Simulation and Measurements of Scintillating Crystals

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Outline

- Crystal ECAL: introduction
- Geant4 Full Simulation of a Single Crystal Bar
  - Impacts of crystal length
  - Uniformity scan in simulation
  - Comparison of different optical models
- Measurements with BGO Crystals: energy spectrum
  - Experiment setup with ^{137}Cs Radioactive Source
  - Impacts of wrapping & surface properties
  - Impacts of crystal length & transverse size
- Conclusions

Motivations

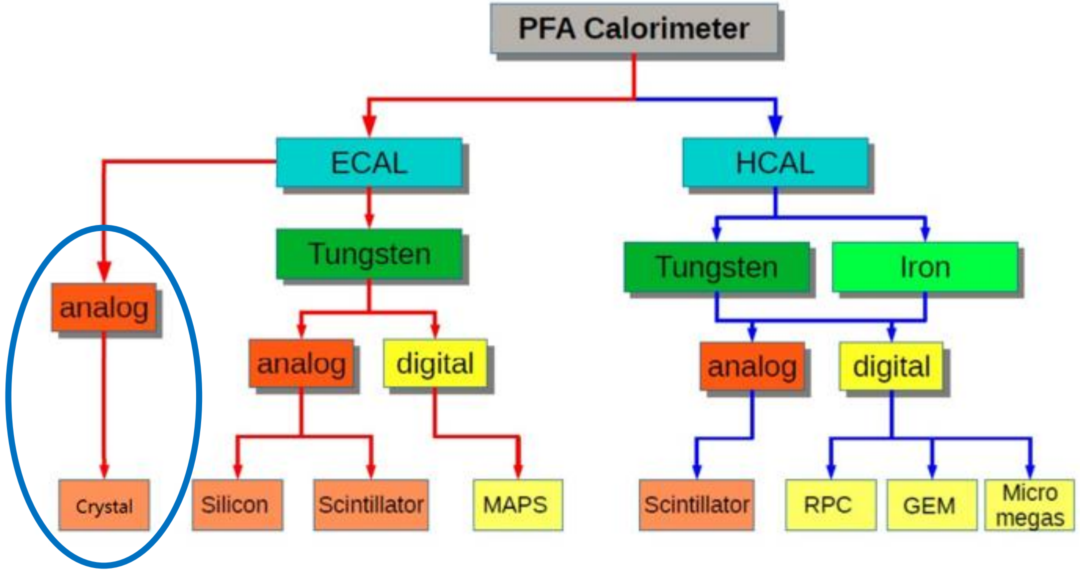
- Detailed studies on crystal performance
  - Energy spectrum: threshold and resolution
  - Temporal profiles in signals: timing resolution
- Geant4 full simulation model as guidance
- Measurements to validate the full simulation

Crystal ECAL: introduction

- Future lepton colliders (e.g. CEPC)
  - Precision measurements with Higgs and Z/W
  - Jet energy resolution of 3%@100GeV is required
  - PFA / dual-readout calorimeter
    - Particle flow approach: High-granularity

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

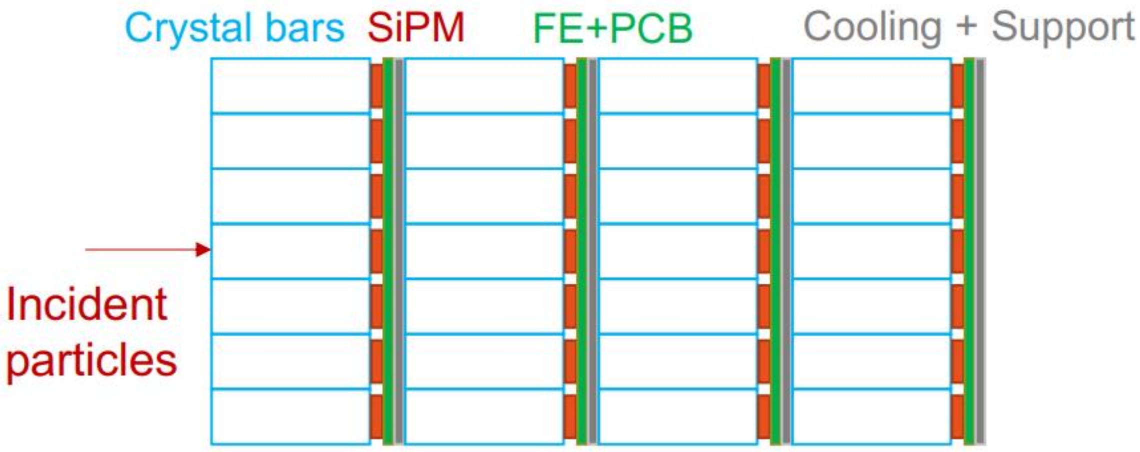
- Why crystal ECAL?
  - Homogeneous structure
    - Intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Energy recovery of electrons
  - Capability to trigger single photons



Crystal ECAL: introduction

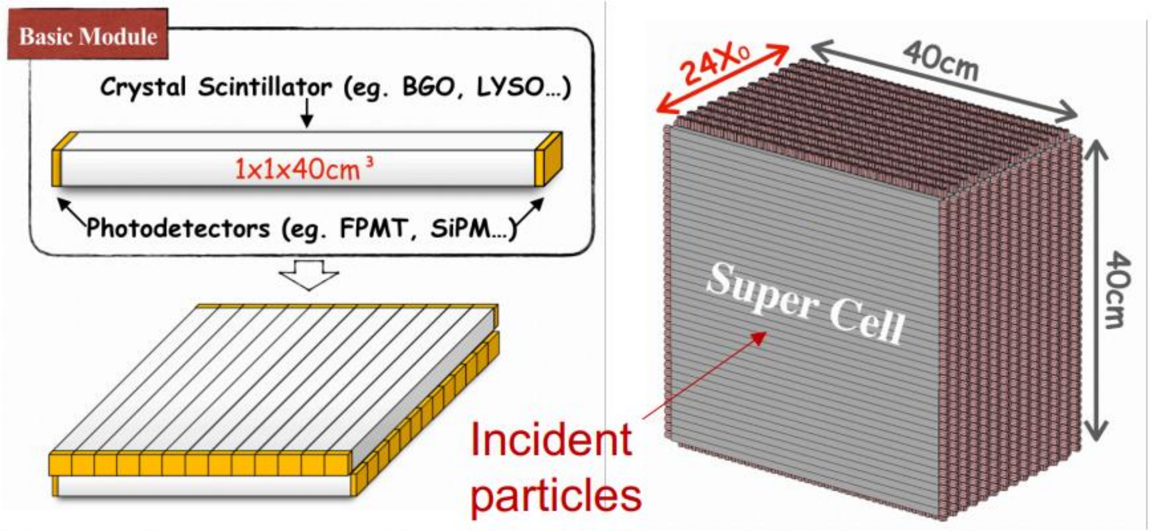
Our major concern

Design 1



- Longitudinal segmentation
- Fine transverse segmentation
  - 1×1cm or 2×2cm cells
- Single-ended readout with SiPM
- Potentials with PFA

Design 2

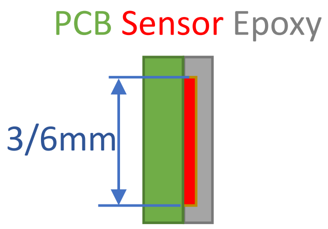


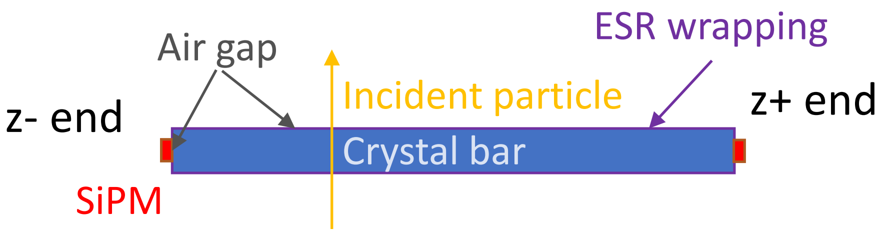
- Long bars: 1×40cm, double-sided readout
  - Super cell: 40×40cm cube
- Crossed arrangement in adjacent layers
- Significant reduction of #channels
- Timing at two sides: positioning along bar

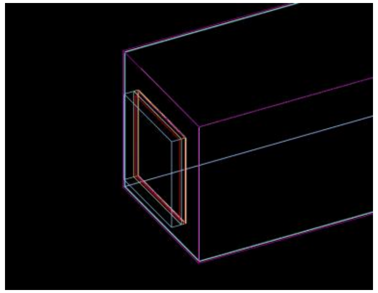
Geant4 Full Simulation of a Single Crystal Bar: overview

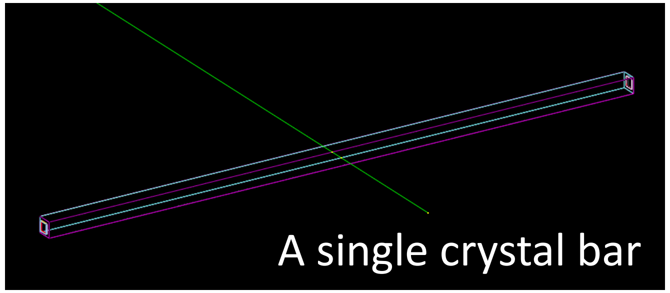
Simulation model

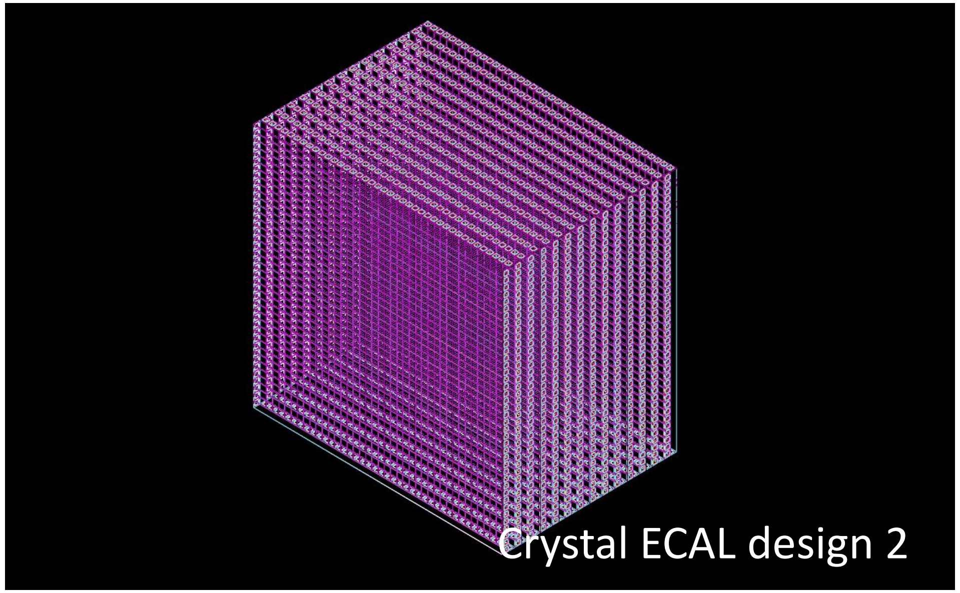
- A single crystal bar wrapped with reflector
- Physics processes
  - Scintillating & Cherenkov
  - Boundary processes and absorption
  - SiPM modelling: geometry and response (PDE)
- Data extracted
  - Number of photons detected by 2 SiPMs
  - Time information of every detected photons







