Pre-shower detector sensitive to incident photon direction

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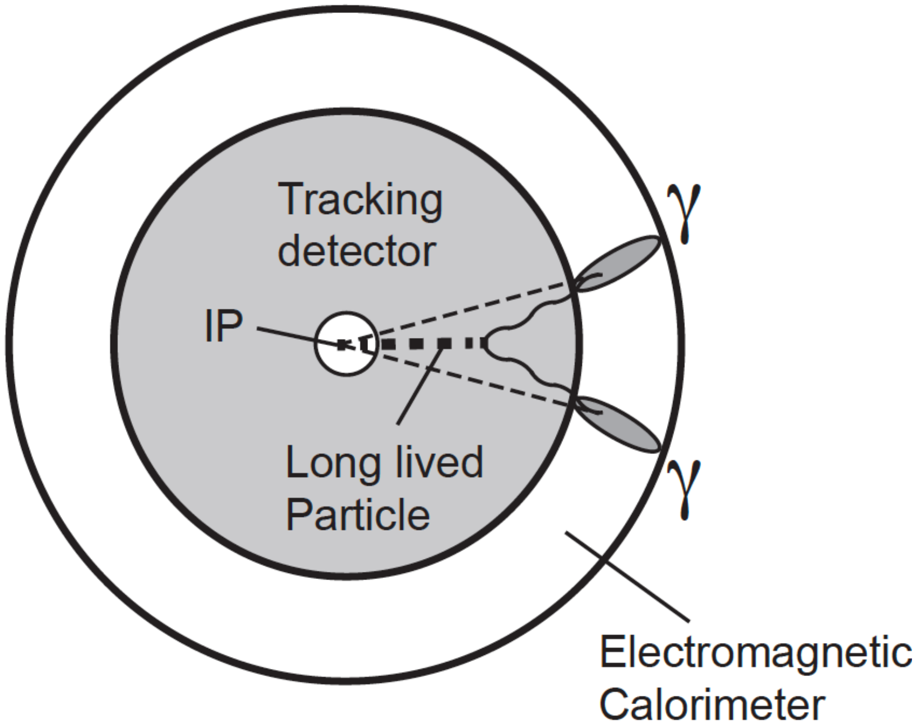
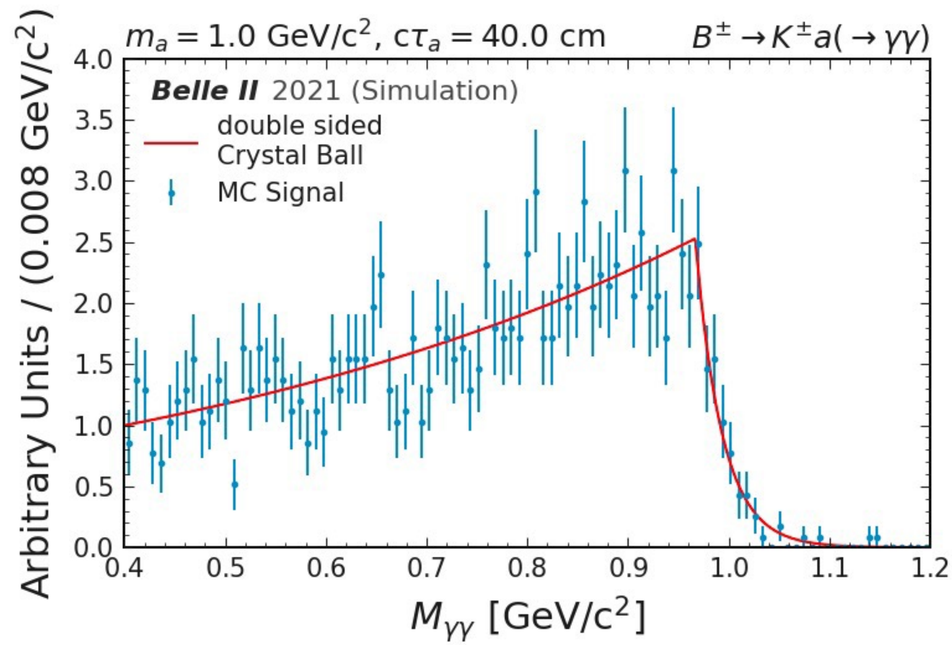
Hadron Experimental Facility

Motivation

- CsI(T*l*) is bright but slow, pile-up noise increase by beam background is seen at SuperKEKB/Belle II.
- Replacing all the crystals too big job to do.
- Does a pre-shower detector help?
  - To mitigate beam background effect (soft photon ~1MeV dominant) by using heavy and fast material
  - Making it sensitive to the photon incident direction gives a physics advantage to detect a long-lived ALP-like particle.
  - Absorber should also be active not to sacrifice energy resolution and efficiency for low energy photon (down to 50 MeV ~ 100 MeV) in SuperKEKB/Belle II environment.

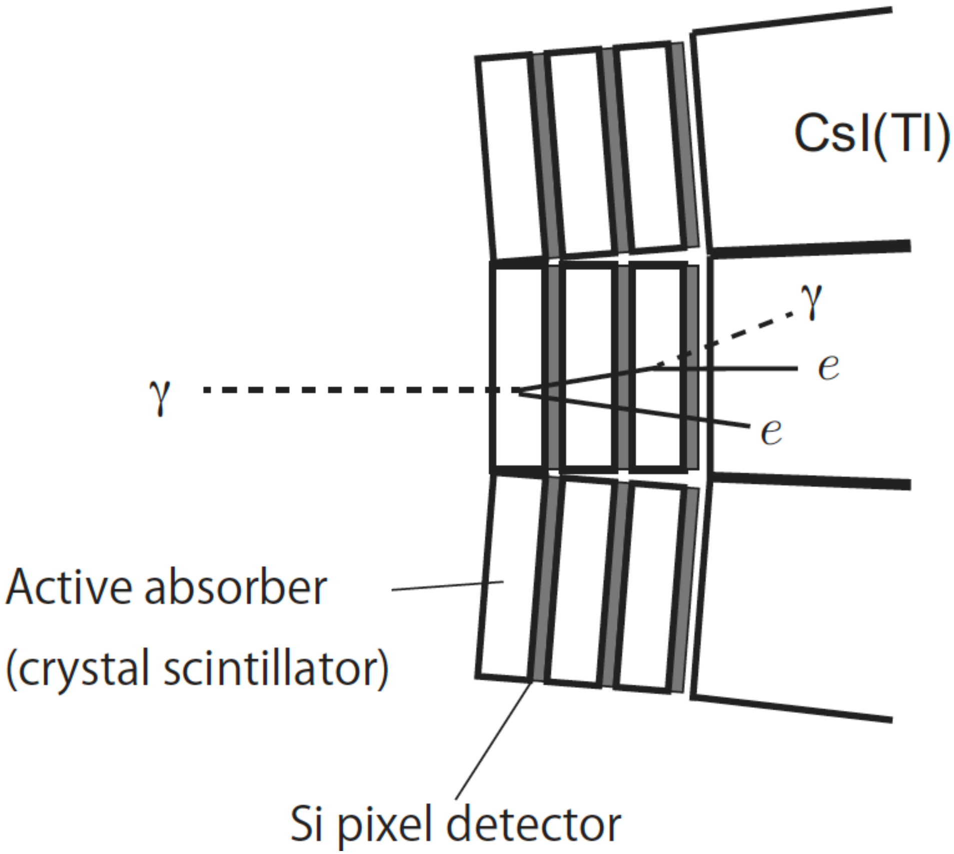
Limitation of mass determination for long-lived ALP-like in $\gamma\gamma$





Since very poor sensitivity for incident photon direction by $5.5 \times 5.5 \times 30 \mathrm{cm}^3$ CsI(T*l*) crystals (in total 8736 pieces), limitation of mass determination for long-lived ALP-like particles.

