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

High Granularity Crystal Calorimeter R&D Progress

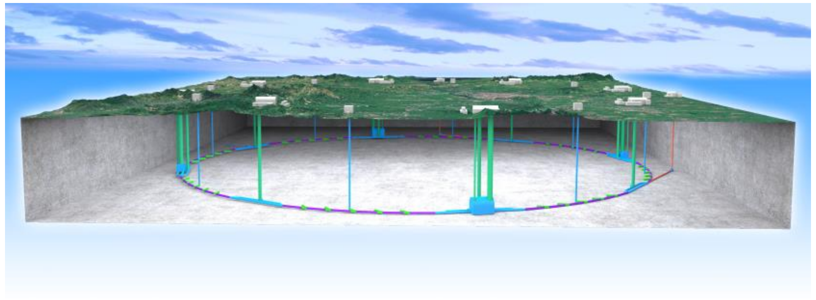
Baohua Qi
On behalf of CEPC Calorimeter Working Group

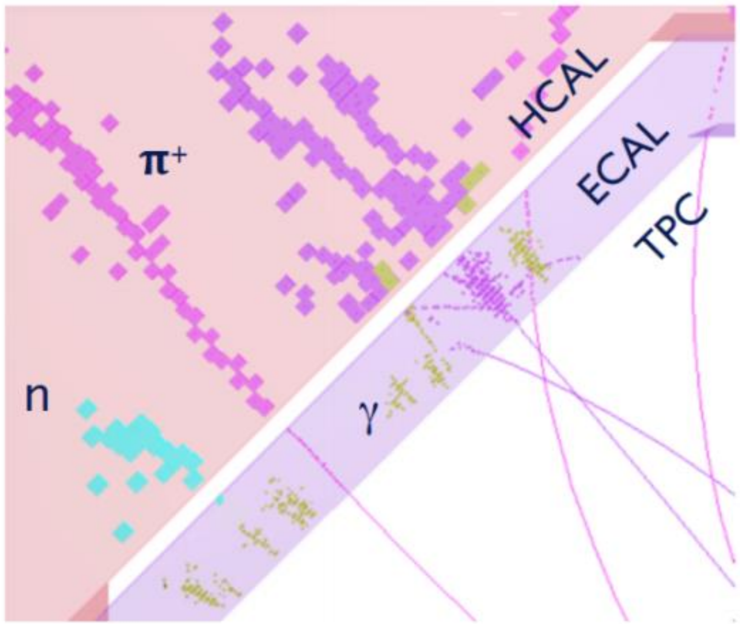
CALICE Collaboration Meeting at University of Göttingen
March 29-31, 2023

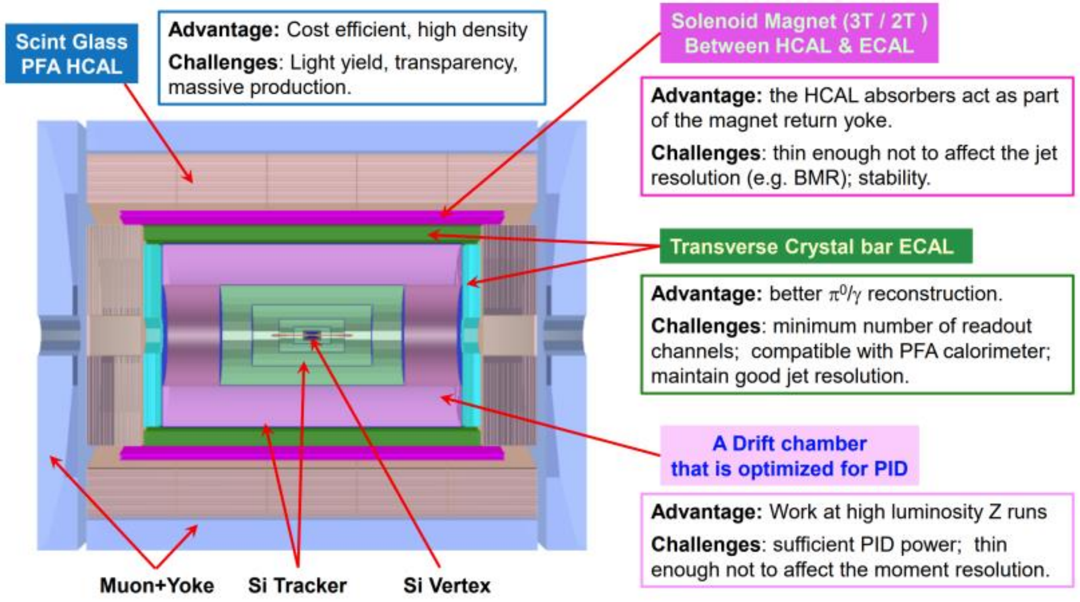
qibh@ihep.ac.cn

Motivations: new detector for CEPC

- CEPC: future lepton collider at 91-240 GeV energy range
  - Higgs/Z/W bosons, BSM searches, etc.
  - Jet energy resolution of 3-4%@100GeV is required
  - 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

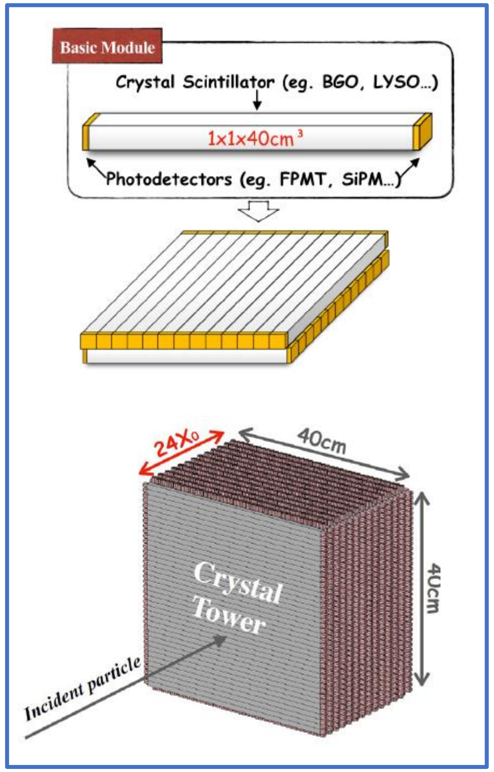


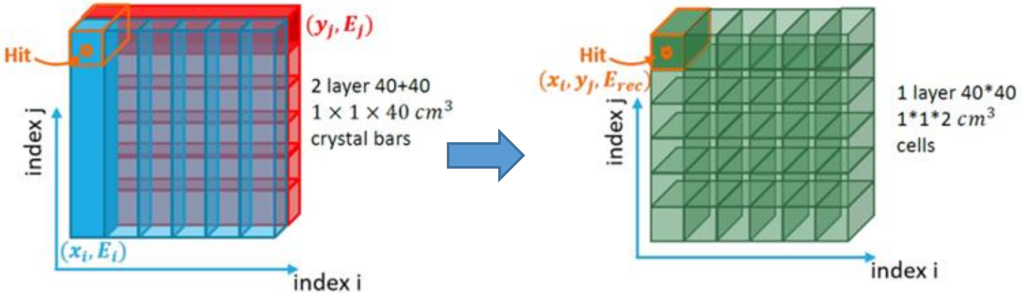




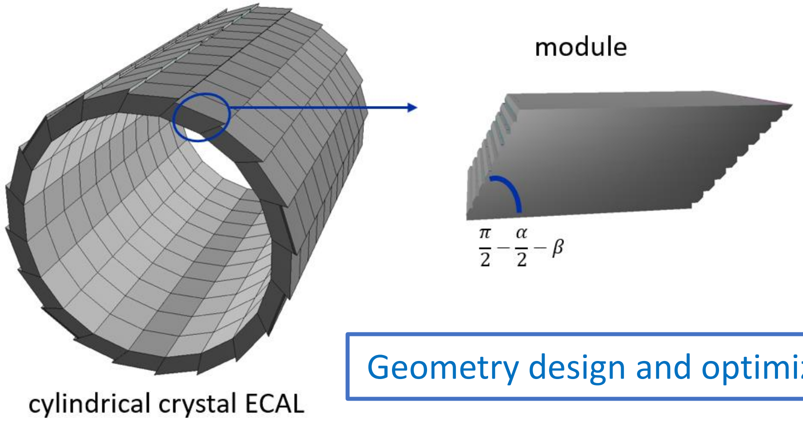
Talk ***Overview of the CEPC Project*** by Haijun Yang, CEPC Joint Workshop 2022, 23-25 May

Crystal calorimeter: R&D overview

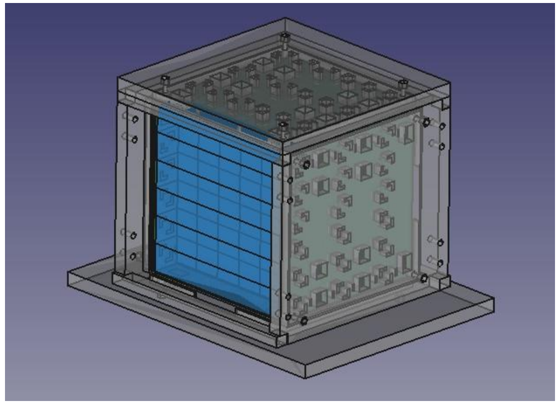




Crossed long bar design: $1{\times}1{\times}2\ cm^3$ granularity after reconstruction



Geometry design and optimization



Hardware development: key questions on design

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

Crystal module development for future beam tests

Overview of this report: R&D status

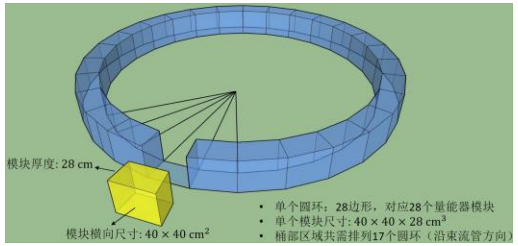
R&D of a highly granular crystal ECAL:

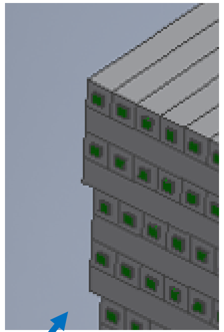
- General geometry design of crystal ECAL
  - Key questions on the detector assembly
  - Energy leakage study: geometry optimization
- Reconstruction algorithm dedicated to crystal ECAL
  - Clustering and particle reconstruction algorithm
  - Occupancy of ECAL towers: challenges on reconstruction
- Activities on small-scale crystal module development
  - Performance check with energy resolution
  - Uniformity scan of BGO crystal bars
  - SiPM calibration with optical fiber
  - Mechanical structure and PCB design

General geometry design of crystal ECAL

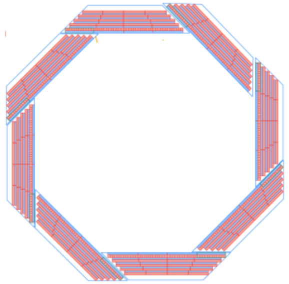
Quan Ji, Chang Shu (IHEP)

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

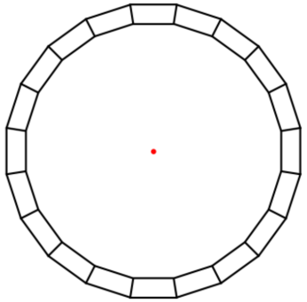




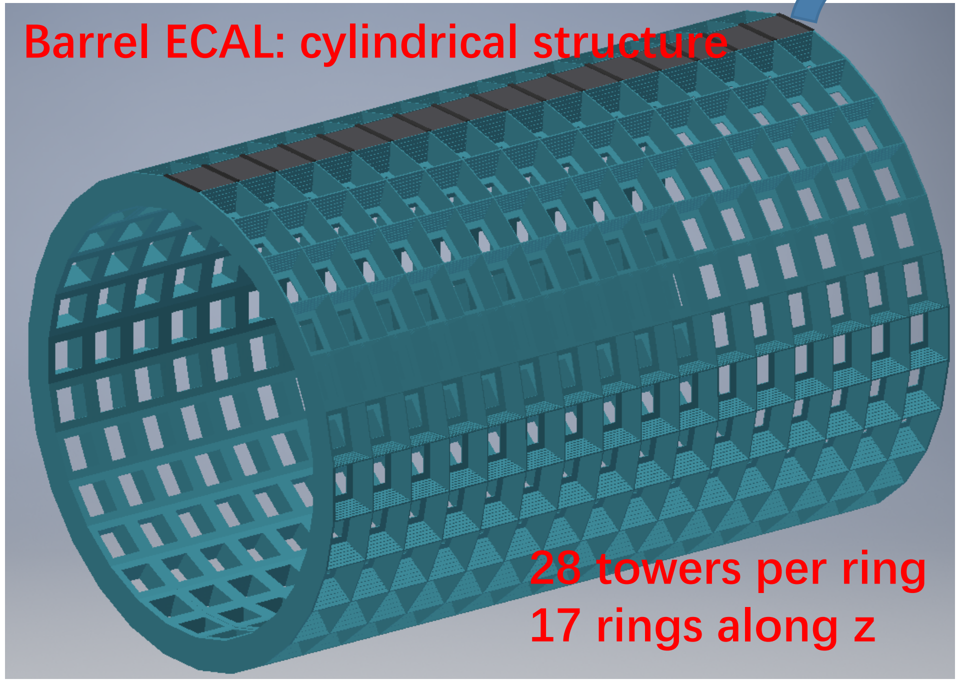
4 layers per “step” with the same transverse size

