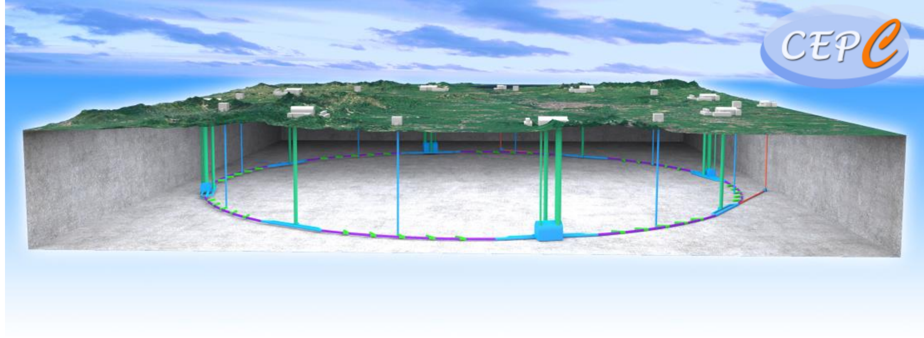
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences



High-granularity crystal calorimeter: R&D status

Baohua Qi
On behalf of CEPC Calorimeter Working Group

Joint Workshop of the CEPC Physics, Software and New Detector Concept in 2022
May 23-25, 2022

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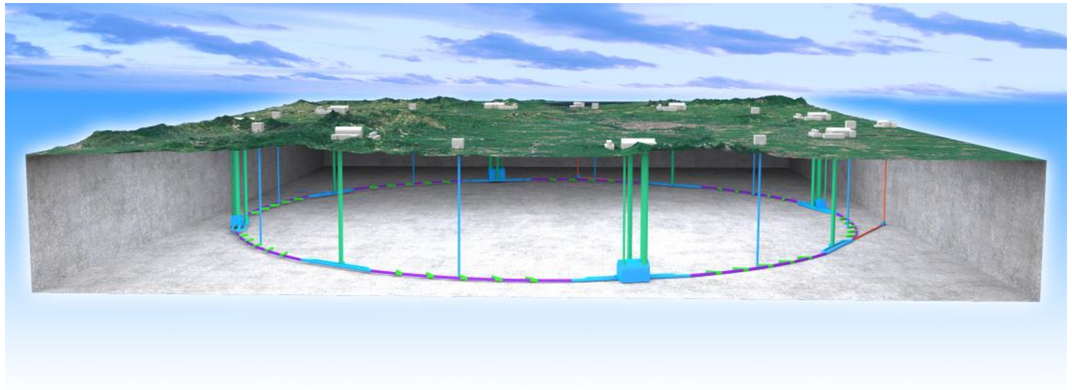
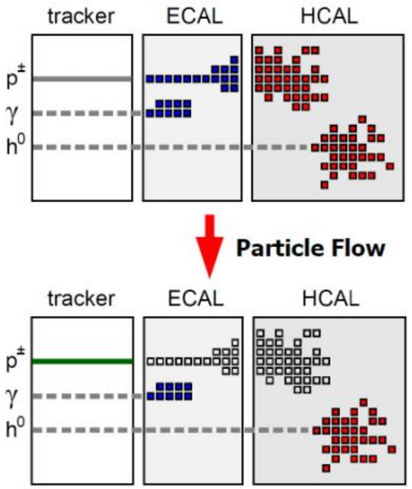
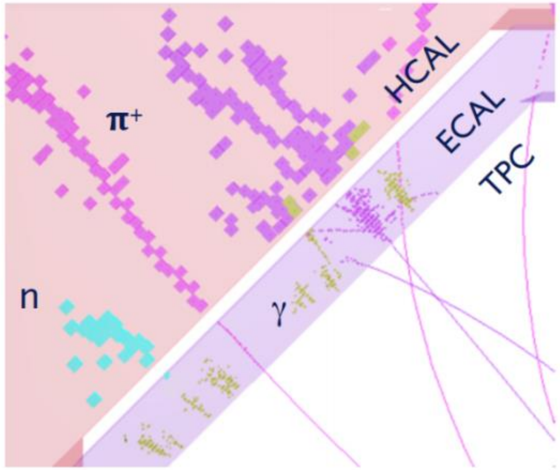
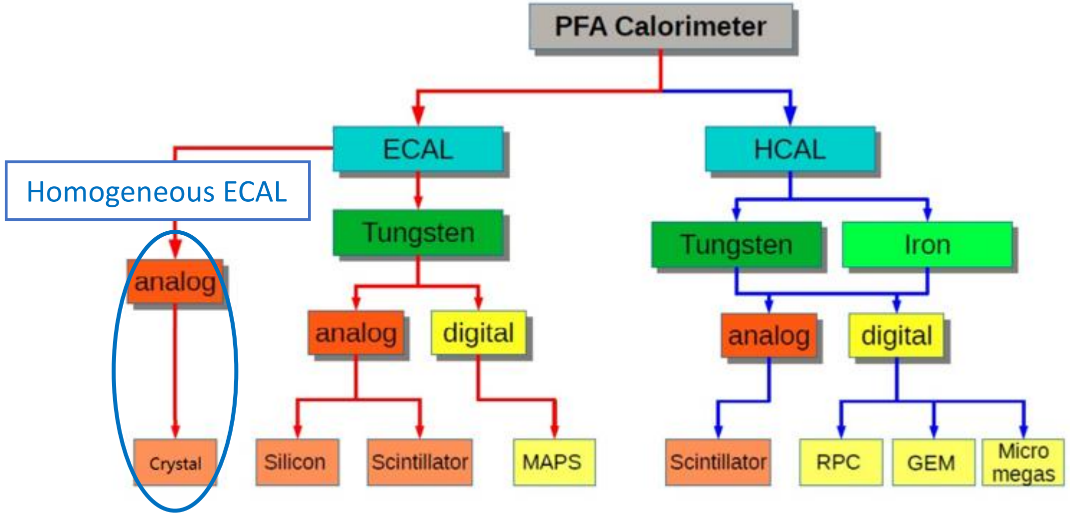
Motivations

- Background: calorimeter for future lepton colliders (e.g. CEPC, FCC-ee, ILC, CLIC…)
  - Precision measurements with Higgs and Z/W
  - Jet energy resolution of 3-4%@100GeV is required
  - Particle flow approach: high-granularity calorimeter
- Particle-flow crystal ECAL
  - Homogeneous structure
    - Intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Energy recovery of electrons: to improve Higgs recoil mass
  - Capability to trigger single photons: precision γ/π^0 reconstruction
  - Focus on low energy particle measurement





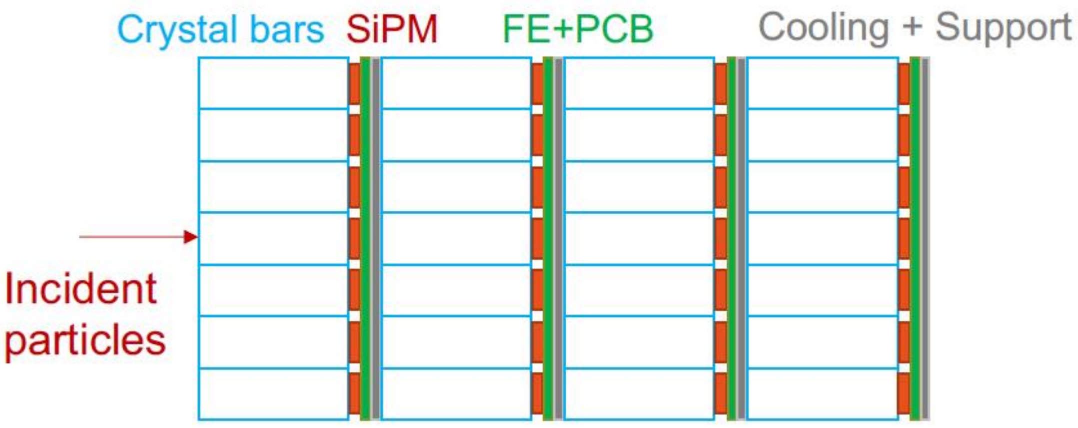




Motivations

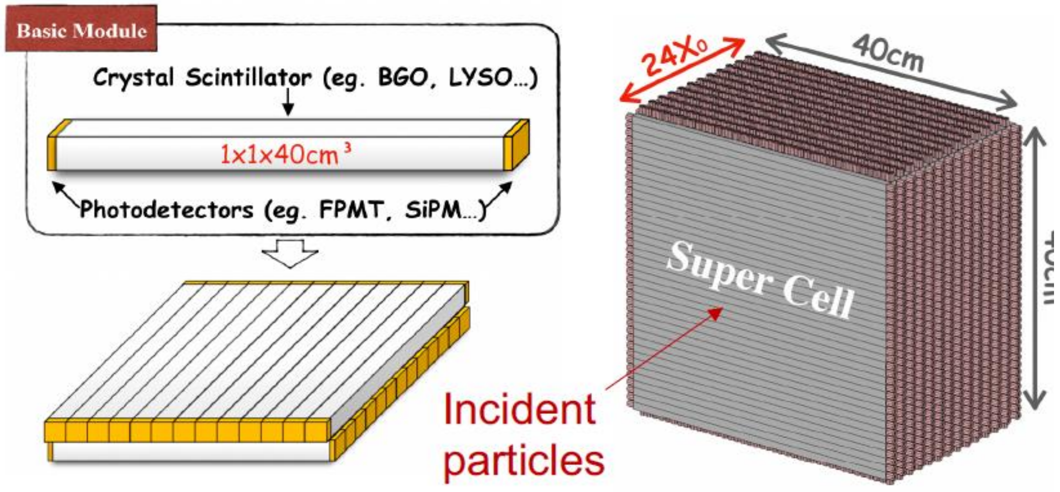
Our major focus

Design 1: short bars



- A natural design compatible with PFA
  - Fine segmentation in both longitudinal and transverse
  - Single-ended readout with SiPM

Design 2: long bars



- Long bars: 1×1×40 cm, double-sided readout
  - Super cell module: 40×40 cm
  - Crossed arrangement in adjacent layers
  - Fine longitudinal granularity
- Save #channels and minimize dead materials
- Timing at two sides: positioning along bar

Overview of this report: R&D status

R&D of a highly granular crystal ECAL:

- PFA performance study
  - Evaluate physics potentials
    - Separation power, Higgs benchmark
- Reconstruction algorithm dedicated to new geometry design
  - Aims & challenges
    - Algorithm development & performance studies
- Detector design and performance
  - Key issues & requirements of hardware development
    - MIP light yield: effect on energy resolution
    - Dynamic range: FEE and SiPMs
    - Energy threshold: capability for low energy measurement
    - Timing resolution: T0 trigger and clustering
    - Response uniformity: energy calibration
    - Further issues: Temperature control, physical gaps, monitoring and calibration…

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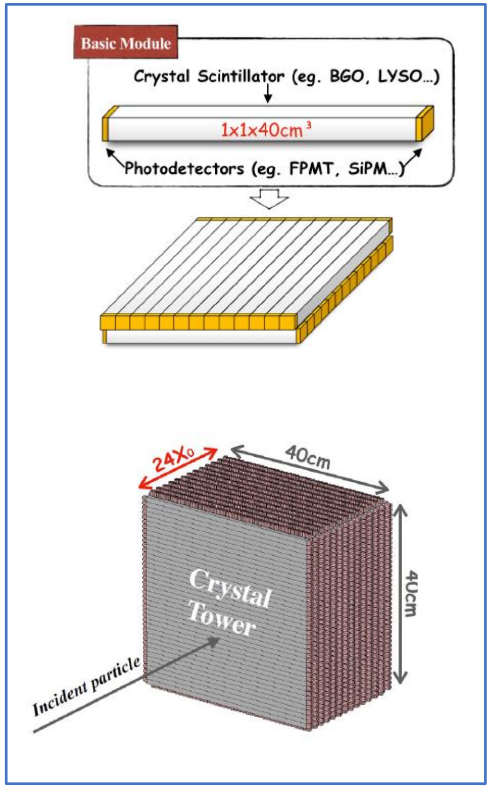
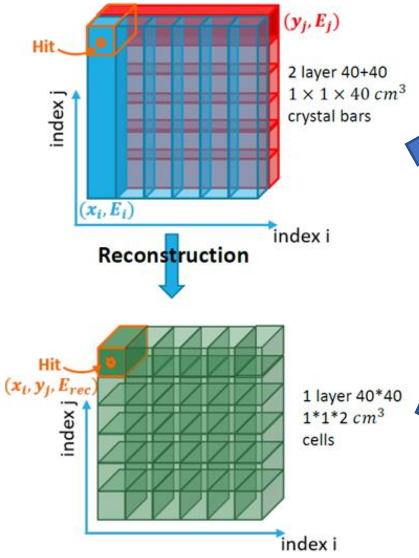
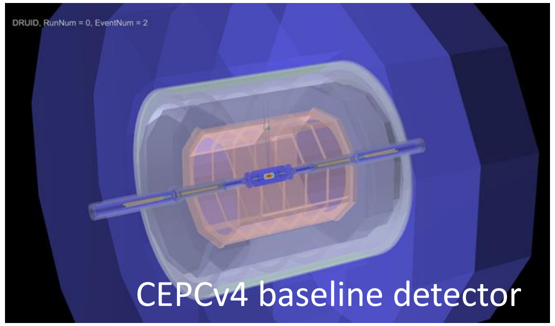
Performance evaluation: introduction

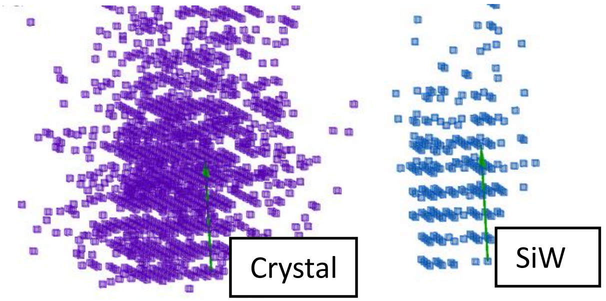
- Adapted from CEPC baseline detector
  - Reference: finely segmented crystal ECAL with crystal cubes
  - Geometry change for digitized crystal bar
  - Application and optimization of Arbor-PFA



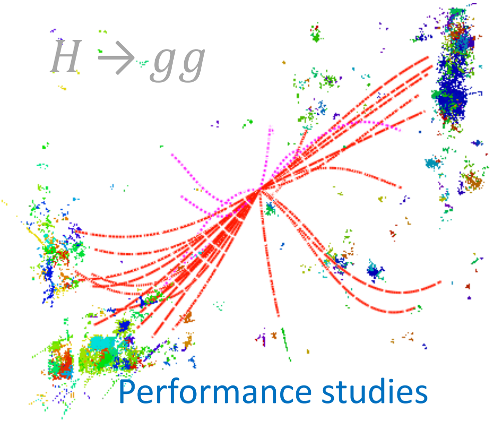


Crossed long bar design:
$1\times1\times2$ cm^3 granularity
after digitization





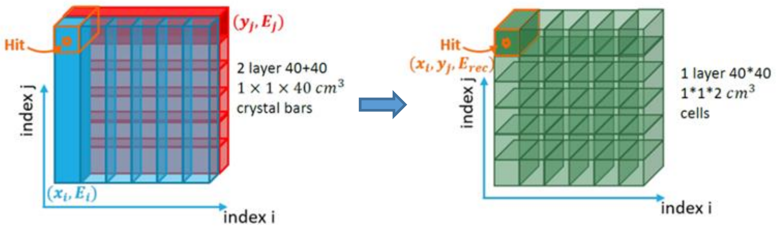
Event display: crystal compared to
SiW: significant increase of #hit