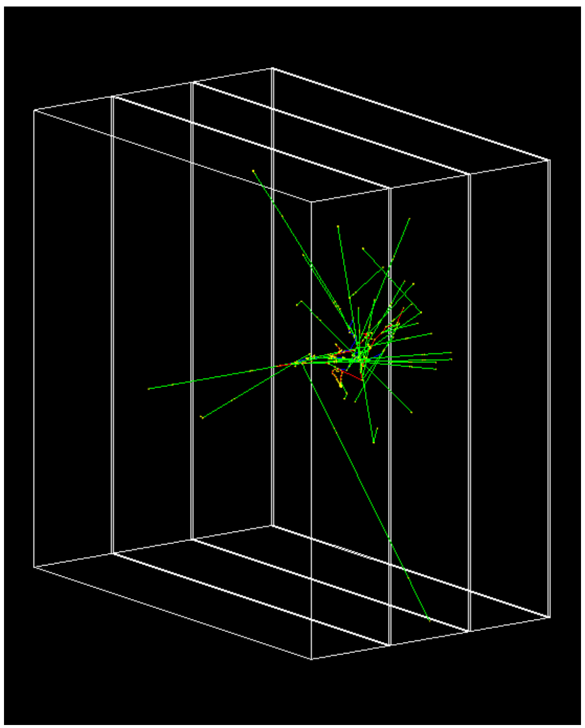
A model of pre-shower detector



- Active absorber made by a crystal scintillator to be active, thin/compact photon sensor is necessary.
- To detect e^+/e^- passage in the shower, pixel detector inserted.
- One layer has 1 X_0 thickness.
- Think about 3 layers case.

To start to look for a possibility

- On a PC (CentOS7 Linux, i7=8cores, 8GB memory) in Nara, GEANT4 v10.6 (latest) has been installed.
- Modify a sampling calorimeter example (B4a).

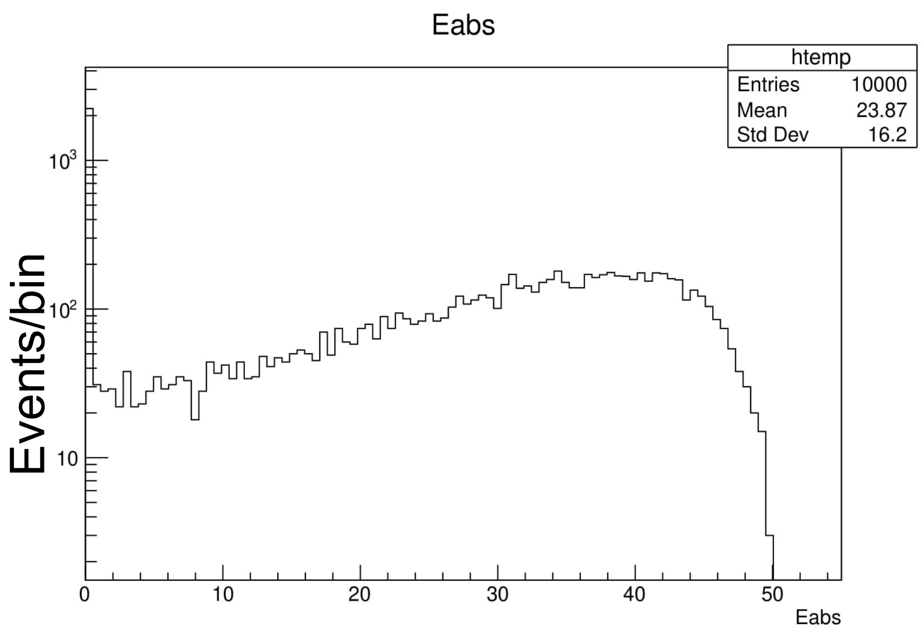


An event with 200 MeV γ incident

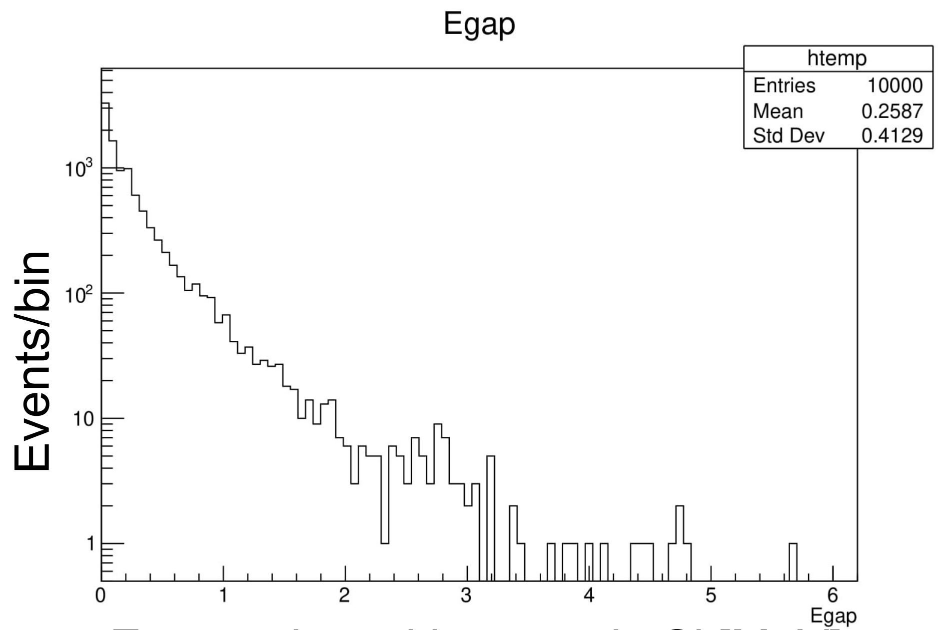
55mm × 55mm cross section.
One layer consists of:

