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 activities and highlights

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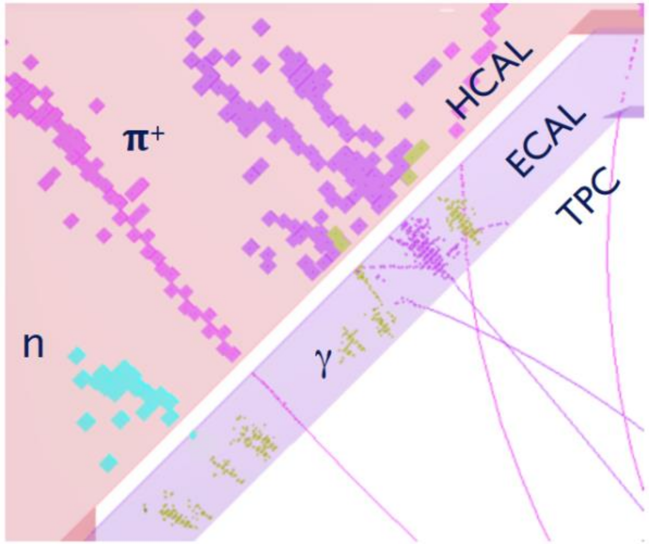
on behalf of the CEPC Calorimetry Working Group

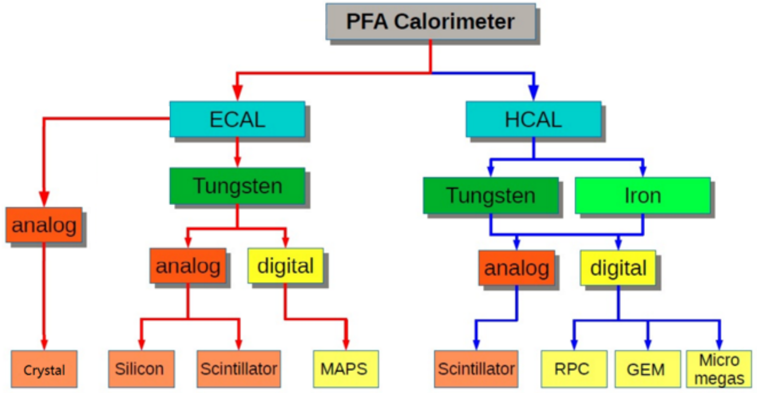
CEPC Day
Sep. 21, 2022

Motivations

- Calorimetry for future lepton colliders (e.g. CEPC, etc.)
  - Precision measurements with Higgs and Z/W
  - Jet energy resolution requires better than $30\%/\sqrt{E_{\mathrm{jet}}(\mathrm{GeV})}$
  - Particle flow paradigm: high-granularity calorimetry

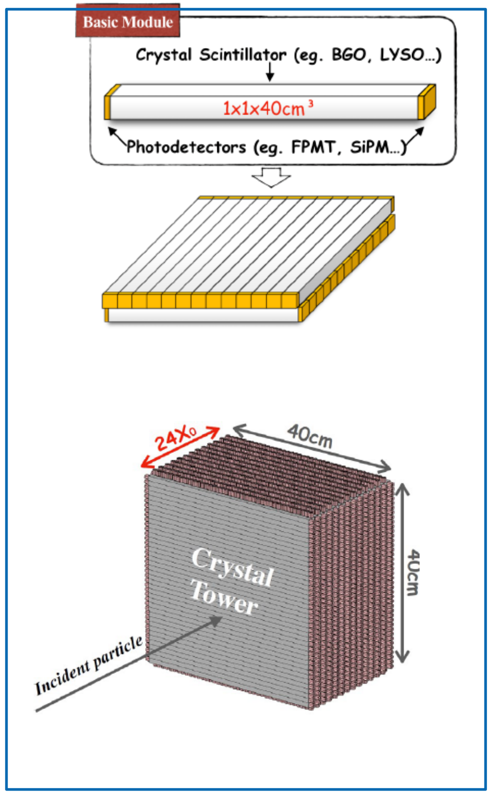
- Why crystal calorimeter?
  - Optimal EM energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
    - High sensitivity to low energy particles
    - Capability to trigger single photons
    - Precision γ/π^0 reconstruction: flavour and BSM physics
  - Fine segmentation: PFA capability for jets (3~4% resolution)

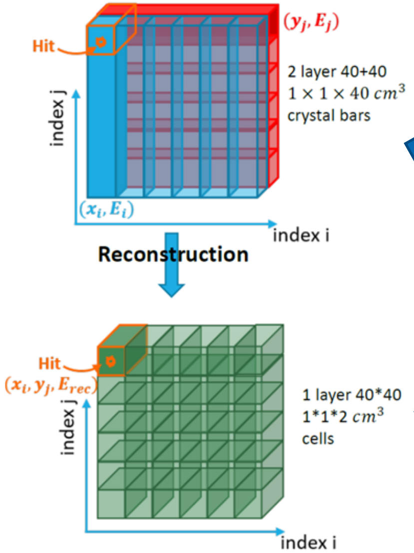




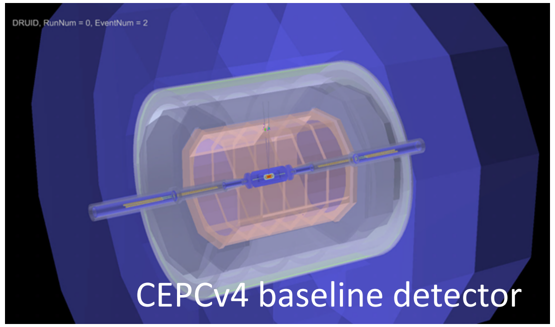
Crystal calorimeter: R&D overview

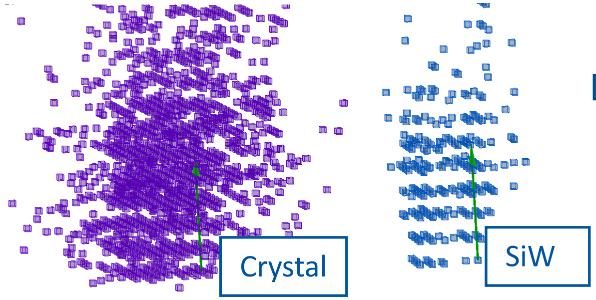
Collaborations within hardware, software and PFA/physics teams



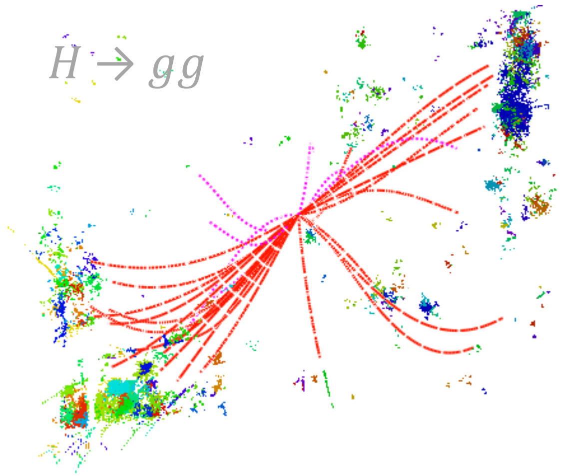


Crossed long bar design:
$1 \times 1 \times 2\ cm^3$ granularity
after digitization





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



Performance with jets from Higgs

Focused within this talk

Hardware development: key questions and specs

- New reconstruction software for long bars
- Arbor-PFA optimization for crystal ECAL

Physics performance evaluation: Higgs benchmarks (+ flavor physics)

Crystal ECAL hardware: key parameters

Highlights shown in this talk; other aspects in the backup

Specifications	Contributions to performance	Limiting factors
MIP light yield	• Energy resolution	• Crystal intrinsic properties • Geometry and surface treatment • Coupling with photosensor
Dynamic range	• Signal saturation • Small signal measurements	• SiPM non-linearity • Front-end electronics
Energy threshold	• Signal to noise ratio • Small signal measurements	• Noises of SiPM and FE-electronics
Timing resolution	• Positioning precision • PID potentials to improve clustering	• Scintillation time of crystal • Time resolution of SiPM + electronics • Power consumption
Response uniformity	• Energy linearity and resolution	• Crystal intrinsic properties + foil • Calibration precision

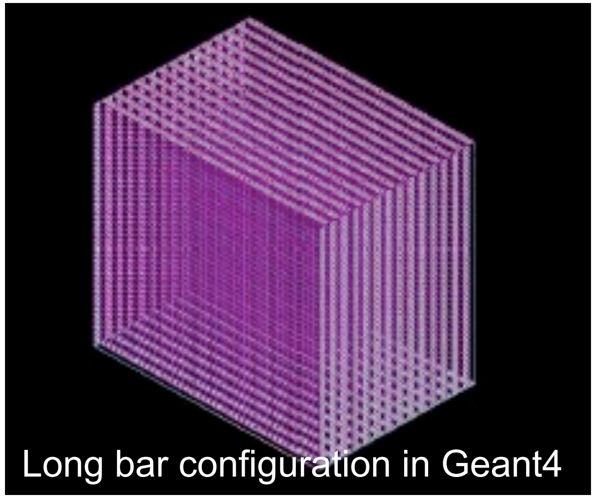
Requirements of a crystal-SiPM detector unit

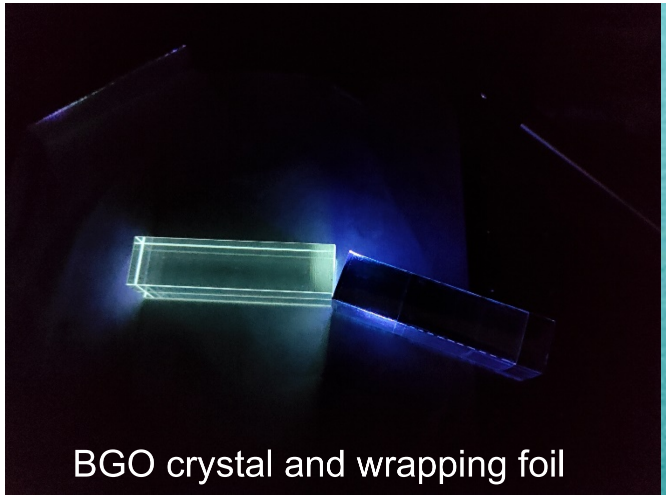
- Key issues at system level
  - Crystal tolerances and gaps
  - Mechanical structure
  - Temperature control and monitor

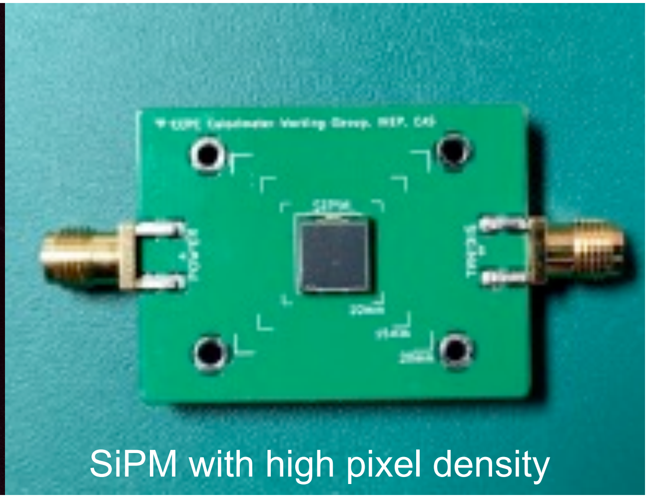
Development of small-scale crystal-SiPM modules

Crystal ECAL hardware activities

- Requirements of a single crystal-SiPM detector unit
  - Key parameters: MIP light yield, dynamic range, timing resolution, etc.
- Development of small-scale crystal-SiPM modules
  - Impacts of transverse size, gaps
  - Crystal quality test stand: crystal uniformity
  - Mechanics design and module assembly

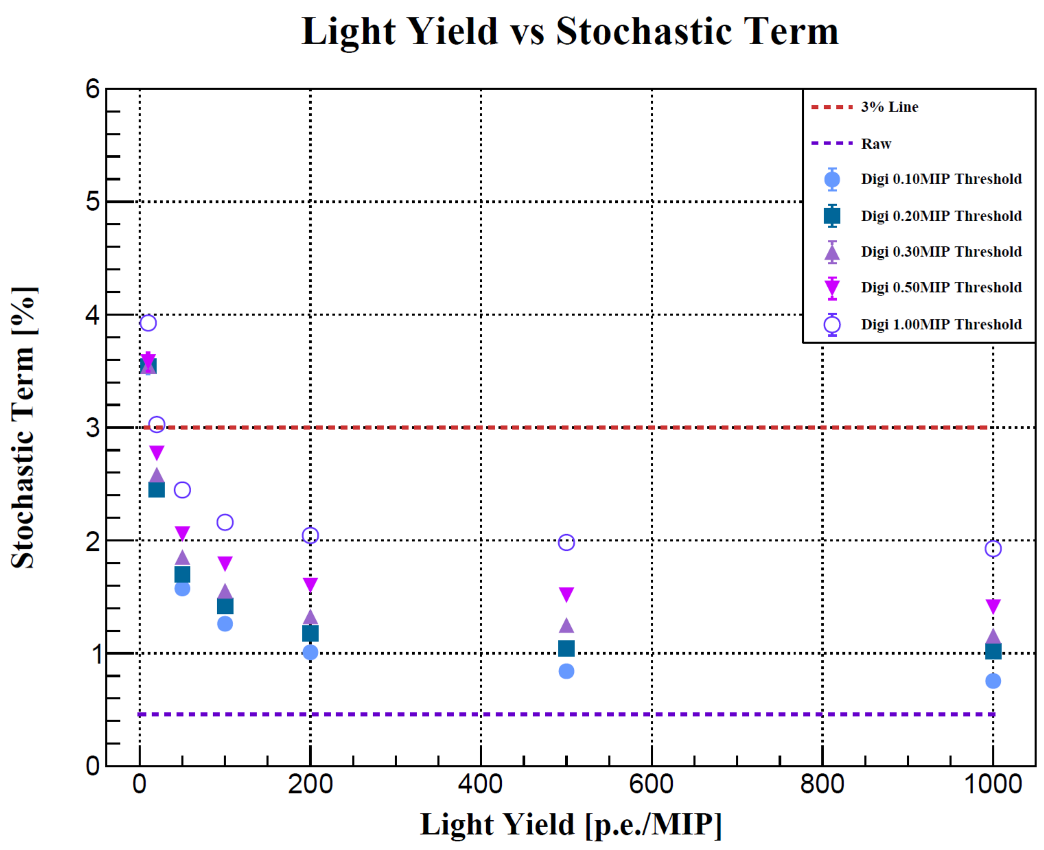

Long bar configuration in Geant4


BGO crystal and wrapping foil

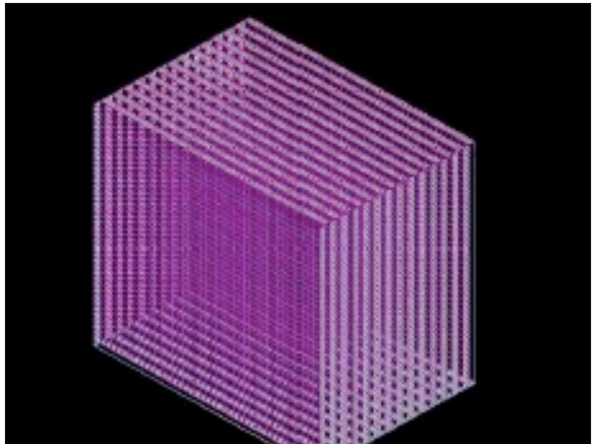

SiPM with high pixel density


SiPM readout electronics

EM energy resolution vs. light yield



Simulation: 40×40×28cm tower (BGO long bars) with 1~40 GeV electrons
Digitization: including Poisson photon-statistics, SiPM gain uncertainty, ADC precision, but excluding SiPM and electronics non-linearity effects

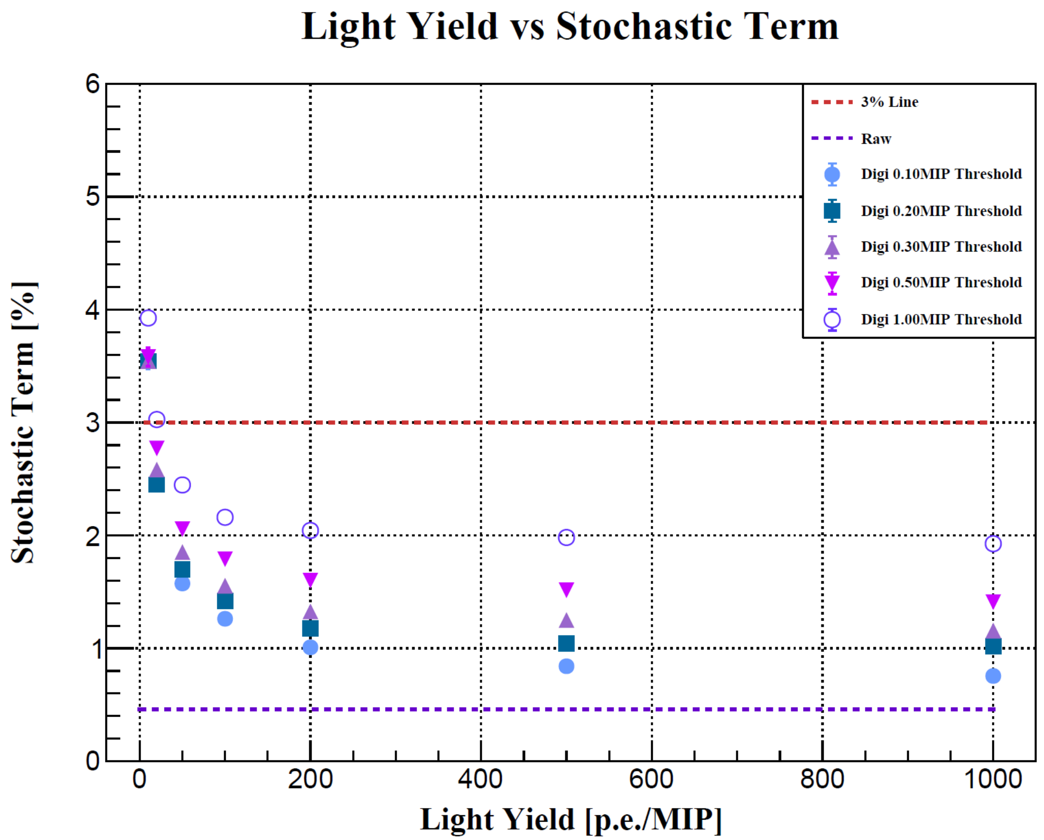


Long bar configuration in Geant4

- Light yield is defined
  - #p.e. detected by SiPM for one MIP per channel
- Electromagnetic shower energy resolution
  - Stochastic term extracted
  - Impacts from energy threshold (per channel)
  - Good resolution requires
    - Moderately high light yield ➔ dynamic range
    - Low energy threshold ➔ noise level

EM energy resolution vs. light yield

Baohua Qi (IHEP)



Simulation: 40×40×28cm tower (BGO long bars) with 1~40 GeV electrons
Digitization: including Poisson photon-statistics, SiPM gain uncertainty, ADC precision, but excluding SiPM and electronics non-linearity effects

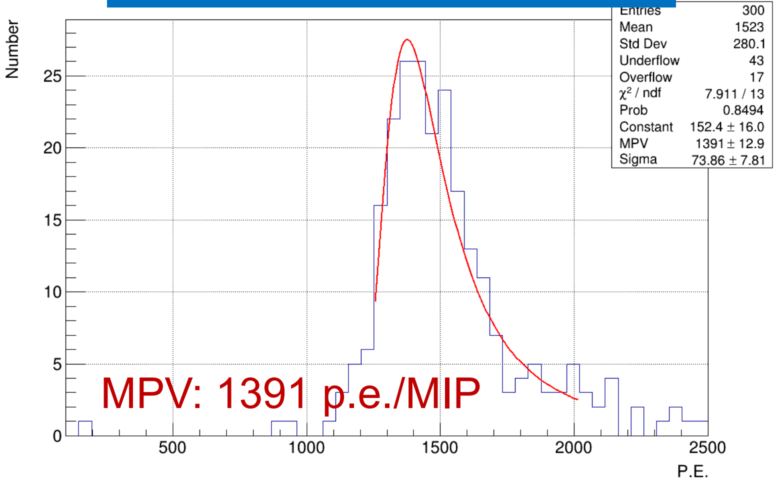
- Light yield: #p.e. detected by SiPM per MIP per channel
- EM energy resolution
  - Impacts from energy threshold (per channel)
  - Requires moderately high light yield and low threshold
- Conclusions on requirements
  - Light yield of ~200 p.e./MIP per channel (2 SiPMs)
    - $\sigma_E/E < 1.5\%/\sqrt{E(GeV)}$
    - Plateau region: headroom for other limitations
    - Balance between light yield and dynamic range
  - Light yield required for a SiPM: ~100 p.e./MIP
    - Beneficial to achieve a low energy threshold, mostly determined by SiPM and electronics noises

