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

CEPC

R&D of a novel high-granularity crystal calorimeter

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On behalf of CEPC Calorimeter Working Group

中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会
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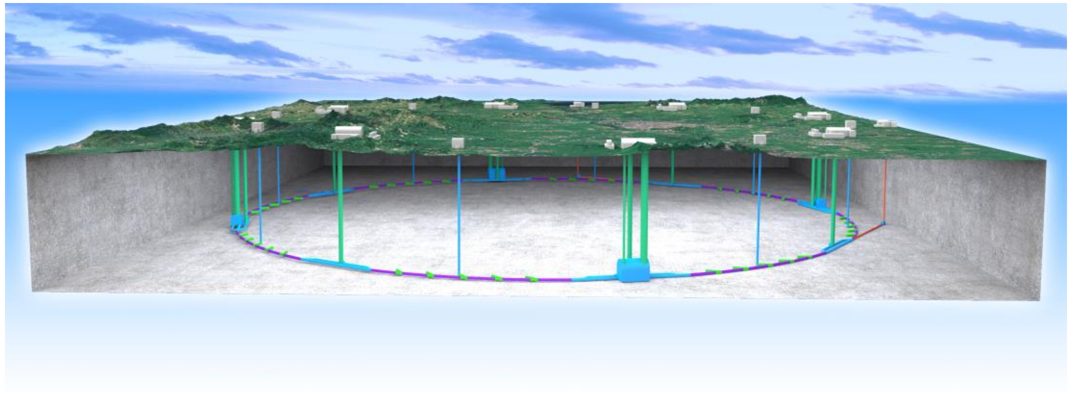
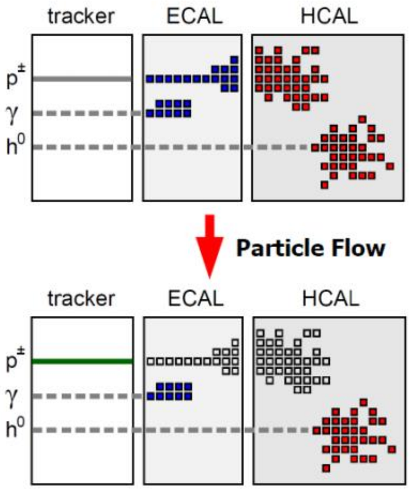
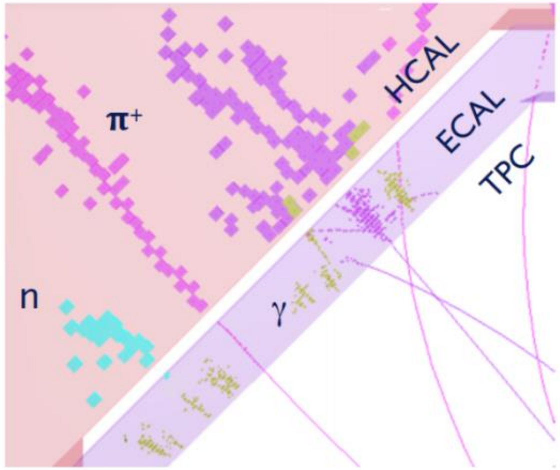
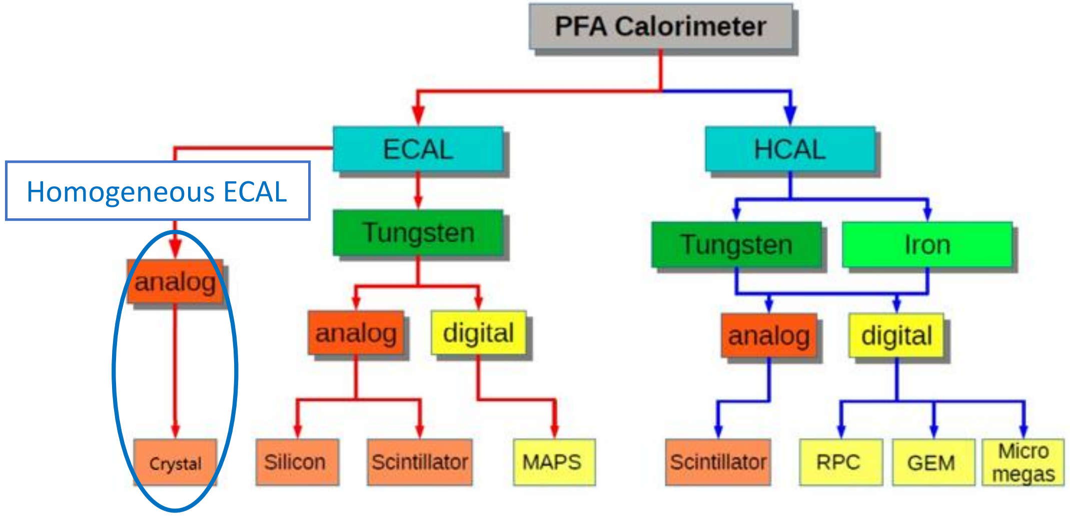
Motivations for crystal ECAL

- Background: calorimeter for future lepton colliders (e.g. CEPC, FCC-ee, ILC, CLIC…)
  - Jet energy resolution of 3-4%@100GeV is required
  - Particle flow approach: high-granularity calorimeter
- Particle-flow crystal ECAL
  - Homogeneous structure
    - Intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Physics benefits
    - 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



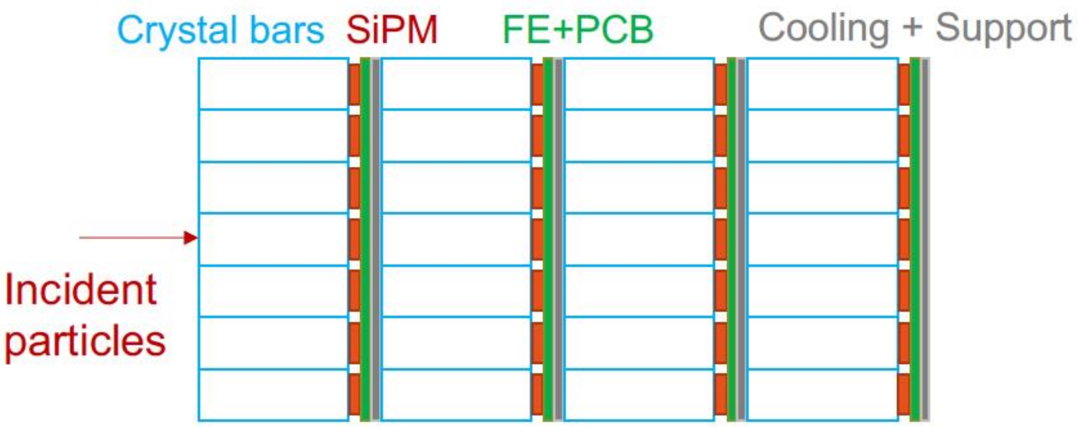






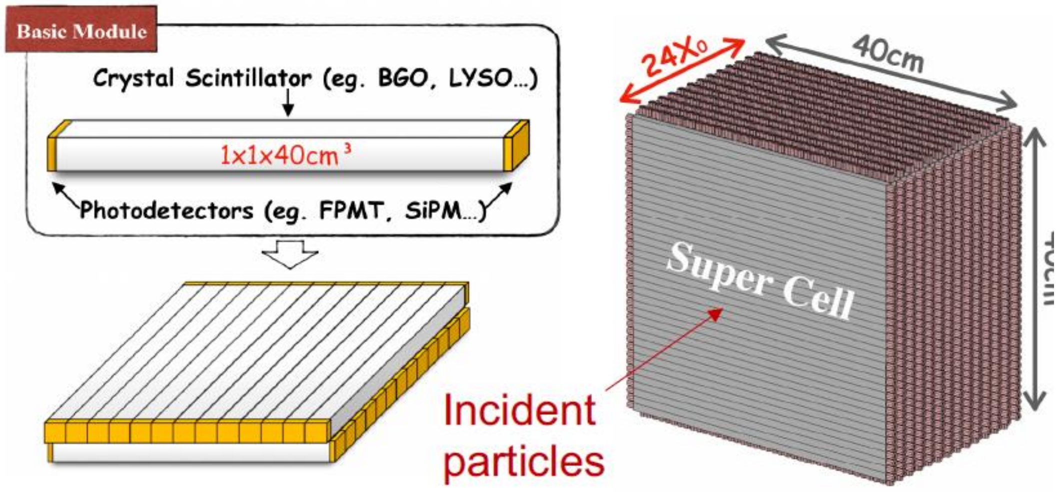
Two designs of crystal ECAL

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



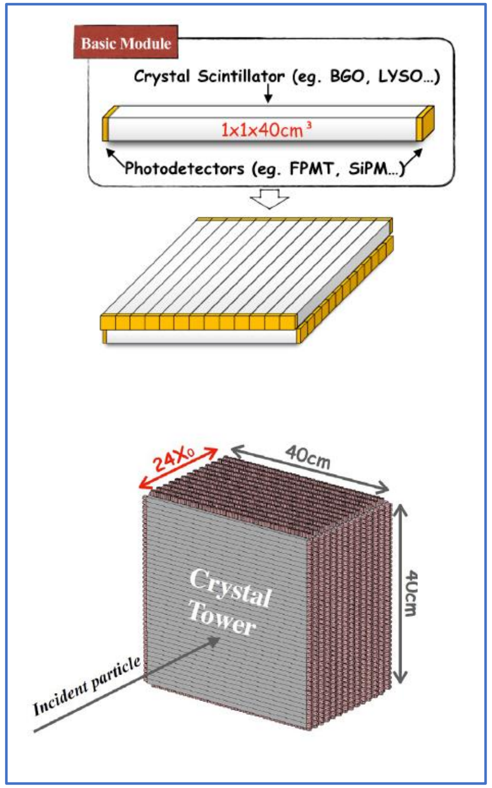
- Long bars: 1×1×40 cm, double-sided readout
  - Super cell module: 40×40 cm
  - Crossed arrangement in adjacent layers
  - Fine longitudinal granularity
- Save #channels and minimize dead materials
- Timing at two sides: positioning along bar

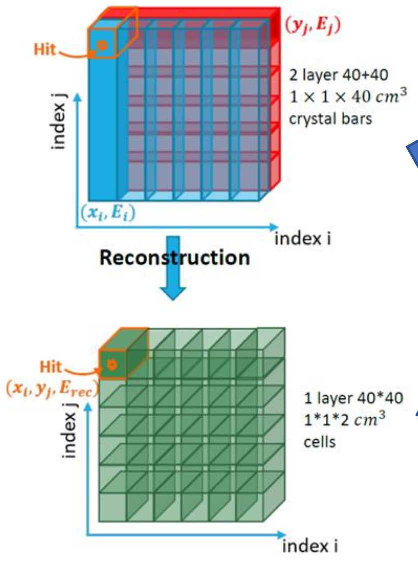
Outline: R&D status

- Performance studies
  - Evaluate physics potentials with Arbor-PFA
    - Separation power, Higgs benchmarks
  - Reconstruction algorithm dedicated to new geometry design
- Detector design and hardware development
  - EM energy resolution: light yield requirements
  - Detector unit characterization: cosmic-ray and radioactive source tests
  - Response uniformity
  - Time resolution
  - SiPM characterization
  - Small-scale detector module design

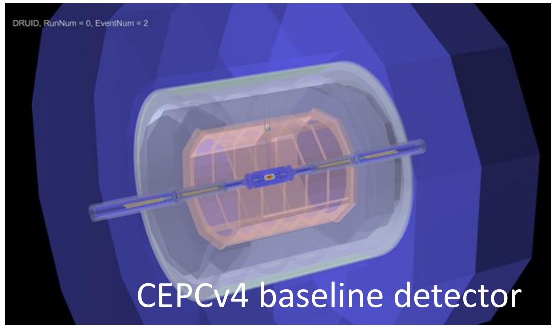
Performance evaluation

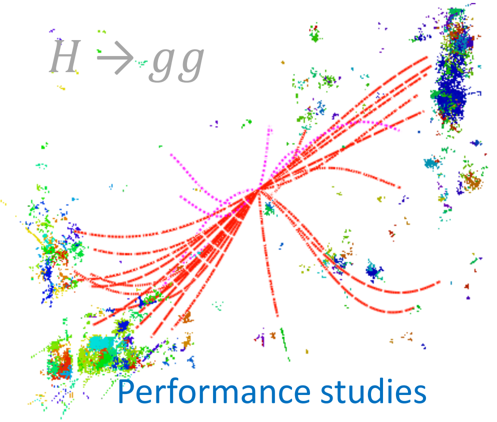
- Adapted from CEPC baseline detector
- Application and optimization of Arbor-PFA

