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

R&D Progress and Requirements on CEPC Crystal ECAL

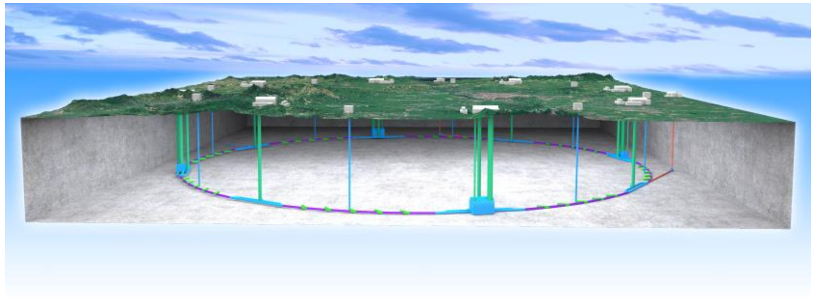
Baohua Qi
On behalf of CEPC Calorimeter Working Group

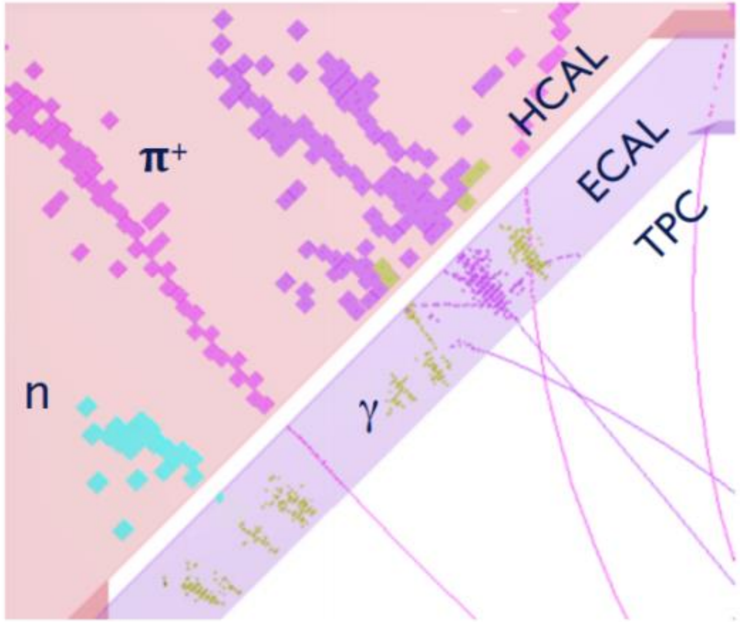
The 2022 CEPC MDI Workshop at Hengyang
March 30 – April 1, 2023

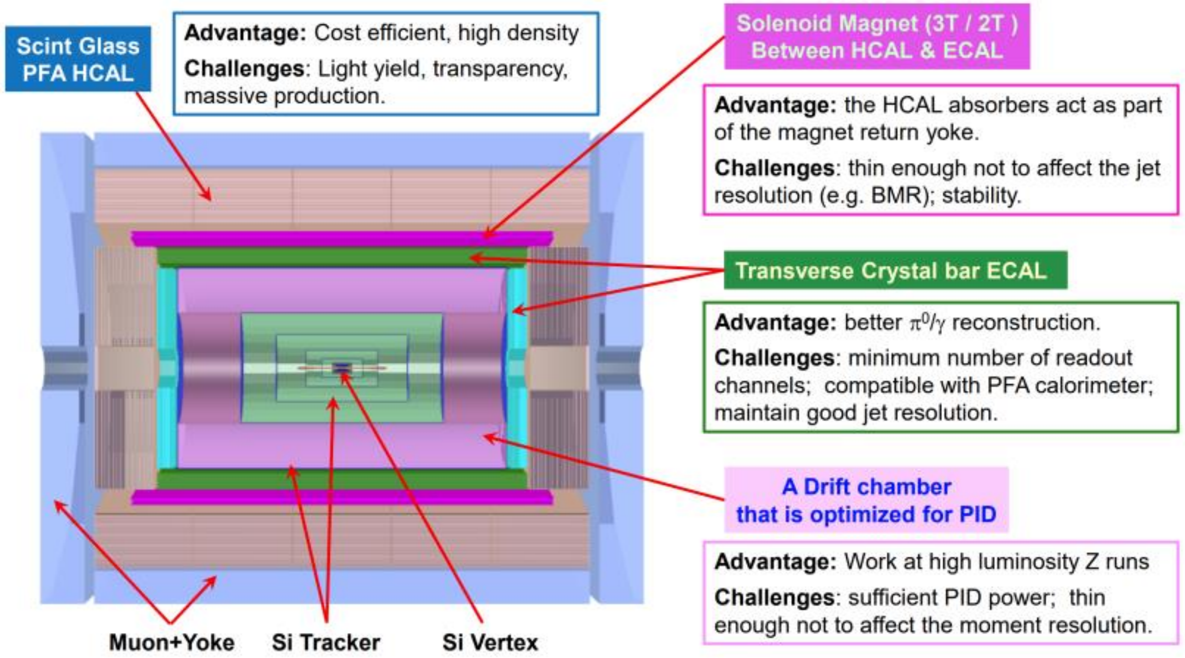
qibh@ihep.ac.cn

Motivations: new detector for CEPC

- CEPC: future lepton collider
  - Higgs/Z/W bosons, BSM searches, etc.
  - Precision jet measurement
  - PFA-oriented high-granularity calorimeter
- PFA-oriented detector "CEPC 4th concept": Drift Chamber + ECAL + HCAL
  - Crystal ECAL: intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Scintillating glass HCAL: high density for better boson mass resolution

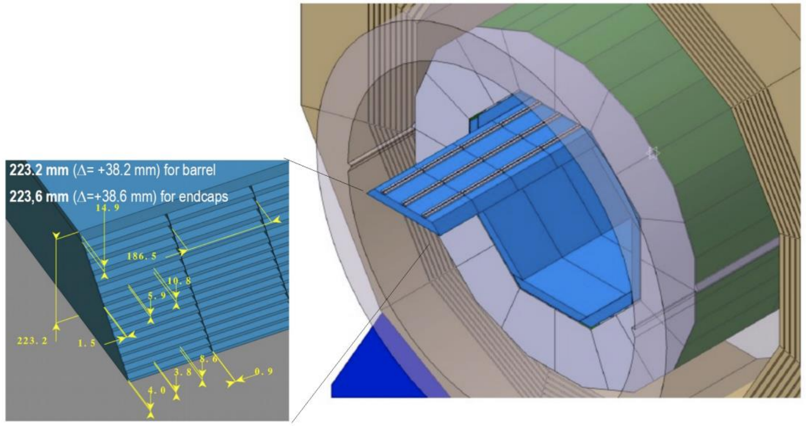


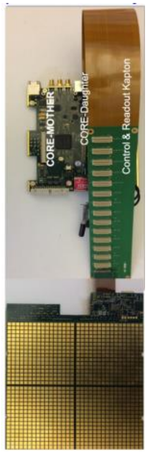




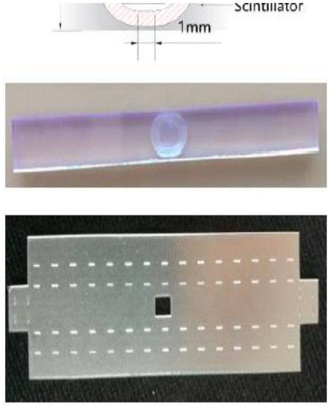
High granularity ECAL

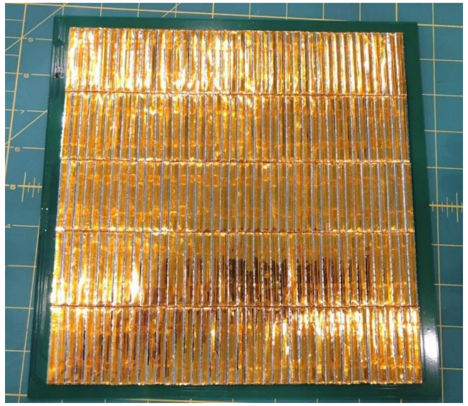
SiW ECAL



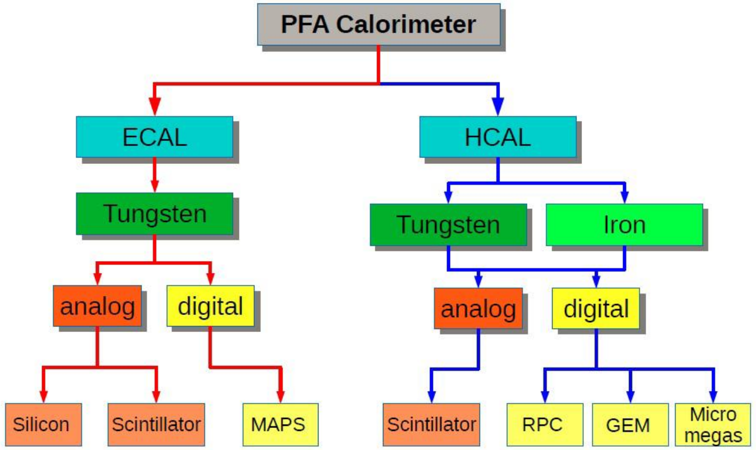


ScW ECAL

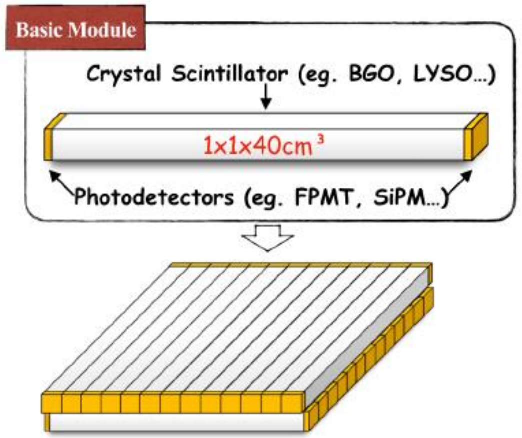


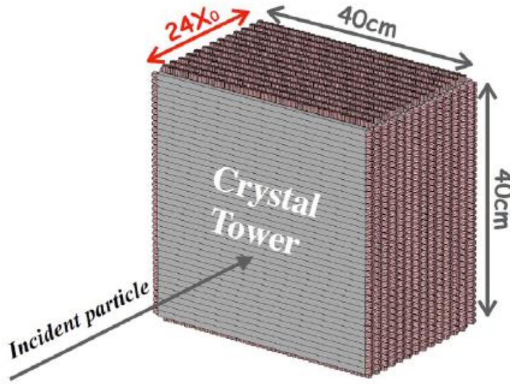


CALICE Collaboration Meeting at University of Göttingen

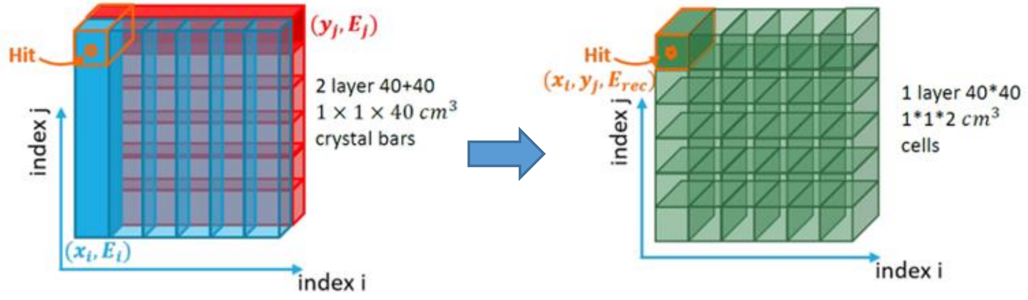


CEPC 4th detector concept: crystal ECAL

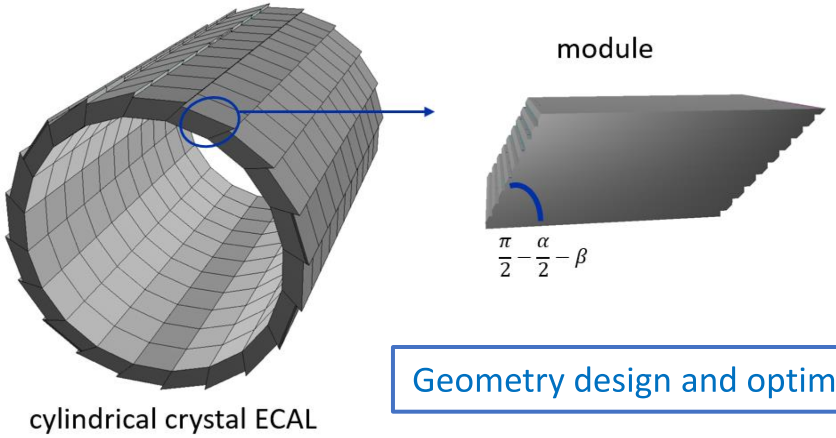




- Crystals arranged to be orthogonal between layers
- Readout from two sides



Crossed long bar design: e.g. $1\times1\times2$ cm^3 granularity



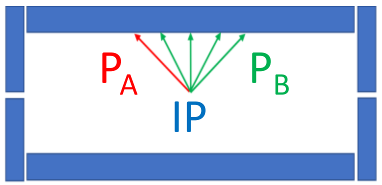
Geometry design and optimization

- New reconstruction software for long bars
- Geometry of barrel ECAL

High granularity crystal ECAL performance with Arbor-PFA

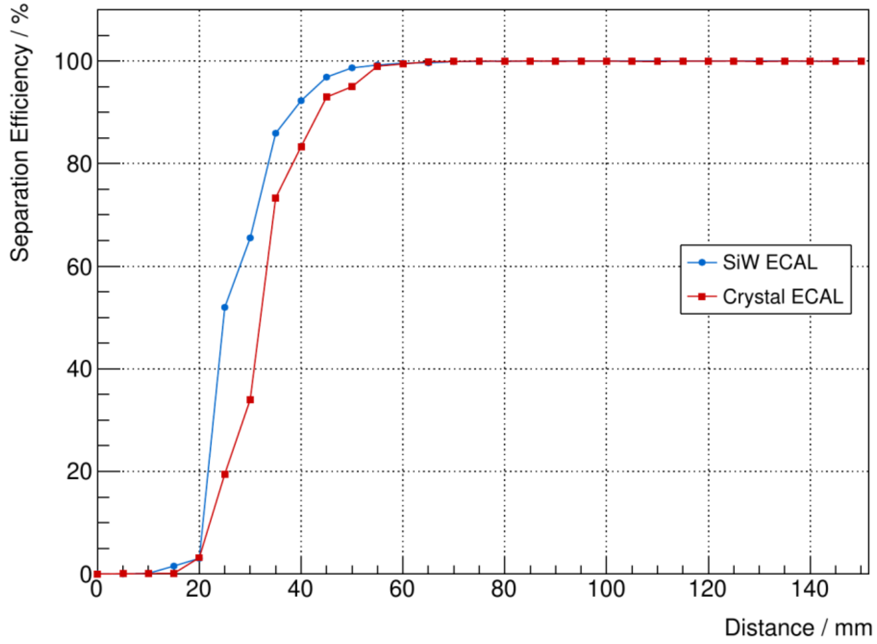
CEPC Software v0.1.1

- Simulation geometry: ideal 1 cm^3 crystal cubes
- For reconstruction of jets: separation of close-by particles

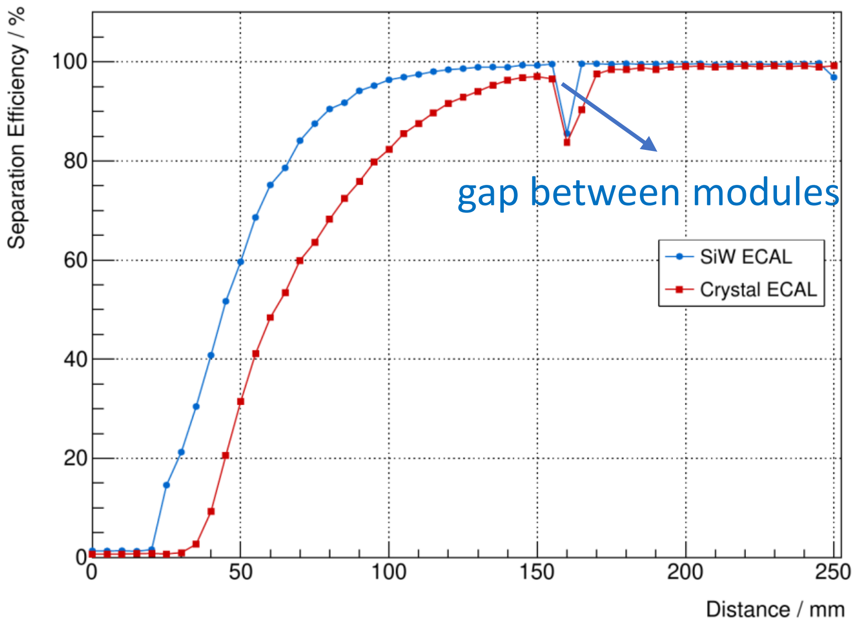


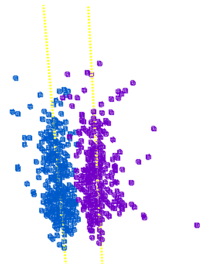
Side view of crystal ECAL

γ/γ separation with barrel ECAL



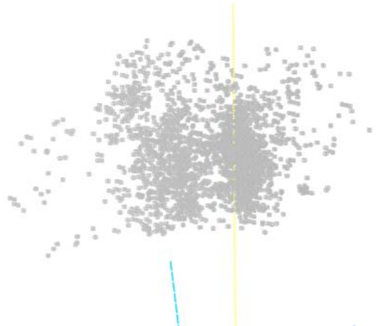
π^+/γ separation with barrel ECAL





Separated γ/γ

Separated π^+/γ



Unseparated π^+/γ

- EM shower: good separation power, similar to SiW ECAL under a high energy threshold
- Hadronic shower: challenges on clustering and matching clusters to tracks
- Arbor-PFA is not fully optimized for crystal option, still room for improvement

