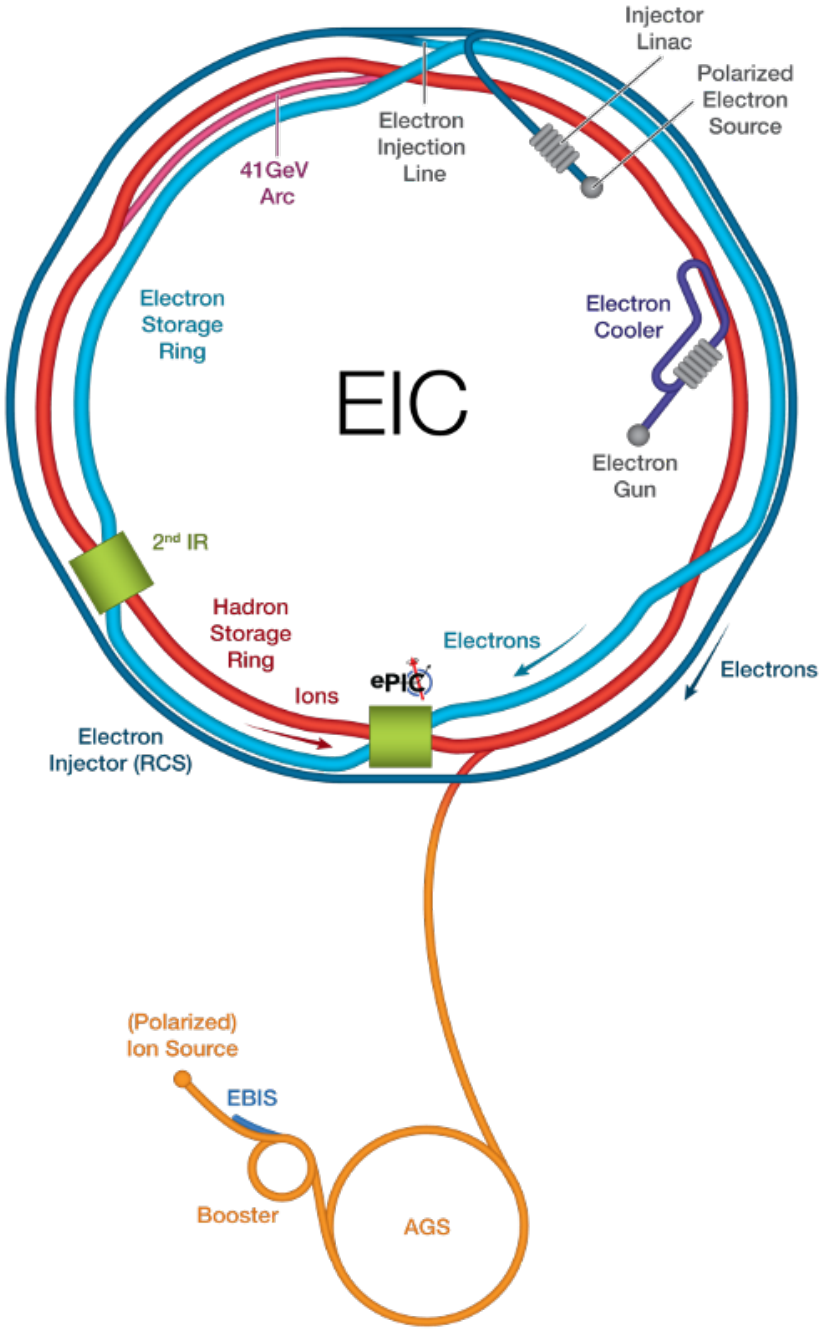
Construction of ZDC with LYSO crystals

Wen-Chen Chang, Kai-Yu Cheng, Chia-Yu Hsieh, Chia-Ming Kuo, Chih-Hsun Lin, Po-Ju Lin, Rong-Shyang Lu, Jen-Chieh Peng

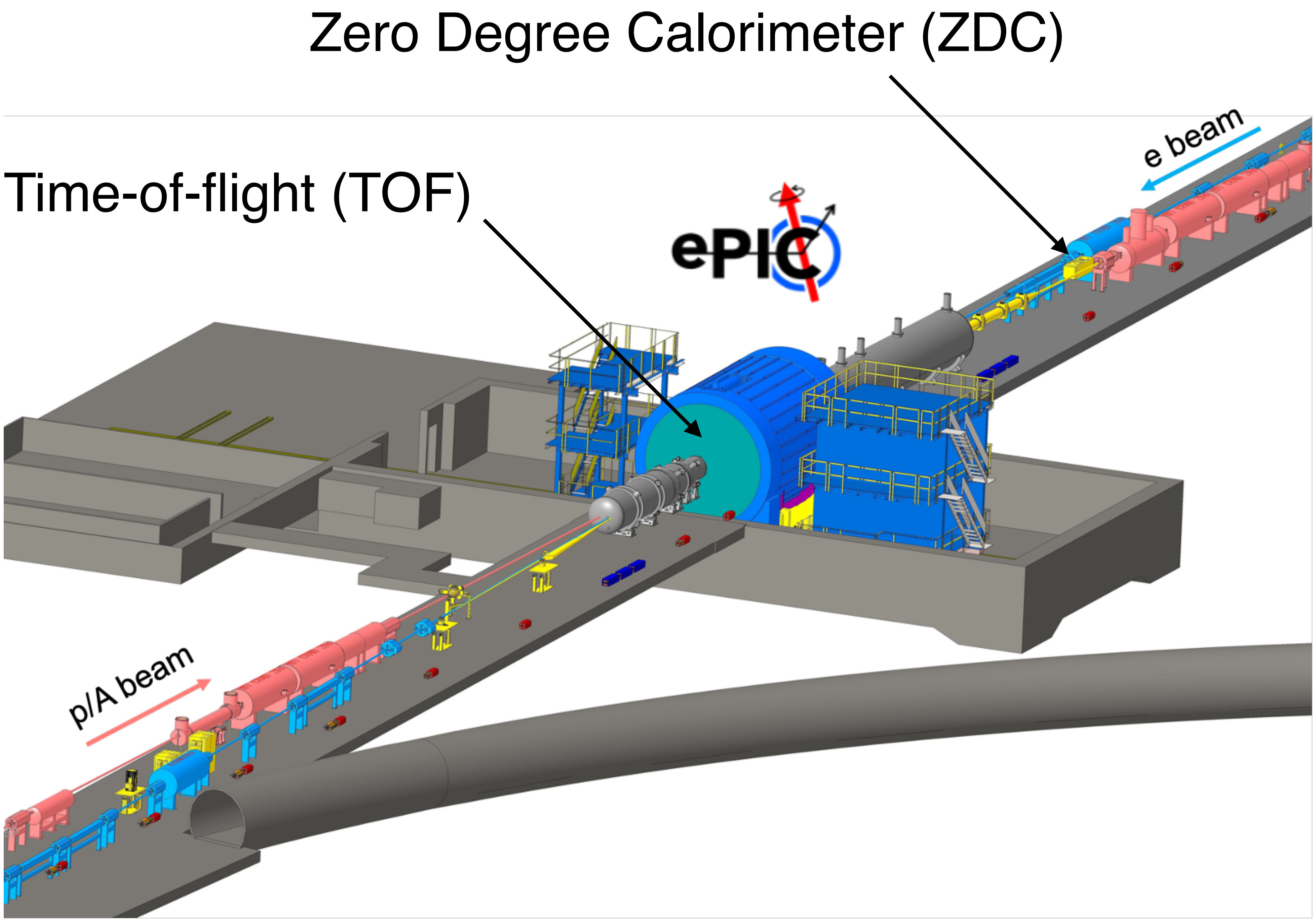
AS/NCU/NTU

The Electron-Ion Collider

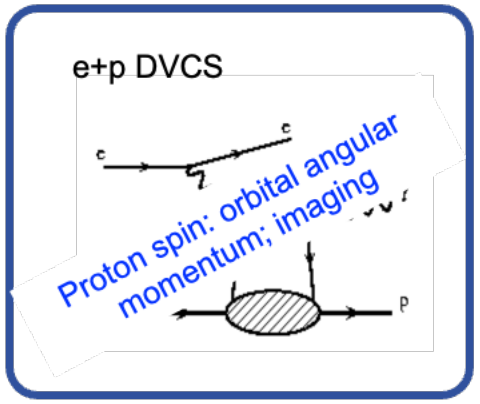
- The EIC will be a machine to unlock the secrets of the strongest force in Nature
- It is a unique, high-energy, high-luminosity, polarized beam collider that will be one of the most challenging and exciting accelerator complexes ever built – the only new collider in the next decades
- The detector R&D has been embarked
- It will come online in 2032

