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

CALICE VLC 2022

R&D Status of a Novel High Granularity Crystal Electromagnetic Calorimeter

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On behalf of CEPC Calorimeter Working Group

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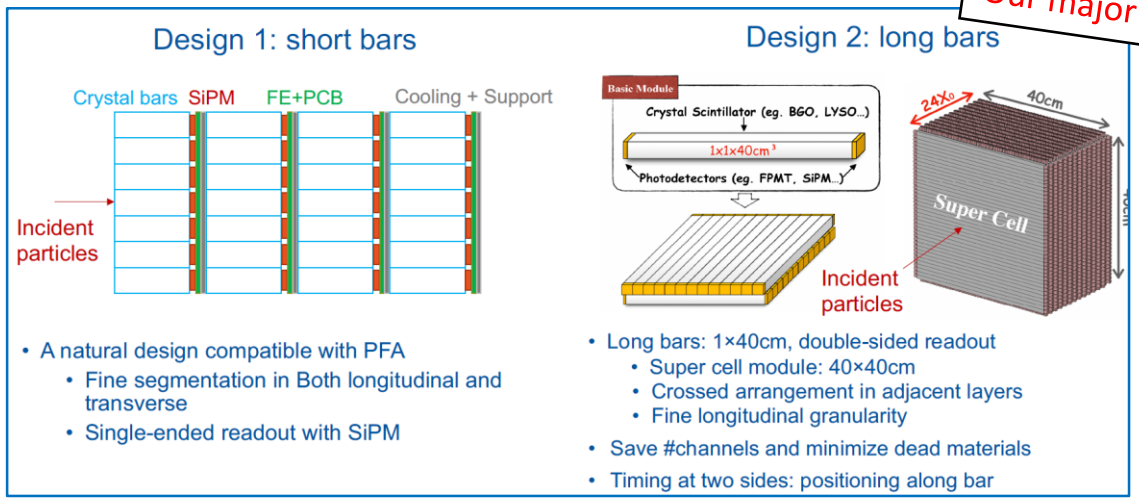
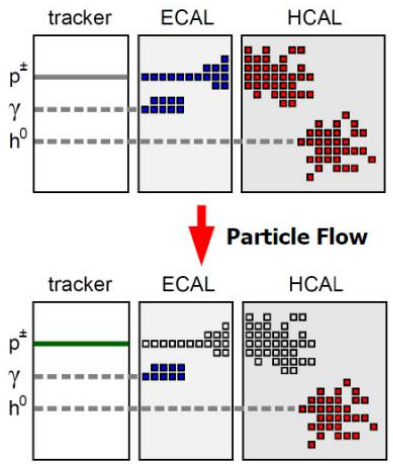
Motivations

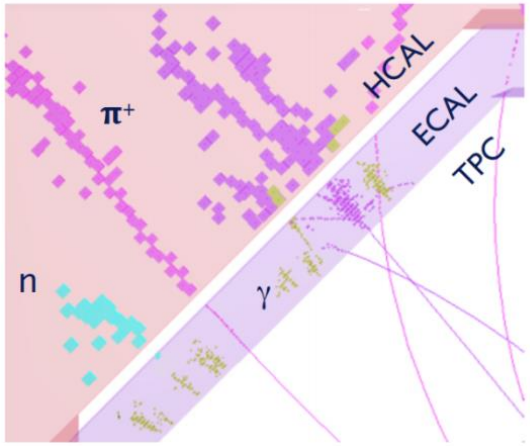
- Background: calorimeter for future lepton colliders (e.g. CEPC)
  - Precision measurements with Higgs and Z/W
  - Jet energy resolution of 3-4%@100GeV is required
  - Particle flow approach: high-granularity calorimeter
- Why crystal calorimeter?
  - Homogeneous structure
    - Intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - 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

Physics process	Measurands	Critical detector	Required performance
$ZH \to l^+l^-X$	m_H, σ_{ZH}	Tracker	$\Delta(1/P_T) = 2\times10^{-5} \oplus \frac{10^{-3}}{P(GeV)\sin^{\frac{3}{2}}\theta}$
$H \to \mu^+\mu^-$	$B(H \to \mu^+\mu^-)$		
$H \to b\bar{b}, c\bar{c}, gg$	$B(H \to b\bar{b}, c\bar{c}, gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(GeV)\sin^{\frac{3}{2}}\theta}(\mu m)$
$H \to q\bar{q}, W^+W^-, ZZ$	$B(H \to q\bar{q}, W^+W^-, ZZ)$	Calo	$\sigma_E^{jet} = 3 \sim 4\%\ @100\,GeV$
$H \to \gamma\gamma$	$B(H \to \gamma\gamma)$	ECAL	$\frac{\Delta E}{E} = \frac{0.20}{\sqrt{E(GeV)}} \oplus 0.01$

Our major focus







Overview of this report: R&D status

R&D of a novel highly granular crystal ECAL:

- PFA performance: key parameters
  - Evaluate physics potentials
  - Separation power, Higgs benchmark
- Reconstruction algorithm dedicated to new geometry design
  - Aims & challenges
  - Algorithm development & performance studies
- Detector design and performance
  - Detector units studies & requirements of hardware development
  - Crystal candidates: BGO / PWO
  - SiPM characterization: laser calibration
  - ^{137}Cs tests on long crystal bar: energy resolution & response uniformity
  - Simulation studies: single bar → crystal module
  - Small-scale detector module design: first glance

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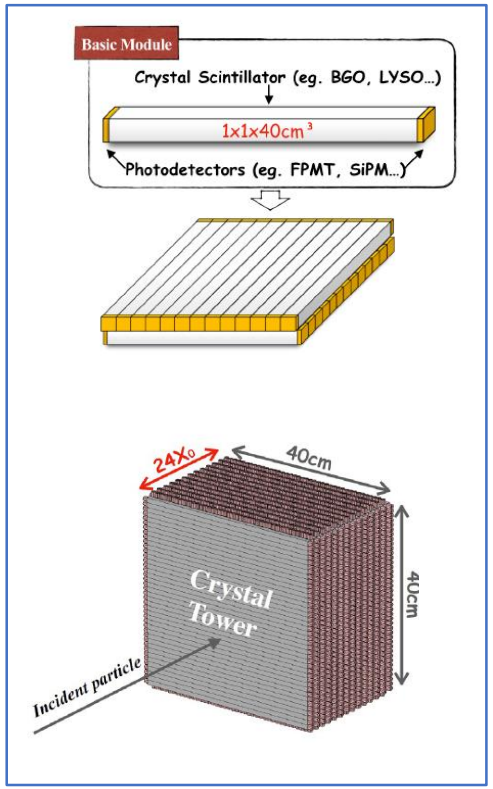
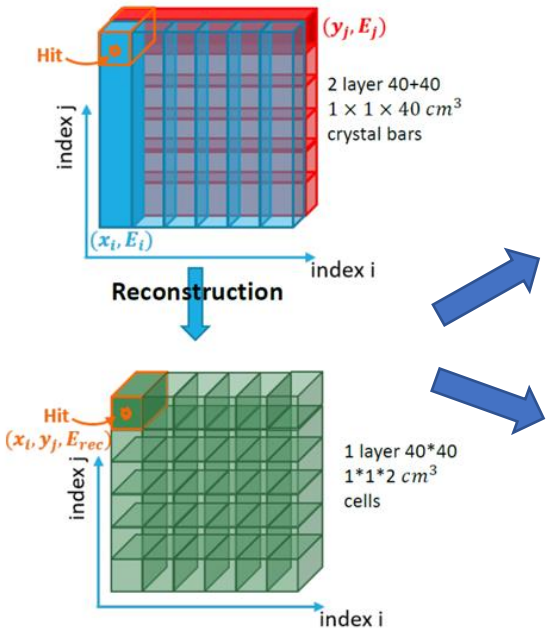
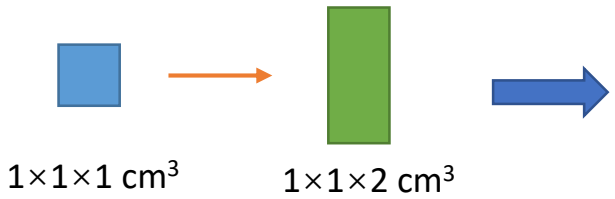
Performance evaluation: introduction

- Adapted from CEPCv4 baseline detector
  - Finely segmented crystal ECAL: crystal cubes
  - Application and optimization of Arbor-PFA

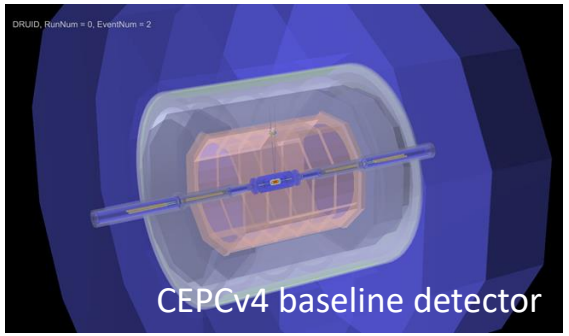


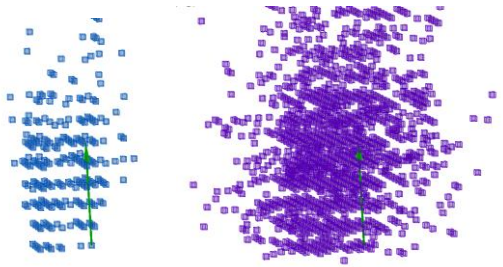


Crossed long bar design:
$1\times1\times2$ cm^3 granularity after digitization

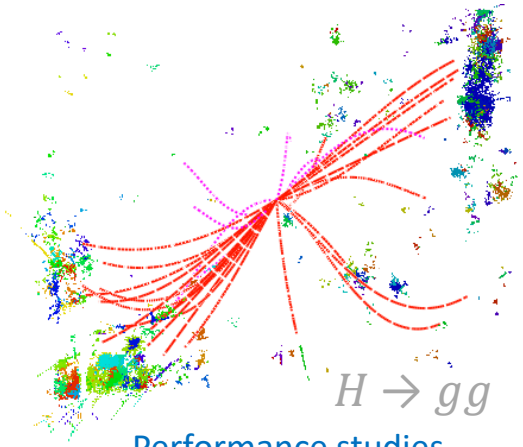


Geometry change:
$1\times1\times2$ cm^3 crystal cubes





Algorithm optimization:
Arbor-PFA for crystal design
Challenge: #hit↗

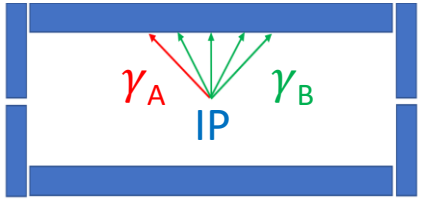


Performance studies

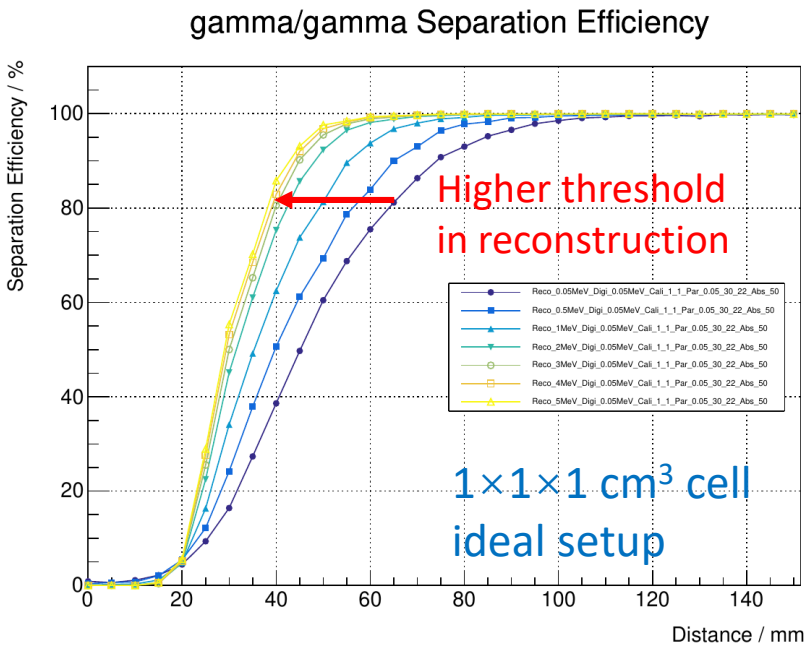
Performance evaluation: separation power

