# Progress on Single Crystal Simulations at UMD

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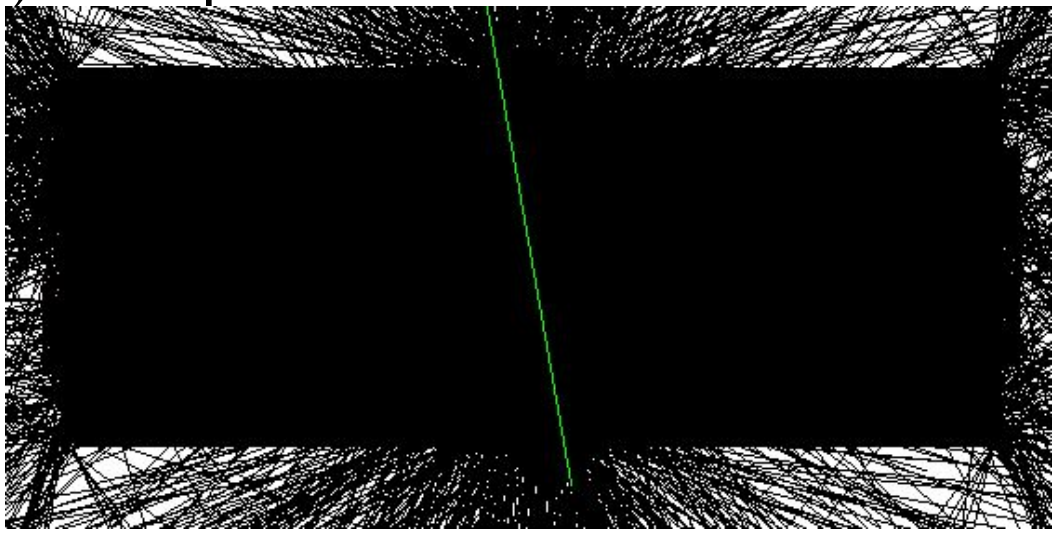
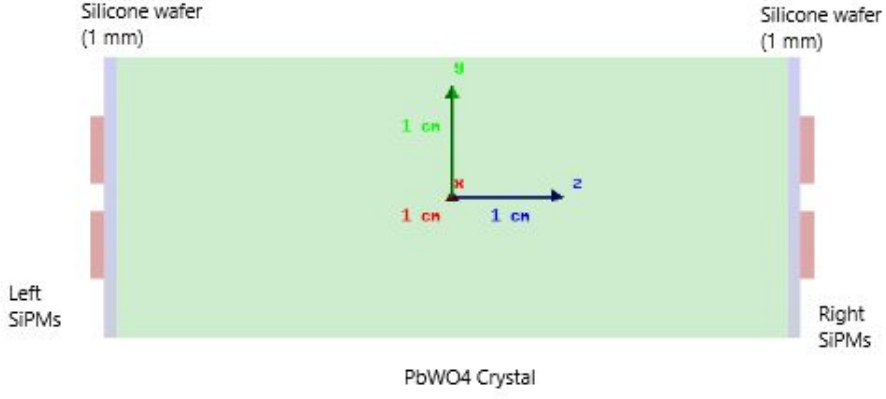
# Recap and Introduction

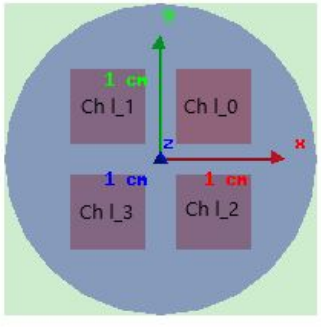
- Simulated a dual-readout crystal detector with GEANT4 + DD4hep
  - Reproduced the 2020 proposal plots (PbWO4)
  - Also simulated BGO and PbF2 crystals
- Simulated two different geometries for two sets of measurements at UMichigan (not fully complete)
  - Cosmic ray setup and test beam setup with 8 MeV electrons (Notre Dame)
- Currently simulating for 120 GeV protons with FNAL Test Beam setup

# FNAL Test Beam (120 GeV protons) - setup

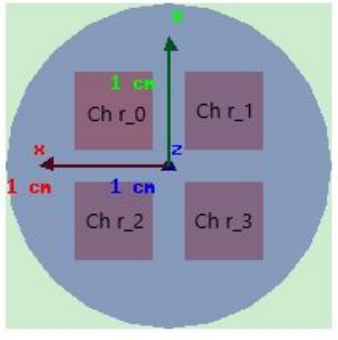
- Crystal dimensions are 2.5 cm × 2.5 cm × 6 cm for all the materials
- Four SiPM channels arranged in a 2 × 2 array on each square face
- Due to several outlying events, an upper cutoff is put on the events having Cerenkov photons > 20000
- Proton passes through the center of the crystal
- Channels 0 and 1 (in the graphs) are the ones farther from the face on which the beam is incident, and channels 2 and 3 are the ones that are closer





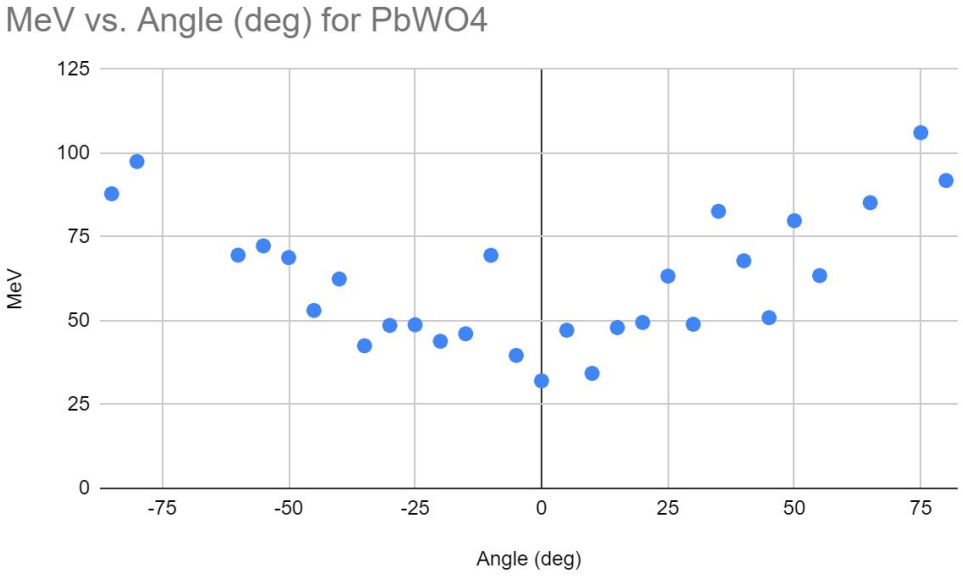

Viewed from the left side

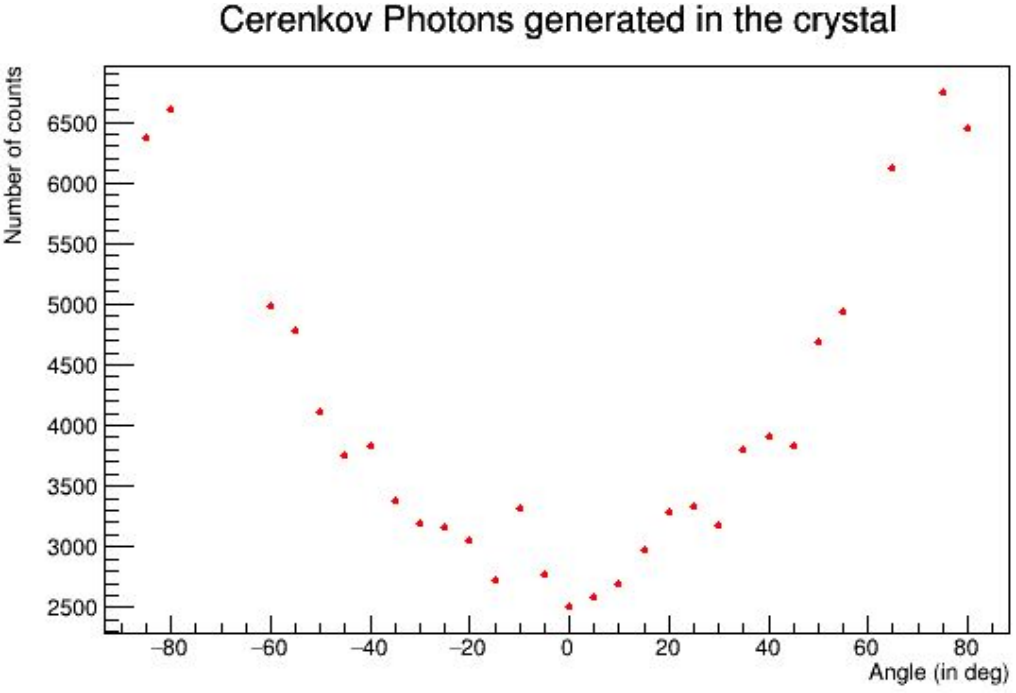


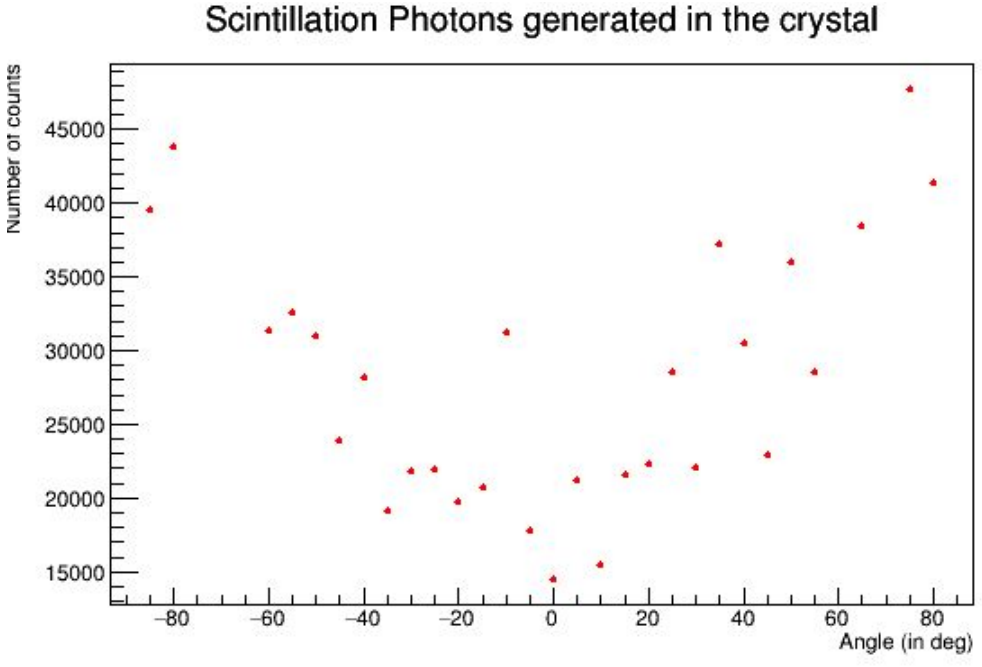

Viewed from the right side

# Plots of angular dependence for PbWO4 - generated photons

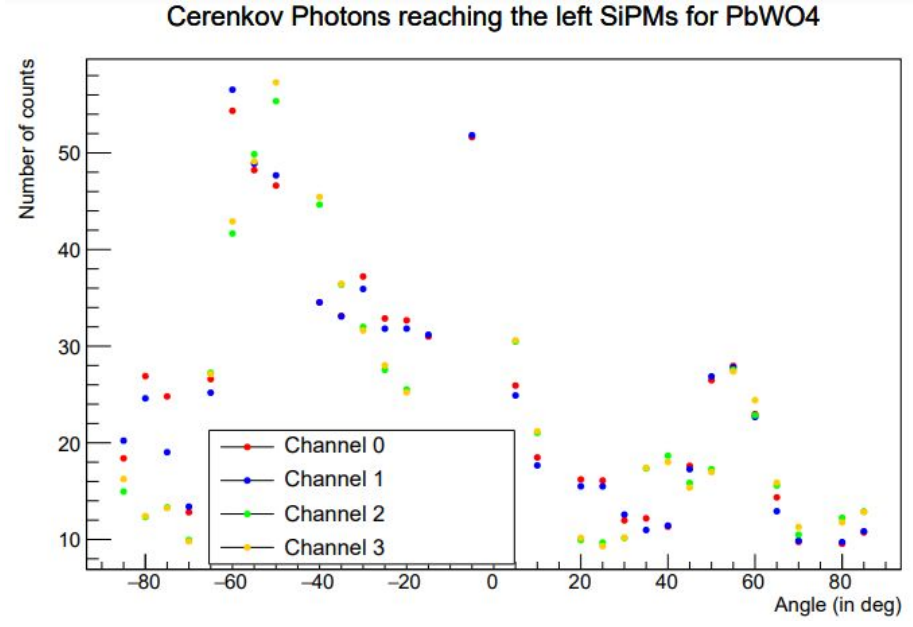
The generated photons seem to be roughly proportional to the path length which varies as 2.5 cm/cosθ up till ~θ = $\tan^{-1}(3/1.25)$ = 67 deg which is where the proton is incident along the diagonal of the long face, after which it dips and then the path length is 6 cm/sinθ

