Progress on Single Crystal Simulations at UMD

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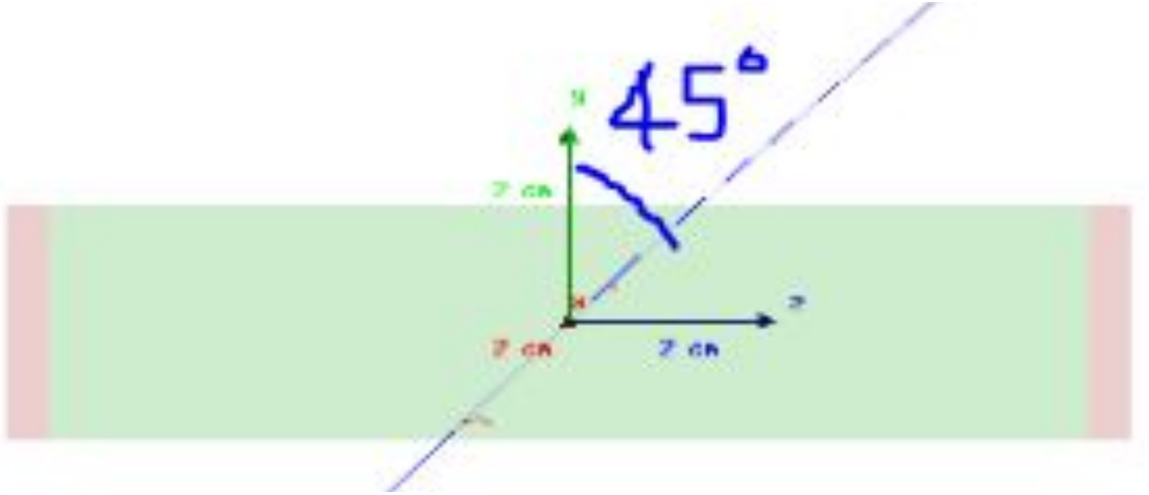
Recap

- Simulated a dual-readout crystal detector with GEANT4 + DD4hep
  - Reproduced the 2020 proposal plots (PbWO4)
- Worked on inclusion of additional effects
  - Tested filters given by Junjie
- Found that it is needed to select better filters for the Cerenkov component

Recap - Earlier Geometry of the crystal and sample display

- We had a PbWO4 crystal of 2.4cm ⨉ 2.4cm ⨉ 10cm 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
- In all subsequent plots, the simulation has been done for a 1 GeV muon whose angle of incidence in the crystal has been measured from the normal to the longest side



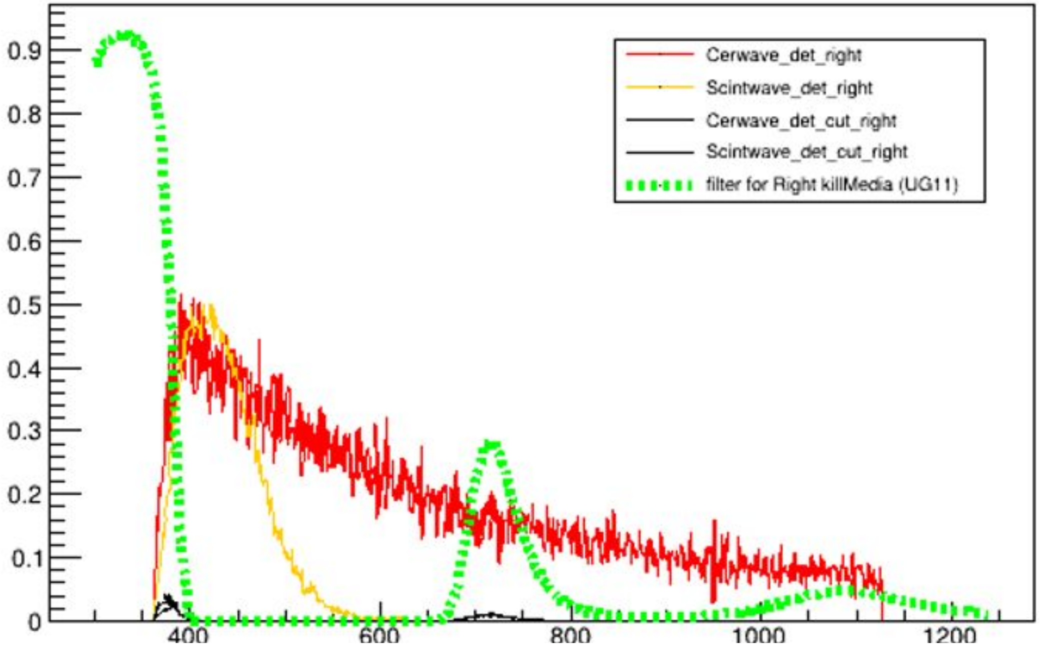
Recap - Earlier filters

- Added filter efficiencies as given by Junjie (UG11 and GG475)
- For the filters, the transmission efficiencies as a function of the wavelength are at present added only to the post processing file
  - Filter material is not added as a physical object yet to the actual simulations
- The UG11 filter was used for the Cerenkov end and the GG475 filter was for the scintillation end