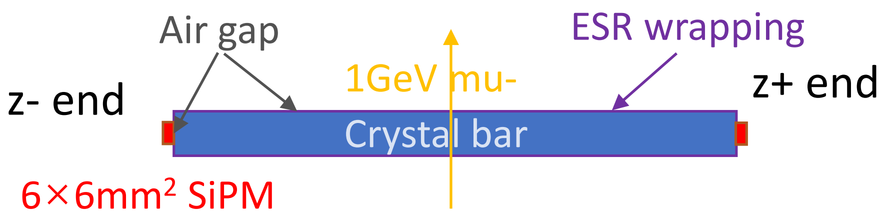


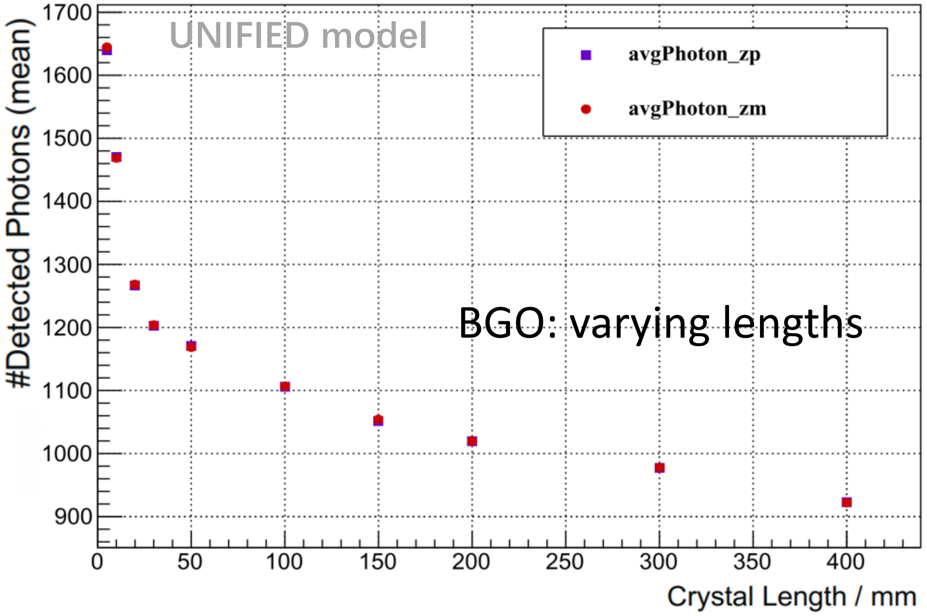


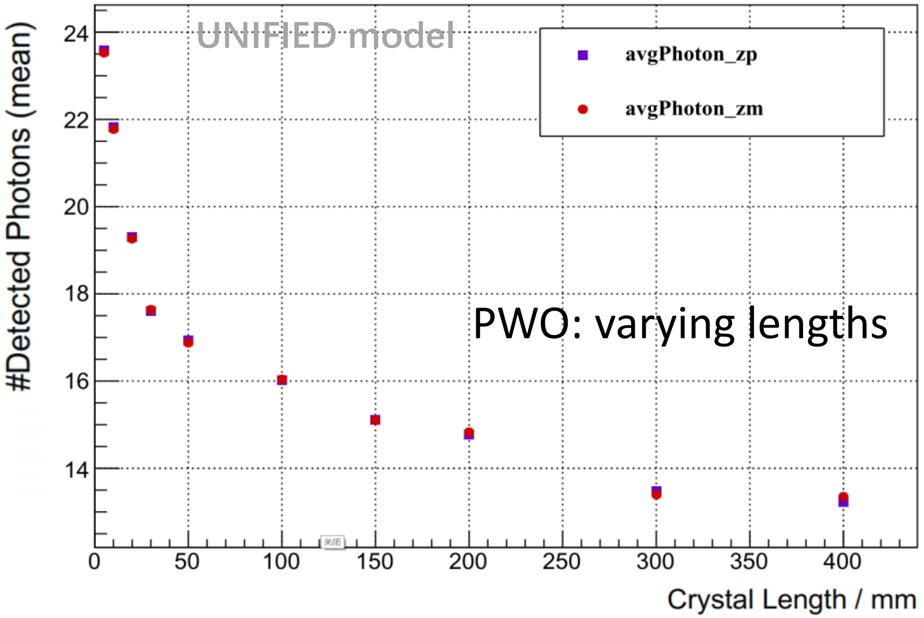
Impacts of crystal length

Geant4 Simulation (v10.7)

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







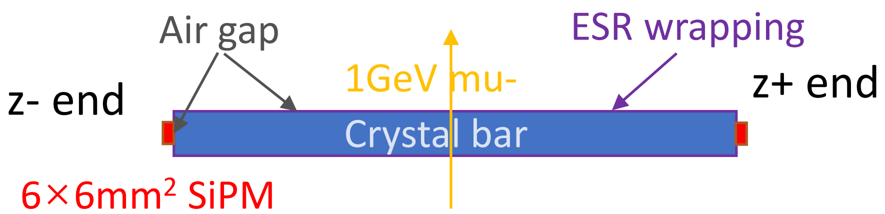
- MIP response significantly depends on crystal length
- Sufficiently high MIP response of 40cm long BGO

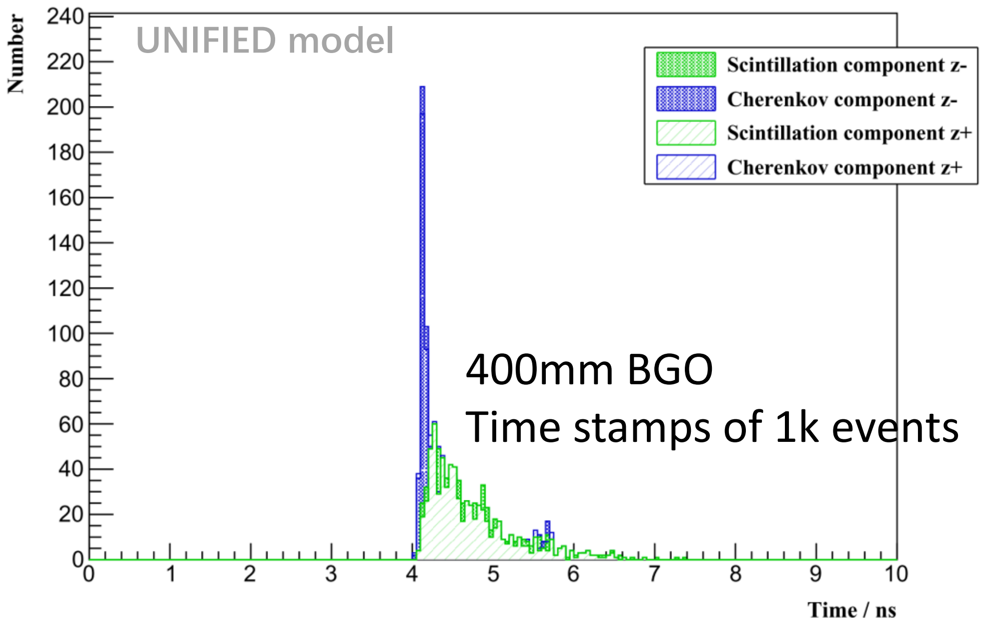
Light yield: 8200/MeV for BGO, 120/MeV for PWO
MIP energy deposition: ~ 9MeV (MPV)

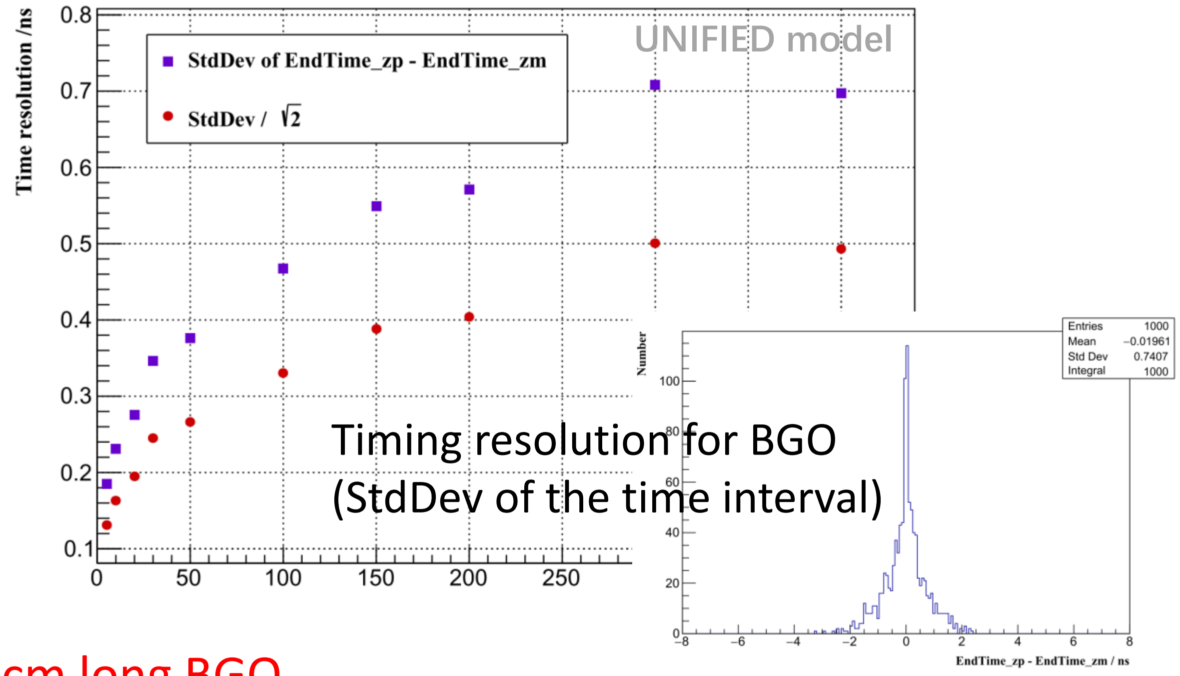
Impacts of crystal length

Geant4 Simulation (v10.7)