- 11.2mm thick BGO (active absorber, corresponding to 1 X_0,thickness must be similar in other scintillator case such as LYSO, etc.)
- 0.3mm thick Si (to detect for e^+ or e^- passage)

Low energy, at 50 MeV γ



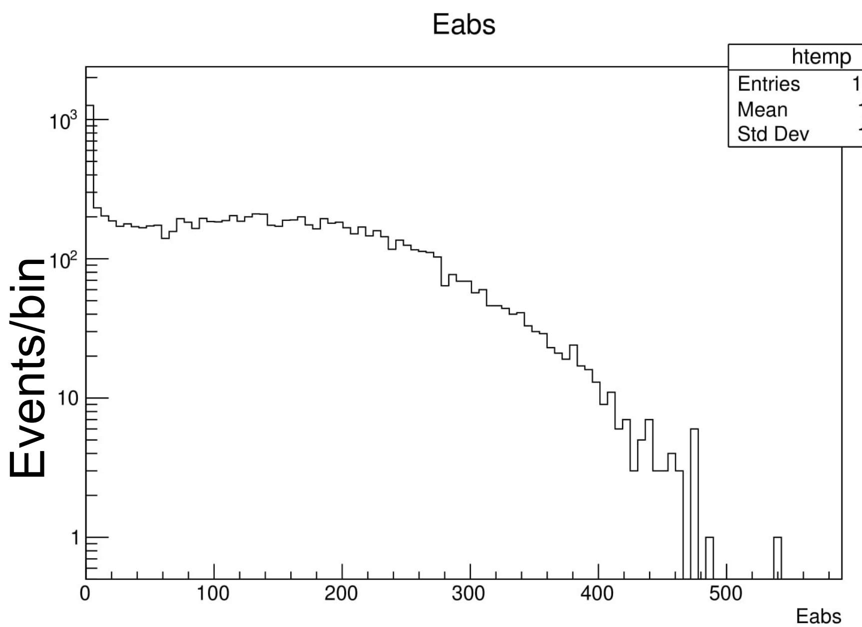
Energy deposition sum in BGO [MeV]



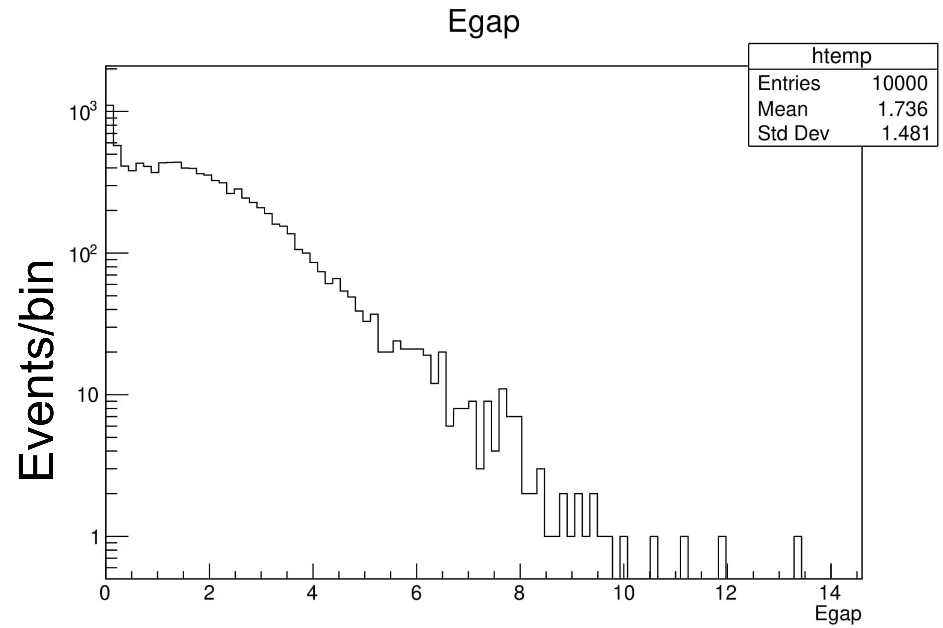
Energy deposition sum in Si [MeV]

25% of events went through without any interaction.
While, significant portion of events lost most of the initial energy, active absorber part should have good energy resolution.
One e^+ or e^- deposits ~0.1 MeV, average number of those is ~2.6.

1 GeV γ case



Energy deposition sum in BGO [MeV]



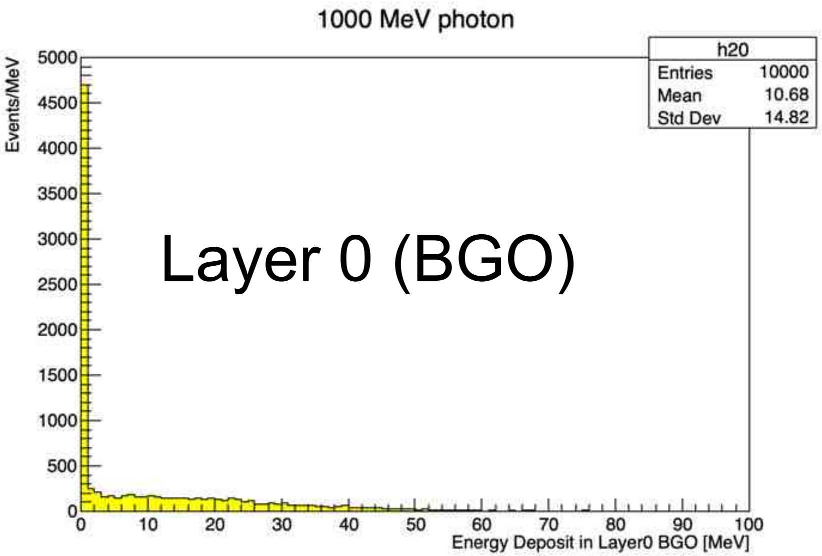
Energy deposition sum in Si [MeV]

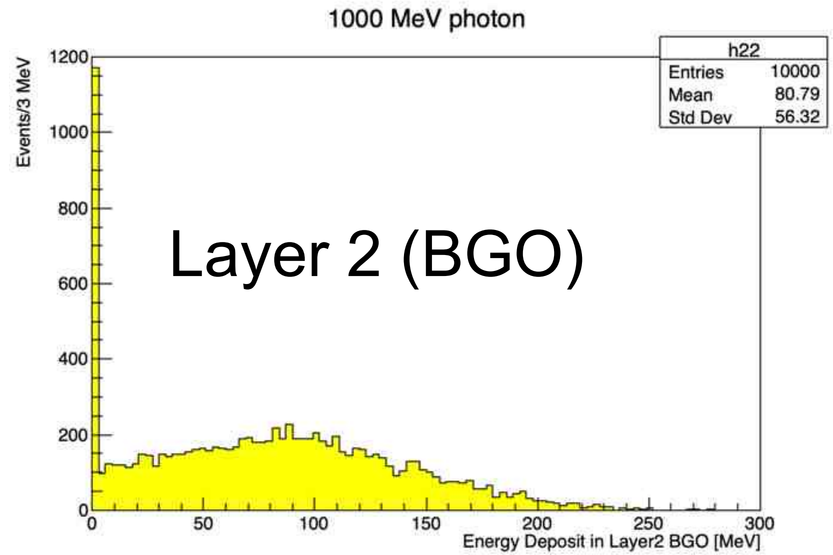
11% of events went through without any interaction.

