Progress on Single Crystal Simulations at UMD

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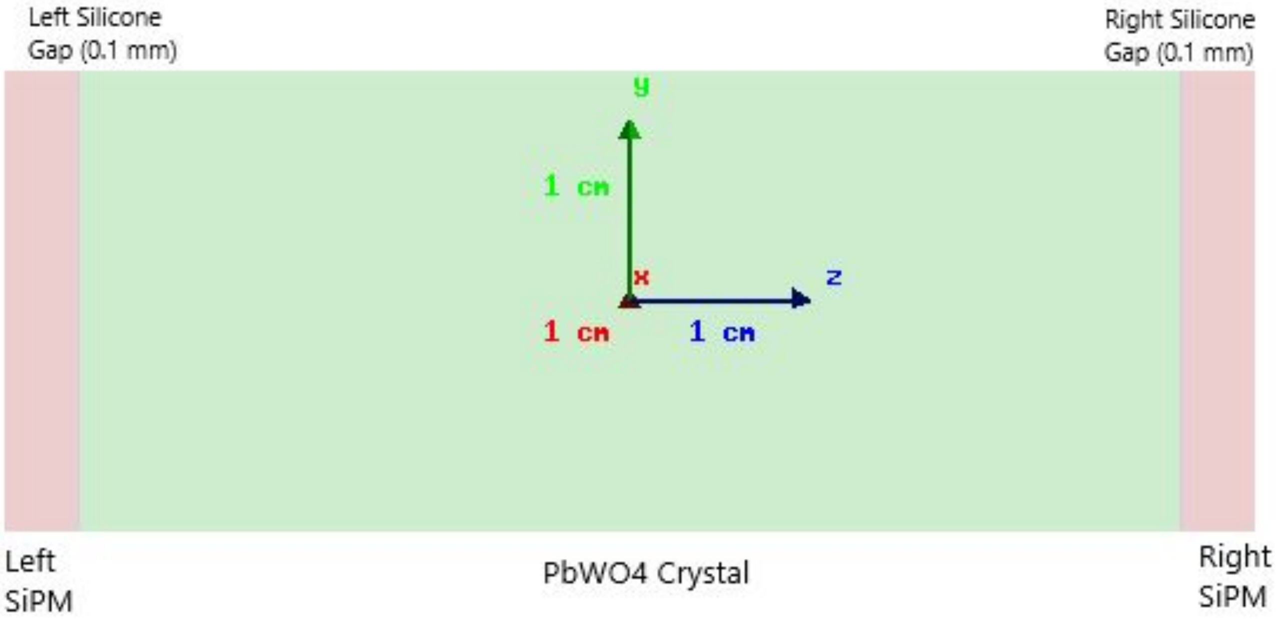
Recap and Introduction

- Simulated a dual-readout crystal detector with GEANT4 + DD4hep
    - Reproduced the 2020 proposal plots (PbWO4)
    - Also simulated BGO and PbF2 crystals
- Made a tentative list of potential wavelength filters for extracting the Cerenkov component
    - Plotted the Punzi optimization values of signal with respect to background as a function of the wavelength cut for the Cerenkov component (Punzi criterion: https://arxiv.org/pdf/physics/0308063.pdf)
- Currently simulating two different geometries for two sets of measurements at UMichigan
    - Cosmic ray setup and test beam setup with 8 MeV electrons (to be done at University of Notre Dame)

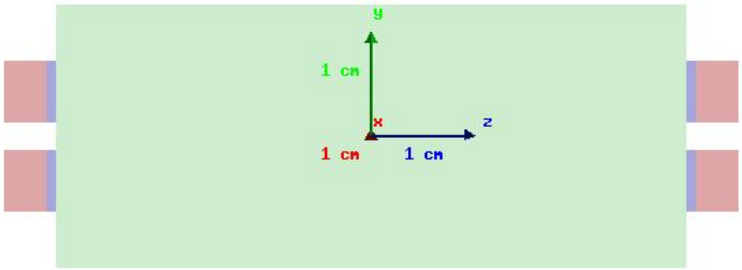
Recap - Earlier Geometry of the crystal

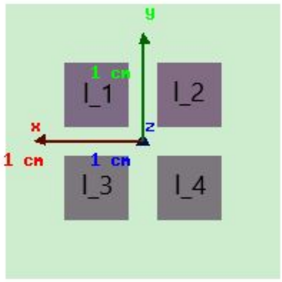
- We had a $PbWO_4$ crystal of 2.5cm ✕ 2.5cm ✕ 6cm flanked by silicone gaps (0.1 mm) on both square surfaces and that was attached to the SiPMs (one SiPM on either of the square faces)
    - The electronic response of the SiPMs has not been modelled in the simulations and the quantum efficiency of the SiPMs (as a function of photon wavelength) has simply been incorporated into the post processing file
- The active area of the SiPMs was considered to be the whole area of the square face (2.5cm ✕ 2.5cm)



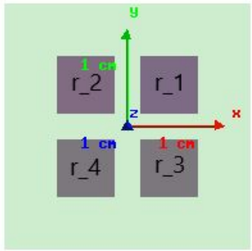
Two distinct geometries for the crystals (mainly PbWO4)

- Two sets of measurements are being done by UMich
  - Cosmic ray setup (mostly high energy muons and their secondaries)
  - Test beam setup with 8 MeV electrons and controlled direction at Notre Dame
- The crystal dimensions in the current simulation are 2.5cm × 2.5cm × 6cm
  - The cosmic ray setup has 4 SiPMs (in red) each of size 6 mm × 6 mm on each square surface arranged in a 2×2 array with a perpendicular spacing of 2.5 mm and a silicone grease of 1 mm thickness (in blue)





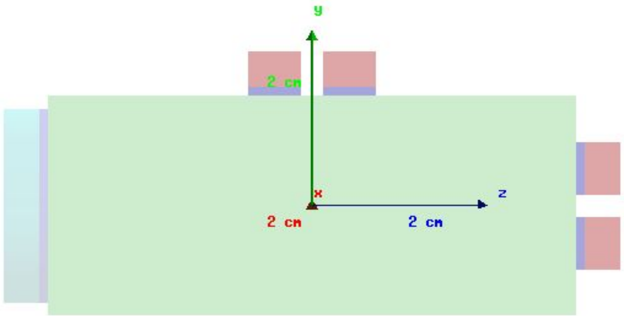
Viewed from the left side

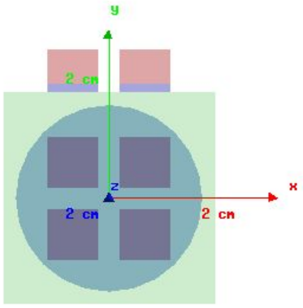


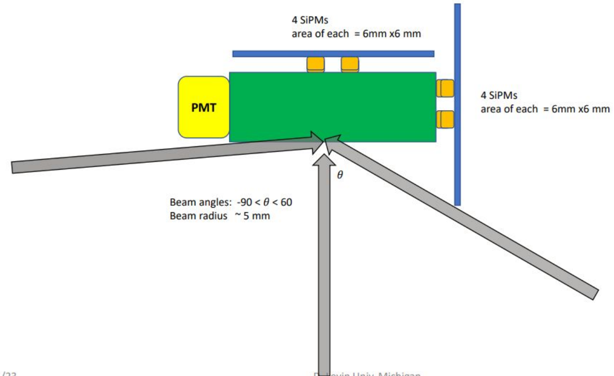
Viewed from the right side

- The test beam setup has a PMT on one square face and one of the SiPM arrays is attached to the long face opposite to the one which has the electron beam incident on it [The other is still attached to the other square face]

Signals available: total 9 channels (8 SiPMs, + 1 PMT)
DAQ channels = 4
Must combine