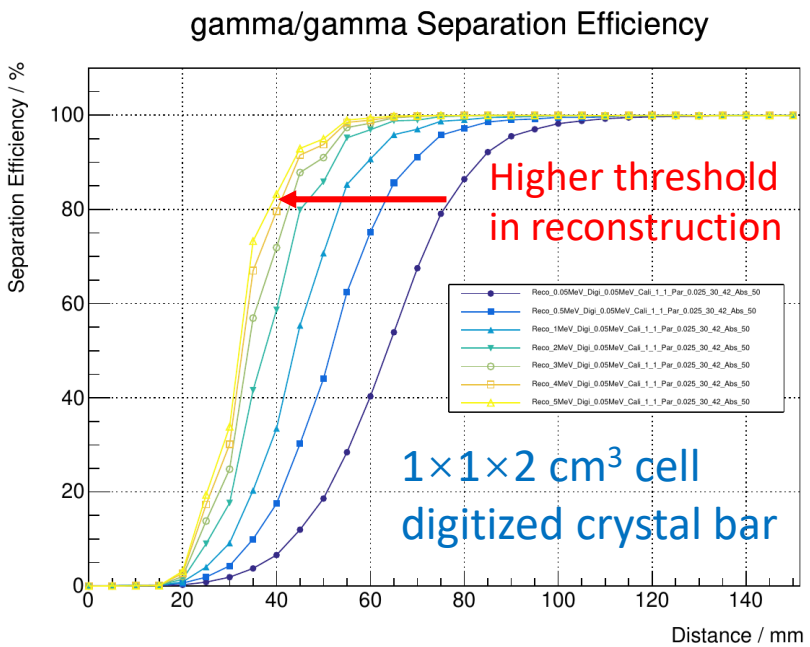
CEPC Software v0.1.1

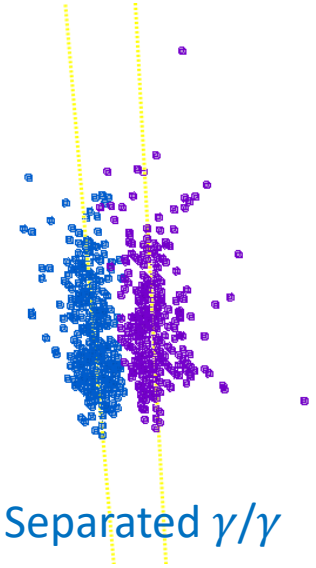
- Reconstruction of jets: separation power of close-by particles
- Changes with Arbor-PFA
  - Ideal segmentation → more realistic design suitable for crystal bar ECAL
  - Multi-threshold method: low threshold in digitization for energy resolution, high threshold in reconstruction for separation
- γ/γ separation study



Side view of crystal ECAL
Two incident particles
Change distance in between







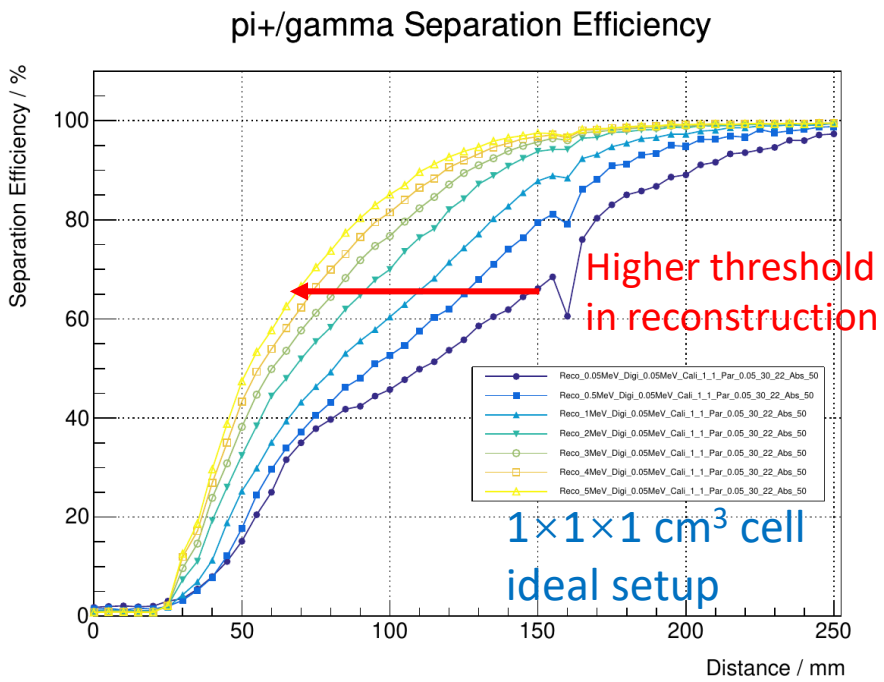
Separated γ/γ

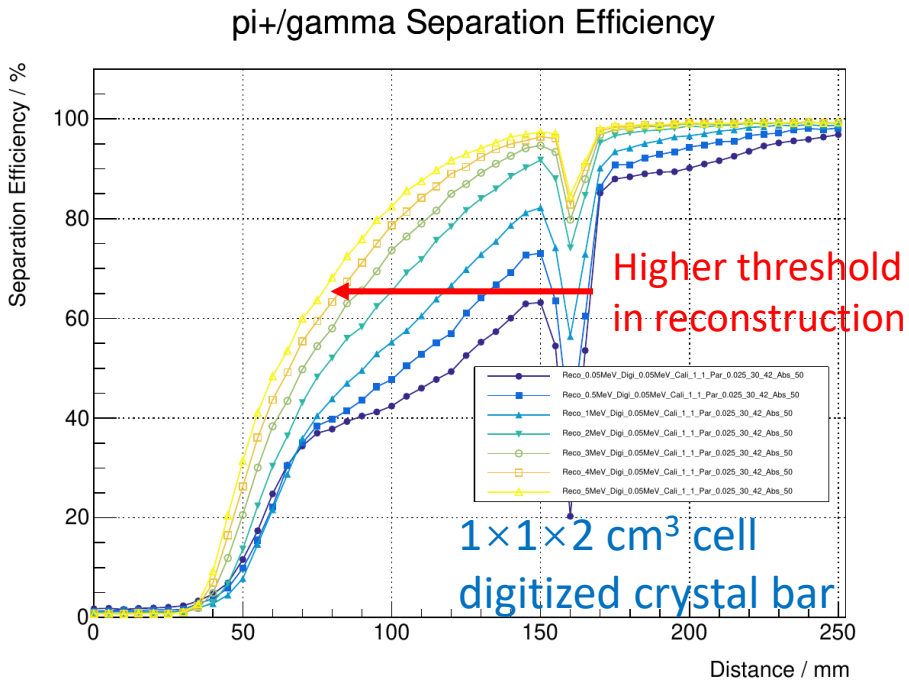
- Similar separation power under high threshold in reconstruction

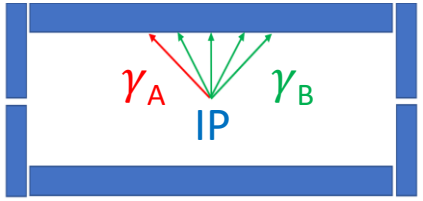
Performance evaluation: separation power

CEPC Software v0.1.1

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







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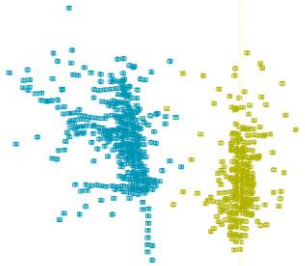
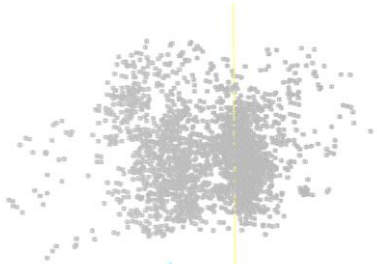


Separated γ/γ



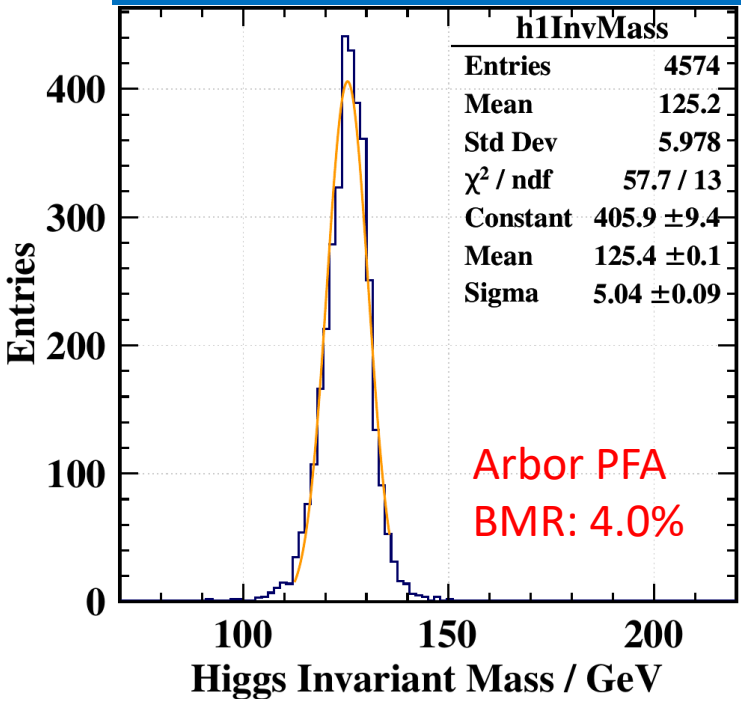
Unseparated π^+/γ

- $1\times1\times2$ cm^3 cubes shows more sensitive to geometrical gaps
- Hadronic shower reconstruction: challenge on clustering
- Matching clusters of charged particle to the tracks in tracker
- The algorithm is being optimizing, still space for improvement

Performance evaluation: Higgs benchmark

- Physics performance: reconstruction of 2-jet benchmark events
  - Boson mass resolution (BMR): ZH ($Z \rightarrow \nu\nu$, $H \rightarrow gg$) at 240 GeV

Detector with 10 mm crystal cube



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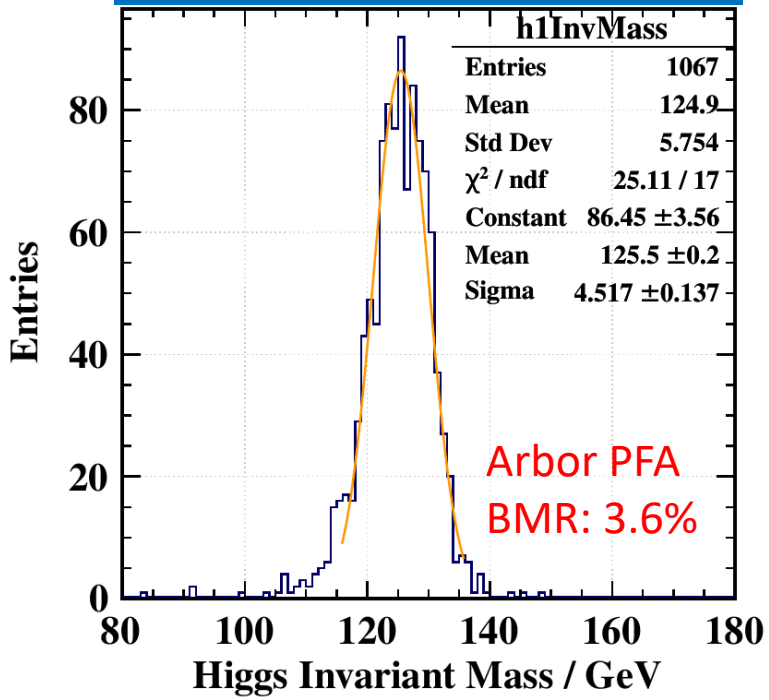

- Significant improvement after Arbor-PFA algorithm optimization
- On going BMR study on 1×1×2 cm^3 cubes…

