

Institute of High Energy Physics
Chinese Academy of Sciences



Development of the BESIII Zero-Degree Calorimeter for Fast Luminosity Monitoring and ISR Photon Tagging

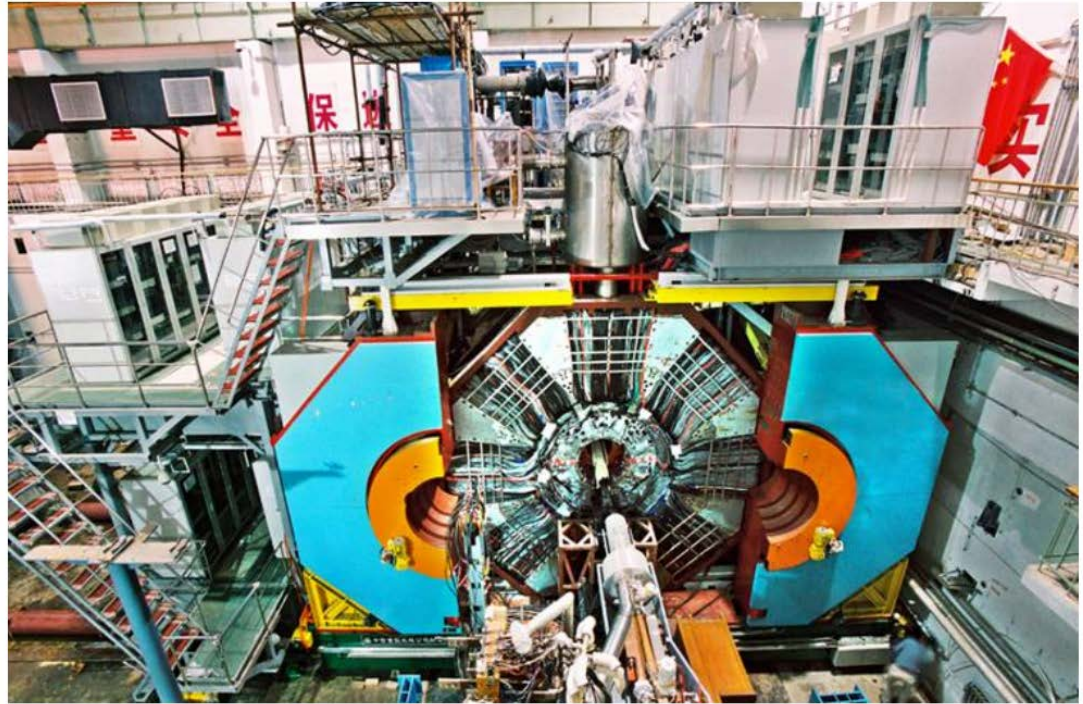
Lei Zhang (张雷), Yuhui Miao (缪语辉), liangliang han(韩亮亮)

, Jiawei Wan (万家威), Yilun Wang (王翊伦),

Xiao Cai (蔡啸), Sheng Dong (董胜), Xiaohui Qian (钱小辉)

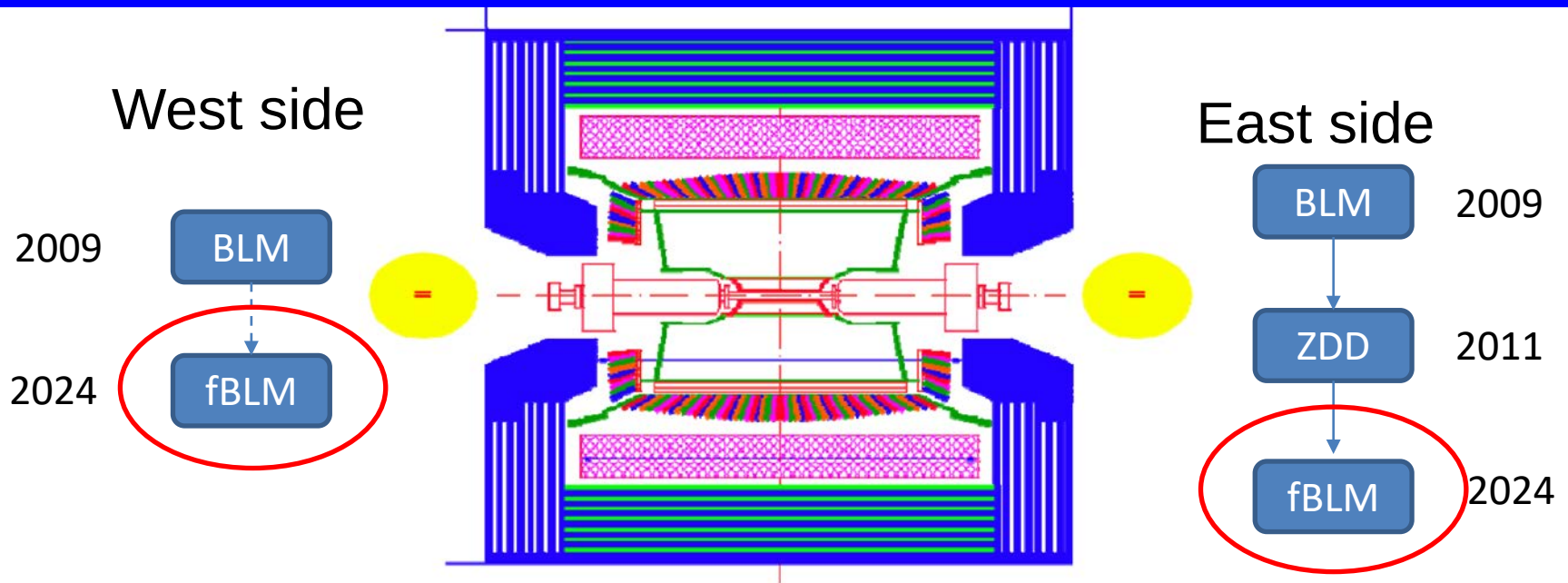
On behalf of the BESIII-ZDC team

BESIII



- Beijing Spectrometer(BESIII) is a general purpose detector at Beijing Electron-positron Collider (BEPCII)
- Broad τ -charm Physics Studies Across 2 - 5GeV

Fast Luminosity Monitor



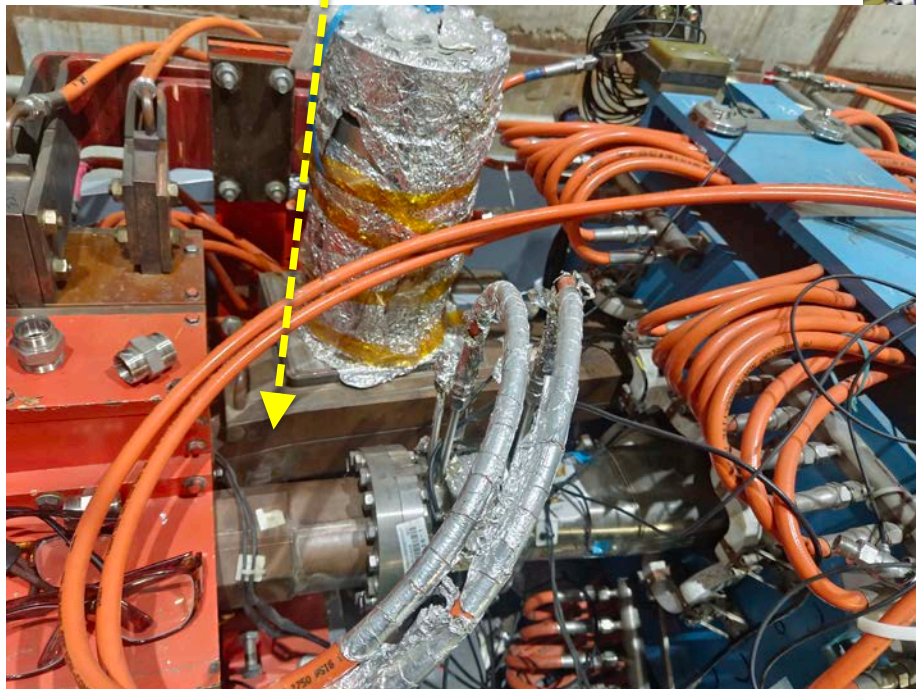
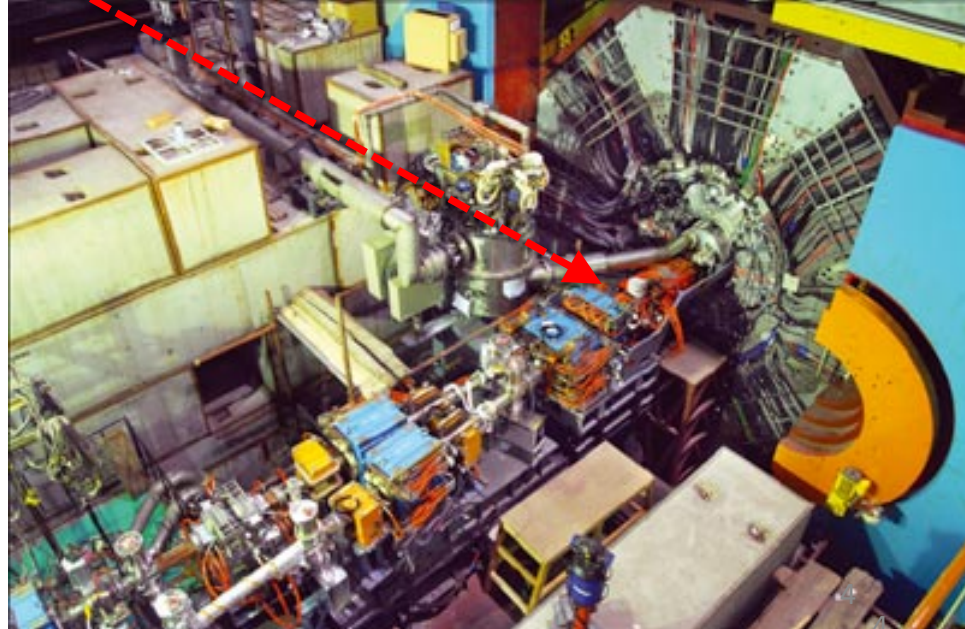
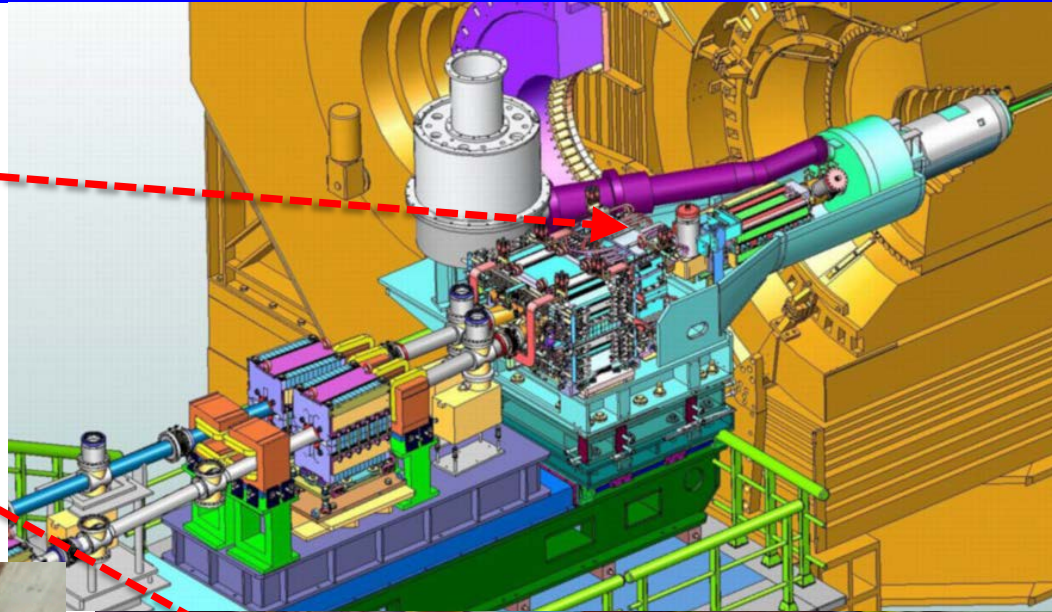
- BLM: BEPC2 Luminosity Monitor, USTC
 - also called small angle luminosity detector
- ZDD: Zero Degree Detector, INFN
- fBLM: fast BLM, IHEP & Nanjing University
 - Upgrade to handle higher luminosity of BEPCII upgrade
 - also called ZDC, zero degree calorimeter

