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

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A novel high-granularity crystal calorimeter

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On behalf of CEPC Calorimeter Working Group

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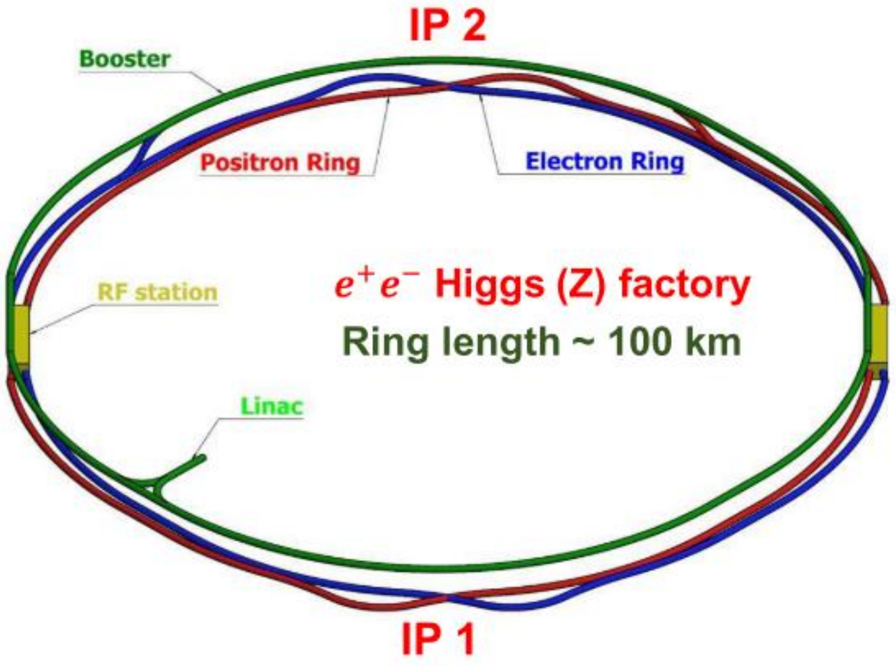
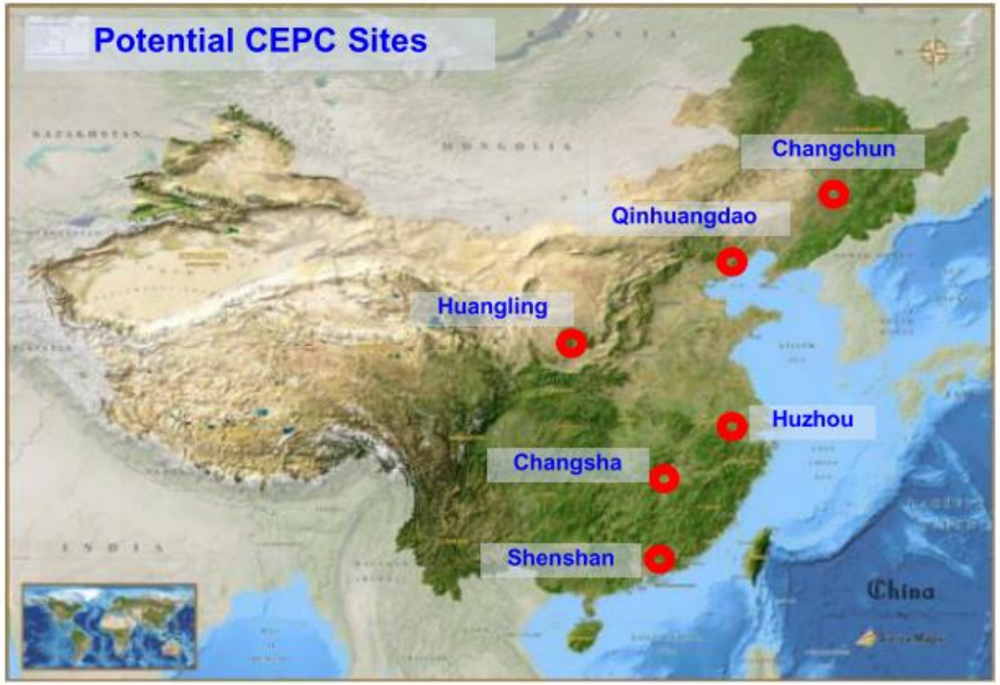
CEPC overview

- The CEPC aims to start operation in 2030's, as a Higgs (Z/W) factory in China.
- To run at $\sqrt{s}$ ~ 240 GeV, above the **ZH** production threshold for ~1M Higgs; at the **Z** pole for ~Tera Z, at the **W^+W^-** pair, and possible $t\bar{t}$ pair production threshold.
- Higgs, EW, flavor physics & QCD, BSM physics (eg. dark matter, EW phase transition, SUSY, LLP, ….)
- Possible Super *pp* Collider (SppC) of $\sqrt{s}$ ~ 50–100 TeV in the future.

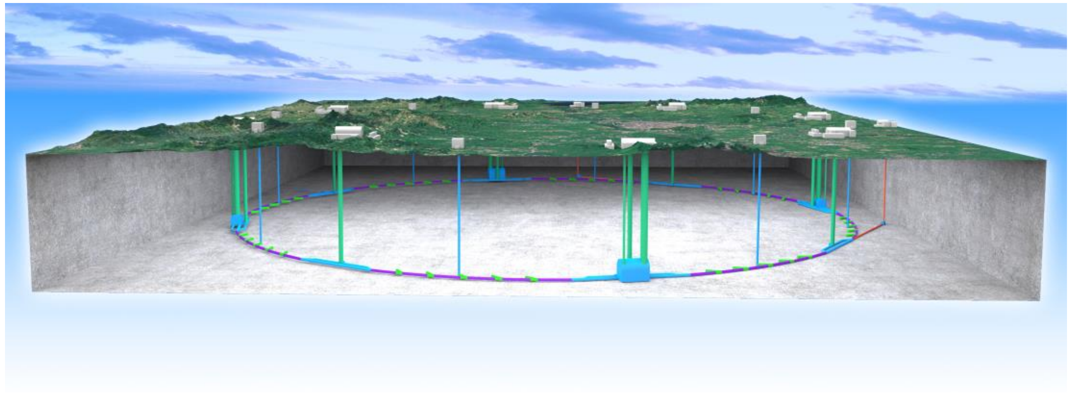


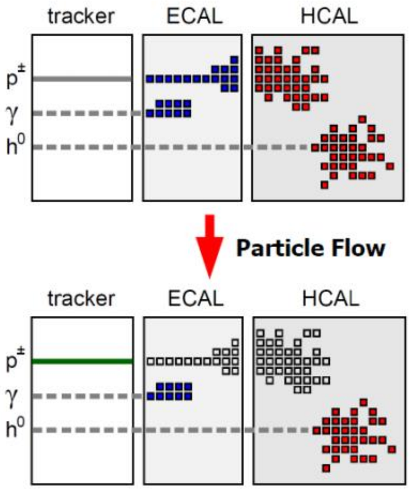


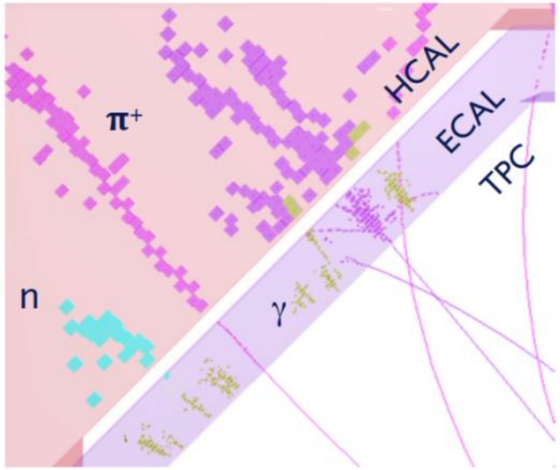
More details:
Haijun Yang's talk on *Joint Workshop of the CEPC Physics, Software and New Detector Concept in 2022*