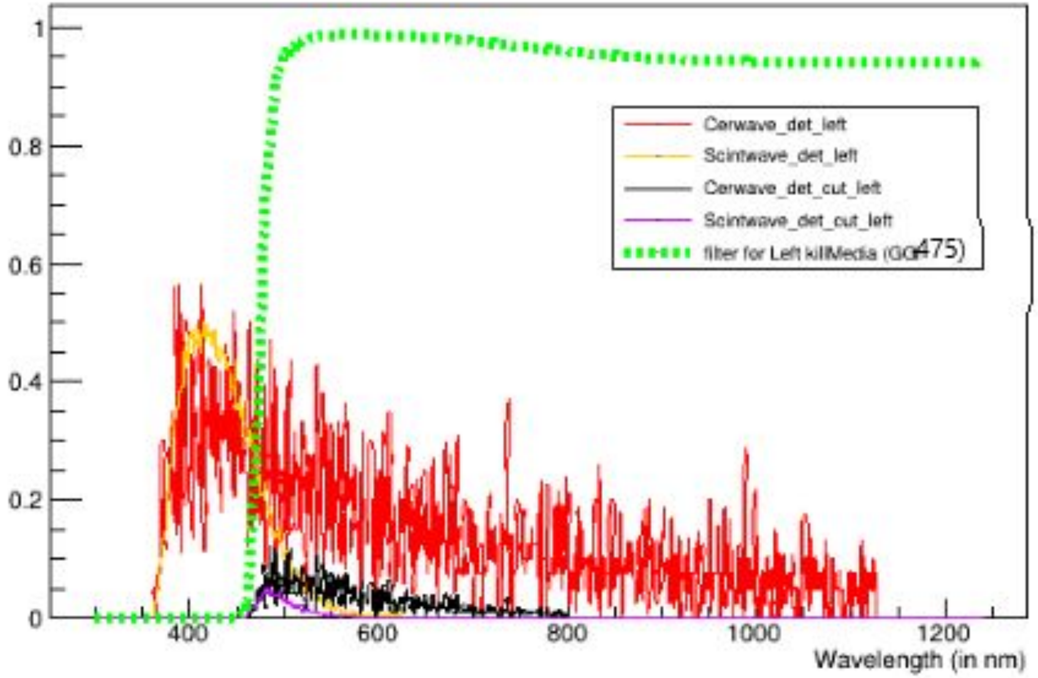
- It is clear from the wavelength distributions in the next slide that the UG11 filter is not very efficient for Cerenkov
- It is also very clear that GG475 does not work as a filter for the Scintillation component (if anything, the ratio of scintillation to cerenkov photons after filtering actually decreases here)

Recap - Filter profiles for initial choices

- Filter for C end (UG11)
  - The UG11 has a window at around 700 nm where it exclusively picks up C photons, and a peak earlier at < 400 nm, but the scintillation spectrum overlaps completely with the Cerenkov part in that region

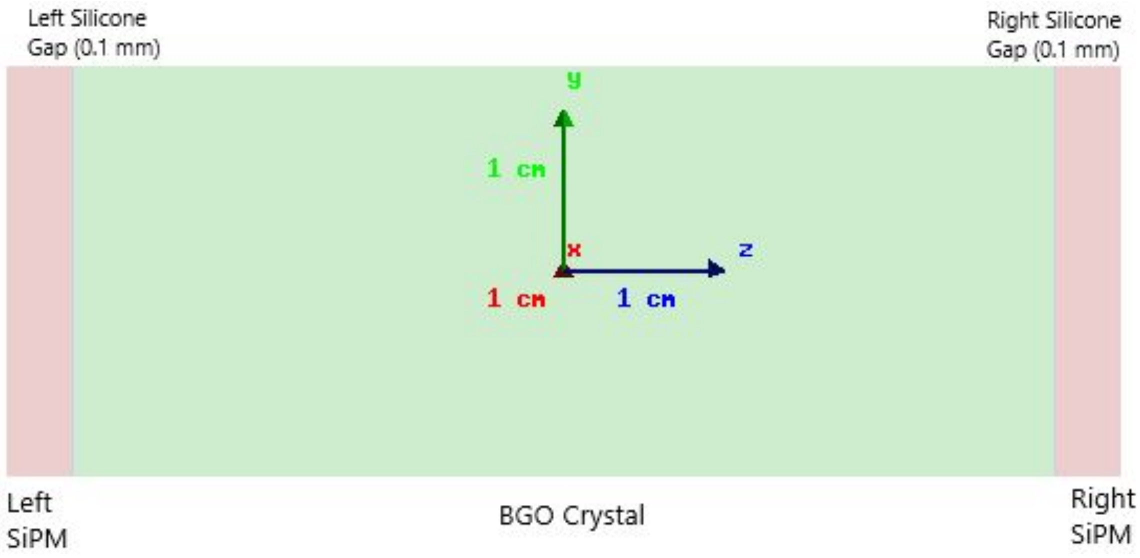


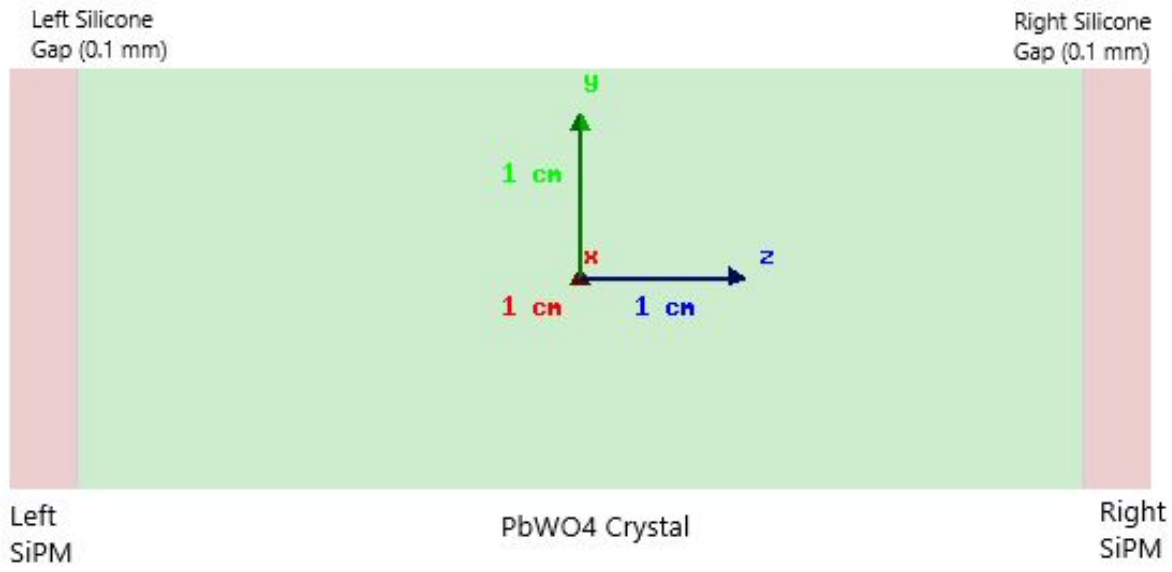
- Filter for S (opposite) end (GG475)
  - The GG475 looks approximately like a step function in the range of interest (step at ~ 460 nm) which picks up C photons in addition to the intended S photons in the whole region



