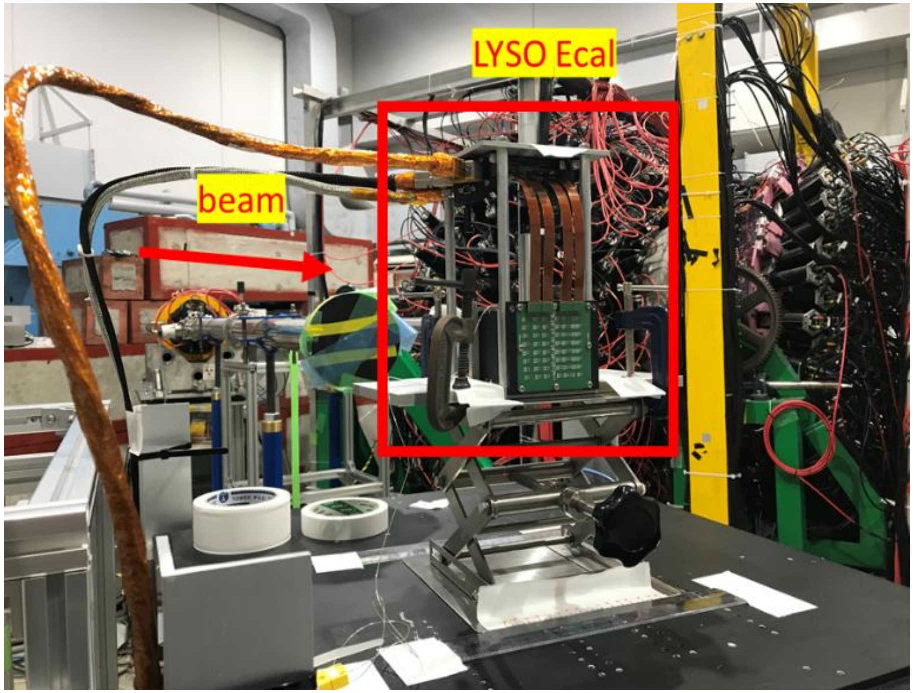
- **Data, slow control** (threshold, gain, etc setup), **online monitoring (**DAQ deadtime, temperature) are all through laptop interface.

- More details concerning **DAQ will be introduced by the talk given by Kai-Yu later.**

CITIROC spec.

- **TRL Technology Readiness Level**: 8 – Full system using ASIC running – learn more
- **Detector Read-Out**: SiPM, SiPM array
- **Number of Channel**: 32
- **Signal Polarity**: Positive
- **Self-Triggers**: Programmable 10-bit DAC with min threshold = 1/3 p.e.
- **OR trigger**: for timestamping and start of conversion
- **Dynamic Range**: 0-400 pC i.e. 2500 photoelectrons @ 10^6 SiPM gain
- **High and low gain branches,** with 1:10 ratio for a total 0.95-600 amplification range
- 8-bit input DAC for channel-by-channel **fine bias adjustment**
- **Slow shaper** with adjustable shaping time from 12.5 to 87.5 ns
- Energy measurements by Track&Hold or Peak Detector
- 1% linearity energy measurements up to 2500 p.e.
- **Power consumption**: 7 mW/channel

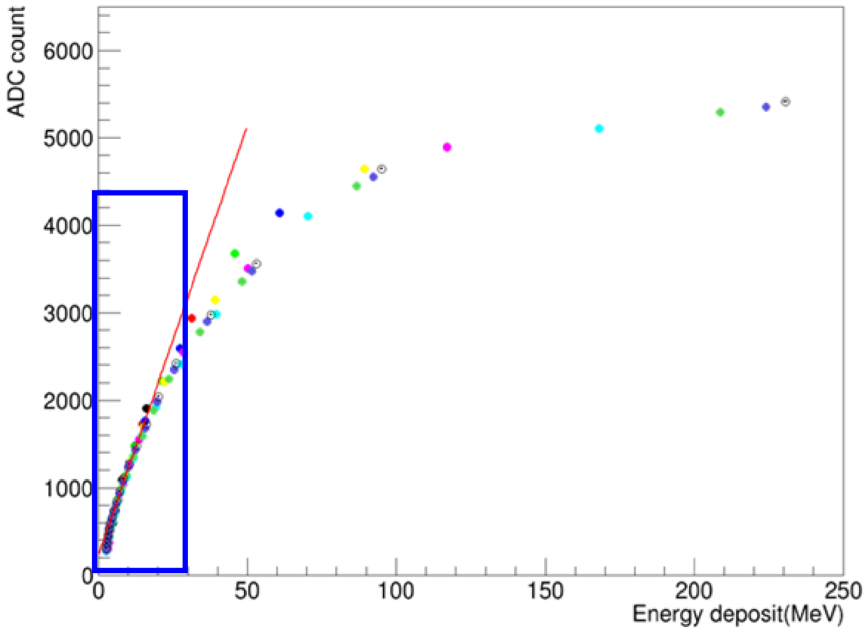
1st Prototype : Beam Test

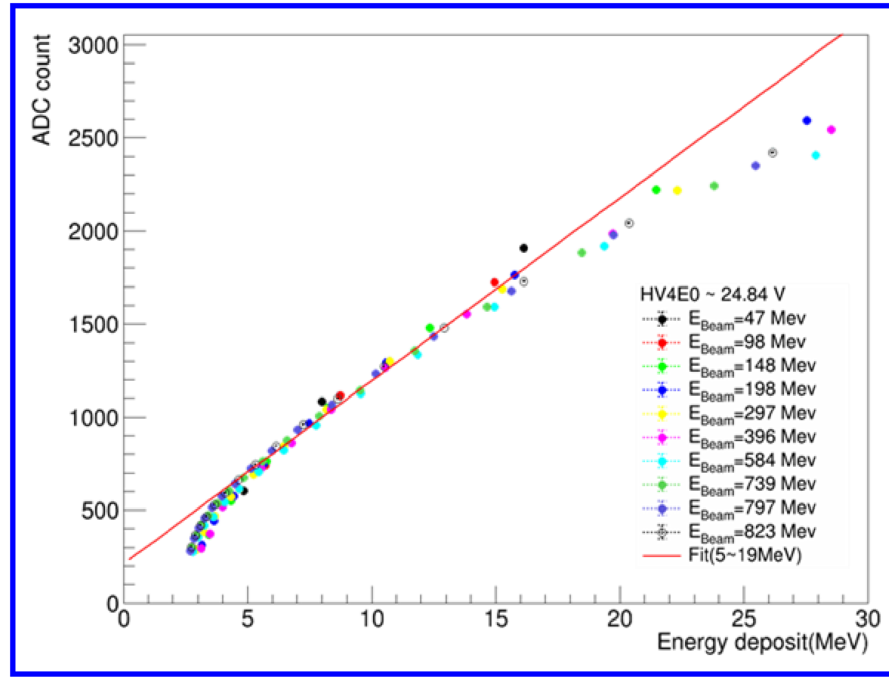


1st Prototype test beam

- **Time:** Feb. 15 – 21, 2024
- **Location:** RARiS, Sendai, Japan
- **Beam: 47 – 823 MeV positron**

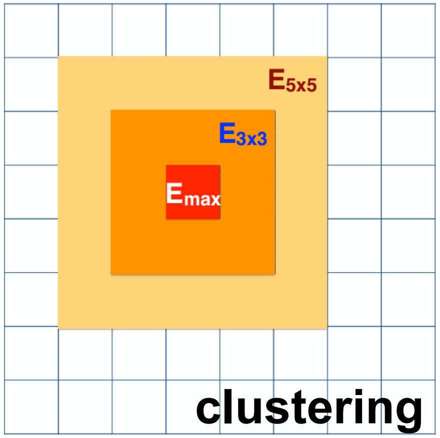
1st Prototype : SiPM Saturation



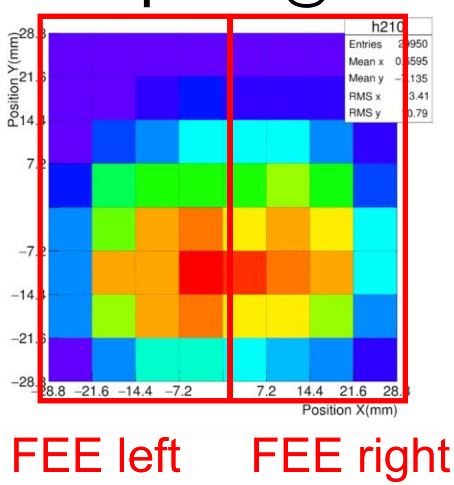


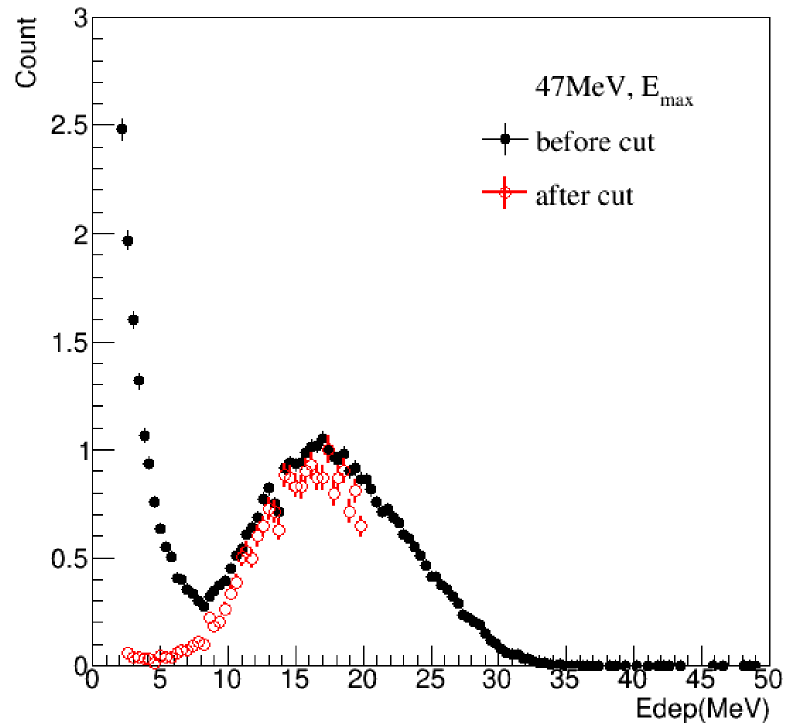
Non-Linearity Observation
- Non-linearity becomes visible above **20 MeV**.
- Most data points fall within the non-linear region.
- Only the **47 MeV** data set has about **60% of events** remaining in the **linear range**.

1st Prototype : Selection Criteria



Beam profile @ 47MeV

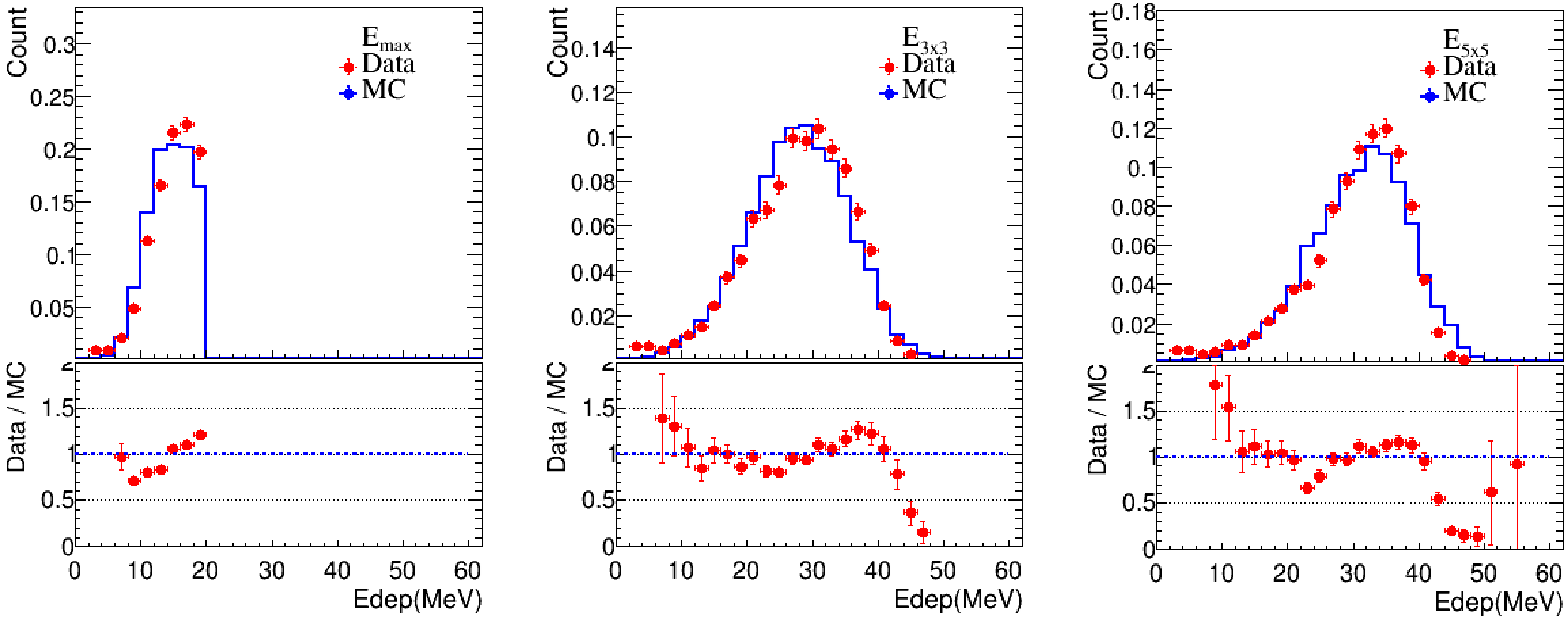




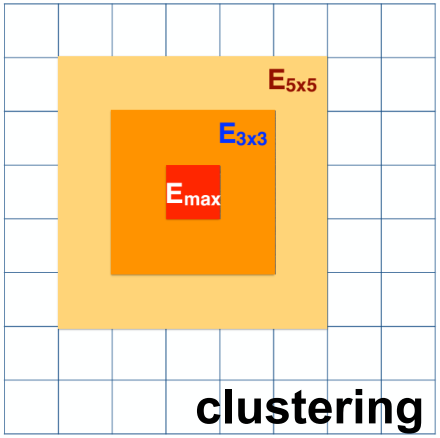
Cut Criteria

1. **2.5 MeV < E_{max} < 20 MeV**
   - Selects data within the linear response range.
   - Removes low-momentum photons originating from the beam.
2. **Both Left and Right Crystals Fired**
   - Requires hits in both FEE-left and FEE-right channels.
   - Eliminates events containing only noise.