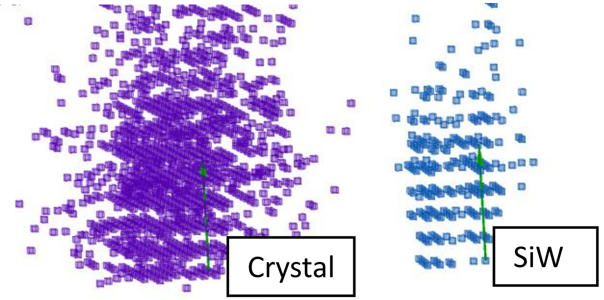




Crossed long bar design: $1\times1\times2$ cm^3 granularity after reconstruction





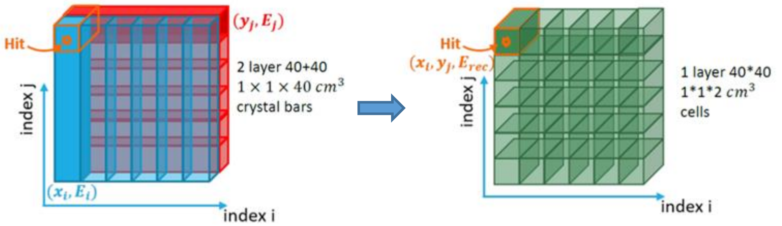


Event display: crystal compared to SiW: significant increase of #hit

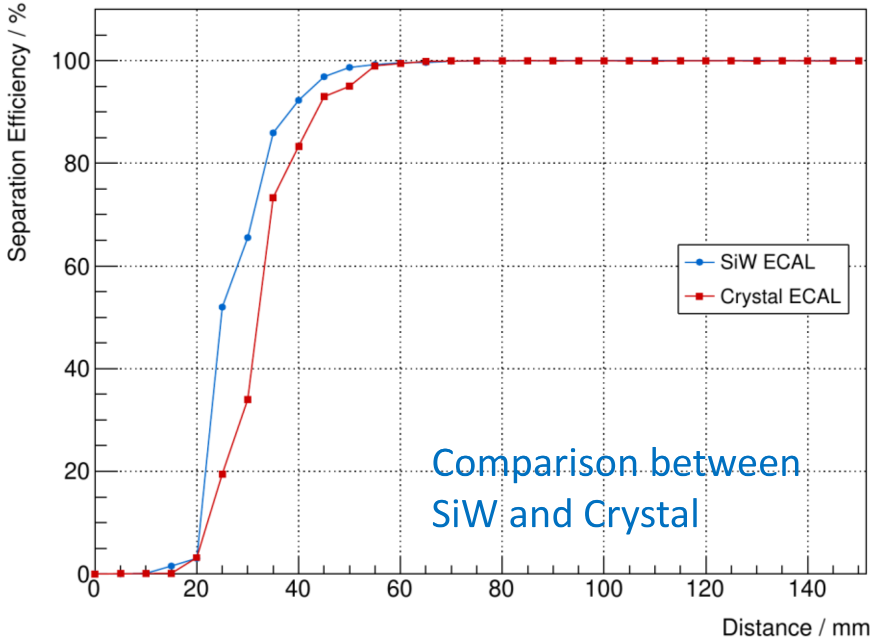
Arbor-PFA: necessary to be optimized for crystal ECAL design

Separation power

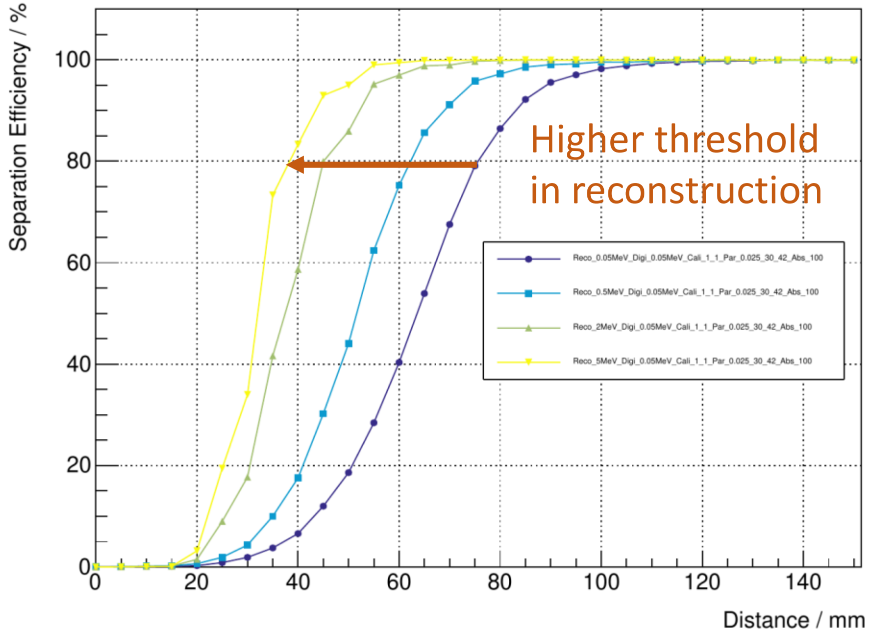
- Reconstruction of jets: separation power of close-by particles
- Arbor-PFA: ongoing optimization
  - (a) find the shower core/axis to separate particles with a high threshold
  - (b) clustering hits with a low threshold for better energy resolution

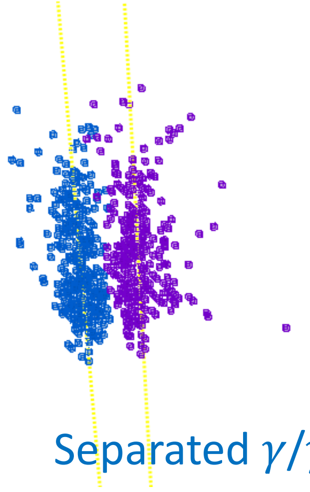


γ/γ separation with barrel ECAL

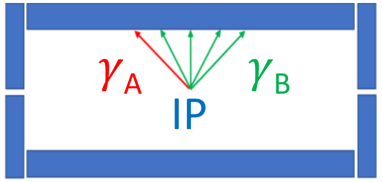


γ/γ separation power vs threshold





Separated γ/γ



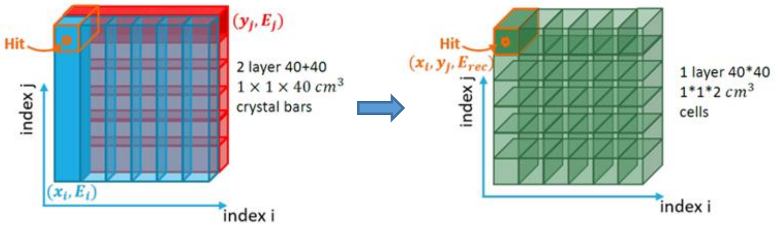
Side view of crystal ECAL

- EM shower: good separation power, similar to SiW under a high energy threshold

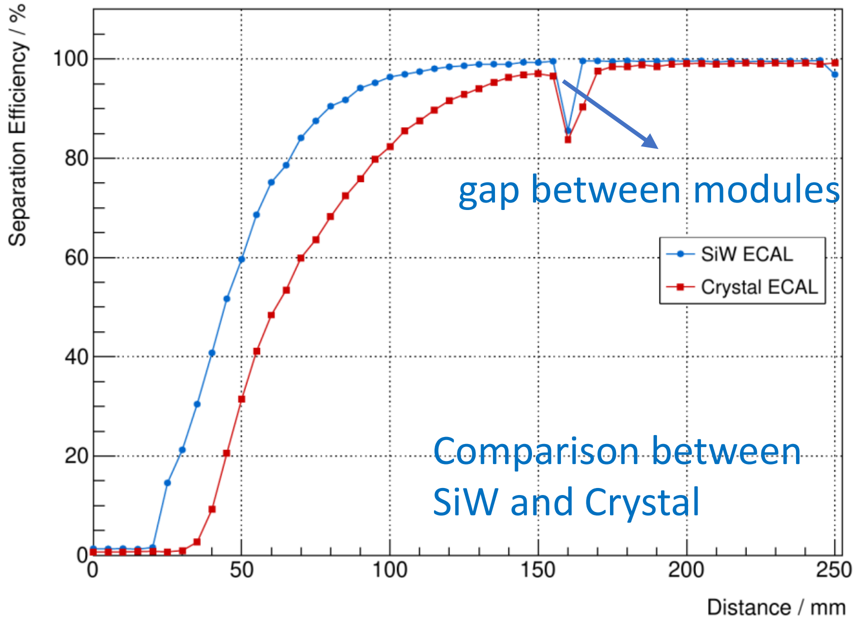
Separation power

CEPC Software v0.1.1

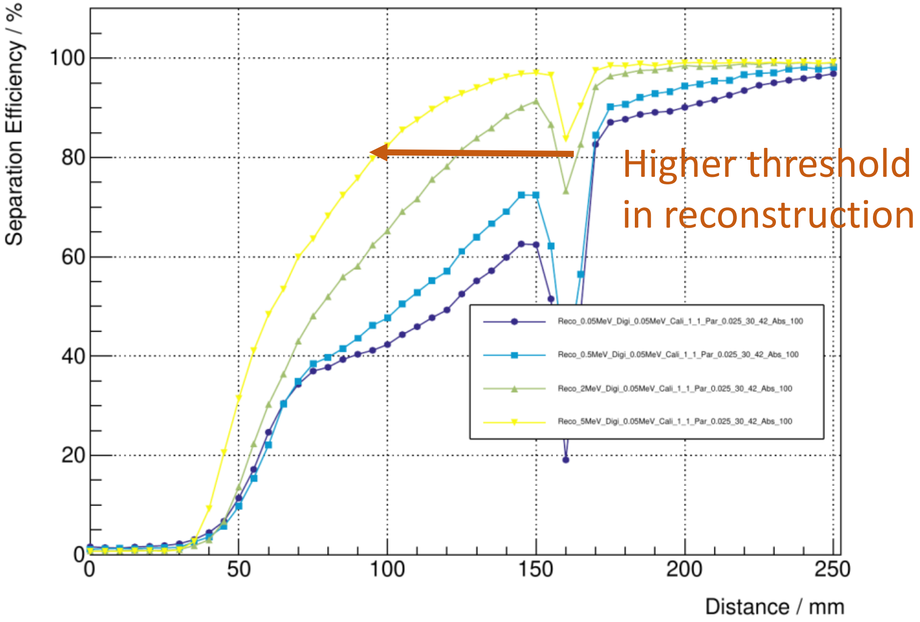
- Reconstruction of jets: separation power of close-by particles
- Arbor-PFA: ongoing optimization
  - (a) find the shower core/axis to separate particles with a high threshold
  - (b) clustering hits with a low threshold for better energy resolution

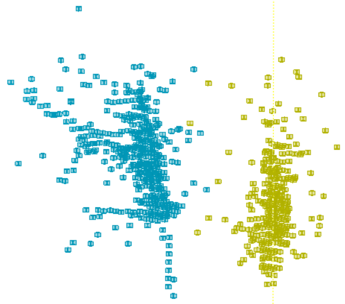


π^+/γ separation with barrel ECAL

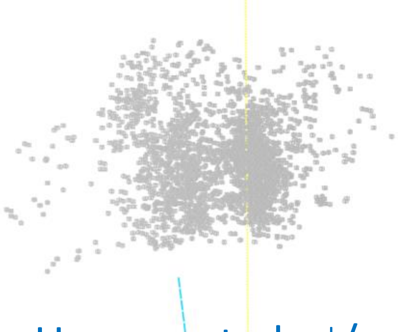


π^+/γ separation power vs threshold





Separated π^+/γ



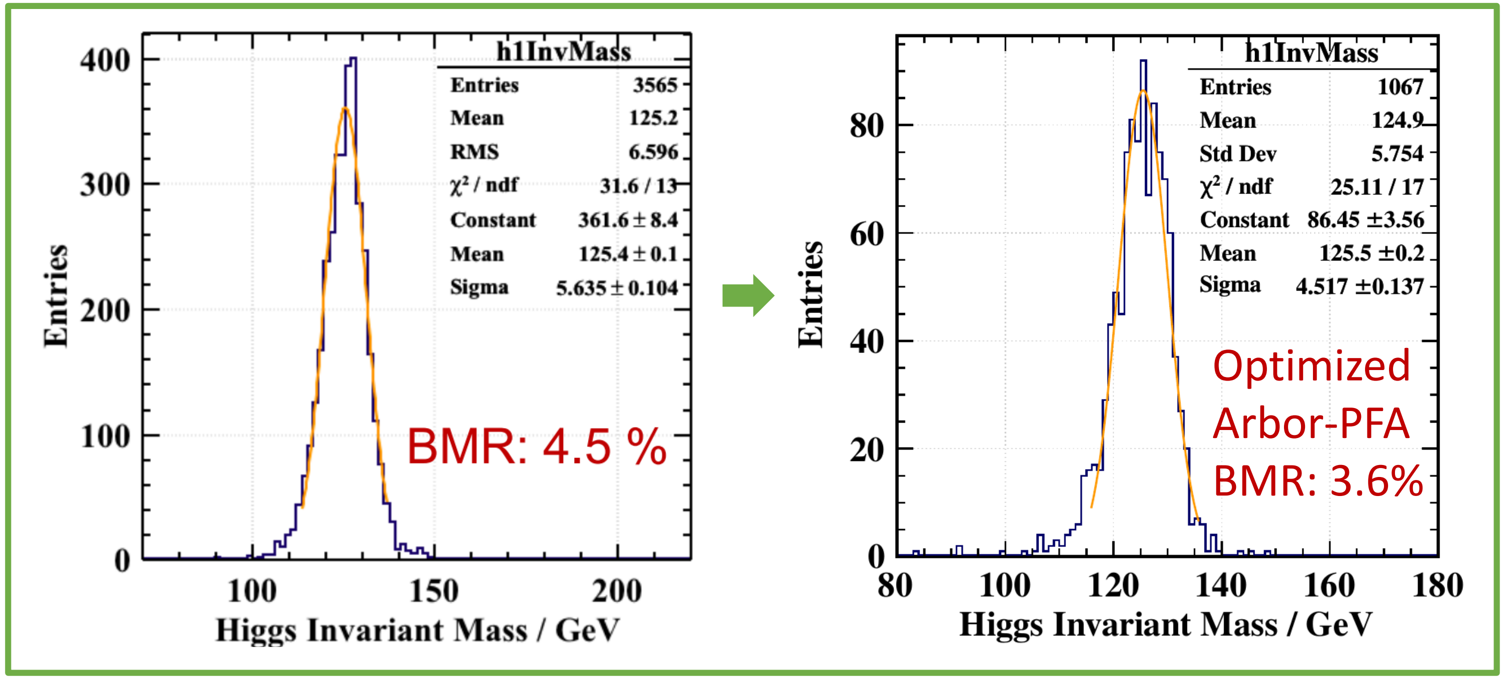
Unseparated π^+/γ

- Hadronic shower: challenges on clustering
- Key question: matching clusters of charged particles to their tracks
- Further optimization of Arbor-PFA