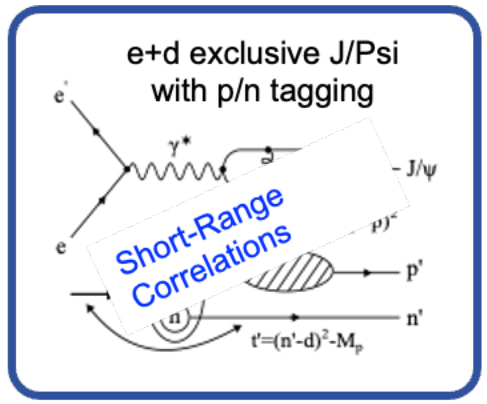


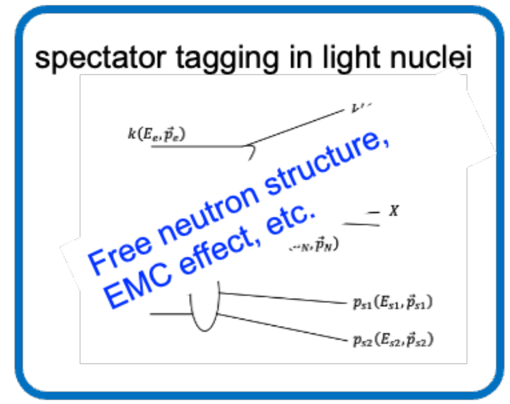
The ePIC Experiment

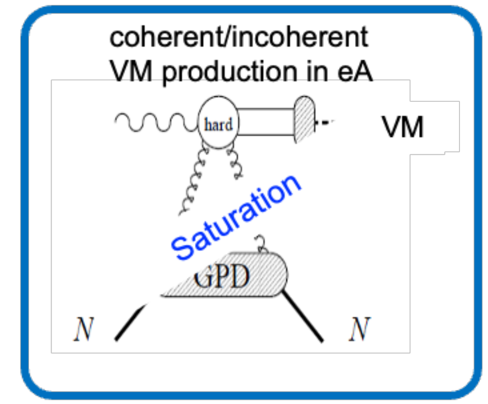


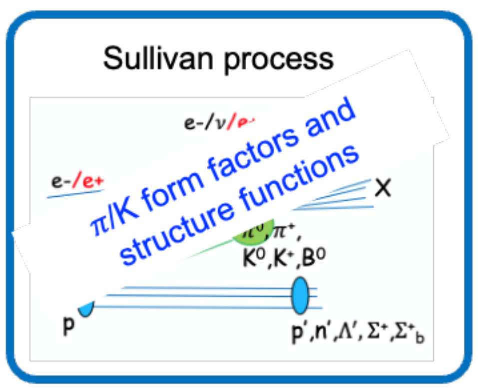
Far-Forward Physics at EIC

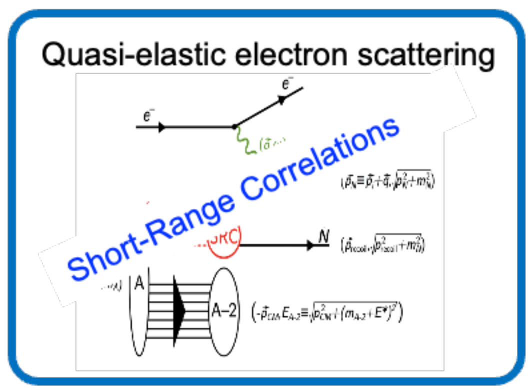


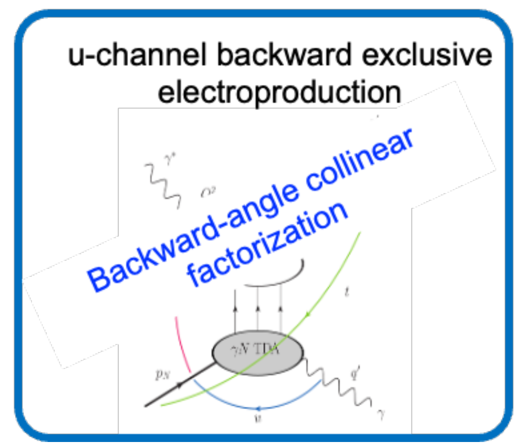


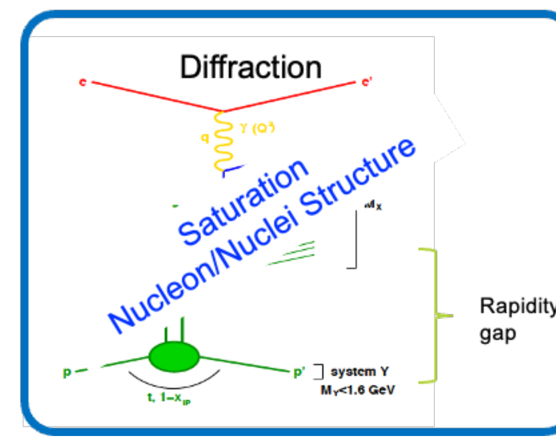










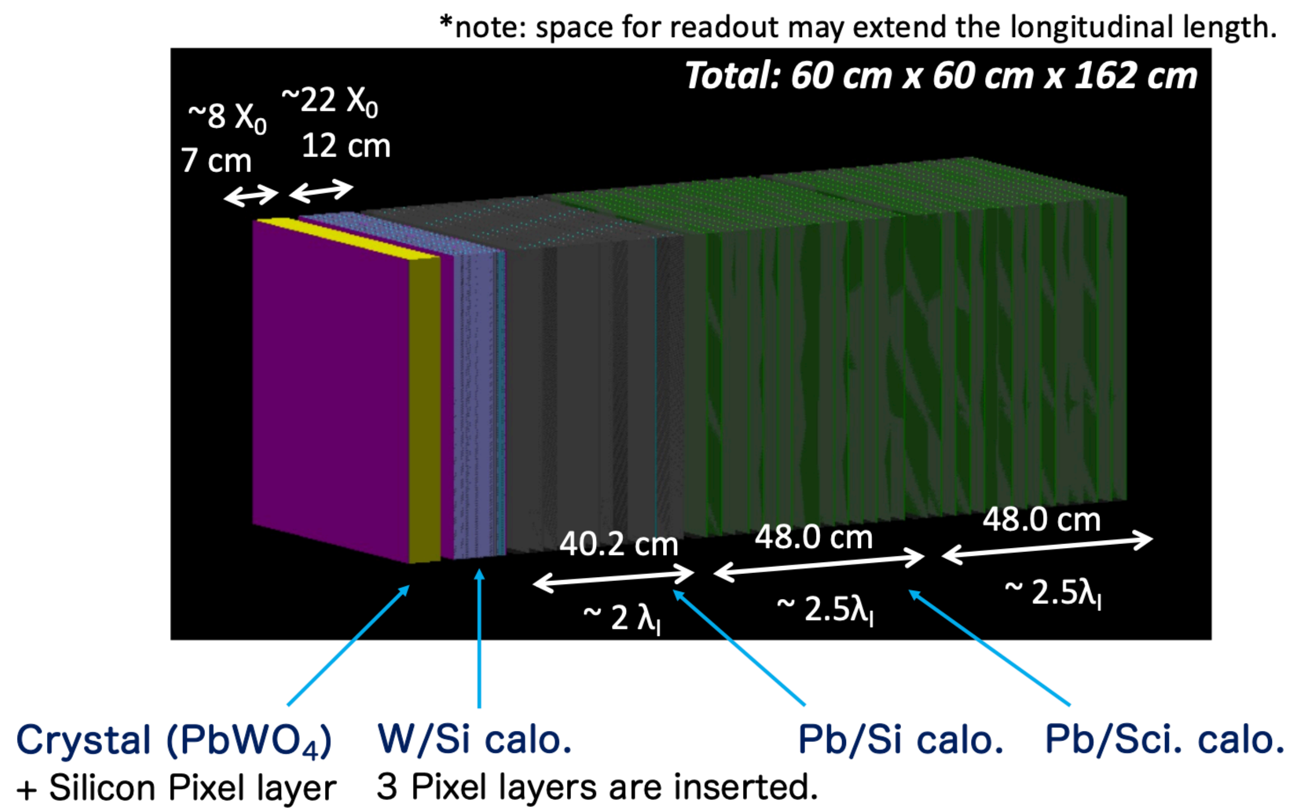


- All these processes require the detection of protons, neutrons, photons and hadrons at small scattering angles → **Major EIC science and detector emphasis**

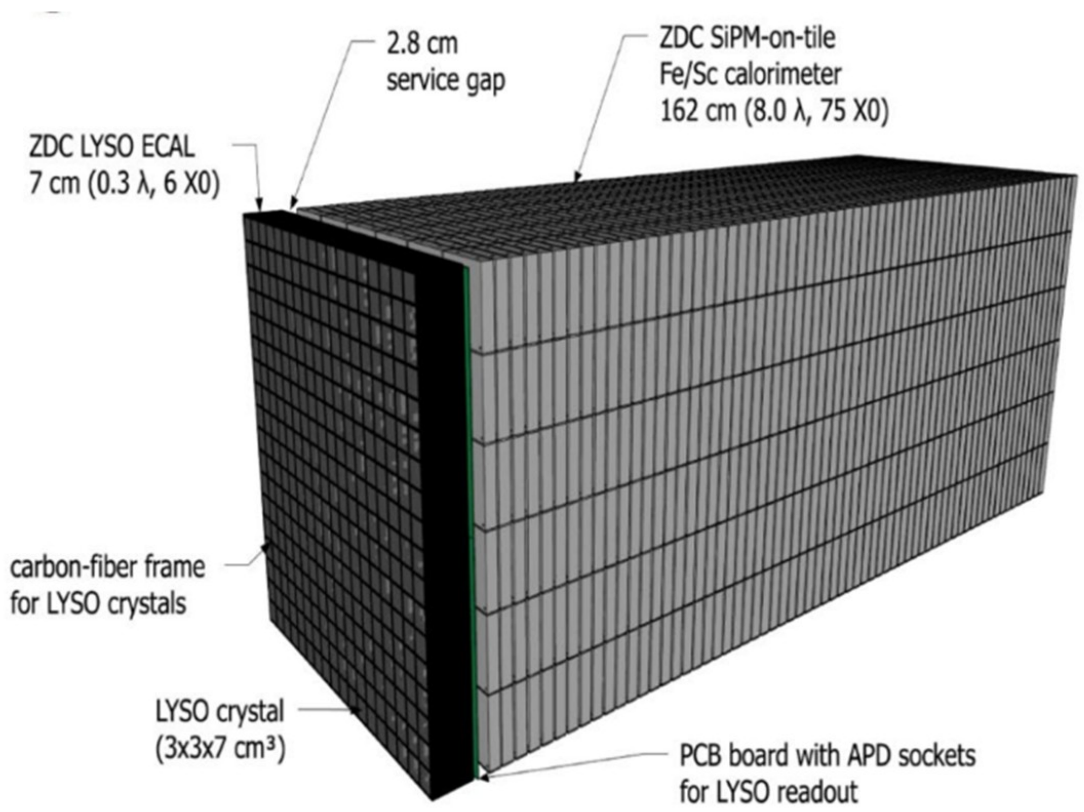
ZDC Requirements

Physics process	Final state particles (for ZDC)	Required HCAL energy resolution	Required HCAL angular resolution	Required ECAL energy resolution	Required ECAL spatial resolution
Spectator tagged e+d breakup	Neutrons	$50\%/\sqrt{E} \oplus 5\%$	2 mrad$/\sqrt{E}$	N/A	N/A
Exclusive π^+ production	Neutrons			N/A	N/A
Incoherent vetoing of e+A events	Neutrons/ photons	$100\%/\sqrt{E}$	N/A	100 MeV photon sensitivity	N/A
u-channel backward VCS	Photons	N/A	N/A	$20\%/\sqrt{E} \oplus 3\%$	<1-2 cm
π/K structure functions	$\Lambda^0 \to n+\pi^0$	$35\text{-}50\%/\sqrt{E} \oplus 3\text{-}5\%$	2 mrad$/\sqrt{E}$	$2\text{-}5\%/\sqrt{E} \oplus 1\text{-}3\%$	<1-2 cm

ZDC



Originally proposed ZDC



Recently proposed ZDC

Comparison of Various Crystals

	X_0	LY (ph/MeV)	T dep. of LY (%/K)	Decay time (ns)	λ_{em} nm
$PbWO_4$ (CMS)	0.89 cm	200	-1.98	5 (73%) 14 (23%) 110 (4%)	420
LYSO	1.14 cm	30,000 (market standard)	-0.28	36	420
GAGG	1.59 cm	40,000 – 60,000		50 – 150	520
SciGlass	2.4-2.8 cm	>100		22 – 400	440-460

Choice of Various Photo Detectors

	PIN (SFH2704)	APD (S12053-05)	SiPM (C10010)
Gain	1	1-50	2×10^5
Output Type	Analogue	Analogue	Analogue or Digital
Operational Bias(V)	6	150-200	24.2-24.7
Spectral Range (nm)	400-1100	200-1000	300-950
Peak Sensitivity (nm)	900	620	420
PDE/QE (%)		80	18
Dark Current (nA)	0.1-25	0.2-5	1-10
Rise Time (ns)	47	0.875	0.3