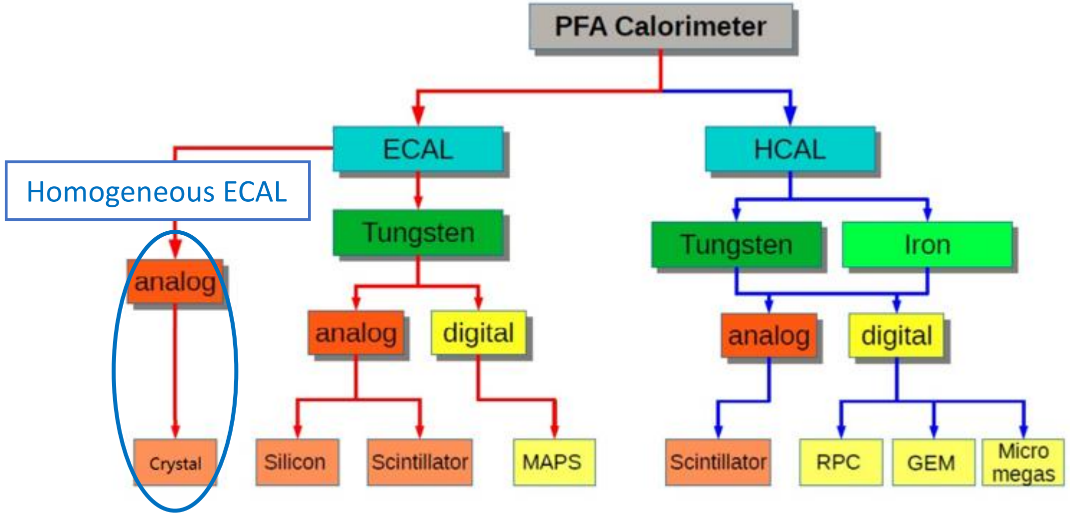
Motivations for crystal ECAL

- 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





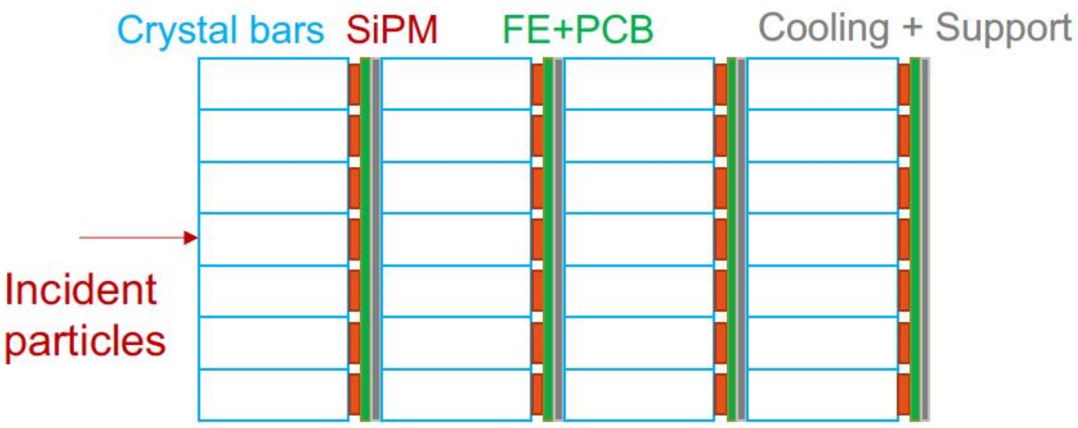




Two designs of crystal ECAL

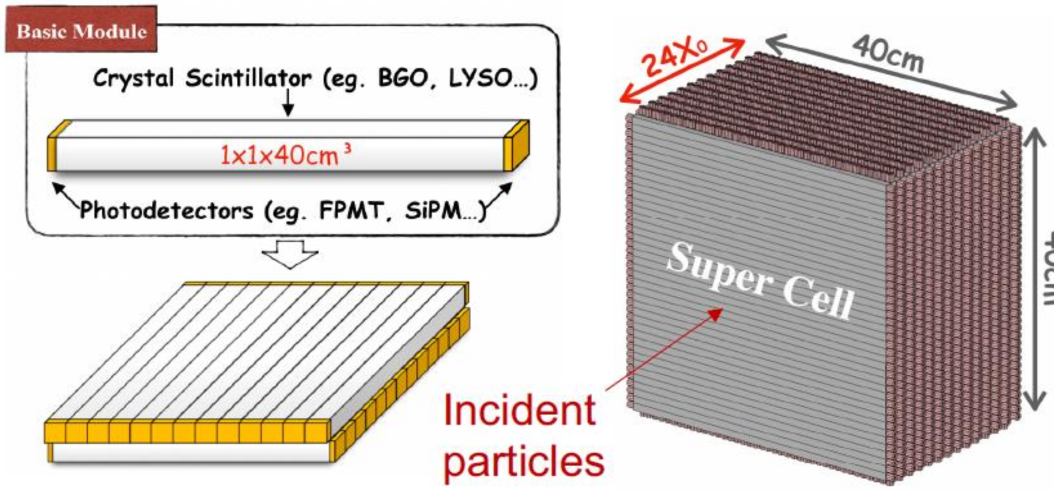
Our major focus

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



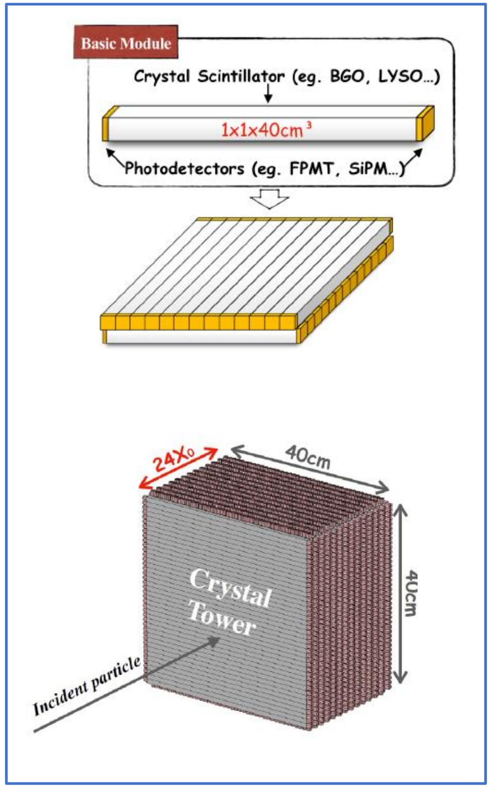
- Long bars: 1×1×40 cm, double-sided readout
  - Super cell module: 40×40 cm
  - Crossed arrangement in adjacent layers
  - Fine longitudinal granularity
- Save #channels and minimize dead materials
- Timing at two sides: positioning along bar

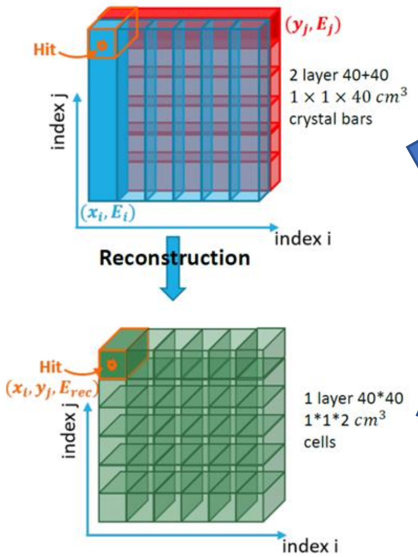
Outline: R&D of a highly granular crystal ECAL

- Performance studies
  - Evaluate physics potentials
    - 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

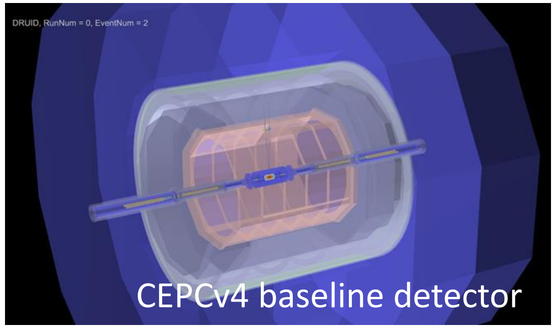
Performance evaluation

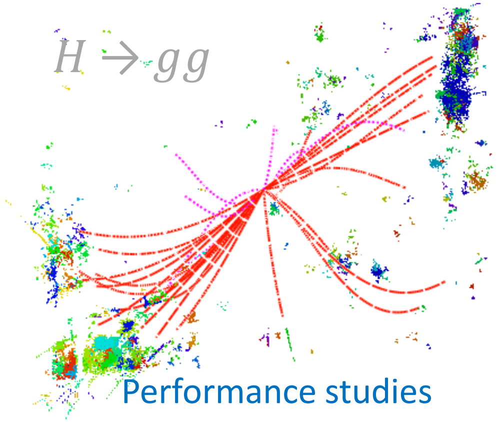
- Adapted from CEPC baseline detector
- Application and optimization of Arbor-PFA

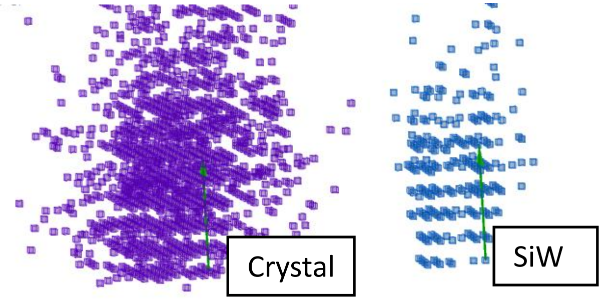




Crossed long bar design: $1\times1\times2$ cm^3 granularity after digitization





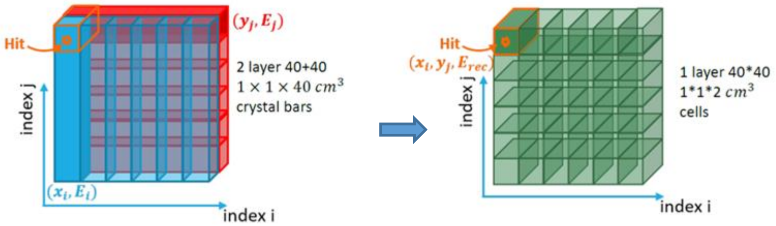


Event display: crystal compared to SiW: significant increase of #hit

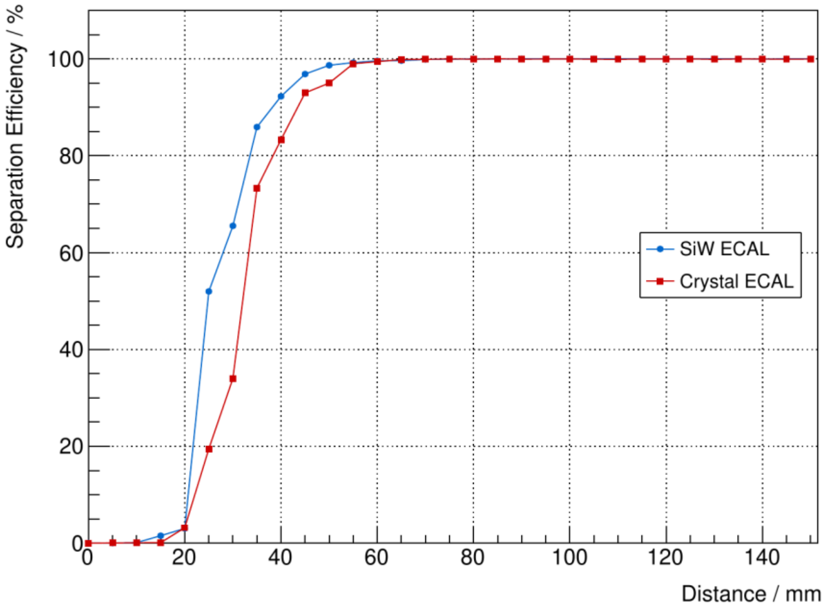
Arbor-PFA: necessary to be optimized for crystal ECAL design

Separation power

- Reconstruction of jets: separation power of close-by particles
- Arbor-PFA: ongoing optimization
  - First find the shower core/axis to separate particles, then do clustering for better energy resolution

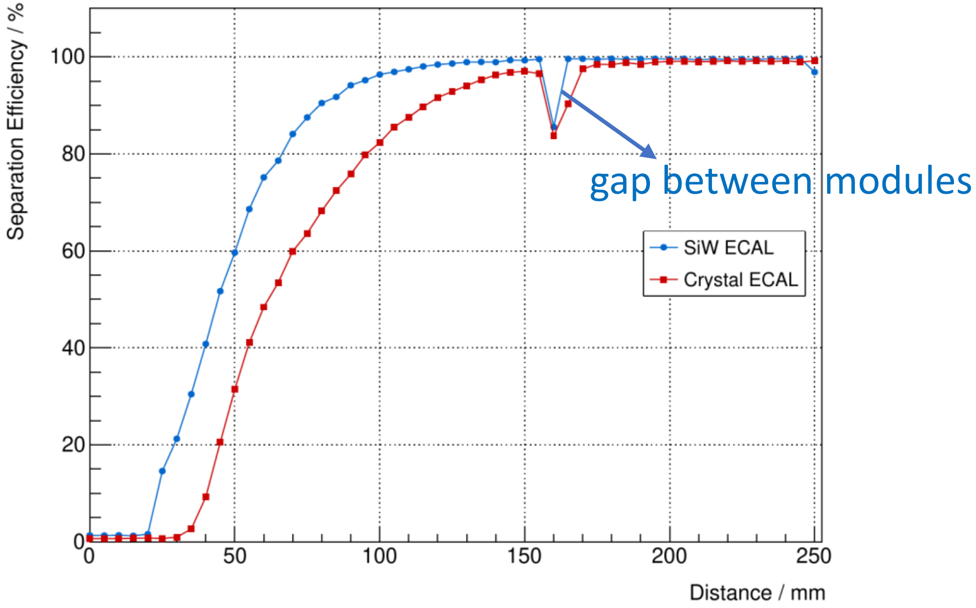


γ/γ separation study with barrel ECAL

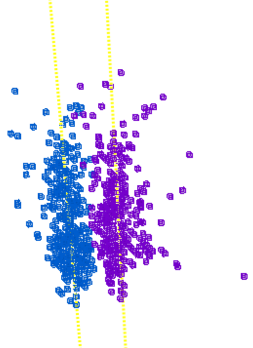


- EM shower: good separation power

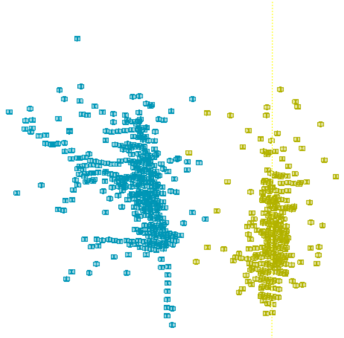
π^{+}/γ separation study with barrel ECAL



