Recent Update of Taiwan ZDC ECAL Activity

EIC Taiwan Meeting @ 20260924

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-Chih-Hsun Lin
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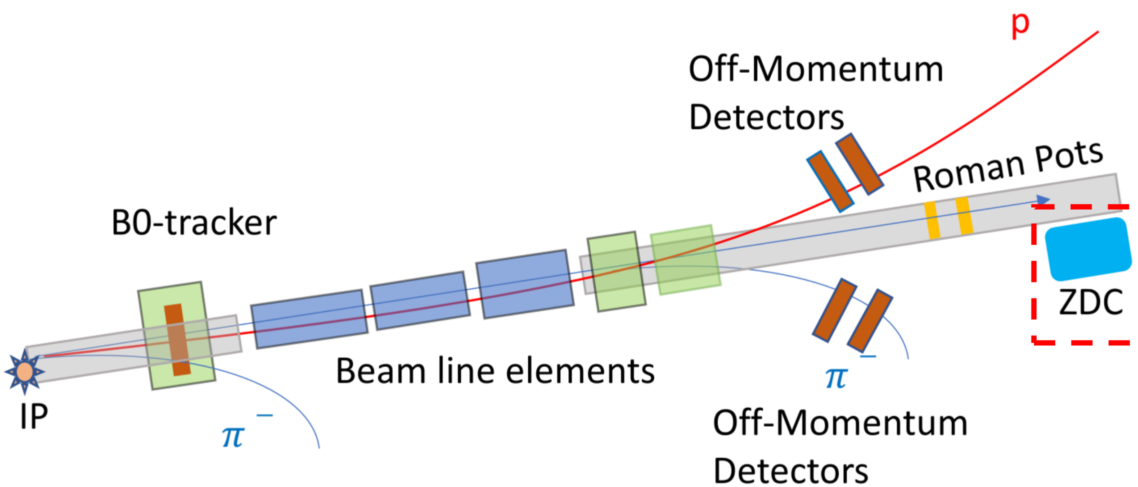
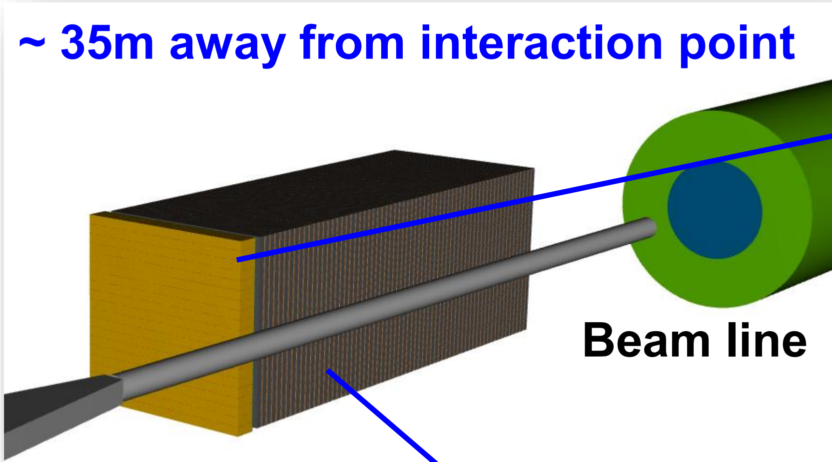
Physics Program for ZDC

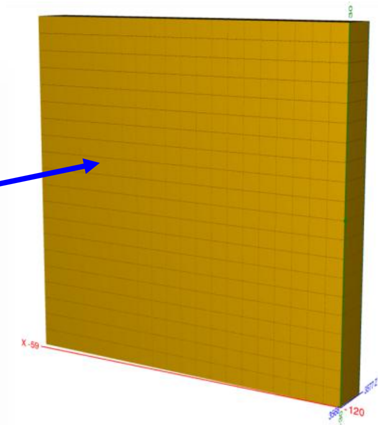


- **Physics for Far-forward detectors**
- **Sullivan process for pion structure** : $e + p \rightarrow e' + X + \boldsymbol{n}$
- **Sullivan process for kaon structure** : $e + p \rightarrow e' + X + \Lambda$ *and* $\boldsymbol{\Lambda} \rightarrow \boldsymbol{n} + \boldsymbol{\pi^0} \rightarrow \boldsymbol{n + 2\gamma}$
- **Spectator-neutron tagging for nuclear physics** : $(1) e + d \rightarrow e' + X + \boldsymbol{n}$ $(2)\ e + A \rightarrow e' + X + (A-1) + \boldsymbol{n}$
- **Background**, secondary photons showers : $\pi^0 \rightarrow \boldsymbol{\gamma\gamma}$

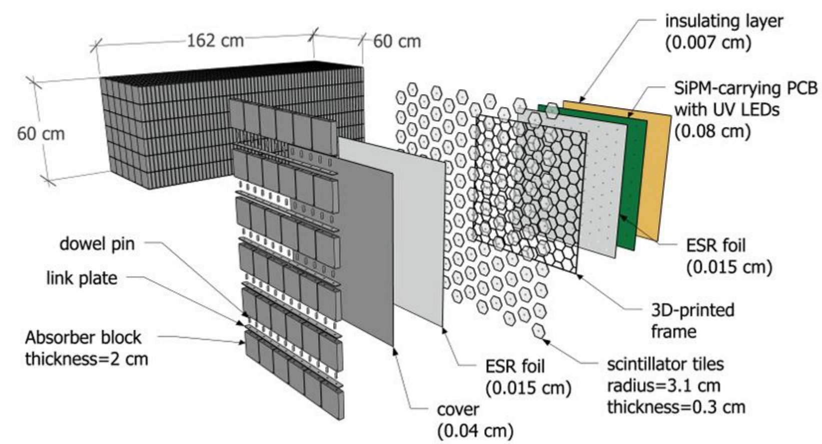
⇒ **Tag forward neutron and gamma detection with good energy and angular/position resolution.**

Baseline Design of ZDC





ECAL
1. **PbWO4**
2. 20*20 cells
3. 3cm*3cm*7cm / cell
4. 60cm*60cm
5. **7cm ~ 6.5X0 in Z**



- **ECAL**
- crystal calorimeter
- provide **good energy resolution**
- Development is leaded by **Taiwan group**

- **HCAL**
- Sampling calorimeter
- provide **good position resolution**
- Developed by **UC riverside**
- **Might be taken over by Japanese group.**

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

Requirements for ZDC

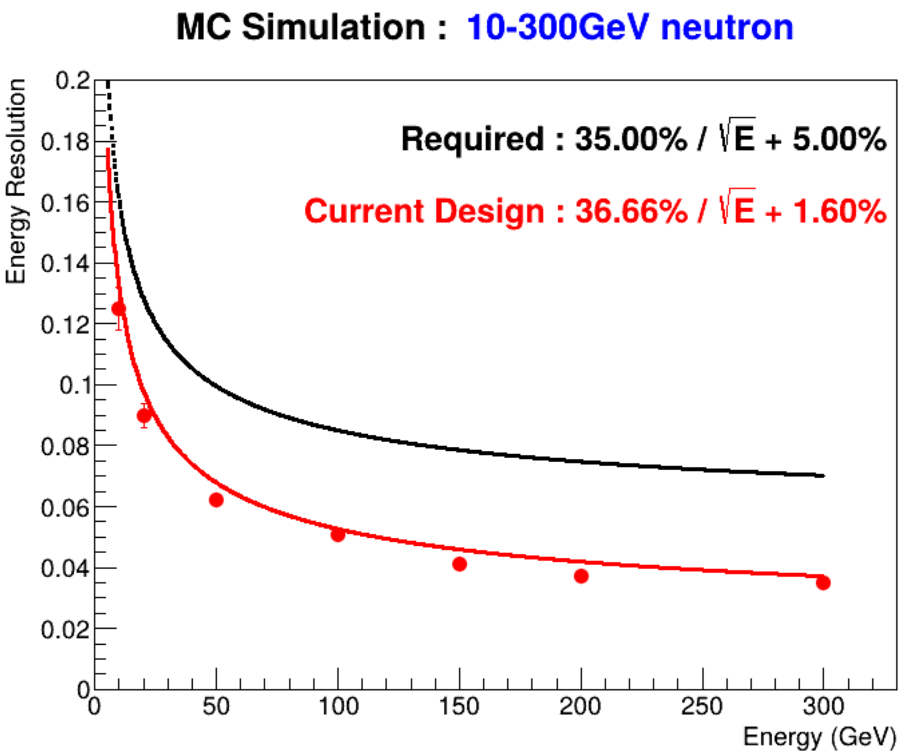
Physics process	Final State particles	Neutron		Photon	
		Energy resolution	Angular resolution	Energy resolution	Spatial resolution
Spectator tagged e+d	Neutrons	$\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{\mathrm{E}}} \oplus 5\%$	$\frac{\sigma_\theta}{\theta} \leq \frac{2\,mrad}{\sqrt{E}}$	N/A	N/A
Incoherent vetoing of e+A	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	Neutrons Photons	$\boldsymbol{\frac{\sigma_E}{E} \leq \frac{35\%}{\sqrt{E}} \oplus 5\%}$	$\boldsymbol{\frac{\sigma_\theta}{\theta} \leq \frac{3\,mrad}{\sqrt{E}}}$	$\boldsymbol{\frac{\sigma_\mathrm{E}}{\mathrm{E}} \leq \frac{20\%}{\sqrt{\mathrm{E}}} \oplus 5\%}$	$\boldsymbol{\frac{\sigma_\theta}{\theta} \leq \frac{3\,mrad}{\sqrt{E}}}$

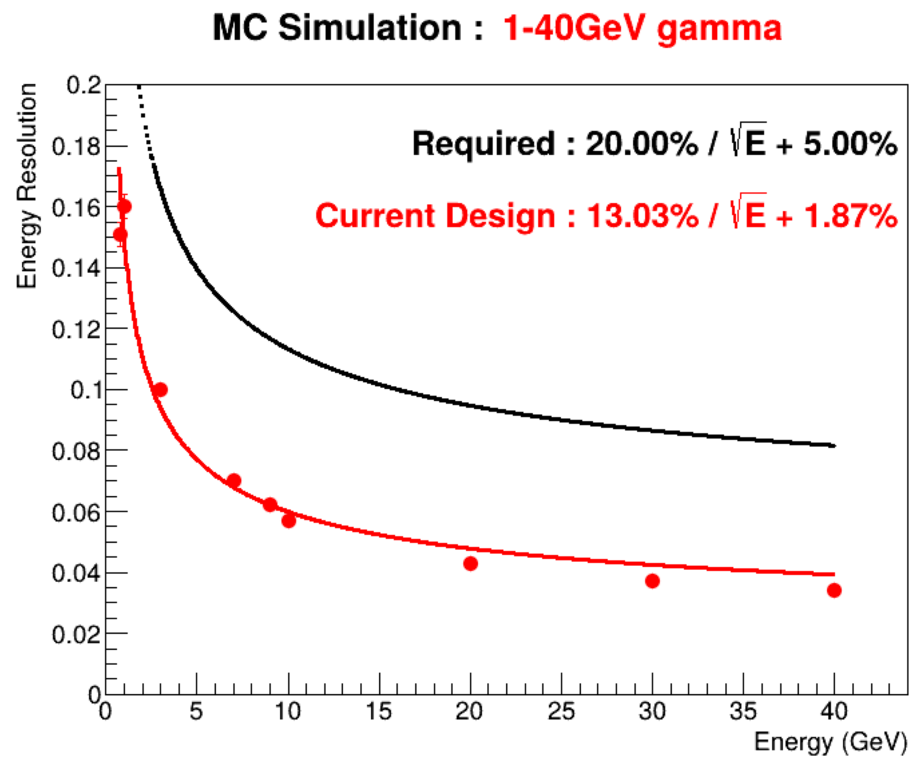
- Neutrons
  - Energy resolution **σ(E)/E < 50%/√E (GeV) + 5%**
  - Angular resolution **σ(θ)/θ < 3 mrad/√E (GeV)**