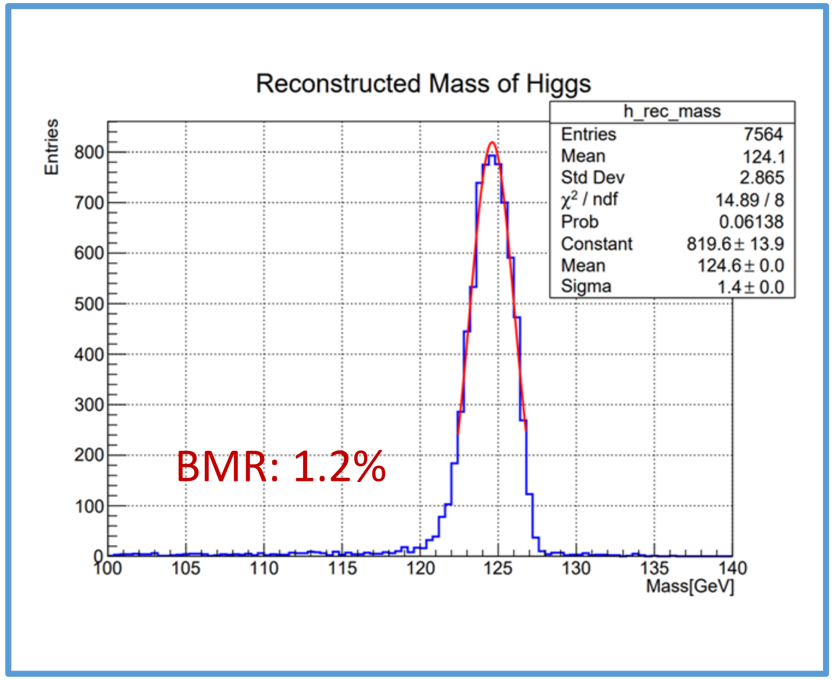
Higgs benchmarks

- Physics performance
  - Boson mass resolution (BMR) for di-jet events: $ZH\ (Z \to \nu\nu,\ H \to gg)$
  - BMR for di-photon events : $ZH\ (Z \to \nu\nu,\ H \to \gamma\gamma)$

BMR $(H \to gg)$



BMR $(H \to \gamma\gamma)$

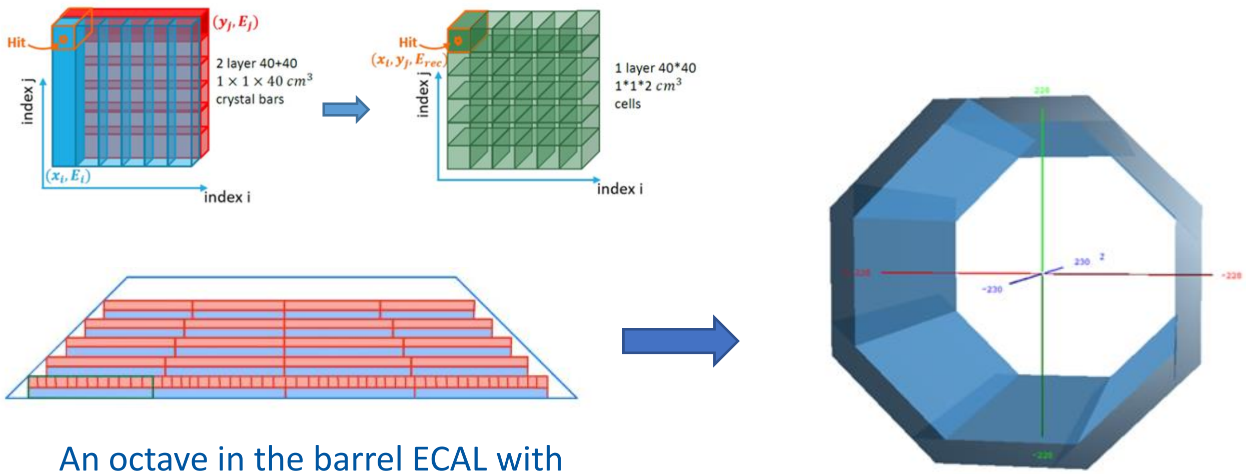


- Significant improvement after Arbor-PFA algorithm optimization
- Ongoing optimization and further BMR study…

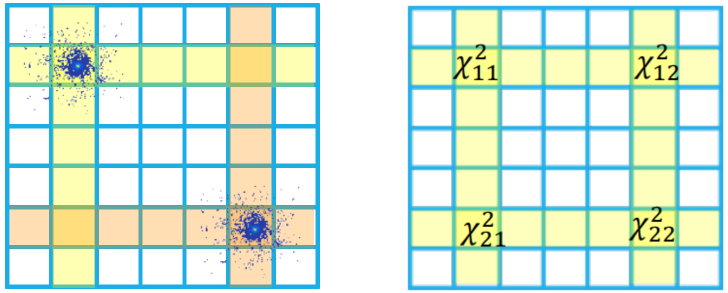
Reconstruction algorithm dedicated to new geometry design

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

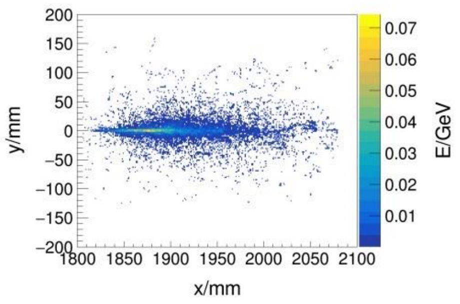
- Detector description
  - Full barrel geometry with DD4HEP
  - 28 longitudinal layers, crossed arrangement
- Reconstruction algorithm: aims
  - Final granularity 1×1×2 cm^3
  - Minimize impact from ghost hits
- Challenges
  - Pattern recognition of clusters
  - Associating charged clusters with tracks



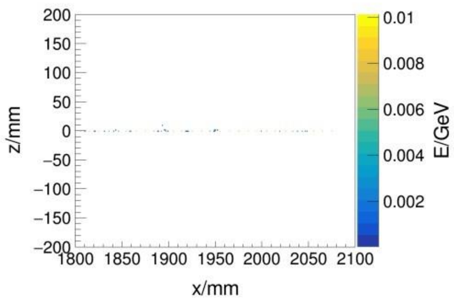
An octave in the barrel ECAL with crossed long crystal bars



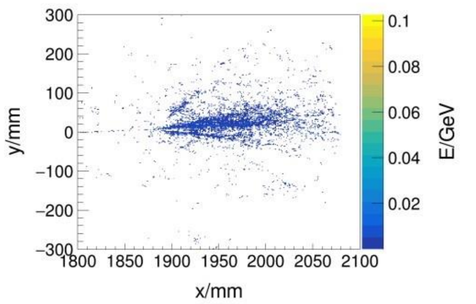
Remove ghost hits



EM cluster



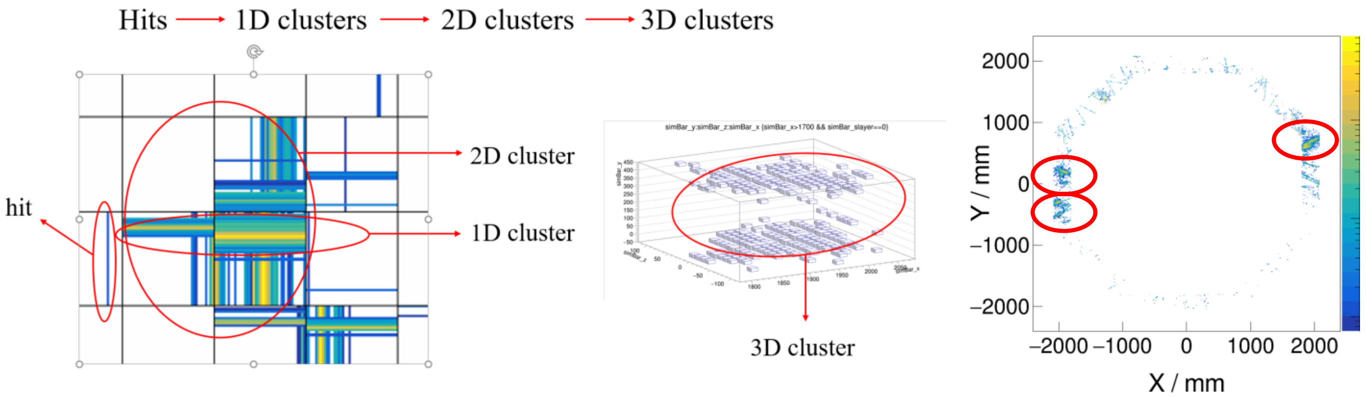
MIP cluster



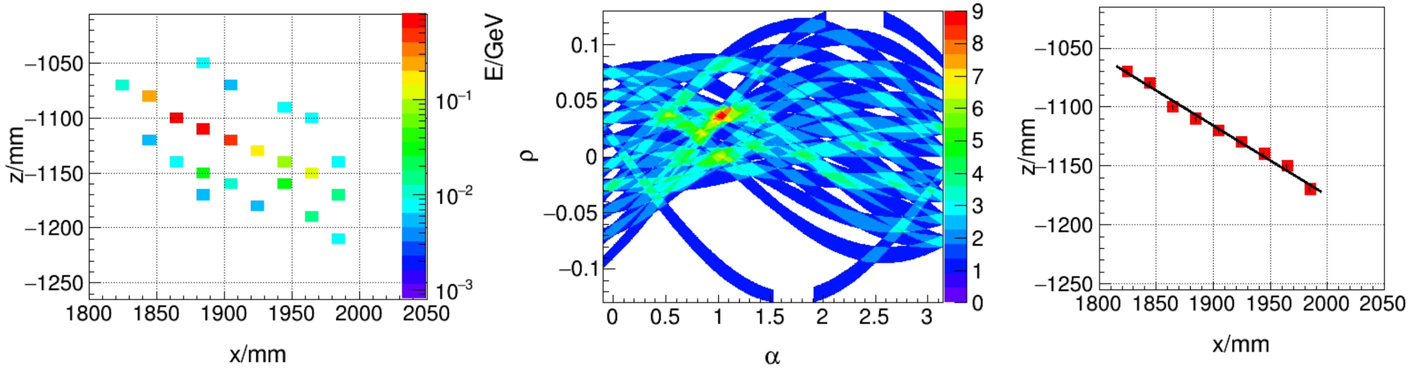
Hadronic cluster

Reconstruction algorithm dedicated to new geometry design: progress

- Clustering algorithm for long crystal ECAL

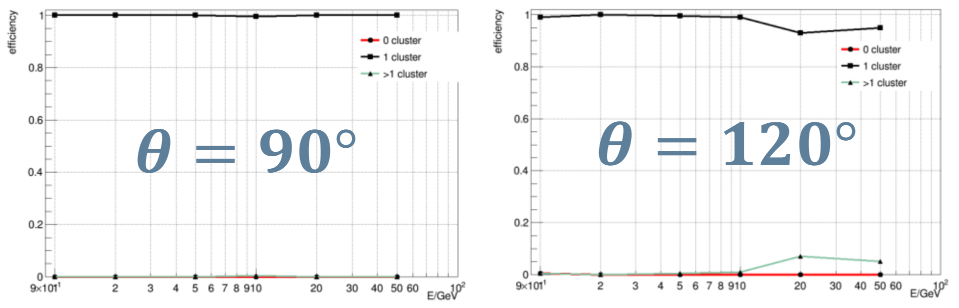


- Reconstruction: application of Hough transformation
  - Local maxima of hits → Bands in Hough space→ Cluster