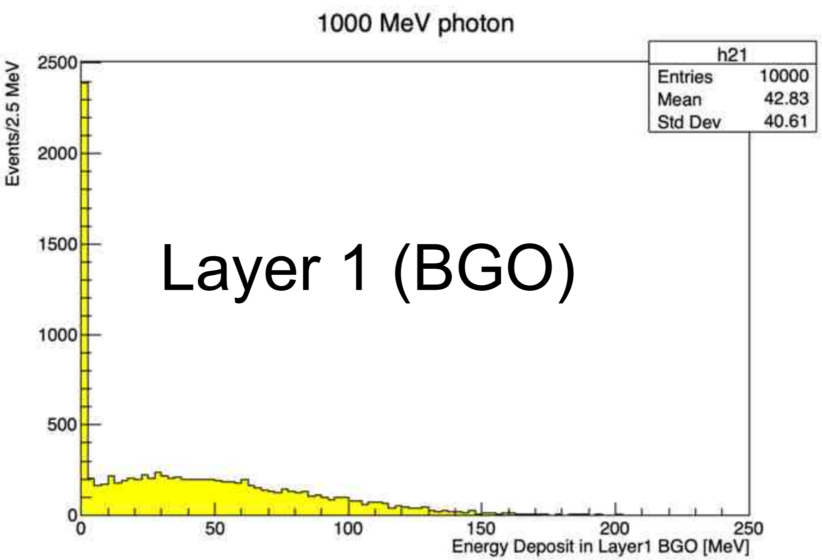
Significant portion of events' energy loss is a few $\times$100 MeV.

One e^+ or e^- deposits ~0.1 MeV, average number of those is ~17.

Shower development, 1 GeV

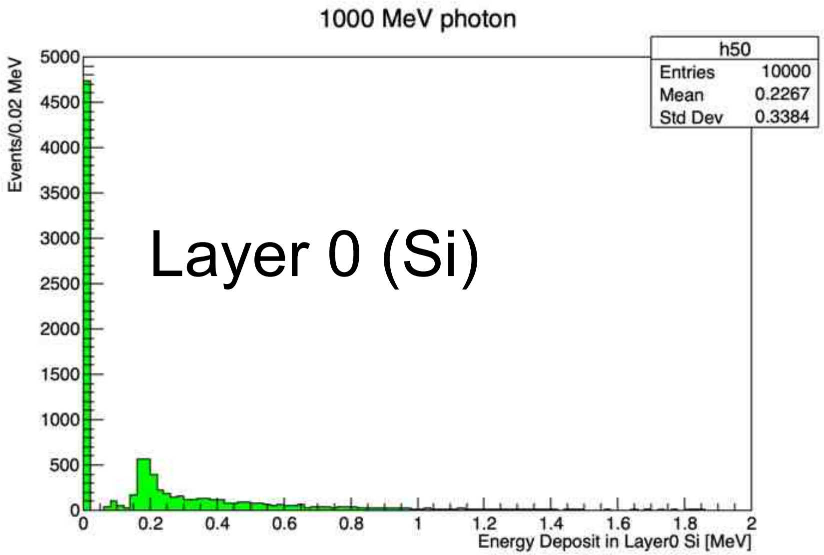


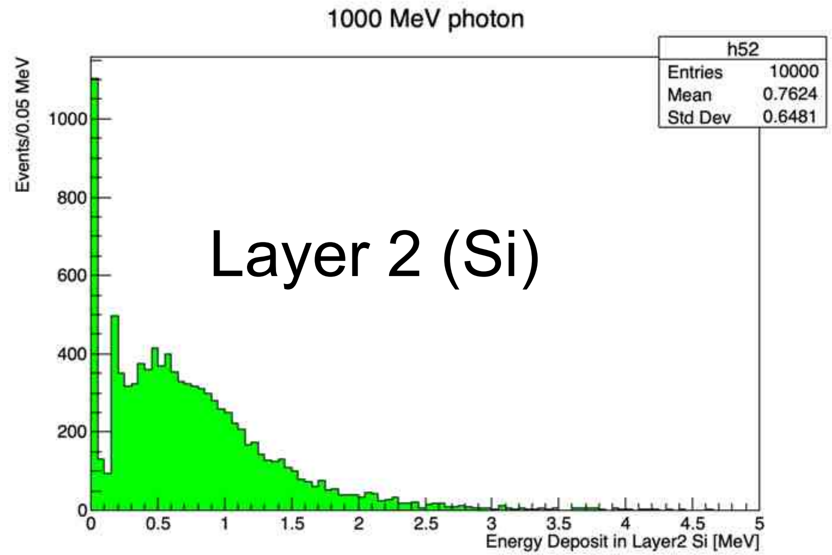


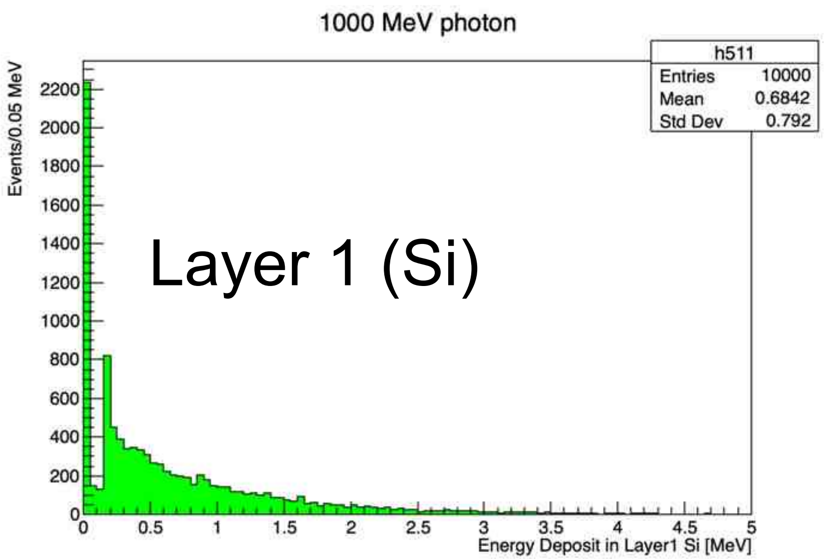


- ~half of events don't interact in the first one X_0.
- Making first part 2 X_0 thick may make sense, as did in the CMS endcap pre-shower (though absorber is tungsten, inactive in their case).