Cosmic-ray test: MIP response of BGO crystal

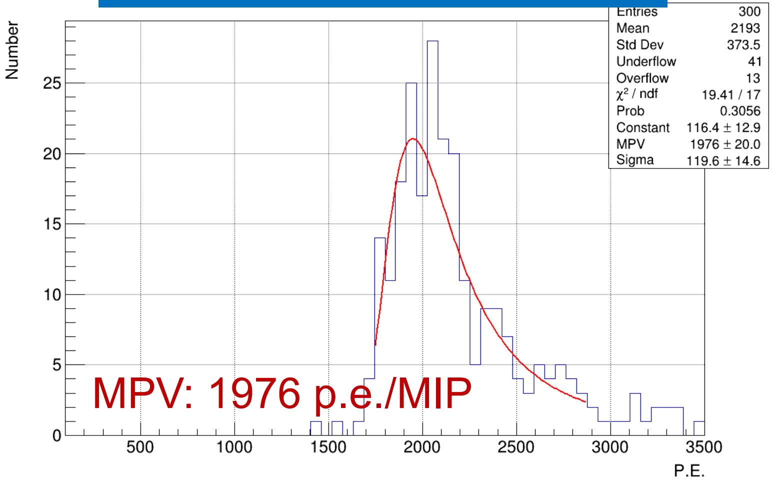
Baohua Qi (IHEP)

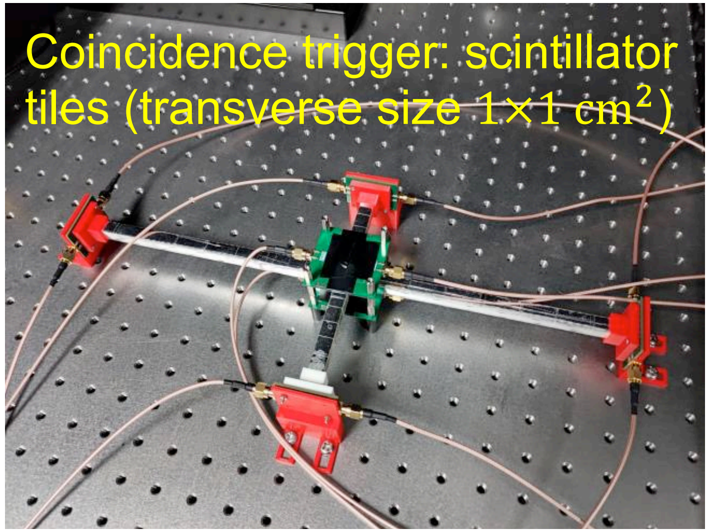
- Cosmic-ray measurements of crystal-SiPM units
  - Two BGO bars: 40cm,16 cm in length; transverse $1\times1\ \mathrm{cm}^2$
- MIP light yield is higher than the requirements

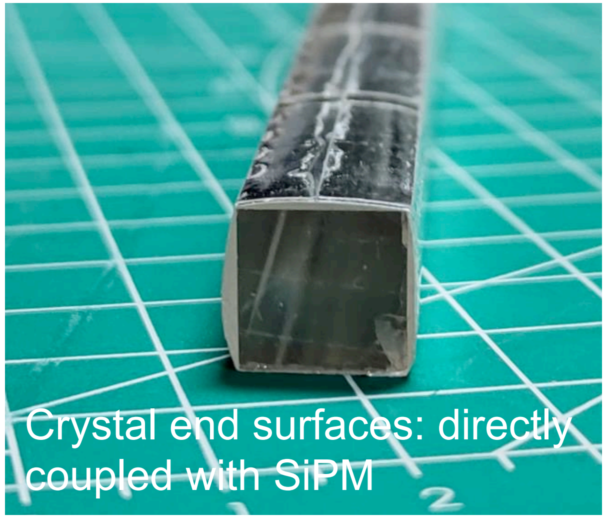
40 cm long BGO + 6╳6 mm² SiPM



16 cm long BGO + 6╳6 mm² SiPM





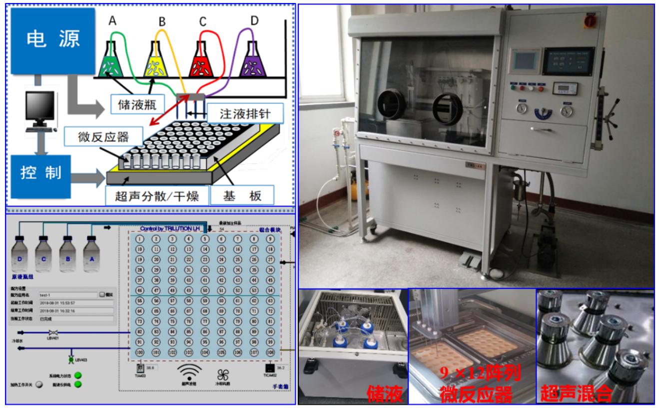


- Proposed solutions
  - Smaller SiPMs: $3\times3\ \mathrm{mm}^2$, pixel pitch $6\mu m/10\mu m$ (ongoing)
  - “Tune” BGO intrinsic light yield by doping (SIC-CAS)

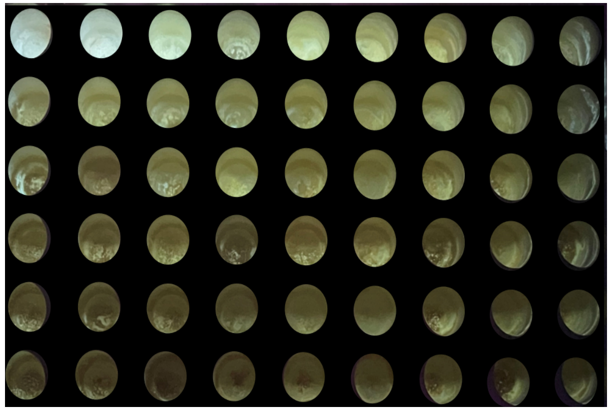
Status of new BGO crystal development at SIC

Dr. Junfeng Chen (SIC)

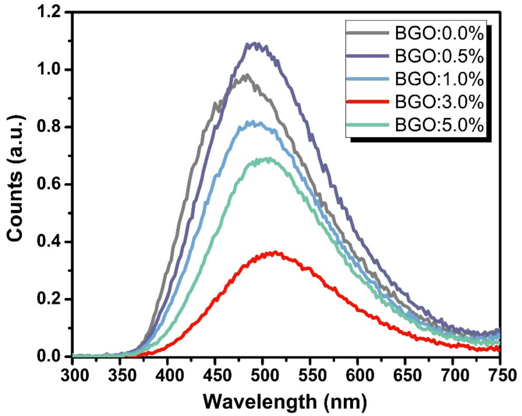
- Motivation: to reduce BGO intrinsic light yield (optimization for a wide dynamic range)



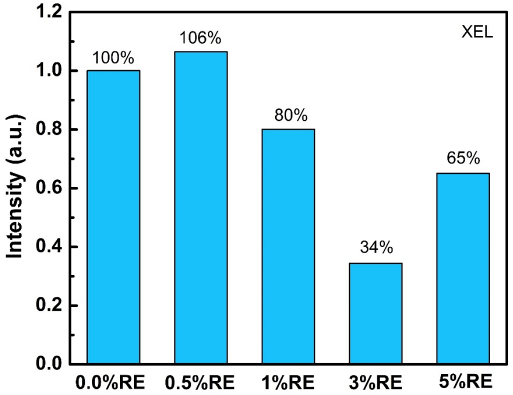
A fast combinatorial design and screening method to optimize the doping concentration



A in-situ luminescence picture of a BGO:RE library under UV excitation



Radioluminescence spectra of as-prepared BGO: RE powers



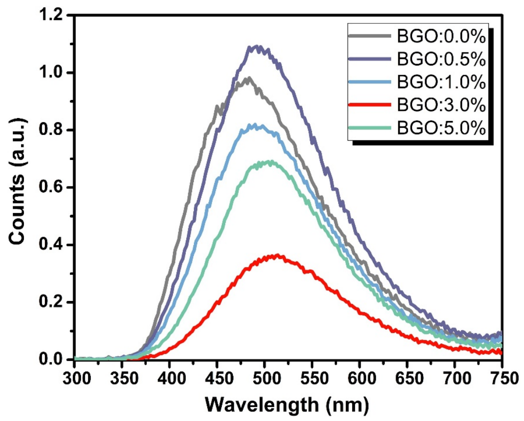
Integral intensity of BGO powers 0-5% RE doping concentration

Results of first-round unsuccessful growth experiment of BGO crystals with different RE doping concentration

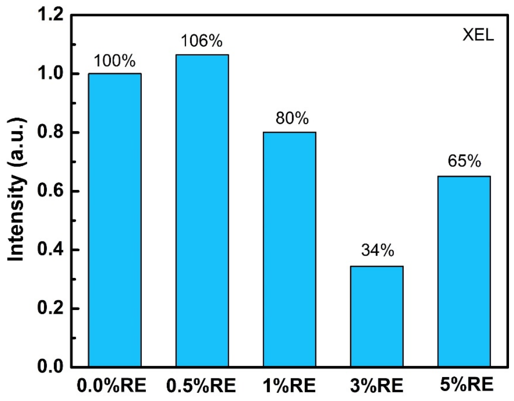
Status of new BGO crystal development at SIC

Dr. Junfeng Chen (SIC)

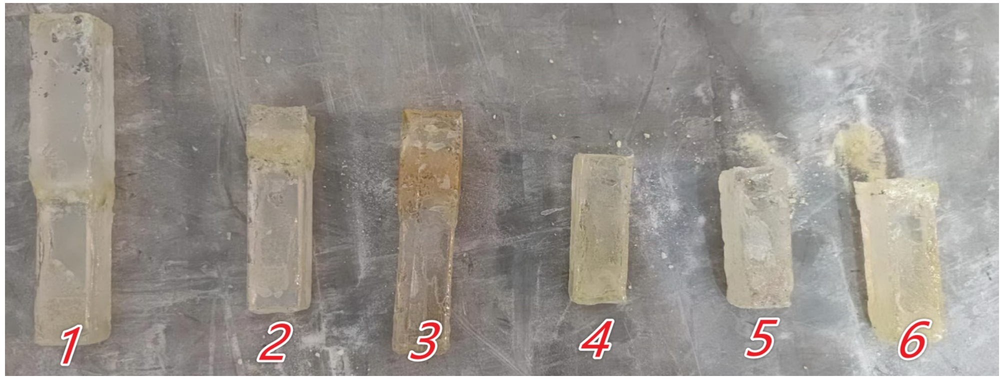
- Ongoing R&D efforts: to "tune" the BGO light output by RE doping



Radioluminescence spectra of as-prepared BGO: RE powers



Integral intensity of BGO powers 0-5% RE doping concentration



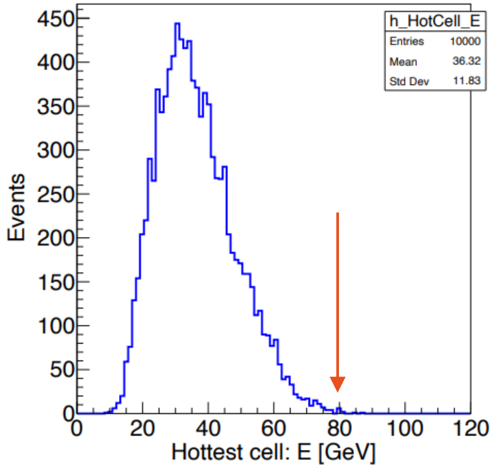
- ➢ A fast combinatorial design and screening method is taken to fasten R&D progress previous to crystal growth
- ➢ The radioluminescence intensity of BGO:3%RE power is reduced to **34%** that of pure BGO powder
- ➢ First-round BGO:RE crystal growth experiment was an unsuccessful one
- ➢ Next round experiments will follow

Dynamic range requirements

- Physics driving the dynamic range requirement
  - $e^+e^- \rightarrow ZH \rightarrow qqgg$ (4 jets): mean of 40 GeV, majority < 80 GeV
  - $H \rightarrow \gamma\gamma$ (Higgs physics) and Bhabha (energy calibration): 100-120 GeV
- 120 GeV electrons within $40{\times}1{\times}1\ \mathrm{cm}^3$ bars
  - Max. energy deposition in a single crystal bar is ~10 GeV

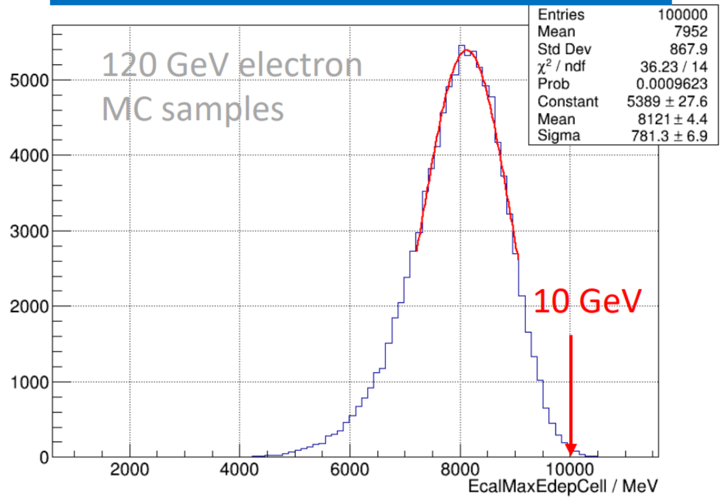
  $\rightarrow$ less than 10% shower energy

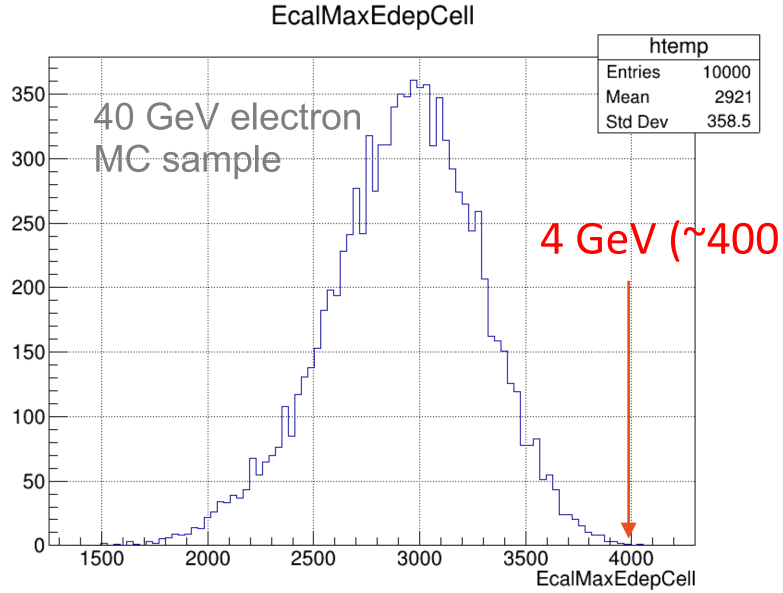
Max. energy within a tower



[Talk](#) by Yuexin Wang (IHEP)

Maximum energy deposition within a bar



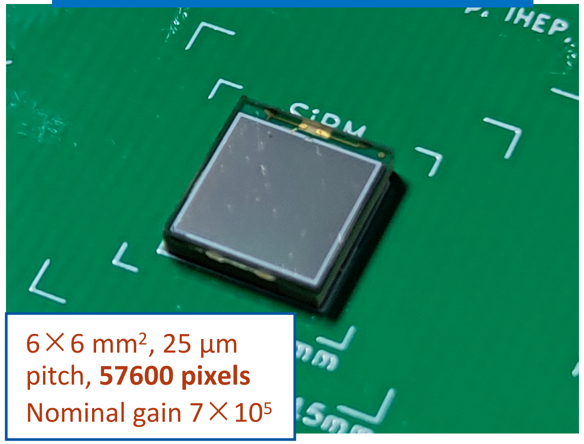


SiPM dynamic range studies

Zhiyu Zhao (SJTU)
Baohua Qi (IHEP)

- SiPM candidates with high pixel density

HPK S13360-6025PE

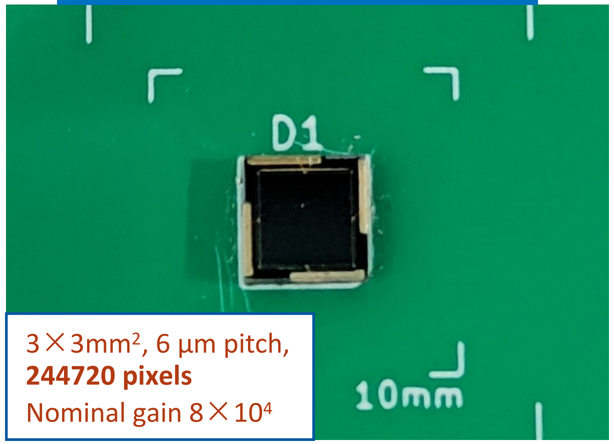


6×6 mm², 25 µm pitch, **57600 pixels**
Nominal gain 7×10^5

HPK S14160-3010PE

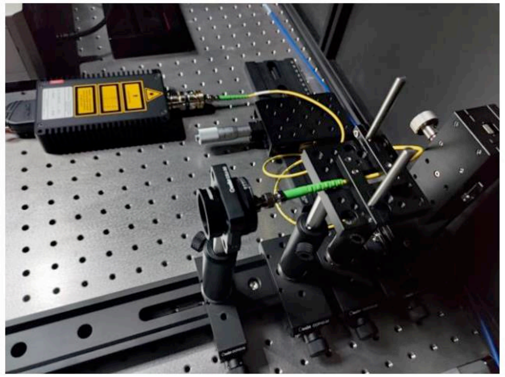
3×3 mm², 10 µm pitch, **89984 pixels**
Nominal gain 1.8×10^5

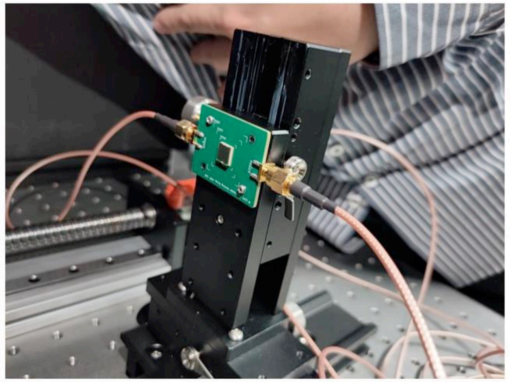
NDL EQR06 11-3030D-S



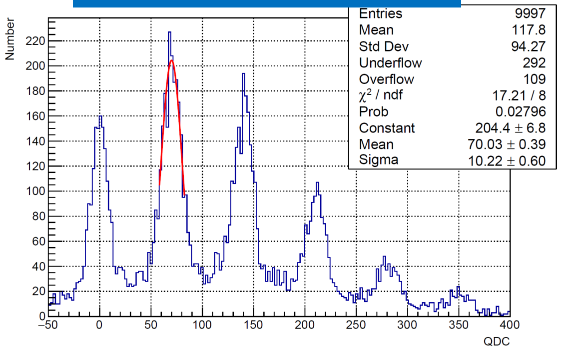
3×3mm², 6 µm pitch, **244720 pixels**
Nominal gain 8×10^4