New geometry for the crystals (PbWO4 and BGO)

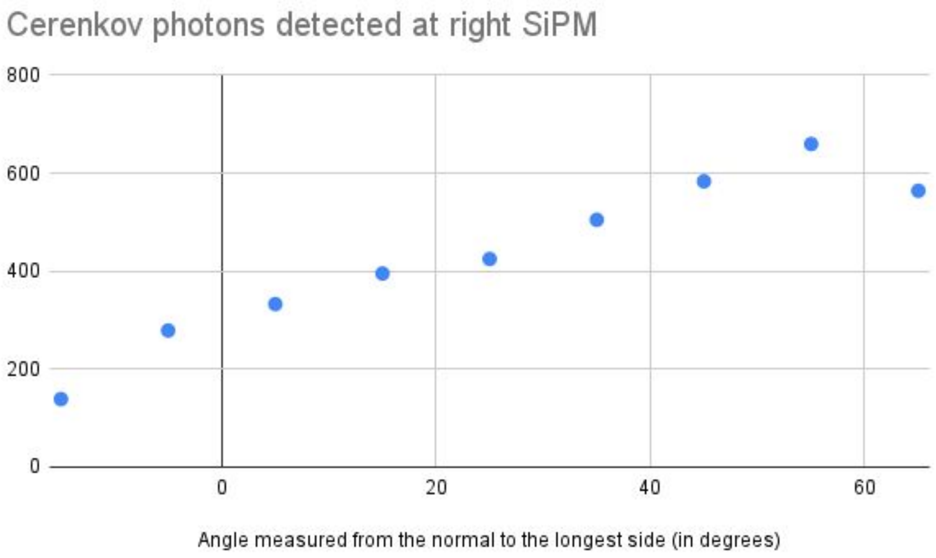
- The dimensions of the crystals have been changed to be identical to the ones being used for the measurements at Michigan
- The new dimensions are 2.5cm × 2.5cm × 6cm
  - Other parameters are the same
  - The crystal dimensions are the same for both PbWO4 and BGO