- Impact on timing: time stamps of the first detected photons
  - Muon shooting the crystal bar center
  - Crystal length varies from 5mm to 400mm
  - Crystal transverse size: $1cm^2$





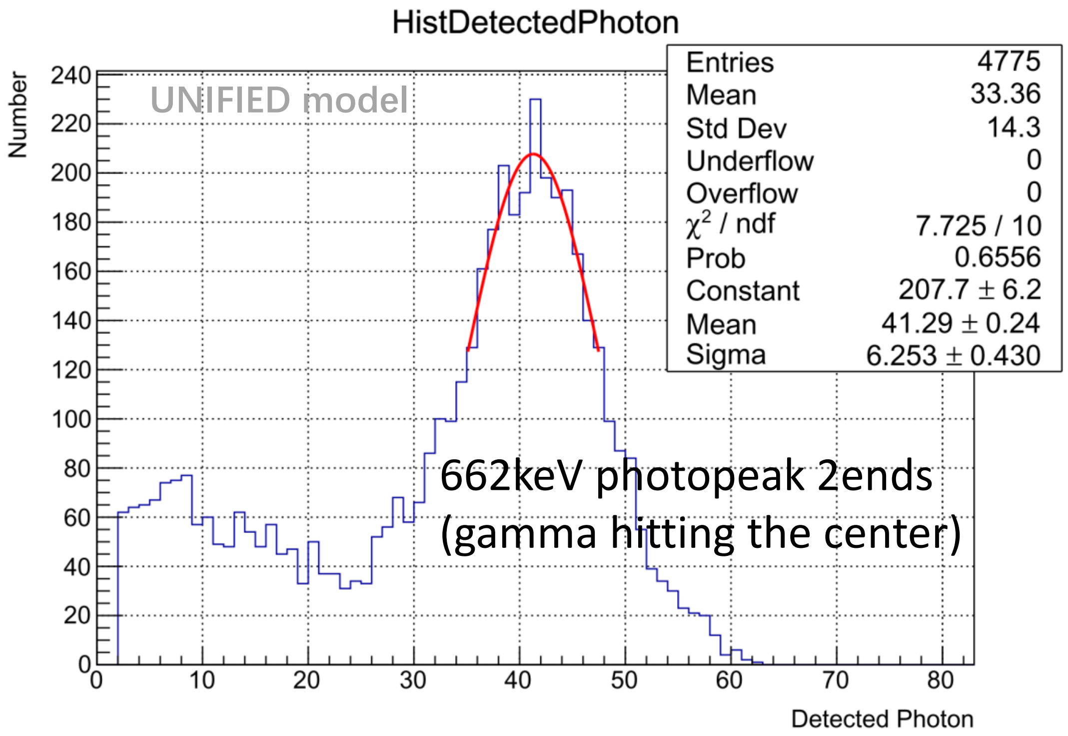


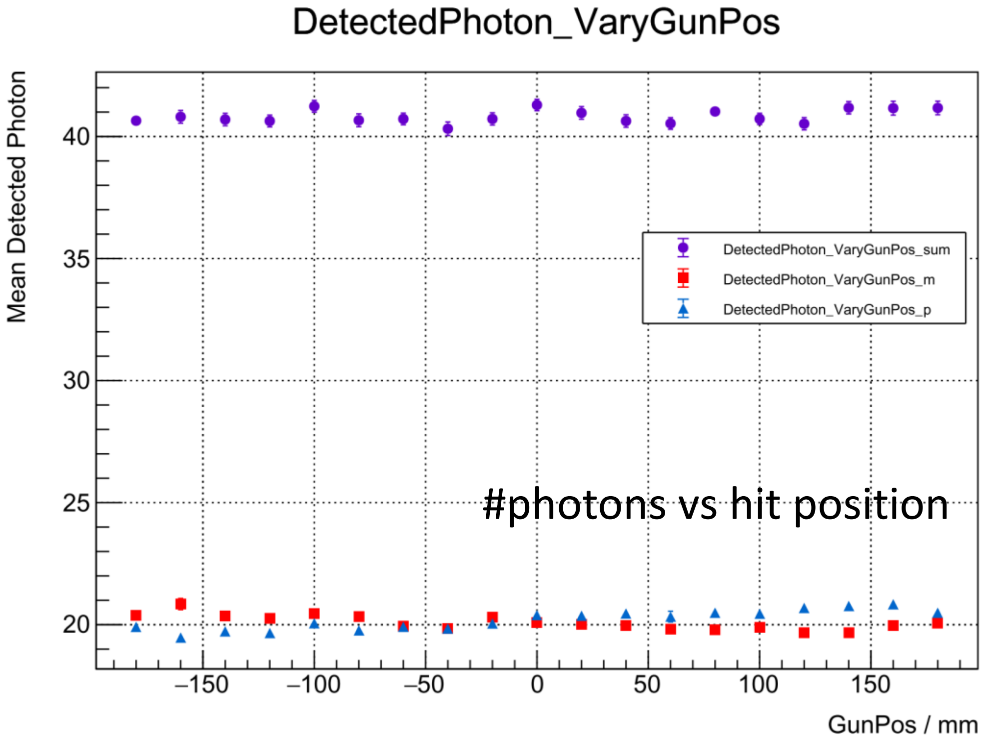
- 0.5~0.7 ns time resolution expected for 40cm long BGO
- Fast and slow components in time spectrum

Uniformity scan in simulation

Geant4 Simulation (v10.7)

- Uniformity scan: 662keV gamma for ^{137}Cs, change hit positions
  - 400mm BGO crystal bar, transverse size: $1cm^2$
  - Fit the 662keV photopeak to get corresponding #photons





- Generally good response uniformity expected in simulation

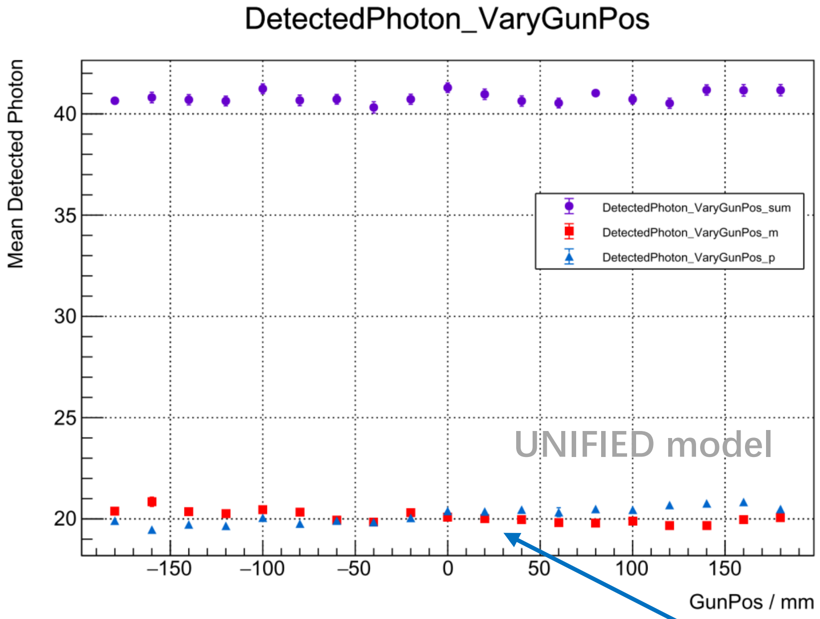
Comparison of different optical surface models

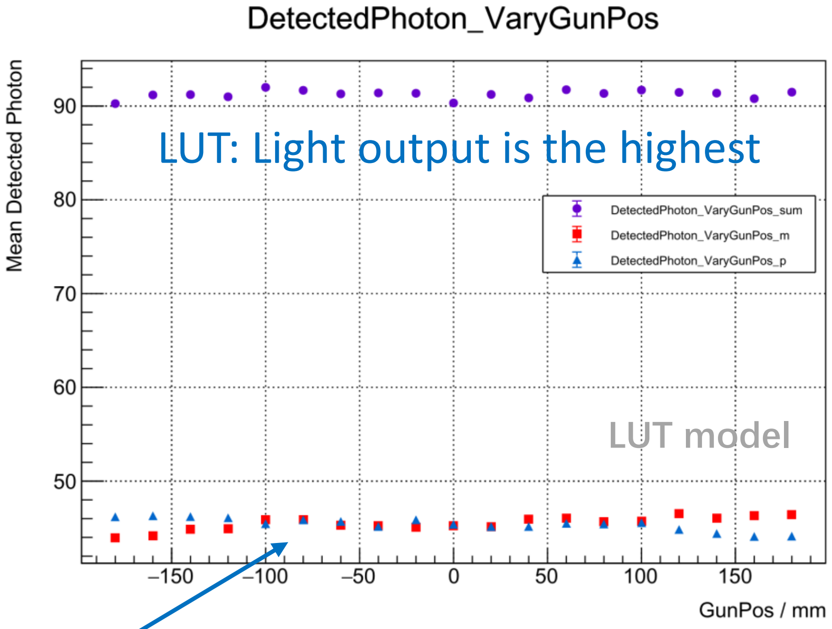
- 3 major models for optical properties in G4
  - UNIFIED model:
    - Based on analytical calculation and modelling of surfaces
    - Relatively fast and accurate
  - LUT model
    - Based on measurements (BGO crystal, hemisphere geometry)
  - LUT_DAVIS model
    - Based on measurements, with an emphasis on crystals for PET (e.g. LYSO)