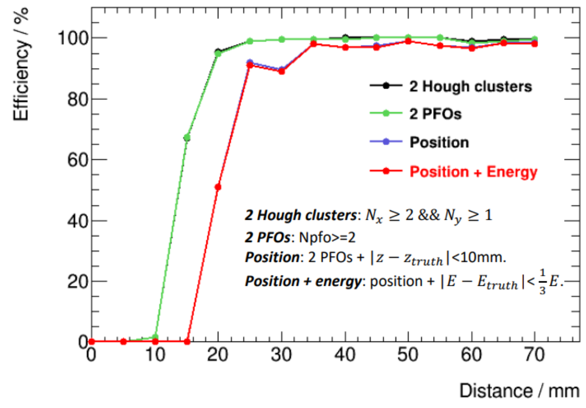


1D cluster cores → Hough transformation → Track in ECAL

- Reconstruction performance of single photons



- Di-photon recognition efficiency



- Ongoing work on hadrons/jets

Talk ***Reconstruction Algorithm for Long Crystal Bar ECAL***
on CEPC Joint Workshop 2022 by WeiZheng Song

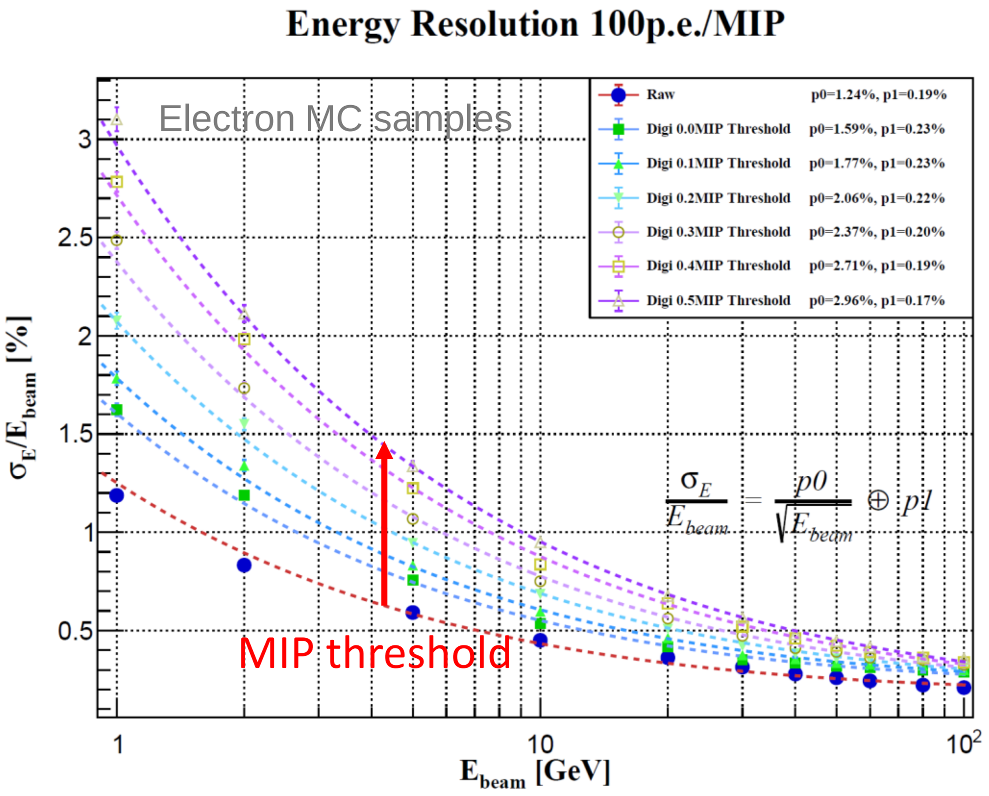
Outline: R&D status

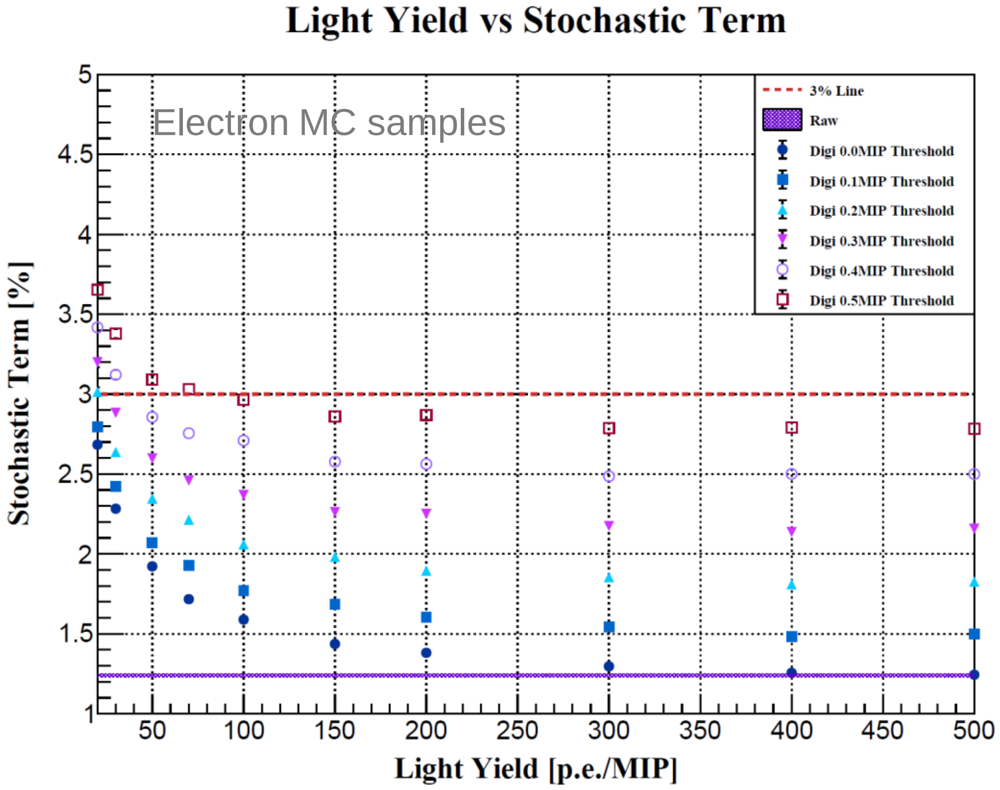
- Performance studies
  - Evaluate physics potentials with Arbor-PFA
    - Separation power, Higgs benchmarks
  - Reconstruction algorithm dedicated to new geometry design
- Detector design and hardware development
  - EM energy resolution: light yield requirements
  - Detector unit characterization: cosmic-ray and radioactive source tests
  - Response uniformity
  - Time resolution
  - SiPM characterization
  - Small-scale detector module design

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

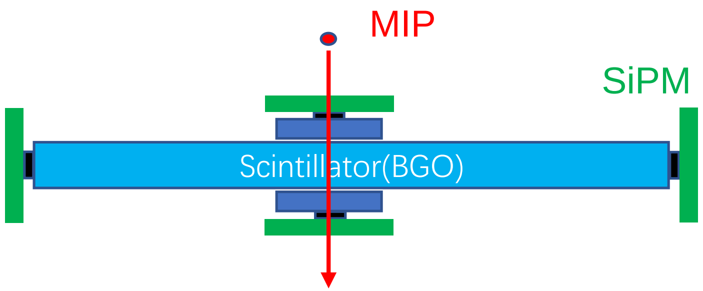




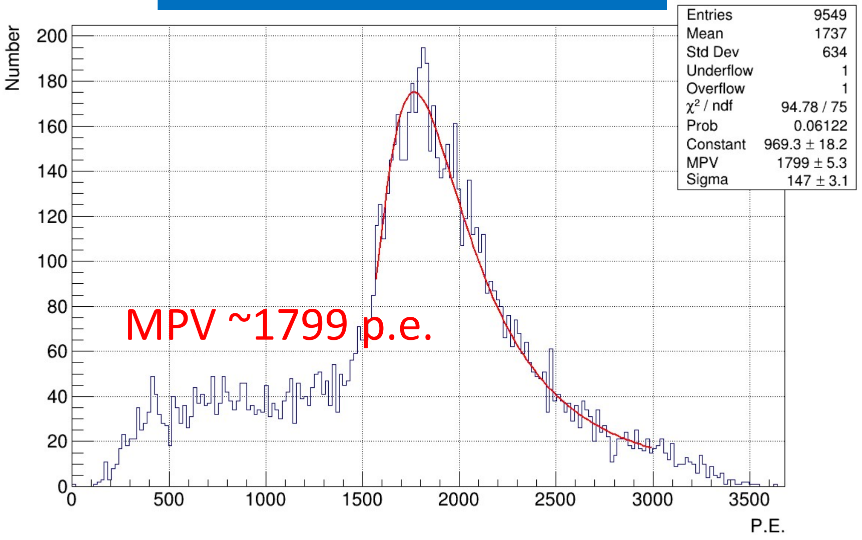
- Moderately high light yield (#detected photons) and low threshold required
- Low energy threshold can be feasible with low crosstalk SiPMs
- >100 p.e./MIP light yield is enough for $\sim 3\%/\sqrt{E}$ energy resolution

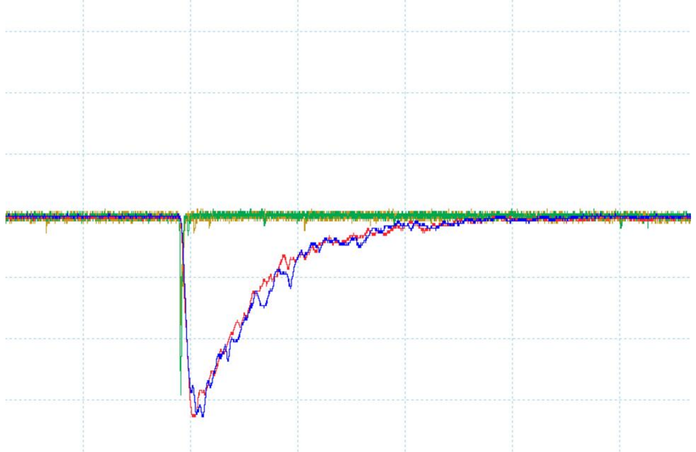
Cosmic-ray test of long crystal bar

- 400×10×10 mm^3 long BGO crystal bar, ESR wrapping
- SiPM readout at both two ends
- Energy deposition in Geant4 simulation: 9.1 MeV/MIP