Location of fBLM

$3.3 \text{ m} < z < 3.5 \text{ m}$

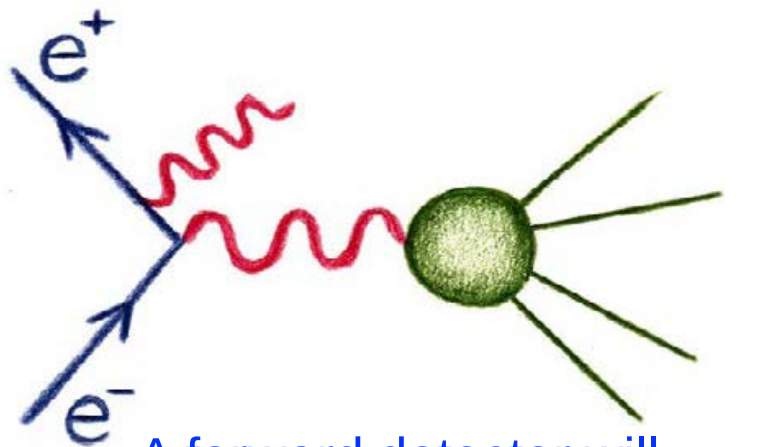
$\theta = 0$ in the CMS frame

Copper window in the
outgoing beam pipe

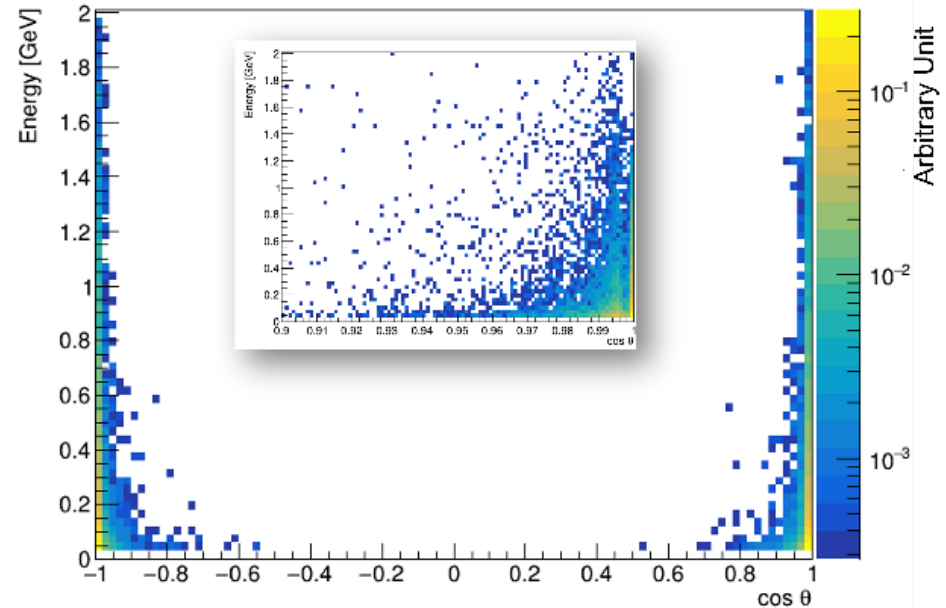


ISR return

- Initial-state radiation (ISR) return
 - $e^+e^- \rightarrow \gamma_{ISR} e^+e^- \rightarrow \gamma_{ISR} X$ lowers the effective e^+e^- collision energy.
- ISR photons are mostly in the forward region ($|\cos\theta| > 0.99$)
 - EMC ($|\cos\theta| < 0.93$) detects only large-angle ISR photons, resulting in low efficiency.



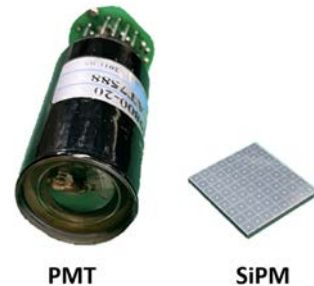
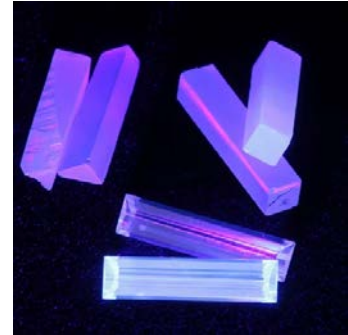
A forward detector will significantly boost ISR physics



- Previous attempts from INFN (ZDD) and Mainz (cZDD)

Technology Choice for ZDC

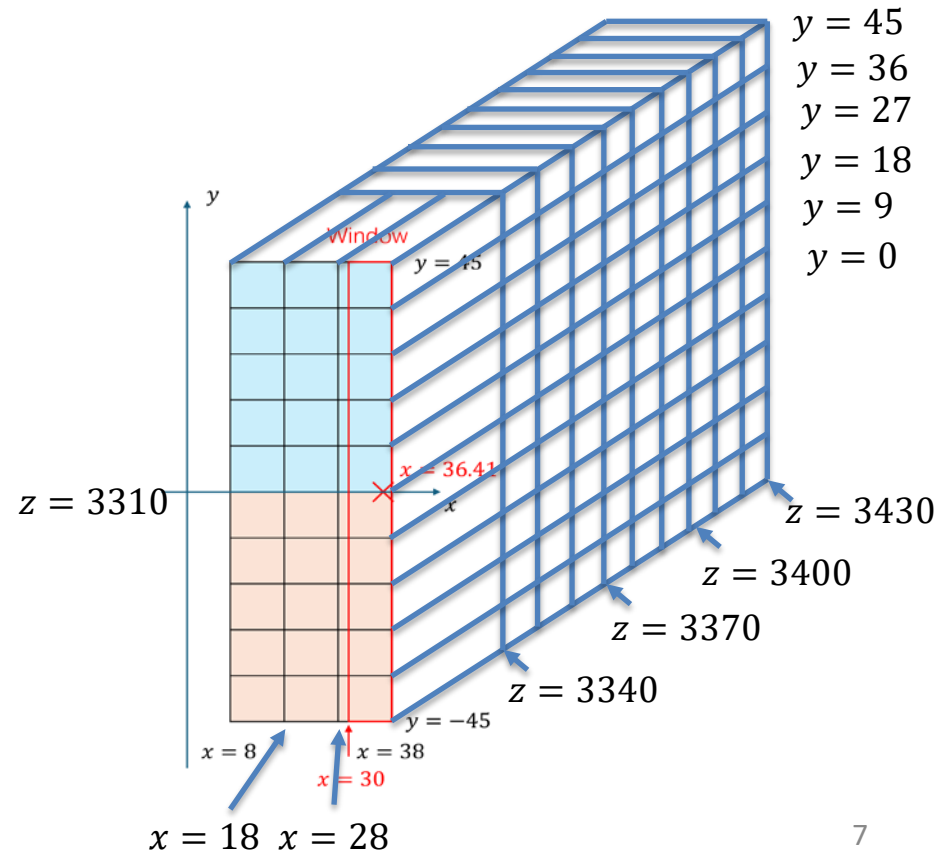
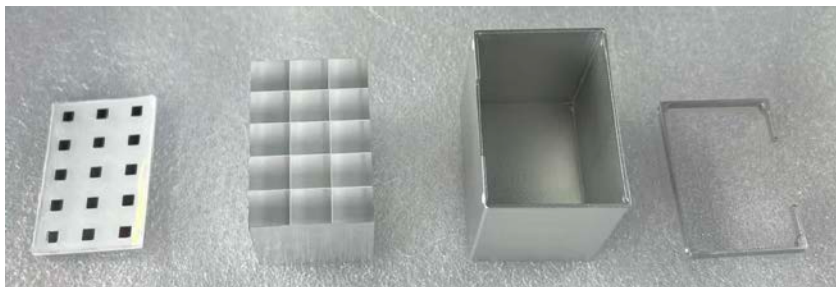
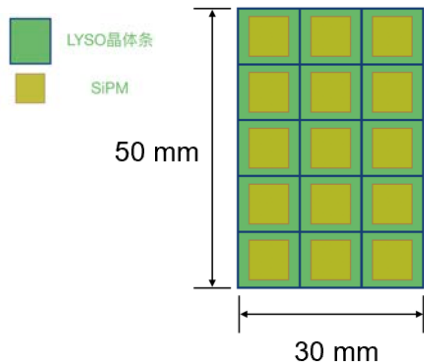
- Challenges
 - High radiation level in the forward region
 - High event rate, difficult for Trigger&DAQ system
- LYSO crystal for calorimetry
 - High light yield and high radiation hardness
- SiPM sensor: Compact, low working voltage, large dynamic range, cost-effective
- Candidates for many proposed future projects
 - SiPM selected by CEPC ref. detector, both calorimeter and Muon
 - LYSO+SiPM: the baseline for CEPC luminometer



Detector Module

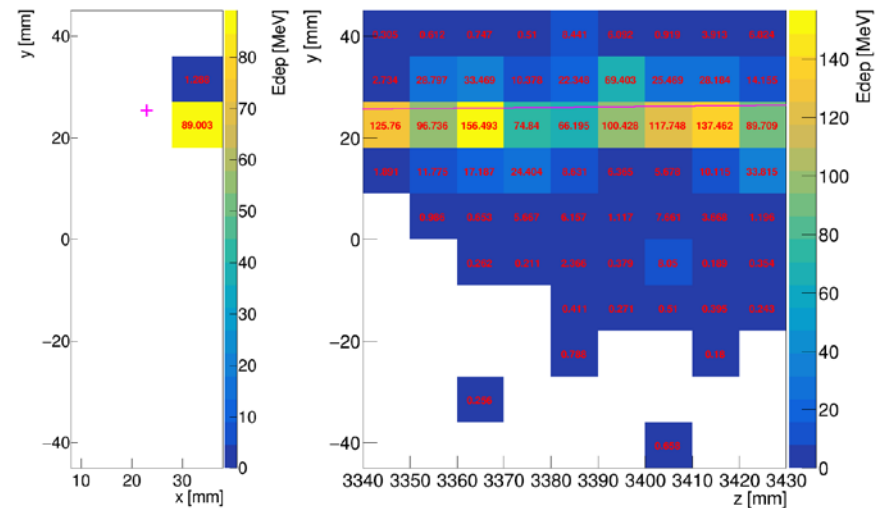
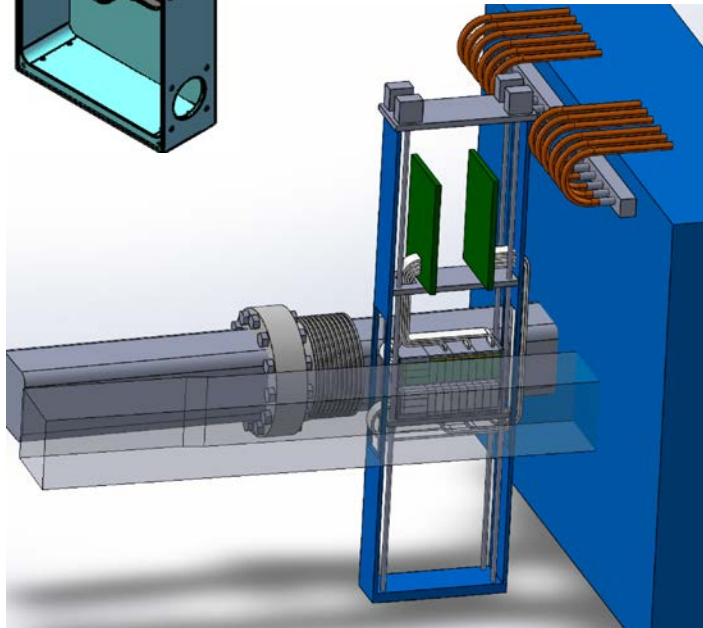
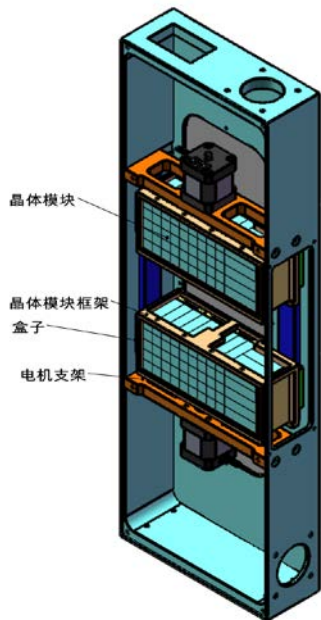
- Module design
 - 3×5 LYSO bar array (bar dimension: $1\text{cm} \times 1\text{cm} \times 3\text{cm}$)
 - SiPM board mounted with the same 3×5 SiPM array
 - 8 module in one sub-detector at each side