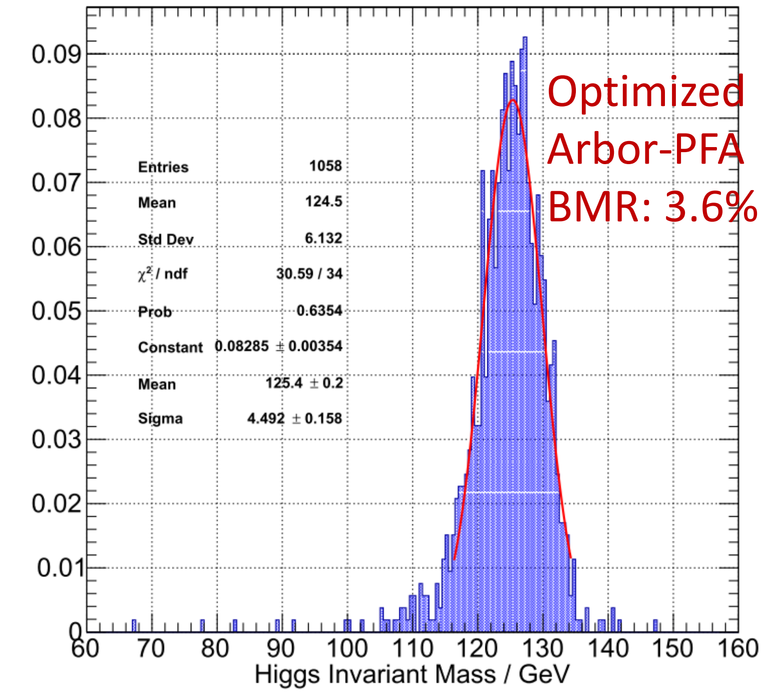
PFA performance: Higgs benchmark

CEPC Software v0.1.1

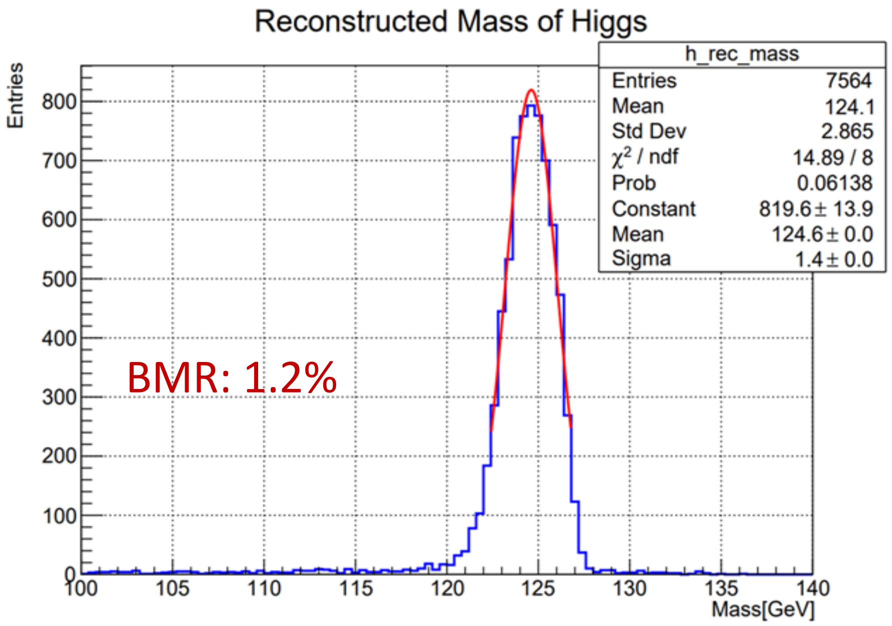
Baohua Qi (IHEP), Zhiyu Zhao (SJTU)

- Physics performance: Boson mass resolution (BMR)
- Studied with 1 cm^3 crystal cubes

BMR ($H \rightarrow gg$)



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

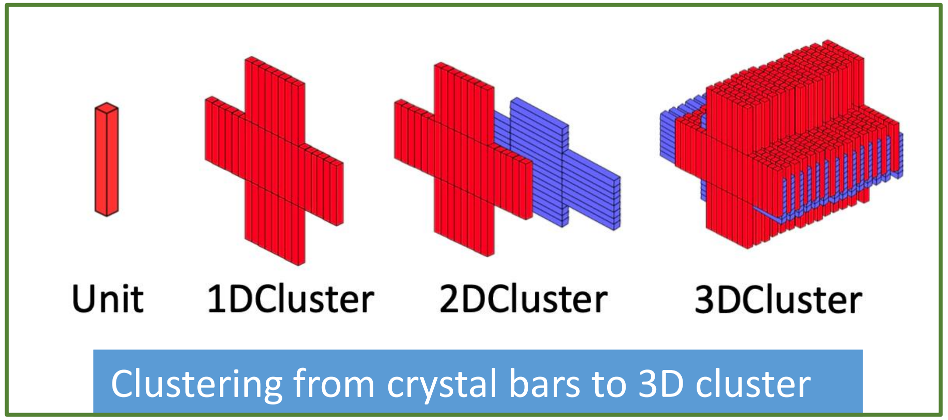


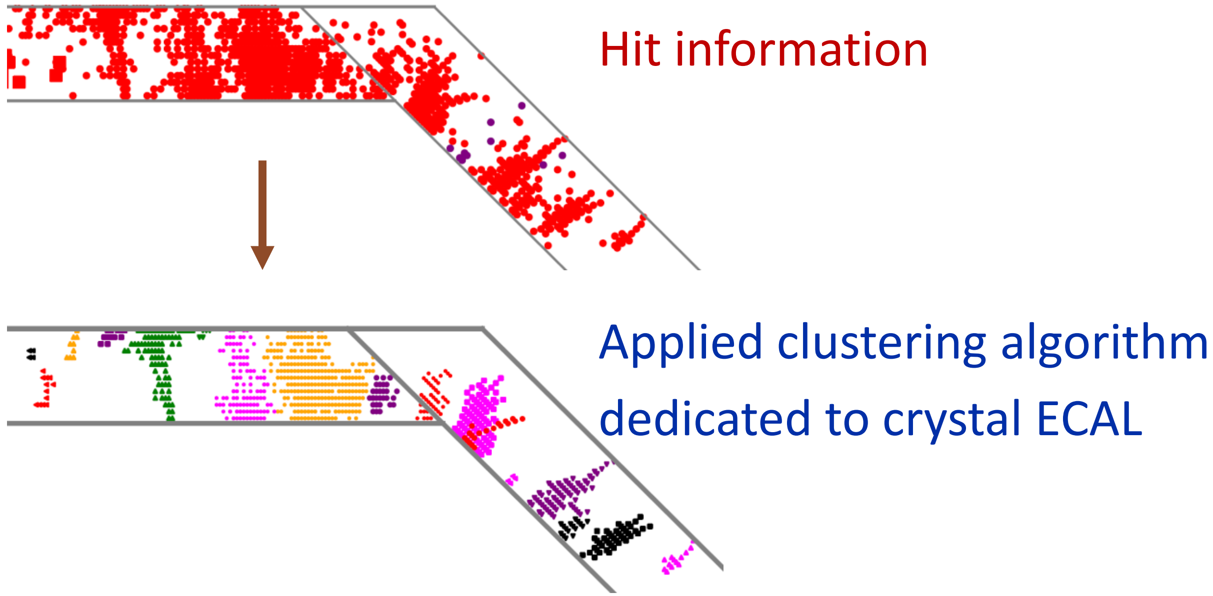
- Good performance with Arbor-PFA algorithm

Reconstruction algorithm dedicated to long crystal bar ECAL

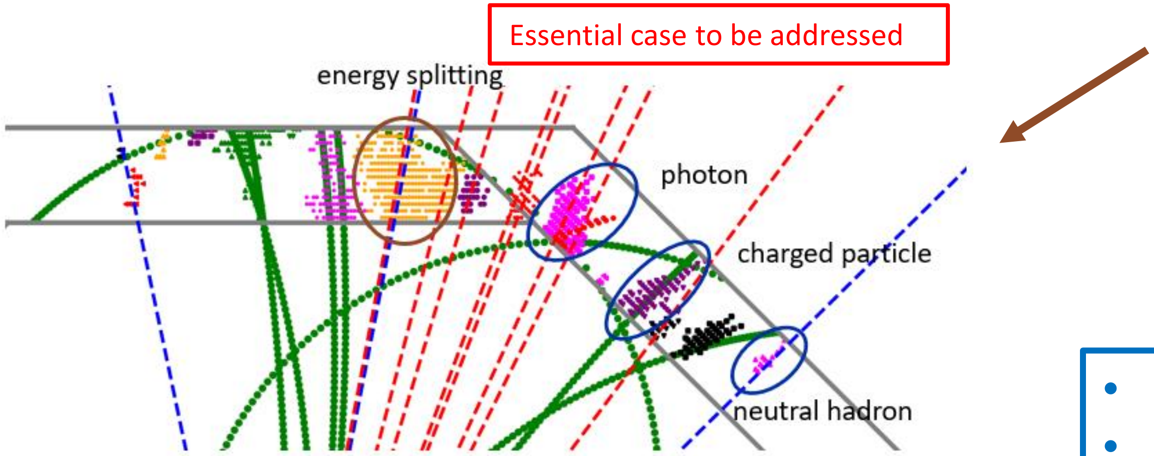
- Clustering algorithm for long bar crystal ECAL

Weizheng Song (IHEP)





- Clustering algorithm test with $H \to gg$ events



- Compare to MC truth: generally consistent

- Consistency between individual clusters and single particles
- Inputs for further particle recognition

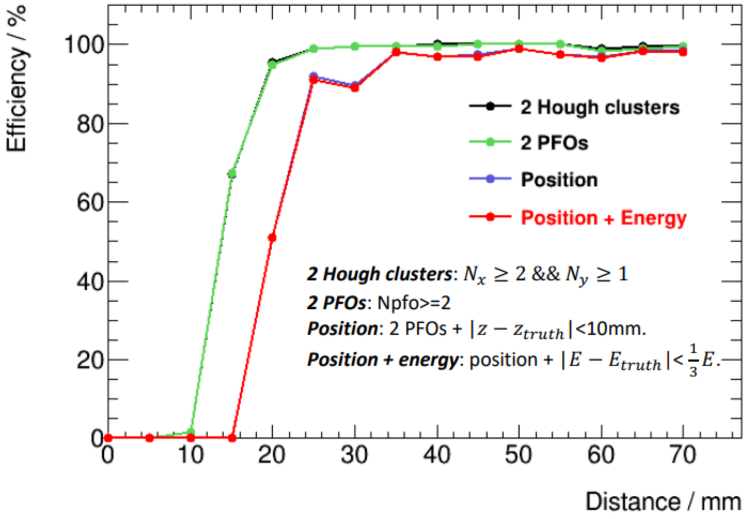
Reconstruction algorithm dedicated to long crystal bar ECAL

- Particle reconstruction for long bar crystal ECAL

Yang Zhang (IHEP)

Basic principles of reconstruction

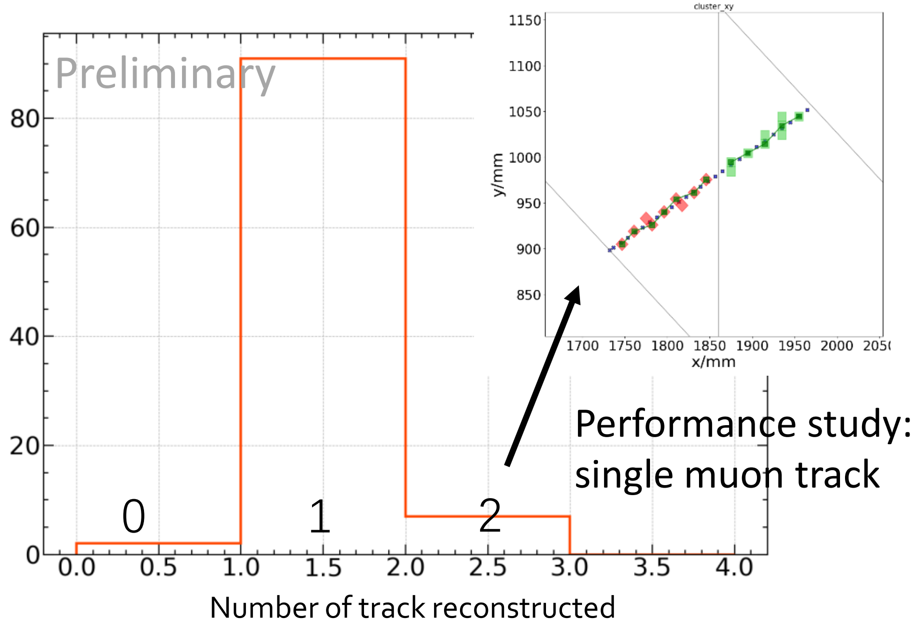
Cluster inputs → shower identification →
- Photon: Hough transformation
- Charged (MIP-like): track matching
- Neutral hadron: cone clustering



Performance study: di-photon recognition efficiency

Talk by Yang Zhang, 2022 CEPC Workshop

Photon reconstruction with Hough transformation



Performance study: single muon track

- Tracking matching algorithm for crystal ECAL
- Two tracks due to ECAL tower boundary

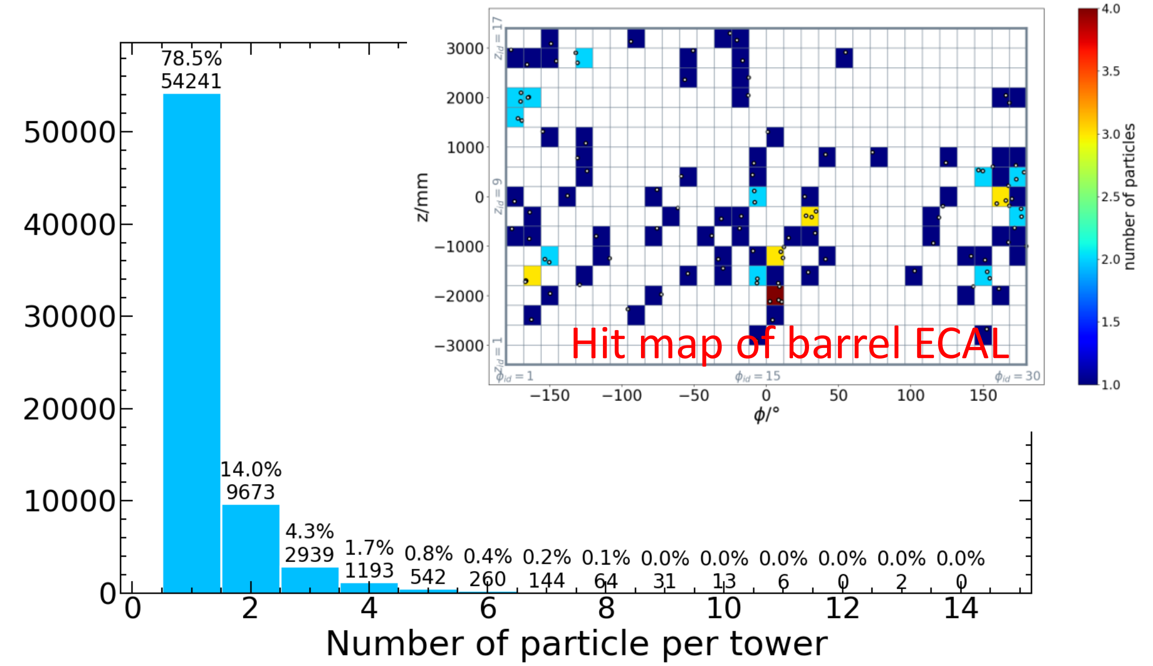
- Reconstruction flow has already been built
- Ongoing work on hadron…