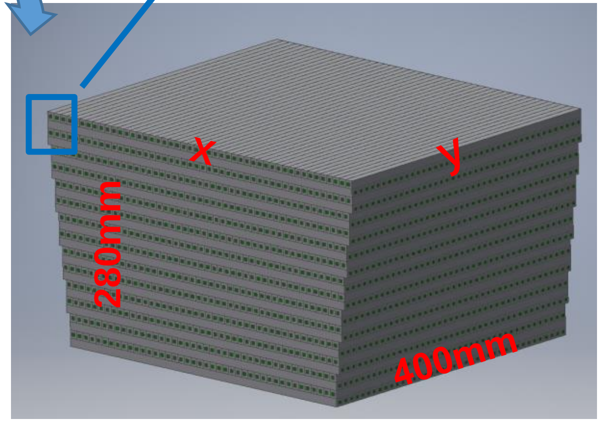


Previous design: octagonal detector



New design: cylindrical crystal ECAL



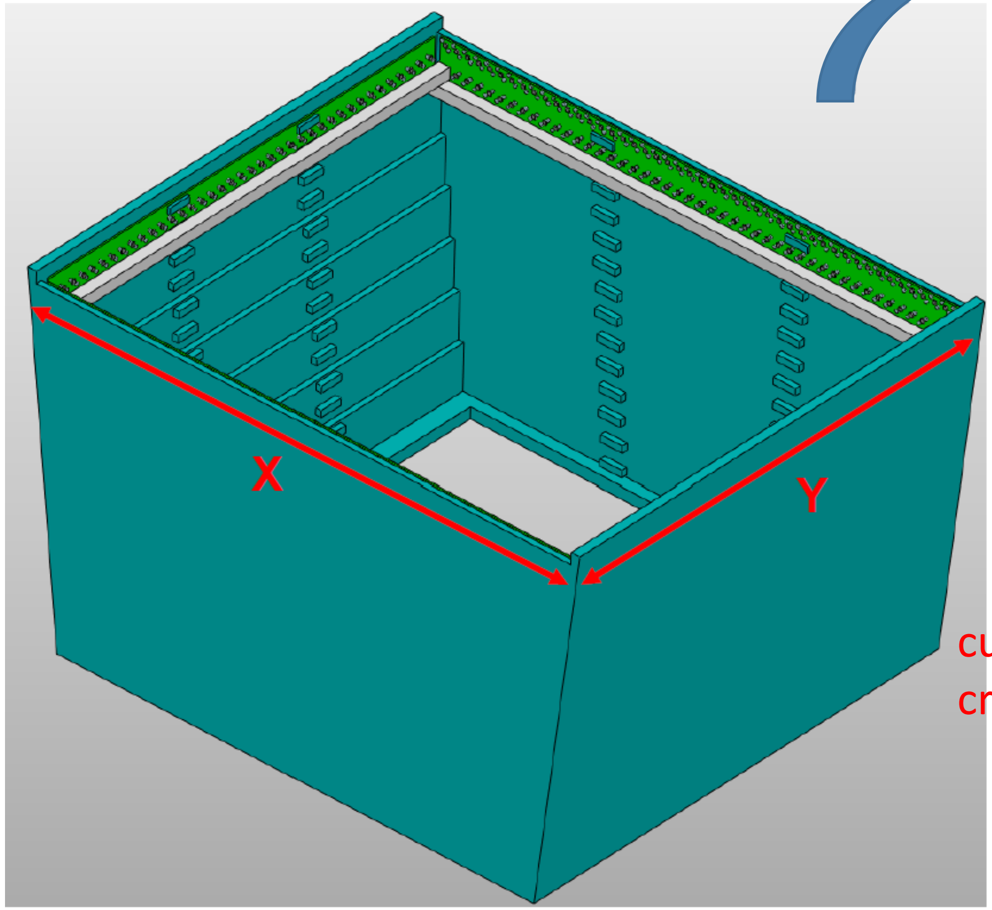


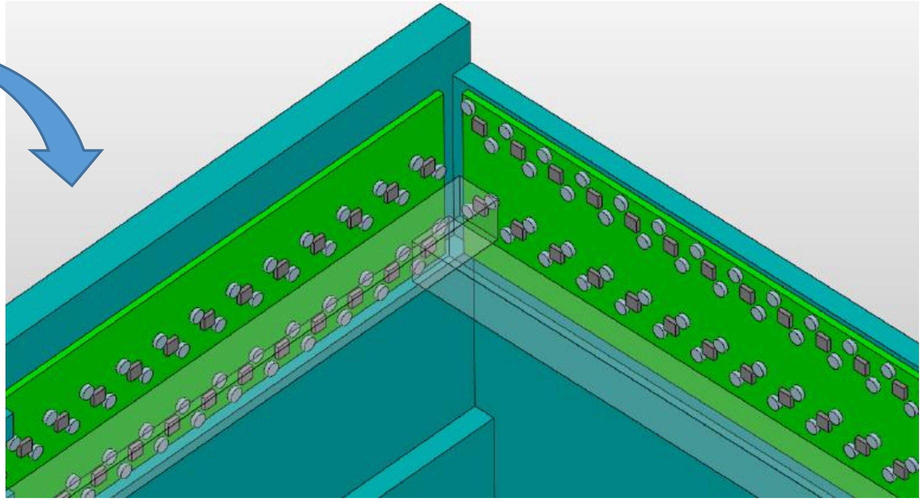
Key questions
- Space for electronics and cooling
- Assembly

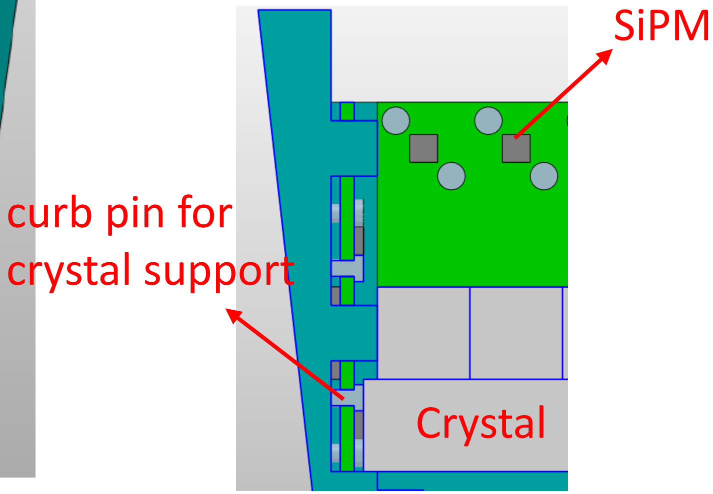
General geometry design of crystal ECAL

- Mechanical assembly: PCB and crystals

Quan Ji, Chang Shu (IHEP)







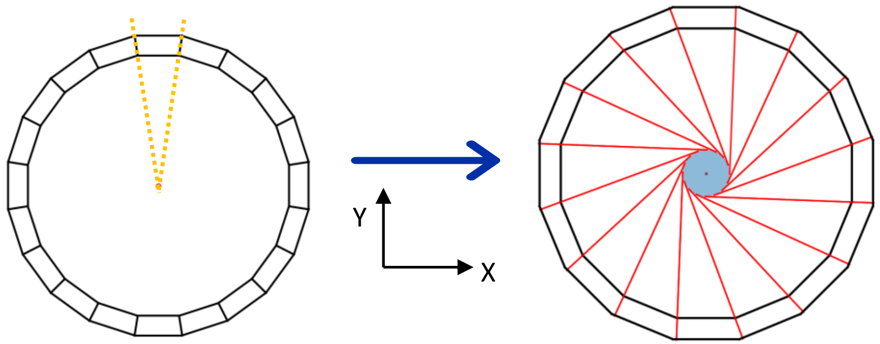
Total mass of the crystals in one tower: 380 kg

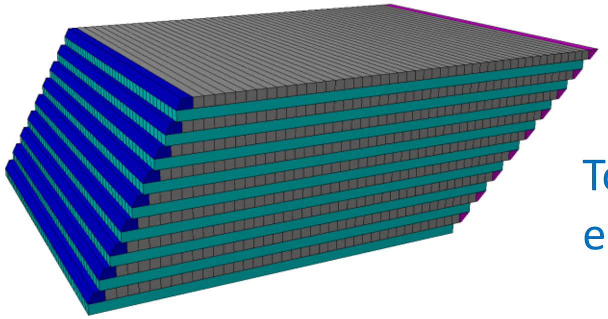
- PCB cannot bear the weight of crystals
- Holes on PCB for external support structure

General geometry design of crystal ECAL

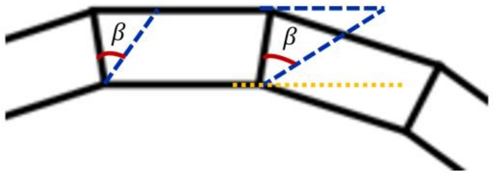
- Energy leakage study: geometry optimization
- Avoid cracks pointing to the interaction point

Weizheng Song (IHEP)