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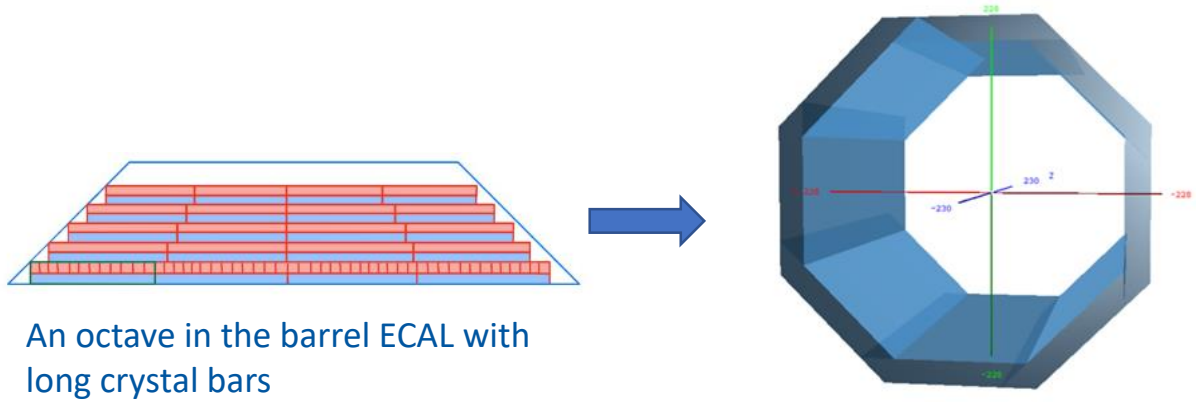
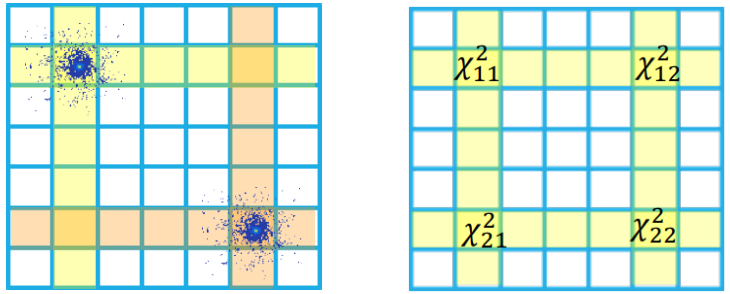
Reconstruction algorithm for long bar design: PFA development overview

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

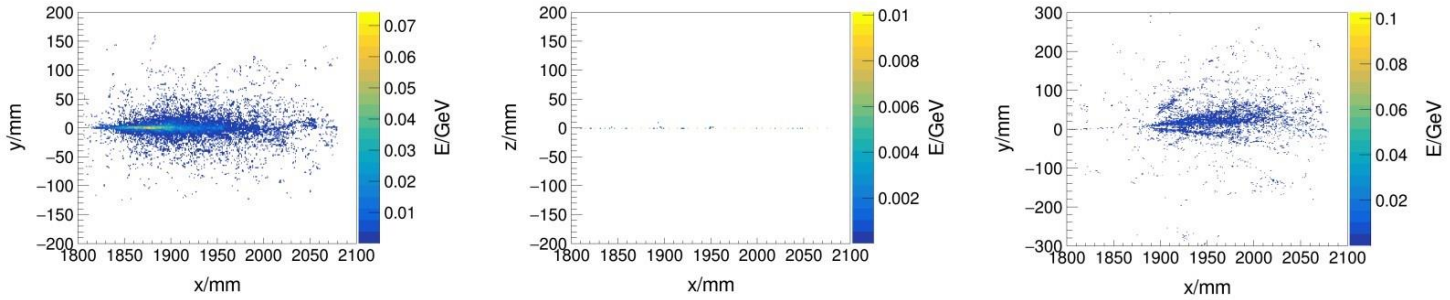
- New software framework: CEPCSW
- Detector description
  - Full barrel geometry with DD4HEP
  - 28 longitudinal layers, crossed arrangement
- Reconstruction algorithm: aims
  - Final granularity $1\times1\times2$ cm^3
  - Minimize impact from ghost hits
- Challenges
  - Pattern recognition of clusters
  - Associating charged clusters with tracks



An octave in the barrel ECAL with long crystal bars



Remove ghost hits

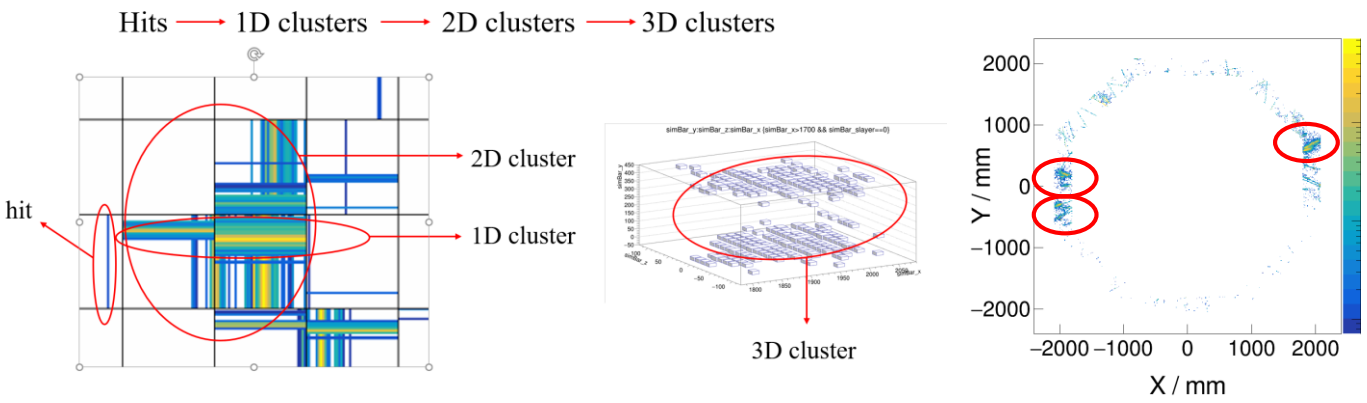


EM cluster MIP cluster Hadronic cluster

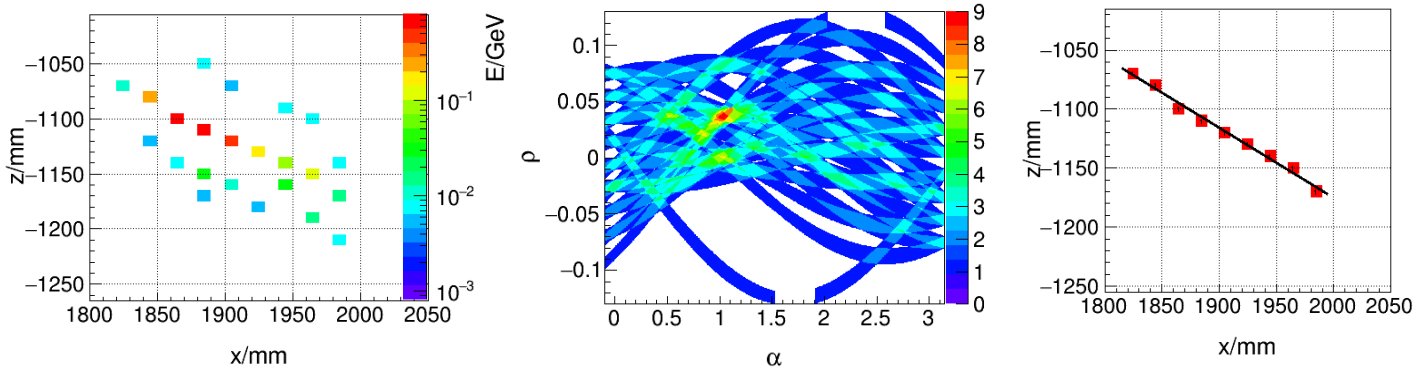
Reconstruction algorithm for long bar design: latest effort

Yang Zhang, Weizeng Song (IHEP)

- Clustering algorithm for long crystal ECAL

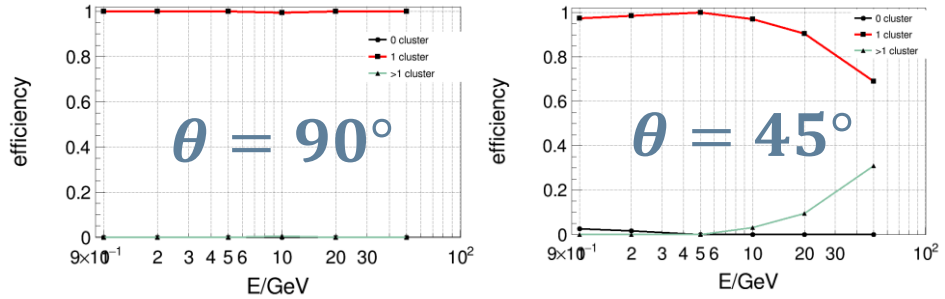


- Reconstruction: application of Hough transformation
  - Local maxima of hit → Hough band → Hough cluster

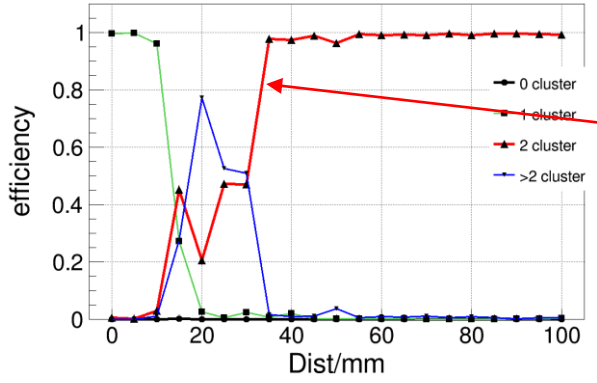


1D cluster cores → Hough transformation → Track in ECAL

- Performance of single photon



- Di-photon recognition efficiency



Separation efficiency

- On-going work on hadrons/jets

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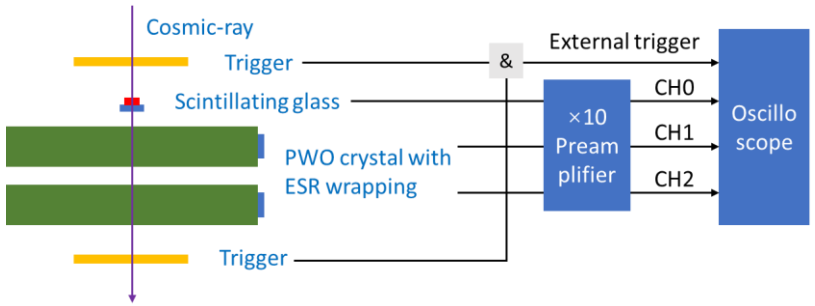
Detector design and performance

- Crystal candidates
  - BGO: light yield ~8000 p.e./MeV, ~300 ns light decay time
  - PWO: light yield ~120 p.e./MeV, ~30 ns light decay time
    - Cosmic-ray test to verify whether it can meet the requirement
- SiPM
  - Single photon spectrum
  - Candidates → features
    - Pixel size and density requirements for future use
- SiPM + crystal
  - MIP response
  - Radioactive source test → energy resolution
  - 1D uniformity → simulation + experiment
  - 2D uniformity → module performance (Geant4 simulation)

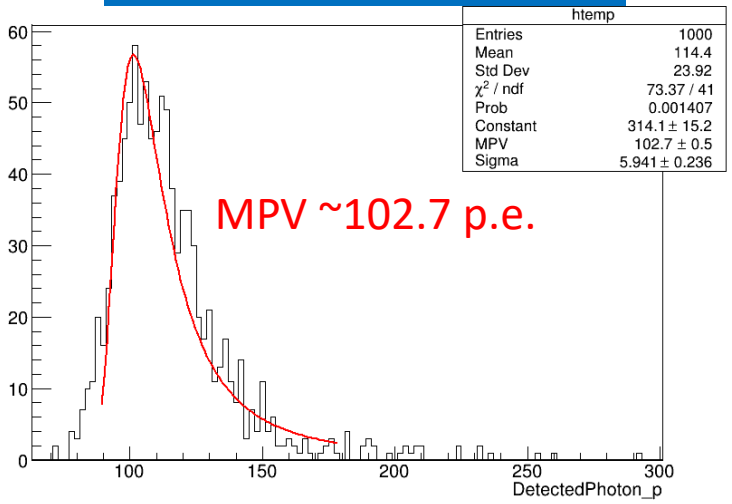
  } Calibration scheme
- Module design
  - Small-scale detector module: first glance