- Hadronic shower: challenge on clustering
- Key question: matching clusters of charged particle to their tracks



Separated γ/γ

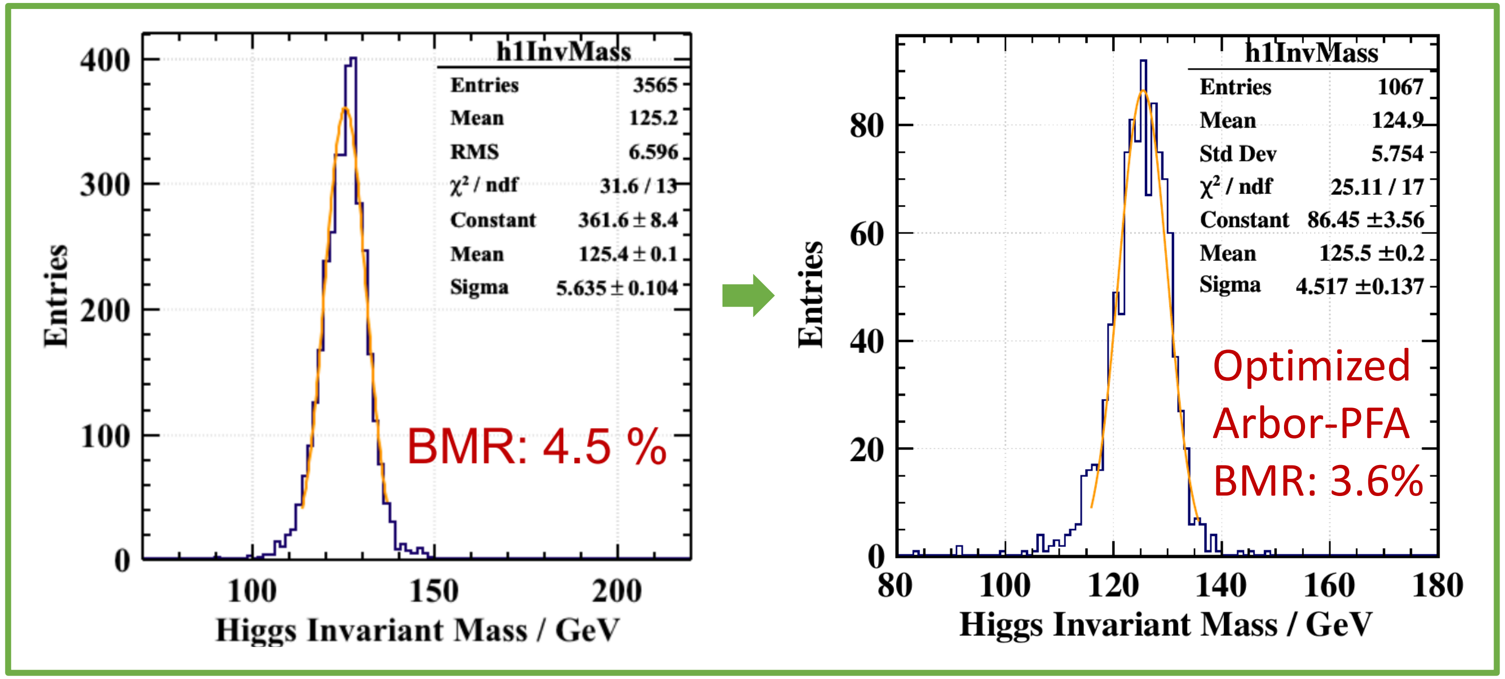


Separated π^{+}/γ

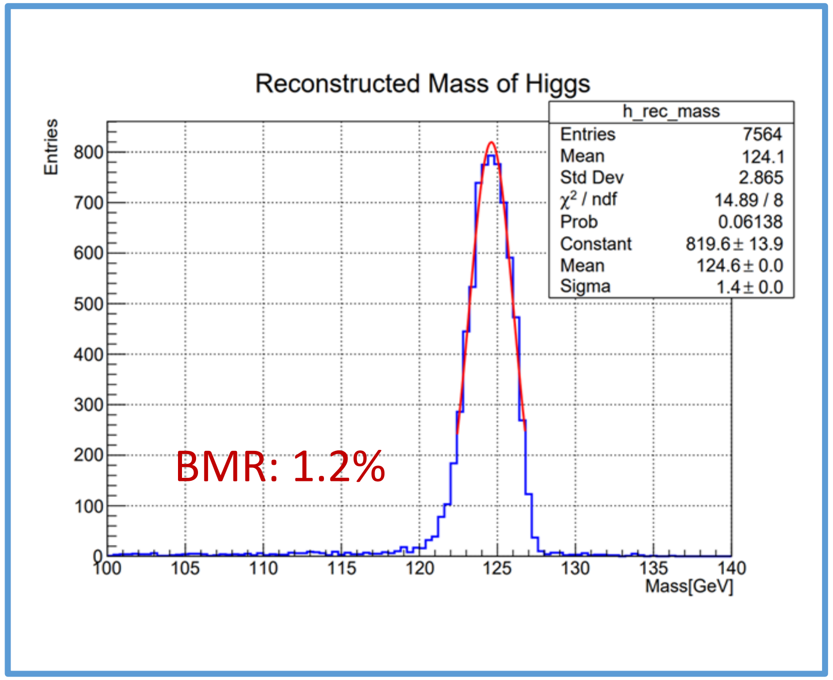
Higgs benchmarks

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

BMR $(H \rightarrow gg)$



BMR $(H \rightarrow \gamma\gamma)$

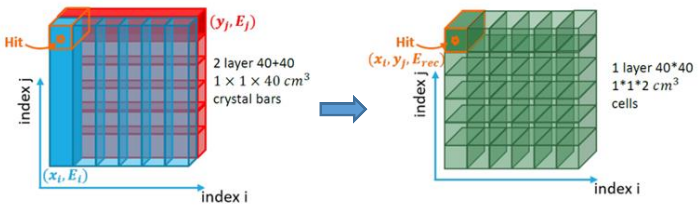


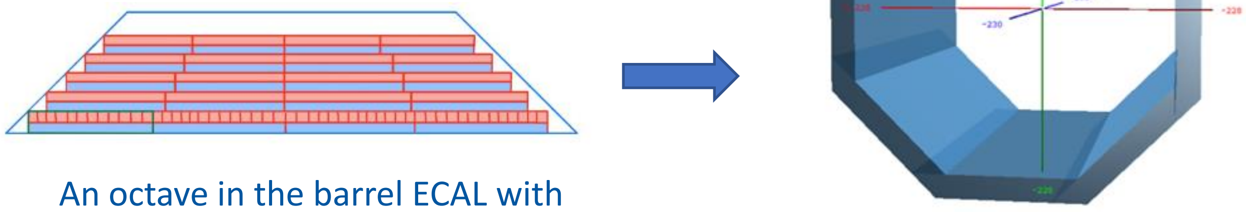
- Significant improvement after Arbor-PFA algorithm optimization
- On-going optimization and further BMR study…

Reconstruction algorithm dedicated to long bar design

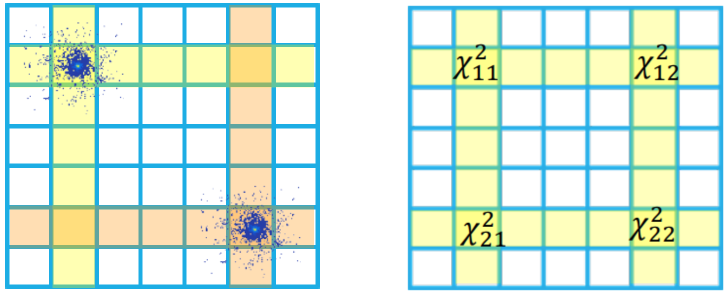
Fangyi Guo, Weizheng Song, Shengsen Sun, Linghui Wu, Yang Zhang (IHEP)

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

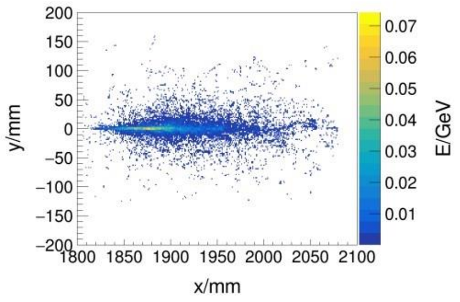




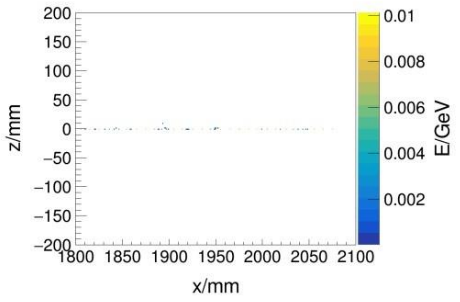
An octave in the barrel ECAL with crossed long crystal bars