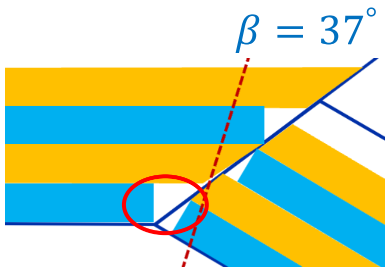


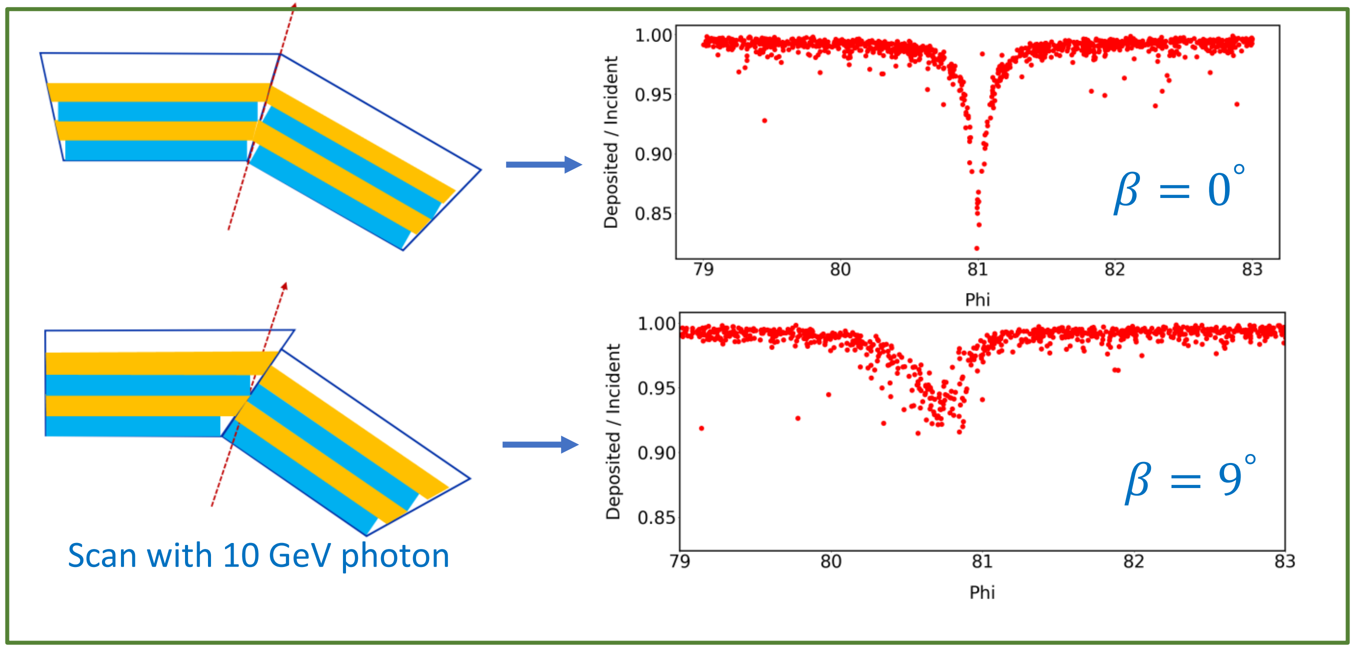


Tower geometry
e.g. $\beta = 37^{\circ}$



- Larger value of β: fewer projectile cracks, but more gaps

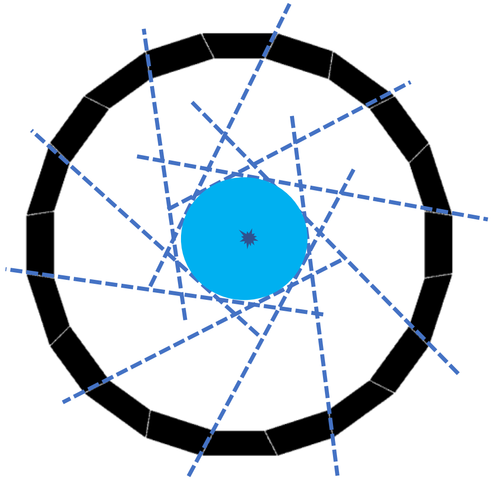


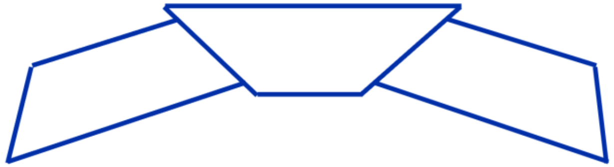


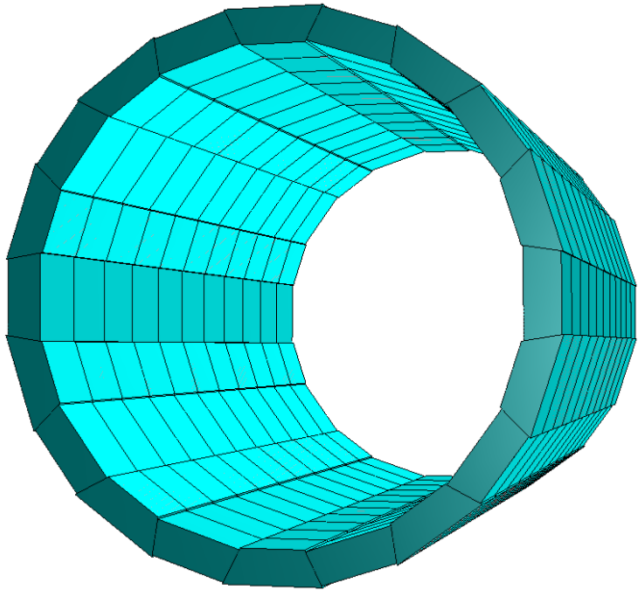
General geometry design of crystal ECAL

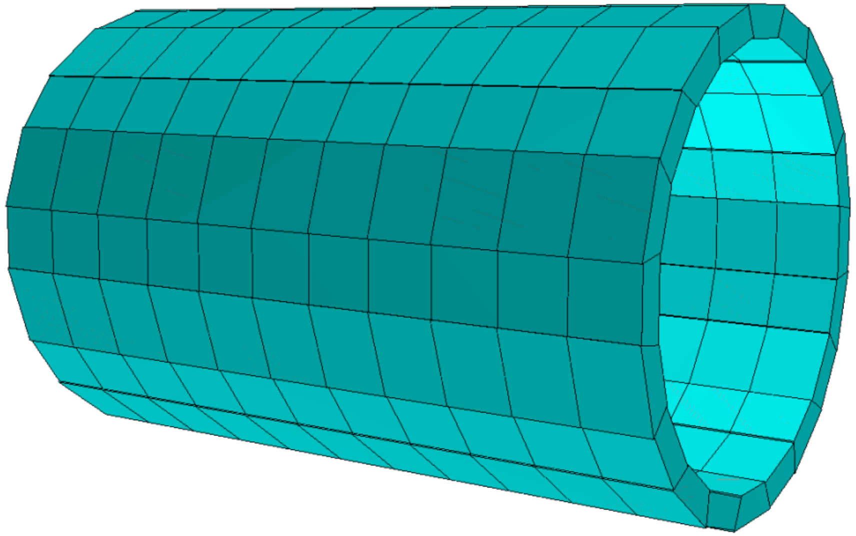
- And other potential designs…

Weizheng Song (IHEP)









- Geometry still being optimized

Overview of this report: R&D status

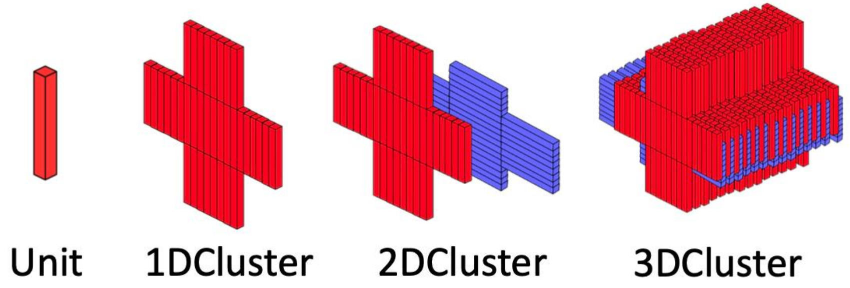
R&D of a highly granular crystal ECAL:

- General geometry design of crystal ECAL
  - Key questions on the detector assembly
  - Energy leakage study: geometry optimization
- Reconstruction algorithm dedicated to crystal ECAL
  - Clustering and particle reconstruction algorithm
  - Occupancy of ECAL towers: challenges on reconstruction
- Activities on small-scale crystal module development
  - Performance check with energy resolution
  - Uniformity scan of BGO crystal bars
  - SiPM calibration with optical fiber
  - Mechanical structure and PCB design

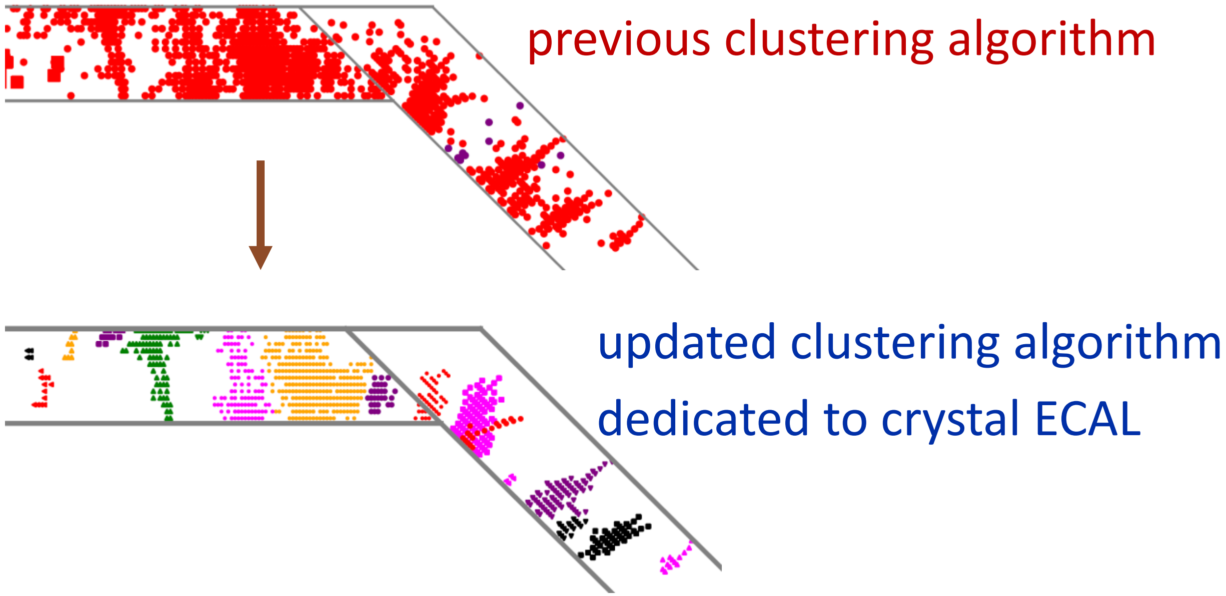
Reconstruction algorithm dedicated to crystal ECAL

- Clustering algorithm for long bar crystal ECAL

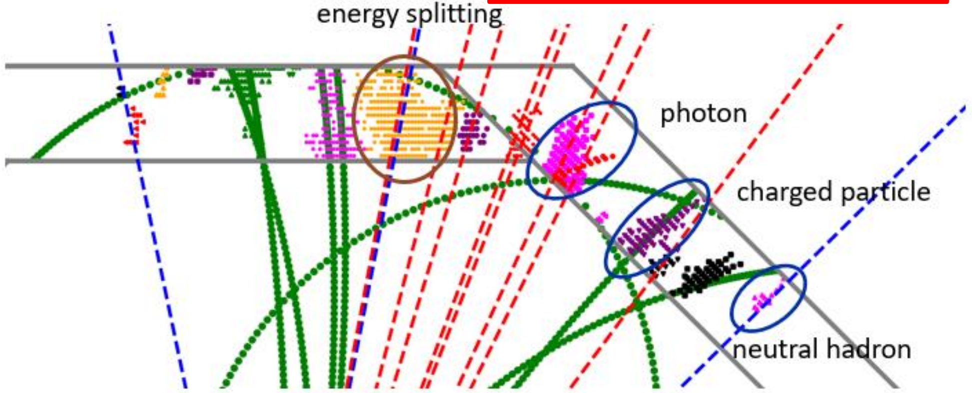
Weizheng Song (IHEP)



Clustering from crystal bars to 3D cluster



Essential case to be addressed



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

- Compare to MC truth: generally consistent

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

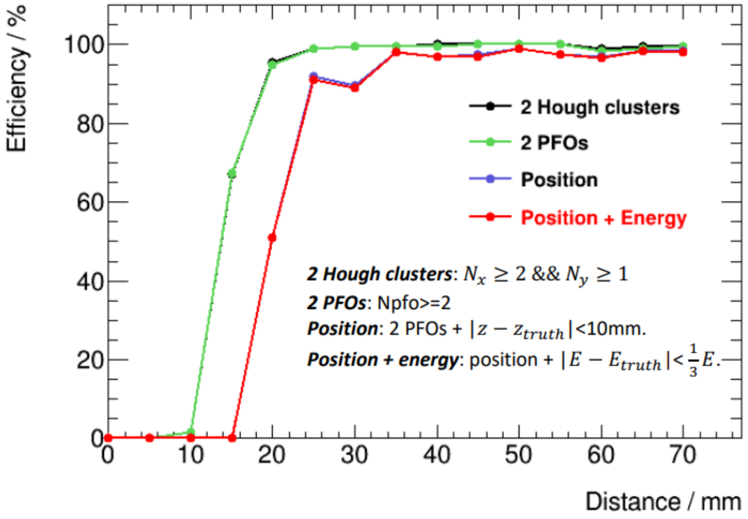
Reconstruction algorithm dedicated to crystal ECAL

- Particle reconstruction for long bar crystal ECAL

Yang Zhang (IHEP)

Basic principles of reconstruction

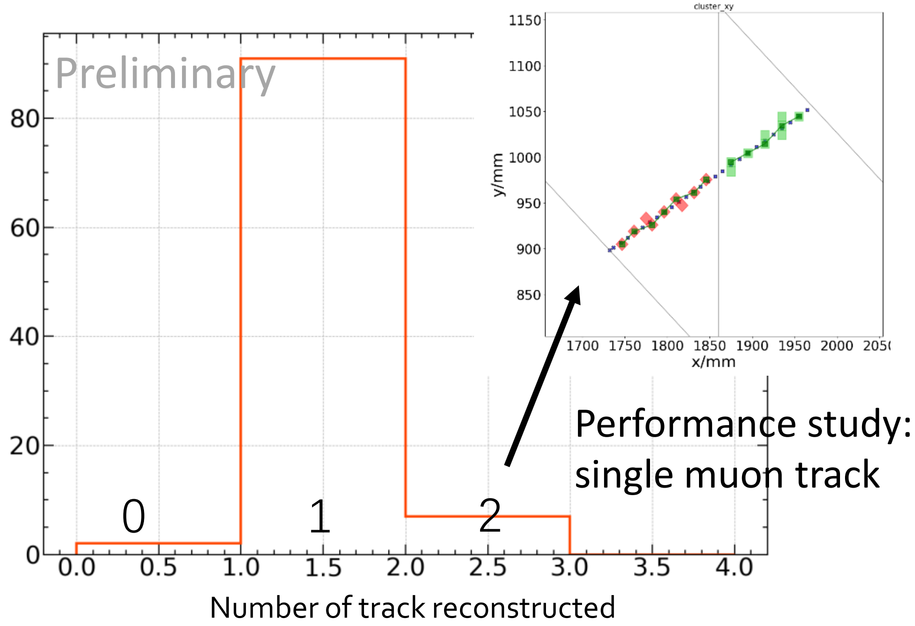
Cluster inputs → shower identification →
- Photon: Hough transformation
- Charged (MIP-like): track matching
- Neutral hadron: cone clustering