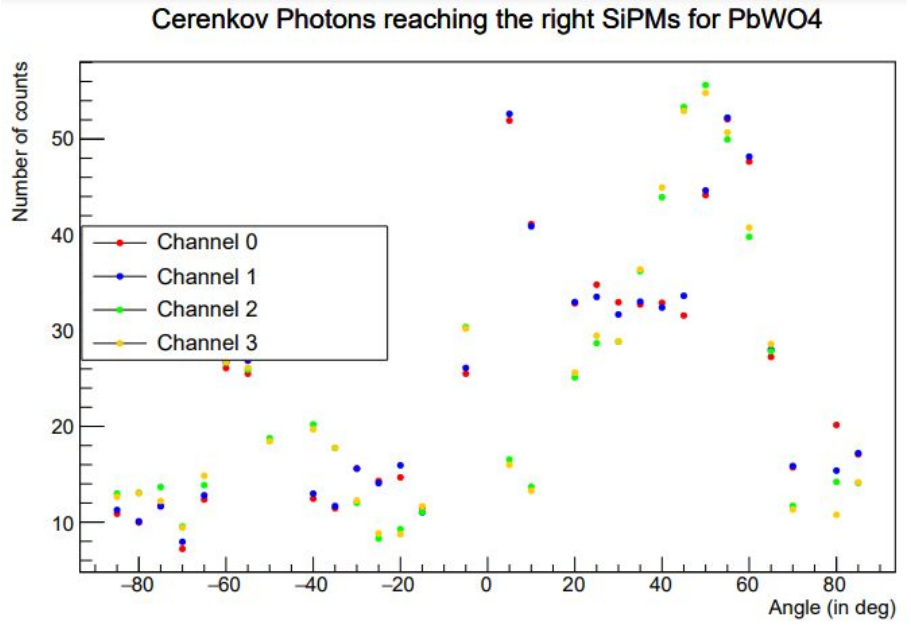


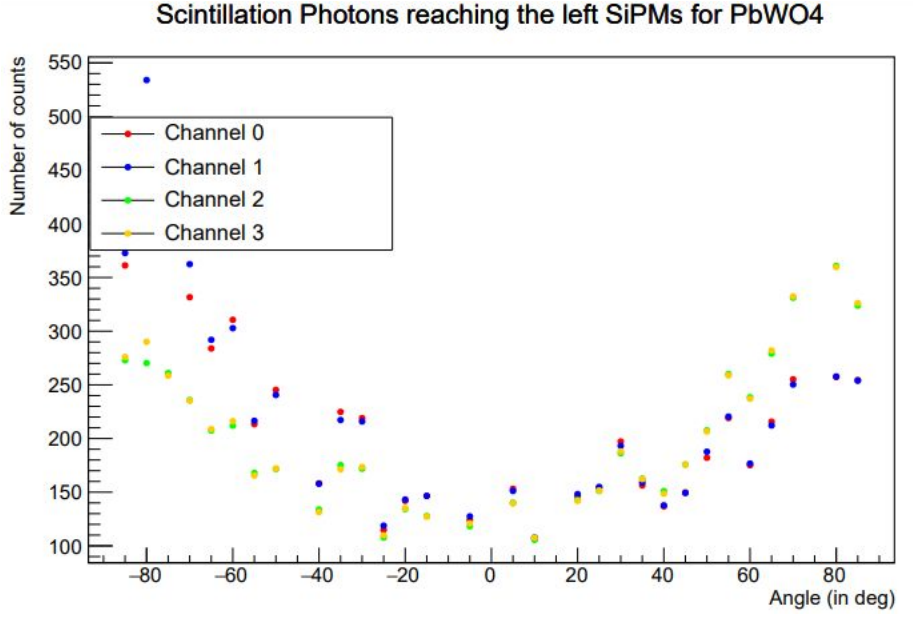



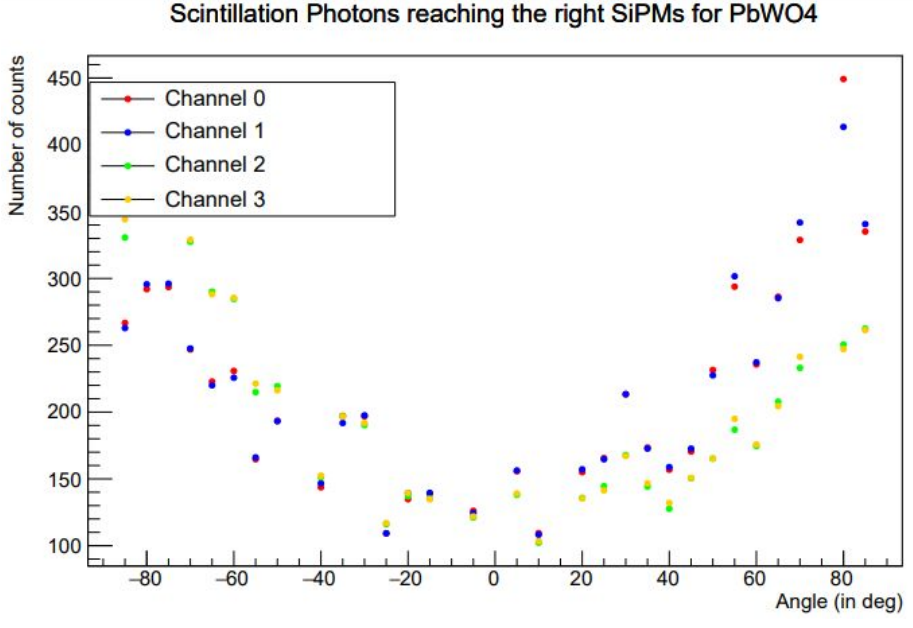



# Plots of angular dependence for PbWO4 - detected photons (1)



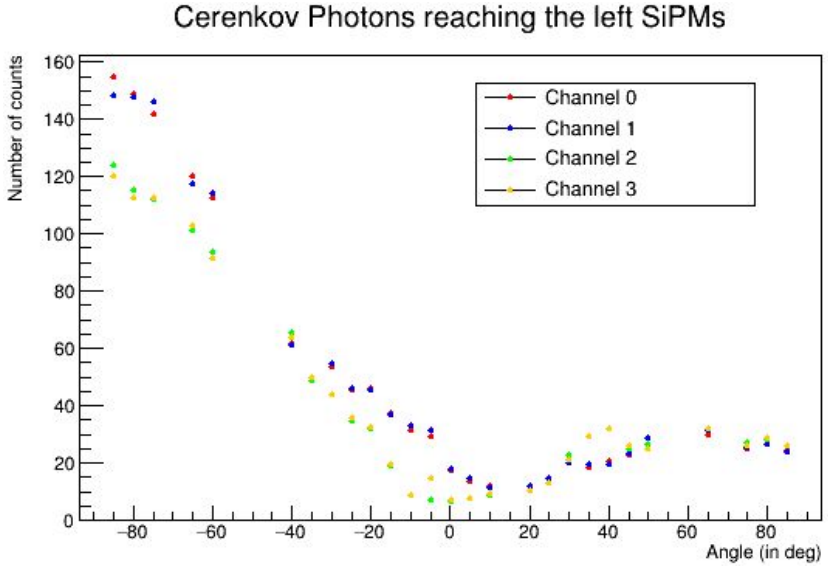



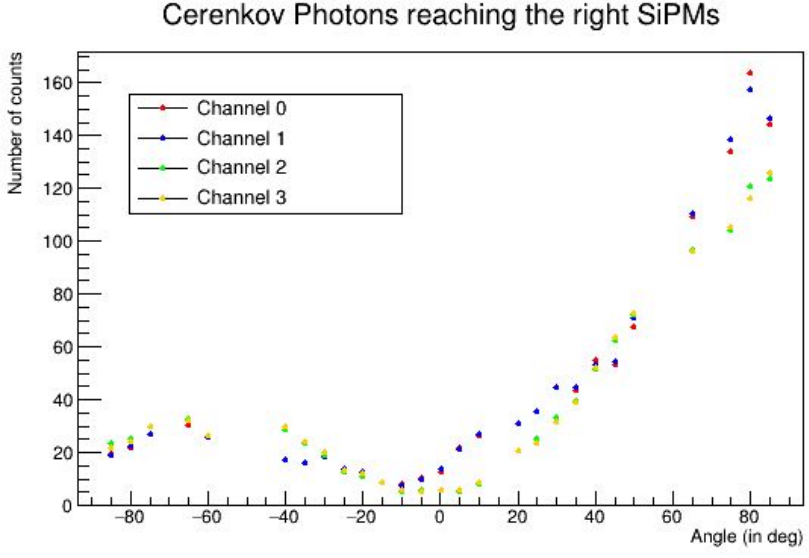



# Plots of angular dependence for PbWO4 - discussion of trends

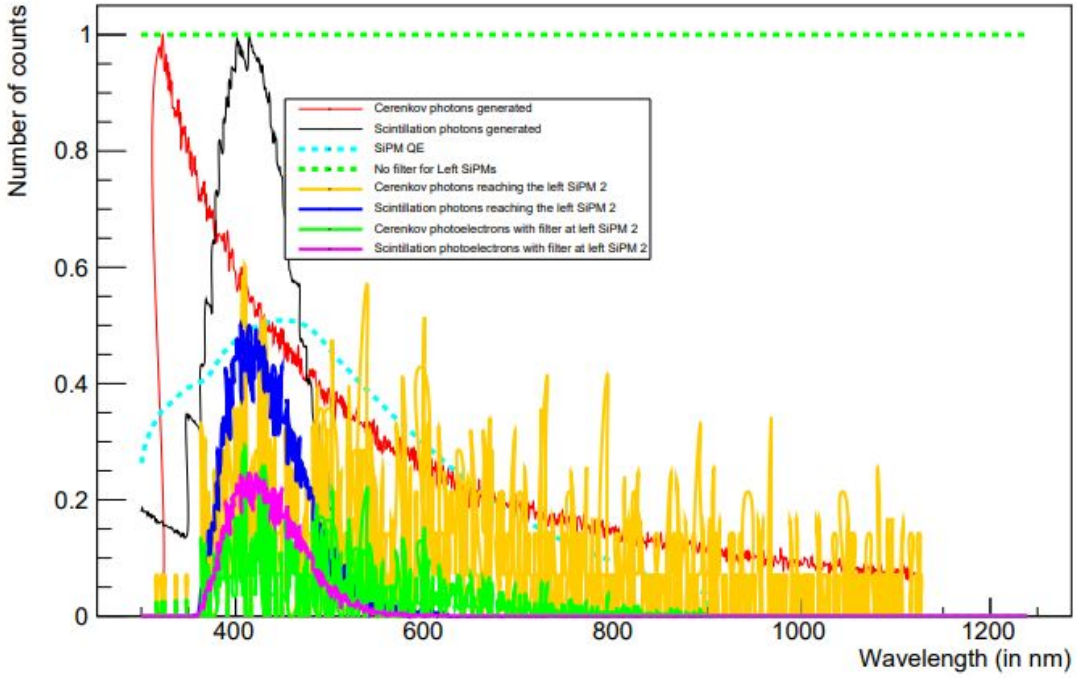
- For the Cerenkov plots, there is a difference of counts between pairs of symmetrically situated channels (0,1 and 2,3) near the 0 deg region (positive angles for the right side and negative angles for the left side)
- This is reduced for the most part by removing the silicone cookie and disabling TIR at the long surface farther from the face at which the beam is incident (purely for investigation)
  - There was a non negligible contribution to the channels 0,1 from TIR in addition to the photons reaching directly at the Cerenkov emission angle
- The peak at higher angles (positive on the right side and negative on the left) is due to TIR at the interface between the crystal and the silicone cookie - we see this shift towards even higher values of angle for PbF2 the refractive index of which is less than that of PbWO4



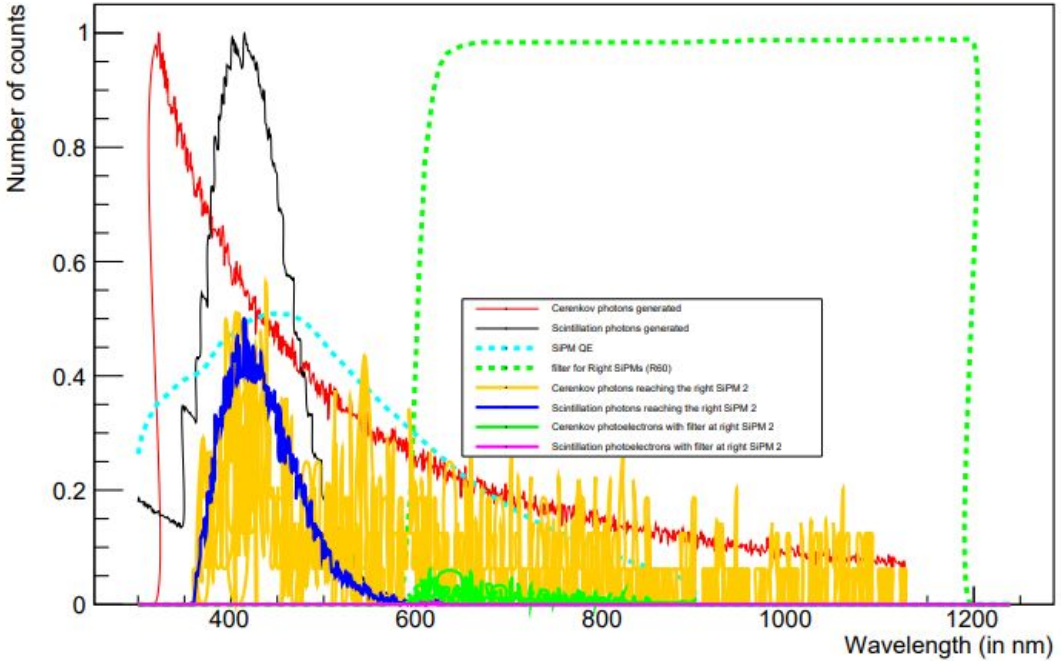

Without silicone cookie, TIR at top surface removed

# Filter profiles - wavelength distributions at SiPMs with PbWO4

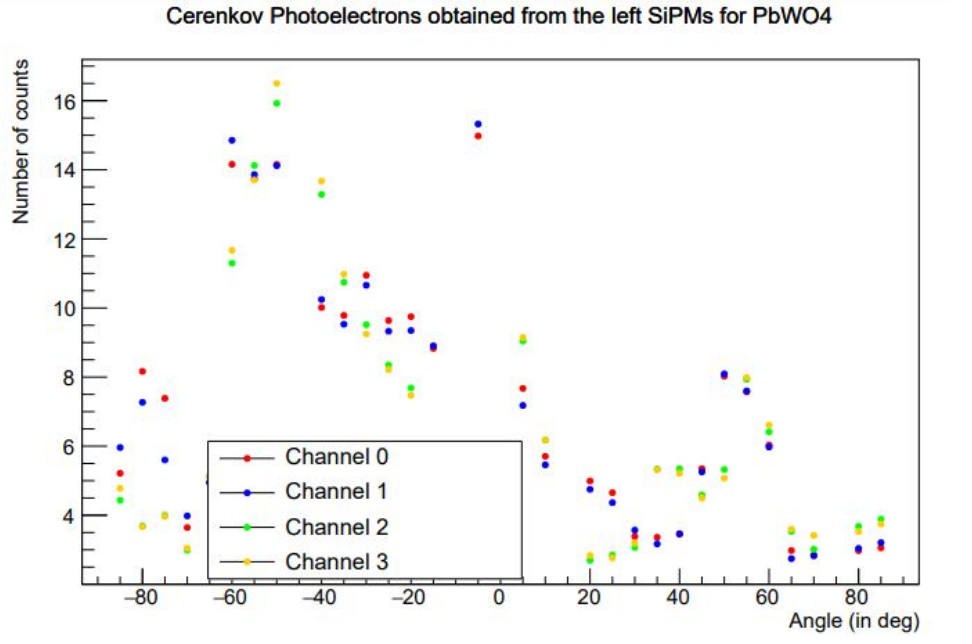


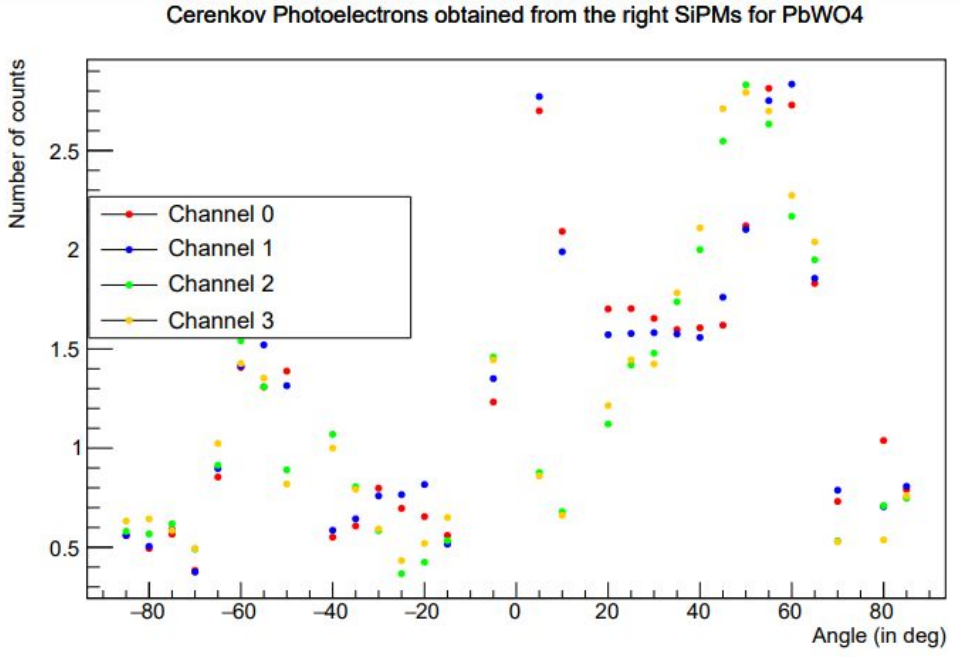

Left side (without filter)

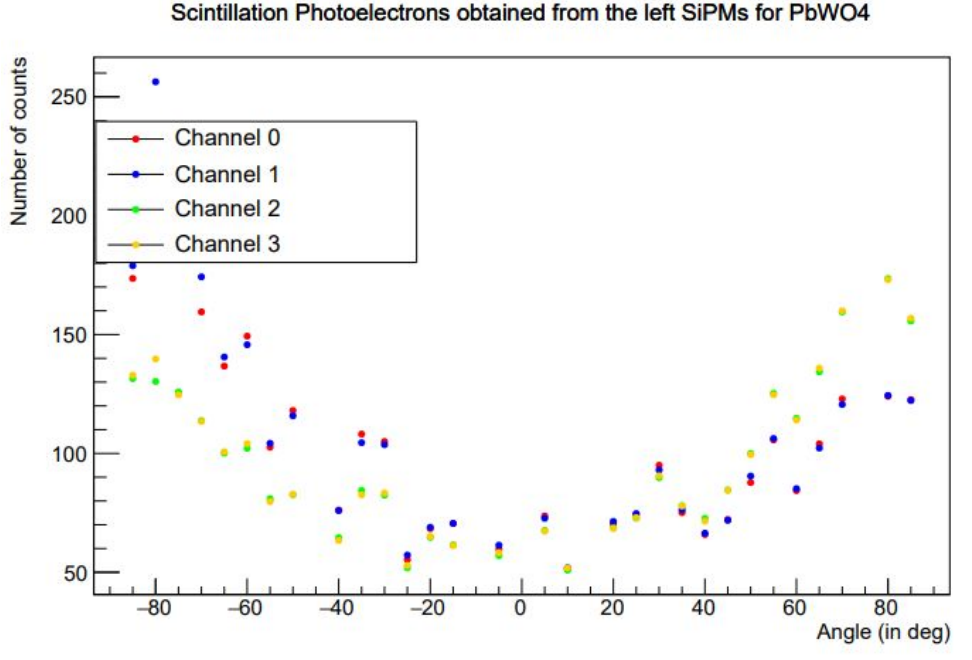
Right side (Filter used - [Hoya R60 (600nm), 25.4mm Dia., 2.5mm Thick, Colored Glass Longpass Filter])