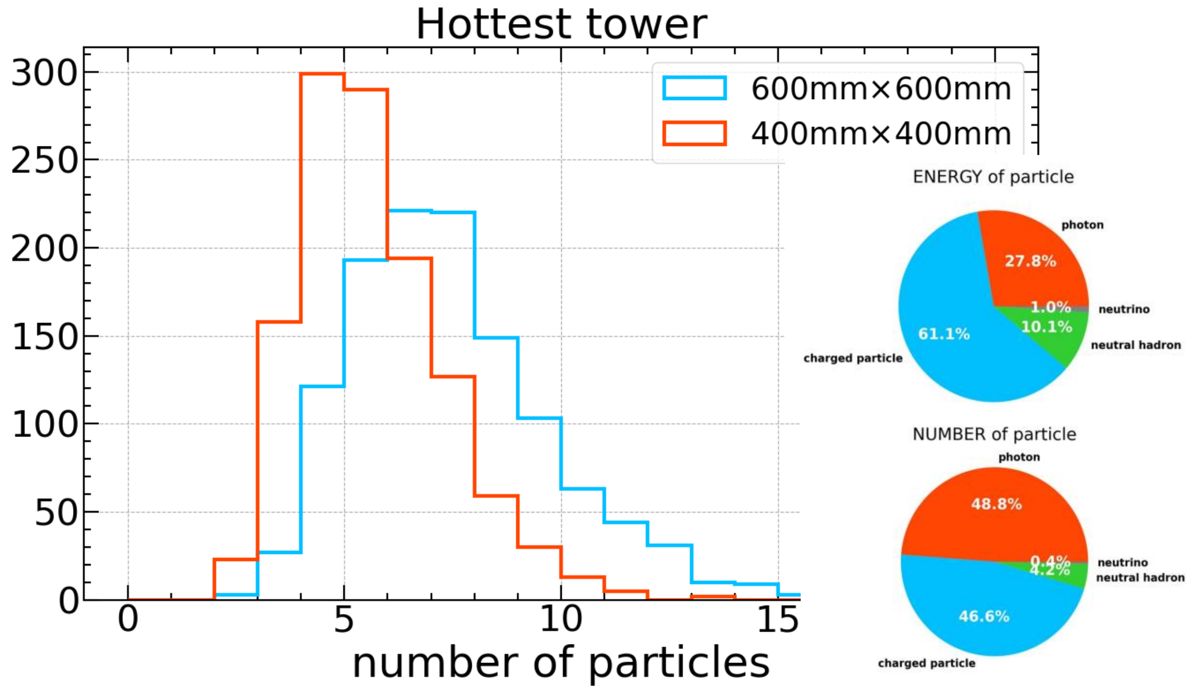
Reconstruction algorithm dedicated to long crystal bar ECAL

Yang Zhang (IHEP)

- Occupancy of ECAL towers: challenges on reconstruction
- Hottest tower: the tower with the largest number of particles hitting on
- 4 jets event: $e^{+}e^{-} \rightarrow ZH, Z \rightarrow q\bar{q}, H \rightarrow gg$

Key issues
- Sophisticated software



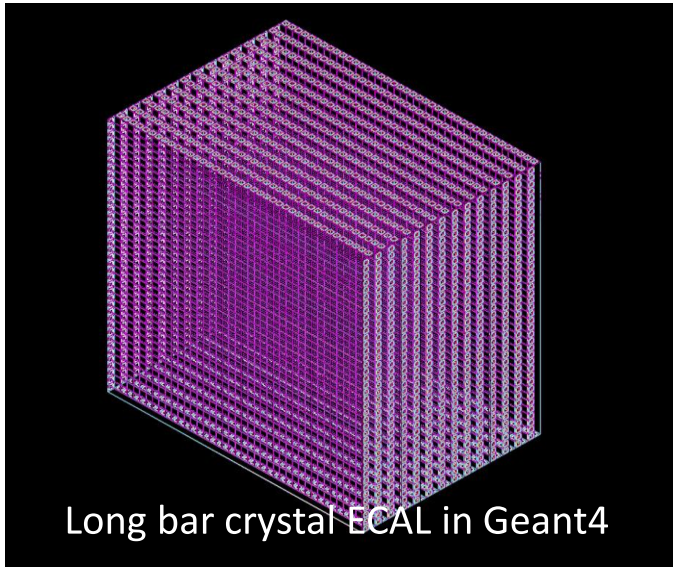


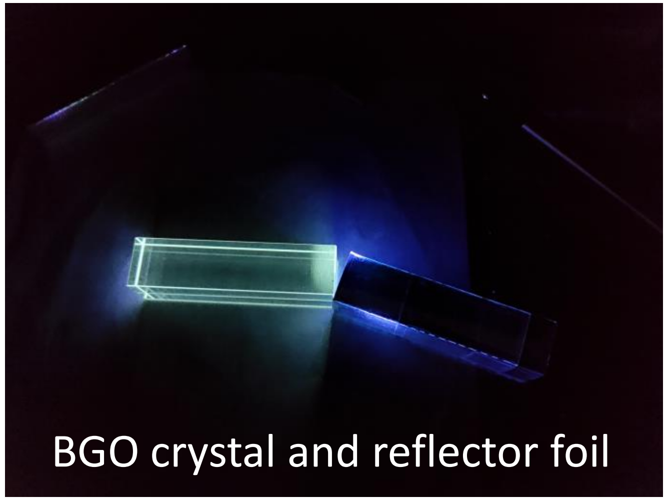
- Most towers have 0~1 particle hitting on
- Occupancy of these towers can be ignored

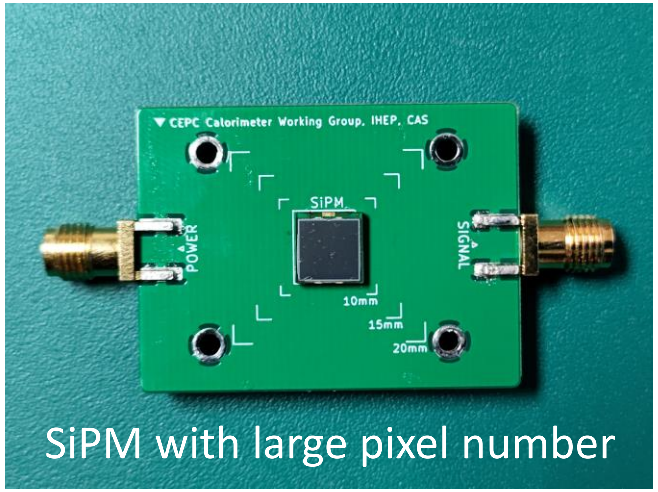
- Always have multiple particles hitting on one tower
- Need to deal with the occupancy by algorithm improvement
- Potential performance degradation needs to be understood

Hardware activities of crystal ECAL

- Study on requirements of crystal-SiPM units
  - Key parameters: MIP light yield, dynamic range, timing resolution, radiation hardness,…
- Preliminary barrel ECAL geometry design
- Development of small-scale crystal modules
  - System-level experiences (via development and beam test)


Long bar crystal ECAL in Geant4


BGO crystal and reflector foil



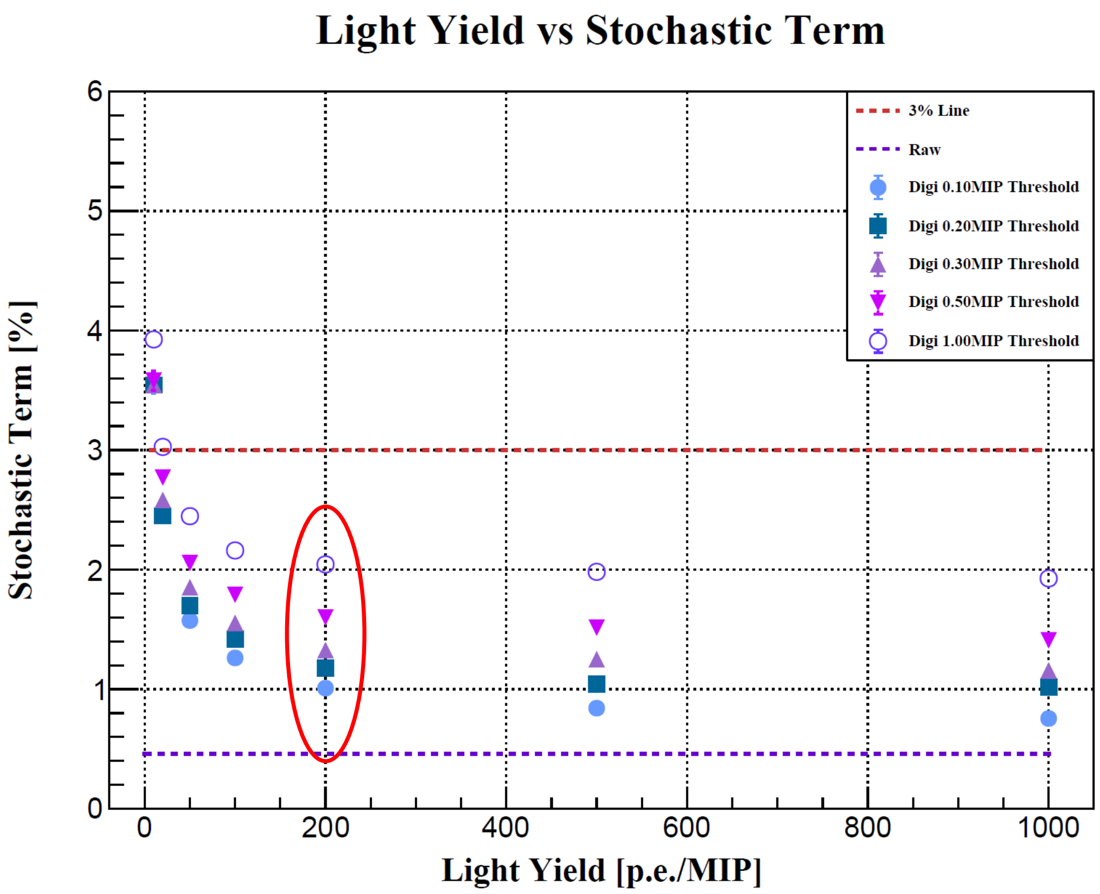
SiPM with large pixel number

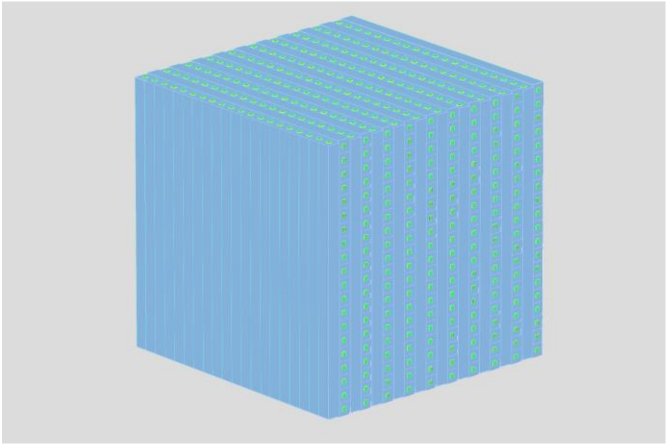

SiPM readout electronics

EM energy resolution: light yield requirements

Geant4 Simulation (v11.0)

- Light yields: number of detected photons per MIP
- Energy resolution: need stochastic term < 3%





Simulation: 40×40×28 supercell, BGO long bars, gaps, 1~40 GeV electrons
Digitization: photon statistics, gain uncertainty, ADC error,…

- Good resolution requires
  - Moderately high light yield → dynamic range
  - Low energy threshold → noise level

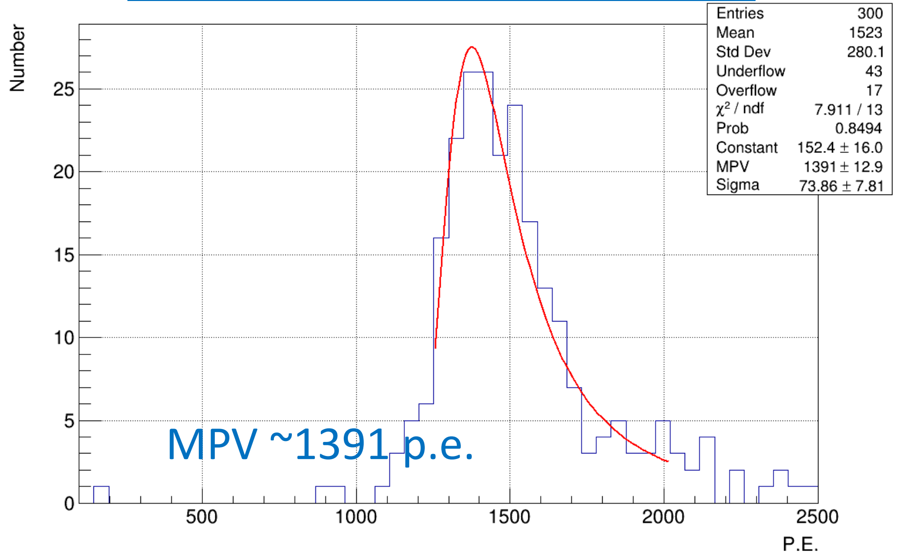
Key requirements

- Light yield required for one crystal: ~200 p.e./MIP (1 cm BGO)
  - Get $< 1.5\%/\sqrt{E}$ energy resolution
  - Requirement for one SiPM: ~100 p.e./MIP

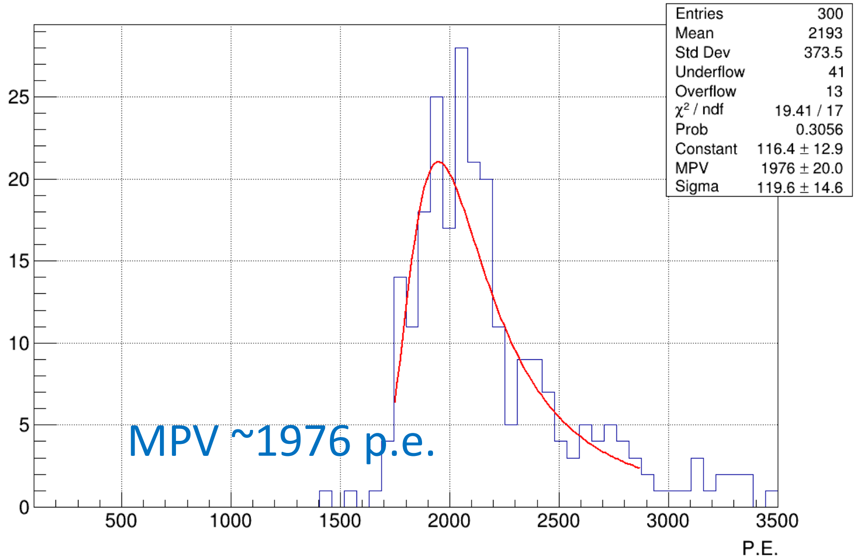
Cosmic-ray test: MIP response of BGO crystal

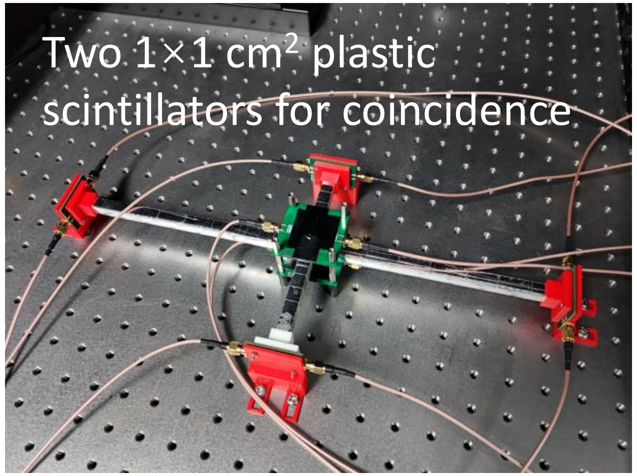
- Measurement of crystal-SiPM units
  - 16 and 40 cm BGO crystals, double-sided readout