- Photons
  - Energy resolution **σ(E)/E < 20%/√E (GeV) + 5%**
  - Angular resolution σ**(θ)/θ < 3 mrad/√E (GeV)**
  - Measurement down to **100 MeV**

https://indico2.riken.jp/event/5568/contributions/28424/attachments/14764/22669/EIC-Asia_2606.pdf

Energy Resolution of Current Design

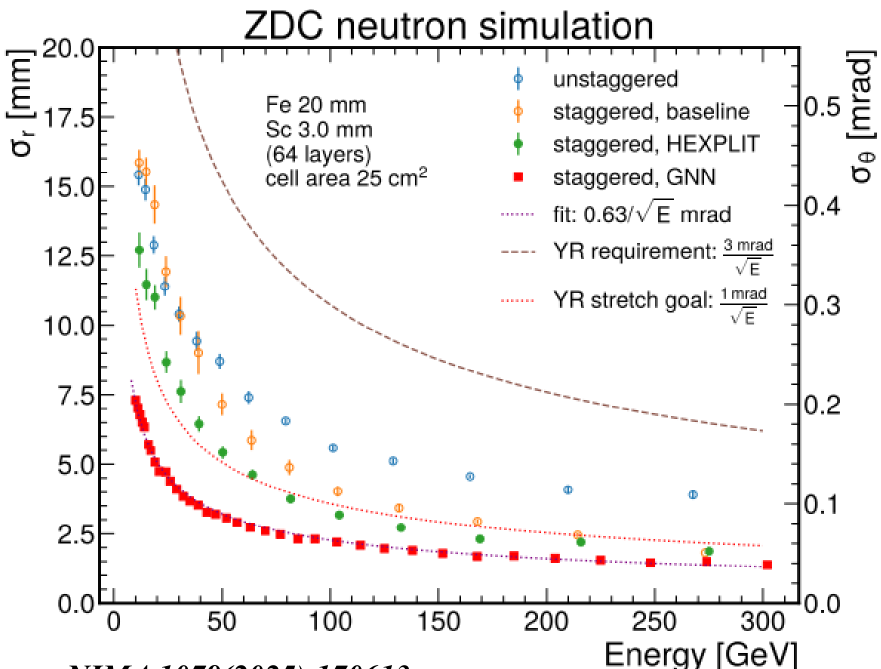




- Energy is mainly reconstructed by ECAL crystal part.
- Current design meets the requirement of energy resolution based on MC simulation.

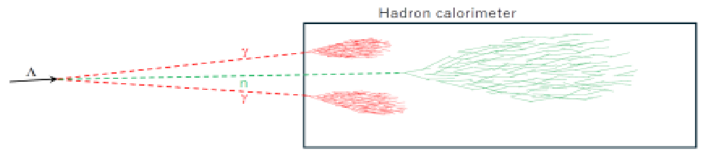
Position Resolution of Current Design

MC Simulation : 10-300GeV neutron

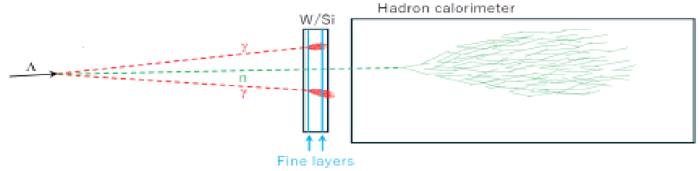


NIMA 1079(2025) 170613

10-40GeV gamma (under discussion)



10 mrad resolution

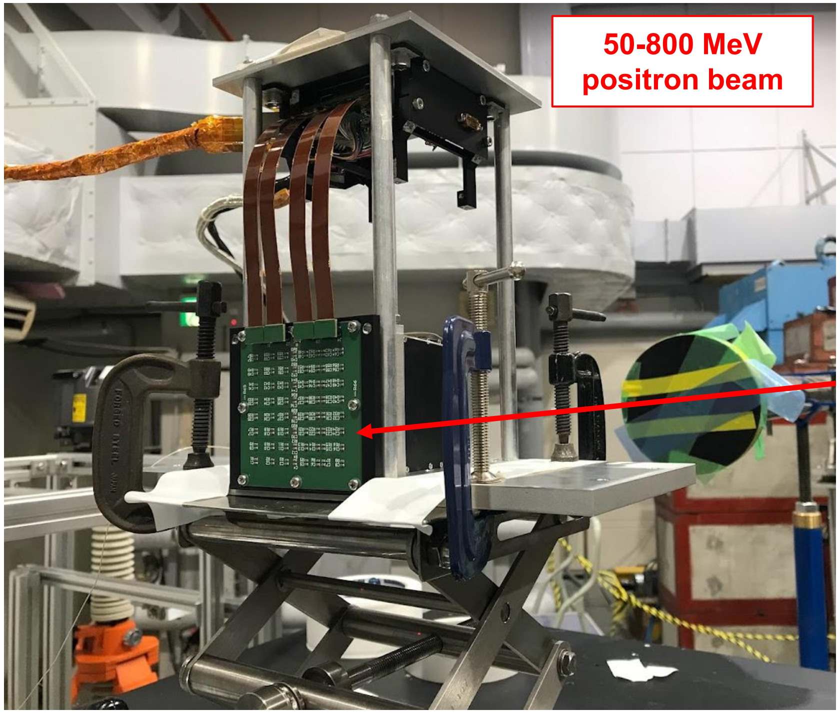


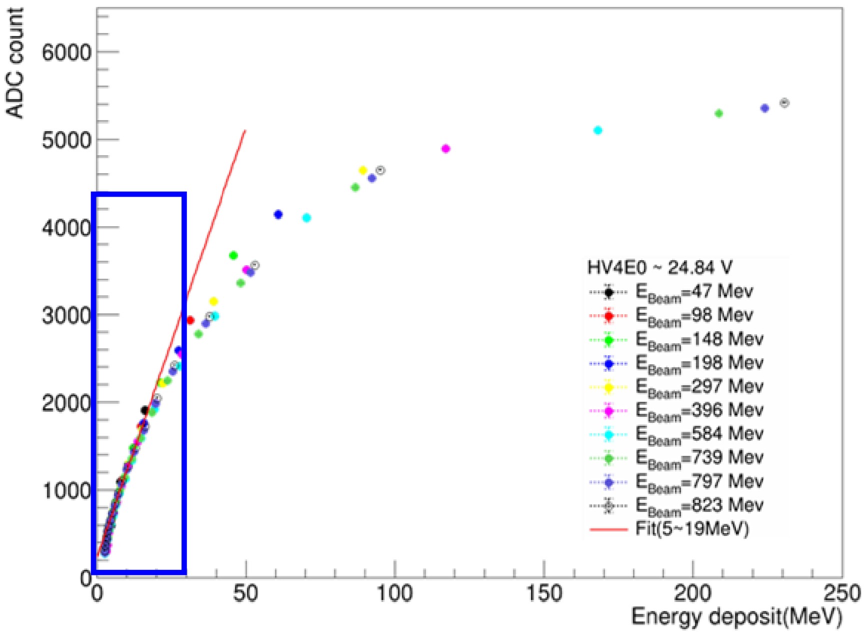
1 mrad resolution

https://indico2.riken.jp/event/5568/contributions/28424/attachments/14764/22669/EIC-Asia_2606.pdf

- **The crystal ECAL has no longitudinal segmentation, so the SiPM-on-tile HCAL does most of the track reconstruction.**
- Neutrons: the current design meets the position-resolution requirement.
- **Photons (kaon structure): HCAL-only reconstruction isn't enough, so we're studying whether a W-Si calorimeter could replace the crystal ECAL.**