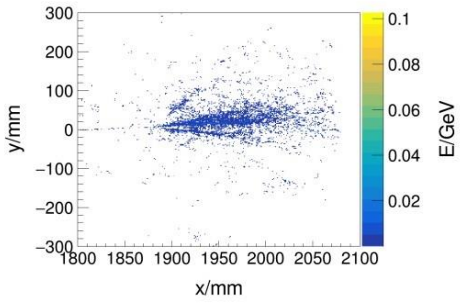
Remove ghost hits



EM cluster



MIP cluster



Hadronic cluster

Outline: R&D of a highly granular crystal ECAL

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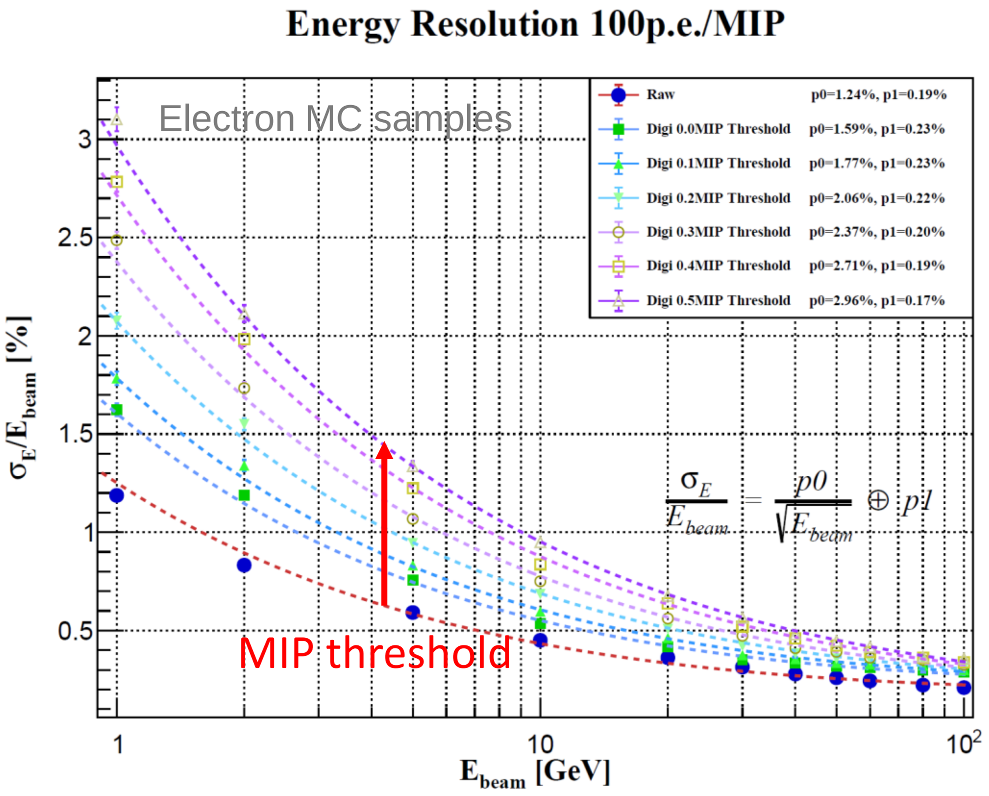
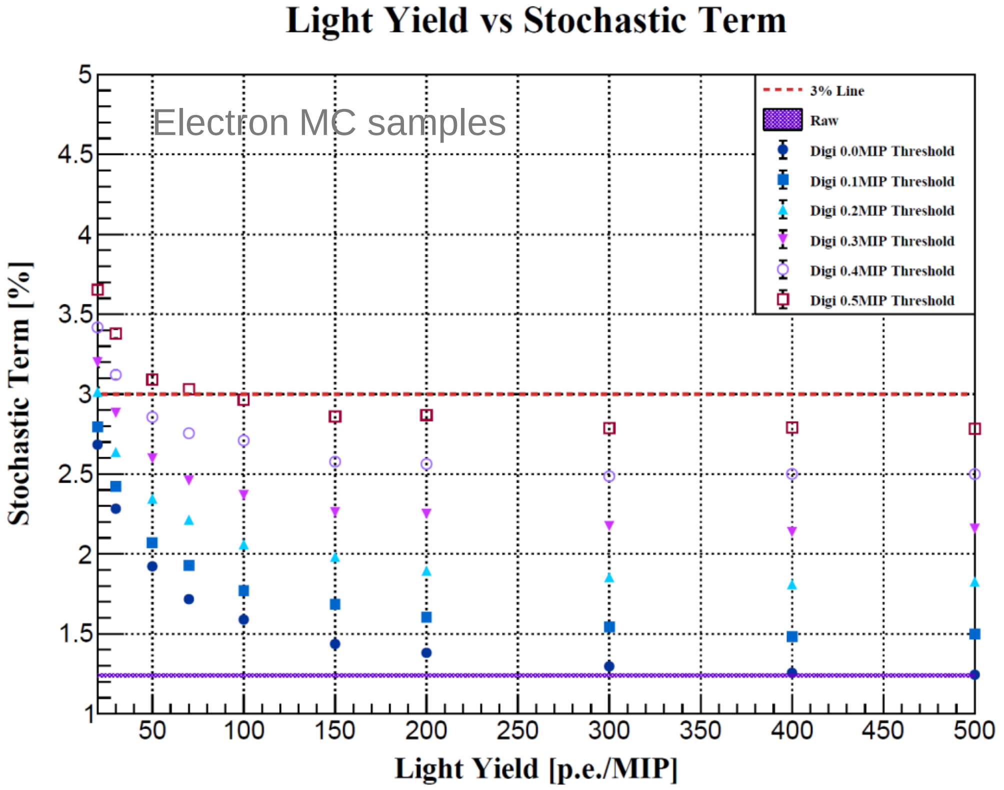
  - Detector unit characterization
    - Cosmic-ray and radioactive source tests
  - Response uniformity
  - Time resolution
  - SiPM characterization
  - Small-scale detector module design

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

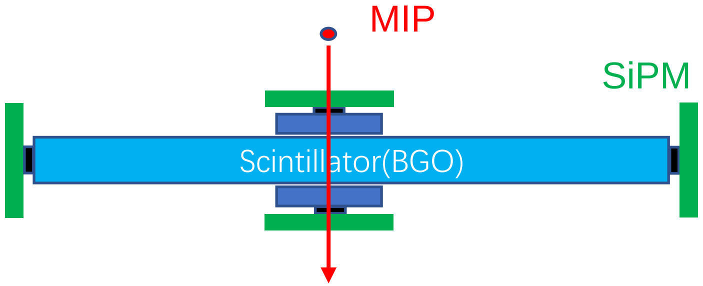




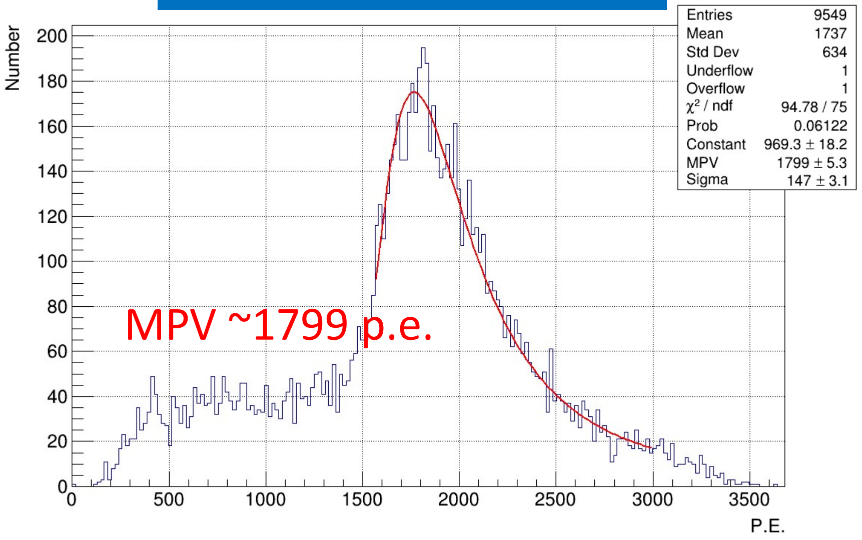
- Moderately high light yield (#detected photons) and low threshold required
- Low energy threshold can be feasible with low crosstalk SiPMs
- >100 p.e./MIP light yield is enough for $\sim 3\%/\sqrt{E}$ energy resolution

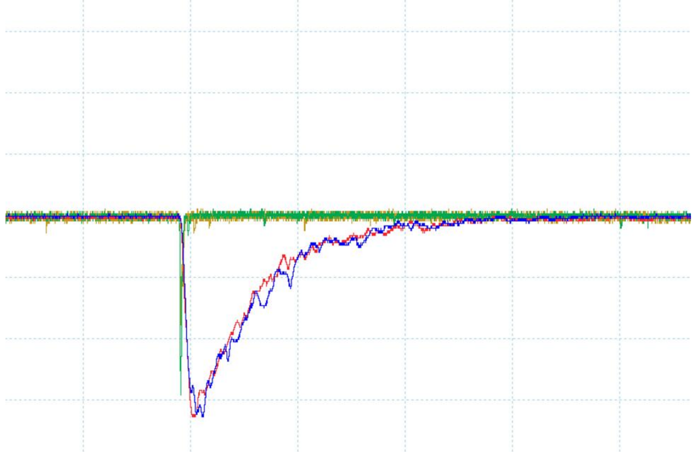
Cosmic-ray test of long crystal bar

- $400\times10\times10$ mm^3 long BGO crystal bar, ESR wrapping
- SiPM readout at both two ends
- Energy deposition in Geant4 simulation: 9.1 MeV/MIP