1st Prototype : Data and MC Comparison

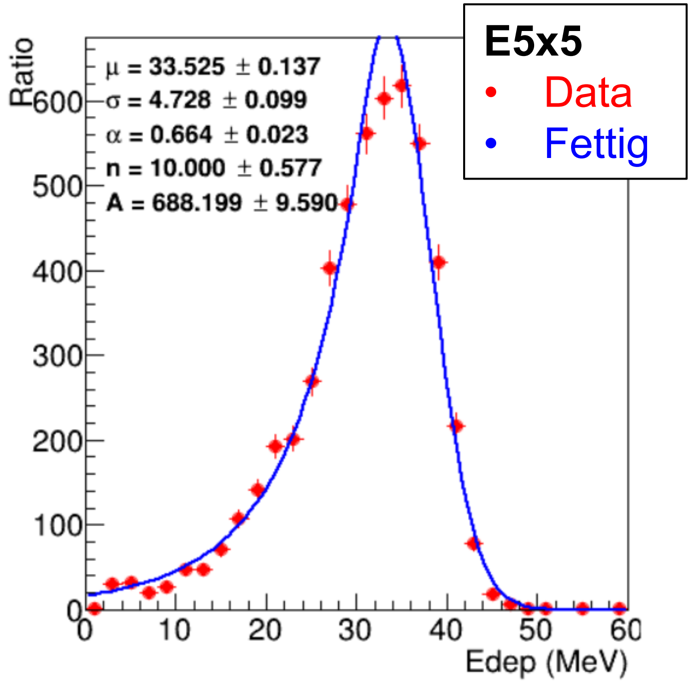


The comparison between data and Monte Carlo (MC) for the 47 MeV positron beam shows **good overall consistency**.



1st Prototype :
Energy Resolution w/o Energy Regression

47MeV positron



I (A)	x_{PS} 制限なし		
	μ_P (MeV/c)	σ_P (MeV/c)	σ_P/μ_P (%)
025	47.18(2)	5.48(1)	11.63(3)
050	98.19(4)	4.92(3)	5.01(3)
075	148.22(4)	4.77(2)	3.22(2)
100	197.94(3)	4.91(2)	2.48(1)
125	247.79(3)	5.00(2)	2.02(0)
150	297.30(2)	5.29(2)	1.78(0)
175	346.81(2)	5.31(1)	1.53(0)

Energy resolution of 47MeV
momentum resolution = 11.6%

Energy resolution without energy regression is **14% for the 47 MeV beam**. After accounting for the beam momentum resolution provided, **the energy resolution improves to approximately 11%.**

Design of 2^{nd} Prototype

Choice of crystal

Material	Light yield (photons/MeV)	Relative to LYSO
LYSO	~32,000 – 38,000	1.0
$PbWO_4$	~200 – 400	**≈ 1/100 of LYSO**

Choice of sensor

Sensor	Typical Gain	Relative
SiPM	~10^5 – 10^6	1.0
APD	~10^2 – 10^3	**≈ 1/1000 – 1/10,000 of SiPM**

- **1^{st} prototype @ 2023-2024 : LYSO + SIPM, saturation**
- **2nd prototype @ 2024-2025 : reduce the gain.**

- **LYSO + APD**

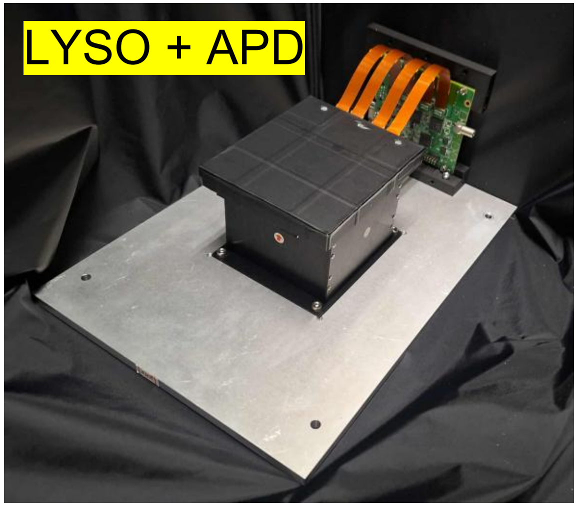
The gain of an APD is about **1000 times lower** than that of a SiPM.

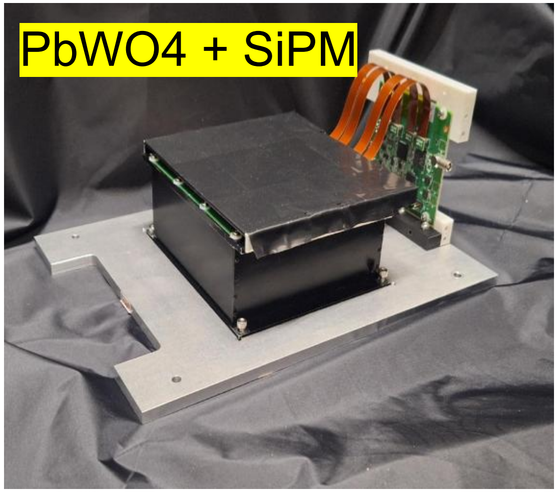
- **$PbWO_4$ + SiPM**

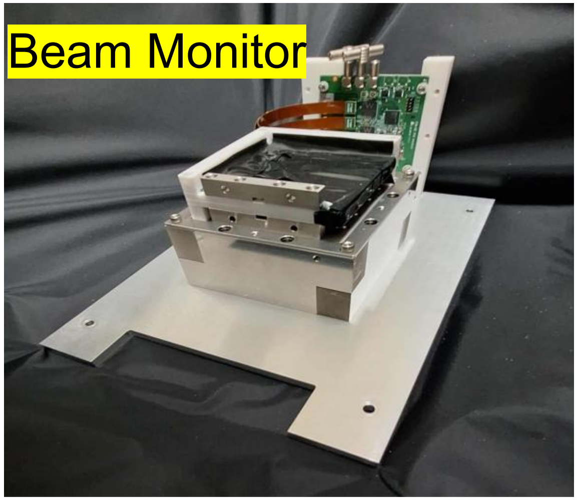
The light yield of $PbWO_4$ is about **100 times lower** than that of LYSO.

- **We continue using CITIROC as DAQ system.**

2nd ZDC ECAL Prototype

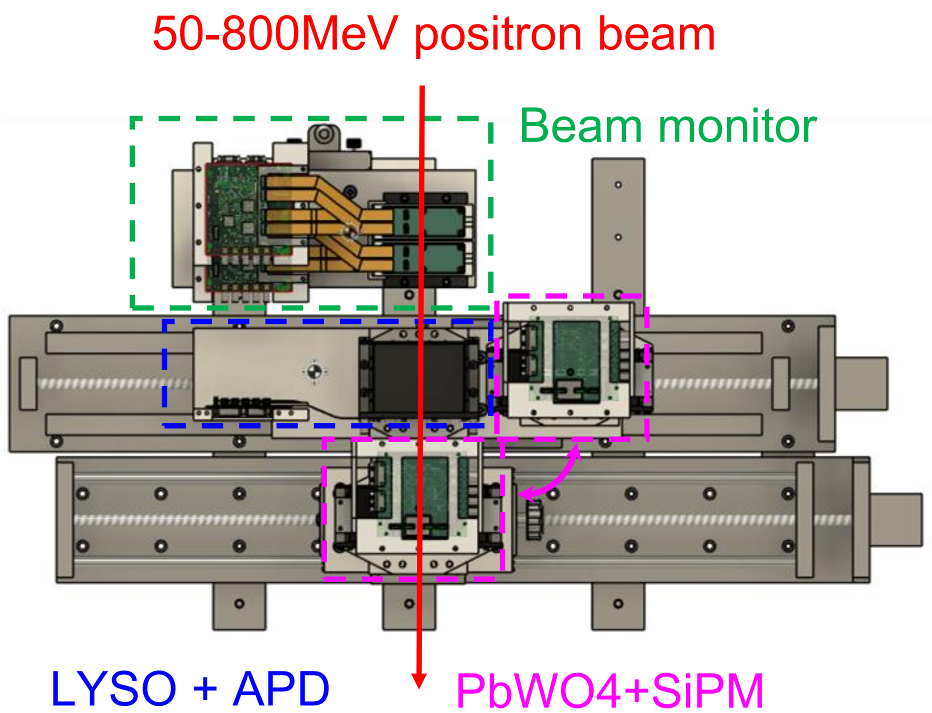


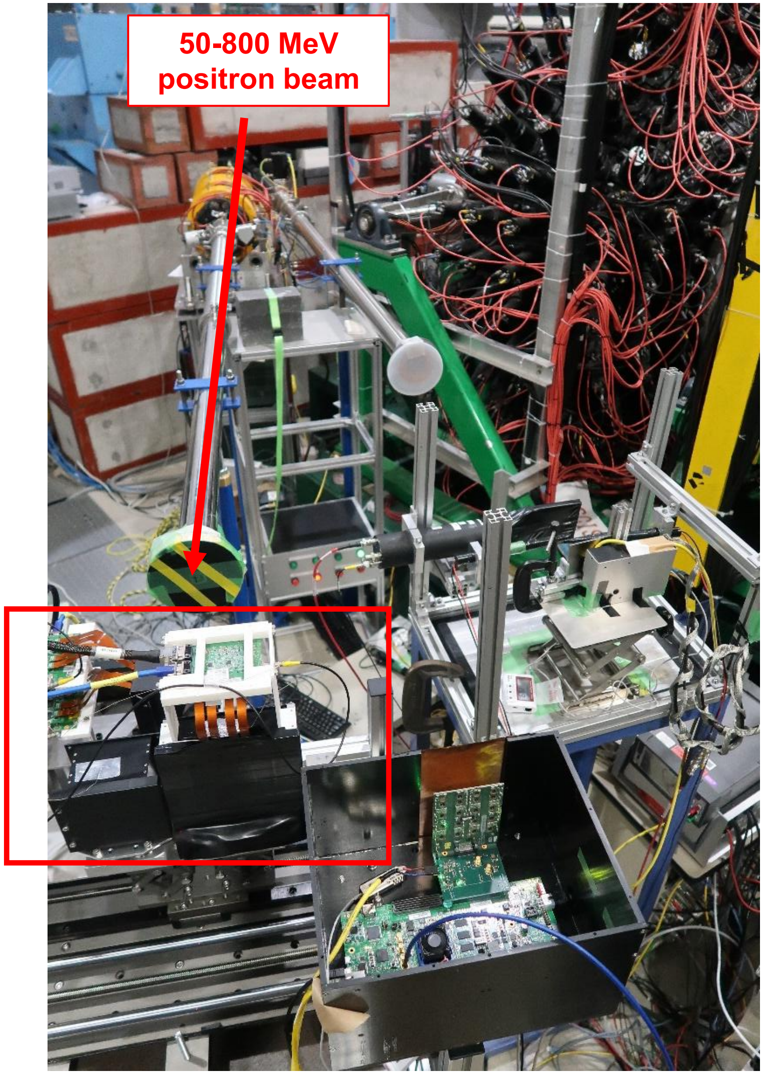




	Detector	Crystal				Sensor		DAQ
		name	Size of one cell	Length	Array	Type	sensor/crystal	
2nd prototype 2024-2025	**LYSO + APD**	LYSO	1cm*1cm	**6.6cm (6X0)**	8x8 8cm*8cm	APD C30739ECERH	1	**CITIROC**
	PbWO4 + SiPM	PbWO4	2cm*2cm	**5.3cm (6X0)**	6x6 12cm*12cm	SiPM Onsemi MICROFC-60035	2	**CITIROC**

2nd Prototype : Test Beam

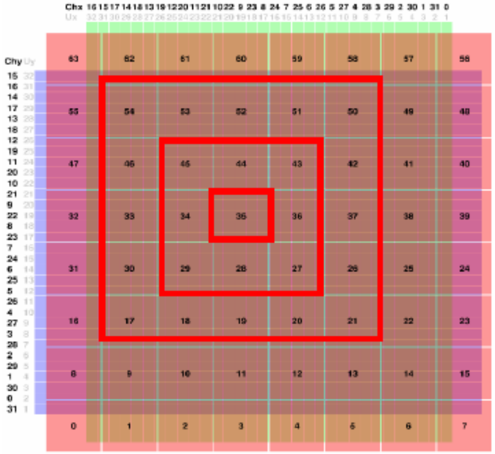




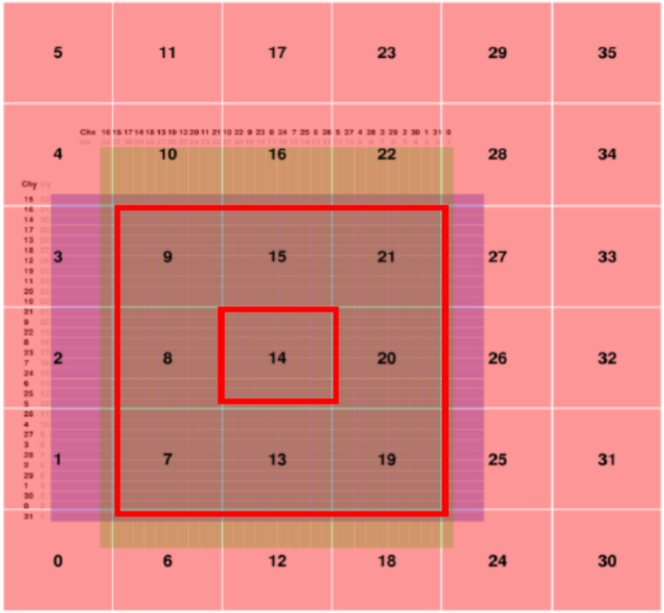
We had test beam at RARiS on 2025 Feb with 2nd prototype system, using **50MeV - 800MeV positron beam.**

Crystal Clustering

LYSO + APD
5x5 clustering (~5cm*5cm)



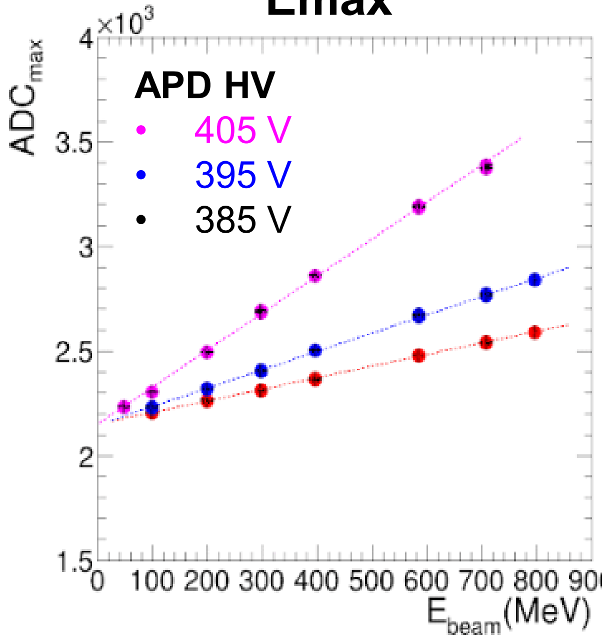
PbWO4 + SiPM :
3x3 clustering (~6cm*6cm)



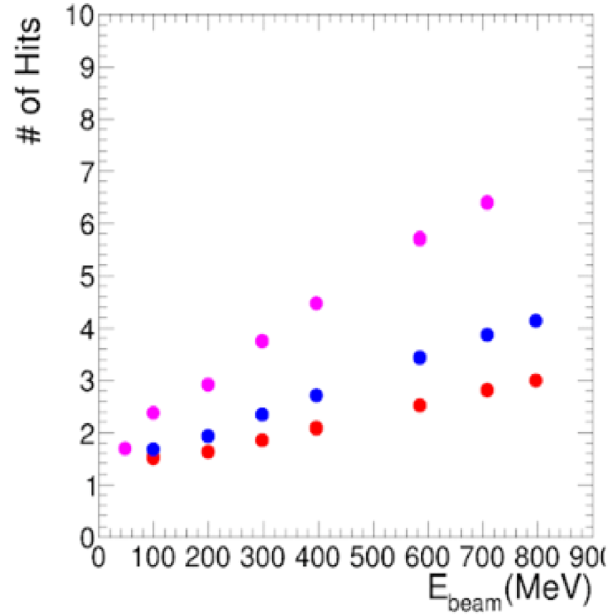
- Both **LYSO** and **PbWO$_4$** crystals have an approximate Molière radius of 2 cm. (A 4 cm × 4 cm cluster captures about 90% of the total energy deposition, while an 8 cm × 8 cm cluster captures around 95%.) Hence, **the two systems collectively achieve 90%–95% energy containment with 5*5 array clustering for LYSO+PAD and 3*3 array for PbWO4+SiPM.**
- During the beam test, we performed **high-voltage** and **beam-energy scans** to study its response under varying operating conditions.