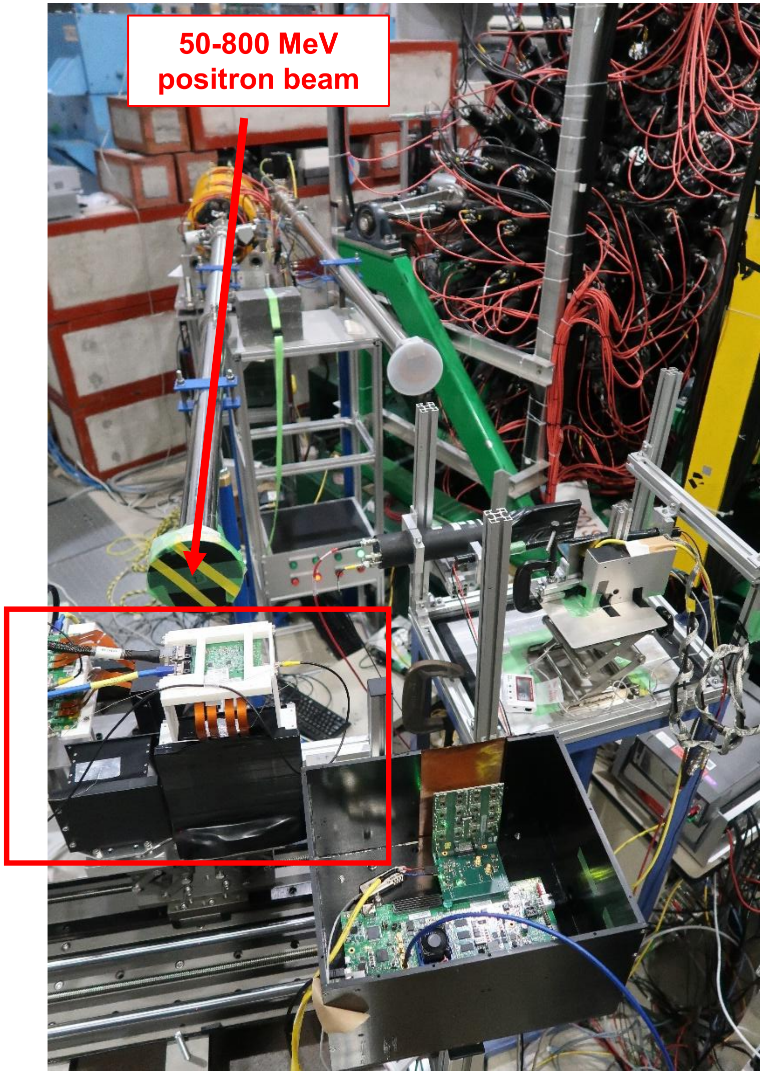
1^{st} Prototype of ZDC ECAL @ 2024

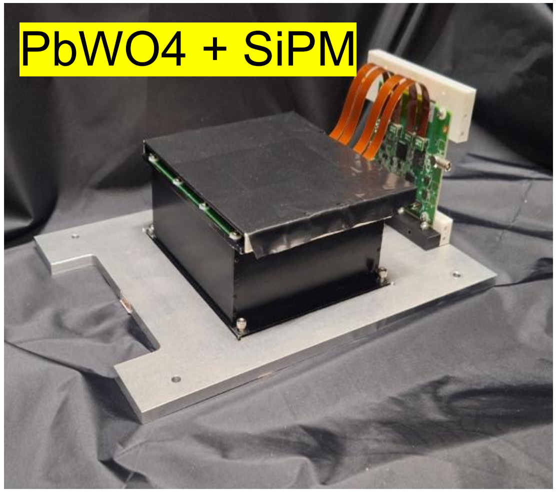


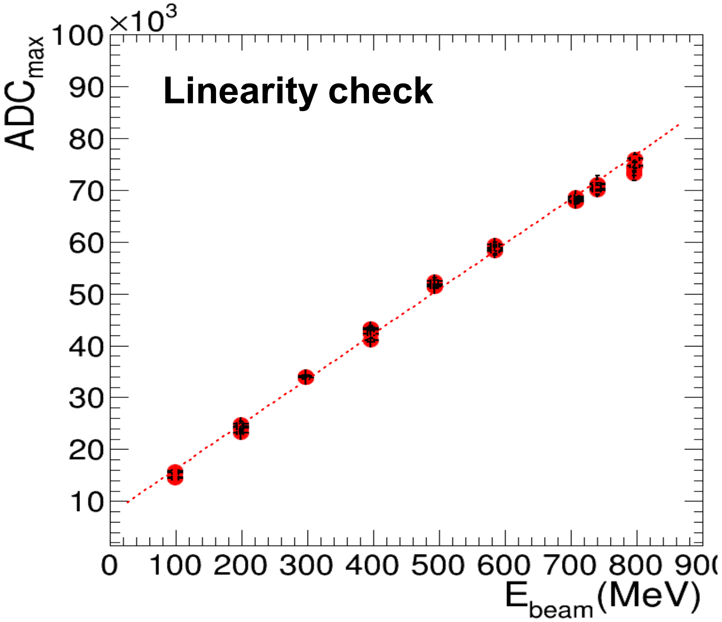


- 1^{st} prototype @ 2024 : LYSO + Onsemi SiPM
- Test bean with 50-800MeV positron beam @ JP
- SiPM saturated above 20MeV positron beam due to high light yield of LYSO crystal.
- Move from LYSO crystal to PbWO4 crystal (1/200 light yield)

2^{nd} Prototype of ZDC ECAL @ 2025

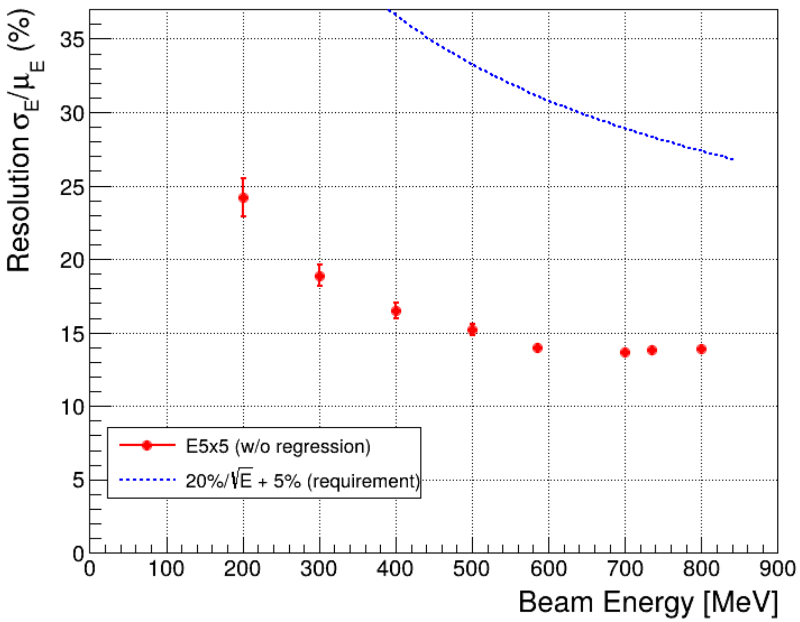




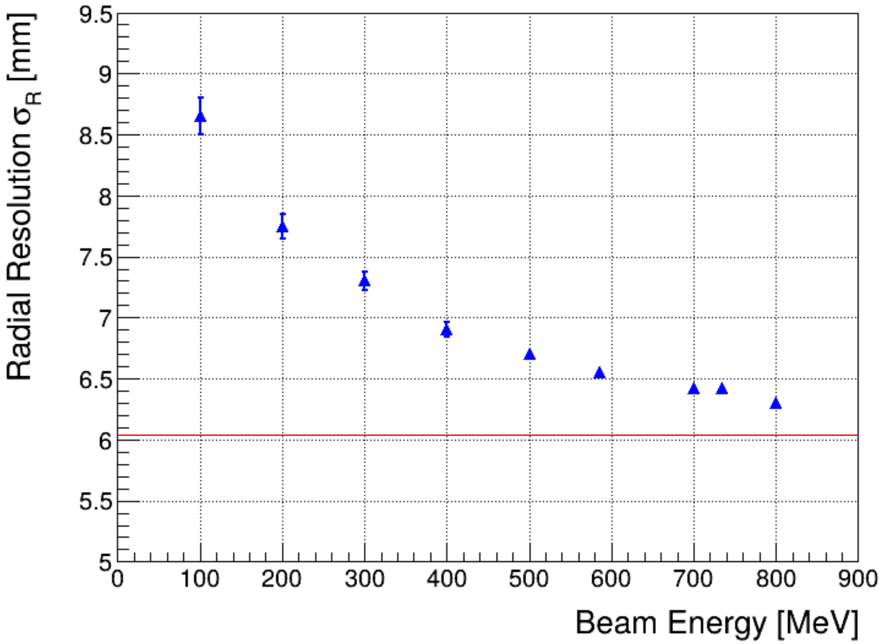


2^{nd} Prototype of ZDC ECAL @ 2025

Energy resolution



Position resolution



- **Energy resolution : ~15% @ 800MeV positron beam**
- **Position resolution : ~ 6.5mm @ 800MeV positron beam**
  Estimated position resolution = 20mm/sqrt(12) ~ 6mm
- 2^{nd} Prototype achieve the good energy resolution; however, we have **no sensitivity to 100MeV positron beam. During the test beam, 50MeV threshold is applied to supress noise.**

3rd Prototype @ 2026

	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/crystal	CITIROC
2nd prototype 2024-2025	LYSO + APD	LYSO	1cm*1cm	6.6cm (6X0)	8x8	APD C30739ECERH	1/crystal	CITIROC
	PbWO4 + SiPM	PbWO4	2cm*2cm	5.3cm (6X0)	6x6	SiPM Onsemi MICROFC-60035	2/crystal	CITIROC
3rd prototype 2025-2026 (developing)	PbWO4 + SiPM	PbWO4	2cm*2cm	5.3cm (6X0)	6x6	**SiPM Hamamatsu S14160-3015PS**	16/crystal	**HGCROC**

- The 3rd prototype suse the same crystals
  - **SiPM** will be changed from **Onsemi** → **Hamamatsu**
  - **DAQ** will be upgraded from **CITIROC** → **H2GCROC (closer to EICROC)**

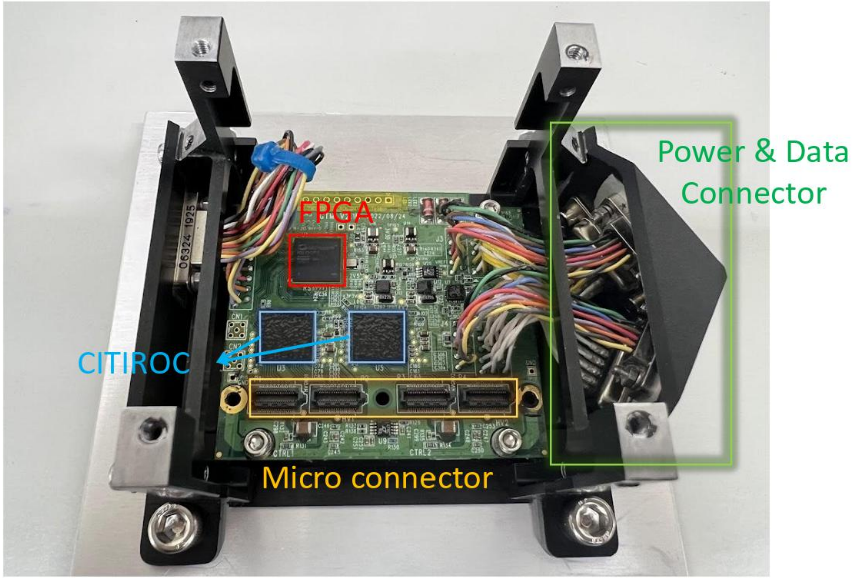
SiPMs

- **Onsemi SiPM (MICROFC-60035)** : https://www.onsemi.com/pdf/datasheet/microc-series-d.pdf
- **Hamamatsu SiPM (S14160-3015PS)** : https://www.hamamatsu.com/us/en/product/optical-sensors/mppc/mppc_mppc-array/S14160-3015PS.html

Feature	2nd prototype onsemi MICROFC-60035	3rd prototype Hamamatsu S14160-3015PS
Active area	6 × 6 mm^2	3 × 3 mm^2
Microcell pitch	35 μm	15 μm
Microcells (total)	18,980	39,984
Microcell density	**527 /mm^2**	**4,443 /mm^2**
Gain	~3 × 10^6	~3.6 × 10^5
Breakdown voltage	~24.5 V	~38 V
PDE (peak)	**~31–41%**	**~32%**

