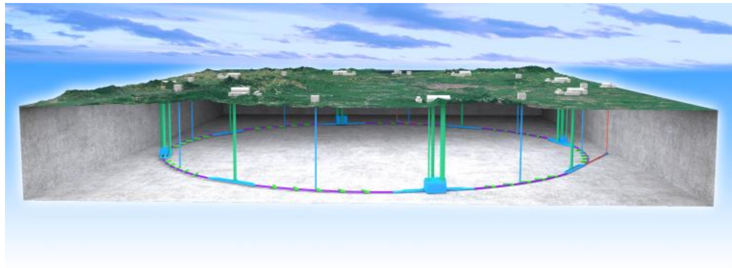
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

CEPC



A novel high granularity crystal electromagnetic calorimeter

Baohua Qi
On behalf of CEPC Calorimeter Working Group

The 2022 International Workshop on the High Energy Circular Electron Positron Collider
October 24-28, 2022

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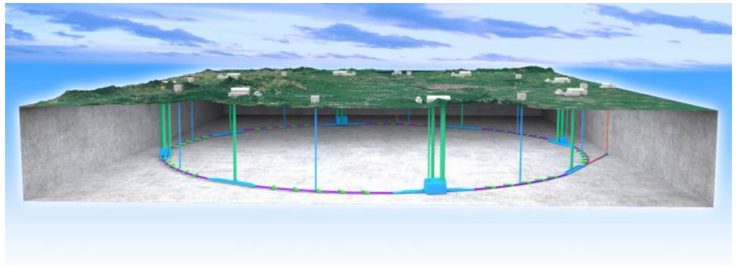
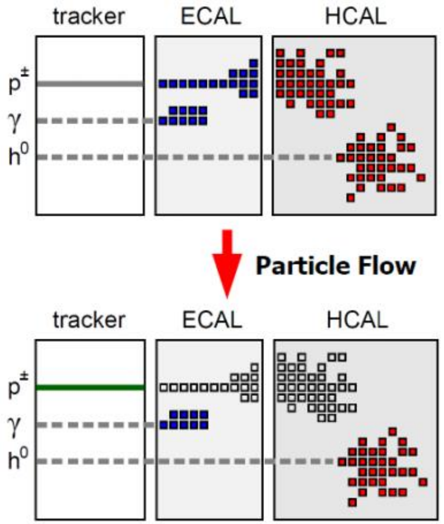
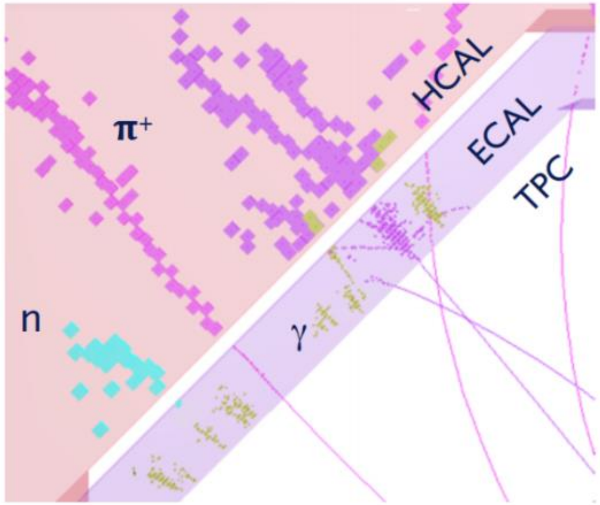
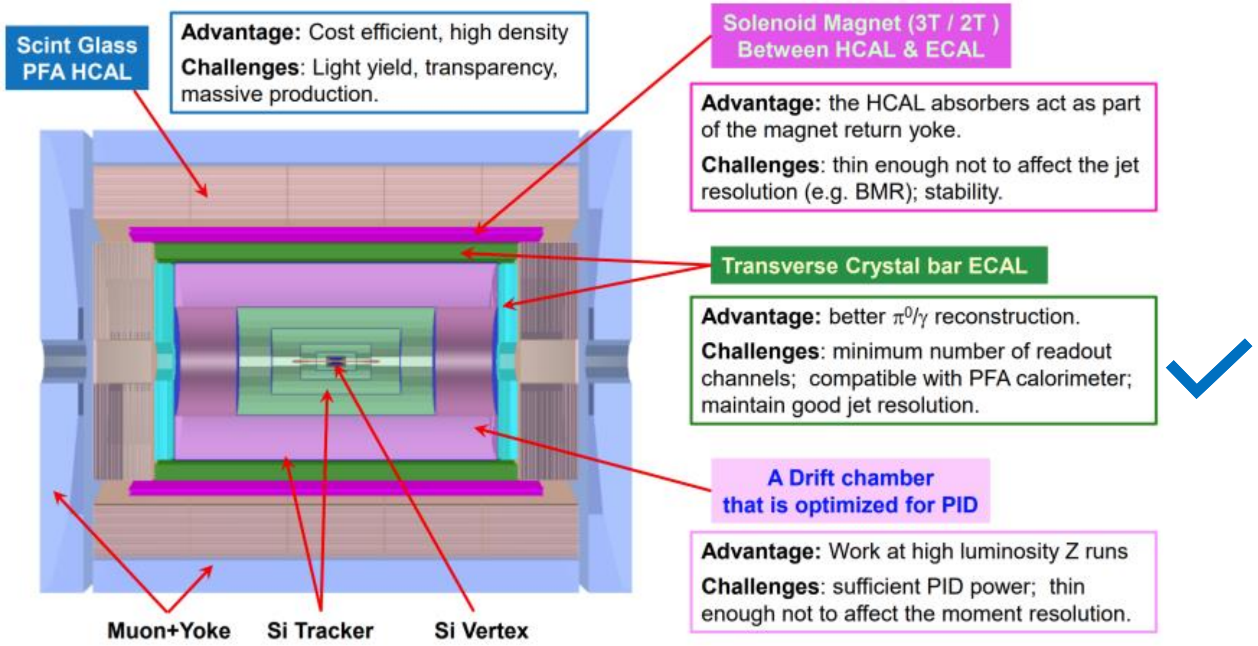
Motivations for crystal ECAL: new detector for CEPC

- 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: 3D spatial + energy + time information
  - Homogeneous structure
    - Intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$





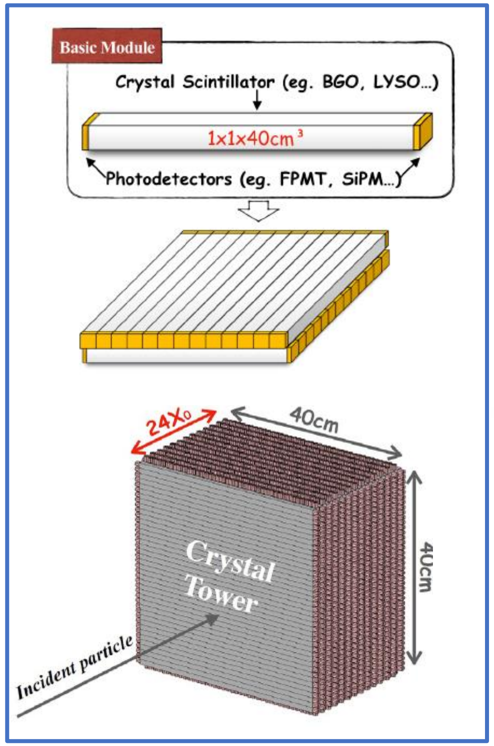


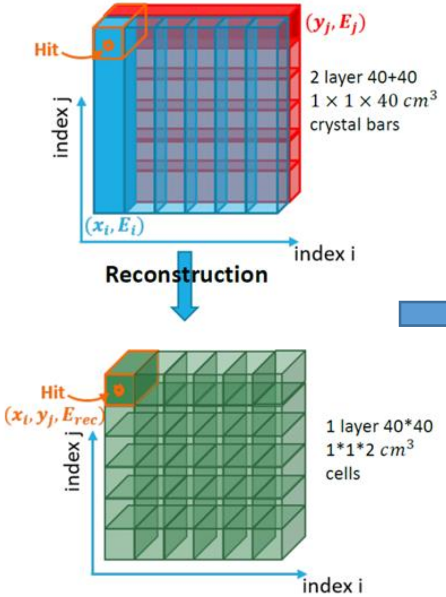


Talk ***Overview of the CEPC Project*** by Haijun Yang, CEPC Joint Workshop 2022, 23-25 May

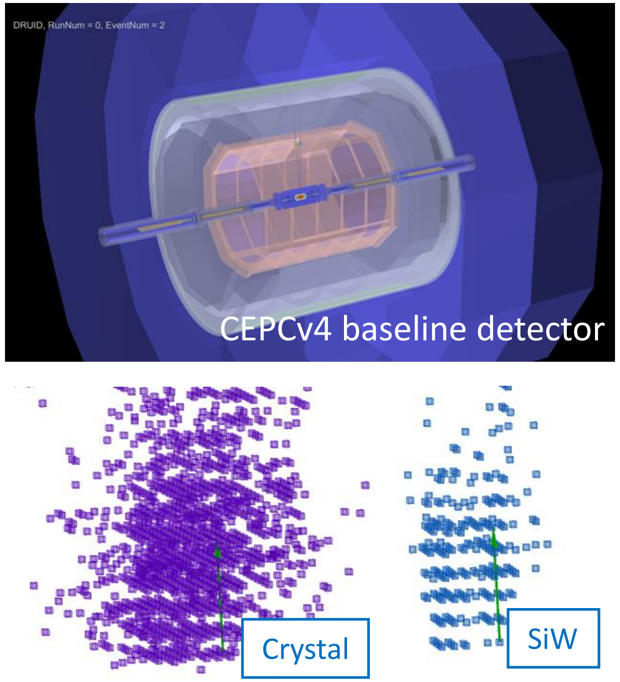
Crystal calorimeter: R&D overview

- Hardware design → Simulation and validation → Performance evaluation

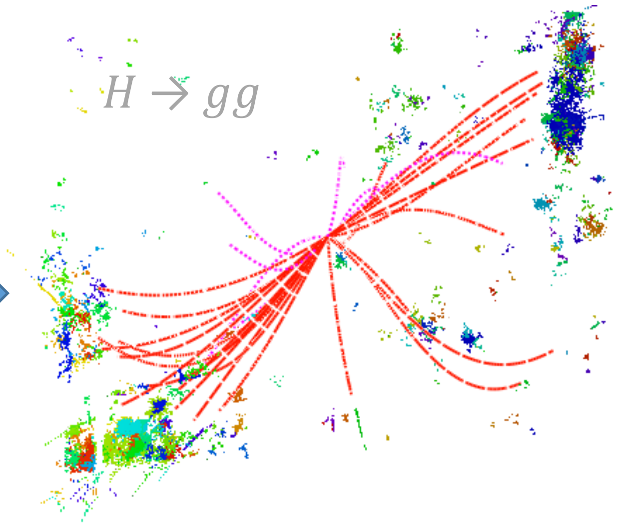




Crossed long bar design: $1\times1\times2$ cm³ granularity after reconstruction



Shower profile of 5 GeV photons: significant increase of #hit due to a larger Molière radius: 2.26 cm (BGO) vs 0.93 (W)