Crystal candidates: cosmic-ray test with PWO crystal

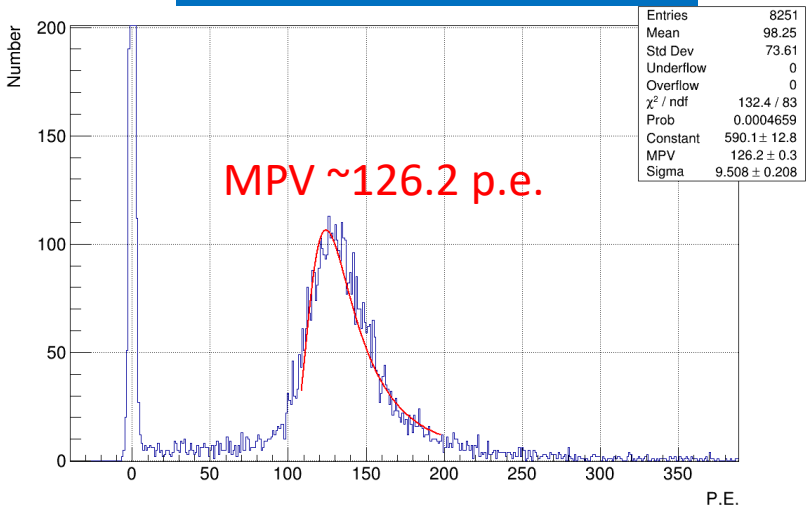
- BGO crystal
  - Leading candidate currently
- PWO crystal
  - To verify whether the MIP response can meet the requirement
    - >100 p.e./MIP light yield is enough for $\sim 3\%/\sqrt{E}$ energy resolution

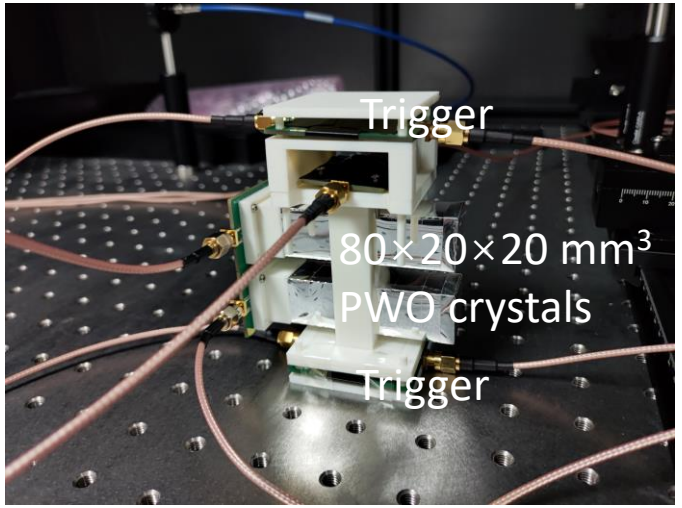


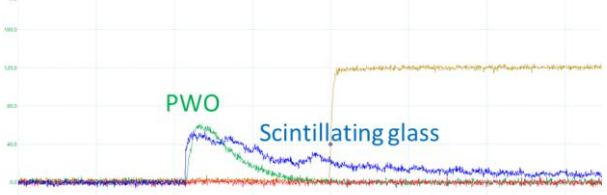
Gean4 optical simulation



Cosmic-ray test





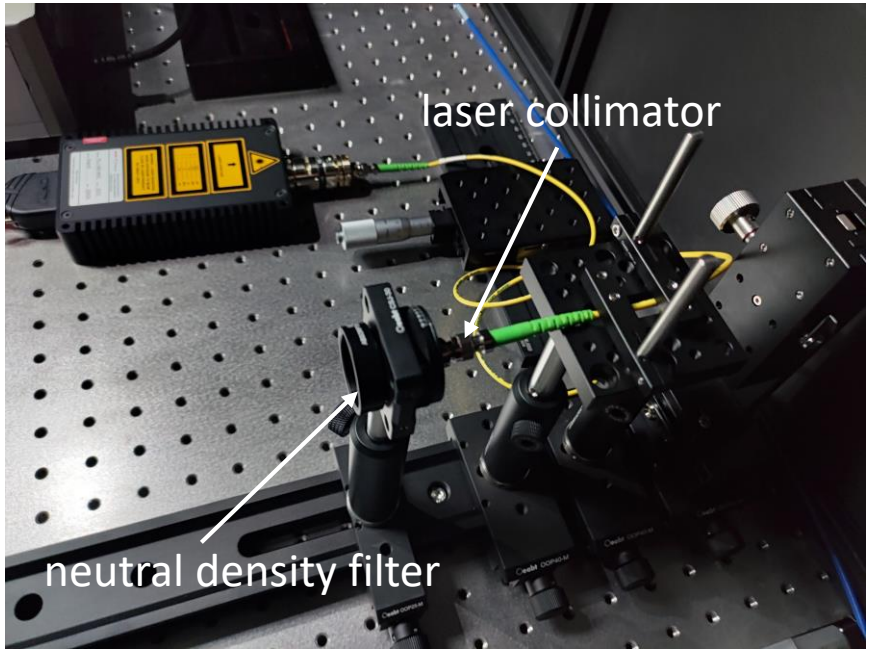


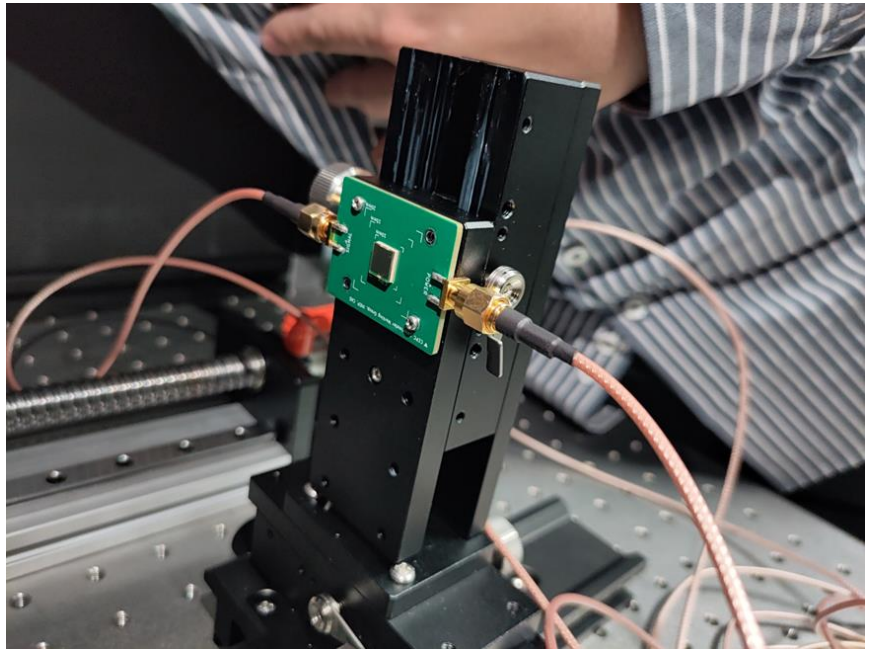
Waveform in the oscilloscope

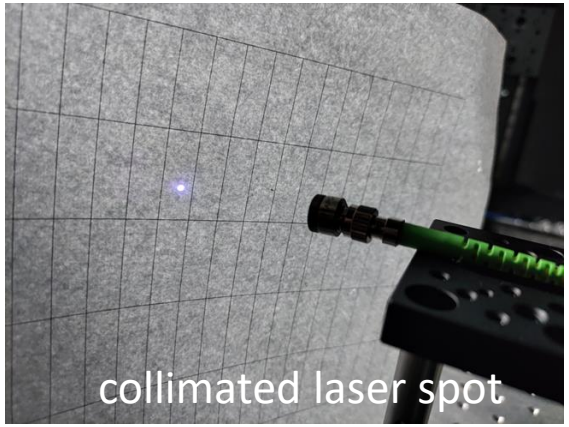
- Measurements show requirement of >100 p.e./MIP can be met
  - Cosmic tests: reasonably consistent with G4 optical simulation
  - Further considerations: higher MIP response desired for more headroom

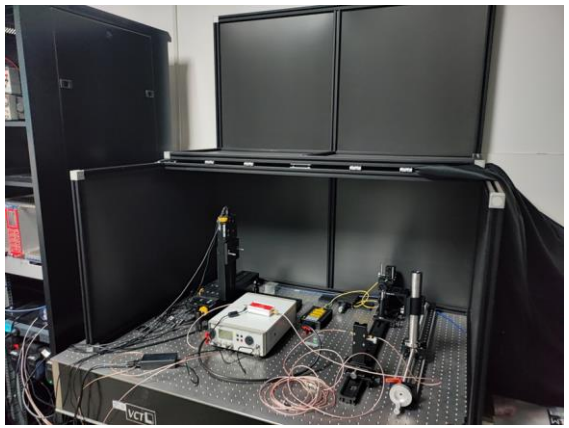
Characterizations of SiPMs: laser calibration of SiPMs

- Motivation
  - For SiPMs with large size and high pixel density, the noise effect is significant
  - Laser calibration to get single photon spectrum
- Laser test stand setup
  - 405nm picosecond laser, collimator, neutral density filter
    - 0.1% transmittance neutral density filter to reduce laser intensity





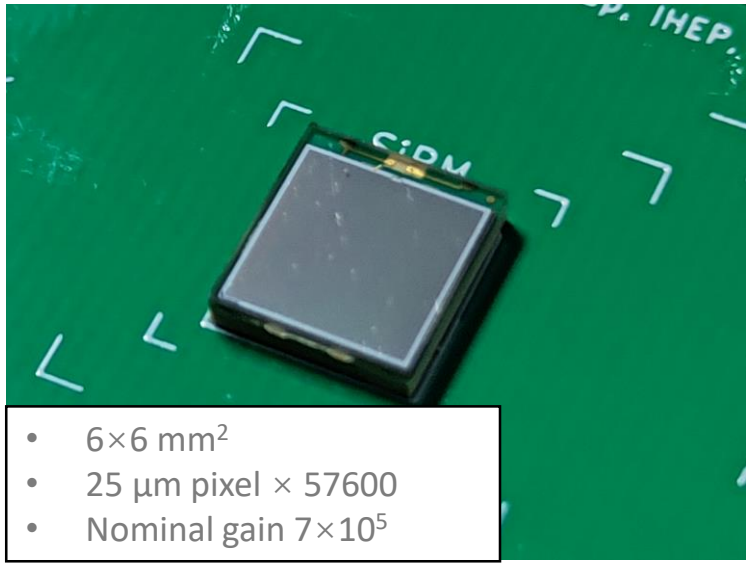




Characterizations of SiPMs: SiPM candidates

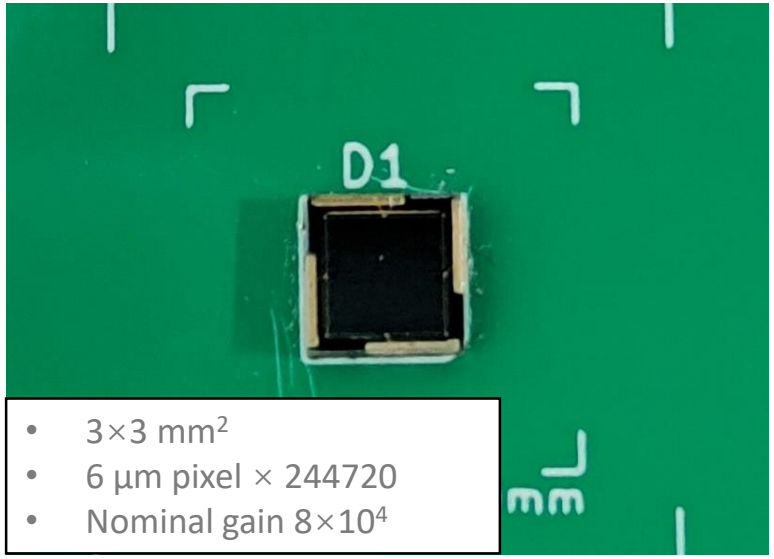
- DUT: HPK & NDL SiPMs, large size and small pixel pitch SiPMs are prefered