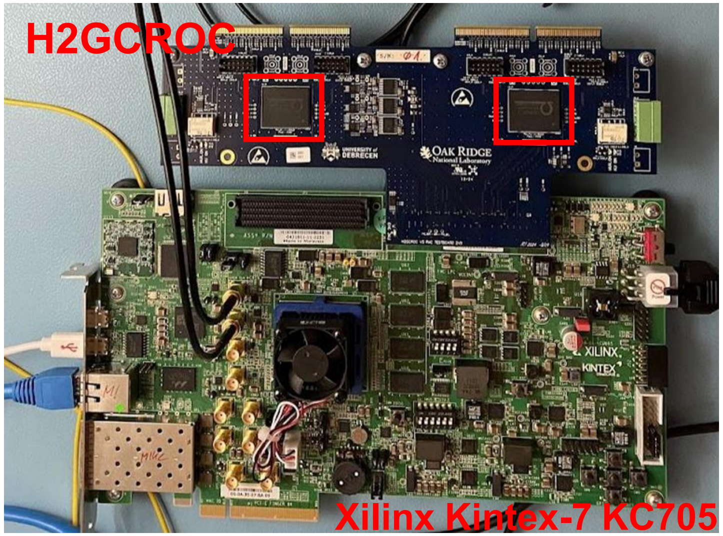
Hamamatsu SiPM
- higher microcell density plus lower PDE
  → (4,443/527) * (0.41/0.32) ~11x more incident photons before saturating → larger dynamic range
- lower PDE → reduced sensitivity at low beam energies

CITIROC VS H2GCROC



2nd prototype
CITIROC : peak-sensing readout

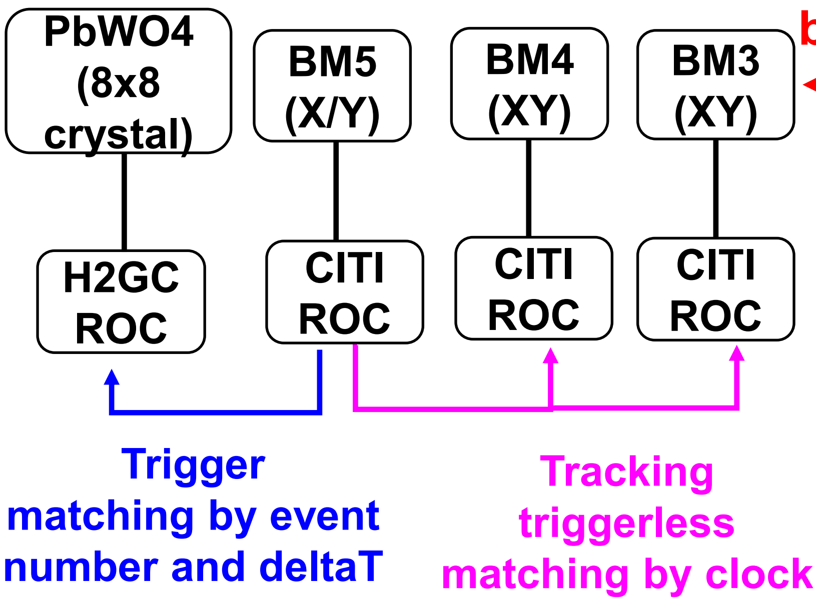
- 32 channels per ASIC
- **dynamic range: 160 fC – 400 pC (~1–2500 p.e.)**
- high- and low-gain preamplifiers and slow shapers.
- pulse height is held by a peak detector, 14-bit ADC, **one ADC value per event**
- Self-trigger mode only, streaming readout.

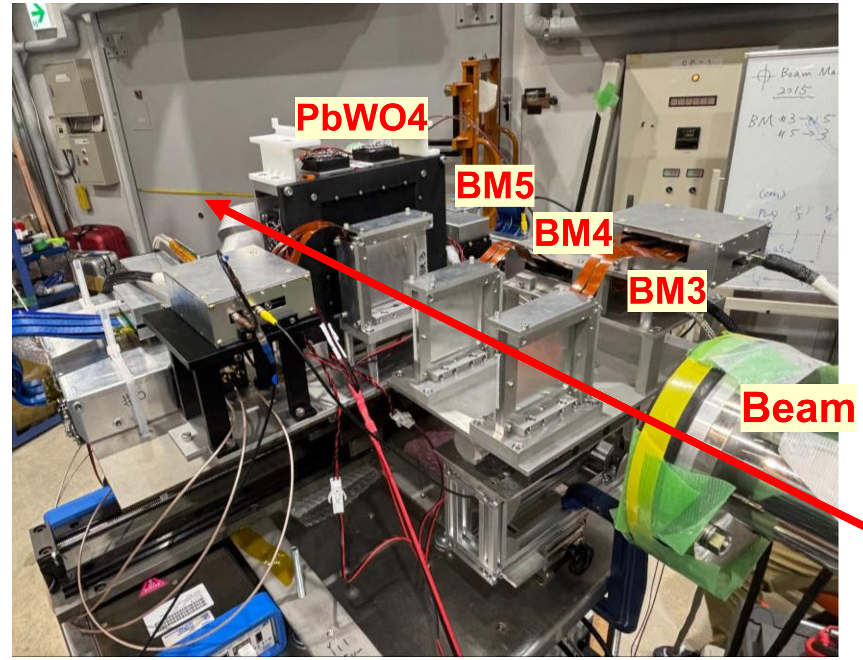


3rd prototype
H2GCROC : waveform sampling

- 72 channels per ASIC
- **dynamic range: 160 fC – 320 pC (~1–2000 p.e.)**
- 10-bit ADC samples the pulse at 40 MHz, so the **full waveform is recorded.**
- Also gives **TOT(10-bit, 25 ps bins) covers large signals and TOA gives timing information.**
- Self- and external-trigger

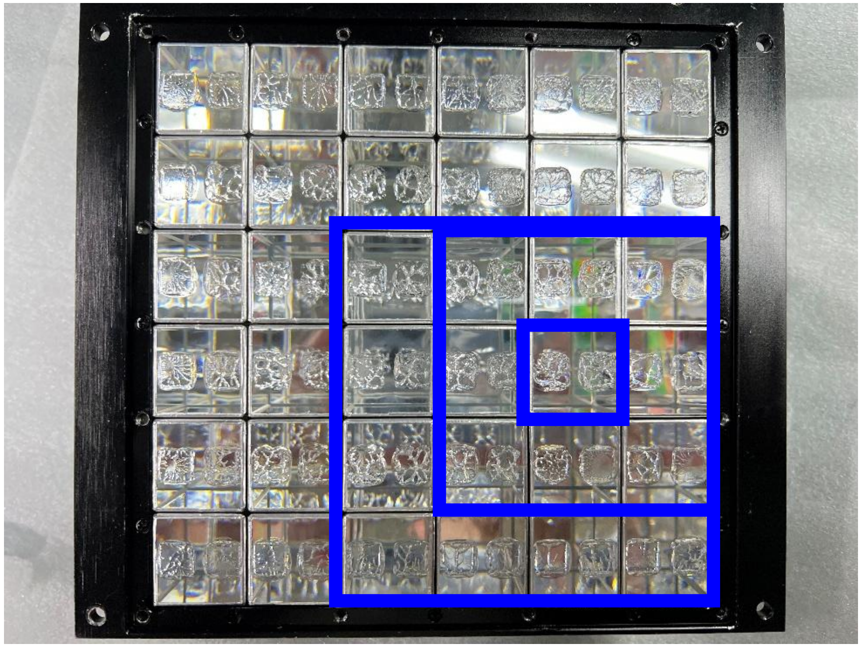
Setup of 3rd Prototype



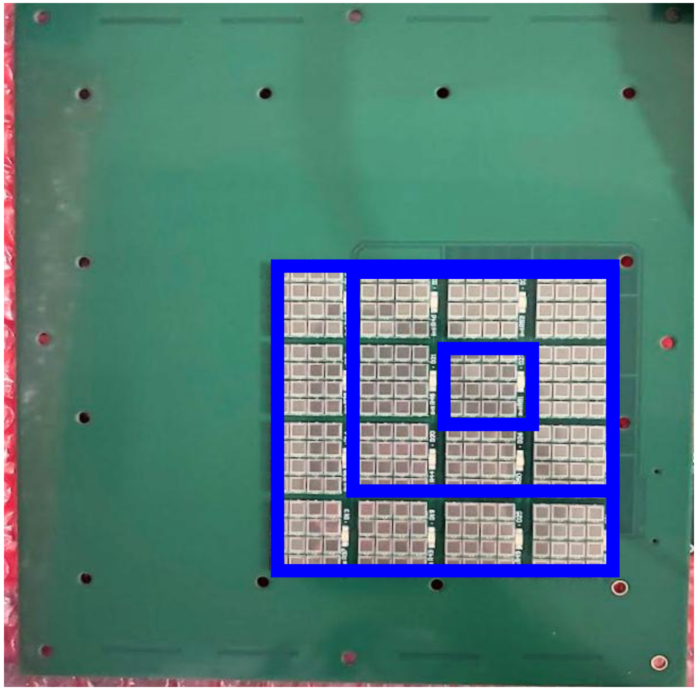


- **Data taking : 4 days in July, 2026**
- **Calibration :** HV scan of all SiPMs/crystals with 705MeV beam => calibration file
- **Beam energy scan#1 :** HV = 45V, Capacitor = 0xA
- **Beam energy scan#2 :** HV = 46V, Capacitor = 0x1 **(higher gain for low energy beam)**
- **Temperature scan @ 19 (default), 18, 25 degree**
- **Runs for TOT and ADC bridging**