- Test stand with pico-second laser





HPK S13360-6025PE



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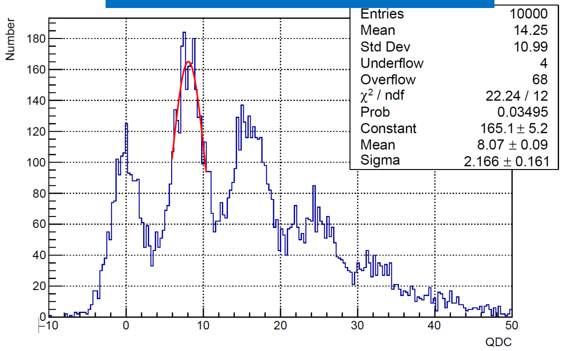
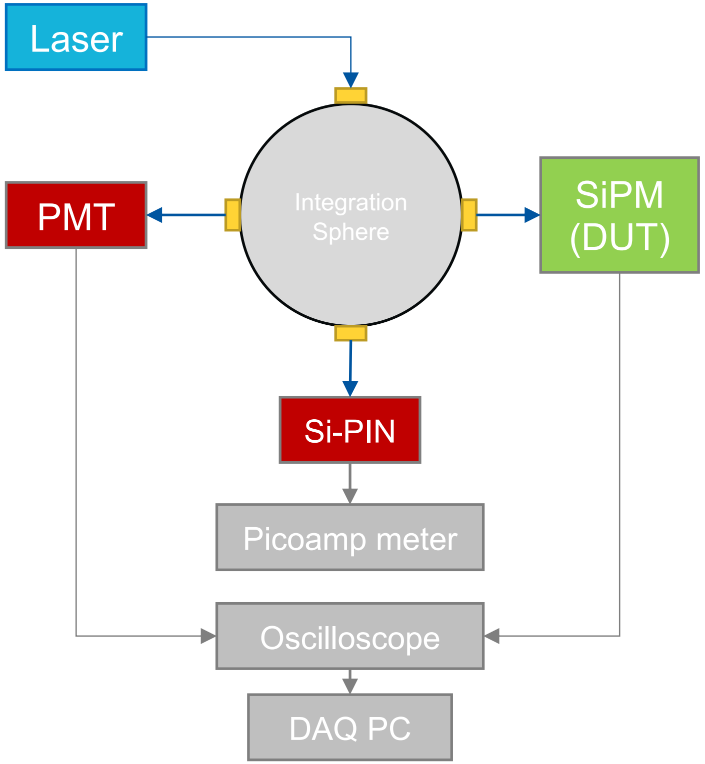
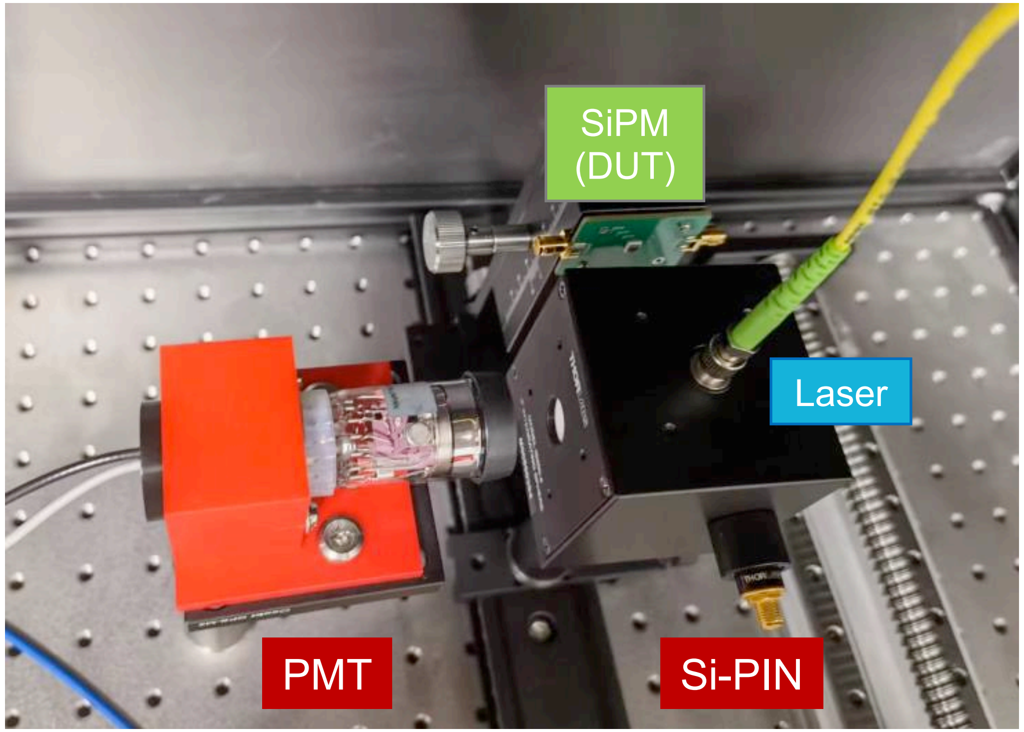


Single Photon Calibration

SiPM dynamic range studies

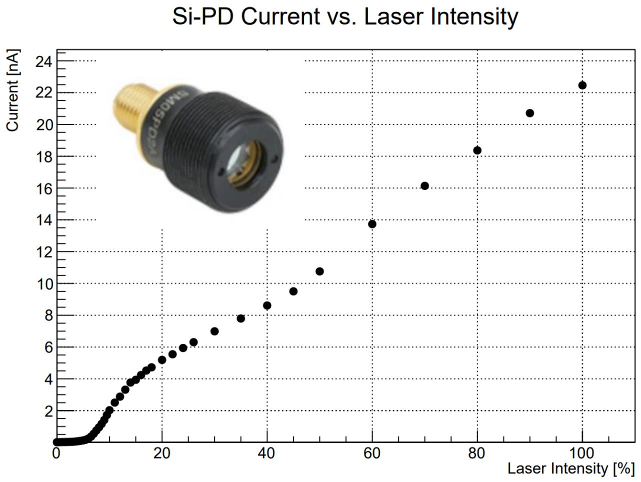
- Setup-I with pico-second laser (405nm)
  - Integration sphere: uniform distribution of light intensity
  - Reference photosensors: PMT and Si-PIN diode

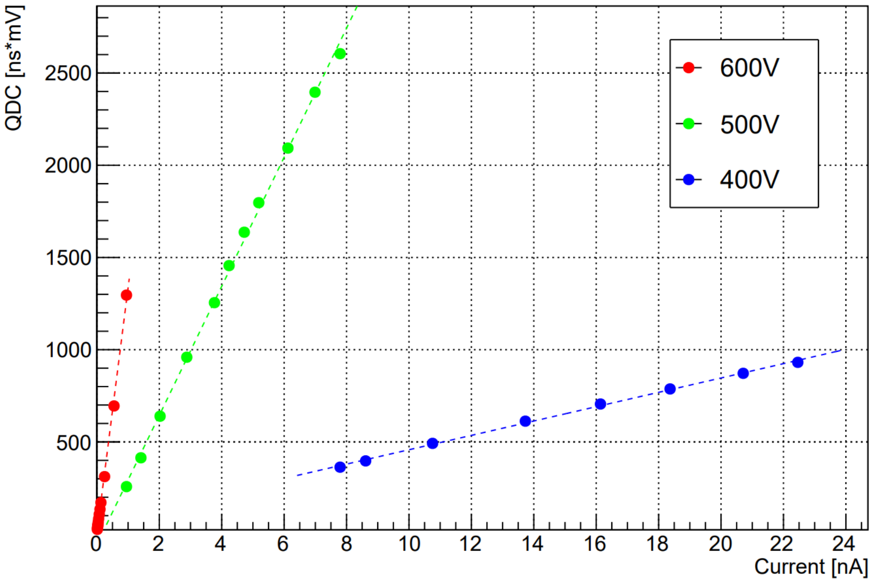


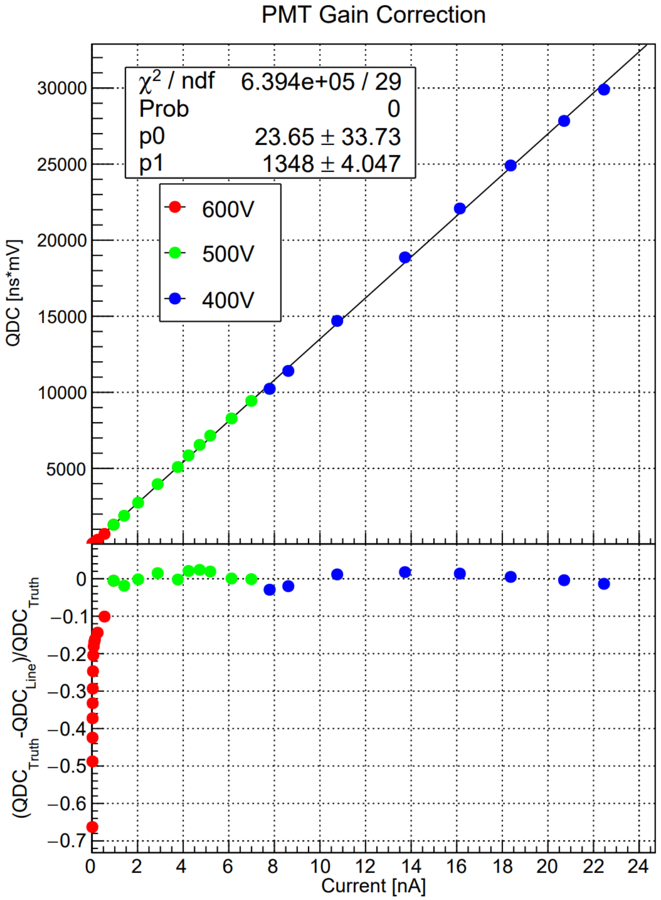


Si-PD and PMT inter-calibration

Laser Calibration with Si-PD

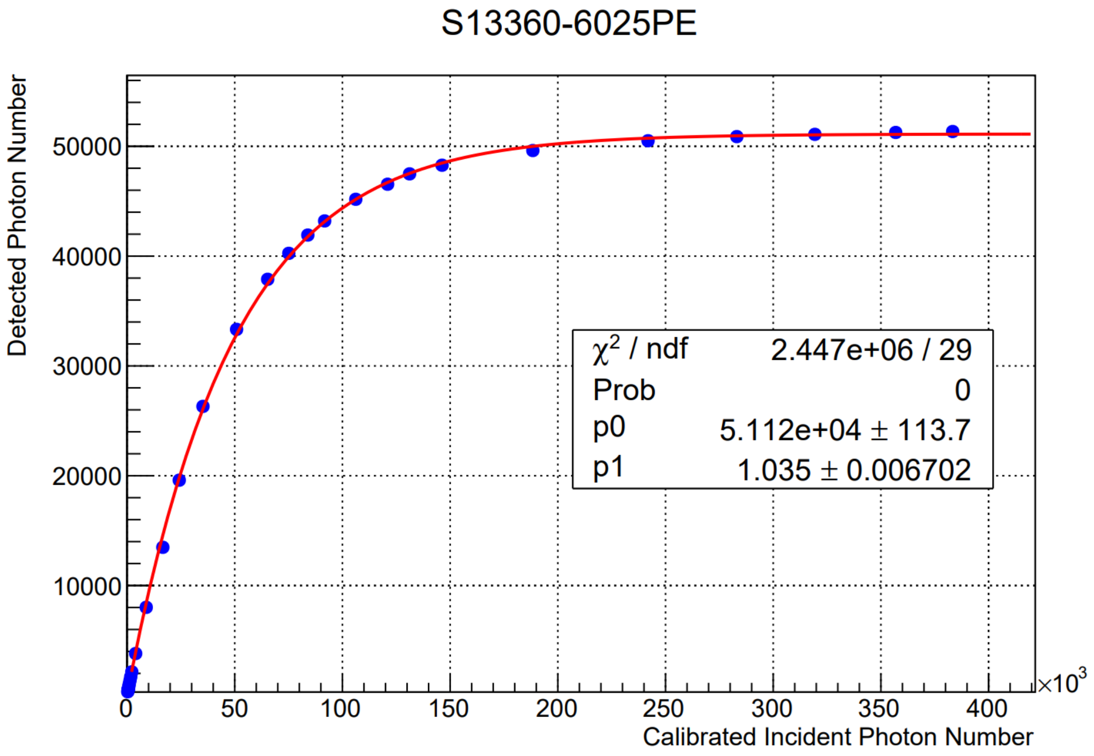




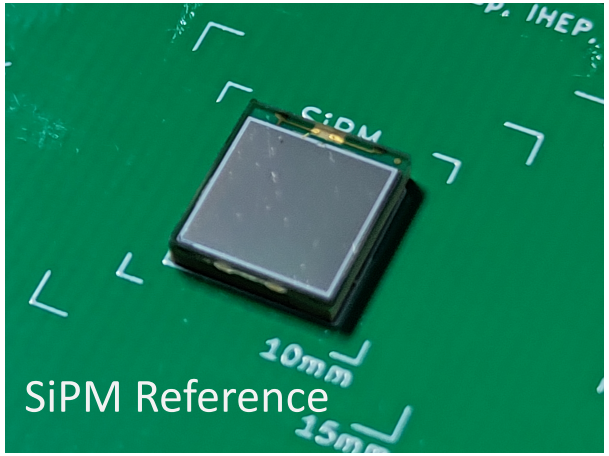


- Varying PMT bias voltage to cover different regions of light intensity
  - PMT response linearity is carefully selected
  - Less than 5% non-uniformity for most intensity regions
    - Uniformity degrades with low light intensity: due to the low Si-PD sensitivity

SiPM response non-linearity measurements

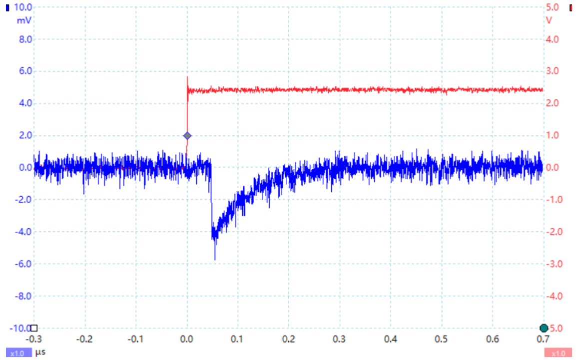


Hamamatsu S13360-6025PE



- Sensitive area: 6×6 mm^2
- 25 µm pixel pitch
- 57600 pixels in total
- Nominal gain: 7×10^5

Typical single-photon pulse

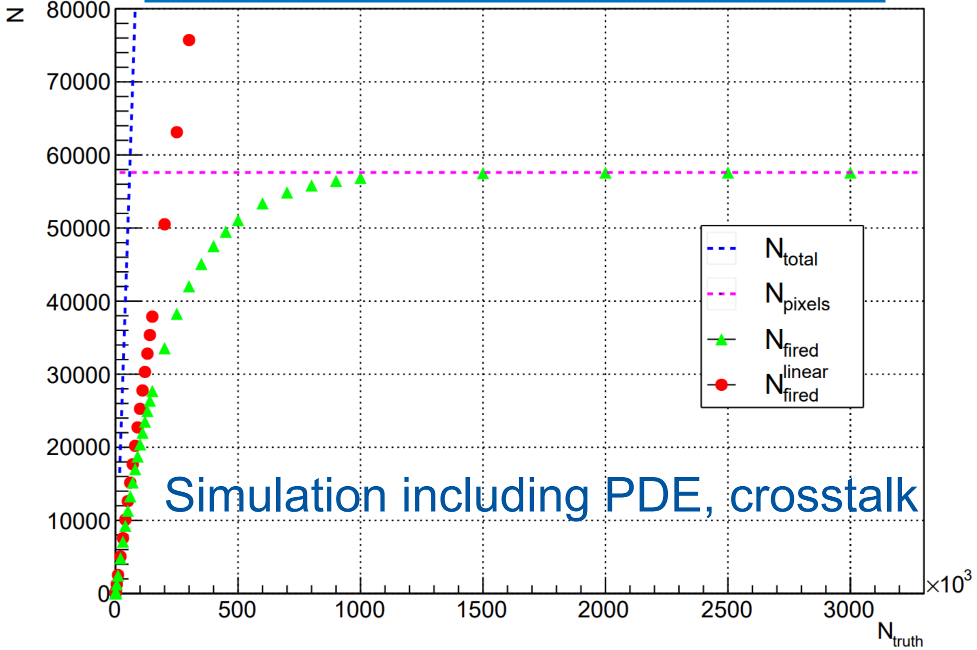


- SiPM pixels can be recovered within ~200ns for this type
  - Pico-second laser ensures no impact of pixel recovery (more effective pixels)
- Saturation plateau region: 5.11×10^4 pixels (slightly less than nominal 5.76×10^4 pixels)

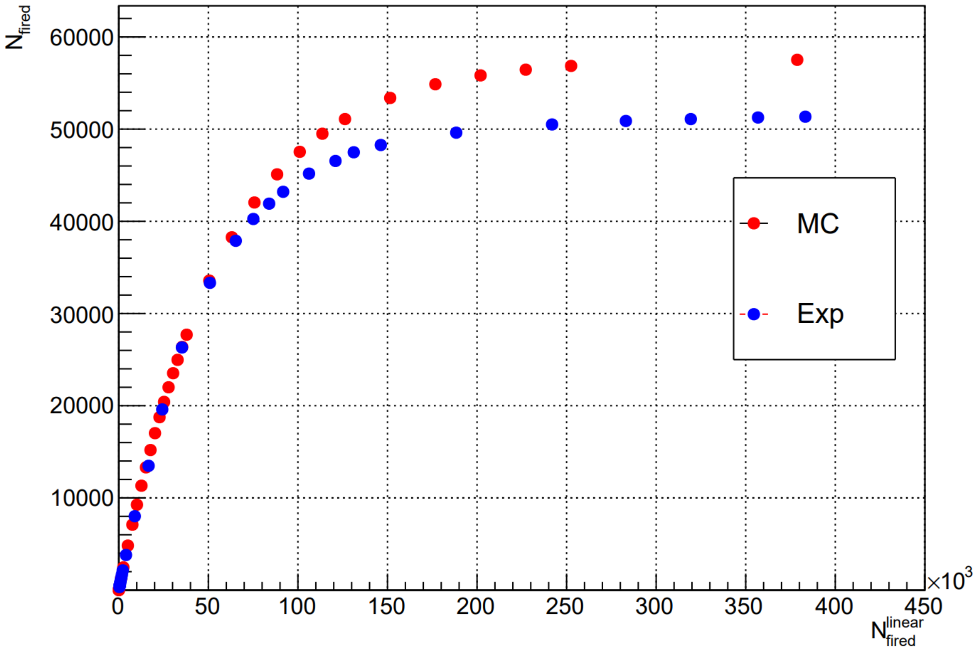
SiPM response non-linearity: simulation vs. data

Zhiyu Zhao (SJTU)

MC simulation for SiPM saturation



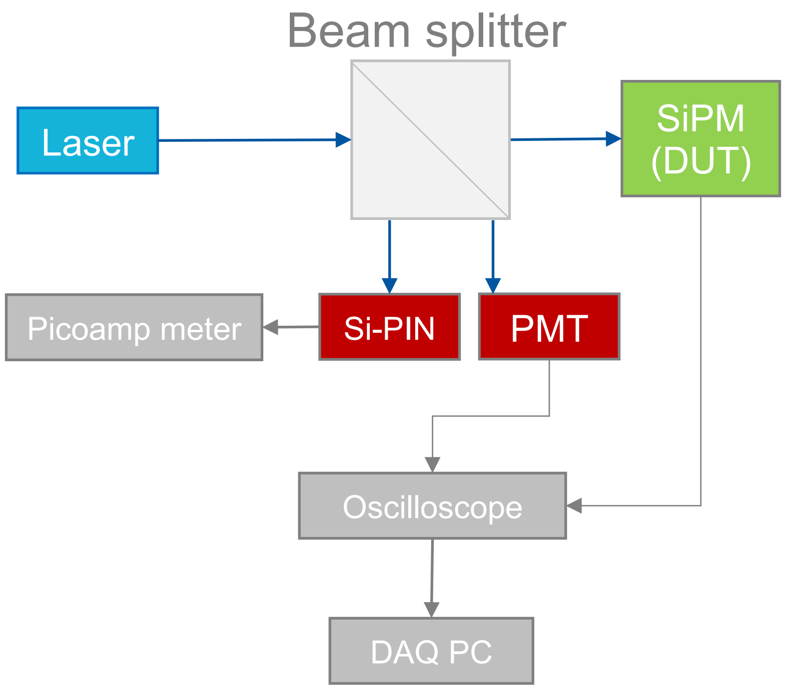
Comparison: simulation and data

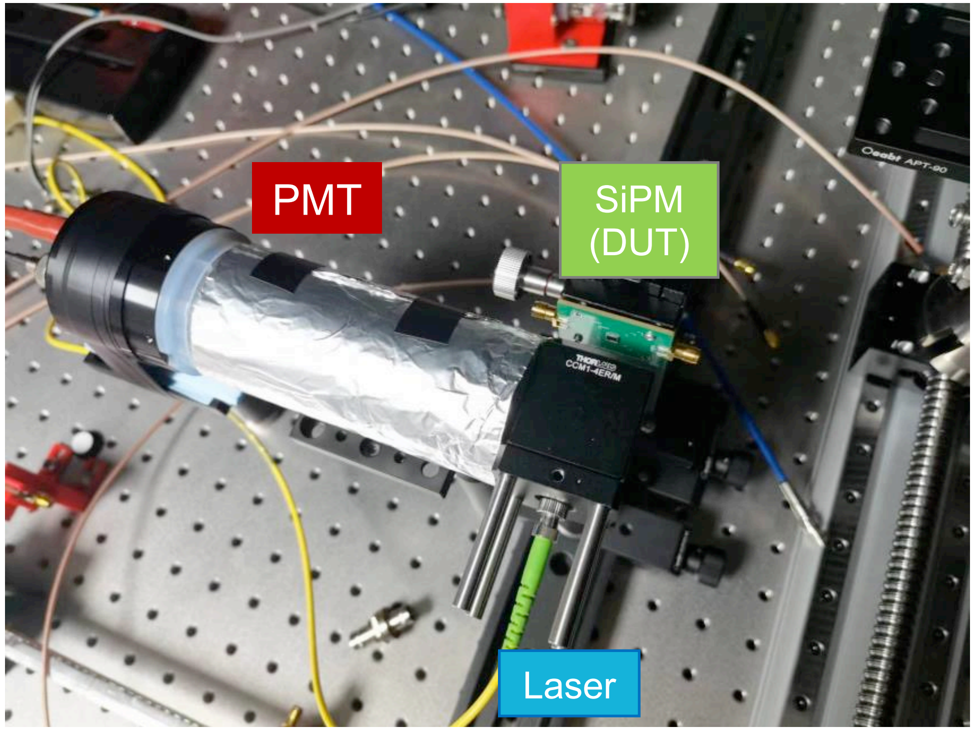


- Saturation region: noticeable discrepancy between simulation and data
- Very interesting results → further investigations
  - SiPM temperature monitoring and correction (→SiPM breakdown voltage)
  - Laser intensity: long-term stability (→ power-meter monitoring)
  - Large SiPM current: possible limitation from readout electronics?