15-channel module



Detector of Zero Degree Calorimeter (ZDC)

- Two sub-detectors with 240 channels in total
 - Fully modalized design, optimal for energy and position

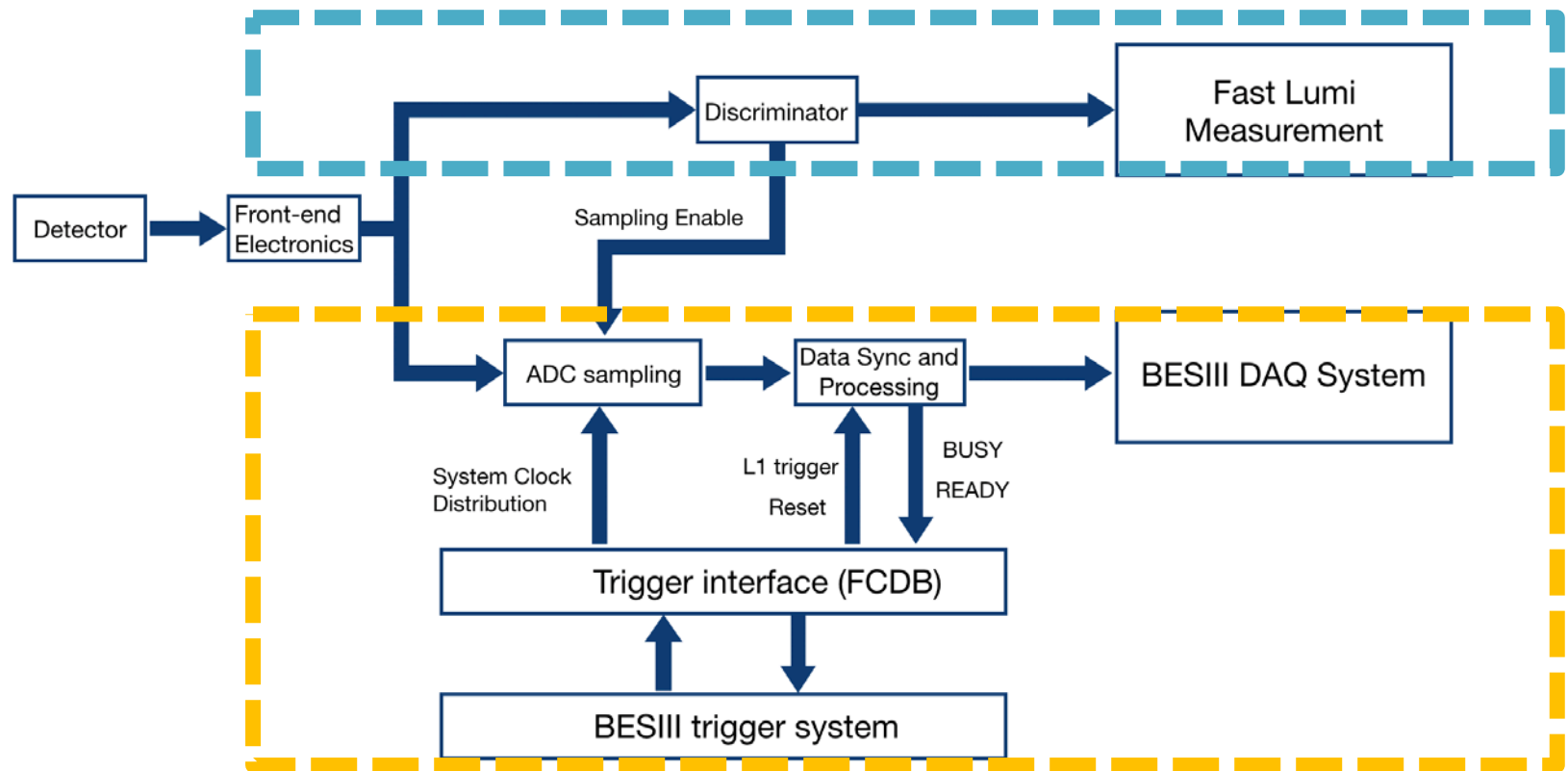


Particle Energy : 2232.37

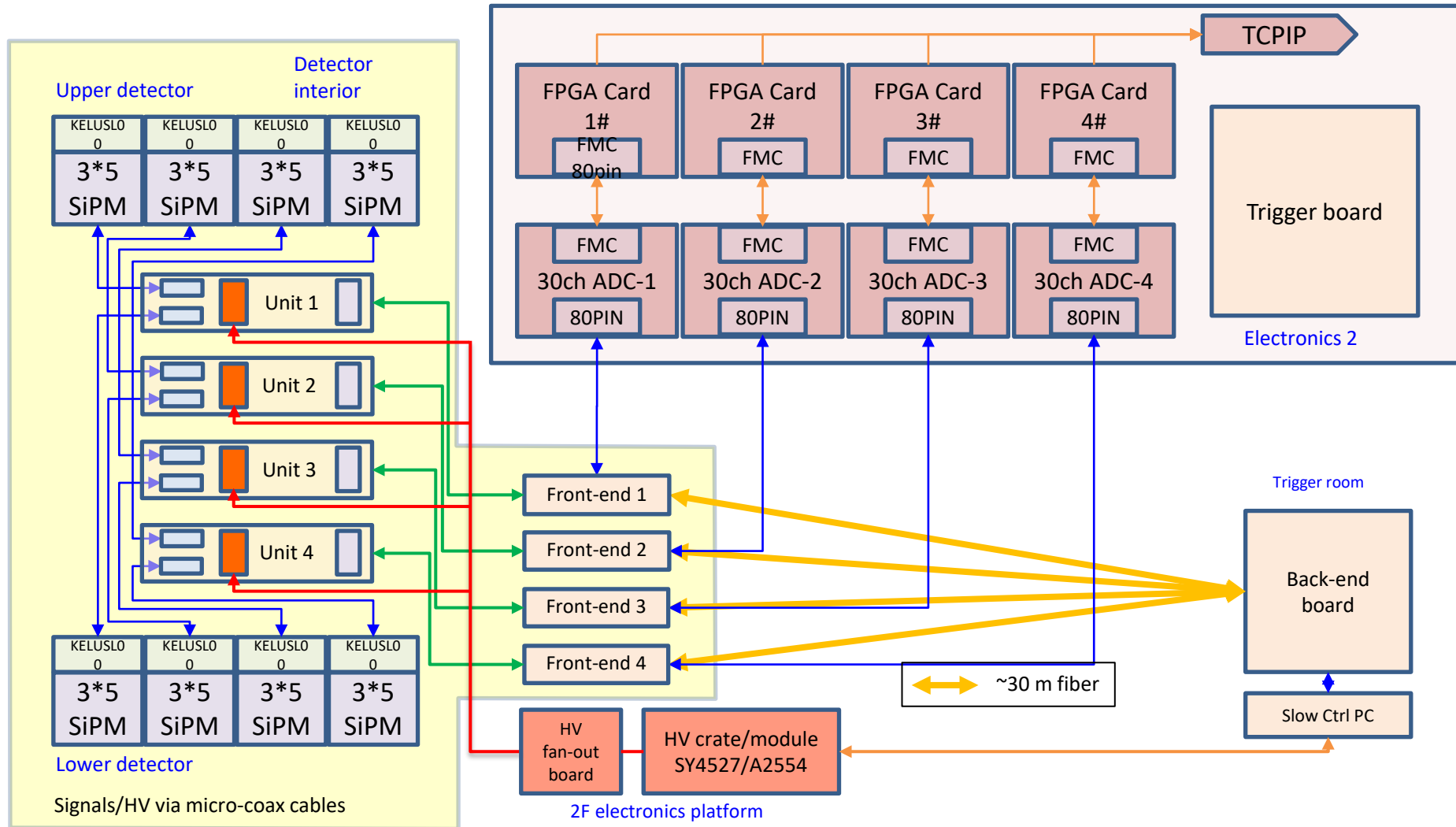
Total Edep : 1481.45

Readout Electronics Architecture

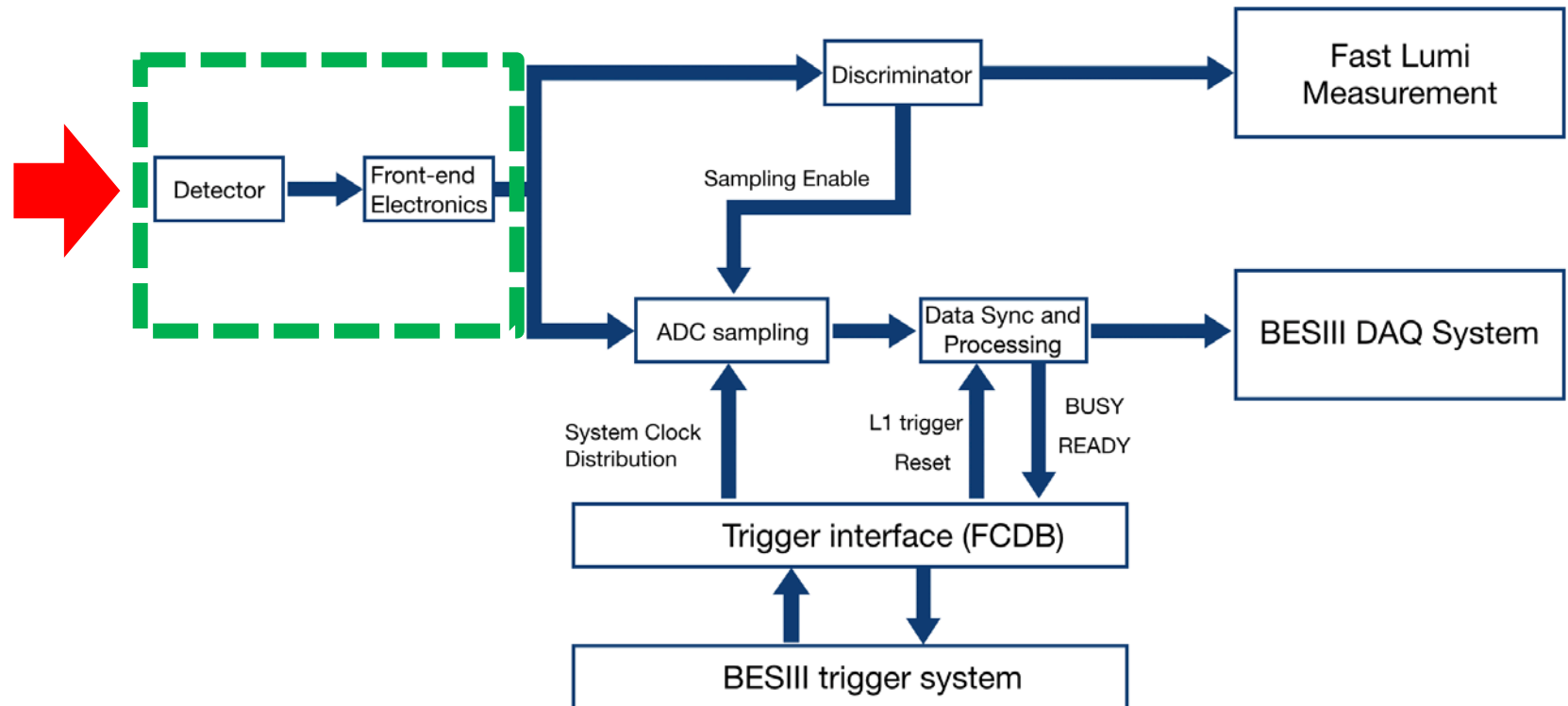
- Three blocks:
 - Front-end, Lumi. monitoring, ISR photon tagging & DAQ