6×6 mm^2 SiPM 40 cm BGO



6×6 mm^2 SiPM 16 cm BGO

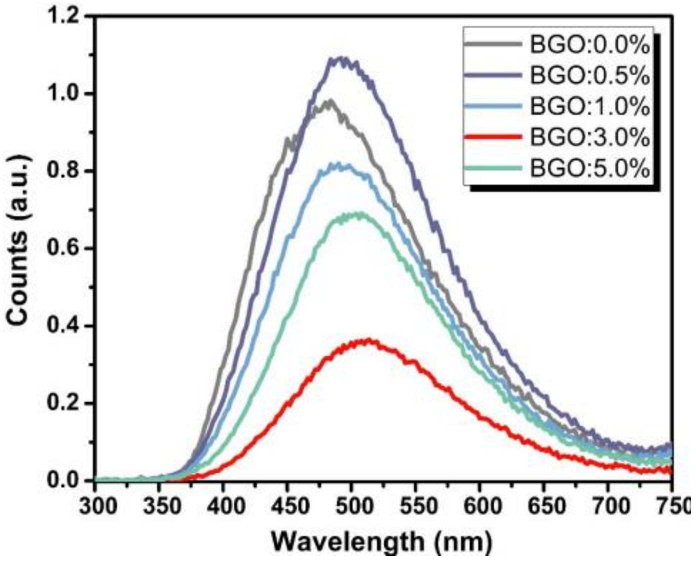




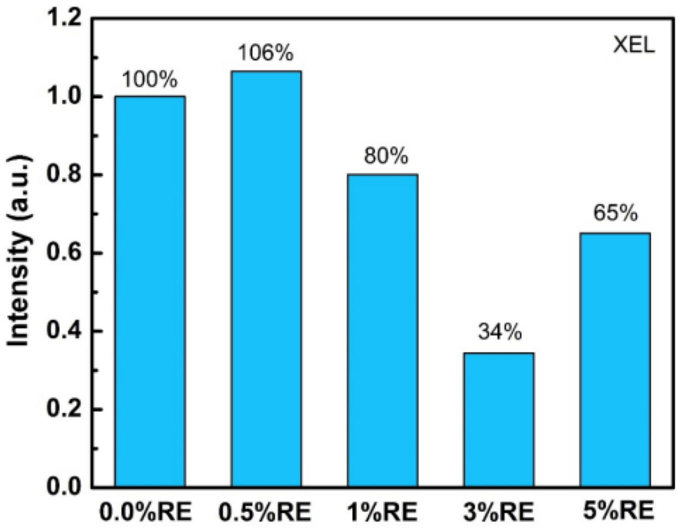
Key issue
- MIP light yield higher than the requirement
  - Smaller SiPMs with high pixel density: 3×3 mm^2, 6μm/10μm
  - "Tune" BGO light yield as well as decay time (with SIC-CAS)

Status of new BGO crystal development at SIC

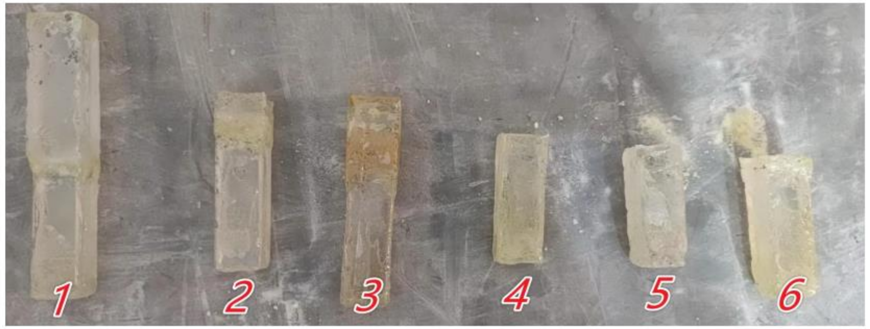
Junfeng Chen (SIC-CAS)



Radioluminescence spectra of as-prepared BGO: RE powders



The relative luminescence intensity of BGO powders with 0-5% RE doping concentration



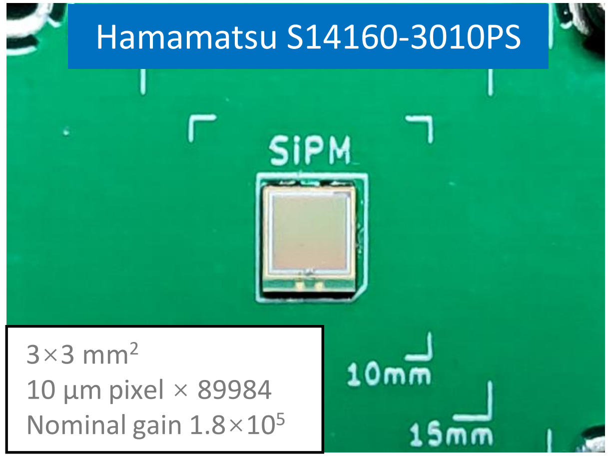
A fast combinatorial design and screening method to optimize the doping concentration

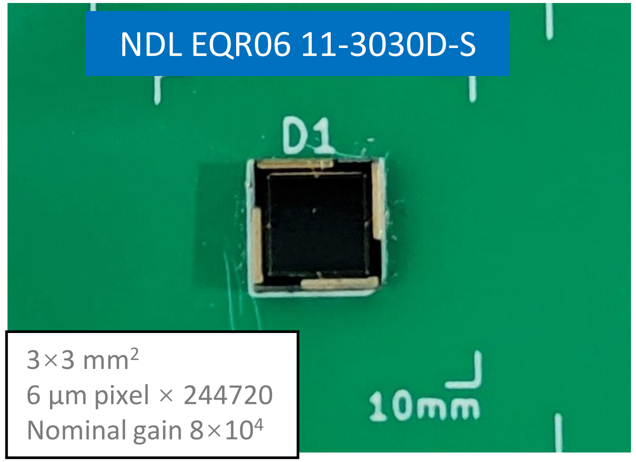
Achieved so far…

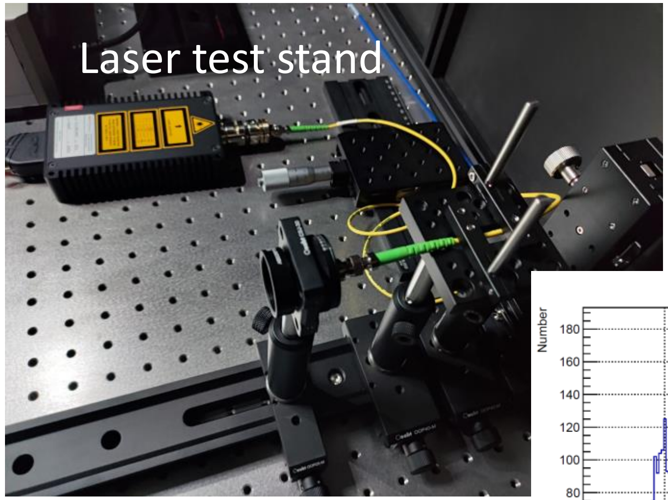
- Light yield reduce ~65% and decay time reduce ~34%

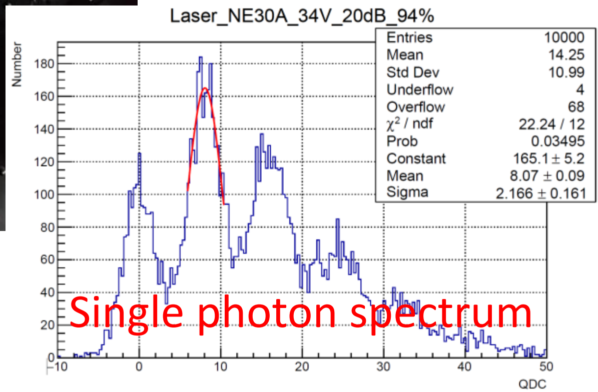
Characterization of large dynamic range SiPMs

Baohua Qi (IHEP), Zhiyu Zhao (SJTU)

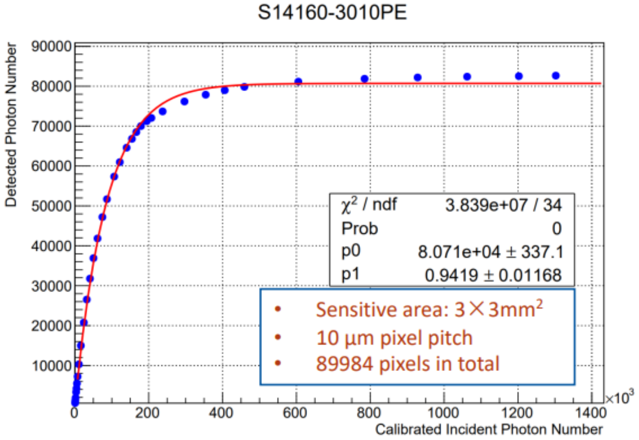


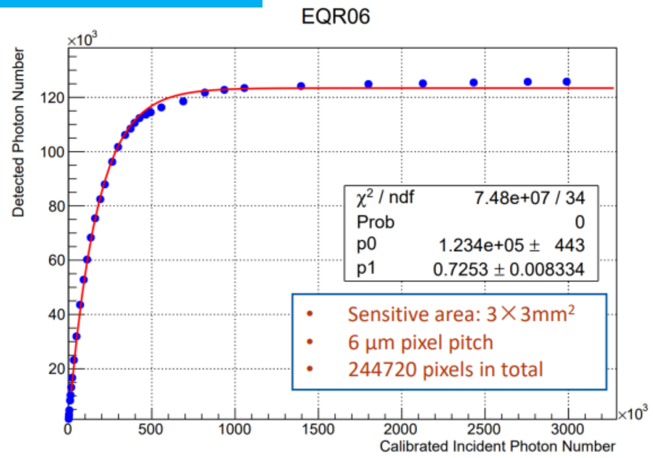






SiPM saturation study





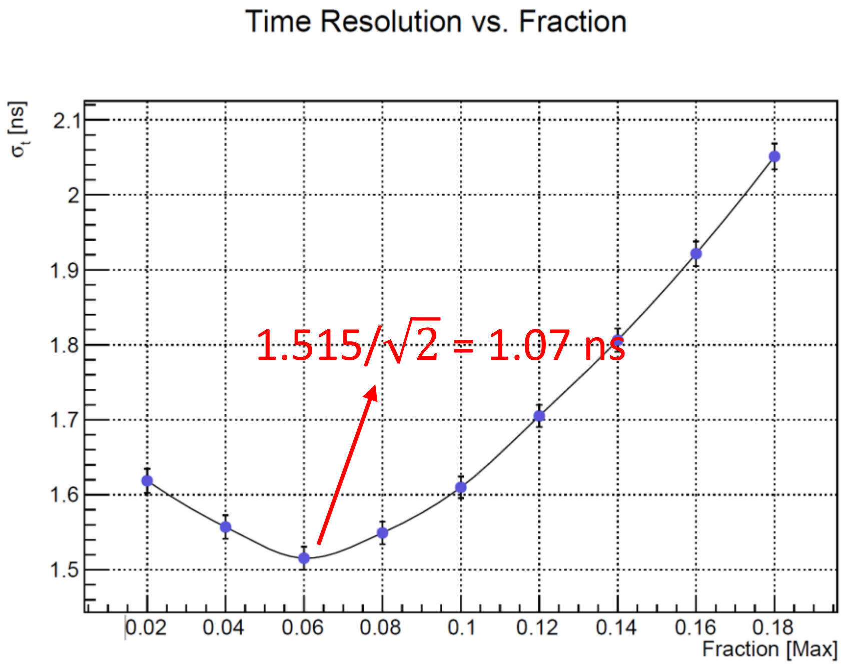
Key issue

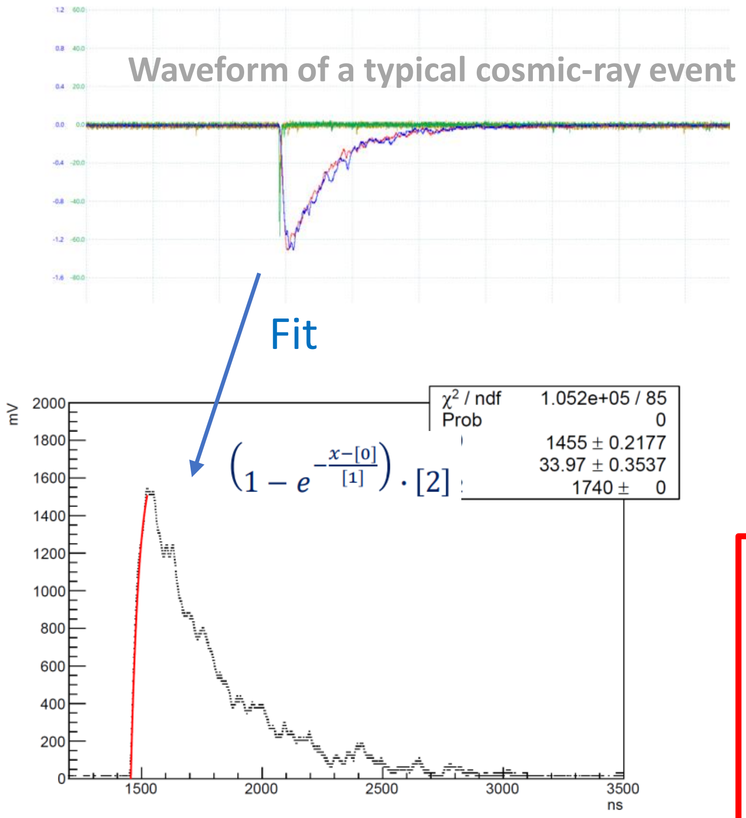
- Limitation from dynamic range

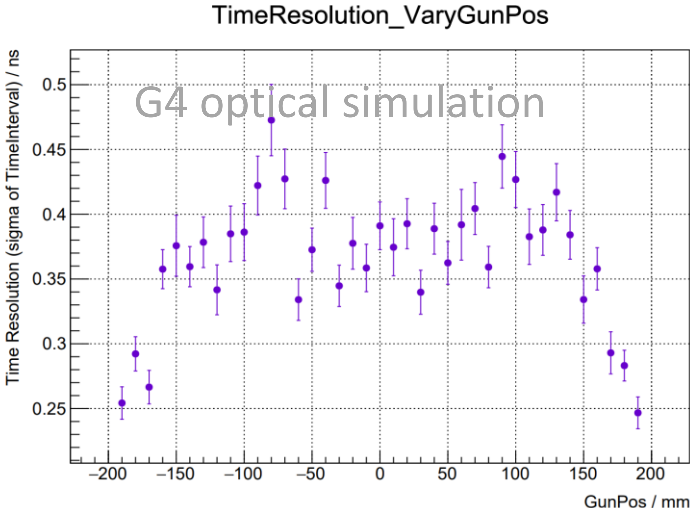
Latest progress on time resolution study

Baohua Qi (IHEP), Zhiyu Zhao (SJTU)

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







Expected time resolution in simulation: ~400 ps

Requirements
- Time resolution: ~400 ps

Limitations:
- Electronics in tests, scintillation properties of BGO crystal, light transmission

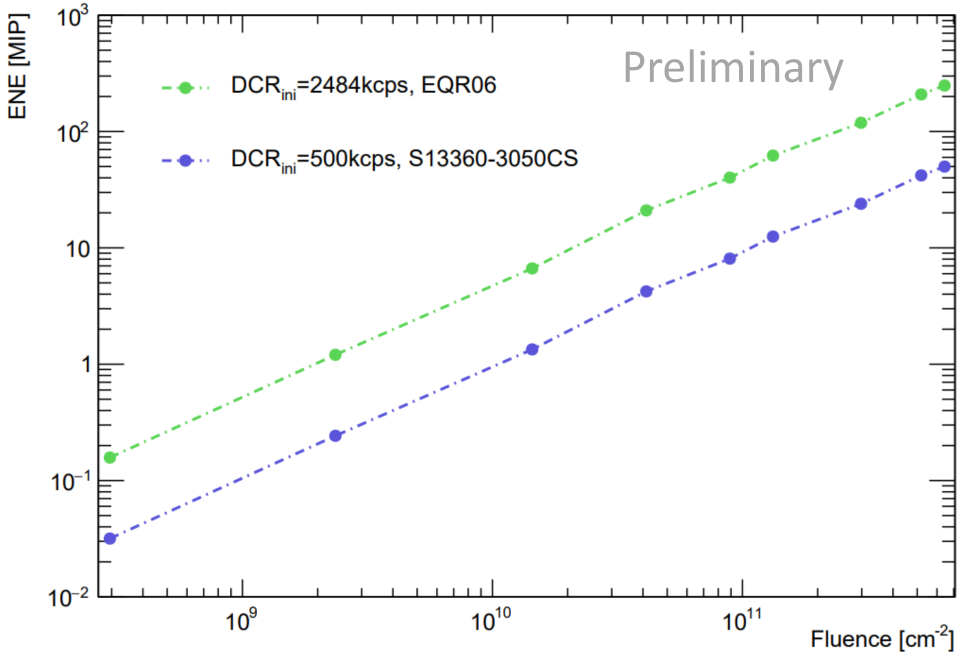
Studies of radiation damage

- SiPM damage: DCR, signal amplitude,…
- Crystal damage: light yield, uniformity,…

- For DCR of SiPM, method to calculate equivalent noise energy (ENE)
  - Count the number of photons from dark noise within one signal, and convert it into energy according to light yield
  - e.g. light yield: $LY = 100\ pe/MIP$, signal width: $t_w = 1\mu s$, $ENE = \frac{DCR \times t_w}{LY}$

Zhiyu Zhao (SJTU)