PbWO4 Crystal + Hamamatsu SiPM



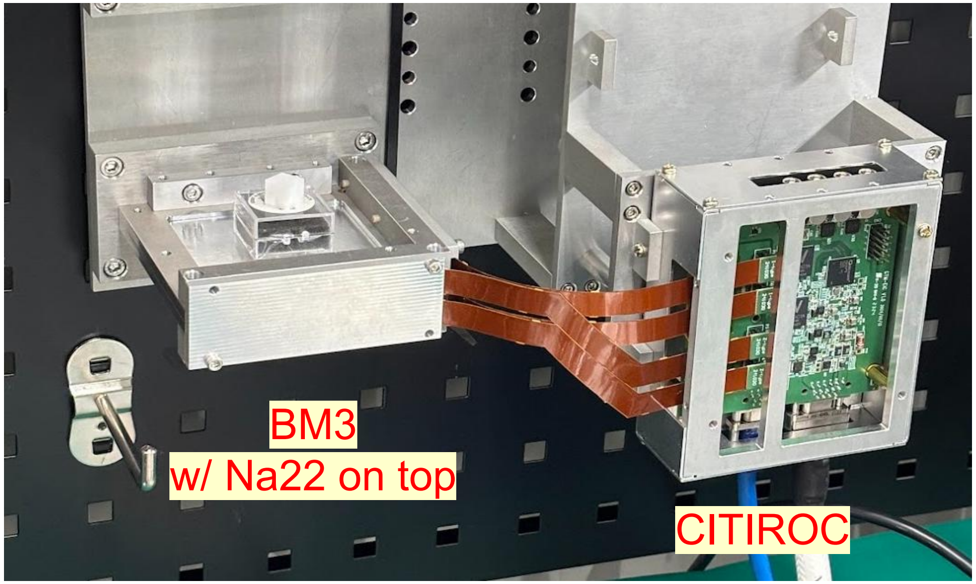
4*4 crystal is read
Study 1x1, 3x3, 5x5



16 SiPMs and a single LED
for each crystal

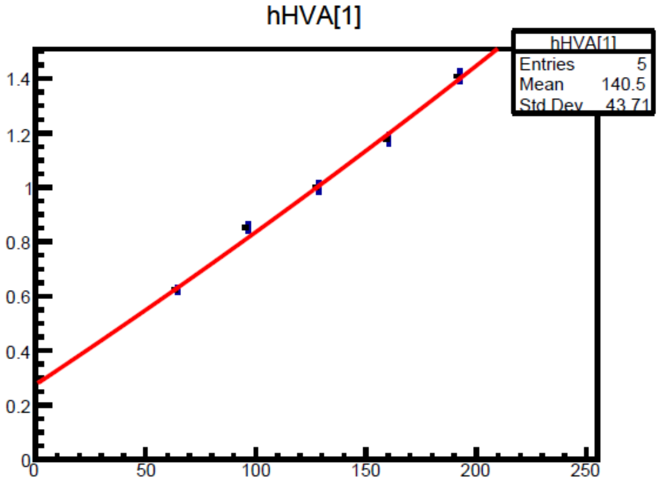
The detector contains an **8 × 8 crystal array**, but DAQ limitations allow only the central **4 × 4 crystals** to be coupled to SiPMs. The H2GCROC system may lose events at high data rates. **Previous prototype tests showed that a 3 × 3 crystal region captures sufficient transverse energy for positron beams below 1 GeV.**

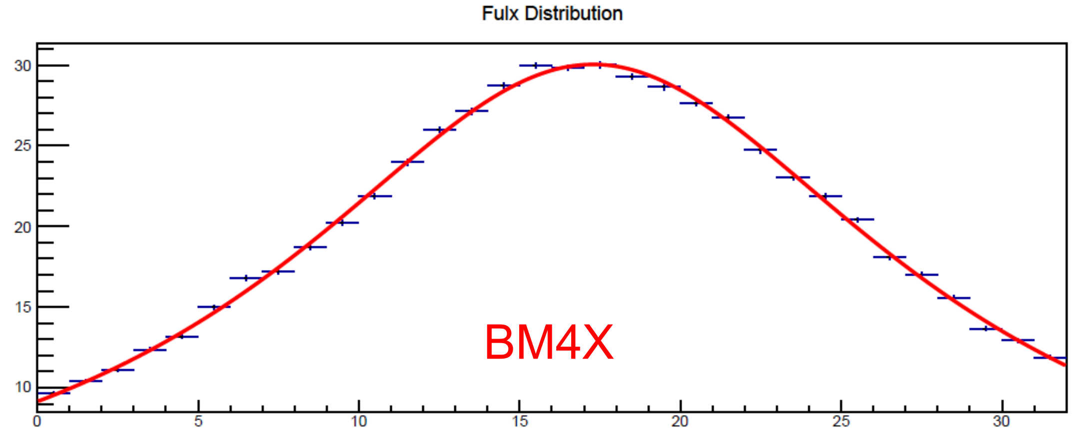
Beam Monitor Calibration



Beam-monitor channel gains were calibrated as follows:

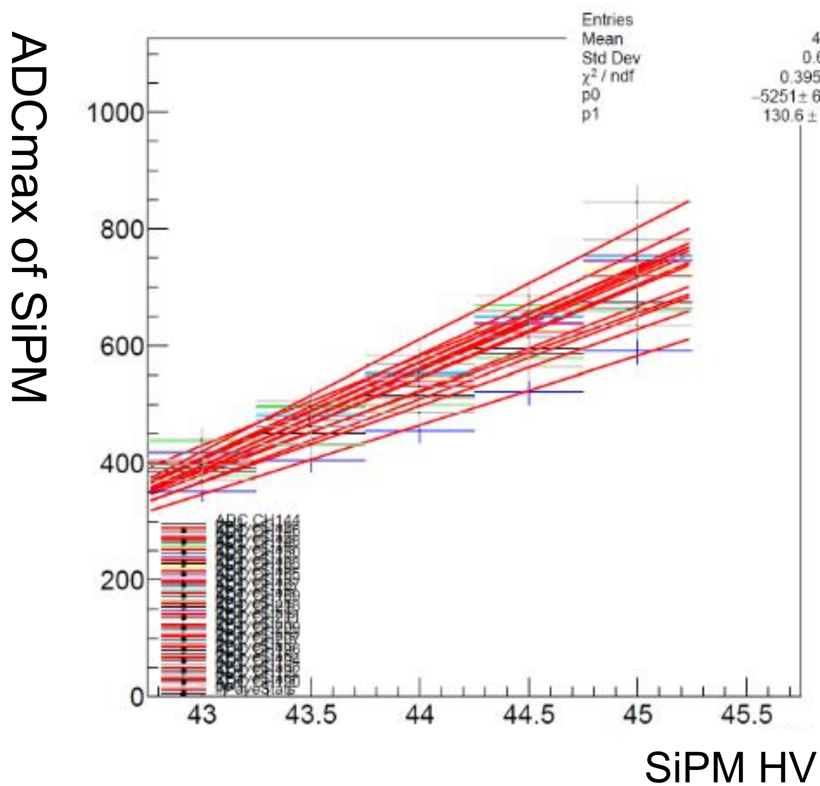
A high-voltage scan was performed at five operating points. For each channel, the **ADC response** was fitted as a function of the applied voltage. The operating voltage was then adjusted according to the fit results to achieve a consistent count rate across all channels.



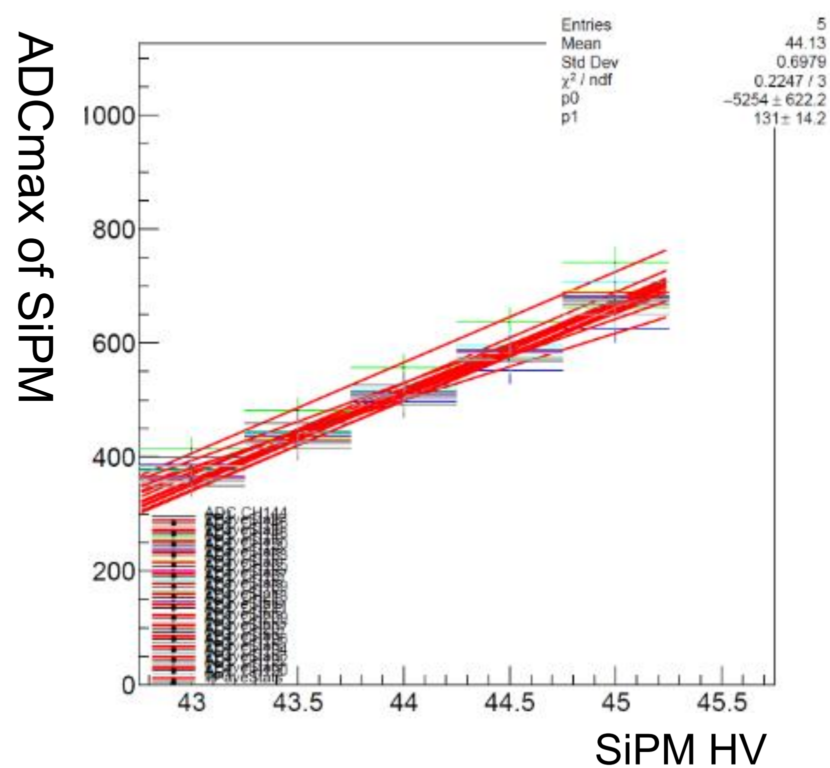


Gain Calibration of SiPM (Online)

BEFORE HV calibration



AFTER HV calibration



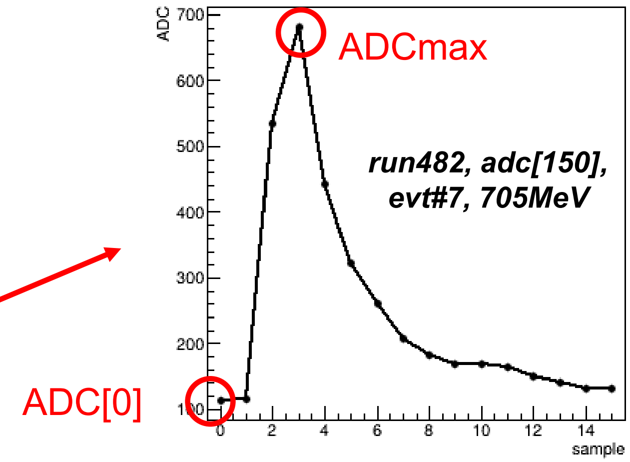
Because SiPM gain differs channel-to-channel even under identical applied HV, each channel's HV is individually adjusted so that all channels produce the same ADC response to the same incident beam energy. This gain equalization improves the detector's response linearity. Pedestal calibration, by contrast, can be done offline and doesn't require dedicated beam time.