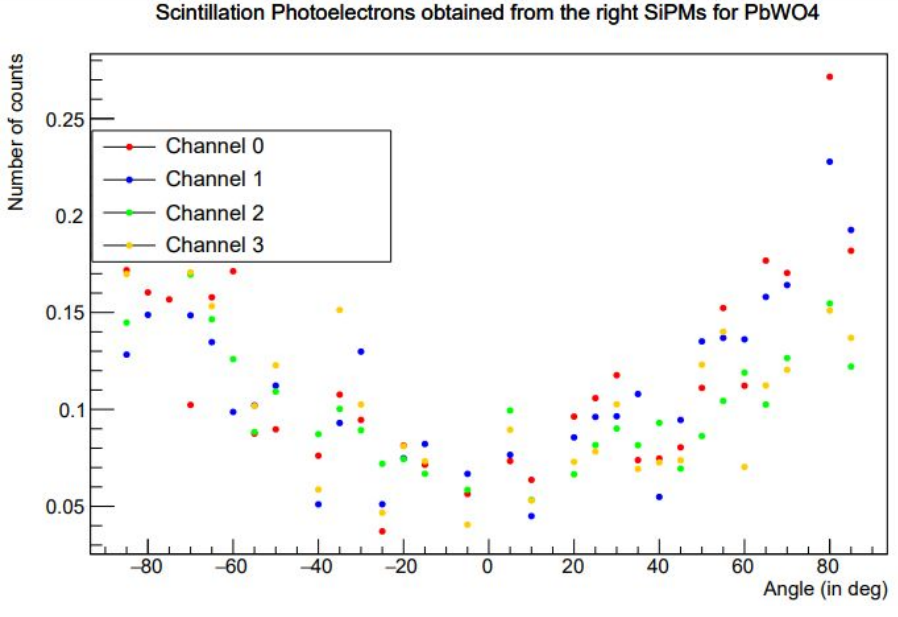


# Plots of angular dependence for PbWO4 - detected photons (with SiPM QE and filter)



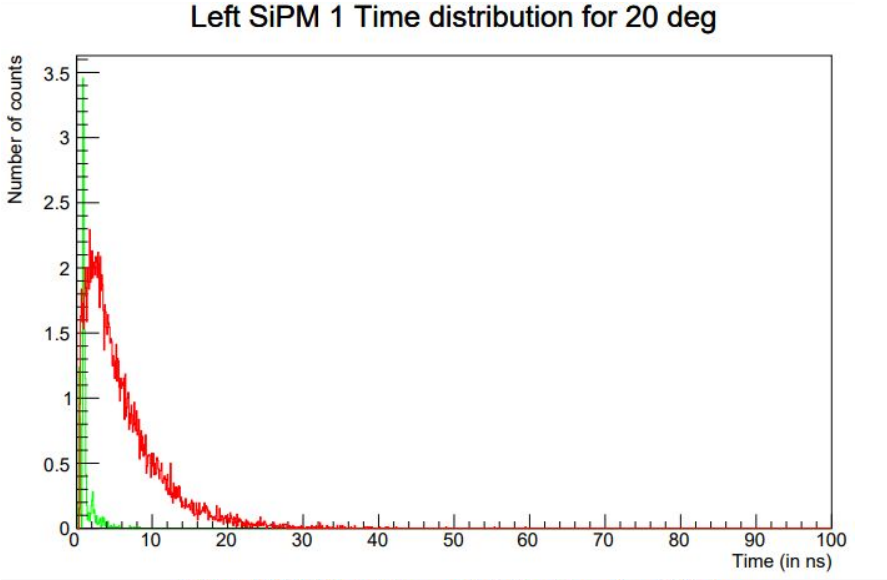



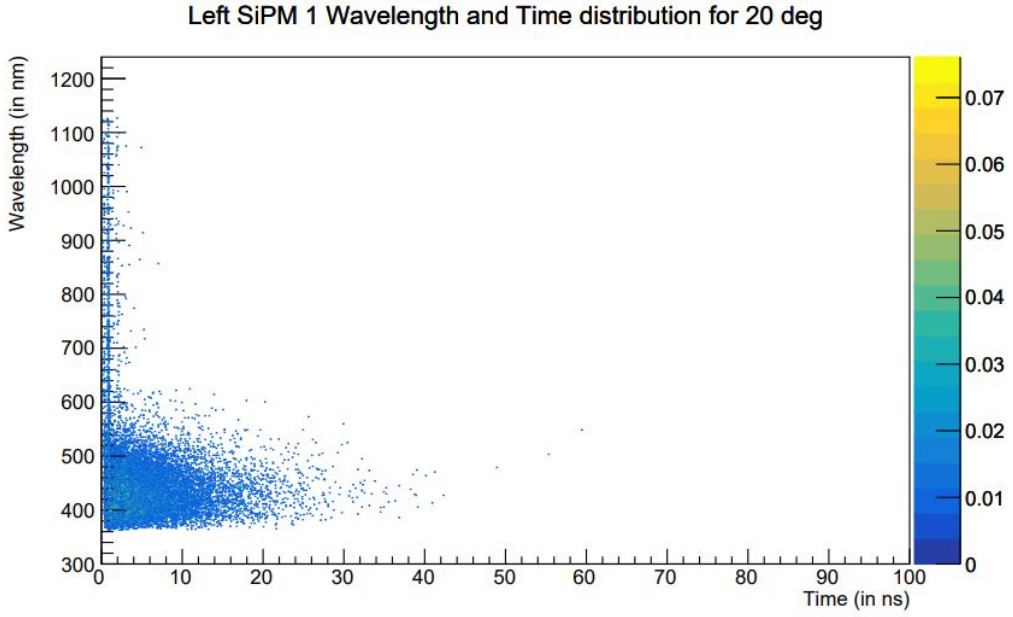



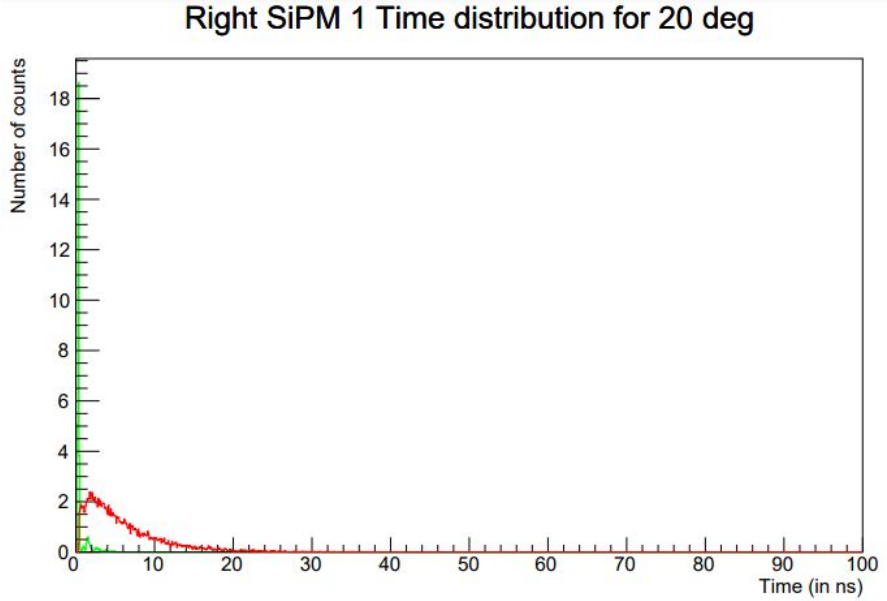



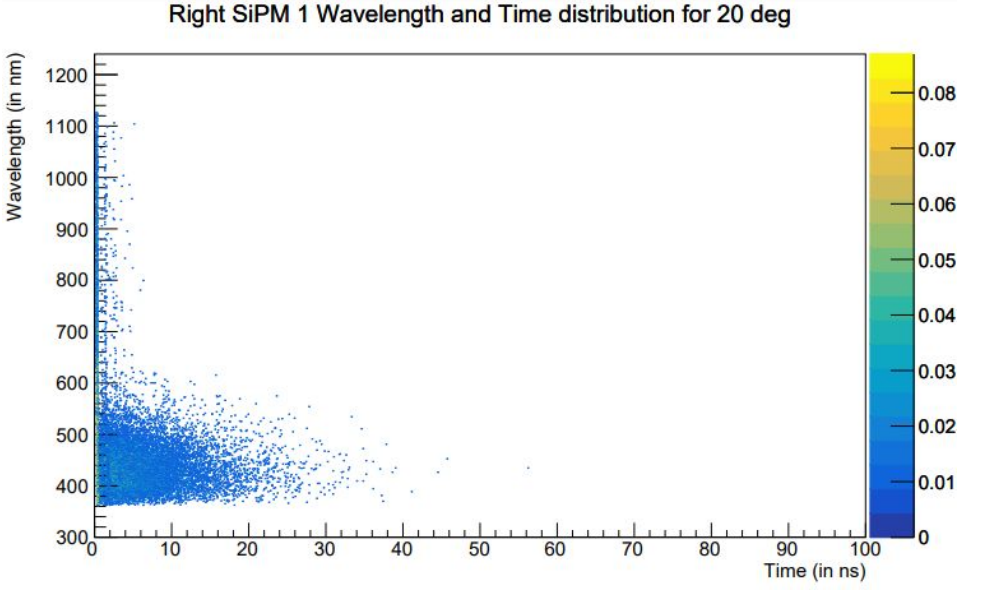
# Optical pulse profiles for PbWO4

- Essentially a histogram of the arrival times of photons at the various channels
- Will also have to look at the time signal after the wavelength filtering, so 2D histograms in wavelength and time for the photons are also plotted
  - 0.1 ns bins used from 0 to 100 ns for the time axis