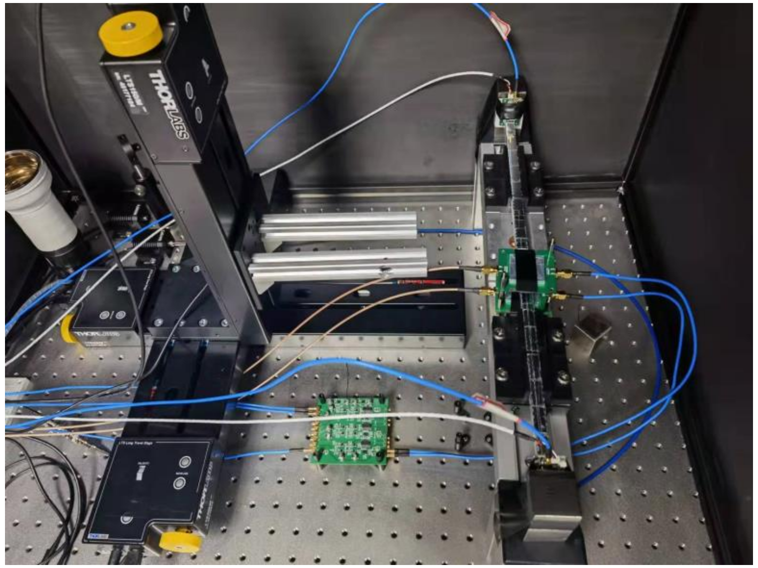


Cosmic-ray test





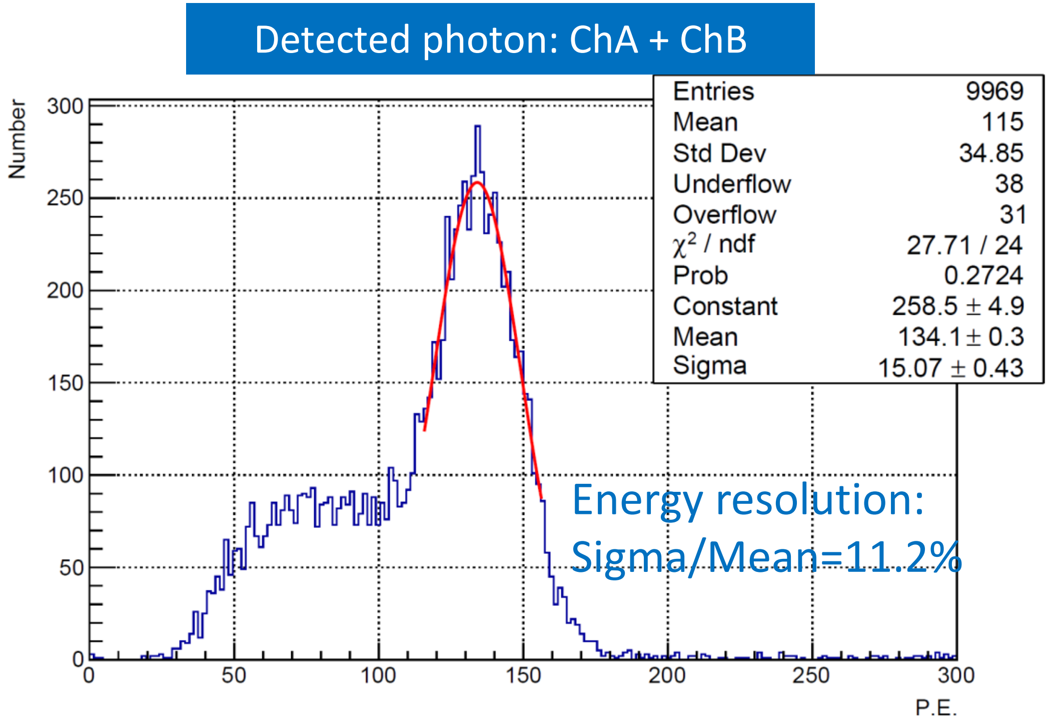
Waveform of a typical cosmic-ray event

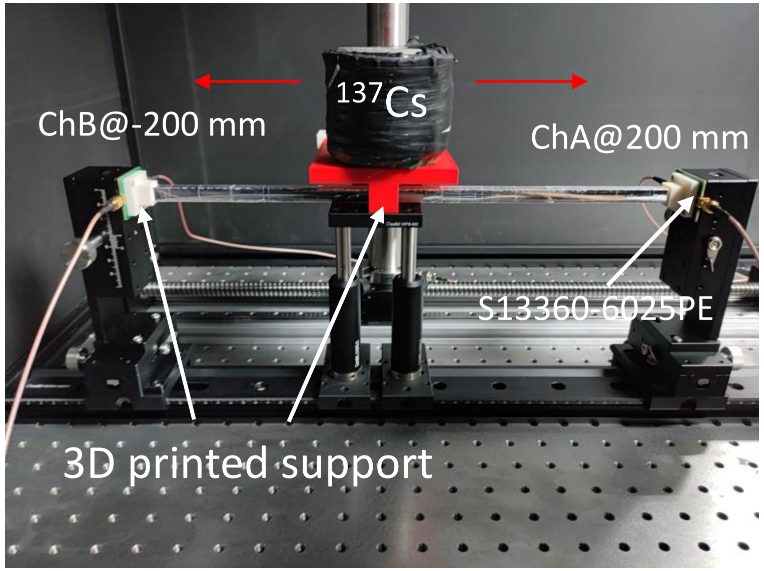


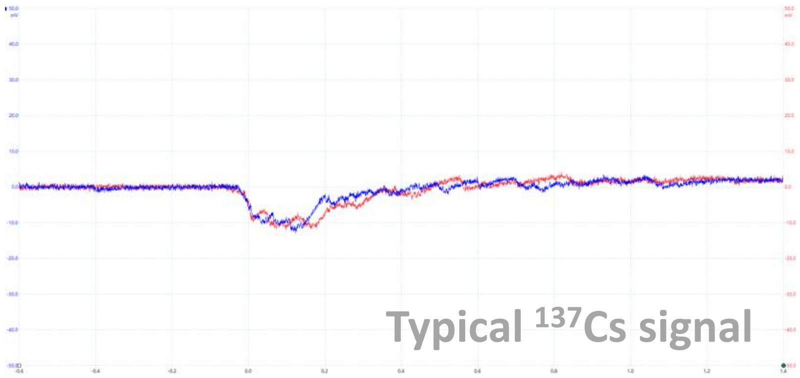
- BGO crystal: high enough light yield

Energy calibration with ^{137}Cs radioactive source

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



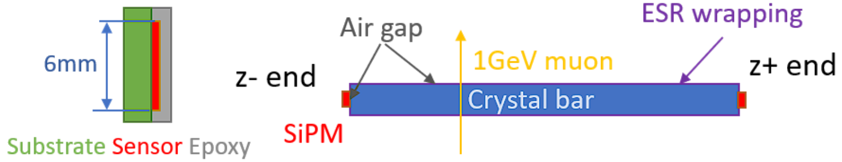




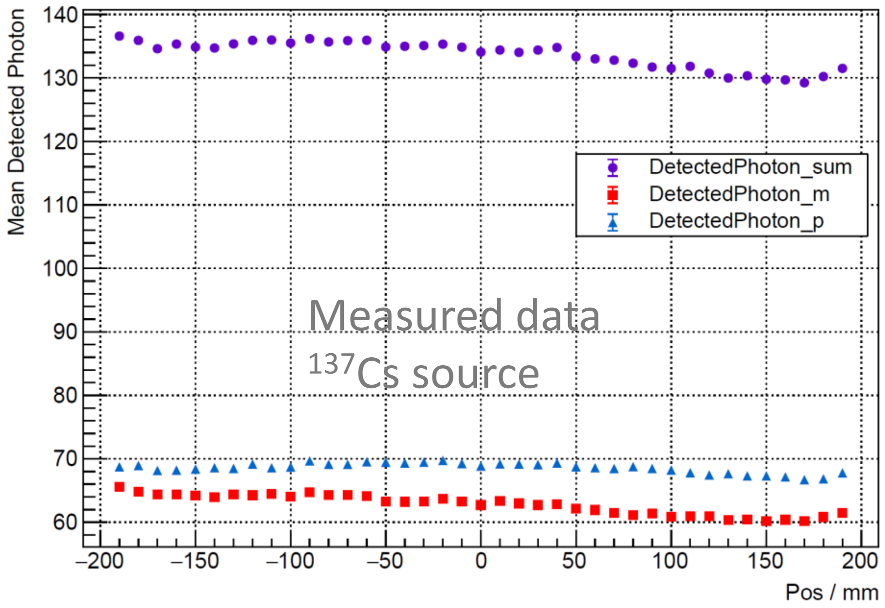
Study on response uniformity of a long crystal bar

Geant4 Simulation (v10.7.3)

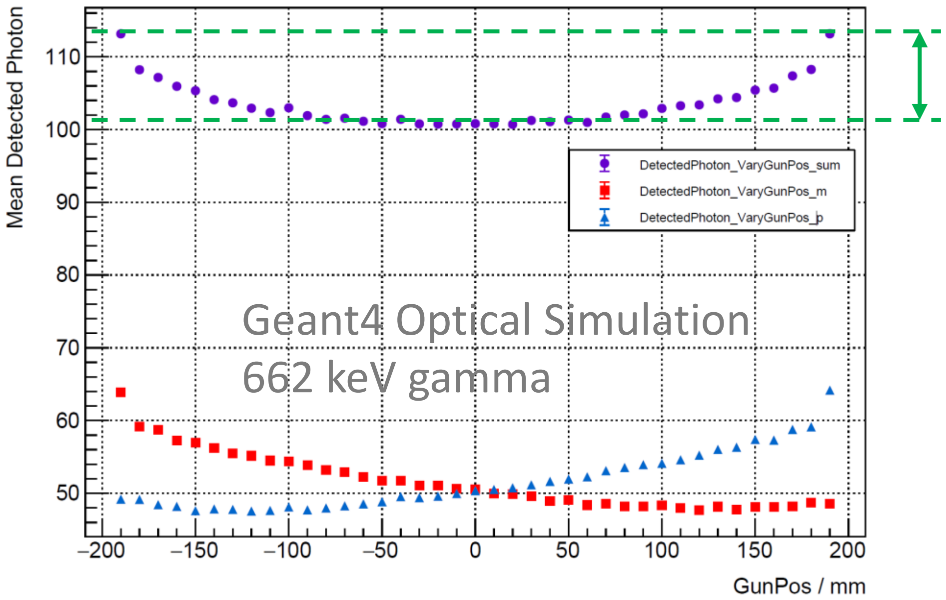
- Uniformity scan: 662 keV gamma for ^{137}Cs, change hit positions
- Geant4 optical simulation: a single BGO crystal bar wrapped with ESR film



Experiment: detected photon



Simulation: detected photon



10% non-uniformity

- Relatively low response near one side: surface defects
- Need more repetitive experiments

- ~10% non-uniformity with current simulation parameters

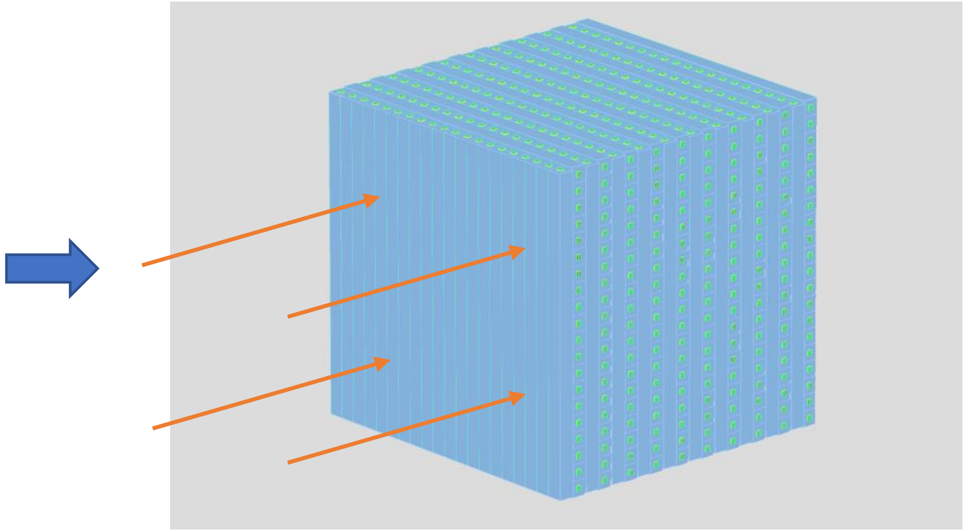
Potential factors: surface defects, coupling...