Shower development, 1 GeV (cont.)

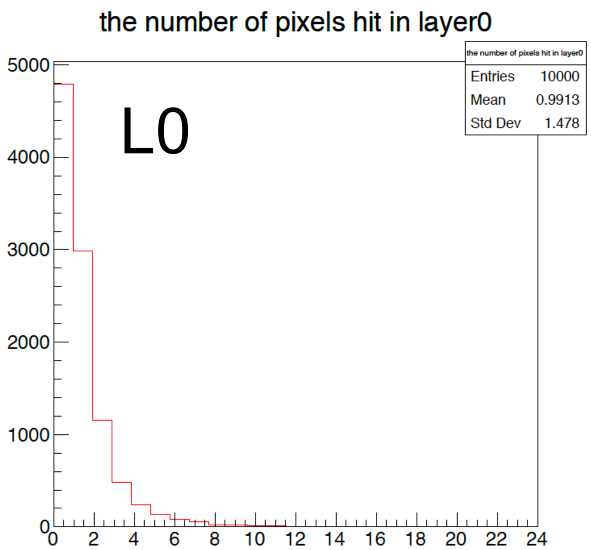




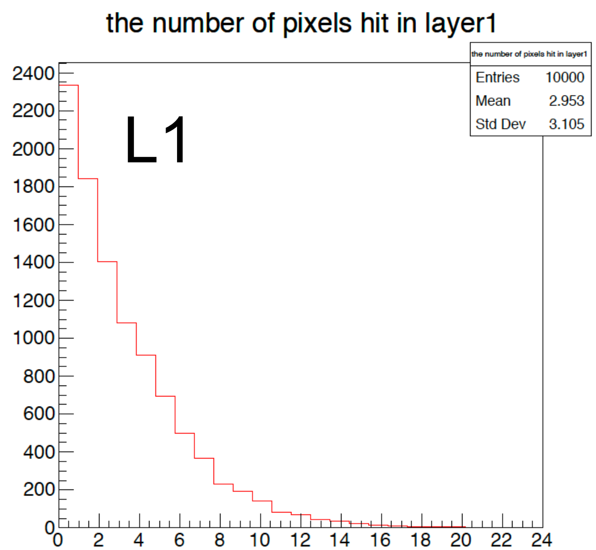


- ~80% of events have hits in 2 layers (or 3 layers) of Si.
- It looks worth to try see if we can reconstruct the direction of the incident γ by dividing Si into proper size pixels

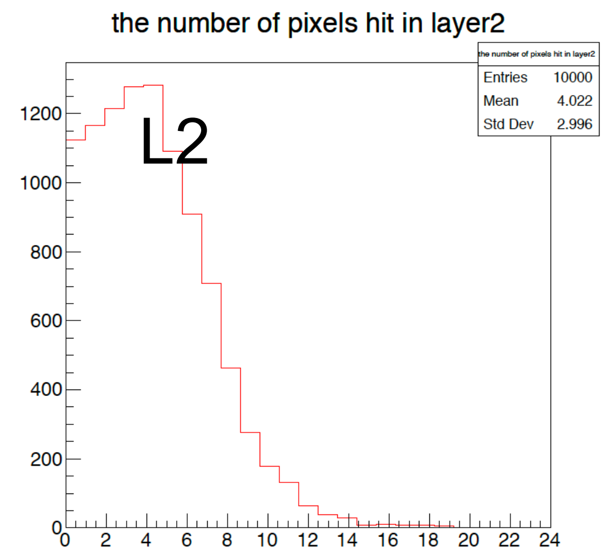
1 GeV γ, $1 \times 1 mm^2$ each



ot fired pixels



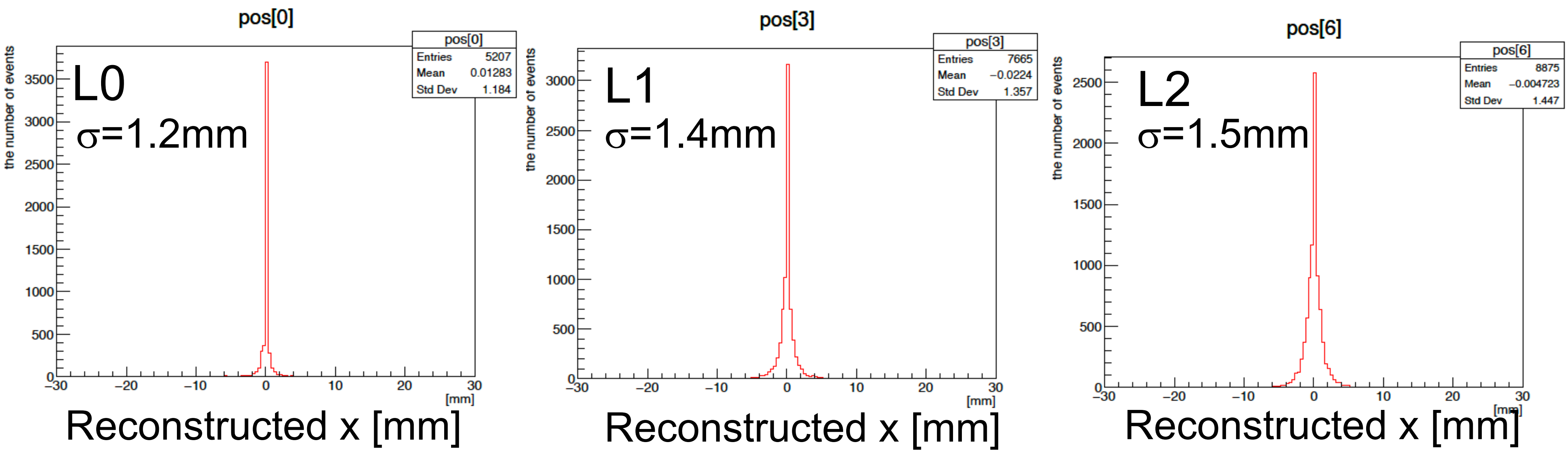
# of fired pixels



# of fired pixels

Just normal incident at the center of the detector.
Looks fine enough to try to reconstruct γ direction.