HPK S13360-6025PE



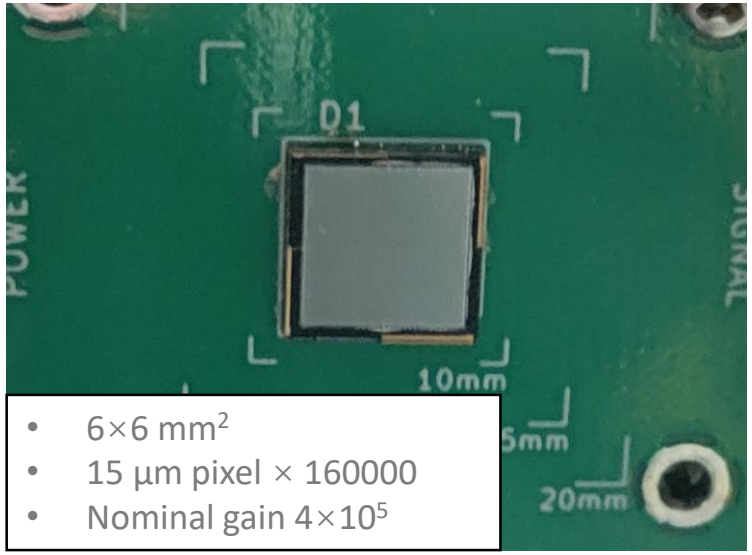
- 6×6 mm^2
- 25 μm pixel × 57600
- Nominal gain 7×10^5

NDL EQR06 11-3030D-S

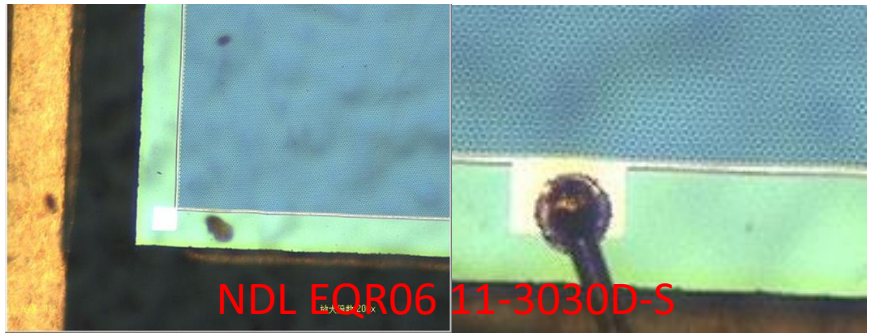


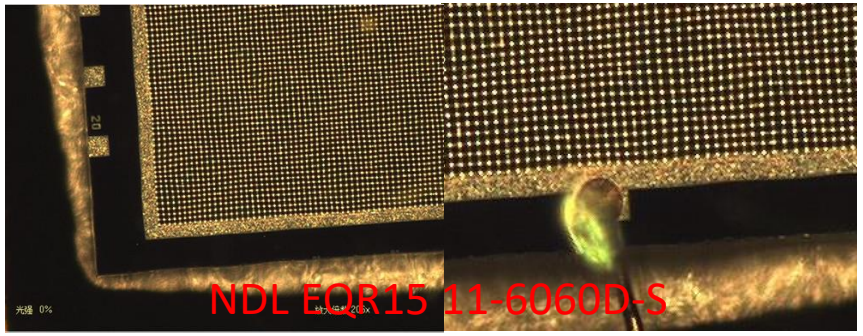
- 3×3 mm^2
- 6 μm pixel × 244720
- Nominal gain 8×10^4

NDL EQR15 11-6060D-S



- 6×6 mm^2
- 15 μm pixel × 160000
- Nominal gain 4×10^5



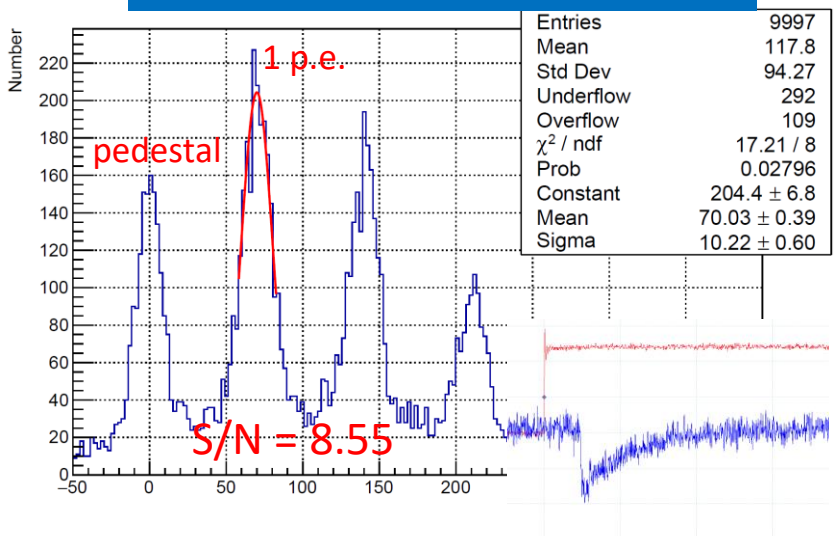


Characterizations of SiPMs: single photon spectrum

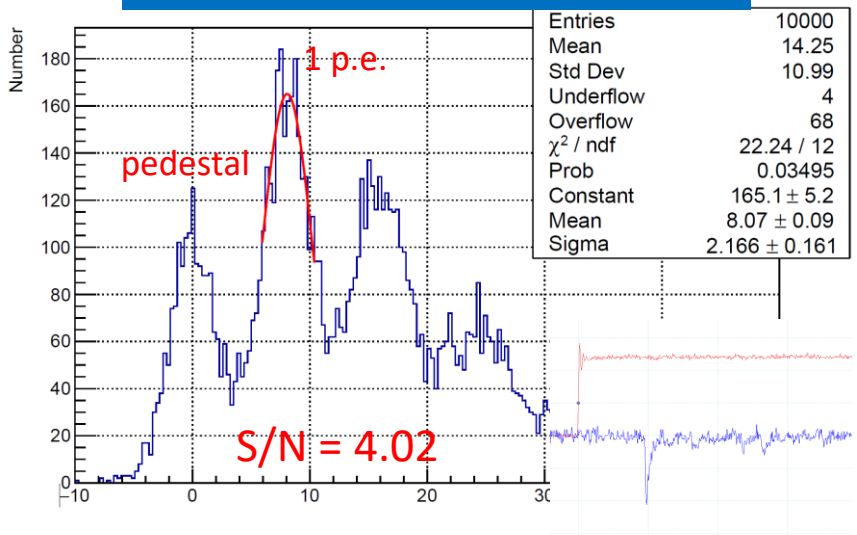
- Single photon spectrum of DUTs

$$S/N = \frac{\mathrm{Mean}_{1p.e.}}{\mathrm{Sigma}_{pedestal}}$$

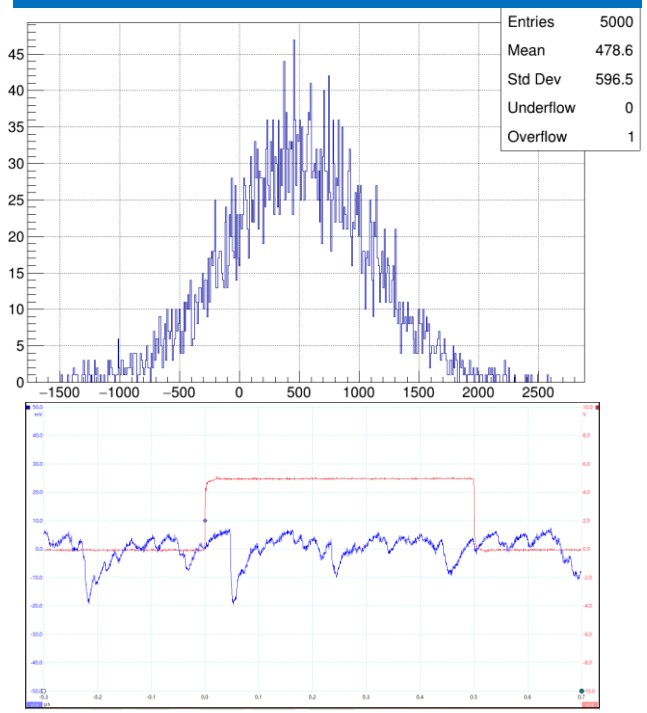
HPK S13360-6025PE



NDL EQR06 11-3030D-S



NDL EQR15 11-6060D-S



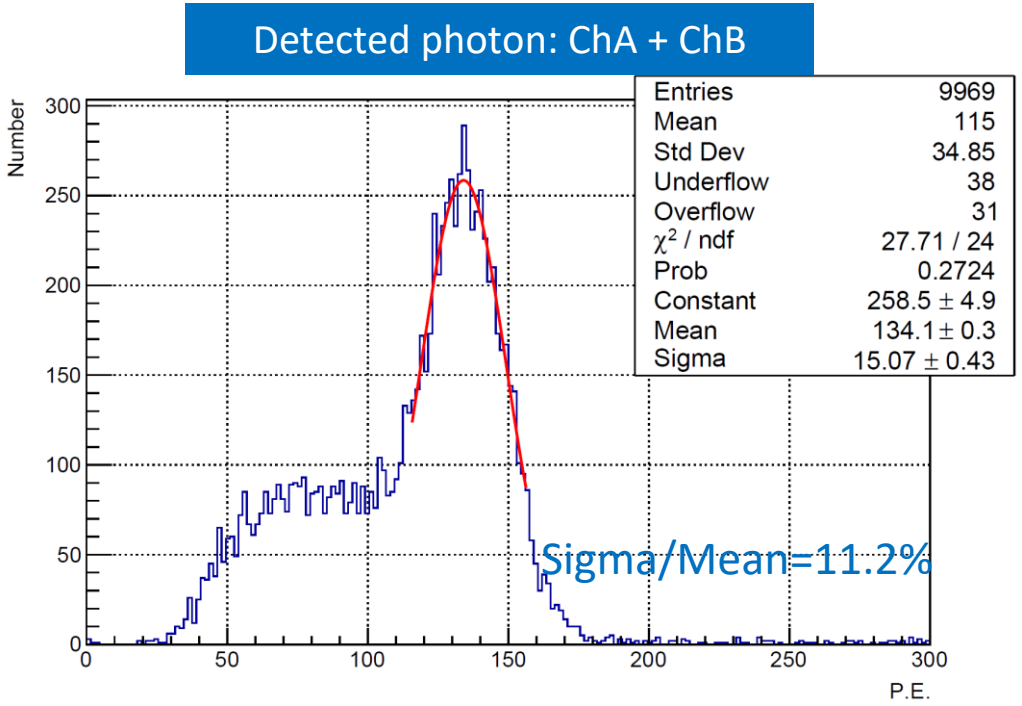
- Criteria for SiPMs: pixel size, gain, price, capability of single photon detection…
- NDL EQR06 series with 6 μm pixel and 3×3 mm^2 active area
  - ×4 more pixels than 25μm HPK one
  - Narrower pulse shape (~10 ns)
  - Half signal to noise ratio

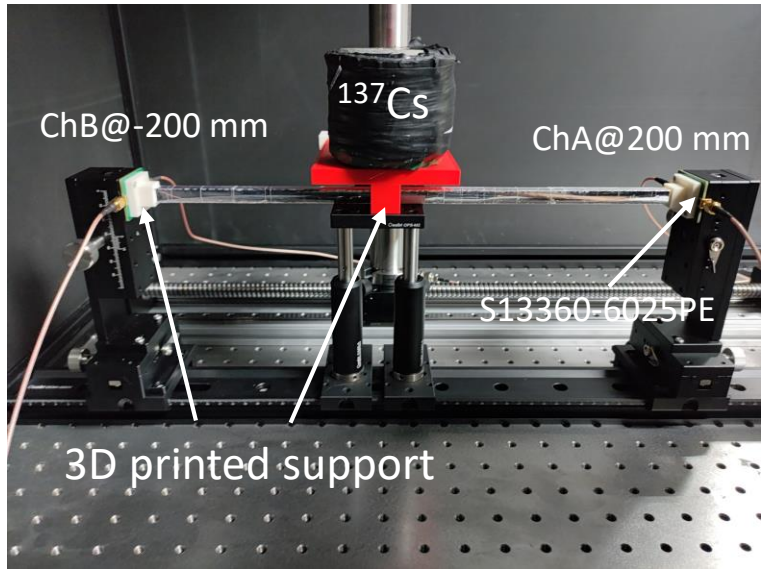
Gain crosscheck:
- $7\times10^5 / 8\times10^4 \approx 70.03 / 8.07$