SiPM dynamic range studies

- Setup-II with a pico-second laser (405nm)
  - Used a beam splitter to achieve much higher light intensity
    - Required by SiPMs with higher pixel density
    - As integration sphere significantly reduces the laser intensity
  - Reference photosensors: PMT and Si-PIN diode

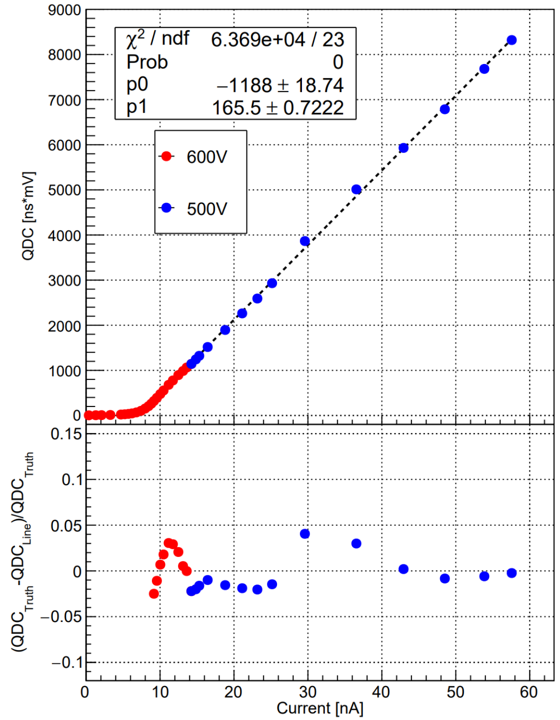


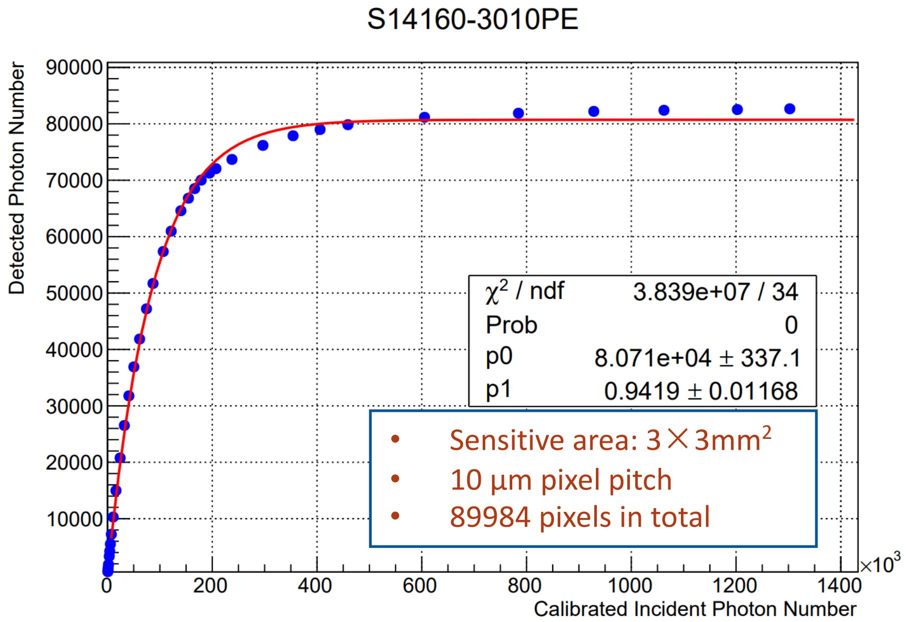


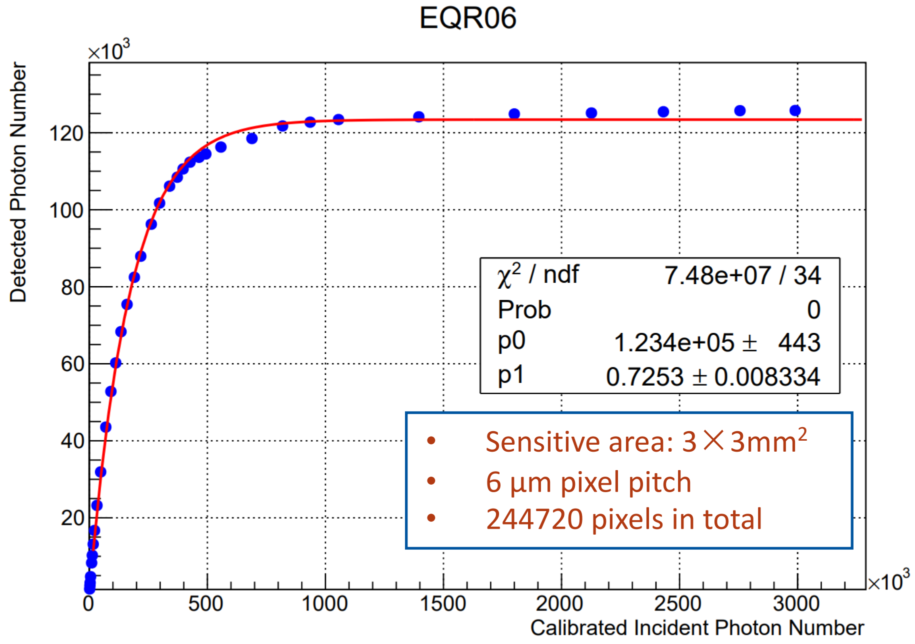
SiPM response non-linearity measurements

Zhiyu Zhao (SJTU)

PMT vs. Si-PD intercalibration







Saturation plateau: $\sim 8.1\times10^4$ pixels
Nominal: $\sim 9.0\times10^4$ pixels

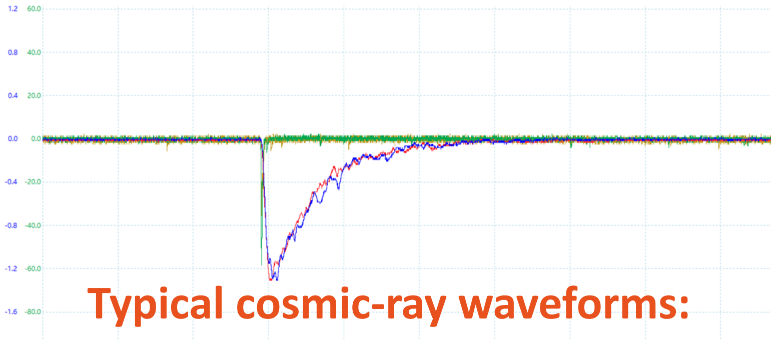
Saturation plateau: $\sim 1.2\times10^5$ pixels
Nominal: $\sim 2.4\times10^5$ pixels

- First studies on SiPMs with extremely high pixel density
  - Observed significantly less pixels than expected → further investigations
- Ongoing discussions with the BNU-NDL team
- Setup upgrade plans: PMT multi-dynode readout, SiPM readout circuit, high-power LED

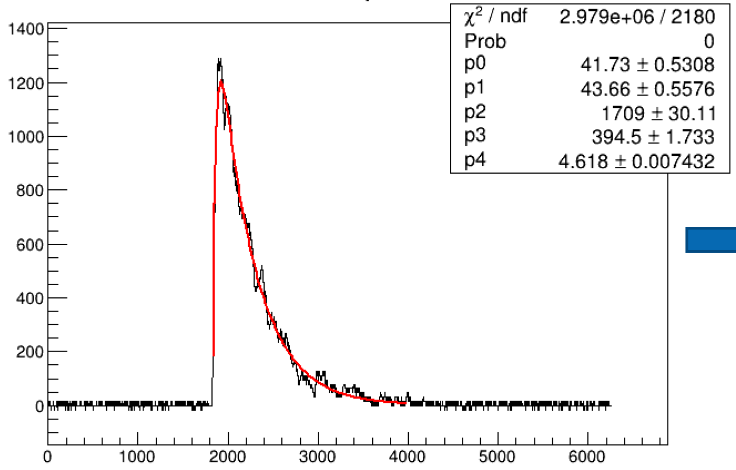
BGO-SiPM: timing performance studies

Zhiyu Zhao (SJTU)
Baohua Qi (IHEP)

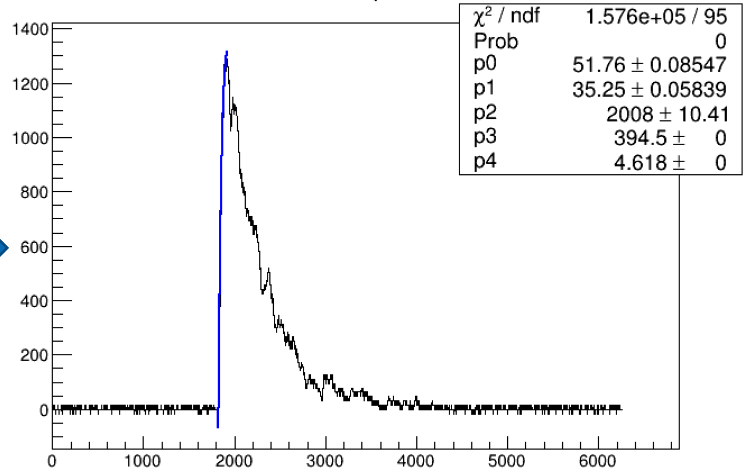
- **Cosmic-ray events** with 40 cm long crystal bar
- Timing methods
  - Conventional: Constant Fraction Discrimination (CFD)
  - Waveform sampling and leading edge fitting
- Waveform fitting significantly better than CFD (in backup)



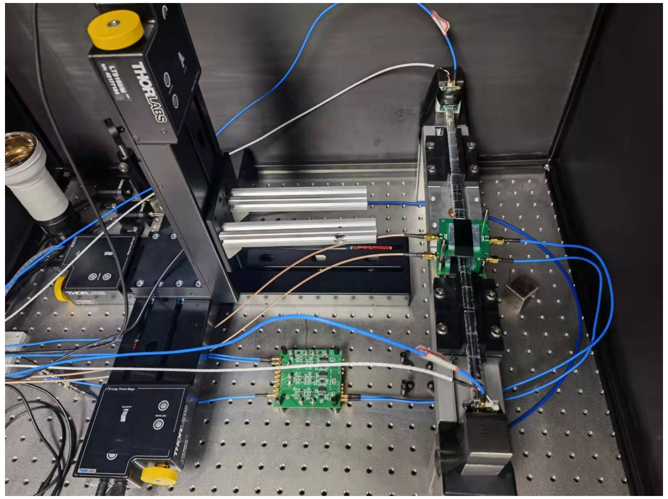
Typical cosmic-ray waveforms: BGO + SiPM



Waveform fitting for T0 (full)



Leading edge fitting for T0

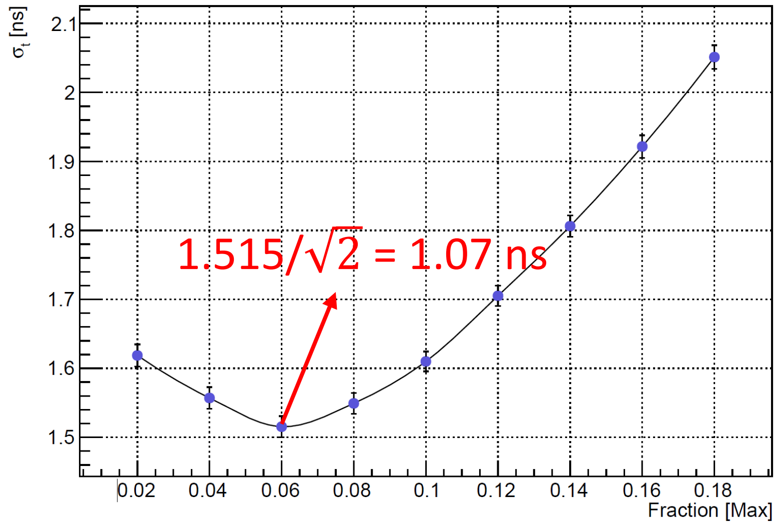


Reference: [Waveform digitization for high resolution timing detectors with silicon photomultipliers]()

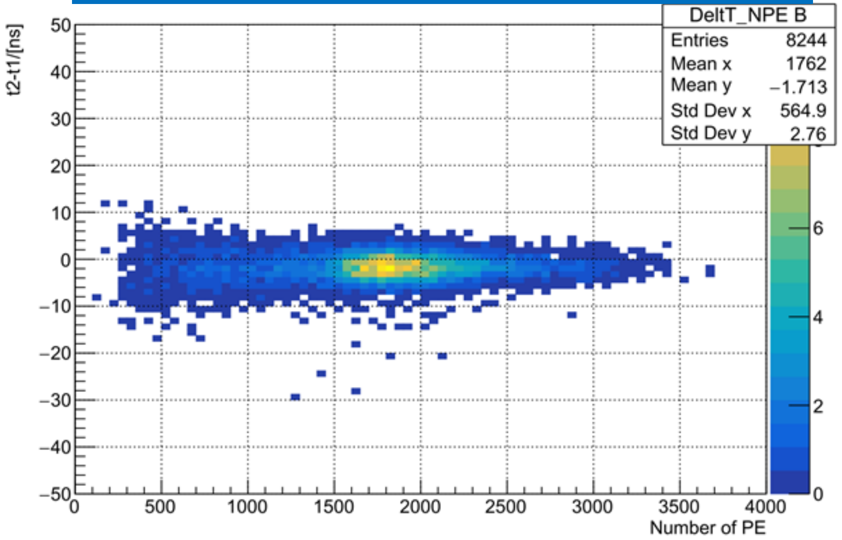
BGO-SiPM: timing performance studies

Zhiyu Zhao (SJTU)
Baohua Qi (IHEP)

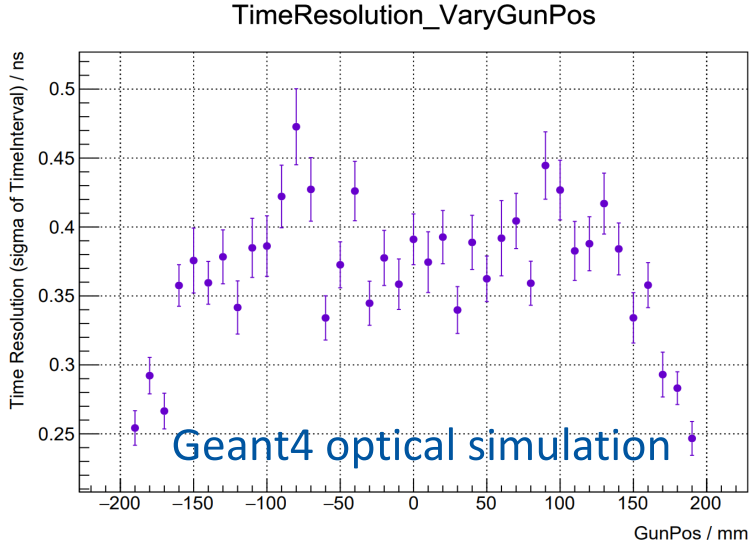
Waveform fitting: T0 (max. amplitude fraction) vs resolution



Timing resolution vs. Integrated signal



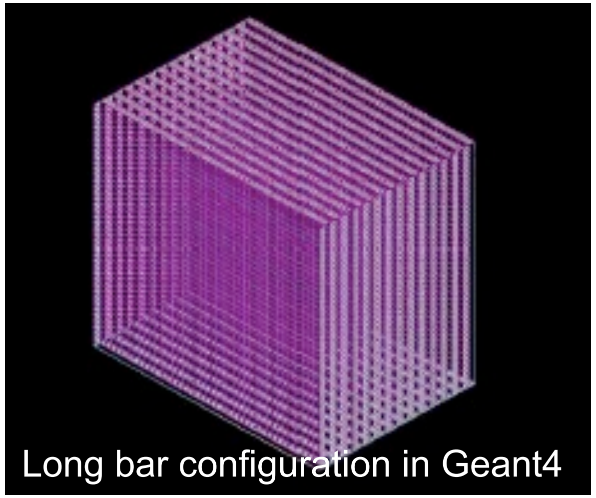
Limits from simulation



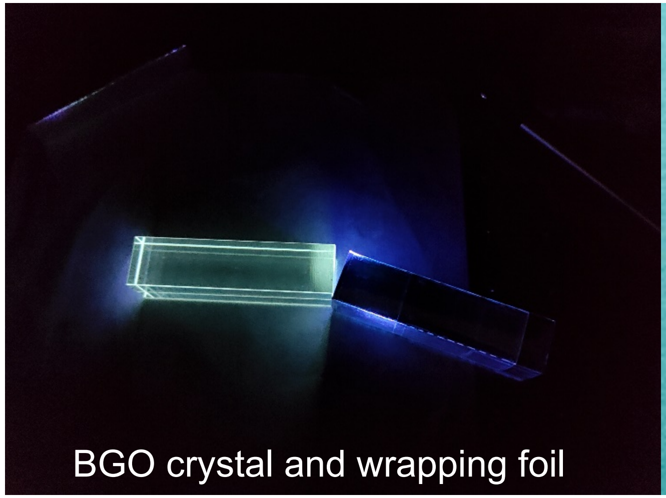
- Waveform fitting: timing resolution (~1ns) close to sampling precision (800ps)
- Plans for further improvements
  - SiPM + front-end electronics: steeper rising edge, higher sampling rate, etc.
  - Geant4 simulation: implementation of realistic modeling of SiPM waveforms
  - Possibility of Cherenkov light detection: feasibility studies with Geant4

