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High-granularity Crystal Calorimeter: R&D Status and Highlights

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on behalf of CEPC Calorimeter Working Group

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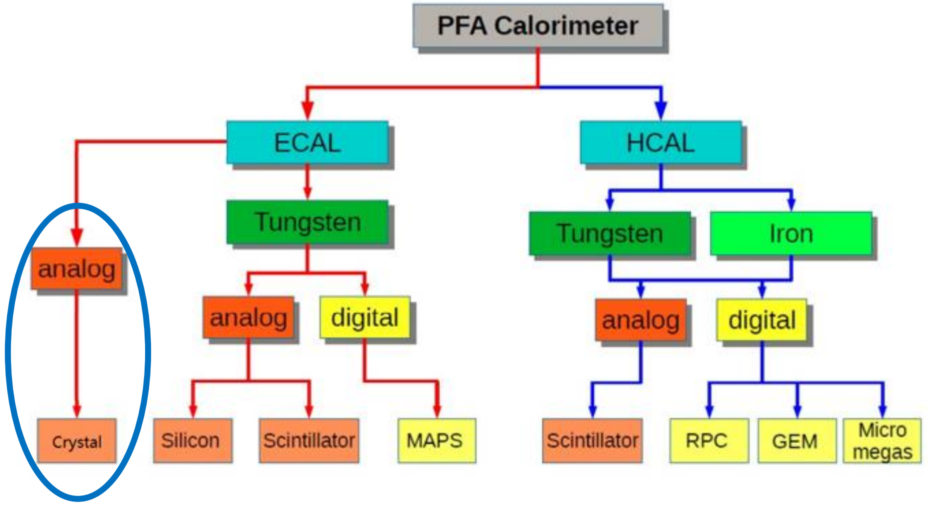
Motivations

- Background: calorimeter for future lepton colliders (e.g. CEPC)
  - Precision measurements with Higgs and Z/W
  - Jet energy resolution of 3-4%@100GeV is required
  - Particle flow approach: high-granularity calorimeter
- Why crystal calorimeter?
  - Homogeneous structure
    - Intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Energy recovery of electrons: to improve Higgs recoil mass
  - Capability to trigger single photons: precision γ/π^0 reconstruction

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	$\frac{\Delta E}{E} = \frac{0.20}{\sqrt{E(GeV)}} \oplus 0.01$


PFA Calorimeter

ECAL

HCAL

analog

Tungsten

Tungsten

Iron

analog

digital

analog

digital

Crystal

Silicon

Scintillator

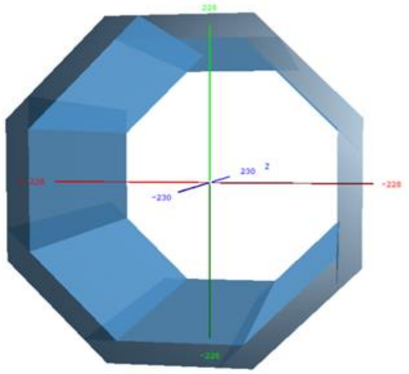
MAPS

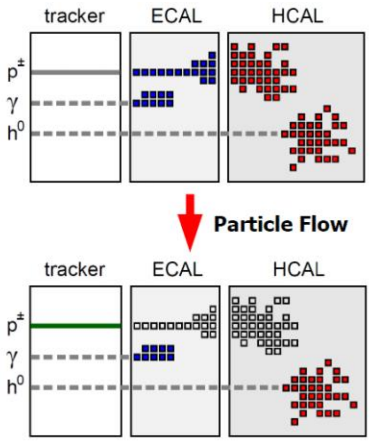
Scintillator

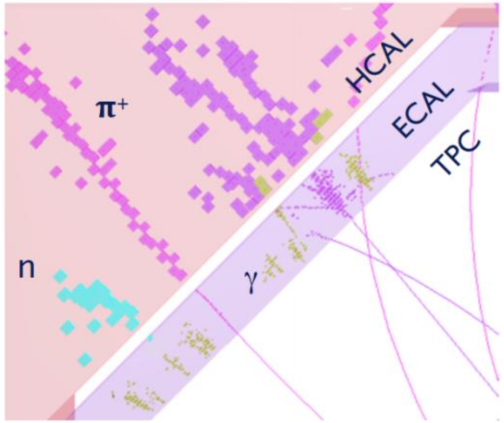
RPC

GEM

Micro megas



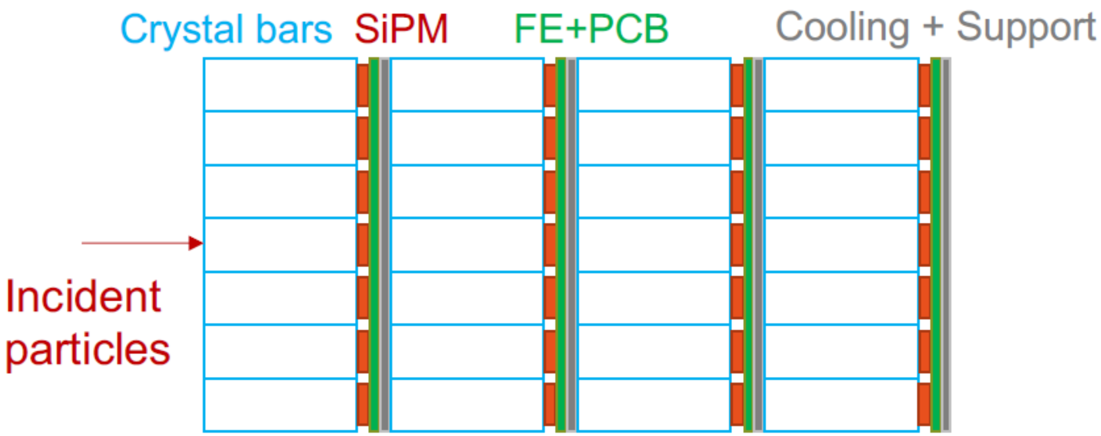




Crystal ECAL: 2 major designs

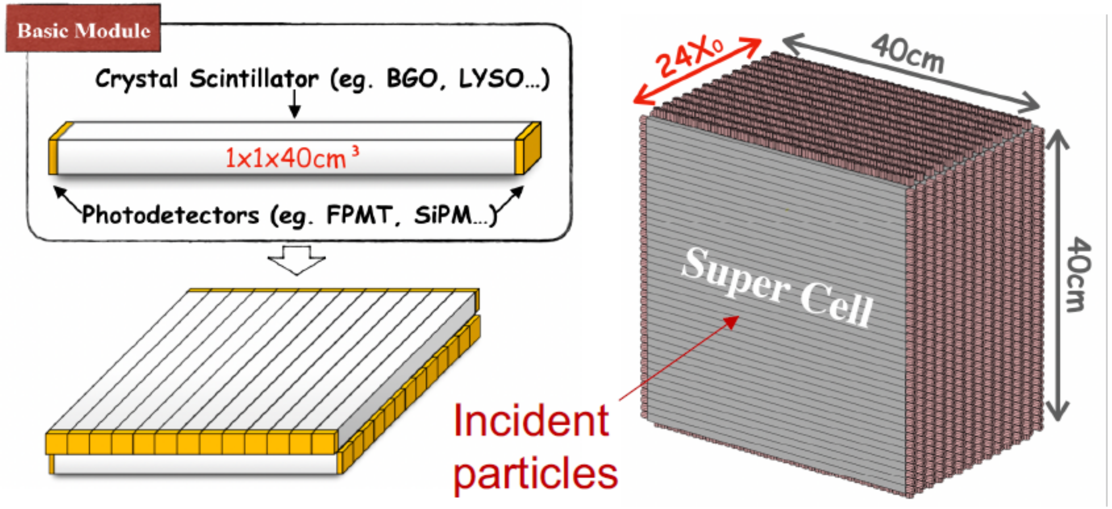
Our major concern

Design 1: short bars



- A natural design compatible with PFA
  - Fine segmentation in Both longitudinal and transverse
  - Single-ended readout with SiPM

Design 2: long bars



- Long bars: 1×40cm, double-sided readout
  - Super cell module: 40×40cm
  - Crossed arrangement in adjacent layers
  - Fine longitudinal granularity
- Save #channels and minimize dead materials
- Timing at two sides: positioning along bar

Overview of this report: R&D status and highlights on key issues

- Updates on crystal ECAL performance studies
  - EM energy resolution: threshold and light yield requirements
  - Arbor-PFA performance
    - Separation power: two close-by particles
    - Reconstruction of π^0: invariant mass resolution
    - Higgs benchmark ZH ($Z \rightarrow \nu\nu, H \rightarrow \gamma\gamma$)

- Reconstruction algorithm for long bar design
  - Status and preliminary performance studies

- Detailed studies on crystal performance
  - Geant4 full simulation of a single crystal bar
    - Response uniformity scan / optical surface models
  - Measurements on BGO crystal
    - Energy resolution and response uniformity: radioactive source test
    - Cosmic ray test: MIP response

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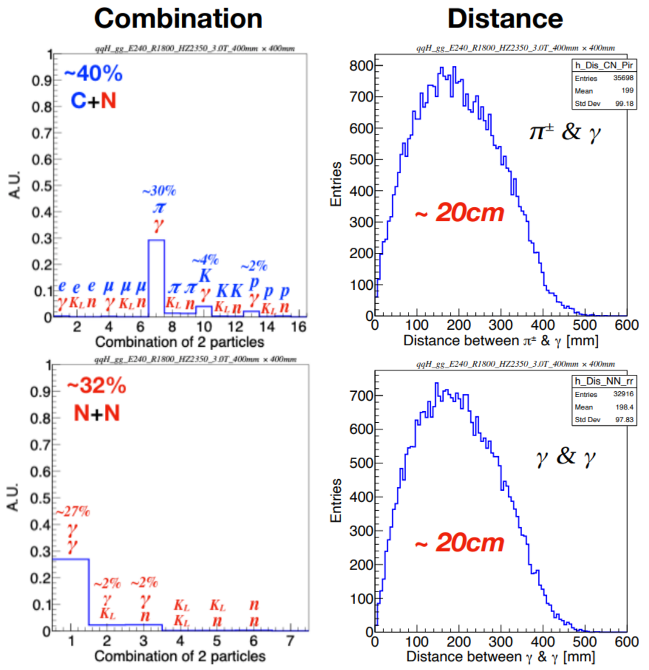
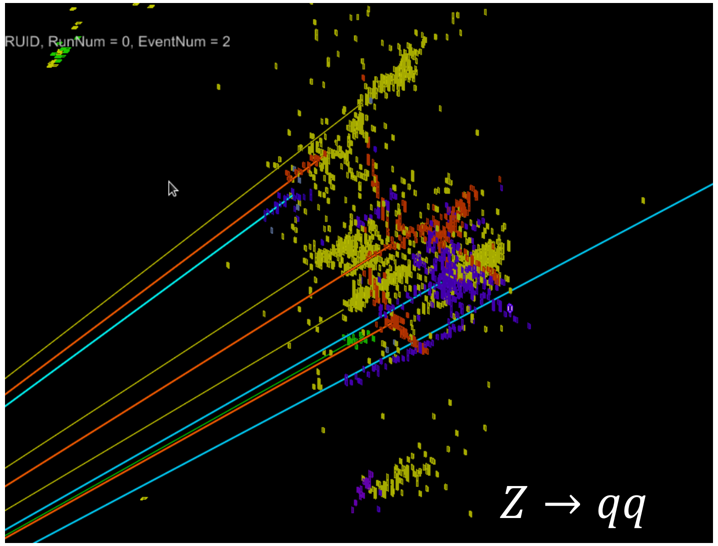
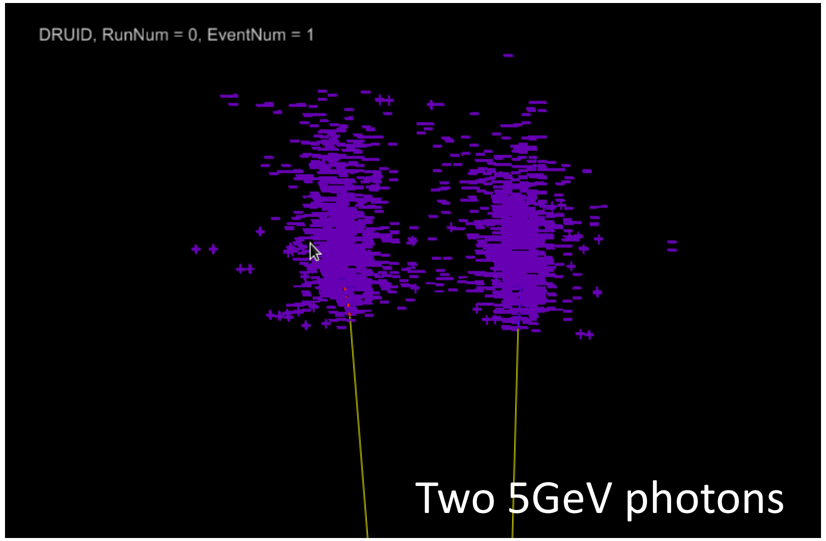
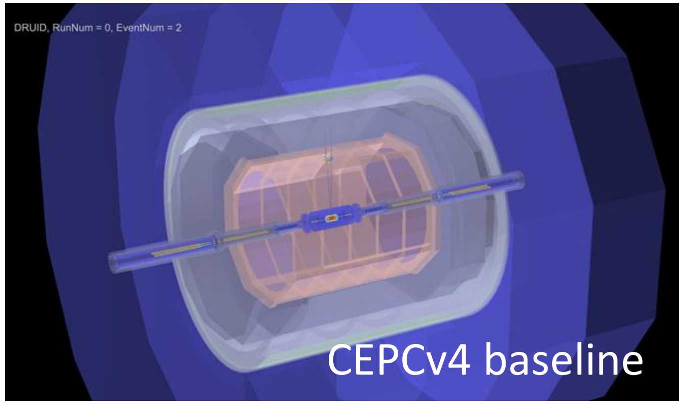
Crystal ECAL with the Arbor-PFA: overview

- Adapted from CEPCv4 baseline detector
  - Finely segmented crystal ECAL: 1cm^3 cubes (ideal)
  - Suitable for Arbor-PFA
- Event display
  - Impressions of topology of EM/hadron showers within jets
- Reconstruction of jets
  - EM/hadron showers → particle combinations → C(charged)+N(neutral)/N+N
  - γ/γ separation, $\pi^{\pm}/\gamma$ separation