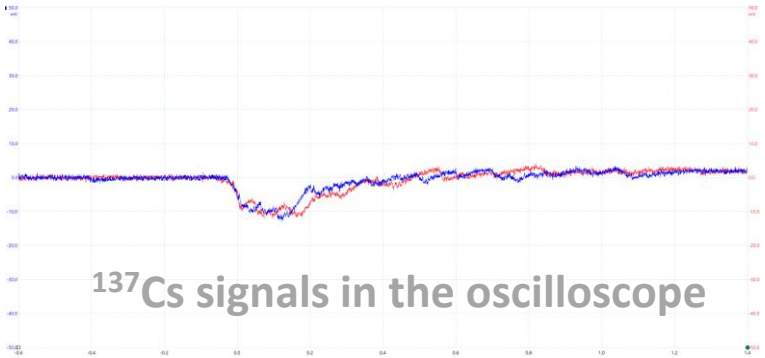
- Too many thermal noise signals
- Unstable baseline
- Unable to perform single photon calibration

Radioactive source test of BGO crystal: energy resolution

- 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
  - 3×3 mm^2 SiPMs with 25 μm pixel, air coupling, double-sided readout





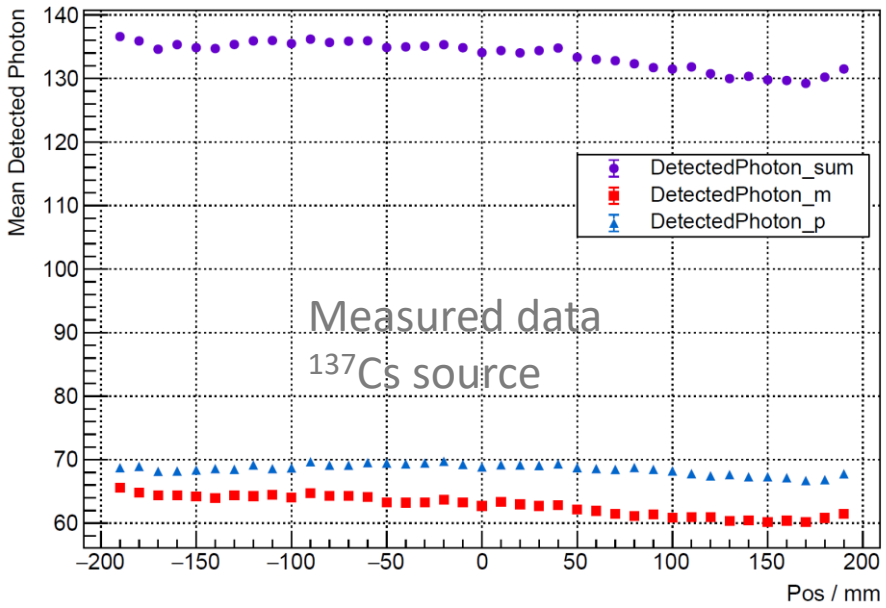


- Energy resolution for 662 keV gamma: ~11.2%

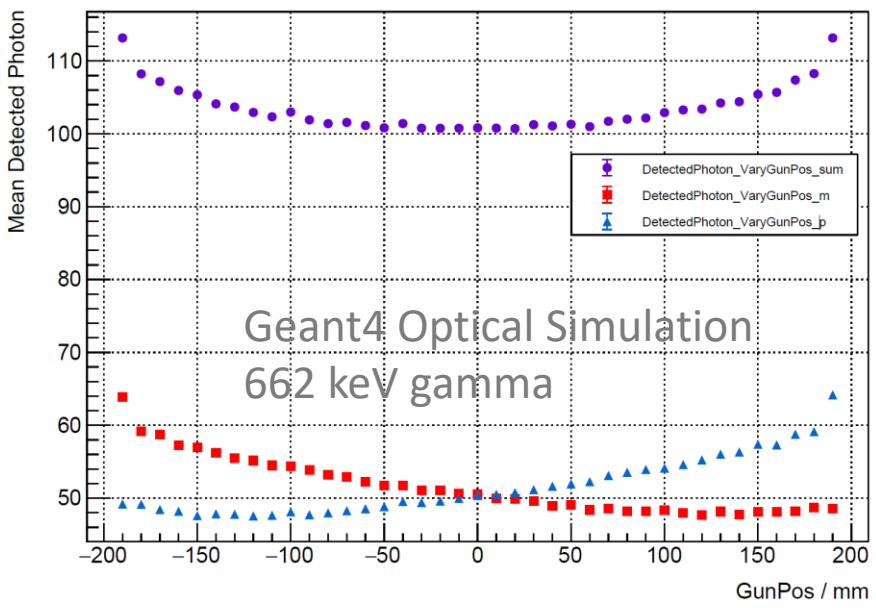
Radioactive source test of BGO crystal: response uniformity

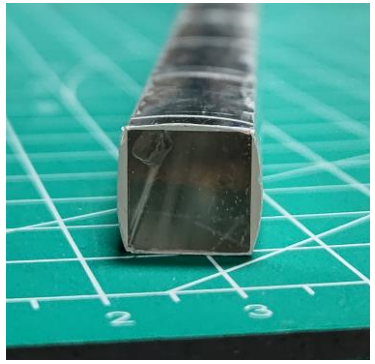
- Uniformity scan: 662 keV gamma for ^{137}Cs, change hit positions

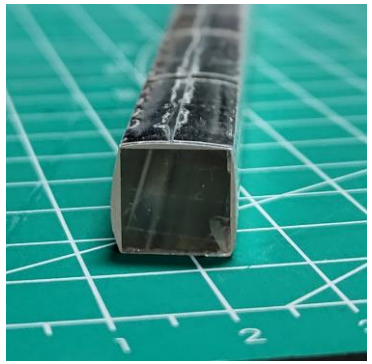
Experiment: detected photon



Simulation: detected photon





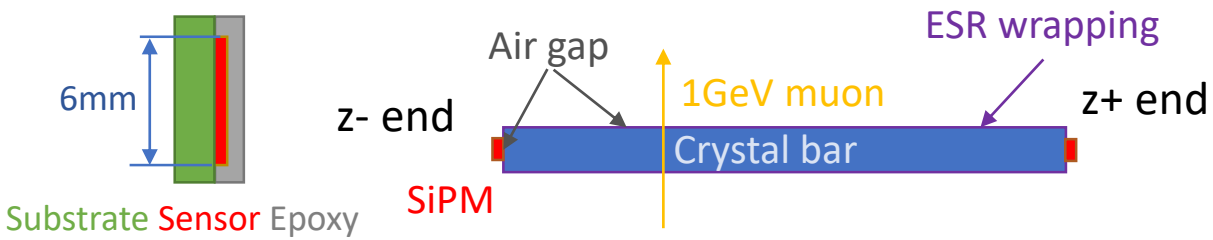


- Less light attenuation effect than expected in simulation
- Relatively low response near one side
- Coupling, positioning, distance between crystal and radioactive source…
- Potential factors related to crystal manufacture

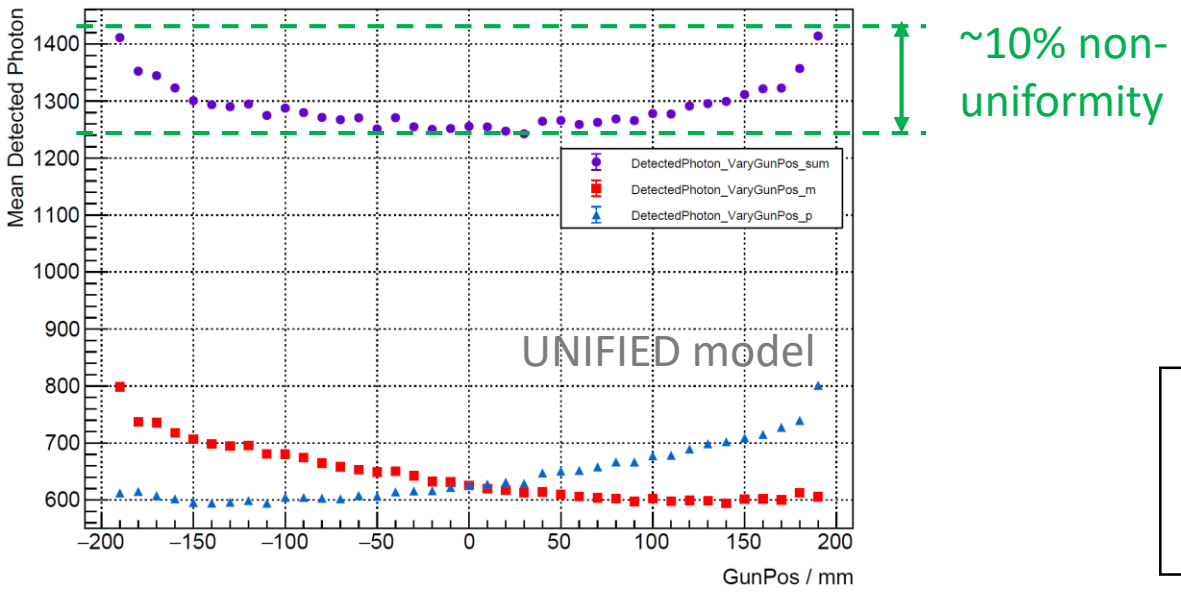
Simulation study: response uniformity of a single crystal bar

Geant4 Simulation (v10.7.3)

- Geant4 optical simulation
  - A single BGO crystal bar wrapped with ESR reflector
- Physics processes
  - Scintillating & Cherenkov
  - Boundary processes and absorption
  - SiPM modelling: geometry and response (PDE)



MIP response vs hit position



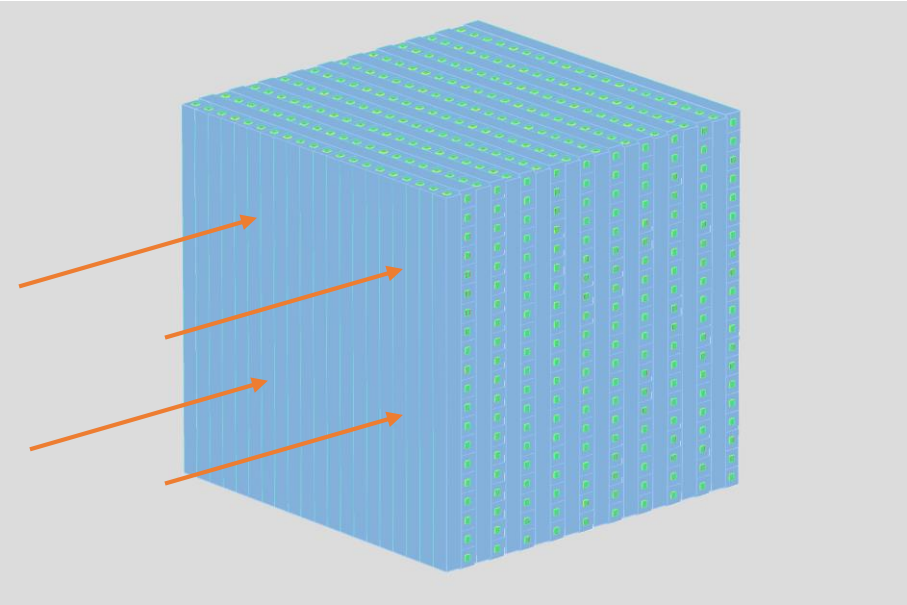
- Over 1000 photons detected per MIP
- ~10% non-uniformity under the current simulation parameters
- Roughly described by a quadratic function
- Non-uniformity: relative difference between the highest and lowest response