Performance study: di-photon recognition efficiency

Talk by Yang Zhang, 2022 CEPC Workshop

Photon reconstruction with Hough transformation



Performance study: single muon track

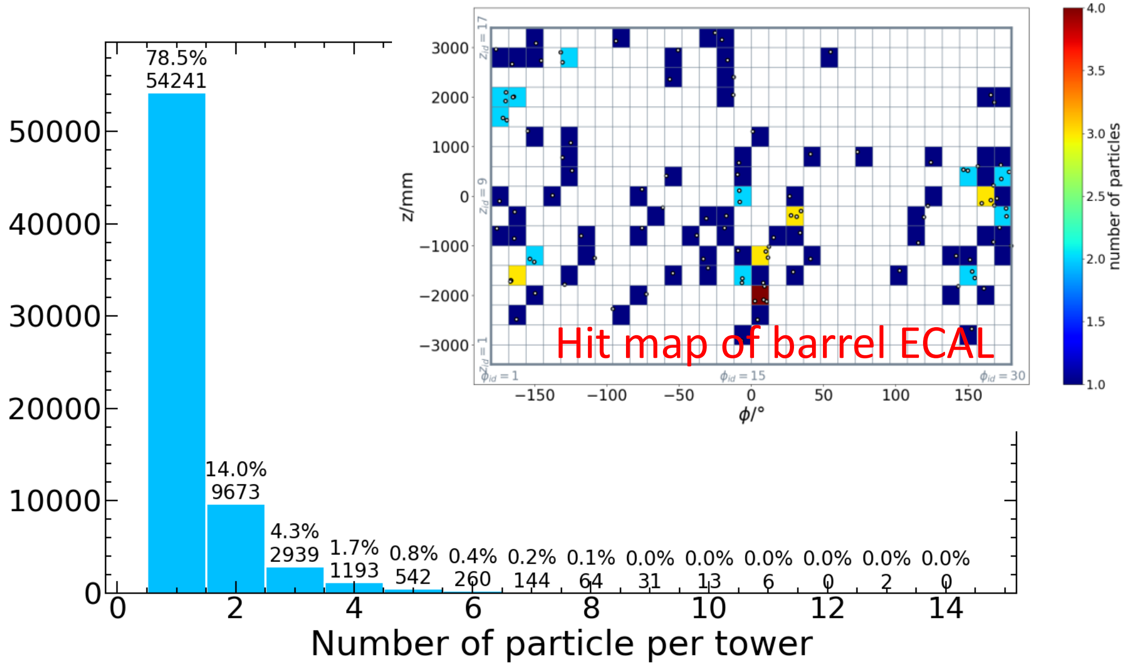
- Tracking matching algorithm for crystal ECAL
- Two tracks due to ECAL tower boundary

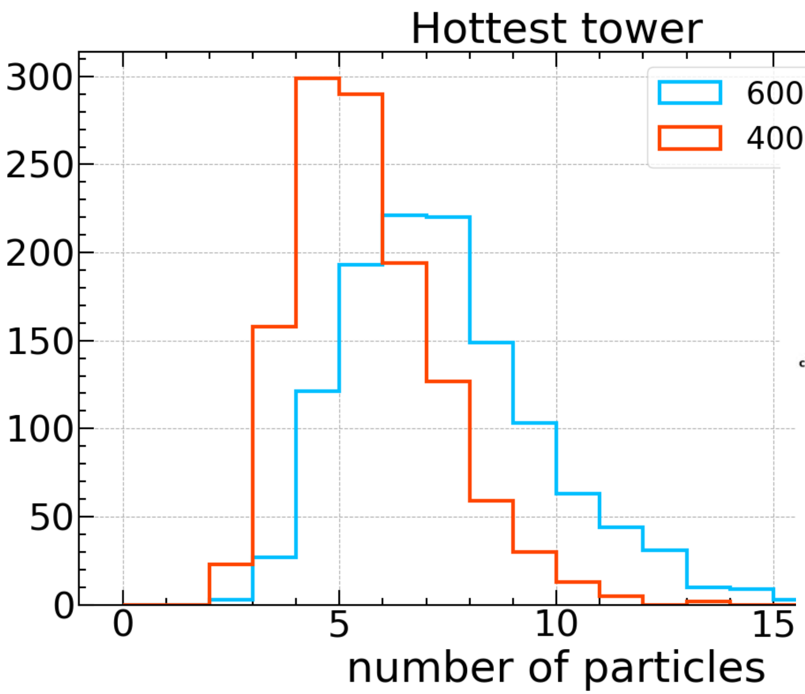
- Reconstruction flow has already been built
- Ongoing work on hadron…

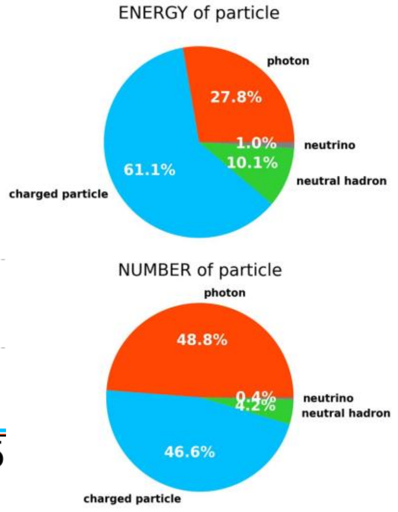
Reconstruction algorithm dedicated to crystal ECAL

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: $e^+e^- \to ZH, Z \to q\bar{q}, H \to gg$







- 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

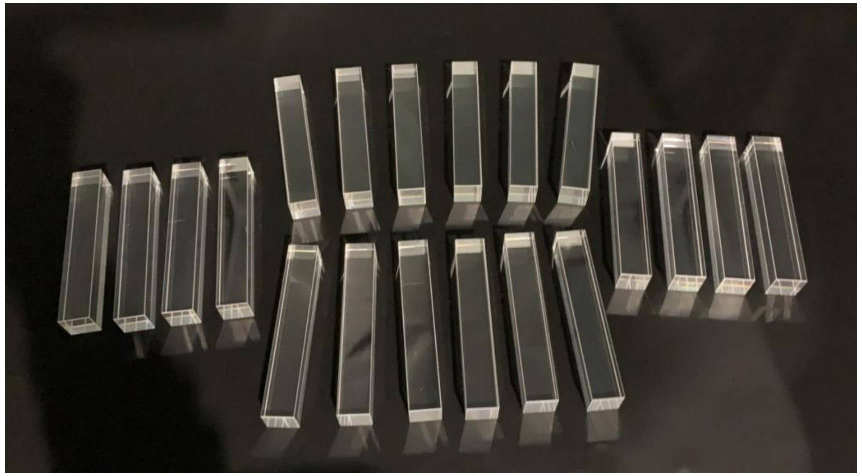
Overview of this report: R&D status

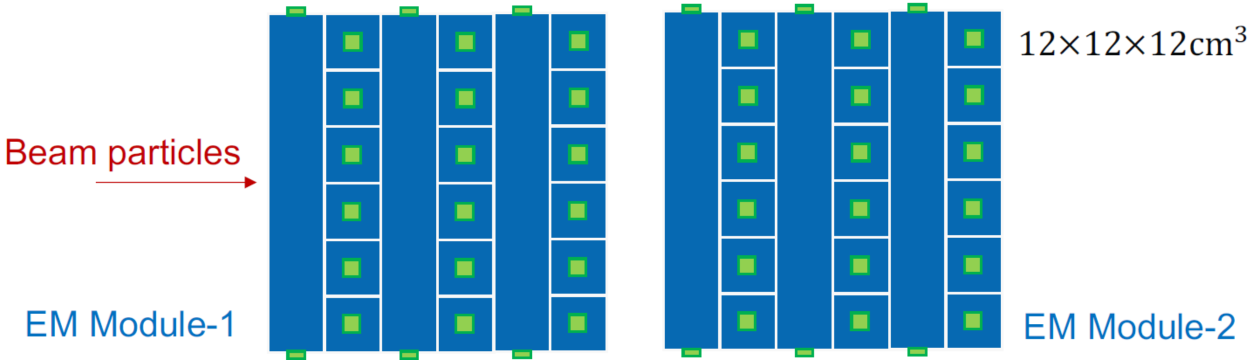
R&D of a highly granular crystal ECAL:

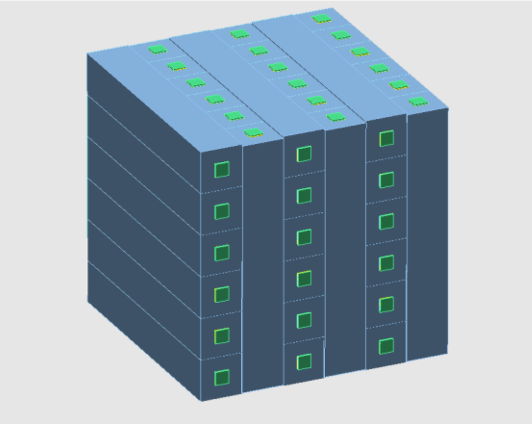
- General geometry design of crystal ECAL
  - Key questions on the detector assembly
  - Energy leakage study: geometry optimization
- Reconstruction algorithm dedicated to crystal ECAL
  - Clustering and particle reconstruction algorithm
  - Occupancy of ECAL towers: challenges on reconstruction
- Activities on small-scale crystal module development
  - Performance check with energy resolution
  - Uniformity scan of BGO crystal bars
  - SiPM calibration with optical fiber
  - Mechanical structure and PCB design

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







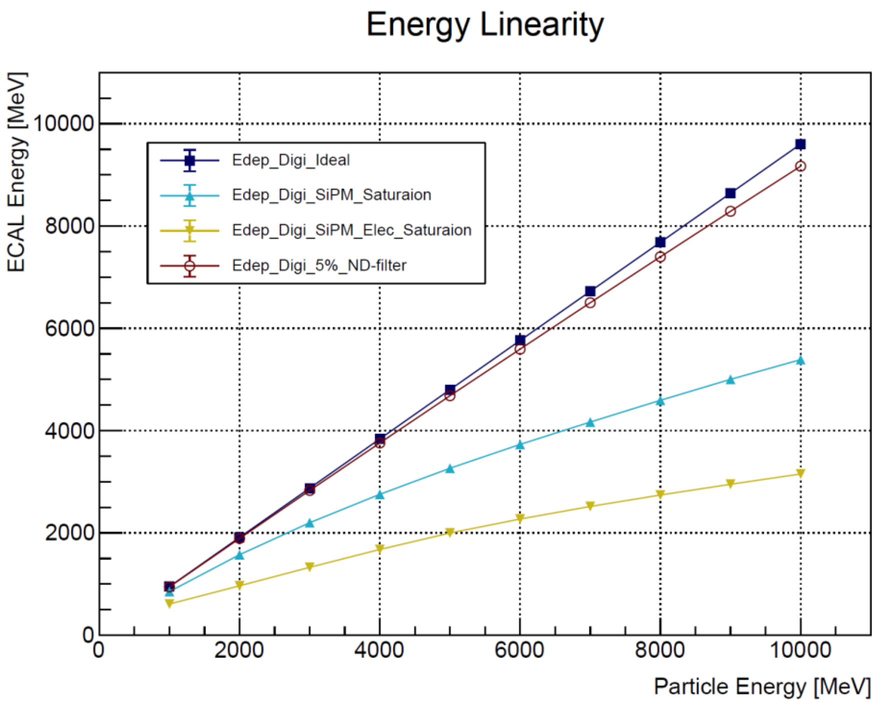
Crystal module
- 36 crystals readout from two sides
- 18 channels per side, 72 channels per module