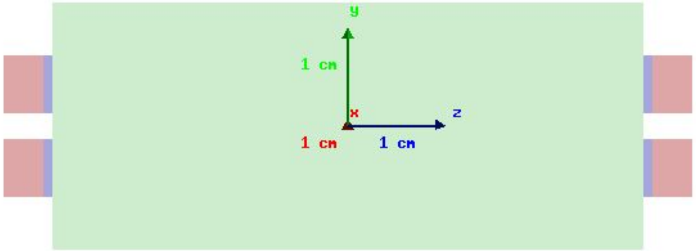


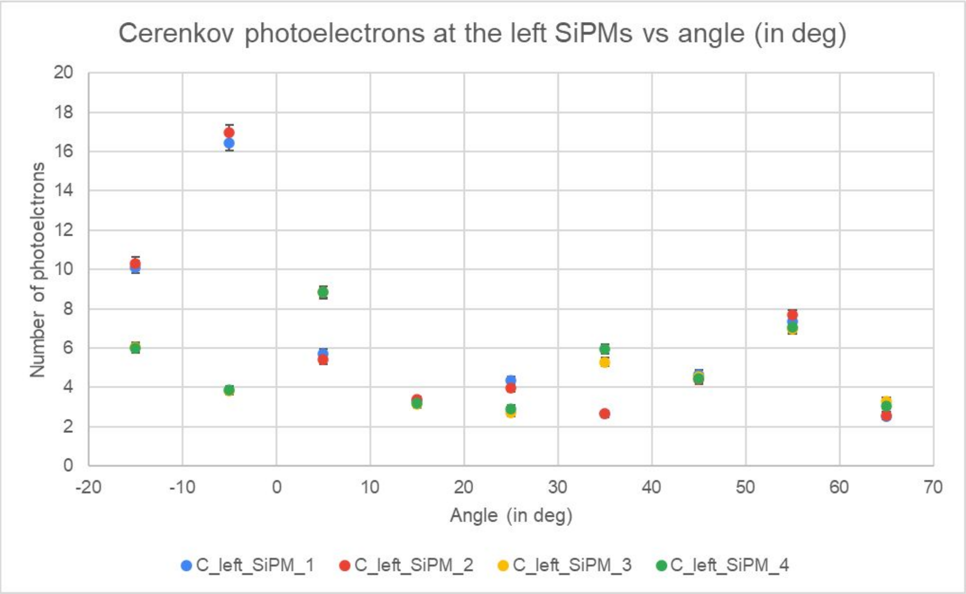


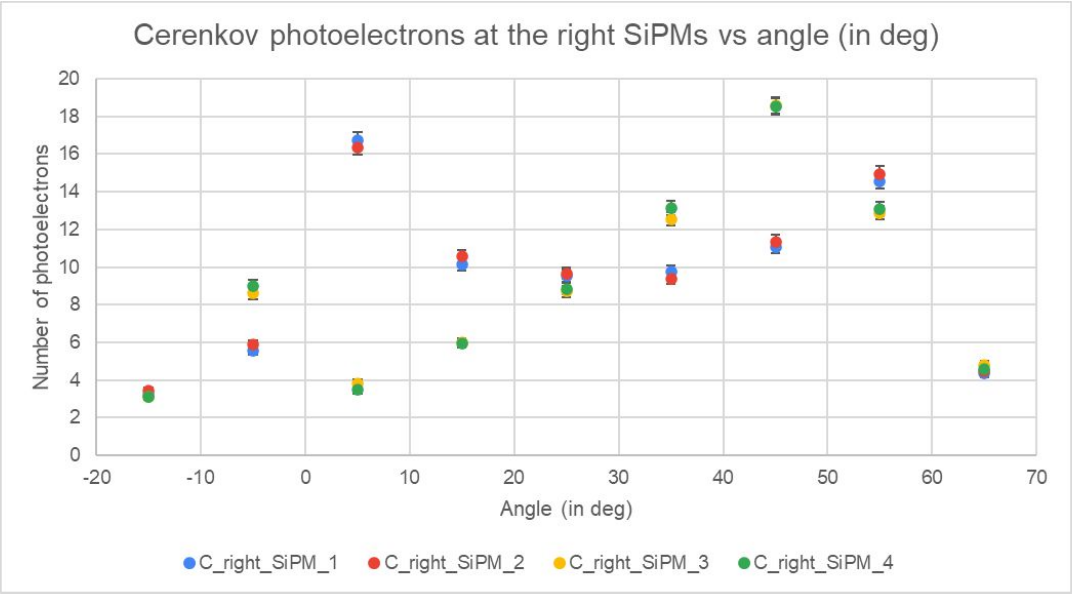


Cosmic ray setup (1)

- The 4 long faces are wrapped with teflon tape (not in the current simulation though)
- The CRY library is also not fully setup so currently using 2 GeV muons with specific angles of incidence (photon counts averaged over 100 events)
- The SiPM numbering convention used previously is also used in the plots of angular dependence (for both C and S components)



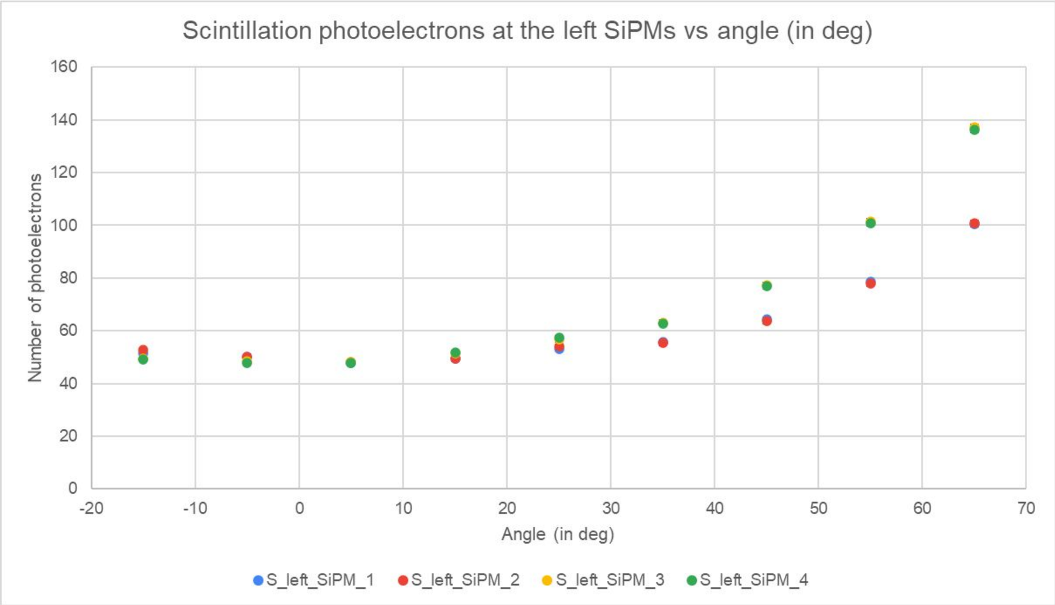


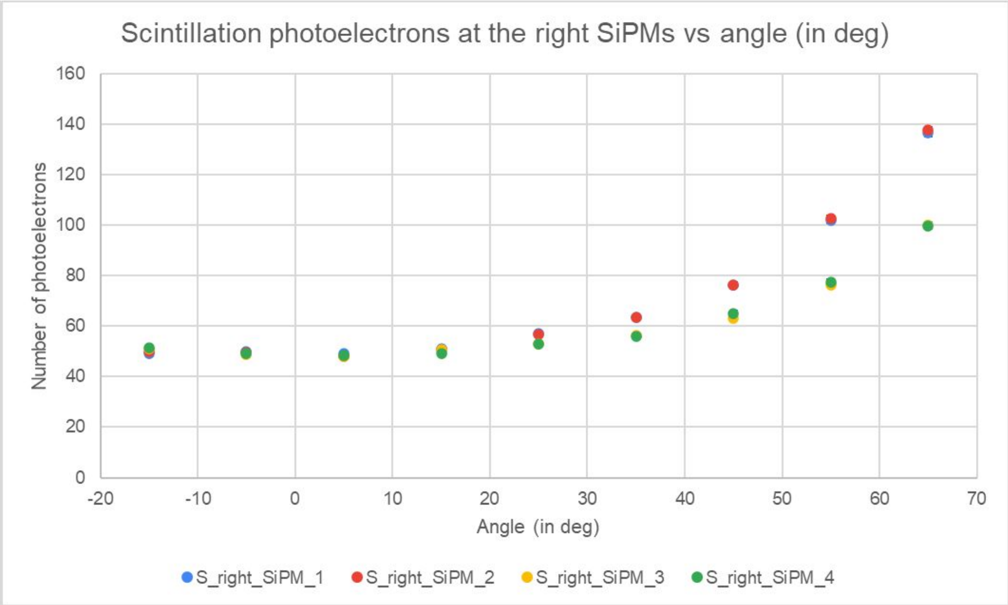


- We note that in both these plots, the photon counts in SiPM 1 and 2 match, and the photon counts in SiPM 3 and 4 also match (This is true for scintillation too, plots in the next slide)
- This is expected, considering the orientation of the beam and the choice of numbering of the SiPMs - #1 and #2 are symmetric wrt to the muon path and on opposite sides of it, and the same holds for #3 and #4 [Of course this will not hold when cosmic rays are included]

Cosmic ray setup (2)

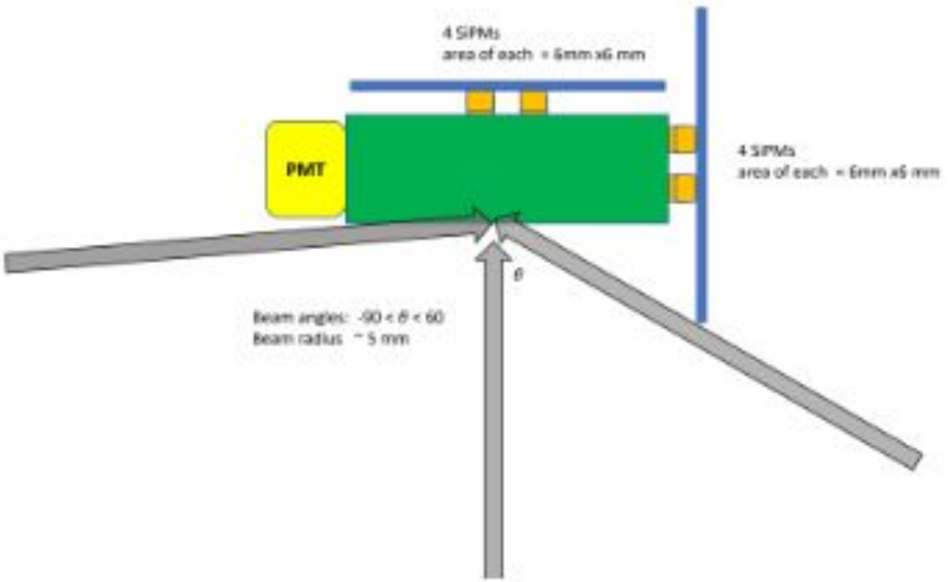
- Specifically there is a divergence seen between the two pairs of channels for the scintillation plots at higher angles
- This is again due to the muon path direction - on the right end of the crystal the photons have to travel less to reach #1 and #2 compared to #3 and #4, and the situation is reversed on the left end