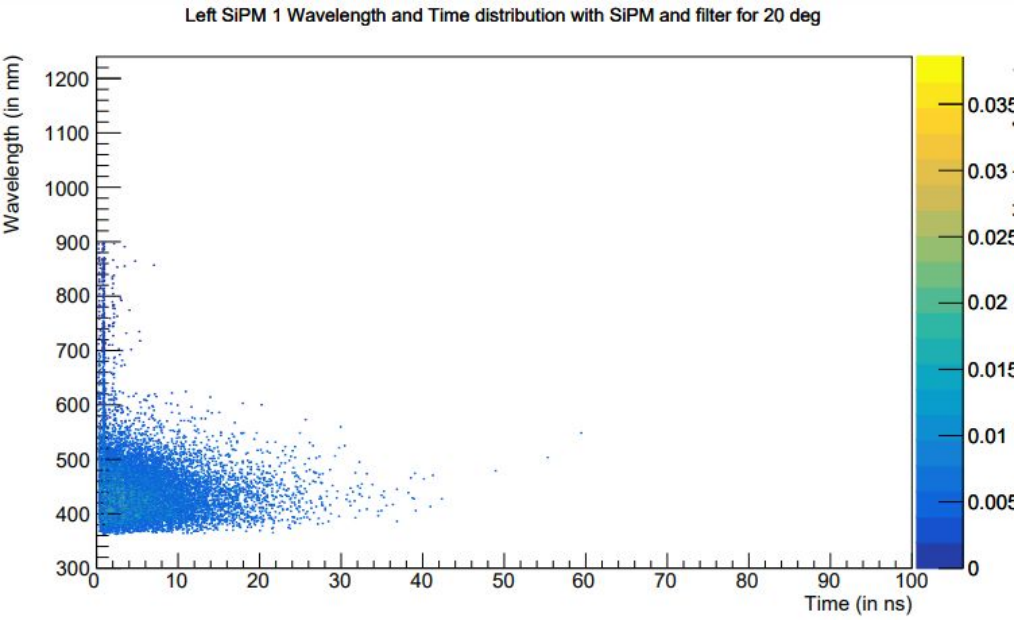


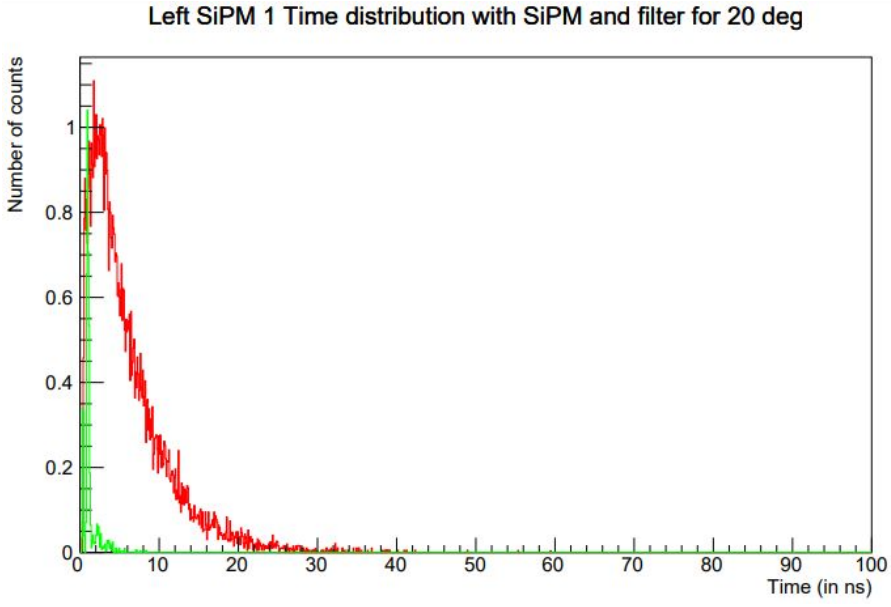



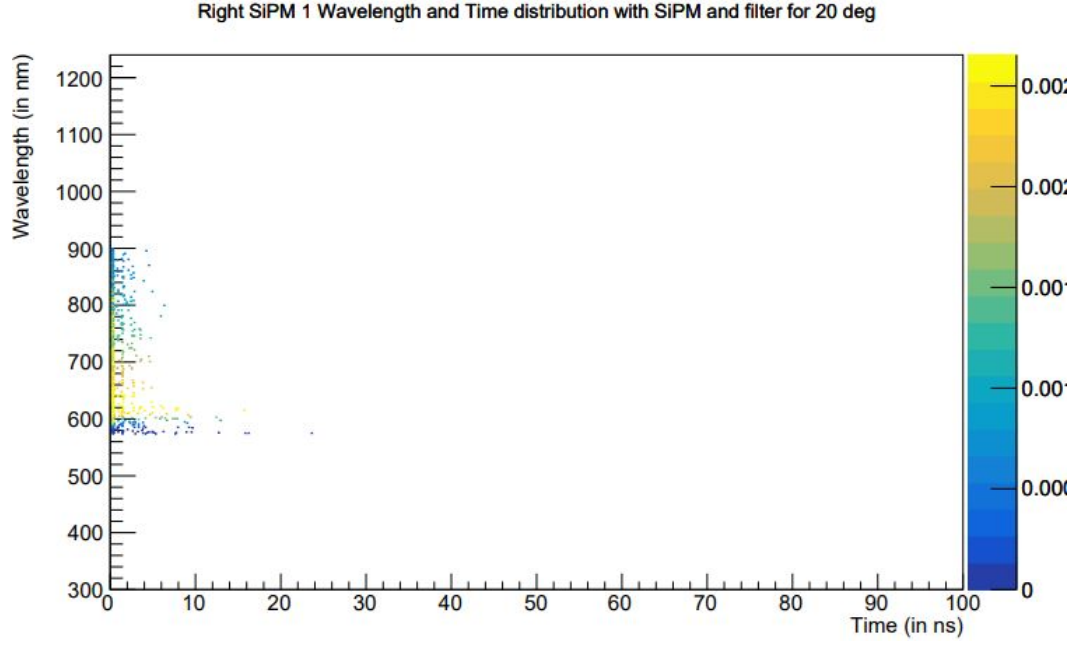



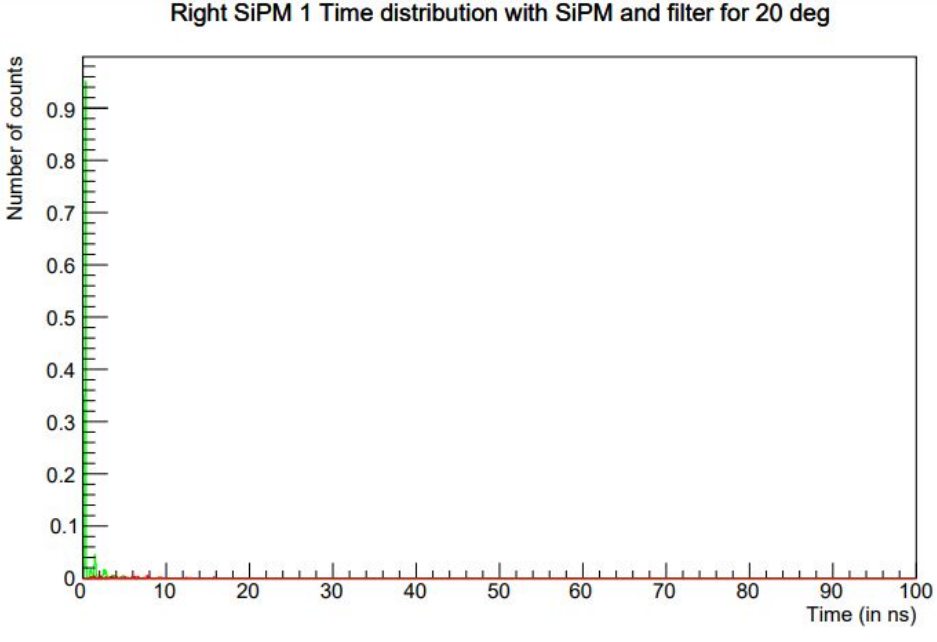



# Optical pulse profiles for PbWO4 - (with SiPM QE and filter)

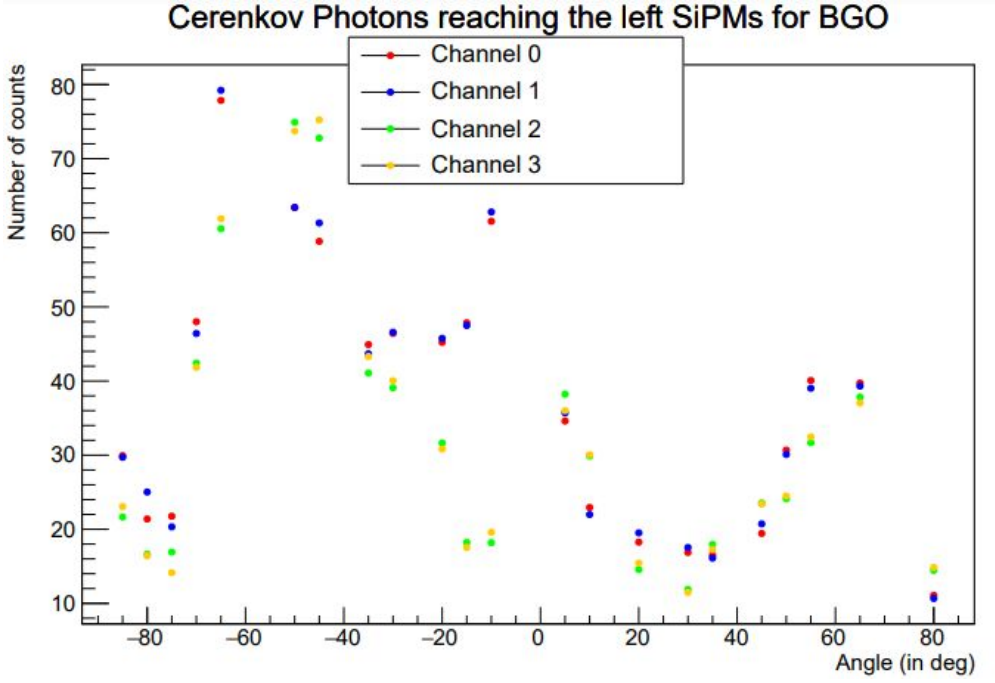


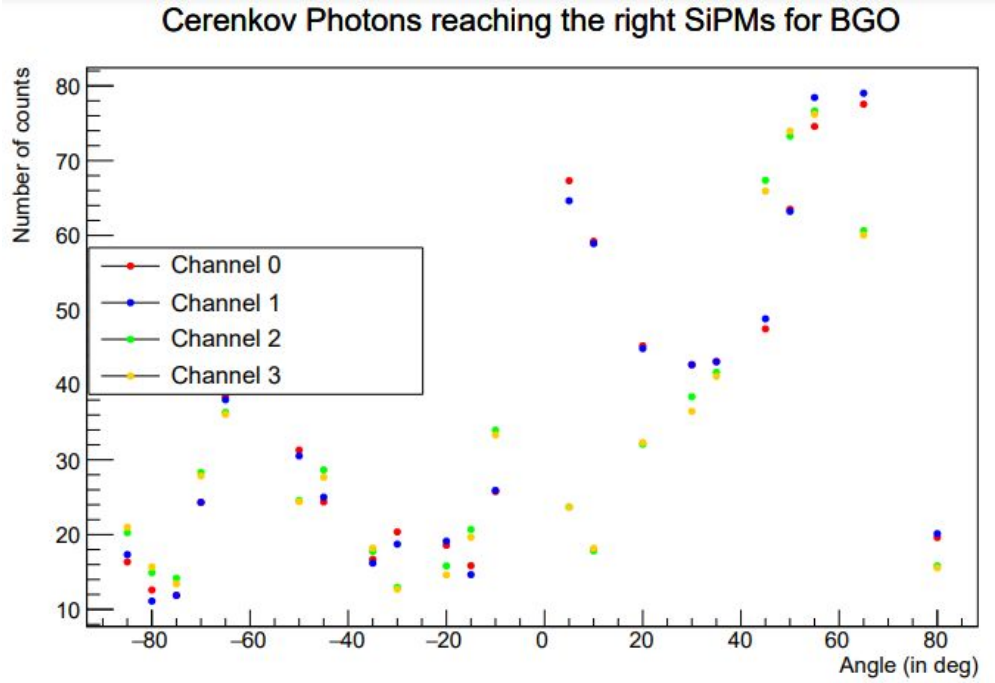



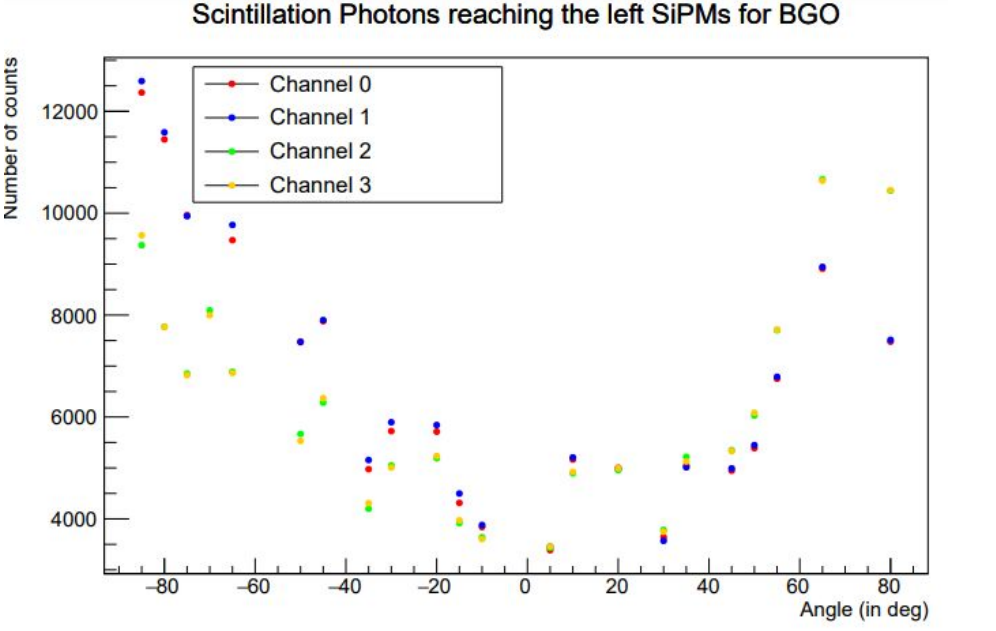



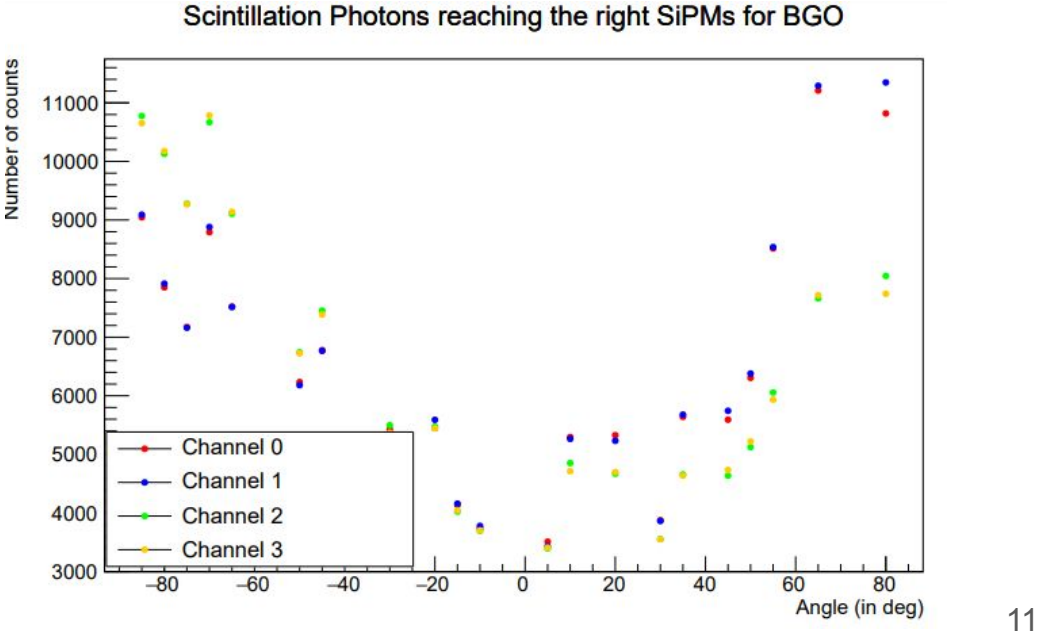



# Plots of angular dependence for BGO - detected photons (1)

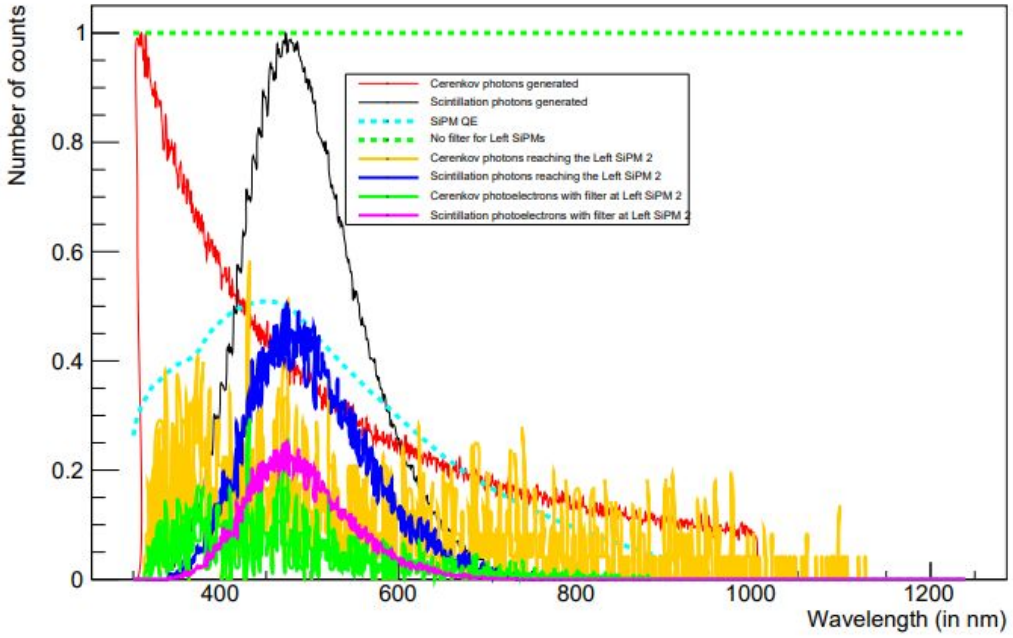


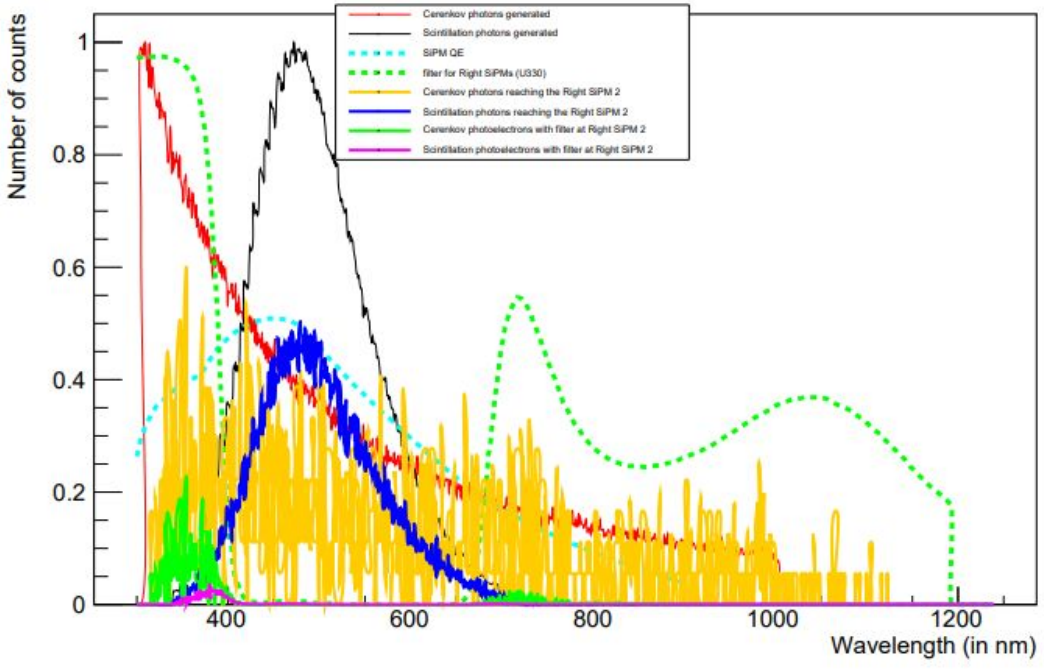



# Filter profiles - wavelength distributions at SiPMs with BGO



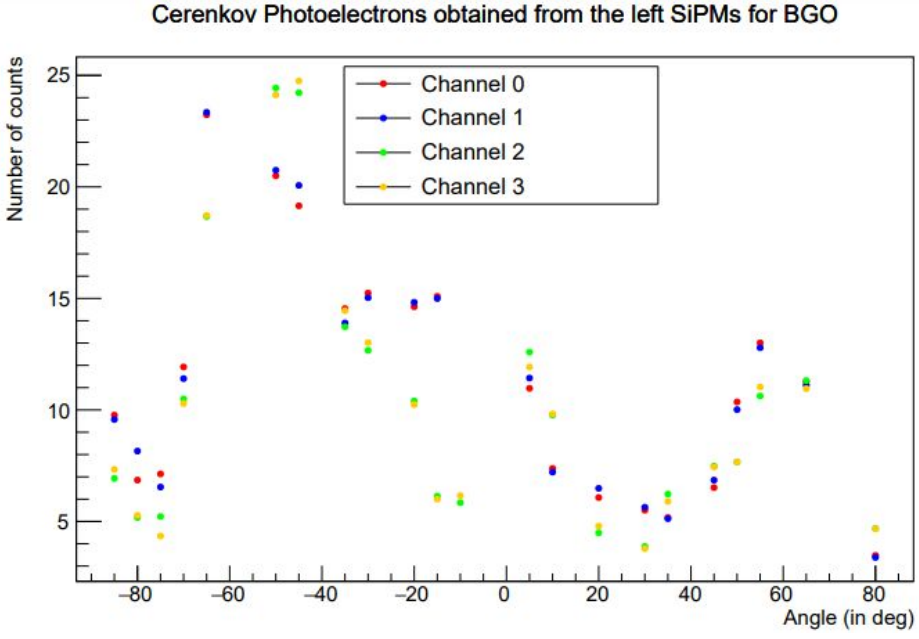

Left side (without filter)

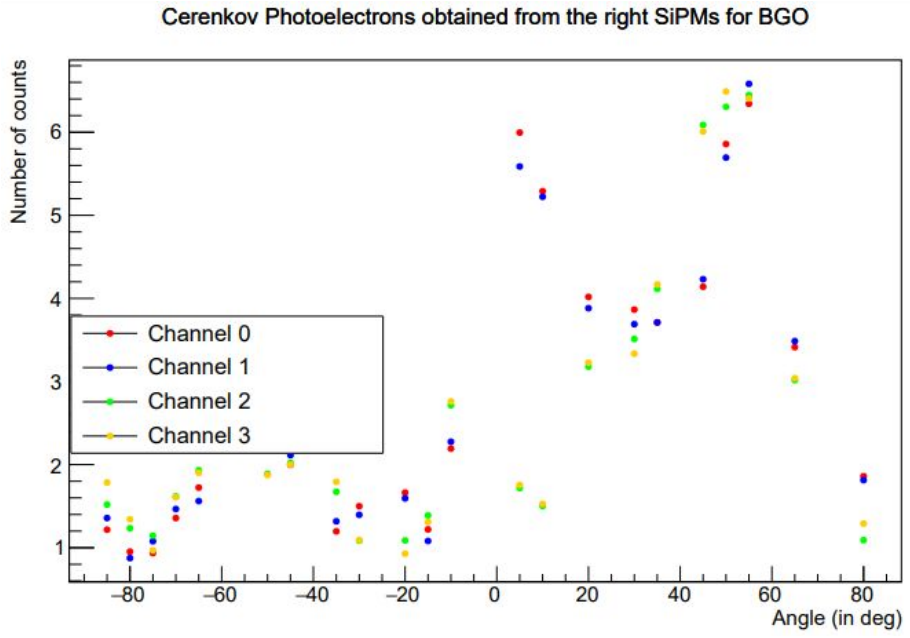
Right side (Filter used - [Hoya U330 (UV) 12mm Dia., Colored Glass Bandpass Filter])