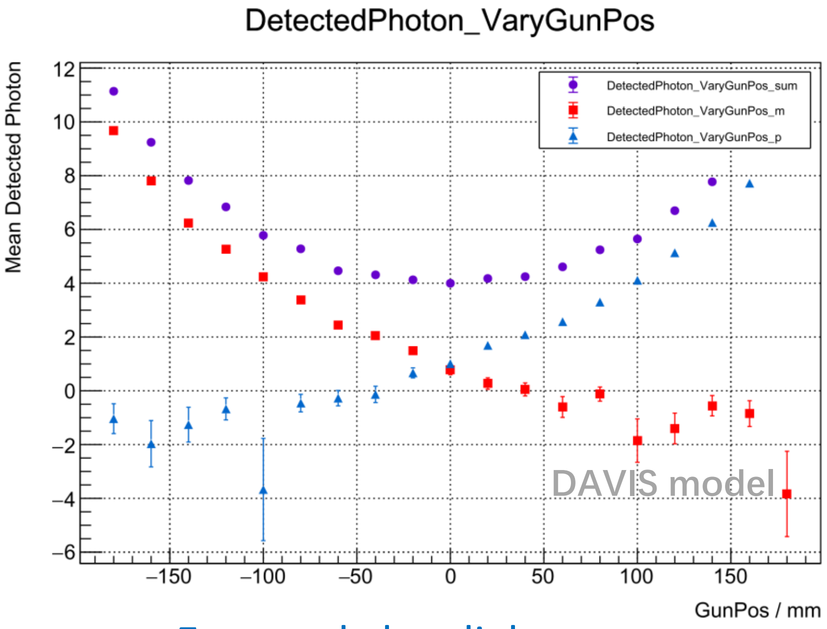
Comparison of different optical surface models

Geant4 Simulation (v10.7)

- Comparison of unified/LUT/DAVIS model on #photons detected
  - Simulation setup: similar to the uniformity scan







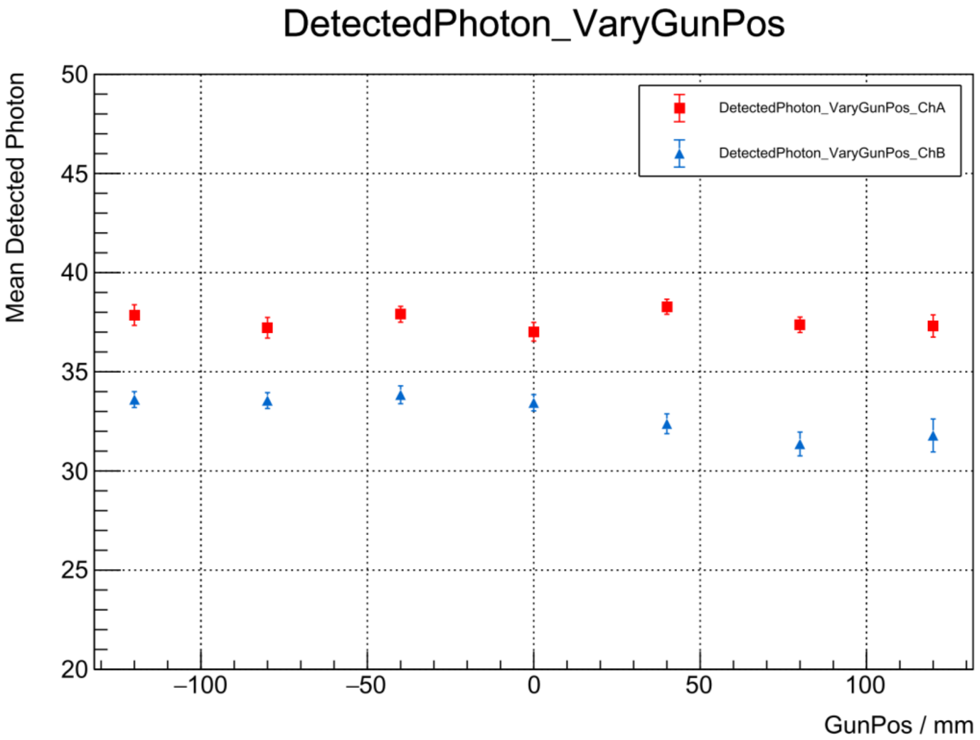
Extremely low light output

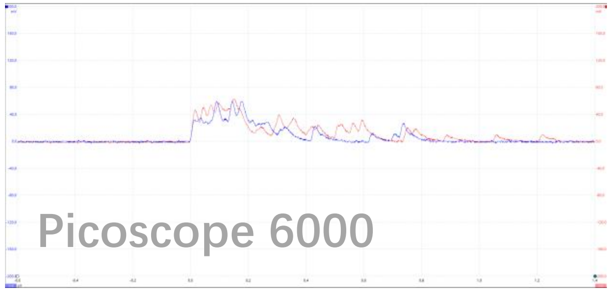
#photons detected by two sides:
Different trends? Need to be understood

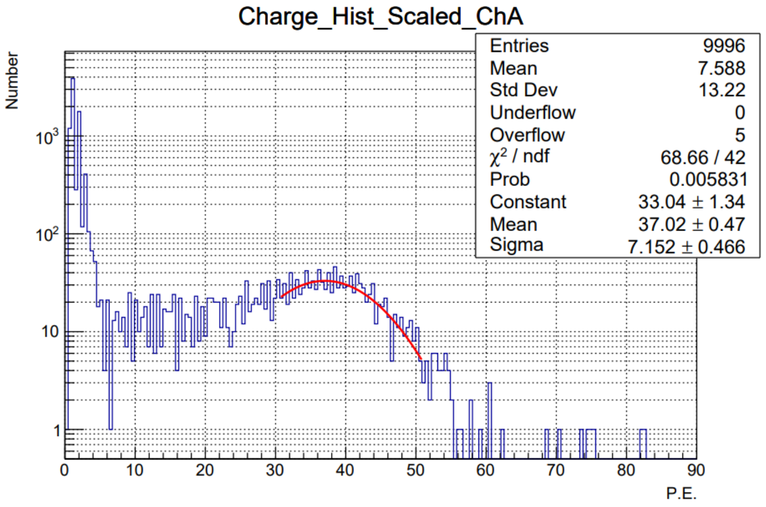
Negative values due to the Gaussian fit;
Poisson fit should be used instead, will be updated

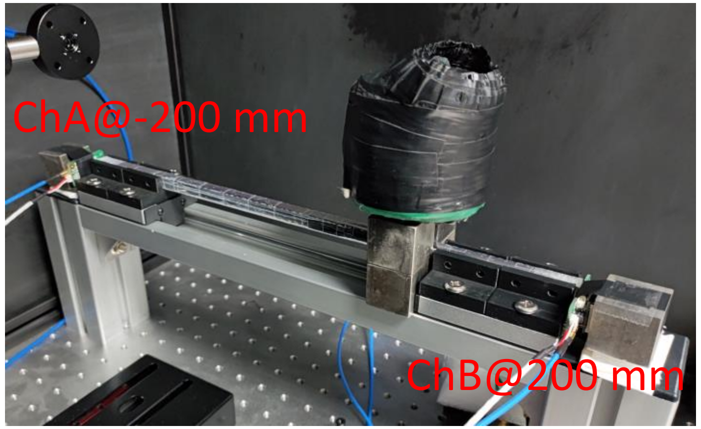
Comparison of different optical surface models

- Experiment: 400mm BGO crystal with ESR wrapping & ^{137}Cs
- The same configuration as the simulation









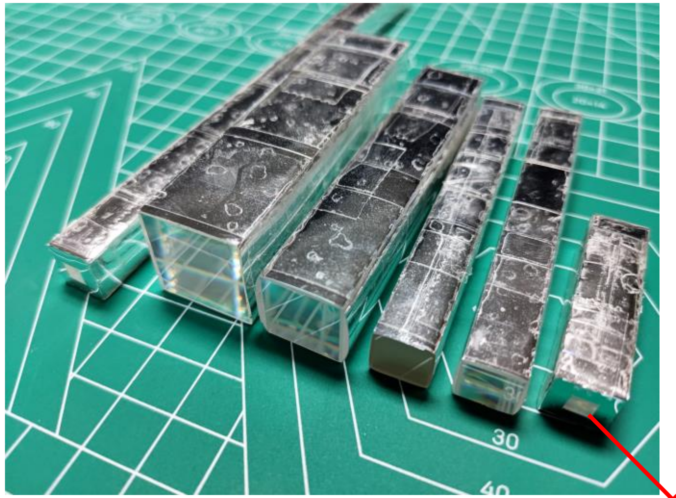
- Trends are not clear enough
- Systematic difference between 2 SiPMs
- Refractive index
  - Air: 1.00029
  - Epoxy: 1.52
  - BGO: 2.15

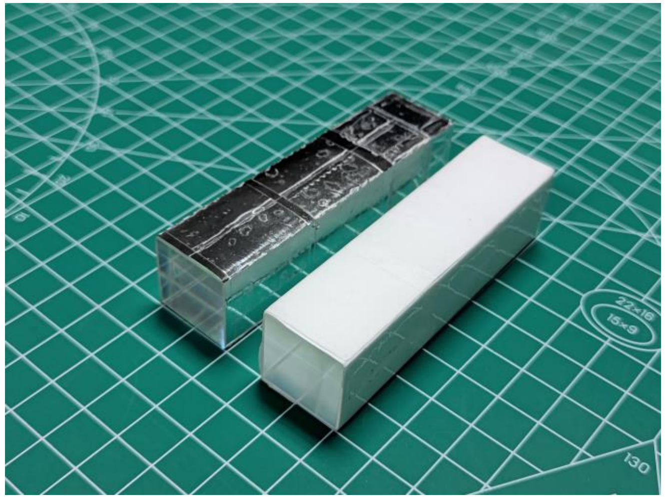
- Will use optical grease to improve the crystal-SiPM coupling and reproducibility

Measurements with BGO Crystals: energy spectrum

BGO Crystal:

- Length: 40/80/160mm
- Width: 20/15/10mm
- Surface: polished/ground
- Tyvek / ESR wrapping