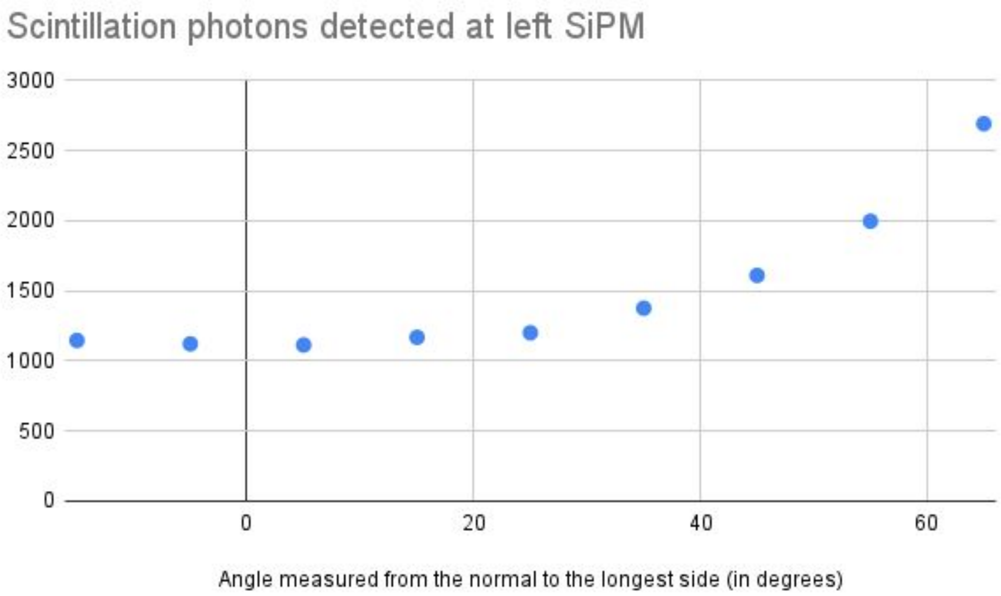


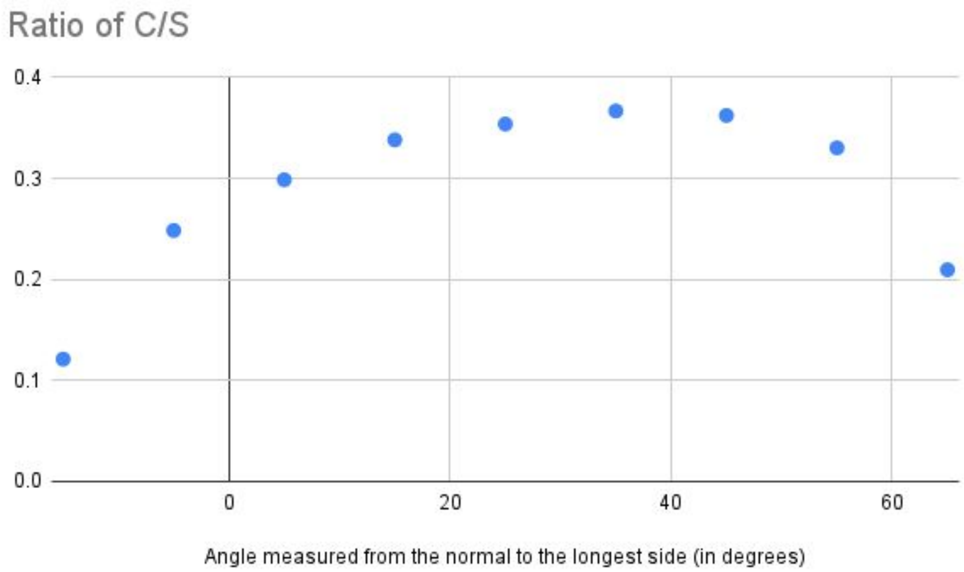


Plots of angular dependence of counts for new geometry (PbWO4)

- In our convention, the C (Cerenkov) end is chosen to be the right end and the S (Scintillation) end is the opposite i.e. the left end
    - Just the photon counts reaching the SiPM and not including the filter and/or quantum efficiency of the SiPM