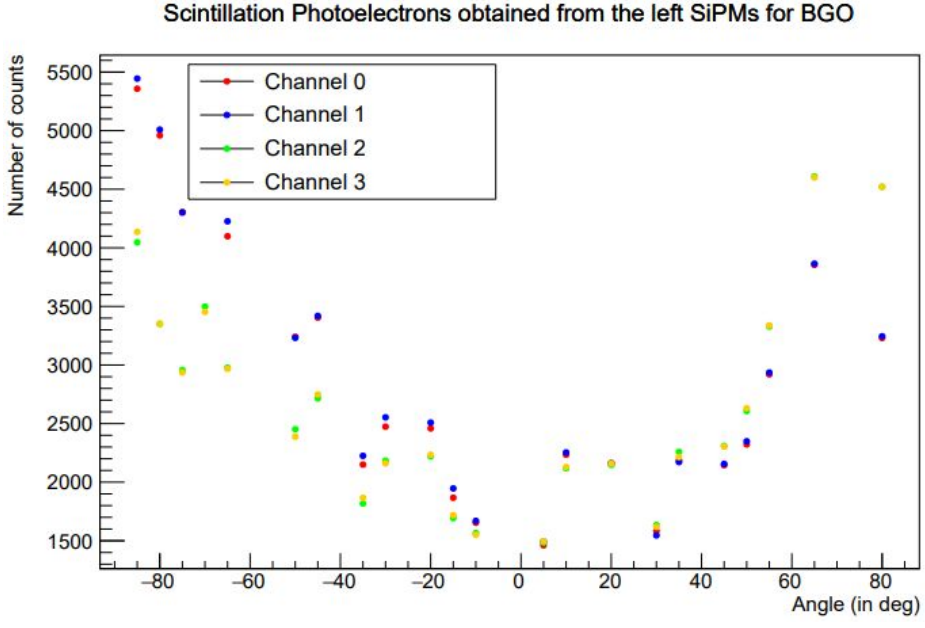


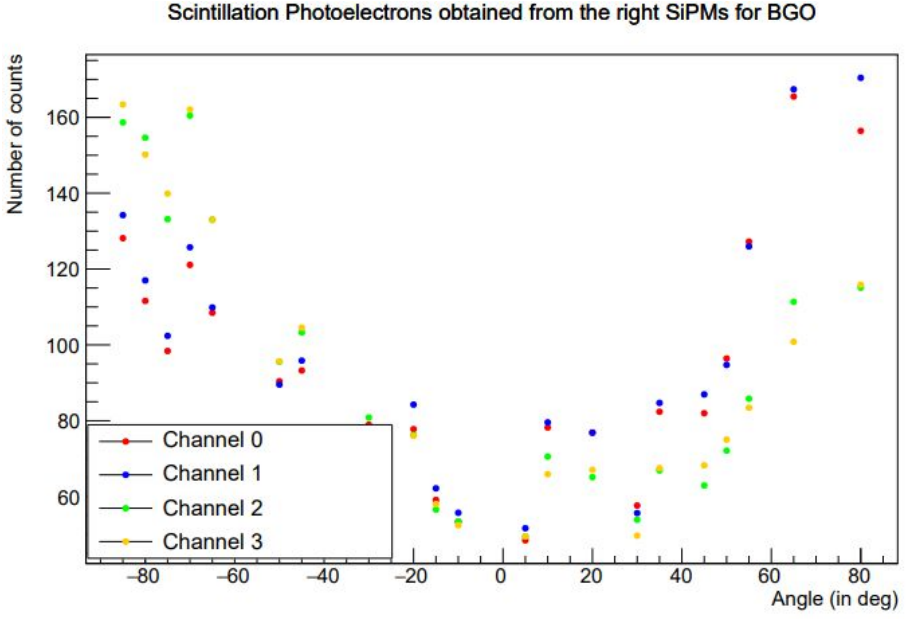
# Plots of angular dependence for BGO - detected photons (with SiPM QE and filter)

- Scintillation component dominating the counts even at the channels with the filter applied