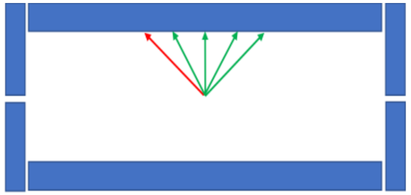




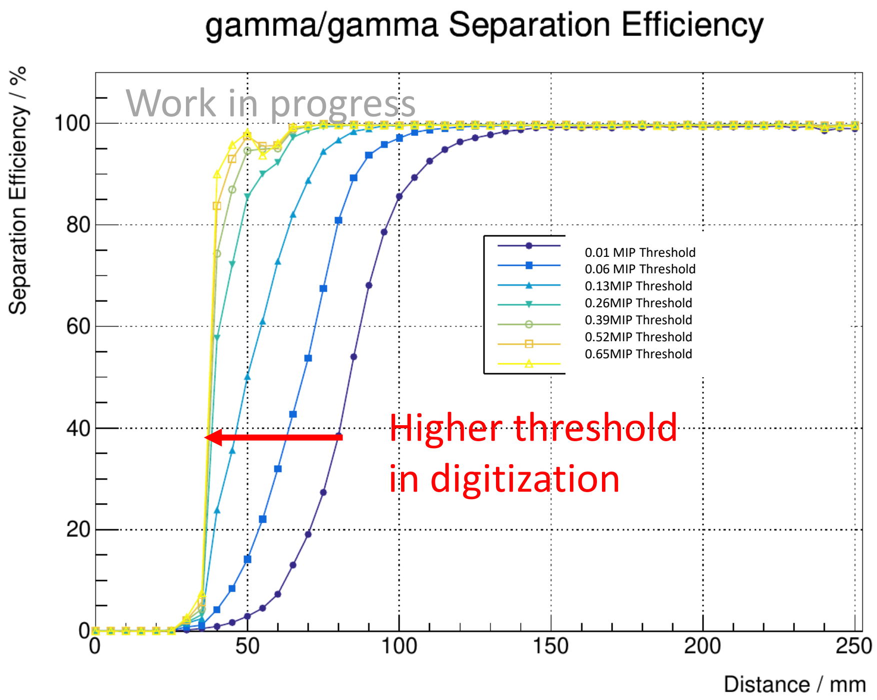


Crystal ECAL with the Arbor-PFA: separation power

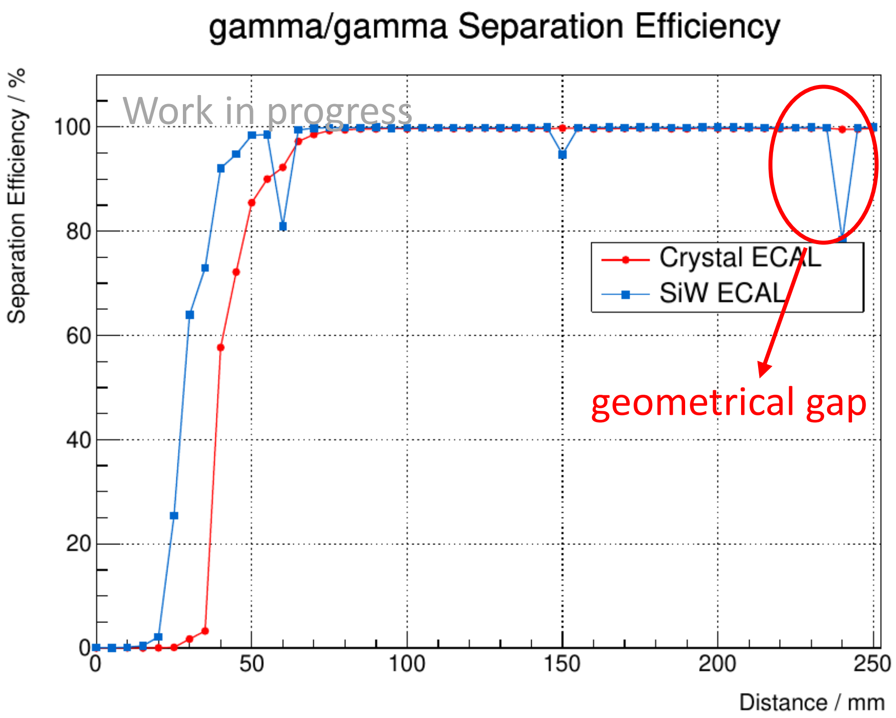
- Adapted from CEPCv4 baseline detector: SiW ECAL
    - Finely segmented crystal ECAL: suitable for Arbor-PFA
- Separation power of two close-by particles:
    - γ/γ: two neutral EM showers



Two 5GeV γ, vary distance
Success reconstruction: 3.3GeV<E_γ<6.6GeV
Events that γ decays in tracker removed



Higher threshold in digitization



geometrical gap

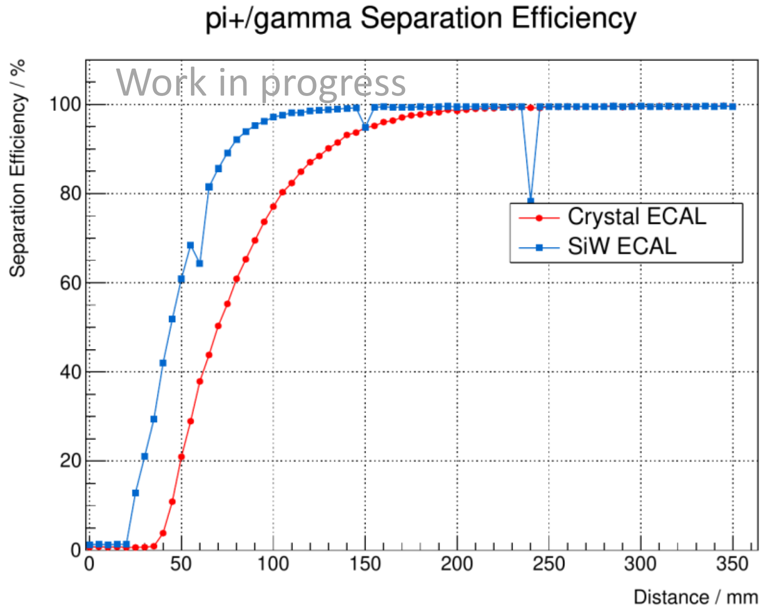
Threshold: SiW ~0.36MIP (default), crystal ~0.26MIP

- High threshold corresponding to good separation power
- Space for improvement: ongoing studies on PFA (threshold, parameters for bush connect and clustering…)

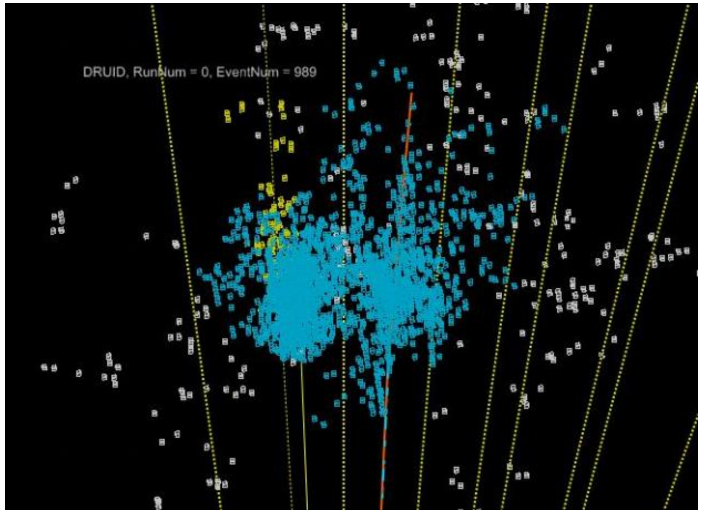
Crystal ECAL with the Arbor-PFA: separation power

- Adapted from CEPCv4 baseline detector: SiW ECAL
  - Finely segmented crystal ECAL: suitable for Arbor-PFA
- Separation power of two close-by particles:
  - π^{+}/γ: charged particle and neutral particle
  - Matching clusters of charged particle to the tracking detector

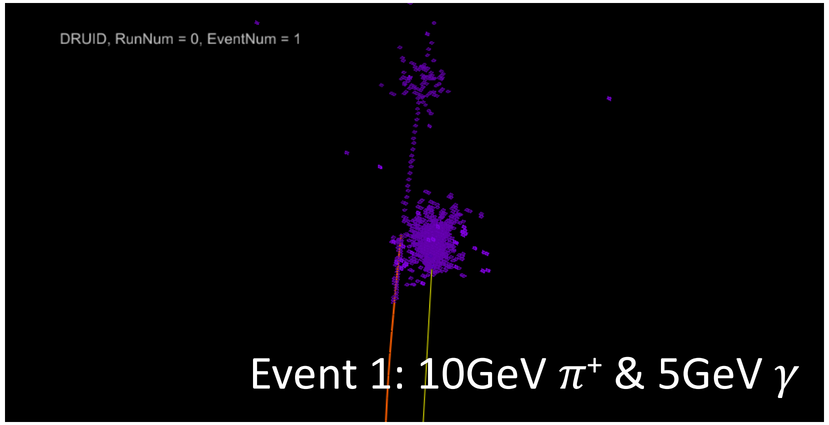
10GeV π^{+} and 5GeV γ, 3T magnetic field, vary distance
Success reconstruction:
3.3GeV<E_{γ}<6.6GeV, 9.9GeV<$E_{\pi+}$ <10.1GeV
Events that π^{+}/γ decays in tracker removed

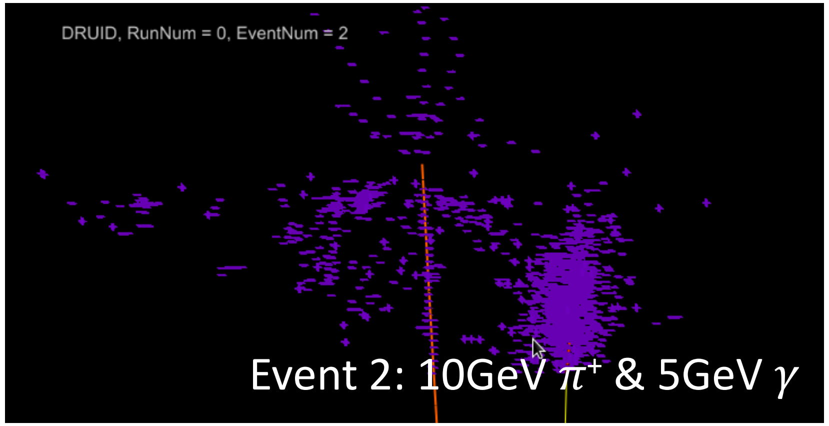


Threshold: SiW ~0.36MIP (default), crystal ~0.26MIP



- Failure: The cluster of photon (left) was merged into the cluster of π+ (right)



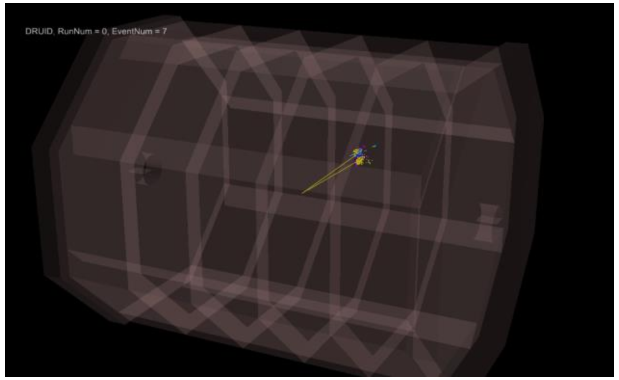


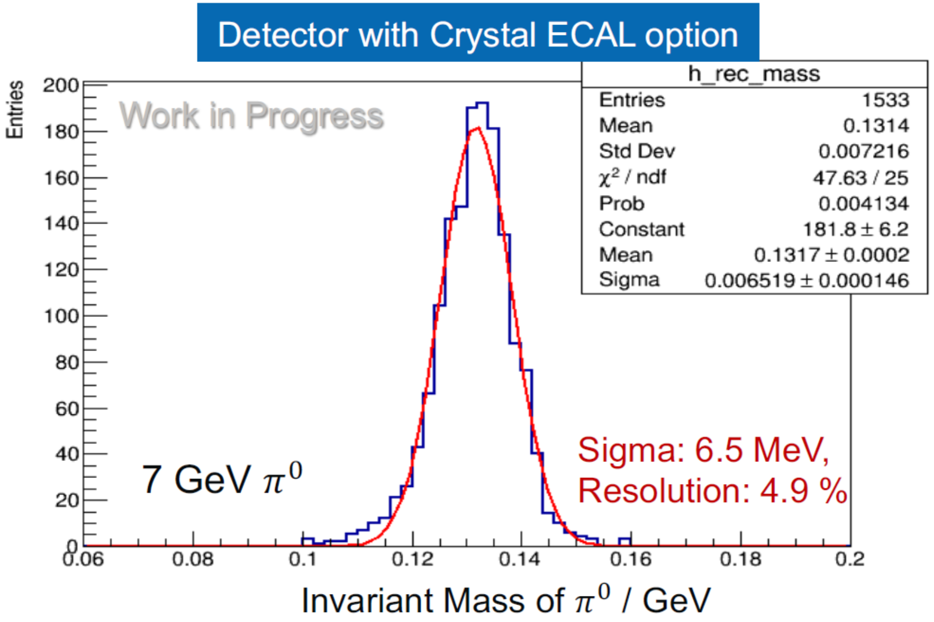
- Hadronic showers: challenge on clustering
- Improvement: use energy information, shower profile…

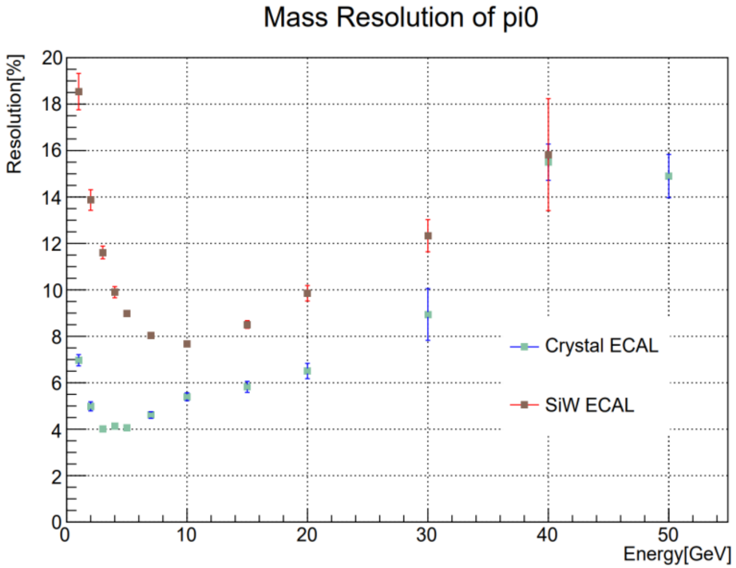
Crystal ECAL with the Arbor-PFA: reconstruction of π^0

Zhiyu Zhao (IHEP/SJTU)

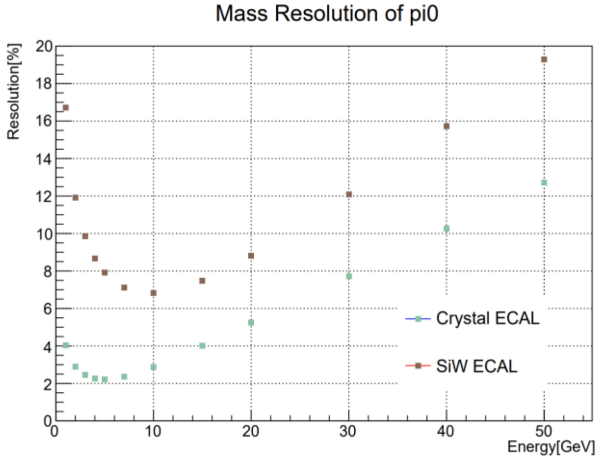
- Adapted from CEPCv4 baseline detector: SiW ECAL
  - Fine granulated crystal ECAL: suitable for Arbor-PFA
- Reconstruction of π^0: invariant mass resolution
  - $\pi^0 \rightarrow \gamma\gamma$: contributions from γ energy resolution & angle between 2γ







$$\frac{\delta m_0}{m_0} = \frac{\delta E_1}{2E_1} \oplus \frac{\delta E_2}{2E_2} \oplus \cot\frac{\alpha}{2}\frac{\delta\alpha}{2}$$



- Crystal: π^0 better mass resolution
- Low energy part: γ energy resolution dominate; high energy part: angle dominate
- Trend is similar to theoretical calculation result

- Theoretical calculation: $E_1 = E_2 = \frac{E_0}{2}$, $\alpha = \alpha_{\min}$, $\delta\alpha_{Crystal} = 0.04°$, $\delta\alpha_{SiW} = 0.06°$