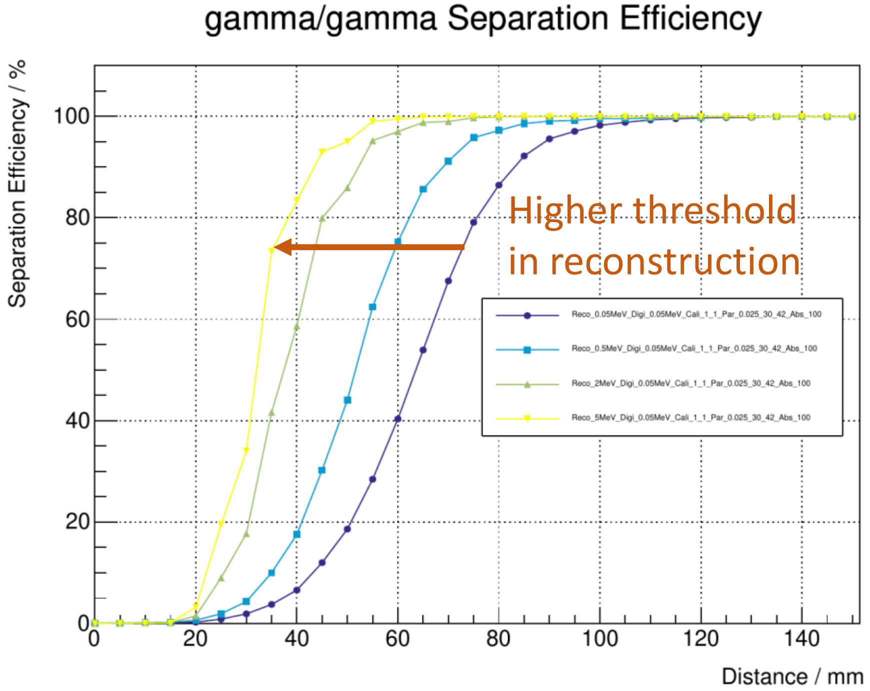


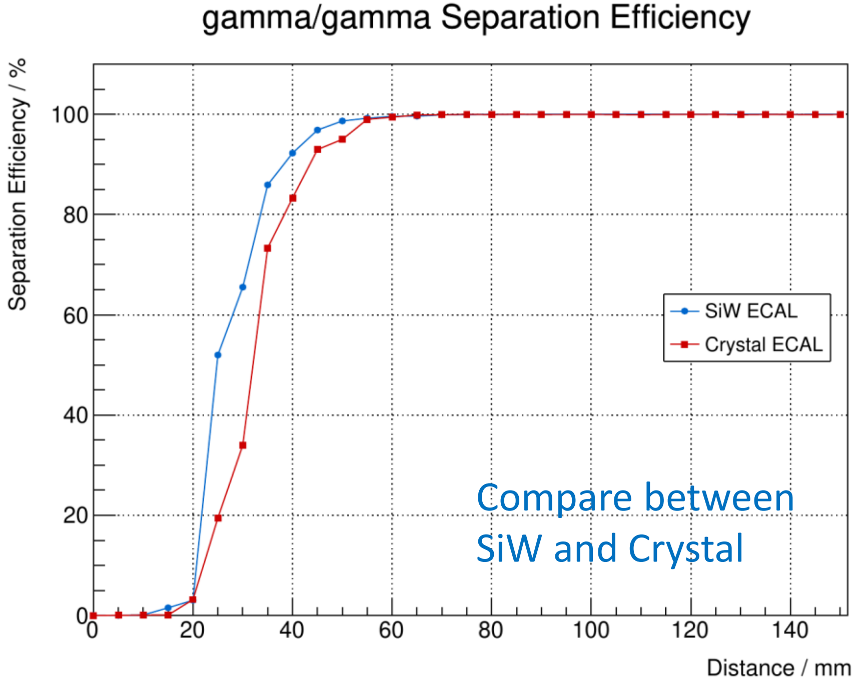
Arbor-PFA: necessary to be optimized for crystal ECAL design

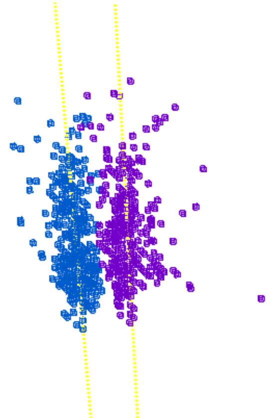
Performance evaluation: separation power

- Reconstruction of jets: separation power of close-by particles
- Optimized Arbor-PFA
  - Multi-threshold method: higher threshold for better separation power, lower threshold for better energy resolution and linearity
- γ/γ separation study with barrel ECAL

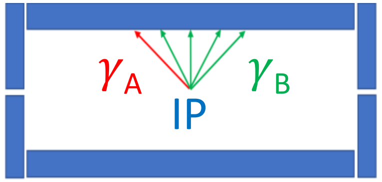








Separated γ/γ

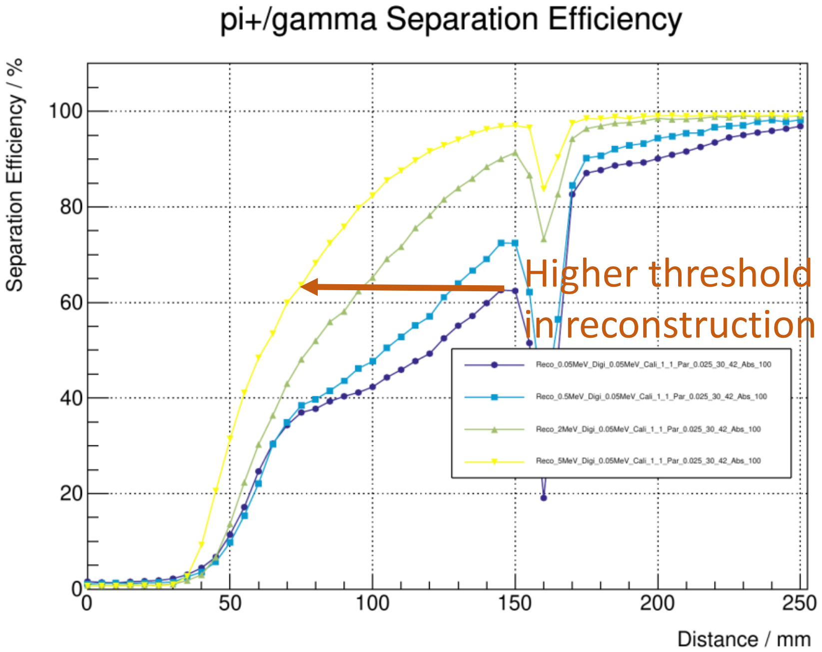


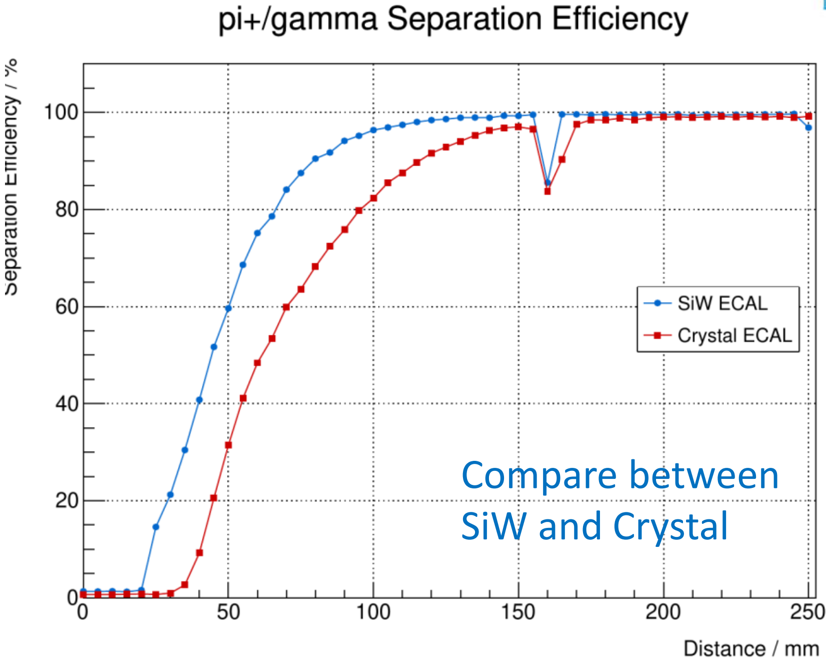
Side view of crystal ECAL

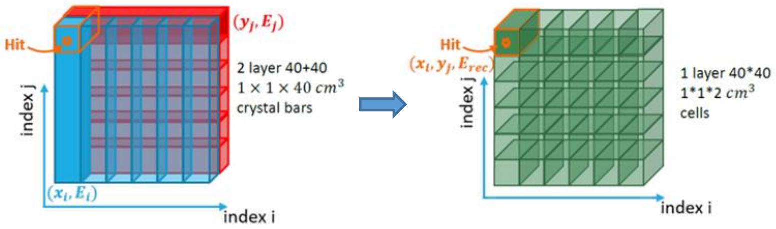
- EM shower: good separation power under high energy threshold in reconstruction

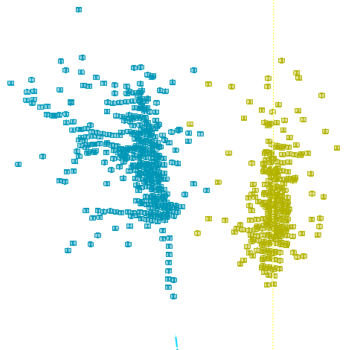
Performance evaluation: separation power

- Reconstruction of jets: separation power of close-by particles
- π^+/γ separation study with barrel ECAL

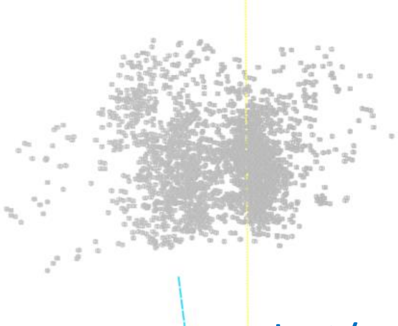








Separated π^+/γ



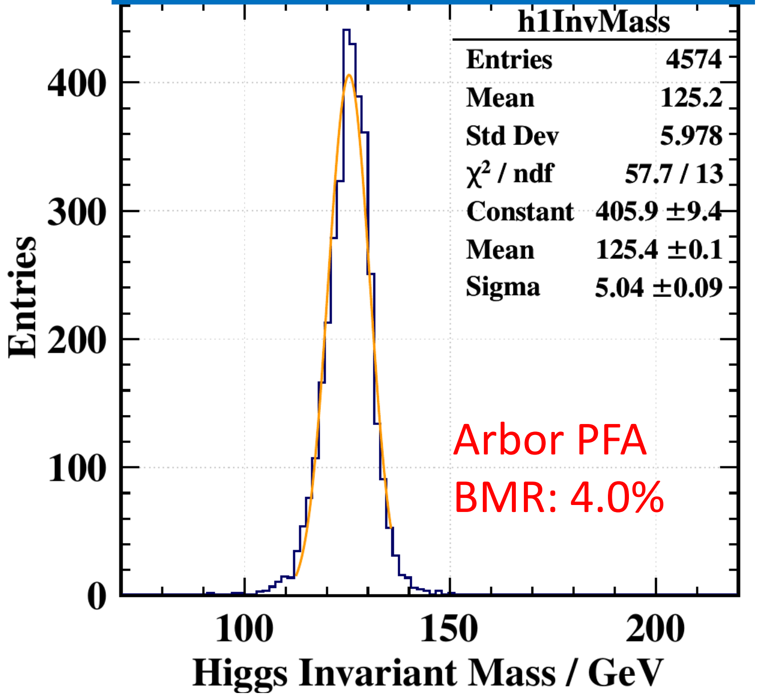
Unseparated π^+/γ

- Hadronic shower reconstruction: challenge on clustering
- Key question
  - Matching clusters of charged particle to the tracks in tracker
- The algorithm is being optimized, still space for improvement

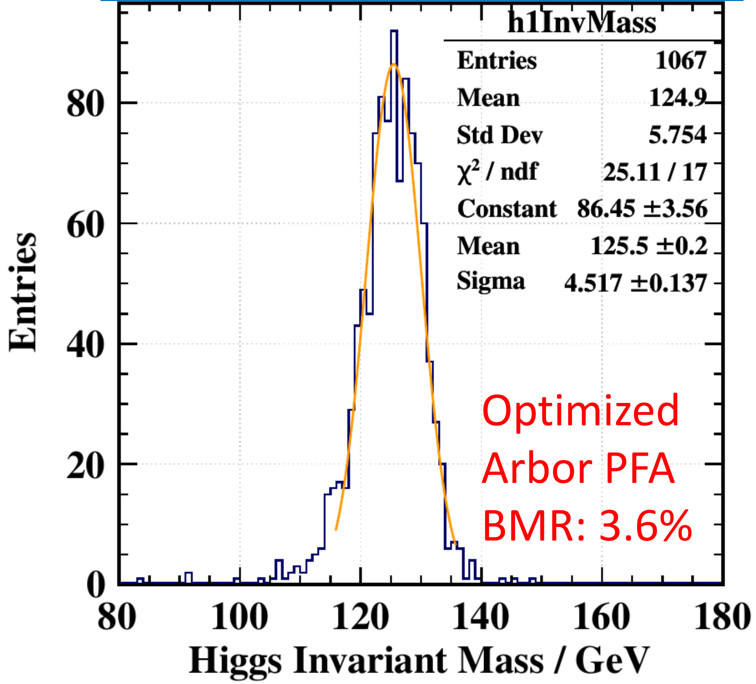
Performance evaluation: Higgs benchmark

- Physics performance: reconstruction of 2-jet benchmark events
  - Boson mass resolution (BMR): ZH ($Z \to \nu\nu$, $H \to gg$) at 240 GeV
  - Preliminary results with 1 cm^3 crystal cubes

CEPCv4 detector with crystal ECAL



CEPCv4 detector with crystal ECAL



- Significant improvement after Arbor-PFA algorithm optimization
- On-going BMR study on 1×1×2 cm^3 cubes…

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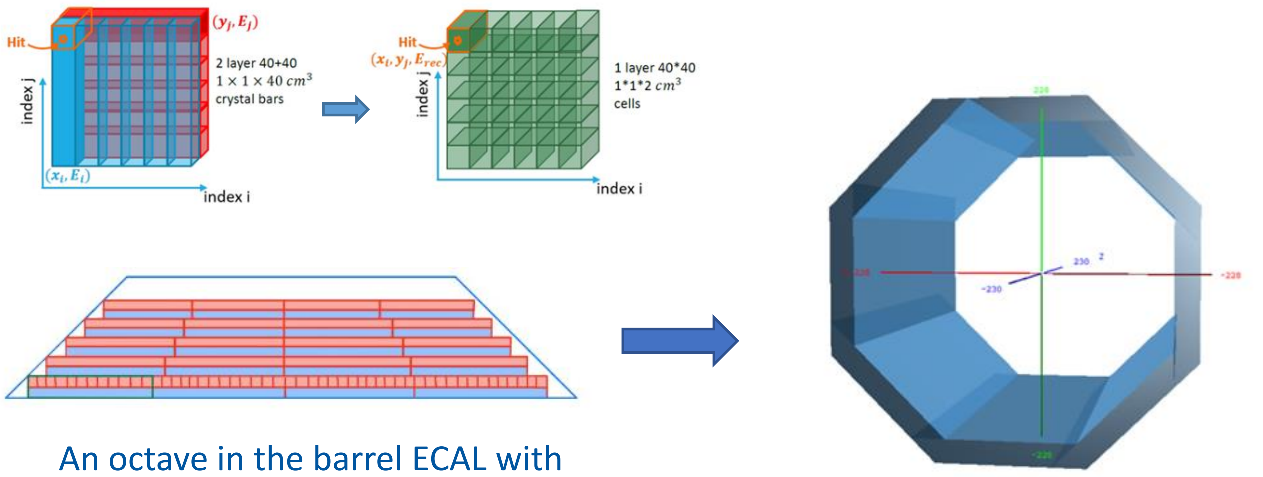
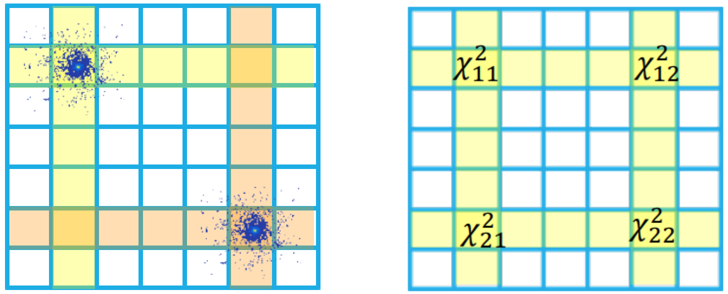
Reconstruction algorithm for long bar design: PFA development overview

Fangyi Guo, Weizheng Song, Shengsen Sun, Linghui Wu, Yang Zhang (IHEP)

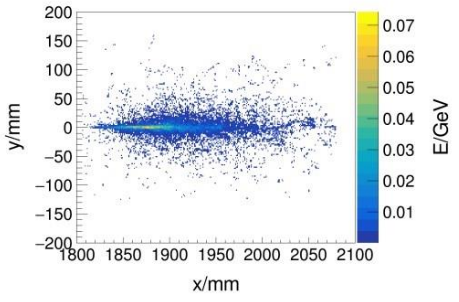
- New software framework: CEPCSW
- Detector description
  - Full barrel geometry with DD4HEP
  - 28 longitudinal layers, crossed arrangement
- Reconstruction algorithm: aims
  - Final granularity 1×1×2 cm^3
  - Minimize impact from ghost hits
- Challenges
  - Pattern recognition of clusters
  - Associating charged clusters with tracks



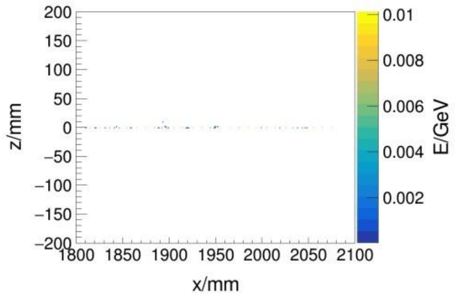
An octave in the barrel ECAL with crossed long crystal bars