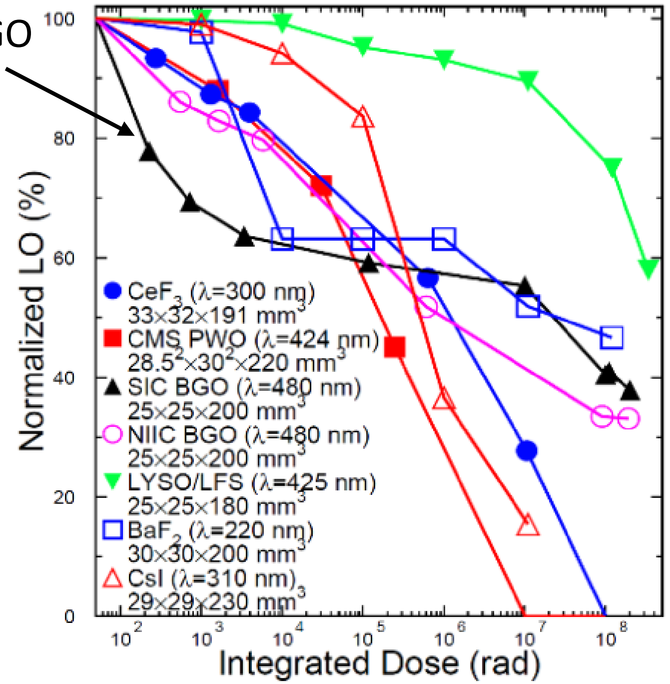
SiPM equivalent noise energy simulation



Simulation with data in https://doi.org/10.1016/j.nima.2022.167488

Change of crystal light output

SIC BGO

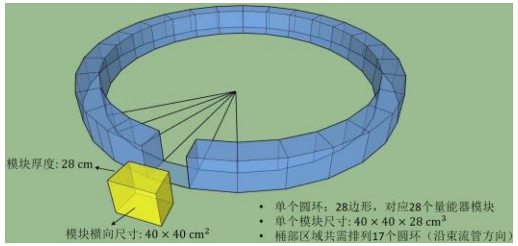


Ultrafast and Radiation Hard Inorganic Scintillators for Future HEP Experiments

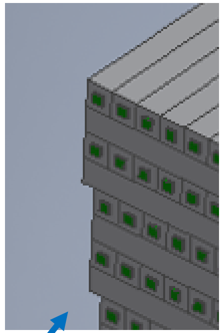
Key issue
- Further understanding of radiation damage
- Radiation hard devices

General geometry design for crystal ECAL

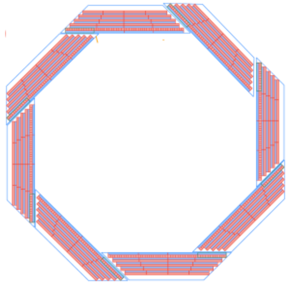
- CEPC crystal ECAL barrel geometry design
  - Finer segmentation of towers
  - Decrease outer radius for lower cost of the outer detectors
  - 28 towers per ring, 17 rings along beam direction
  - ~25 radiation length: 28 layers



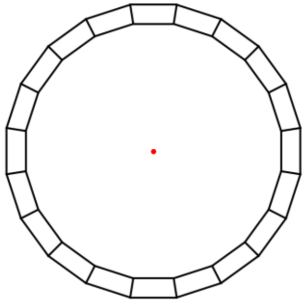
Quan Ji, Chang Shu (IHEP)



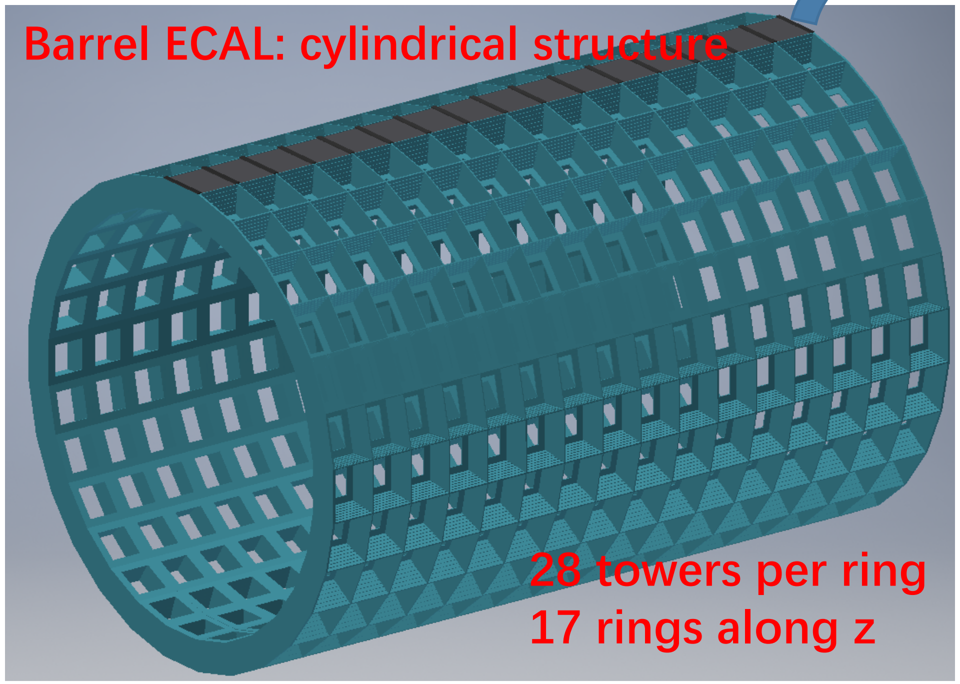
4 layers per "step" with the same transverse size

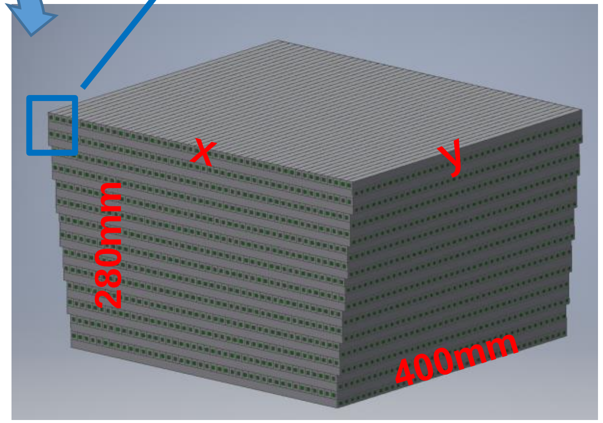


Octagonal detector



Cylindrical crystal ECAL



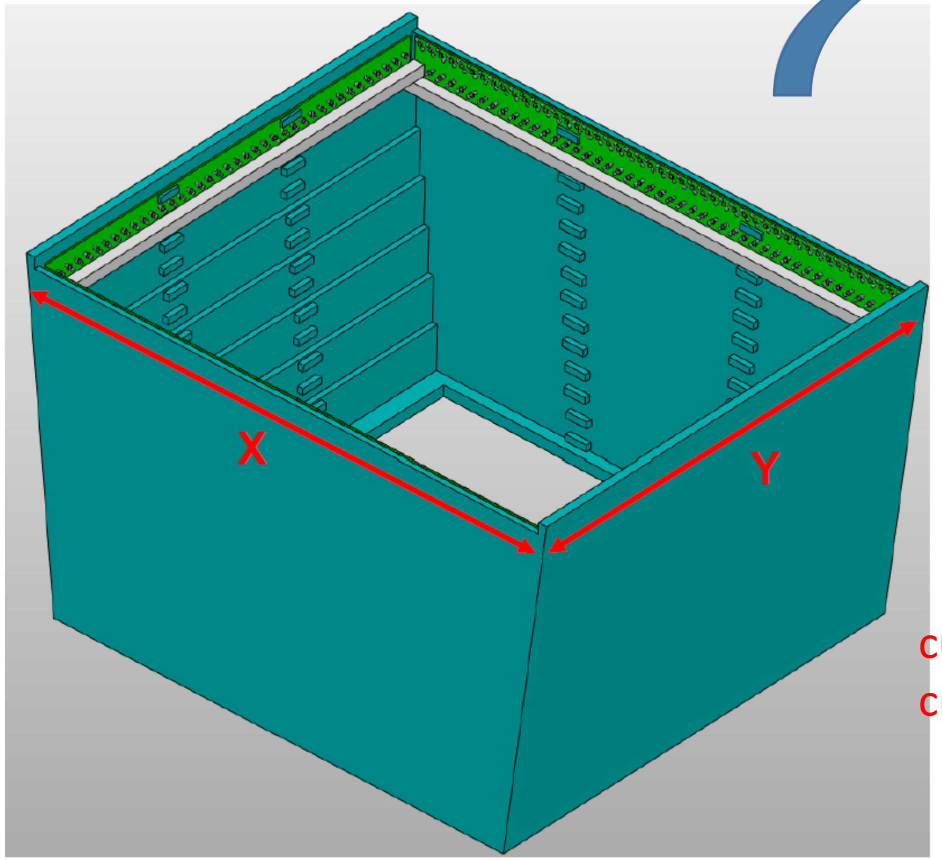


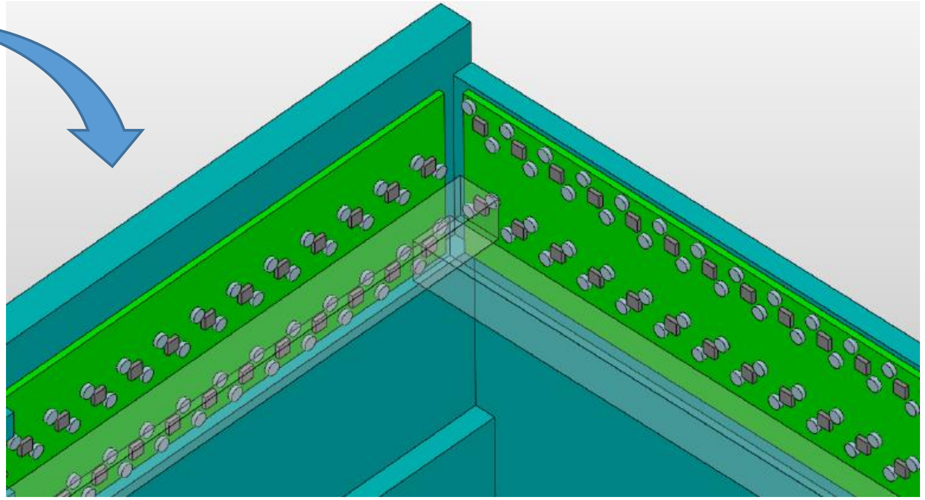
Key questions
- Space for electronics and cooling
- Assembly

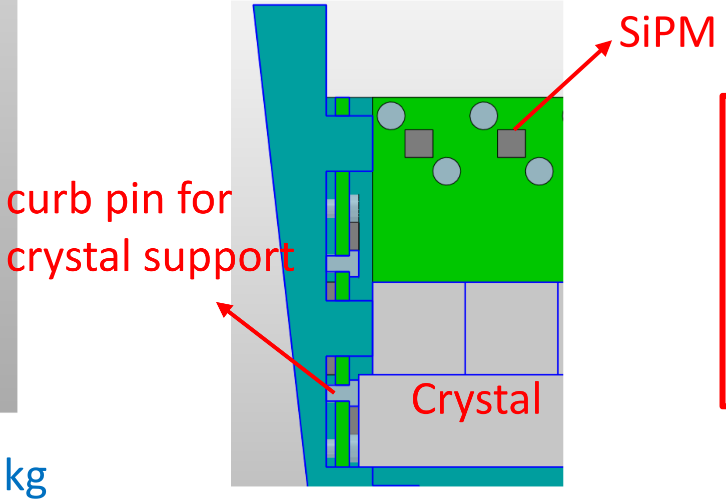
Detailed assembly of PCB and crytal

- Mechanical assembly: crystals will be supported by curb pins through hole on PCB

Quan Ji, Chang Shu (IHEP)





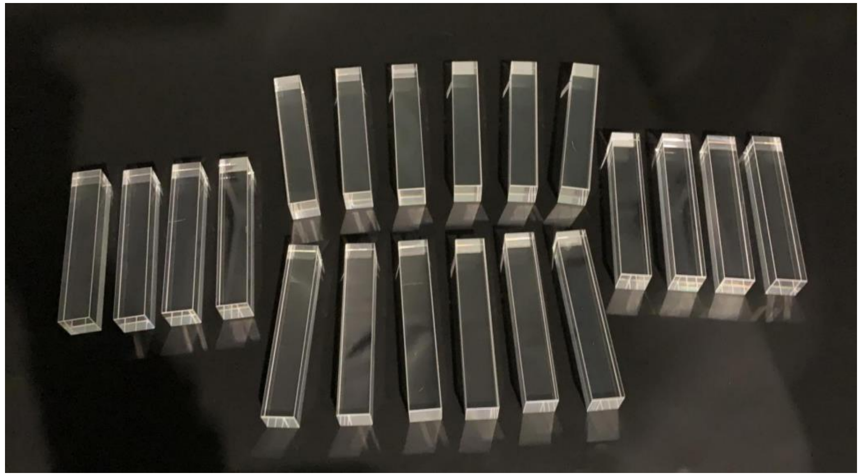


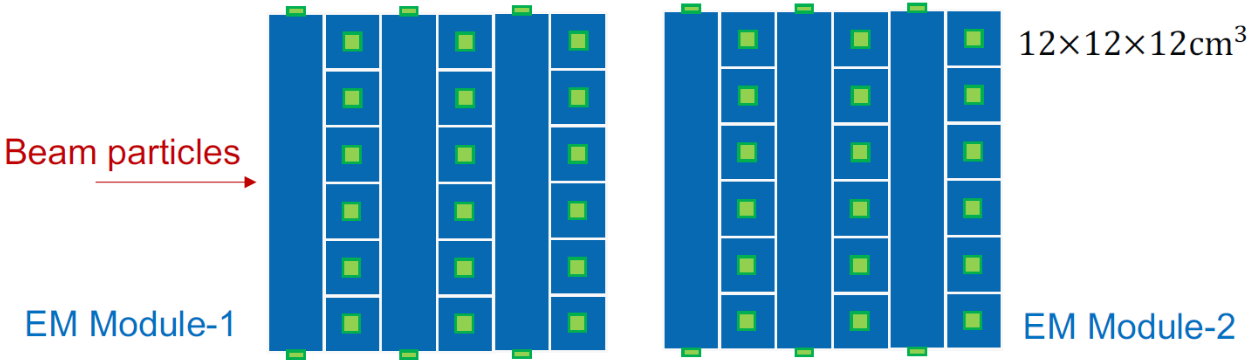
Key questions
- PCB cannot bear the weight of crystals
- Holes on PCB for external support structures

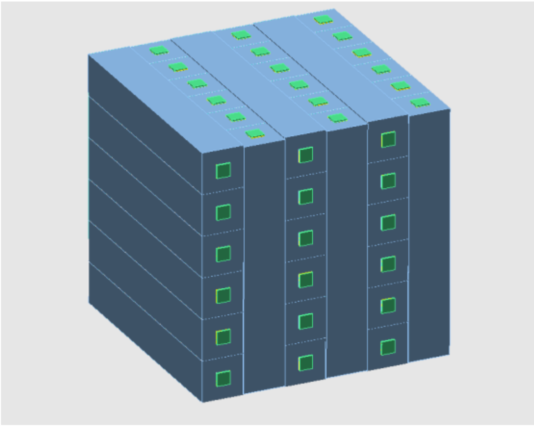
- Total mass of the crystals in one tower: ~380 kg

Activities on small-scale crystal module design

- 12×12×12 cm^3 BGO modules development
- Motivations: address critical issues at system level
- Beam test studies
  - Energy resolution, shower profiles
  - Validation of simulation and digitization tool
  - Application of the new reconstruction software
- SiPM option: NDL/HPK, 6/10 μm pixel size, 3×3 mm^2 sensitive area
- Electronics option: commercial products available, e.g. Citiroc-1A
- Crystal option: BGO crystal (12×2×2 cm^3) from SIC-CAS
- Beam test plan: 2 modules serial arrangement







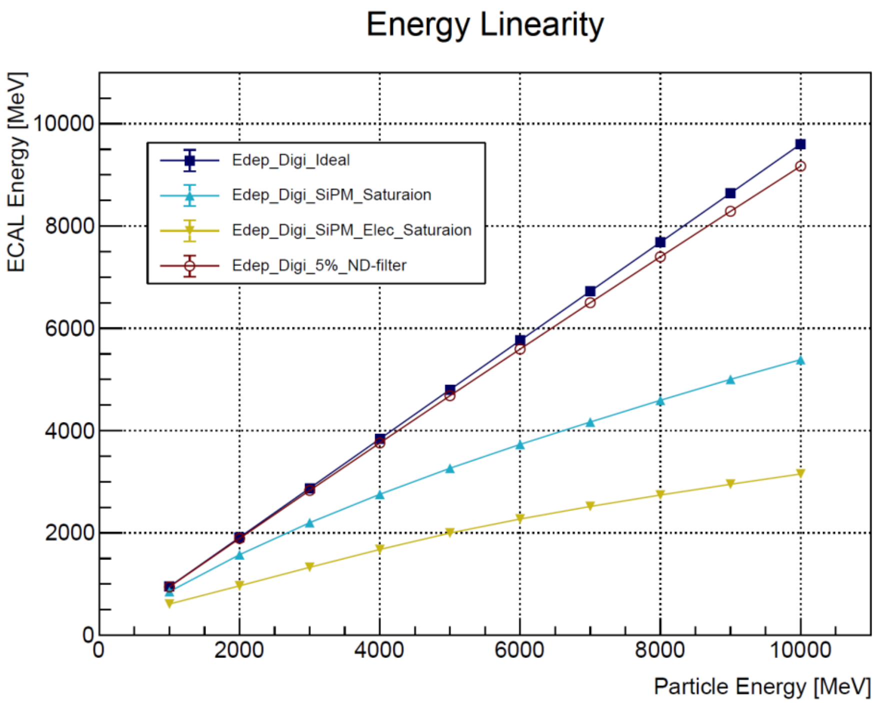
Crystal module
- 36 crystals readout from two sides
- 18 channels per side, 72 channels per module