Performance study with multiple jets events of Higgs decay

Hardware development: crossed long crystal bars

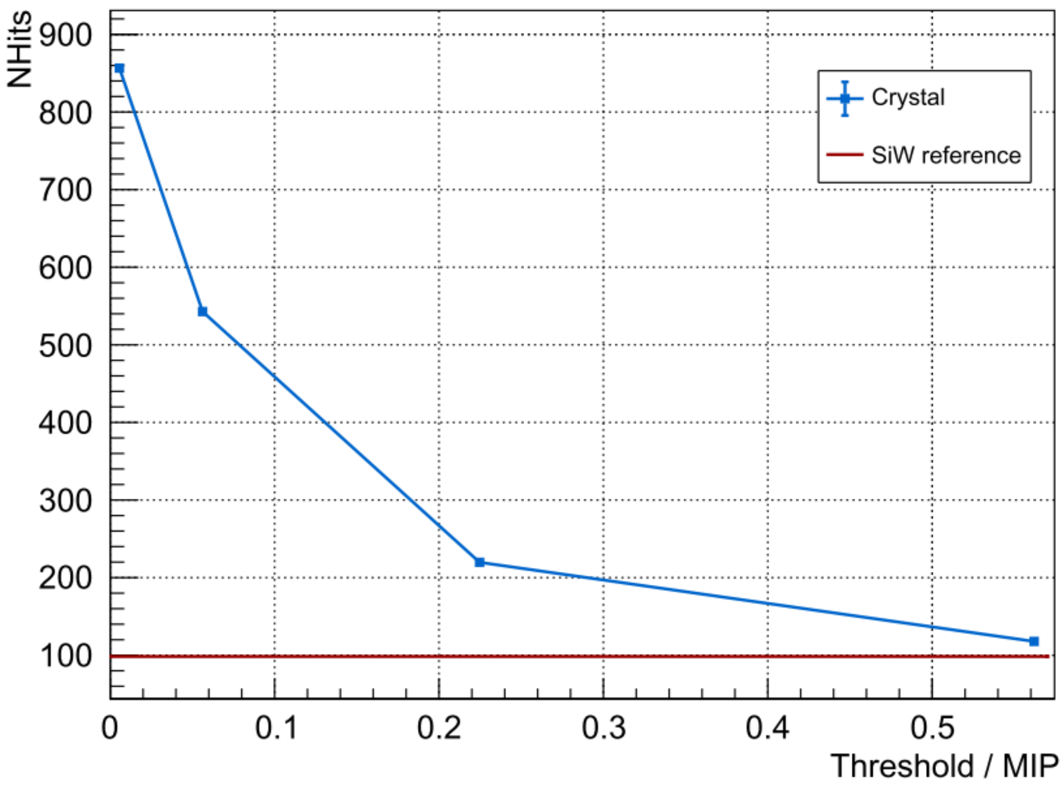
- New reconstruction software for long bars
- Optimizations of the Arbor-PFA for crystal ECAL

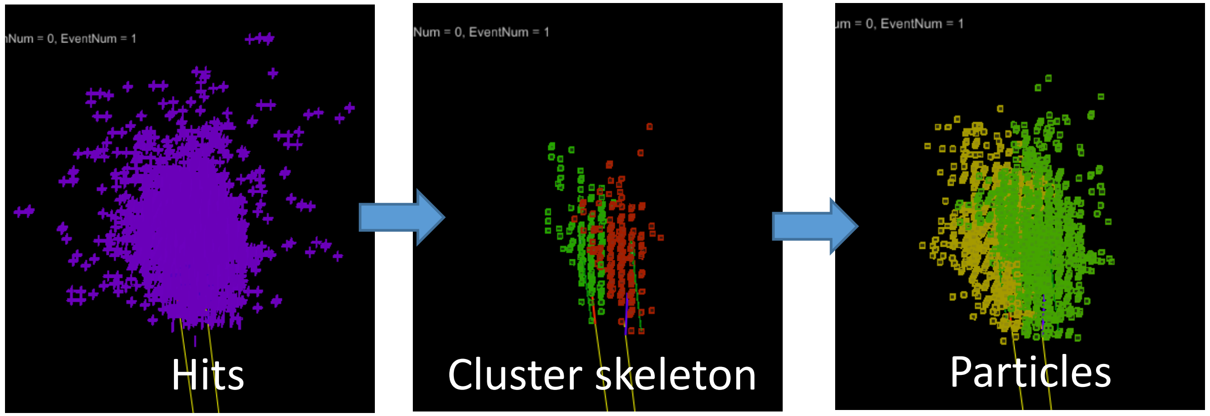
Physics performance evaluation with Higgs benchmarks

Arbor-PFA optimization for crystal ECAL

- Crystal ECAL + 2-stage thresholds Arbor algorithm
  - (1) Use a relatively high energy threshold to search for the cluster skeleton
  - (2) Re-cluster low-energy hits with a relatively low energy threshold

Nhits vs Energy Threshold for 5 GeV Photons

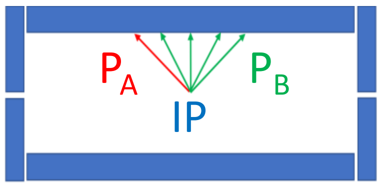




- Significant reduction in the number of hits after high energy threshold cut
- Better capability for pattern recognition for the clustering algorithm
- Re-absorbing of low energy hits for better energy reconstruction