2^{nd} Prototype **LYSO + APD : Linearity**

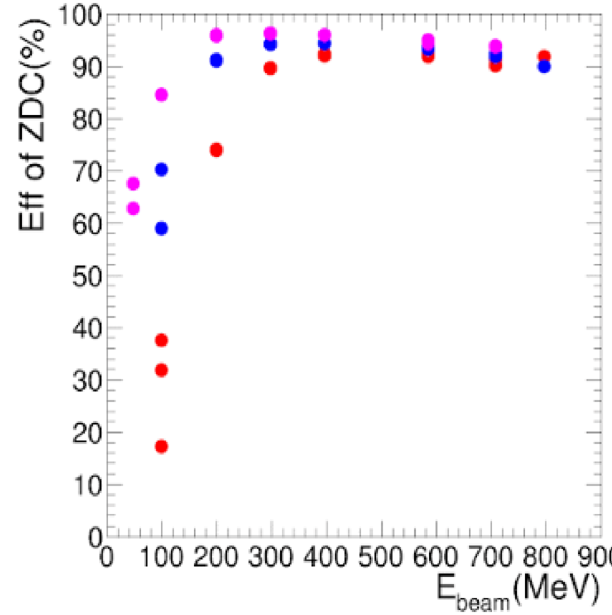
Emax



Num. of Hits



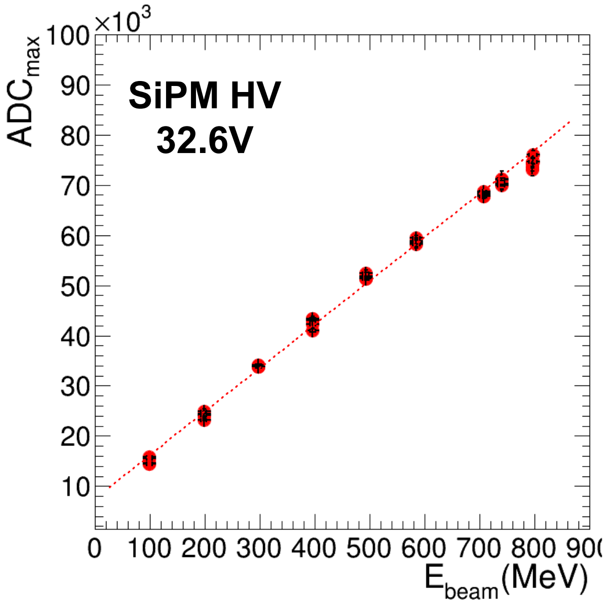
Efficiency



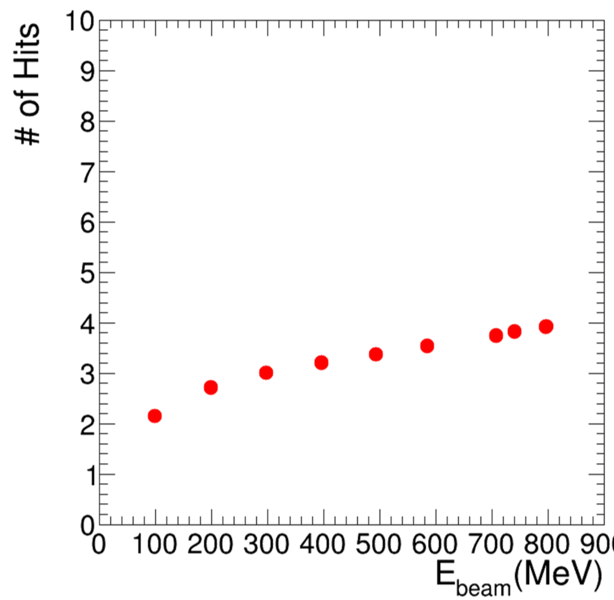
- **Linearity:** The detector showed **good linearity** when tested with an electron beam from 50 MeV to 800 MeV.
- **Efficiency:** Defined as ***Eff = (LYSO && BM) / BM***, with only timing matching verified.
- **Best Performance: Reached >90% at an APD bias voltage of 405 V.**

2^{nd} Prototype **PbWO4 + SiPM : Linearity**

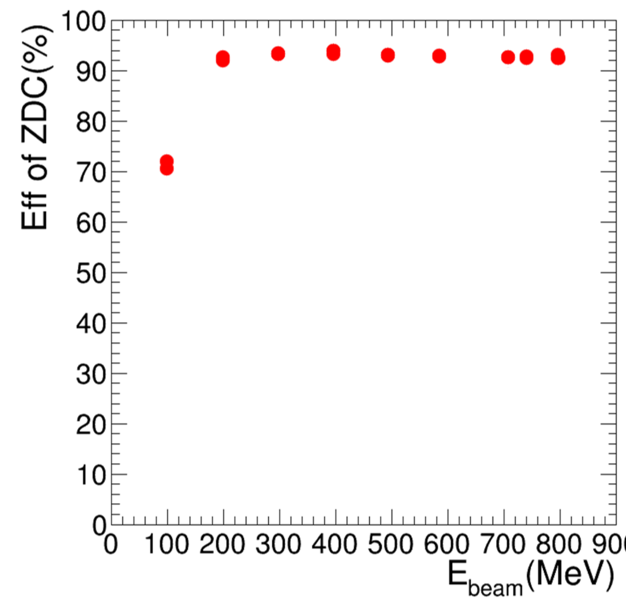
Emax



Num. of Hits



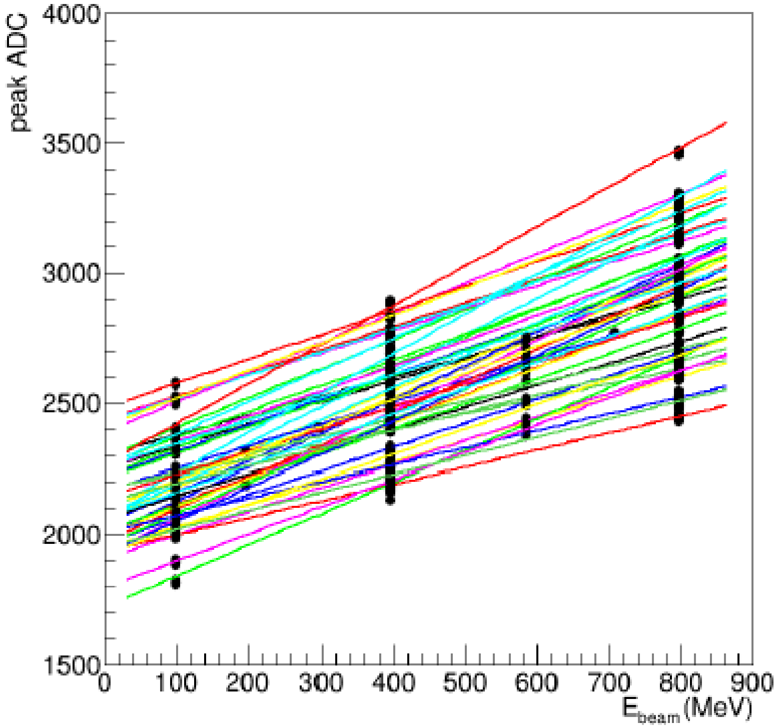
Efficiency



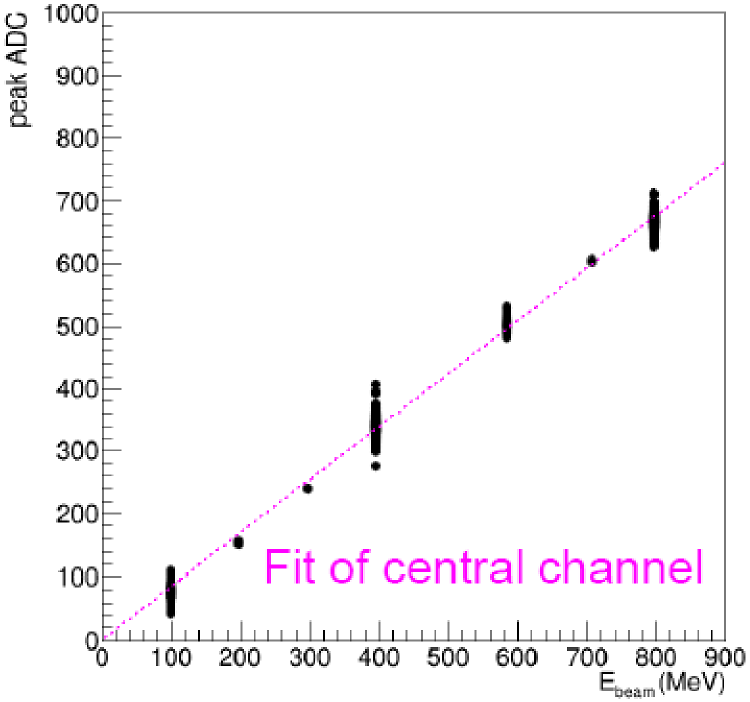
- **Linearity:** The response is consistent and shows **good linearity**.
- **Efficiency:** Approximately **95%** for beam energies above 200 MeV.

2^{nd} Prototype **LYSO + APD** : Gain Calibration

Gain before Calibration



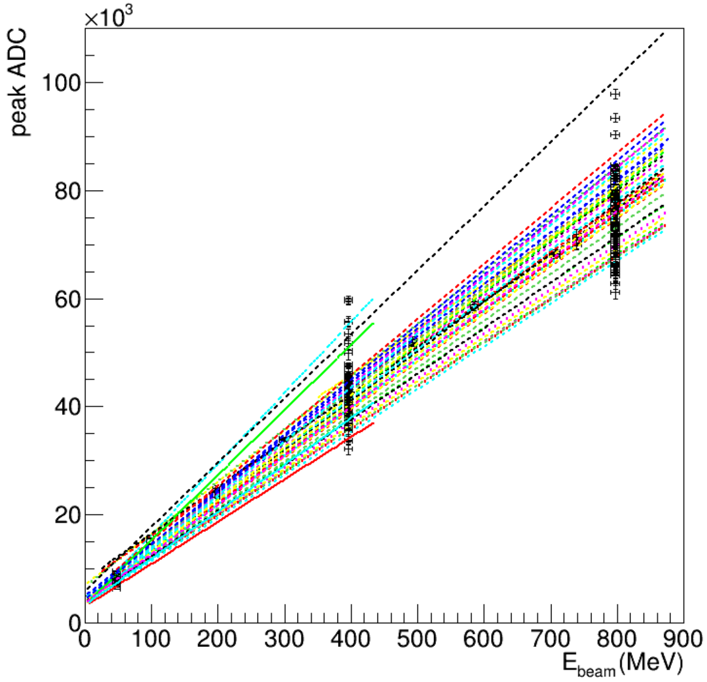
Gain after Calibration



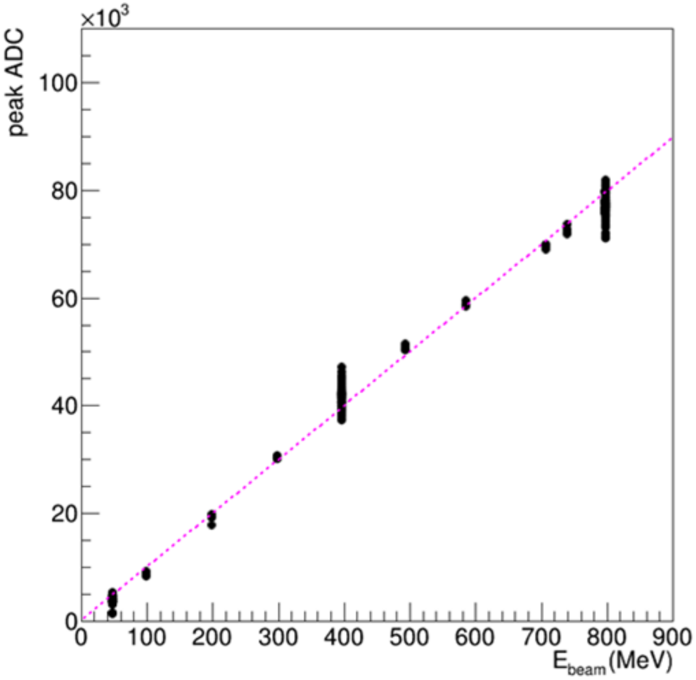
Calibration procedure:
The beam energy was varied to scan all channels in the 5×5 crystal array. The gain of each channel was then adjusted (scaled and shifted) so that its response aligned with that of the central channel.