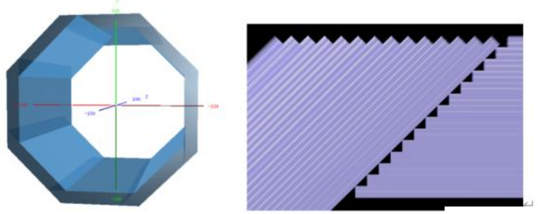
Crystal ECAL with the Arbor-PFA: Higgs benchmark

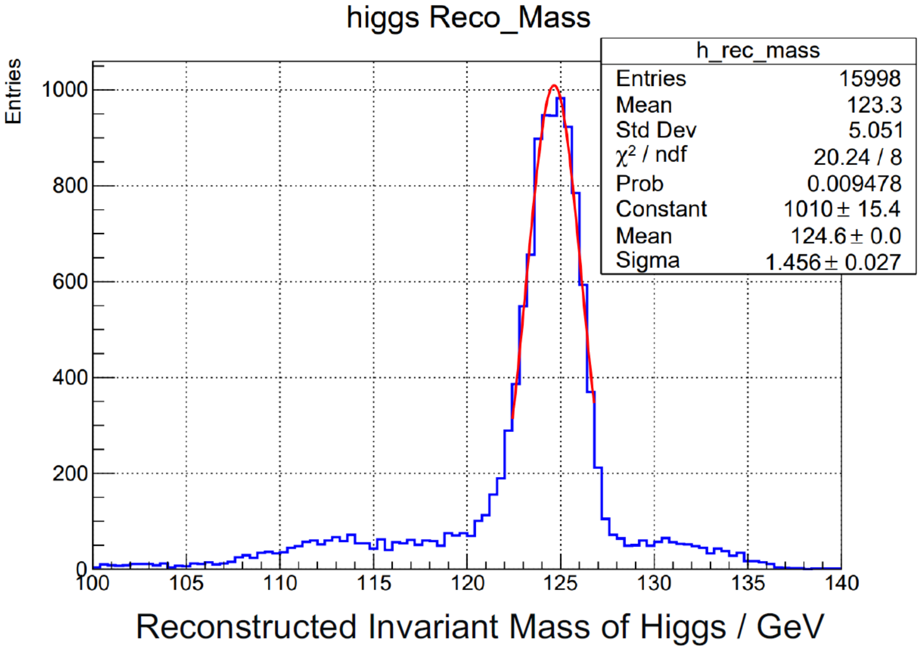
CEPC Software v0.1.1

Zhiyu Zhao (IHEP/SJTU)

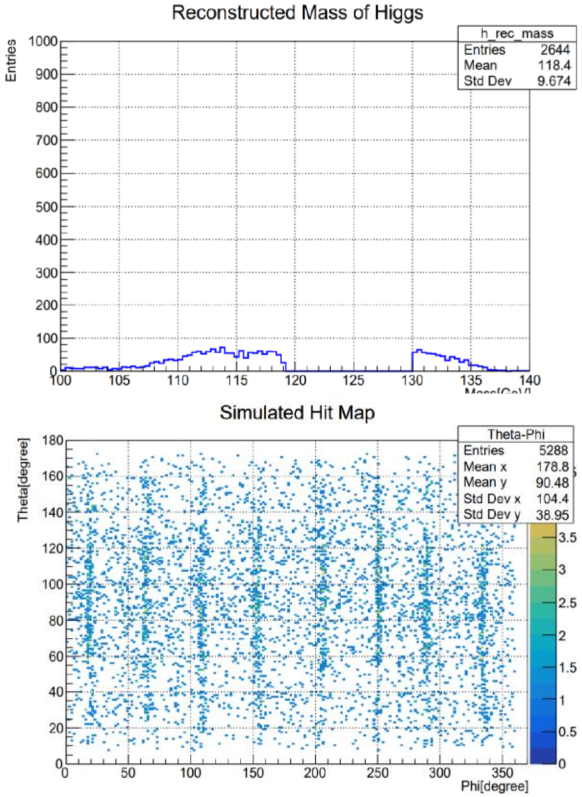
- Adapted from CEPCv4 baseline detector: SiW ECAL
  - Fine granulated crystal ECAL: suitable for Arbor-PFA
- Higgs benchmark ZH ($Z \rightarrow \nu\nu, H \rightarrow \gamma\gamma$)

Gaps in the barrel ECAL (octaves)

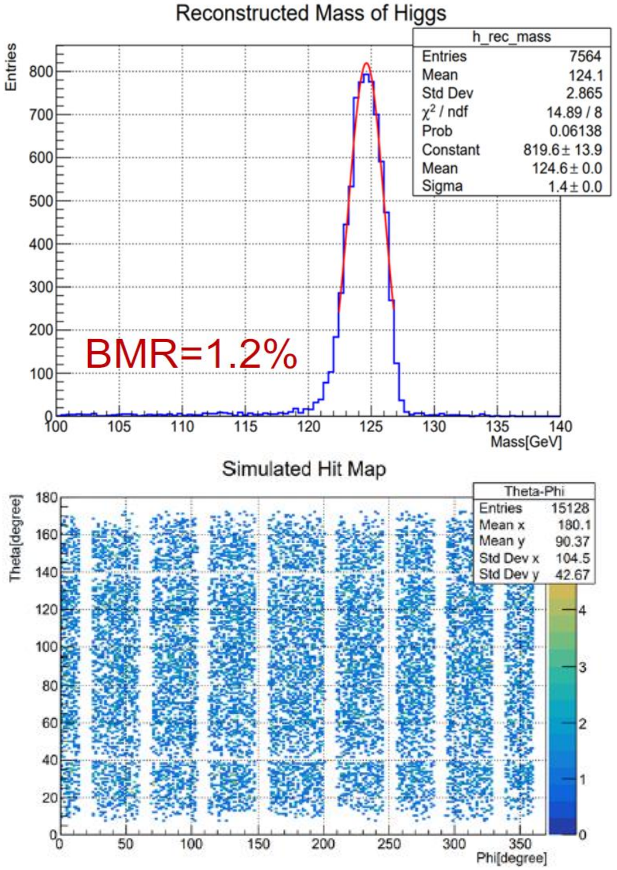




- BMR: 1.2%
- Inspiration on geometrical design: gaps should be concerned



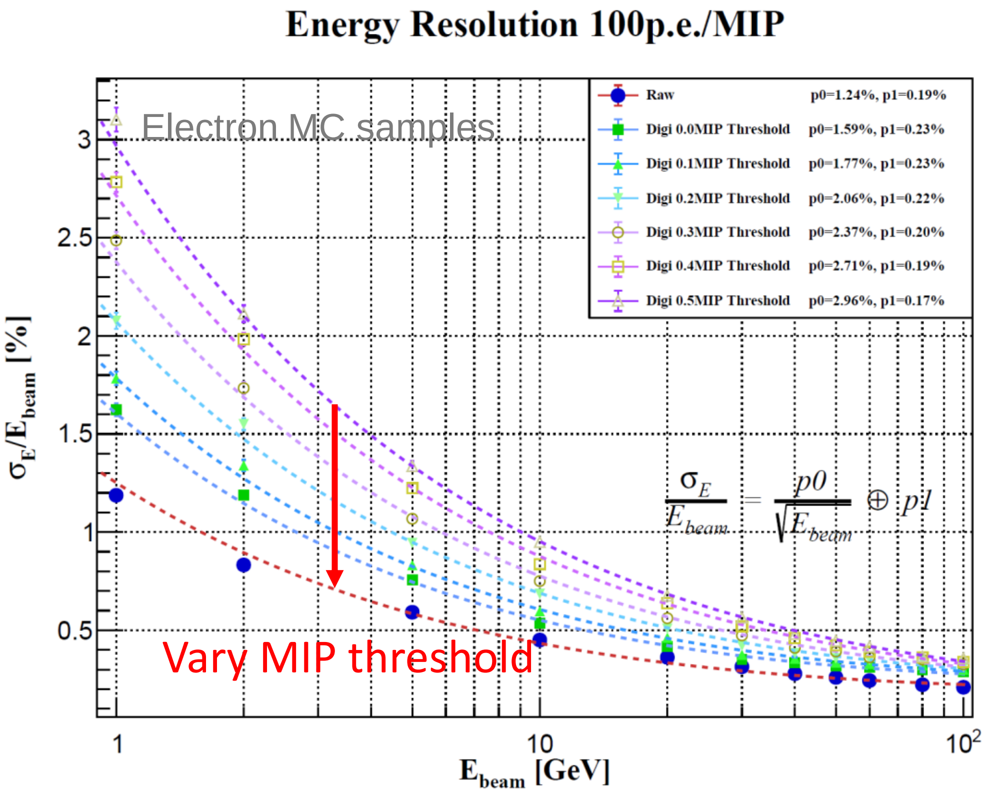
- Structures introduced by geometry boundaries

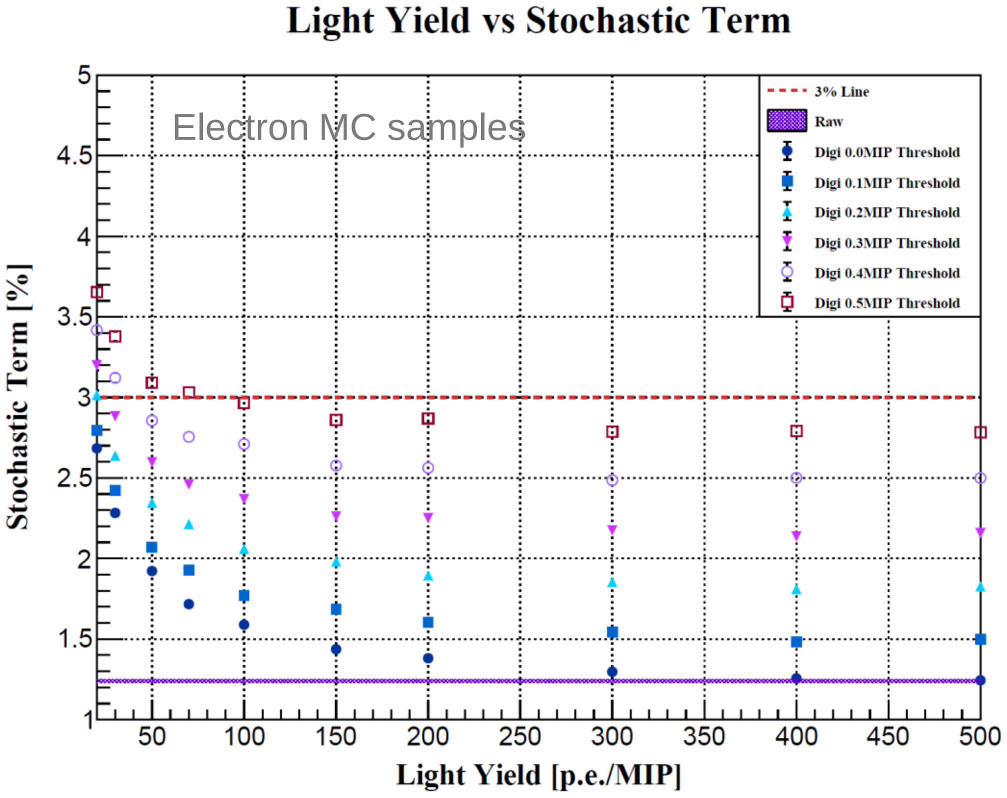


EM energy resolution: threshold and light yield requirements

Geant4 Simulation (v10.7)

- Impact on energy threshold (in MIP) and light yield (in p.e./MIP)
  - Digitization: photon statistics (crystal + SiPM), electronics resolution





- Moderately high light yield and low threshold required for better than 3% stochastic term

R&D status and highlights on key issues

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        - Higgs benchmark ZH $(Z \rightarrow \nu\nu, H \rightarrow \gamma\gamma)$
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- Reconstruction algorithm for long bar design
    - Status and preliminary performance studies

- Detailed studies on crystal performance
    - Geant4 full simulation of a single crystal bar
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    - Measurements on BGO crystal
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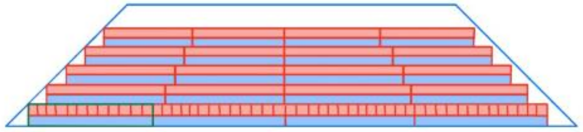
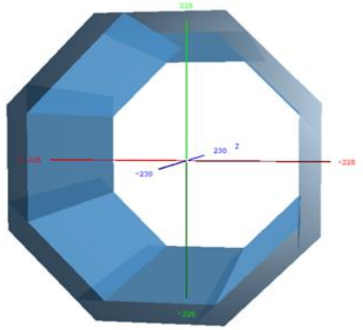
Layout with long crystal bars: from simulation to reconstruction

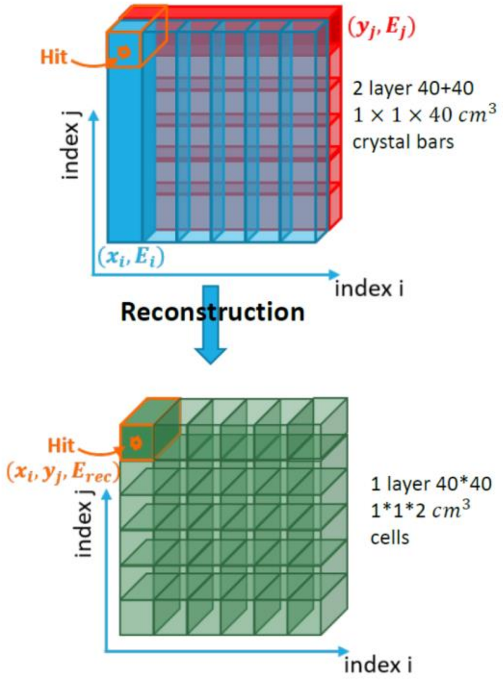
CEPCSW

- Simulation: full barrel geometry with DD4HEP
- Digitization:
  - Time resolution: 0.5 ns smearing
  - Energy threshold: 100 keV



An octave in the barrel ECAL with long crystal bars

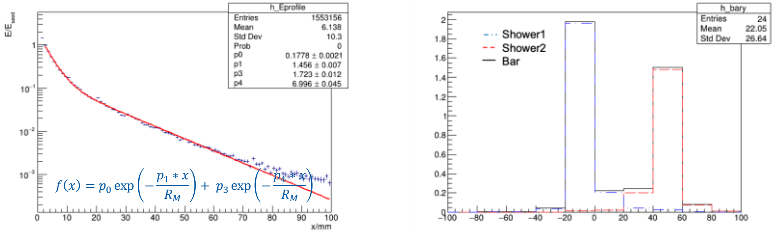




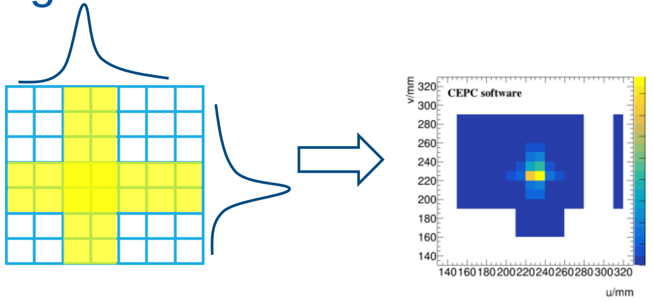
Fangyi Guo (IHEP)

Reconstruction:

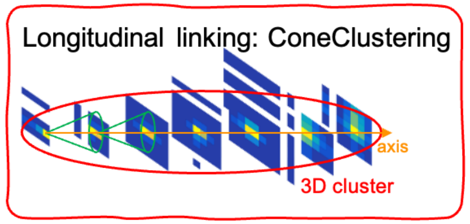
- 1D clustering & cluster splitting:
  - “Seed” in 1D cluster: local maximum && E>5MeV (~0.5MIP).
  - If ≥ 2 seeds in one cluster: split with transverse profile.