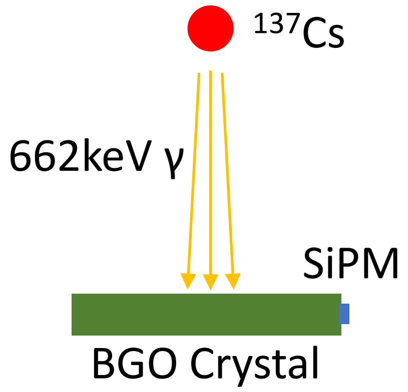


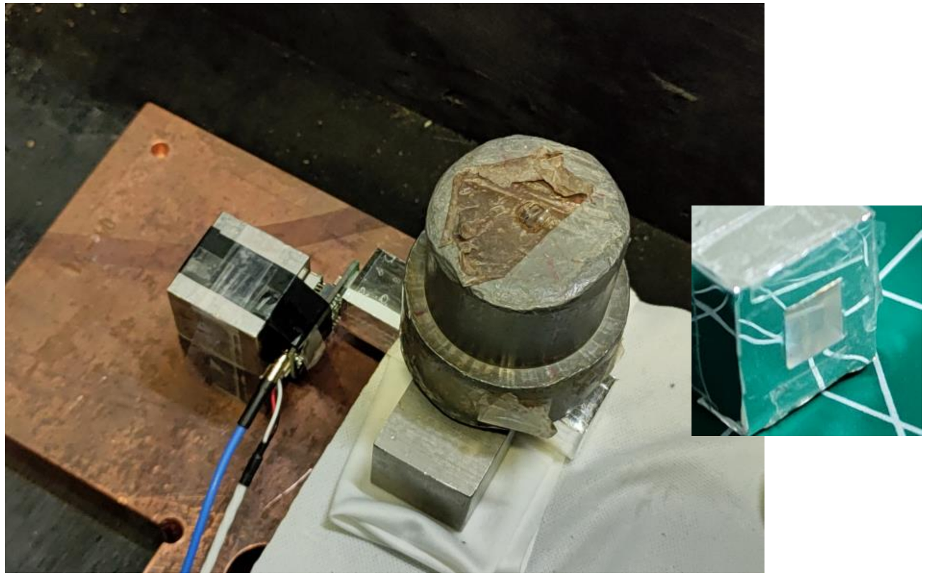
4×4mm^2 window for SiPM readoout

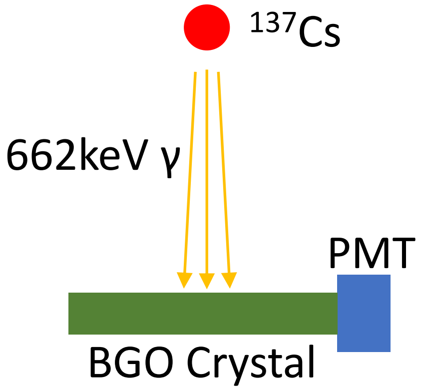
Photosensitive Device:

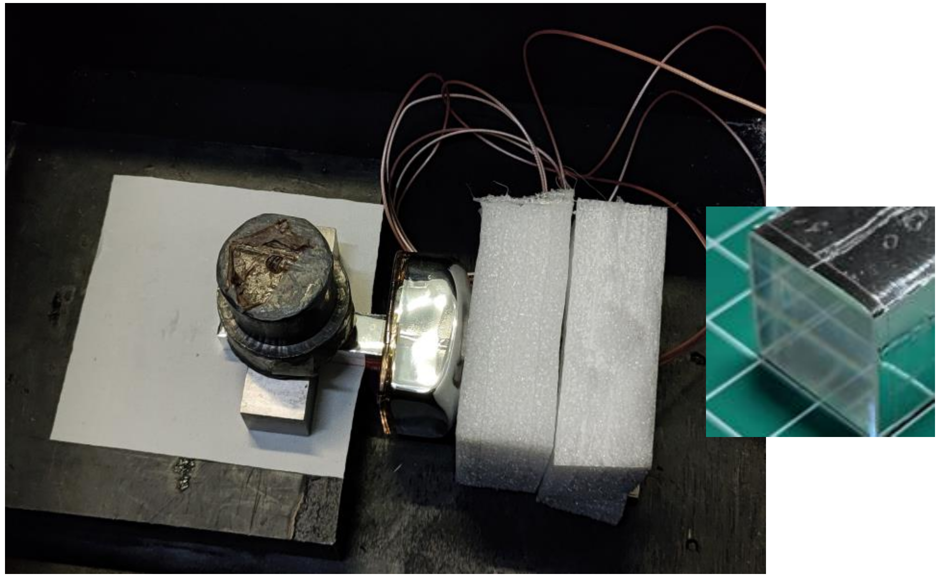
- SiPM & PMT
- SiPM: S13360-3050CS
  - 50μm pitch, 3×3mm^2, 3600 pixels
- PMT: R11065
  - 76mm (3”), gain: 5×10^6