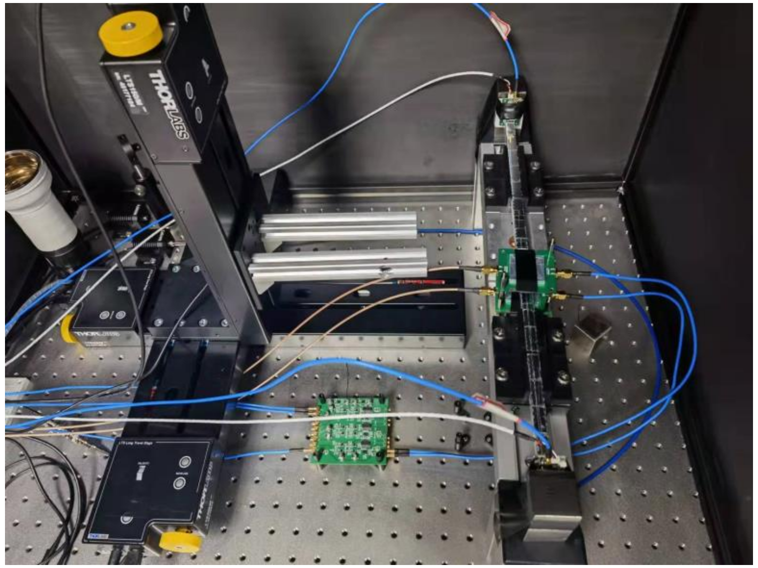


Cosmic-ray test





Waveform of a typical cosmic-ray event

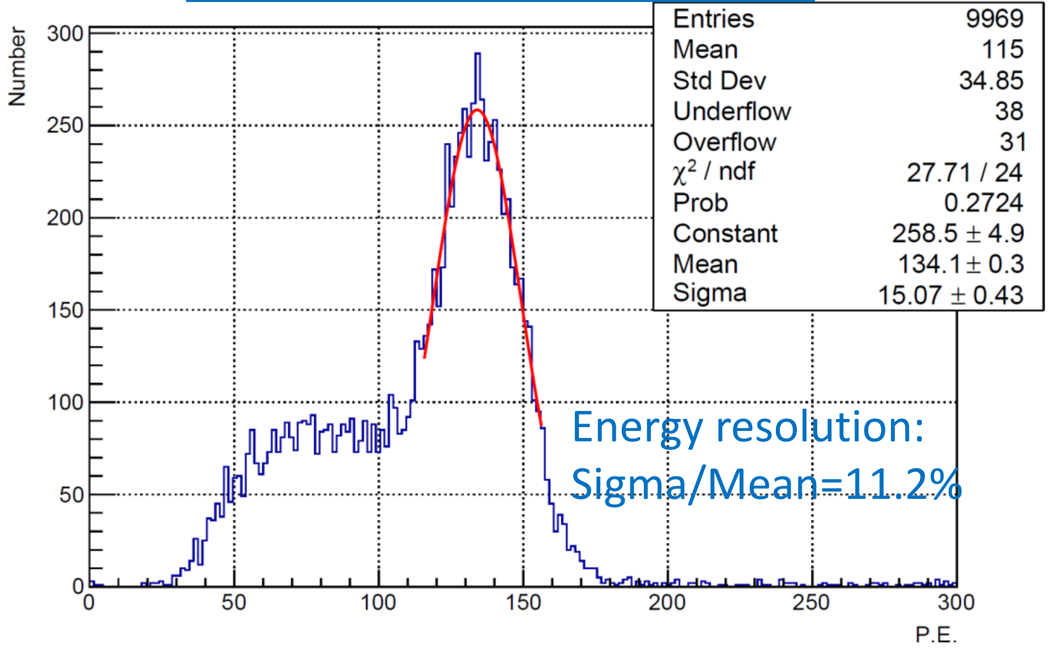


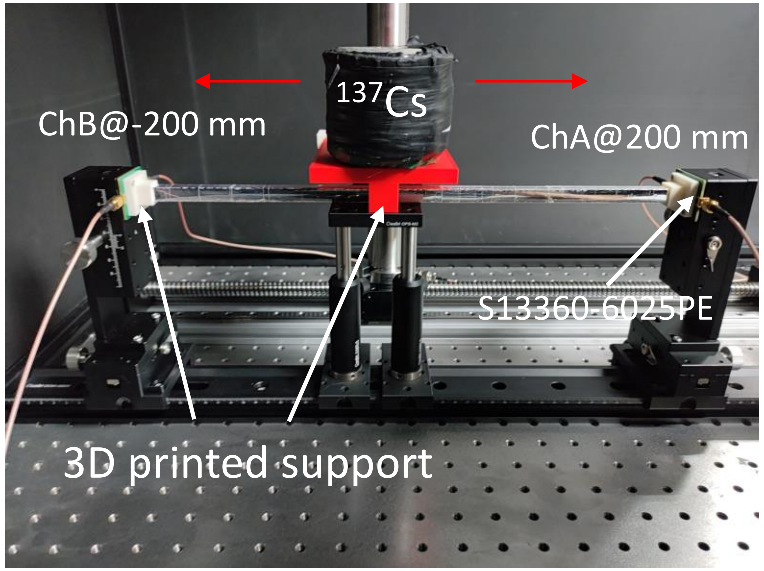
- BGO crystal: high enough light yield

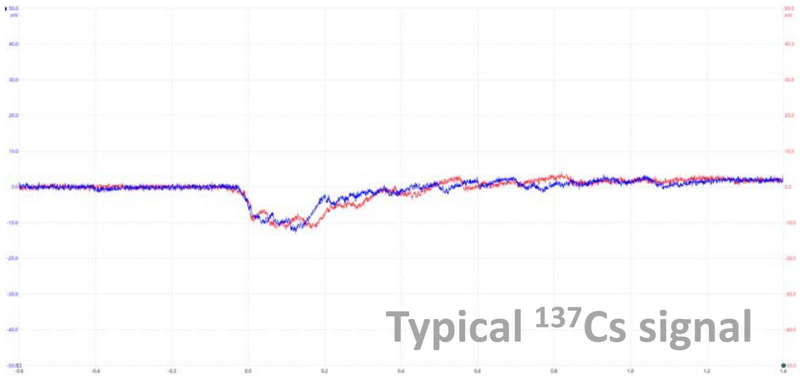
Energy calibration with ^{137}Cs radioactive source

- Experiment setup
  - 662 keV gamma form ^{137}Cs, 1D moveable support
  - ~5 mm spread of gamma source
  - $400\times10\times10$ mm^3 BGO crystal bar, ESR wrapping
  - 6×6 mm^2 SiPMs with 25 μm pixel, air coupling, double-sided readout

Detected photon: ChA + ChB



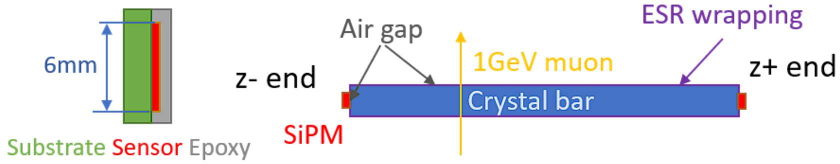




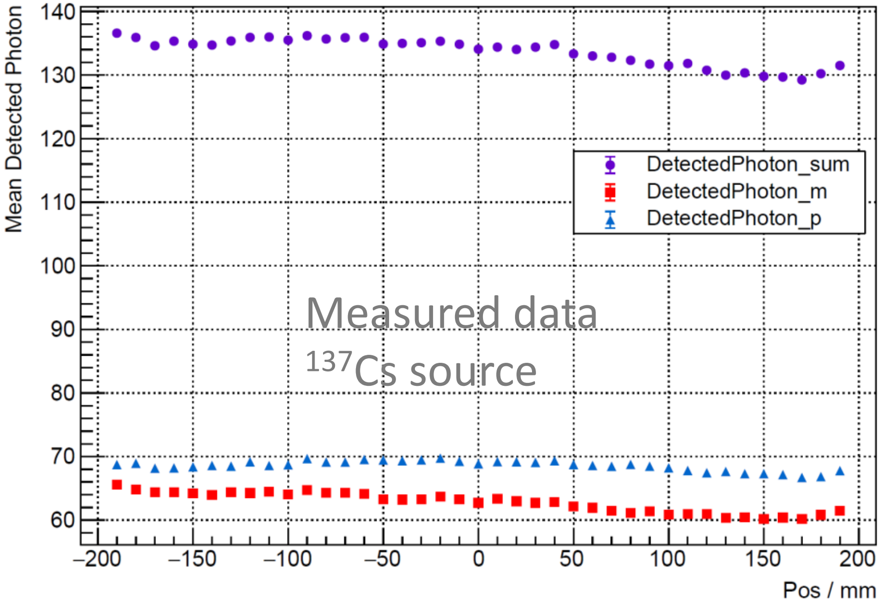
Study on response uniformity of a long crystal bar

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 film

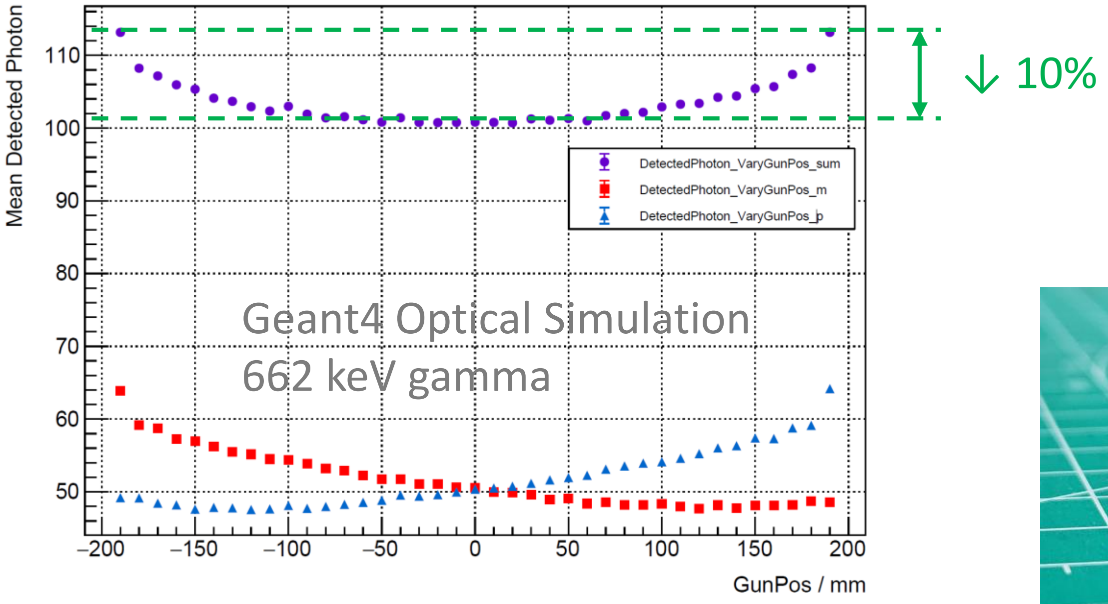


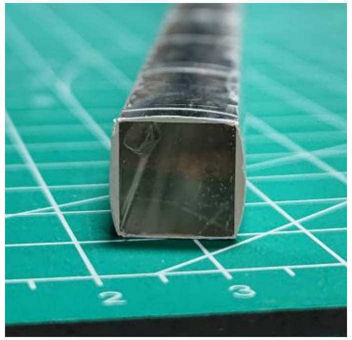
Experiment: detected photon



- Relatively low response near one side
  - surface defects, scintillation uniformity, geometry…
- Repetitive experiments show similar results
- Further studies are ongoing…

Simulation: detected photon





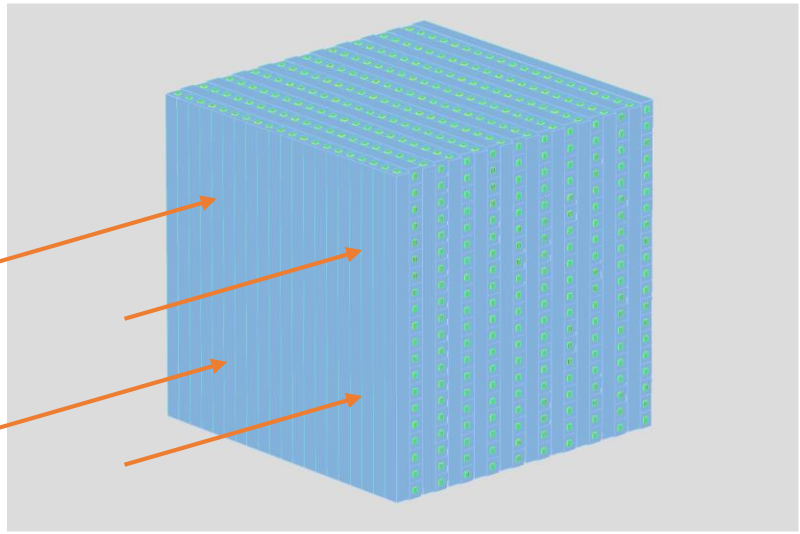
- Stronger non-uniformity effect in simulation with current parameters

MIP response uniformity of crystal ECAL module

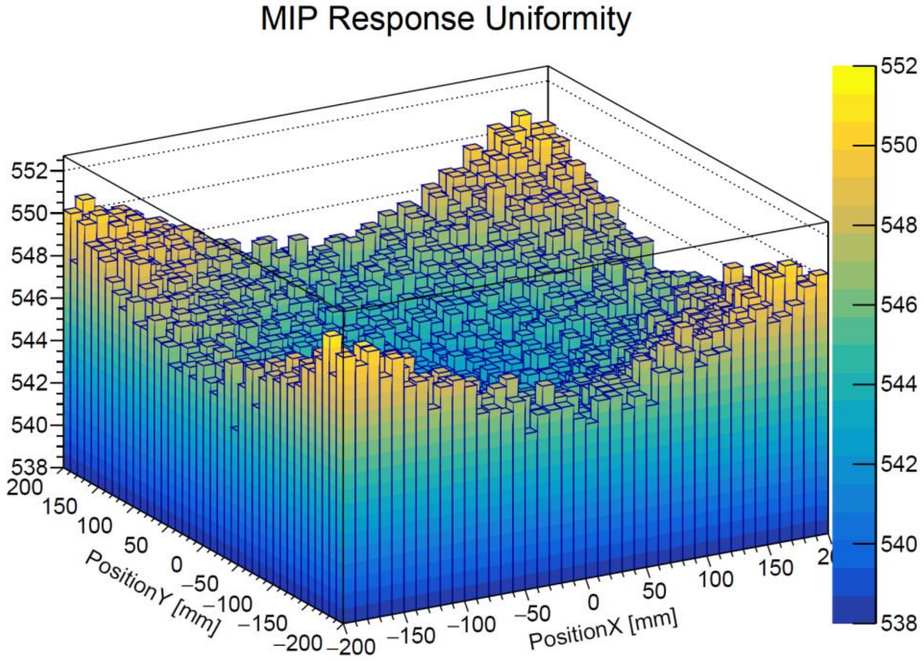
Geant4 Simulation (v10.7.3)

- Simulation setup
  - $400\times10\times10$ mm^3 BGO crystal Bar
  - Crossed bar arrangement
  - 1 GeV muon: perpendicular incidence
  - Response has been parameterized (based on optical simulation)