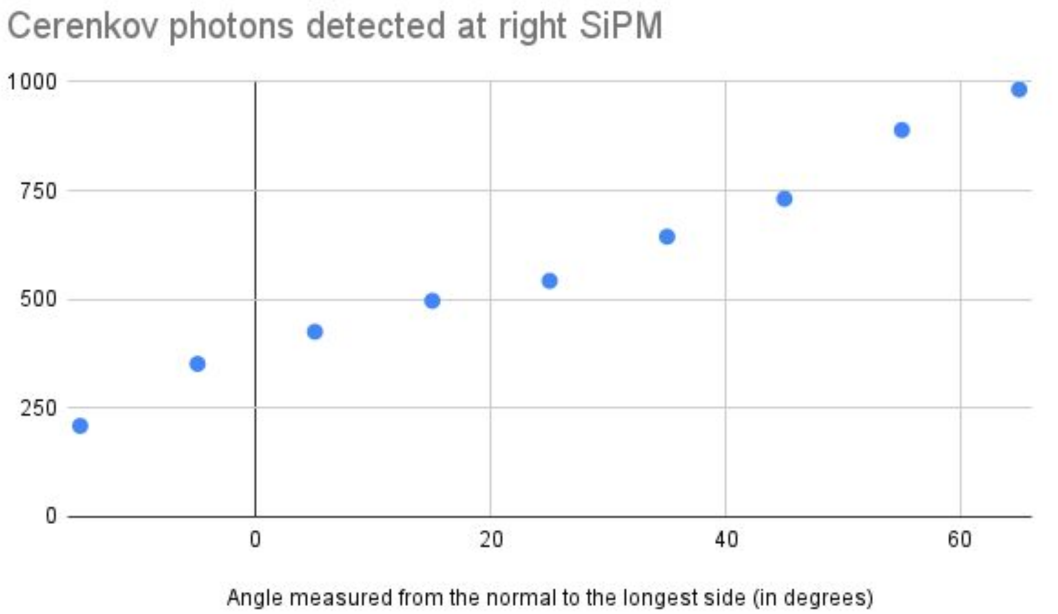


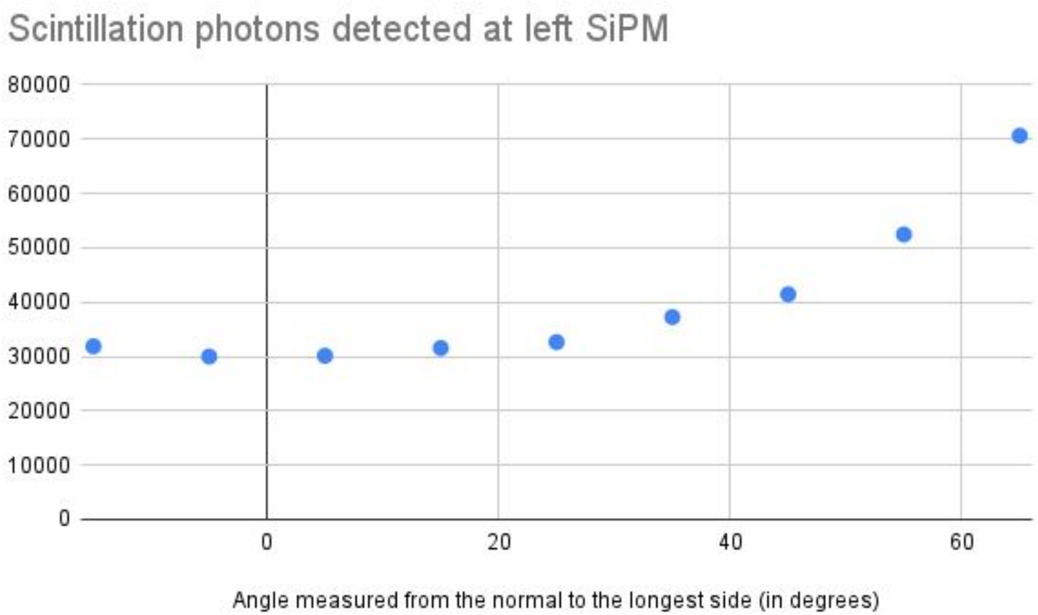


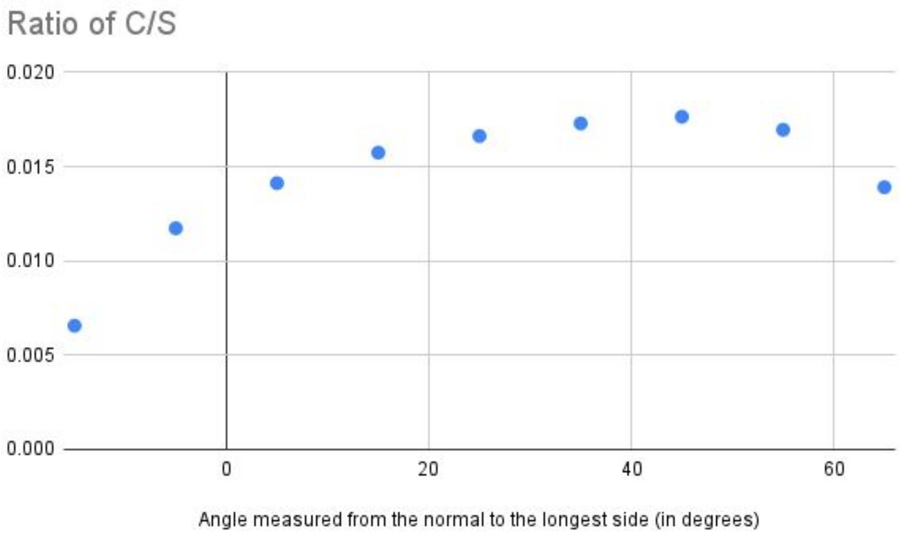


Plots of angular dependence of counts for new geometry (BGO)

- Note that there is no dip at the 65 deg point in the Cerenkov graph for BGO (as opposed to PbWO4)
    - This is likely because the refractive index of BGO is less than that of PbWO4, so the critical angle for the silicone gap - crystal pair is greater for BGO, which limits the possibility of total internal reflection for the same angle of incidence at the interface, a bit more







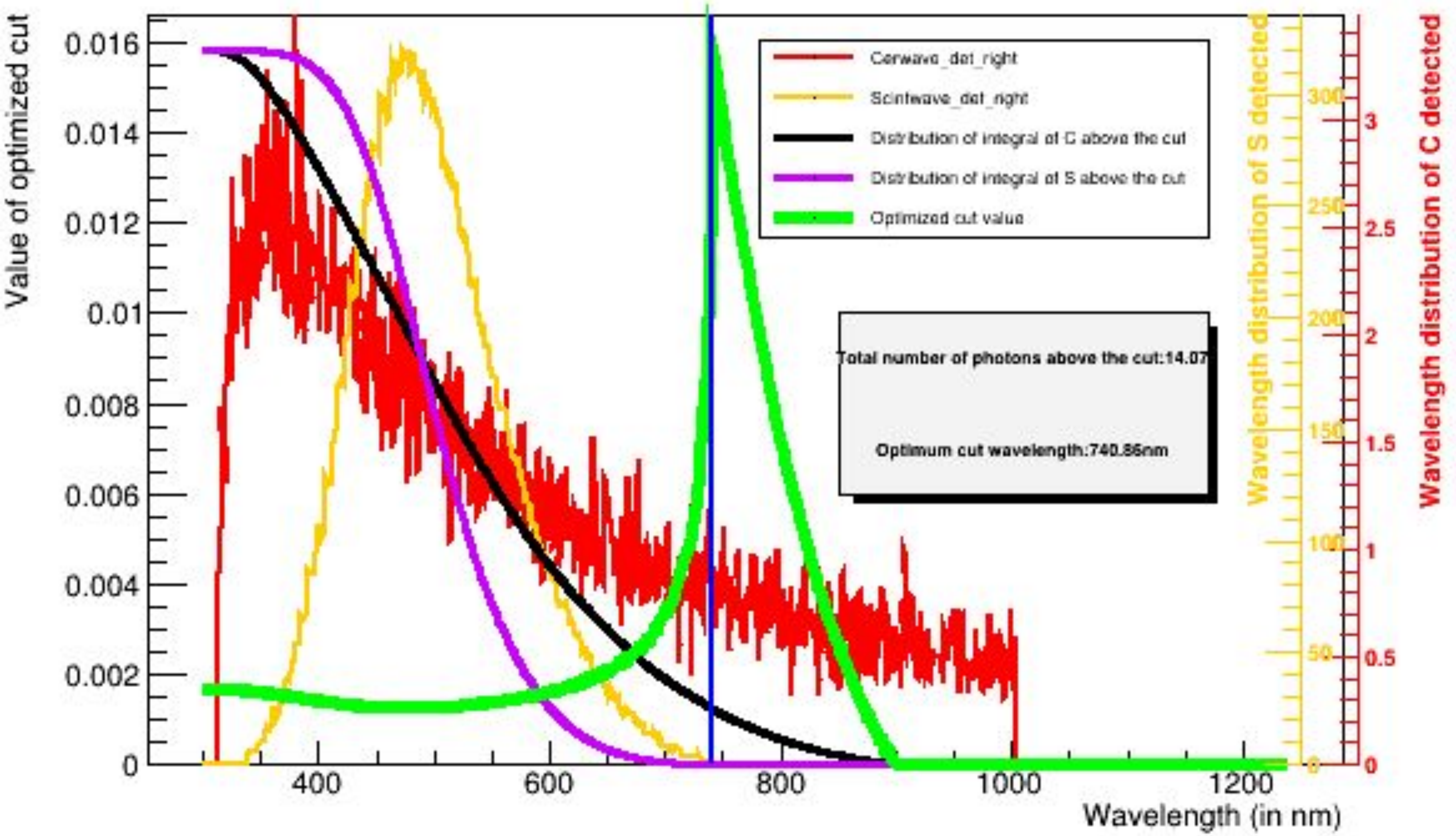
New filter selection for Cerenkov end

- Assuming a hard lower cutoff (longpass) in wavelength for selecting Cerenkov, an optimization is performed over all the possible cut values to get a good Cerenkov measurement
- The optimization formula used was this: $\varepsilon/((a/2)+\sqrt{B})$ [Punzi's criterion]
    - (where ε is the efficiency of cuts for Cerenkov which is the signal, and Scintillation is the background, and 'a' is chosen to be the desired number of σ here)