- 2D matching: match X-Y bars to showers in plane:



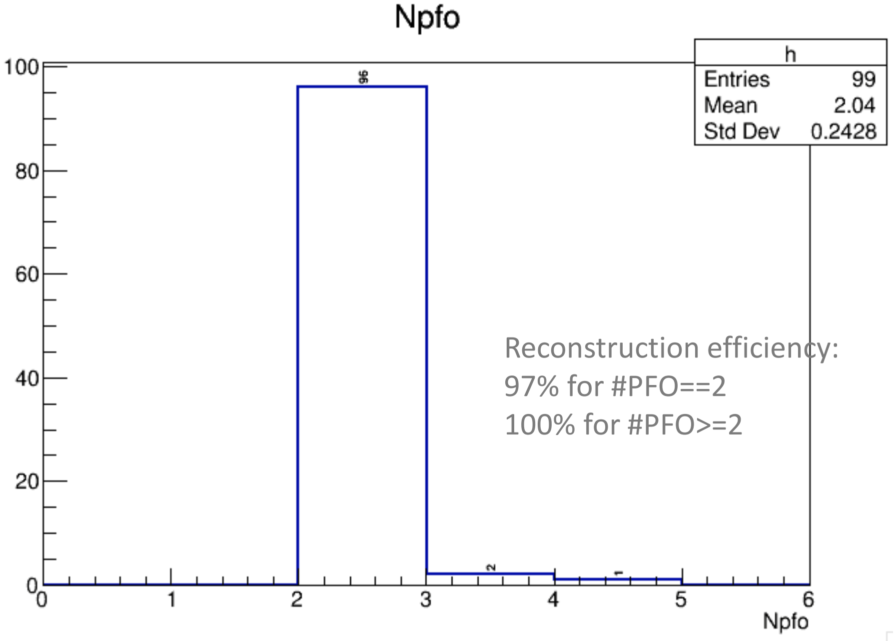
- 3D clustering:



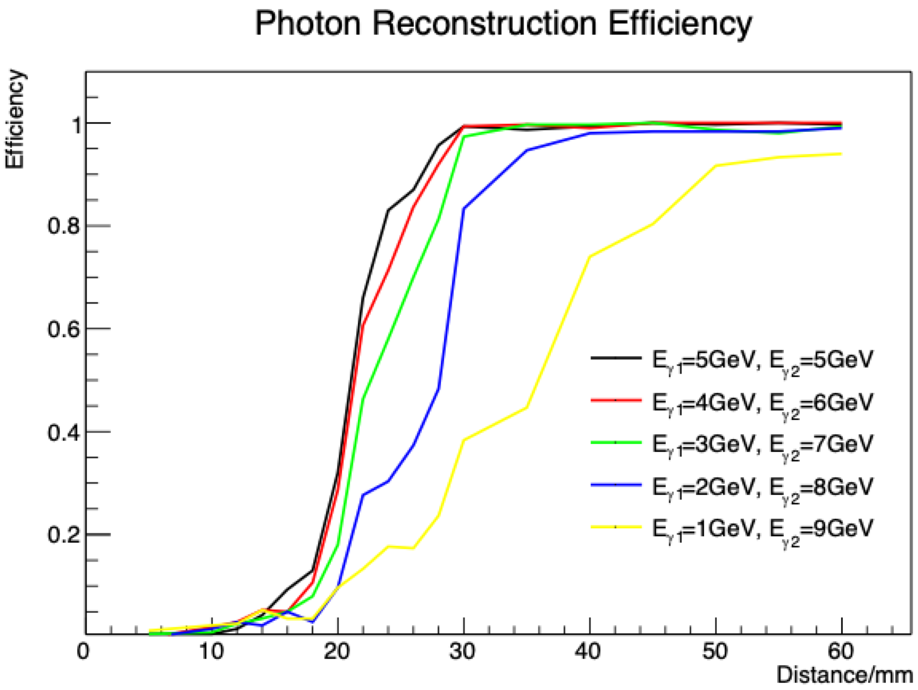
Reconstruction development: reconstruction of 2 photons

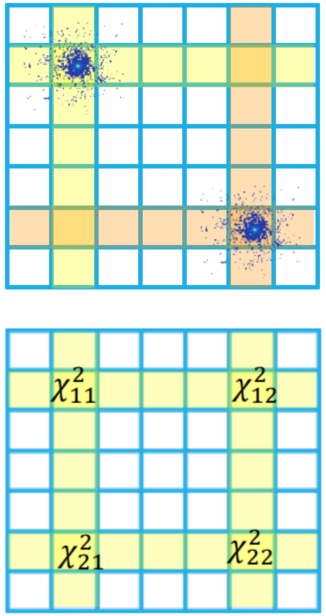
- Performance study with 2 photons (add up to 10GeV), $\Delta x = \Delta y = 5\mathrm{cm}$

Fangyi Guo (IHEP)



Reconstruction efficiency:
97% for #PFO==2
100% for #PFO>=2





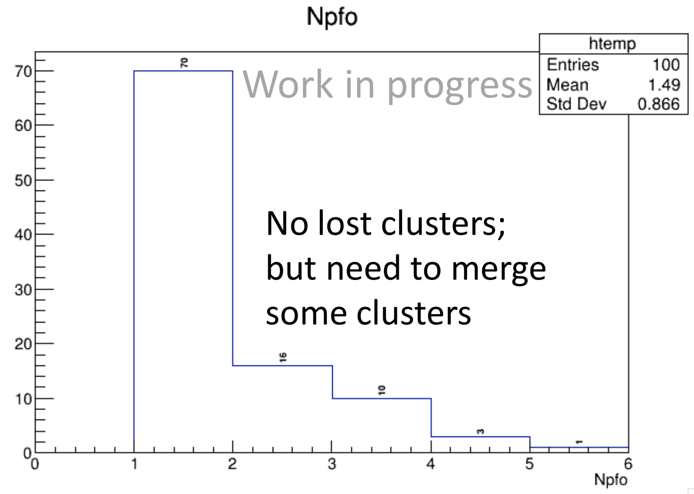
- Separation efficiency curve with different energy photons and with varying distances

- Good separation efficiency
- New algorithm can handle ambiguities of 2 photons

Reconstruction development: hadronic showers in ECAL

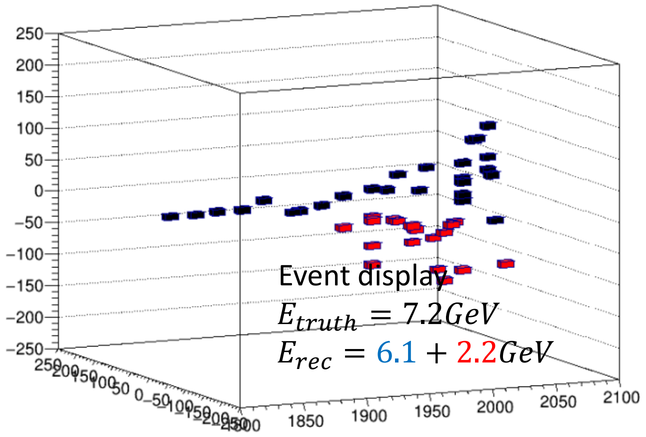
- Performance with single π^- reconstruction: preliminary results

Fangyi Guo (IHEP)



Work in progress

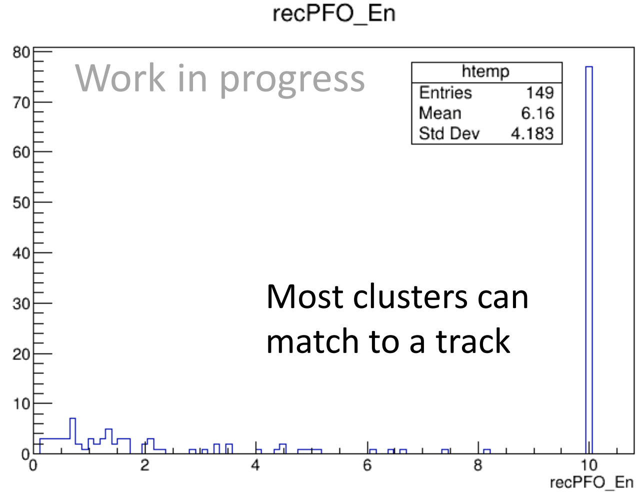
No lost clusters;
but need to merge
some clusters



Event display

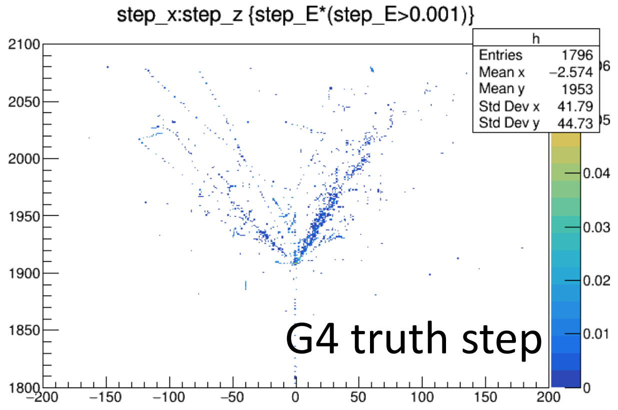
$E_{truth} = 7.2GeV$

$E_{rec} = 6.1 + 2.2GeV$



Work in progress

Most clusters can
match to a track



G4 truth step

- Difficulties in hadronic shower reconstruction
    - Multiple secondary particles in the shower
    - Hard to use longitudinal information
    - A large amount of ghost hits
- Ideas and possible solutions
    - Use Arbor's ideas to connect hits
    - Reduce the iteration times
    - New χ^2 algorithm for ghost hits: match with minimum χ^2 and reduce hit conditions.
    - (Ongoing) Merge clusters with specific topology
    - (Ongoing) Identify and tag photons and MIPs first

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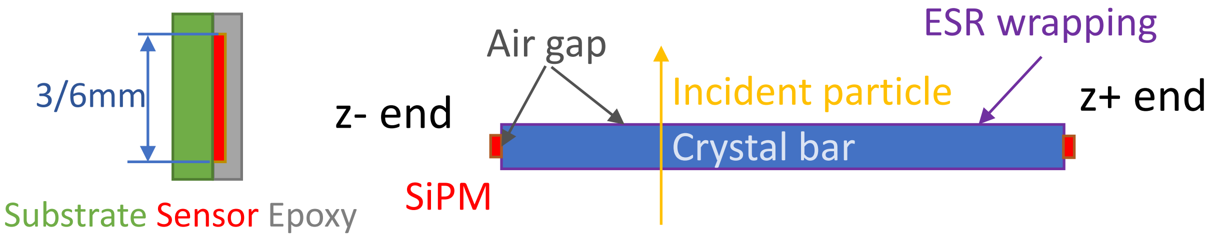
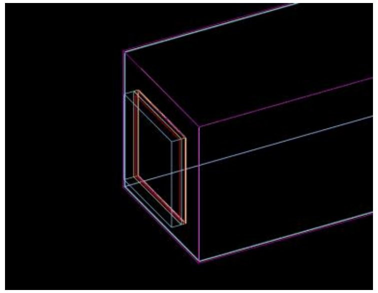
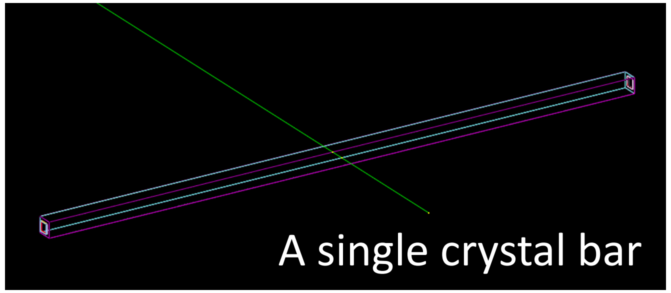
Geant4 full simulation of a single crystal bar: overview

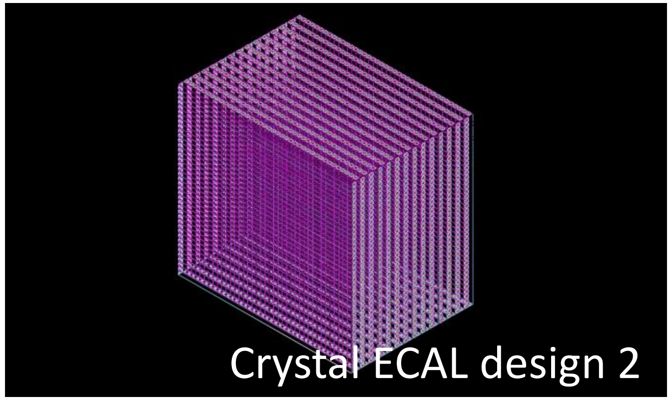
- A single crystal bar wrapped with reflector
- Physics processes
  - Scintillating & Cherenkov
  - Boundary processes and absorption
  - SiPM modelling: geometry and response (PDE)
- Key quantities
  - Number of photons detected by 2 SiPMs
  - Time stamps of each detected photons
- Key questions to be addressed
  - Comparison with measurements of crystals in the lab
  - Comparison of models of optical processes in Geant4







A single crystal bar



Crystal ECAL design 2

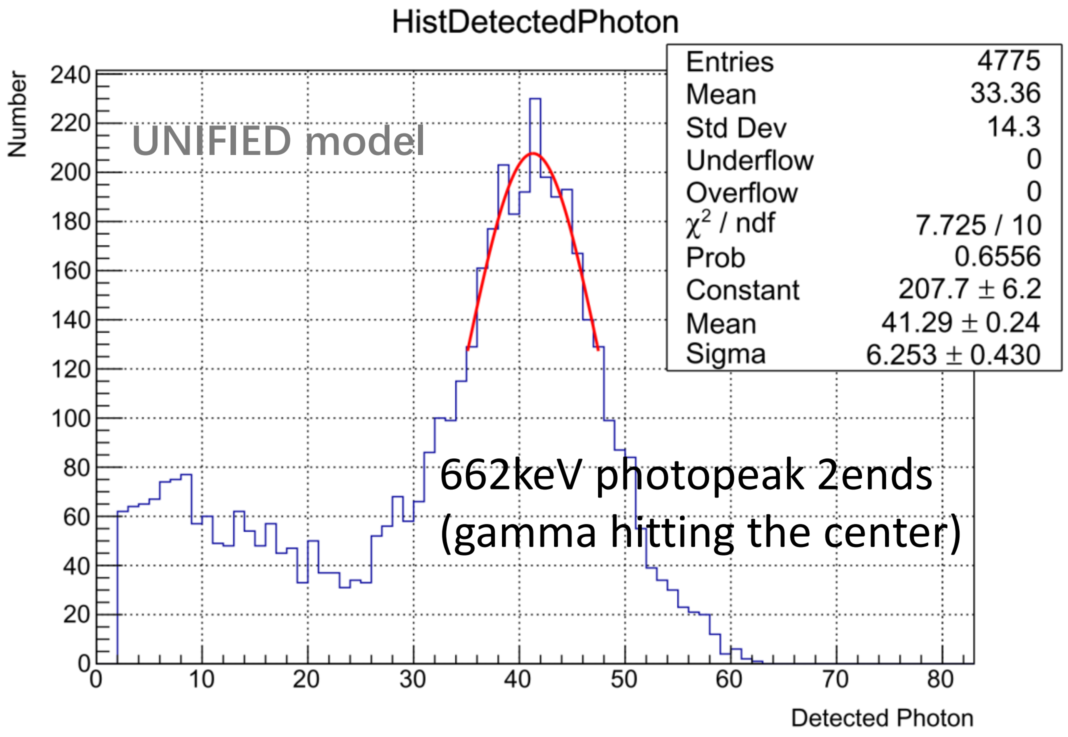
3 major models for optical properties in Geant4