Crystal ECAL hardware activities

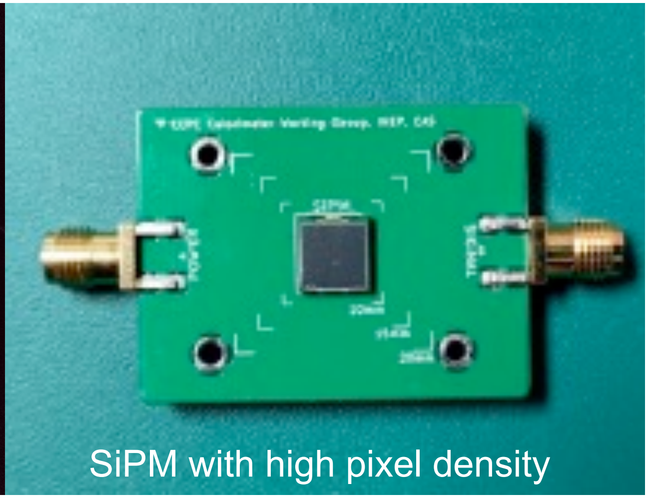
- Requirements of a single crystal-SiPM detector unit
  - Key parameters: MIP light yield, dynamic range, timing resolution, etc.
- Development of small-scale crystal-SiPM modules
  - Impacts of transverse size, gaps
  - Crystal quality test stand: crystal uniformity
  - Mechanics design and module assembly



Long bar configuration in Geant4



BGO crystal and wrapping foil

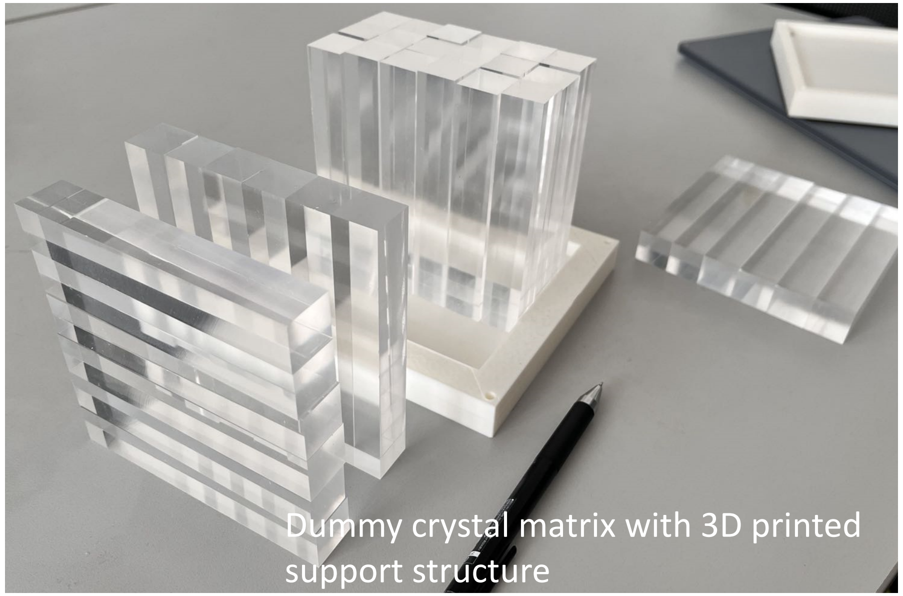


SiPM with high pixel density

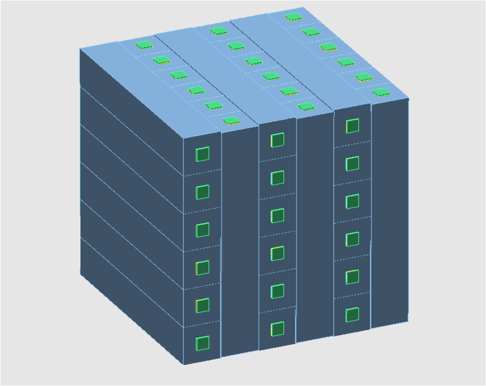
SiPM readout electronics

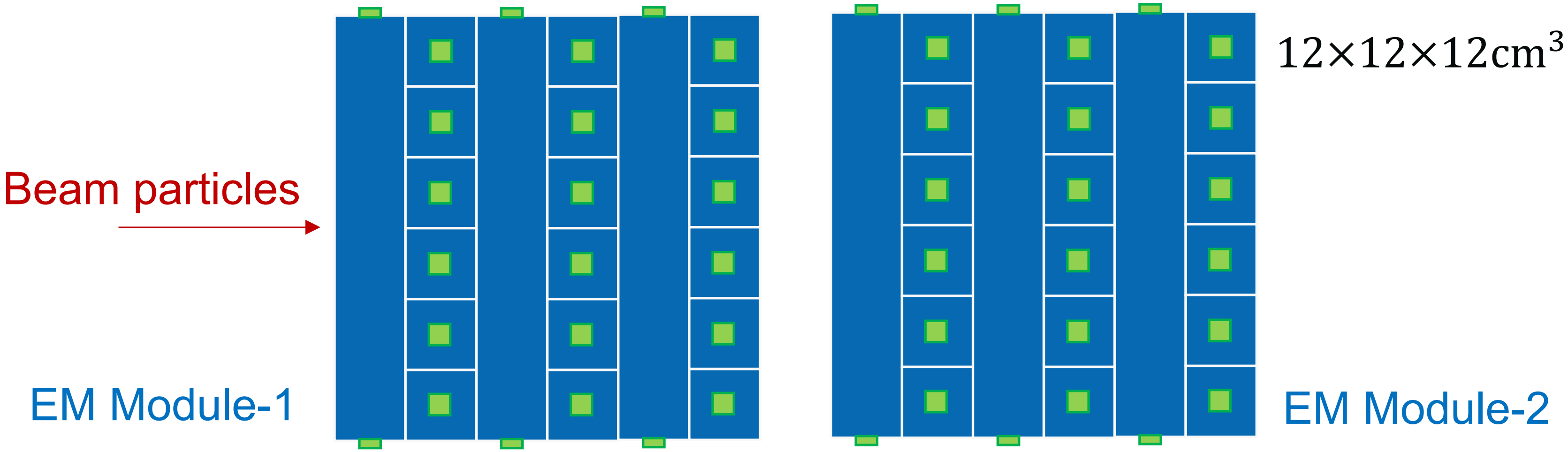
Crystal-SiPM EM modules

- Motivations
  - To address critical issues at system level
    - Small-scale modules will be sufficient (next page)
  - Evaluate EM performance with beam tests
    - Energy resolution, shower profiles
    - Validation of simulation and digitization tool
    - Application of the new reconstruction software
- Status
  - Working on the 1st EM module (36 bars, 72-ch)



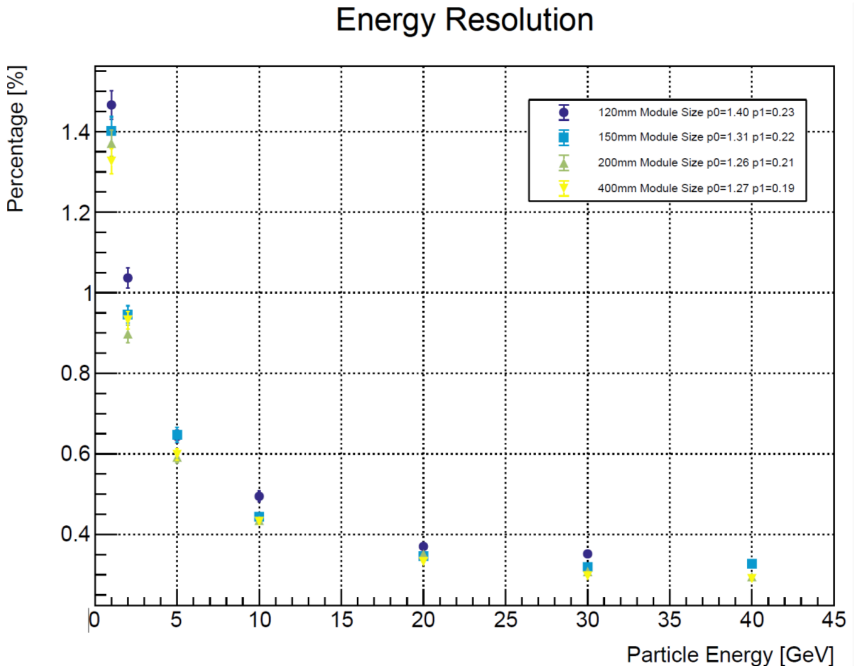
Single EM module

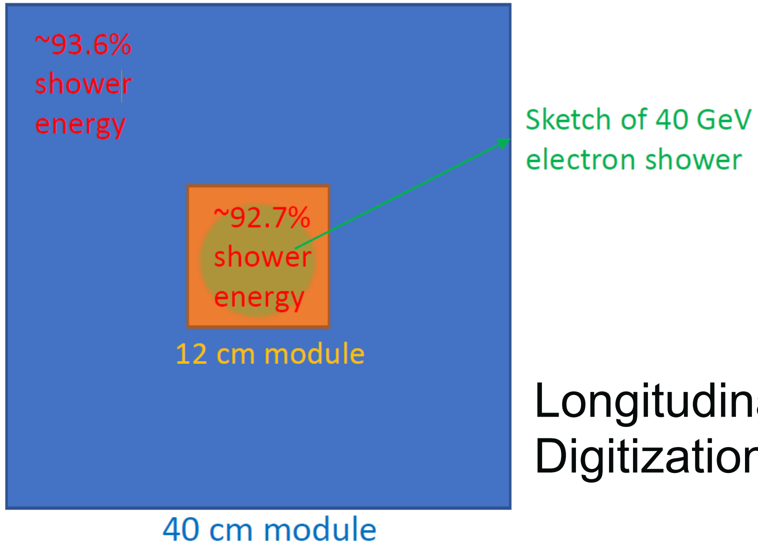




Crystal-SiPM EM module: impacts of transverse size

- Compact EM showers: not necessarily as large as the full size ($40\times40\times28$ cm^3 tower)
- Geant4 simulation: vary transverse size in steps from 400 mm to 120 mm (crystal length)



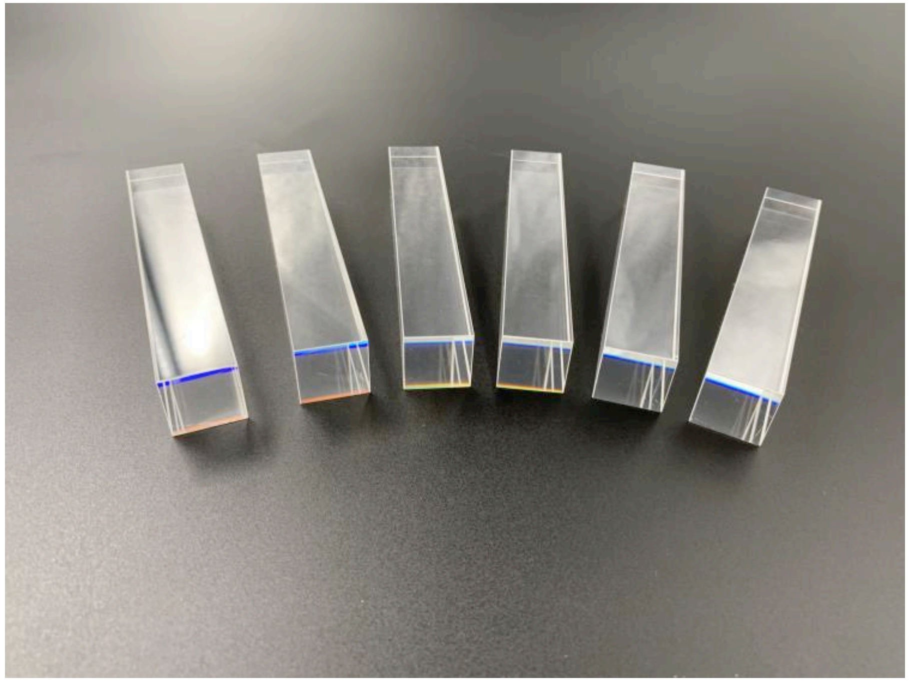


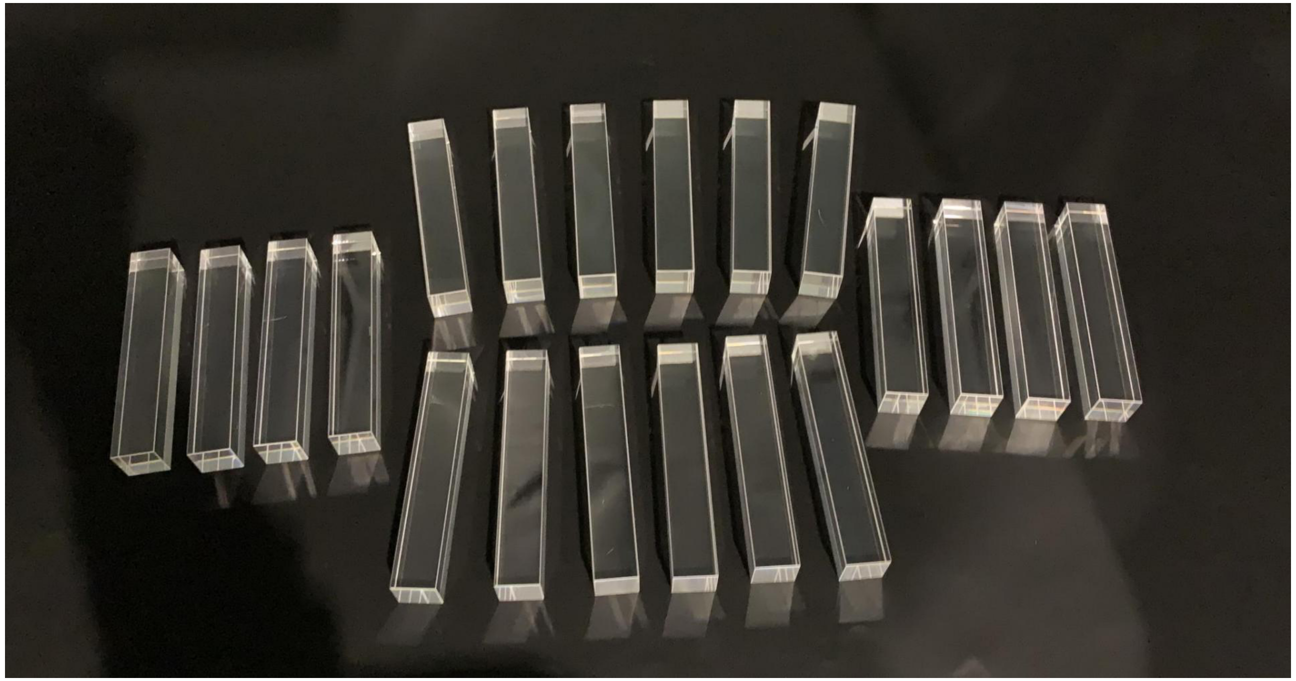
Longitudinal depth fixed at 28cm;
Digitization included

- For EM showers, the transverse size of 12 cm is enough to contain most shower energy
  - Degradation of EM energy resolution: absolute values at ~0.1% level
  - Assuming that particles hit on the module center

BGO crystals for EM module

- Ordered the first batch of 40 BGO bars from SIC-CAS
  - Delivered to IHEP with wrapping
  - ESR film (optimal reflectivity) + Aluminum foil (mechanical reinforcement)



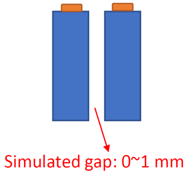


First batch of BGO crystals from SIC-CAS

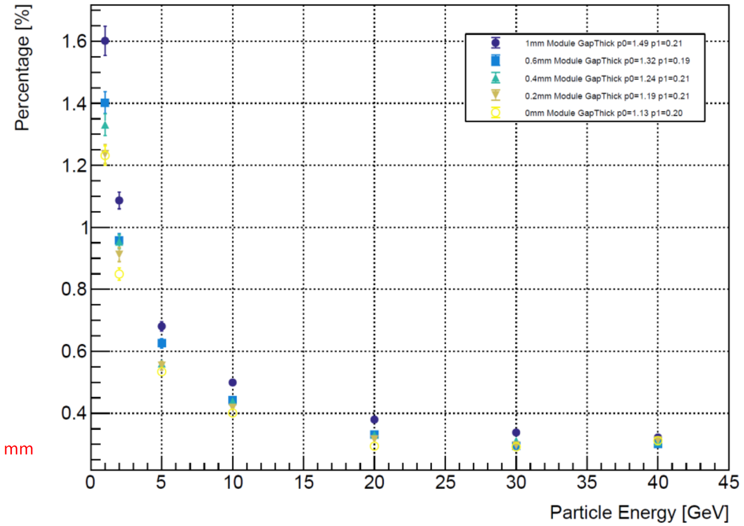
Crystal-SiPM module design: impact of gaps

Baohua Qi (IHEP)

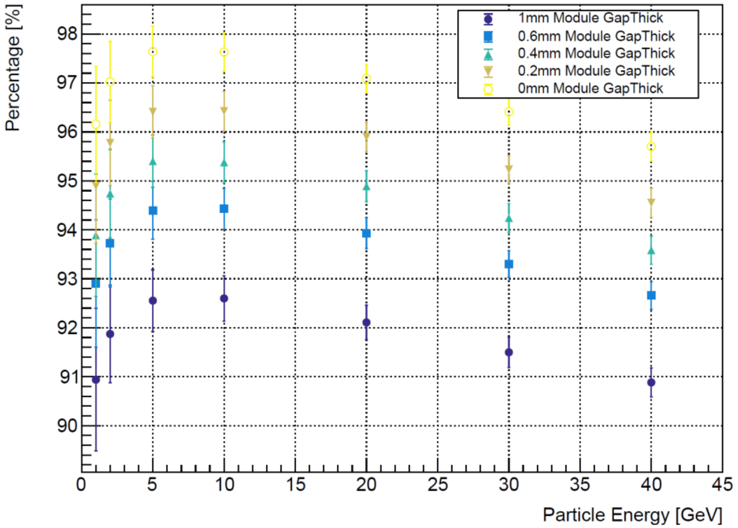
- Gaps implemented in the simulation of 40×40×28 cm^3 tower
  - Materials: ESR film, Al foil, air (the same as real crystals + wrapping)
  - Density set to 2 g/cm^3