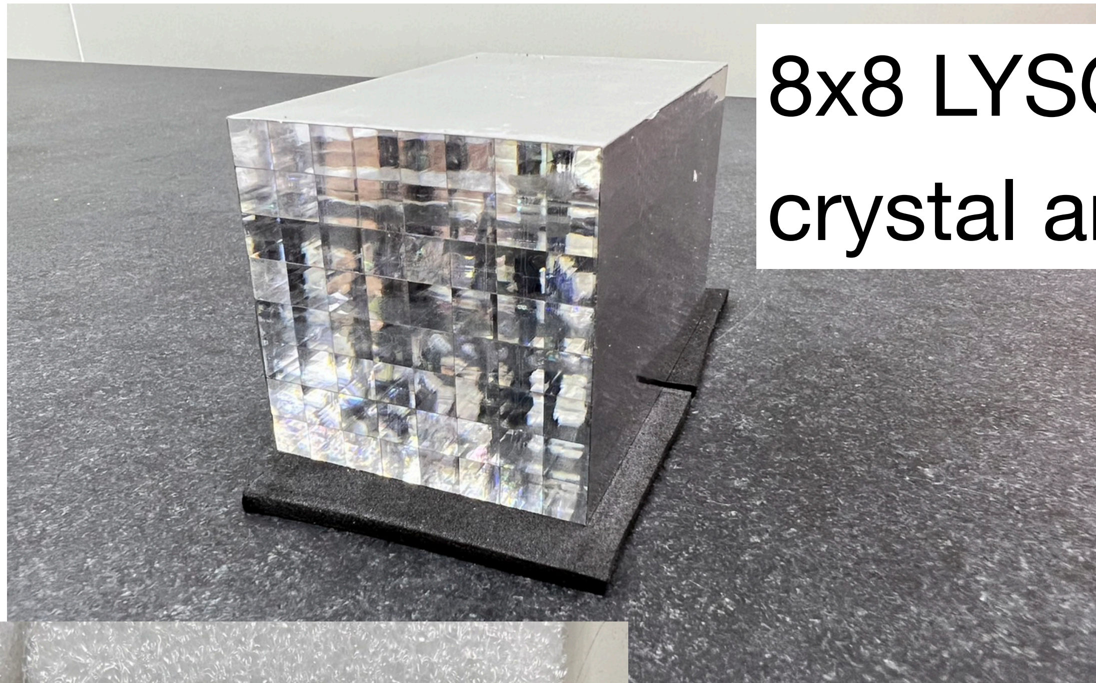
Proposed LYSO Crystals to ePIC

Taiwan's contribution and plans for the ZDC

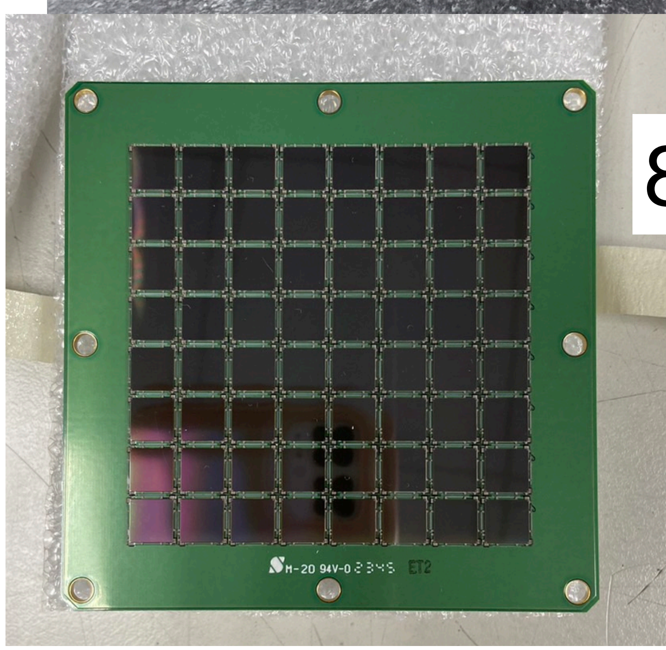
Chia-Ming Kuo (NCU, Taiwan)
on behalf of the EIC-Taiwan team

2023/3/17 EIC Asia Workshop at RIKEN, Japan

ZDC ECAL Prototype with LYSO Crystals

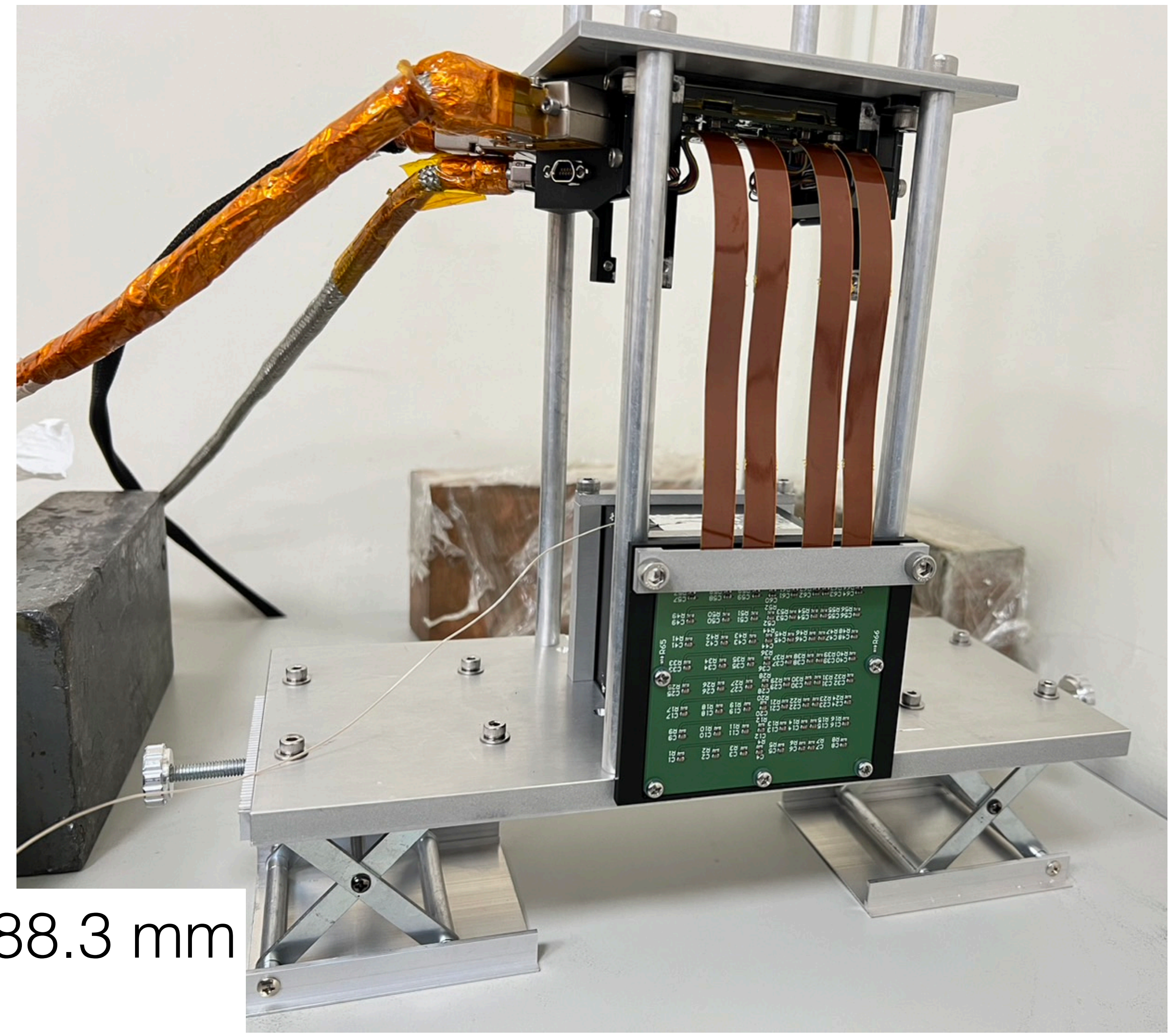


8x8 LYSO crystal array



8x8 SiPM array

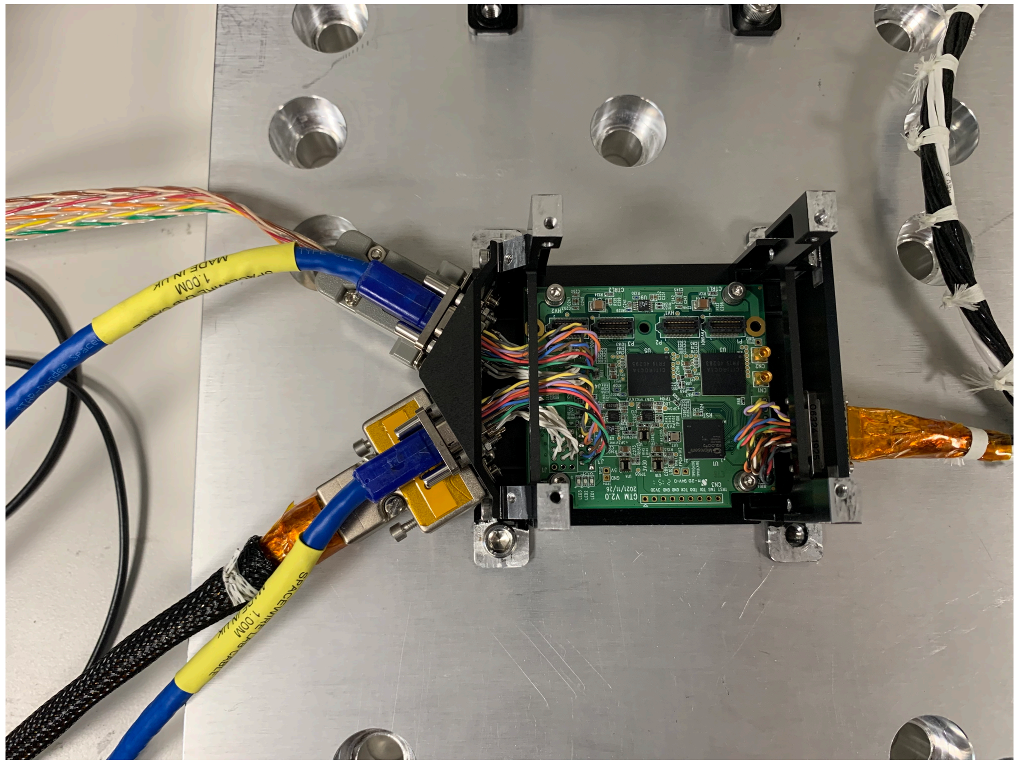
LYSO calorimeter prototype



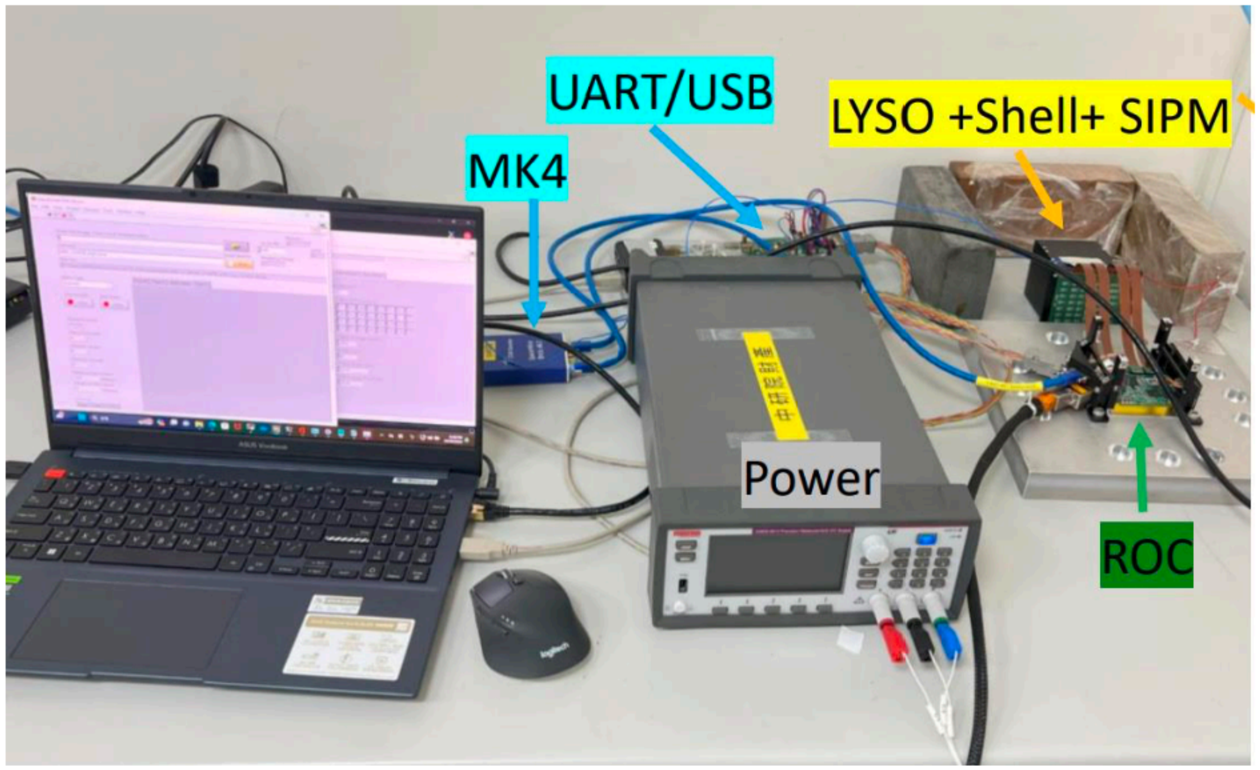
One crystal: 7.12 mm x 7.12 mm x 88.3 mm
8x8 array: 56.96 mm x 56.96 mm