- UNIFIED model: analytical calculation and modelling of surfaces
- 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)

Uniformity scan in Geant4 simulation

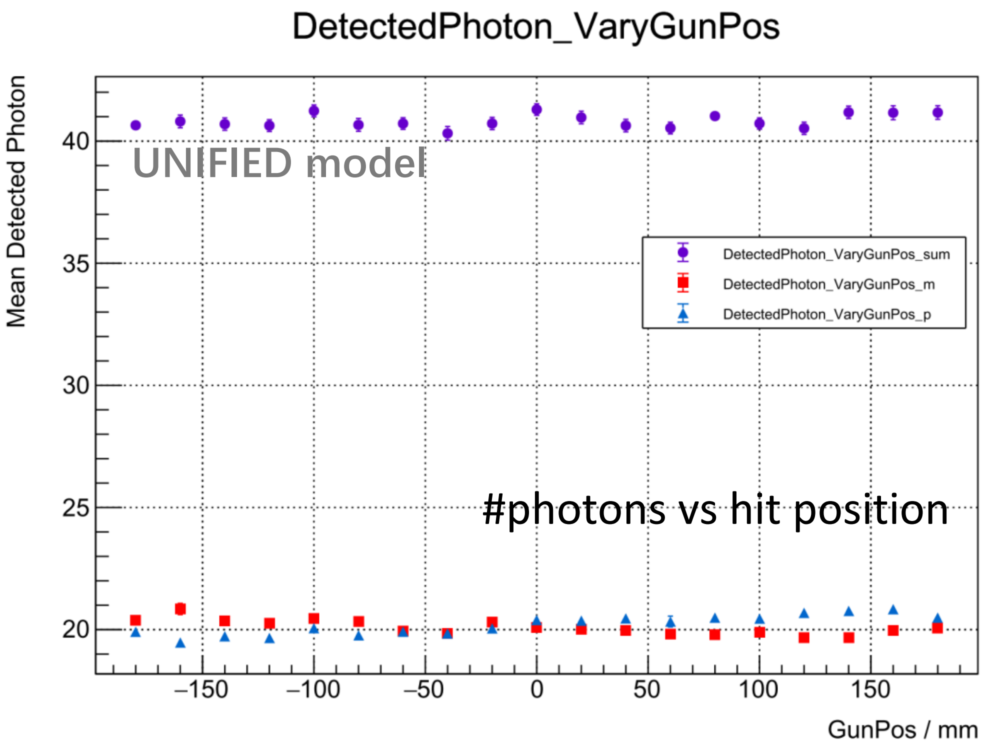
Geant4 Simulation (v10.7)

- Uniformity scan: 662keV gamma for ^{137}Cs, change hit positions
  - 400mm BGO crystal bar, transverse size: 1cm^2, 3×3mm^2 SiPMs
  - Fit the 662keV photopeak to get corresponding #photons



UNIFIED model

662keV photopeak 2ends (gamma hitting the center)



UNIFIED model

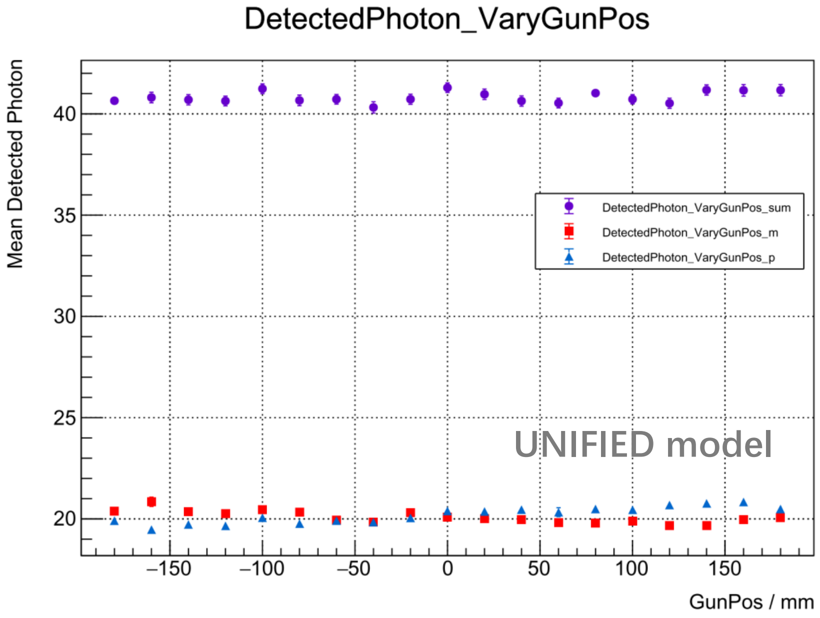
#photons vs hit position

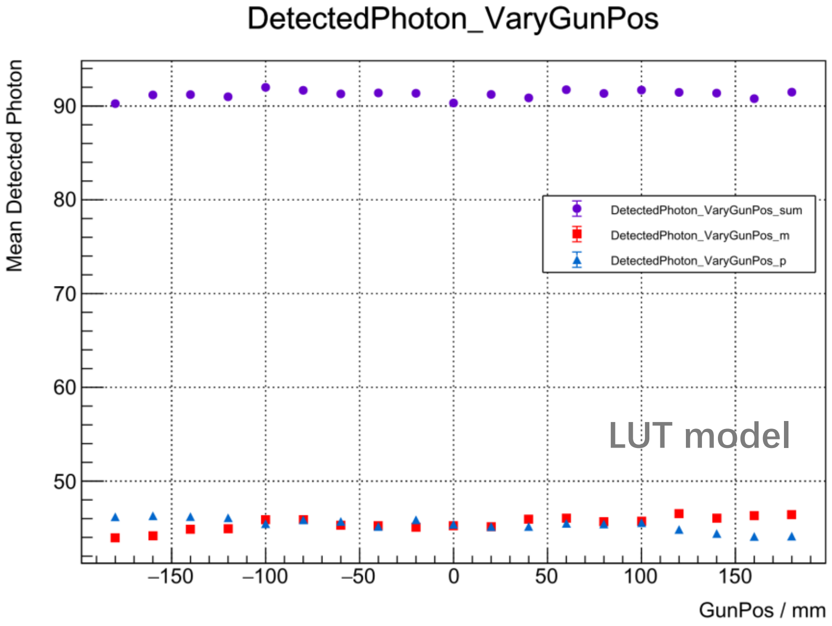
- Generally good response uniformity expected in simulation

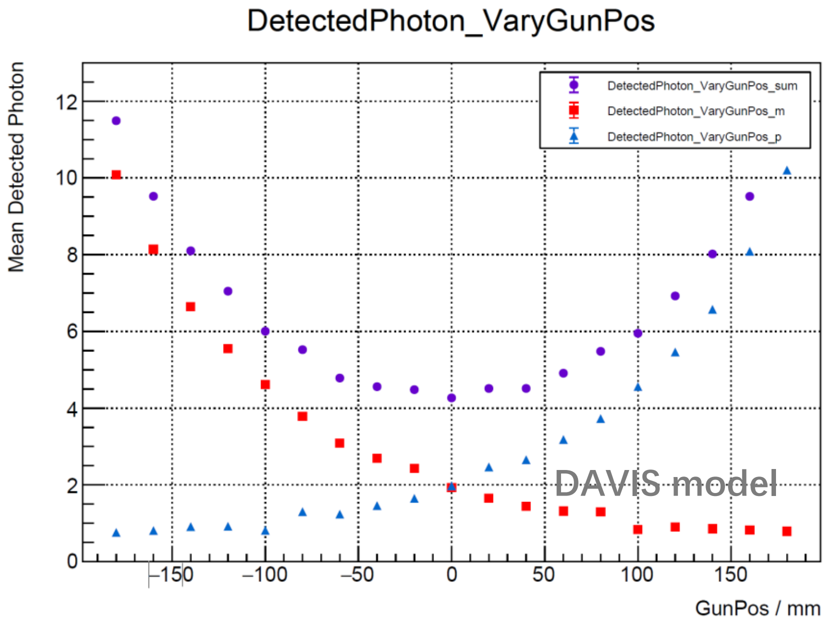
Comparison of different optical surface models

Geant4 Simulation (v10.7)

- Comparison of UNIFIED/LUT/DAVIS model on #photons detected
  - 400mm BGO crystal, two 3×3mm^2 SiPMs, air coupling





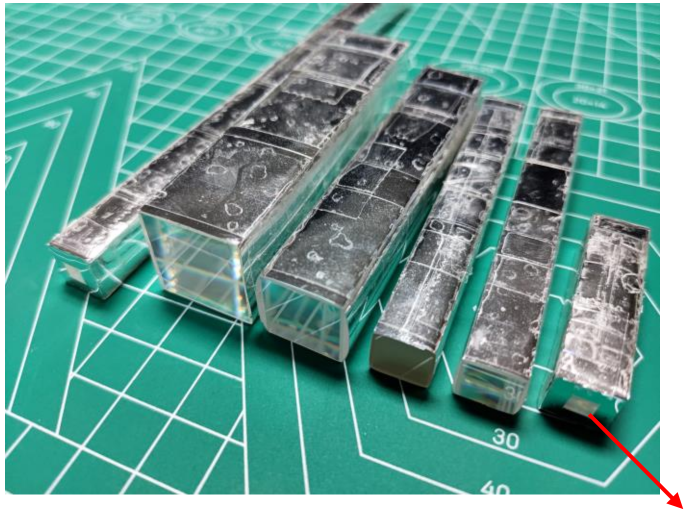


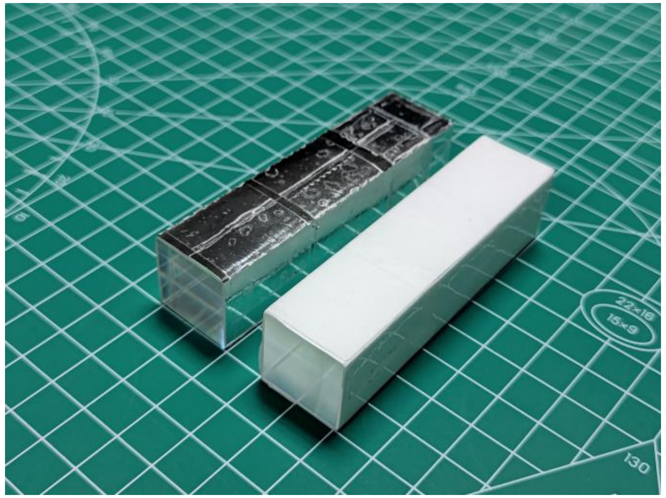
- UNIFIED & LUT: minor difference, need to be understood
- DAVIS: too low light output

Measurements on BGO crystal: ^{137}Cs energy spectrum

BGO Crystal:

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





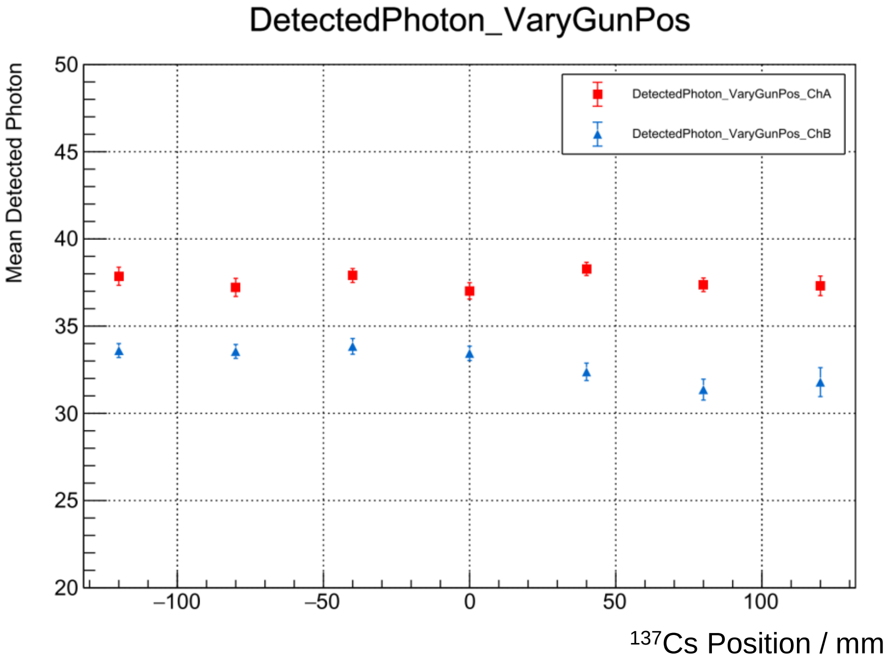
4×4mm^2 window for SiPM readoout

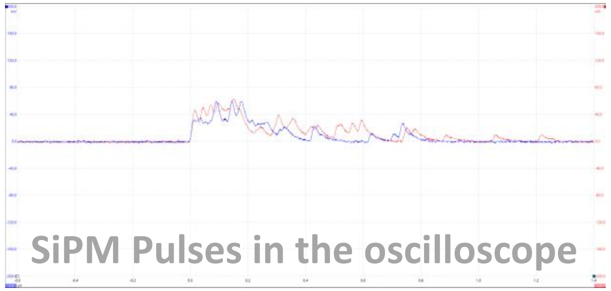
Photosensitive Device:

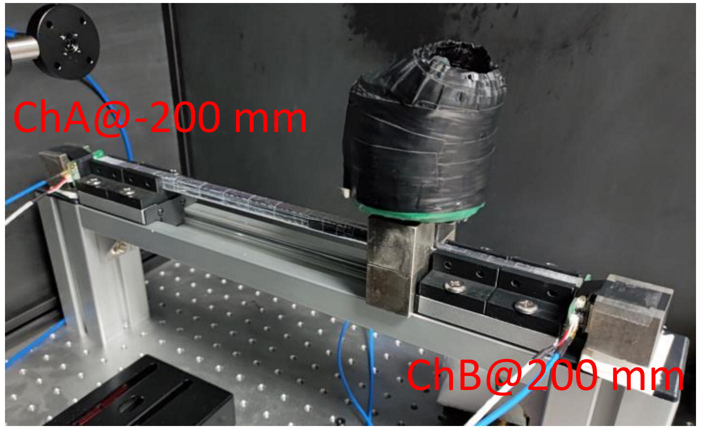
- SiPM & PMT
- SiPM: S13360-3050CS
  - 50µm pitch, 3×3mm^2, 3600 pixels
- PMT: R11065
  - 76mm (3”), gain: 5×10^6

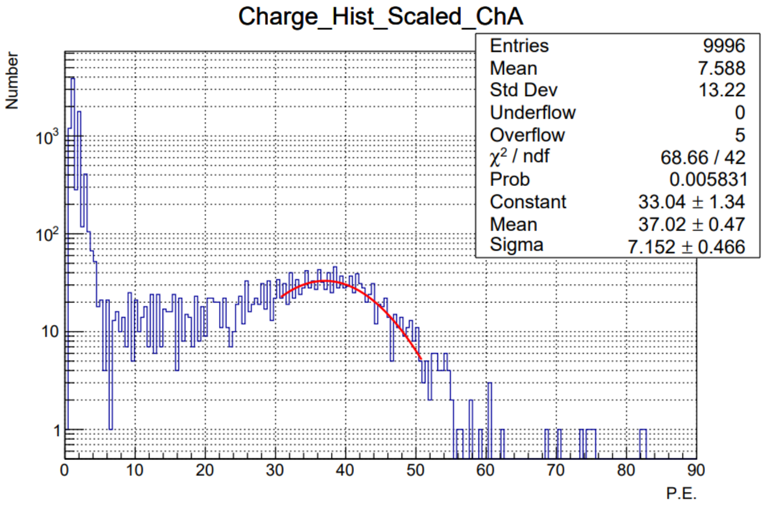
Uniformity scan with radioactive source

- Experiment: 400mm BGO crystal with ESR wrapping & ^{137}Cs
- Two 3×3mm^2 SiPMs, air coupling