MIP response uniformity of crystal ECAL module

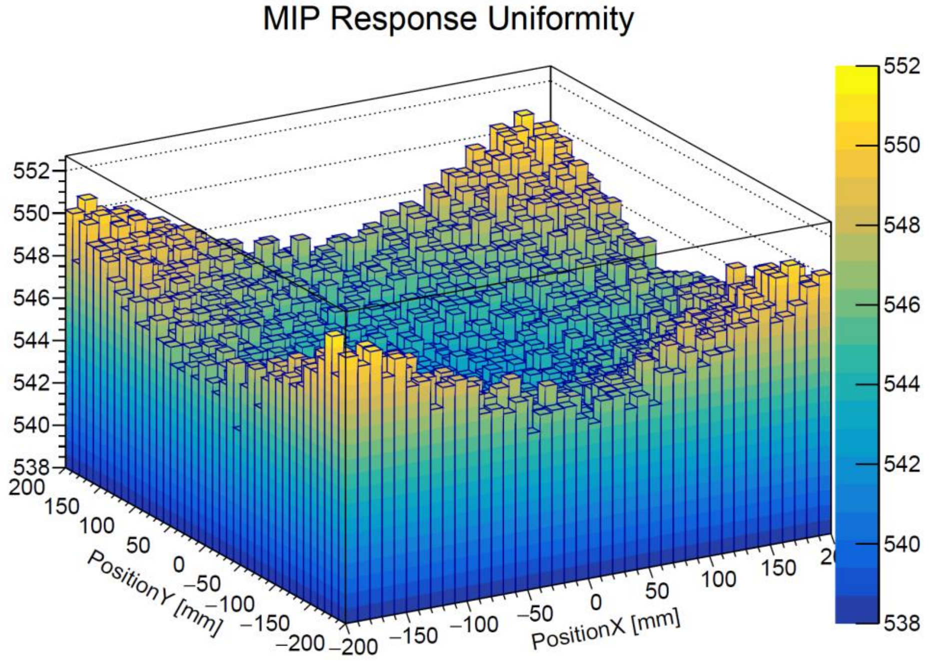
Geant4 Simulation (v10.7.3)

- Simulation setup
  - 400×10×10 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

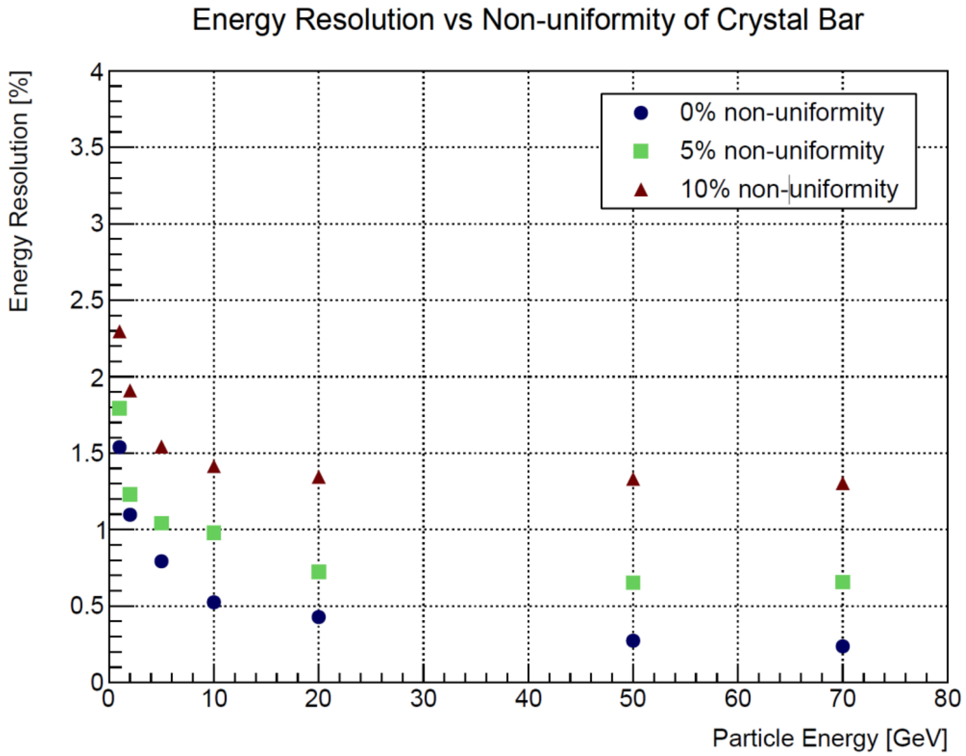


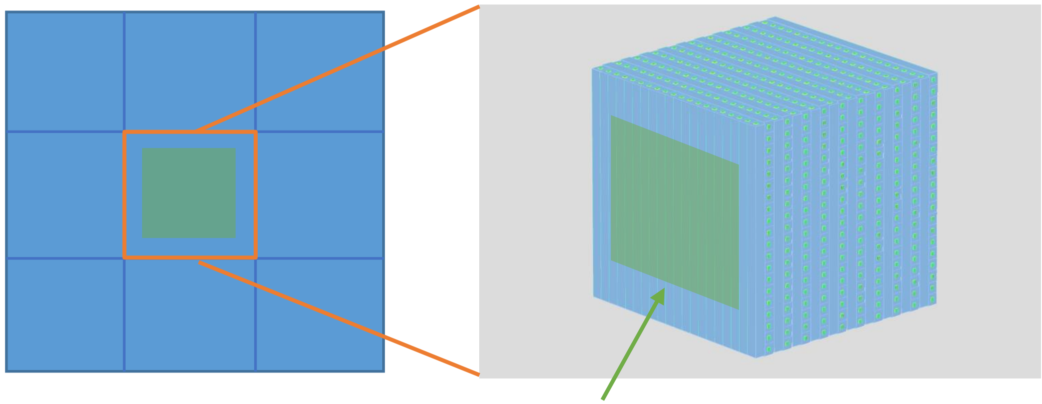
- Responses depend on hit positions
  - Time information for positioning
- Can be calibrated with position information

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





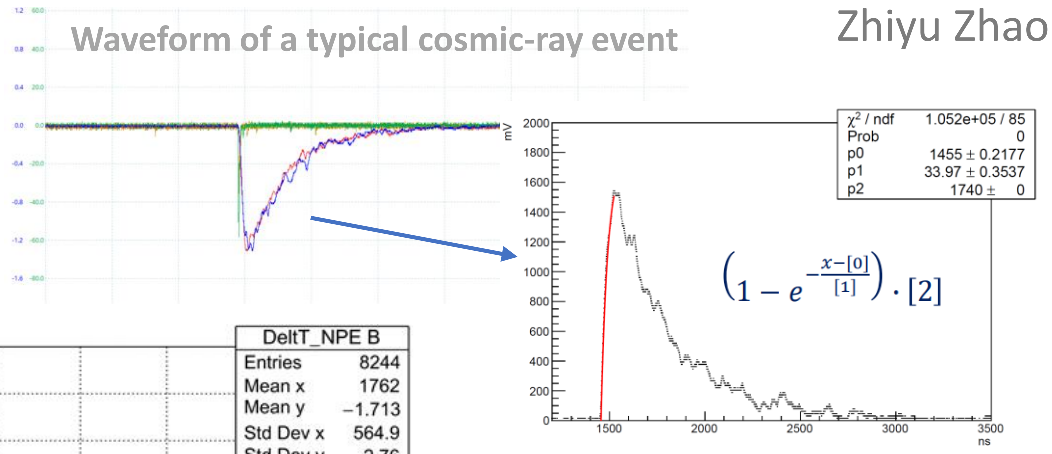
Incident particles randomly hit this area of the middle module

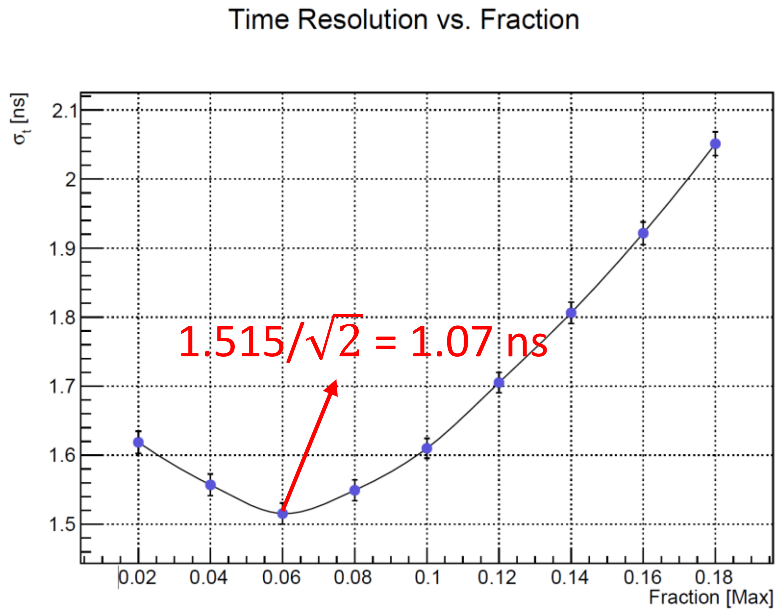
- Severe distortion of energy resolution
  - Effect on energy distribution
  - Major contribution to constant term
- Response non-uniformity need to be calibrated
  - Goal: non-uniformity < 1% after calibration

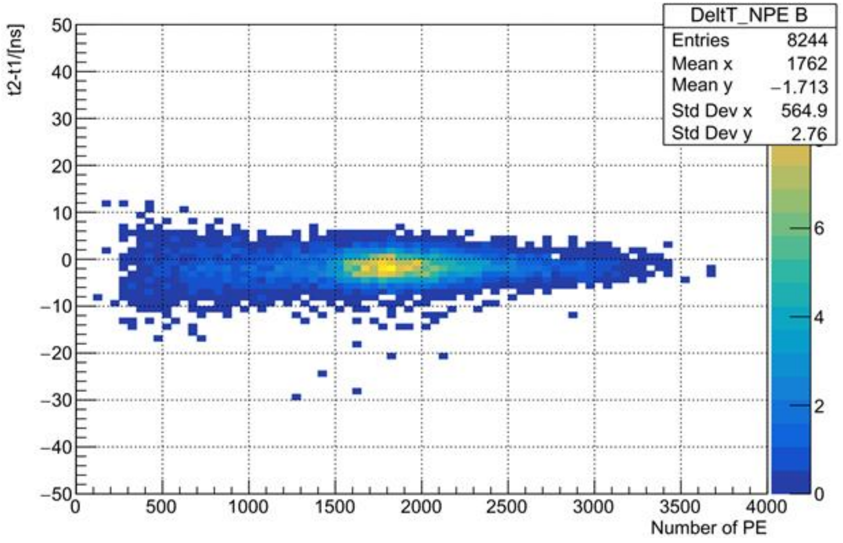
Latest progress on time resolution study

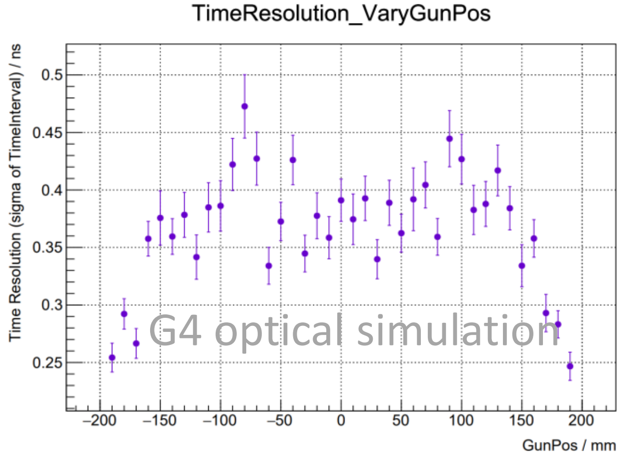
Zhiyu Zhao (SJTU)