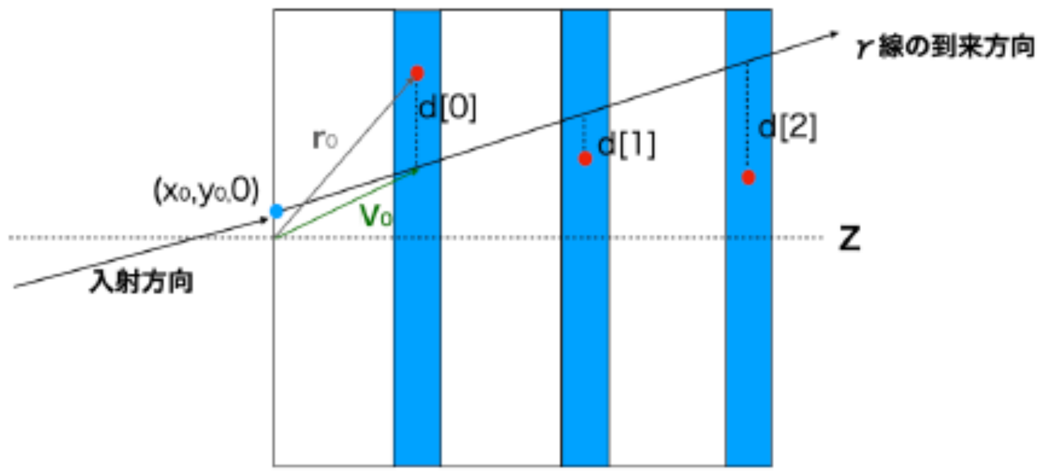
1 GeV γ, $1 \times 1\text{mm}^2$ pixel



In this simulation, fired pixels position are weighted by the energy deposition. In reality, binary readout of pixel information is very likely → further study item.

Incident angle reconstruction

γ momentum vector

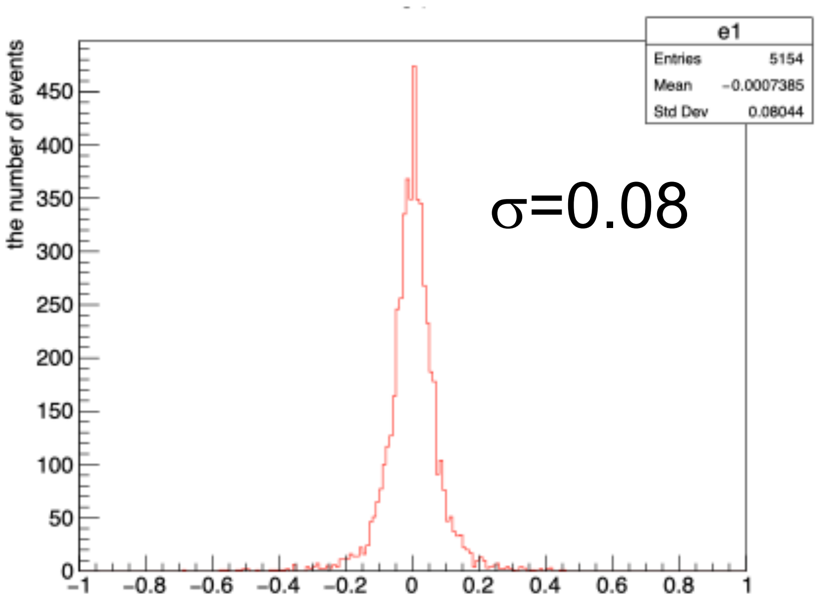


Straight-line fit to reconstruct γ momentum vector direction.
The parameters obtained by the fit are:

- unit vector of γ direction, (e_x, e_y, e_z)
- incident point (x_0, y_0)

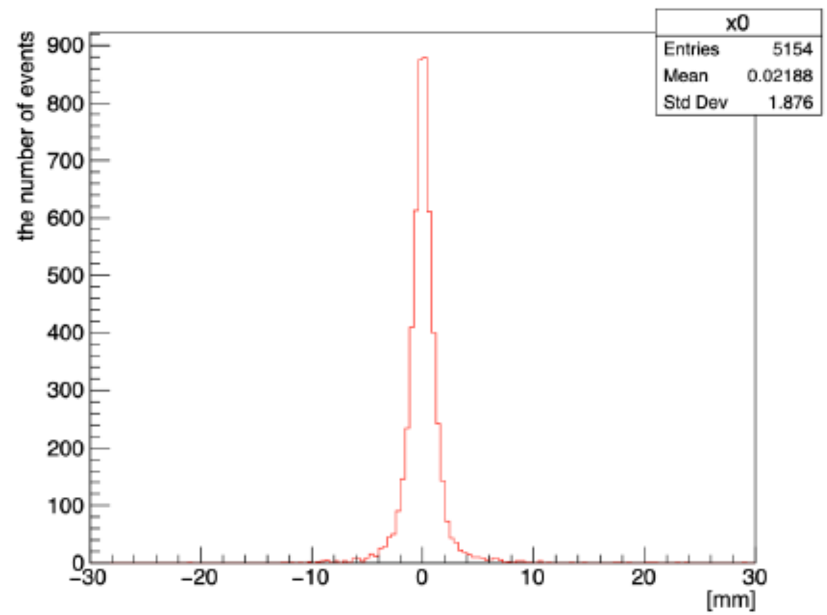
Angle and position resolutions

Normal incident 1 GeV γ at the center of the detector.



e_x

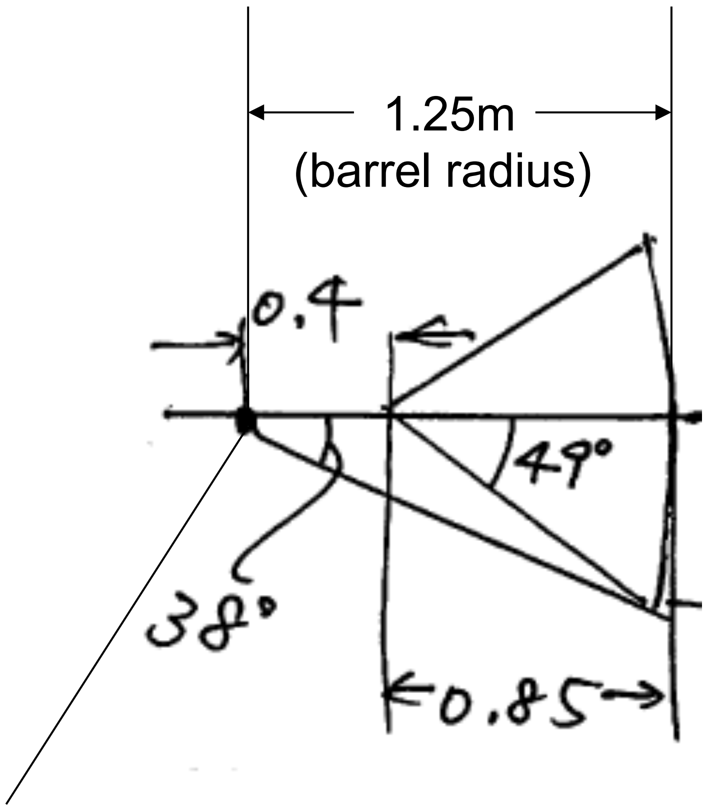
Since e_z~1, incident angle resolution is estimated to be ~80 mrad.



x_0

incident position resolution is estimated to be ~1.9 mm.