Readout Electronics Architecture



Electronics for Lumi. monitoring

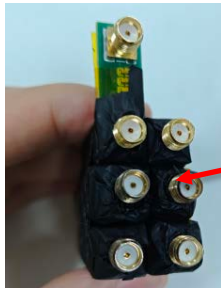


Long and careful R&D processes

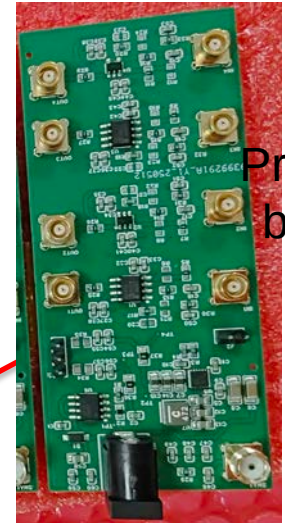
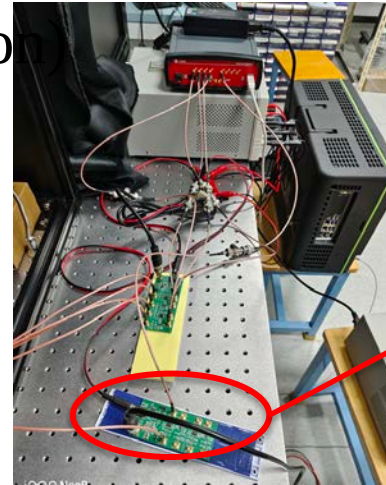
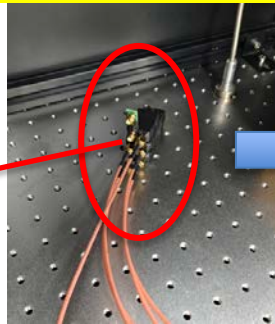
- LYSO+SiPM module and readout integration

- Front-end electronics (first version)

SiPM board

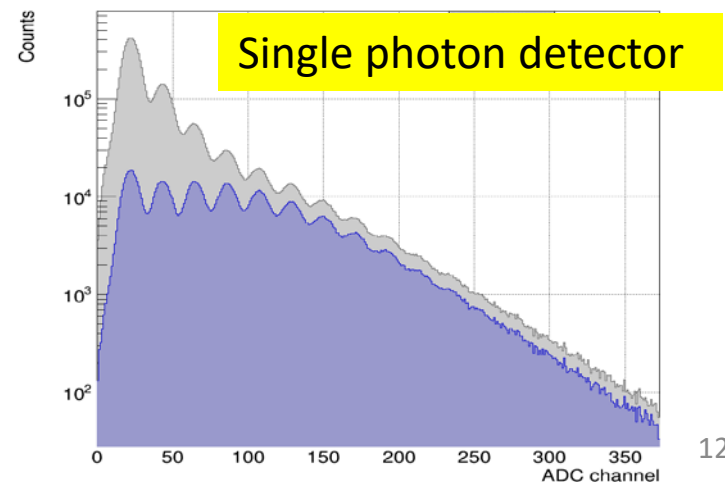
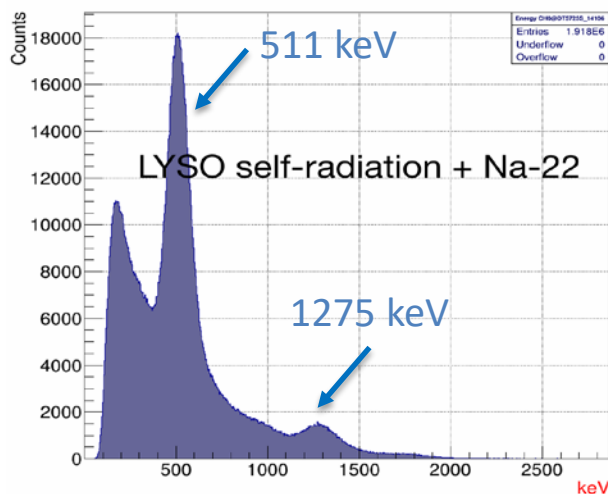


LYSO+SiPM module



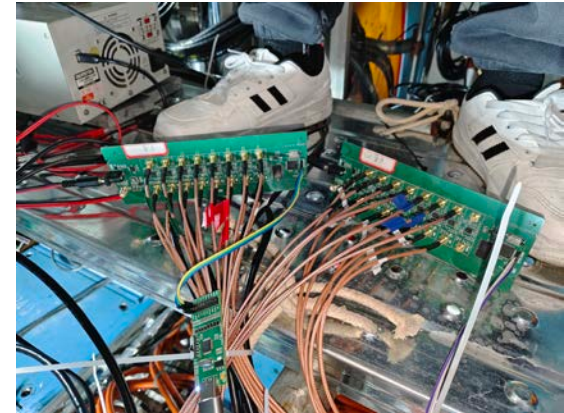
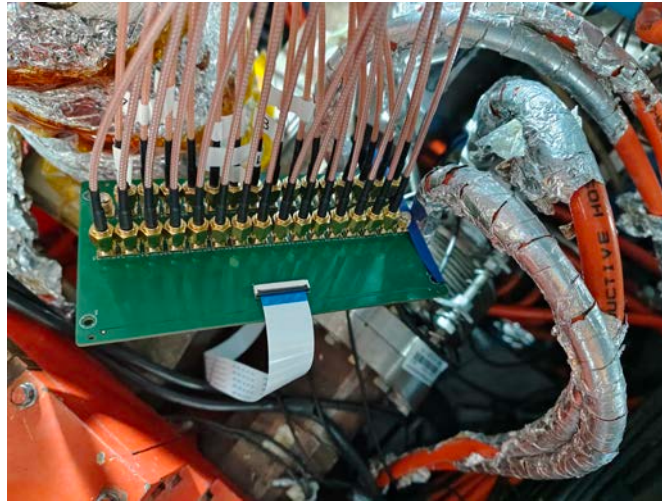
Preamplifier board

- Lab tests with radioactive sources and a laser system

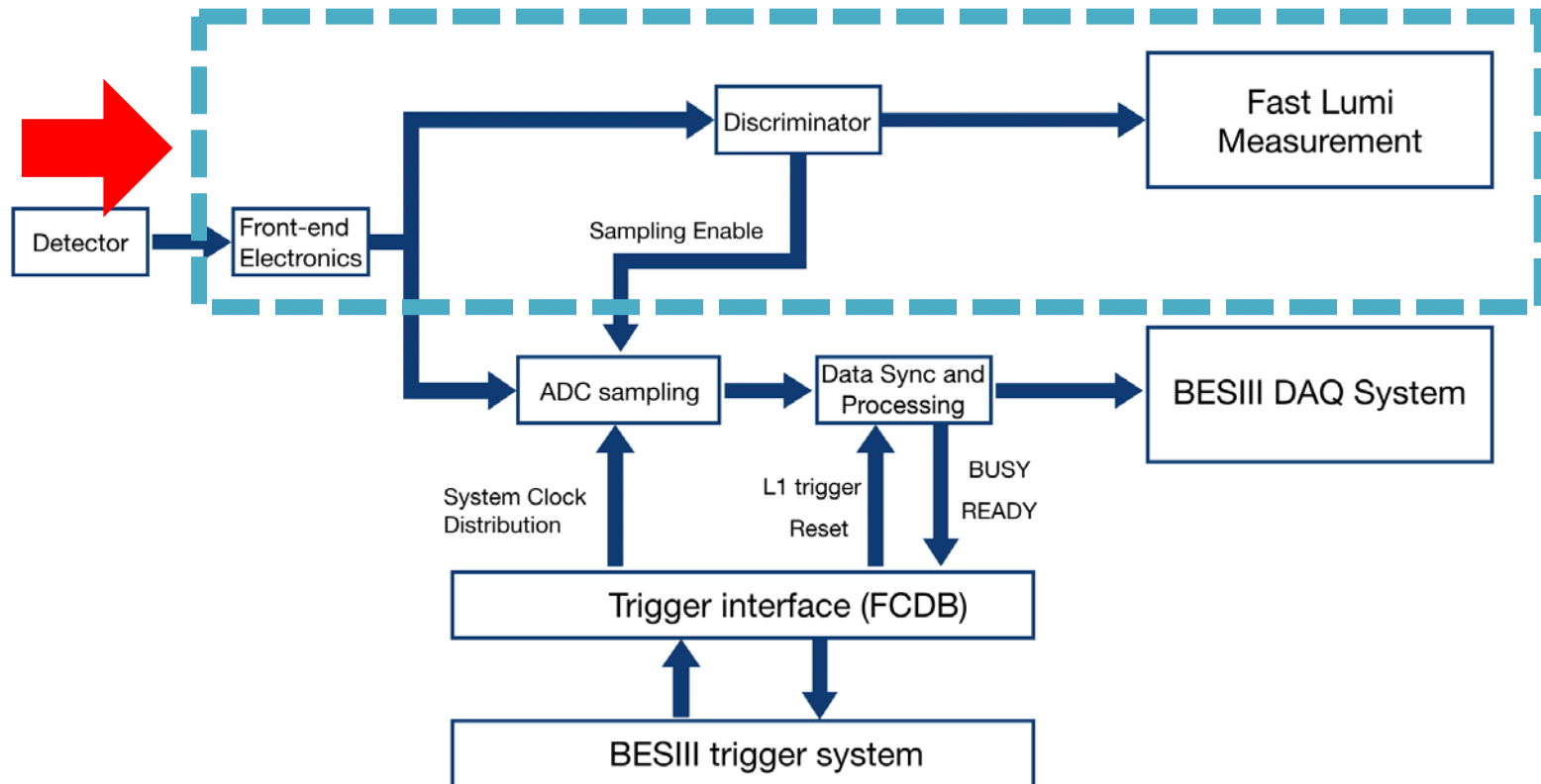


Long and careful R&D processes

- Insitu test at BEPCII:
 - Prove the reliability of LYSO and SiPM



Electronics for Lumi. monitoring



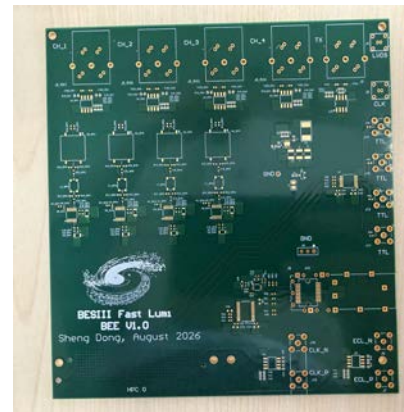
Fast luminosity electronics

- Front-end electronics (FEE)
 - Amplification, fan-out, discrimination and pulse shaping