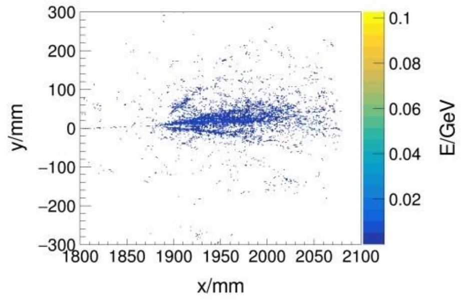
Remove ghost hits



EM cluster



MIP cluster

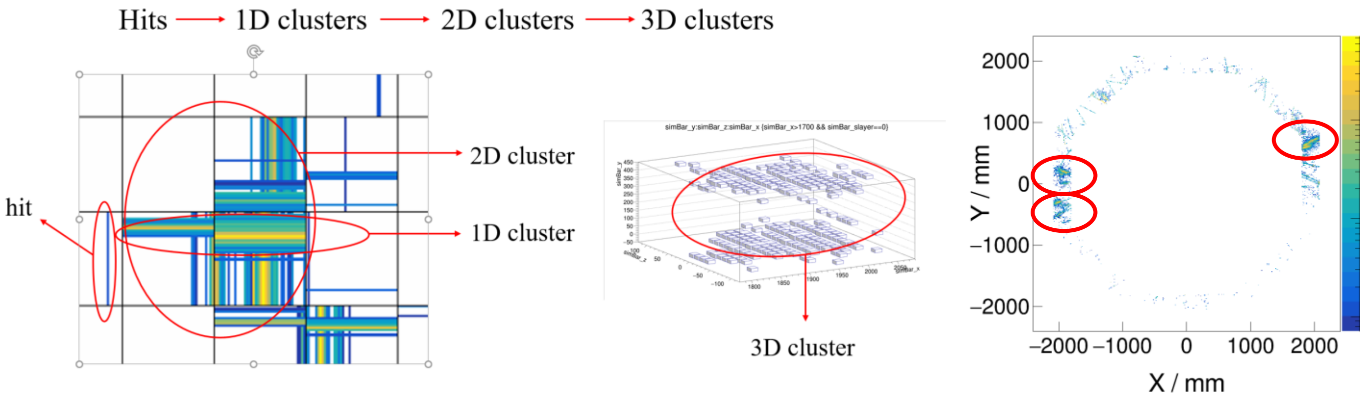


Hadronic cluster

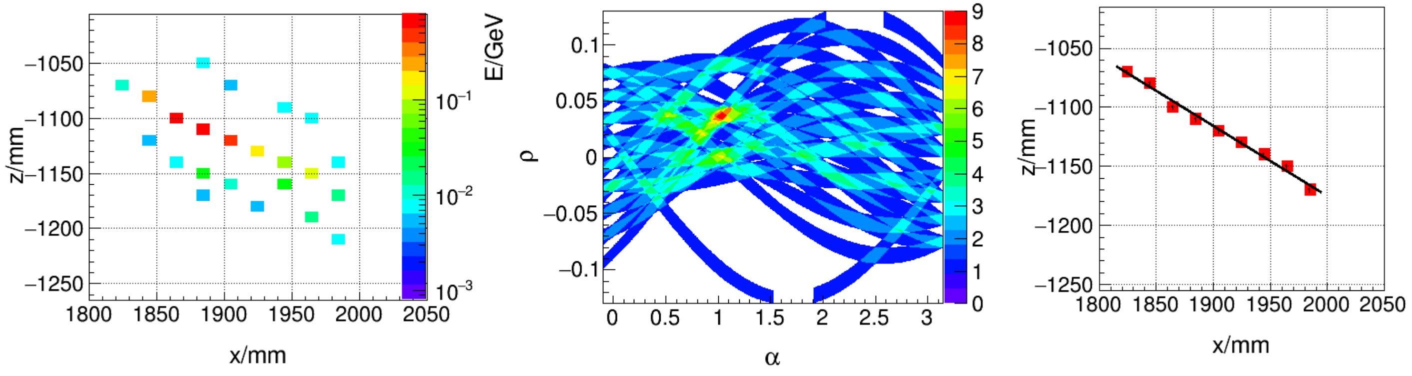
Reconstruction algorithm for long bar design: latest effort

- Clustering algorithm for long crystal ECAL

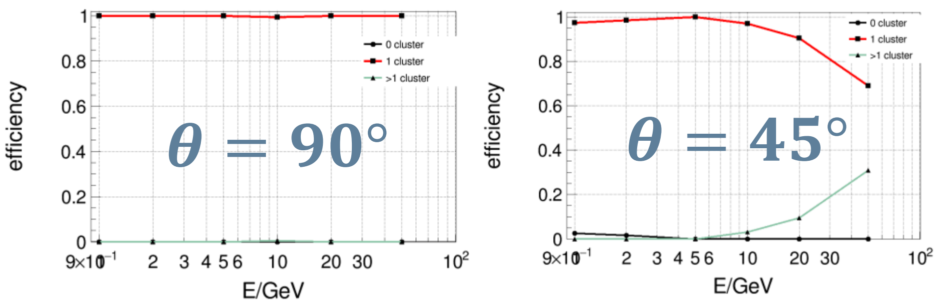
Yang Zhang, Weizheng Song (IHEP)



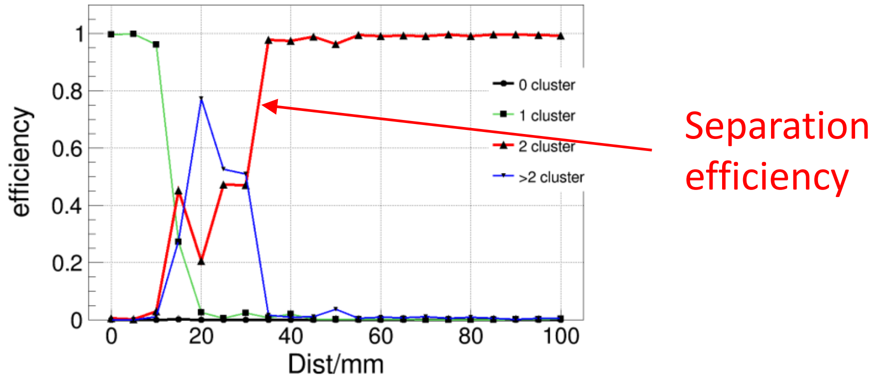
- Reconstruction: application of Hough transformation
  - Local maxima of hit → Bands in Hough space→ Cluster



- Reconstruction performance of single photons



- Di-photon recognition efficiency



- On-going work on hadrons/jets

Talk ***Reconstruction Algorithm for Long Crystal Bar ECAL*** on Wednesday by WeiZheng Song

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Review of recent R&D efforts on crystal ECAL

Goal: specify the requirements for crystal ECAL:

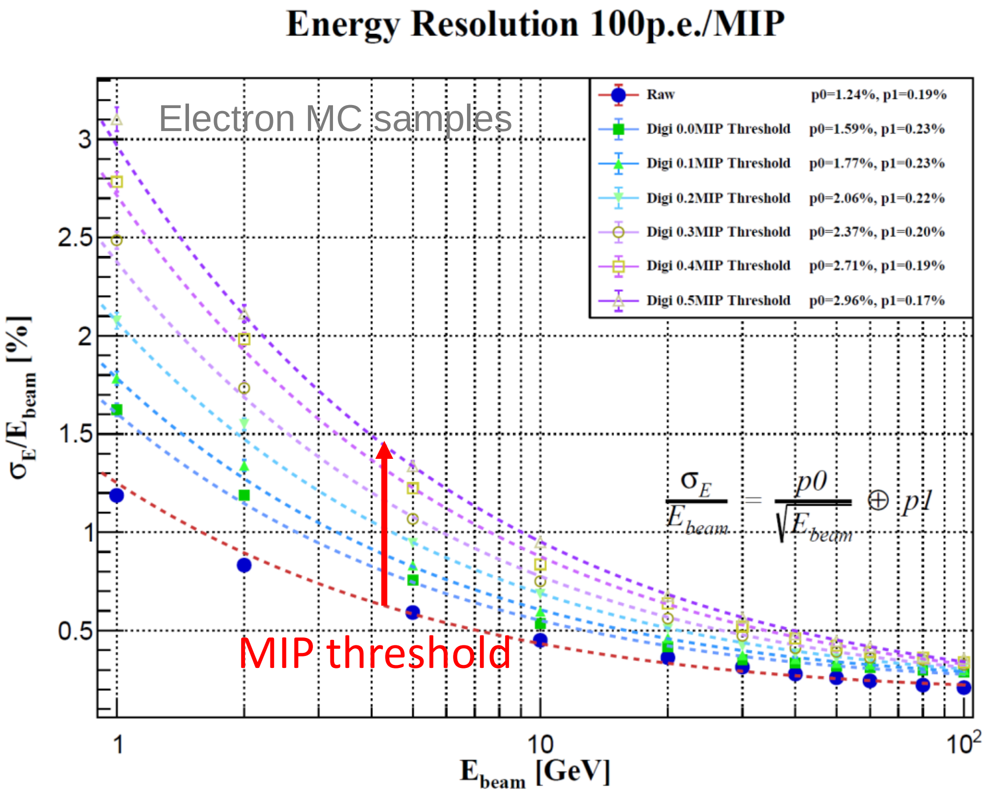
Specifications	Contributions to performance	Limiting factors
MIP light yield	• Energy resolution	• Crystal intrinsic properties • Geometry and surface treatment • Coupling
Dynamic range	• Signal saturation • Small signal measurements	• Power consumption • Expense
Energy threshold	• Signal to noise ratio • Small signal measurements	• Electronic noise
Timing resolution	• Positioning • T0 timing • Potential benefits for clustering	• Scintillation rising time of crystal • Time resolution of electronics
Response uniformity	• Energy linearity and resolution	• Crystal intrinsic properties • Light transmission

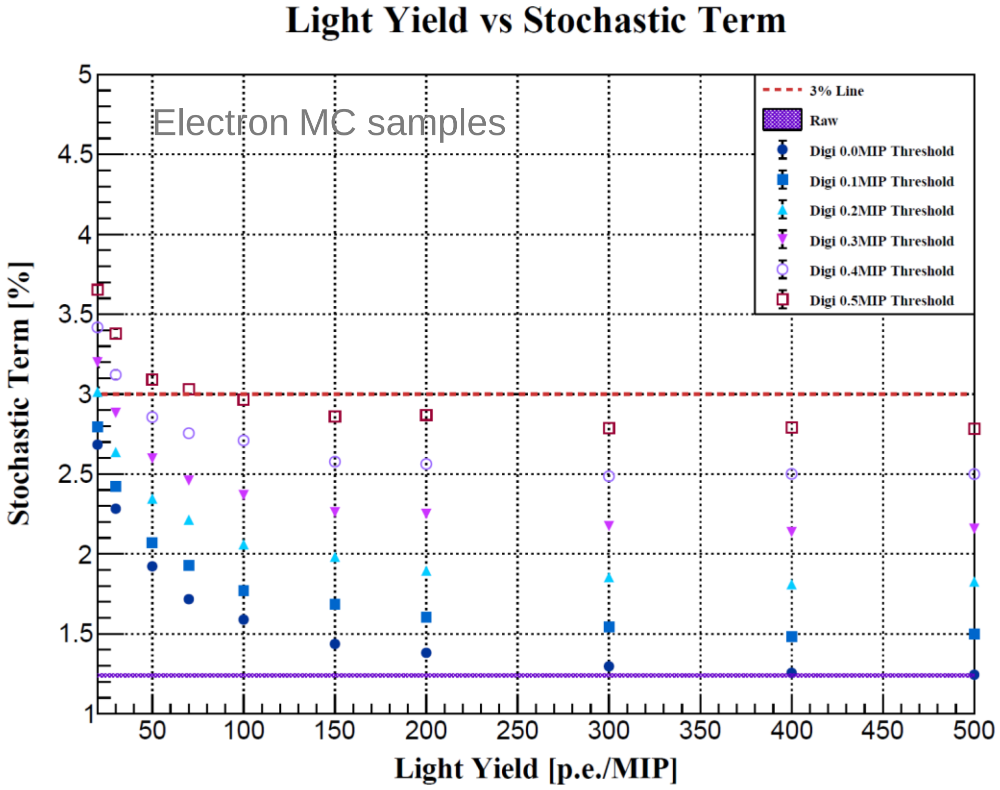
- Realistic ECAL: temperature control, physical gaps, mechanical design, monitoring and calibration…

EM energy resolution: light yield requirements

Geant4 Simulation (v10.7)

- Impact of energy threshold (in MIP) and #detected photons (in p.e./MIP)
  - Digitization: photon statistics (BGO crystal + SiPM), electronics resolution

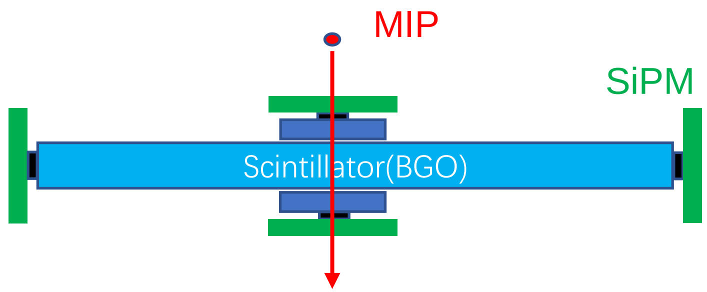




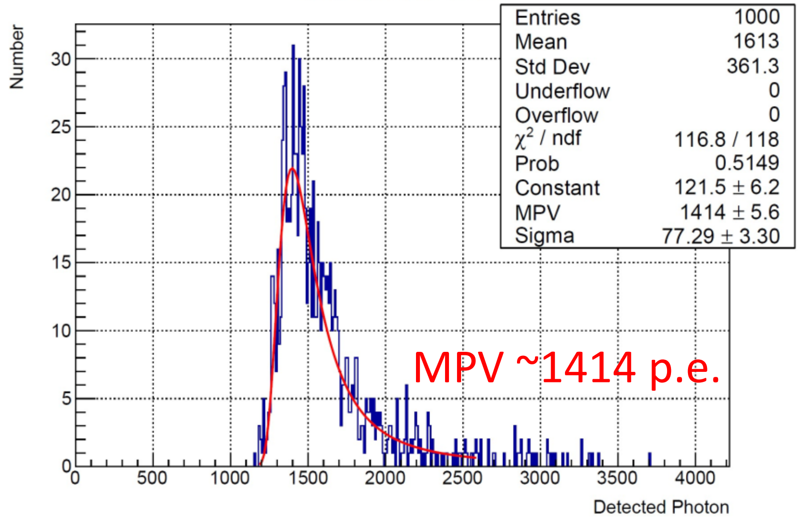
- Moderately high light yield (#detected photons) and low threshold required for better than 3% stochastic term
- >100 p.e./MIP light yield is enough for $\sim 3\%/\sqrt{E}$ energy resolution
- Low energy threshold can be feasible with low crosstalk SiPMs

Crystal candidates: cosmic-ray test

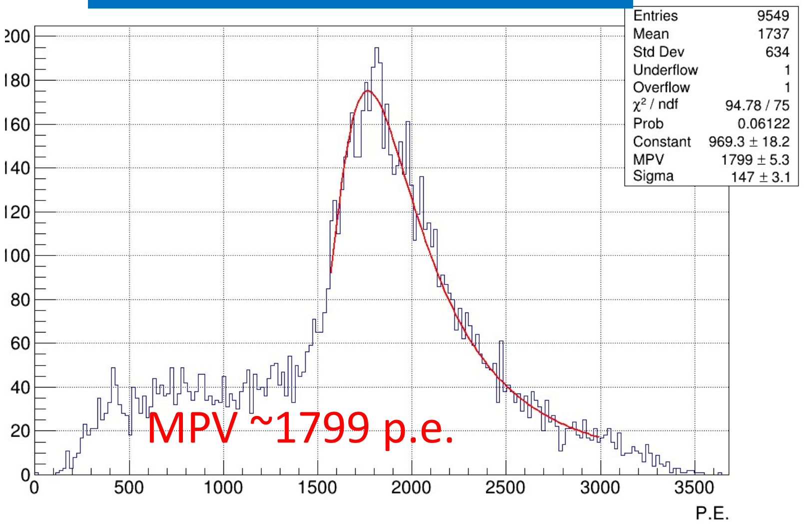
- BGO crystal
  - 40×1×1 cm^3 long BGO crystal bar, ESR wrapping
  - Energy deposition in Geant4 simulation: 9.1 MeV/MIP