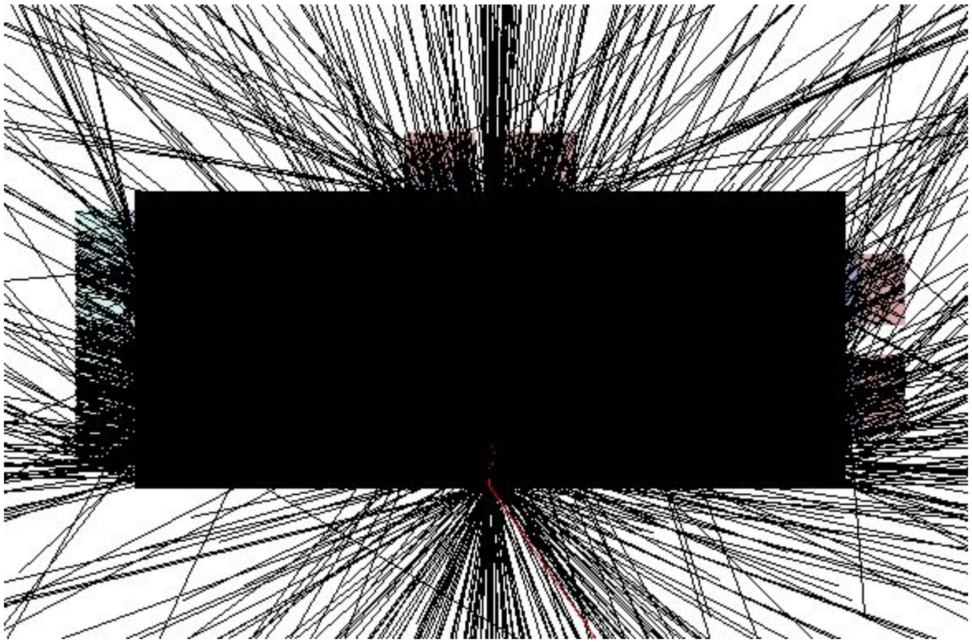
Test beam setup (8 MeV electrons) for PbWO4 (1)

- The range of angles of incidence do not span the entire 180 deg because the beams sent from the right side at an angle > 60 deg will be blocked due to the PCB
  - The active diameter of the PMT is 22 mm
  - The beam position is such that it hits the long face at its center
  - This crystal is polished but not wrapped



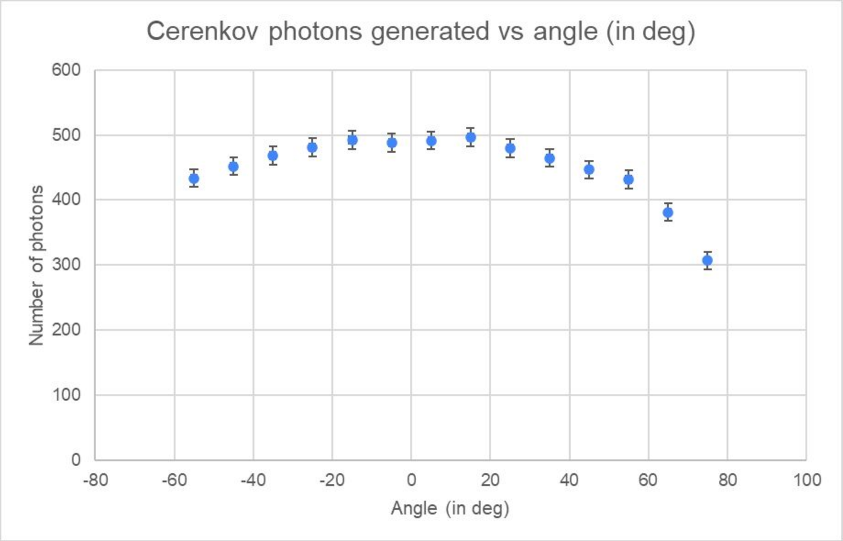
- At this energy, the electron penetrates barely 1-1.5 mm inside the crystal

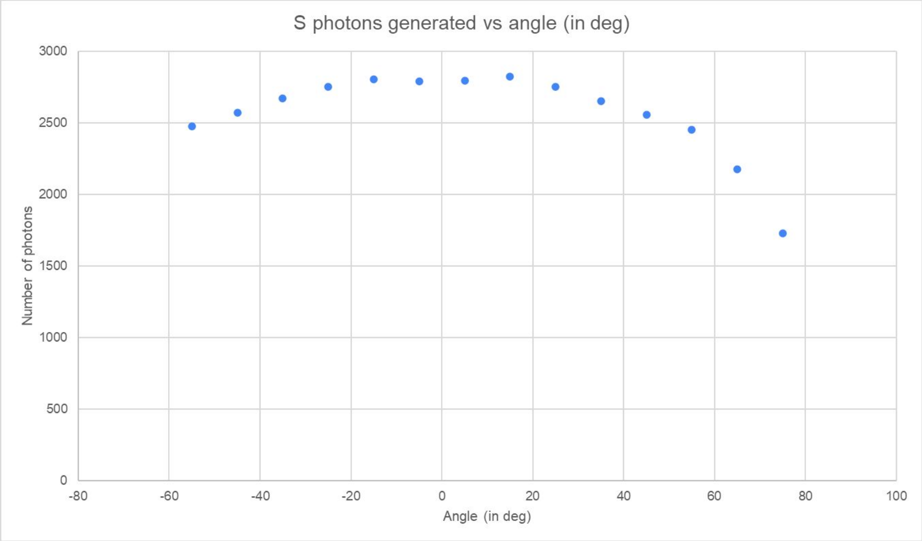
- Sample display for angle of incidence -35 deg (measured with respect to the normal from the longest side; angles on the right are taken to be negative)
- For the subsequent plots of angular dependence, the photon and photoelectron counts are averaged over 1000 events

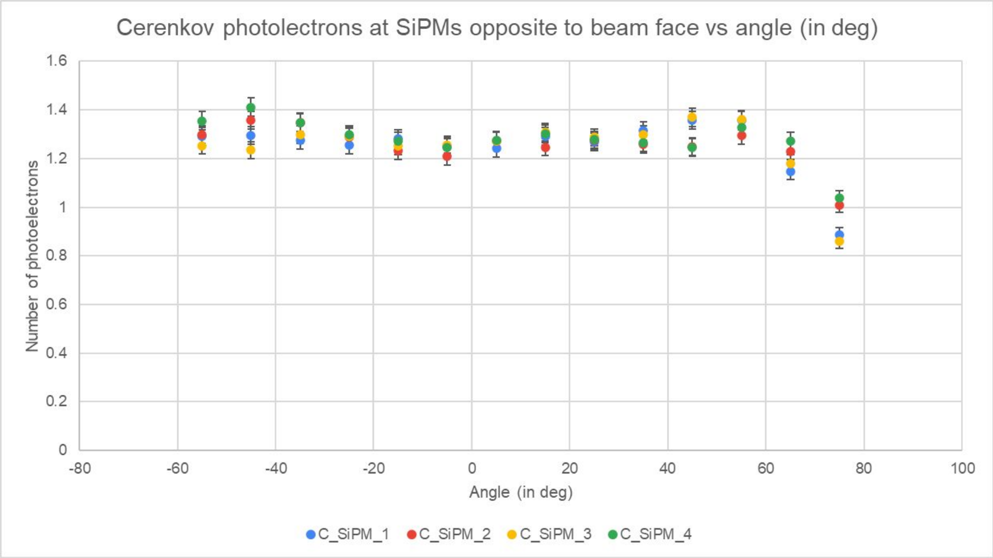


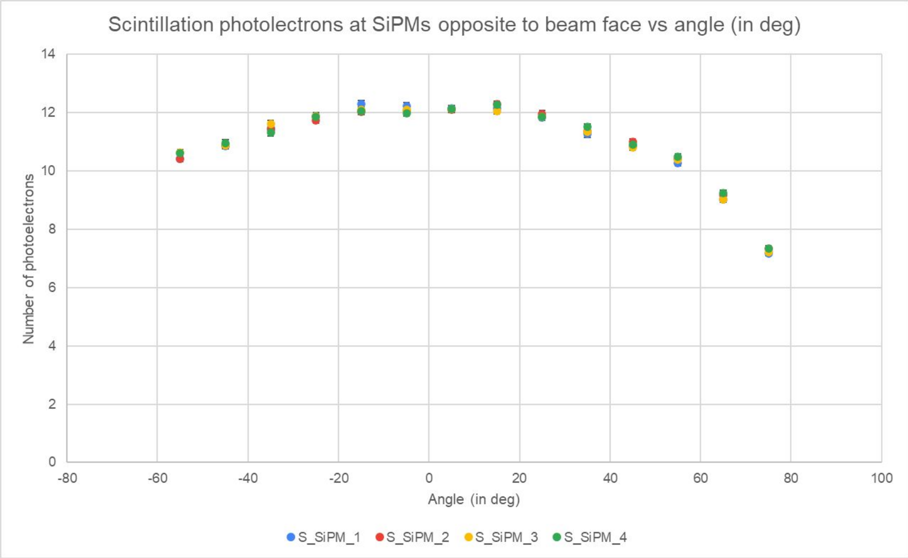
Test beam setup (8 MeV electrons) for PbWO4 (2)

- Here the electron does not pass fully through the crystal and there is no well defined path length, so we do not observe the 1/cos dependence for the generated photons, that was seen in case of the 1 GeV muons
- However, the number of photons generated (both Cerenkov and scintillation) are symmetric about the 0 deg incidence angle, as expected
- This symmetry is also seen for the photoelectrons at the SiPMs on the face opposite to the beam incidence