SiPM Pulses in the oscilloscope

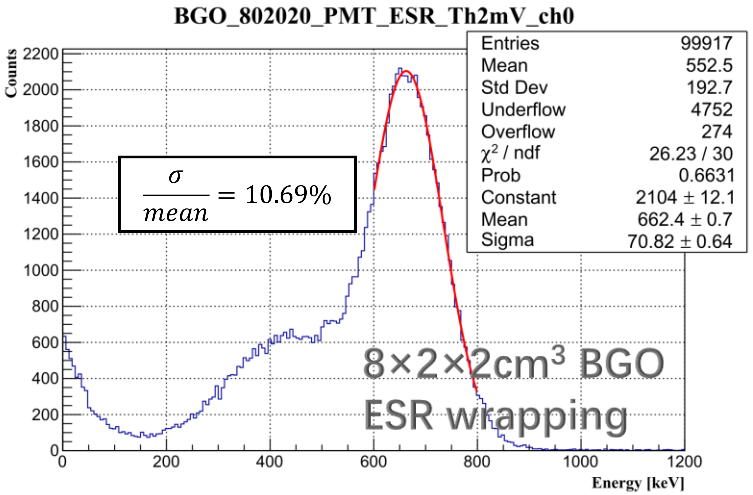




- Trends are not significant enough due to the systematic difference between 2 SiPMs
- Refractive index
  - Air: 1.00
  - Epoxy: 1.52
  - BGO: 2.15

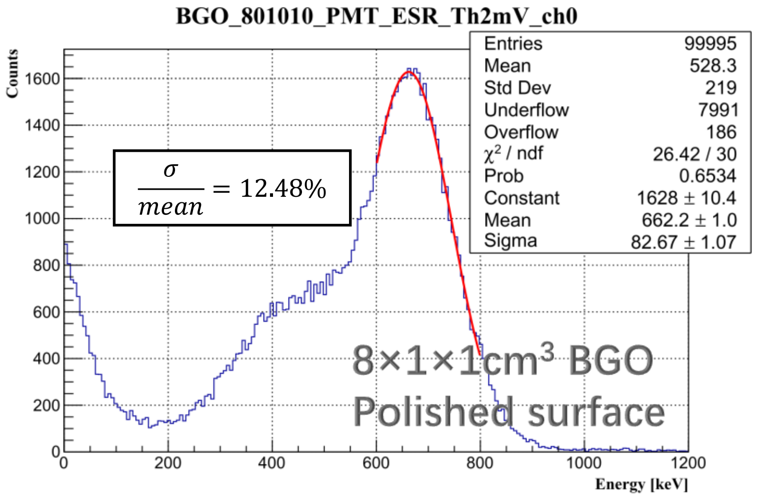
- Relatively uniform response
- Will use optical grease and stable test stand to improve the crystal-SiPM coupling and reproducibility
- To be updated with larger SiPMs (6×6mm^2)

Measurements on BGO crystal: impacts of wrapping & surfaces



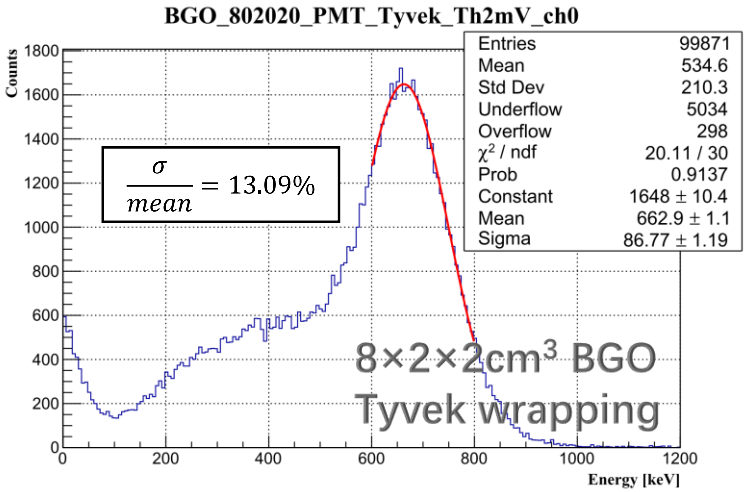
Entries	99917
Mean	552.5
Std Dev	192.7
Underflow	4752
Overflow	274
χ^2 / ndf	26.23 / 30
Prob	0.6631
Constant	2104 ± 12.1
Mean	662.4 ± 0.7
Sigma	70.82 ± 0.64

$$\frac{\sigma}{mean} = 10.69\%$$



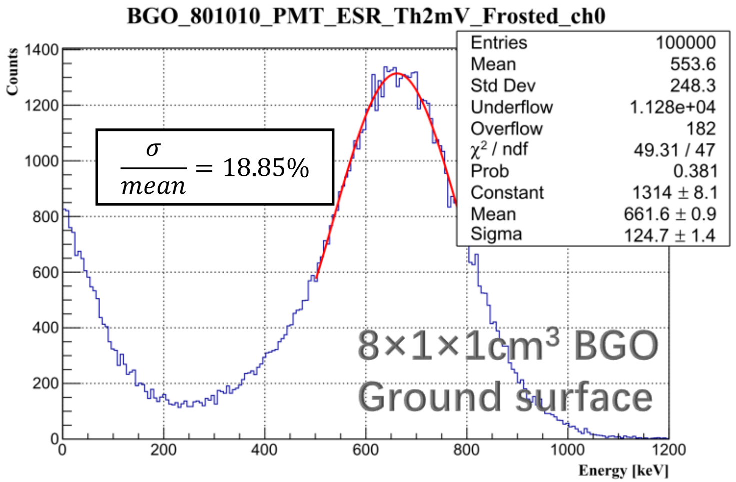
Entries	99995
Mean	528.3
Std Dev	219
Underflow	7991
Overflow	186
χ^2 / ndf	26.42 / 30
Prob	0.6534
Constant	1628 ± 10.4
Mean	662.2 ± 1.0
Sigma	82.67 ± 1.07

$$\frac{\sigma}{mean} = 12.48\%$$



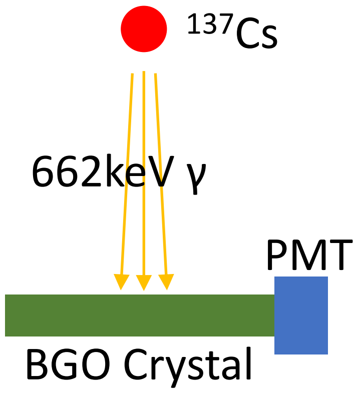
Entries	99871
Mean	534.6
Std Dev	210.3
Underflow	5034
Overflow	298
χ^2 / ndf	20.11 / 30
Prob	0.9137
Constant	1648 ± 10.4
Mean	662.9 ± 1.1
Sigma	86.77 ± 1.19

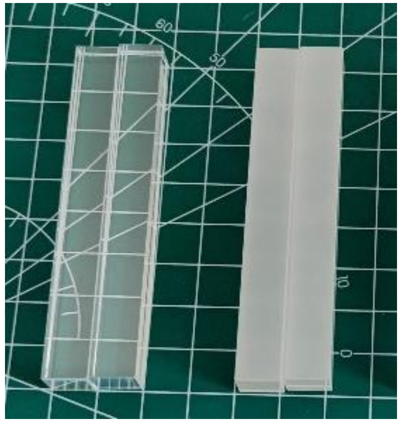
$$\frac{\sigma}{mean} = 13.09\%$$

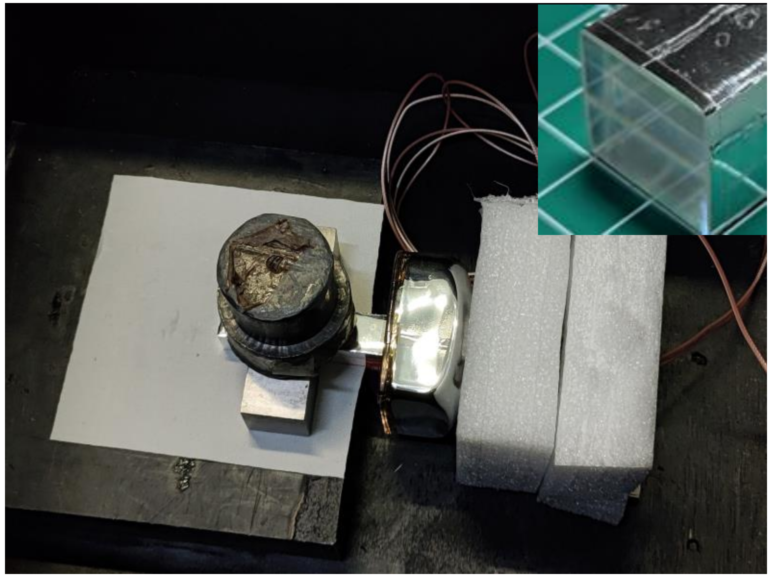


Entries	100000
Mean	553.6
Std Dev	248.3
Underflow	1.128e+04
Overflow	182
χ^2 / ndf	49.31 / 47
Prob	0.381
Constant	1314 ± 8.1
Mean	661.6 ± 0.9
Sigma	124.7 ± 1.4

$$\frac{\sigma}{mean} = 18.85\%$$



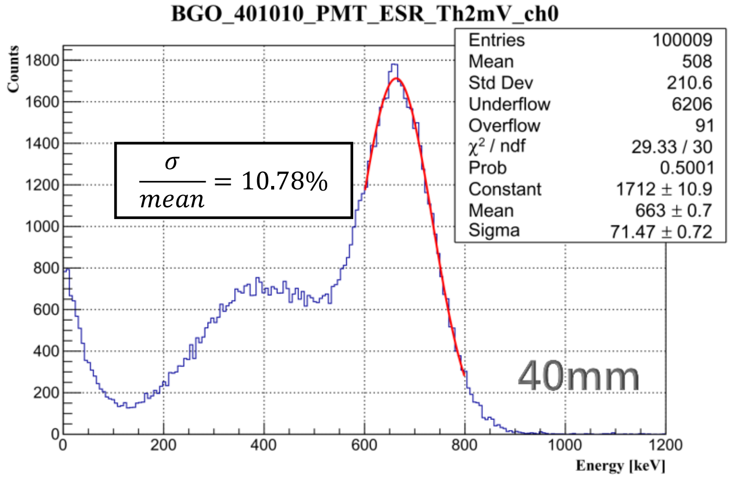


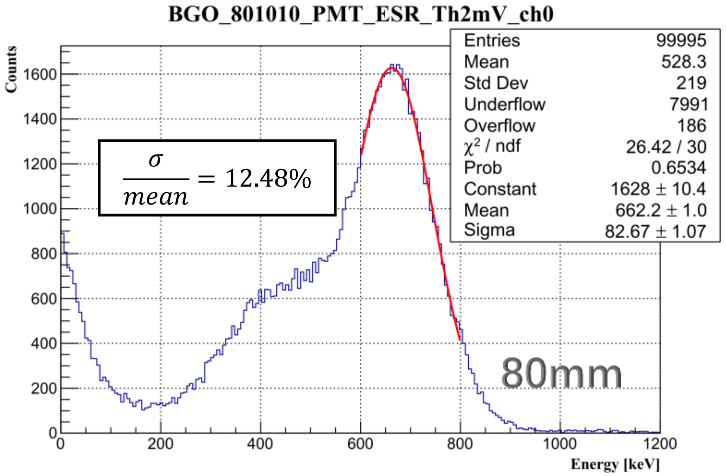


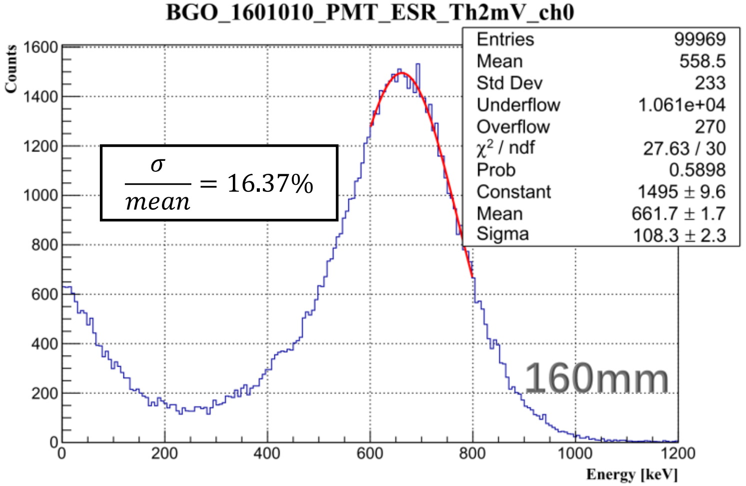
- ESR foil wrapping and polished surface show better energy resolution

Measurements on BGO crystal: impacts of crystal length

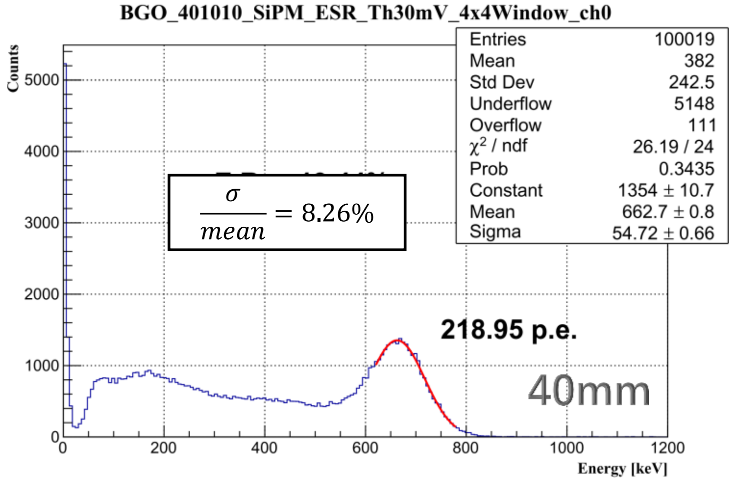
PMT

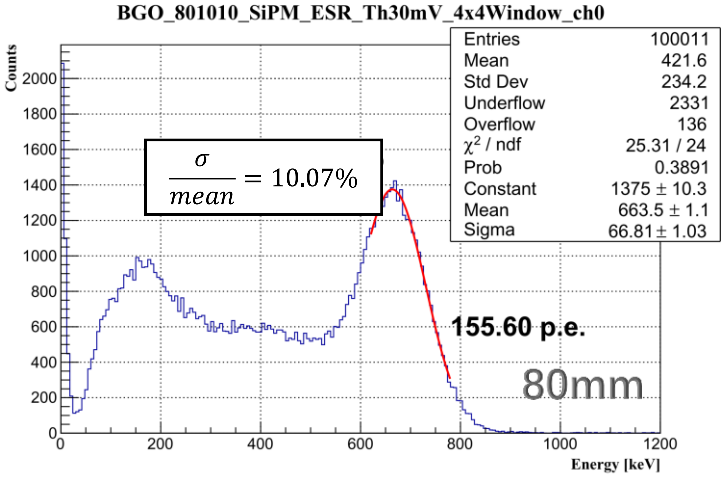


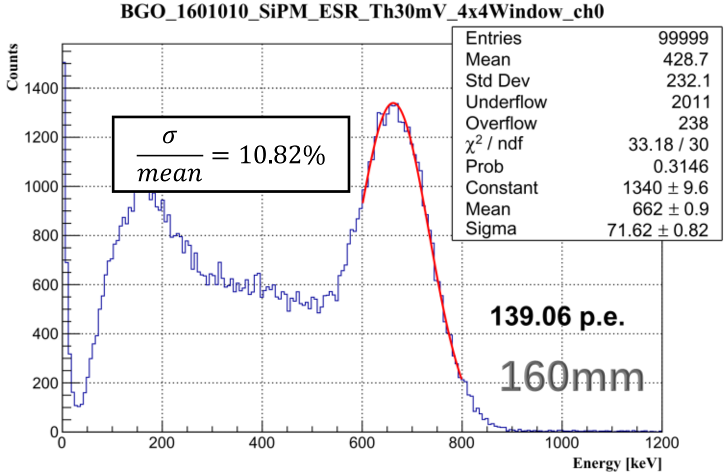




SiPM



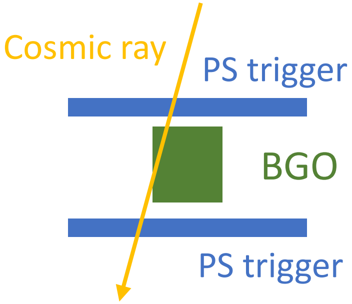




- Attenuation effect is lower when using shorter crystal bar
- PMT has better acceptance (full coverage of crystal transverse area) than SiPM
- Energy resolution of PMT expected better than SiPM if we increase the high voltage