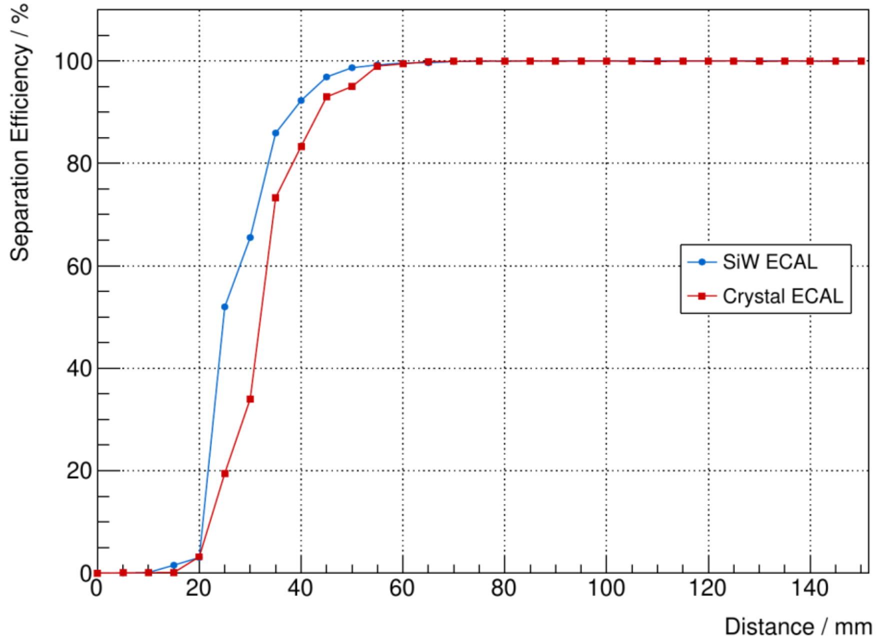
PFA performance: separation power

- Reconstruction of jets: separation of close-by particles

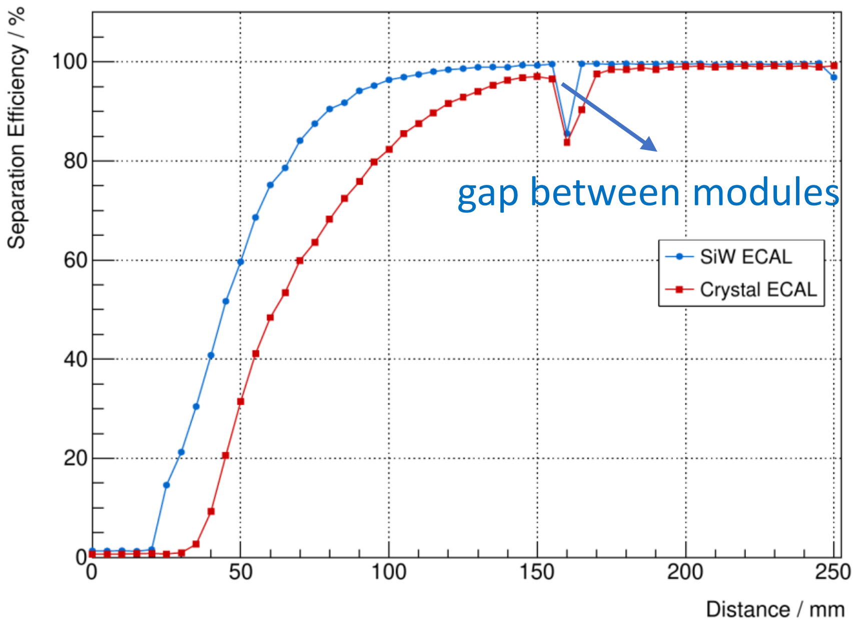


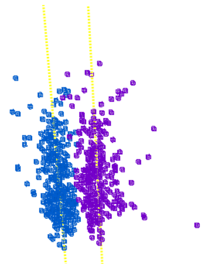
Side view of crystal ECAL

γ/γ separation with barrel ECAL



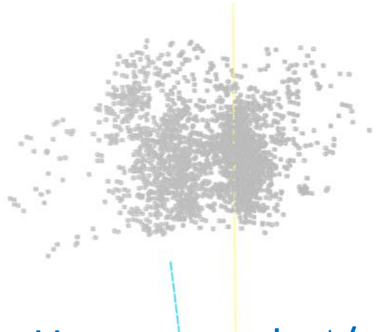
π^{+}/γ separation with barrel ECAL





Separated γ/γ

Separated π^{+}/γ

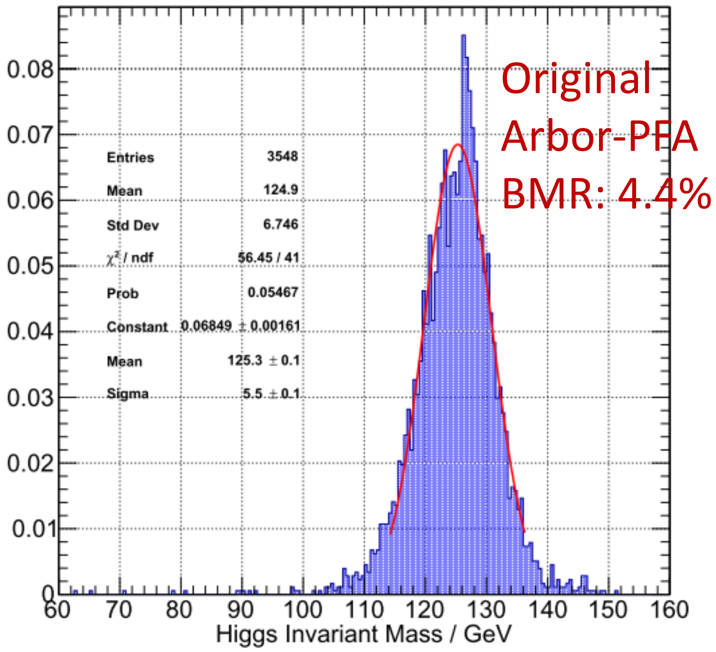


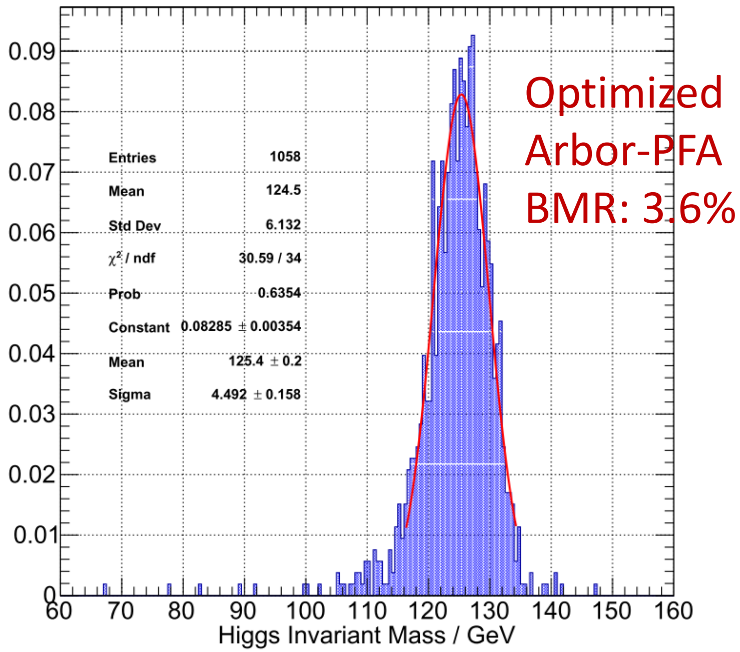
Unseparated π^{+}/γ

- EM shower: good separation power, similar to SiW ECAL under a high energy threshold
- Hadronic shower: challenges on clustering and matching clusters to tracks
- Further optimization of Arbor-PFA

- 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 ($H \to gg$)

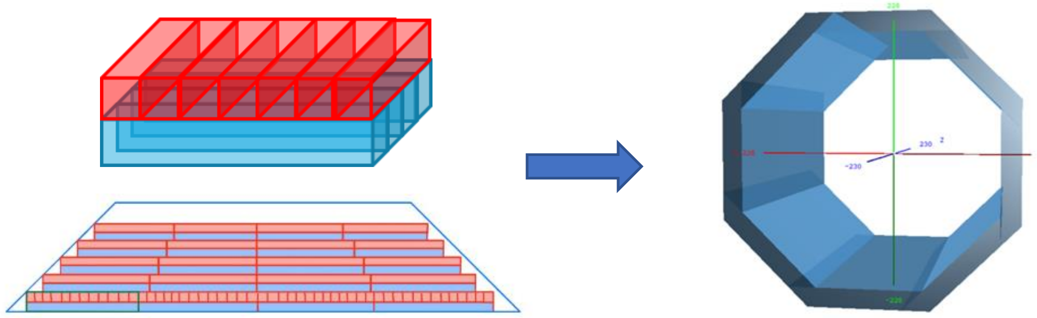




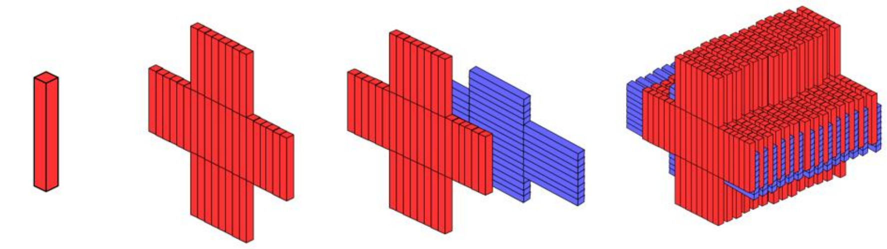
Reconstruction algorithm dedicated to new geometry design

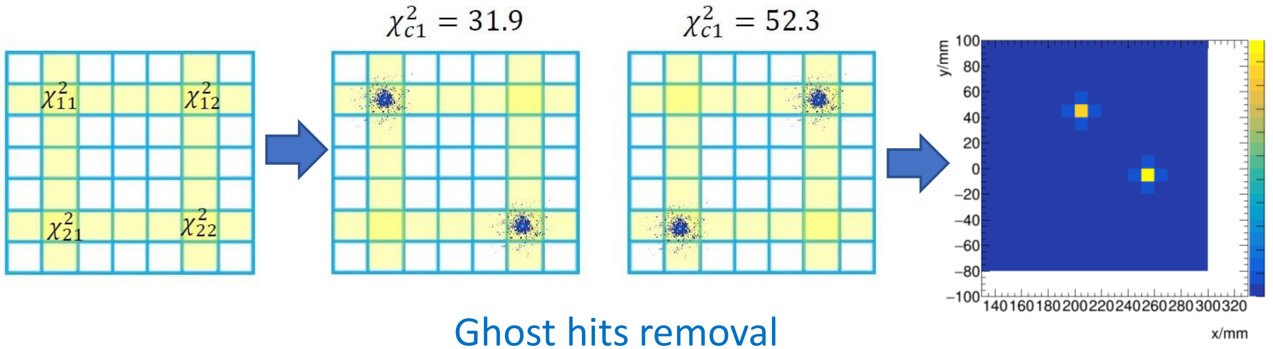
Fangyi Guo, Weizheng Song, Shengsen Sun, Linghui Wu, Yang Zhang (IHEP)

- Detector description: 28 longitudinal layers, crossed bars
- Ongoing development of new reconstruction algorithm:
  - Aims at a granularity of 1×1×2 cm^3
  - Minimize impact from ghost hits
- Challenges: pattern recognition, track-calo matching

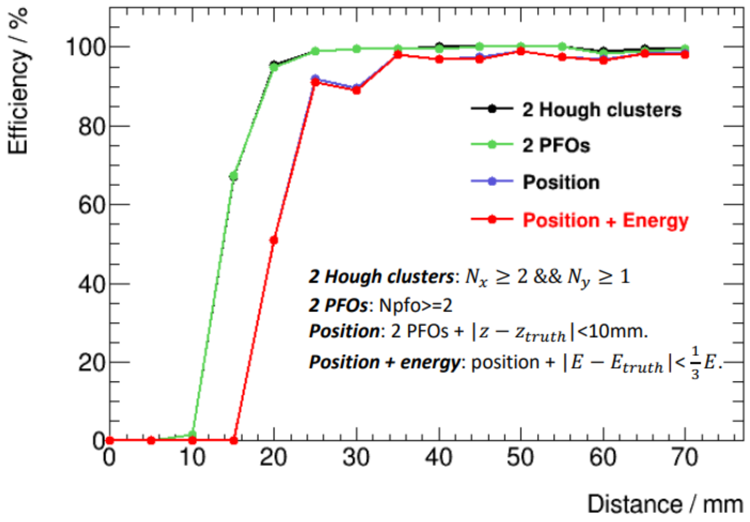


Basic principles of clustering algorithm





Ghost hits removal

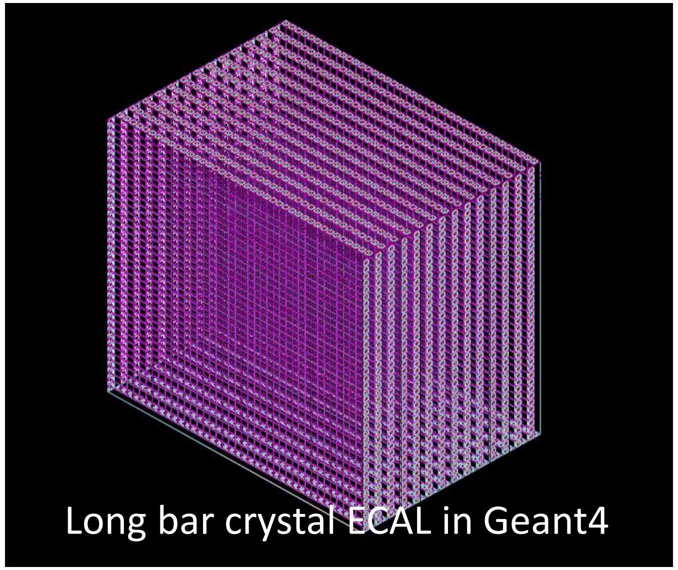


Performance study: di-photon recognition efficiency

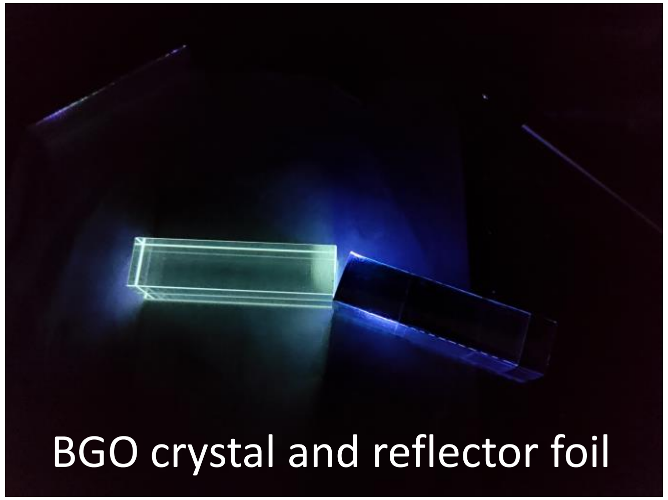
For details please refer to the talk on Friday by Yang Zhang