FEE V0.1

- Back-end electronics (BEE)
 - Data aggregation, SPI communication and Ethernet data output

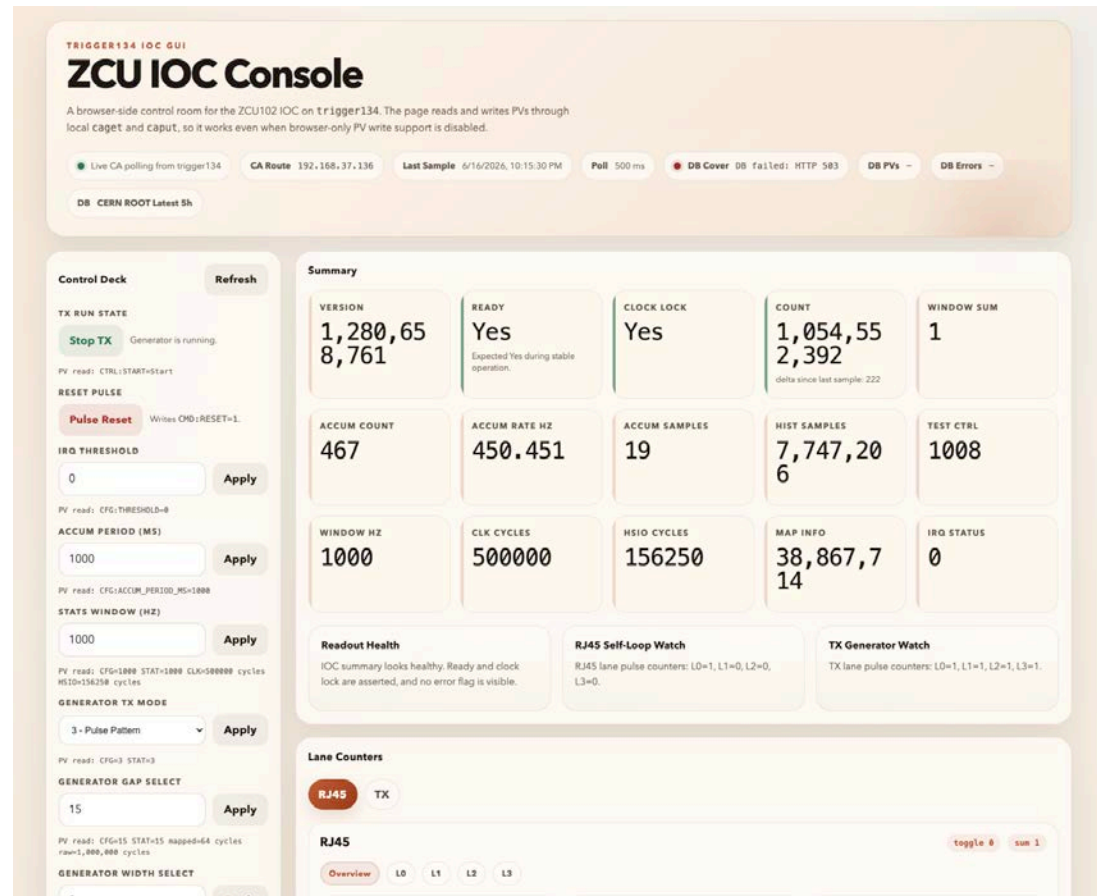
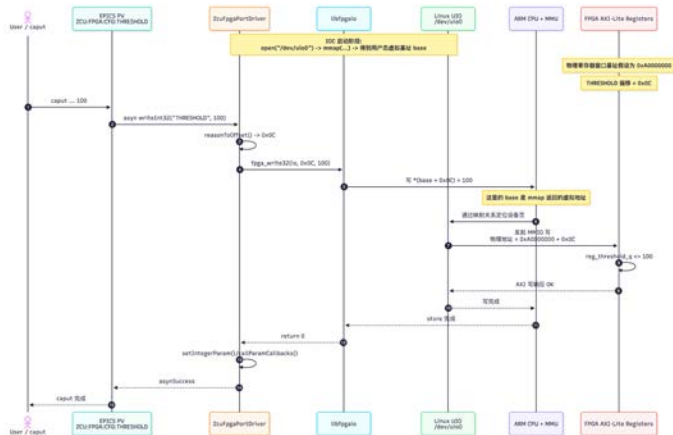
BEE test setup



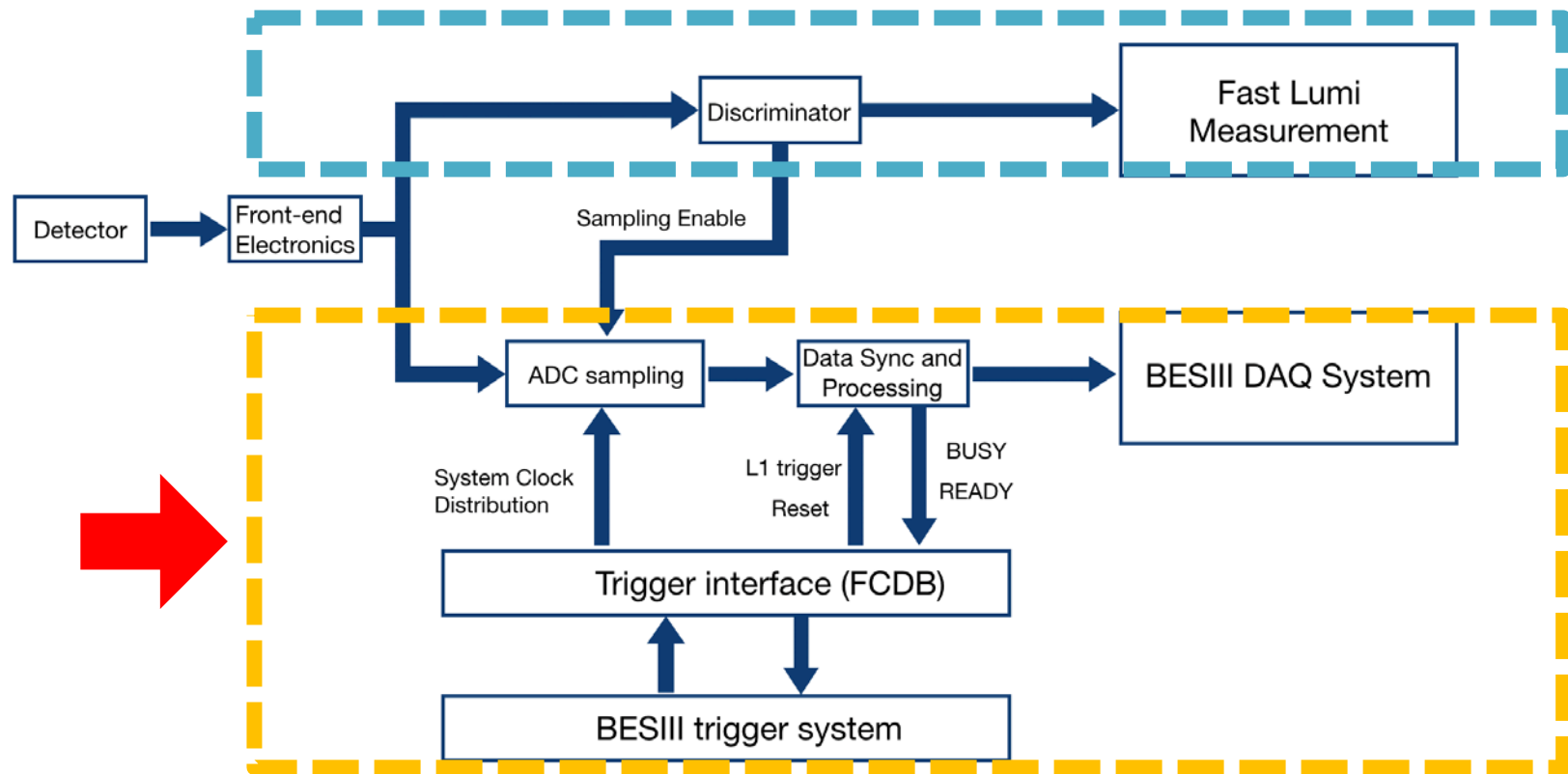
BEE V1.0

Fast luminosity control software

- Control software
 - Count readout, count-rate monitoring, slow control of detector by SPI

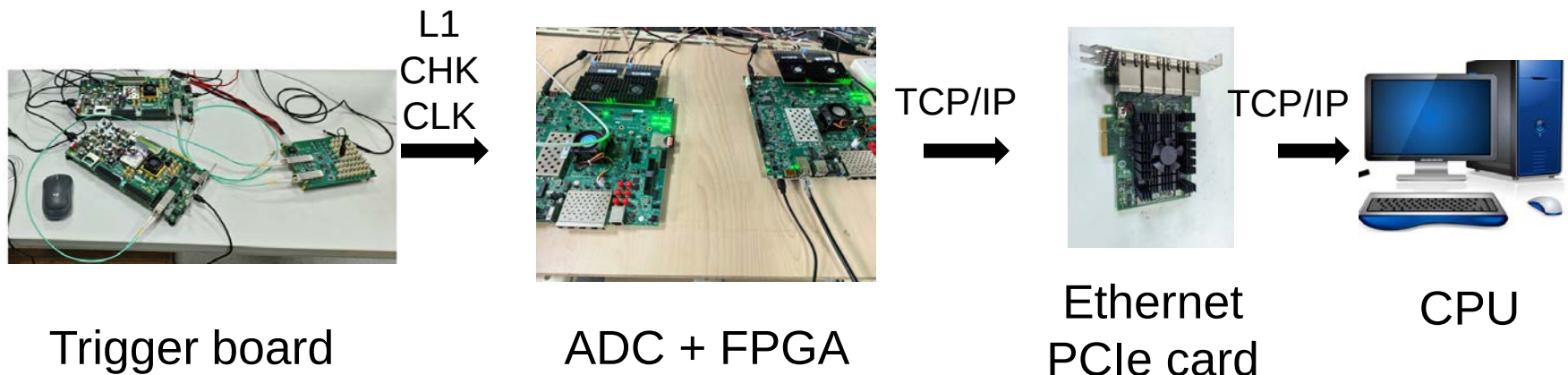


Electronics for ISR photon tagging



Readout integration and synchronization

- Full readout chain passed all tests
 - Sampling, event building, buffering and network transfer
 - LYSO/SiPM→preamplifier→ADC→ FPGA → CPU → Ethernet
 - Events matched across boards using trigger IDs and CHK signals
 - Multiple FPGAs synchronized with stable latency
 - Stable laboratory operation with a packet loss rate $< 10^{-8}$



Hardware: Trigger board

- Timing Synchronization:
 - Fan-out to distribute BESIII's CLK/L1/CHK signals to different boards
 - Enable system-wide timing synchronization of 120 channel