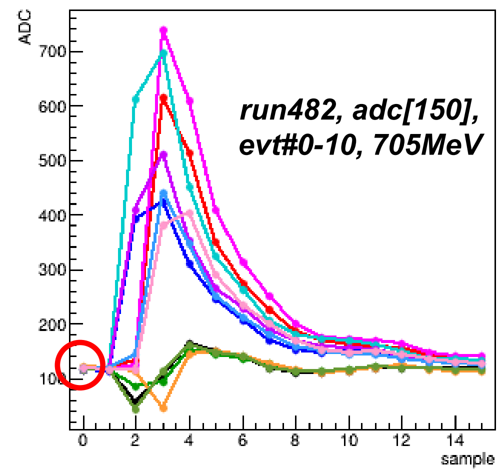
Data Analysis(1) : Raw Waveform

Channel Mapping (Front View)

Y \ X	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Cystal #1 (J5)				Cystal #2 (J5)				Cystal #3 (J1)				Cystal #4 (J1)			
	LED#56				LED#60				LED#80				LED#76			
1	6	14	25	33	63	55	46	36	181	183	185	187	189	191	193	195
2	4	12	23	31	65	57	48	38	198	200	202	204	208	210	212	214
3	2	10	21	29	67	59	50	40	145	147	149	151	155	157	159	160
4	0	9	19	27	69	61	52	42	[illegible]	[illegible]	[illegible]	[illegible]	172	174	176	178
	Cystal #5 (J6)				Cystal #6 (J6)				Cystal #7 (J2)				Cystal #[illegible] (J2)			
	LED#52				LED#64				LED#88				LED#84			
5	18	20	22	24	28	30	32	34	144	146	148	150	153	154	156	158
6	1	3	5	7	11	13	15	16	163	165	167	169	171	173	175	177
7	54	56	58	60	64	66	68	70	213	211	209	207	205	203	201	199
8	37	39	41	43	45	47	49	51	196	194	192	190	186	184	182	180
	Cystal #9 (J7)				Cystal #10 (J7)				Cystal #11 (J3)				Cystal #12 (J3)			
	LED#48				LED#68				LED#96				LED#92			
9	124	122	120	118	114	112	110	108	253	255	257	259	261	263	265	267
10	141	139	137	135	133	131	129	127	270	272	274	276	280	282	284	286
11	91	93	95	97	99	101	103	105	217	219	221	223	227	229	231	232
12	72	74	76	78	81	82	84	86	234	236	238	240	244	246	248	250
	Cystal #13 (J8)				Cystal #14 (J8)				Cystal #15 (J4)				Cystal #16 (J4)			
	LED#44				LED#72				LED#104				LED#100			
13	90	92	94	96	100	102	104	106	216	218	220	222	225	226	228	230
14	73	75	77	79	83	85	87	88	235	237	239	241	243	245	247	249
15	126	128	130	132	136	138	140	142	285	283	281	279	277	275	273	271
16	109	111	113	115	117	119	121	123	268	266	264	262	258	256	254	252

central crystal



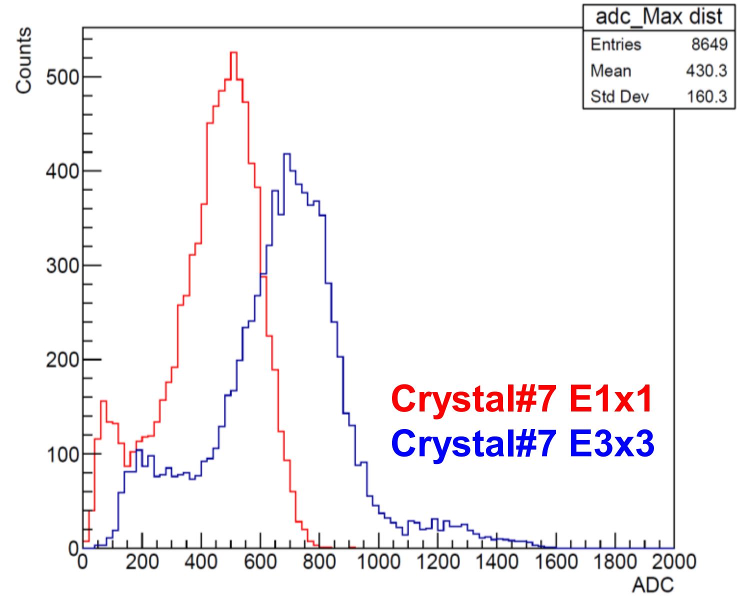


H2GCROC gives waveform of each SiPM, event by event, 16 points per event.
ADC = ADCmax – ADC[0]

Data Analysis (2) : Clustering

Channel Mapping (Front View)

Y \ X	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Cystal #1 (J5)				Cystal #2 (J5)				Cystal #3 (J1)				Cystal #4 (J1)			
	LED#56				LED#60				LED#80				LED#76			
1	6	14	25	33	63	55	46	36	181	183	185	187	189	191	193	195
2	4	12	23	31	65	57	48	38	198	200	202	204	208	210	212	214
3	2	10	21	29	67	59	50	40	145	147	149	151	155	157	159	160
4	0	9	19	27	69	61	52	42	162	164	166	168	172	174	176	178
	Cystal #5 (J6)				Cystal #6 (J6)				Cystal #7 (J2)				Cystal #8 (J2)			
	LED#52				LED#64				LED#88				LED#84			
5	18	20	22	24	28	30	32	34	144	146	148	150	153	154	156	158
6	1	3	5	7	11	13	15	16	163	165	167	169	171	173	175	177
7	54	56	58	60	64	66	68	70	213	211	209	207	205	203	201	199
8	37	39	41	43	45	47	49	51	196	194	192	190	186	184	182	180
	Cystal #9 (J7)				Cystal #10 (J7)				Cystal #11 (J3)				Cystal #12 (J3)			
	LED#48				LED#68				LED#96				LED#92			
9	124	122	120	118	114	112	110	108	253	255	257	259	261	263	265	267
10	141	139	137	135	133	131	129	127	270	272	274	276	280	282	284	286
11	91	93	95	97	99	101	103	105	217	219	221	223	227	229	231	232
12	72	74	76	78	81	82	84	86	234	236	238	240	244	246	248	250
	Cystal #13 (J8)				Cystal #14 (J8)				Cystal #15 (J4)				Cystal #16 (J4)			
	LED#44				LED#72				LED#104				LED#100			
13	90	92	94	96	100	102	104	106	216	218	220	222	225	226	228	230
14	73	75	77	79	83	85	87	88	235	237	239	241	243	245	247	249
15	126	128	130	132	136	138	140	142	285	283	281	279	277	275	273	271
16	109	111	113	115	117	119	121	123	268	266	264	262	258	256	254	252



$$E_{1x1} = \frac{1}{N}\sum_{i=1}^{N} E_{SiPM_i}$$

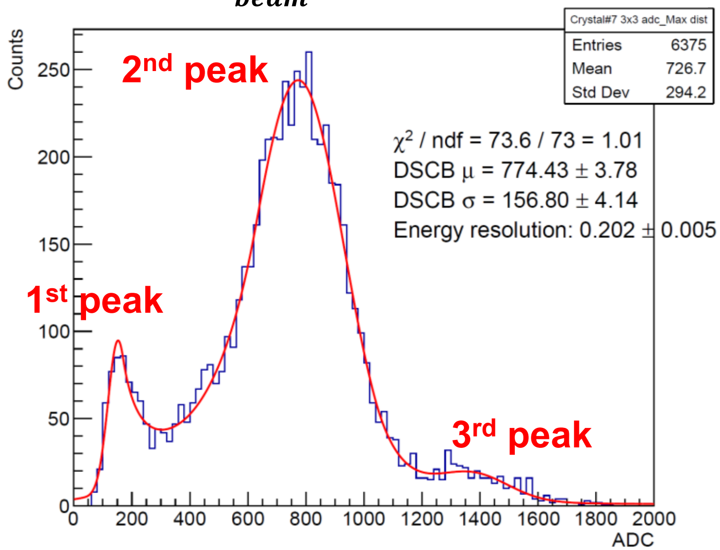
Some of SiPMs have problem so excluded from analysis.

$$E_{3x3} = \sum_{j=1}^{9} E_{1x1,j}$$

Represent the total energy.

Data Analysis (3) : DSCB Fitting

$E_{beam} = 823MeV$



Double-Sided Crystal Ball function (DSCB)

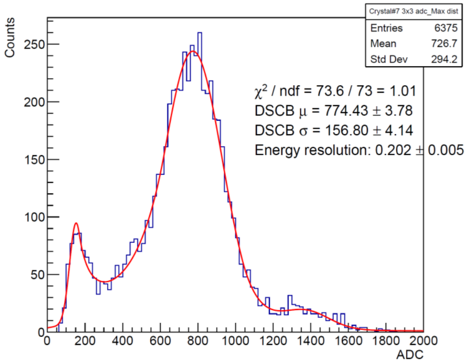
$$f(x;\mu,\sigma,\alpha_L,n_L,\alpha_R,n_R) = N\begin{cases} A_L\left(B_L - \frac{x-\mu}{\sigma}\right)^{-n_L} & \text{for } \frac{x-\mu}{\sigma} \le -\alpha_L \\ \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) & \text{for } -\alpha_L < \frac{x-\mu}{\sigma} < \alpha_R \\ A_R\left(B_R + \frac{x-\mu}{\sigma}\right)^{-n_R} & \text{for } \frac{x-\mu}{\sigma} \ge \alpha_R \end{cases}$$

Double-Sided Crystal Ball consists of a gaussian core that smoothly transitions into a power-law tail on the both sides.

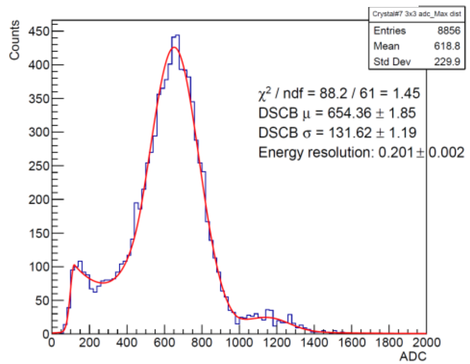
- **1st peak :** fit by DSCB, background, expect to be removed if apply tracking.
- **2nd peak :** fit by DSCB, **E3x3 main peak, energy resolution sigma/mean.**
- **3rd peak :** fit by gaussian, should not be there, problem with **timing matching of 2 FPGAs on DAQ**, low percentage. We are now trying to realign the data. Expect this bump disappear after.