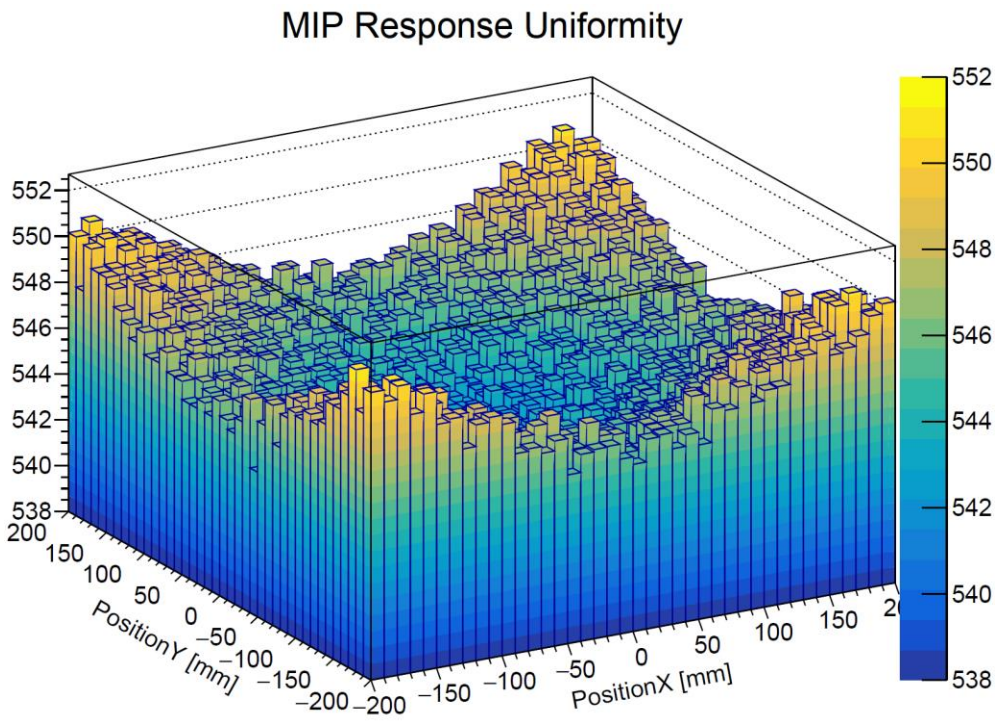
Parameters
- Model: UNIFIED, with adjustable surface roughness
- Absorption length, emission spectrum: measured data
- Reflectivity, Rindex, SiPM PDE…: available data from documentations

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)



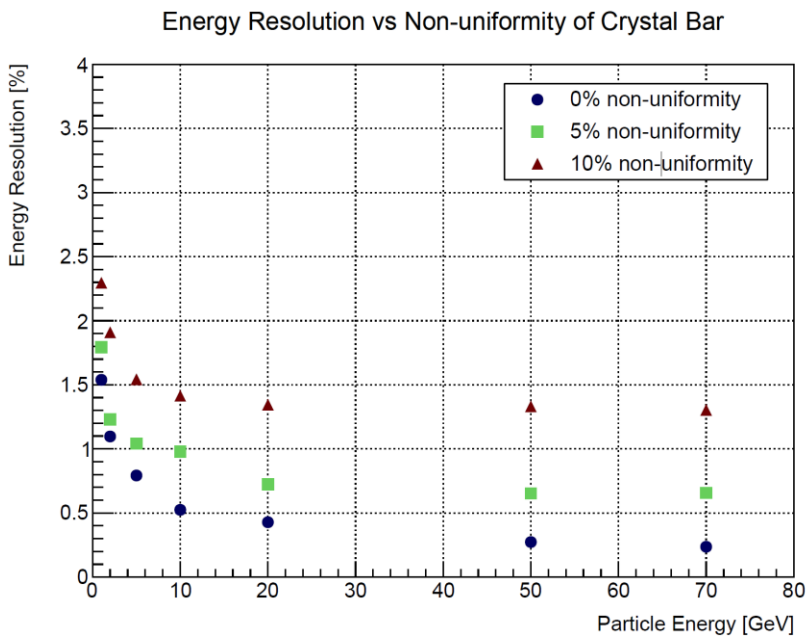


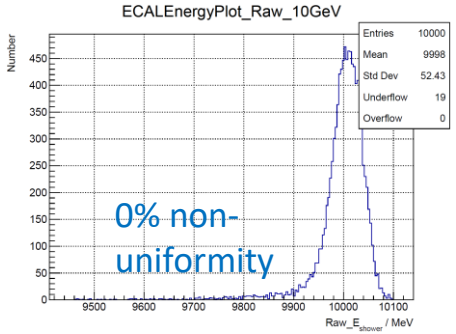
- MIP Response of four corners is higher
- 2D non-uniformity seems lower than 10%
- Calibration constants depend on hit positions
  - Good reconstruction algorithm is required to get precise position resolution

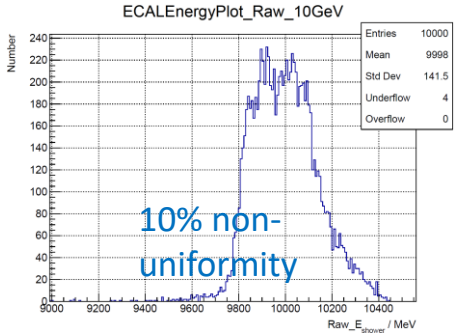
Simulation study: response uniformity of crystal ECAL module

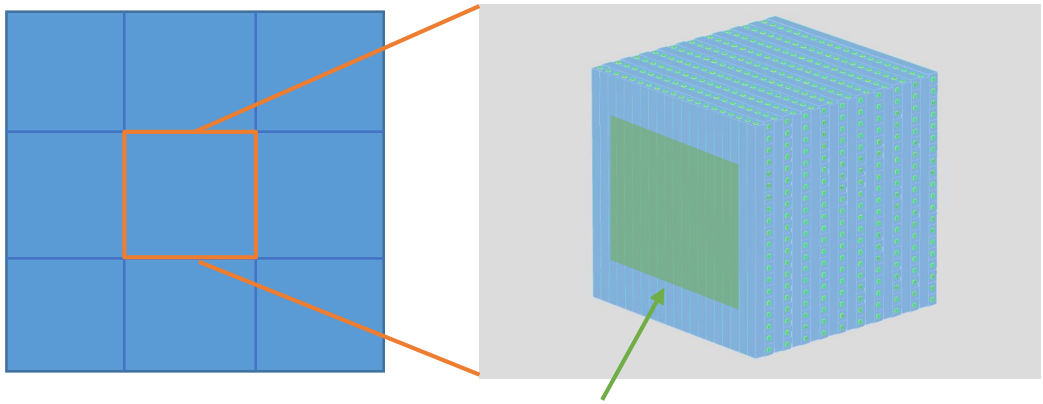
Geant4 Simulation (v10.7.3)

- 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





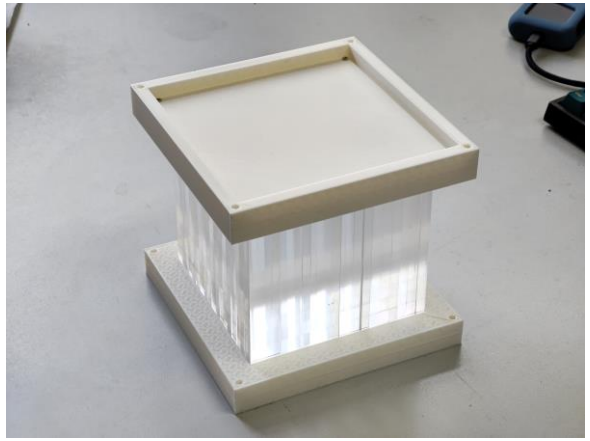




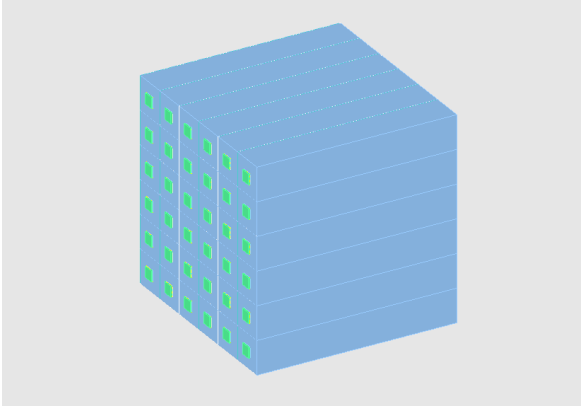
- For higher value of non-uniformity, there is significant energy loss effect
- Severe distortion of energy resolution
  - Major contribution to constant term
- Response non-uniformity need to be calibrated
  - Requirements on calibration

Small-scale detector module design: first glance

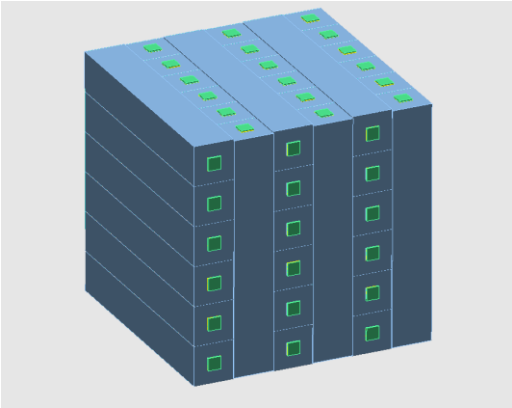
- Motivations: crystal module development
  - EM shower profiles are intrinsically compact
    - e.g. R_M = 2.26 cm for BGO
  - Small-scale modules is sufficient for EM showers
  - Crucial to have beam tests for system level studies
  - Identify critical questions/issues for the final detector
  - Evaluate performance with data and to validate simulation
- Module design: crystal module ($12\times12\times12$ cm^3)
- Future beam test: on-going study



A dummy crystal matrix with 3D printed support structure



6×6 crystal matrix



crossed crystal bar

Summary & prospects

R&D of a novel highly granular crystal ECAL:

- PFA performance: key parameters
  - Evaluate physics potentials
  - Separation power, Higgs benchmark
- Reconstruction algorithm dedicated to new geometry design
  - Aims & challenges
  - Algorithm development & performance studies
- Detector design and performance
  - Detector units studies & requirements of hardware development
  - Crystal candidates: BGO / PWO
  - SiPM characterization: laser calibration
  - ^{137}Cs tests on long crystal bar: energy resolution & response uniformity
  - Simulation studies: single bar → crystal module
  - Small-scale detector module design: first glance

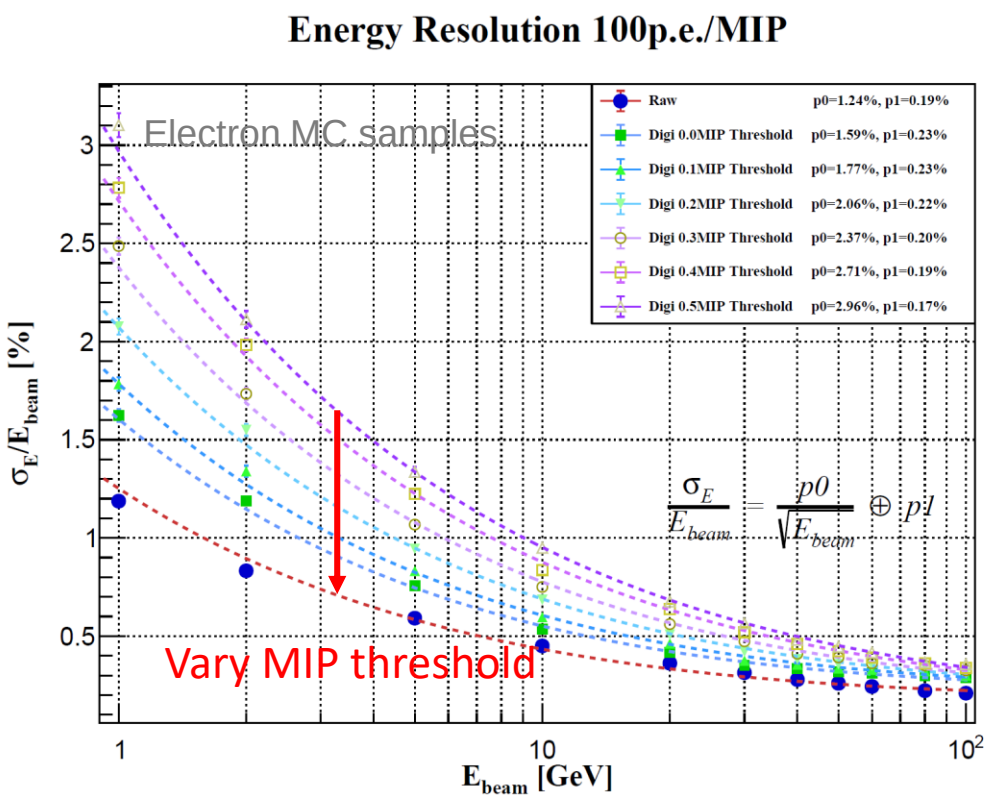
- Prospects
  - Challenge on PFA: still optimizing
  - Detailed simulation studies on crystal ECAL performance
  - Address key issues on module design
  - …