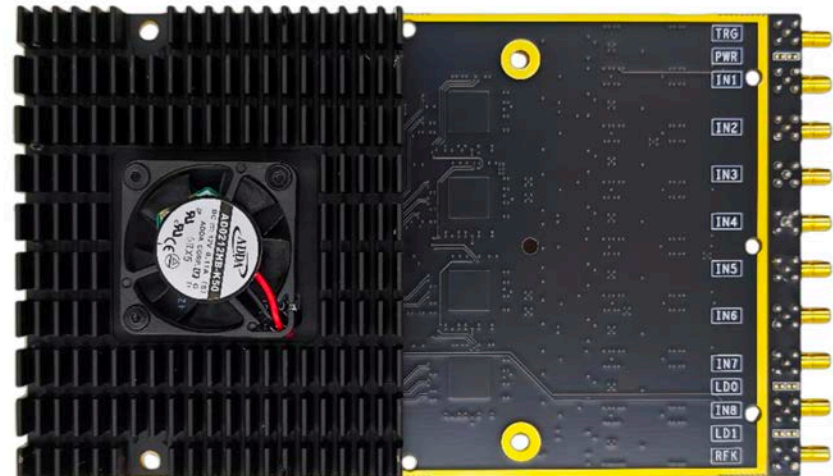
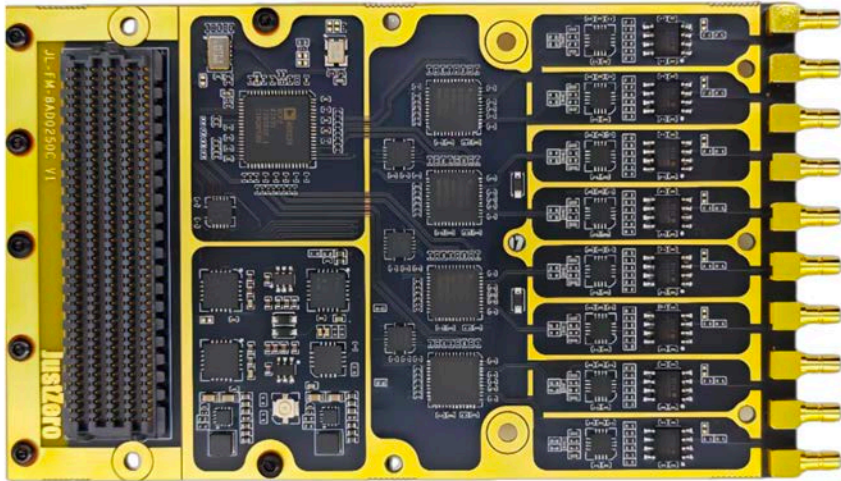


CLK/L1/CHK



ADC board status

- Front-end ADC board
 - Sampling rate: 250 MSPS, 14-bit ADC resolution;
 - Effective number of bits (ENOB): approximately 9–10
- Testing completed
 - Energy resolution: 12% FWHM/E at 1274 keV



FPGA board and cpu processor

- FPGA board
 - ZCU102 with AMD Zynq UltraScale+ XCZU9EG



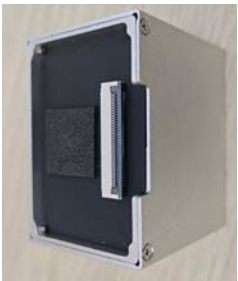
- One CPU processor connected to 8 FPGA (120 channel)
 - Two CPU in total to perform energy measurement

Monitoring interface and event display

- Interactive event visualization and waveform monitoring.



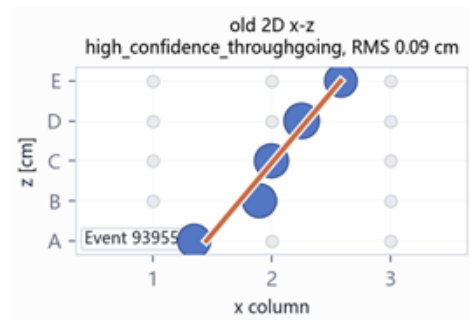
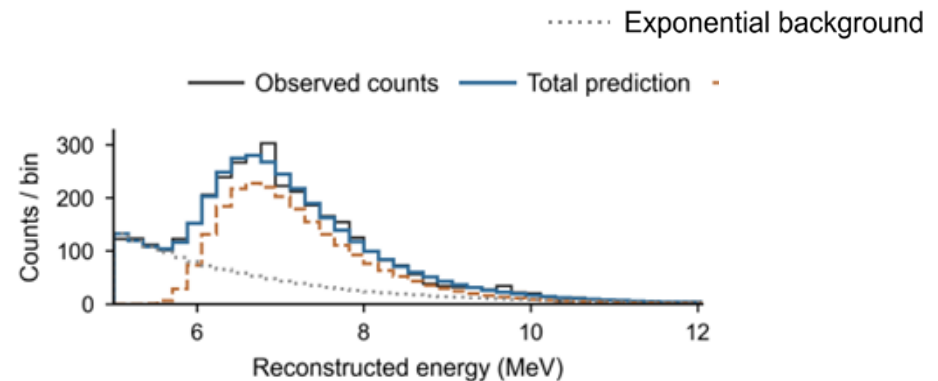
Cosmic-ray test of the integrated prototype



- Two FPGA boards read out 15-channel
 - LYSO+SiPM module (7 + 8 channels)
- Cosmic-ray tests the full chain
 - Online: detector module, front-end, ADC/FPGA and DAQ
 - Offline: energy rec. and track-let rec.

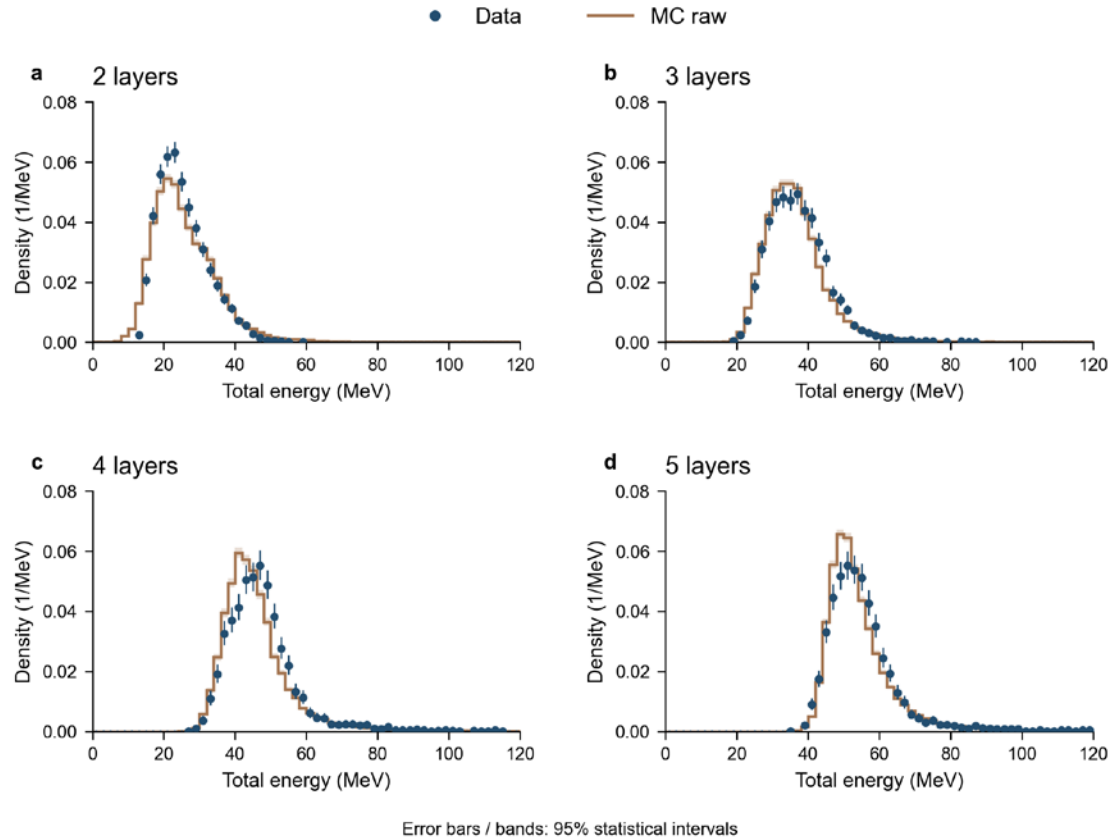
Energy deposits (MeV)

	latest energy [MeV]		
E	2.0	6.8	1.8
D	2.3	8.2	2.4
C	2.3	6.7	2.4
B	2.3	6.1	2.2
A	1.7	4.7	1.6
	x=1	x=2	x=3



Reconstruct
track-let

Data-MC comparison on MIP

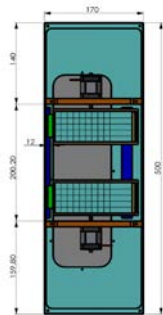


- Measured cosmic-ray spectra show a good agreement with the MC simulation from GEANT4

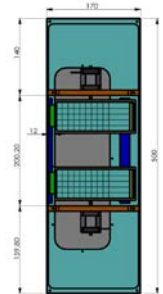
Towards full system 240 CH readout

- From 32 channels to 120 channels each side (240 in total)

ZDC (west side)

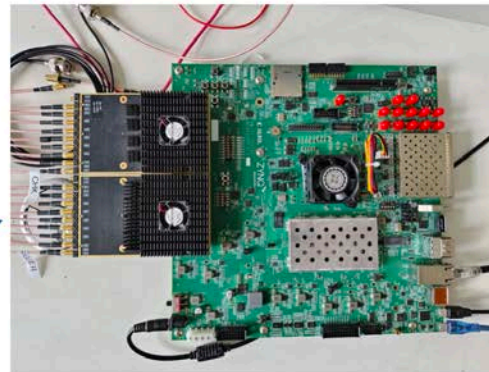


ZDC (east side)



fanout—>120 CH

fanout—>120 CH

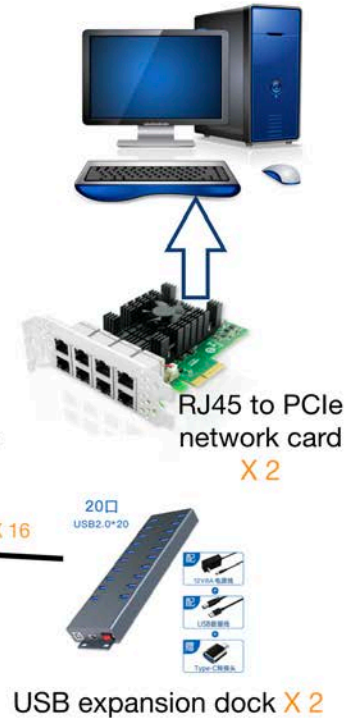


ADC board+ZCU102

X 16

Ethernet
X 16

USB-UART X 16



Summary

- Next generation BEPCII fast luminosity monitor presented
 - R&D stage completed and installation planned within this year
- Upgrade for ISR photon tagging (ZDC)
 - R&D for energy and timing measurement system
 - Fast ADC, high performance FPGA for data processing
 - Synchronization among channels, and with BESIII detector
- Expected to boost BESIII physics potential significantly
- Platform for
 - High radiation hardness detectors R&D
 - Forward physics studies

The end

BEPCII Upgrade and ZDC Motivation

Higher luminosity and shorter bunch spacing expose the limits of the aging ZDD/BLM monitors.

~3x

Luminosity at $\sqrt{s} > 3$ GeV
after the 2024 BEPCII
upgrade

6 ns

Bunch-collision period
after the upgrade

Existing ZDD / BLM

Aging hardware and limited timing resolution cause frequent data loss and larger monitoring errors.

The current monitors support beam tuning only and cannot join the BESIII physics DAQ.



A new ZDC combines fast relative-luminosity monitoring with synchronized forward photon and electron measurements.

BESIII-ZDC team

- Nanjing University
 - Lei Zhang, Shenjian Chen, Yuhui Miao, Jiawei Wan, Yilun Wang, Guangyan Xiao, Shuxian Liu
 - Detector design, sim.&rec. software, detector unit R&D, Backend & Readout electronics, Energy measurement system, ...
- IHEP
 - Xiao Cai, Fei Li, Jingzhou Zhao, Sheng Dong, Xiaohui Qian
 - Frontend electronics, Luminosity system, Trigger&DAQ global system
- Close collaborators
 - Tianjun Li (HNU), Xiaoshuai Qin (SDU), Xiaolin Kang (CUG), ...
- More collaboration are welcome!