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







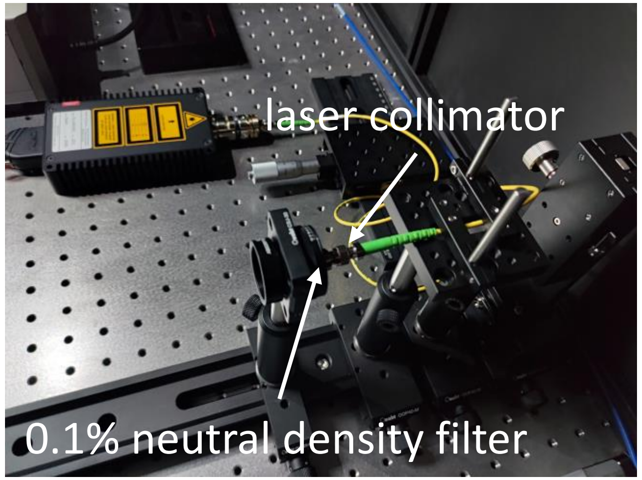


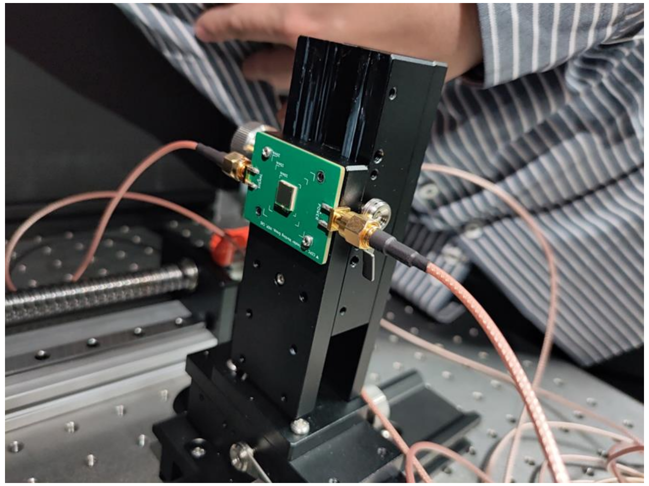
- Large #photons helps to improve time resolution
- Limitations:
  - SiPM signal rising edge, front-end electronics
  - Scintillation properties of BGO crystal, light transmission

Expected time resolution in simulation: ~400 ps

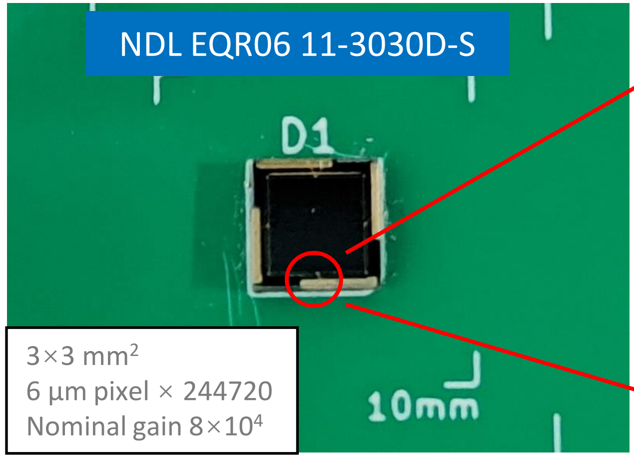
Laser calibration of SiPMs

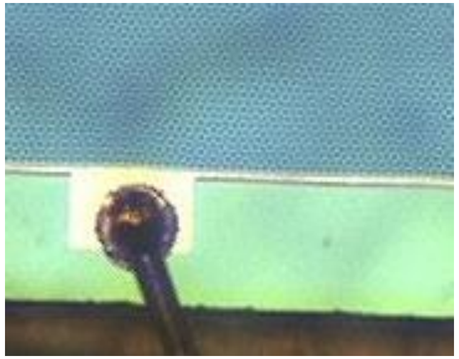
- Motivation: characterization of large dynamic range SiPMs





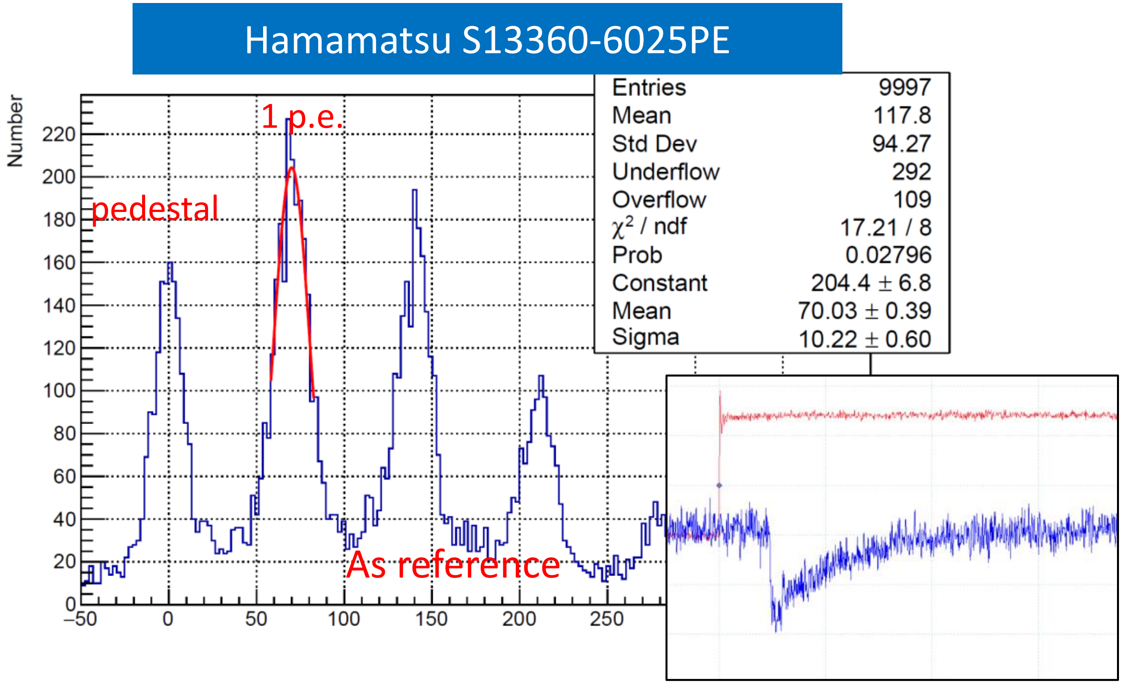
- DUT: Hamamatsu & NDL SiPMs, large size and small pixel pitch SiPMs are preferred

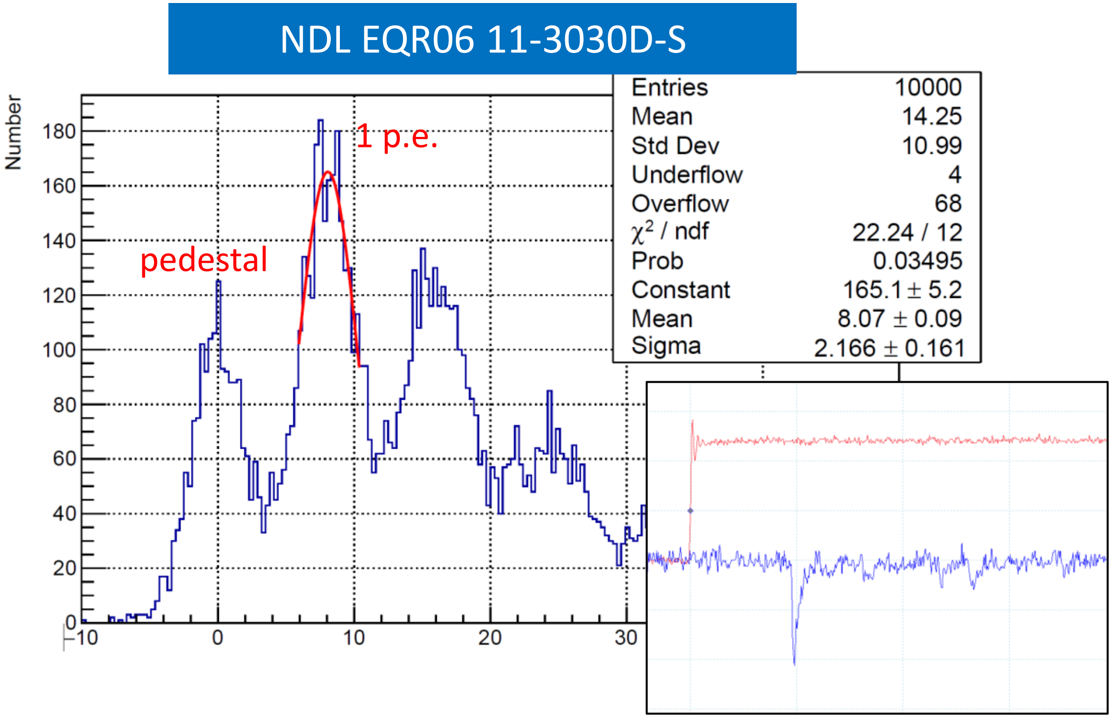




Single photon spectrums of SiPMs

- Single photon spectrums of DUTs

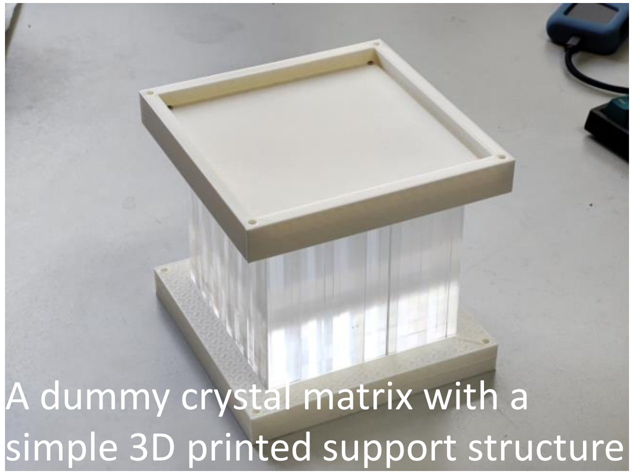


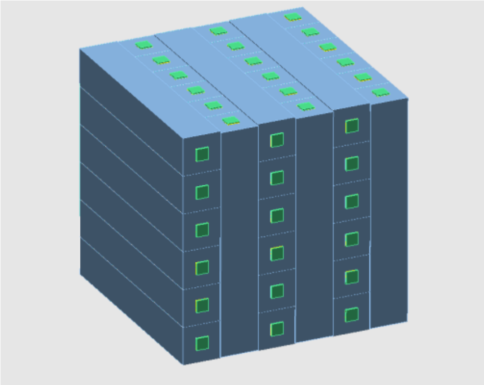


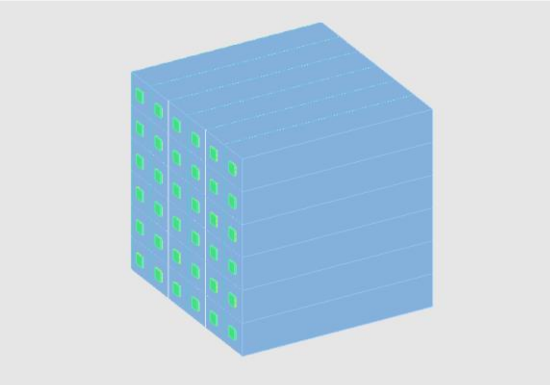
- Criteria for SiPMs: dynamic range, gain, price, crosstalk, capability of single photon detection…
- NDL EQR06 series with 6 μm pixel and 3×3 mm^2 active area
  - High pixel density (244720 pixels), narrow pulse shape (~10 ns)
- Ongoing tests on response linearity