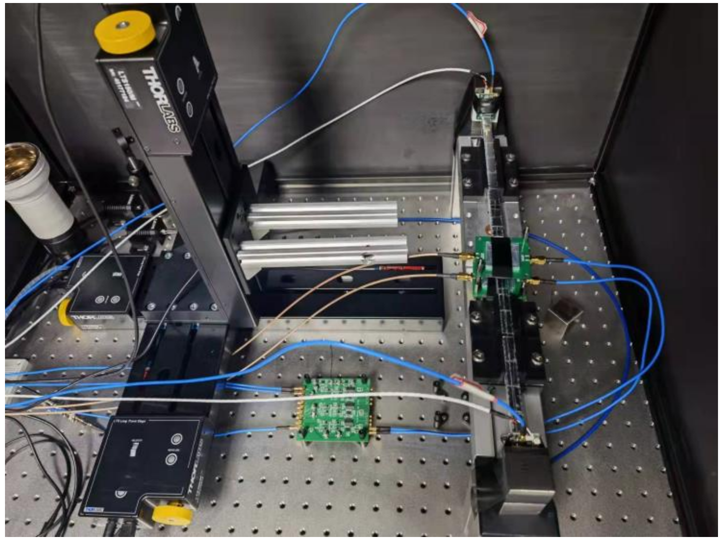


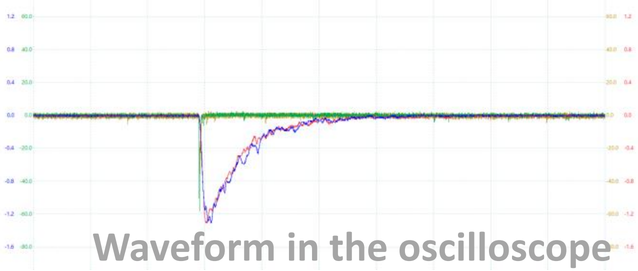
Gean4 optical simulation



Cosmic-ray test







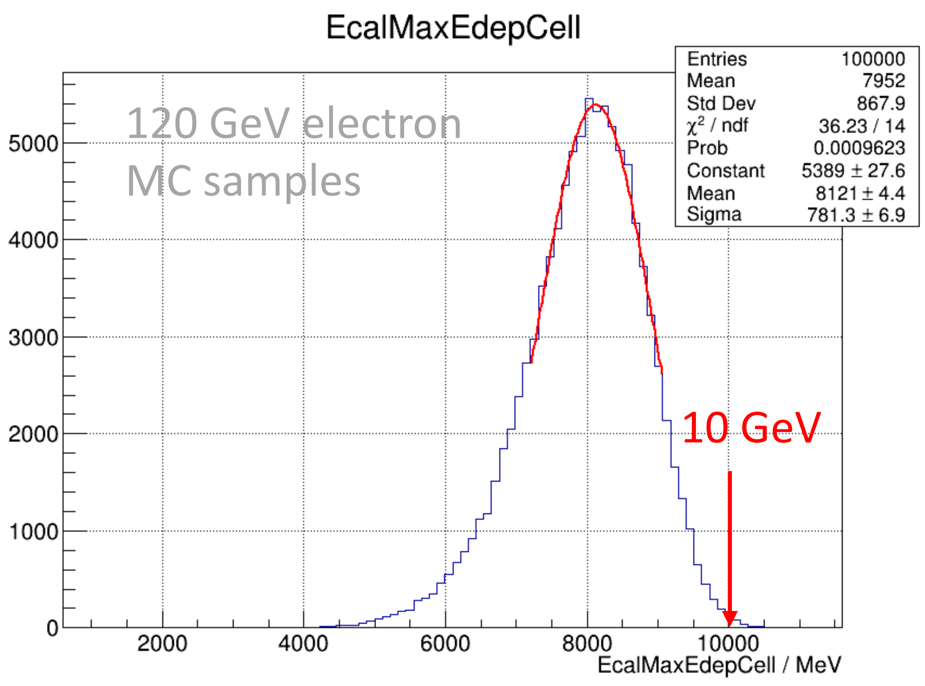
Waveform in the oscilloscope

- High enough light yield expected in cosmic-ray test
  - #detected photon is higher than that from Geant4 optical simulation

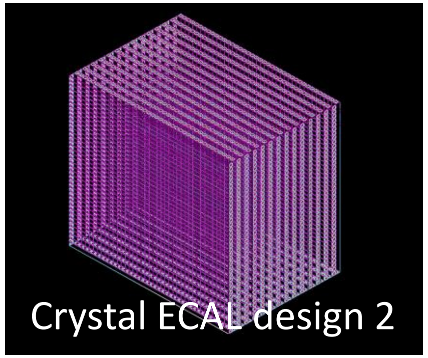
Requirements on dynamic range

Geant4 Simulation (v10.7.3)

- Maximum energy deposition within a single bar with energetic Bhabha electrons
- BGO crystal ECAL supercell: 40×40×28

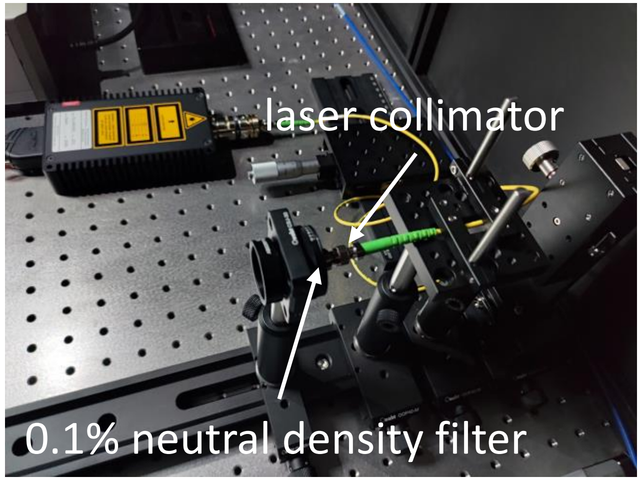


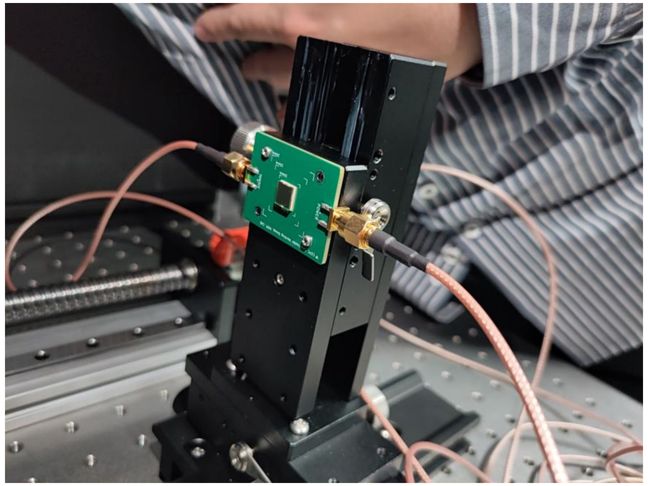
- Generally energy deposition in a single crystal bar < 10 GeV
- Dynamic range: 0.05~10^3 MIP
  - ~10 MeV/MIP in 1 cm BGO
  - Capability down to 0.05 MIP?
- Possible solutions for high dynamic range
  - Reduce BGO light yield via doping (collaboration with Shanghai Institute of Ceramics, CAS)
  - SiPM with high pixel density
  - Neutral density filter
  - Si-PIN photodiode
  - TOT technique
  - …

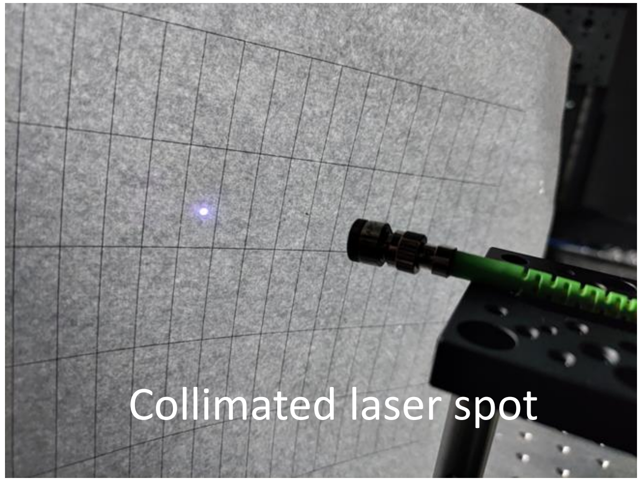


Characterizations of SiPMs: laser calibration

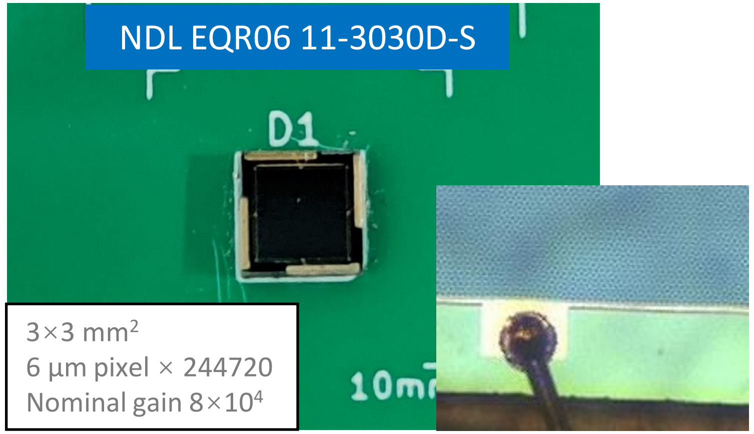
- Motivation: characterization of large dynamic range SiPMs
  - For SiPMs with high pixel density, the noise effect is significant







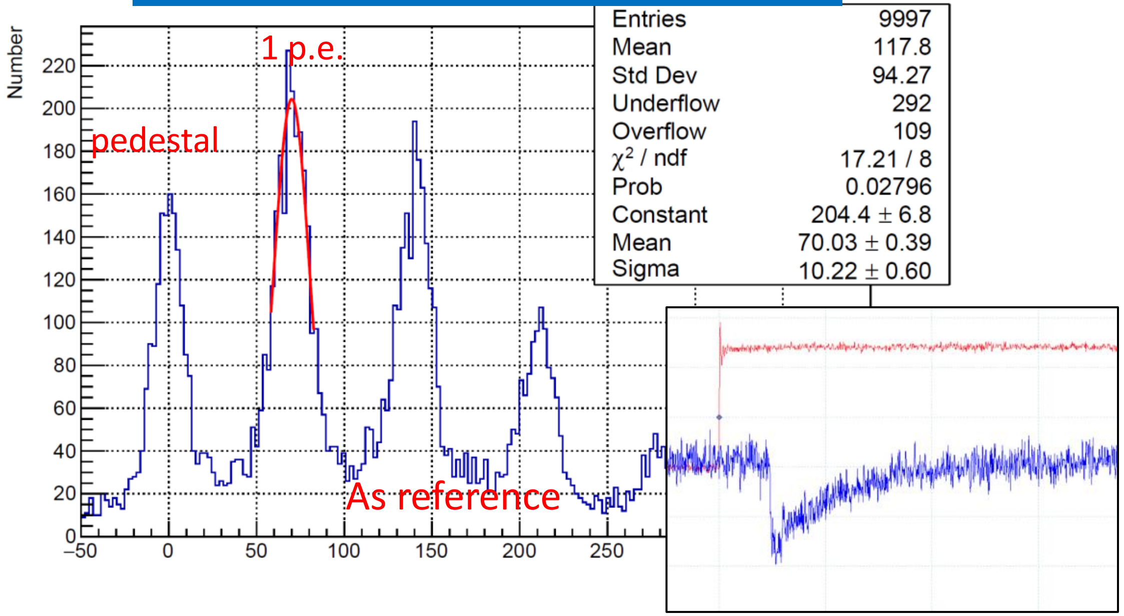
- DUT: Hamamatsu & NDL SiPMs, large size and small pixel pitch SiPMs are prefered



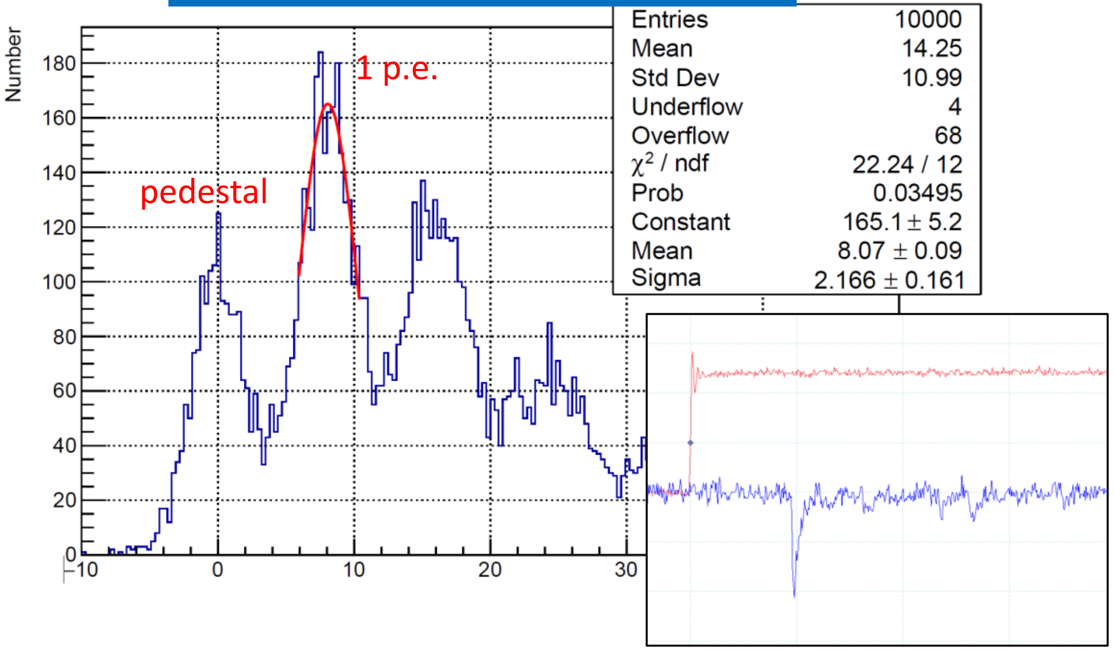
Characterizations of SiPMs: single photon spectrum

- Single photon spectrum of DUTs

Hamamatsu S13360-6025PE



NDL EQR06 11-3030D-S

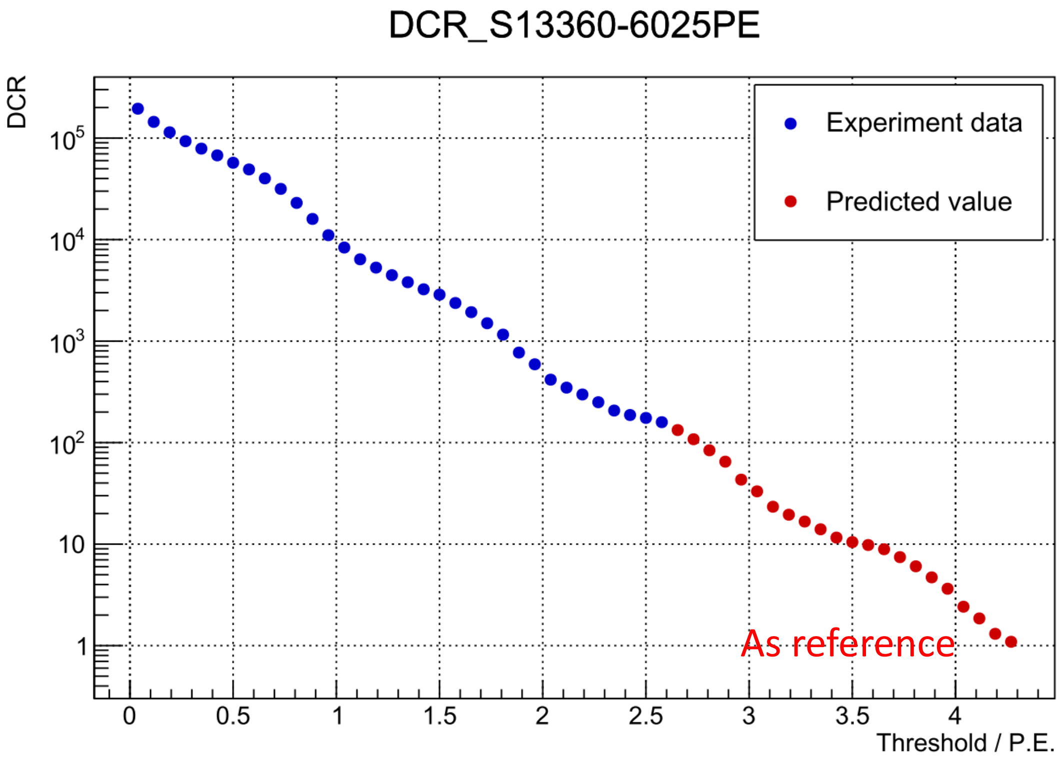


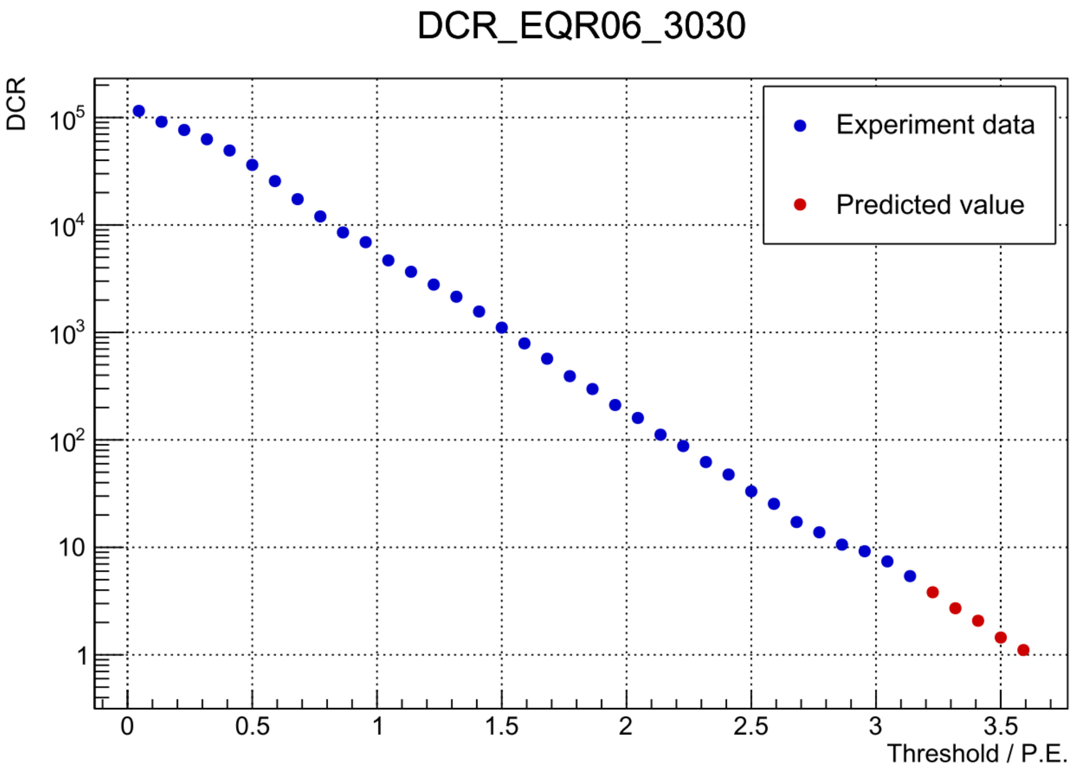
- Criteria for SiPMs: dynamic range, gain, price, crosstalk, capability of single photon detection…
- NDL EQR06 series with 6 μm pixel and 3×3 mm^2 active area
  - High pixel density (244720 pixels), narrow pulse shape (~10 ns)
- Response linearity test: to be done