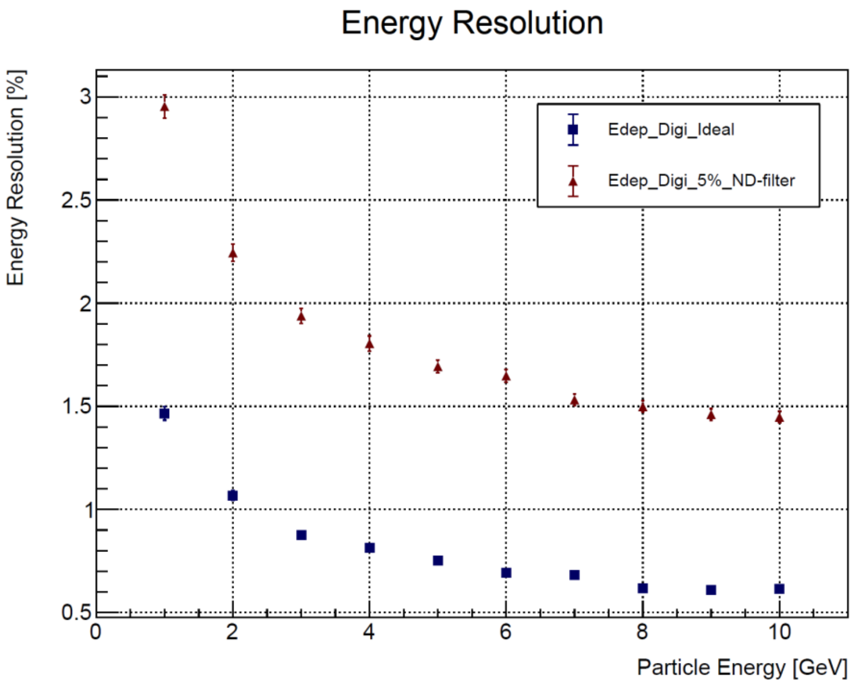
Activities on small-scale crystal module design

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





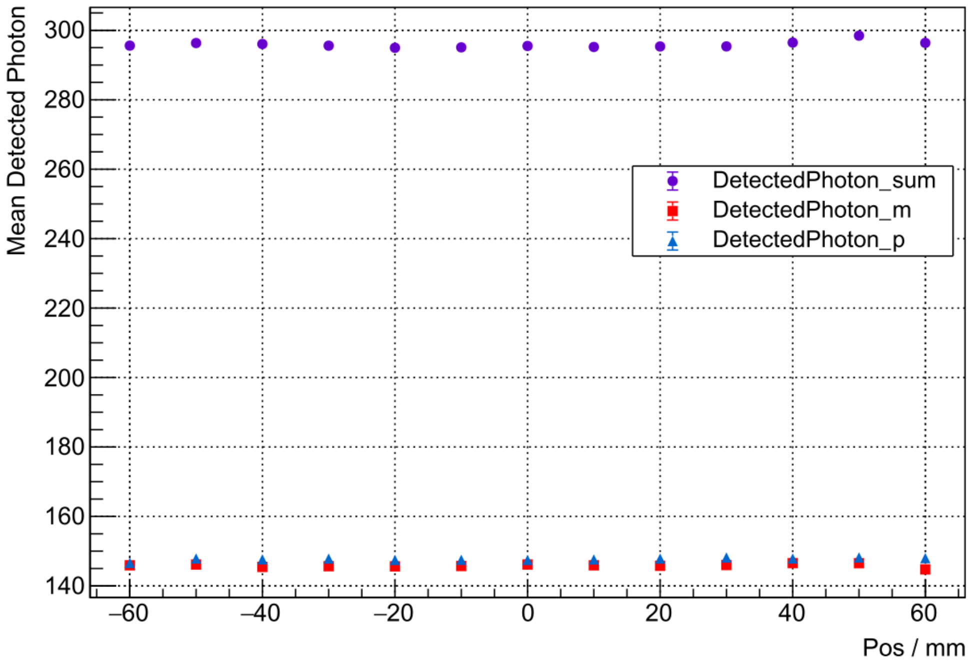
- SiPM non-linearity should be further calibrated
- Saturation of electronics can be avoided via high dynamic range ASIC
- 5% neutral density filter can mitigate the saturation effect but will introduce additional uncertainty

Activities on small-scale crystal module design

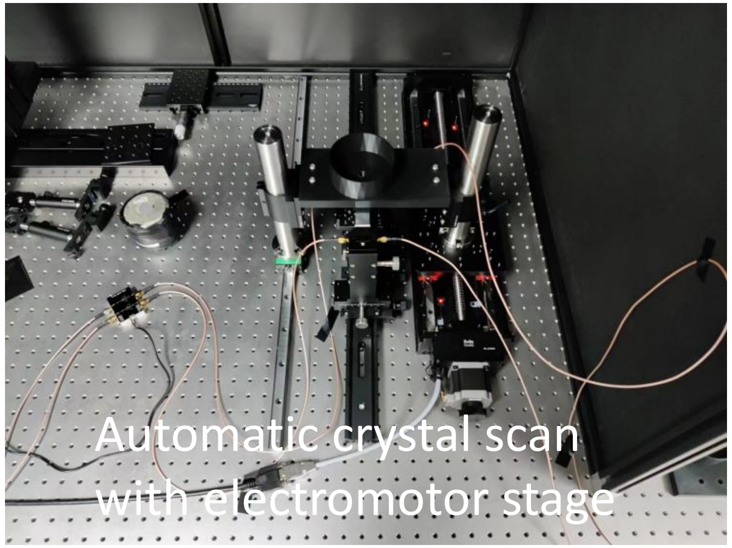
Zhikai Chen (IHEP/USC)

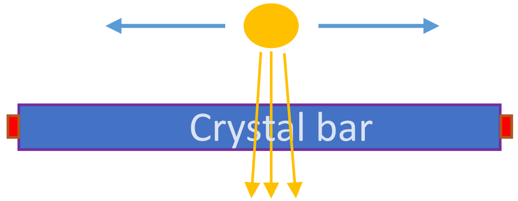
- Batch test of SIC-CAS BGO crystal bars
  - 40 crystals with ESR and Al foil wrapping
  - Scan with Cs-137 radioactive source

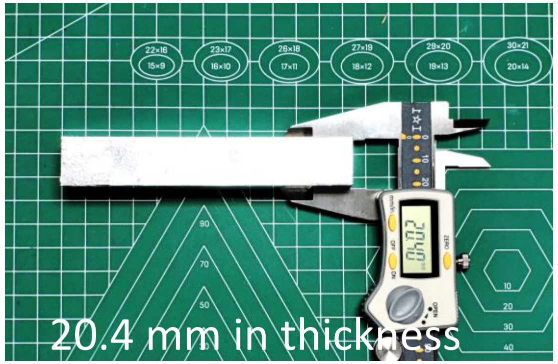
Response uniformity along bar



- Generally good uniformity along a single bar





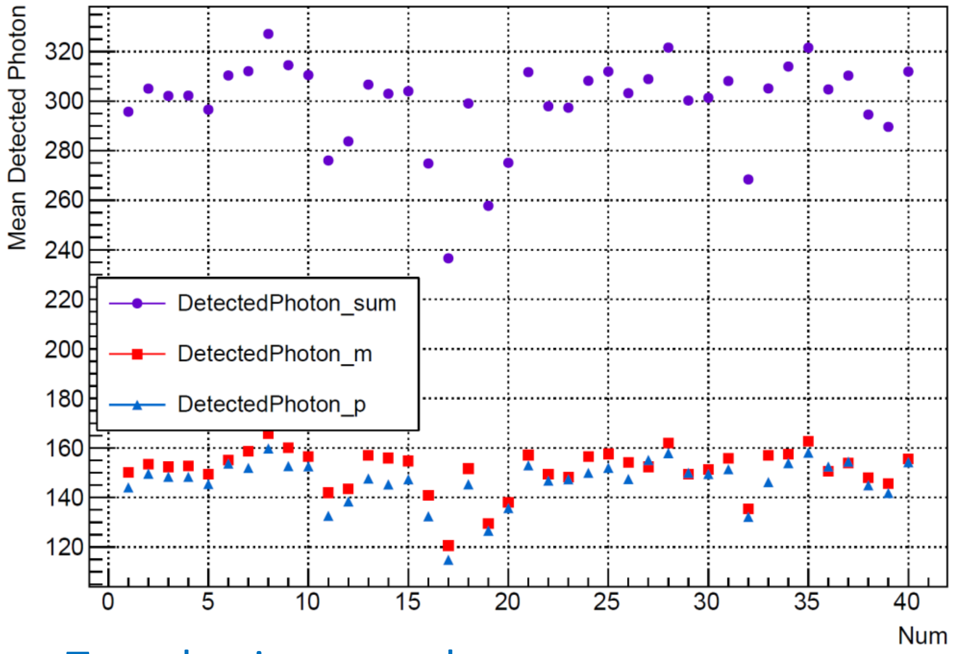


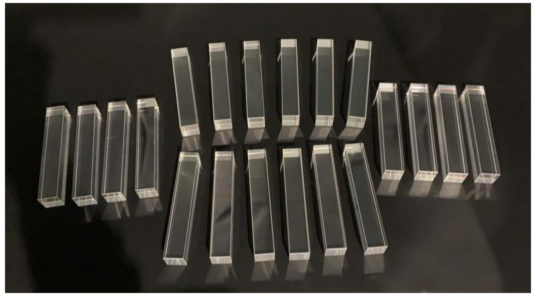
Activities on small-scale crystal module design

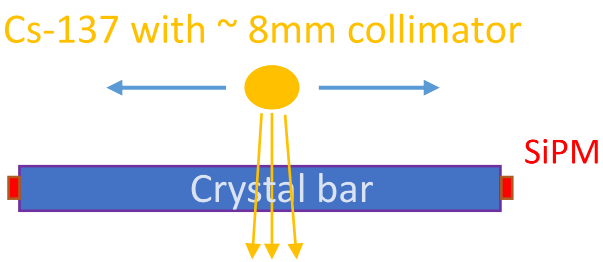
- Batch test of SIC-CAS BGO crystal bars
  - 40 crystals with ESR and Al foil wrapping
  - Scan with Cs-137 radioactive source

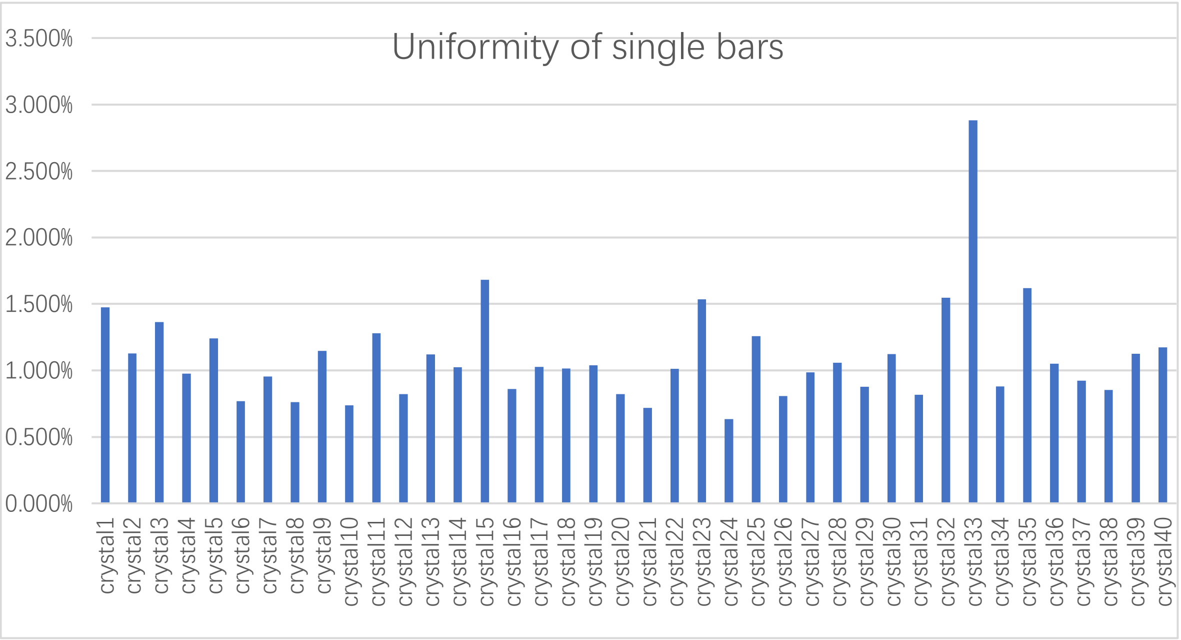
Zhikai Chen (IHEP/USC)