Cosmic ray test: MIP response

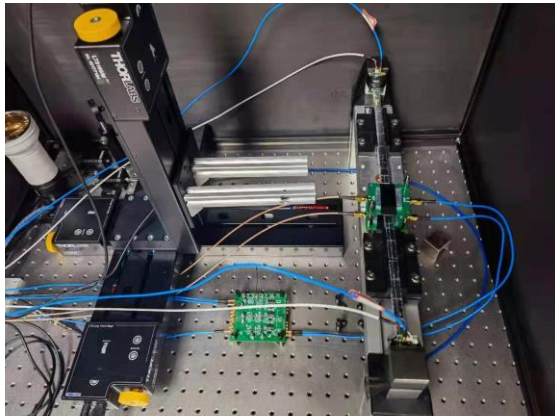
- 400mm BGO crystal bar, two SiPMs double-sided readout
- Two 3×3cm^2 plastic scintillators as triggers

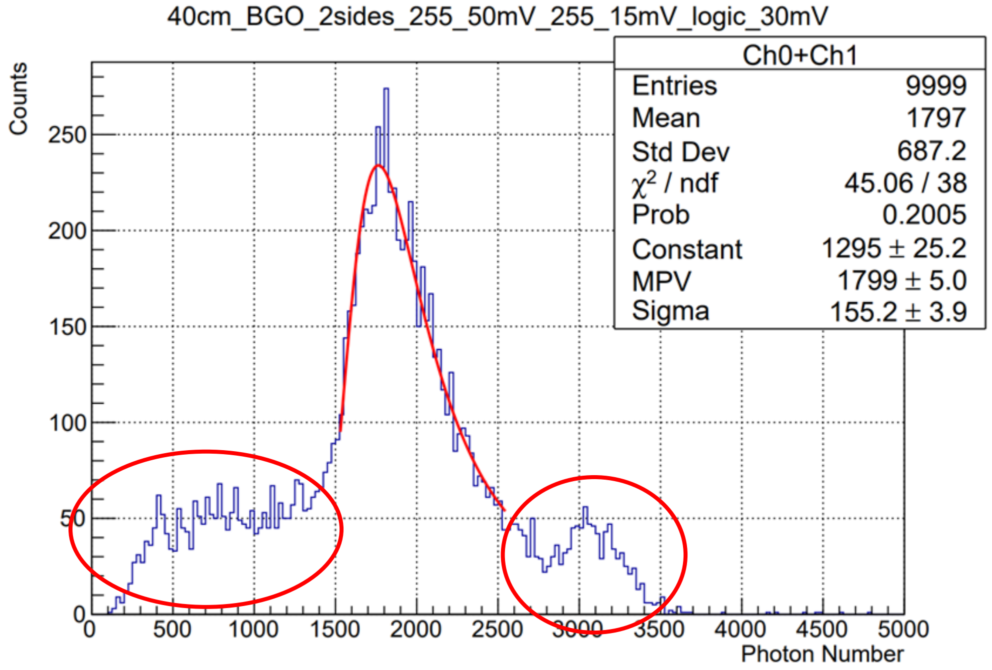

Cosmic ray

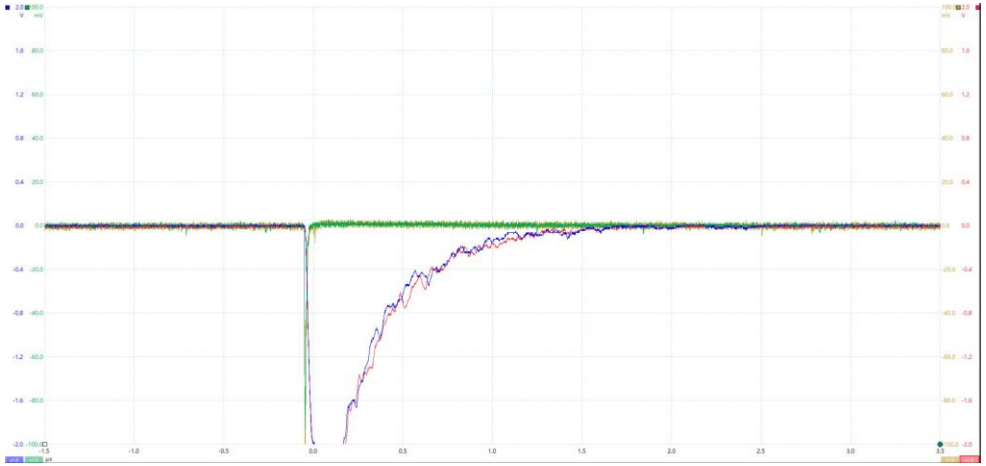
PS trigger

BGO

PS trigger







- MIP response MPV: ~1800p.e. (high enough for crystal ECAL)
- Plastic scintillator triggers cover larger area than crystal does, a lot of comic rays cross part of the crystal
- Some signal pulses exceed the voltage limit of oscilloscope, the Landau tail is limited

Summary & prospects

- ECAL performance studies
  - EM energy resolution: threshold and light yield requirements
  - Separation power / π^0 mass resolution / Higgs benchmark ZH
  - Next: study of $H \rightarrow gg$ / jets…
- Reconstruction algorithm for long bar design
  - Status and preliminary performance studies
  - Next: single hadrons / multi-particles / jets…

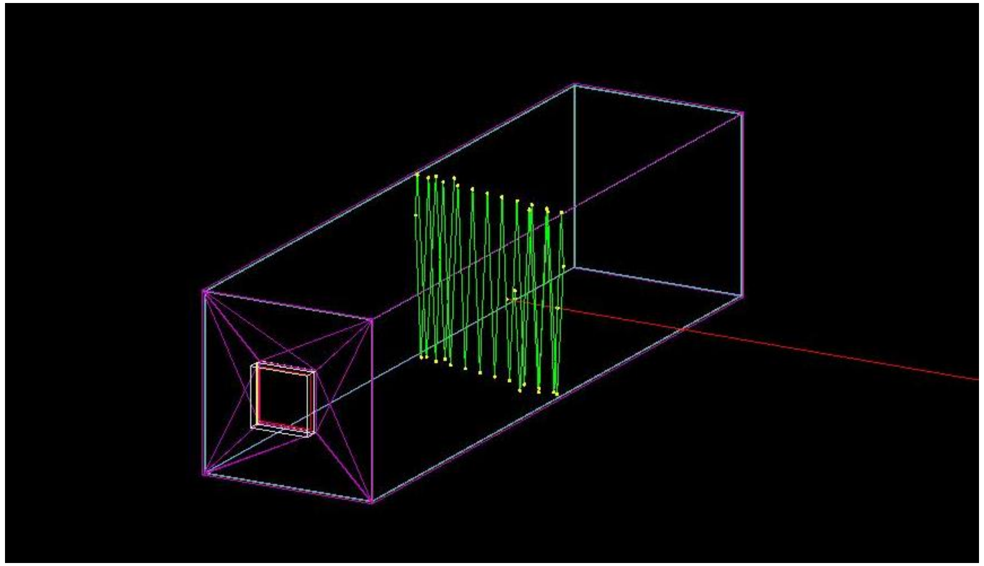
- Detailed studies on crystal performance
  - Geant4 full simulation of a single crystal bar
    - Response uniformity scan / optical surface models
    - Next: adjust parameters obtained from measurements
  - Measurements on BGO crystal
    - Energy resolution and response uniformity: radioactive source test
    - Cosmic ray test: MIP response
    - Next: SiPM test / crystal test / timing studies…

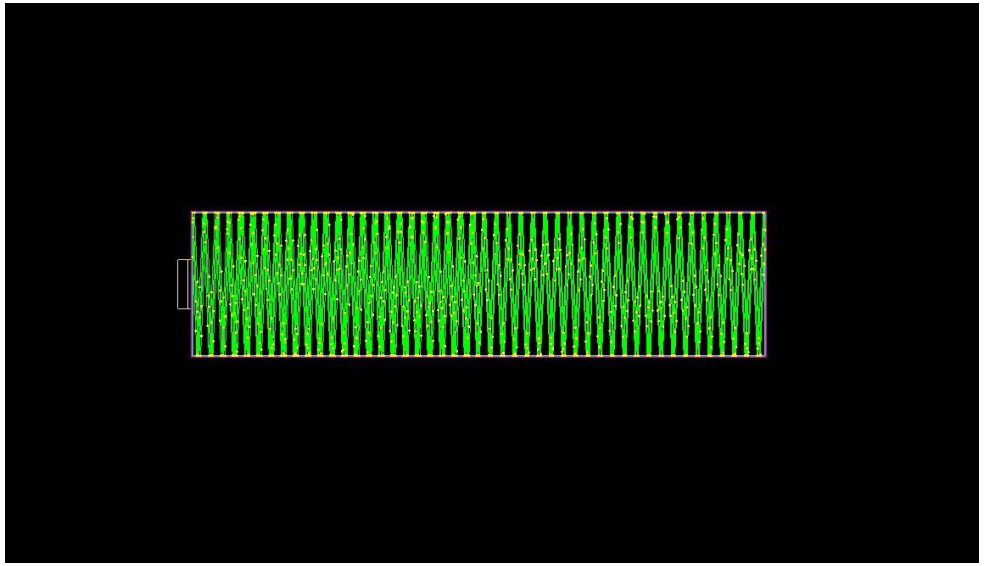
Backup

Comparison of different optical surface models

Geant4 Simulation (v10.7)

- Drawback of with ideally polished surface in simulation: trapped photons
  - Due to the ideal configuration in UNIFIED model

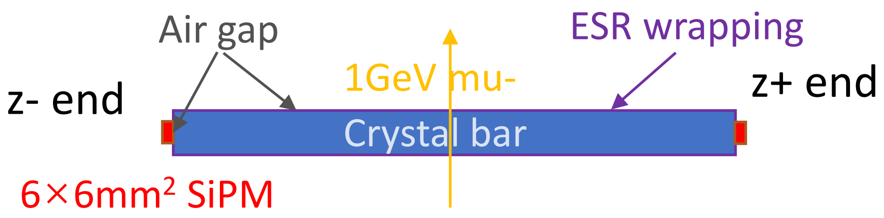


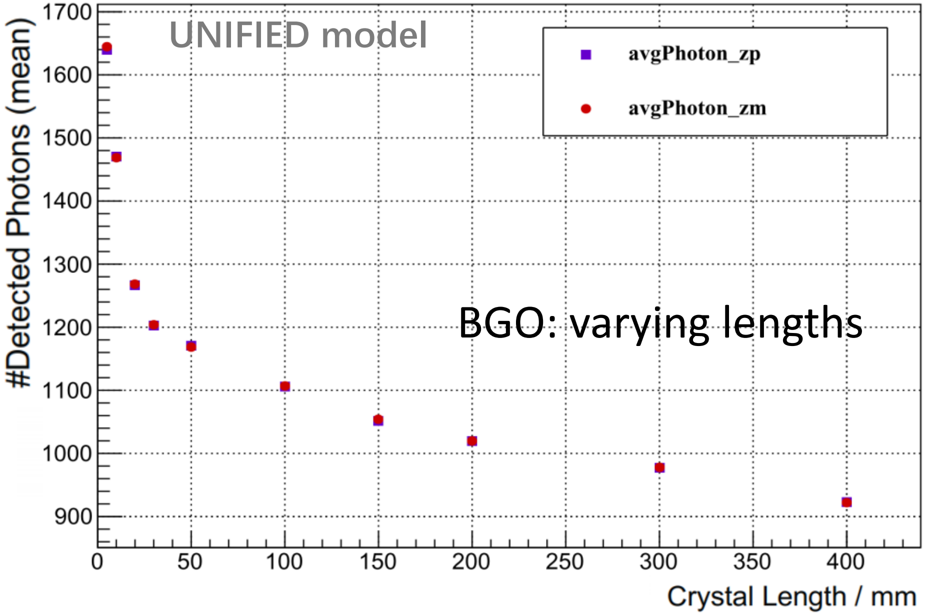


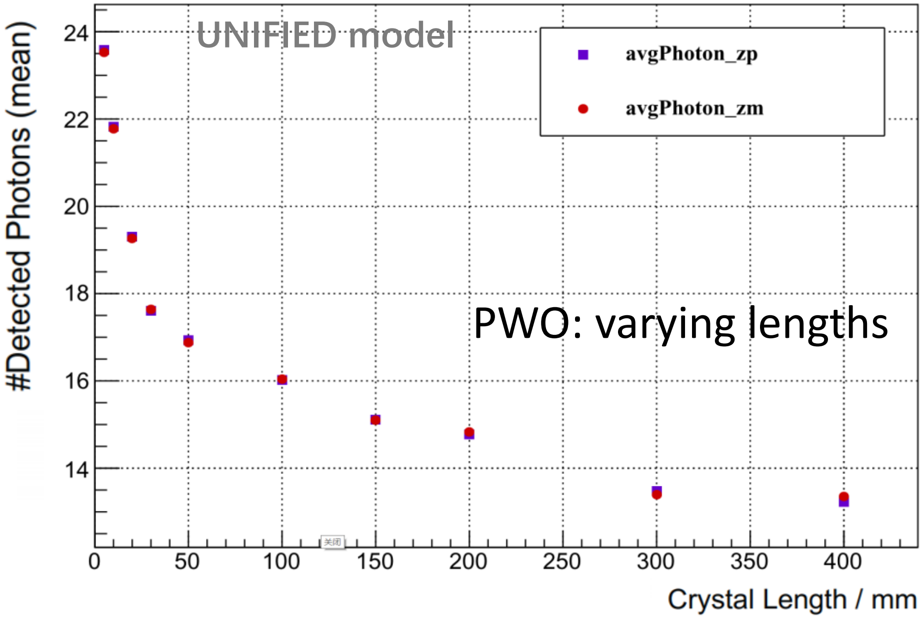
Impacts of crystal length

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







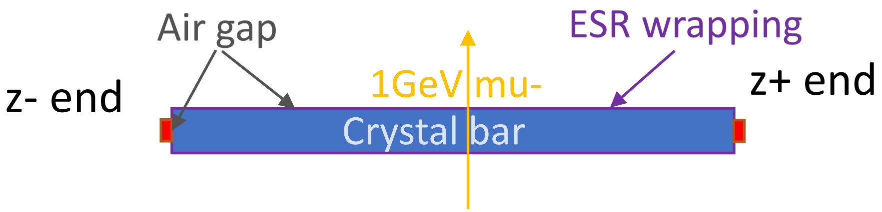
- MIP response significantly depends on crystal length
- Sufficiently high MIP response of 40cm long BGO