Readout for the ZDC ECAL Prototype with LYSO Crystals

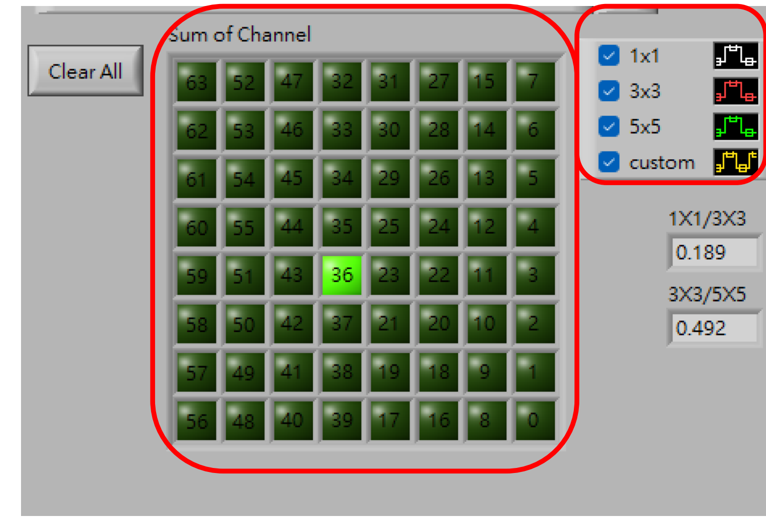
- **Designed by Chih-Hsun Lin of Academia Sinica**
- 64 channels
- Trigger:
    - Self-triggered
    - Can accept external timing signal → needs to be studied
    - May accept external trigger → needs to be studied



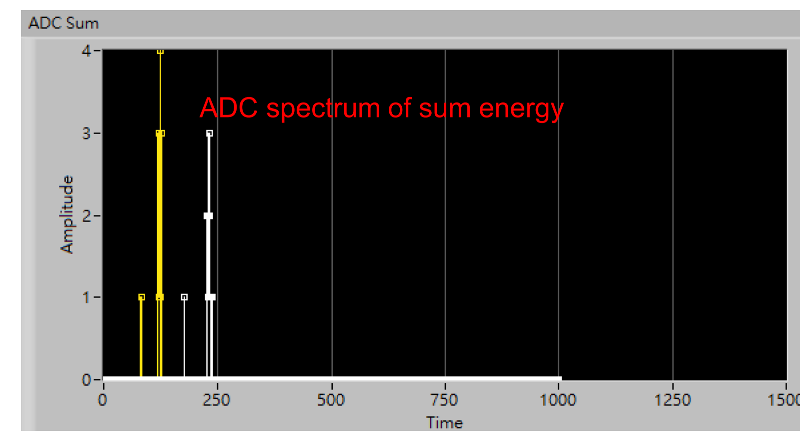
Test Setup



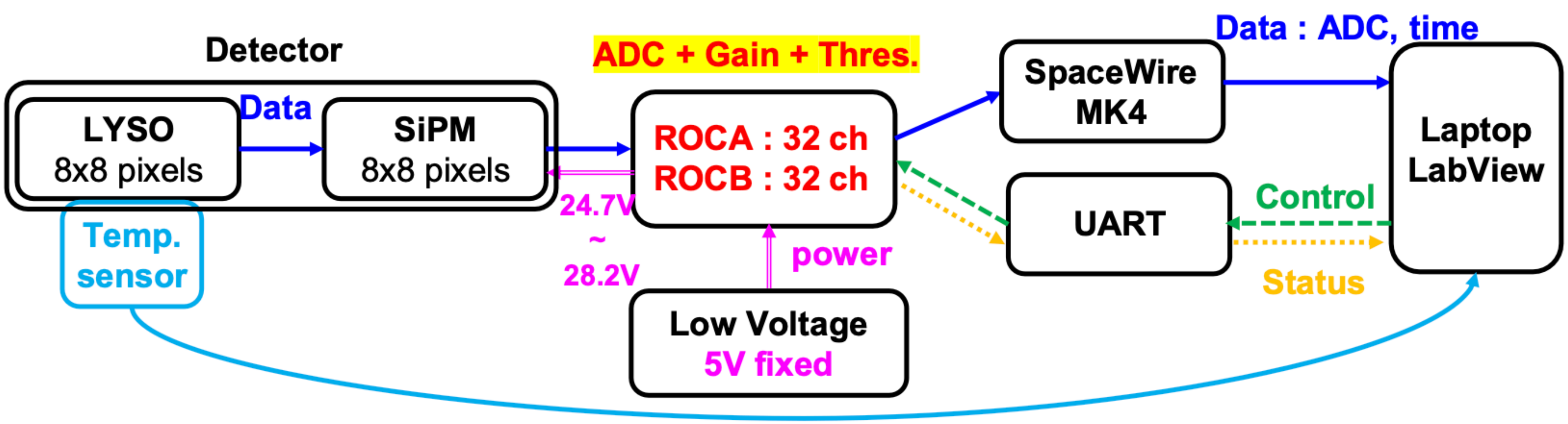
UART/USB
MK4
LYSO +Shell+ SIPM
Power
ROC



Clear All
Sum of Channel
63 52 47 32 31 27 15 7
62 53 46 33 30 28 14 6
61 54 45 34 29 26 13 5
60 55 44 35 25 24 12 4
59 51 43 36 23 22 11 3
58 50 42 37 21 20 10 2
57 49 41 38 19 18 9 1
56 48 40 39 17 16 8 0
1x1
3x3
5x5
custom
1X1/3X3
0.189
3X3/5X5
0.492

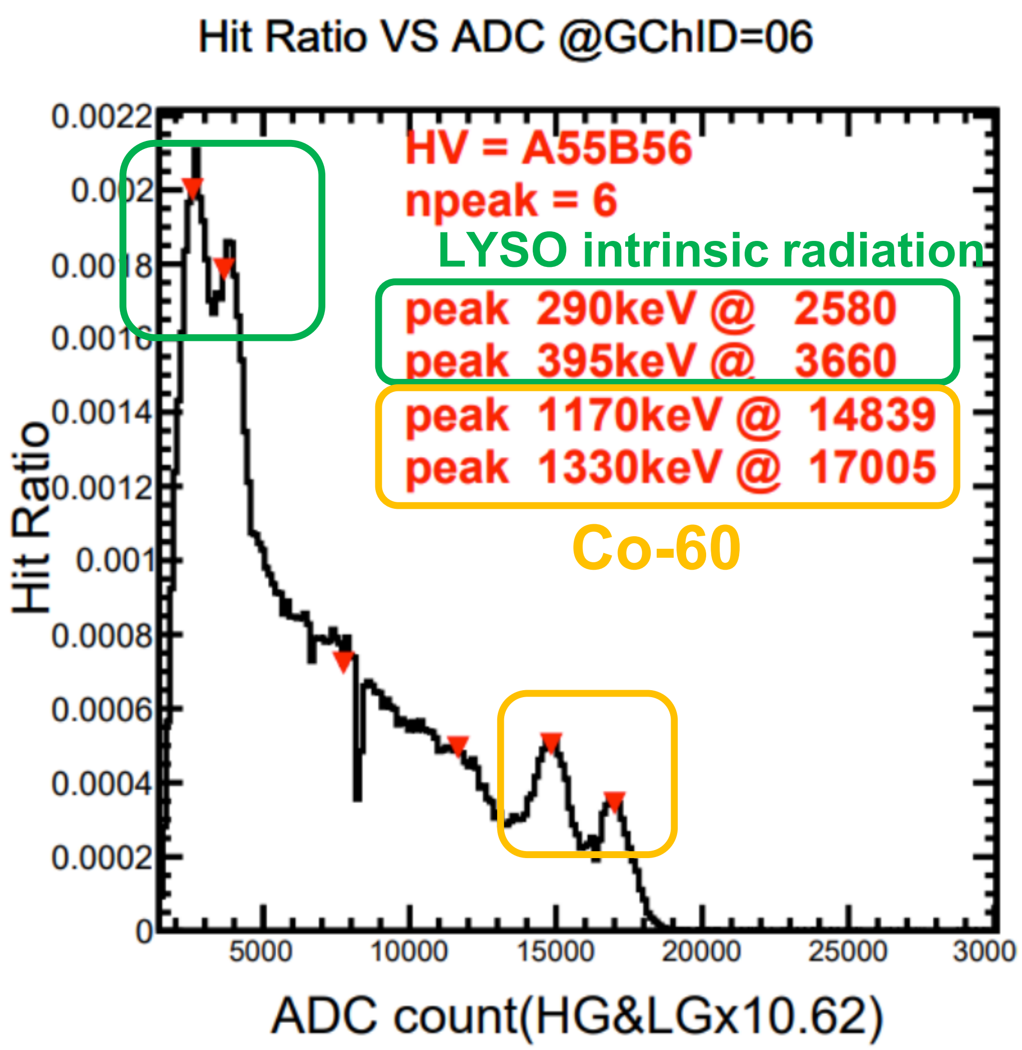


ADC Sum
ADC spectrum of sum energy
Amplitude
Time
0
250
500
750
1000
1250
1500



Detector
LYSO
8x8 pixels
Data
SiPM
8x8 pixels
Temp.
sensor
ADC + Gain + Thres.
ROCA : 32 ch
ROCB : 32 ch
24.7V
~
28.2V
power
Low Voltage
5V fixed
SpaceWire
MK4
UART
Data : ADC, time
Laptop
LabView
Control
Status

Tests with Co-60



We use Co-60 and LYSO intrinsic radiation to calibrate the detector.