2^{nd} Prototype **PbWO4 + SiPM:** Gain Calibration

Gain before Calibration

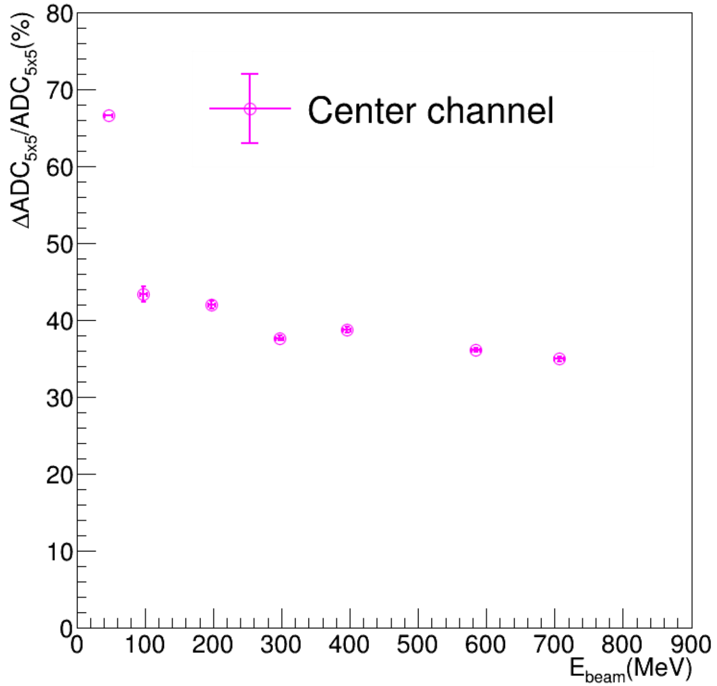


Gain after Calibration

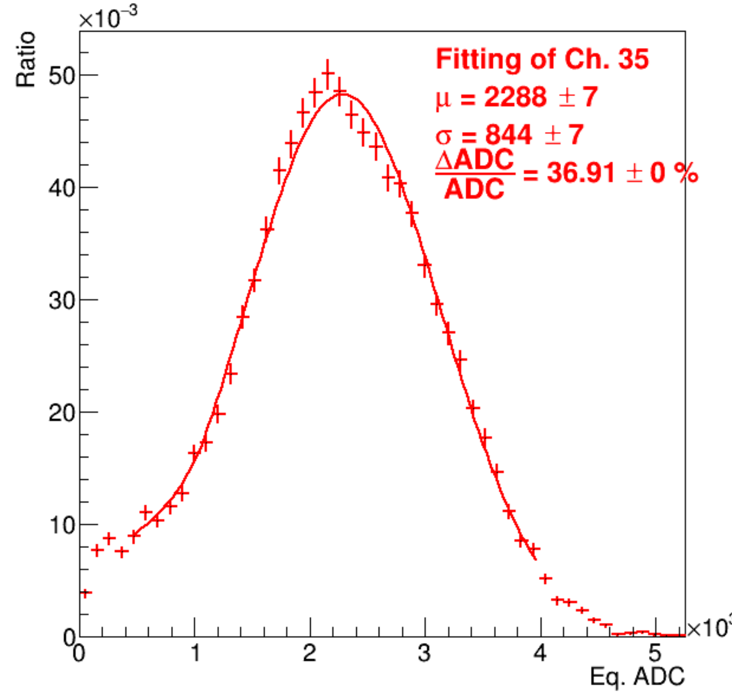


2^{nd} Prototype **LYSO + APD :** **Energy Resolution w/o Event Selection and Regression**

Energy Resolution (APD = 405V)



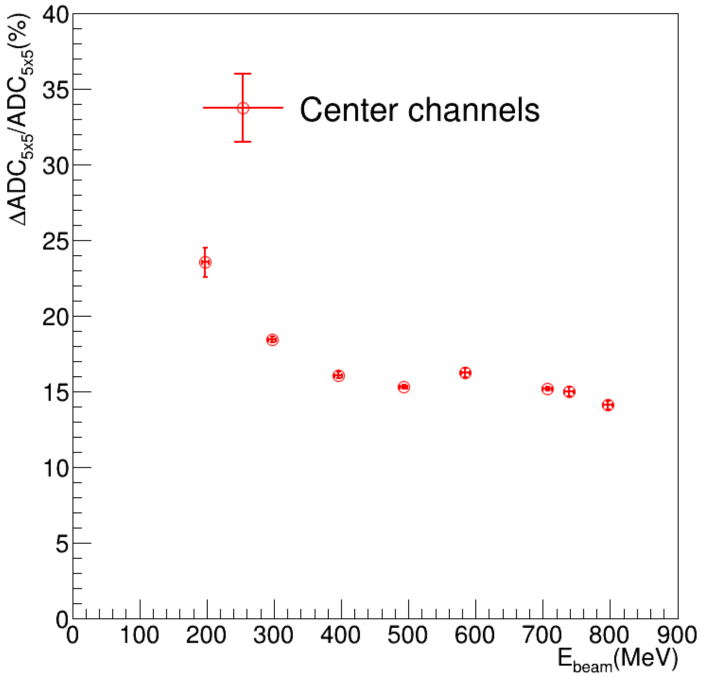
APD= 405V @ 706MeV



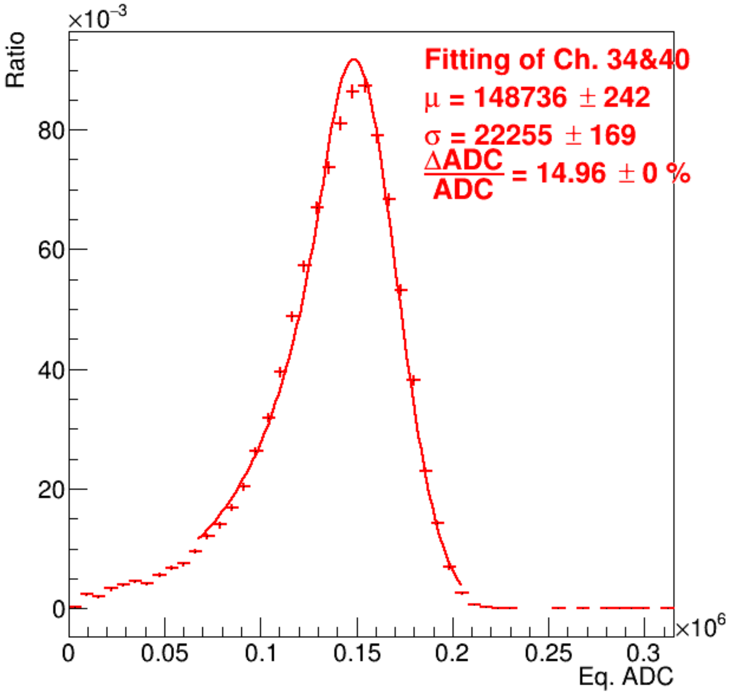
Poor performance for **LYSO + APD system ~ 35% energy resolution (w/o event selection and energy resolution).**

2^{nd} Prototype **PbWO4 + SiPM :**
Energy Resolution w/o Event Selection and Regression

Energy Resolution

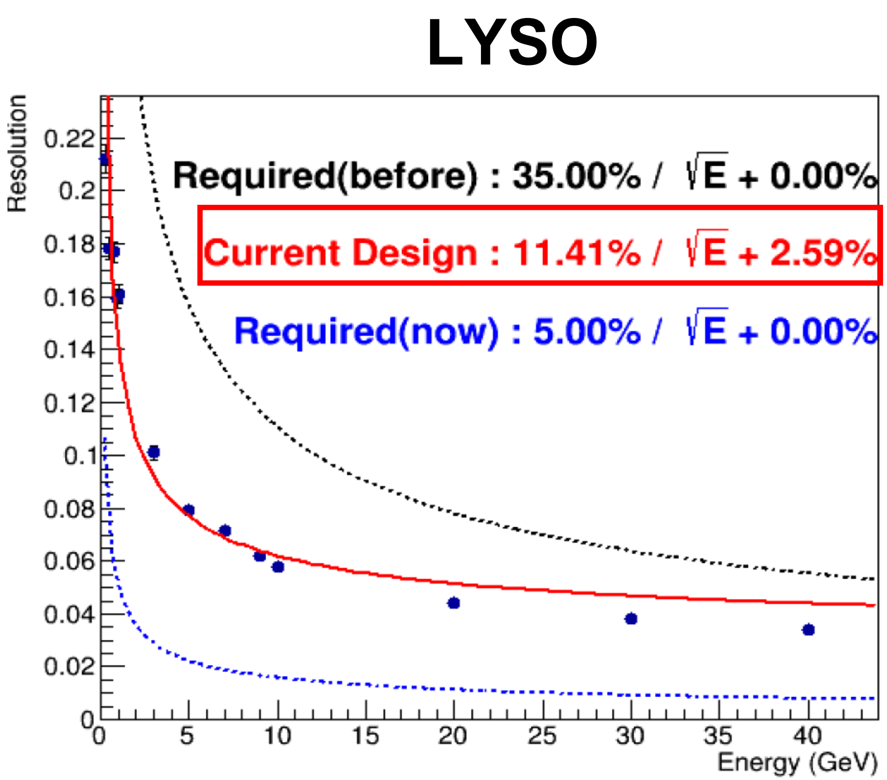


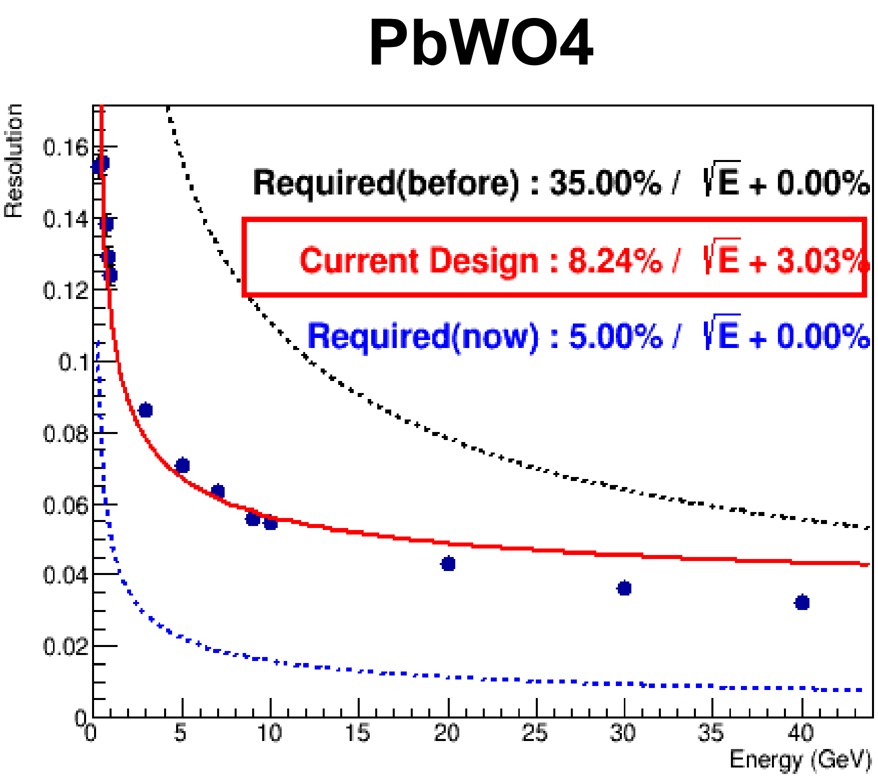
706MeV



Reasonable performance for **PbWO4 + SiPM system ~ 15% energy resolution (w/o event selection and energy resolution).**

ePIC MC Simulation

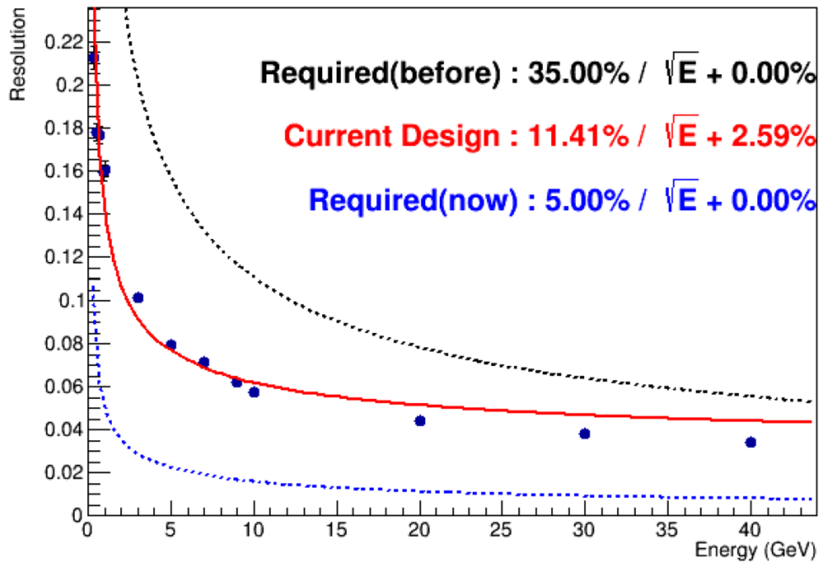




- Both LYSO and $PbWO_4$ crystals exhibit comparable performance in Monte Carlo simulations. In the first prototype (LYSO + SiPM), the energy resolution reaches approximately 15%. **Therefore, the degraded resolution observed in the LYSO + APD configuration is likely due to an issue with the APD itself.**
- Since the performance requirements have been updated, the current design no longer meets the new criteria. **We need to explore a new configuration.**

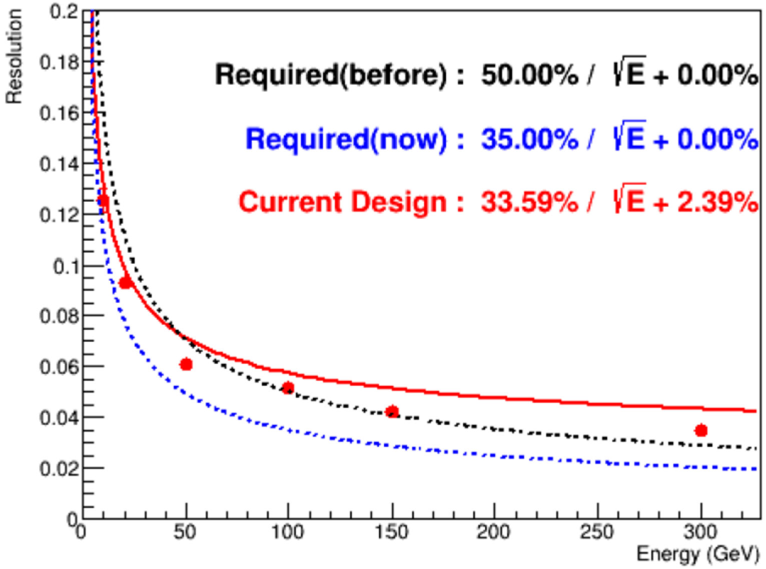
ePIC MC Simulation

Energy resolution : 10-40GeV gamma



ECAL met the requirements of the previous design but does not satisfy the updated ones.