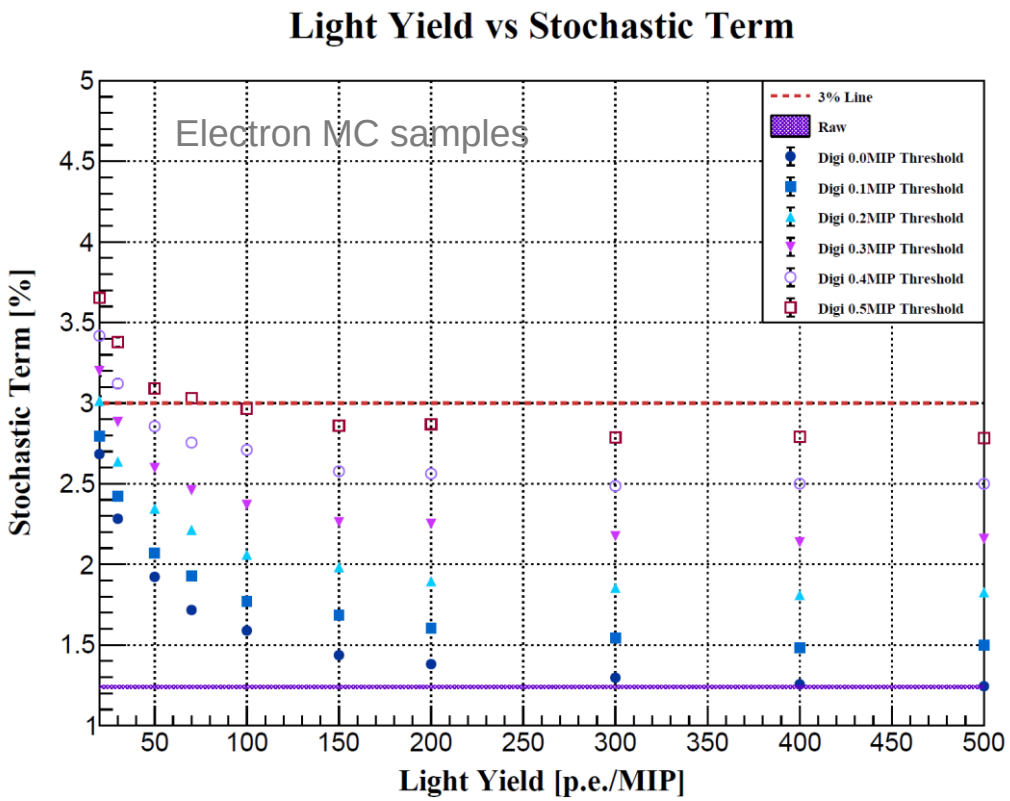
Backup

EM energy resolution: threshold and light yield requirements

Geant4 Simulation (v10.7)

- Impact on energy threshold (in MIP) and light yield (in p.e./MIP)
  - Digitization: photon statistics (crystal + SiPM), electronics resolution



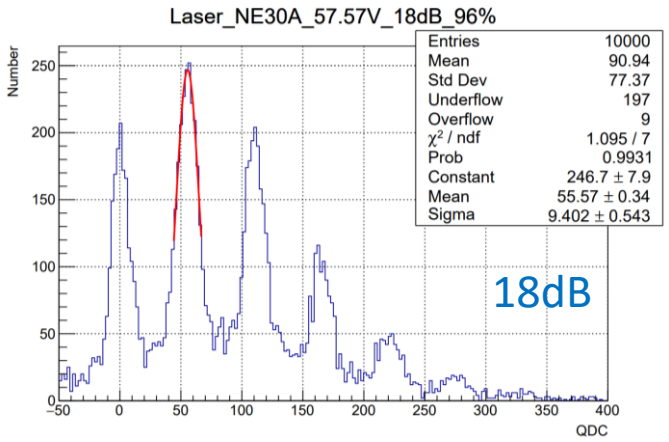


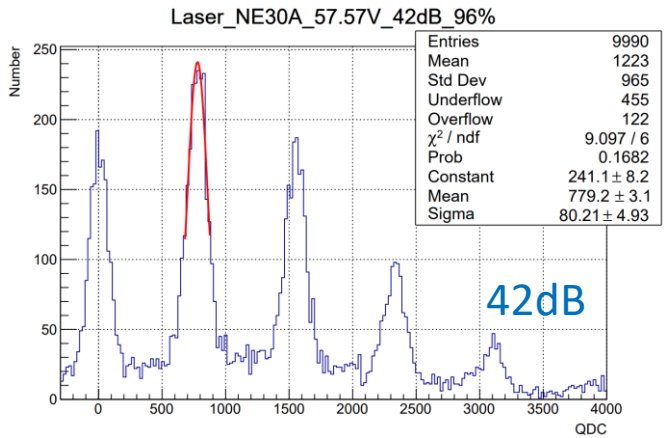
- Moderately high light yield and low threshold required for better than 3% stochastic term

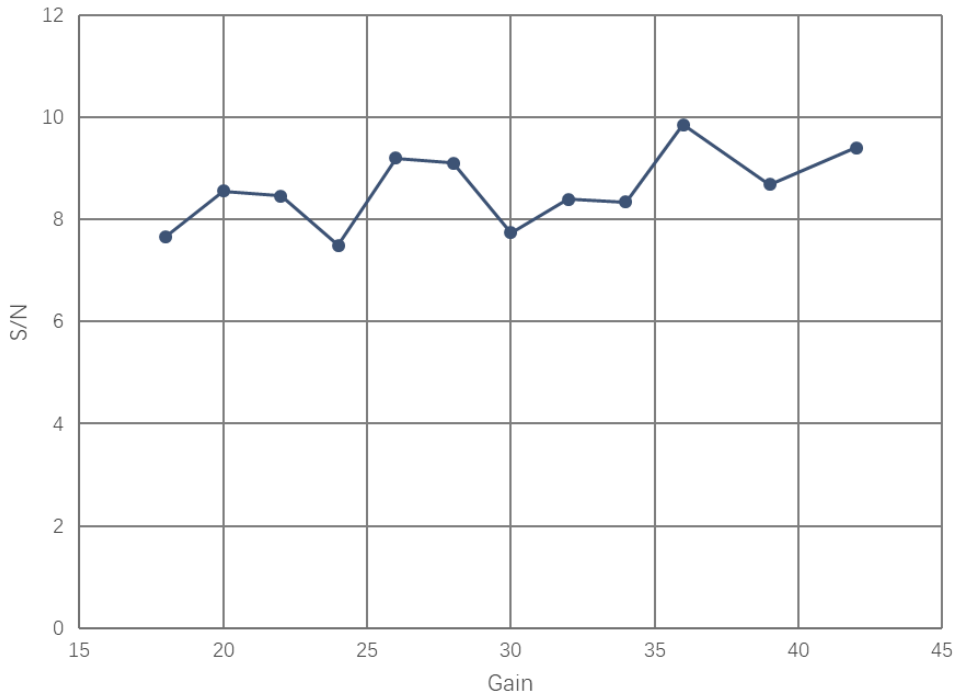
Characterizations of crystals and SiPMs: laser calibration of SiPMs

- S/N versus gain of preamplifier
  - HPK S13360-6025PE + CAEN A1423B

$$S/N = \frac{\mathrm{Mean}_{1p.e.}}{\mathrm{Sigma}_{pedestal}}$$



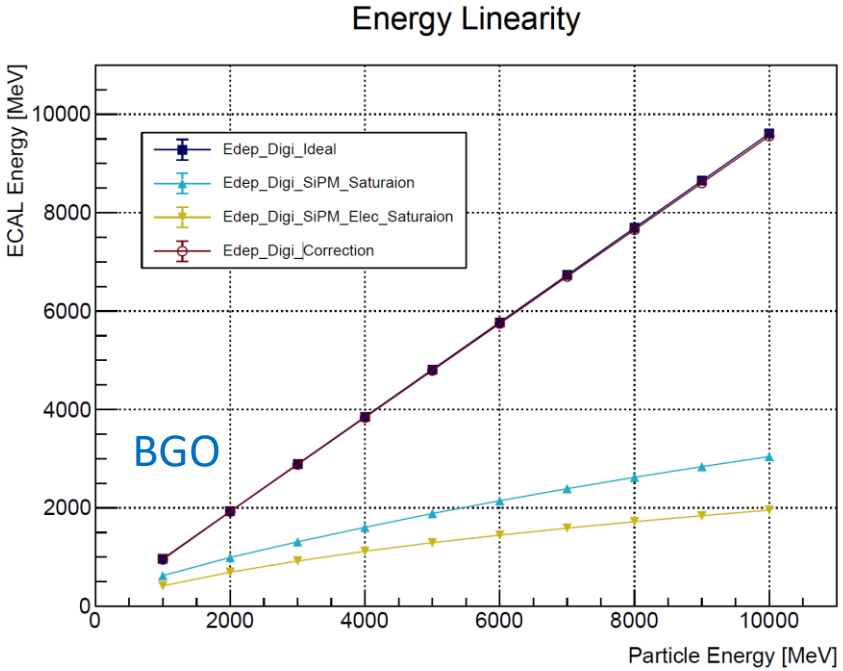


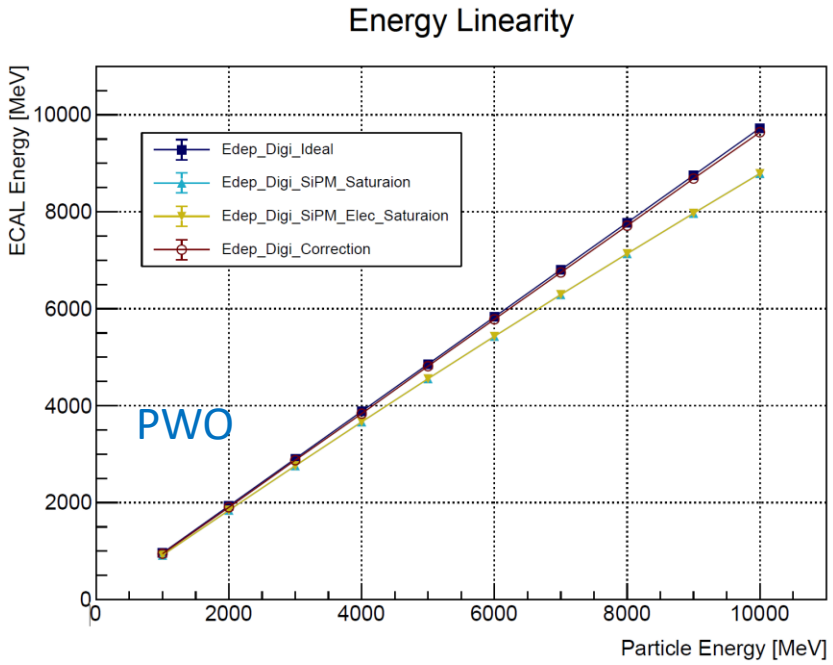


- S/N did not change significantly form 18 dB to 42 dB
- Operation under low gain can reduce the pressure on electronics while maintaining a good S/N

Small-scale detector module design: first glance

- 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…
- Realistic mechanical and electronic design…