- **@HV = 27.00V**

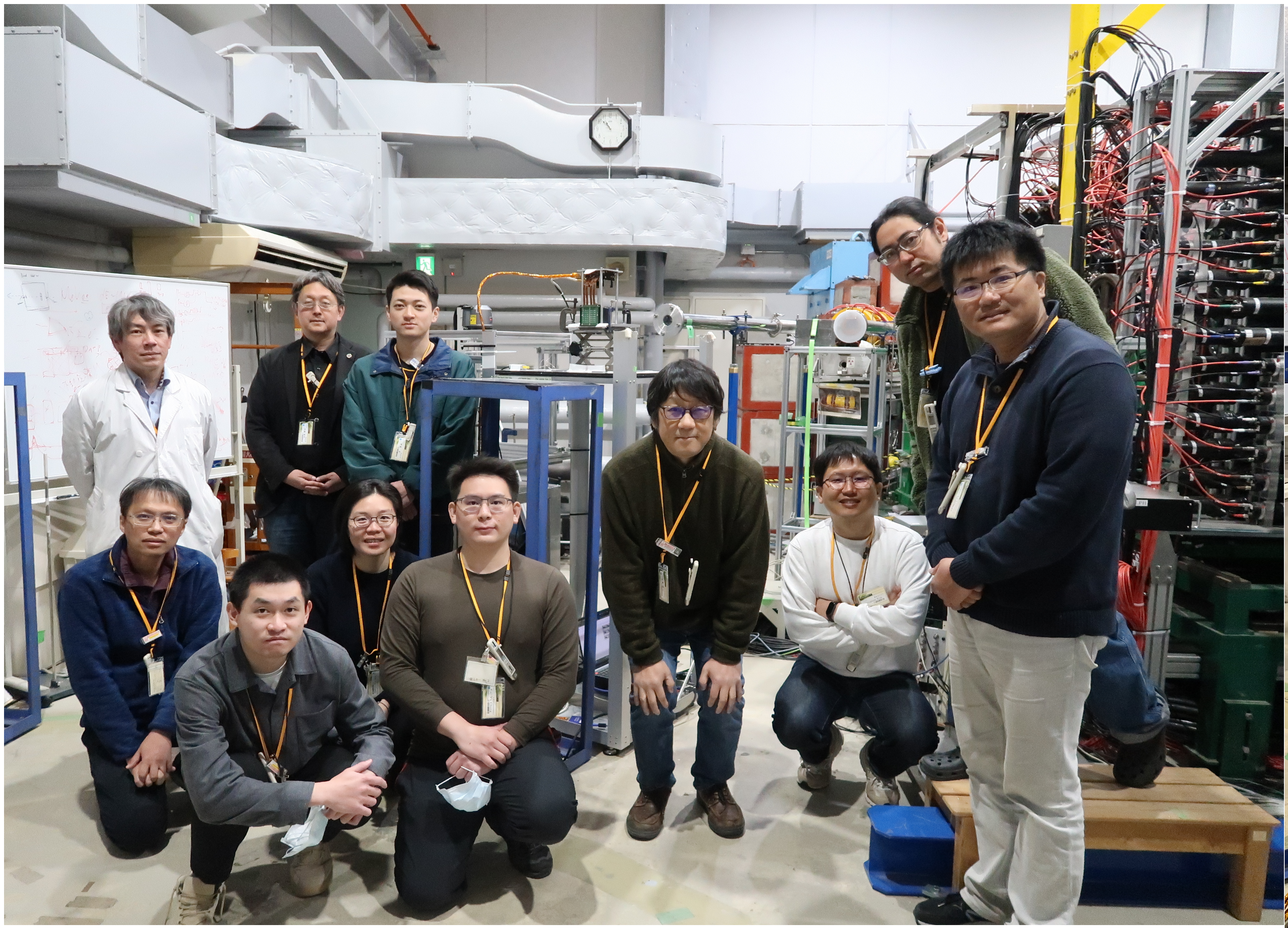
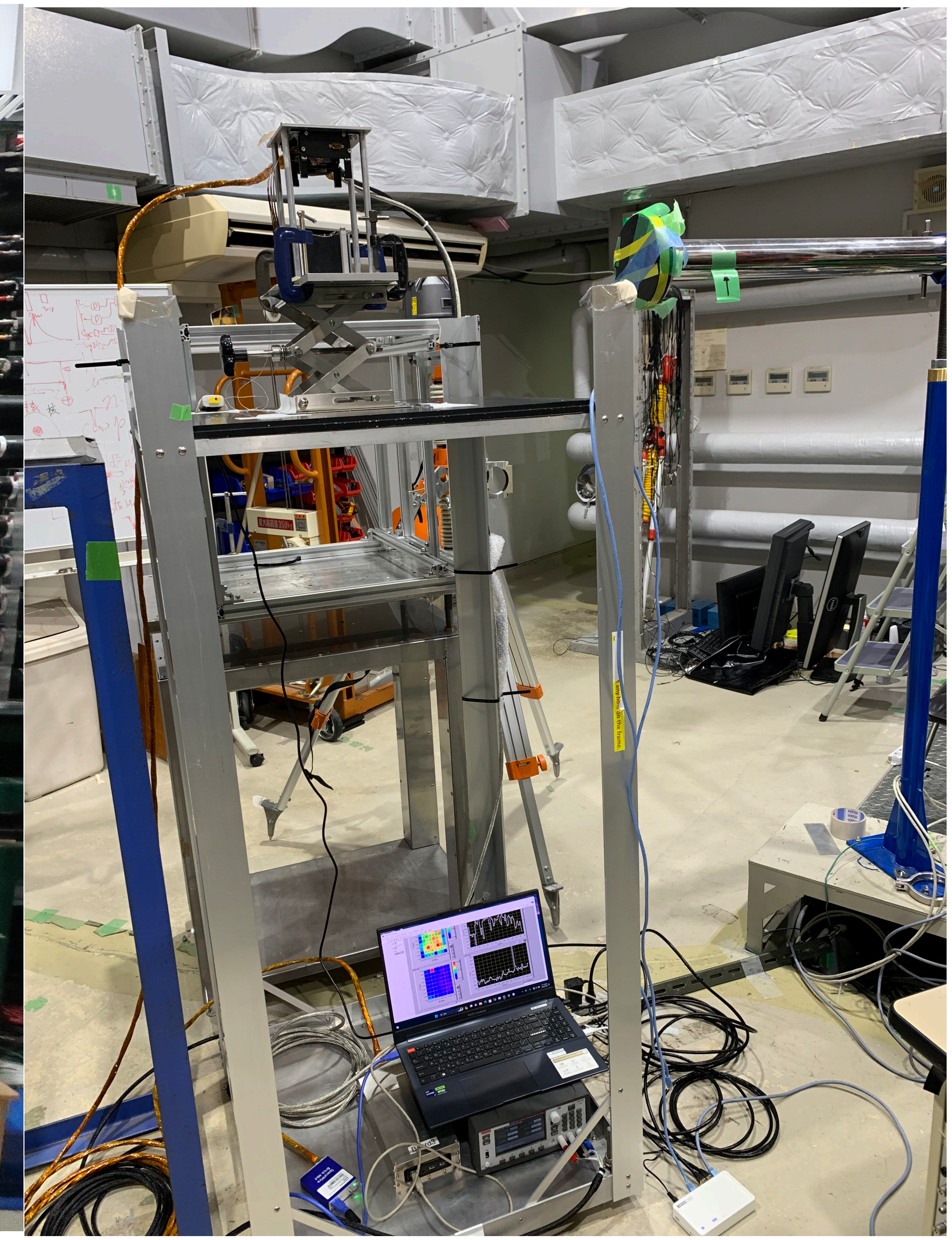
➔ 1.330 MeV @ 17005 digit
➔ 1.330 MeV / 17005 digit ~ 7.8e-5 MeV / digit
Saturated digit = 11, 0000 digit
➔ 11,0000 digit * 0.1268MeV = 8.6MeV
➔ **Saturated at 8.6MeV**
This HV/gain is too high for our beam test condition.

- HV setting range = 24.7V to 28.2V

Beam Test @ ELPH

- A beam test with positrons was conducted at the ELPH, Tohoku University, between **15 and 21 February 2024**
- Beam time: ~36 hours (**19 and 21 February 2024**)
- Beam energy: 47.18 MeV up to 823.26 MeV
- Rate: 1,000 – 3,000 Hz
- Participants: RIKEN, Tsukuba University, Tsukuba University of Technology, Sejong University, EIC-Taiwan

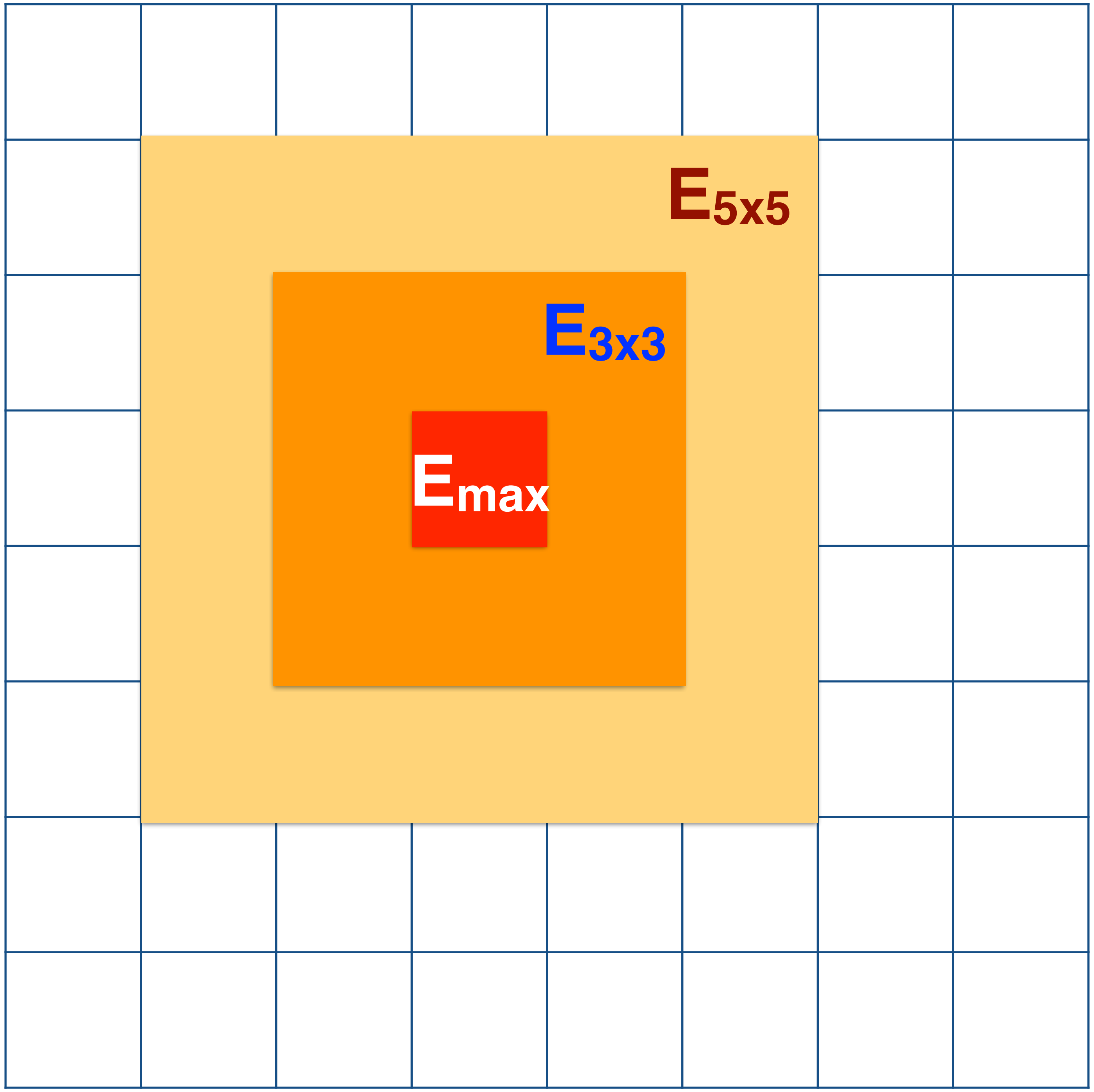
Beam Test @ ELPH

Run List

	Run range	Source/Beam	Purpose
HV Scan	1 – 20	Co60 (1–6, 20) Na22 (7 – 19)	Verify gains
“Background”	21 – 33	Intrinsic radiation	Understand instrinsic radiation rate with threshold cuts
Gain Calibration	33 – 36	Na22 (34 – 37)	Calibrate each channel
HV and Beam Energy Scan	41 – 99	Beam (47 – 823 MeV)	Understand detector performance and study energy resolution and shower shapes
Position Scan	101 – 129	Beam (197 MeV)	
HV and Beam Energy Scan at Low Energy	129 – 157	Beam (< 297 MeV)	
With Absorbers	160 – 225	Beam (197 – 823 MeV)	
Rotation	227 – 238	Beam (98, 197, 297 MeV)	Understand detector performance