Response uniformity among 40 bars









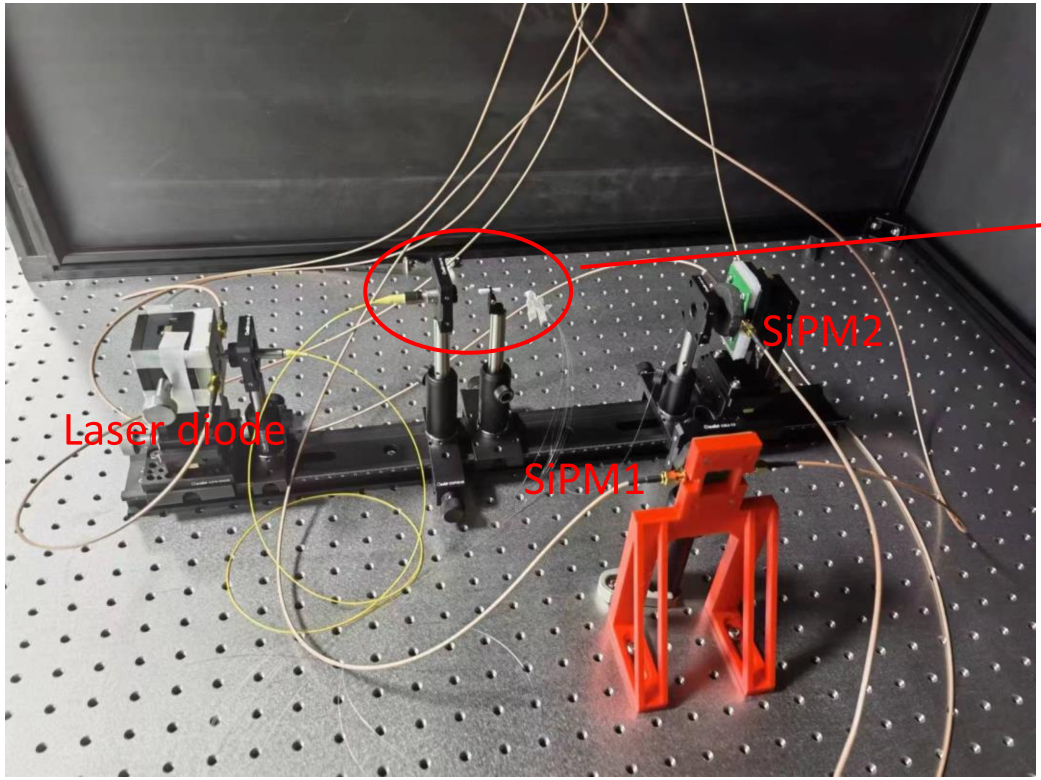
- Tested point: crystal center
- Response varies among bars: coupling? wrapping?

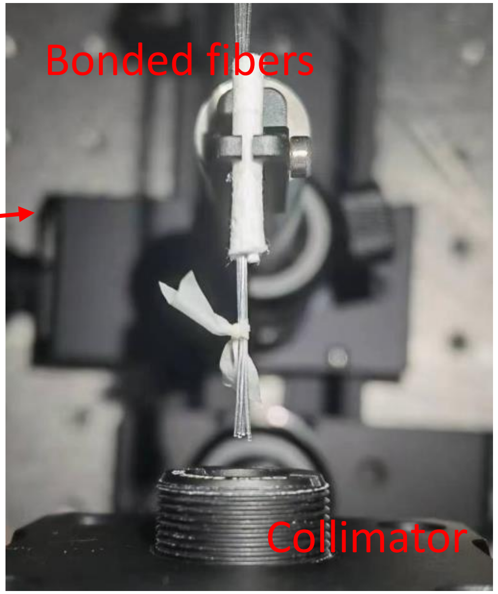
- Uniformity = (Max - Min)/Mean
- Generally uniformity of single bars at 1% level

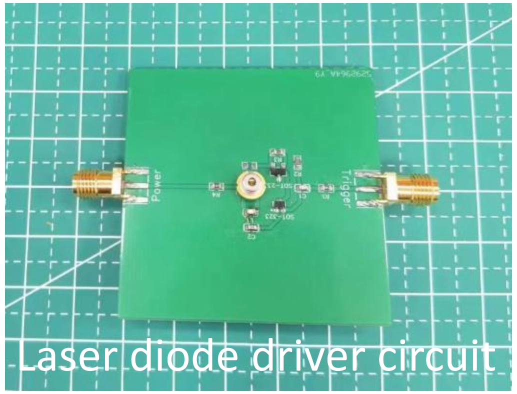
Activities on small-scale crystal module design

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 diode driver circuit


Plastic fiber, Φ 0.5 mm

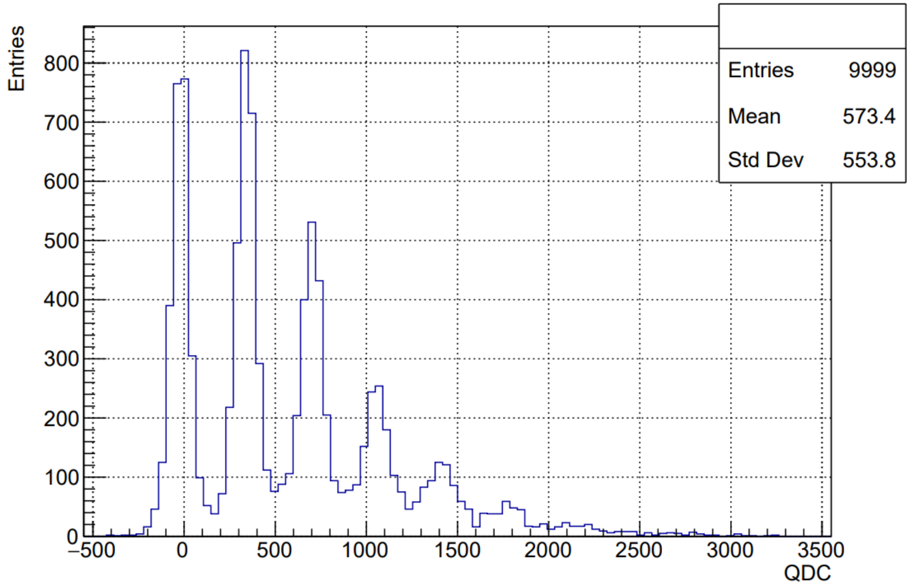
- Laser should be collimated to fiber ends
- Fibers should be bonded for better light acceptance

Activities on small-scale crystal module design

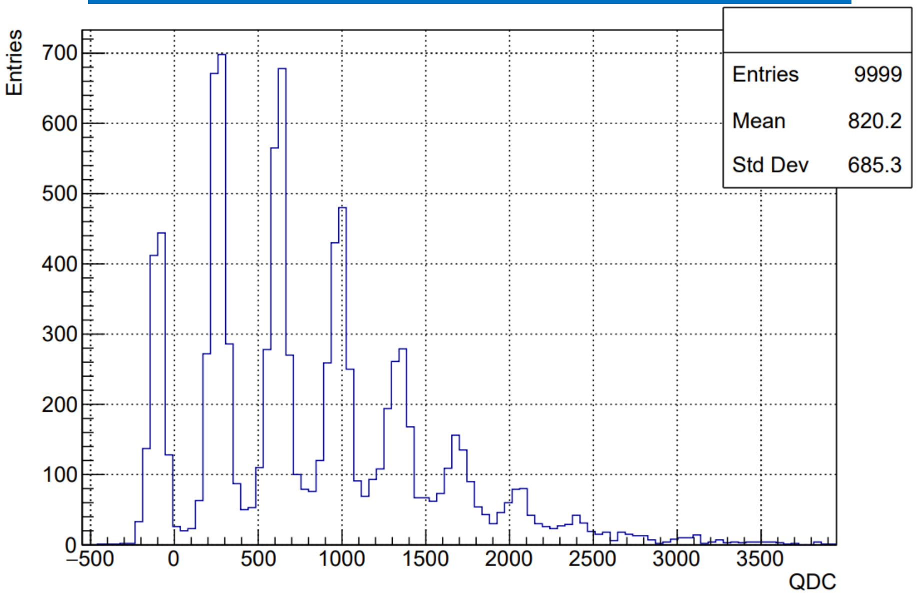
Zhiyu Zhao (SJTU)

- 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



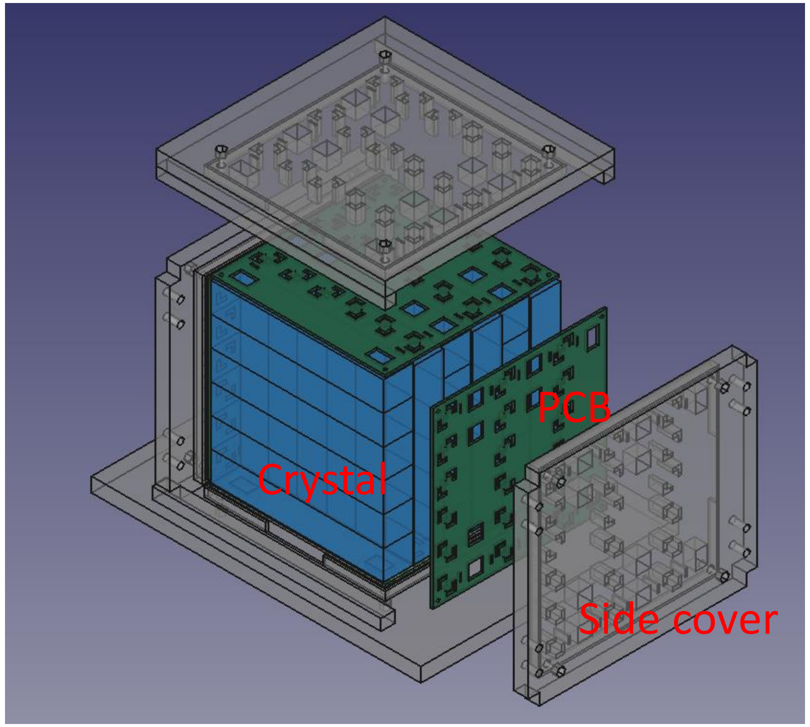
Single photon spectrum EQR15-2

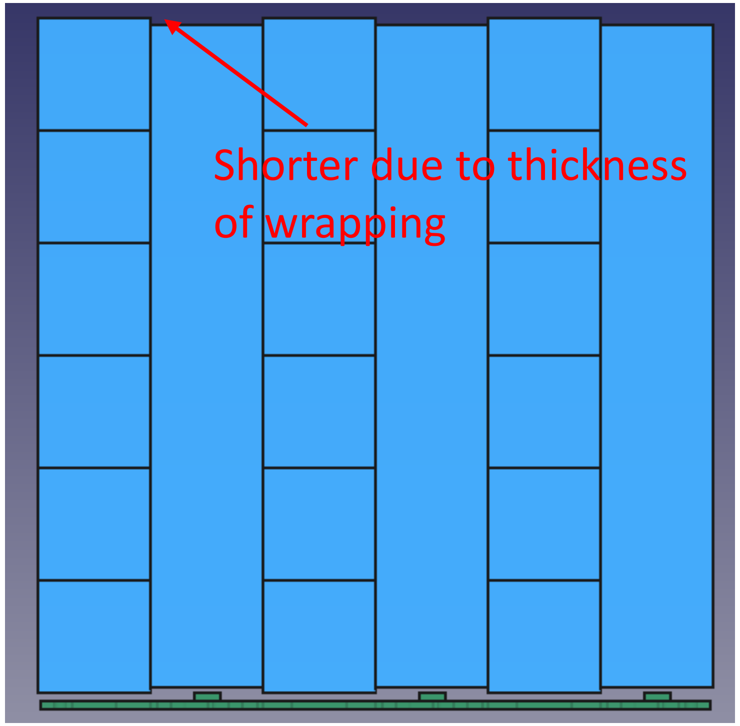


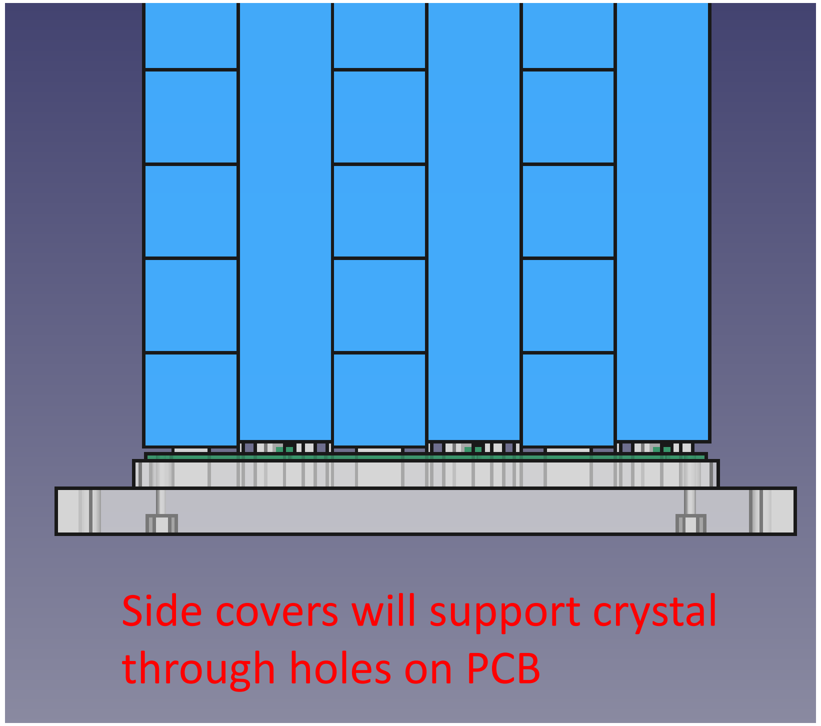
- Both SiPMs shows clear photon peaks
- Good consistency between the arbitral selected 2 fiber channels