Response differs along the bar



MIP response of crystal module

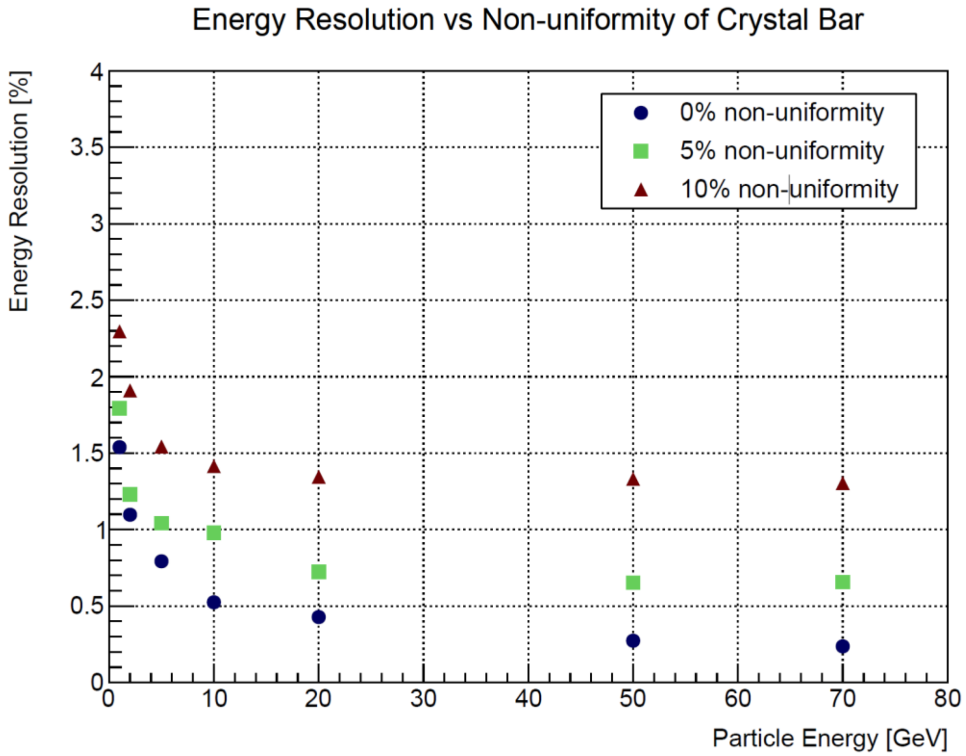


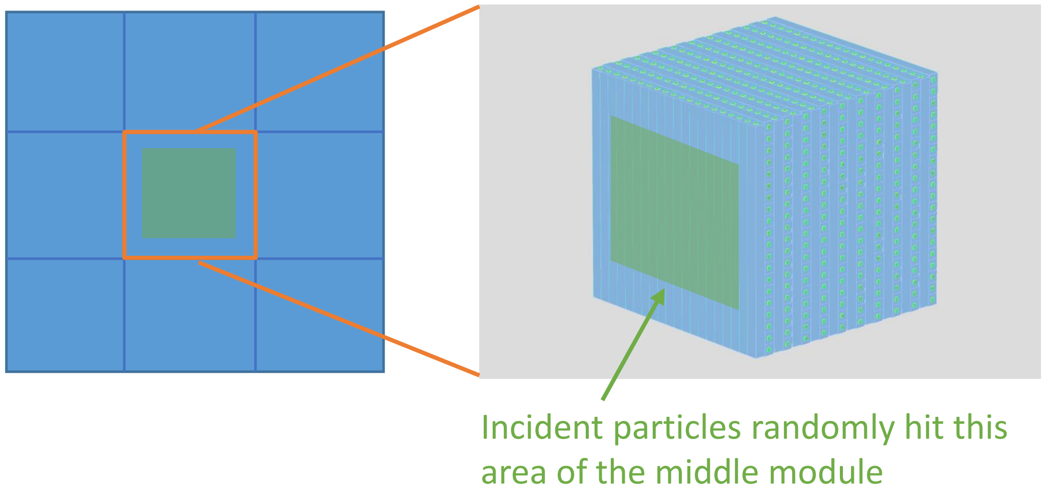
- Responses depend on hit positions
  - Time information for positioning
- Can be calibrated with position information

Response uniformity: impact on energy resolution

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



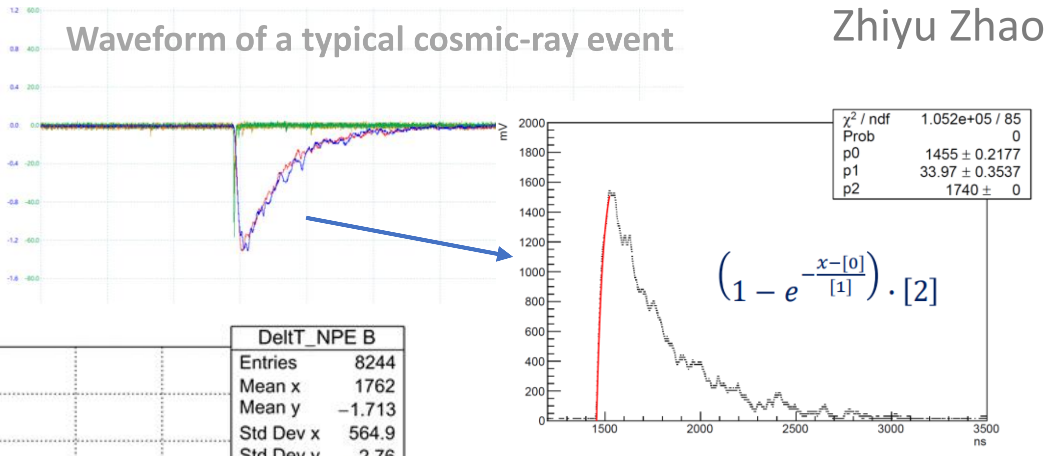


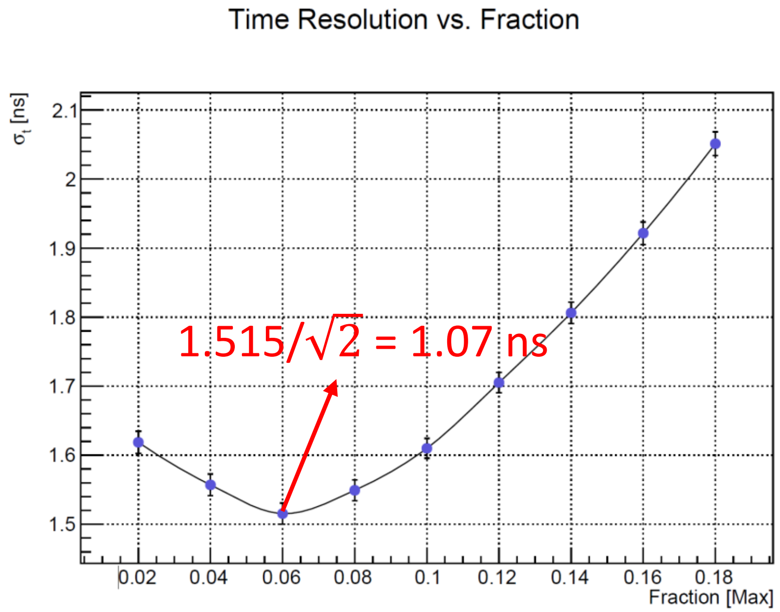
- Severe distortion of energy resolution
  - Effect on energy distribution
  - Major contribution to constant term
- Response non-uniformity need to be calibrated
  - Goal: non-uniformity < 1% after calibration

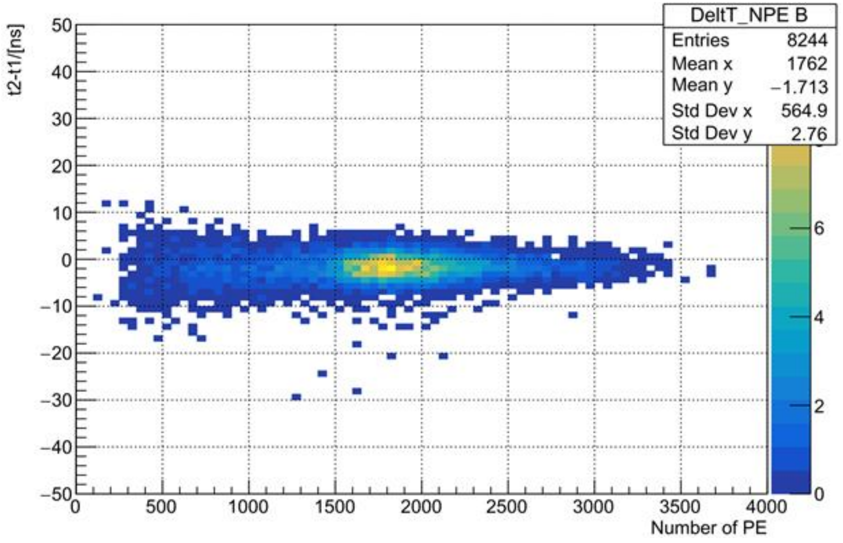
Latest progress on time resolution study

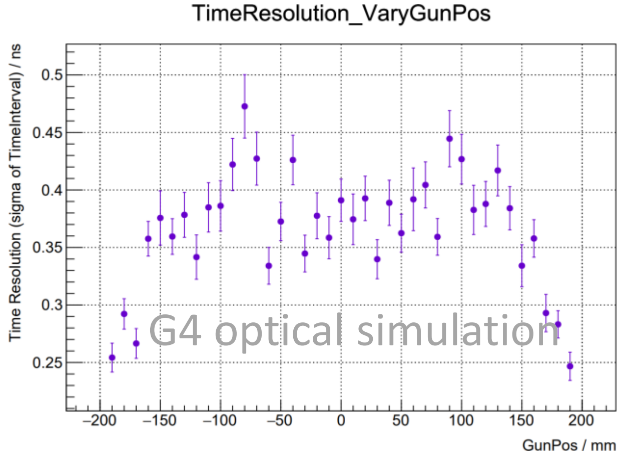
Zhiyu Zhao (SJTU)

- Cosmic-ray events with 400 mm long crystal bar
- Fit the leading edge of SiPM signals
- Timing method: constant fraction







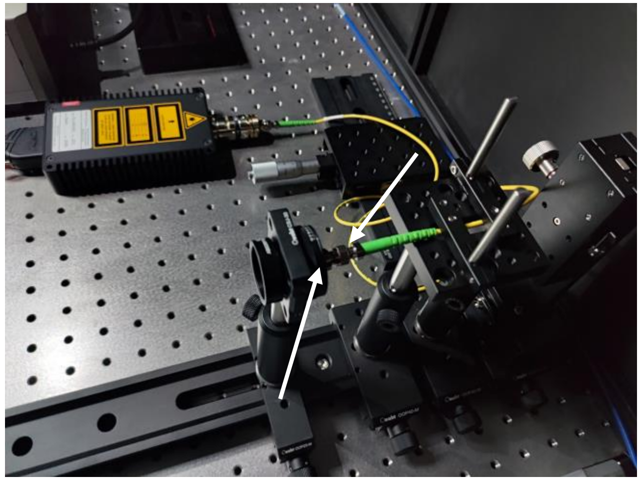
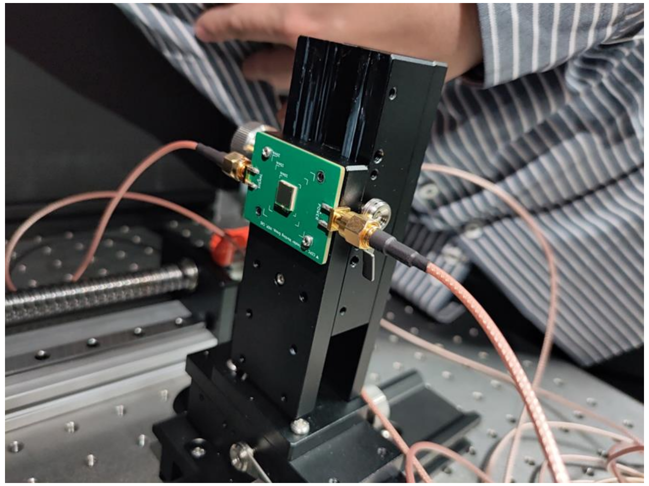
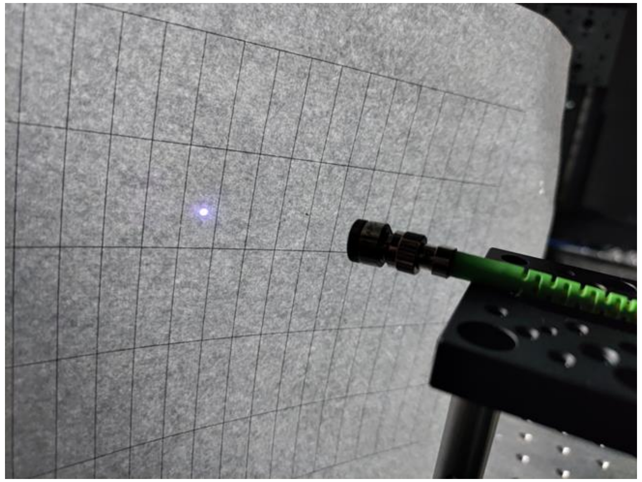