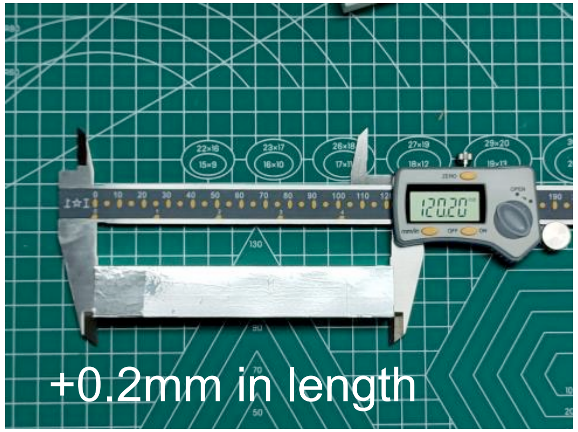
EM Energy Resolution

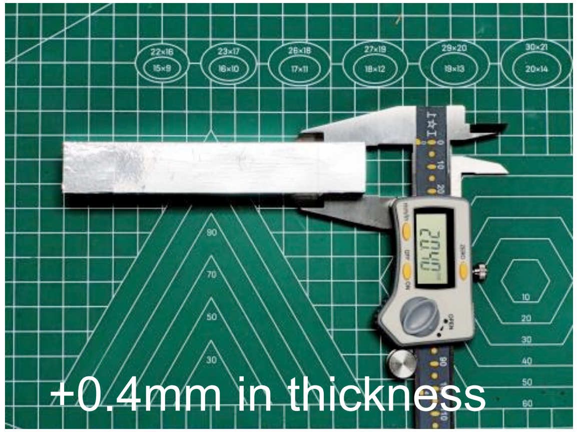


EM Shower Containment



BGO bar with wrappings: dimension measurements



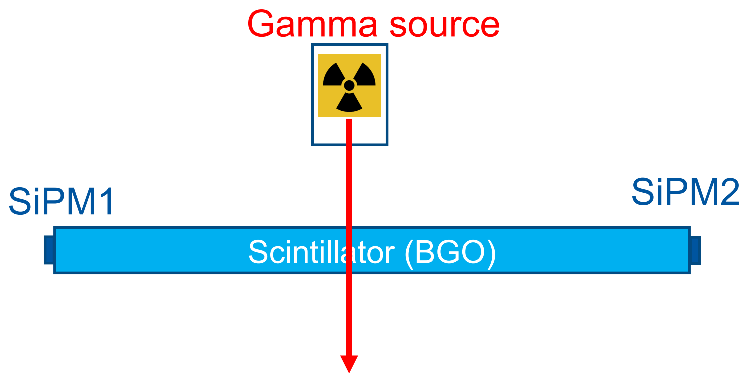


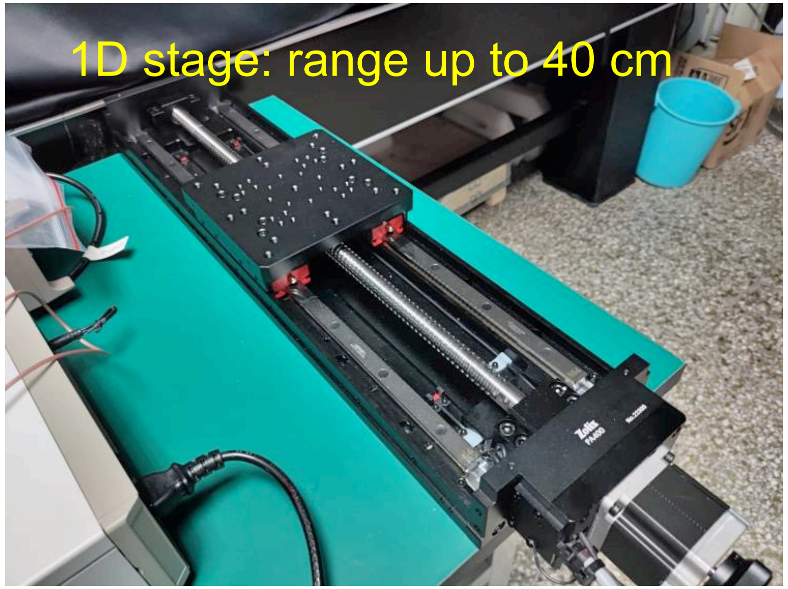
- Impact of gaps is more significant, compared with than transverse size
- Gaps around ~0.4 mm (transverse) for 12×2×2 cm^3 crystals
- Control of gaps for 40cm long crystals: a key issue

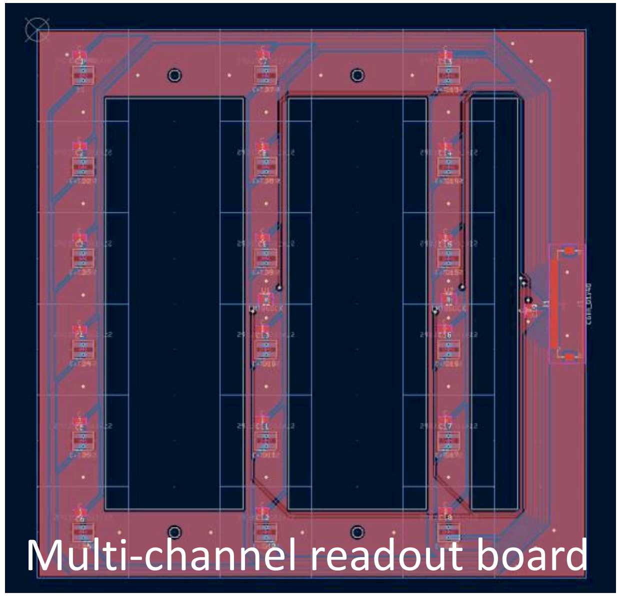
Small-scale module: ongoing activities

- Test stand for crystal quality control and uniformity
  - Automated setup BGO bars (40x in the first batch)
- Tests with other NDL/Hamamatsu SiPMs
- PCB design for multi-channel SiPM readout
- Mechanical structure and module assembly

Fixture for holding the source is mounted on the 1D stage



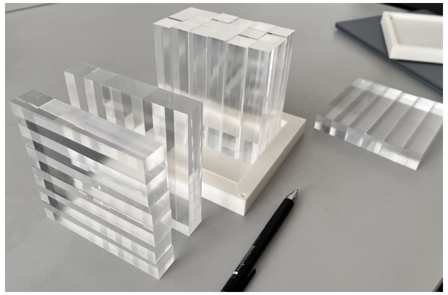


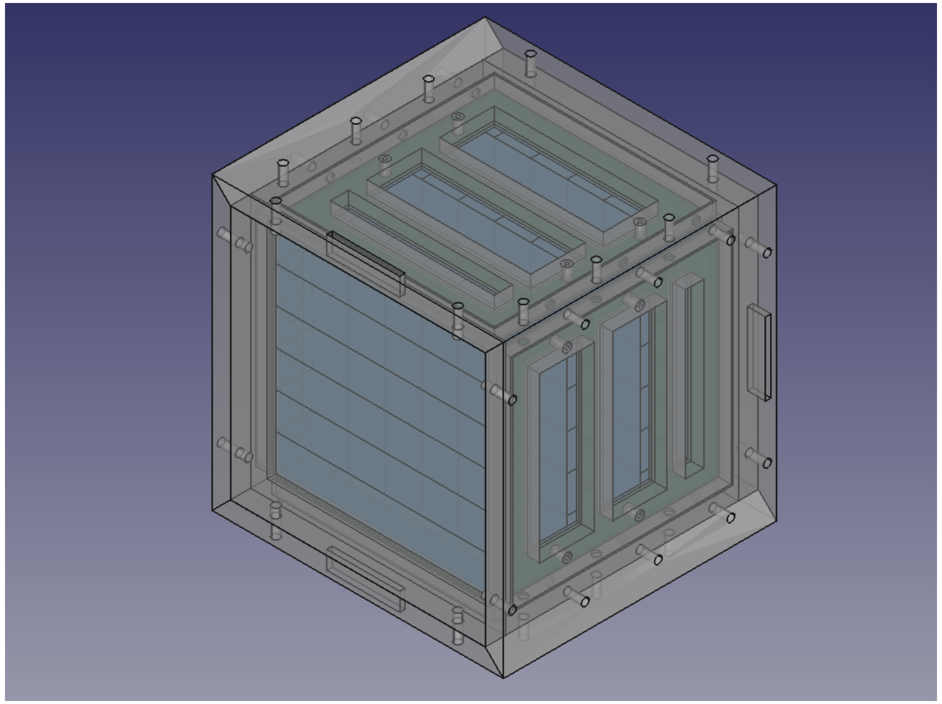


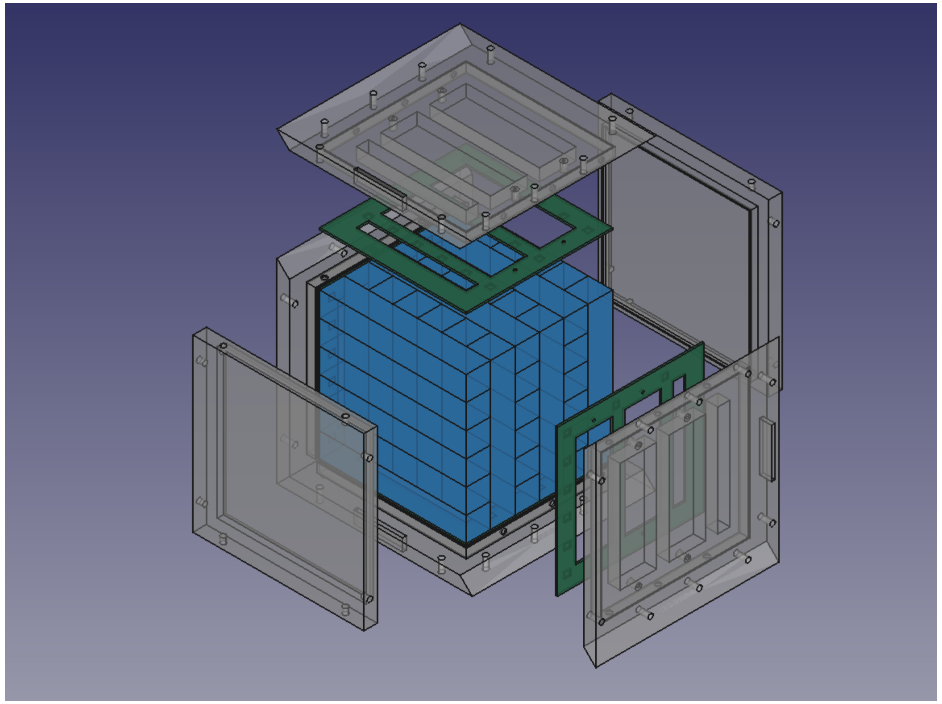
Small-scale module: ongoing activities

Baohua Qi (IHEP)

- Mechanical structure and module assembly
  - Challenges: crystal weight, stable SiPM coupling
  - Made a first design draft
  - Plan to be exercised with dummy crystal bars and real PCBs







Crystal calorimeter: specifications

Key Parameters	Value	Notes
MIP light yield	~100 p.e./MIP	9.1 MeV/MIP in 1 cm BGO
Dynamic range	$0.05 \sim 10^3$ MIPs	Energy range of 500 keV to 10 GeV
Energy threshold	15 p.e.	Equivalent to 0.5 MeV (~0.05 MIP)
Timing resolution	~400 ps	Limits from G4 simulation → validation
Response non-uniformity	<1%	After calibration
Temperature stability	Stable at ~ 0.05 ℃	Reference of CMS ECAL
Gap tolerance	~100 μm	TBD via module development

- Note: this table needs more validation studies
- Development of EM modules will help
    - To gain experiences of realistic limitations
    - To address system-level issues

Summary and prospects

- Crystal calorimeter: major R&D aspects
  - <u>Hardware development: key questions and specs (focused in the talk)</u>
  - New reconstruction software dedicated to long bar geometry
  - Arbor-PFA optimization for crystal ECAL
  - Physics performance evaluation

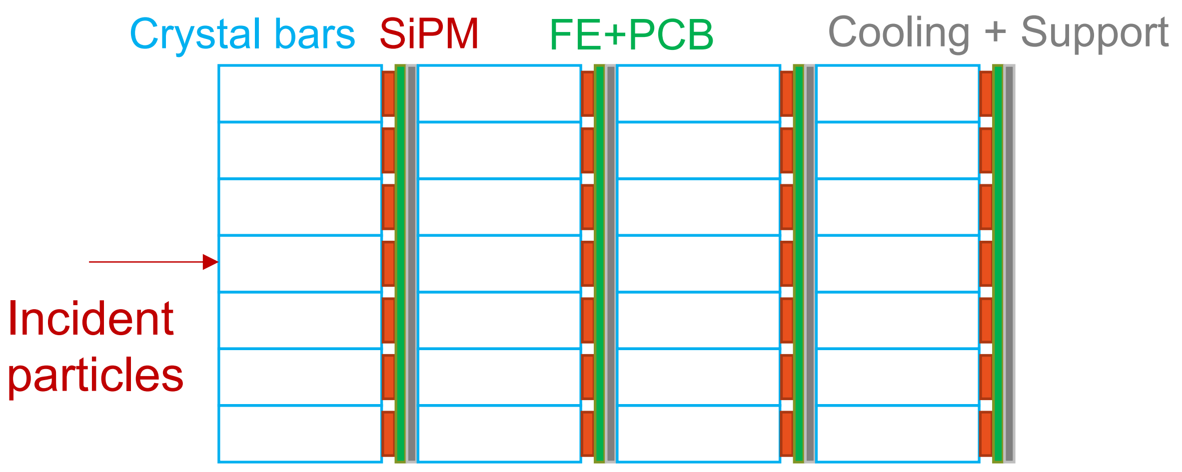
- Ongoing hardware R&D activities to address
  - Key parameters: light yield, dynamic range, timing resolution, etc.
  - Key issues at system level: EM module development

- Plans
  - The first small-scale BGO module: system integration
  - Preparations for beam tests in 2023: focusing on EM shower performance

Backup slides

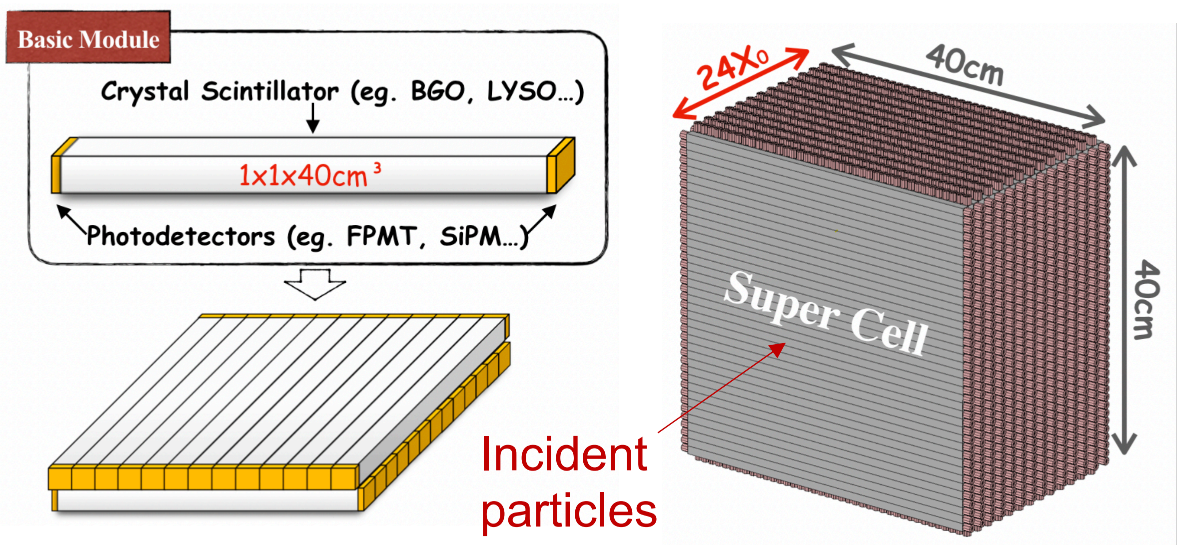
High-granularity crystal ECAL: 2 major designs

Design 1: short bars



- **Focus on <u>PFA performance</u> studies**
- Crystal cubes (ideal granularity) for physics benchmarks
- Inputs for optimization of the existing PFA for crystals

Design 2: long bars

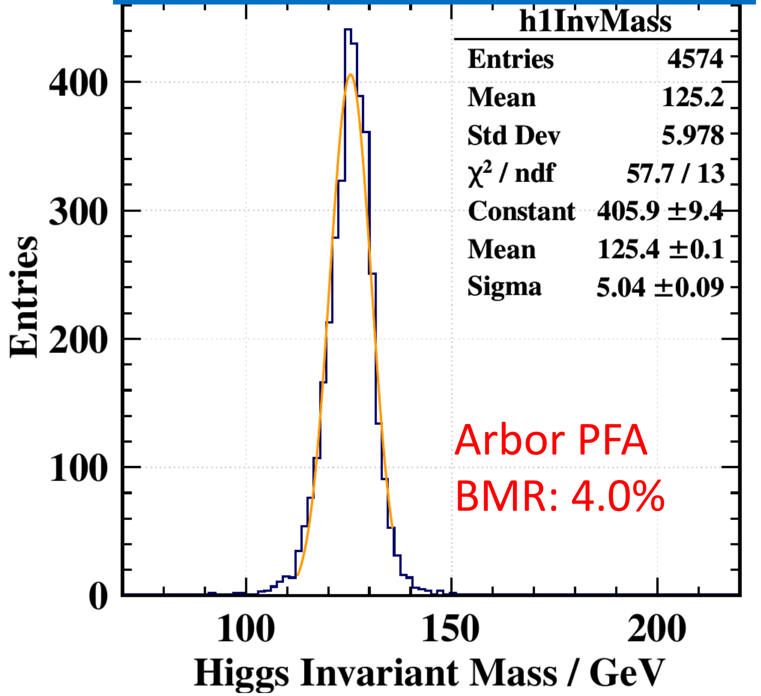


- **Focus on <u>new reconstruction algorithm</u> development**
- **Key issues**
  - Separation capability of multiple incident particles (resolving “ghost hits”)
  - Impact to PFA performance

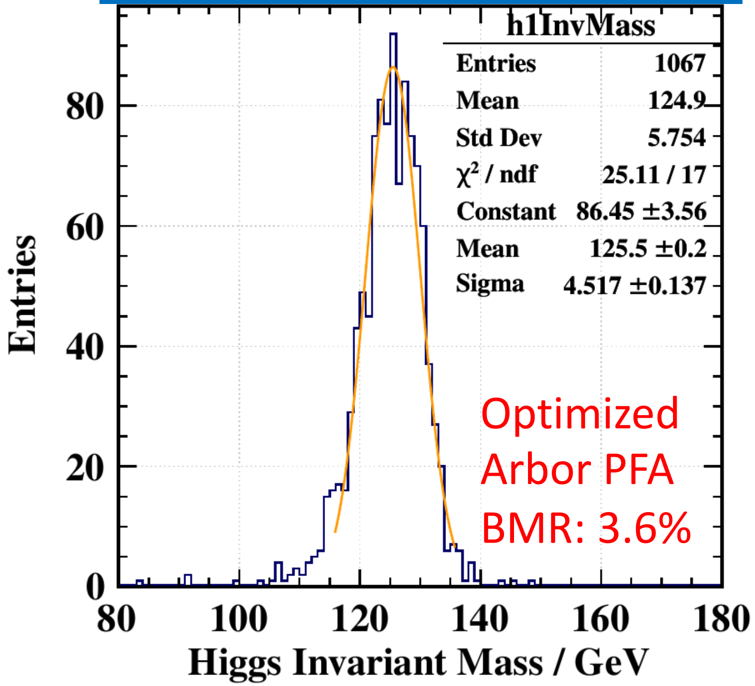
Physics performance evaluation: Higgs benchmark (reminder)

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

CEPCv4 detector with crystal ECAL



CEPCv4 detector with crystal ECAL



- Significant improvement after Arbor-PFA algorithm optimization
- On-going PFA studies on impacts of granularity

Preliminary results with 1 cm^3 crystal cubes

BGO dimension tolerances

- BGO crystals for the DAMPE experiment
  - Specifications: 25（+0/-0.1）mm×25（+0/-0.1）mm×600（+0/**-0.4**）mm
  - Measurements: 25（+0/-0.1）mm×25（+0/-0.1）mm×600（+0/**-0.3**）mm

Values provided by courtesy of
Dr. Junfeng Chen (SIC-CAS)

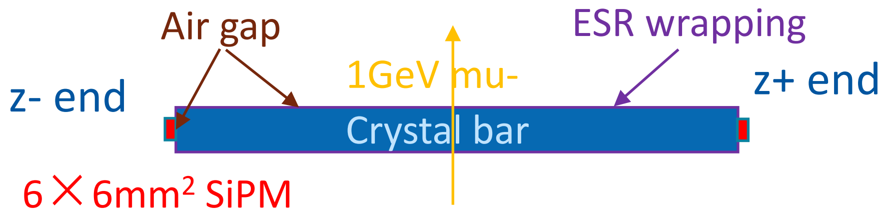
- BGO crystals for CEPC crystal-SiPM module
  - Specifications: 20（+0/-0.1）mm×20（+0/-0.1）mm×120（+0/**-0.1**）mm
  - Measurements: pending
  - Nominal foil thickness: 100-165 um in total