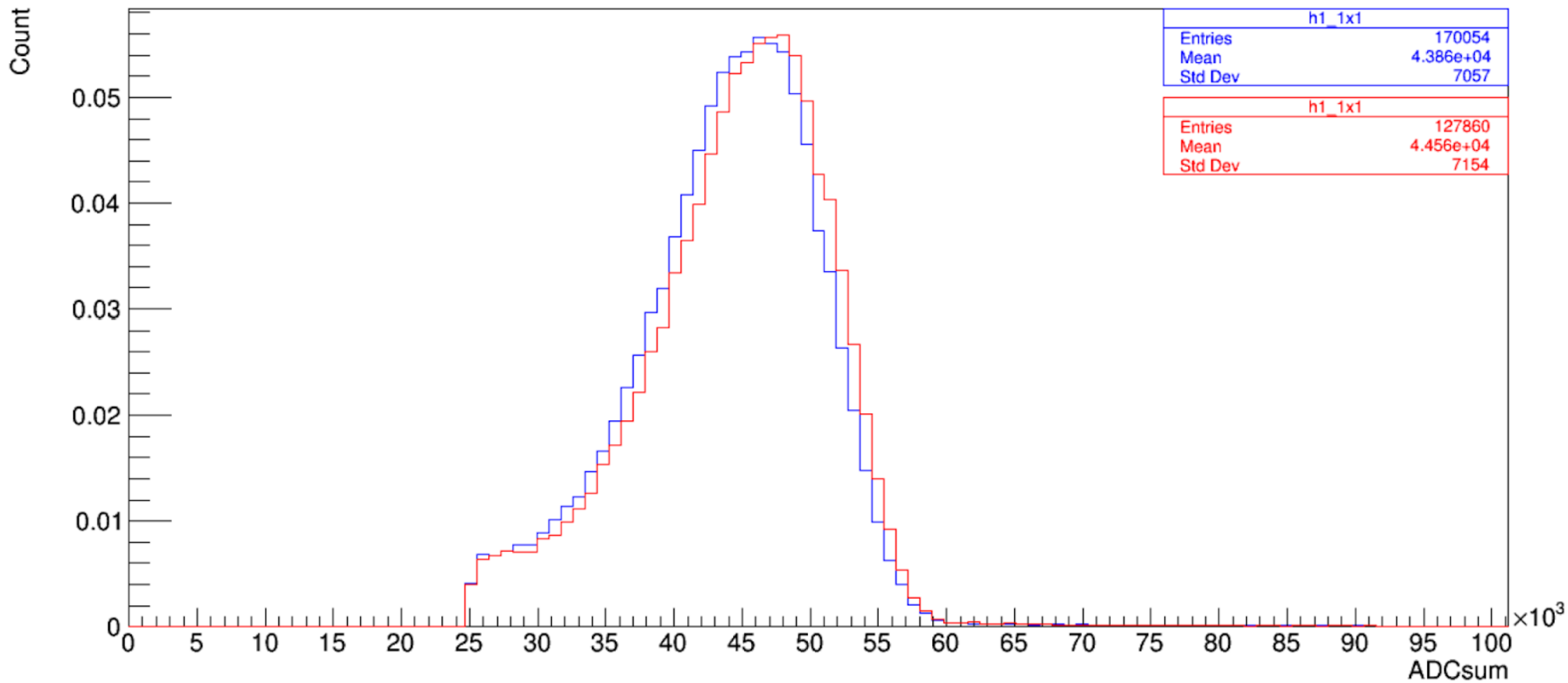
Clustering



Things to be Studied

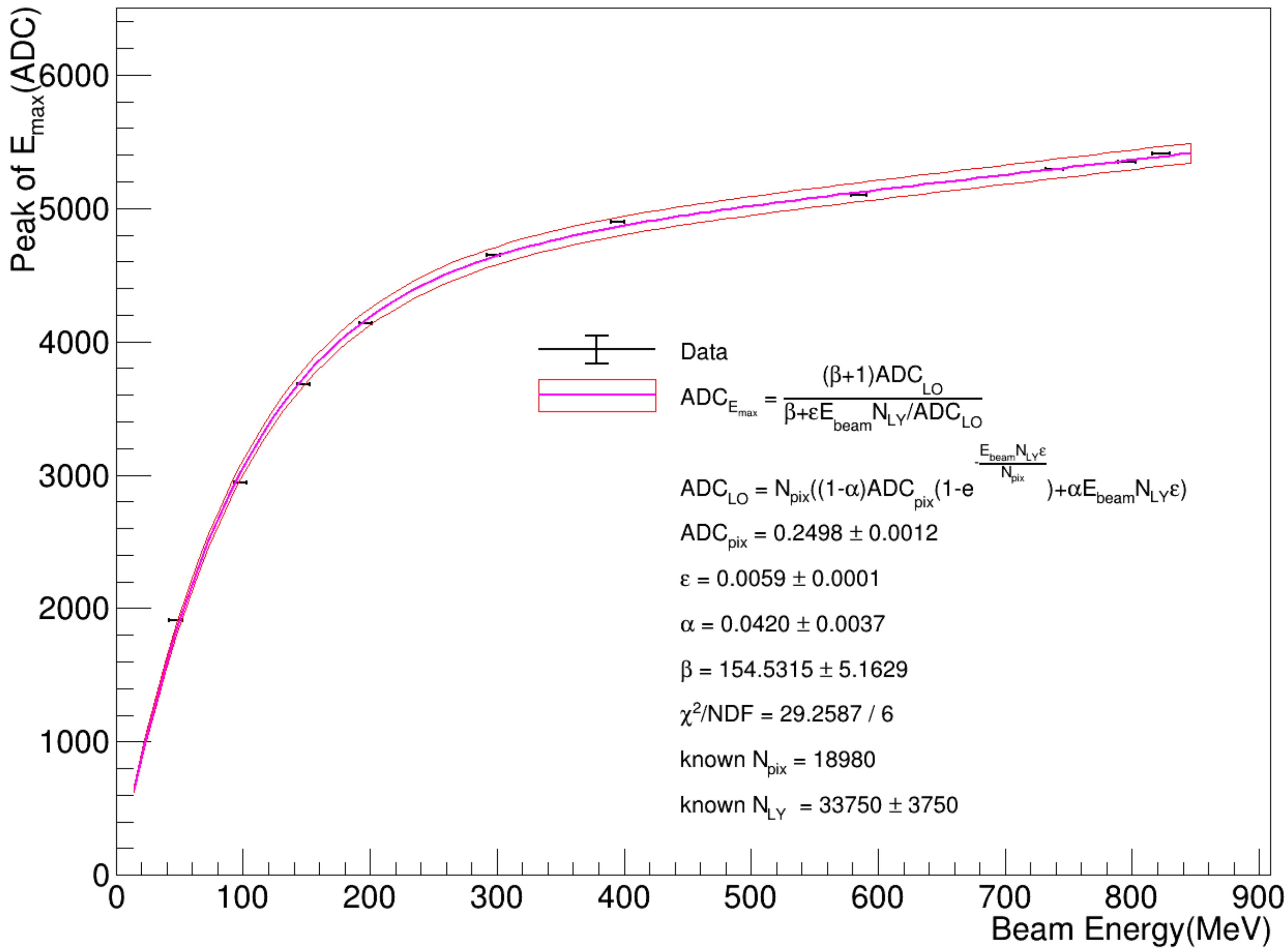
- Detector performance
- Comparison between data and simulation
- E_{max} vs E_{beam} at different SiPM HVs
- Hit multiplicity
- Energy spectra (E_{max}, E_{3x3}, E_{5x5})
- Shower shapes (E_{max}/E_{5x5}, E_{3x3}/E_{5x5}, E_{max}/E_{3x3}, E_{2x5}/E_{5x5}, σ_X, σ_Y, …)
- Beam profile
- Energy resolution as a function of beam energy

Channel-by-Channel Gain Calibration



- Channel-by-channel gain calibration was performed using radiation source and beam, respectively
- The calibration obtained with the radiation source is not significantly different from the one obtained with high energy beam

E_{max} vs Beam Energy (1/2)



- SiPM saturation effect was observed as epxected and parameterized

Model SiPM Saturation Effect

Ref: https://arxiv.org/abs/1510.01102

- LO: the charge produced in a pixel is the same if it is hit by one, two or more photons

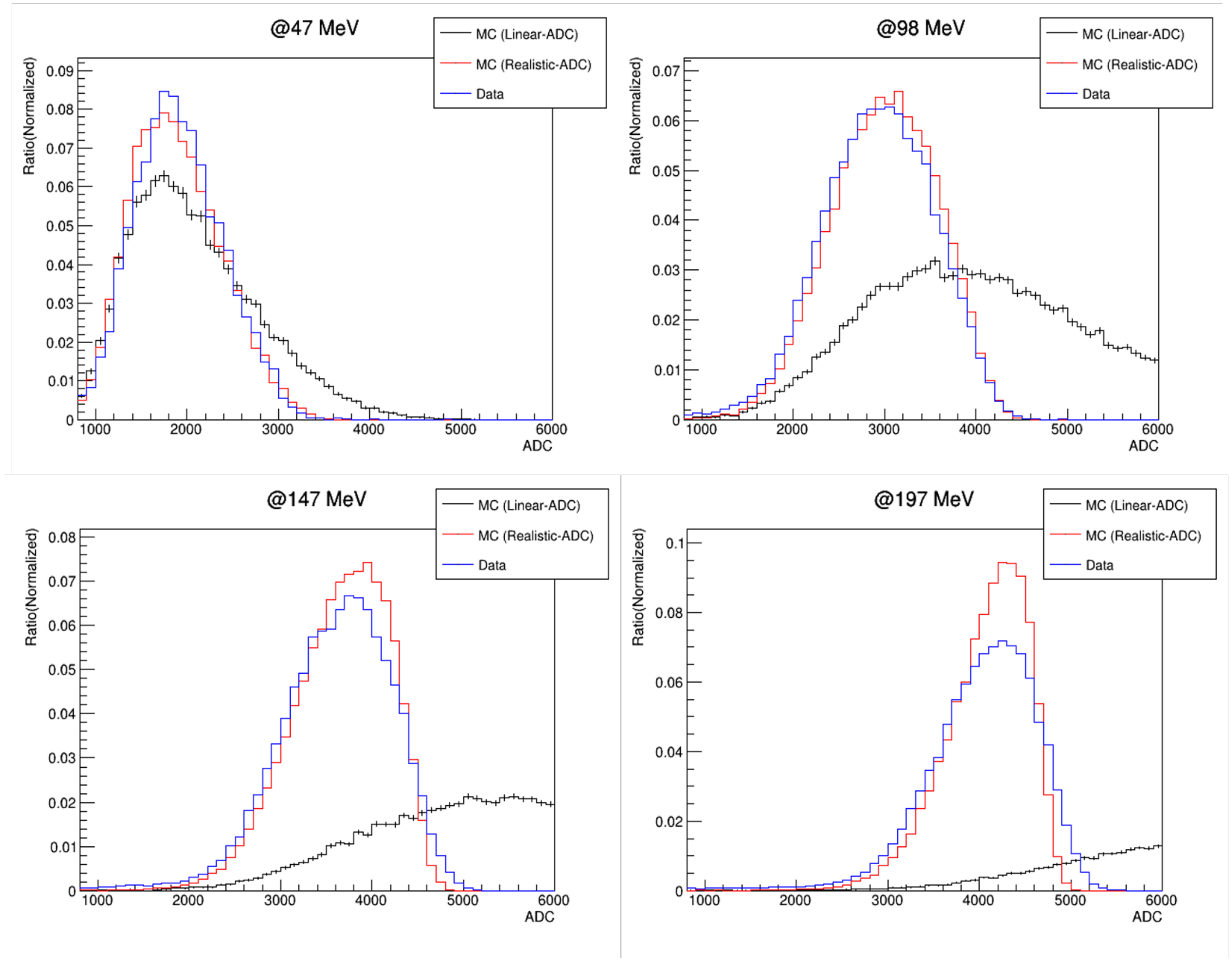
$$N_{fire}^{LO} = N_{pix}(1 - e^{\frac{-\epsilon N_{in}}{N_{pix}}})$$