Hardware activities of crystal ECAL: overview

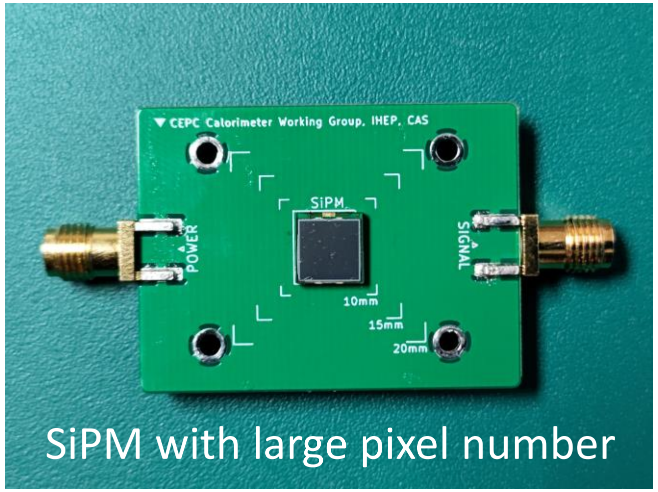
- Study on requirements of crystal-SiPM units
  - Key parameters: MIP light yield, dynamic range, timing resolution,…
- Development of small-scale crystal modules
  - Impacts of transverse size, gaps
  - Crystal quality test stand: crystal uniformity
  - Mechanical design and module assembly



Long bar crystal ECAL in Geant4



BGO crystal and reflector foil



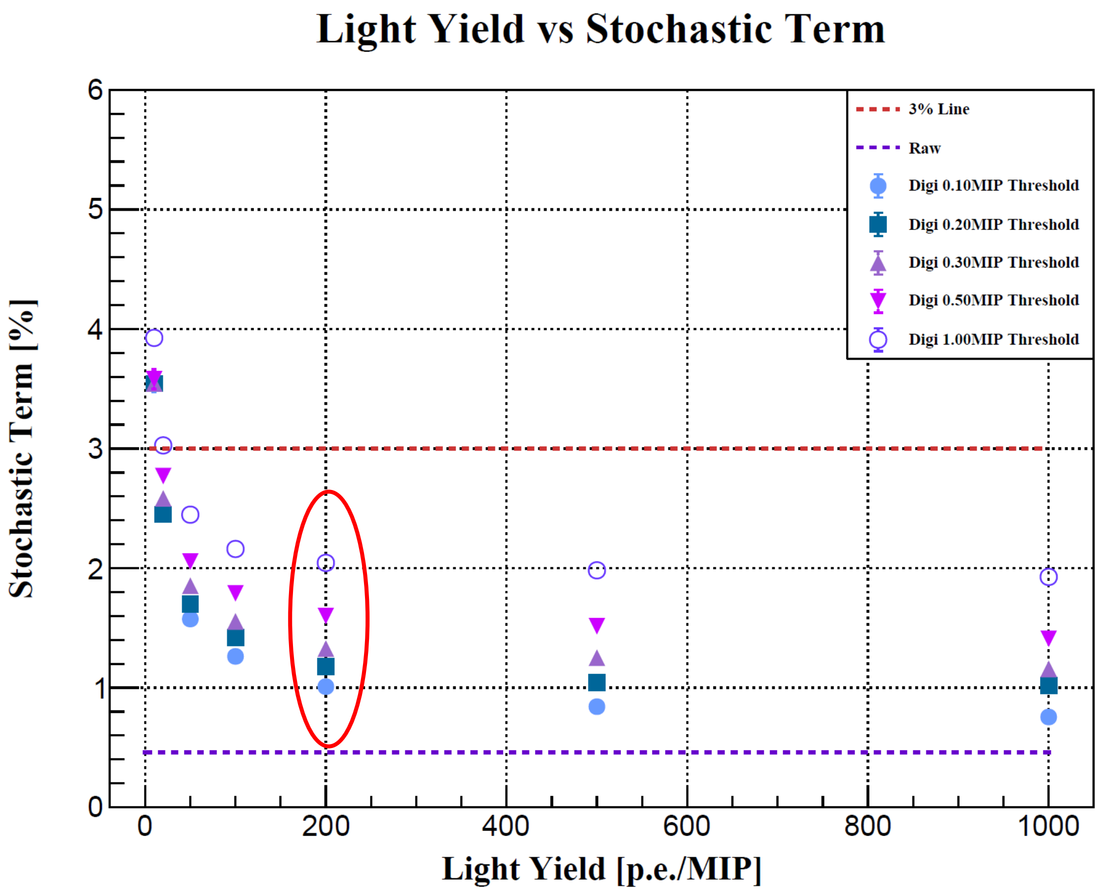
SiPM with large pixel number

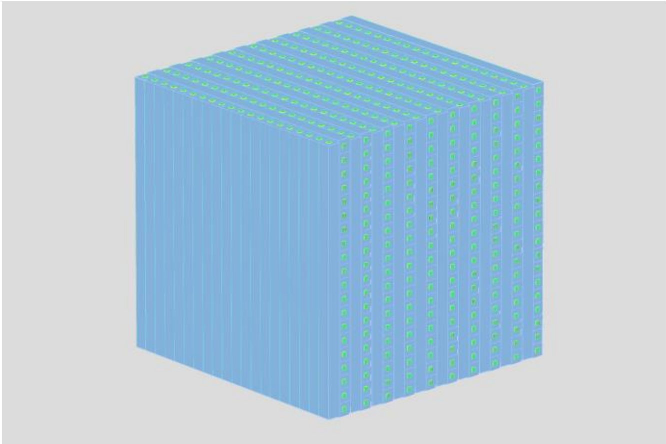
SiPM readout electronics

EM energy resolution: light yield requirements

Geant4 Simulation (v11.0)

- Light yields: number of detected photons per MIP
- Energy resolution: stochastic term





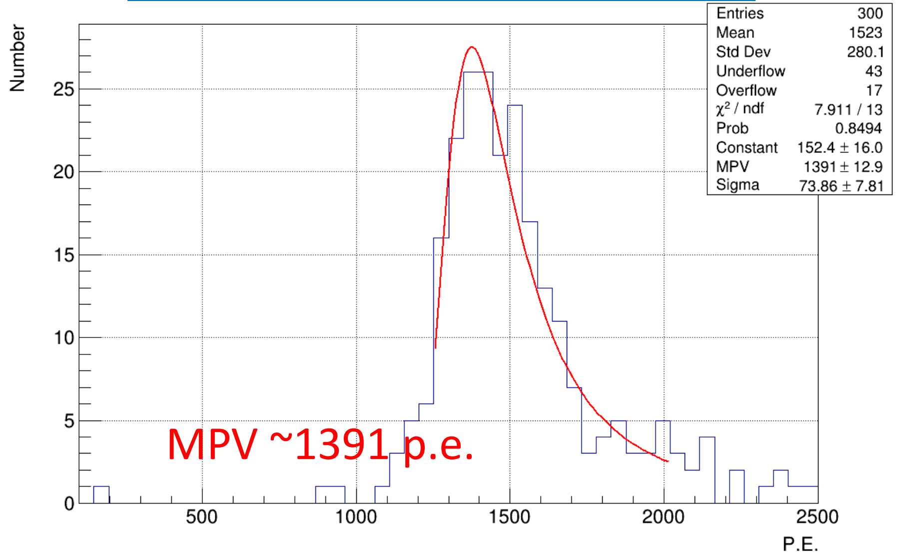
Simulation: 40×40×28 supercell, BGO long bars, gaps, 1~40 GeV electrons
Digitization: photon statistics, gain uncertainty, ADC error,…

- Good resolution requires
  - Moderately high light yield → dynamic range
  - Low energy threshold → noise level
- Light yield required for one channel: ~200 p.e./MIP
  - $< 1.5\%/\sqrt{E}$ energy resolution
  - Requirement for a SiPM: ~100 p.e./MIP
    - Beneficial to set a low energy threshold
    - Limitation from dynamic range

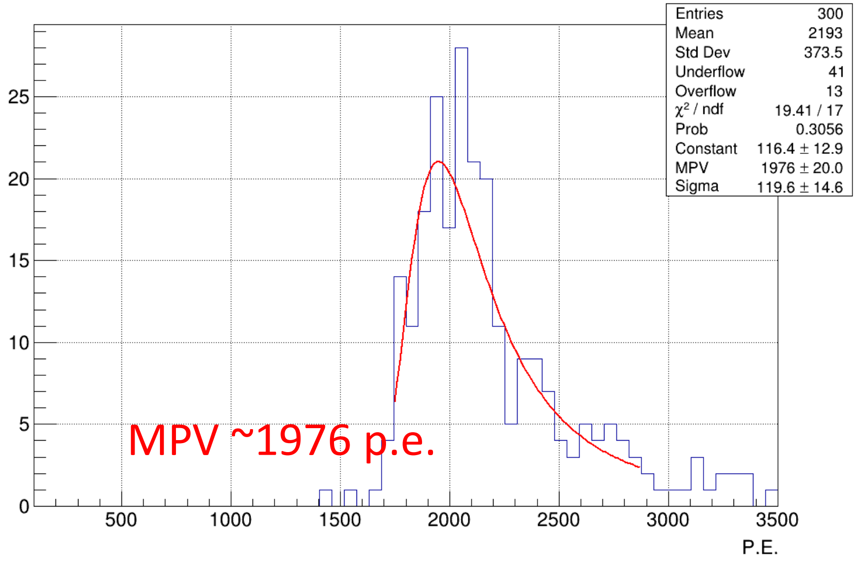
Cosmic-ray test: MIP response of BGO crystal

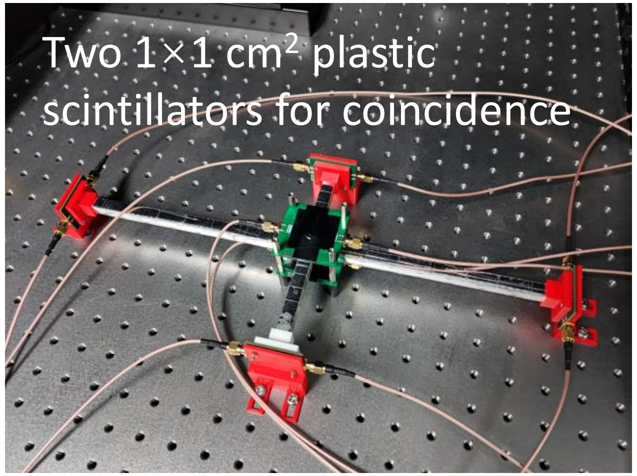
- Measurement of crystal-SiPM units
  - 16 and 40 cm BGO crystals, double-sided readout

6×6 mm^2 SiPM 40 cm BGO



6×6 mm^2 SiPM 16 cm BGO



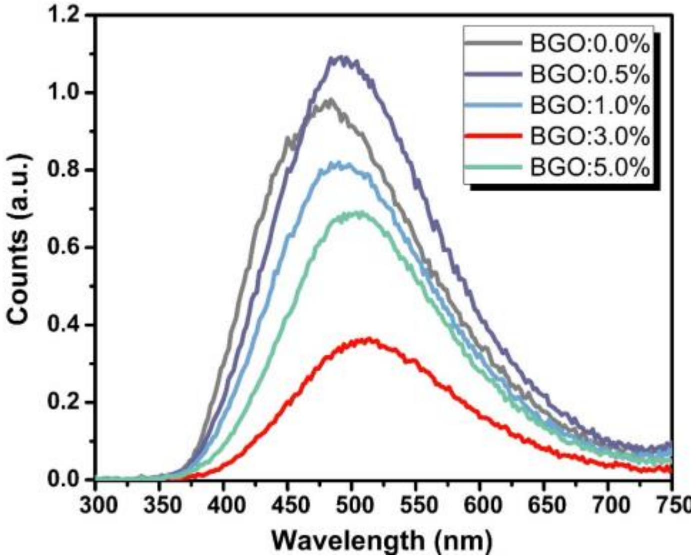


- MIP light yield higher than the requirement
  - Use smaller SiPMs with high pixel density: 3×3 mm^2, 6μm/10μm (ongoing)
  - “Tune” BGO intrinsic light yield by doping (SIC-CAS)