- Large #photons helps to improve time resolution
- Limitations:
  - SiPM signal rising edge, front-end electronics
  - Scintillation properties of BGO crystal, light transmission

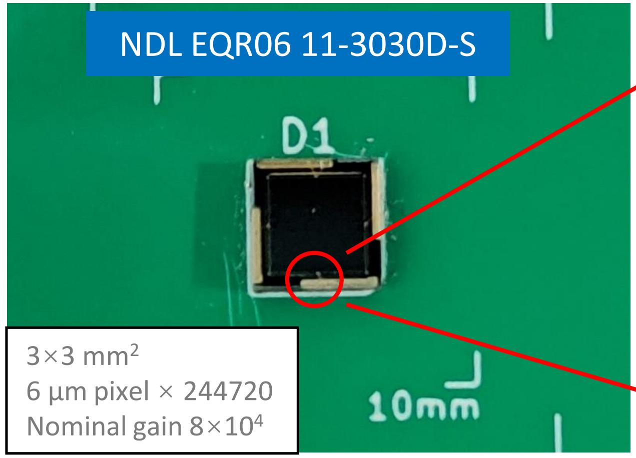
Expected time resolution in simulation: ~400 ps

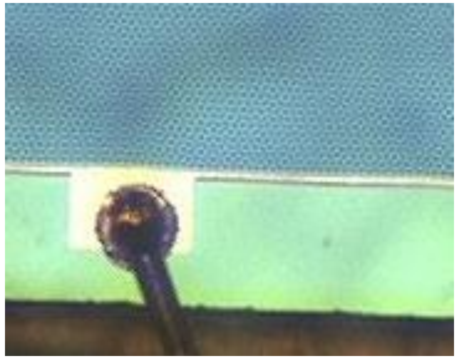
Laser calibration of SiPMs

- Motivation: characterization of large dynamic range SiPMs

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

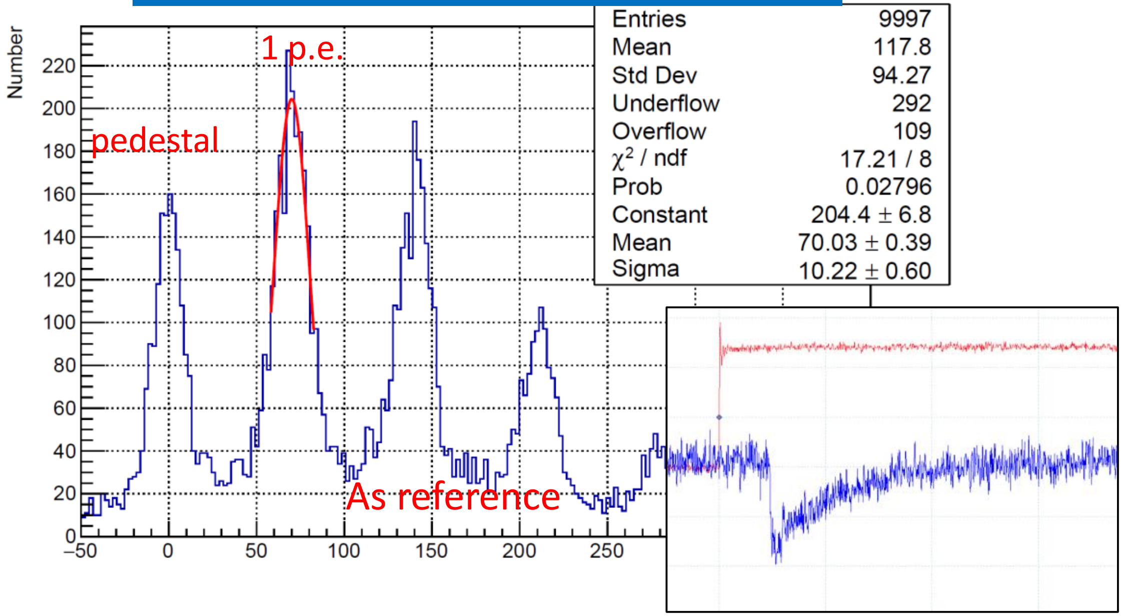




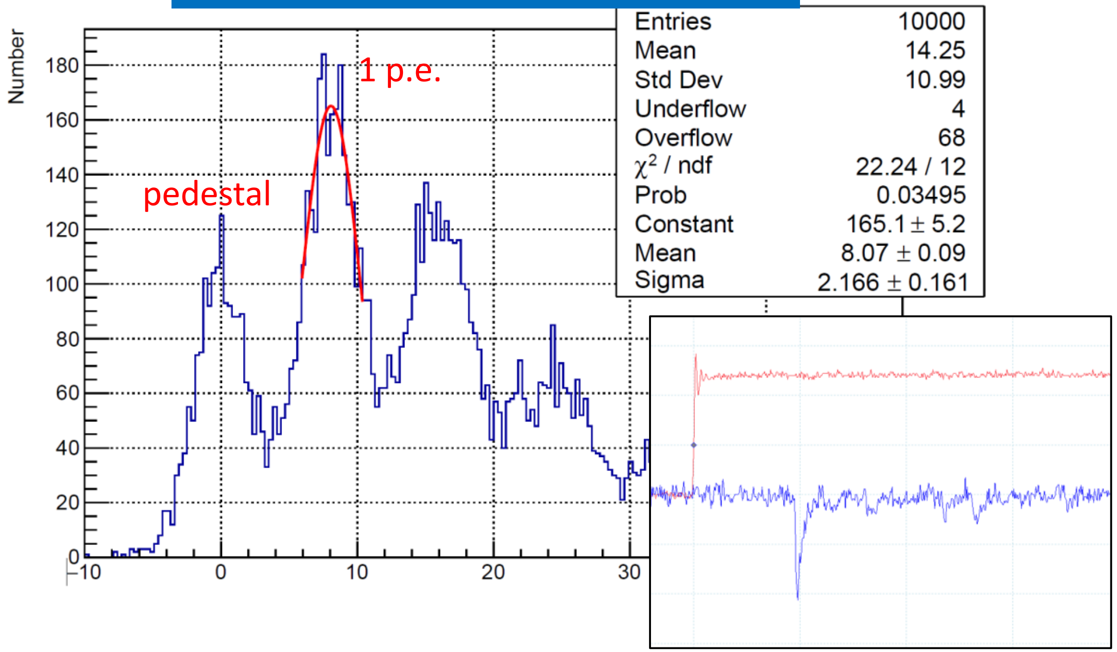
Single photon spectrums of SiPMs

- Single photon spectrums of DUTs

Hamamatsu S13360-6025PE



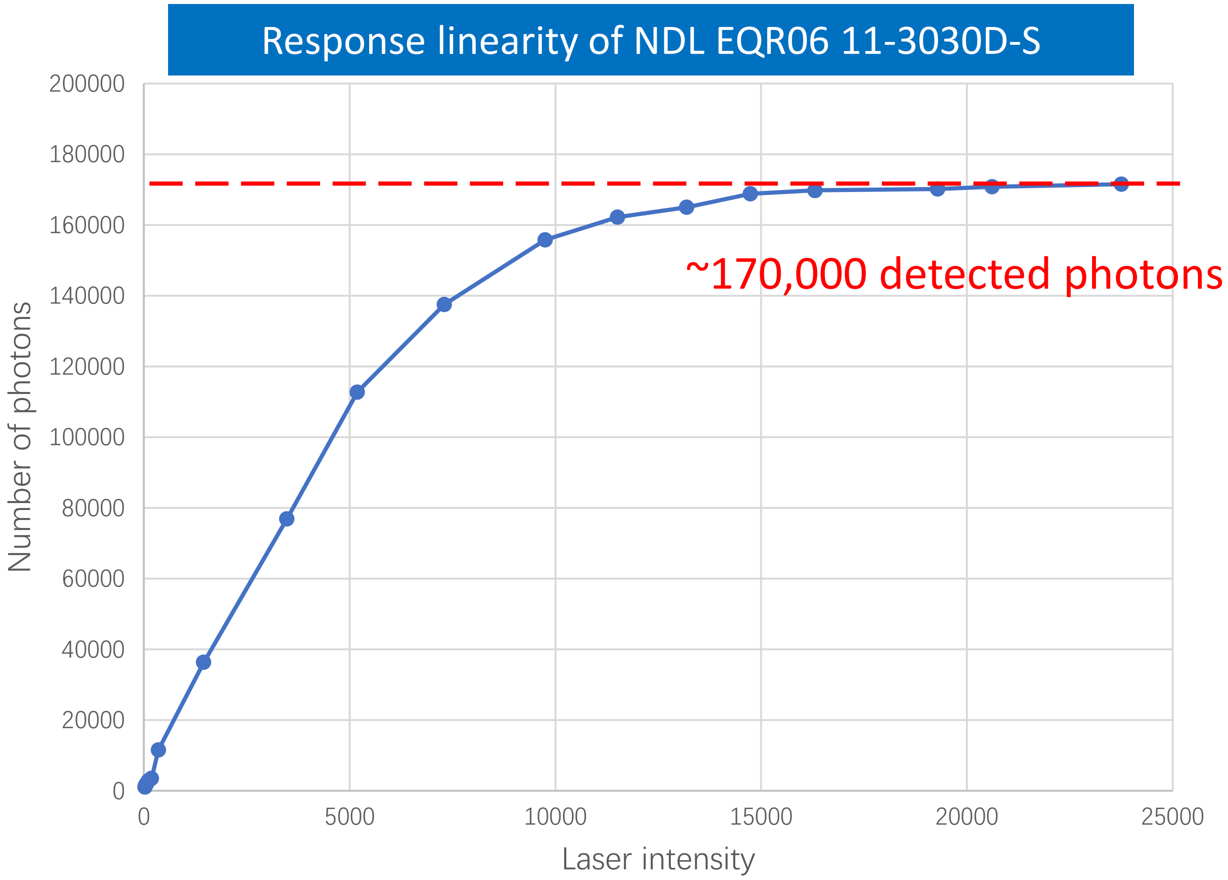
NDL EQR06 11-3030D-S



- 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: SiPM saturation

- Saturation study of NDL EQR06 SiPMs (preliminary results)



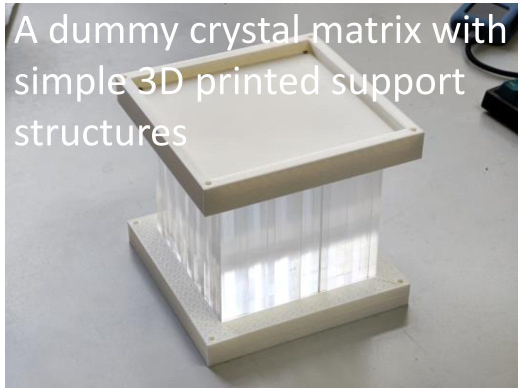
Type	EQR06 11-3030D-S
Effective Pitch	6 μm
Element Number	1×1
Active Area	3.0×3.0 mm^2
Micro-cell Number	244720
Typical Breakdown Voltage (V_B)	24.5 V
Temperature Coefficient for V_B	23 mV / ℃
Recommended Operation Voltage	V_B + 8 V
Peak PDE @420nm	30 %
Gain	8.0×10^4
Dark Count Rate (DCR)	276 kHz / mm^2
Terminal Capacitance	5.1 pF / mm^2

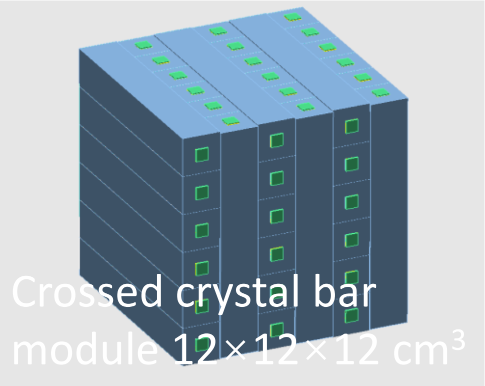
Above parameters are measured at their recommended operation voltage and 20 ℃.