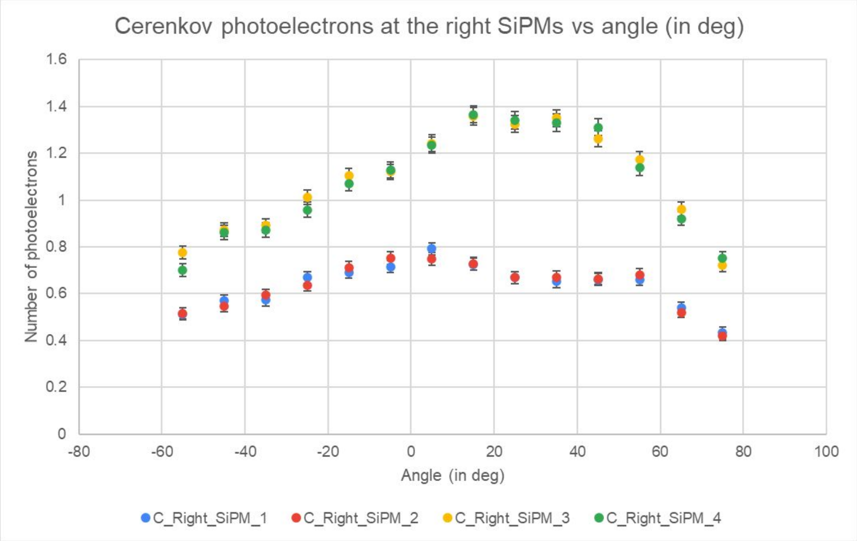


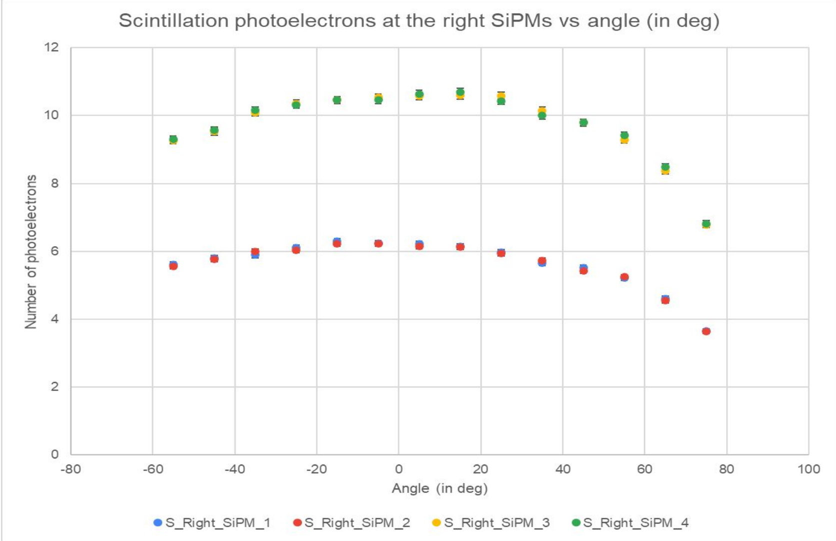


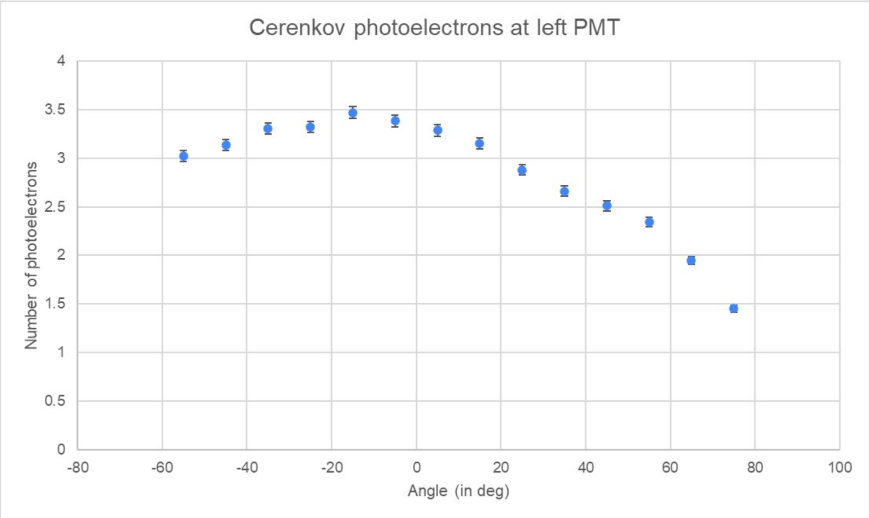


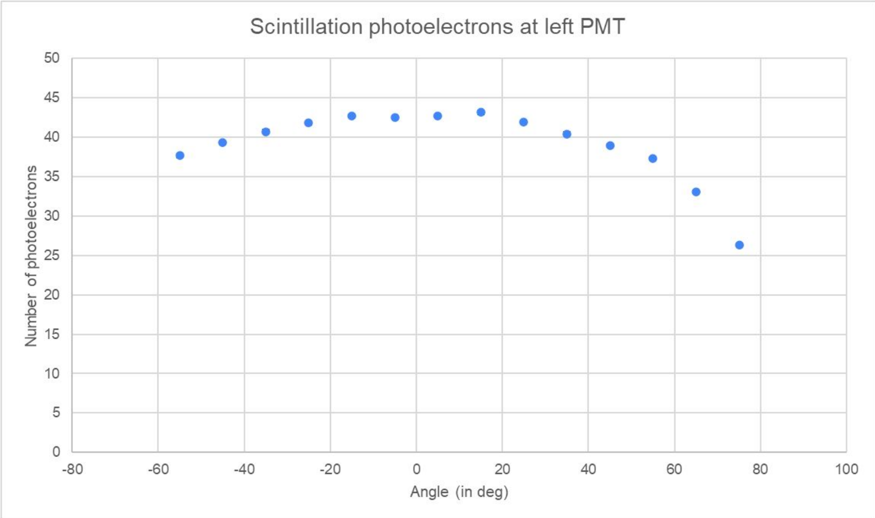
Test beam setup (8 MeV electrons) for PbWO4 (3)

- Again there is a difference of counts between pairs of SiPM channels (1,2) and (3,4) on the right for both S and C parts
- This is also expected considering that (1,2) are on opposite sides of the beam plane (i.e. symmetric) and (3,4) as well
- But (3,4) are closer to the point where the electron gets 'stopped' so their photon counts are more



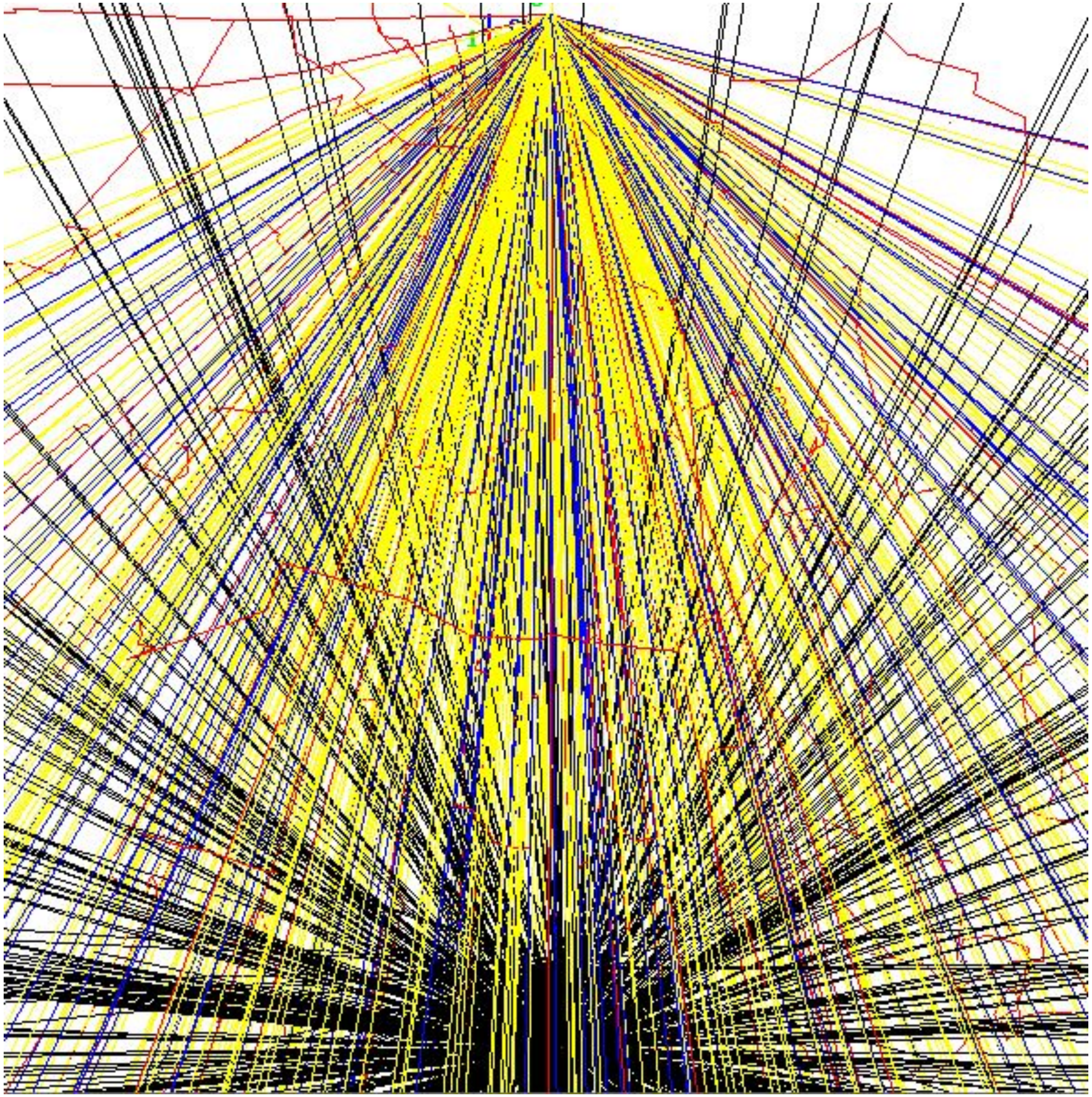






Sample display of using the CRY library

- For integration of the CRY (cosmic ray) library, all the events are being produced starting from z=0 and going towards negative values of z
- So to have a shower that goes ‘downwards’ from the top, we have shifted the crystal in the negative z direction - this is pure translation and there is no rotation involved
- This also mimics the actual setup where the crystal is placed vertically i.e. with one of the square surfaces facing downwards
- Here the vertical is the z direction, the ‘starting’ point of the rays is at z = 0, and the center of the crystal is at z = -50 cm i.e. at the bottom of the figure
- 1000 individual events from the CRY code at a latitude of 0 deg and altitude of 0 m
- SubboxLength is set to 0.005