A simple estimation



B at rest, B → Ka, a→γγ, m_a=2GeV, 40 cm flight

When a→γγ symmetric energy, opening angle between them ~98°.
The angle between γ direction and the straight line toward IP is 49° - 38°=190 mrad, ~2σ separation.

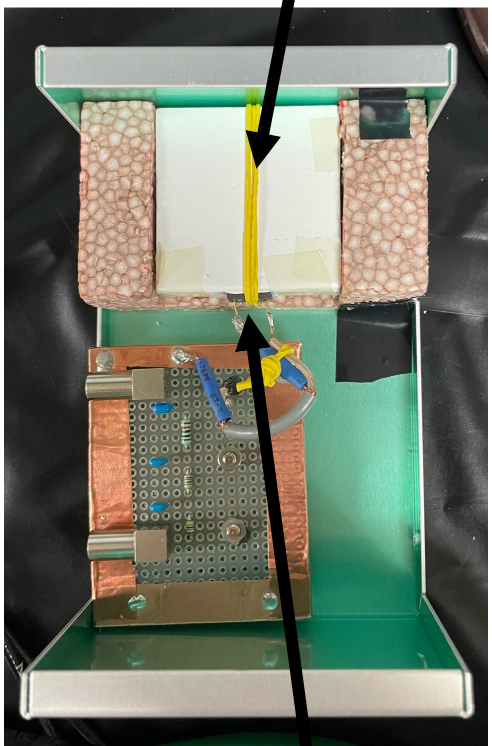
In e^+e^-→γa, a→γγ, m_a=4GeV, decaying after 40 cm flight case, similar separation from the γ_s from the IP.

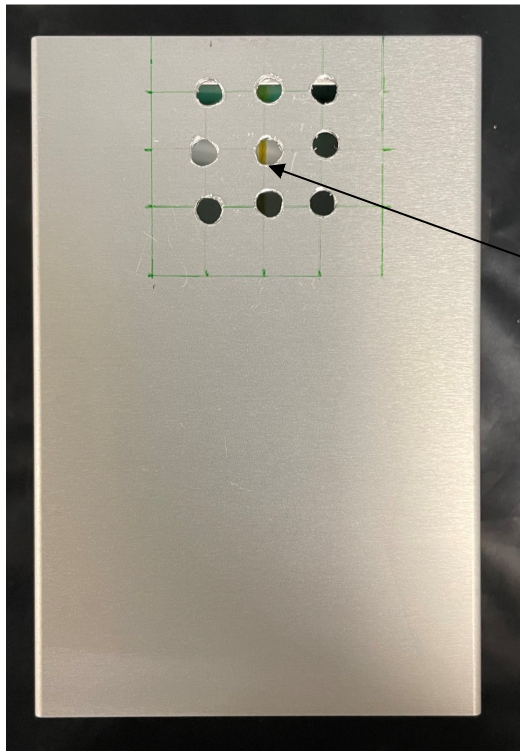
More thoughts

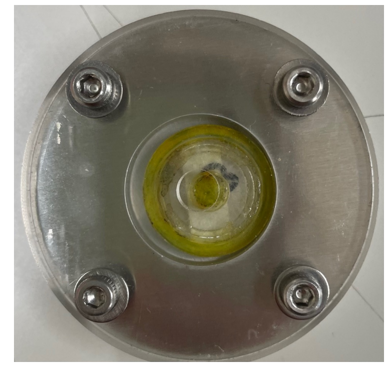
- 0.08 rad angular resolution looks limited by the pixel size (1mm) and absorber thickness(12mm).
- While it may be limited by the multiple scattering during passing through the absorber ($1X_0$).
- Need simulation with finer pixel pitch → on going.
- As for the pixel sensor solution(s), we need experts' help: SoI, MAPS, etc. could be candidate(s).
- All these pixel detector solutions are binary readout of pixel hits, need to be studied by simulation.

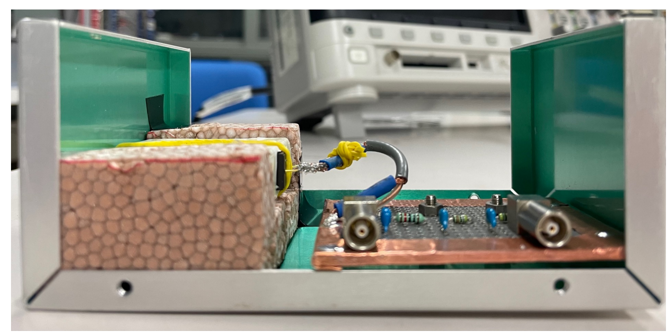
Light output measurement

Crystal scintillator(BGO or FastLGSO)
4×4×1.2 cm^3
Wrapped by GoreTex(reflector)