Experiment setup with ^{137}Cs Radioactive Source

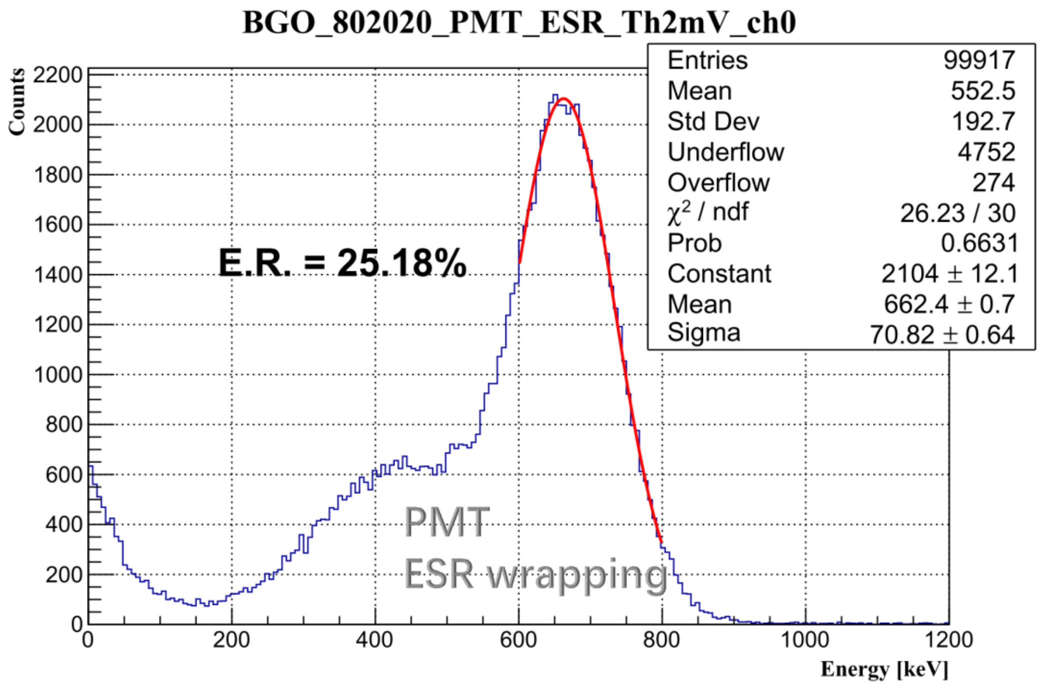


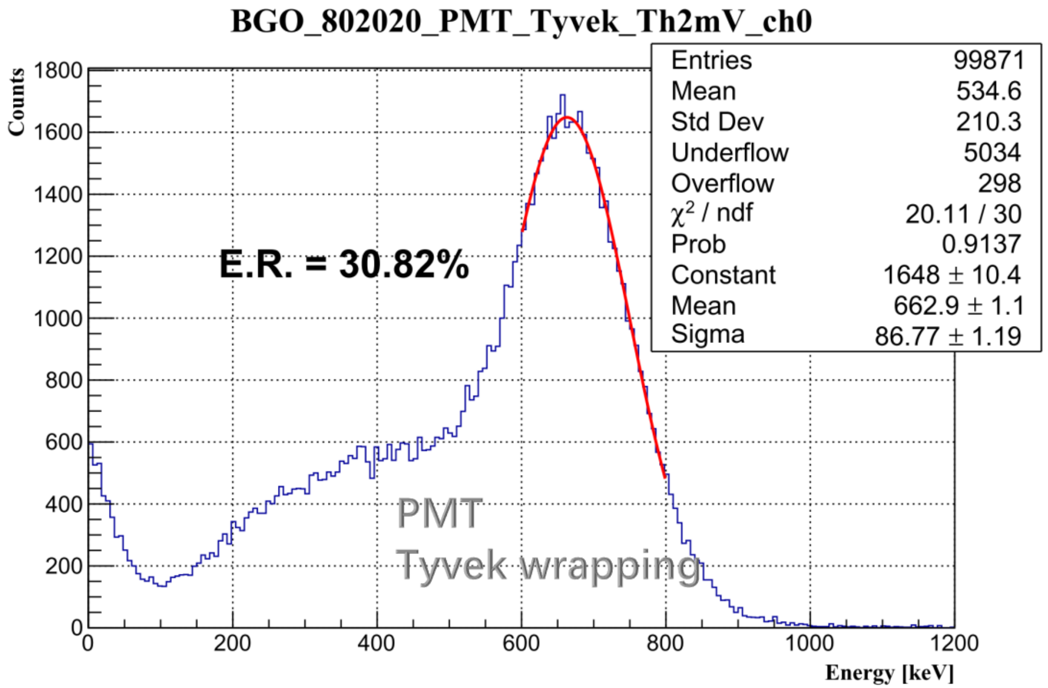






Impacts of wrapping & surface properties

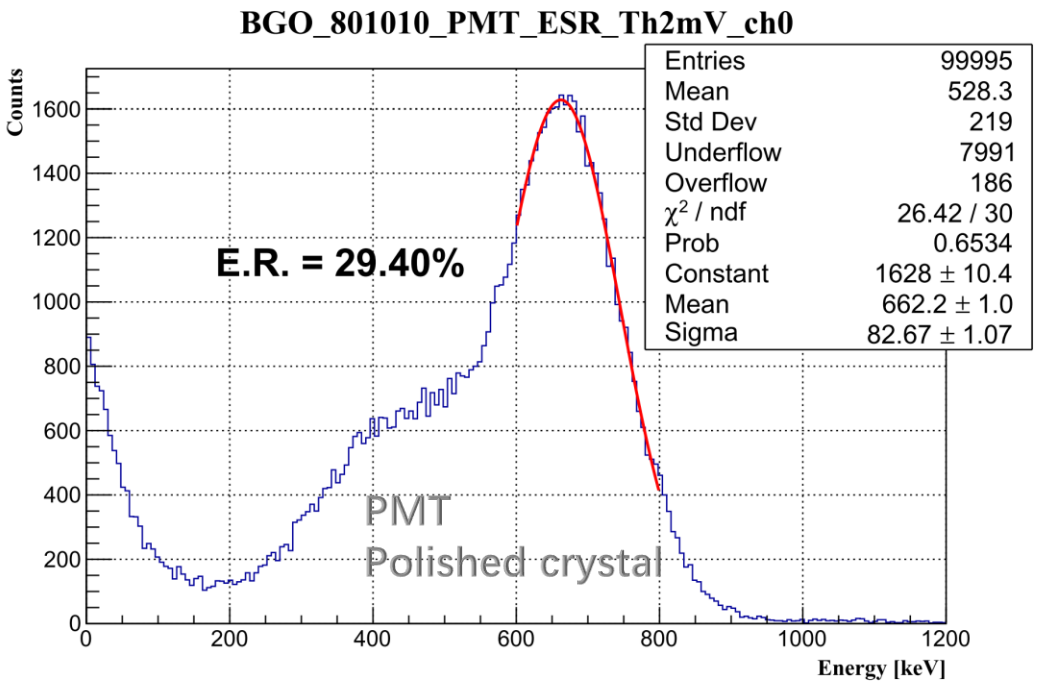


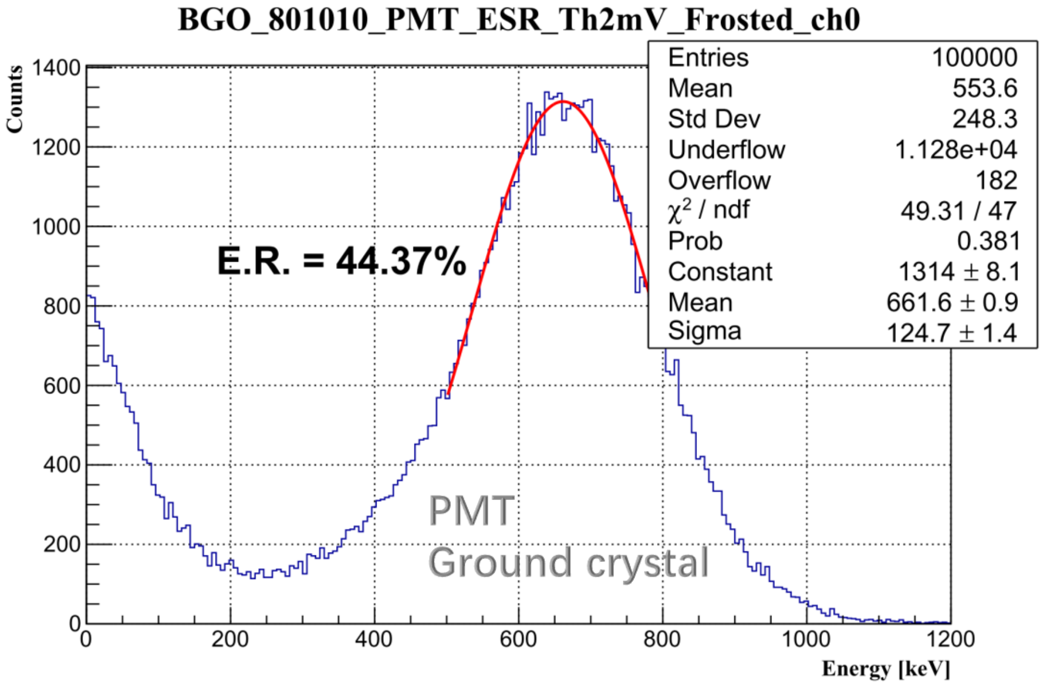


- ESR wrapping shows better energy resolution
  - Due to #photon detected is larger
  - ESR wrapping was chosen for the following experiments

Energy Resolution (E.R.) = $2.355\times\frac{\sigma}{mean}$, defined as FWHM

Impacts of wrapping & surface properties



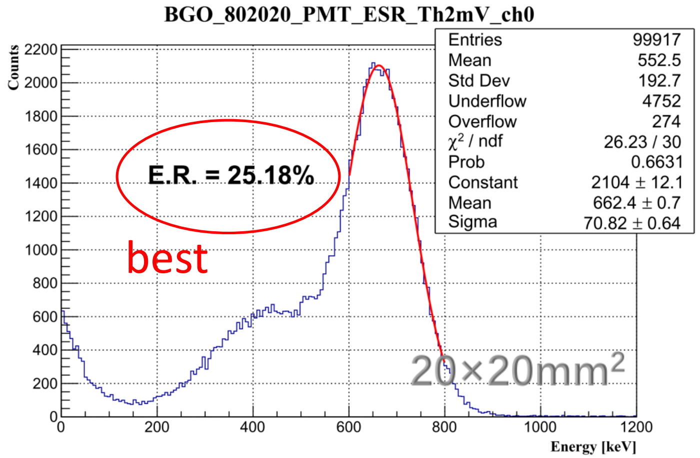


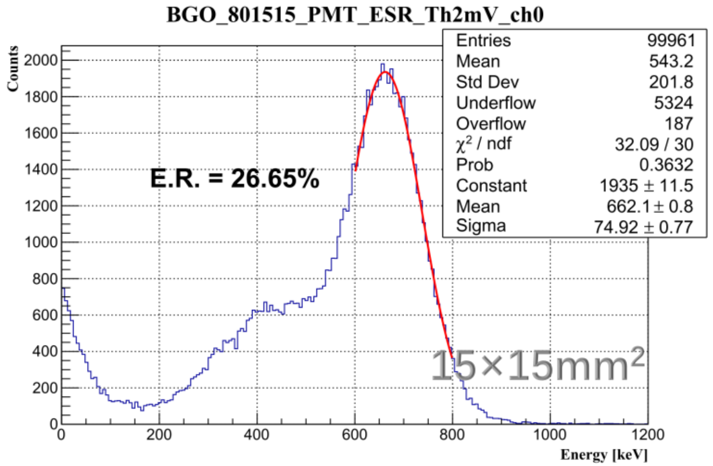
- The Compton plateau disappears in ground crystal
- Polished crystal has much better energy resolution
  - Due to #photon detected is larger

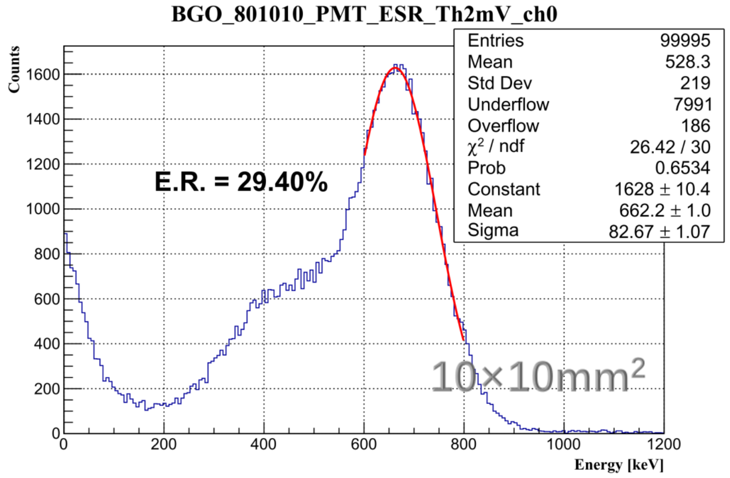
Energy Resolution (E.R.) = $2.355\times\frac{\sigma}{mean}$, defined as FWHM