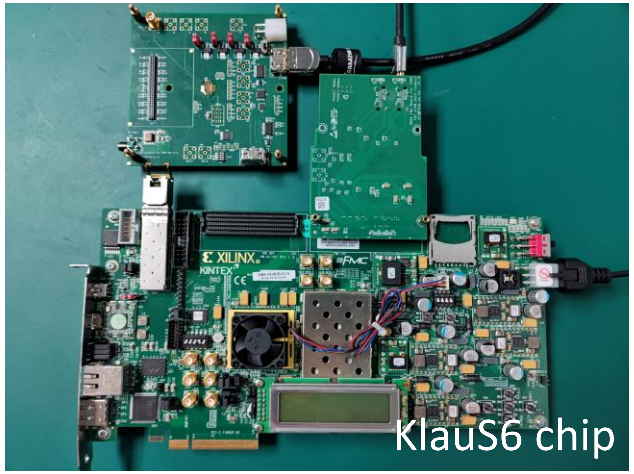
Small-scale detector module design

- Motivations: to develop crystal modules
  - Small-scale modules is sufficient for compact EM showers
  - Identify critical questions/issues on system level
- 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
  - Energy resolution, shower profiles


A dummy crystal matrix with a simple 3D printed support structure


1) crossed crystal bar


2) 6×6 crystal matrix



KlauS6 chip


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	—	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

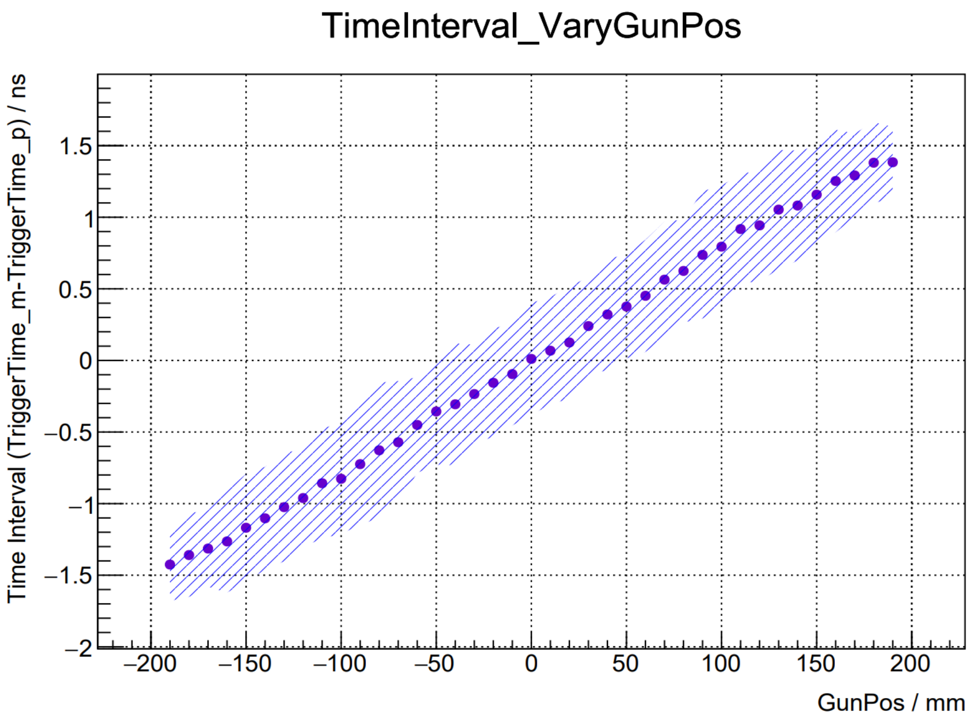
R&D of a highly granular crystal ECAL:

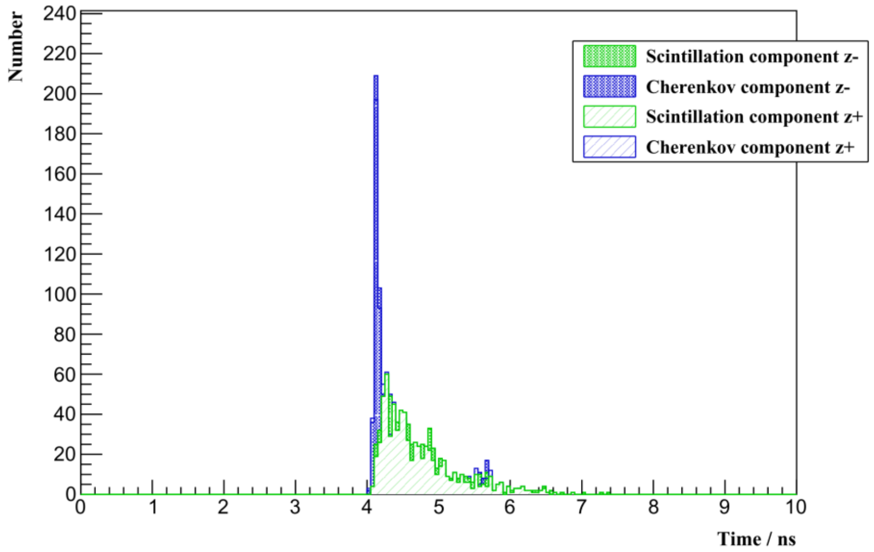
- Performance studies: PFA & reconstruction algorithm
- Hardware development

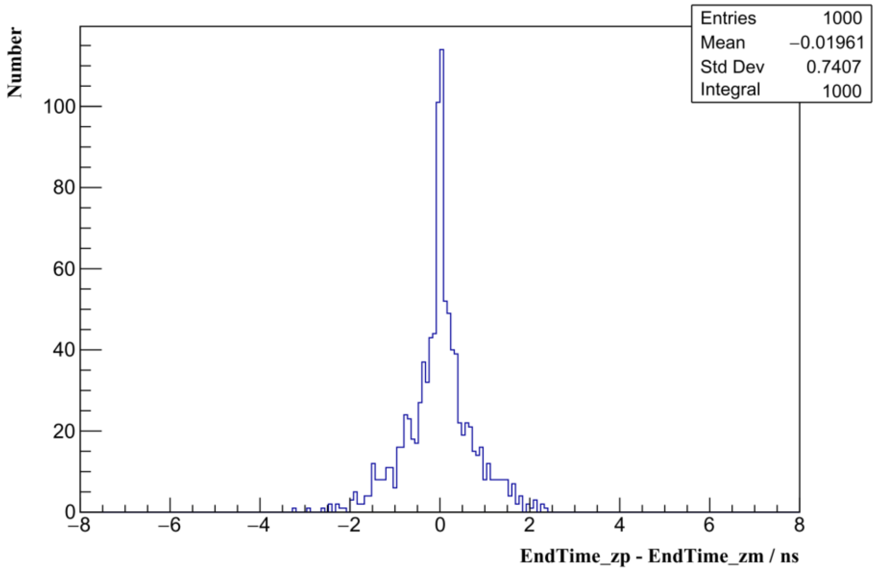
- Prospects
  - Challenge on PFA: still optimizing
  - Detailed simulation studies on crystal ECAL performance
  - Address key issues of crystal ECAL through module development

Backup

Latest progress on time resolution study

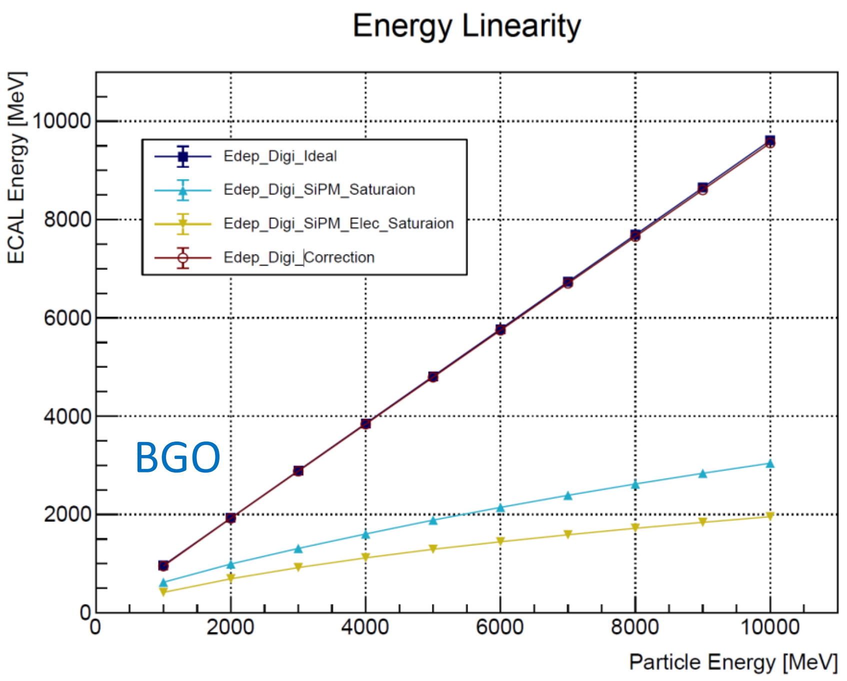


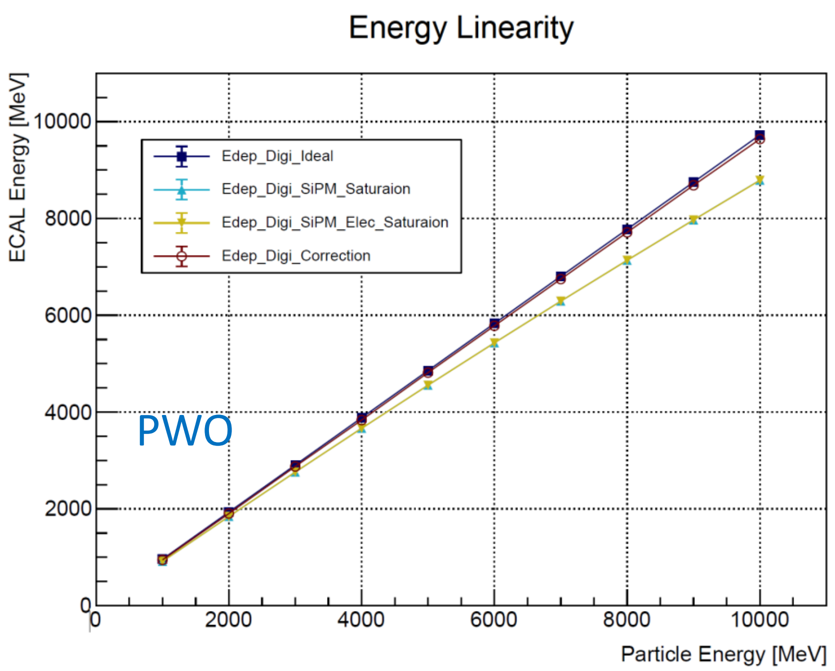




Small-scale detector module design: saturation effect

- 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…

R&D efforts on 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 • T_0 timing • Potential benefits for clustering	• Time constants of crystal scintillation • 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…