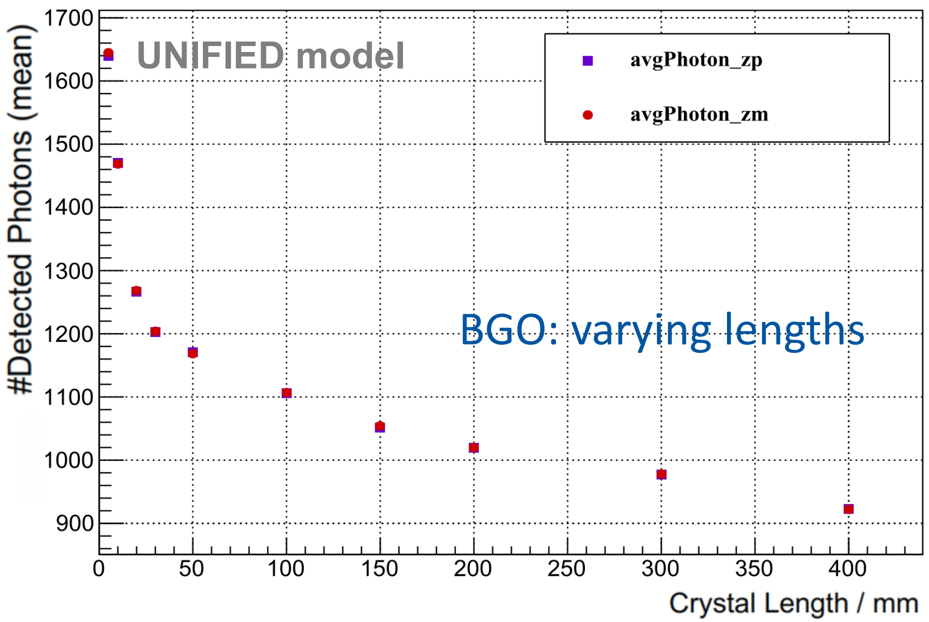
MIP response with various crystal lengths

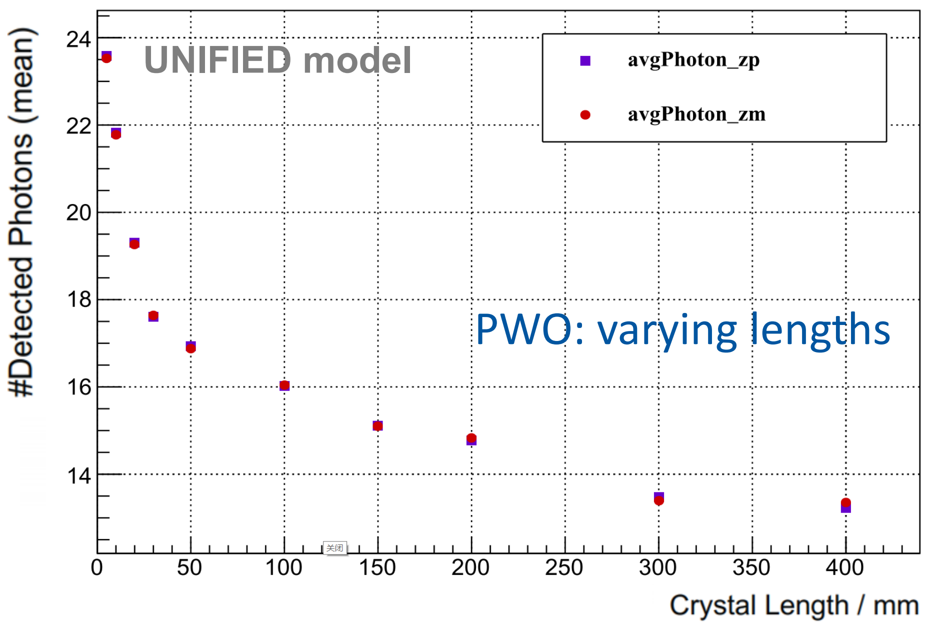
Baohua Qi (IHEP)

Geant4 10.7

- MIP response: number of detected photons
  - Muon shooting the crystal bar center
  - Crystal length varies from 5mm to 400mm
  - Crystal transverse size: $1cm^2$





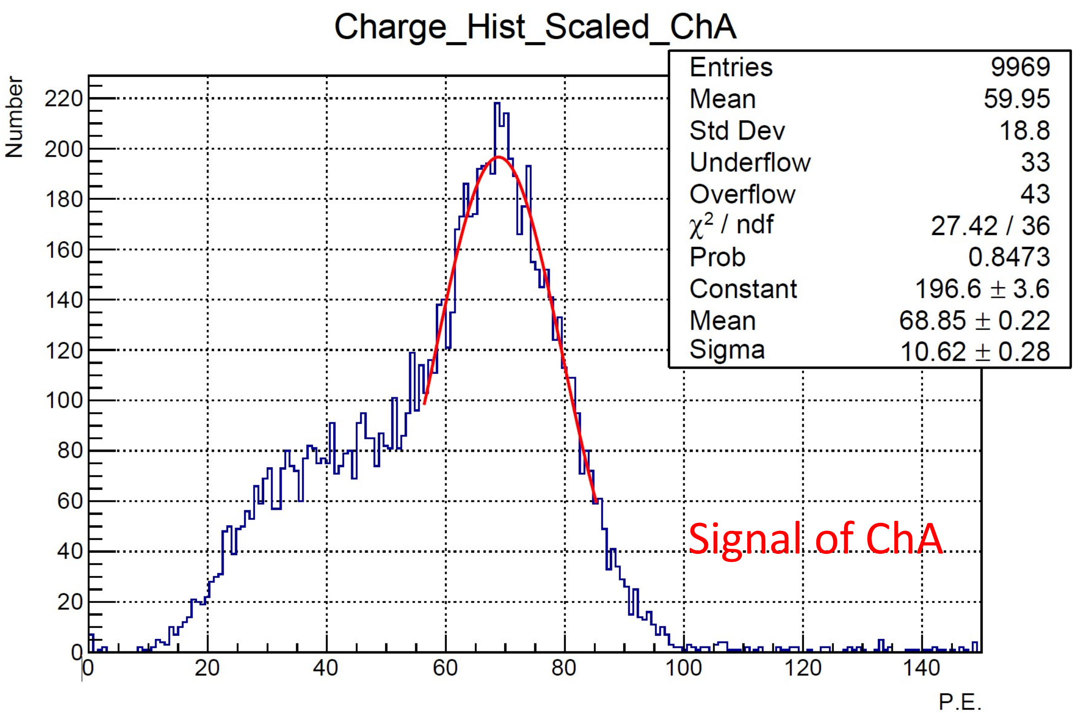


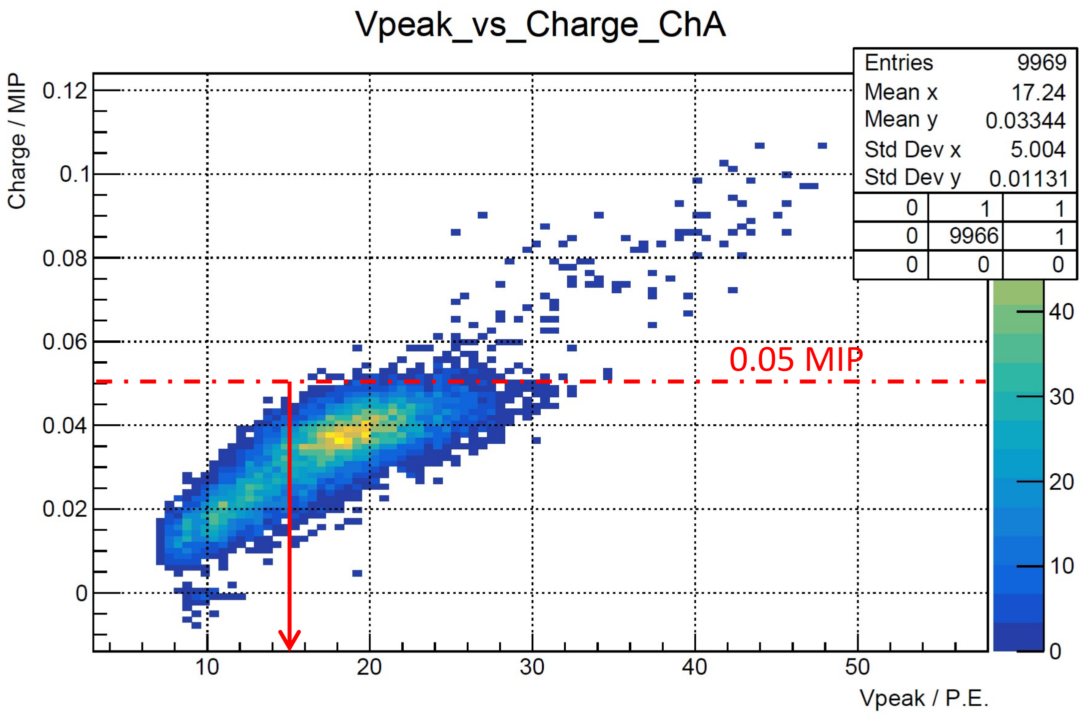
- MIP response significantly depends on crystal length
- Sufficiently high MIP response of 40cm long BGO

Light yield: 8200/MeV for BGO, 120/MeV for PWO
MIP energy deposition: ~ 9MeV (MPV)

Energy threshold for low energy particles

- Signal amplitude is roughly linear with integrated charge (QDC)





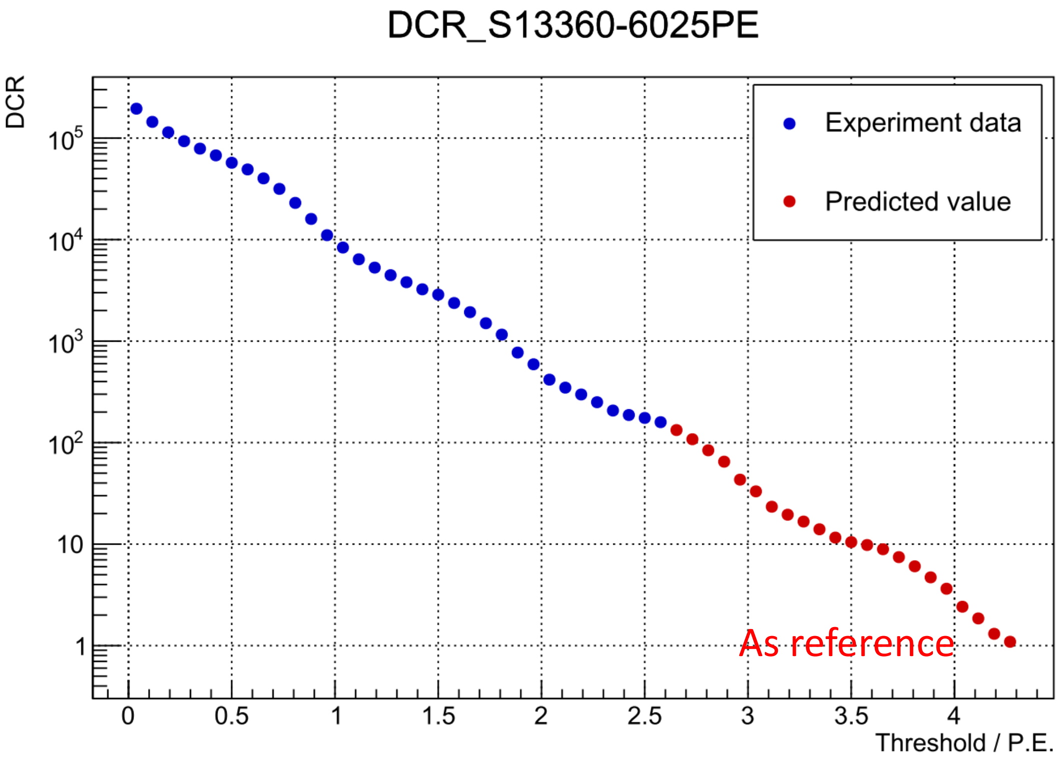
- 662 keV gamma ~0.07 MIP (ChA + ChB)
  - Signal in ChA ~0.04 MIP
- Requirement on dynamic range : 0.05~10^3 MIP

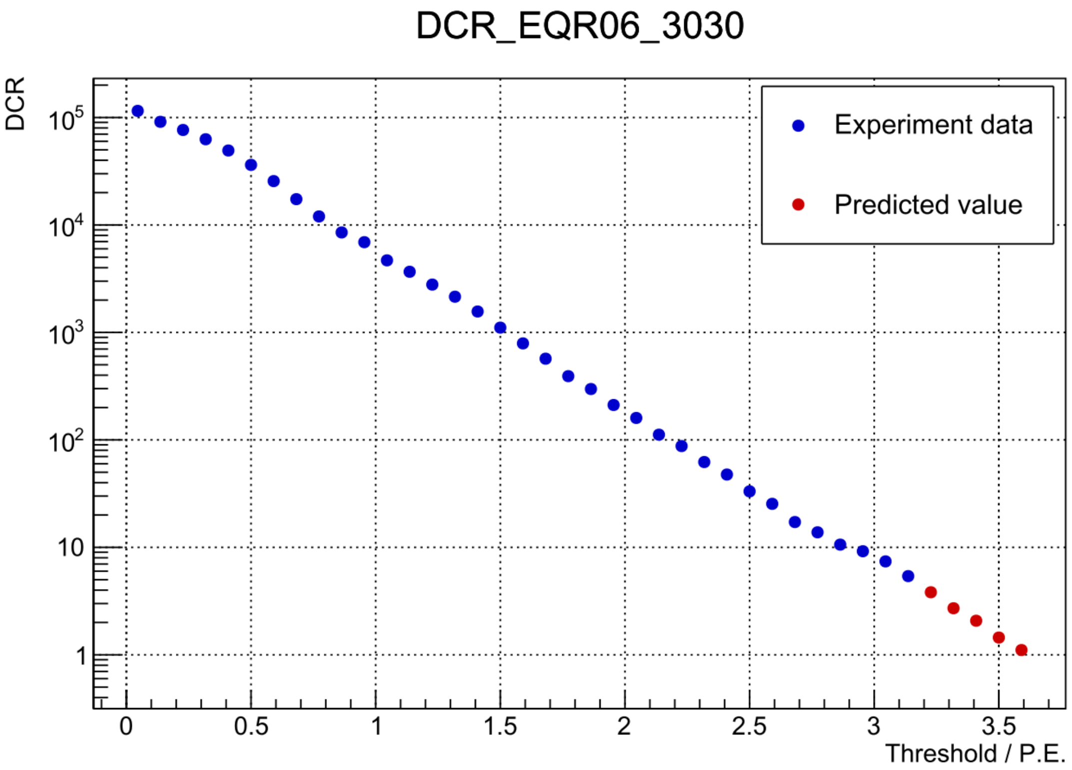
- Voltage threshold: 15 p.e. is feasible
  - DCR is low enough at 15 p.e.
- Capable to detect low energy particles
  - Pressure on dynamic range: 2×10^4
  - Benefits for physics?

Characterizations of SiPMs: noise level vs. threshold

- Dark count rate versus voltage threshold (in p.e.)

Cross-check and further studies ongoing

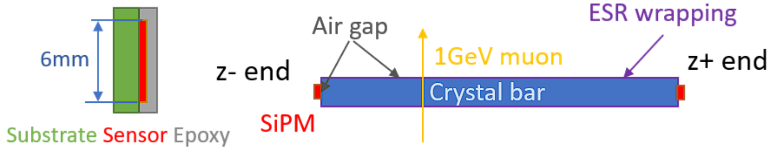


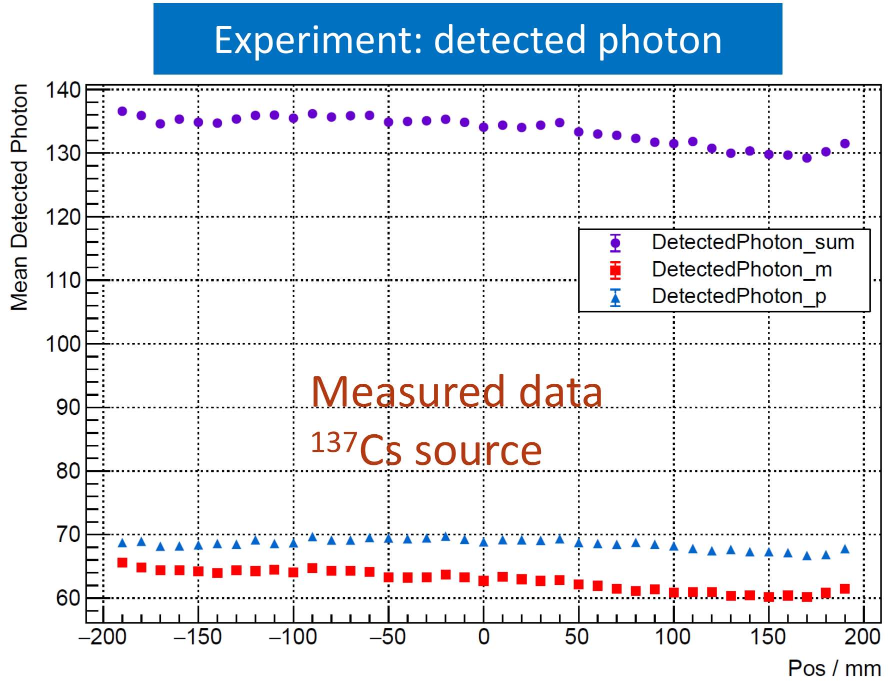


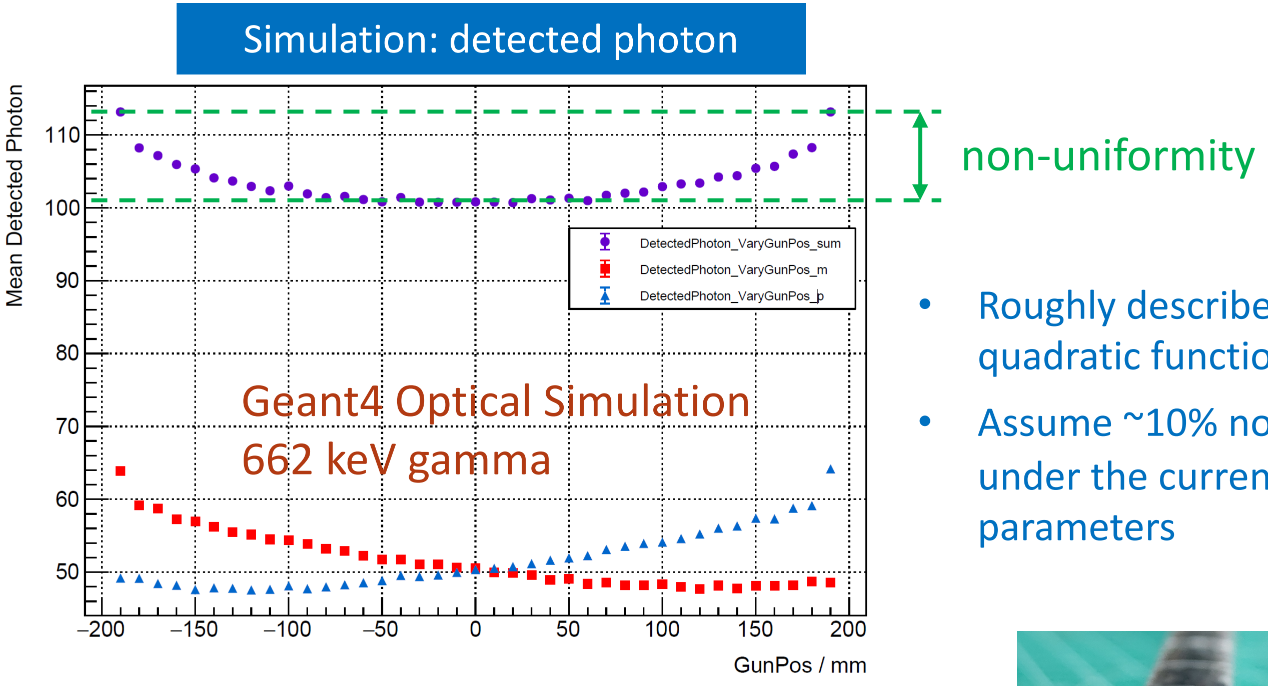
- Dark count rate can be lower than 1 Hz with relatively low voltage threshold
- Potential on low energy particle detection

Long crystal bar: uniformity response

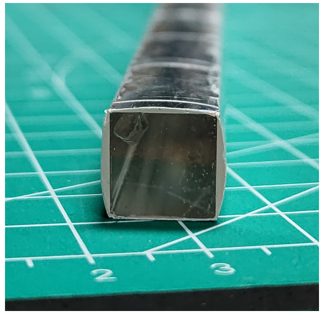
- Uniformity scan: 662 keV gamma for ^{137}Cs, change hit positions
- Geant4 optical simulation: a single BGO crystal bar wrapped with ESR reflector