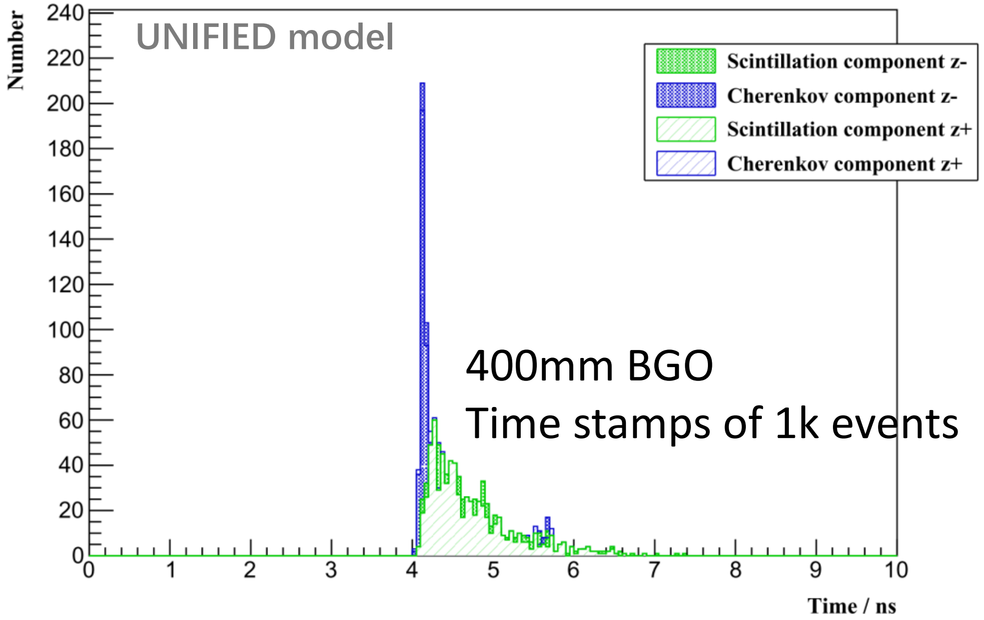
Light yield: 8200/MeV for BGO, 120/MeV for PWO
MIP energy deposition: ~ 9MeV (MPV)

Timing studies in simulation

Geant4 Simulation (v10.7)

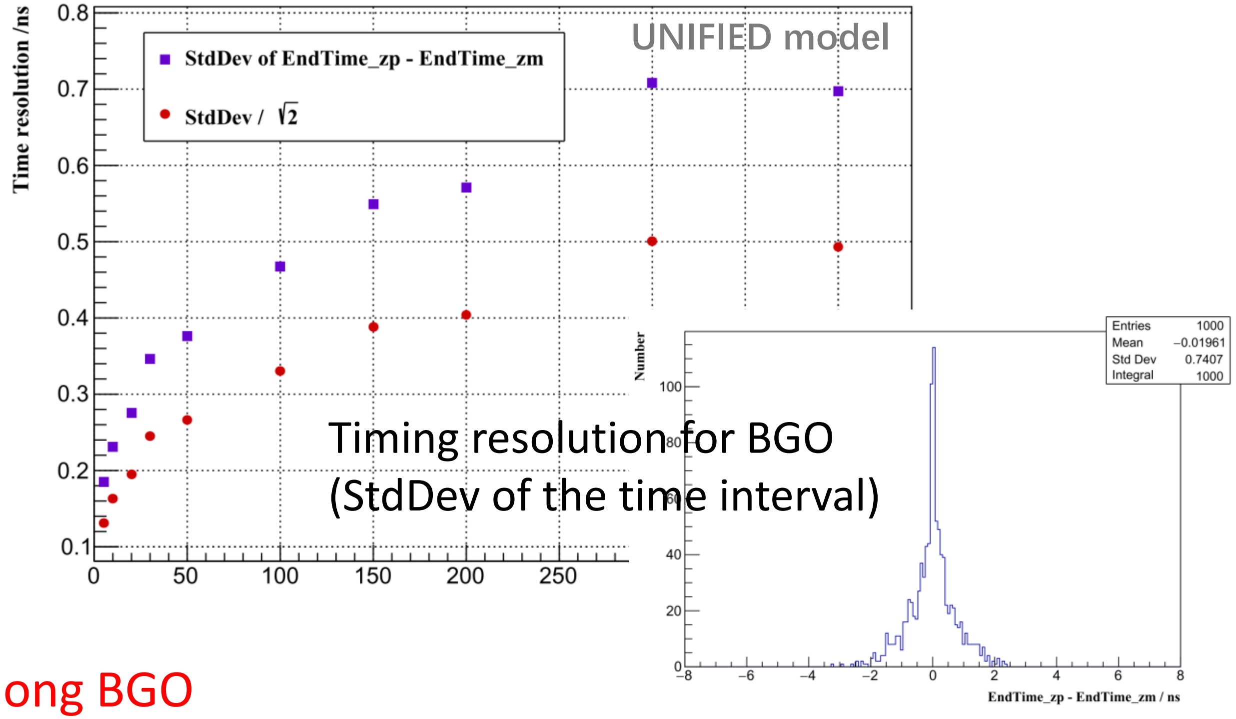
- Impact on timing: time stamps of the first detected photons
  - Muon shooting the crystal bar center
  - Crystal length varies from 5mm to 400mm





400mm BGO

Time stamps of 1k events



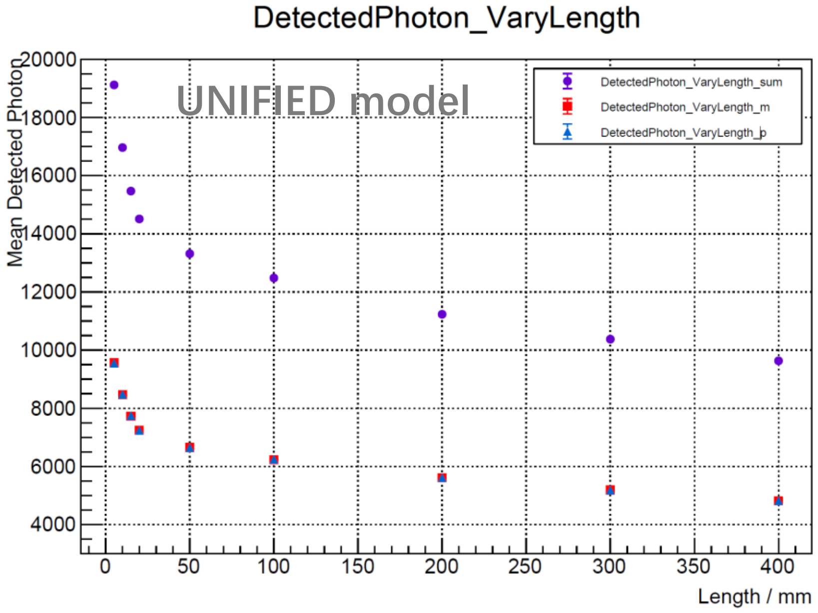
Timing resolution for BGO

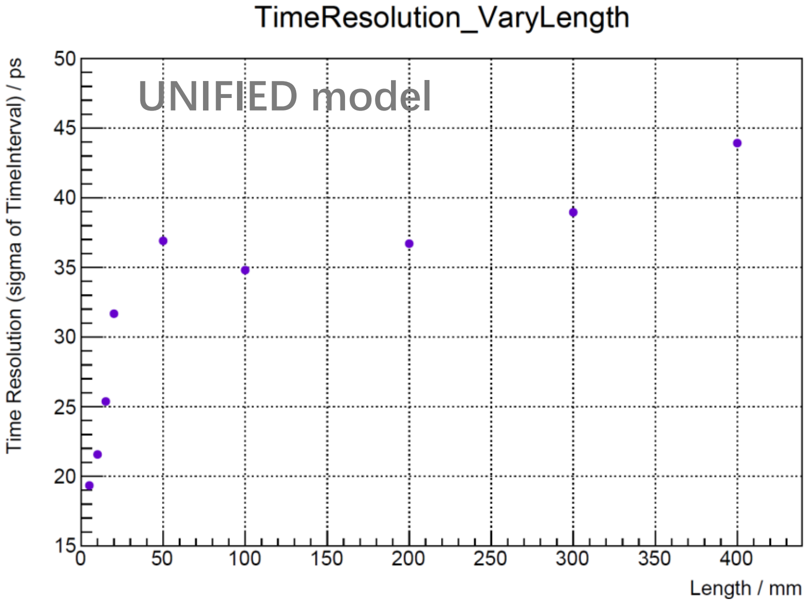
(StdDev of the time interval)

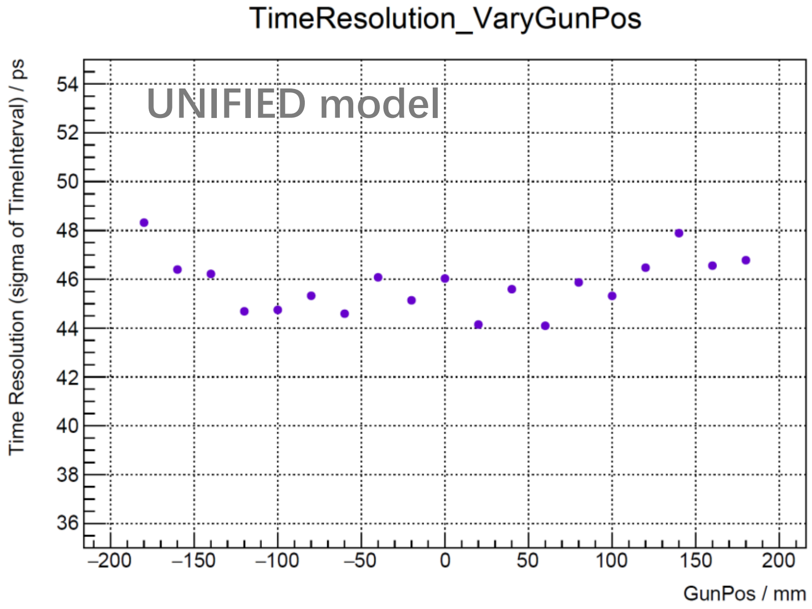
- 0.5~0.7 ns time resolution expected for 40cm long BGO
- Fast and slow components in time spectrum

Timing studies: LYSO:Ce

Geant4 Simulation (v10.7)





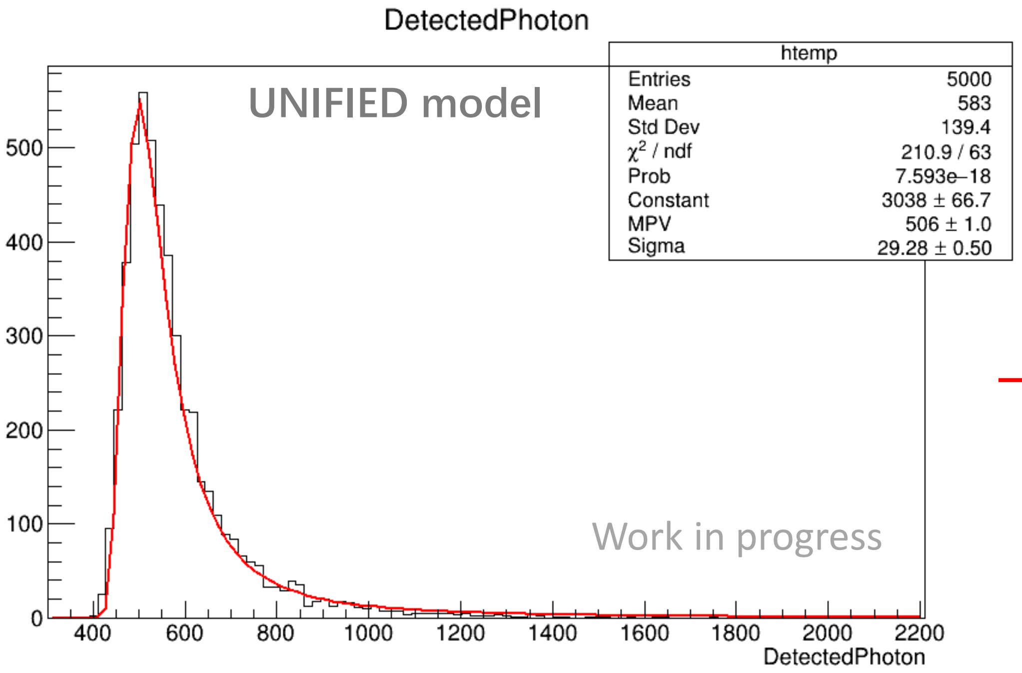


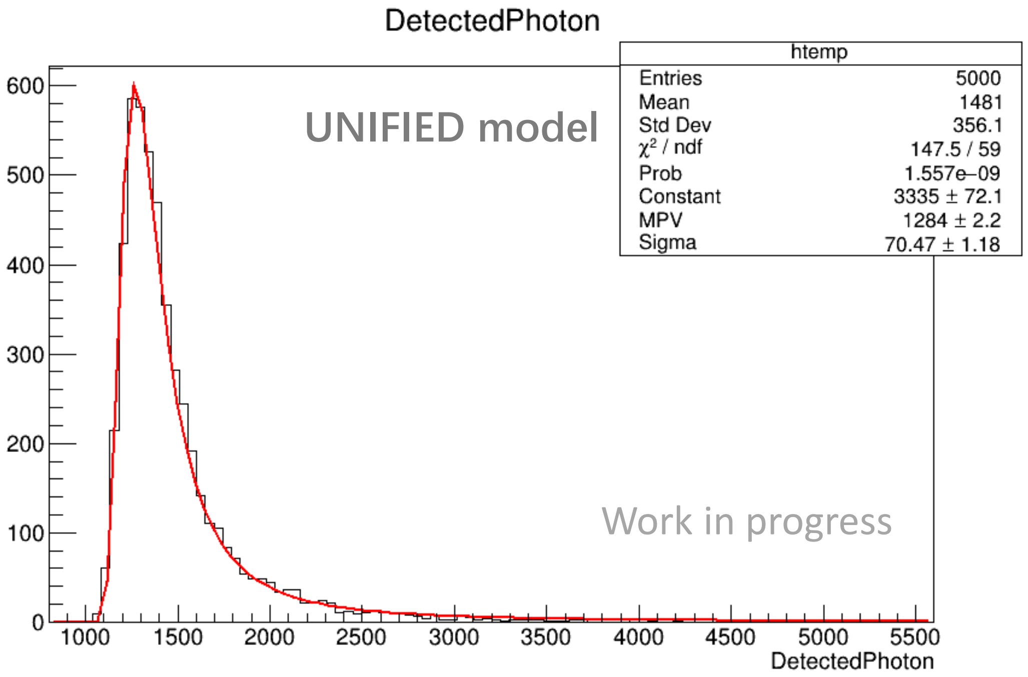
- Higher light output: ~3000p.e./MIP
- Good time resolution: ~45ps

Improvement with optical grease in simulation

Geant4 Simulation (v10.7)

- Improvement with optical grease
  - BC-631: refraction index 1.465, 0.976g/cm^3
  - 400mm BGO crystal with ESR wrapping, 3×3mm^2 SiPMs





- Light output increased 2.5 times: 506p.e.→1284p.e.

Impacts of crystal transverse size

*FWHM	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

- 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