- The optimum cut value (i.e. Maximum of the green curve) is found where the photons in the scintillation spectrum drop to 0, so this result also depends on the accuracy of the scintillation spectrum values entered for the simulation

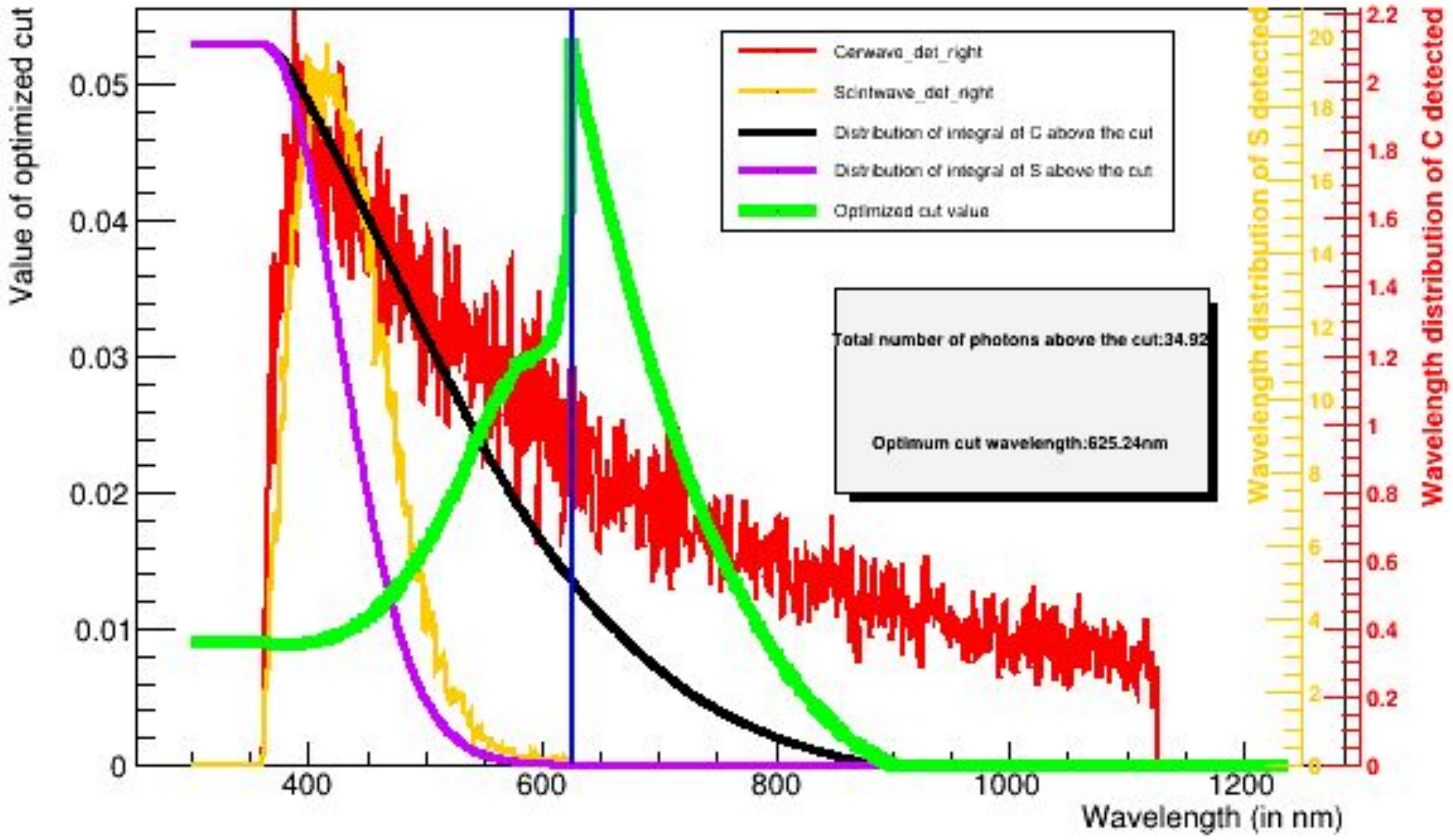
Value of Optimization function for BGO

- 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

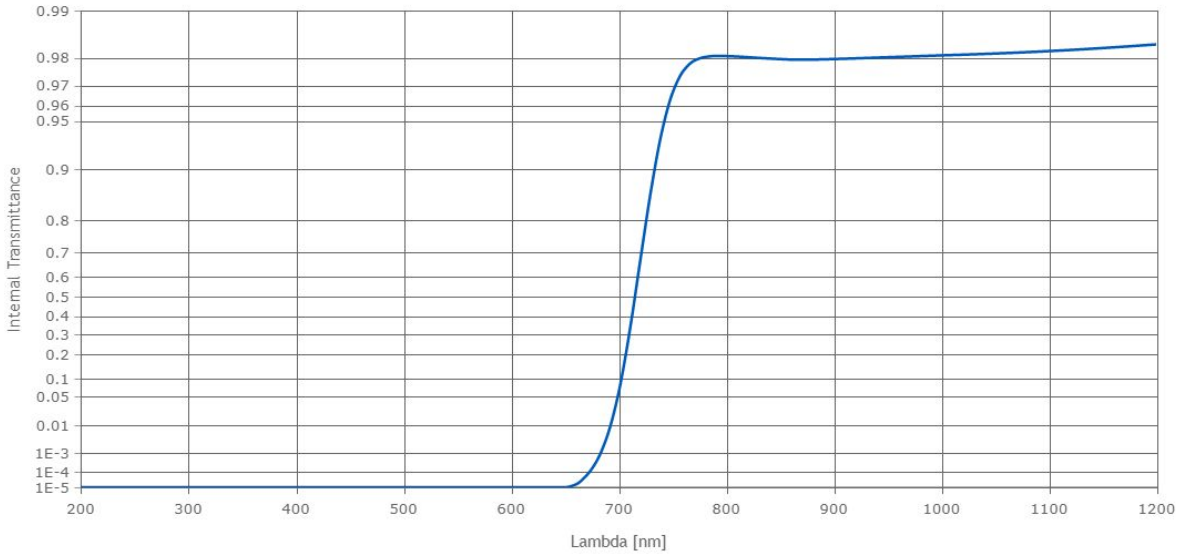
Choice of colored glass filters (Schott) for BGO

- Preliminary choice is going to be colored glass (uncoated) filters as opposed to interference filters because that means we do not need to worry about the dependence of the efficiency as a function of wavelength on the angle of incidence of the photons

- For BGO, RG715 and RG780 seem to be two of the better options