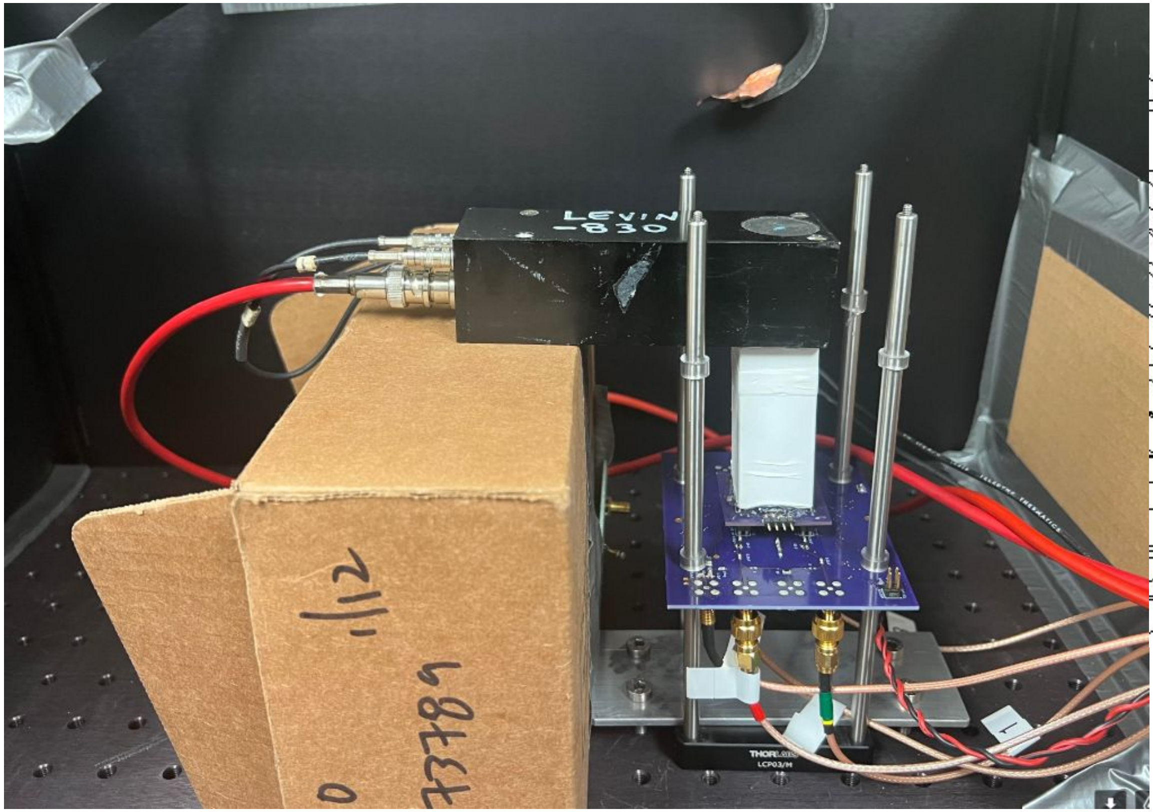
Summary

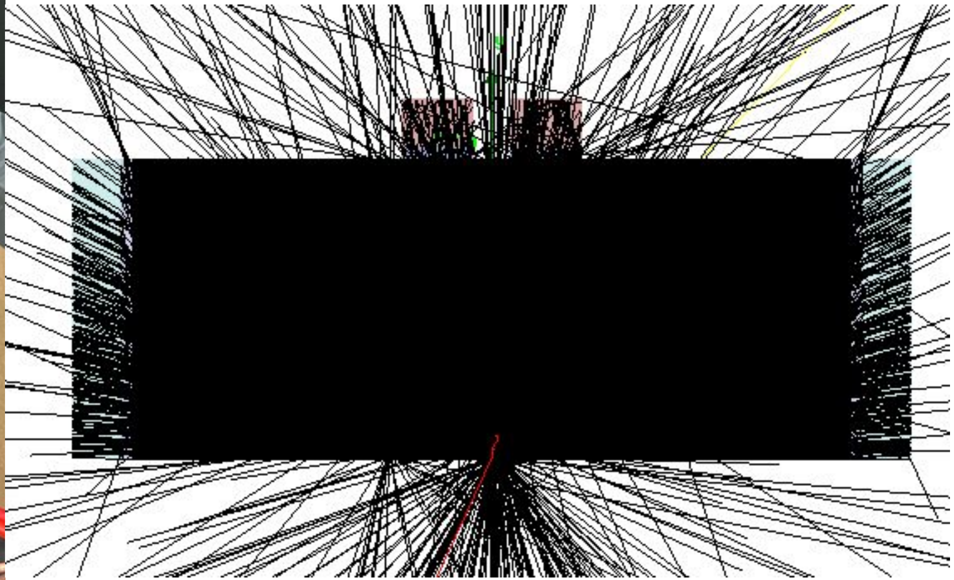
- Prepared 2 slightly different arrangements of photodetectors for the cosmic ray setup and the test beam setup
  - Made angular dependence plots for all the photodetector channels for both the Cerenkov and scintillation components

- To do
  - Include the (reflective) effects of the PCB on which the SiPMs are mounted, and also account for the extra silicone grease that covers the gaps between the PCB and the crystal
  - Wrap the teflon tape around the long faces (side faces) of the crystal in the cosmic ray setup
  - Adjust CRY library parameters to closely mimic cosmic ray properties

Backup

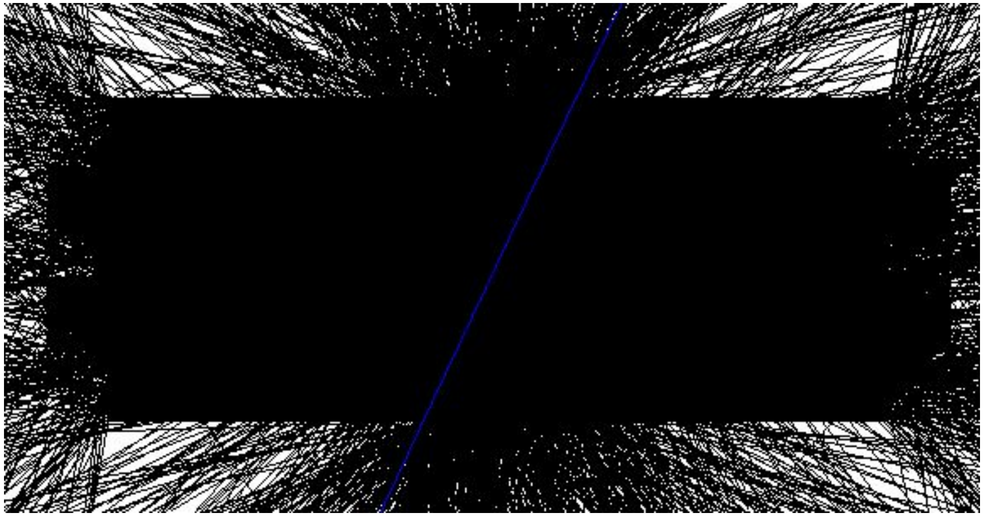
Actual setup (with 1 SiPM array) and new event display (surface not wrapped or mirrored)