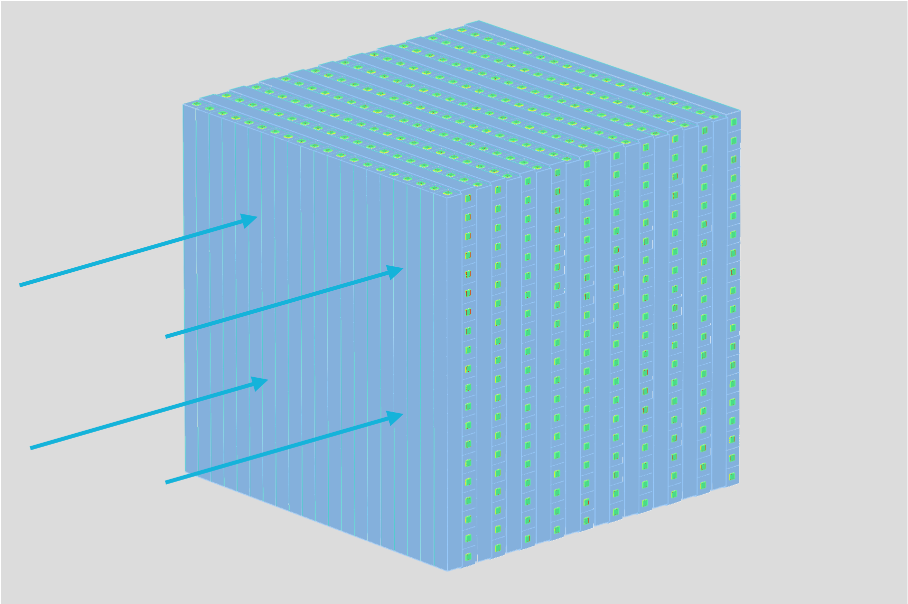
- Roughly described by a quadratic function
- Assume ~10% non-uniformity under the current simulation parameters

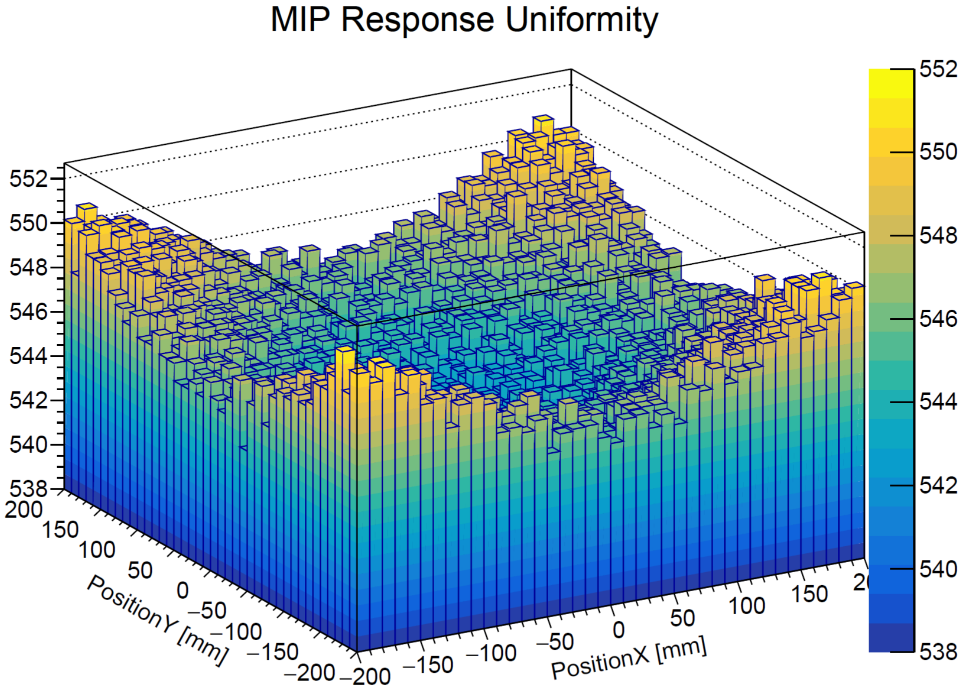


- Less light attenuation effect than expected in simulation
- Relatively low response near one side
  - Coupling, positioning, distance between crystal and radioactive source…
  - Potential factors related to crystal manufacture
- Repeat more measurements to reduce systematic uncertainty

Response uniformity: impacts to crystal ECAL module

- 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)

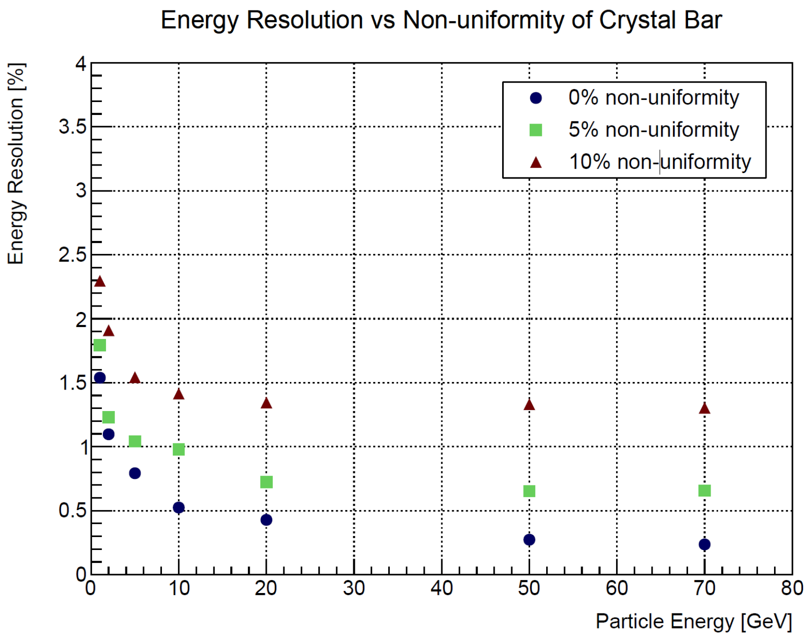


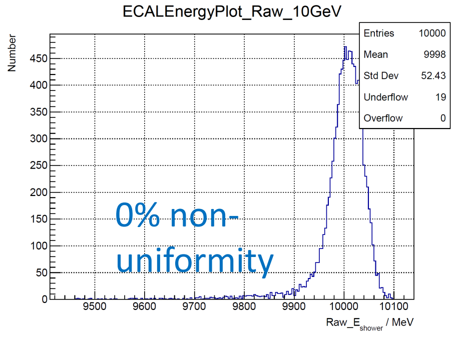


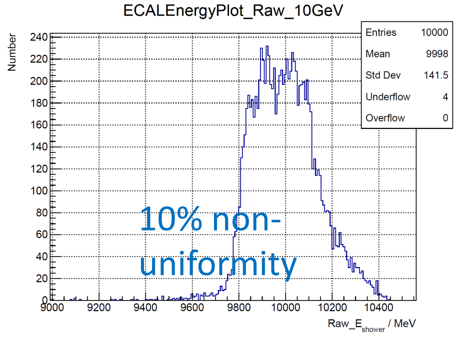
- MIP Response of four corners is higher
- 2D non-uniformity lower than 10%
- Responses depend on hit positions
  - Good reconstruction algorithm is required to get precise position resolution
  - Timing information for positioning

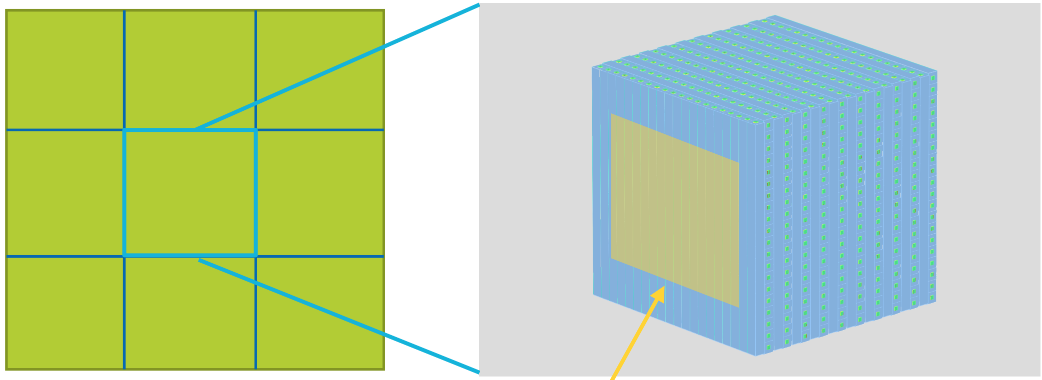
Response uniformity: impacts to crystal ECAL module

- Impact on energy resolution
  - 1-100 GeV electron
  - 3×3 modules are used to prevent energy leakage
  - Digitization and energy calibration are implemented
  - Energy resolution = Mean/StdDeV





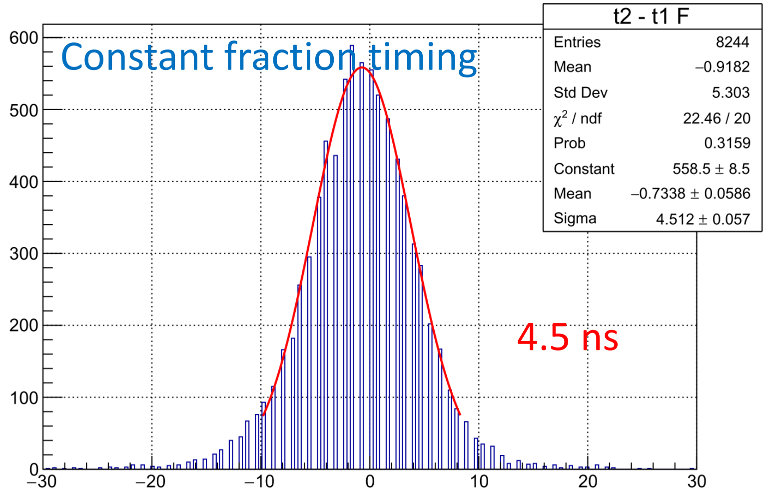


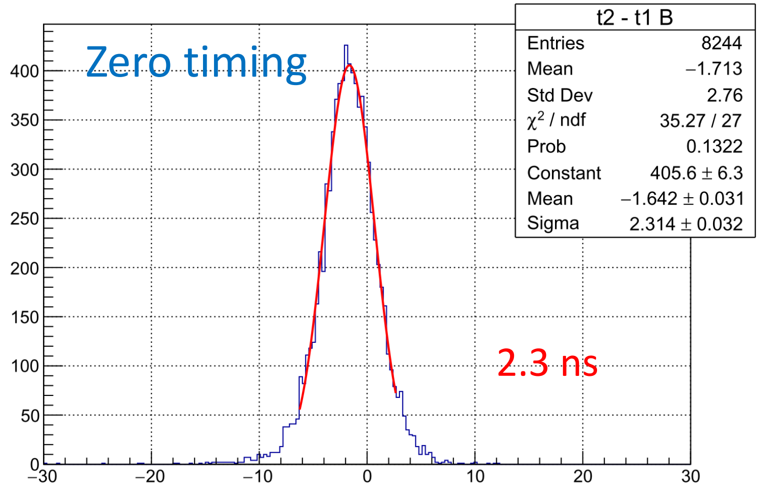


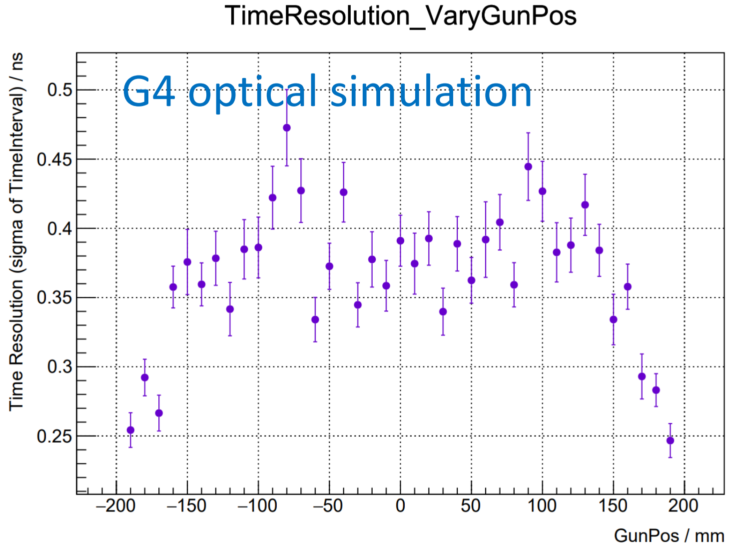
Incident particles randomly hit this area of the middle module

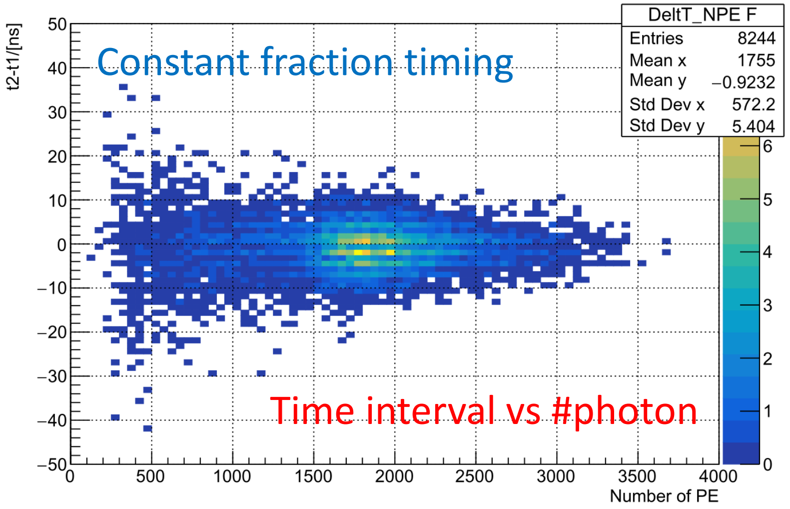
- Severe distortion of energy resolution and linearity
  - Effect on energy distribution
  - Major contribution to constant term
- Response non-uniformity need to be calibrated
  - Non-uniformity < 1% after calibration

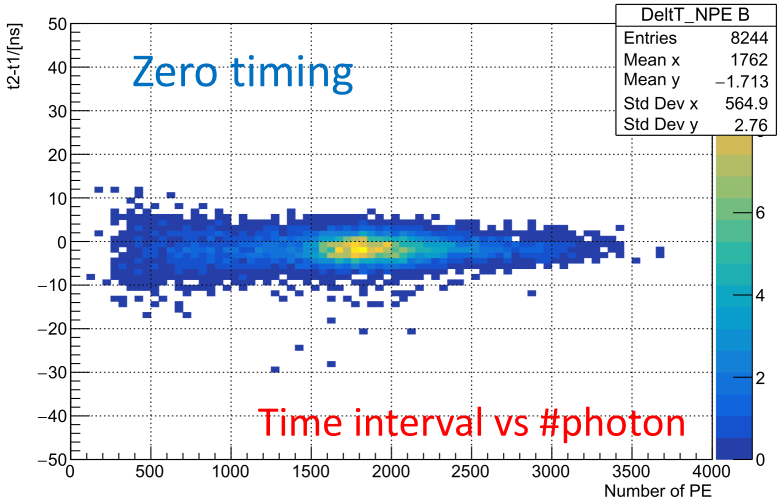
BGO-SiPM timing performance studies







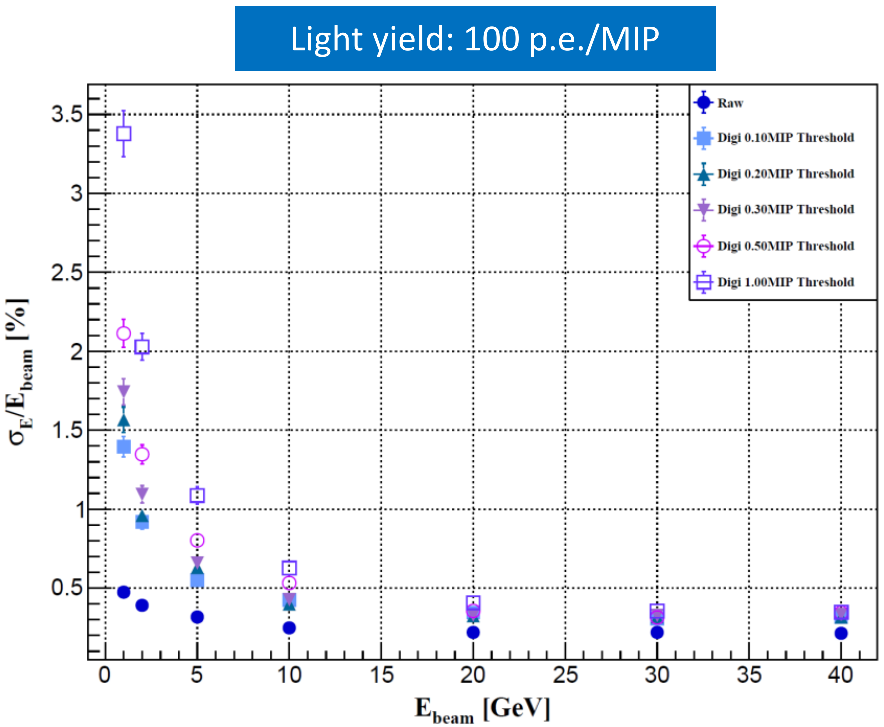


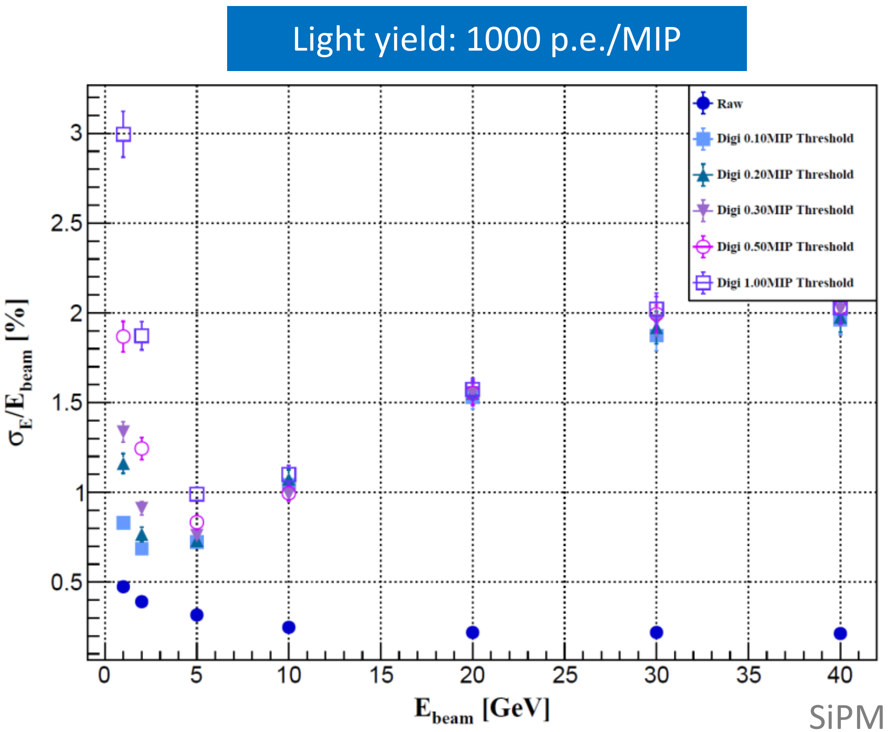


- Time resolution in simulation: ~400 ps
- Large #photons helps to improve time resolution
- Limitations:
  - SiPM rising edge of SiPM pulse
  - Front-end electronics
  - Scintillation properties of BGO crystal
  - Light transmission of long crystal bar

EM energy resolution: requirements on light yield

Baohua Qi (IHEP)





SiPM pixel recovery effects have not been included in plots

- Energy resolutions vary with energy thresholds and light yields
  - Digitization: consider SiPM saturation (NDL SiPM with $\sim 2.4\times10^5$ pixels)
- Significant saturation effect observed when light yield is too high
- Requirement on light yield: 100 p.e./MIP → 10^5 photons (10^3 MIPs)