Energy resolution : 10-400GeV neutron

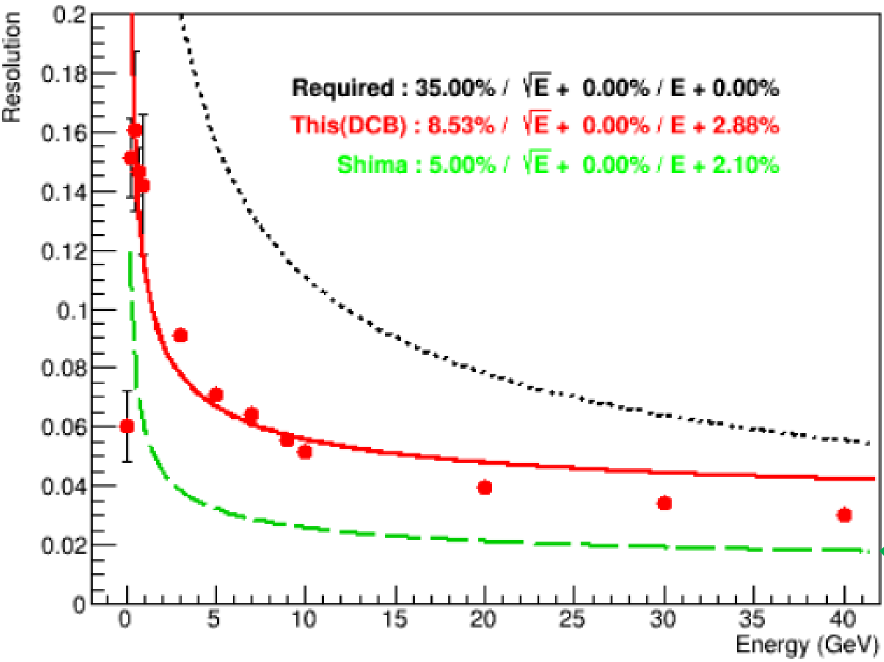


HCAL satisfies both the previous and the updated requirements.

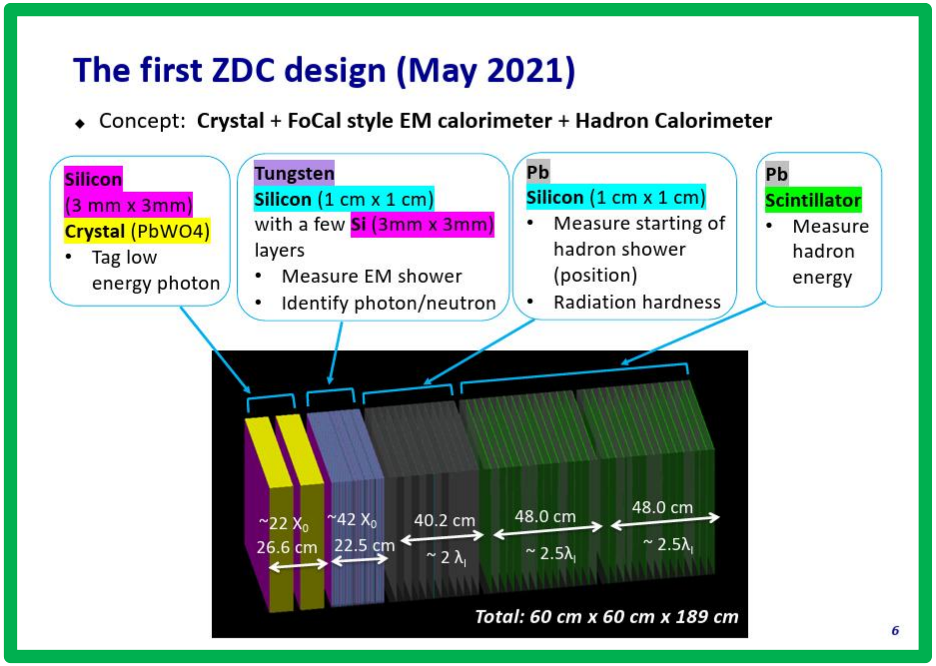
The existing ZDC ECAL prototypes are still based on the current design, a update of the design may be necessary soon.

ePIC MC Simulation

Energy resolution : 10-40GeV gamma

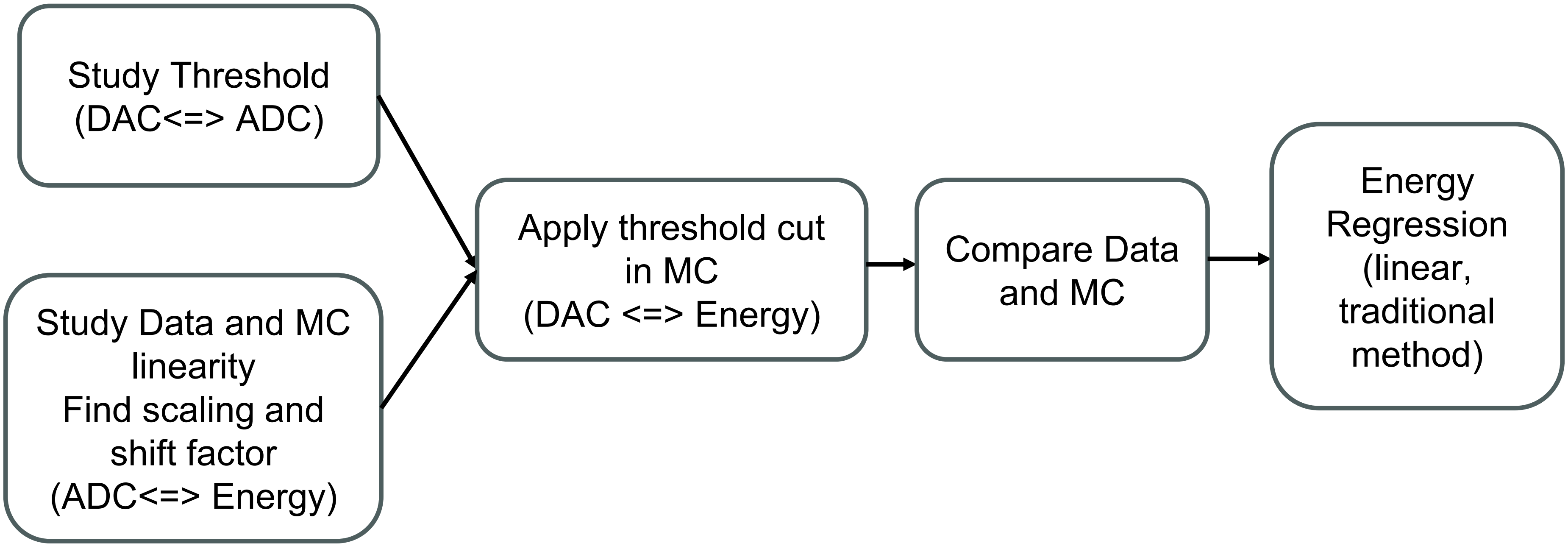


Shima's study



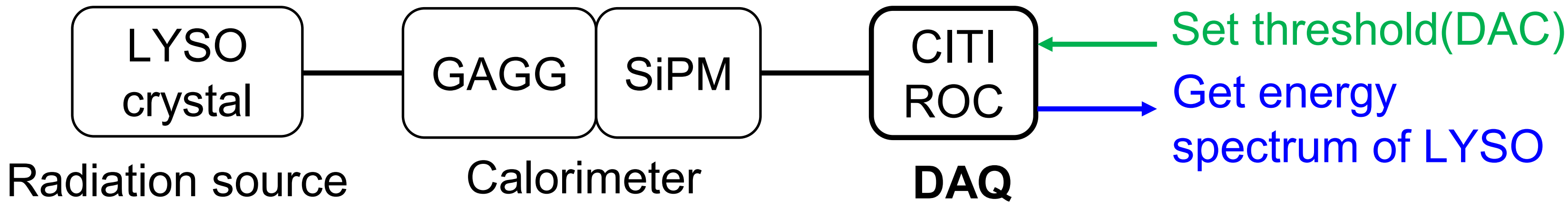
Design in 2021 could satisfy the requirement.

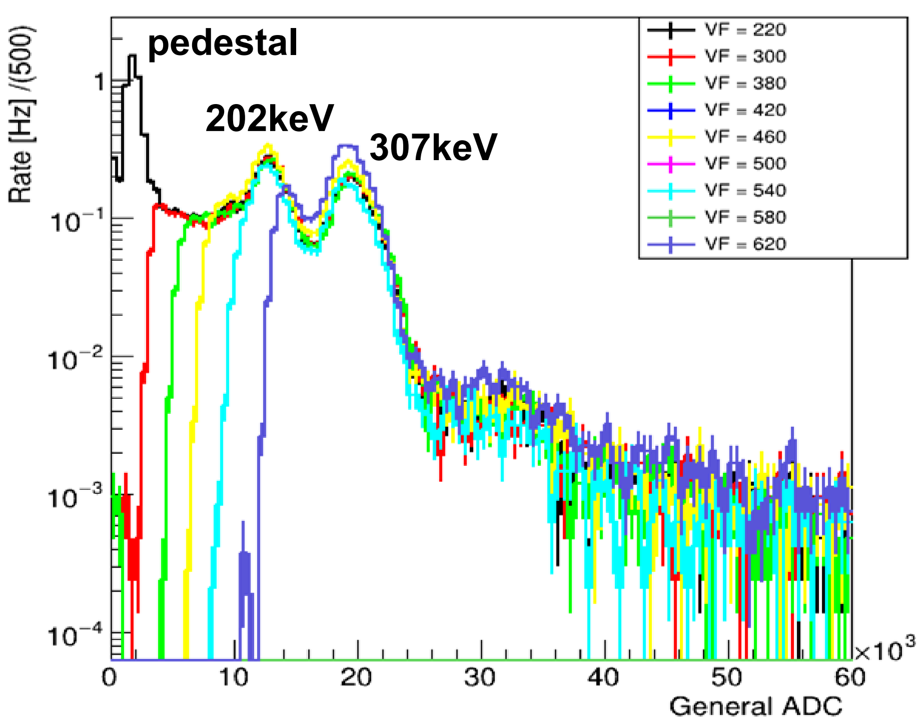
Strategy for Energy Regression

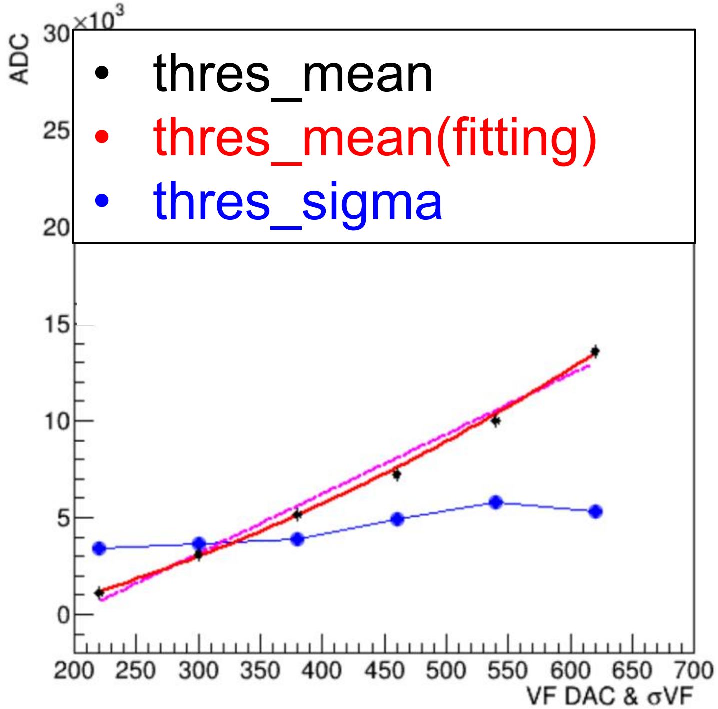


Preparation for energy regression :
=> Good data and MC consistency
=> Find DAC ⇔ Energy mapping to apply threshold cut on MC
=> Find “DAC ⇔ ADC mapping” and “ADC ⇔ Energy mapping”

2^{nd} Prototype **PbWO4 + SiPM :** Study Threshold (Find DAC to ADC Mapping)

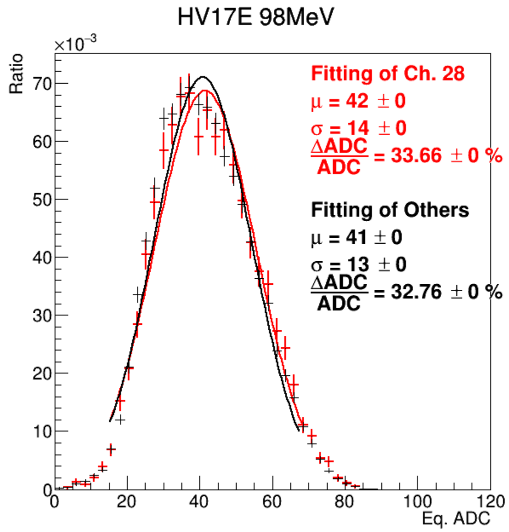




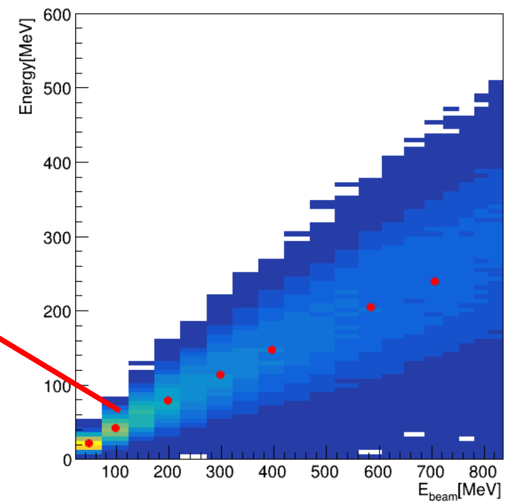


We study the radiation source (LYSO) spectrum to access DAC to ADC mapping.