In line with future projects in China

CEPC

EM calorimeter: BGO+SiPM

Hadronic calorimeter: Glass+SiPM

LumiCal: LYSO+SiPM



STCF

EM calorimeter: pCsl+APD

Muon: Scint.+WLS+SiPM (one of two options)



LYSO crystal and SiPM

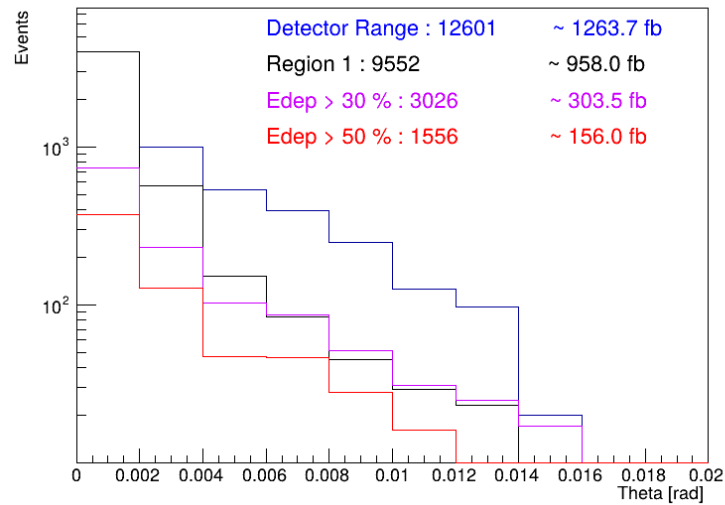
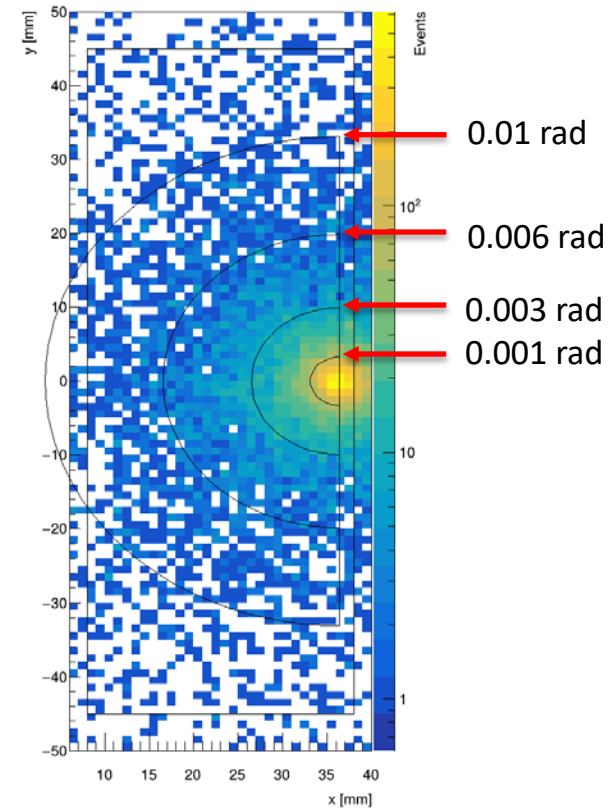
Quality & Yield improved significantly over recent years

BESIII Zero Degree Calorimeter

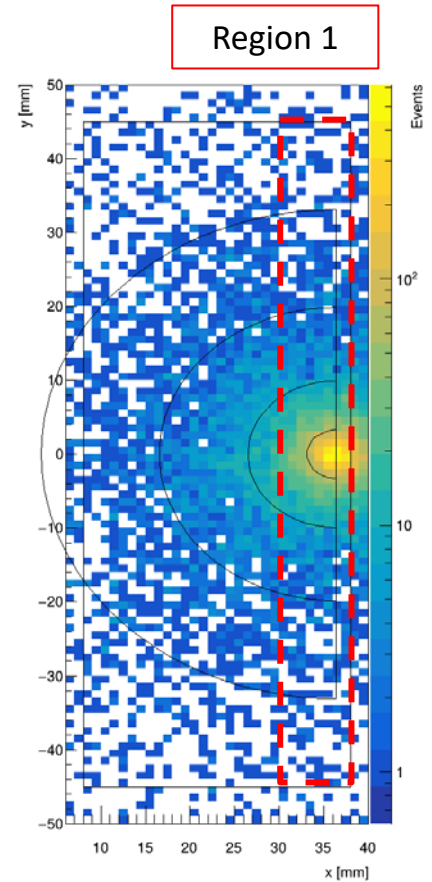
A great platform for the future projects R&D

Phokhara, $e^+e^- \rightarrow \gamma_{ISR} + n\bar{n}$, $\sqrt{s} = 4.68 \text{ GeV}$

$22^\circ < \theta_n < 158^\circ$ ($|\cos \theta_n| > 0.93$)

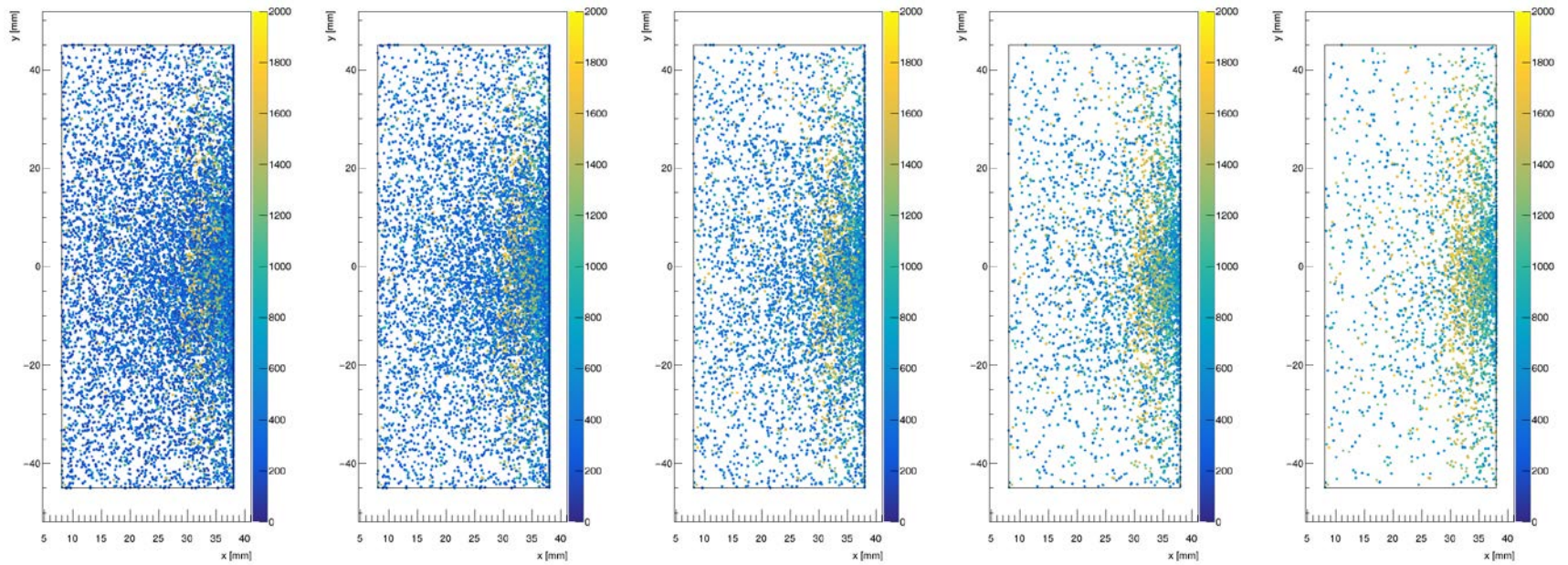


(MC Particle Truth, not Simulation)



Phokhara, $e^+e^- \rightarrow \gamma_{ISR} + \pi^+\pi^-$, $\sqrt{s} = 4.68 \text{ GeV}$

Simulation



> 100 MeV

> 200 MeV

> 300 MeV

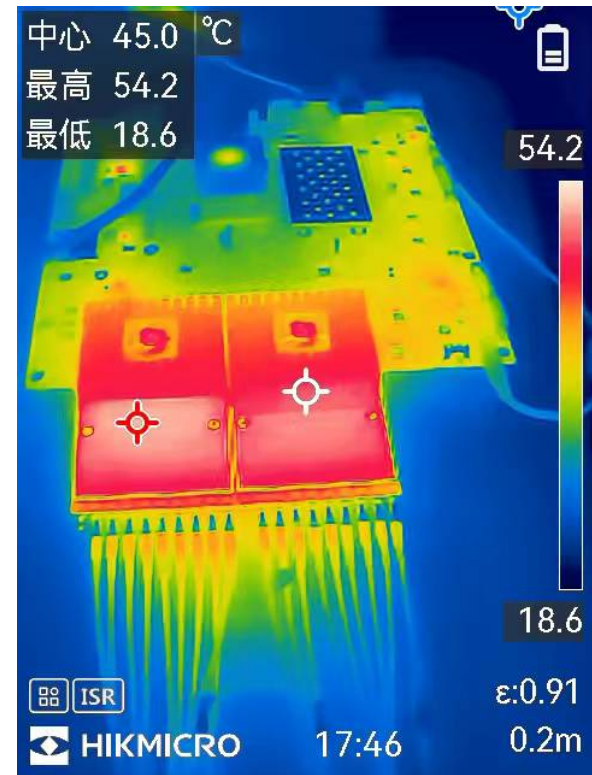
> 400 MeV

> 500 MeV

Thermal performance



Hardware setup



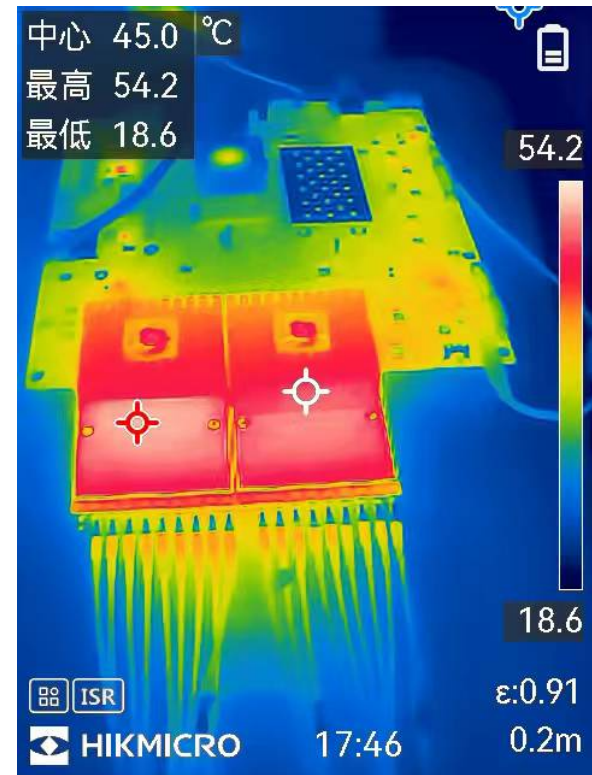
Surface temperature map

- The system remained stable during one week of continuous operation at full load, with the maximum measured surface temperature remaining below 55 °C.