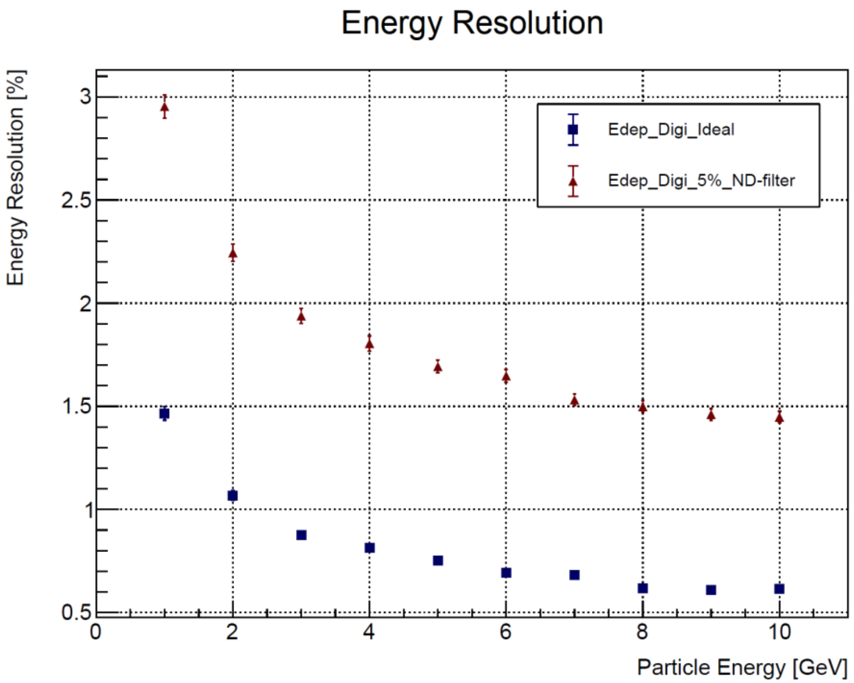
Activities on small-scale crystal module design

Geant4 Simulation (v11.0)

- Performance check: Geant4 simulation with 1~10 GeV electron
- Saturation considering S14160-3010PS SiPM and Citiroc-1A chip
- 5% (σ = 0.1%) transmittance neutral density filter is used for light attenuation

Digitization: photon statistics, SiPM gain error, ADC error, MIP threshold





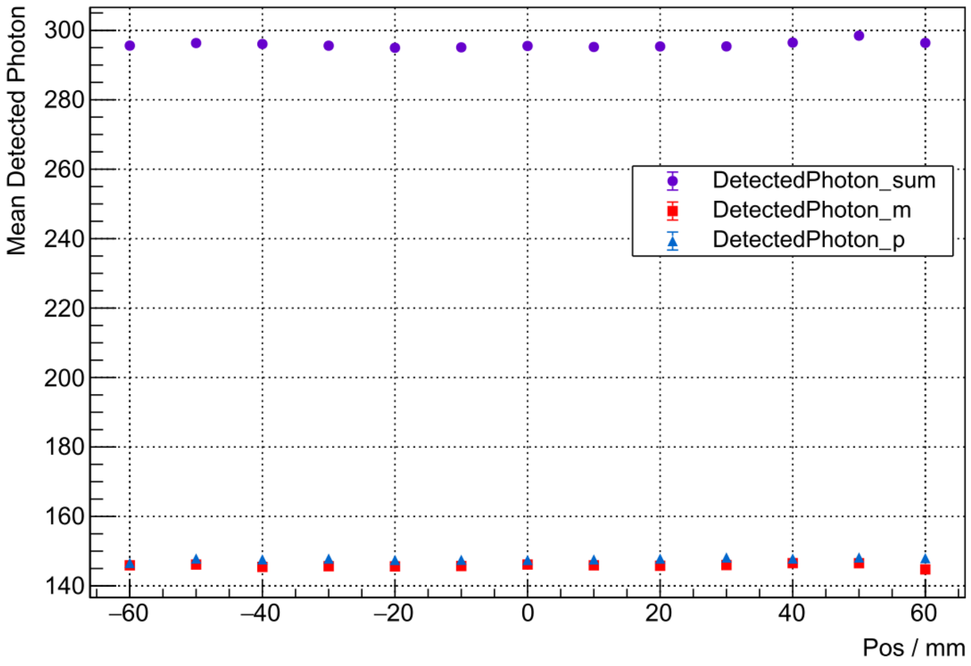
- SiPM non-linearity should be further calibrated
- Saturation of electronics can be avoided via high dynamic range ASIC
- 5% neutral density filter can mitigate the saturation effect but will introduce additional uncertainty

Activities on small-scale crystal module design

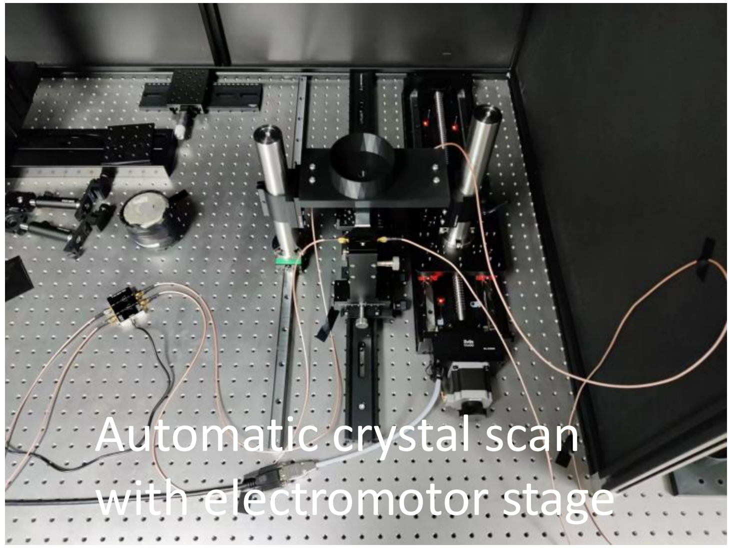
Zhikai Chen (IHEP/USC)

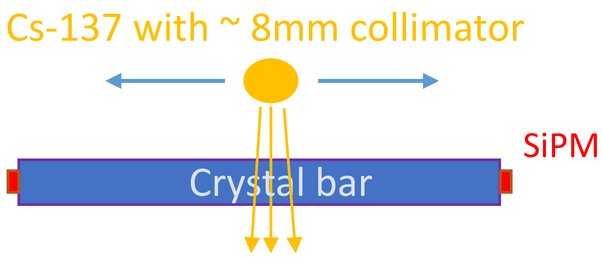
- Batch test of SIC-CAS BGO crystal bars
  - 40 crystals with ESR and Al foil wrapping
  - Scan with Cs-137 radioactive source

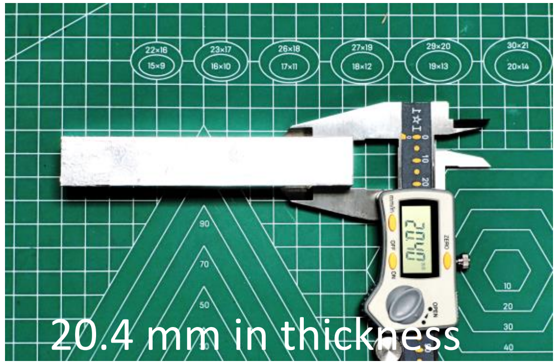
Response uniformity along bar



- Generally good uniformity along a single bar

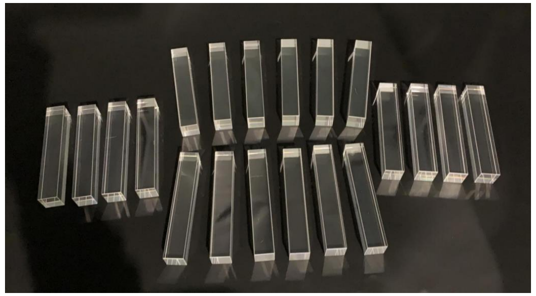


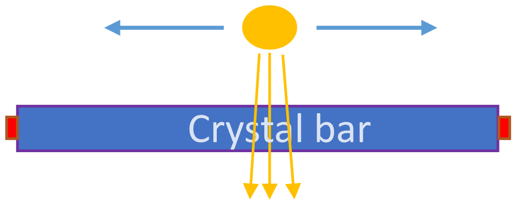




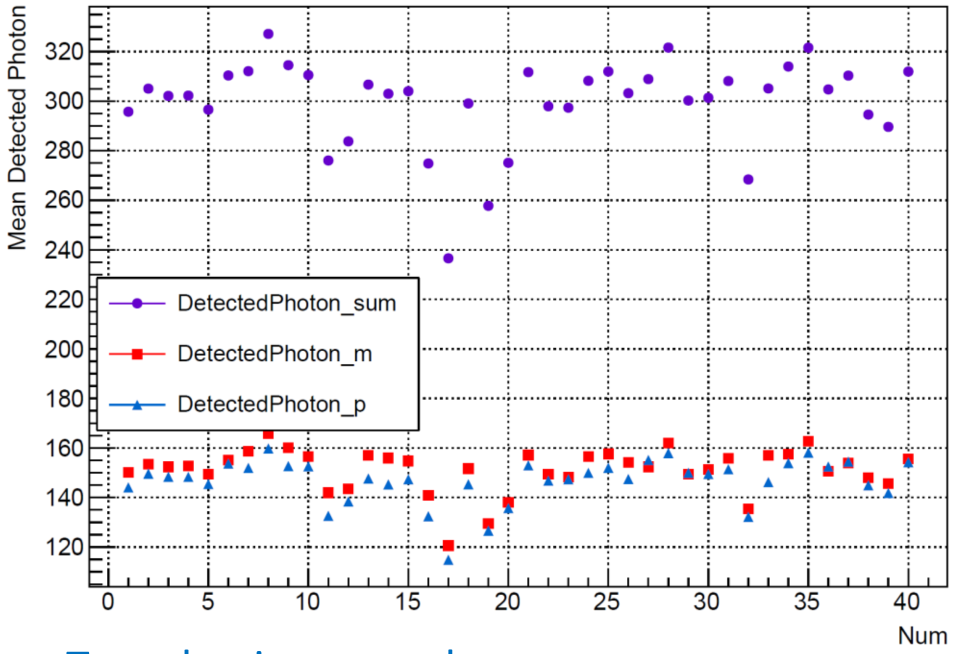
Activities on small-scale crystal module design

- Batch test of SIC-CAS BGO crystal bars
  - 40 crystals with ESR and Al foil wrapping
  - Scan with Cs-137 radioactive source

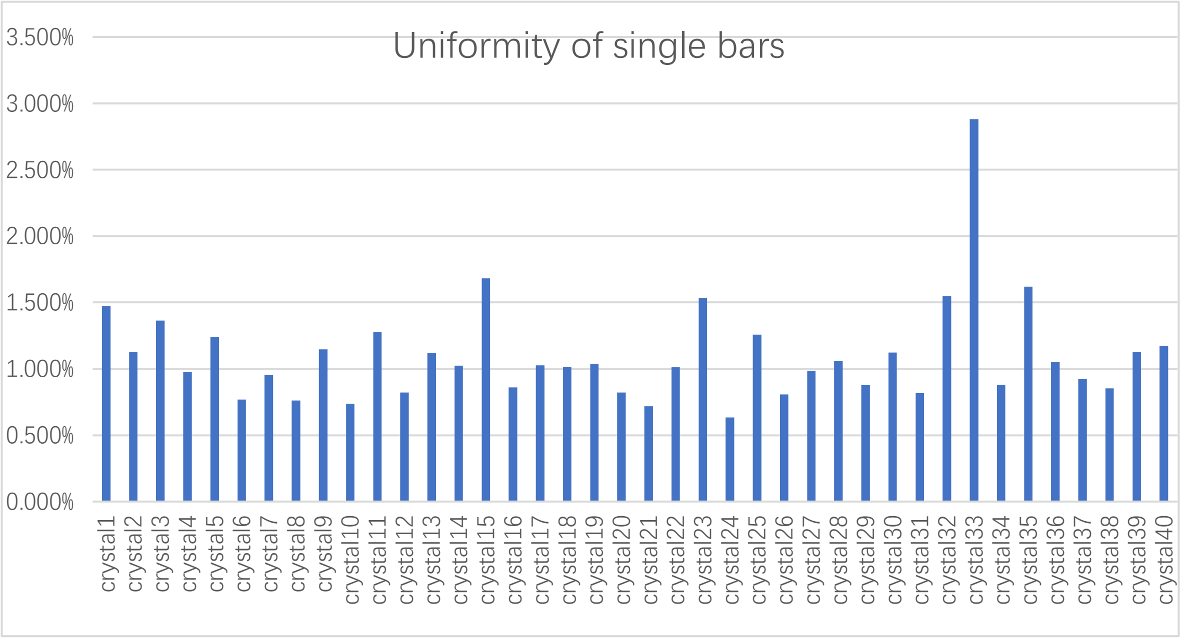




Response uniformity among 40 bars



- Tested point: crystal center
- Response varies among bars: coupling? wrapping?

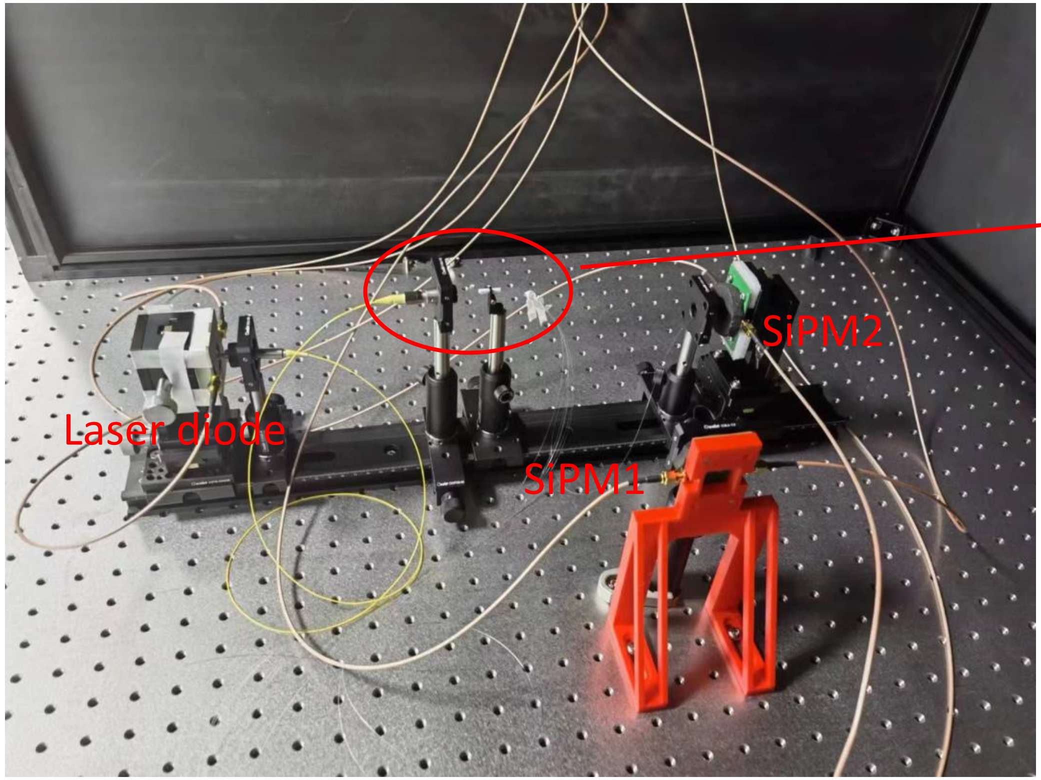


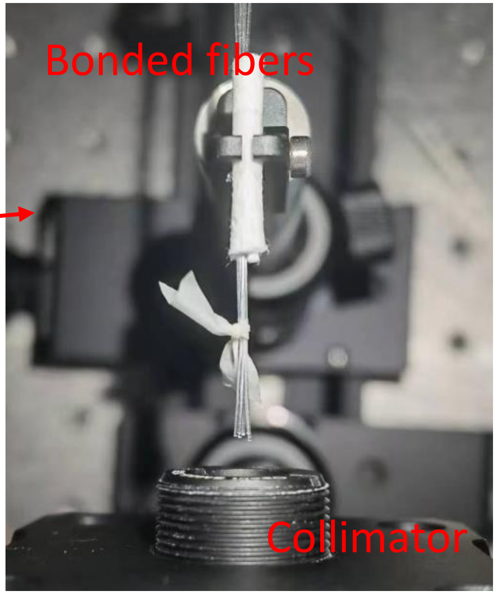
- Uniformity = (Max - Min)/Mean
- Generally uniformity of single bars at 1% level