- RG780 is more likely to give a signal purer in Cerenkov, but the tradeoff will be that the number of photons might be too low
- The curve for RG715 starts at slightly below 700 nm, which means the ratio of C/S after filtering will be ~40 - 50%, so more filtering based on timing considerations will be required

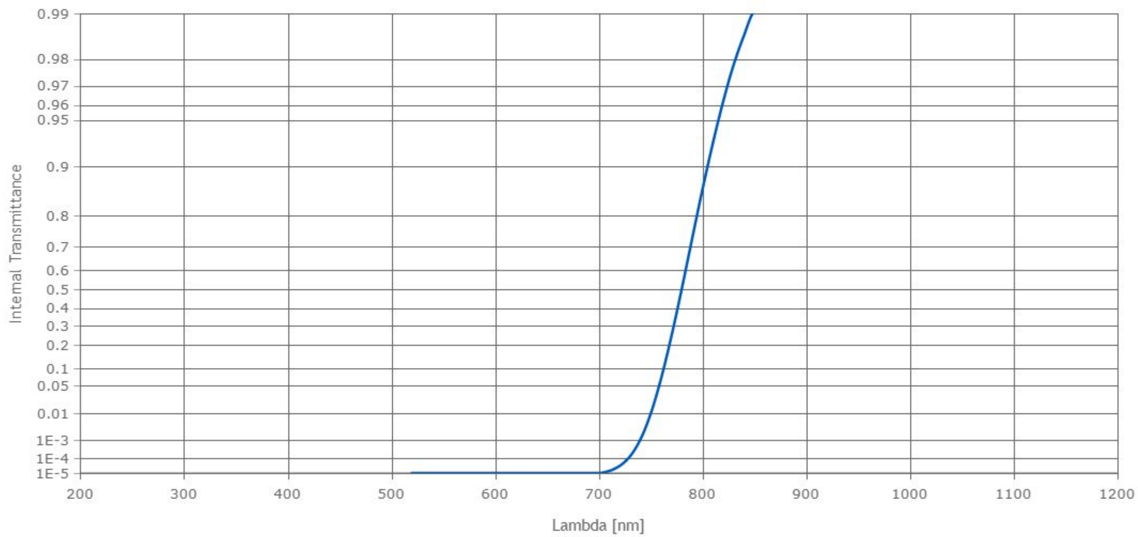
Transmittance as a function of wavelength for BGO filters

- Transmittance as a function of wavelength for RG715



SCHOTT RG715 - RG715, Thickness 3.0, Reflection factor 0.0000

- Transmittance as a function of wavelength for RG780

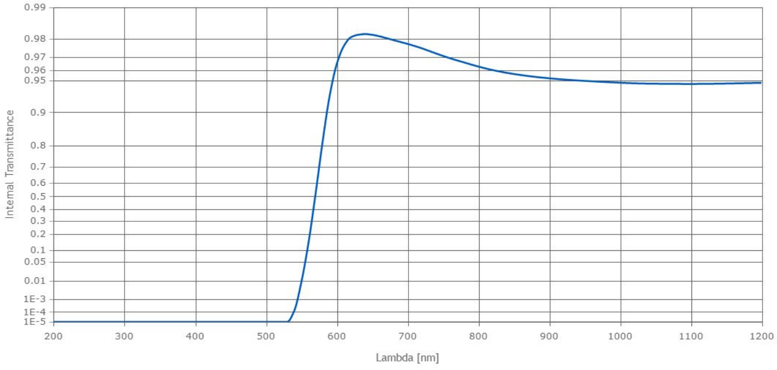


SCHOTT RG780 - RG780, Thickness 3.0, Reflection factor 0.9082

Choice of colored glass filters (Schott) for PbWO4

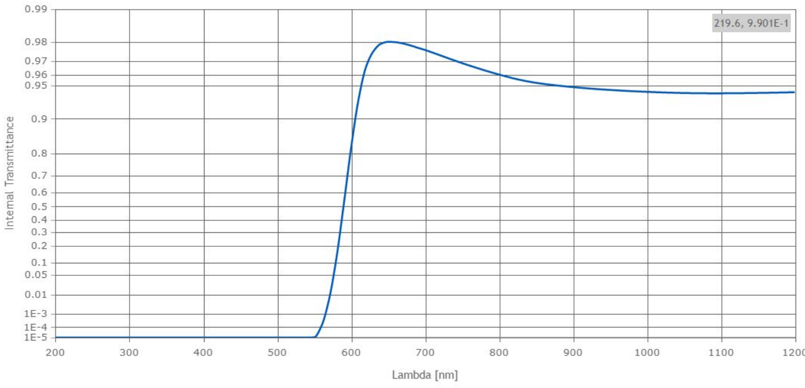
- For PbWO4, any of OG570, OG590, and RG610 could be chosen