Unable to perform single photon calibration with NDL EQR15 series SiPMs since too many thermal noise signals lead to unstable baseline

Characterizations of SiPMs: dark count rate

- Dark count rate versus voltage threshold (in p.e.)

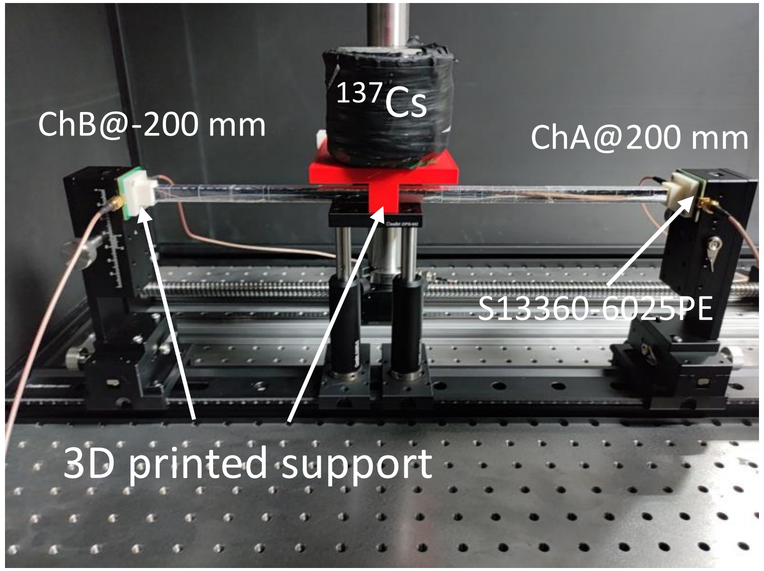




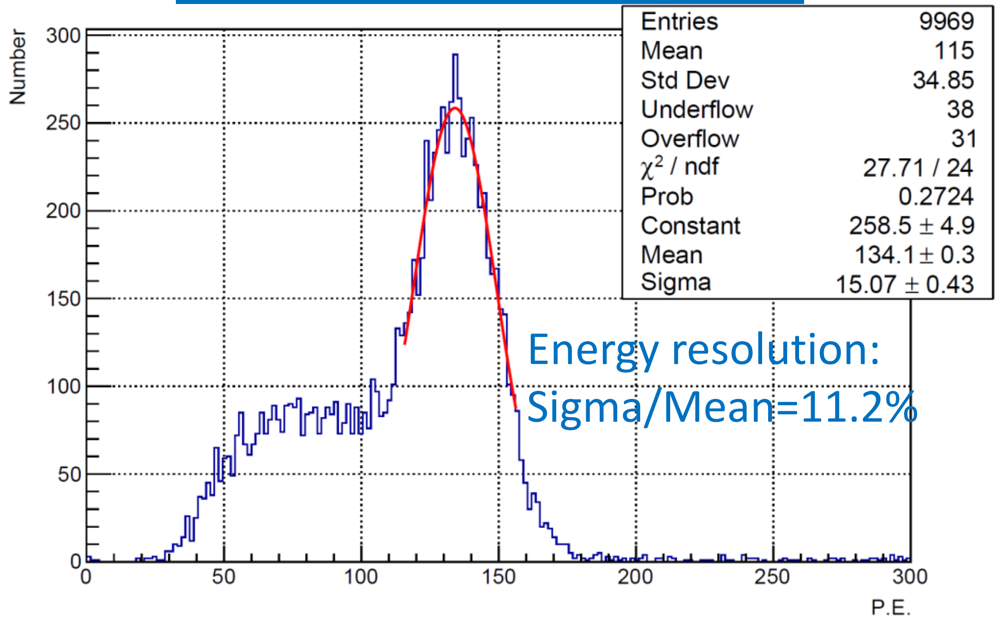
- Dark count rate can be lower than 1 Hz with relatively low voltage threshold
- Potential on low energy particle detection

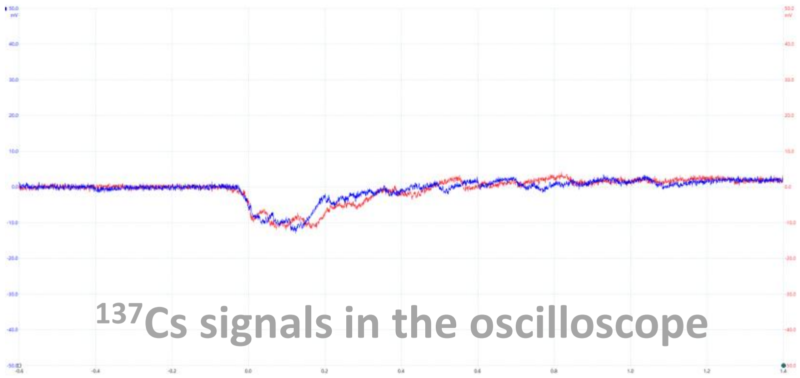
Energy calibration with ^{137}Cs radioactive source

- Experiment setup
  - 662 keV gamma form ^{137}Cs, 1D moveable support
  - ~5 mm spread of gamma source
  - 400×10×10 mm^3 BGO crystal bar, ESR wrapping
  - 6×6 mm^2 SiPMs with 25 μm pixel, air coupling, double-sided readout
- Determine threshold for low energy particle detection



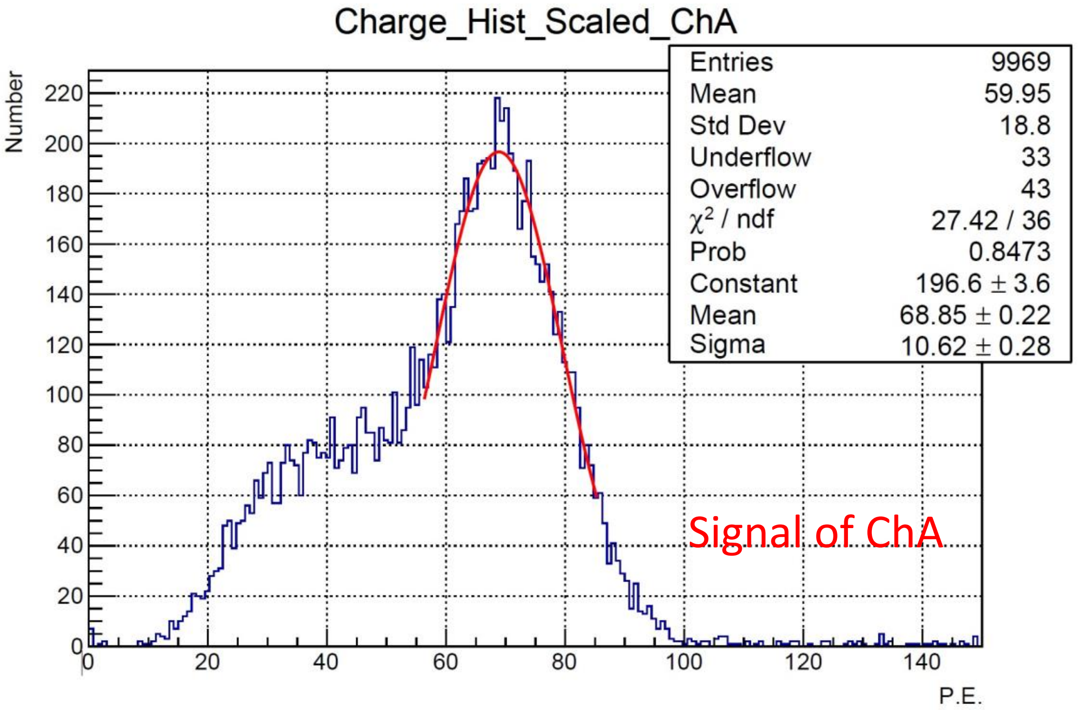
Detected photon: ChA + ChB

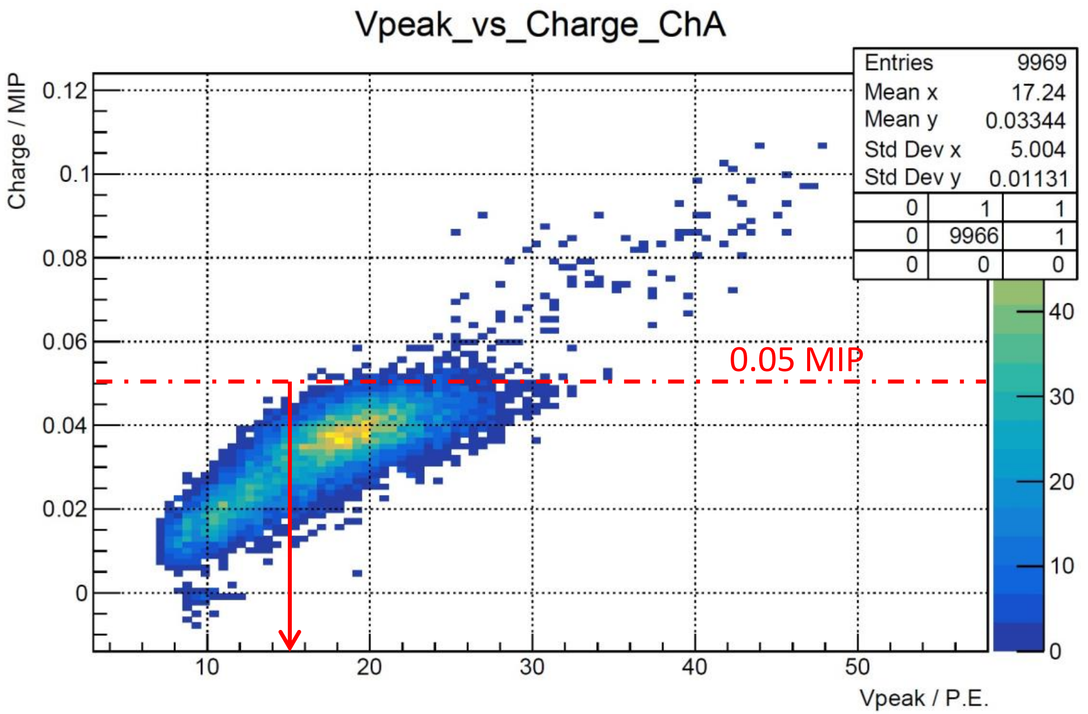




Energy threshold for low energy particles

- Voltage peak is roughly linear with QDC channel





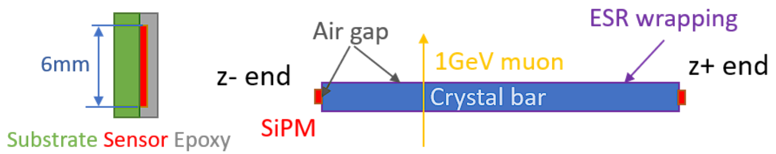
- 662 keV gamma ~0.07 MIP (ChA + ChB)
  - Signal in ChA ~0.04 MIP
- Requirement on dynamic range : 0.05~10^3 MIP

- Voltage threshold: 15 p.e. is feasible
  - DCR is low enough at 15 p.e.
- Capable to detect low energy particles
  - Pressure on dynamic range: 2×10^4
  - Benefit/necessity for physics?

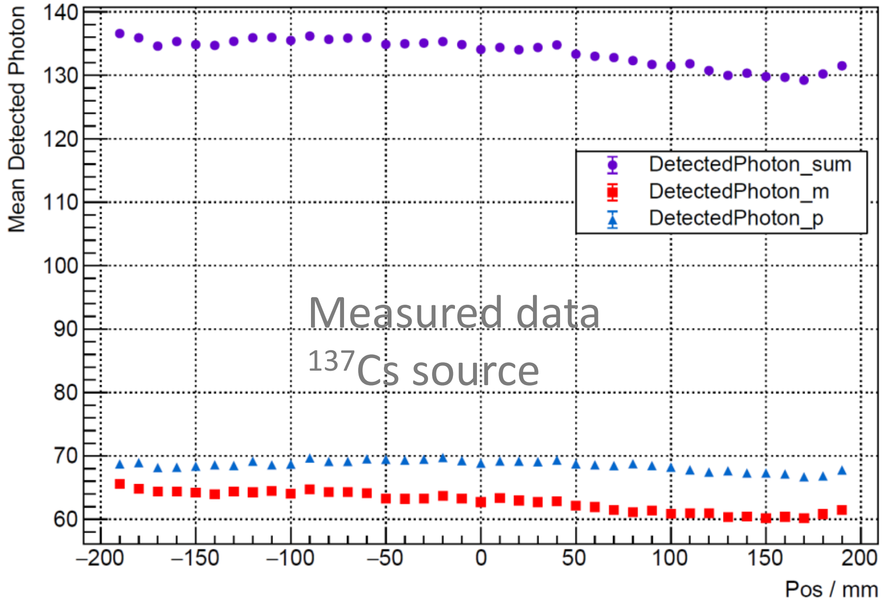
Study on response uniformity of long crystal bar

Geant4 Simulation (v10.7.3)

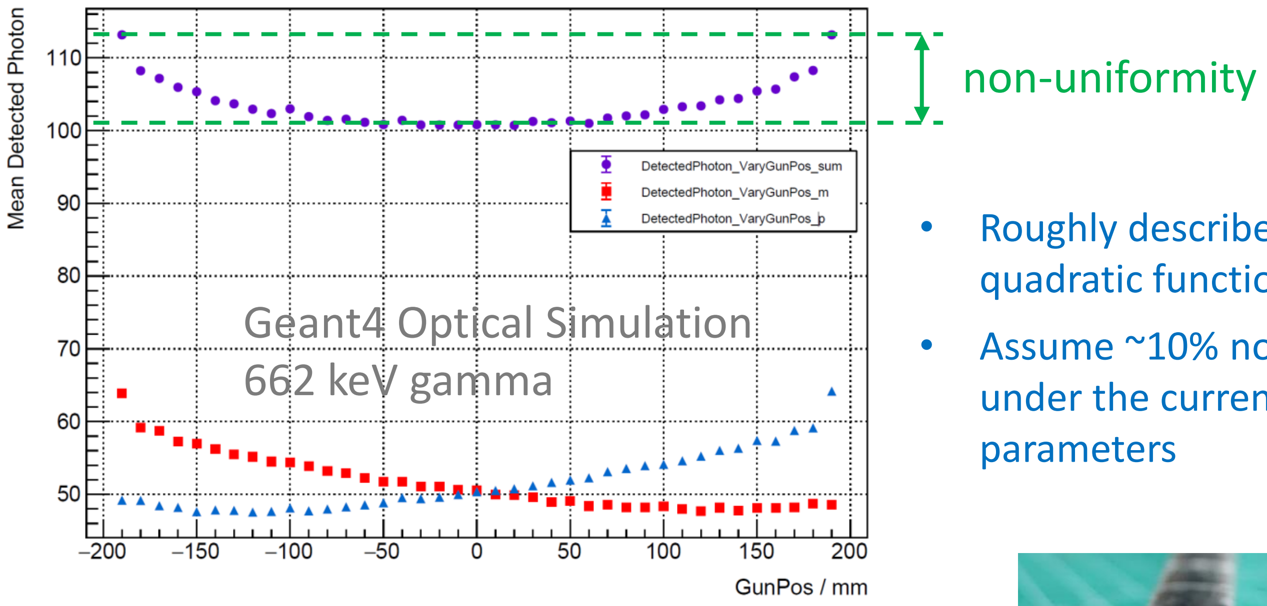
- Uniformity scan: 662 keV gamma for ^{137}Cs, change hit positions
- Geant4 optical simulation: a single BGO crystal bar wrapped with ESR reflector