- However, when the recovery time of the SiPM pixels is shorter than the input light pulse, a single pixel can contribute more than once to the output signal

- Additionally, there are effects of fluctuations of gain by charge release at pixels, dark noise, crosstalk, and after pulse

$$N_{\mathrm{fire}}^{\mathrm{NLO'_{C\cdot A}}} = N_{\mathrm{fire}}^{\mathrm{NLO'}}\left(1 + P_{\mathrm{cross}} \cdot \mathrm{e}^{-\epsilon N_{\mathrm{in}}/N_{\mathrm{pix}}}\right) \cdot (1 + P_{\mathrm{after}})$$

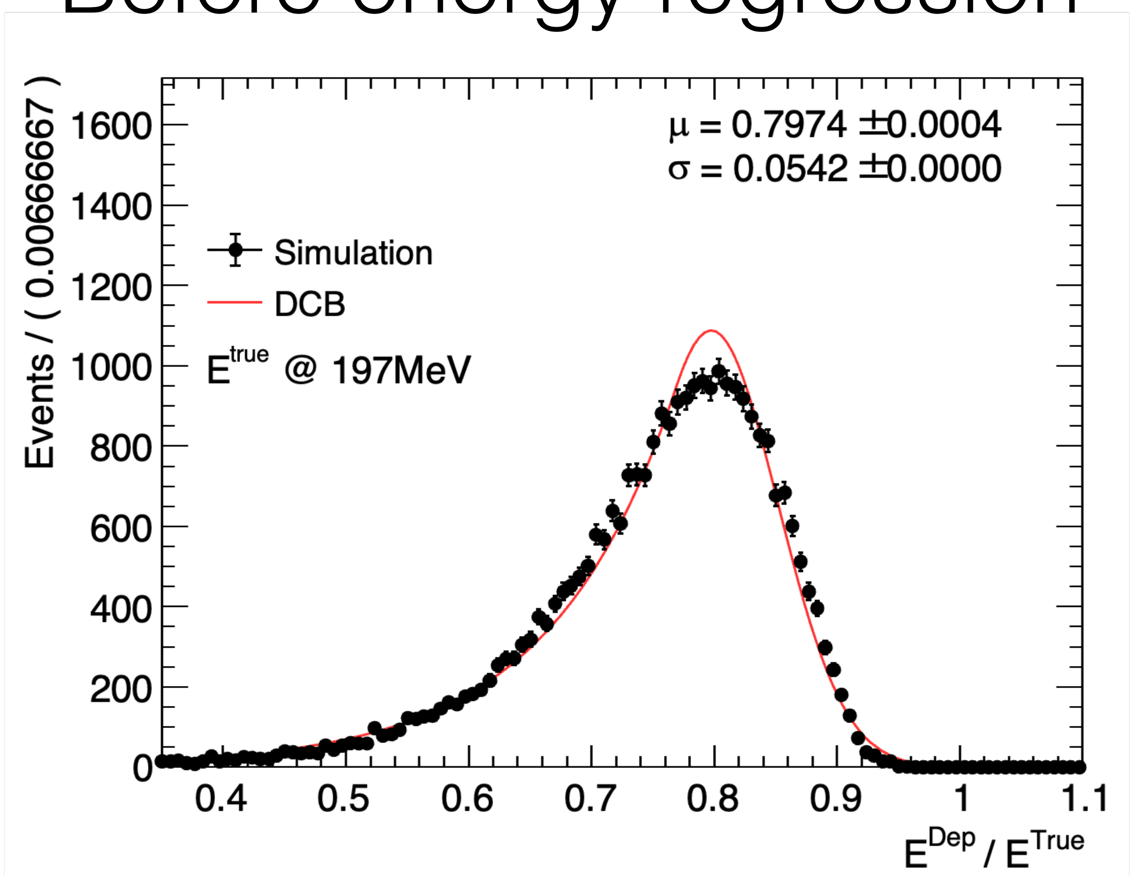
E_{max} vs Beam Energy (2/2)



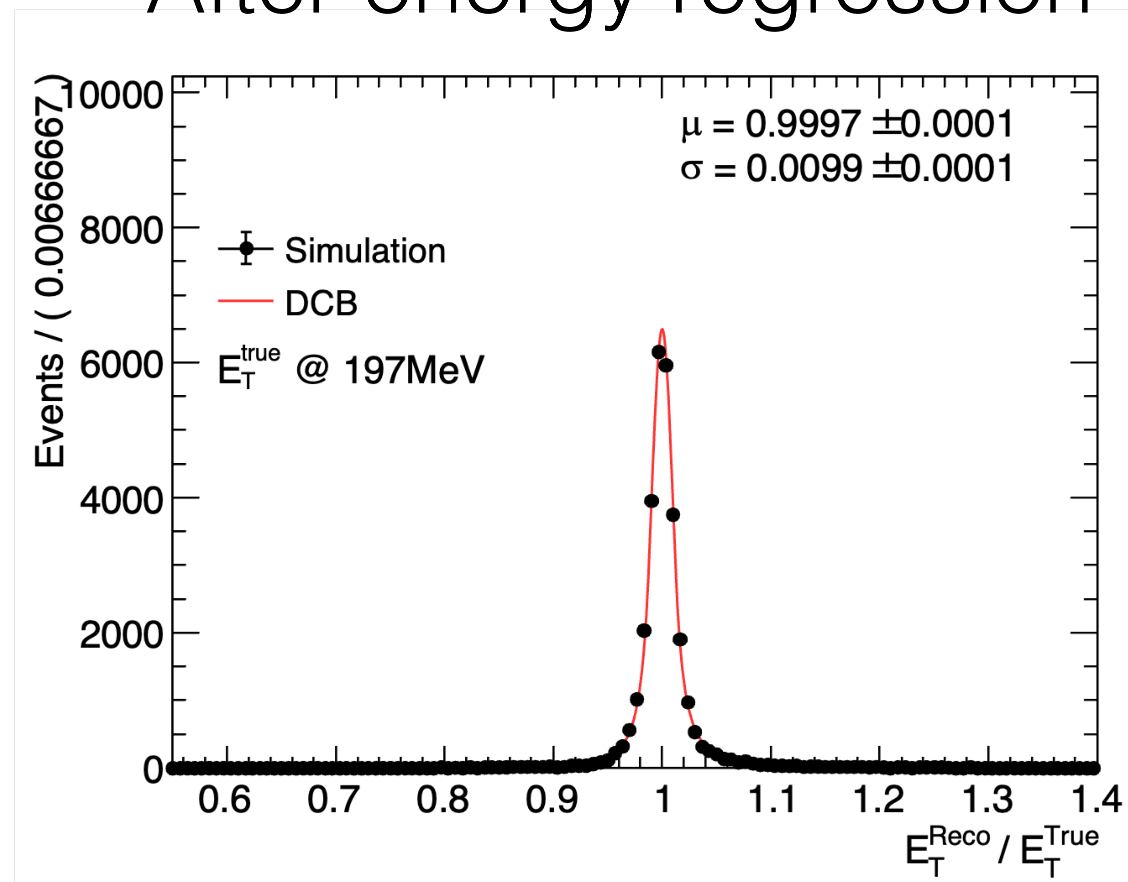
- The energy scale agrees better after the corrections
- However, more work is needed to correct the energy scale and resolution further

Energy Regression

Before energy regression



After energy regression



- Try to apply the ML technique for energy reconstruction

Future Plan:

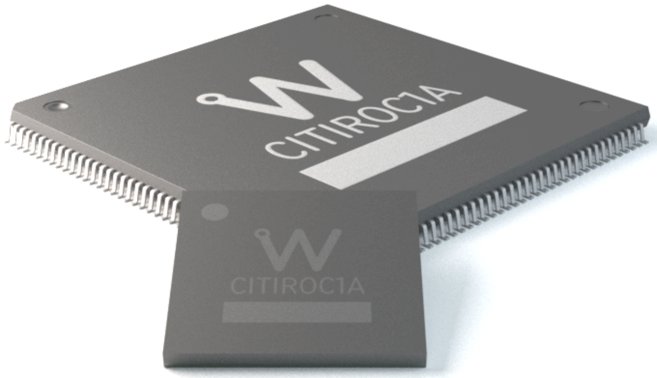
- Finalize the analysis of beam test data as soon as we can
- Target at another beam test at ELPH in October
  - LYSO + APD
  - $PbWO_4$ + SiPM
  - GAGG + APD
  - Combine with other detectors
- Target at beam tests at ELPH (50-800 MeV positrons) and also KEK (5 GeV electrons) in the future
- Perform simulation studies for the final ZDC EMCal design

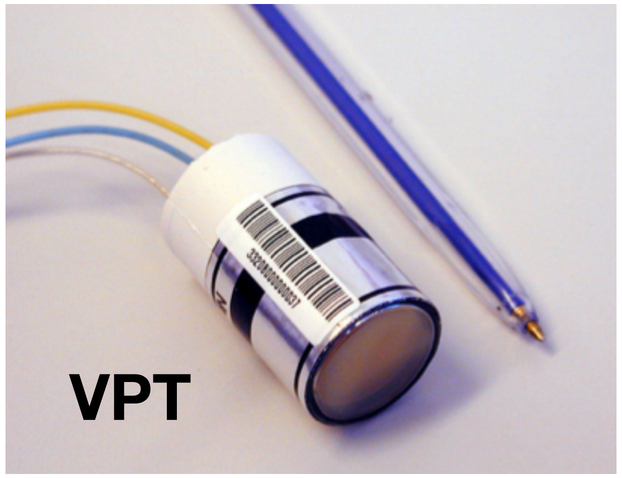
Summary

- We had the first beam test for the prototype of ePIC ZDC EMCal with LYSO+SiPM at ELPH
- Both data analysis and simulation are on-going
- We hope to be able to test different combinations of crystals and photodetectors in October and the future