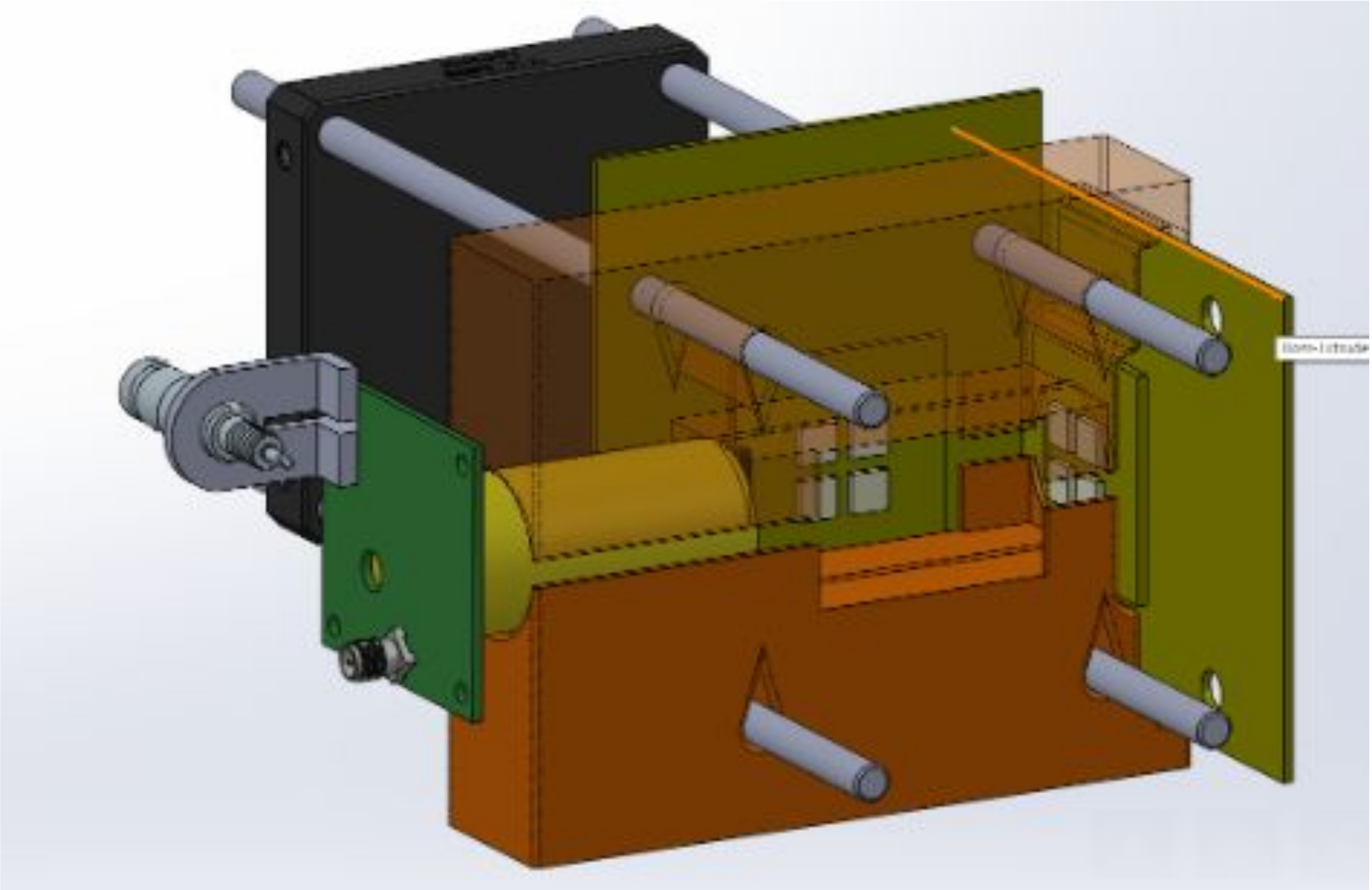


Test beam (8 MeV electrons) - 25 deg angle of incidence

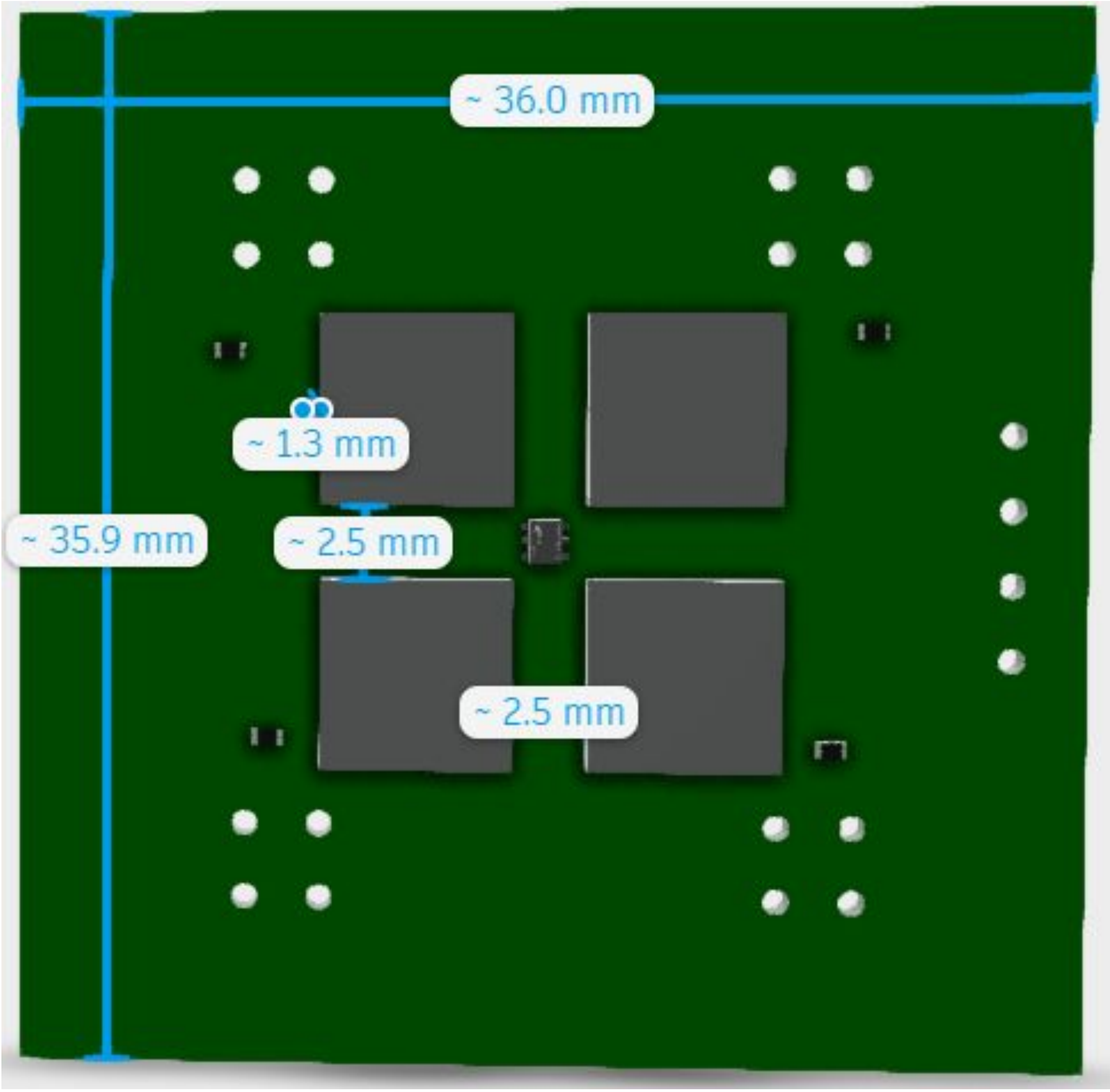
Cosmic ray setup with 2 GeV muons - 25 deg angle of incidence (to the right)