Data Analysis(4) : E3x3 of All Energies

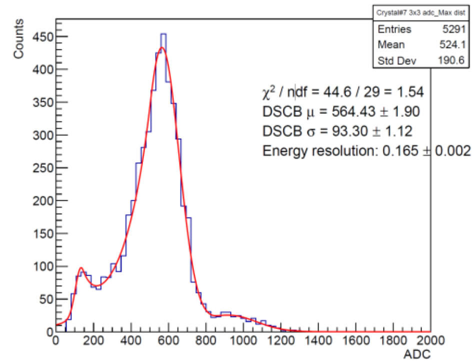
$E_{beam} = 823MeV$



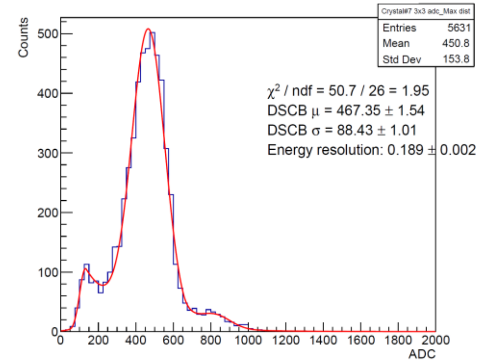
$E_{beam} = 705MeV$



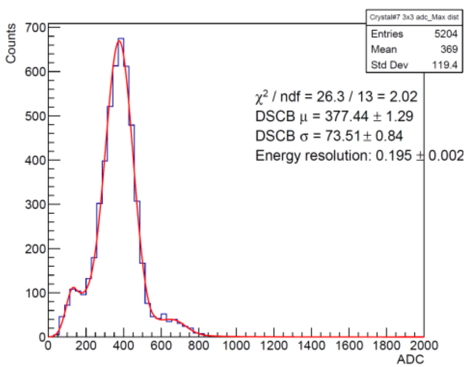
$E_{beam} = 584MeV$



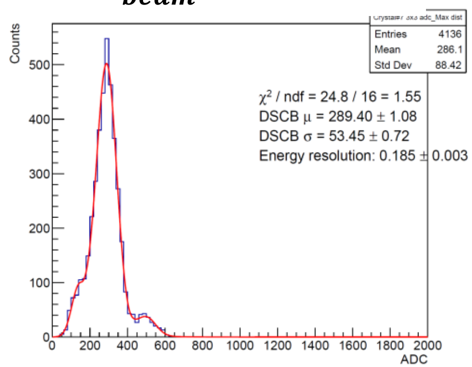
$E_{beam} = 492MeV$



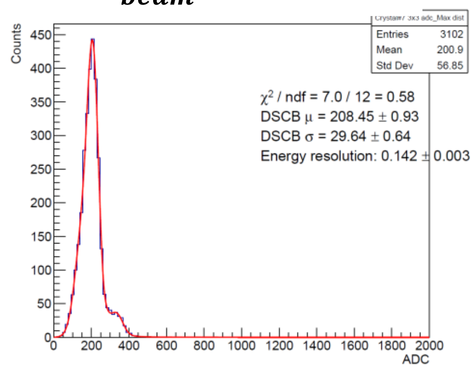
$E_{beam} = 395\ MeV$



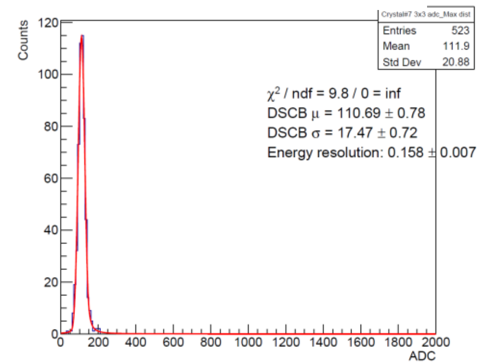
$E_{beam} = 297\ MeV$



$E_{beam} = 197MeV$

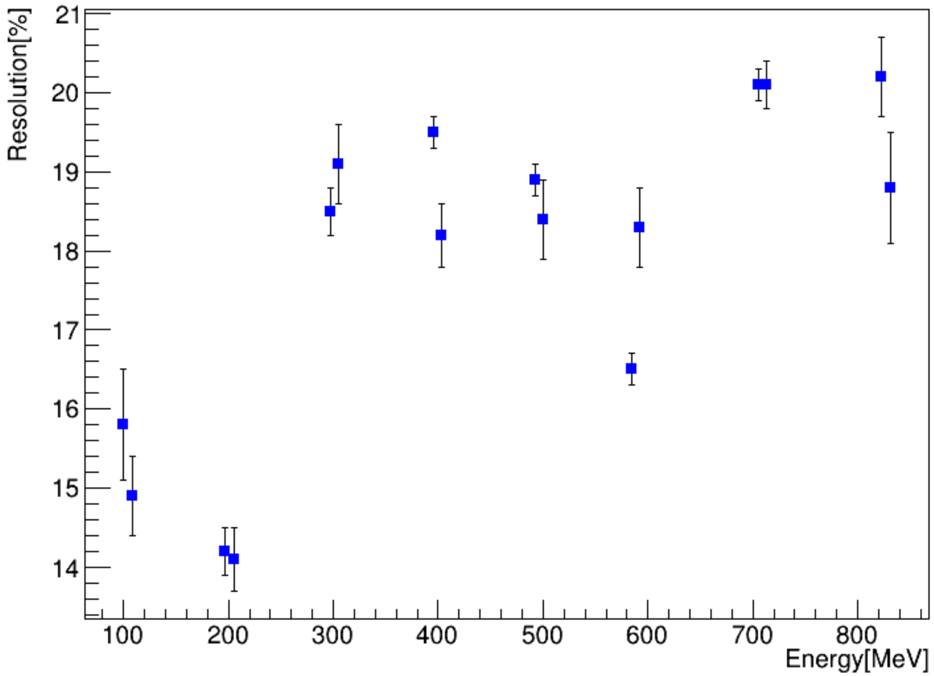


$E_{beam} = 100\ MeV$

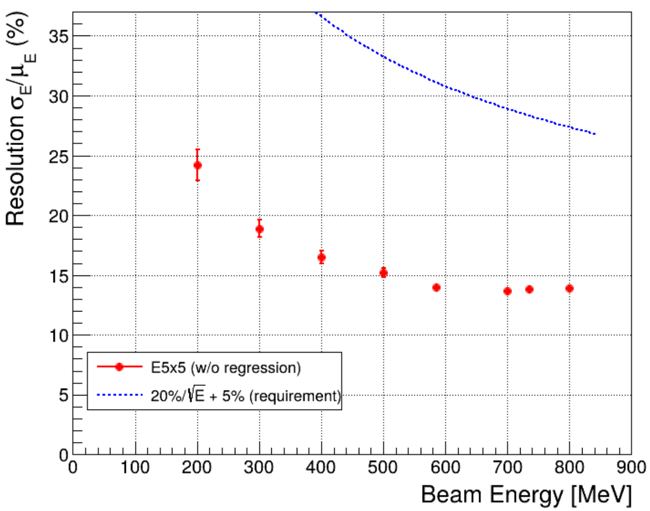


Data Analysis (3) : Energy Resolution

3rd prototype Energy resolution (preliminary)

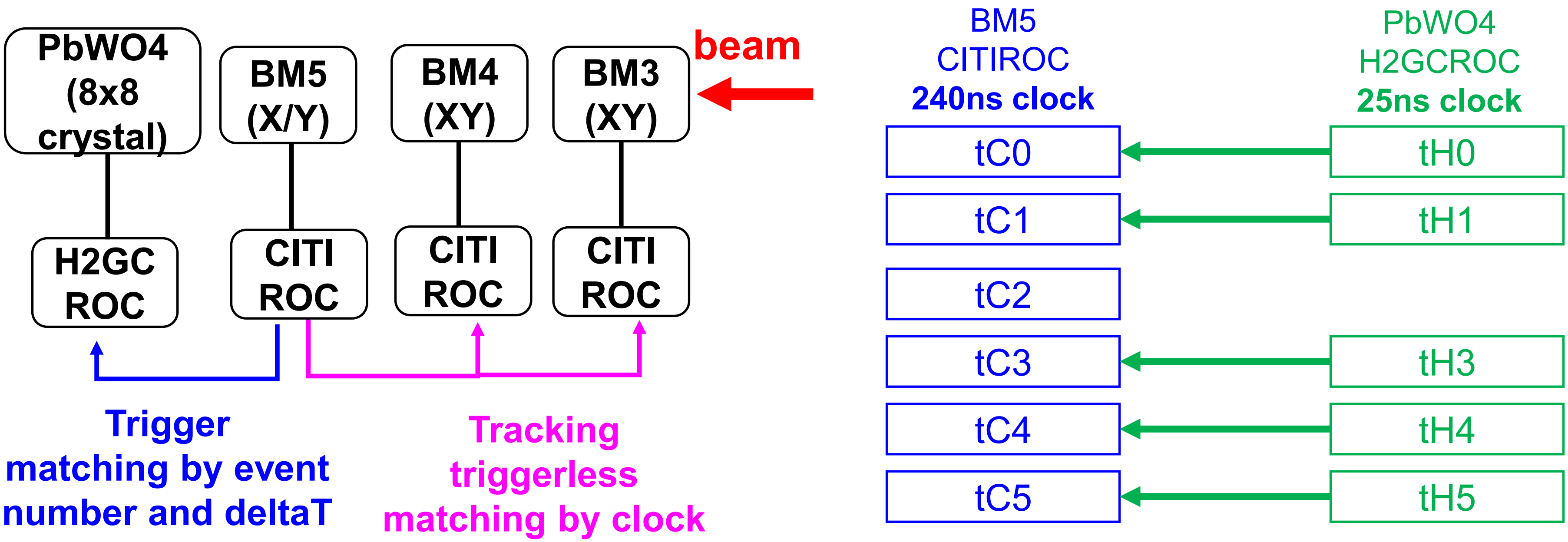


2nd prototype



Preliminary results from the 3rd prototype (19% @ 800MeV) are somewhat worse than those from the 2nd prototype (14% @ 800MeV), though they still meet the requirement. A number of things remain to be investigated.

To Do : Tracking



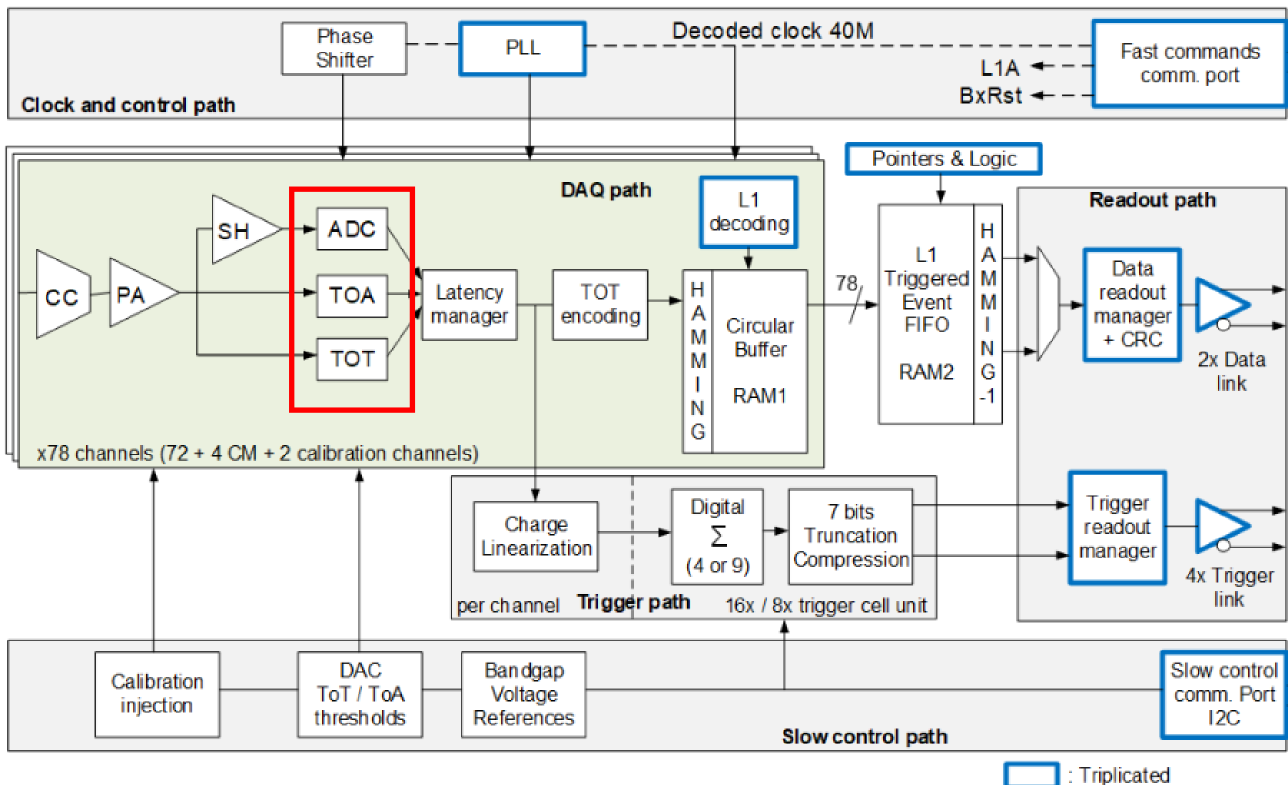
Tracking, BM5XY/BM4XY/BM3XY: Clocks are the same and synchronized. These are read out triggerless and matched to each other purely by 250ns clock/timestamp.