Impacts of crystal transverse size

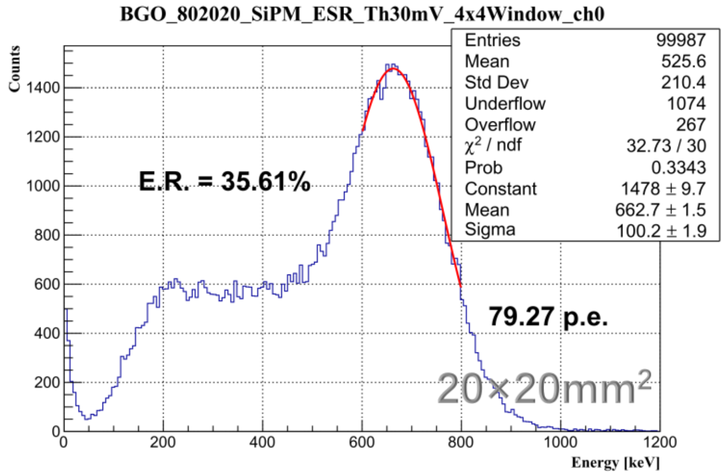
PMT

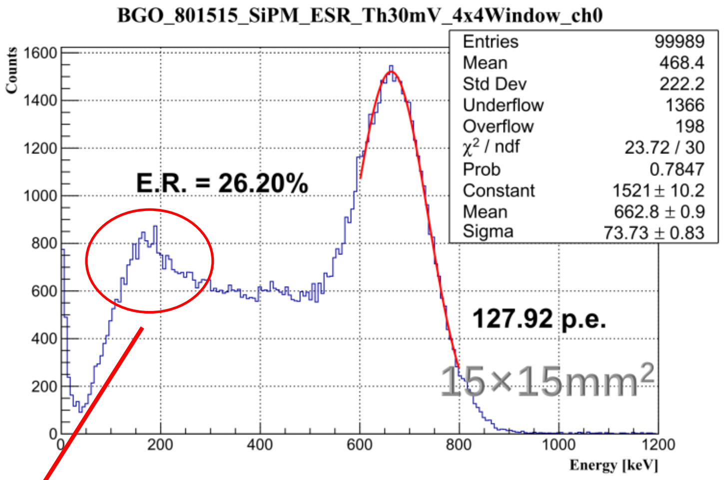


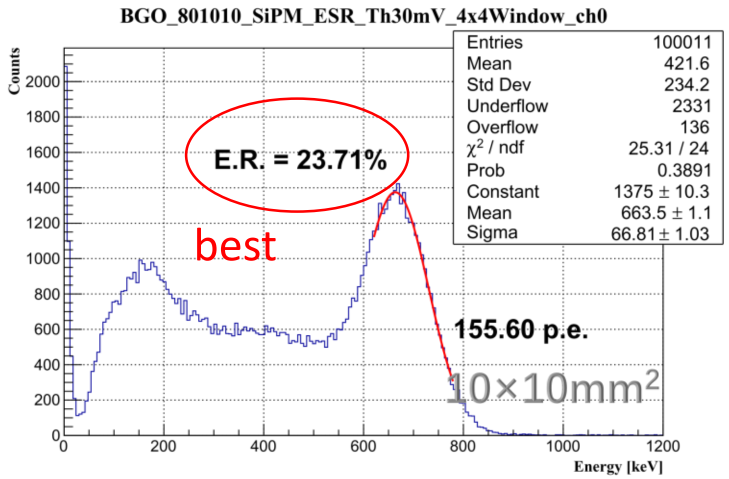




SiPM







180 keV Compton backscattering peak

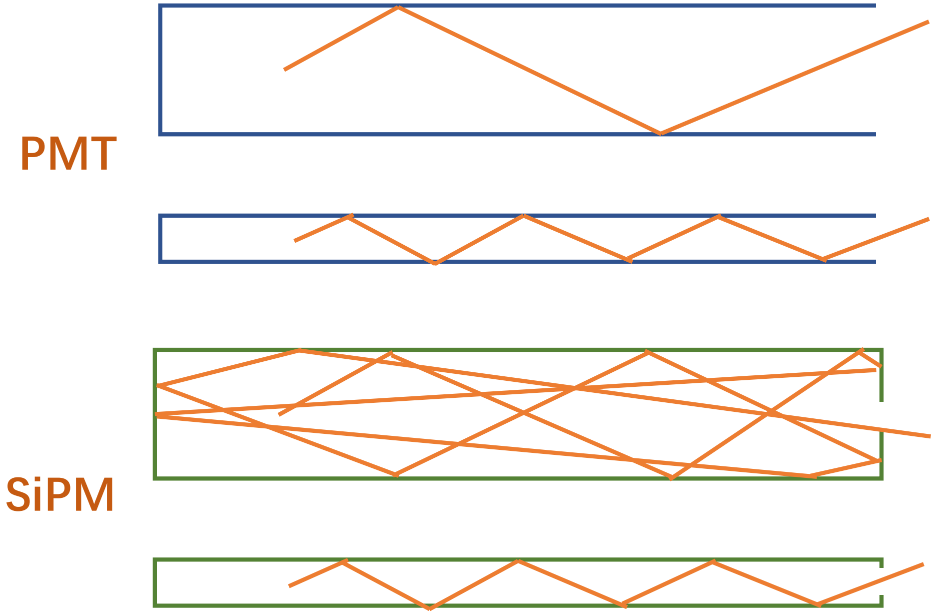
Energy Resolution (E.R.) = $2.355 \times \frac{\sigma}{mean}$, defined as FWHM

Impacts of crystal transverse size

	20×20	15×15	10×10
PMT	25.18%	26.65%	29.40%
SiPM	35.61%	25.20%	23.71%

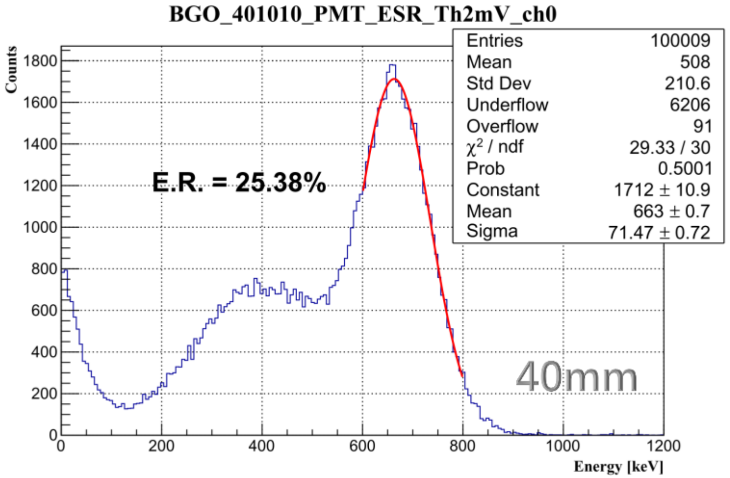
- PMT
  - 20×20mm^2 crystal has best E.R. and most photons detected
  - No Compton backscattering peak, maybe due to the threshold of discriminator
- SiPM
  - 10×10mm^2 crystal has best E.R. and most photons detected
  - 2 peaks at 662keV and 180keV

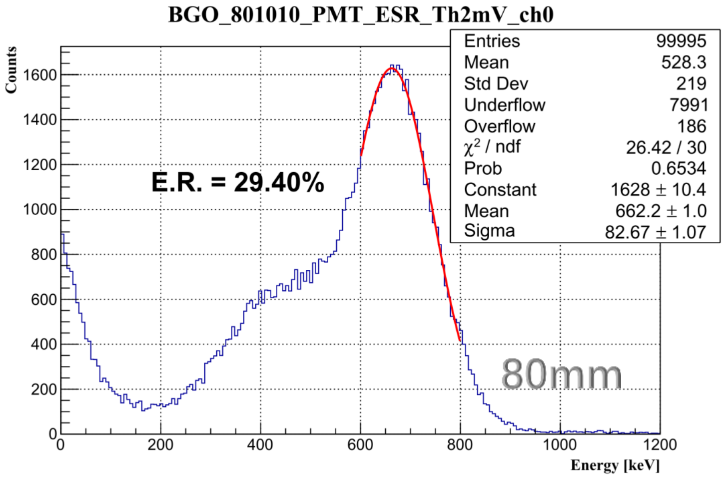
- An explanation of the different trends:
  - PMT: large transverse size, less reflection times
  - SiPM: small window size, bigger transverse size make the light output harder