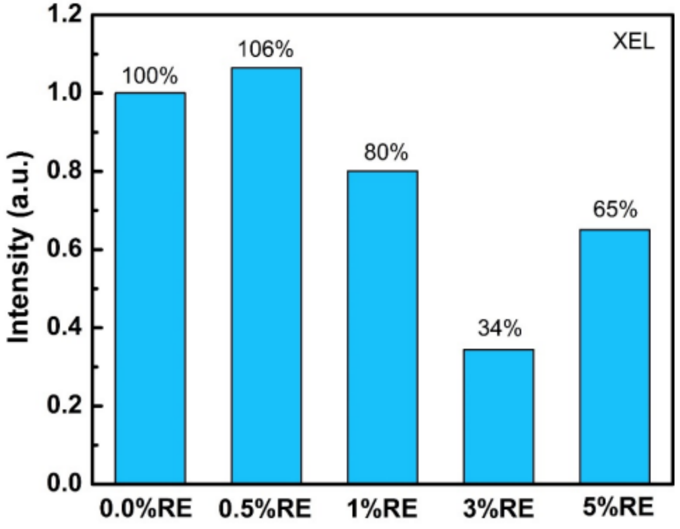
Status of new BGO crystal development at SIC

Junfeng Chen (SIC-CAS)

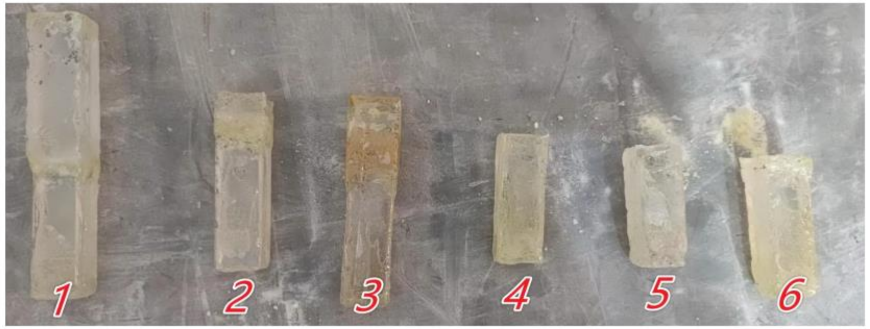
- Adjust doping to decrease the light yield of the BGO crystal
- The radioluminescence intensity of BGO
  - Reduced to 34% of pure BGO powder with 3% RE powder



Radioluminescence spectra of as-prepared BGO: RE powders



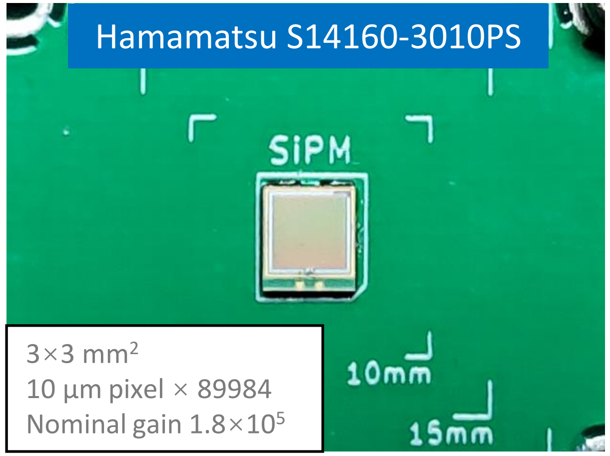
The relative luminescence intensity of BGO powders with 0-5% RE doping concentration

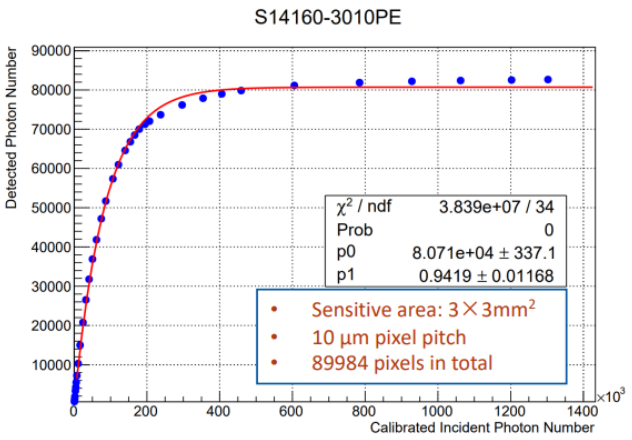


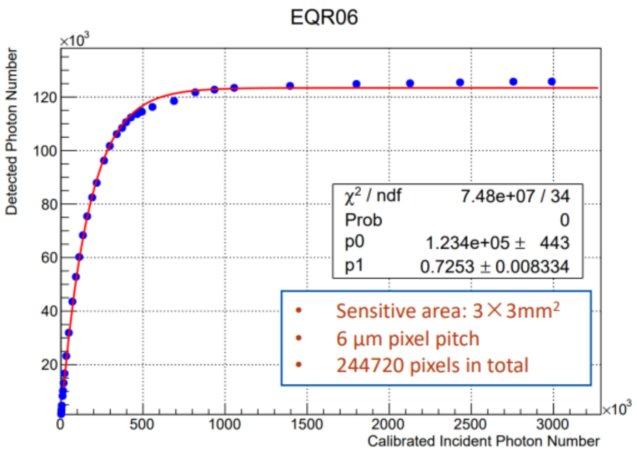
A fast combinatorial design and screening method to optimize the doping concentration

SiPM dynamic range studies

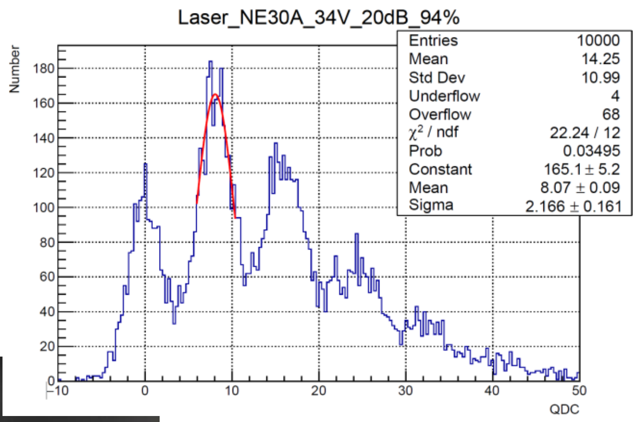
- Motivation: characterization of large dynamic range SiPMs

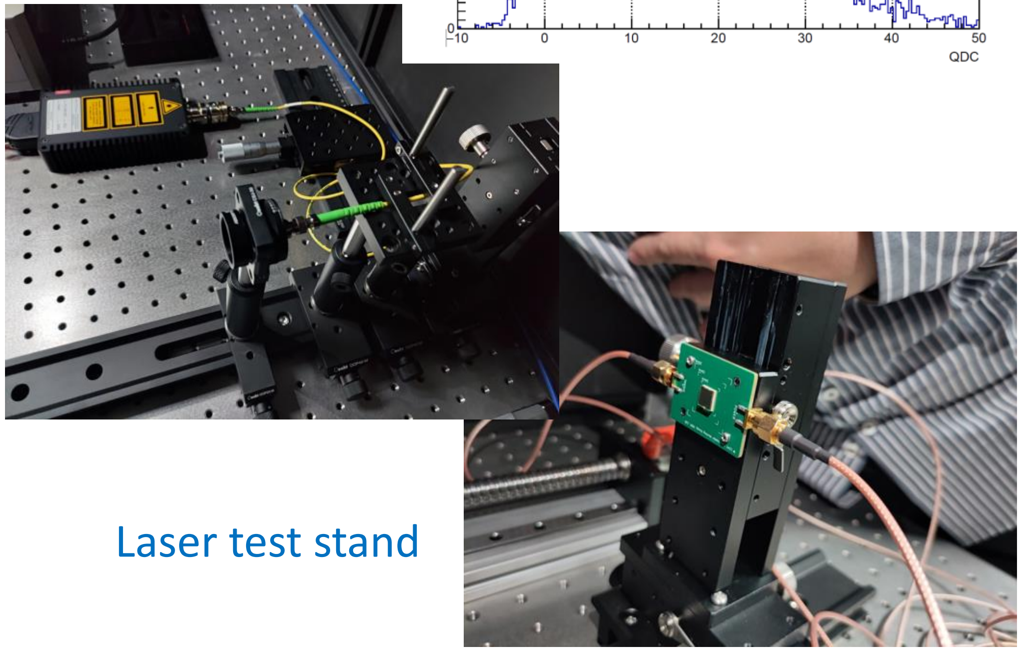






Also studies of single photon spectrum, timing resolution, …





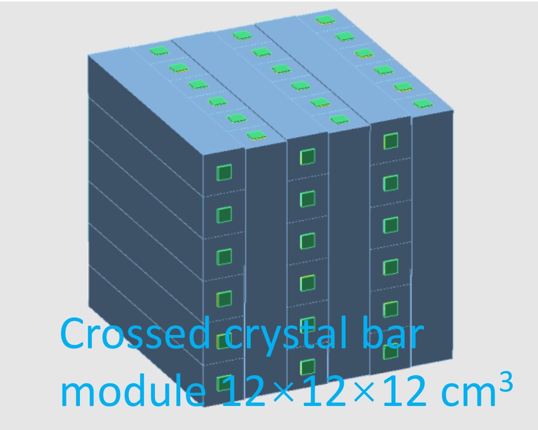
Laser test stand

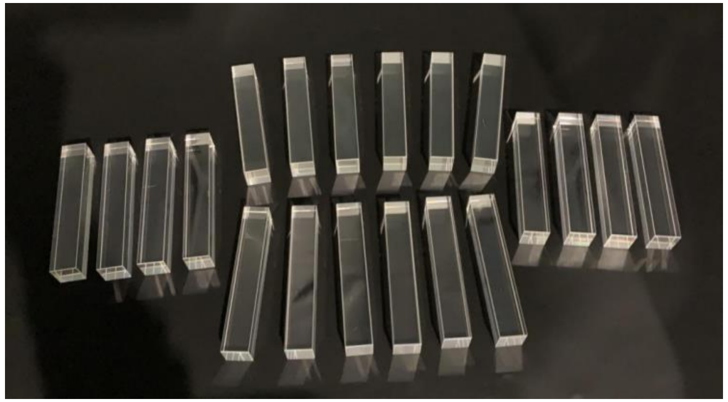
For details please refer to the talk today by Zhiyu Zhao