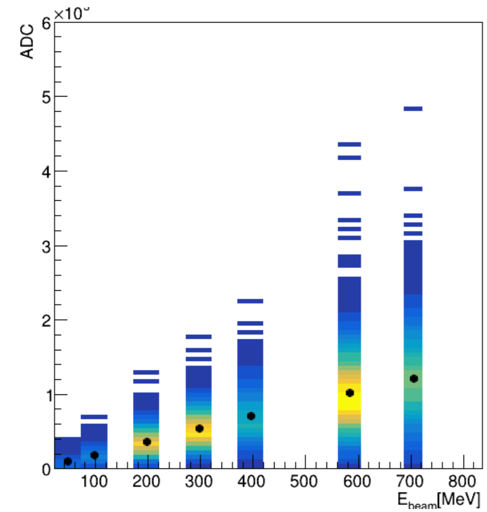
2^{nd} Prototype **PbWO4 + SiPM**
Find ADC to Energy Correlation



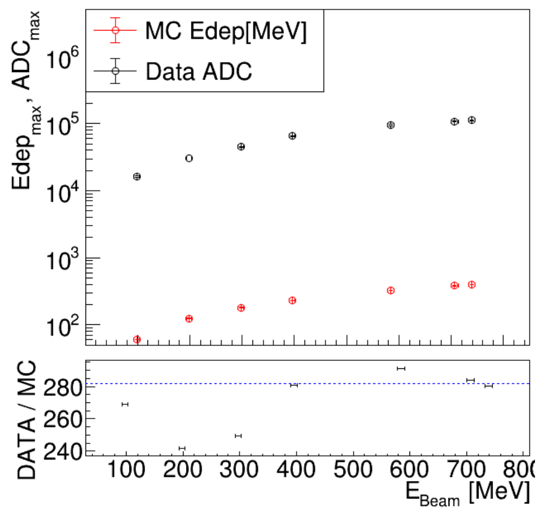
MC : Ebeam VS Emax



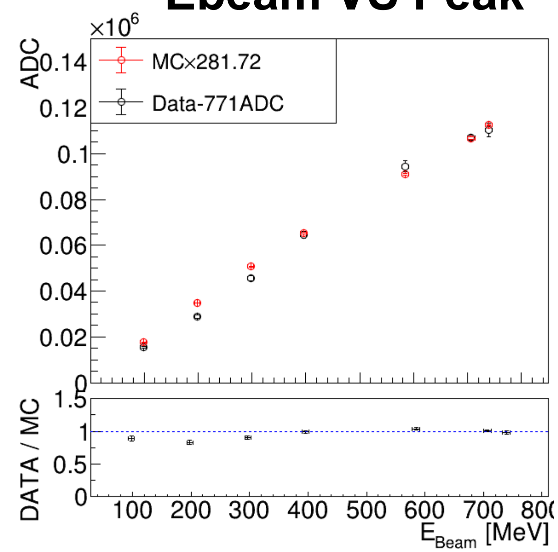
Data : Ebeam VS ADC



Ebeam VS Peak



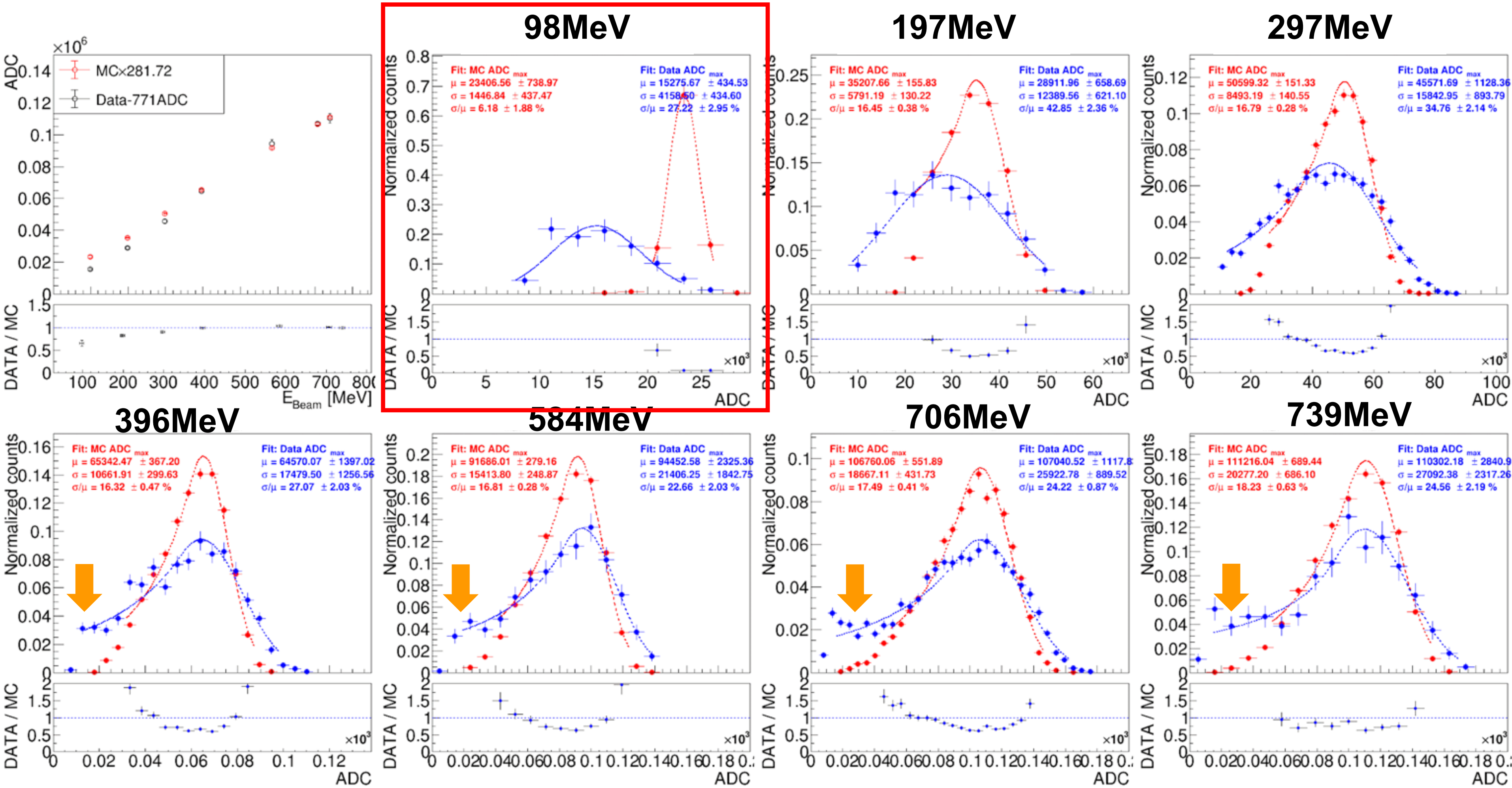
Ebeam VS Peak



- **Both the experimental data and the Monte Carlo simulation exhibit good energy linearity.**
- The relationship between ADC counts and energy is expressed as: **ADC(Count) = Energy(MeV) × 281.72) + 771**

2nd Prototype **PbWO4 + SiPM**
Compare Data and MC : **Emax**

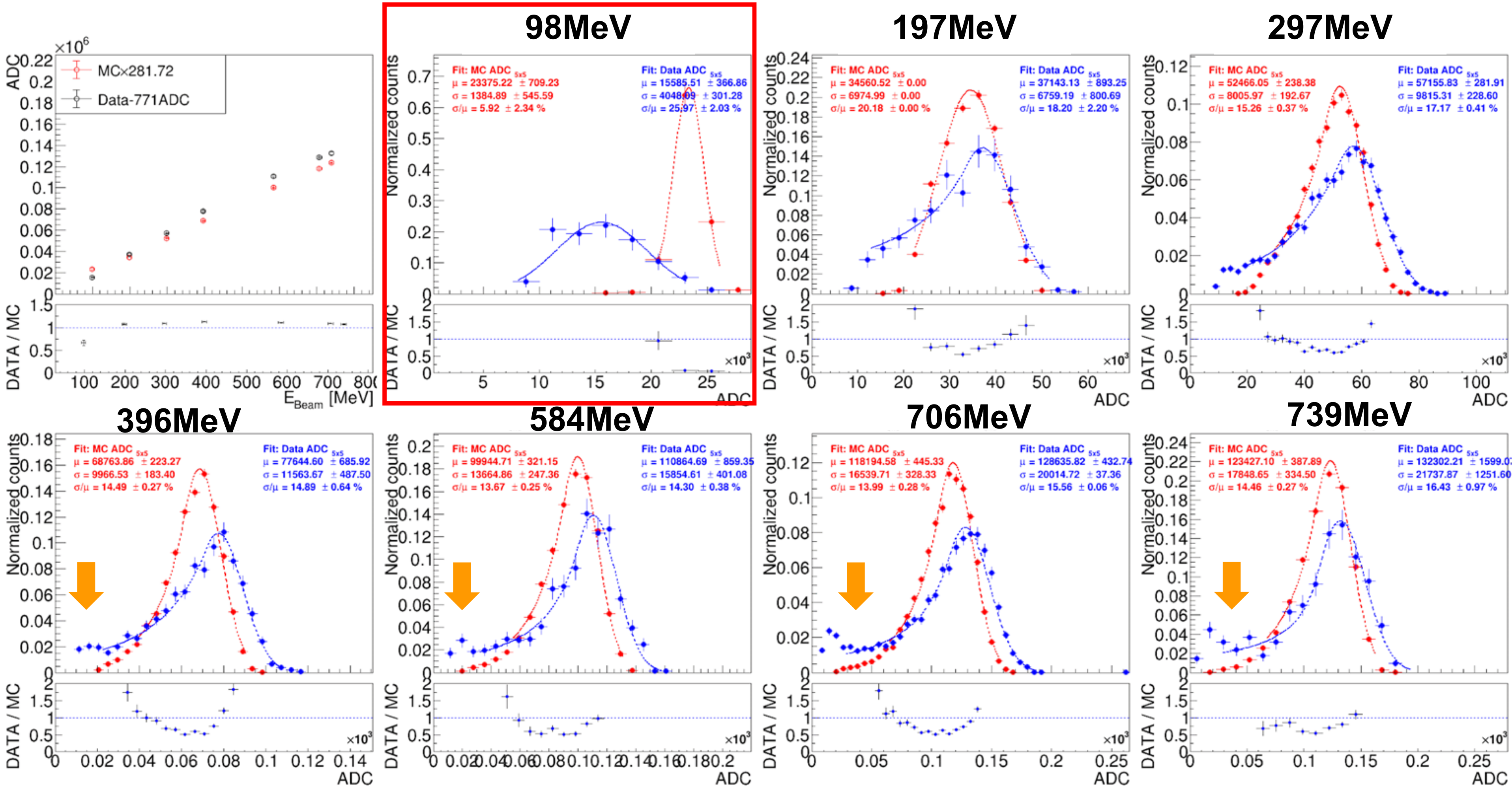
- Data (threshold ~ 50MeV)
- MC (threshold ~ 50MeV)



- The threshold cut removes too many hits at 98 MeV.
- Many low-energy hits observed in the data (noise, cross talk?)

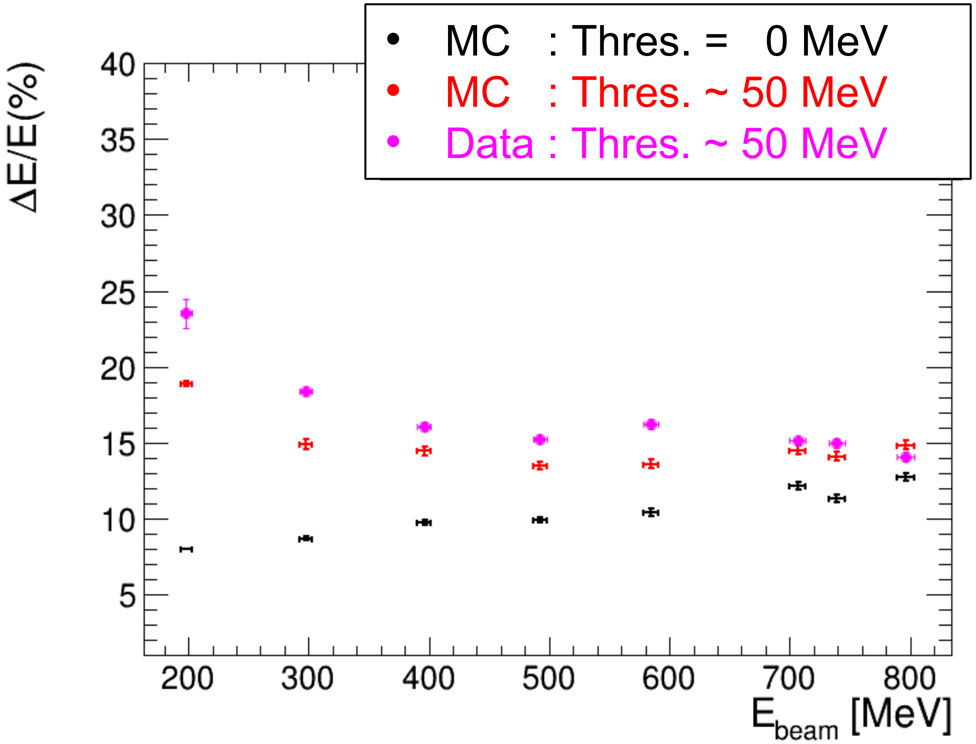
2nd Prototype **PbWO4 + SiPM**
Compare Data and MC : **E5x5**

- Data (threshold ~ 50MeV)
- MC (threshold ~ 50MeV)



After applying threshold cut, the situation is reversed. We have worse consistency with Ebeam<300MeV but a better one with the rest.

2nd Prototype **PbWO4 + SiPM** Energy Resolution (w/o Energy Regression)



- Comparing data and MC with this 50MeV threshold applied, the MC shows a 1–4% better energy resolution than the data.
- The energy resolution improves as the threshold is lowered based on MC study.
- Our consistency between data and MC are still not good enough to do energy regression. Work is undergoing.

ZDC ECAL Prototypes

	Detector	Crystal				Sensor		DAQ
		name	Size of one cell	Length	Array	Type	sensor/crystal	
1st prototype 2023-2024	LYSO + SiPM	LYSO	1cm*1cm	**6.6cm (6X0)**	8x8	SiPM Onsemi MICROFC-60035	1	CITIROC
2nd prototype 2024-2025	LYSO + APD	LYSO	1cm*1cm	**6.6cm (6X0)**	8x8	APD C30739ECERH	1	CITIROC
	PbWO4 + SiPM	PbWO4	2cm*2cm	**5.3cm (6X0)**	6x6	SiPM Onsemi MICROFC-60035	2	CITIROC
3rd prototype 2025-2026 (developing)	LYSO + SiPM	LYSO	1cm*1cm	**6.6cm (6X0)**	8x8	SiPM Hamamatsu S14160-3015PS	4	**HGCROC**
	PbWO4 + SiPM	PbWO4	2cm*2cm	**5.3cm (6X0)**	6x6	SiPM Hamamatsu S14160-3015PS	16	**HGCROC**

- **1st prototype @ 2023-2024 : Based on MC design**

LYSO + SiPM + CITIROC — showed **non-linearity**; the overall gain was too high.

- **2nd prototype @ 2024-2025 : reduce the gain.**

- LYSO + APD + CITIROC (The gain of an APD is about **1000 times lower** than that of a SiPM.)
- $PbWO_4$ + SiPM + CITIROC (The light yield of $PbWO_4$ is about **100 times lower** than that of LYSO.)

- **3rd prototype @ 2025-2026 : test the H2GCROC readout.**

Kai-Yu will later present details about the DAQ system, including both CITIROC and H2GCROC developments.

Summary and Future Plan

- **Test beam analysis**
  - **1st prototype : LYSO + SiPM with saturation effect**
  - **2nd prototype: the saturation issue was resolved.**
    1. **LYSO + APD:** demonstrated about **35% energy resolution**, likely due to an **APD operation issue**.
    2. **$PbWO_4$ + SiPM**: achieved about **15% energy resolution**, **consistent with MC expectations. However, not satisfied with updated requirement = 2%-5%. Redesign ECAL might be necessary.**
- **Plans in 2026**
  - **2nd prototype "PbWO4 + SiPM"**
    1. energy regression
    2. Beam track reconstruction => study special resolution (1cm to 2cm required)
    3. better noise control => test beam in March 2026
    4. new H2GCROC => test beam in March 2026
  - **2nd prototype "LYSO + APD" : debug ADP operation**
  - **3rd prototype**
    1. **PbWO4 crystal**
    2. A new **SiPM chip : Hamamatsu S14160-3015PS**
    3. A new **DAQ system : H2GCROC** (see Kai-Yu's presentation).