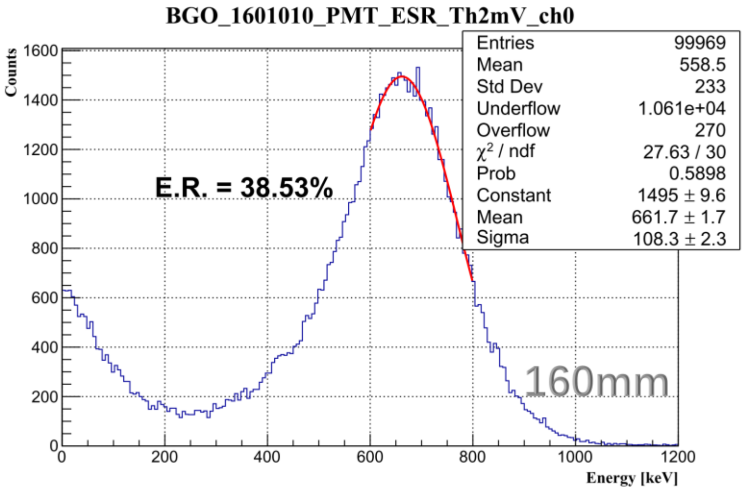


Impacts of crystal length

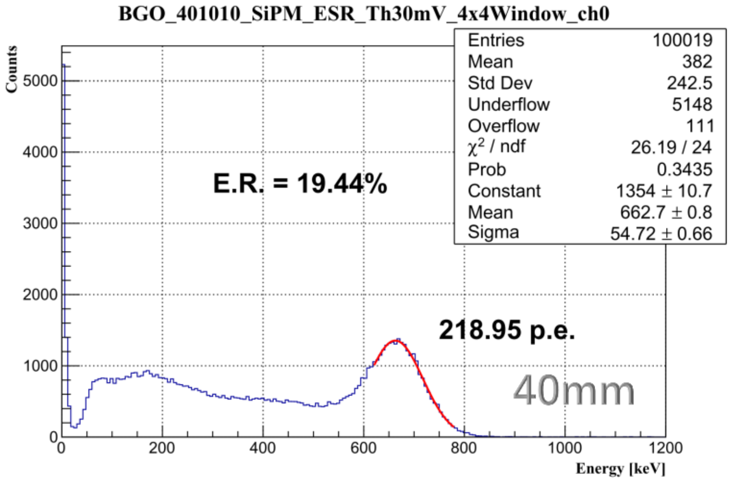
PMT

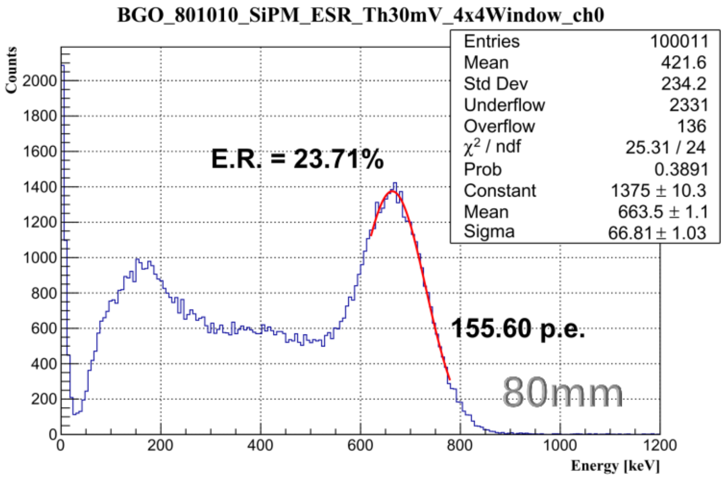


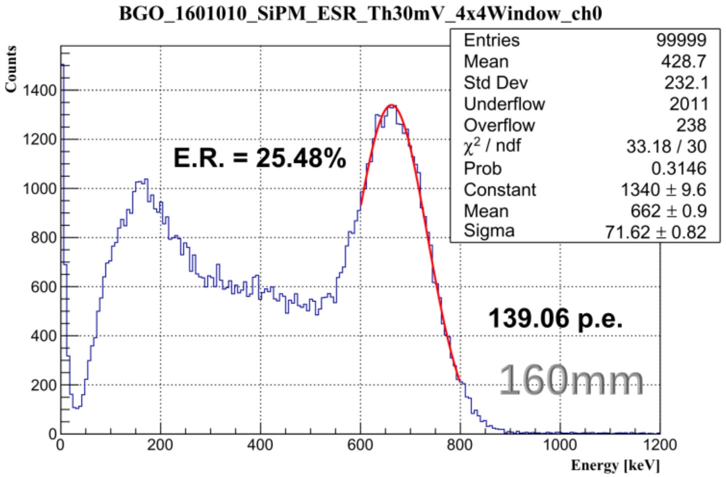




SiPM







Energy Resolution (E.R.) = $2.355\times\frac{\sigma}{mean}$, defined as FWHM

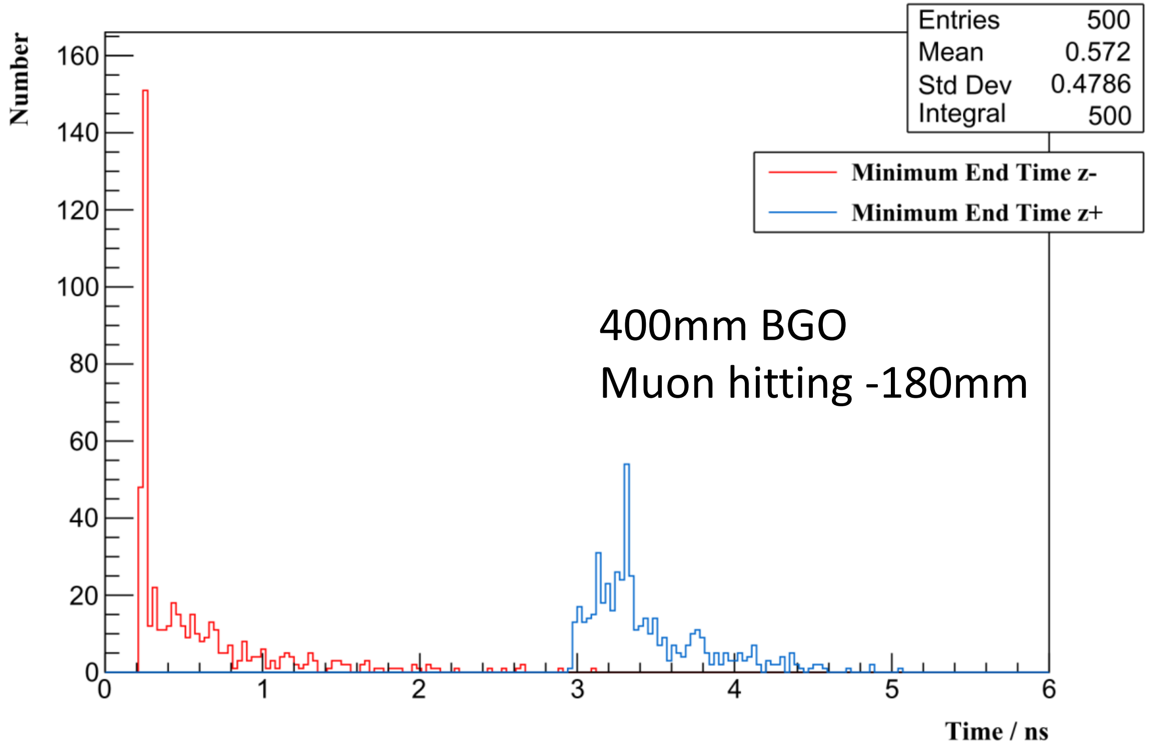
Conclusions

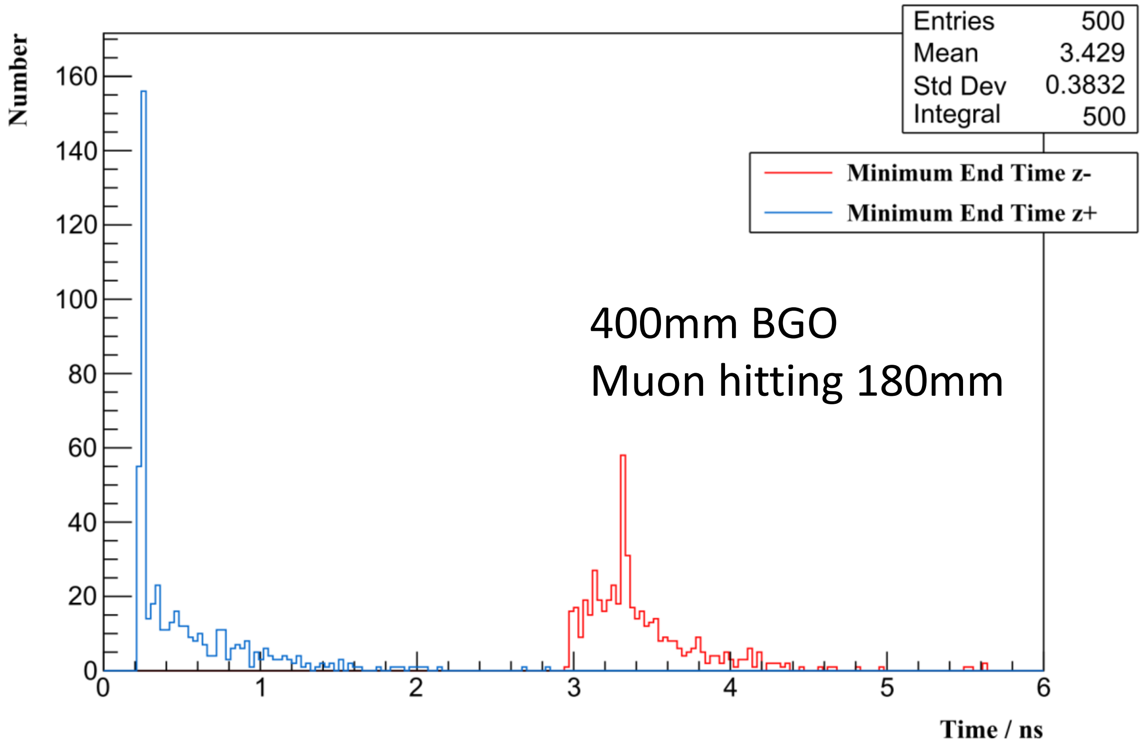
- MIP response significantly depends on crystal length
  - The #photons detected decreases exponentially with the length of the crystal
- 0.5~0.7 ns time resolution expected for 40cm long BGO
- Generally good response uniformity expected in simulation
- Optical model: both UNIFIED & LUT models can be used at present
- For crystal calorimeter, sensitivity to low energy photons at the order of 100 keV

Backup

Time stamps: varying hit position

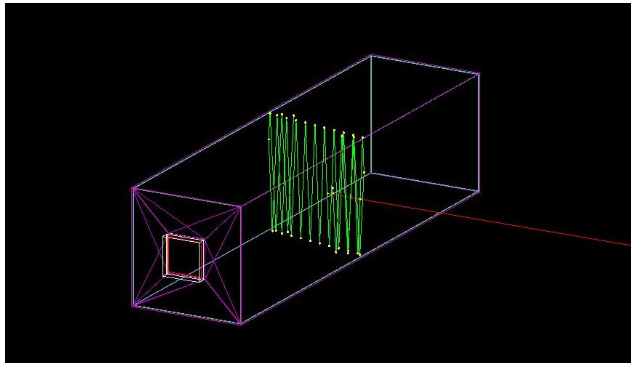
Geant4 Simulation (v10.7)

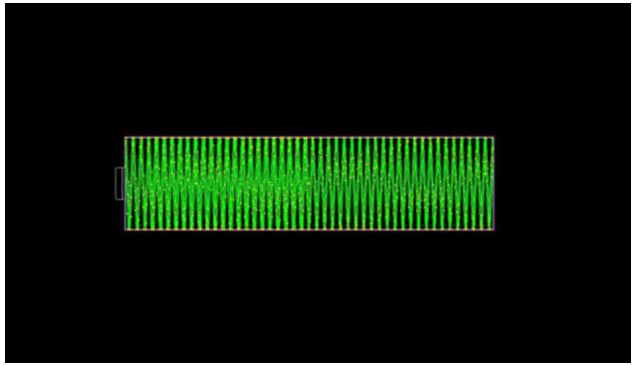




Comparison of different optical surface models

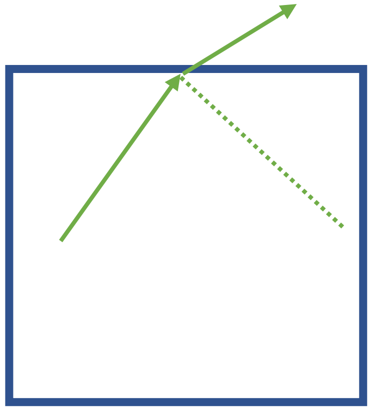
- Drawback of unified model with ideally polished surface: trapped photons





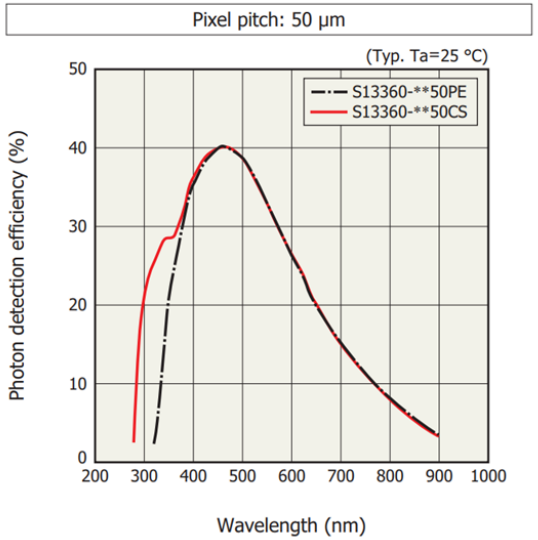
- Due to the ideal configuration in the UNIFIED model

- Drawback of LUT model: wrong direction of reflected photons

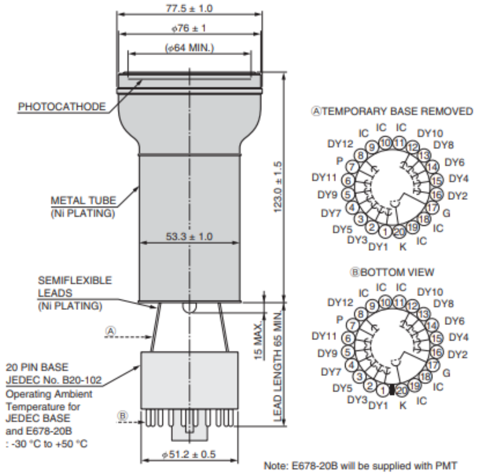


- Some reflected photons transmit towards outside of the crystal bar
- Need more studies

Photosensitive Device: SiPM & PMT



- Module: C13365-3050SA
- SiPM: S13360-3050CS
- 50μm pitch, 3mm×3mm, 3600 pixels
- ±5V power supply
- Auto bias adjustment
- Built-in temperature probe
- PDE: 40%max@450nm



- PMT: R11065
- Diameter: 76mm (3")
- Spectrum: 200~650nm
- Typically 1500V power supply
- Q.E. at peak: 25%
- Gain: 5×10^6