Activities on small-scale crystal module design

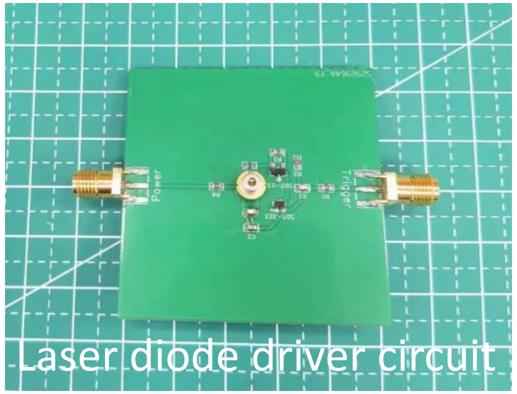
Zhiyu Zhao (SJTU)

- SiPM calibration with optical fiber and laser diode
  - Motivation: online single photon calibration for a 72-channel module
  - Collimated laser diode for enough light intensity
  - Light will be guided to SiPMs (NDL EQR15 series) by plastic optical fiber





- Laser should be collimated to fiber ends
- Fibers should be bonded for better light acceptance

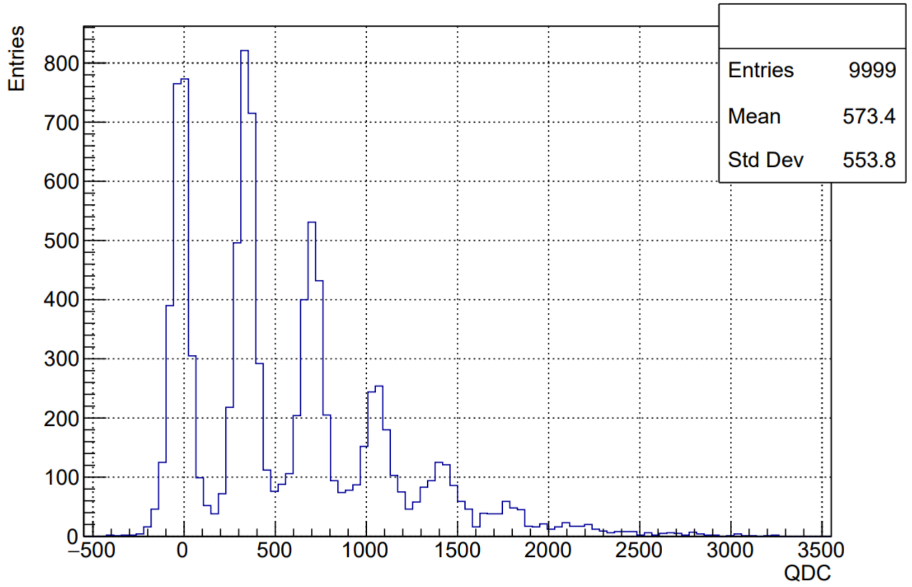


Activities on small-scale crystal module design

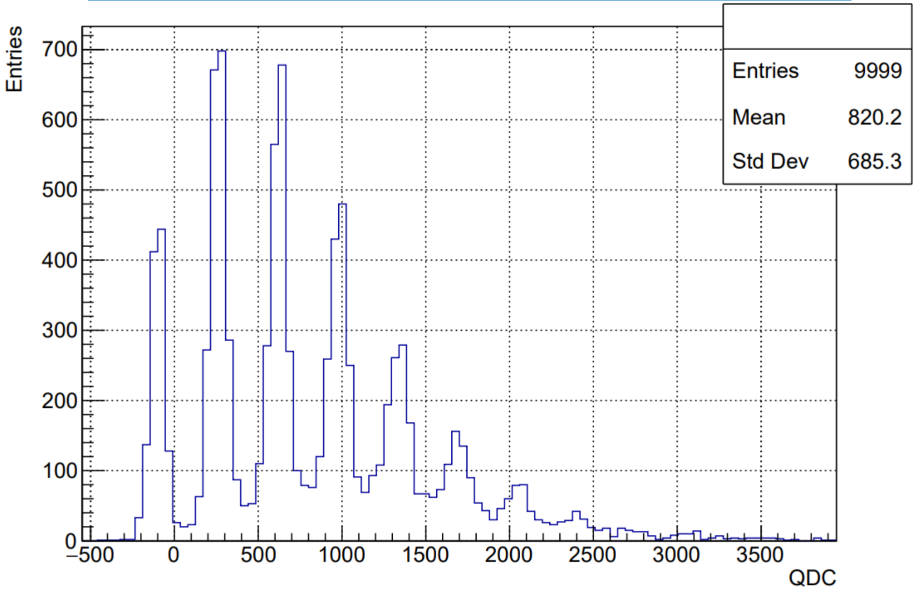
Zhiyu Zhao (SJTU)

- SiPM calibration with optical fiber and laser diode
  - Motivation: online single photon calibration for a 72-channel module
  - Collimated laser diode for enough light intensity
  - Light will be guided by plastic optical fiber to SiPMs (NDL EQR15 series)

Single photon spectrum EQR15-1



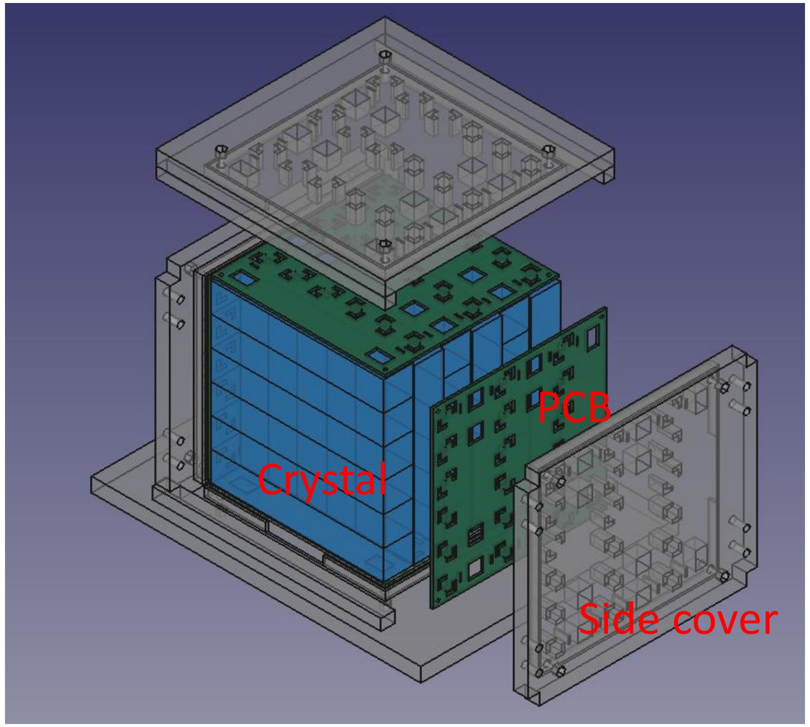
Single photon spectrum EQR15-2

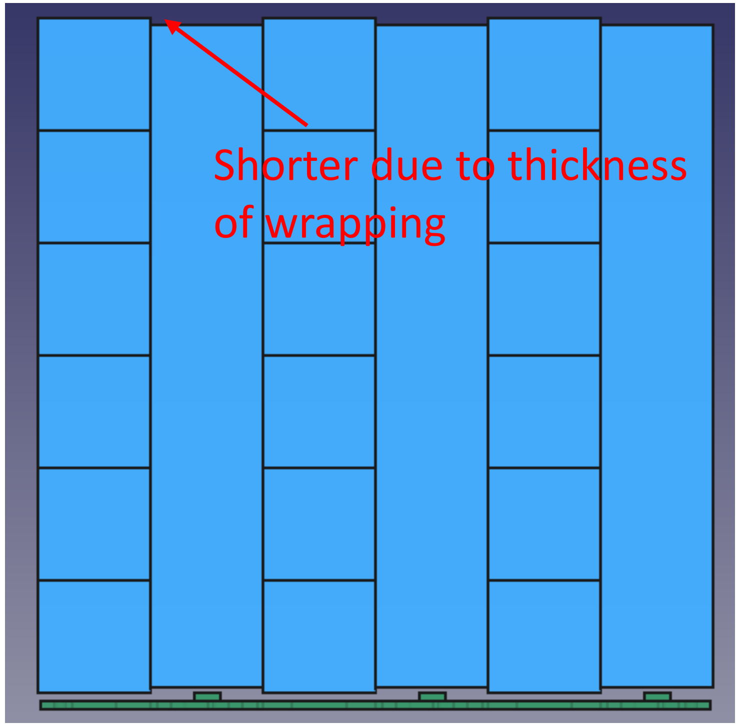


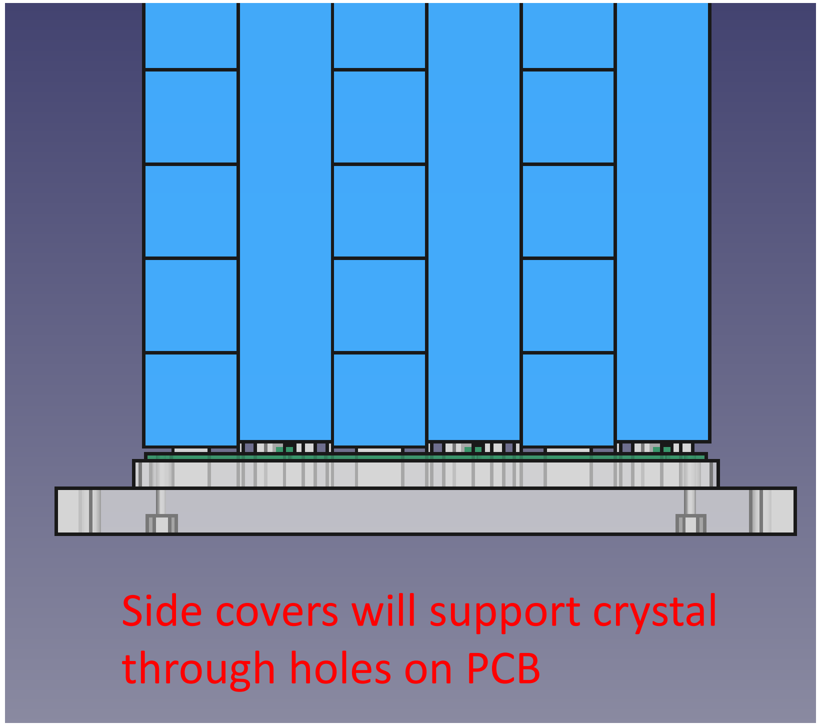
- Both SiPMs shows clear photon peaks
- Good consistency between the arbitral selected 2 fiber channels

Activities on small-scale crystal module design

- Mechanical structure and module assembly



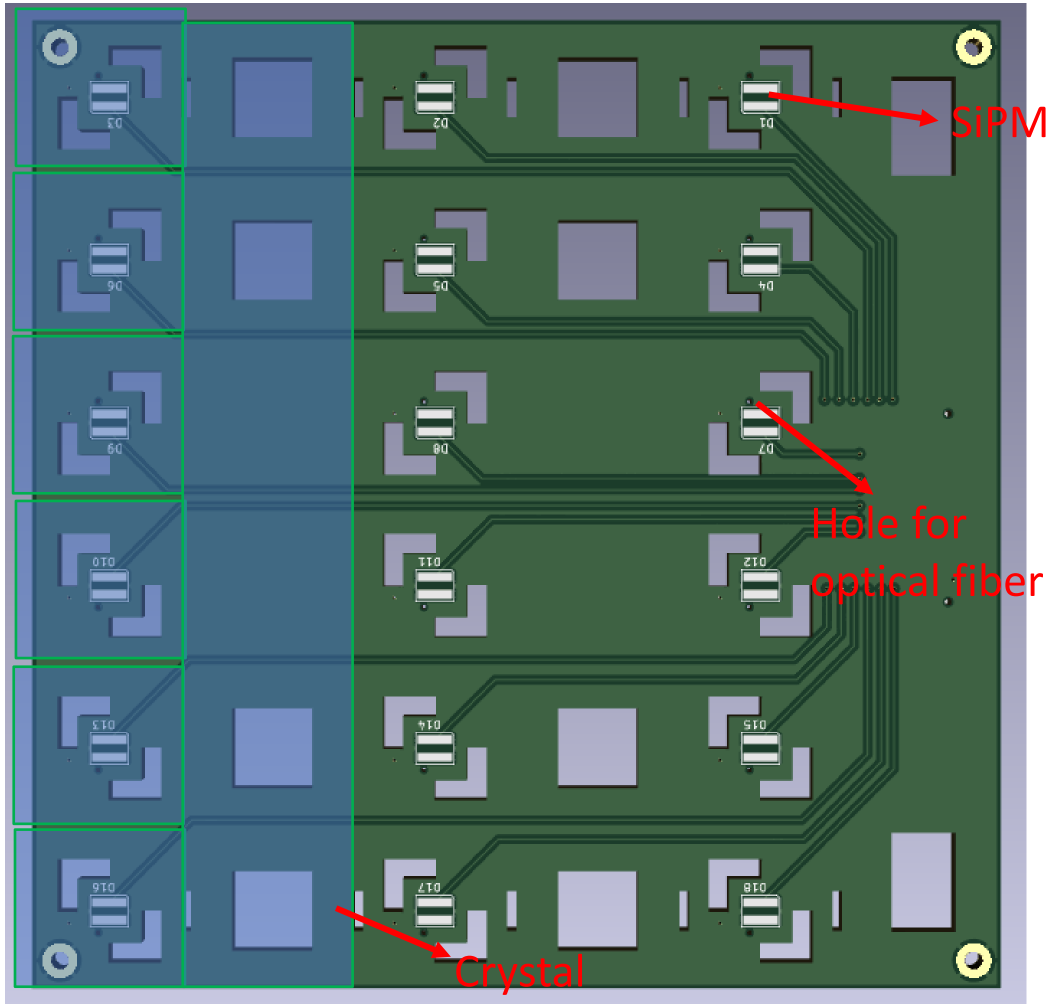




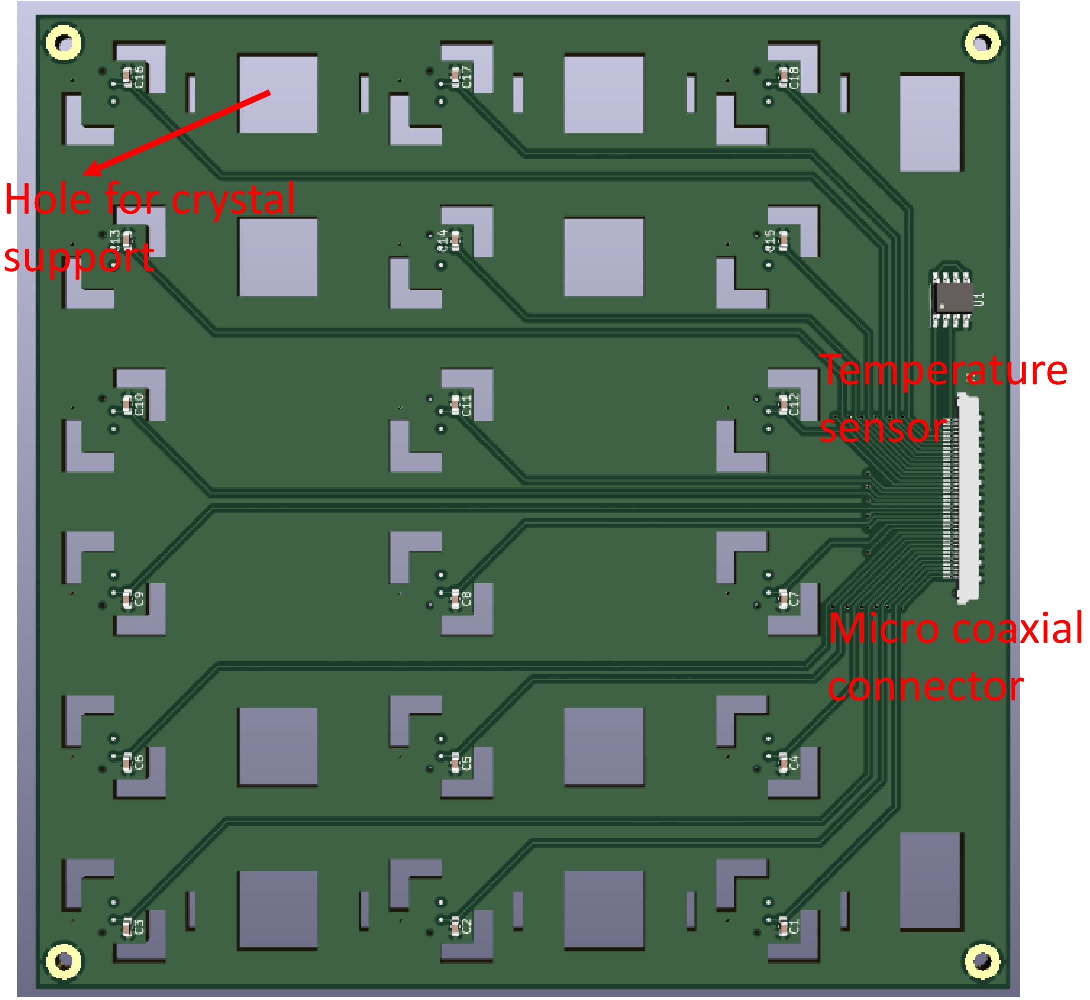
- Difficulties on mechanical design
  - Readout from 4 sides, PCB is non-load-bearing and should be decoupled
  - Module assembly is hard since crystals should be placed orthogonally