Activities on small-scale crystal module design

- Mechanical structure and module assembly



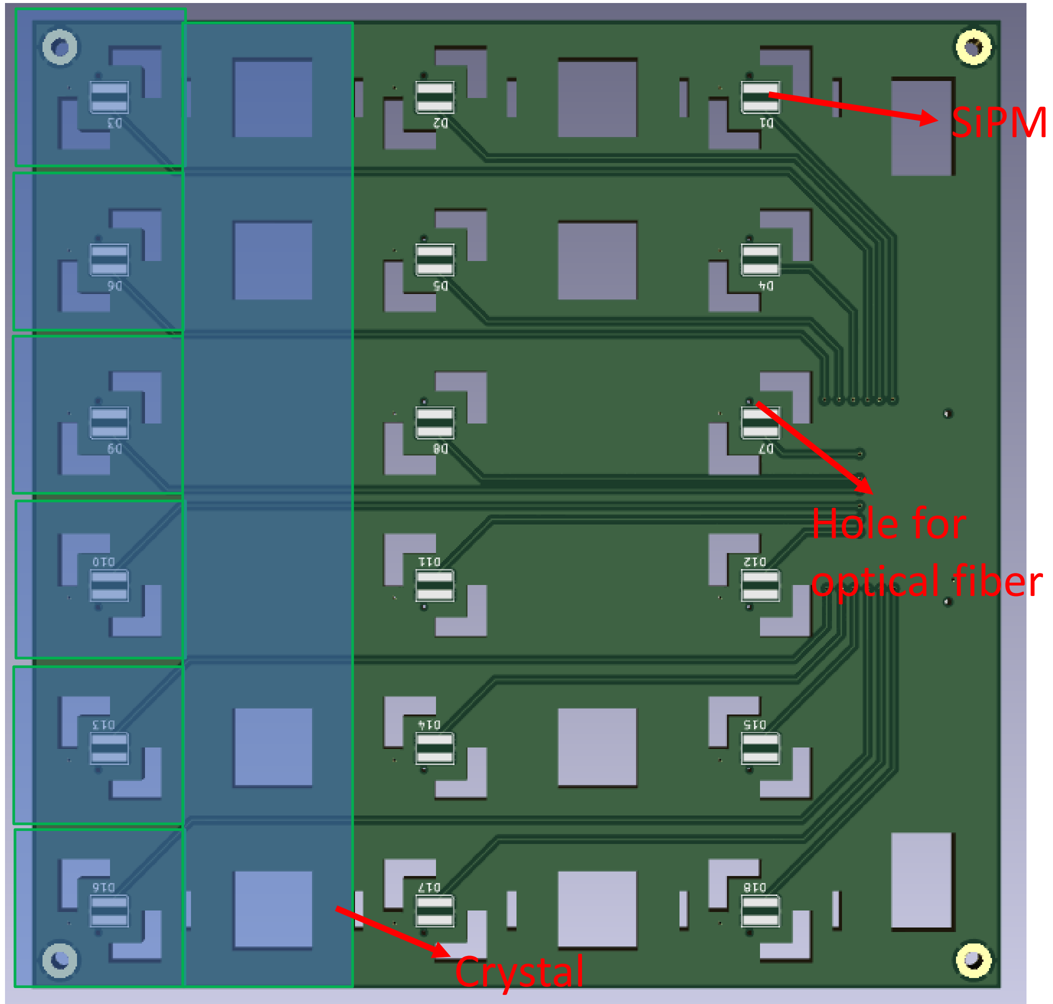




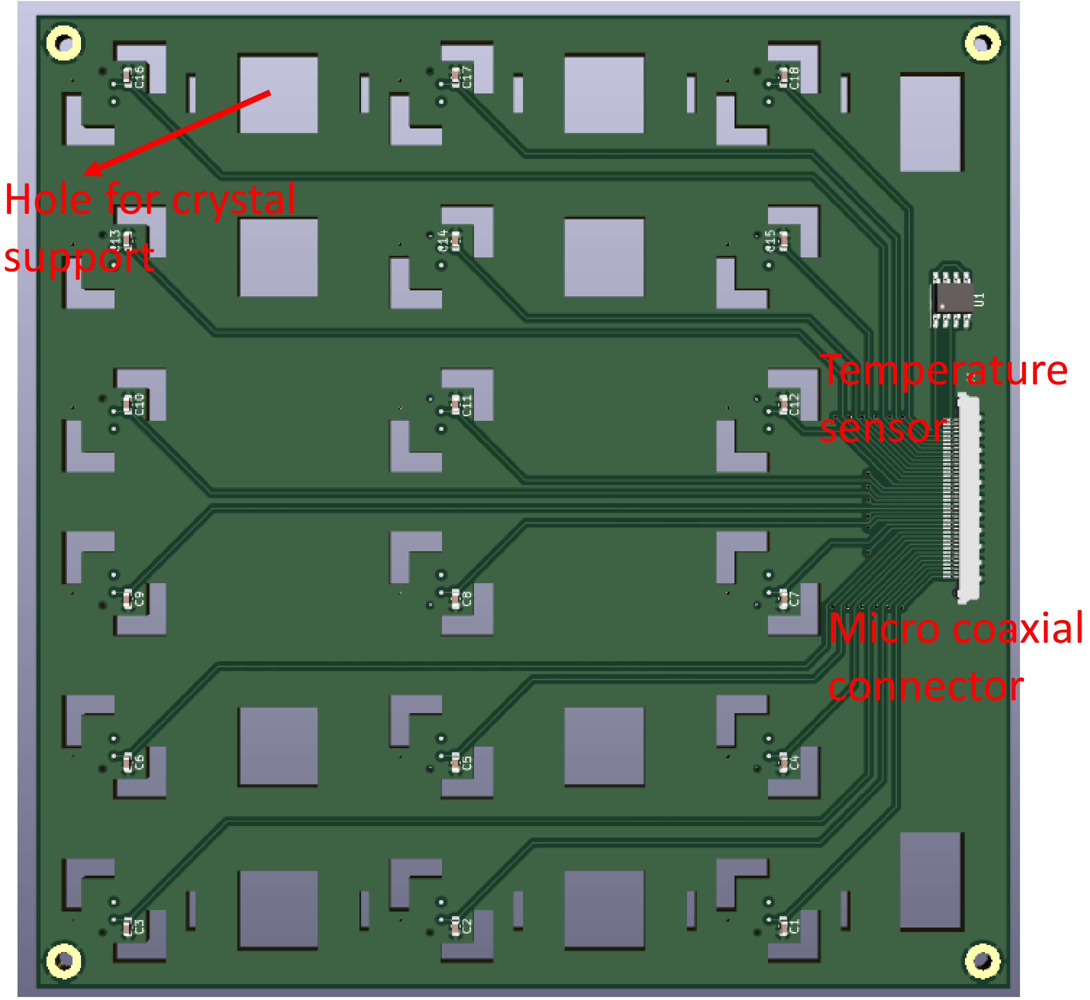
- Difficulties on mechanical design
  - Readout from 4 sides, PCB is non-load-bearing and should be decoupled
  - Module assembly is hard since crystals should be placed orthogonally

Activities on small-scale crystal module design

- PCB layout



Front side



Back side

Summary & prospects

R&D of a highly granular crystal ECAL:

- Preliminary geometry design of barrel ECAL
  - Key questions on dead material and assembly
  - Optimization to avoid projectile cracks
- Reconstruction algorithm
  - Clustering and reconstruction workflow
  - First studies on occupancy of ECAL towers
- Activities on small-scale crystal module development
  - Performance check: ND-filter seems necessary
  - Uniformity studies of SIC-CAS BGO crystal bars
  - SiPM calibration through optical fiber
  - Mechanical design status and challenges

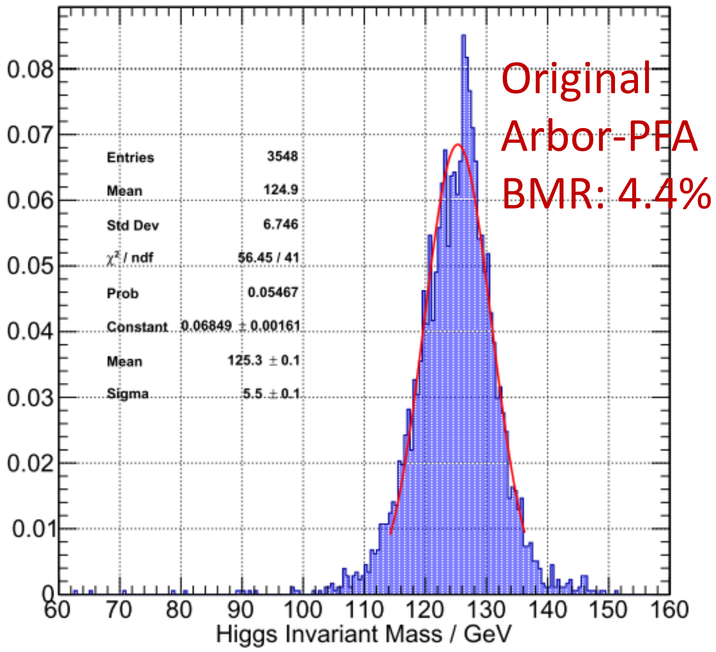
- Prospects
  - Ongoing geometry optimization and cooling simulation
  - Algorithm development and validation
  - Crystal module: prepare for latest beam test
    - Mechanical assembly
    - Joint test with fiber calibration system
    - Test on readout electronics
    - …

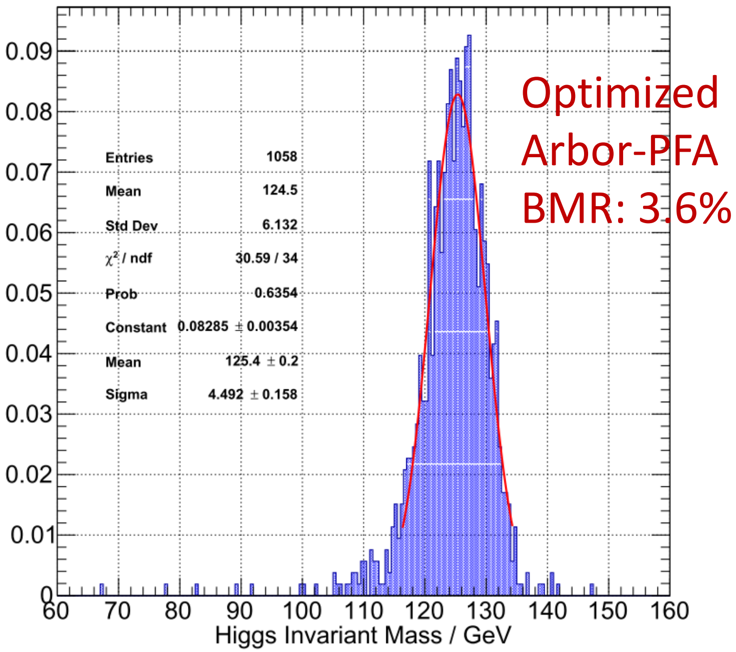
Backup

PFA performance: Higgs benchmark

- Physics performance
  - Boson mass resolution (BMR) for di-jet events: ZH ($Z \to \nu\nu$, $H \to gg$)
  - Studied with 1 cm^3 crystal cubes
  - Significant improvement after Arbor-PFA algorithm optimization

BMR ($H \to gg$)