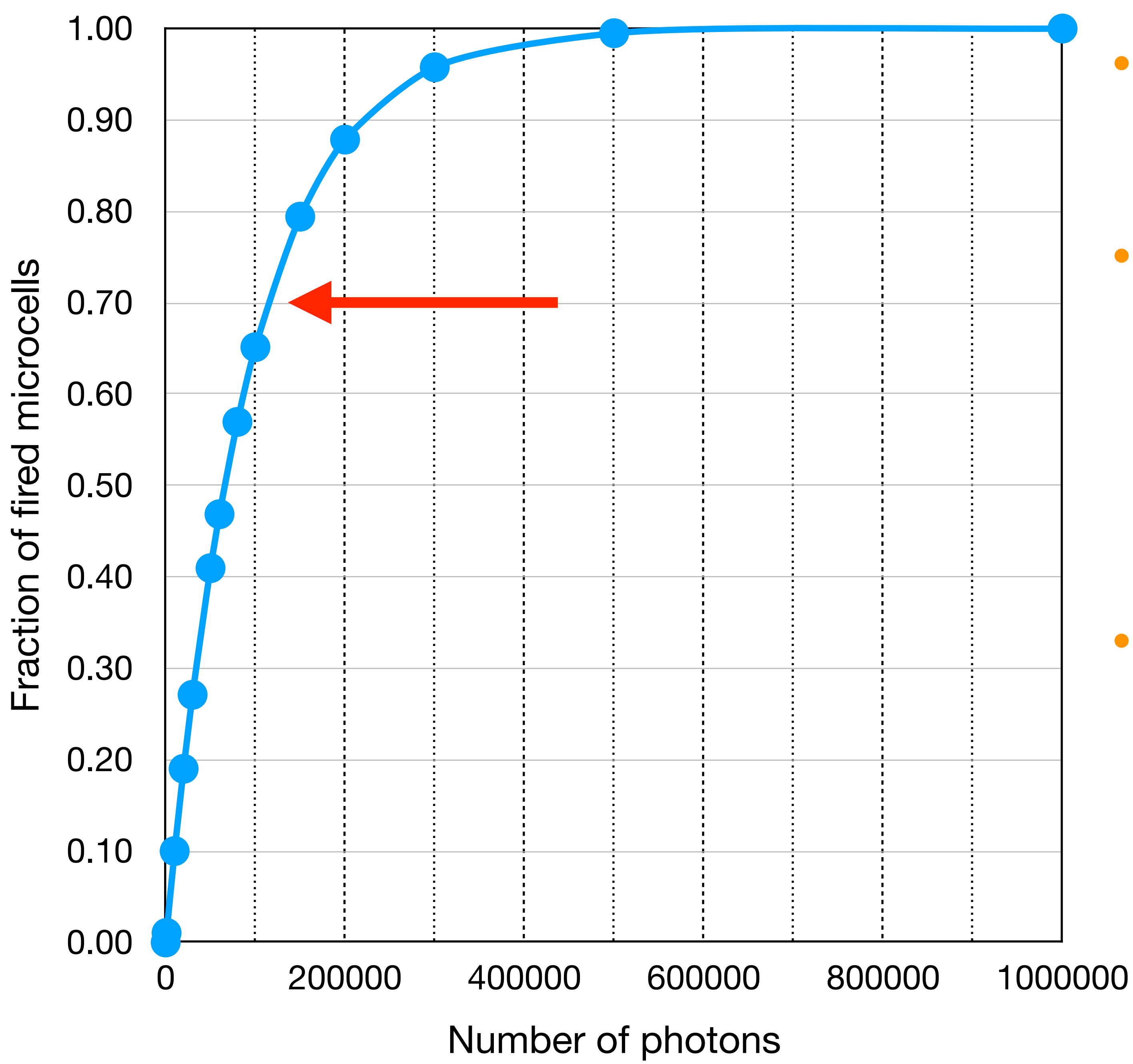
Why SiPM?

- available readout board with Citiroc1A from wee roc for multichannel SiPM (Chih-Hsun Li, Academia Sinica) → can be used for first prototype study
- need a suitable photodetector for critical fluence value ($10^{14}/cm^2$)
    - CMS ECAL
        - barrel: APD, up to $4 \times 10^{13}/cm^2$, gain: $1-100$
        - endcap: VPT (vacuum phototriodes), up to $7 \times 10^{15}/cm^2$
    - CMS MTD BTL (LYSO tiles with SiPM readout)
        - radiation (4/ab): $2 \times 10^{14}/cm^2$, gain: 2×10^5



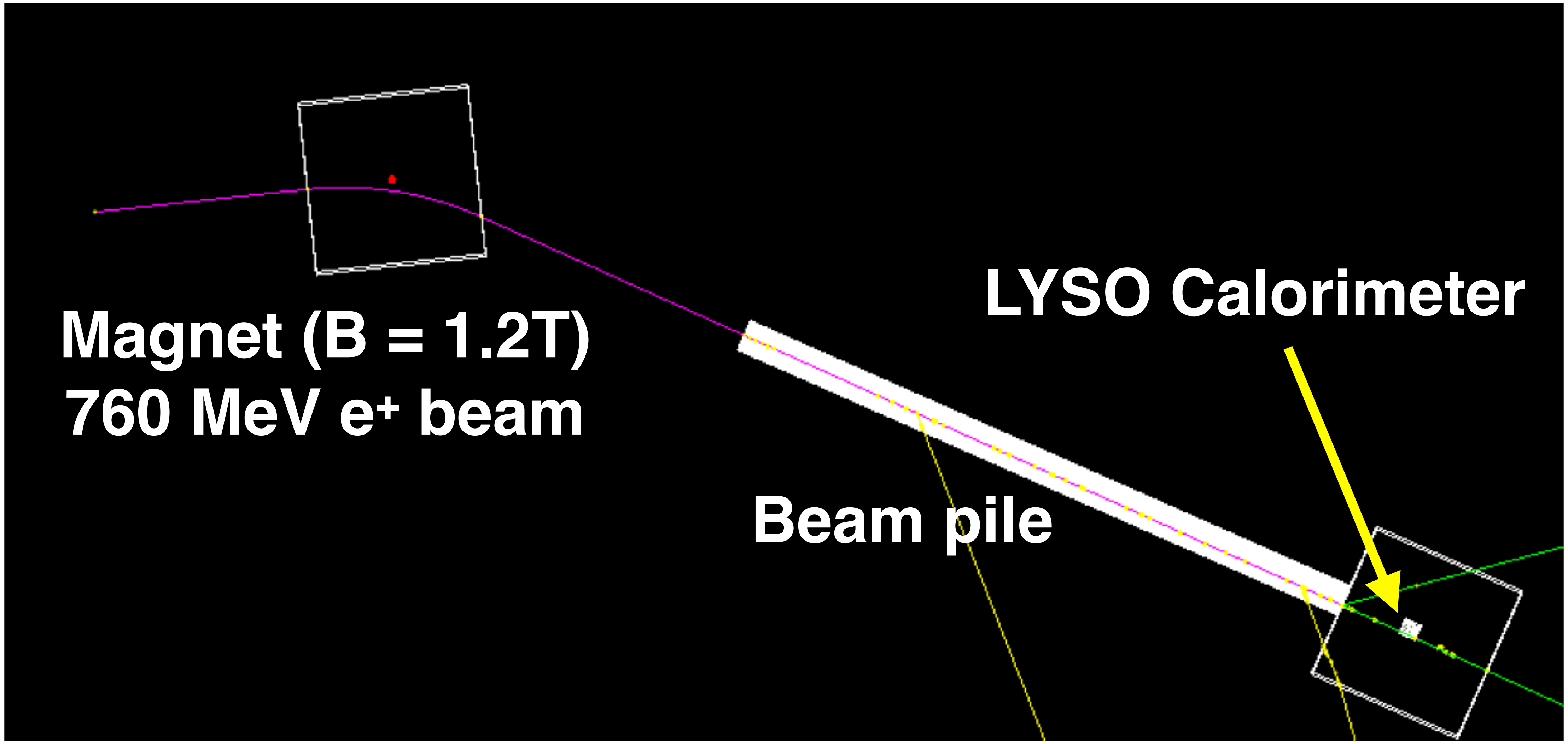


SiPM Performance vs Number of Photons



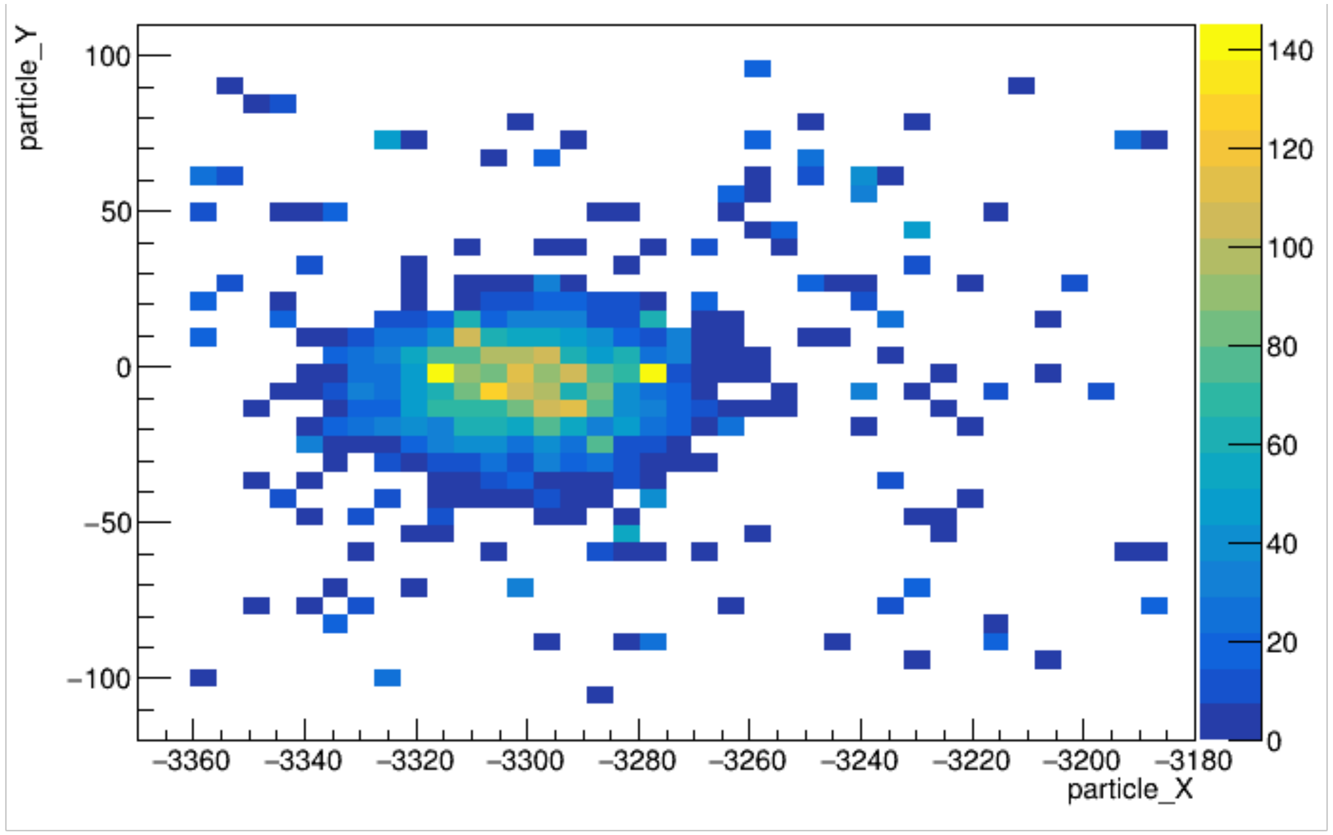
- Need the fraction of fired microcells of a SiPM below 70% for a linear response
- Number of microcells in currently used SiPM: 18,980
  - the one from HPK used by CMS BTL has 40,000 microcells
- LYSO light yield for 500MeV energy deposit: 500MeV × 40,000 photons/MeV × 0.2 (photon detection efficiency) × 0.25 (light collection efficiency) = 1,000,000 photons

Simulation with “Realistic Beam”



Very Preliminary Simulation Results

Beam Profile



Particle Momentum