Test beam setup display in SolidWorks

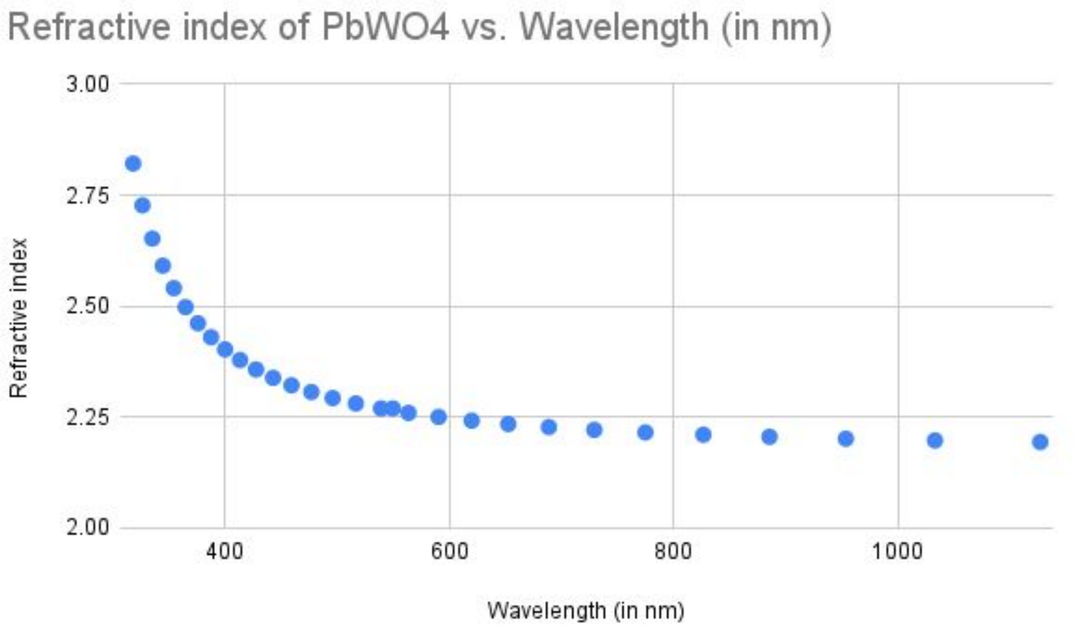


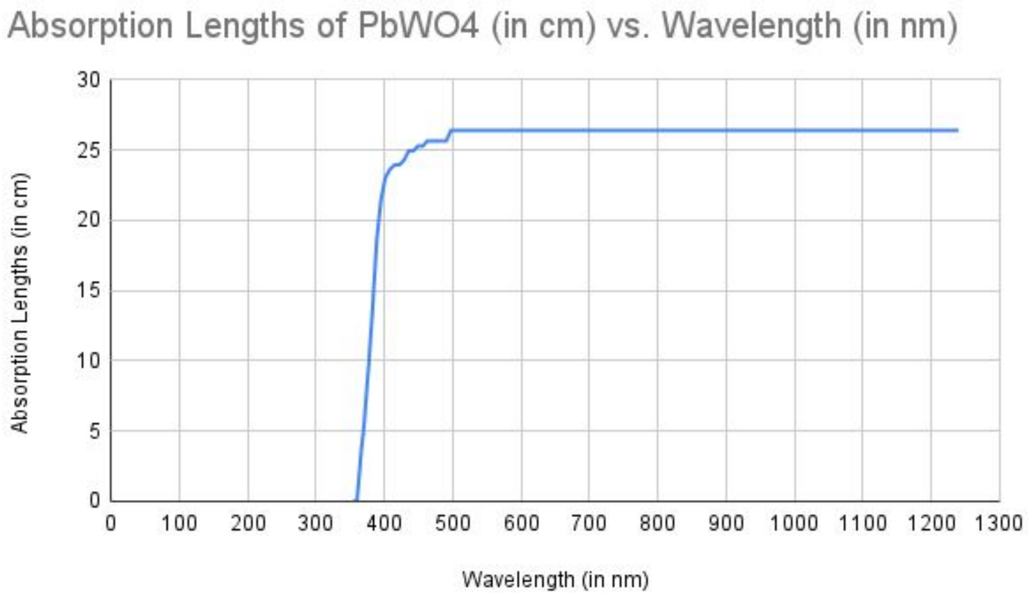
Dimensions of PCBs for the SiPMs

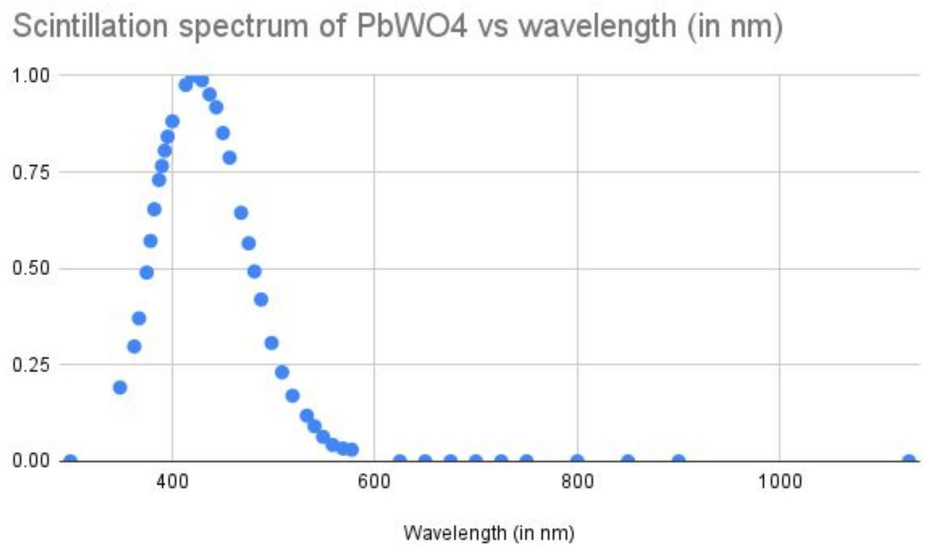


Material Properties for PbWO4

- Shown here are plots of Refractive index, scintillation spectrum and absorption lengths as a function of wavelength for PbWO4

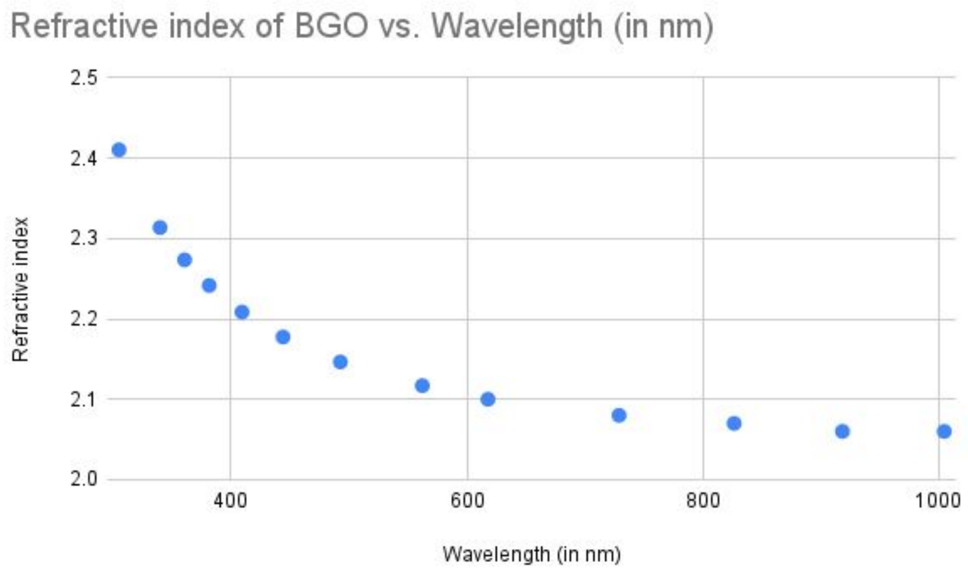


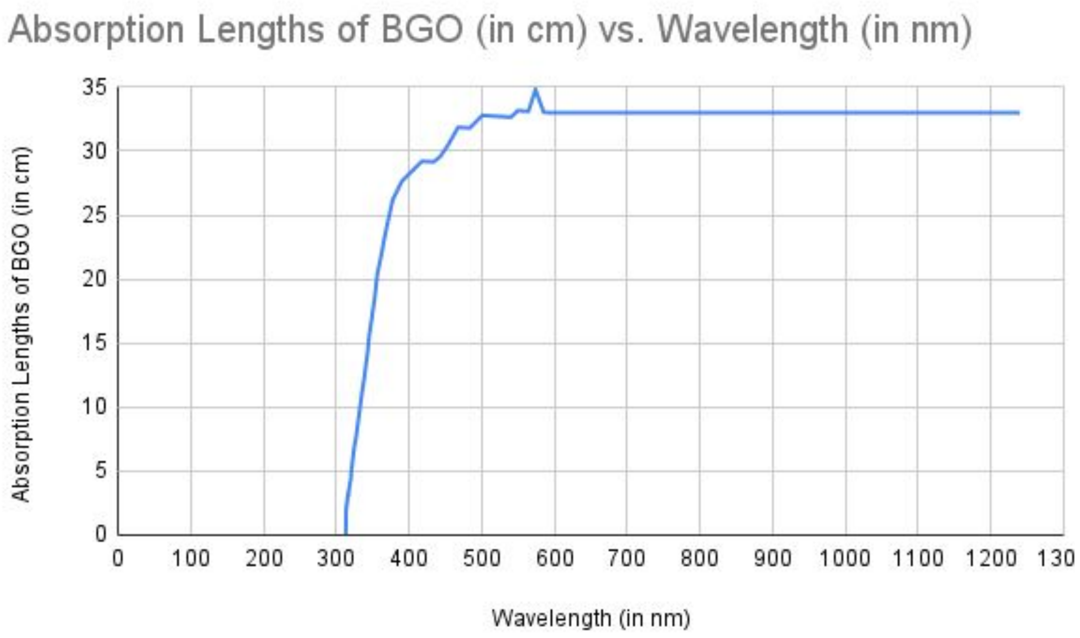


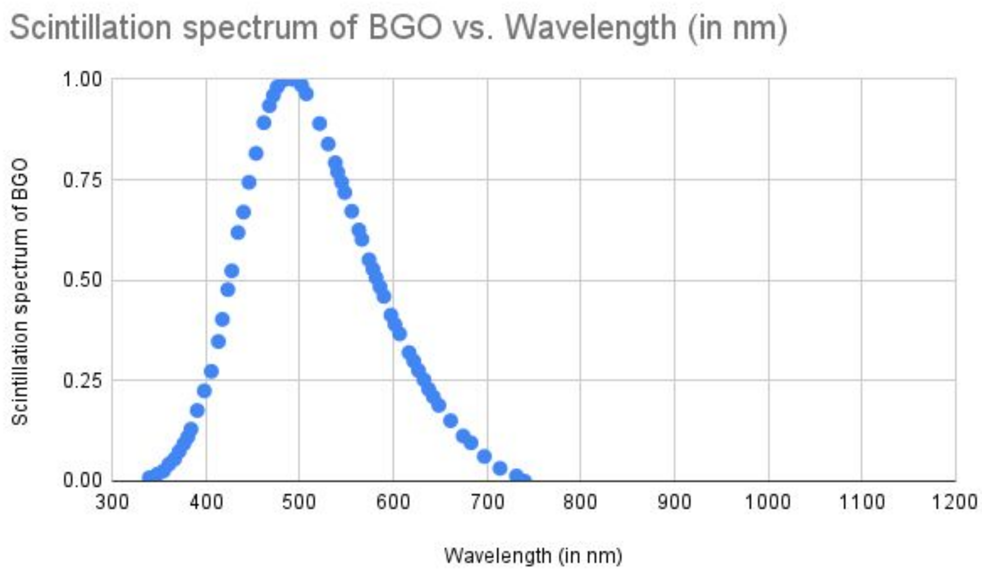


Material Properties for BGO

- Shown here are plots of Refractive index, scintillation spectrum and absorption lengths as a function of wavelength for BGO