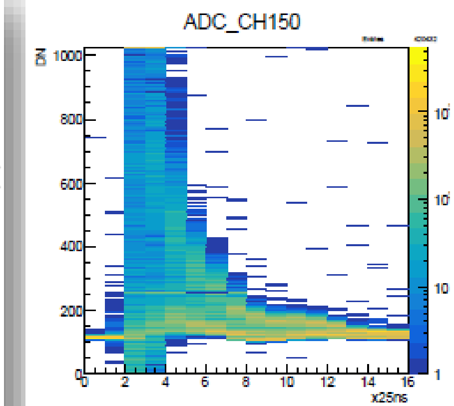
PbWO4 + BM5 : H2GCRO and CITOIROC run on independent clocks. Event numbers alone can't be trusted for matching once events are lost — only fine-time matching works reliably.
(1) Confirm sync on the first pair of events: **check (tC0 − tC1) = (tH0 − tH1)**
(2) Take tC0 and tH0 as each system's time origin, define relative times : **tCi' = tCi − tC0, tHi' = tHi − tH0**
(3) Match events where **|tCi' − tHi'| < 240 ns**

To Do : ADC and TOT Bridging

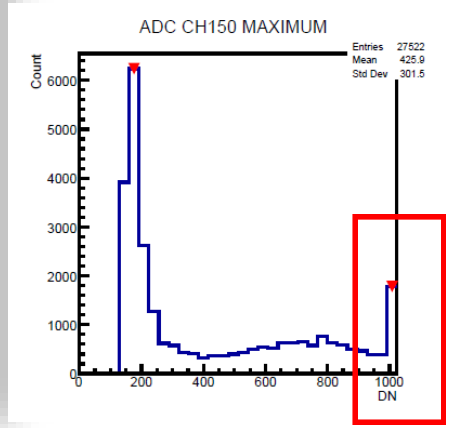
1 H2GCROC3b: architectural overview

The overall block diagram is described as per below.



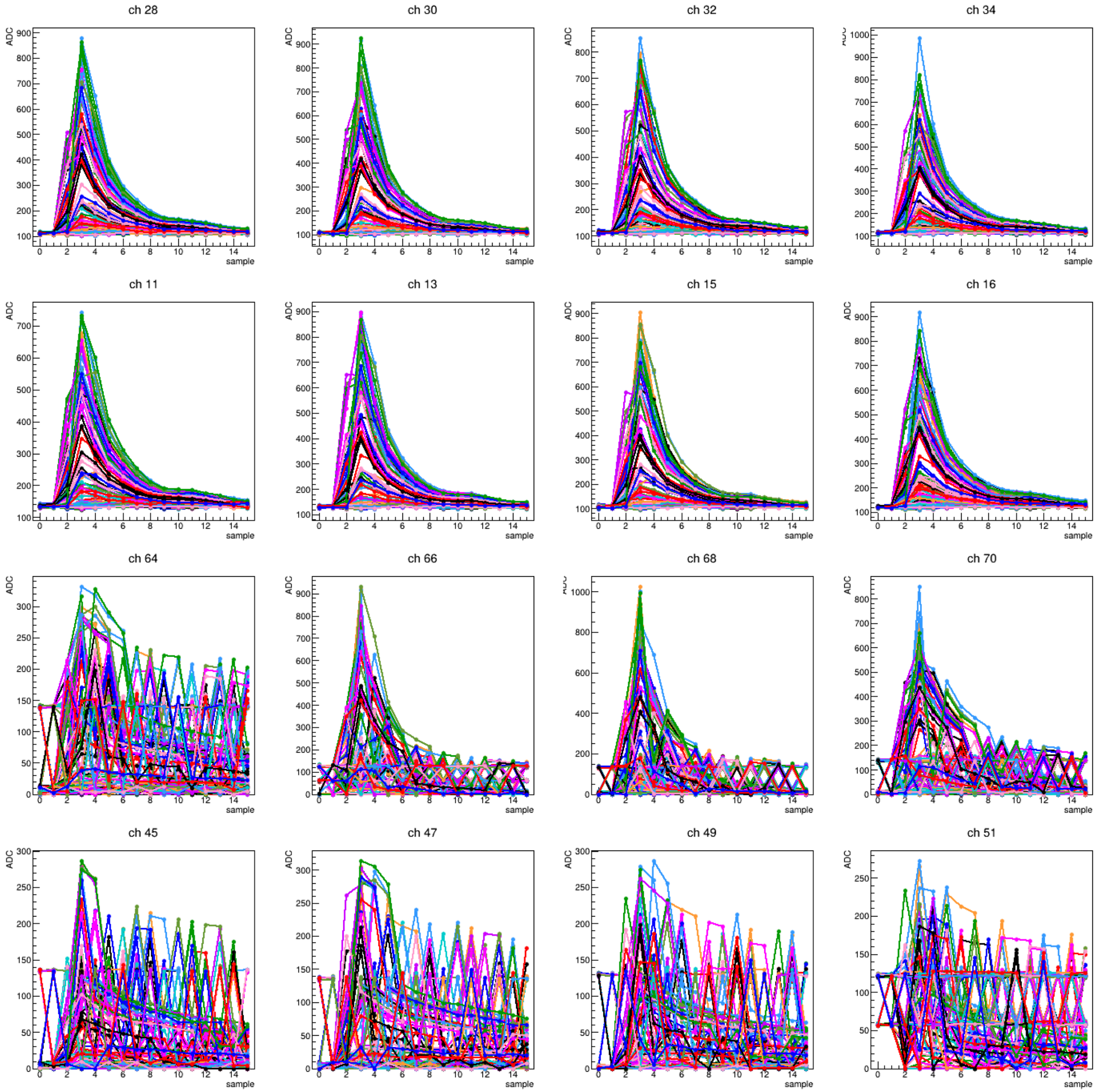


run575, adc[150], evt#7, 823MeV



For some high energy and high gain runs, ADCmax of SiPM channels are overflow (ADCmax=1024). One need to use TOT instead of ADC instead. To find the TOT to ADC mapping/bridging is important.

To Do : Bit Flip Issue(?)



run482, crystal#6, evt#0-200, 705MeV

Summary and To Do

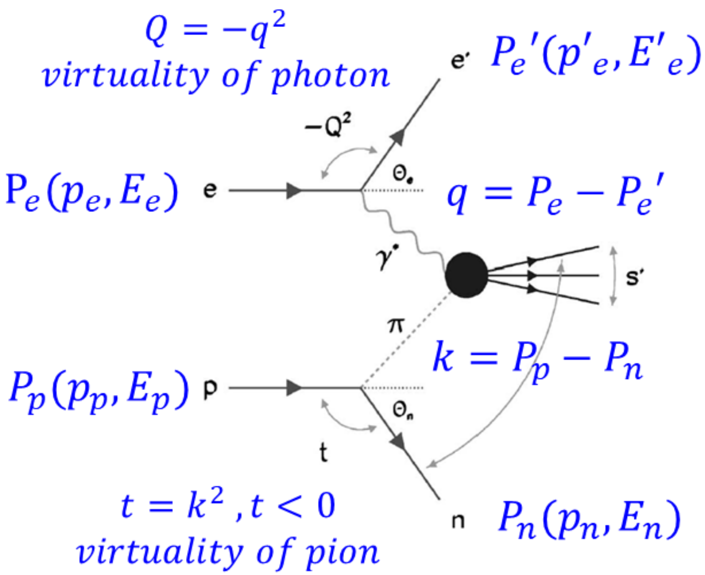
- **Summary**
  Preliminary results from the 3rd prototype (19% @ 800 MeV) are somewhat worse than the 2nd prototype (14% @ 800 MeV), though still within requirement. Several issues remain under investigation.

- **To do in analysis**
- Fix the timing mismatch between the two FPGAs
- Apply tracking for event selection
- Bridge TOT and ADC for the high-gain setting

- **Next test beam — Dec 2026**
- Same system, targeting the existing issues
- SiPM dead-channel issues
- Low BM efficiency (~50%) — under investigation

Back up

Sullivan Process for Pion Structure Study



J.D. Sullivan, *"One-pion exchange and deep-inelastic electron–nucleon scattering"*, Phys. Rev. D 5, 1732 (1972).

- **Pion kinematics**

① $t = k^2 = (1 - x_L)m_p^2 - p_T^2/x_L - [(1 - x_L)/x_L]m_n^2$, **pion virtuality, t<0**

② $x_\pi = \frac{Q^2}{(2k \cdot q)} \approx \frac{x}{(1 - x_L)}$, **momentum fraction of parton in pion**

- **Neutron observables**

① $x_L \approx E_n / E_n$: **Neutron longitudinal momentum**

② $p_T \approx x_L E_p \theta_n$: **Neutron transverse momentum**

The essential measured quantities are x_L and p_T of very forward angle neutron ➔ zero-degree calorimeter.

The nucleon is not a rigid 3-quark system; **it is dressed by a cloud of mesons.** Therefore, the proton's wavefunction is expanded not just as a bare $|\,uud\rangle$ state, but as **a superposition that includes pion–baryon and kaon-hyperon components.** The **pion and kaon structures can be explored through the Sullivan process** from DIS data.

$$|p\rangle = \boxed{Z^{1/2}|uud\rangle} + \boxed{a\,|n\pi^+\rangle + b\,|p\pi^0\rangle + c\,|\Delta^{++}\pi^-\rangle} + \boxed{d\,|\Lambda K^+\rangle + e\,|\Sigma^0 K^+\rangle + f\,|\Sigma^+ K^0\rangle + \cdots}$$

probe proton   probe pion   probe kaon