Backup

Requirements of Zero Degree Calorimeter (ZDC)

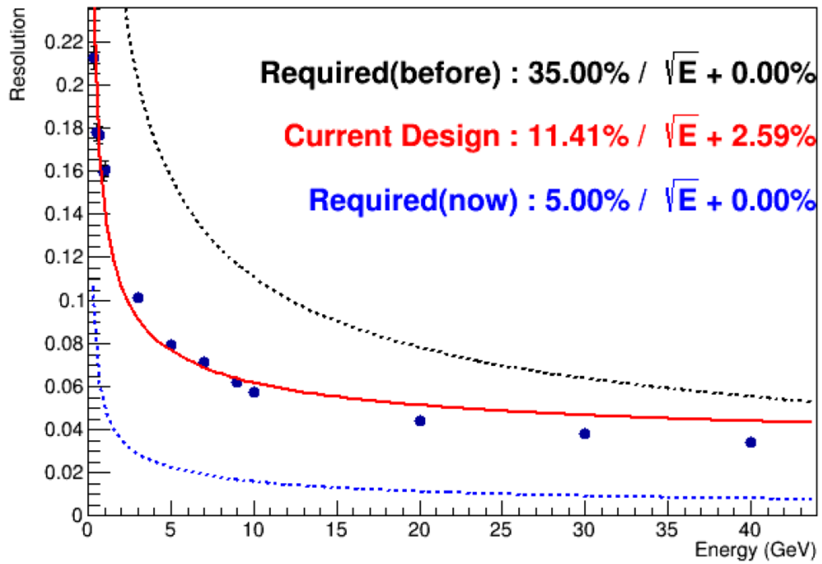
Physics process	Final State particles	HCAL		ECAL	
		Energy resolution	Angular resolution	Energy resolution	Spatial resolution
Spectator tagged e+d breakup	Neutrons	$\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{\mathrm{E}}} \oplus 5\%$	$\frac{\sigma_\theta}{\theta} \leq \frac{2\,mrad}{\sqrt{E}}$	N/A	N/A
Incoherent vetoing of e+A events	Neutrons photons	$\frac{\sigma_E}{E} \leq \frac{100\%}{\sqrt{\mathrm{E}}}$	N/A	**100 MeV photon sensitivity**	N/A
u-channel backward DVCS	Photons	N/A	N/A	$\frac{\sigma_E}{E} \leq \frac{20\%}{\sqrt{E}} \oplus 3\%$	< 1–2 cm
Pion/Kaon structure functions	Neutrons photons	$\boldsymbol{\frac{\sigma_E}{E} \leq \frac{35-50\%}{\sqrt{E}} \oplus 3-5\%}$	$\boldsymbol{\frac{\sigma_\theta}{\theta} \leq \frac{2\,mrad}{\sqrt{E}}}$	$\boldsymbol{\frac{\sigma_E}{E} \leq \frac{2-5\%}{\sqrt{E}} \oplus 1-3\%}$	**< 1–2 cm**

- **Requirement of ZDC**
- **35-50% energy resolution and 2 mrad angular resolution for HCAL (neutron).**
- **2-5% energy resolution and 1-2 cm position resolution for ECAL (gamma).**

- **Development group** :
- Japan (RIKEN, Kobe, Shinshu, Tsukuba)
- Taiwan (NCU, NTU Academia Sinica)
- Korea (Sejong)
- USA (Kansas, PNNL, UC Riverside).

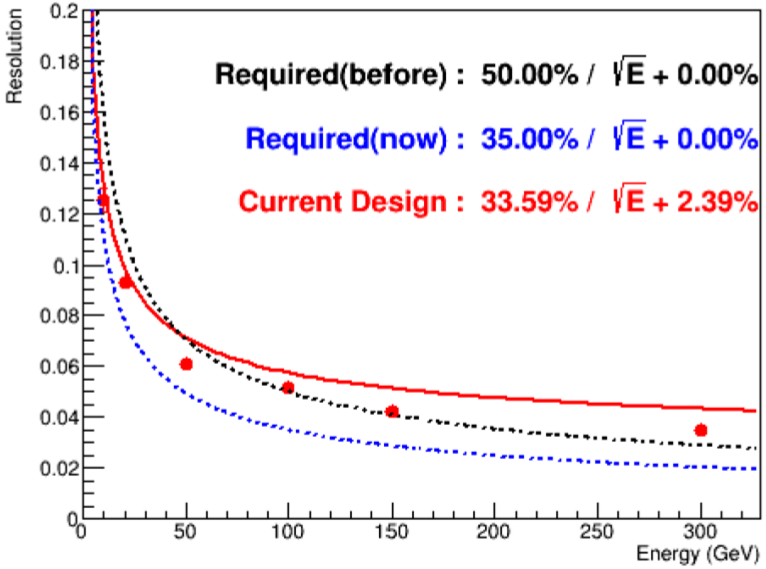
ePIC MC Simulation

Energy resolution : 10-40GeV gamma



ECAL met the requirements of the previous design but does not satisfy the updated ones.

Energy resolution : 10-400GeV neutron

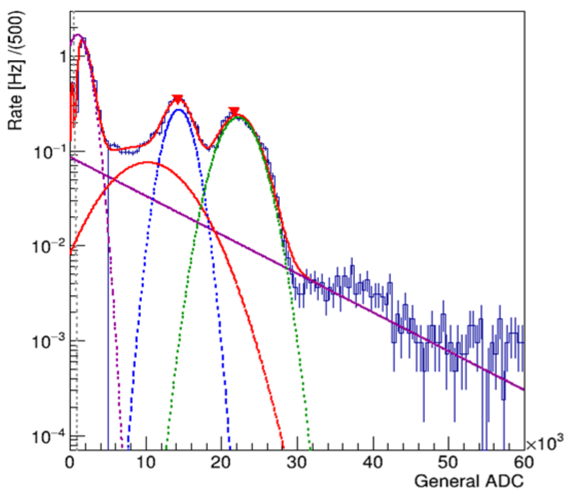


HCAL satisfies both the previous and the updated requirements.

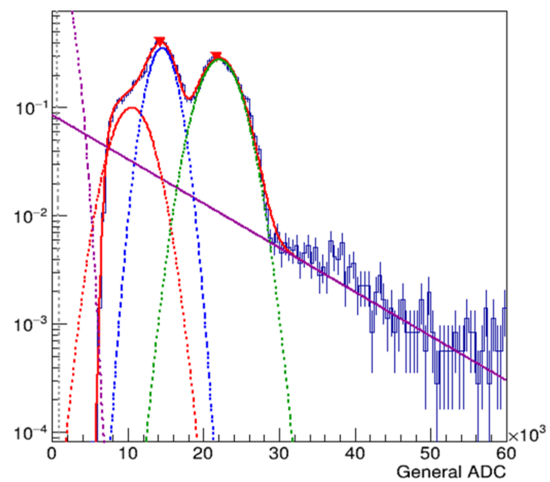
The existing ZDC ECAL prototypes are still based on the current design, a update of the design may be necessary soon.

Study Threshold (Find DAC to ADC Mapping)

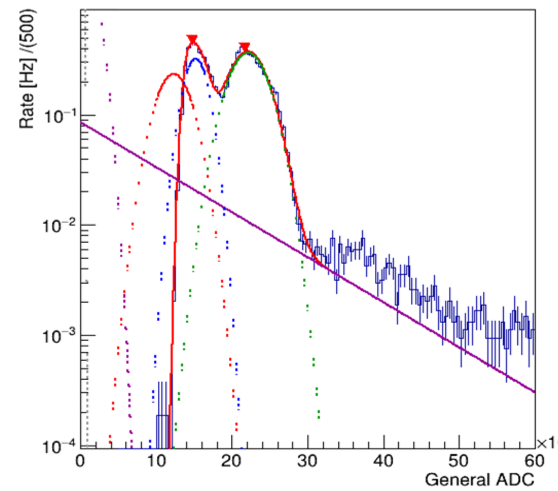
DAC = 220 (digit)

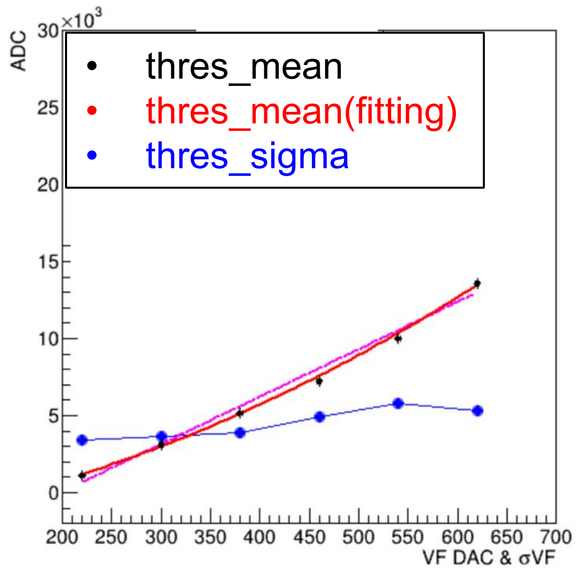


DAC = 300 (digit)



DAC = 580 (digit)

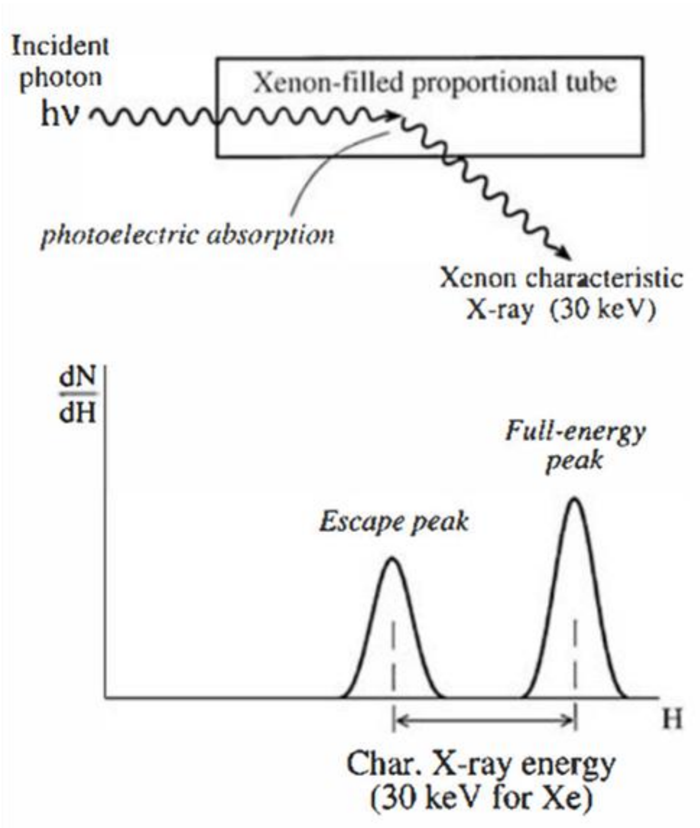




- Total fitting function
    1. pedestal
    2. 202keV gaussian peak
    3. 307keV gaussian peak
    4. Gamma escape energy gaussian peak
    5. Exponential background

Get the ADC value of left edge of total fitting function (Gaussian CDF).

Escape Energy



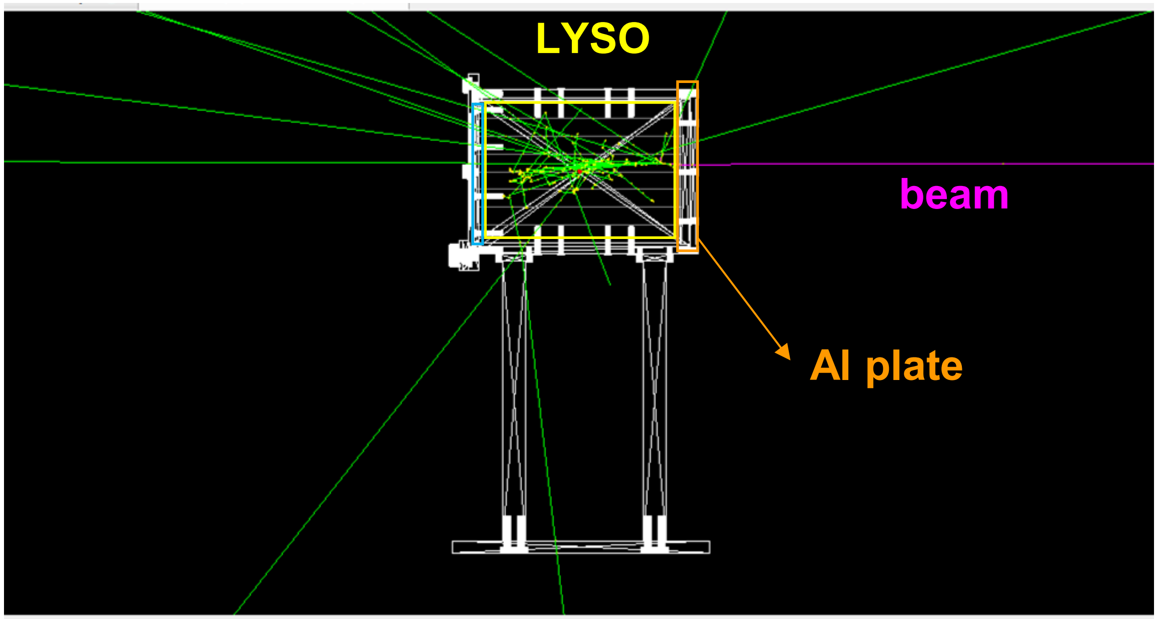
G. F. Knoll, *Radiation Detection and Measurement*, 4th ed. (Wiley, 2010)

- An incident photon is absorbed by scintillator, it excited atoms/molecules in material via the photoelectric effect, The ionized atom emits a photon with the same energy of incident photon.

(1) Full-energy peak :
full energy of emitted photon is observed by PMT.

(2) Escape Peak :
the emitted photon interacted with the other atoms/molecules through Compton scattering or pair production, not full energy is received by PMT.