Thermal performance



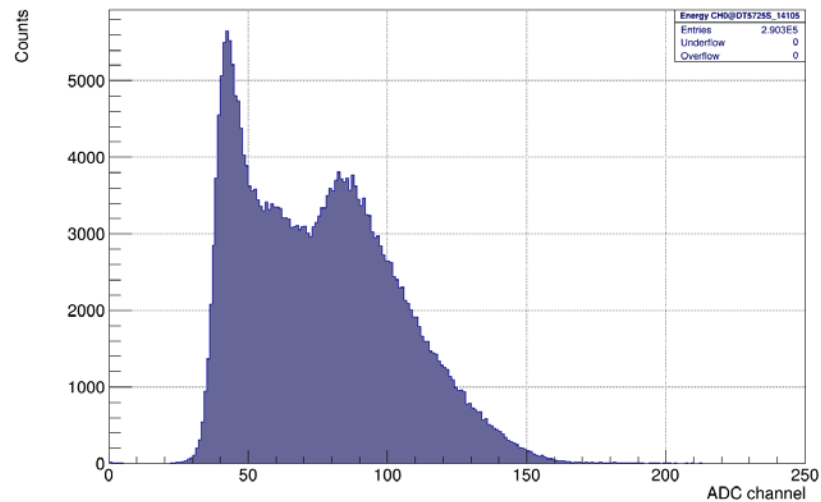
Hardware setup



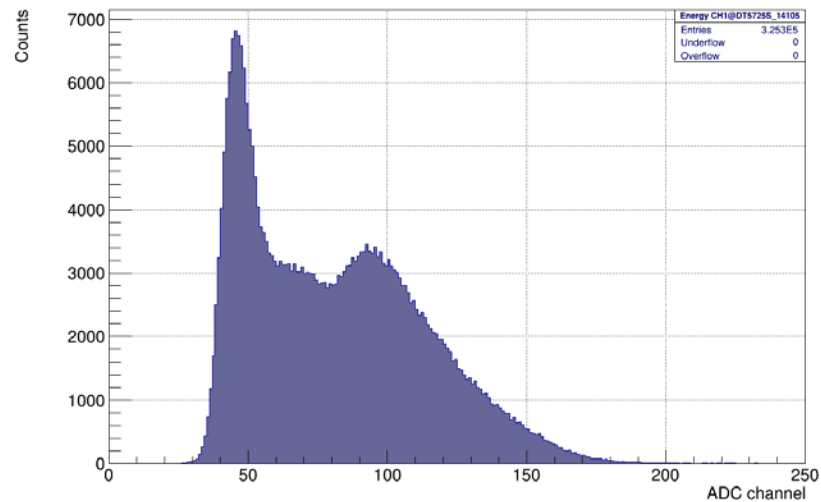
Surface temperature map

- The system remained stable during one week of continuous operation at full load, with the maximum measured surface temperature remaining below 55 °C.

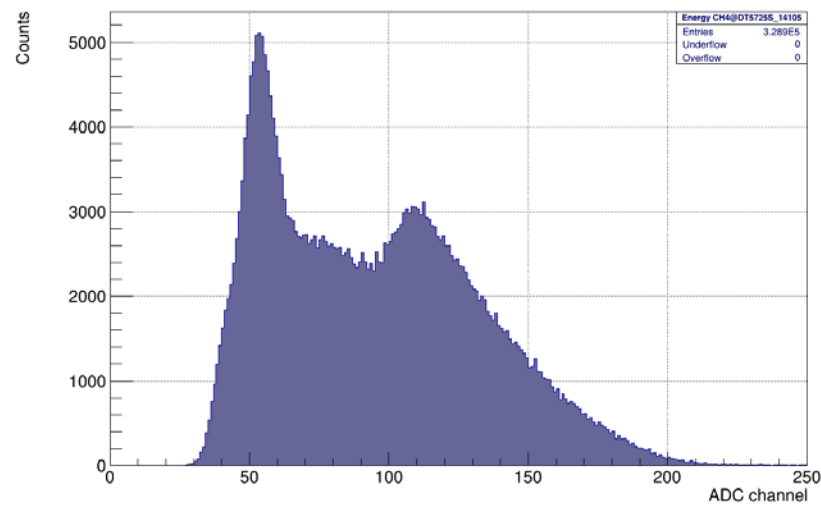
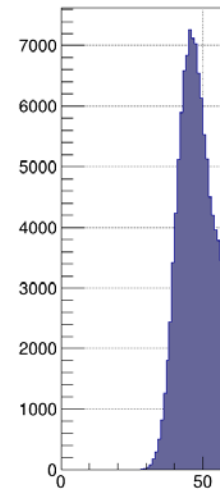
能谱



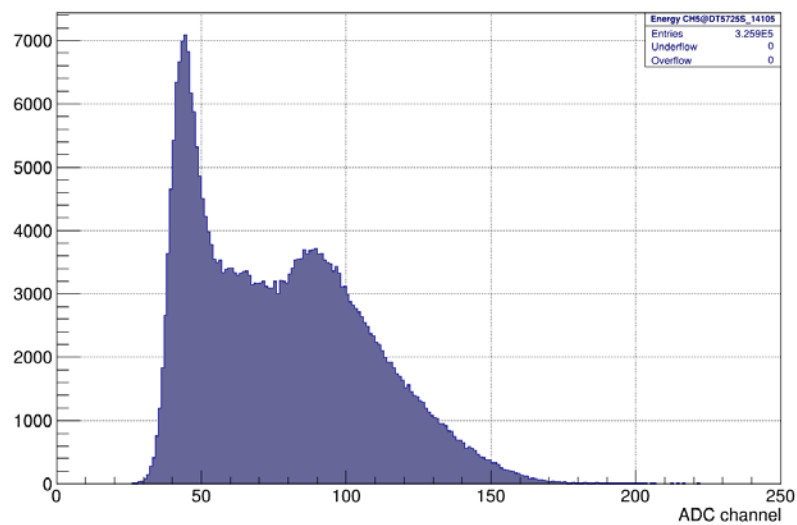
CH1



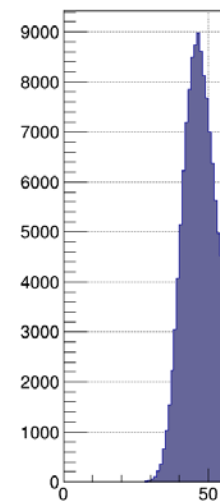
CH2



CH5

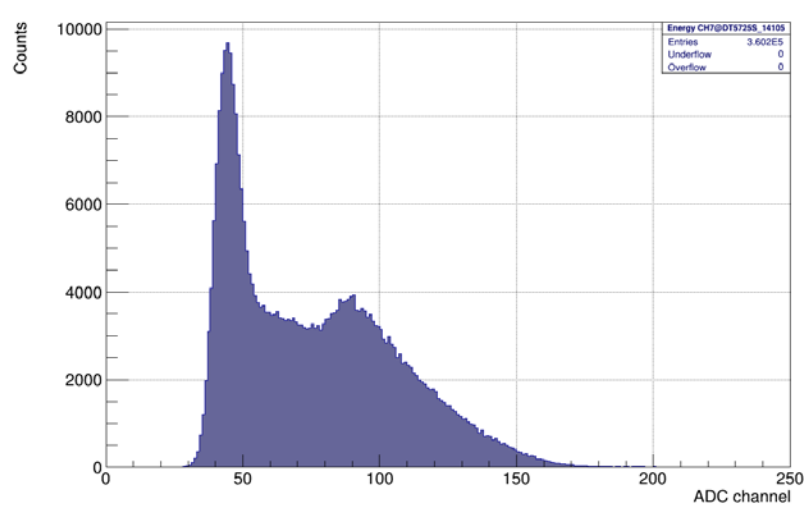


CH6

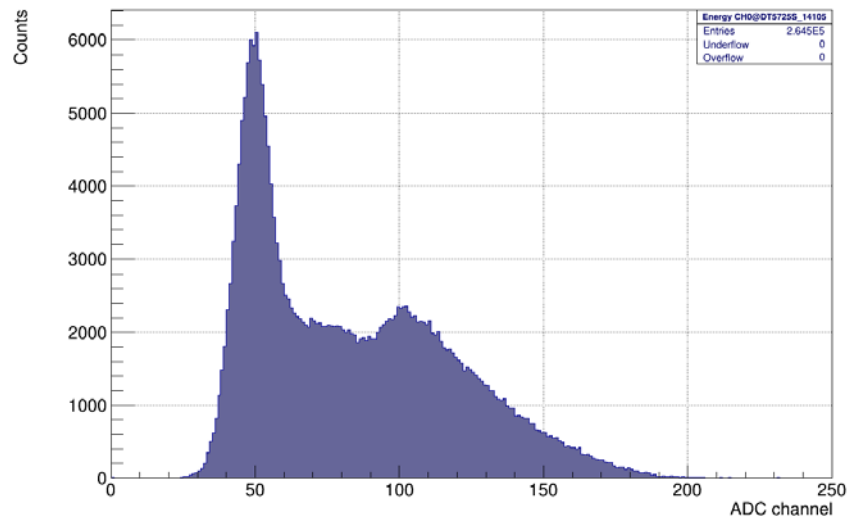


35

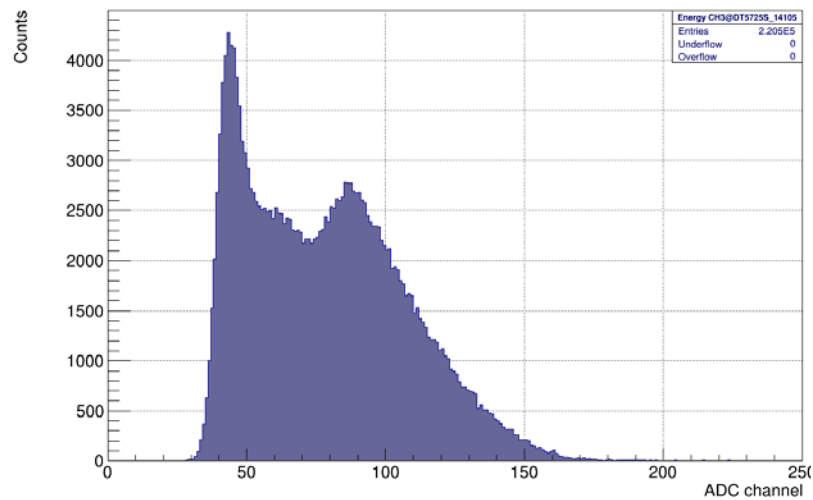
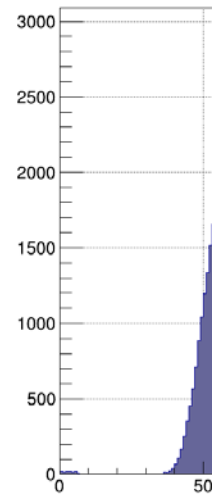
能谱



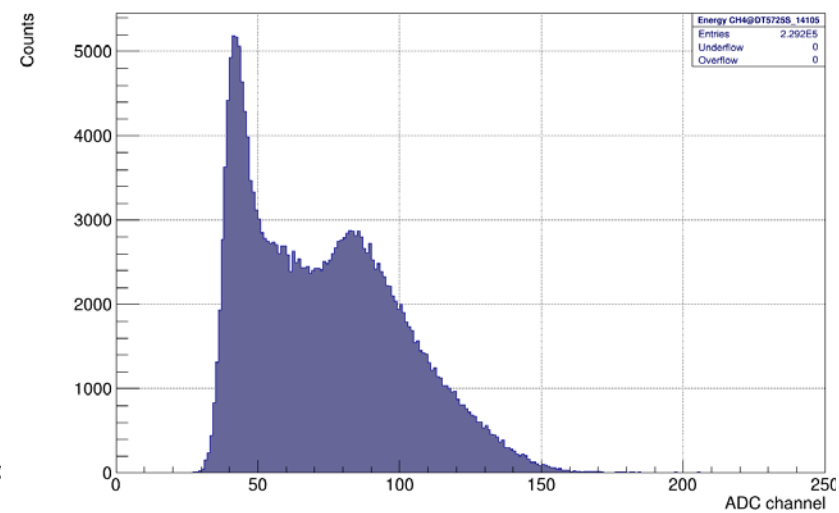
CH8



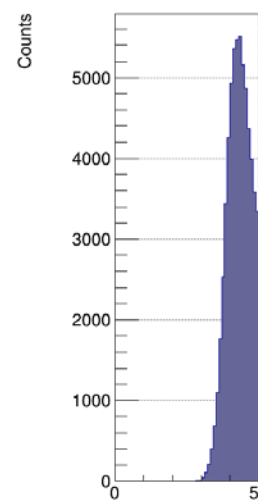
CH9



CH11



CH12



36