Experiment: detected photon

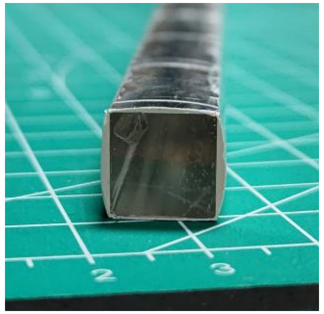


Simulation: detected photon



- Roughly described by a quadratic function
- Assume ~10% non-uniformity under the current simulation parameters

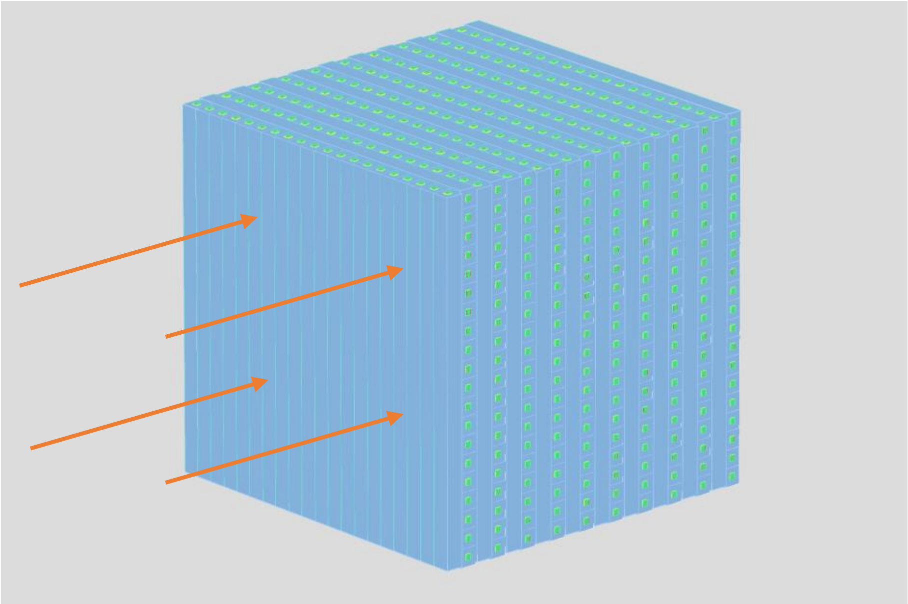
- Less light attenuation effect than expected in simulation
- Relatively low response near one side
  - Coupling, positioning, distance between crystal and radioactive source…
  - Potential factors related to crystal manufacture
- Repeat more measurements to reduce systematic uncertainty

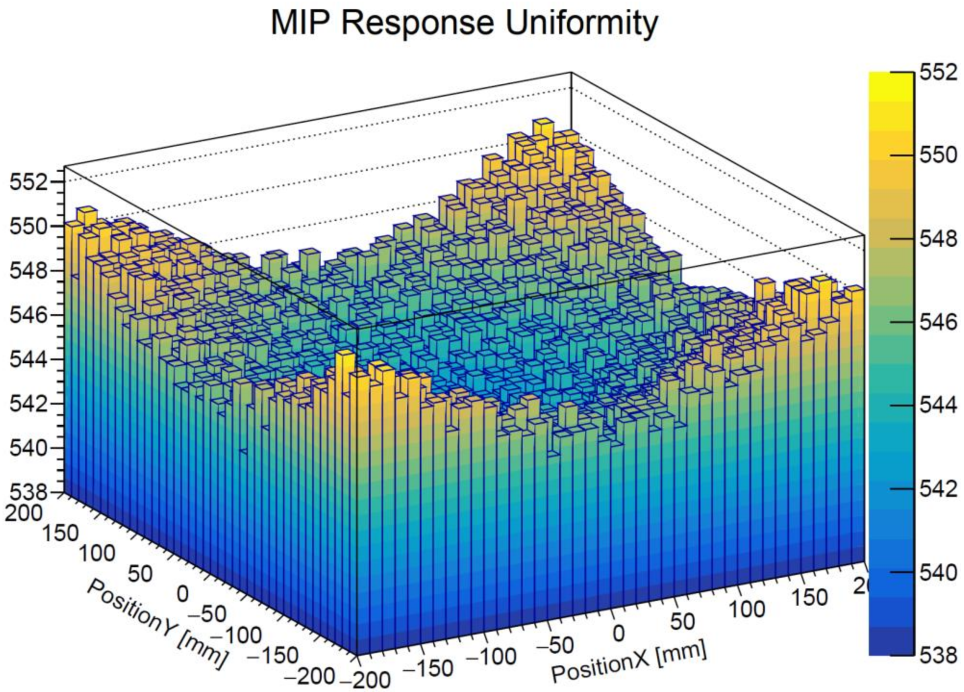


Simulation study: response uniformity of crystal ECAL module

Geant4 Simulation (v10.7.3)

- Simulation setup
  - 10×10×400 mm^3 BGO crystal Bar
  - Crossed bar, 40×40×60 module
  - 1 GeV muon, 2D uniformity scan
  - Response has been parameterized (simulated without optical process)



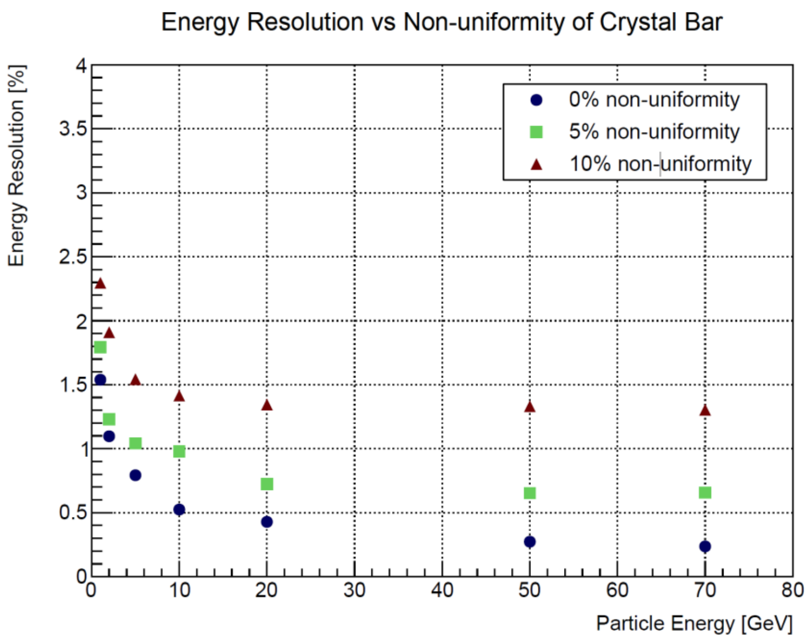


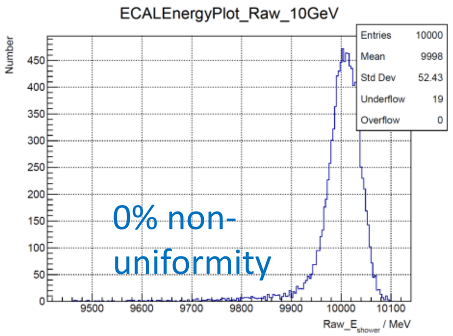
- MIP Response of four corners is higher
- 2D non-uniformity lower than 10%
- Responses depend on hit positions
  - Good reconstruction algorithm is required to get precise position resolution
  - Timing information for positioning

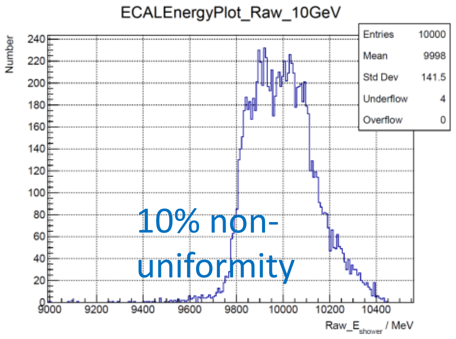
Simulation study: response uniformity of crystal ECAL module

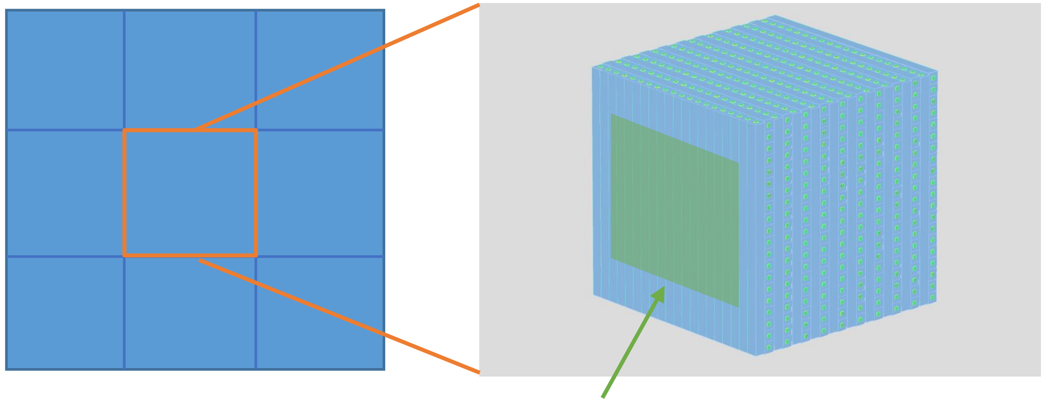
Geant4 Simulation (v10.7.3)

- Impact on energy resolution
  - 1-100 GeV electron
  - 3×3 modules are used to prevent energy leakage
  - Digitization and energy calibration are implemented
  - Energy resolution = Mean/StdDeV









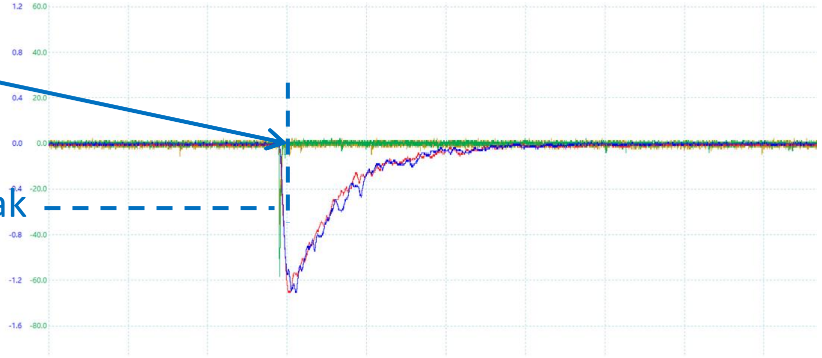
Incident particles randomly hit this area of the middle module

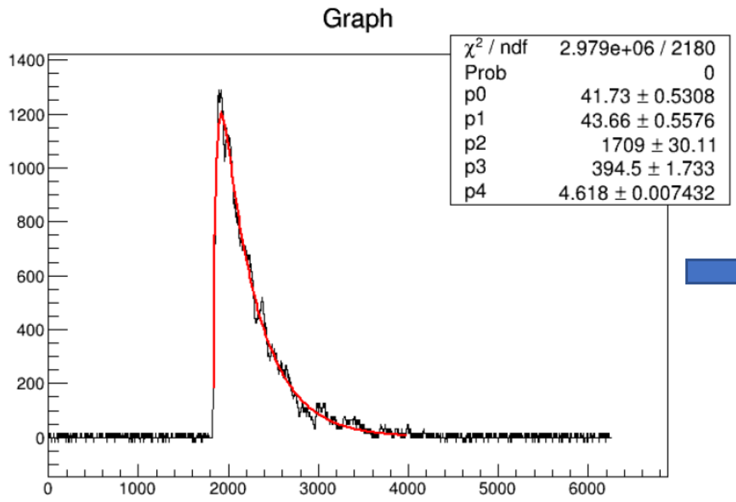
- Severe distortion of energy resolution and linearity
  - Effect on energy distribution
  - Major contribution to constant term
- Response non-uniformity need to be calibrated
  - Non-uniformity < 1% after calibration

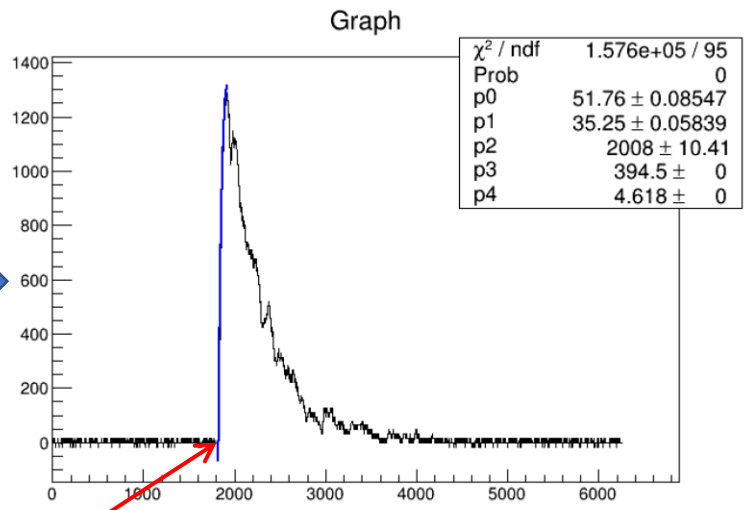
Latest progress on time resolution study

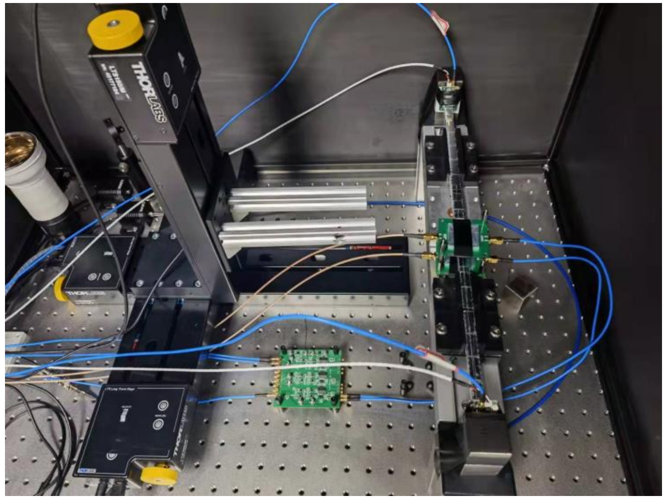
Zhiyu Zhao (SJTU)

- Cosmic-ray events with 40 cm long crystal bar
- Get smooth rising edge: fitting SiPM signals
  - Fit function: $(1 - e^{ax+b}) \cdot c \cdot e^{dx+f}$
- Timing method:
  - Constant fraction timing (without fitting)
  - Zero timing (fitted signal, V=baseline)