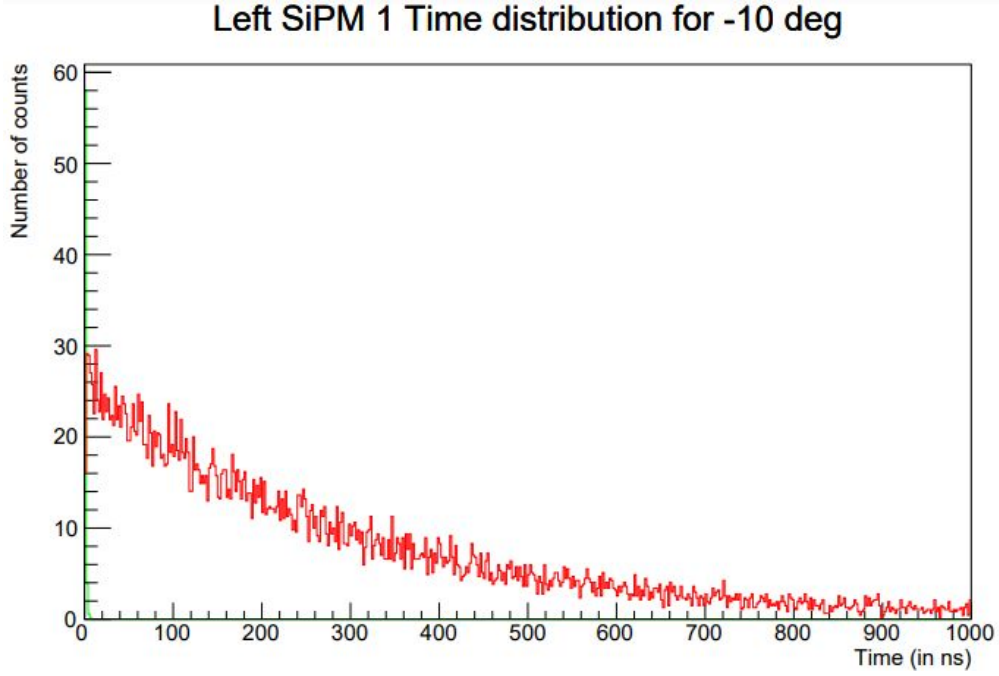


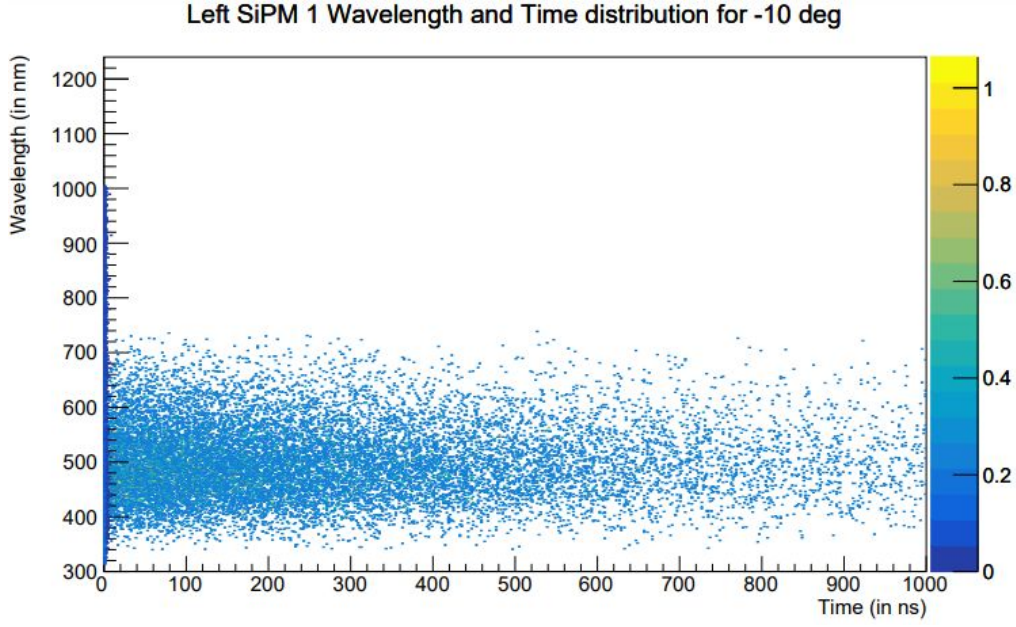



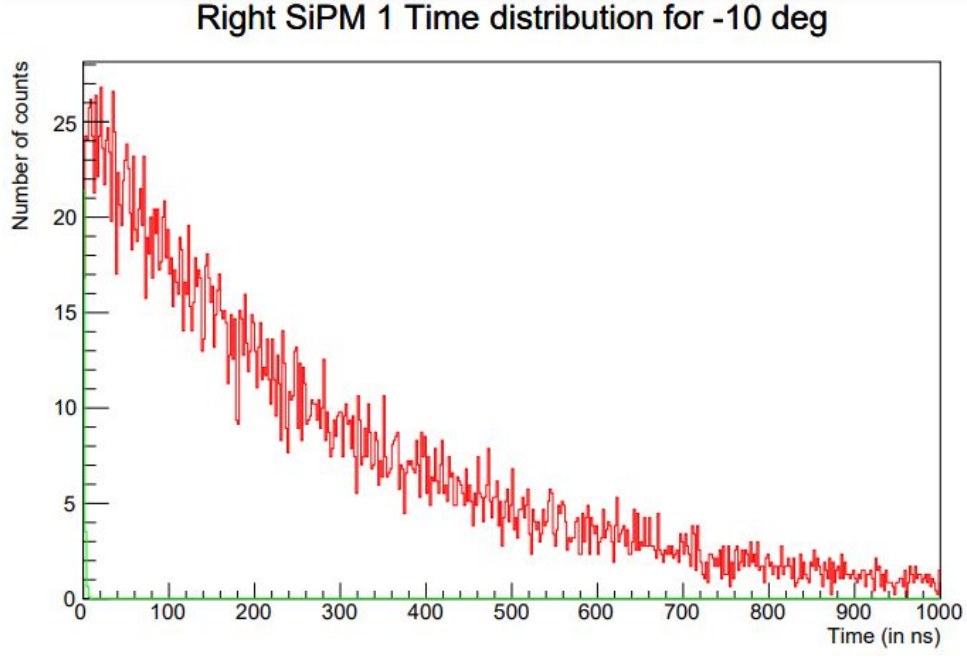



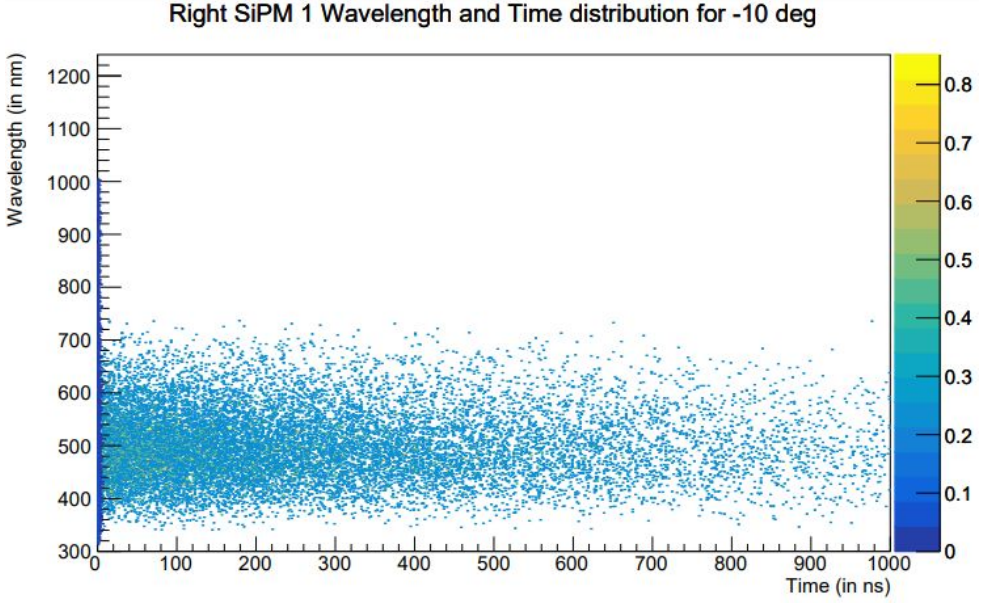



# Optical pulse profiles for BGO

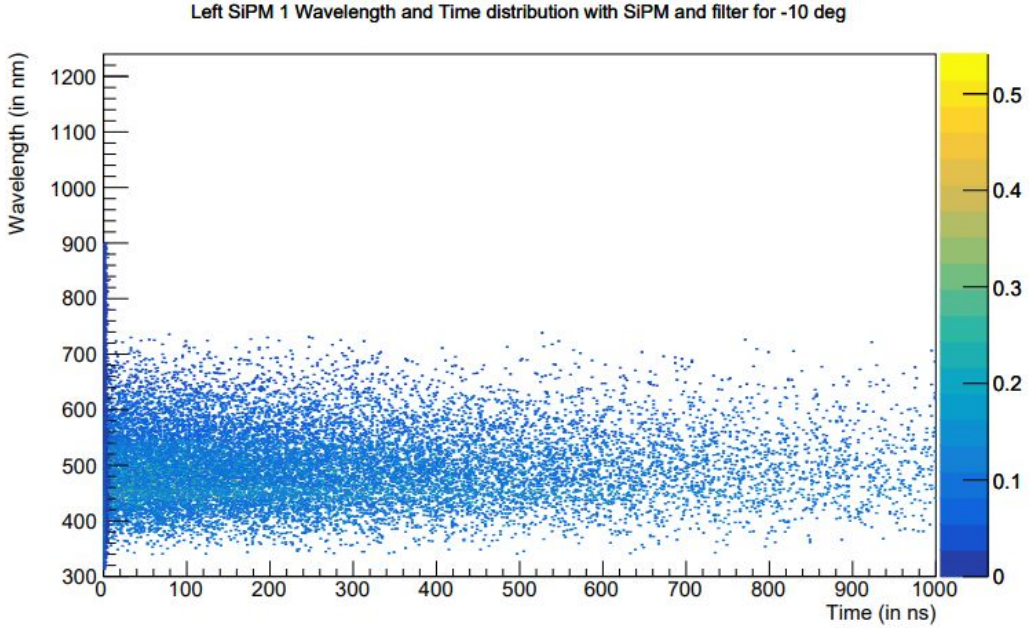


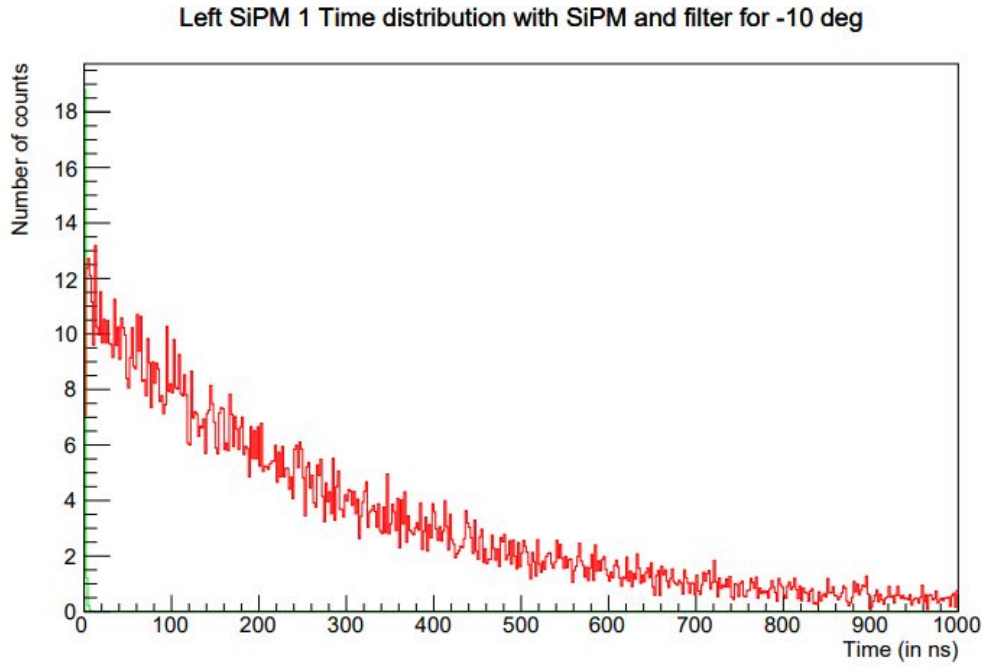



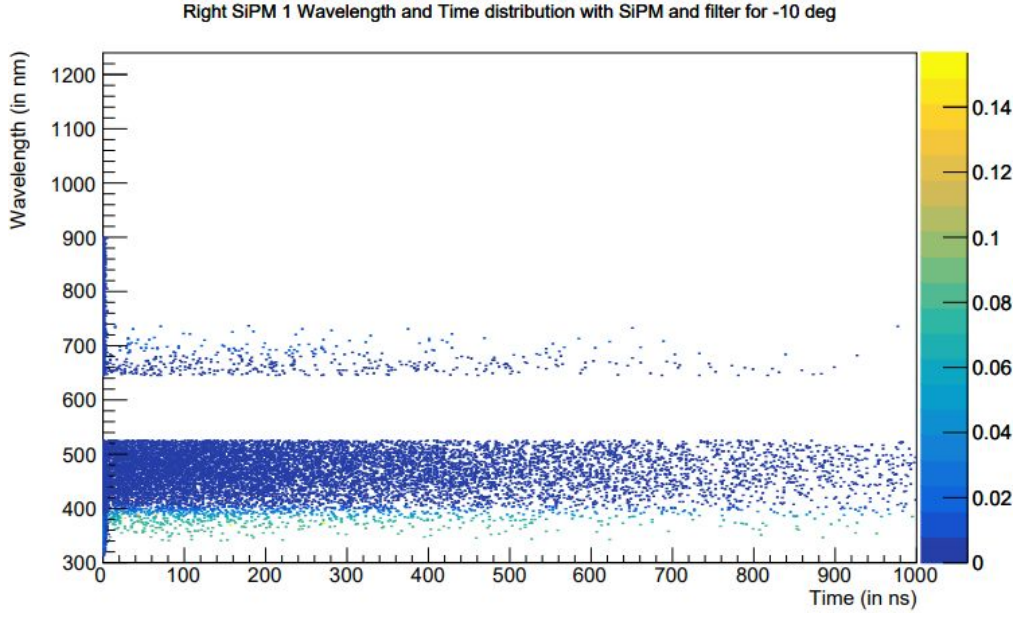



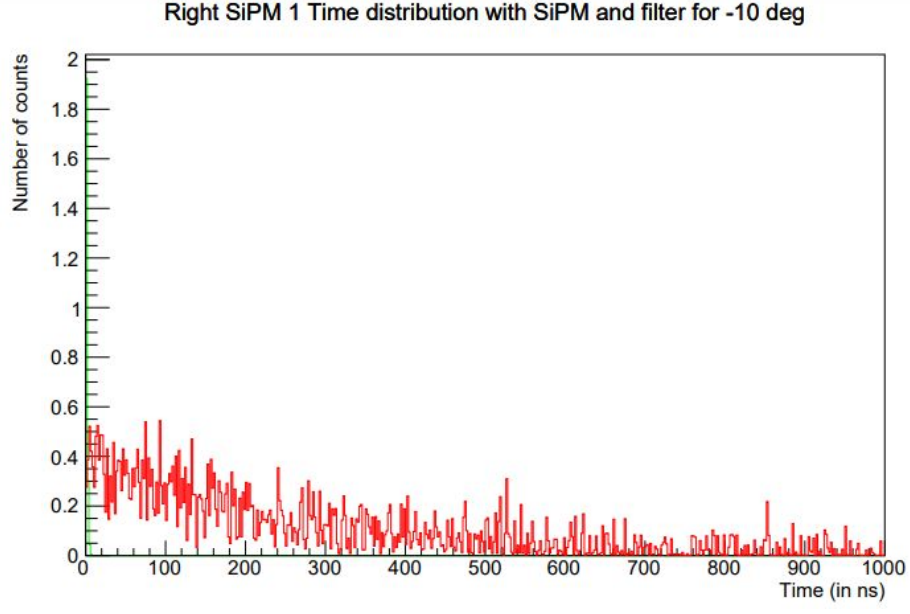



# Optical pulse profiles for BGO - (with SiPM QE and filter)

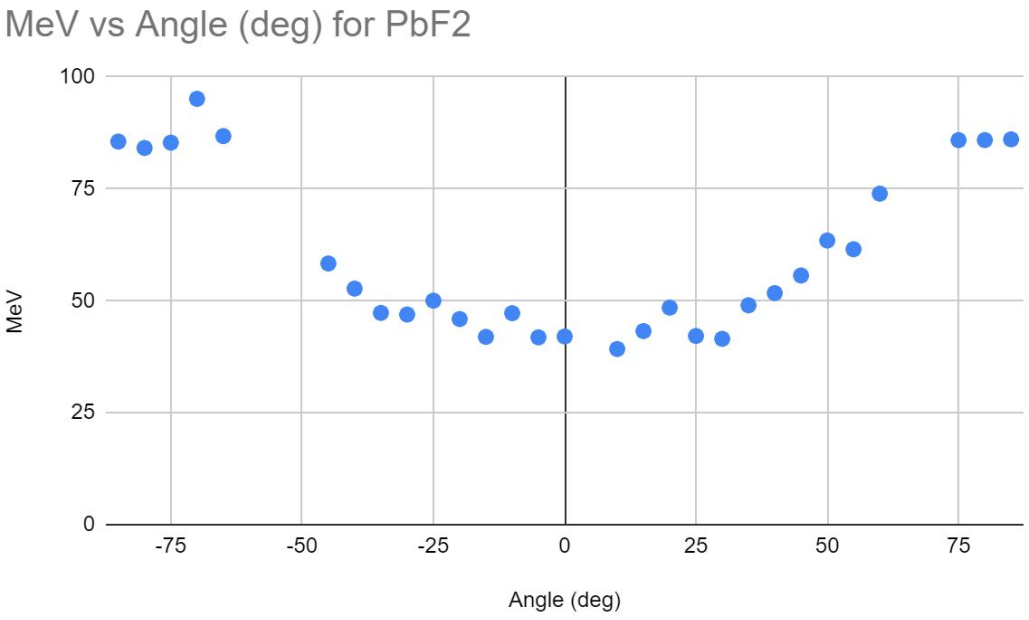


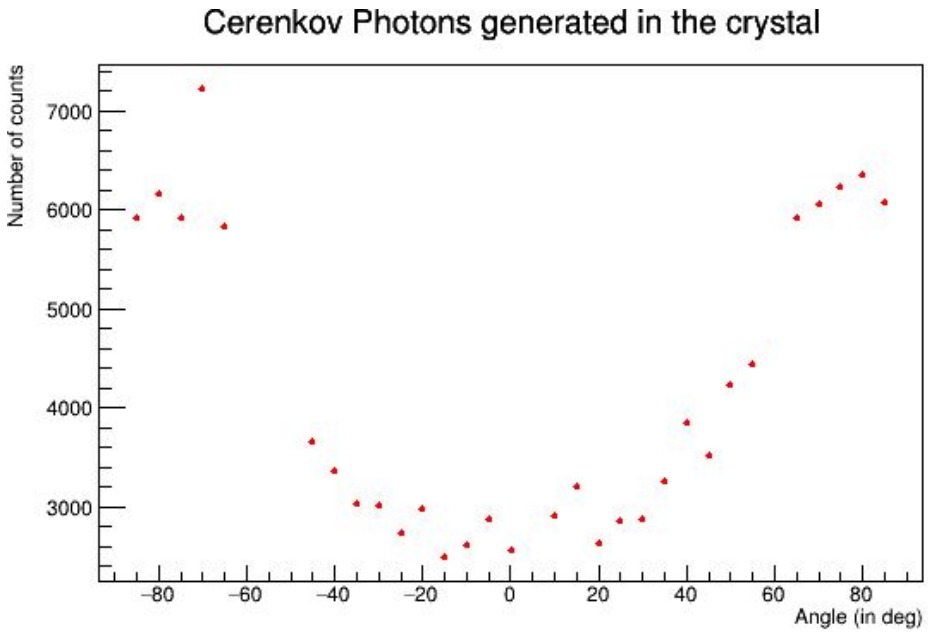



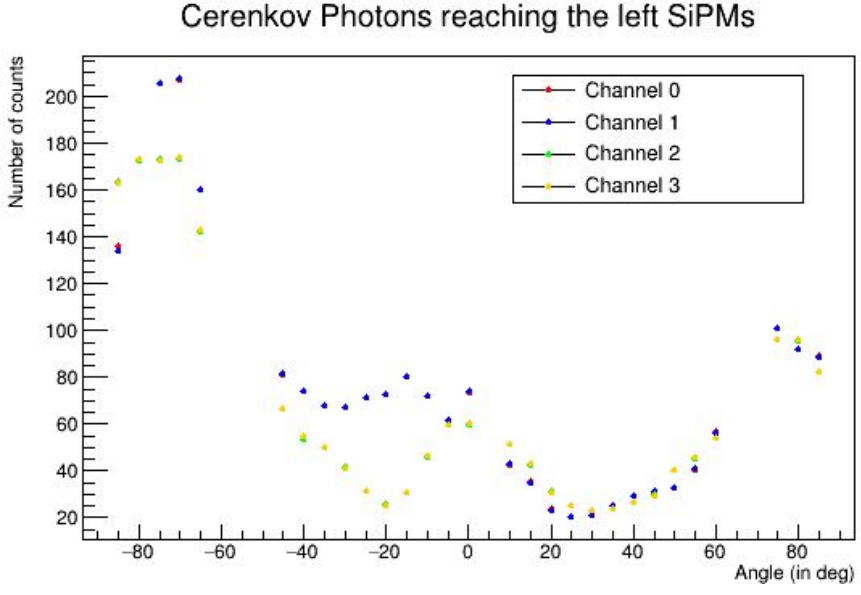



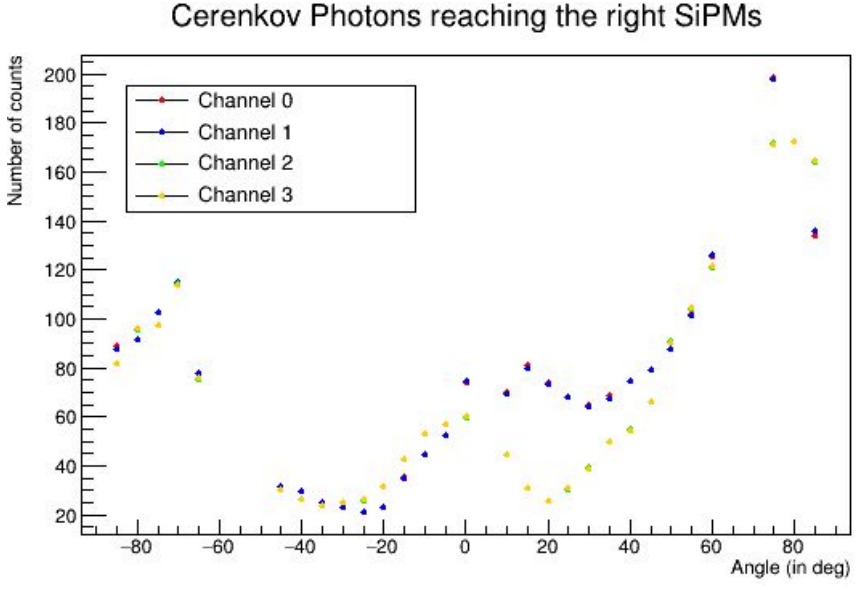



# Plots of angular dependence for PbF2



# Summary

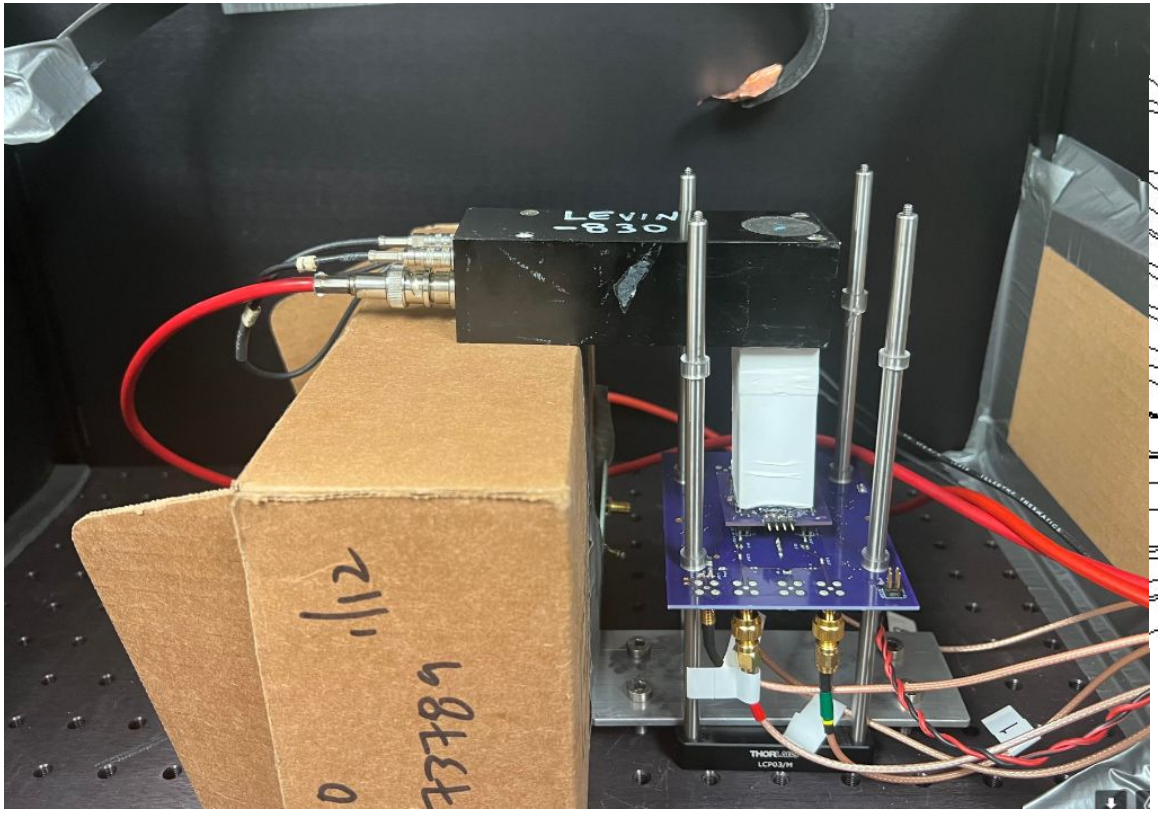
- Made angular dependence plots for all the photodetector channels for both the Cerenkov and scintillation components for PbWO4, BGO, and PbF2

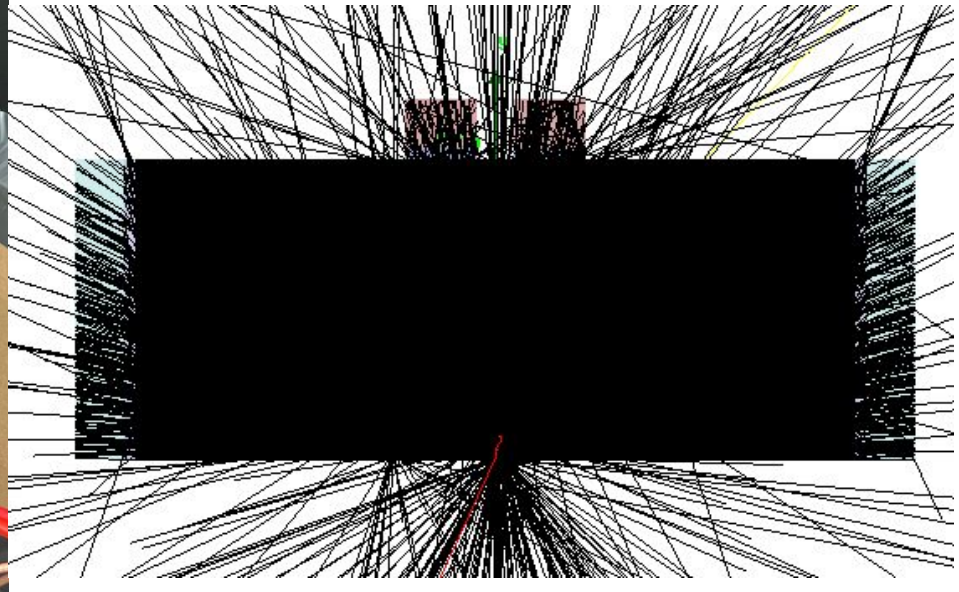
- Made timing distributions for PbWO4 and BGO

- To do
  - Make the timing plots for PbF2
  - Simulate these profiles with the effect of the SiPMs
  - Make the timing plots for the Notre Dame test beam (8 MeV electrons) as well