Small-scale crystal-SiPM module design

- Motivations
  - Address critical issues at system level
- Beam test study with two modules
  - Energy resolution, shower profiles
  - Validation of simulation and digitization tool
  - Application of the new reconstruction software
- Crystal options
  - $12\times2\times2$ cm^3 BGO crystal from SIC-CAS
    - ESR wrapping, Al foil for enhancement
- SiPM options
  - NDL EQR06 / HPK S14160-3010PS
- Electronics
  - FERS-5200 system / …


Dummy crystal matrix with 3D printed support structure


Crossed crystal bar module $12\times12\times12$ cm^3

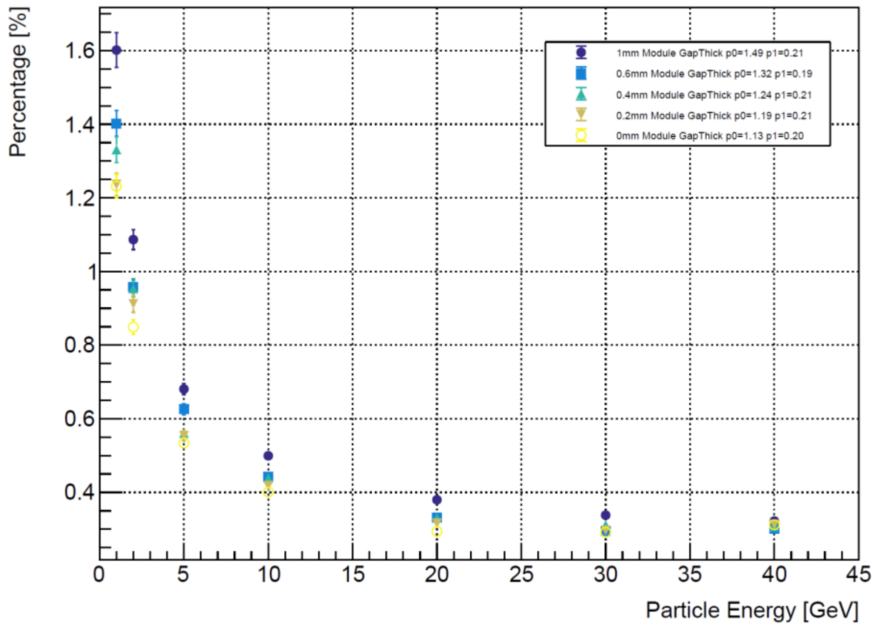


Small-scale crystal-SiPM module design: impact from gaps

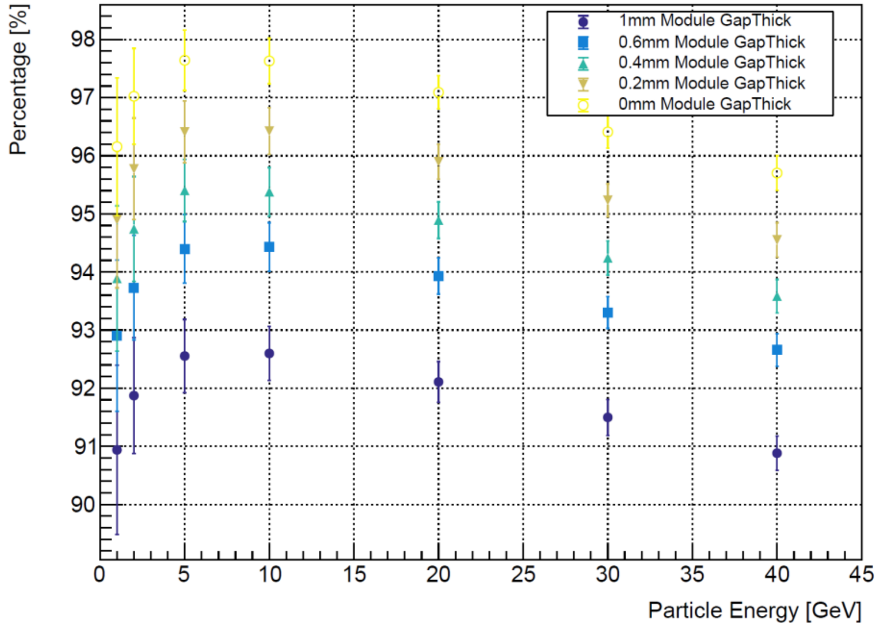
Geant4 Simulation (v11.0)

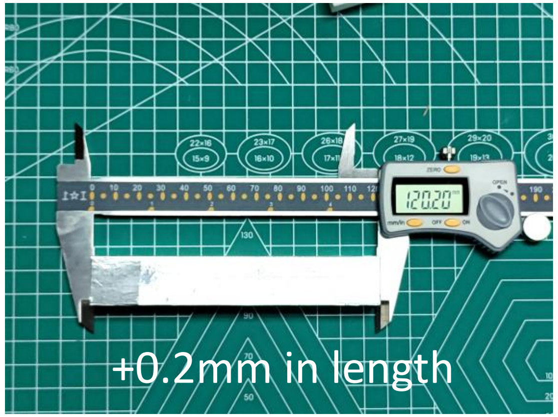
- Gap material in 40×40×28 supercell: ESR film, Al foil, Air
- Density set to 2 g/cm^3

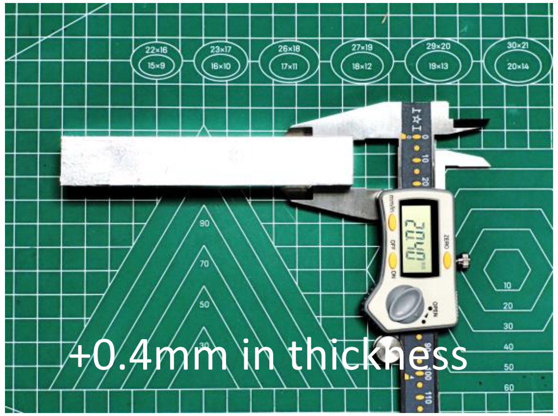
EM energy resolution



EM shower containment





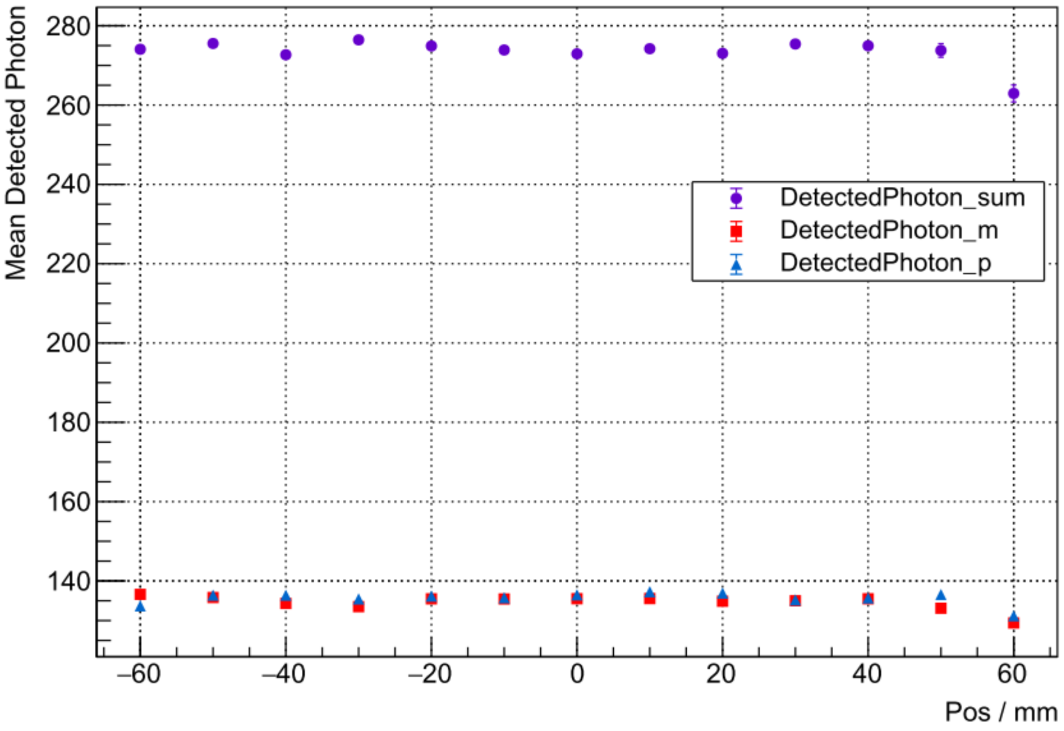


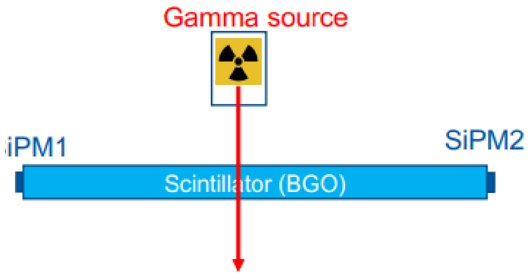
- Impact of gaps is significant
- Gaps for 12×2×2 cm^3 cm crystal: ~0.4 mm
- Control of gaps will be harder with longer crystals: key issue

Small-scale crystal-SiPM module design: uniformity scan

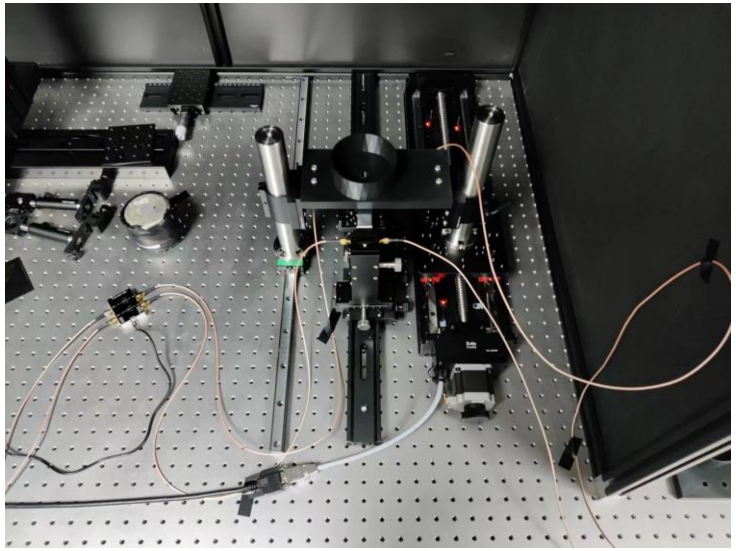
- Test stand for crystal quality control
  - Automated scan of BGO bars with 1D moveable stage