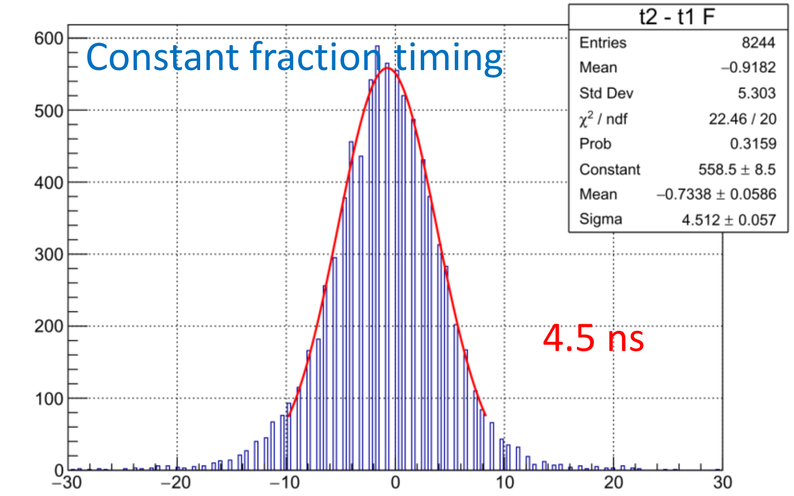


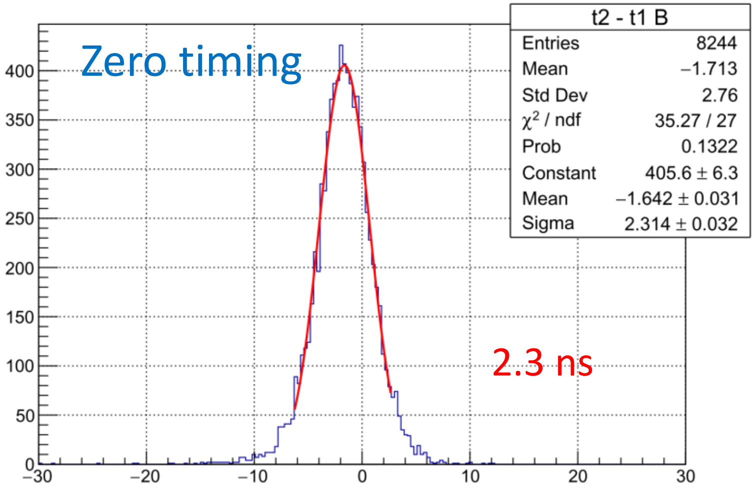


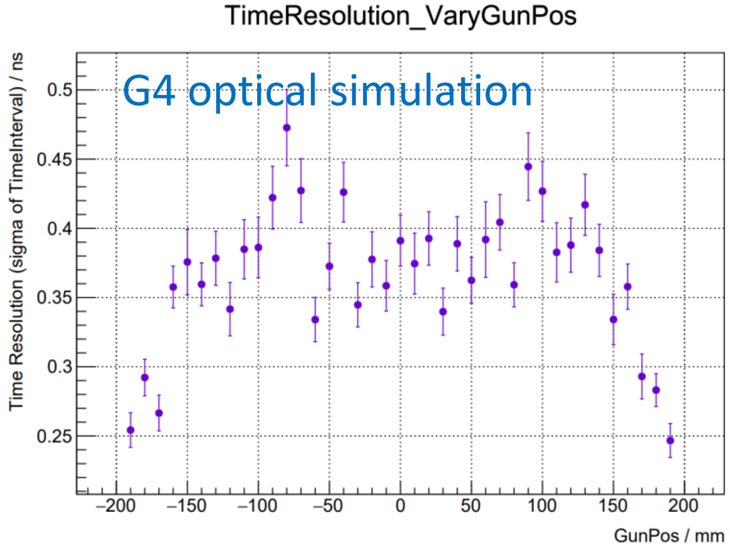


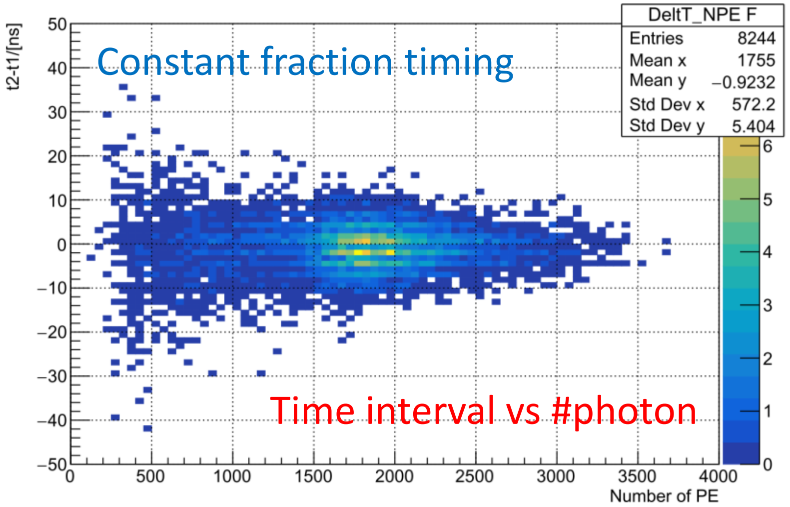
Reference of fitting method: https://doi.org/10.1016/j.nima.2011.11.083

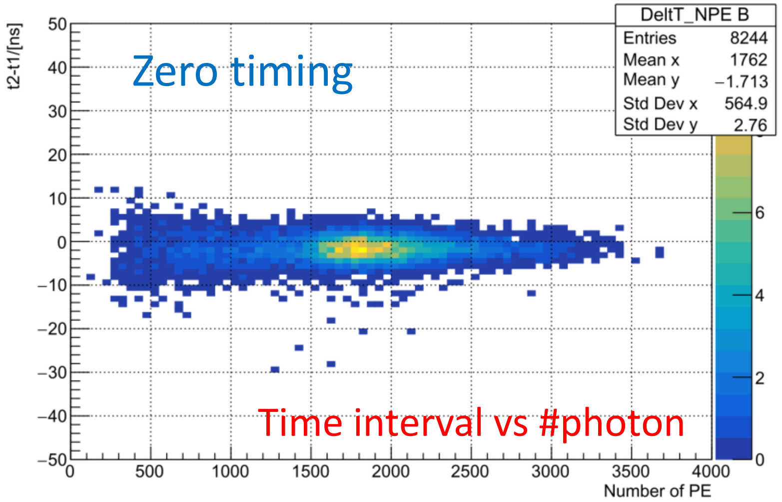
Latest progress on time resolution study







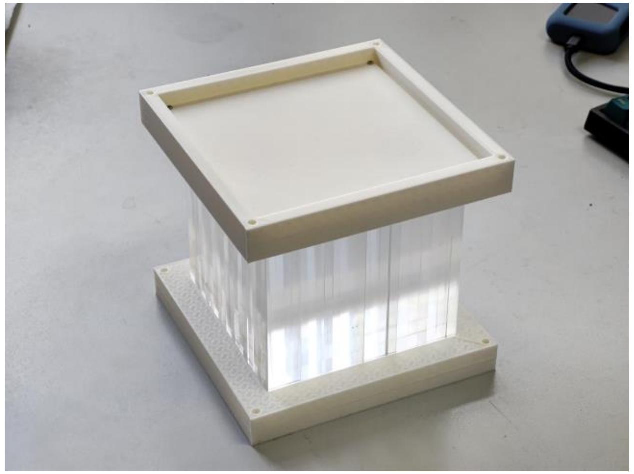




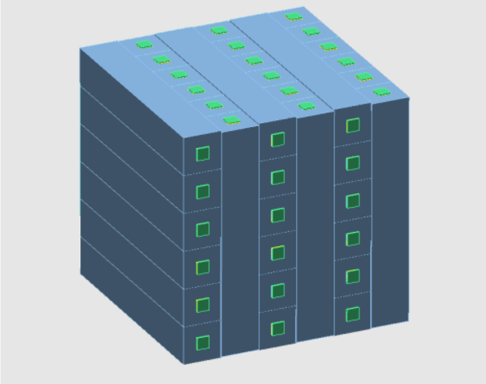
- Time resolution in simulation: ~400 ps
- Large #photons helps to improve time resolution
- Limitations:
  - SiPM rising edge of SiPM pulse
  - Front-end electronics
  - Scintillation properties of BGO crystal
  - Light transmission of long crystal bar

Small-scale detector module design: first glance

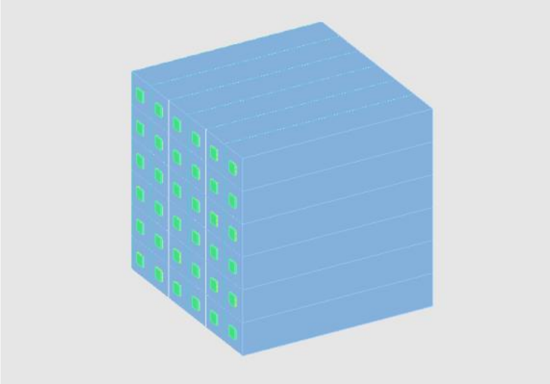
- Motivations: to develop crystal modules
  - Small-scale modules is sufficient for compact EM showers
  - Identify critical questions/issues on system level
  - Evaluate performance with beam test data
- Key issues
  - Temperature control and monitoring
  - Mechanical design: crystal fixture, tolerance, gaps
  - Space for readout electronics
  - Dynamic range of SiPMs and FEE
- Preparations for future beam tests



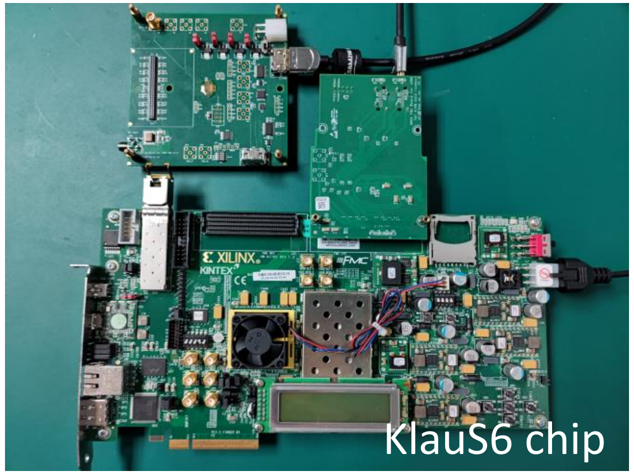
A dummy crystal matrix with 3D printed support structure



crossed crystal bar

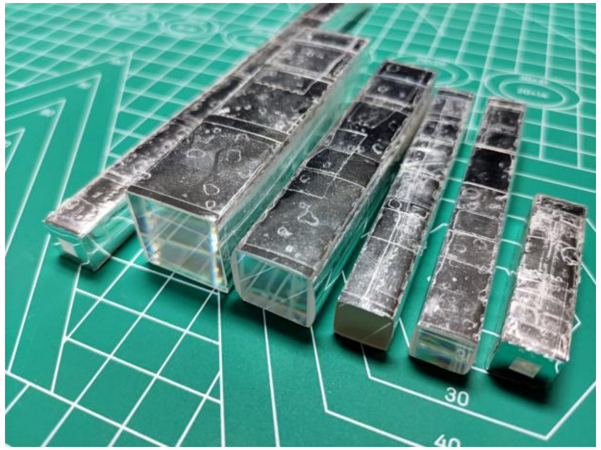


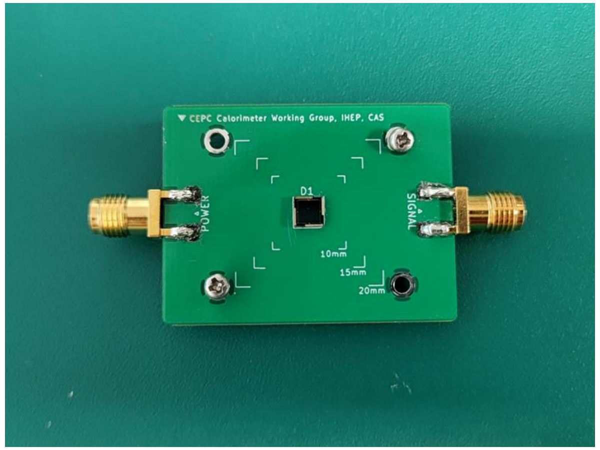
6×6 crystal matrix



Hardware design of a highly granular crystal ECAL

- Crystal candidates
  - BGO: light yield ~8000 p.e./MeV, ~300 ns light decay time
    - Most promising candidate currently
  - PWO: light yield ~120 p.e./MeV, ~30 ns light decay time
    - Faster, low light yield, hard to manufacture
- SiPM candidates
  - Generally 6~10 μm pixel SiPMs are preferred
  - Low crosstalk/DCR to operate under low threshold
  - NDL EQR06 series
    - Good performance, need further tests
- Front-end electronics
  - Module test: KlauS6 chip, CAEN readout system
  - Dedicated ASIC
- Other issues
  - Identify from module design





Summary of crystal ECAL specifications

Key Parameters	Value	Notes
MIP light yield	>100 p.e./MIP	9.1 MeV/MIP in 1 cm BGO
Dynamic range	0.05~10^3 MIP	About 500 keV~10 GeV
Energy threshold	15 p.e.	Feasible for 0.05 MIP signal
Timing resolution	~400 ps	Expected value from simulation
Crystal non-uniformity	<1%	After calibration
Temperature stability	Stable at the level of 0.05 Celsius	CMS ECAL value
Gap tolerance	—	TBD through module development

Further issues:

- Temperature control
  - Temperature dependent properties (SiPM crystal)
  - Cooling system for Front-end electronics
- Calibration schemes
  - LED single photon calibration of SiPMs
  - Transmittance of crystal: radiation damage
  - Operation and maintenance: MIP calibration

Summary & prospects

R&D of a highly granular crystal ECAL:

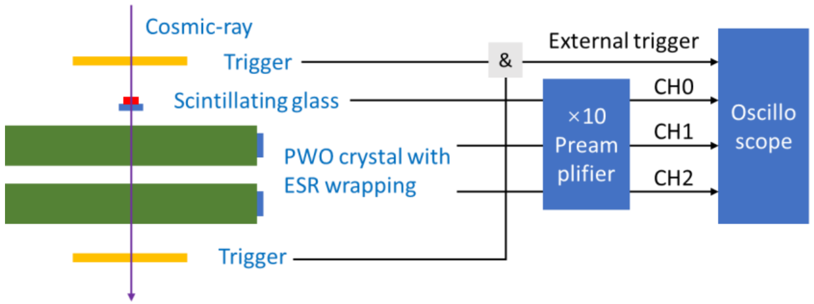
- PFA performance study
- Dedicated reconstruction
- Set up requirements for detector design

- Prospects
    - Challenge on PFA: still optimizing
    - Detailed simulation studies on crystal ECAL performance
    - Address key issues of crystal ECAL through module development
    - …

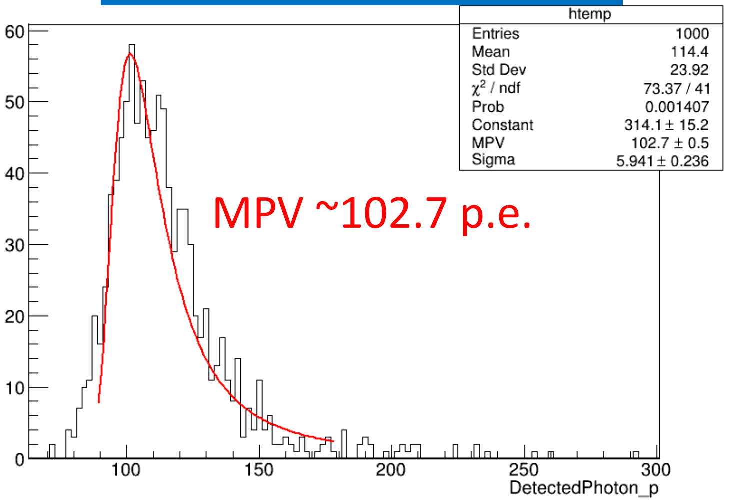
Backup

Cosmic-ray test of PWO crystal

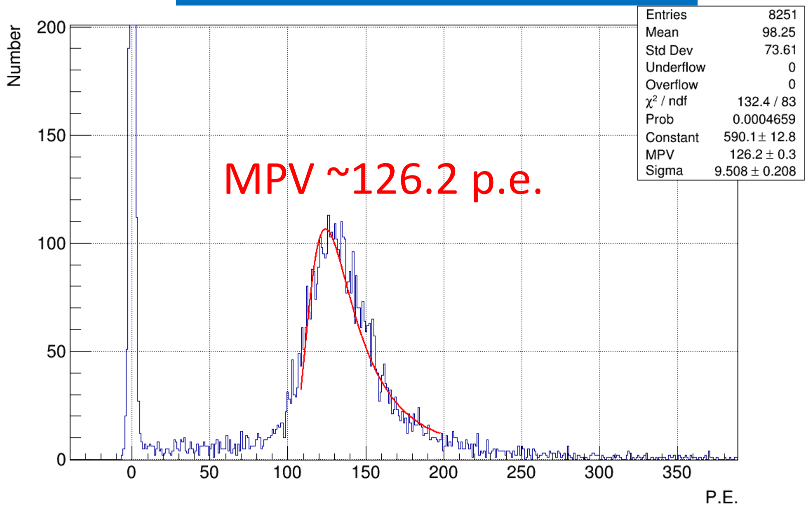
- PWO crystal
  - 8×2×2 cm^3, ESR warping
  - Energy deposition in Geant4 simulation: 20.8 MeV/MIP