# Backup

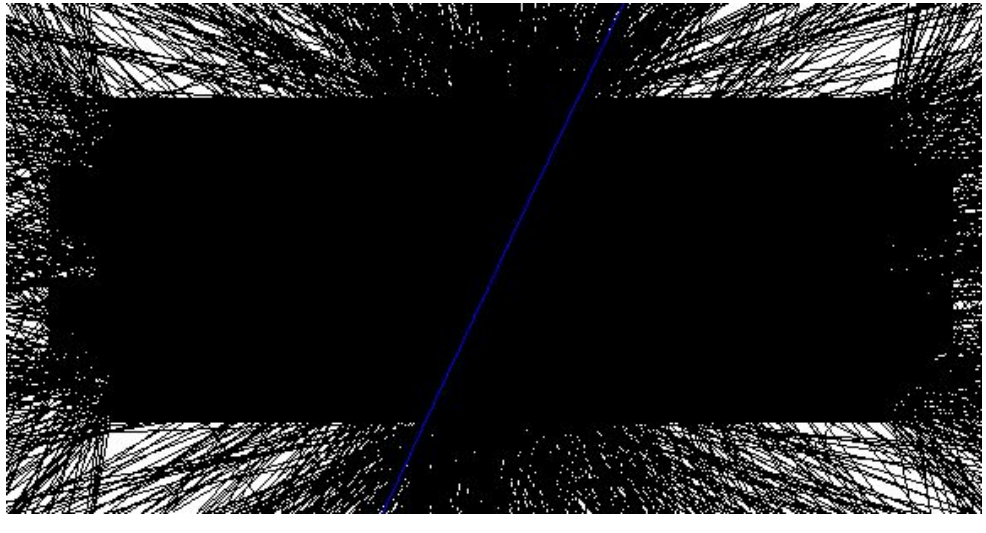
# Actual setup (with 1 SiPM array) and new event display (surface not wrapped or mirrored)



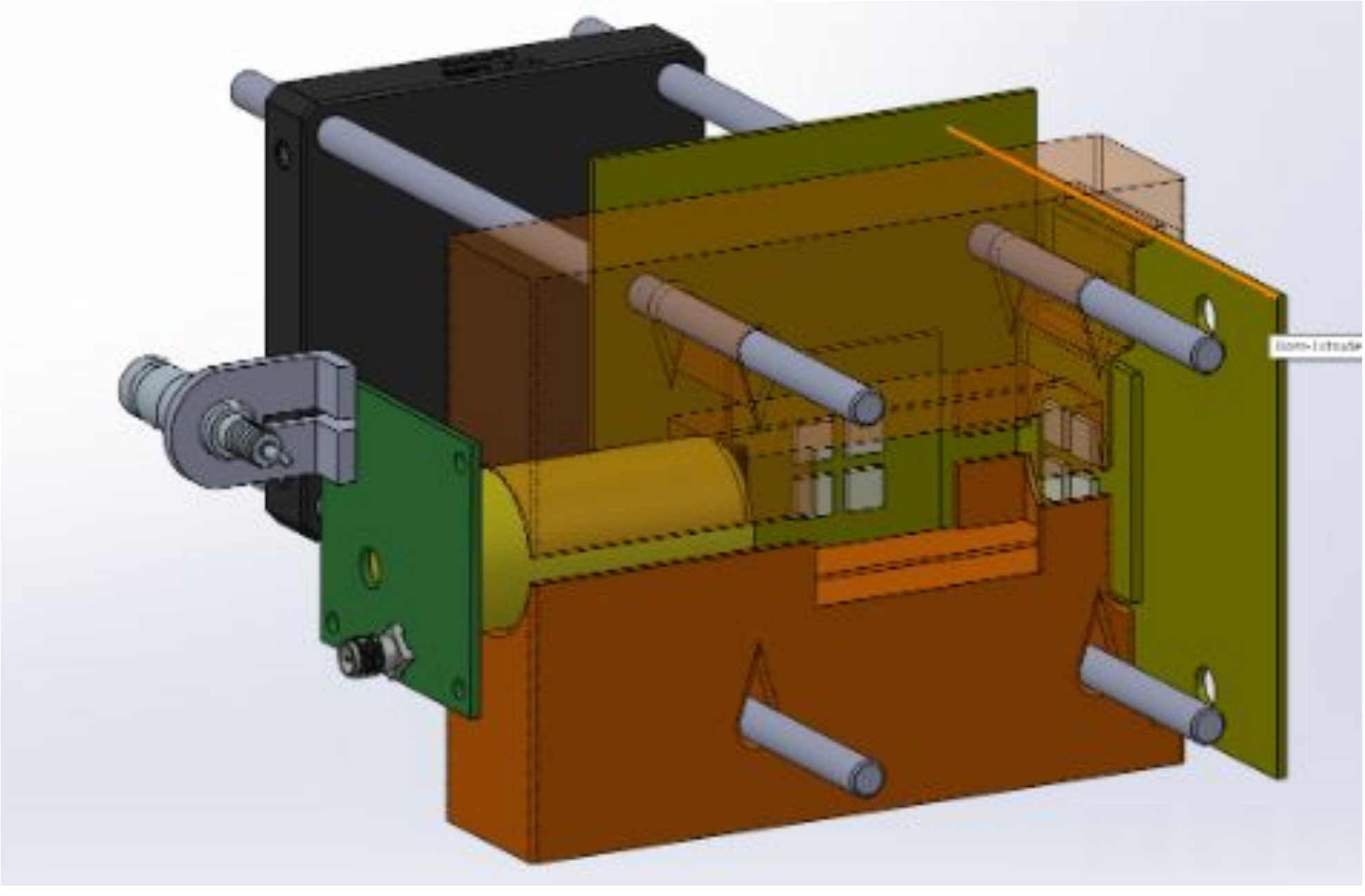


Test beam (8 MeV electrons) - 25 deg angle of incidence

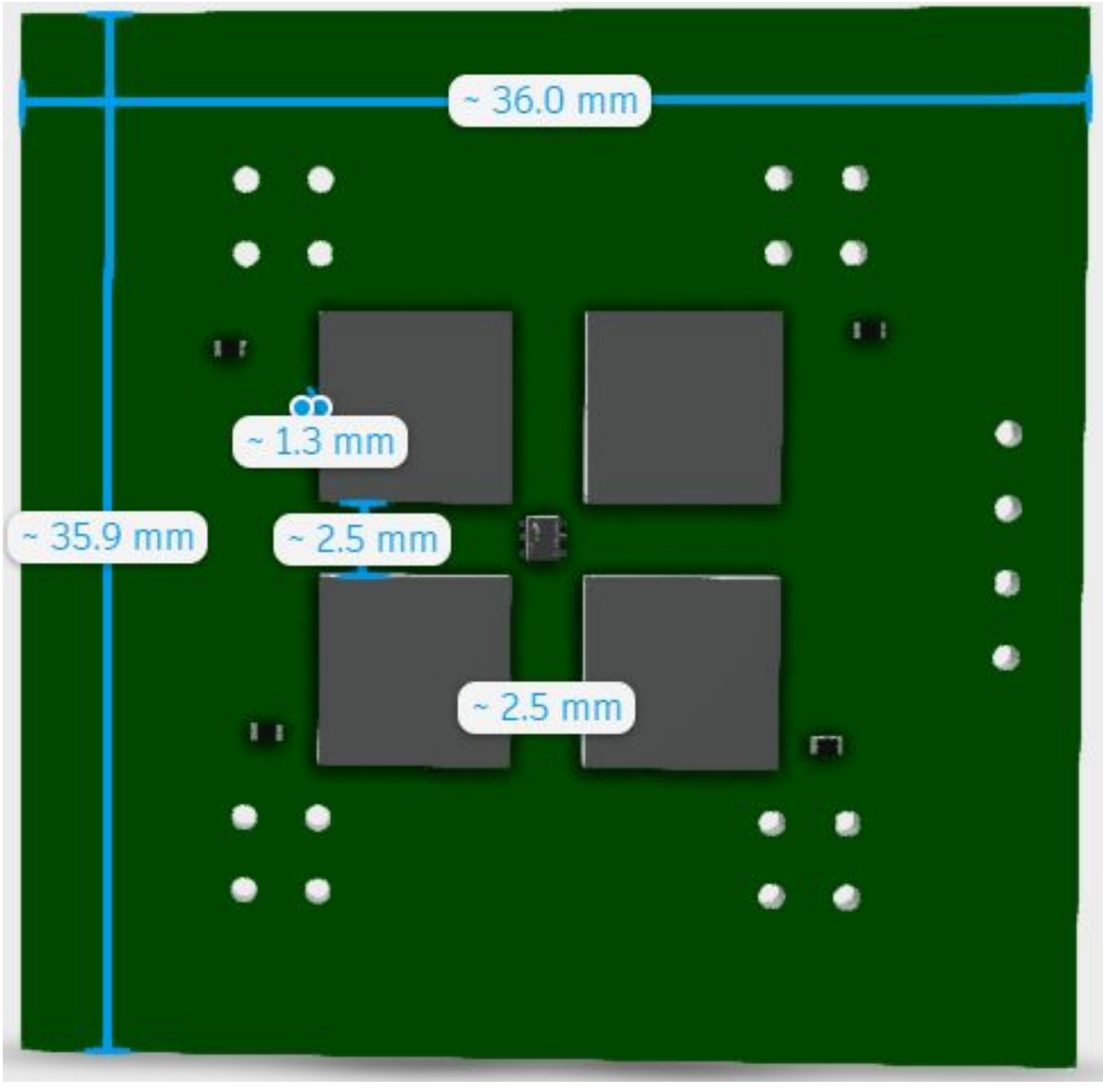
Cosmic ray setup with 2 GeV muons - 25 deg angle of incidence (to the right)