Activities on small-scale crystal module design

- PCB layout



Front side



Back side

Crystal ECAL: specifications

Key Parameters	Value/Range	Remarks
MIP light yield	> 200 p.e./MIP	8.9 MeV/MIP in 1 cm BGO
Dynamic range	0.1~10^3 MIPs	Energy range from ~1 MeV to ~10 GeV
Energy threshold	0.1 MIP	Equivalent to ~1 MeV energy deposition
Timing resolution	~400 ps	Limits from G4 simulation (validation needed)
Crystal non-uniformity	< 1%	After calibration
Temperature stability	Stable at ~0.05 Celsius	Reference of CMS ECAL
Gap tolerance	~100 μm	TBD via module development

Challenges/issues…

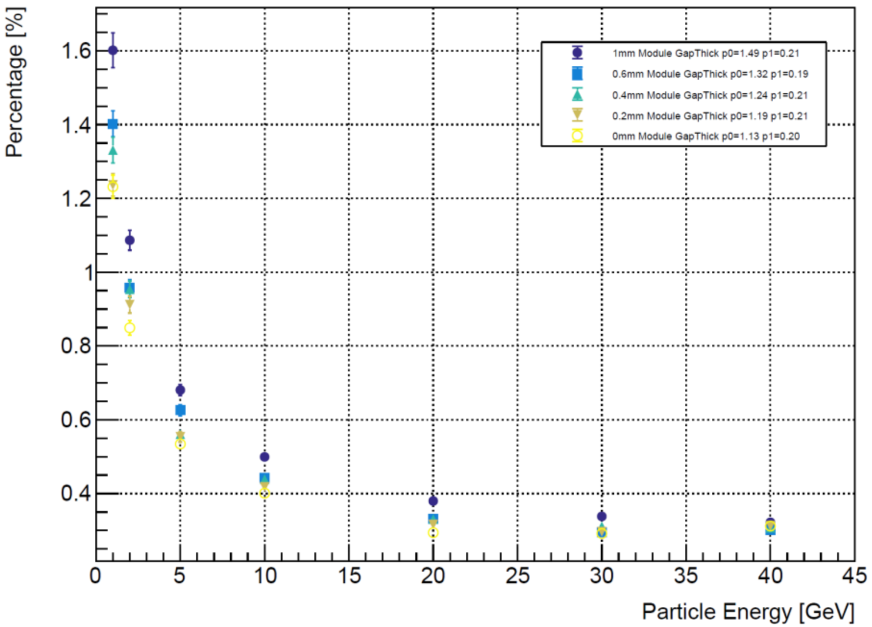
- Crystal size optimization, as well as realistic ECAL geometry design
- Sophisticated software for long bar crystal ECAL
- New BGO crystal with lower light output and faster decay time (collaboration with SIC-CAS)
- Limitation from SiPM dynamic range
- Radiation damage

Backup

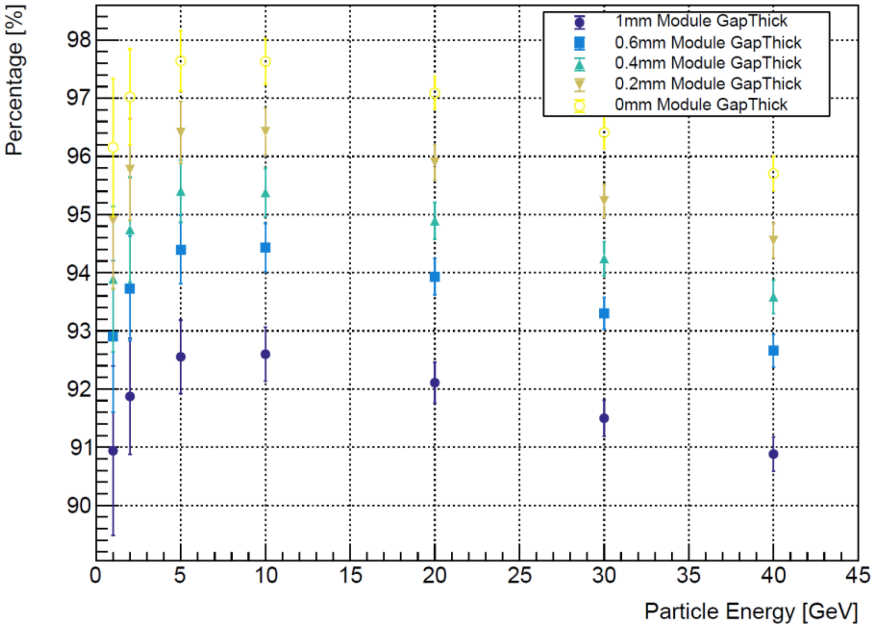
Small-scale crystal module design: impact of gaps

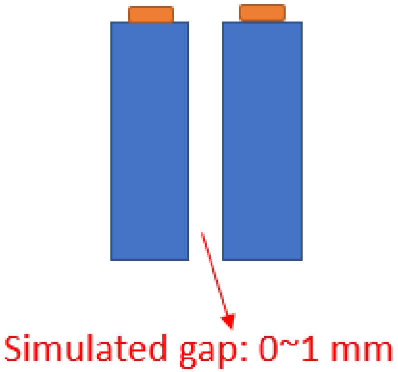
- Gap material in 40×40×28 supercell: ESR film, Al foil, Air
- Density set to 2 g/cm^3

EM energy resolution



EM shower containment

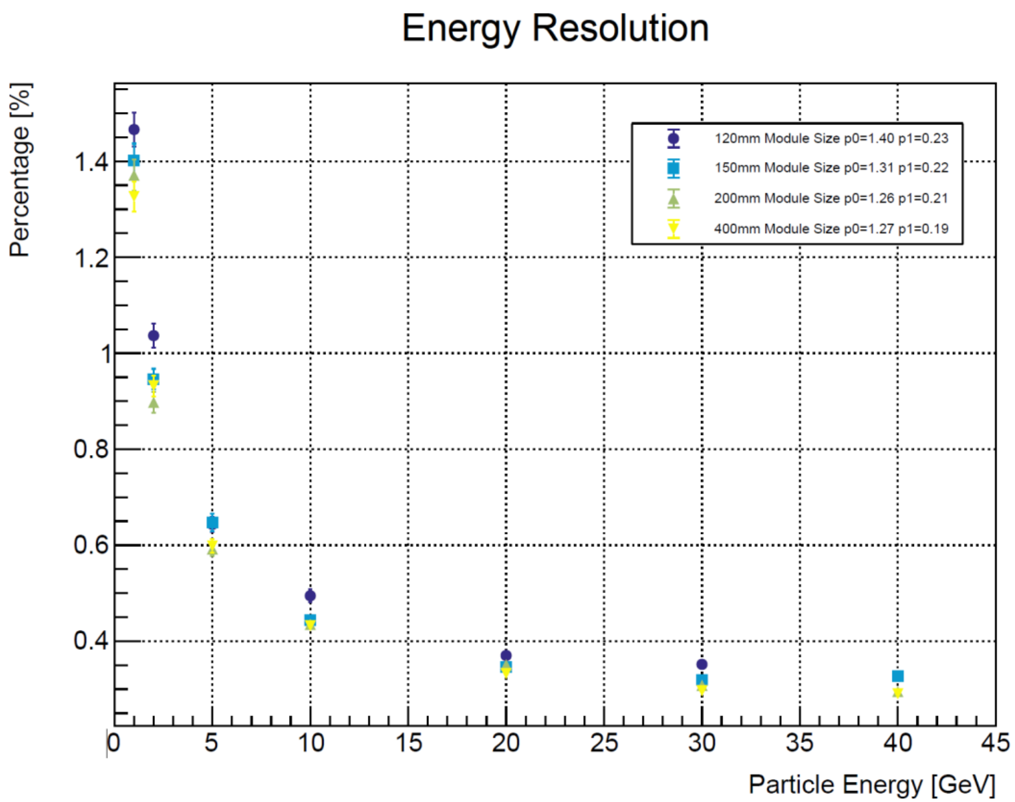


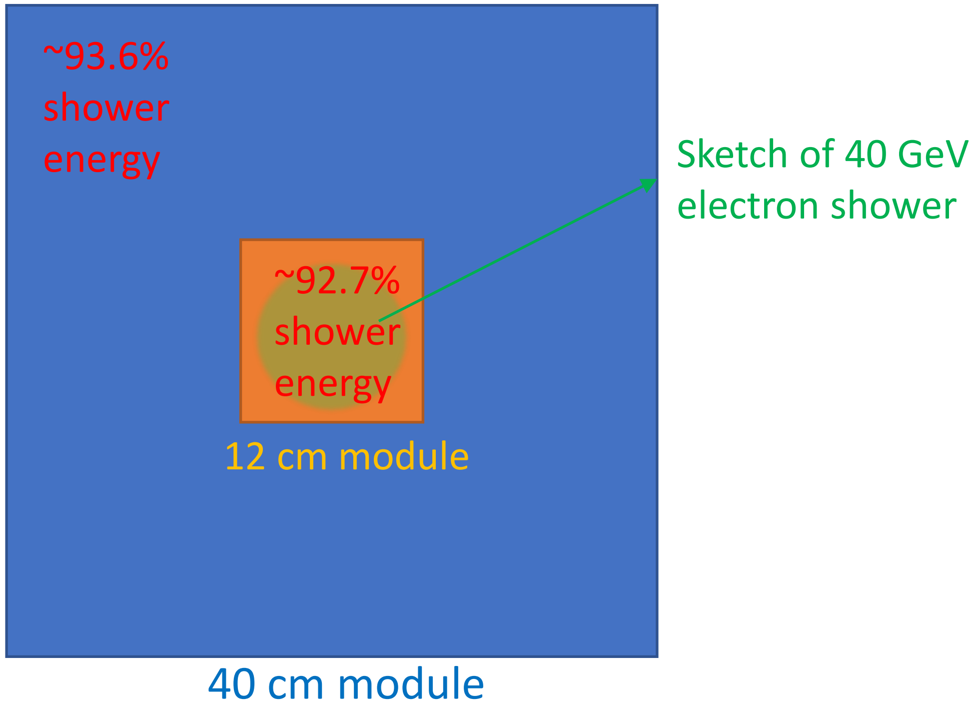


- Impact of gaps is significant
- Gaps for 12×2×2 cm^3 cm crystal: ~0.4 mm
- Control of gaps will be harder with longer crystals: key issue

Small-scale crystal module design: impact of module size

- 40×40×28 supercell: change the length of the crystal bar from 400 mm to 120 mm



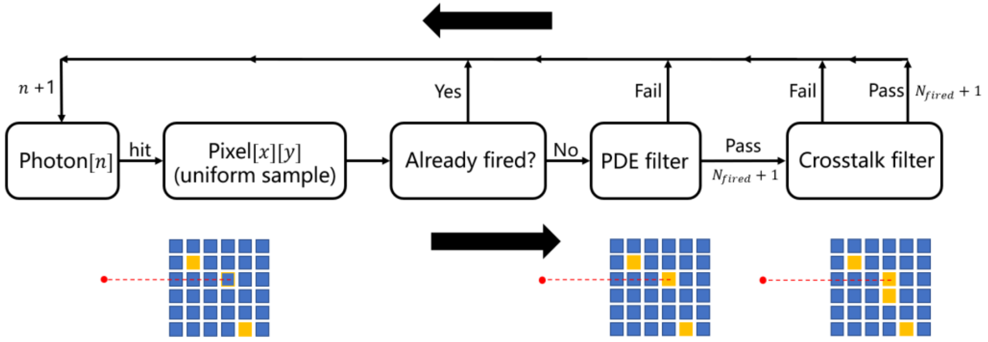


- For EM showers, 12 cm size is enough to contain most of the energy when particles hit on the center of the module
- Degradation of energy resolution: ~0.1% level

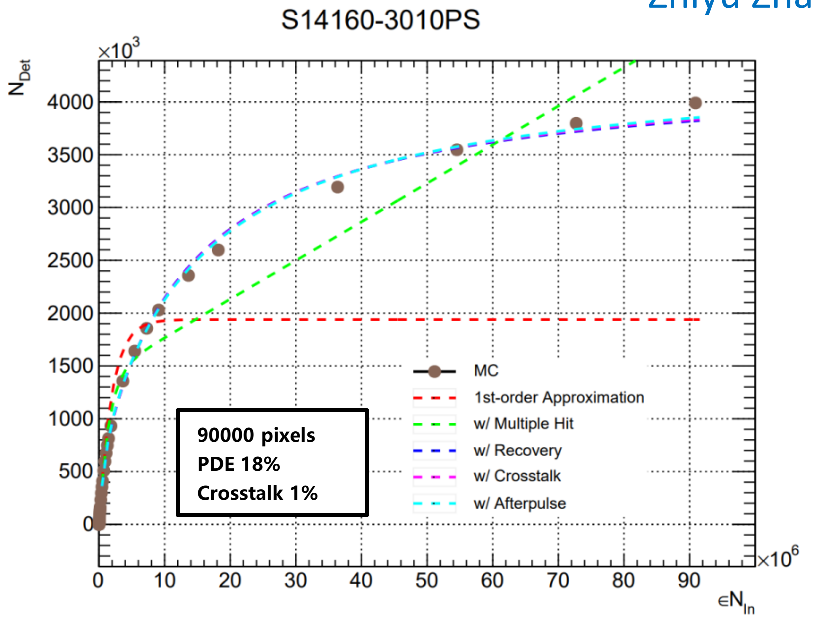
SiPM response non-linearity study

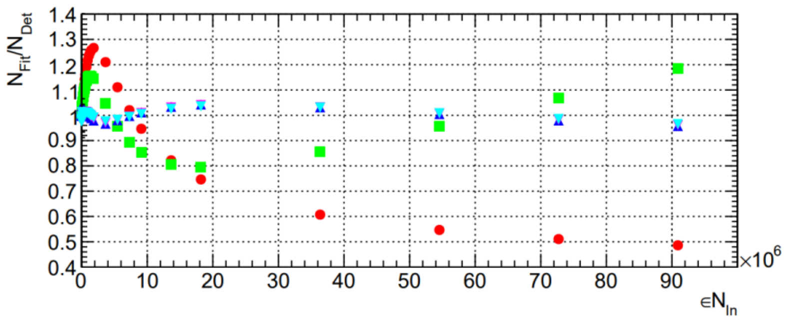
- ## SiPM response simulation and fitting

Zhiyu Zhao (SJTU)



- PDE filter: the random number is smaller than PDE
- Crosstalk filter: random number smaller than crosstalk probability && at least one adjacent pixel is not in fired





- First order:

$$N_{\rm fire}^{\rm LO'} = N_{\rm pix}^{\rm eff}\left(1 - e^{-\epsilon N_{\rm in}/N_{\rm pix}^{\rm eff}}\right).$$

- One pixel receive more than one photon

$$N_{\rm fire}^{\rm NLO} = N_{\rm fire}^{\rm LO} + \alpha N_{\rm R}.$$

- Charge distribution of a photon: considering pixel recovery and scintillation decay

$$N_{\rm fire}^{\rm NLO'} = N_{\rm fire}^{\rm NLO}\frac{\beta + 1}{\beta + \epsilon N_{\rm in}/{\rm LO}}.$$

- Crosstalk and afterpulse

$$N_{\rm fire}^{{\rm NLO'}_{\rm C\cdot A}} = N_{\rm fire}^{\rm NLO'}\left(1 + P_{\rm cross}\cdot e^{-\epsilon N_{\rm in}/N_{\rm pix}}\right)\cdot(1 + P_{\rm after}),$$

ICASiPM_Krause_final.pdf (gsi.de)

[1510.01102] Describing the response of saturated SiPMs (arxiv.org)