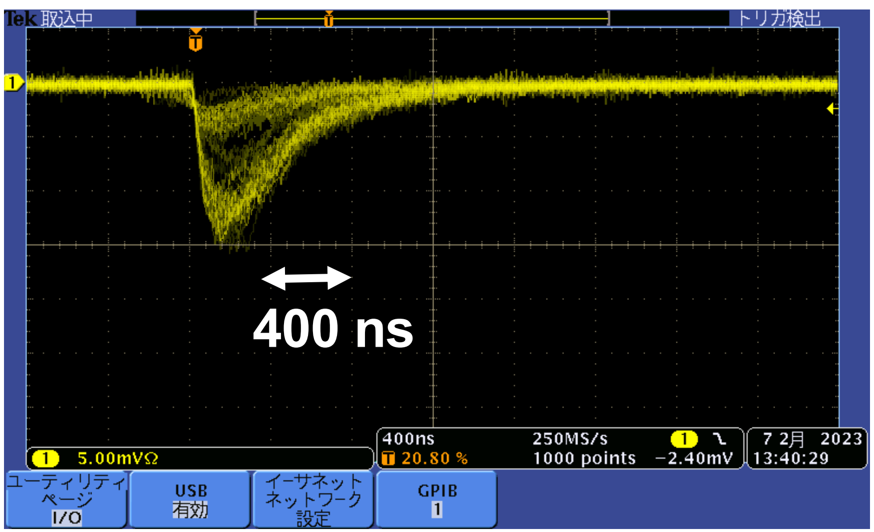


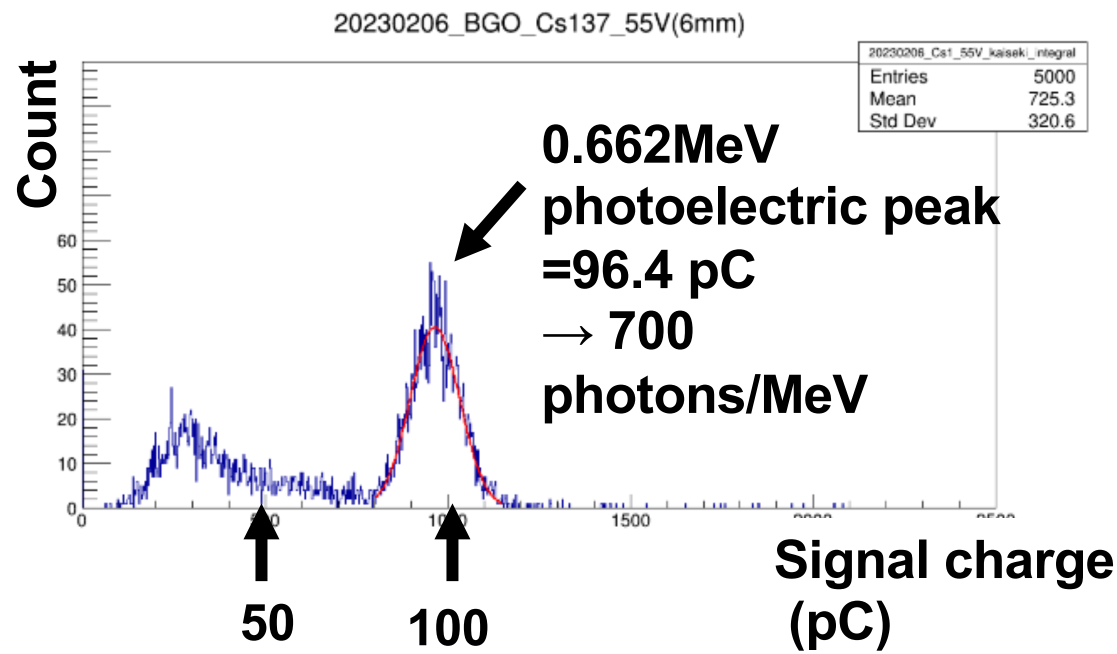


6×6mm^2 MPPC(S13360-6050CS)

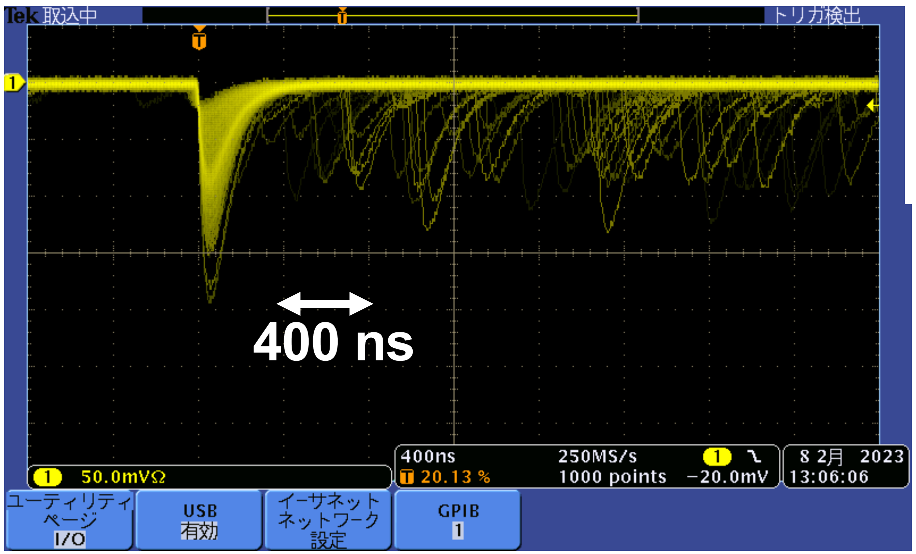
Light output (BGO)

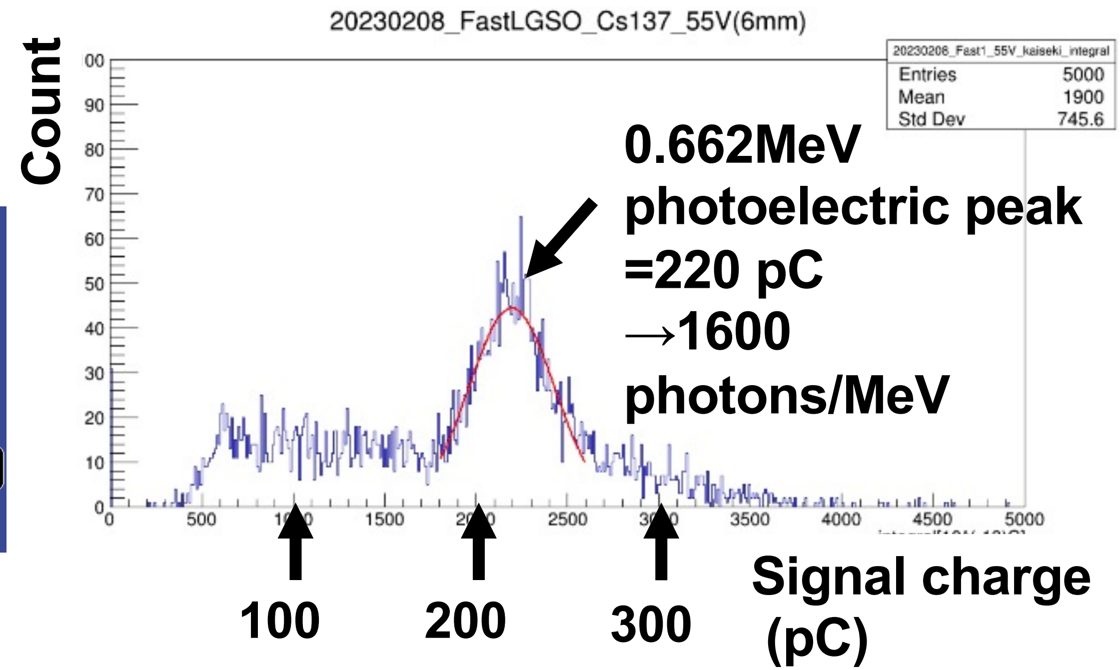
Signal read out by DPO3034 digital oscilloscope.
Waveform is taken by 250Msa/s, 1000 points, numerical summing up them gives the signal charge.





Light output (Fast LGSO)





- Higher light output, faster scintillation decay time than BGO, as expected.
- S13360-6050CS has 14400 pixels, measurement is still safe from the saturation due to the number of pixels.

Remarks

- In actual Belle II detector, the TOP counter is just in front of the CsI(*Tl*) calorimeter.
  - Criticism "There is no space to put it".
- Still worth to pursuit
  - Figuring out how much physics sensitivity gain.
  - Similar detector configuration is also being considered in other experiments, EIC, etc.
- Entire project is pretty large
  - Both crystal scintillation detector (active absorber) and silicon pixel detector (e^+/e^- passage detector) are necessary to be handled.
  - Needs interested friends involvement.

Acknowledgement and reference

- Tsukasa Konno for graduation thesis FY2019
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- Hina Tagashira for work as master student
- Iori Okada for graduation thesis FY2022
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