# Test beam setup display in SolidWorks

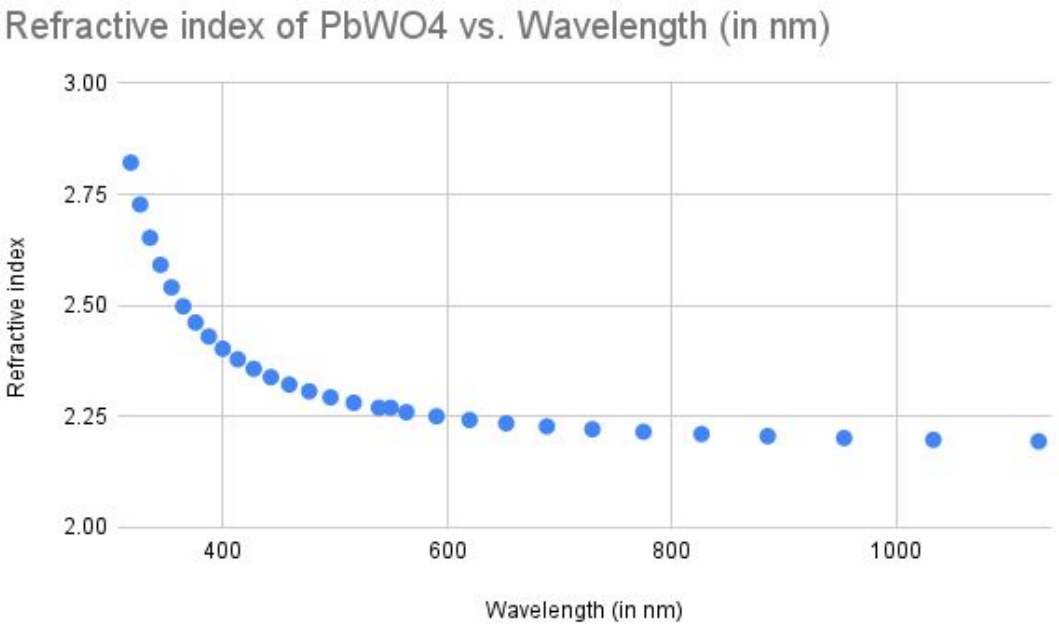


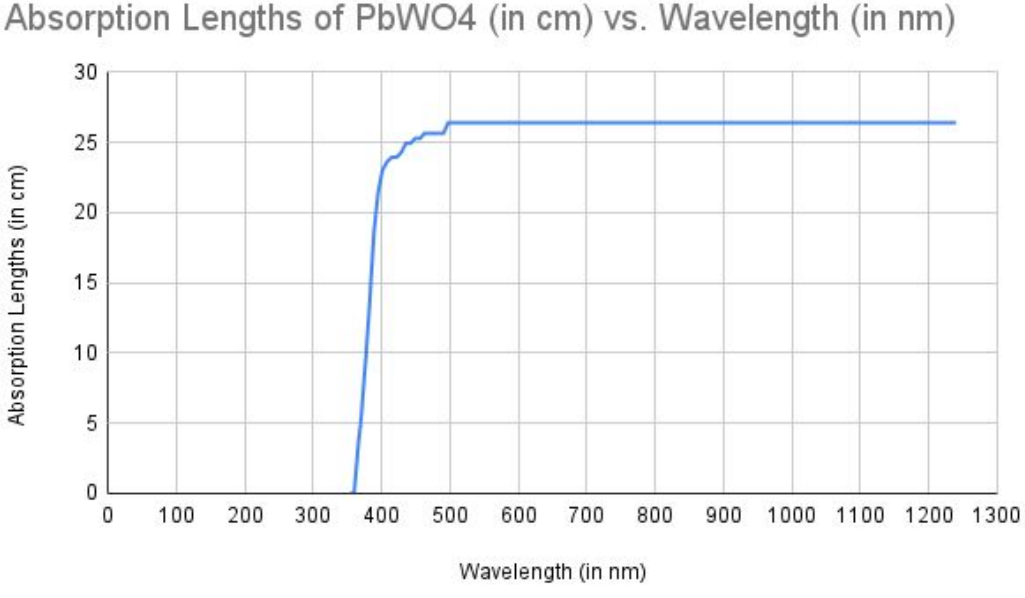
# Dimensions of PCBs for the SiPMs

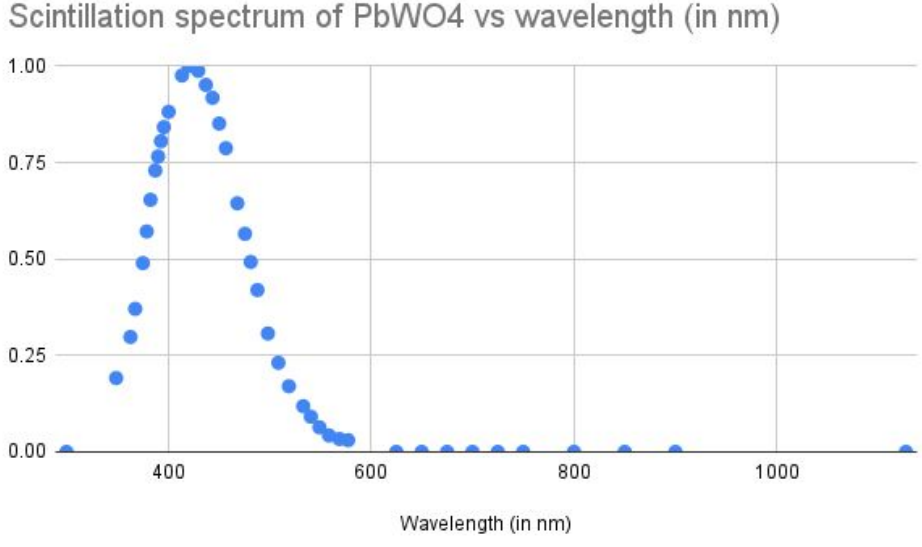


# Material Properties for PbWO4

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

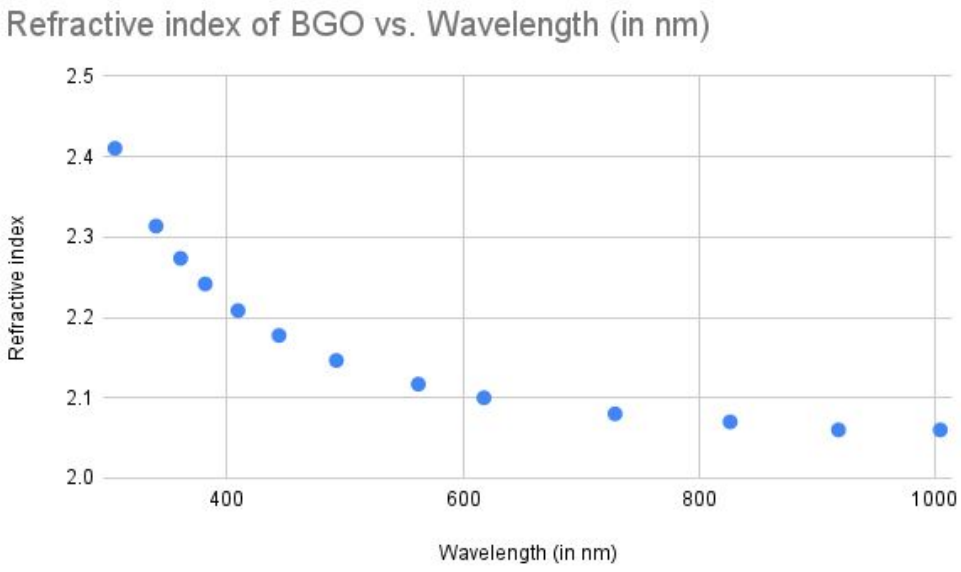


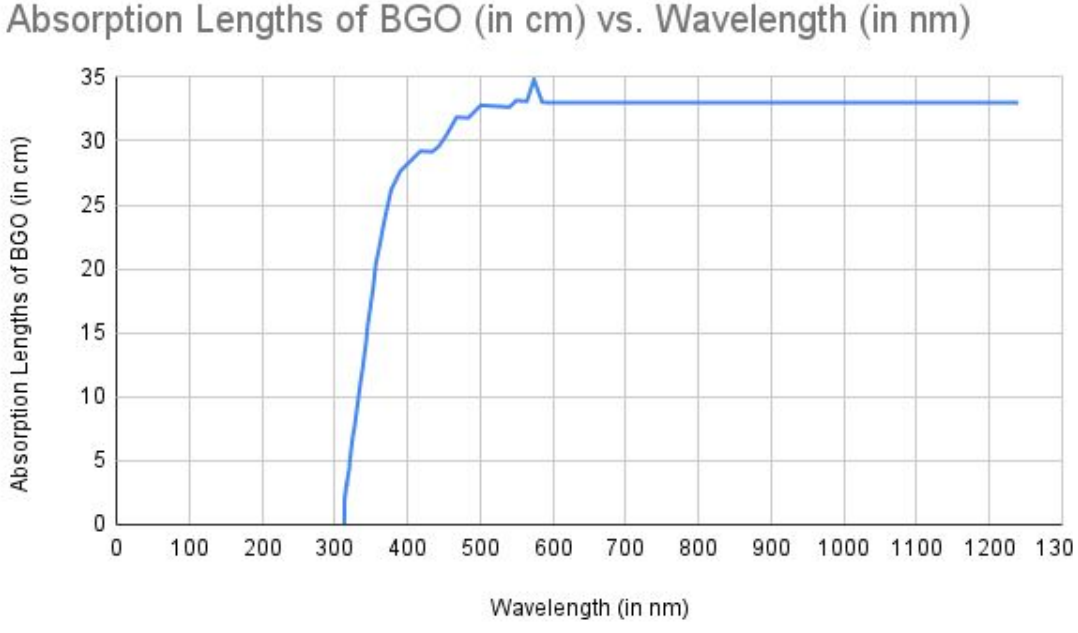



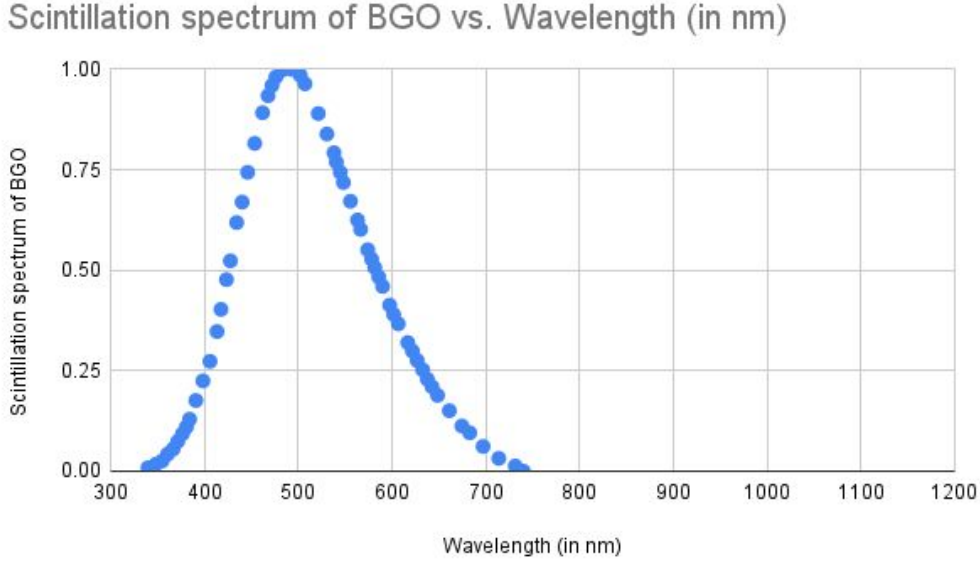



# Material Properties for BGO

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

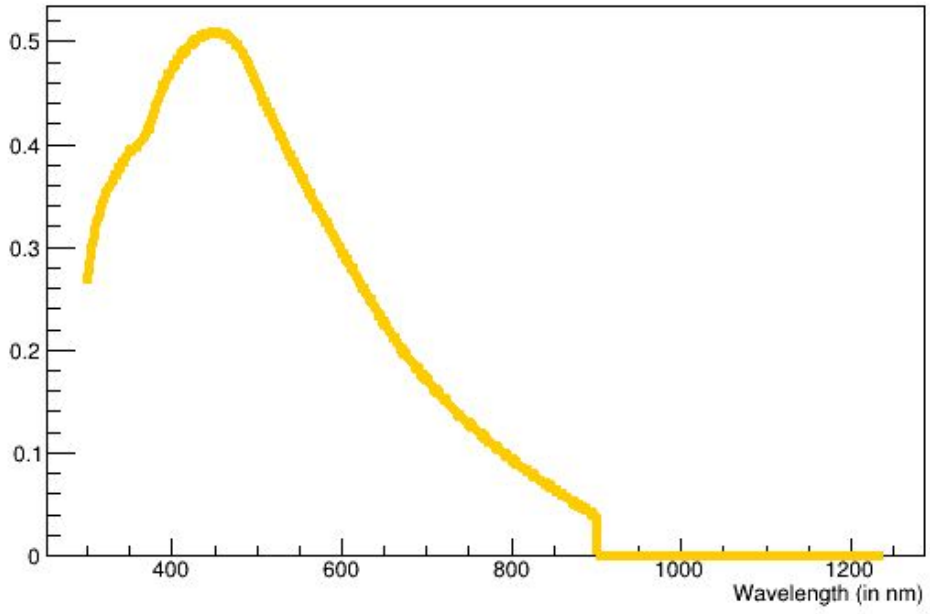


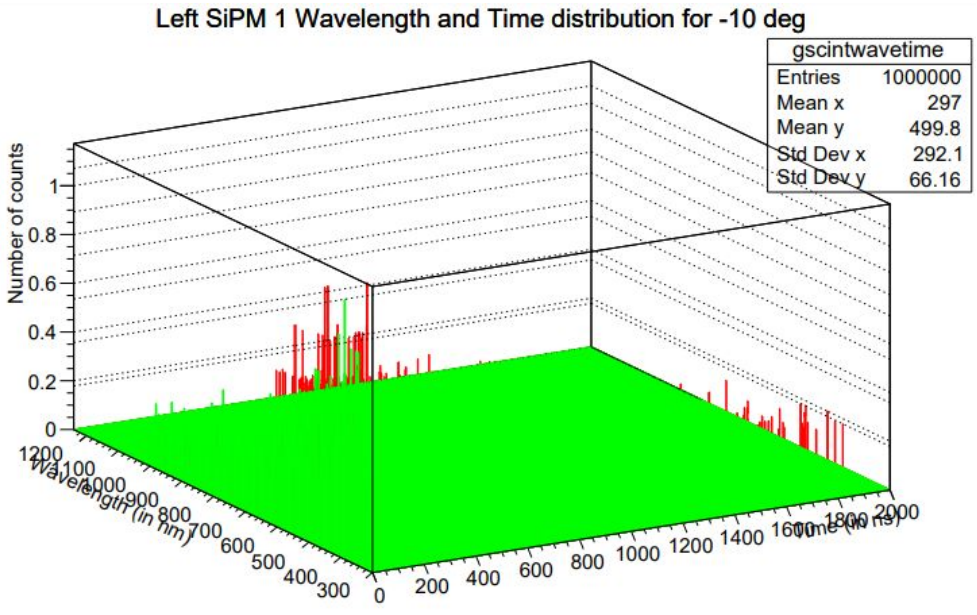



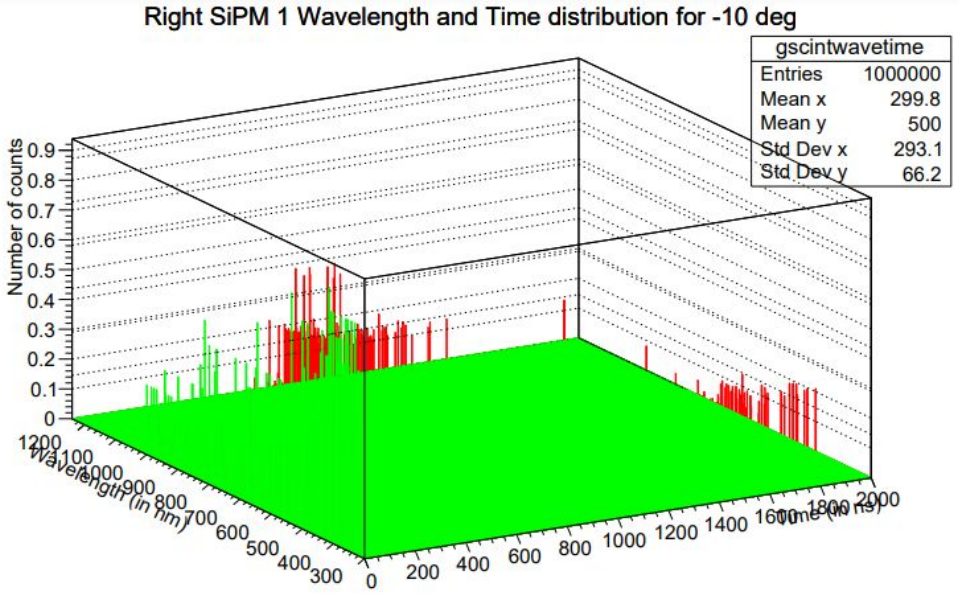
# Photon detection of SiPM (S14160 - 3050S)

- 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



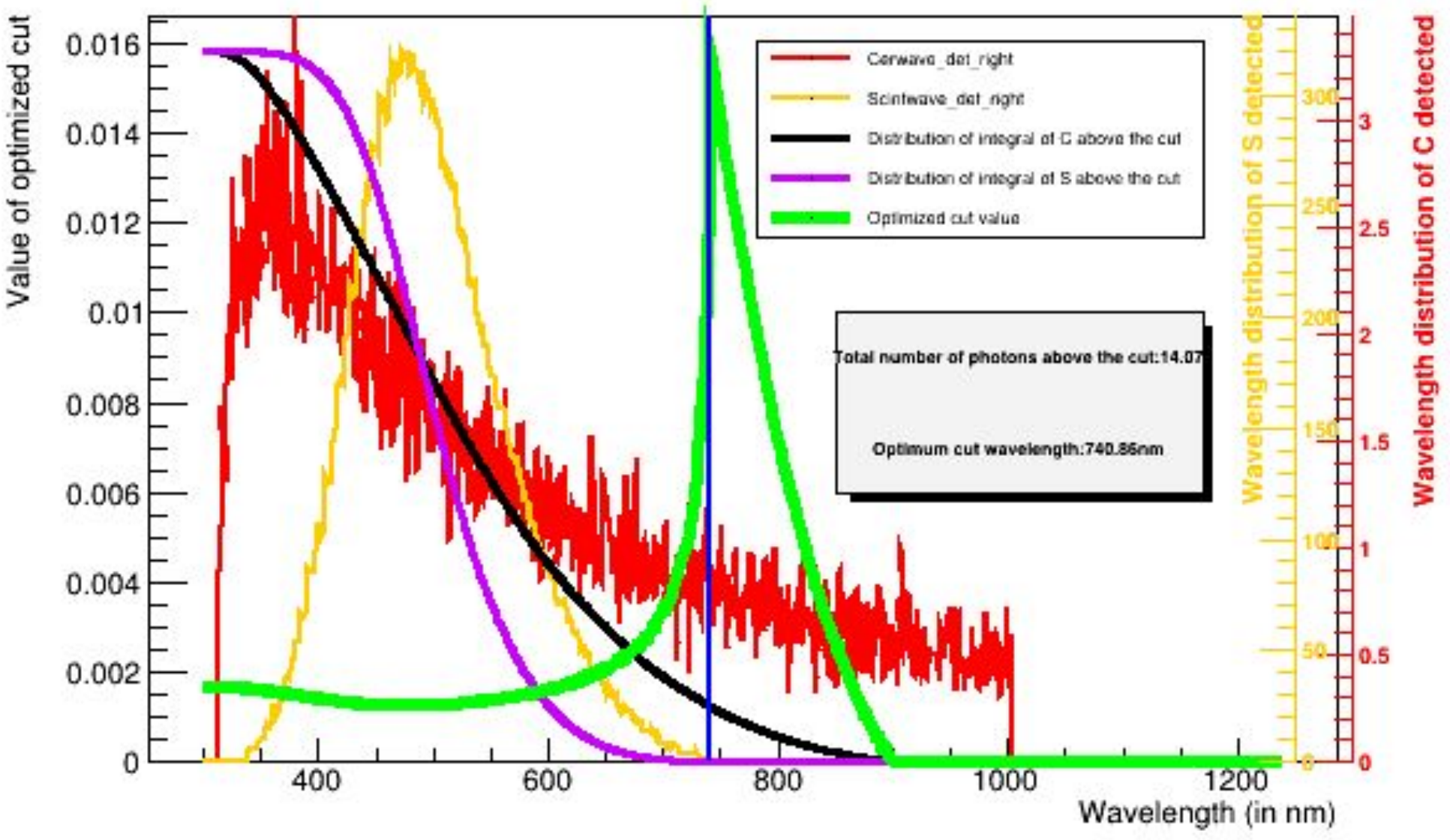
# Optical pulse profiles for BGO and PbWO4 (Lego format)



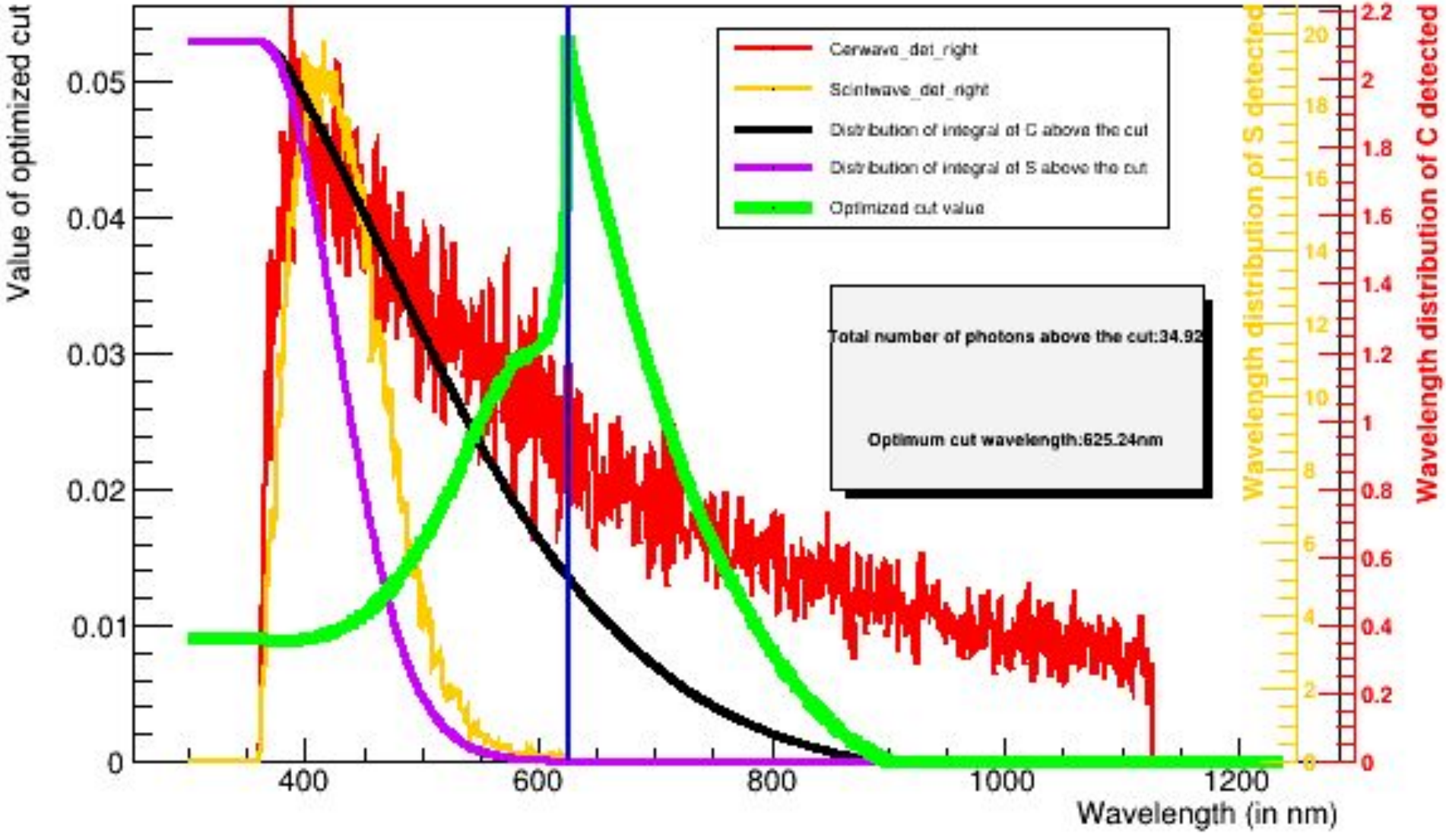
# Value of Optimization function for BGO

- 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 PbWO4

- The optimization cut wavelength for both crystals is fairly constant with the change of angle of incidence of the muon beam
- For PbWO4, 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