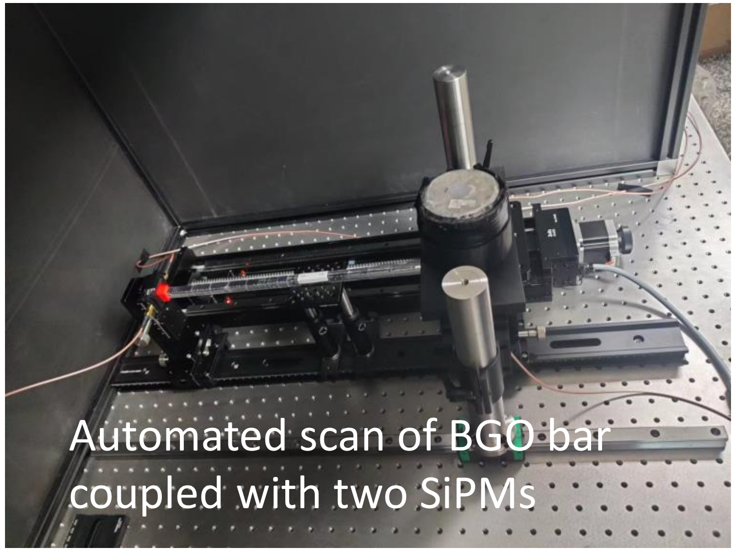
Response uniformity along 12 cm BGO bar





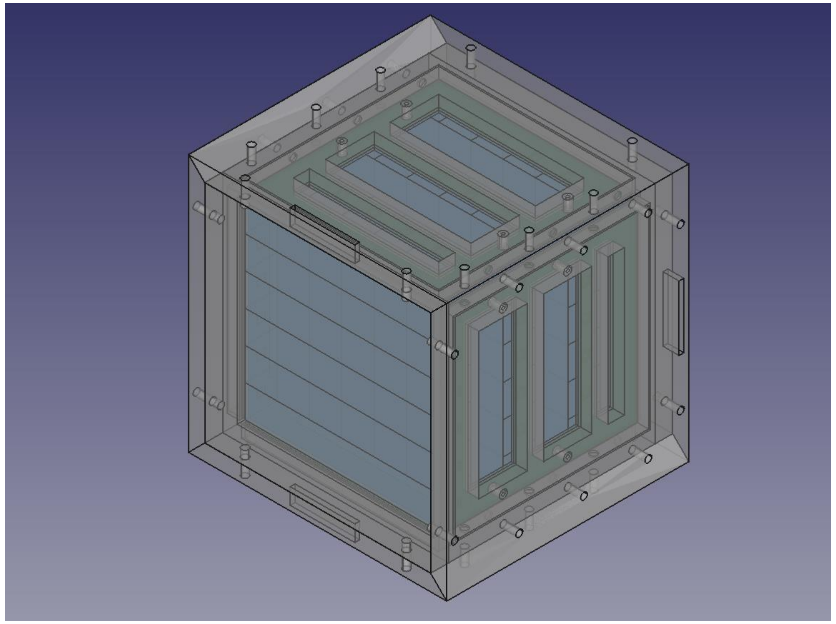
Preliminary results
- Difference along the bar generally <1% (source seems to be moved outside crystal at 60 mm)
- Difference of two ends <1%

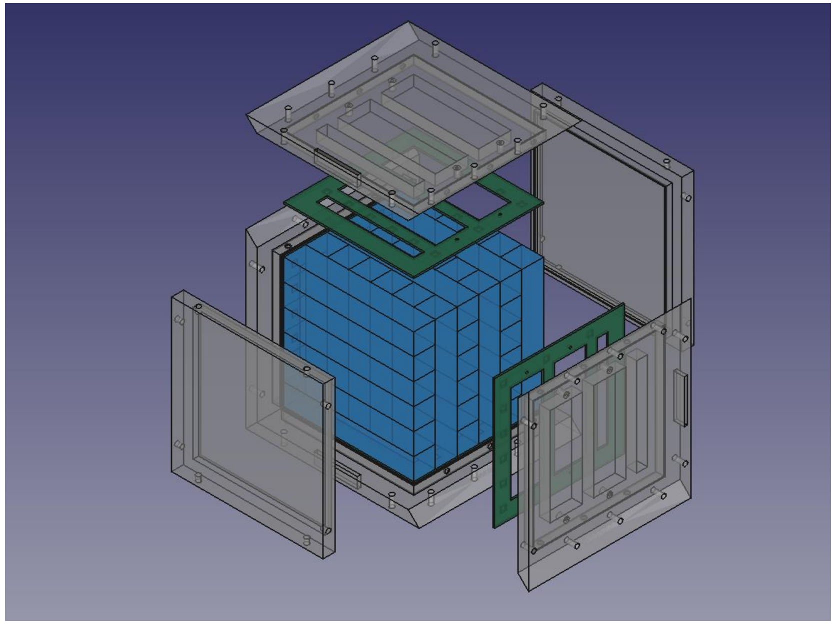


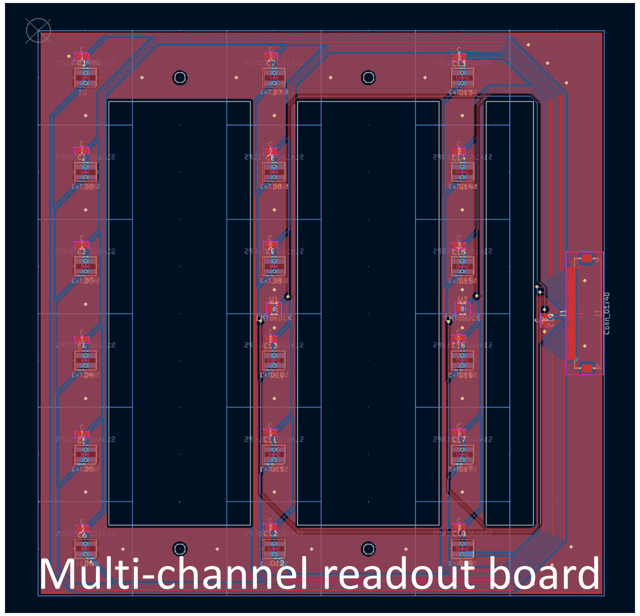


Small-scale module: mechanical design

- Mechanical structure and module assembly
  - Challenges: crystal weight, stable crystal-SiPM coupling
  - A first design draft of the cover and readout board
  - Plan to be exercised with dummy crystal bars, real PCBs and 3D printed cover







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

- Validation studies and further updates are ongoing
- Further issues:
  - Temperature monitoring and control
  - LED calibration
  - …

Summary & prospects

R&D of a highly granular crystal ECAL:

- Physics performance study: optimization of Arbor-PFA
- New reconstruction algorithm dedicated to crystal ECAL
- Hardware development
  - Key parameters: light yield, dynamic range,…
  - Small-scale module development: impact from gap, crystal uniformity, mechanical design,…

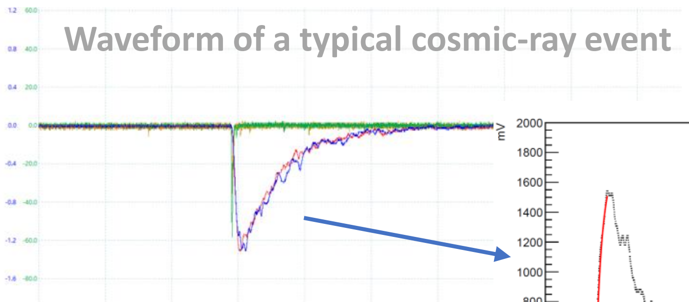
- Prospects
  - PFA optimizing and further simulation validations
  - System integration of the first small-scale EM module
  - Preparations for beam tests in 2023

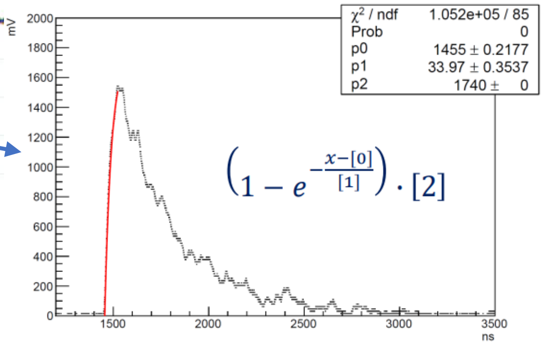
Backup

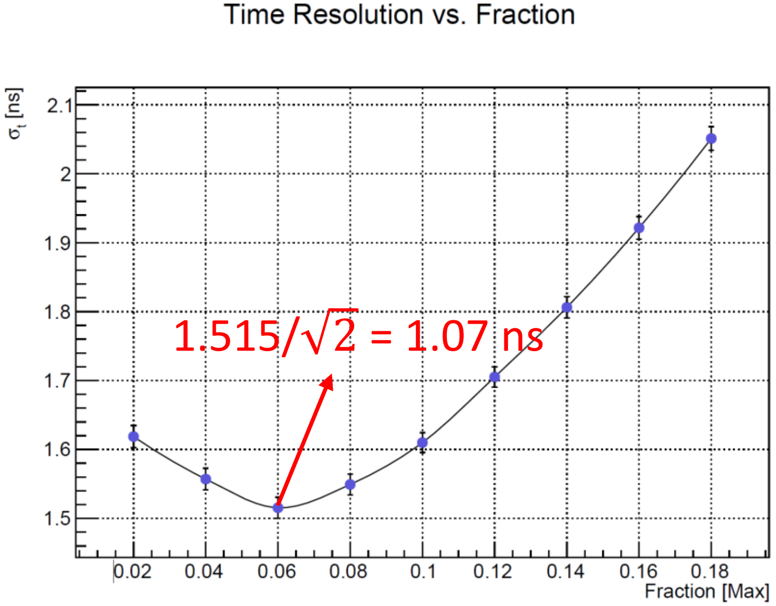
Latest progress on time resolution study