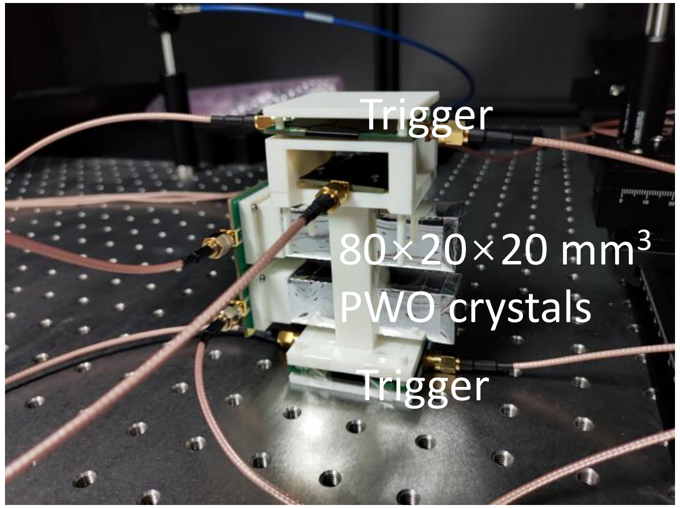


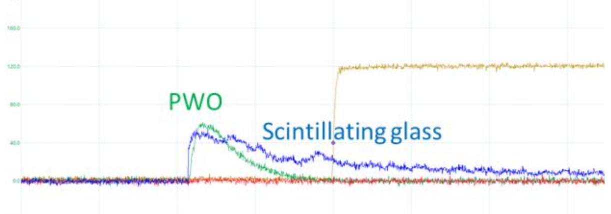
Gean4 optical simulation



Cosmic-ray test



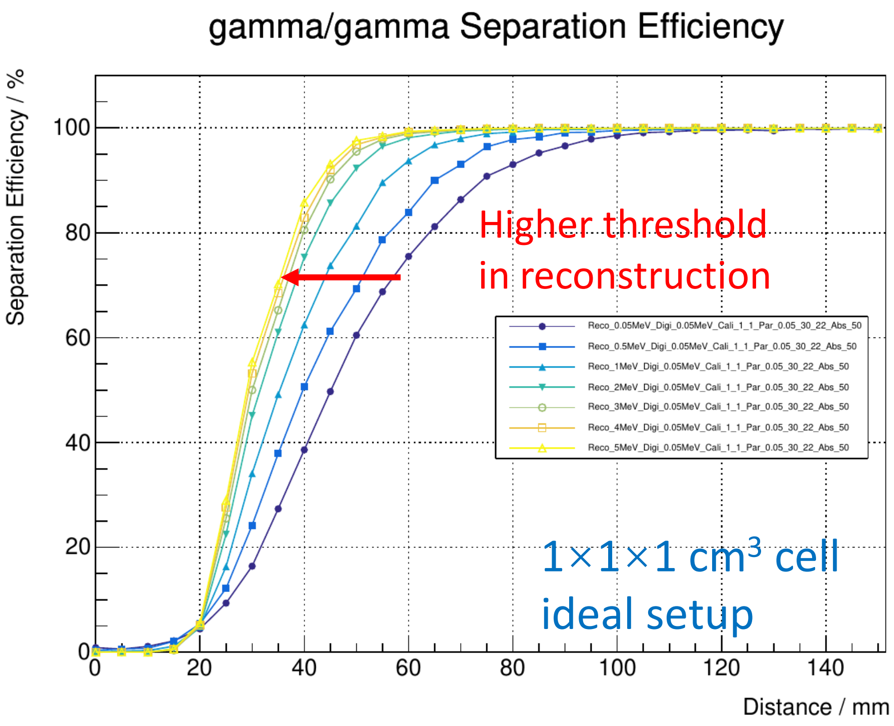


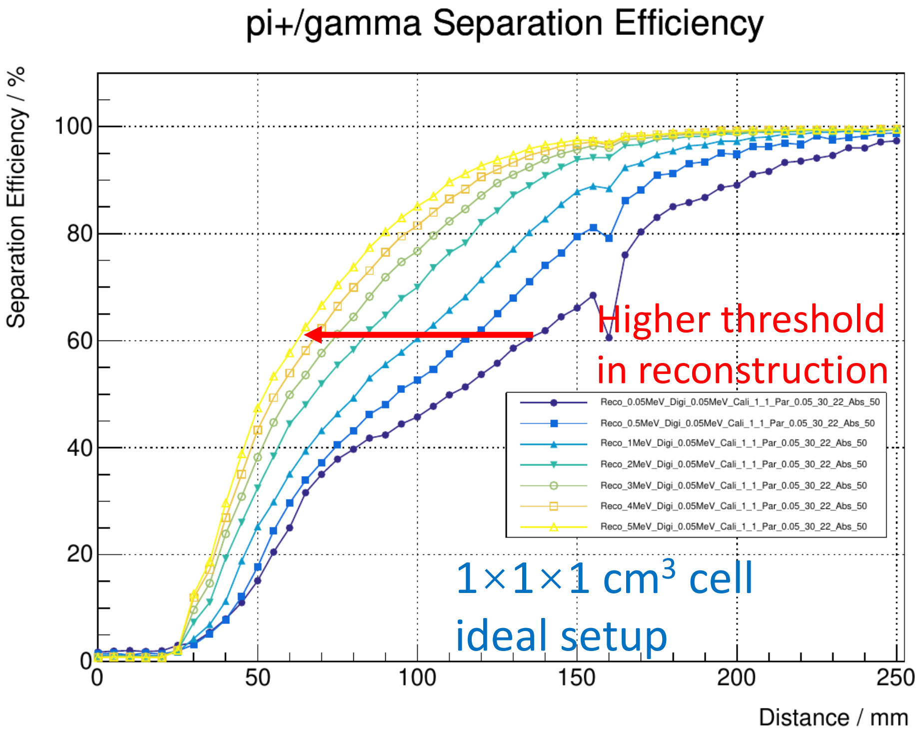


Waveform in the oscilloscope

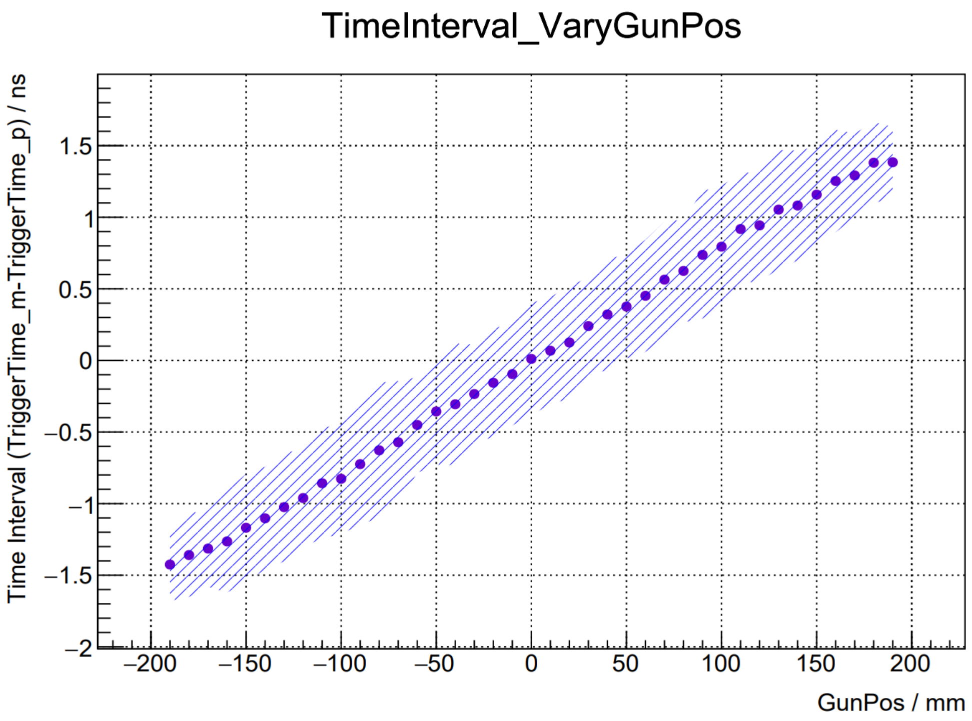
- Cosmic tests: reasonably consistent with Geant4 optical simulation
- Higher MIP response desired for more headroom

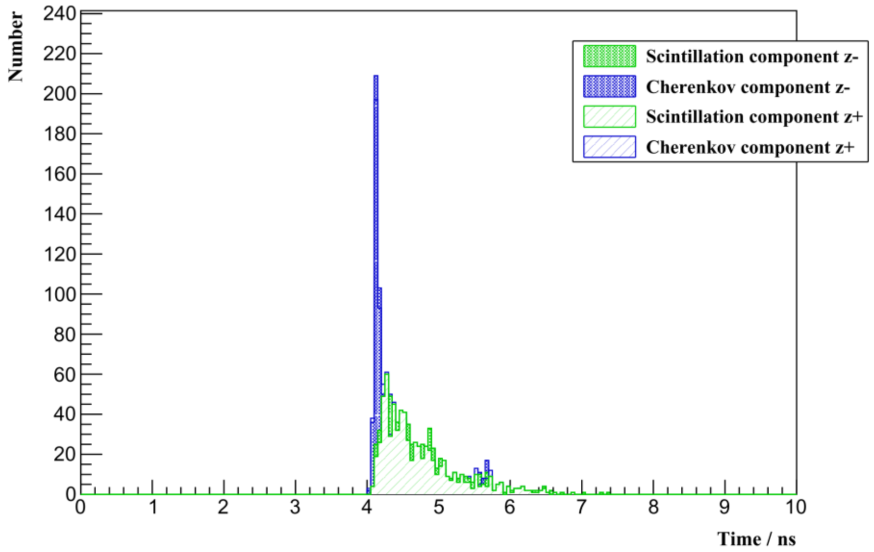
Performance evaluation: separation power

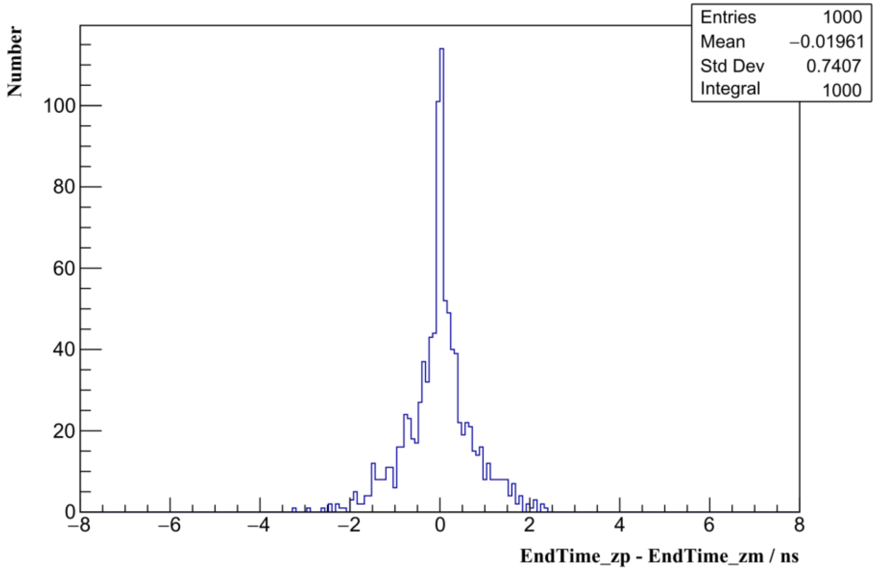




Latest progress on time resolution study

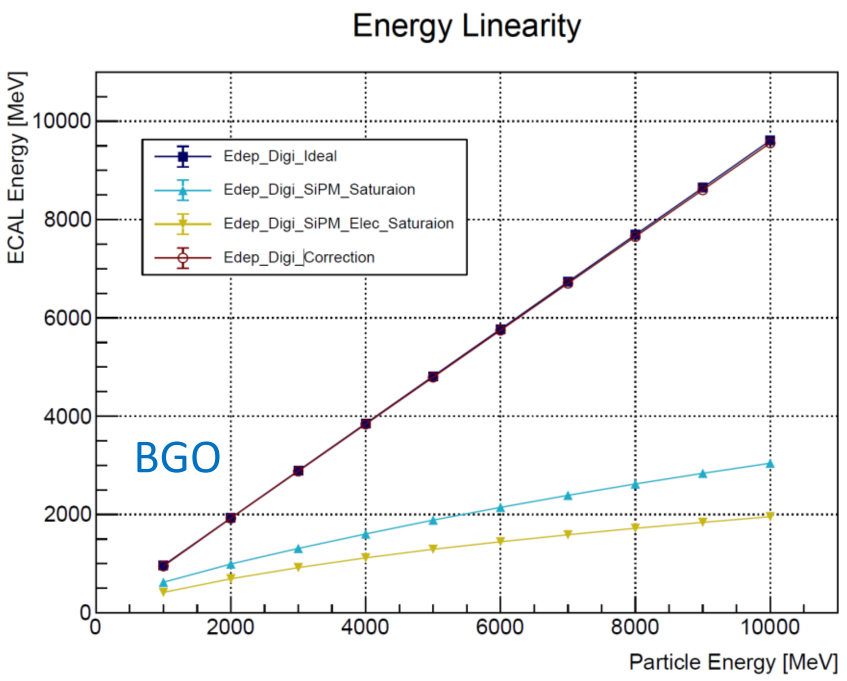


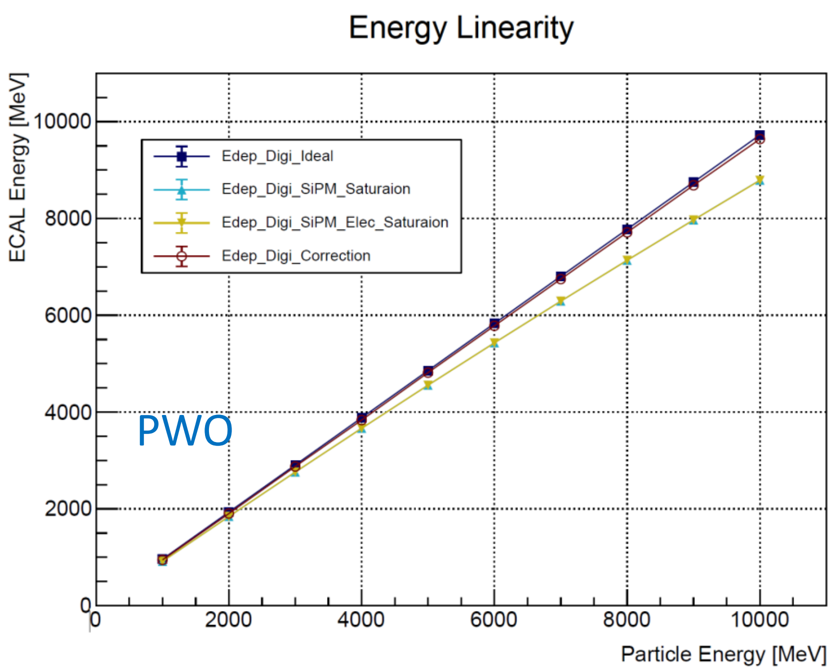




Small-scale detector module design: saturation effect

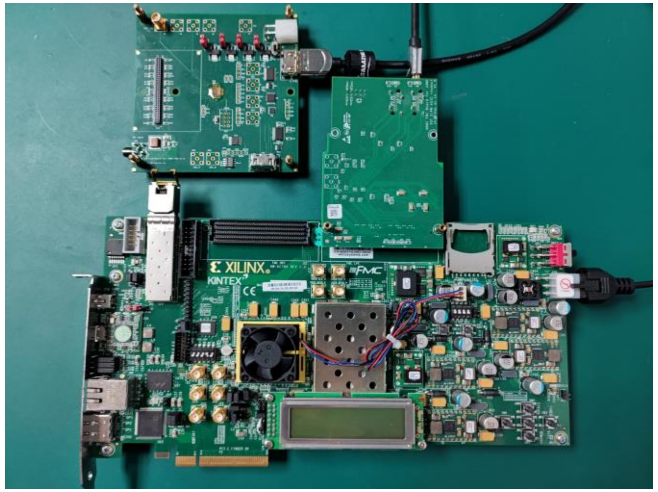
- Simulation of BGO/PWO crystal matrix for beam test: saturation of SiPMs and front-end electronics





- Saturation effects: severely degrade energy linearity (as well as resolution)
  - Adjust the fluorescence property of BGO crystal (collaboration with Shanghai Institute of Ceramics, CAS)
  - Neutral density filter, Si-PIN photodiode, TOT technique…

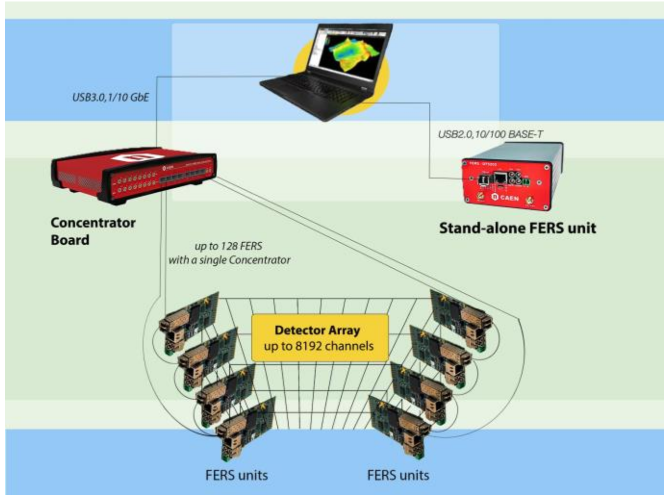
Readout electronics



KlauS6 chip

CAEN DT5550W Readout System with 32/64/128-channel configuration

CAEN DT5702 32 Channel
SiPM Readout Board



FERS-5200 128 Channel
Front-End Readout System