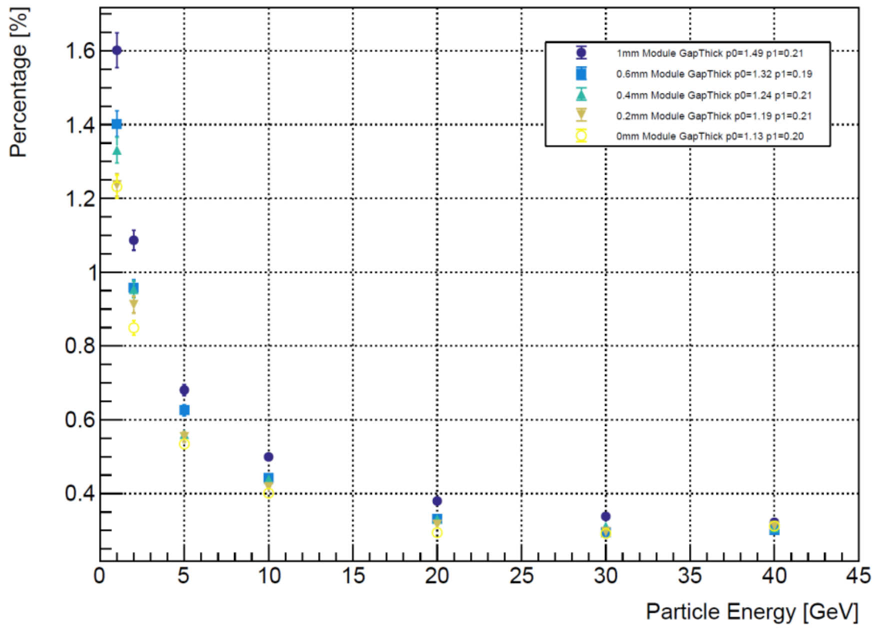




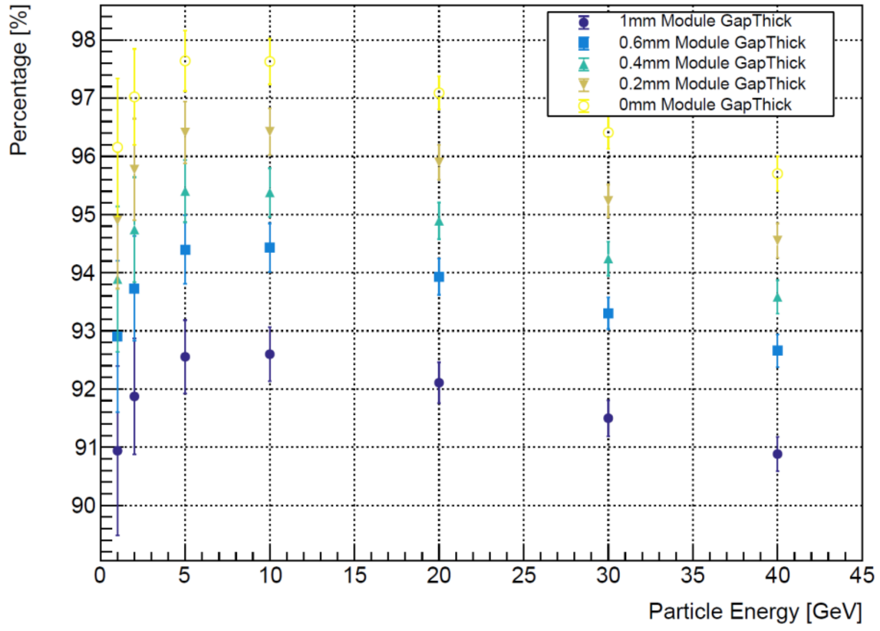
Small-scale crystal module design: impact of gaps

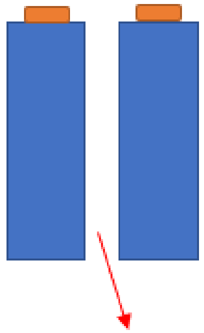
- Gap material in 40×40×28 supercell: ESR film, Al foil, Air
- Density set to 2 g/cm^3

EM energy resolution



EM shower containment



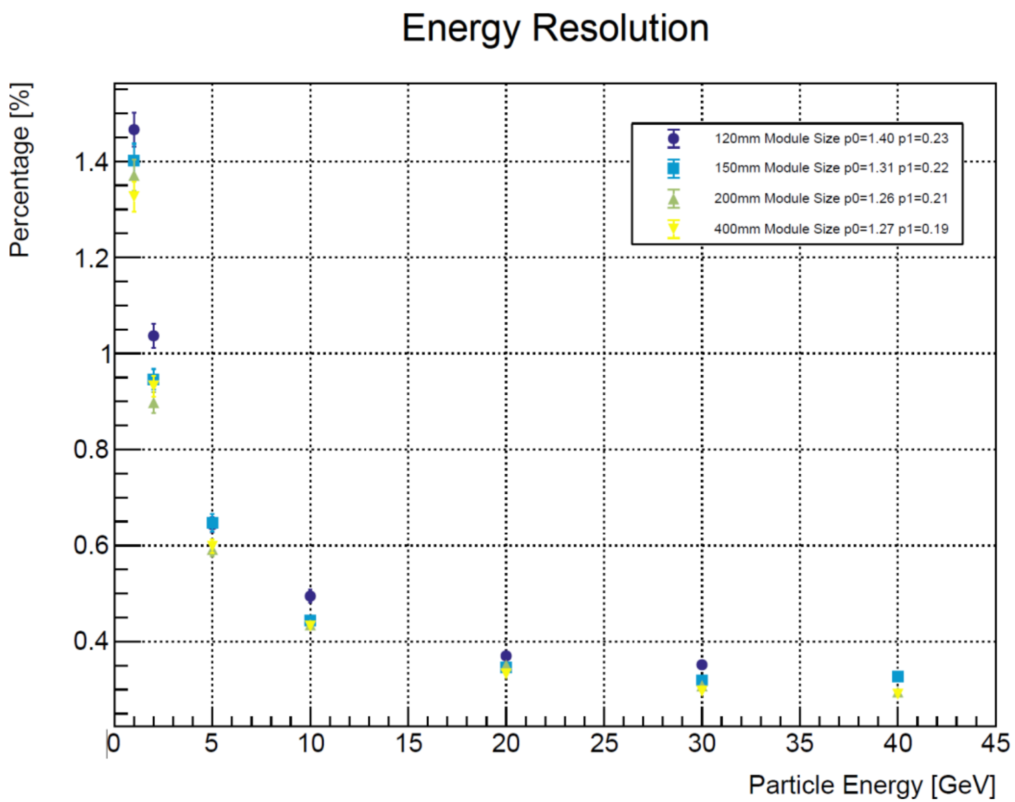


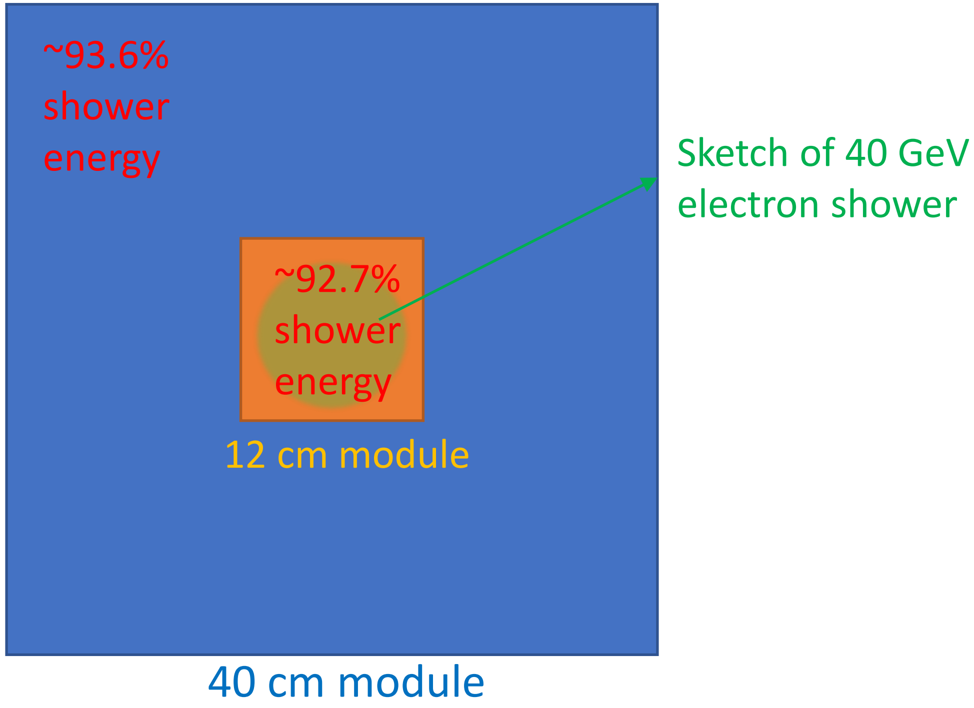
Simulated gap: 0~1 mm

- 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



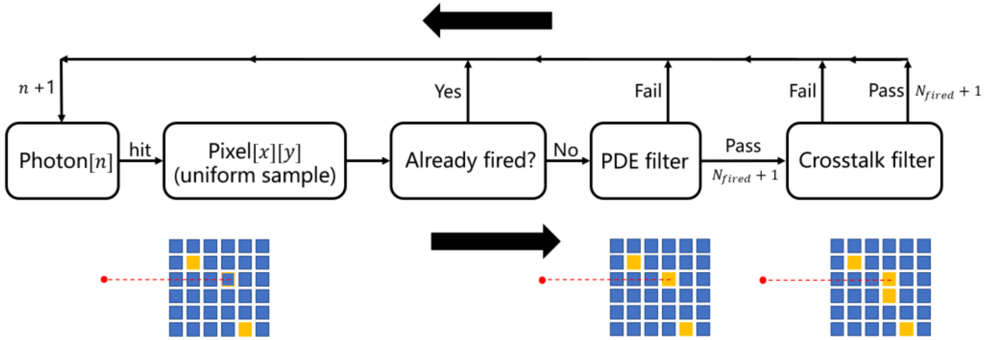


- For EM showers, 12 cm size is enough to contain most of the energy when particles hit on the center of the module
- Degradation of energy resolution: ~0.1% level

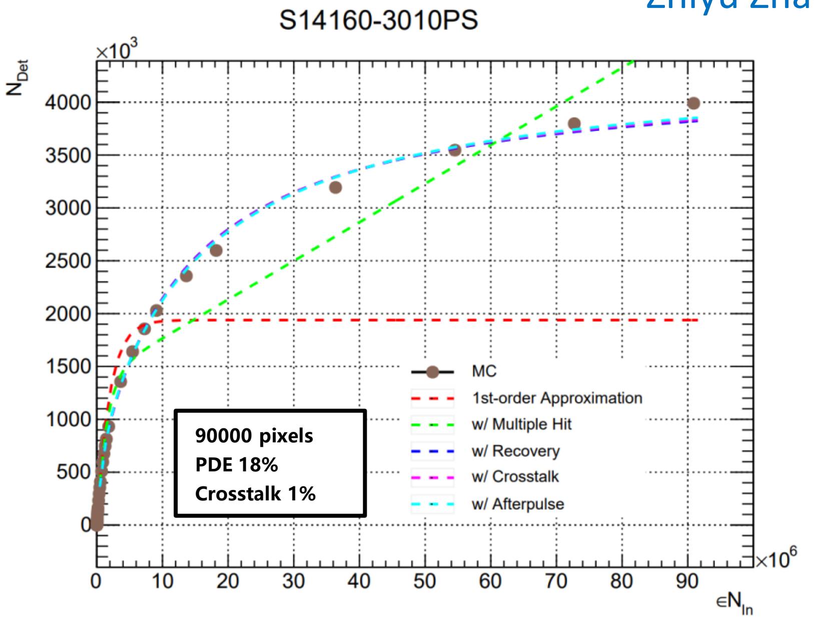
SiPM response non-linearity study

- 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:

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

- One pixel receive more than one photon

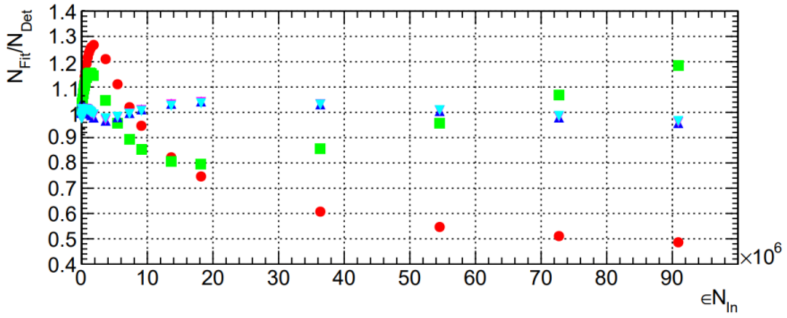
$$N_{\rm fire}^{\rm NLO} = N_{\rm fire}^{\rm LO} + \alpha N_{\rm R}.$$

- 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

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



[ICASiPM_Krause_final.pdf (gsi.de)]

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