1st Prototype : MC Simulation

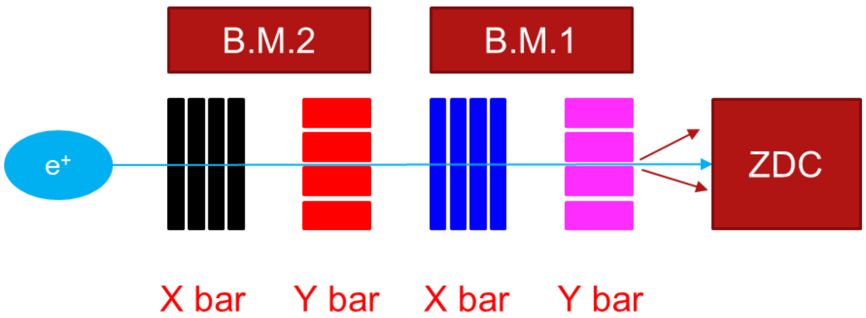


- **MC Implementation**
  - Detector geometry and materials
  - Beam momentum (with resolution)
  - Beam profile
  - Beam incident angle: **90°**
- **SiPM response not implemented**

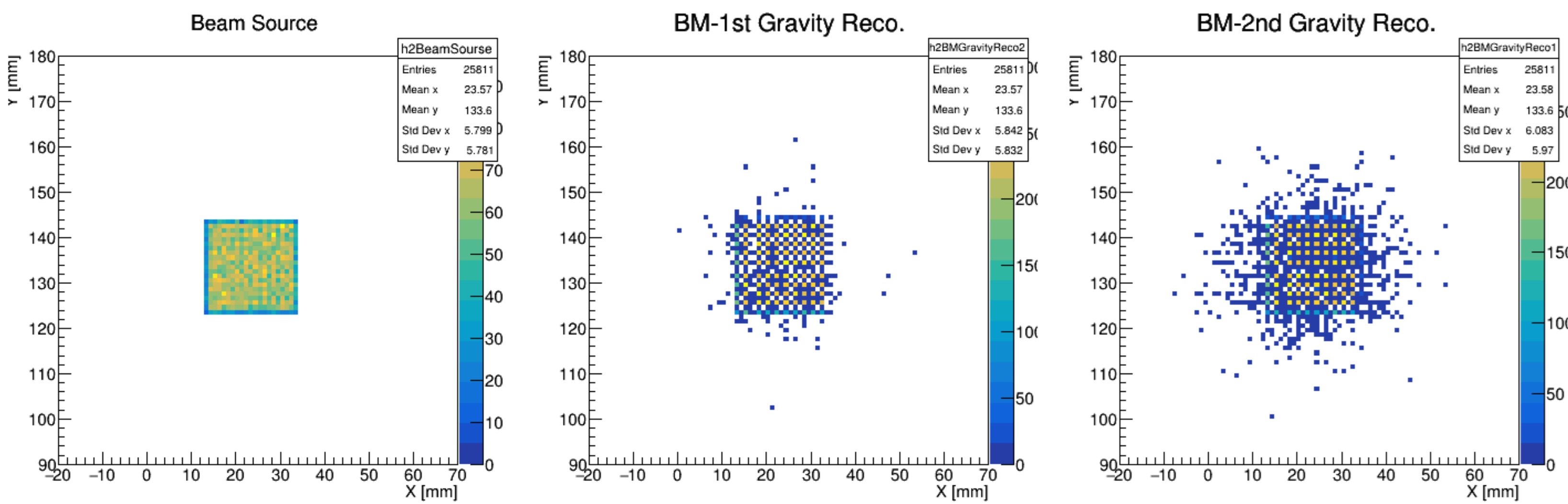
I (A)	x_{PS} 制限なし μ_P (MeV/c)	σ_P (MeV/c)	σ_P/μ_P (%)
025	47.18(2)	5.48(1)	11.63(3)
050	98.19(4)	4.92(3)	5.01(3)
075	148.22(4)	4.77(2)	3.22(2)
100	197.94(3)	4.91(2)	2.48(1)
125	247.79(3)	5.00(2)	2.02(0)
150	297.30(2)	5.29(2)	1.78(0)
175	346.81(2)	5.31(1)	1.53(0)

Energy resolution of 47MeV momentum resolution = 11.6%

2nd Prototype : MC Setting



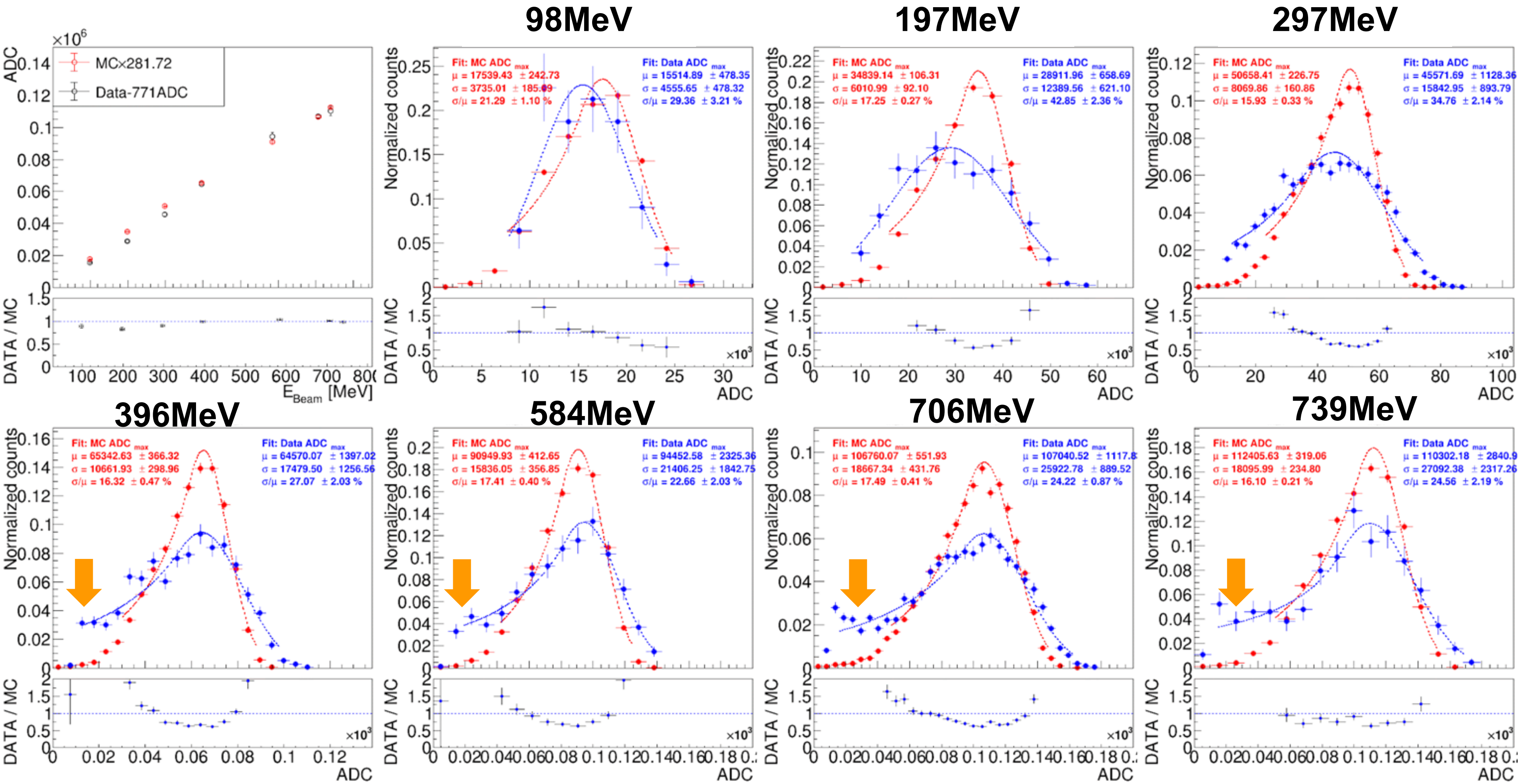
- **Particle:** Positron
- **Beam position:** spread beam
- **Beam direction:** perpendicular to ZDC surface
- **Experimental Setup :** same as test beam
- **With optical photon turned on**
- **No APD/SiPM simulation**



We update the beam setting and turn on optical photons.

2^{nd} Prototype **PbWO4 + SiPM** Compare Data and MC : **Emax**

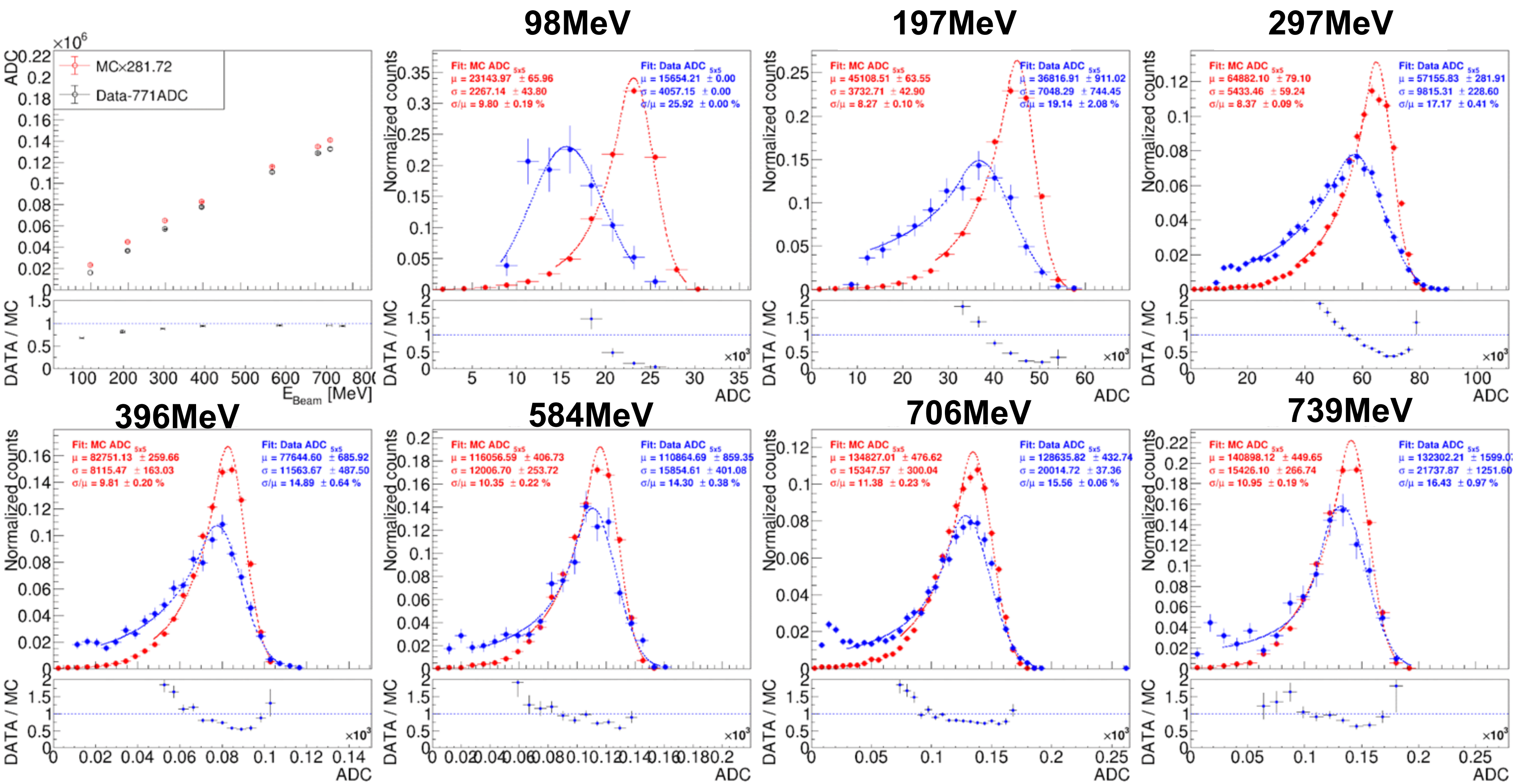
- Data (threshold ~ 50MeV)
- MC (no threshold cut)



- The energy resolution of the data is worse than that of the MC.
- A large number of low-energy hits observed in the data.

2nd Prototype **PbWO4 + SiPM**
Compare Data and MC : **E5x5**

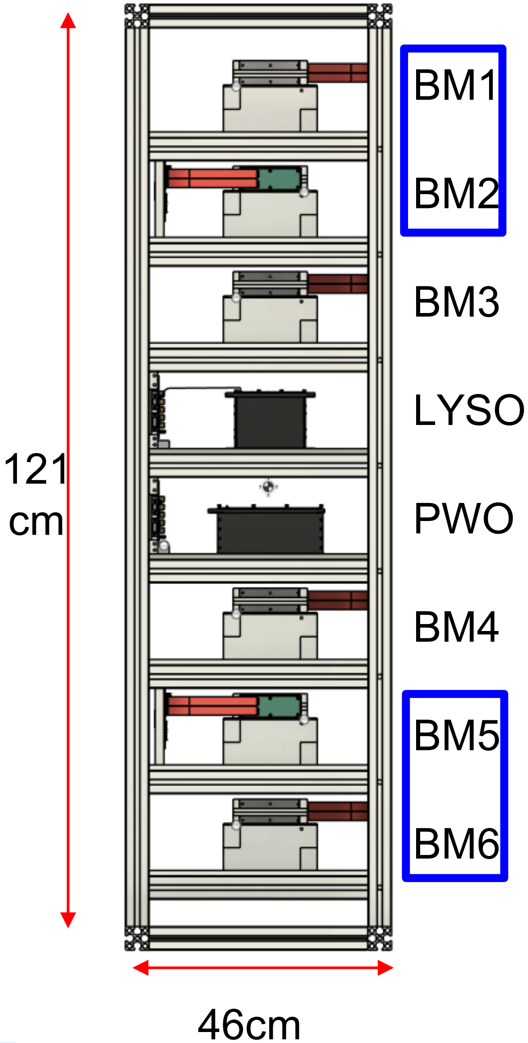
- Data (threshold ~ 50MeV)
- MC (no threshold cut)

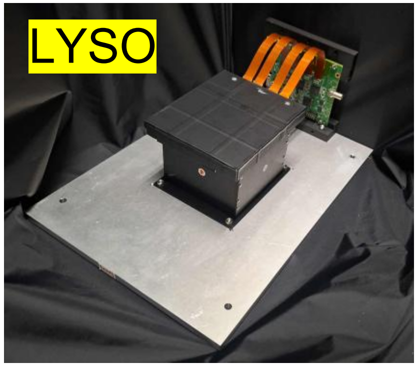


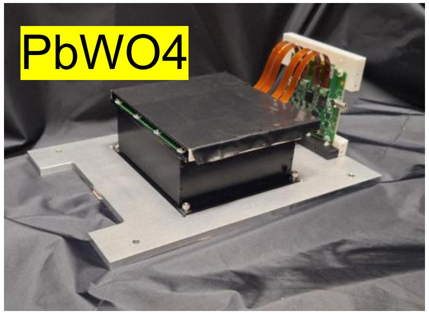
- Bad consistency for Ebeam<300MeV.
- Better consistency for Ebeam>300MeV.

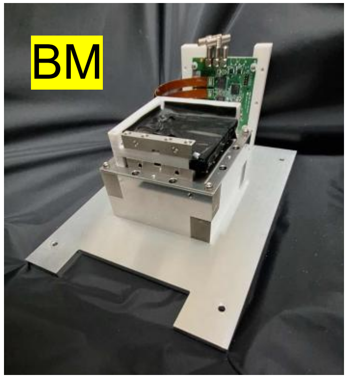
Cosmic Ray Test in Taiwan

Future Plan









Cosmic ray data collection is currently in progress. A high noise level has been observed in the Taiwan setup, and we plan to investigate improvements to the shielding system.