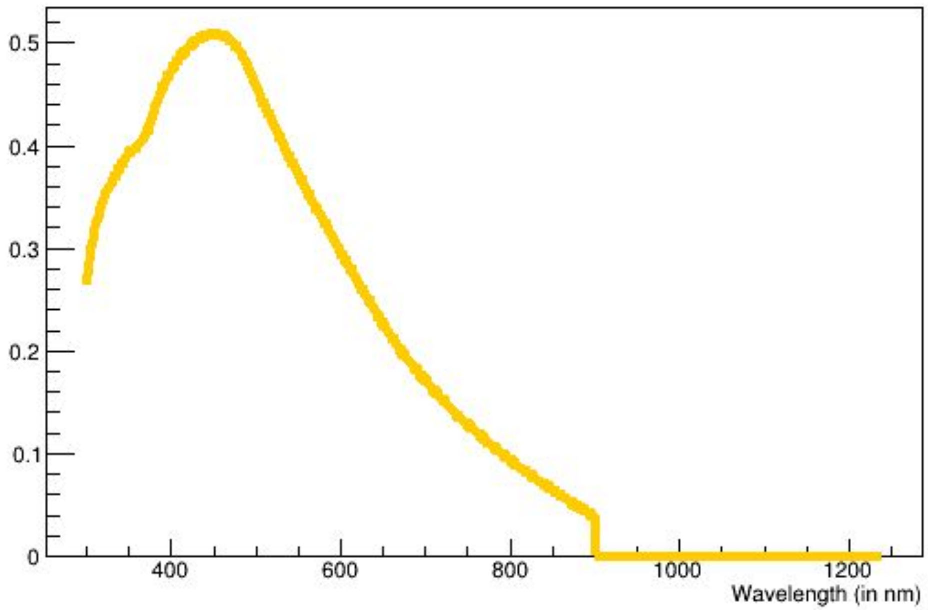






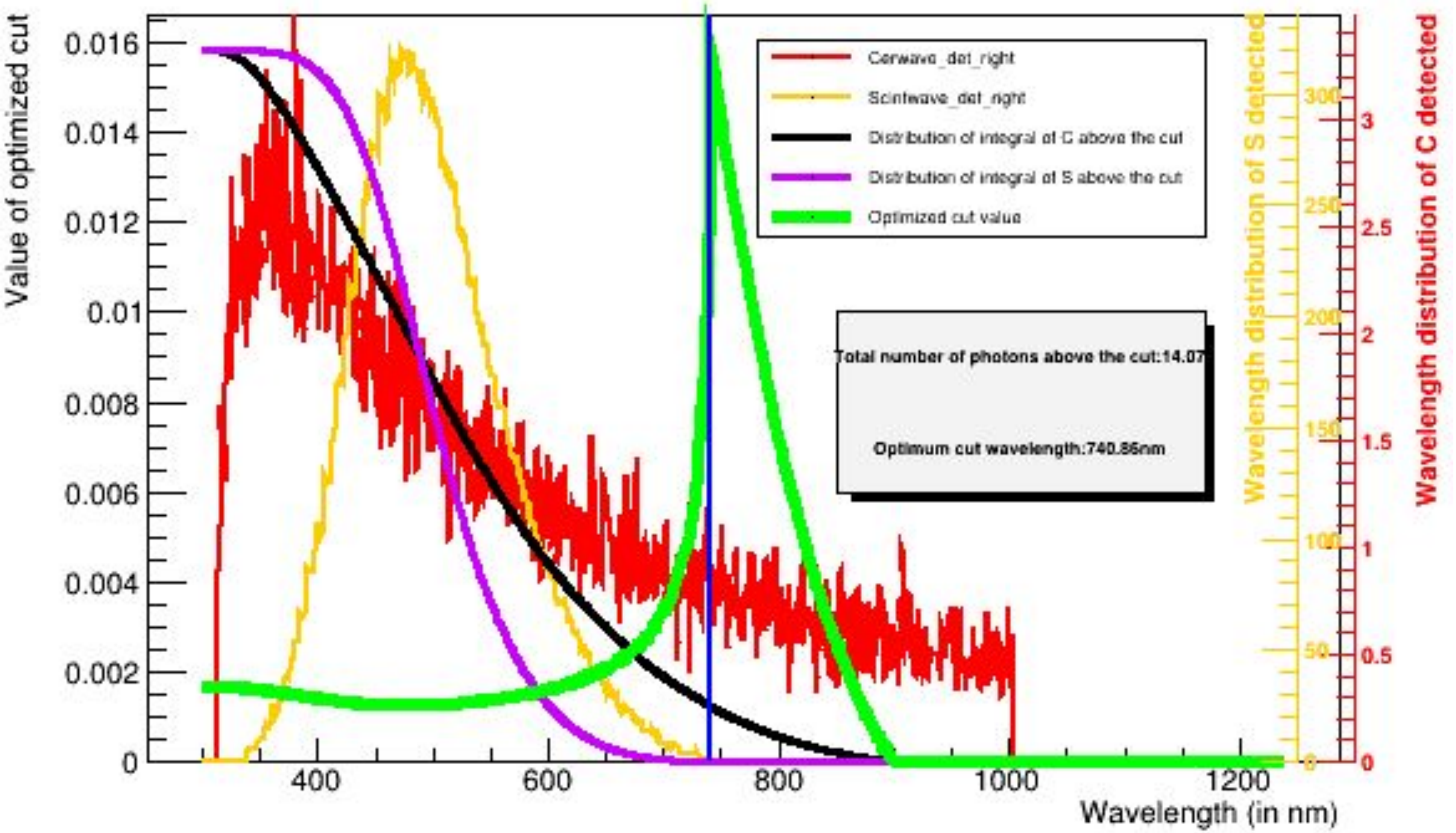
Photon detection of SiPM (S14160 - 3050S)

- The plot is included by digitizing from https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160_s14161_series_kapd1064e.pdf
- Maximum efficiency is ~ 50% at around 450 nm and the higher cutoff is at around 900 nm



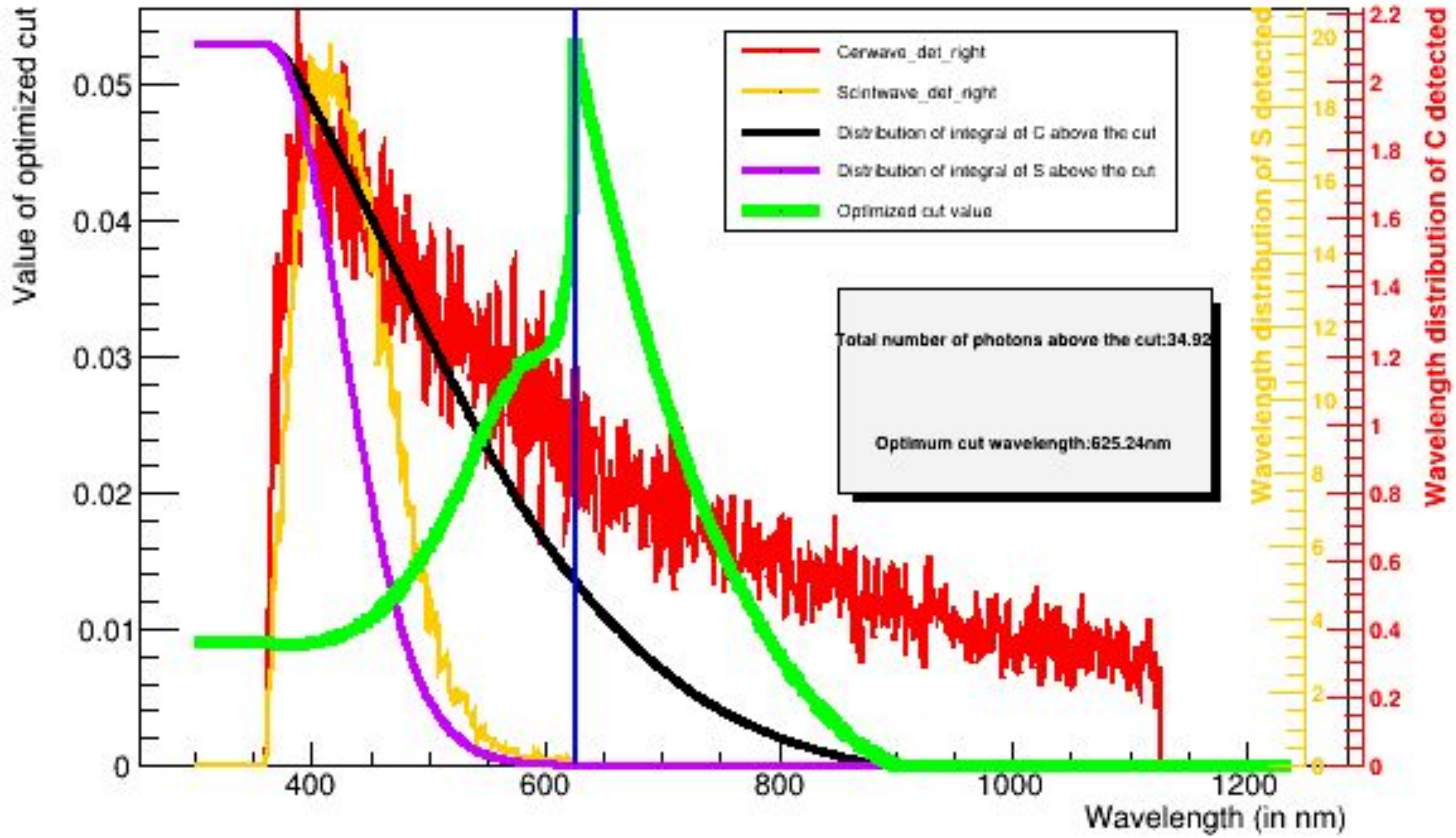
Value of Optimization function for BGO

- Graph for BGO (Ideal cutoff ~ 740.86 nm looking at the maximum of the green curve)
  - Here a = 2σ and angle of incidence for the muon beam = 55 degrees is chosen



Value of Optimization function for PbWO4

- Graph for PbWO4 (Ideal cutoff ~ 625.24 nm looking at the maximum of the green curve)
  - Here again a = 2σ and angle of incidence for the muon beam = 55 degrees is chosen



Value of Optimization function for $PbWO_4$

- The optimization cut wavelength for both crystals is fairly constant with the change of angle of incidence of the muon beam
- For $PbWO_4$, however, instead of choosing 625 nm as the cutoff, we also have a choice of any cutoff wavelength above 574 nm because of the fairly low scintillation yield and consequently the low amount of Scintillation photons detected in that wavelength region

- A lower cutoff of ~574 nm gives an increase in the Cerenkov photons of 42-47% in comparison to the number obtained after a cut of ~625 nm (varies with the angle of incidence for the muon beam) while only having ~1-4 Scintillation photons that pass the cut