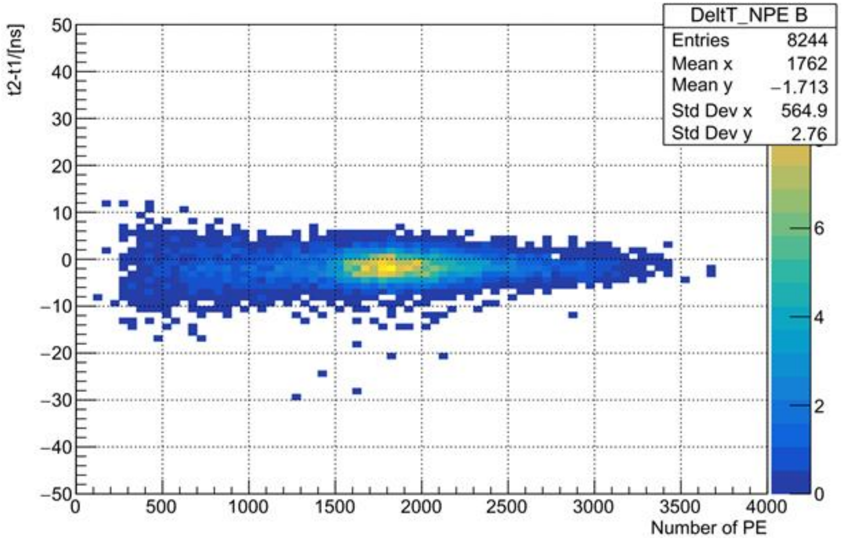
Zhiyu Zhao (SJTU)

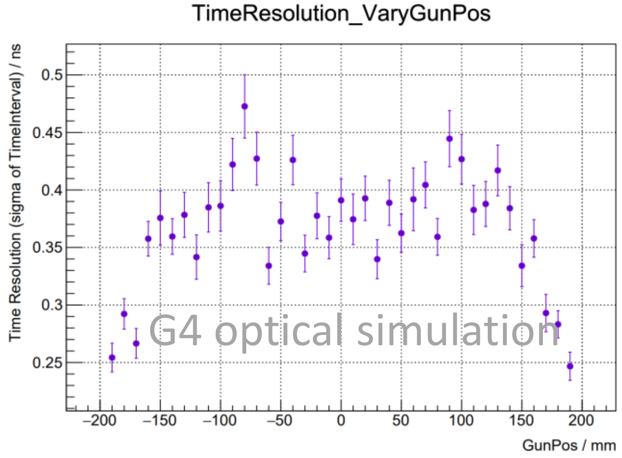
- Cosmic-ray events with 400 mm long crystal bar
- Fit the leading edge of SiPM signals
- Timing method: constant fraction











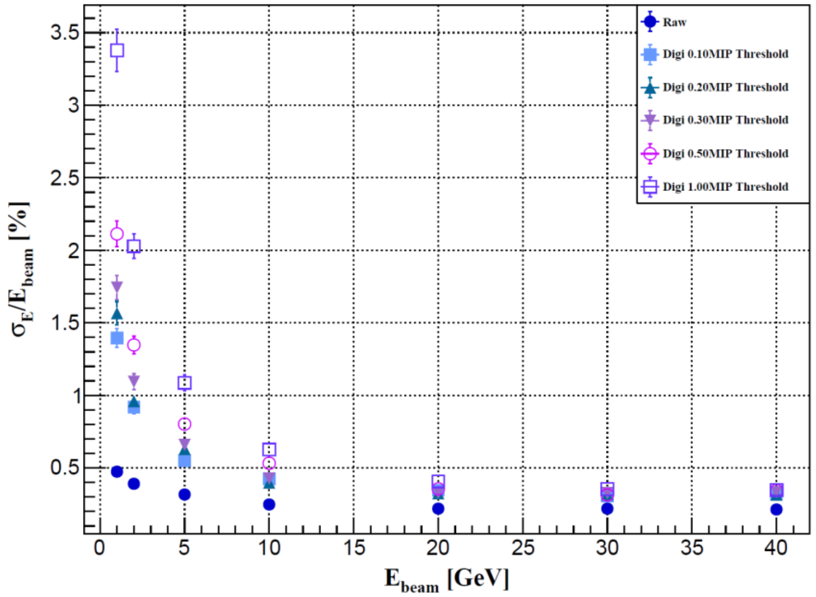
Expected time resolution in simulation: ~400 ps

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

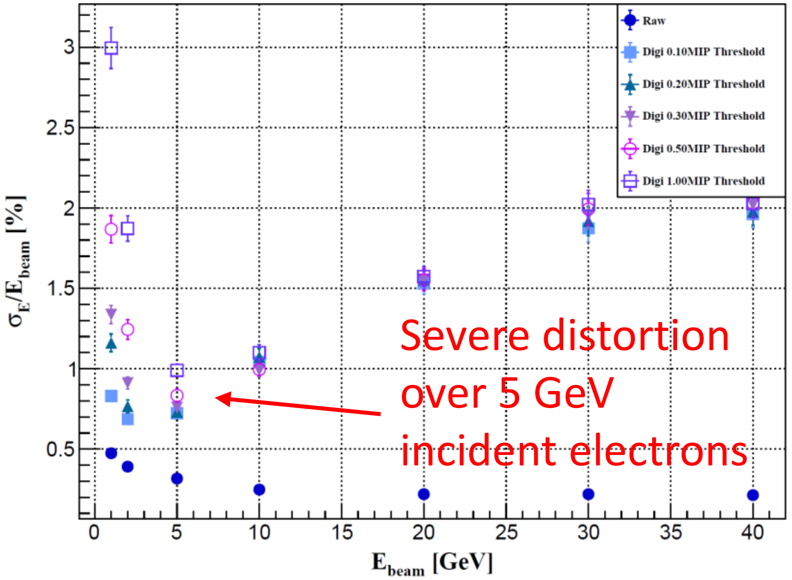
EM energy resolution: requirements on light yield

- Energy resolutions vary with energy thresholds and light yields (in number of detected photons per MIP)
  - Digitization: consider SiPM saturation (NDL SiPM with ~240,000 pixels)

Energy resolution under 100 p.e./MIP



Energy resolution under 1000 p.e./MIP



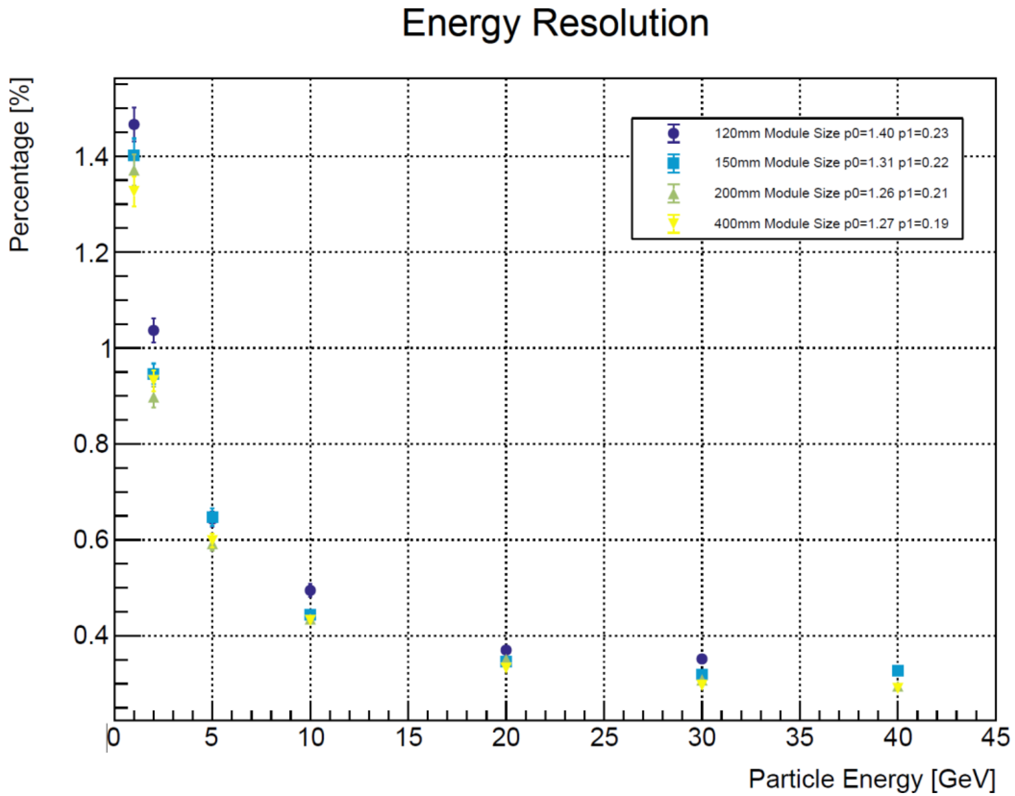
Energy Resolution at 40 GeV and 0.3 MIP threshold	
10 p.e./MIP	0.53%
20 p.e./MIP	0.44%
50 p.e./MIP	0.31%
100 p.e./MIP	0.33%
200 p.e./MIP	0.52%
500 p.e./MIP	1.17%
1000 p.e./MIP	2.02%

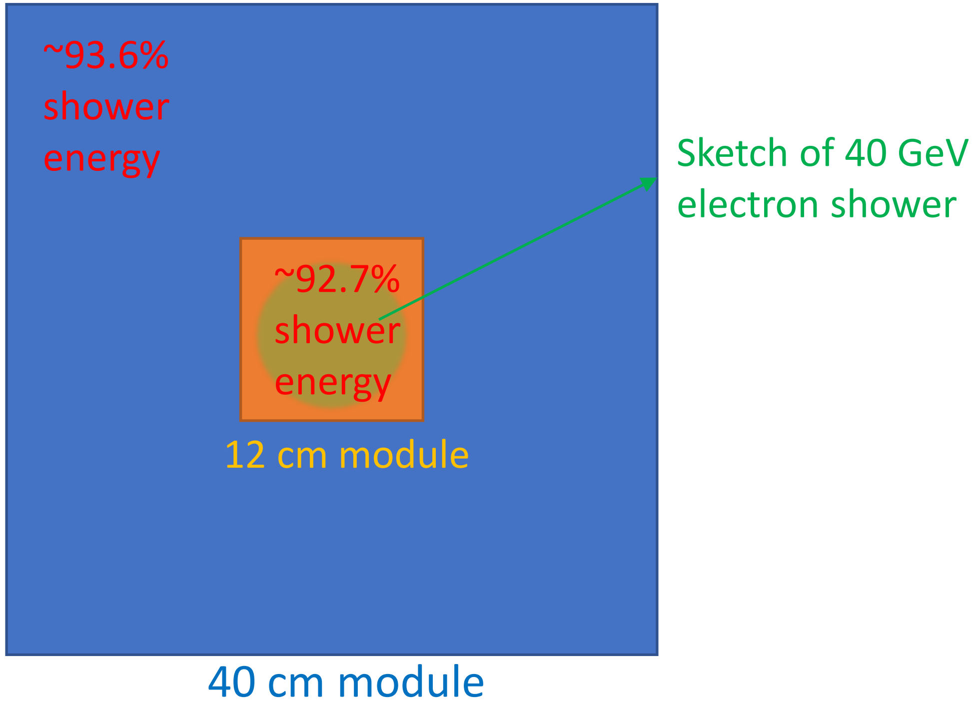
- Significant SiPM saturation effect observed
- Requirement on light yield: 200 detected photons per MIP seems feasible

The recovery time of SiPM pixels has not been considered here

Crystal-SiPM 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