- Laser test: photons arrived at the same time (within ~60 ps), recovery effect excluded
- NDL EQR06 SiPMs: larger dynamic range expected due to a short recovery time
- Ongoing work for better photon calibration

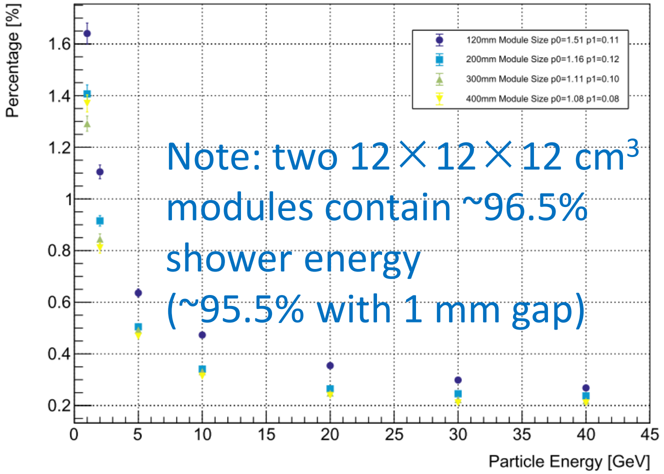
Small-scale detector module design

- Motivations: to develop crystal modules
  - Identify critical questions/issues on system level
- Key issues
  - Mechanical design: crystal fixture, tolerance, gaps
  - Electronics: front-end ASIC options
  - Temperature control and monitoring: case and sensors
  - Dynamic range of SiPMs and FEE: crucial question
- Preparations for future beam tests
  - Energy resolution, shower profiles

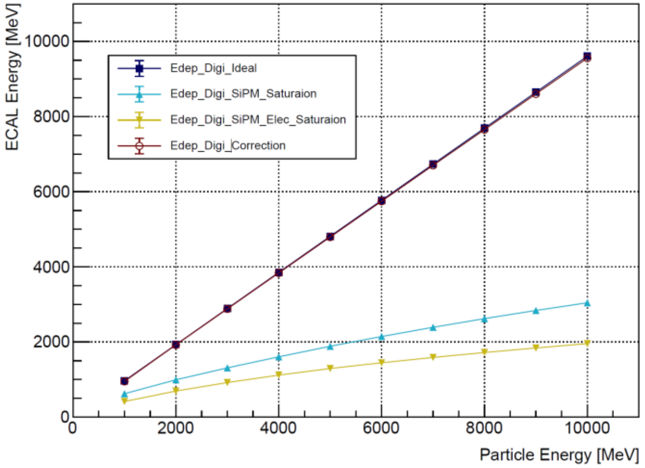


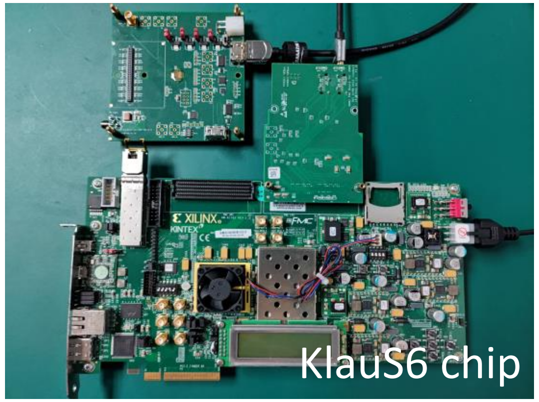


Impact of module size on energy resolution



Impact of saturation on energy linearity





A5202 unit (FERS-5200)

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	< 0.5 mm (?)	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:

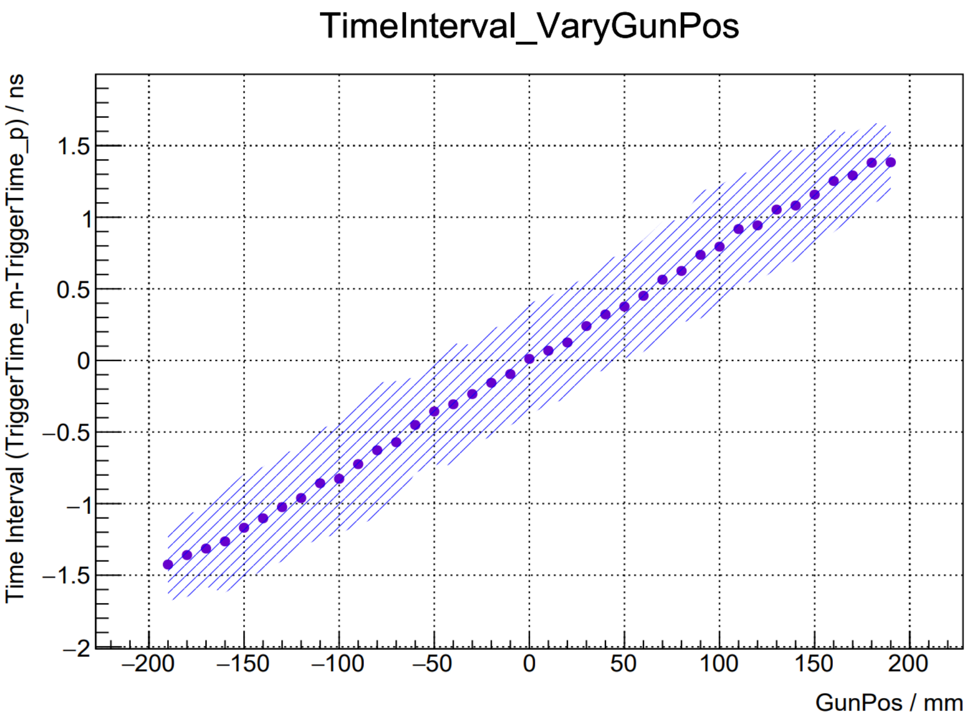
- Performance studies: PFA & reconstruction algorithm
- Hardware development

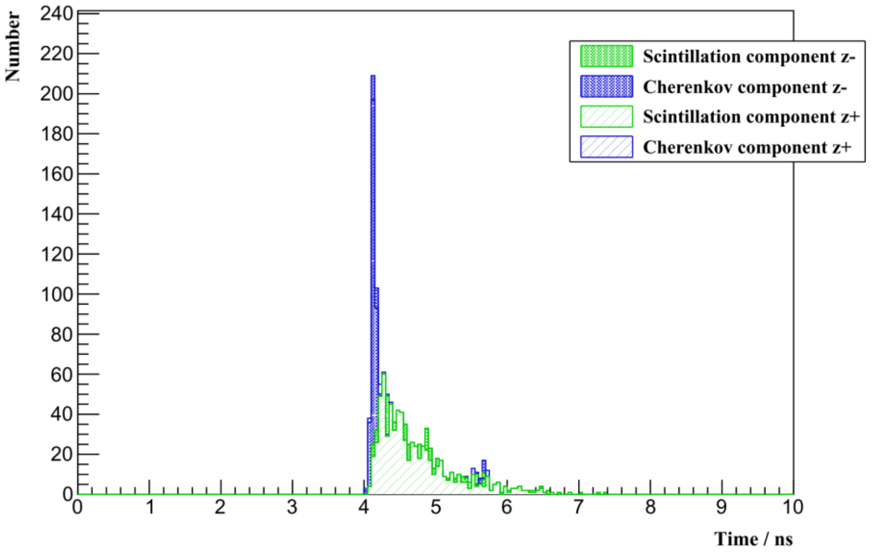
- Prospects
  - Challenge on PFA: still optimizing
  - Detailed simulation studies on crystal ECAL performance
  - Address key issues of crystal ECAL through module development

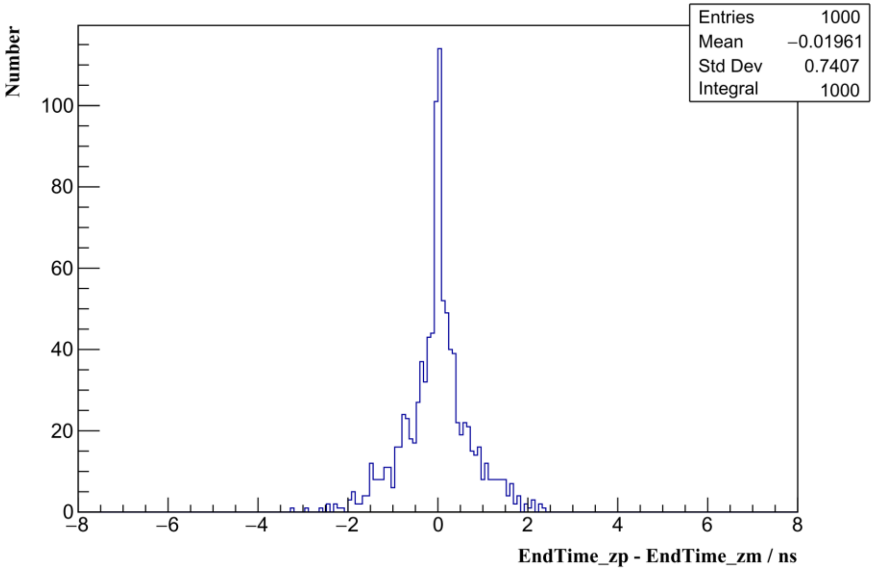
Backup

Latest progress in time resolution study

- Simulation: time resolution of long crystal bars

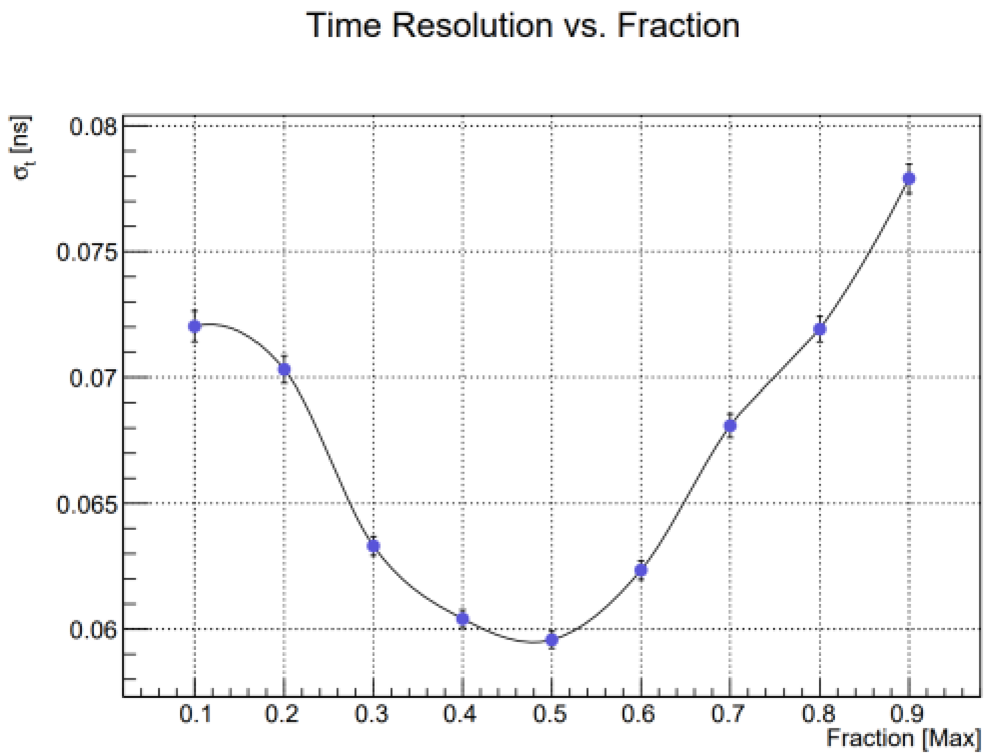


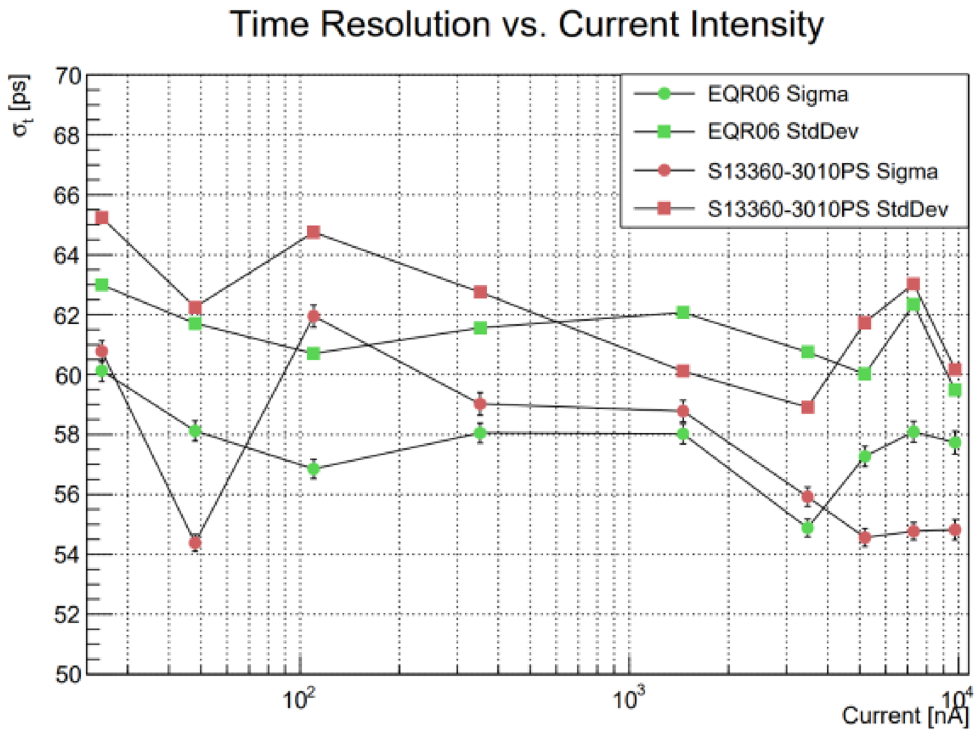




Latest progress in time resolution study

- Time resolution of SiPMs with picosecond laser
- Limited by the sampling rate of the oscilloscope





50% Fraction