Transmittance as a function of wavelength for OG570

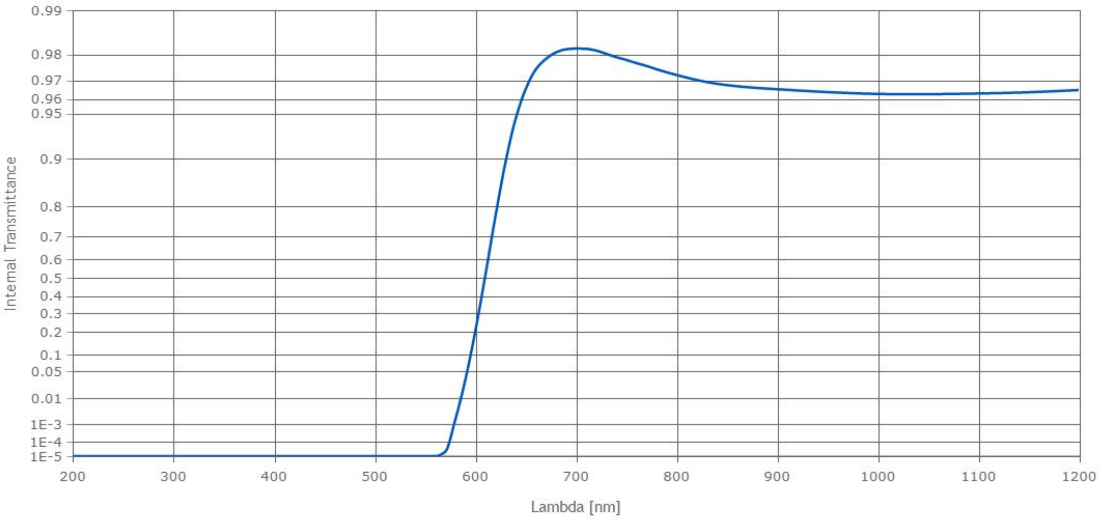


SCHOTT OG570 - OG570, Thickness 3.0, Reflection factor 0.9207

Transmittance as a function of wavelength for OG590



SCHOTT OG590 - OG590, Thickness 3.0, Reflection factor 0.9207



SCHOTT RG610 - RG610, Thickness 3.0, Reflection factor 0.9183

- Transmittance as a function of wavelength for RG610 (to the left)

Summary

- Added BGO as a crystal material along with $PbWO_4$ and replaced the dimensions used in the 2020 proposal with the one used in measurements

- Plotted the optimization values of signal with respect to background as a function of the wavelength cut for the Cerenkov component

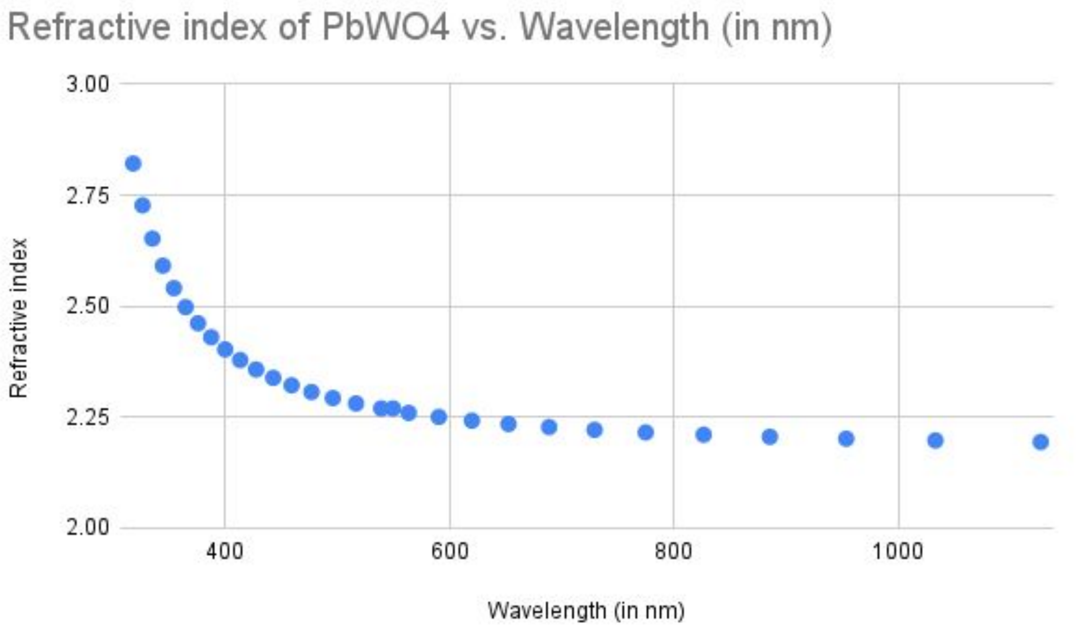
- Made a tentative list of potential filters for extracting the Cerenkov component

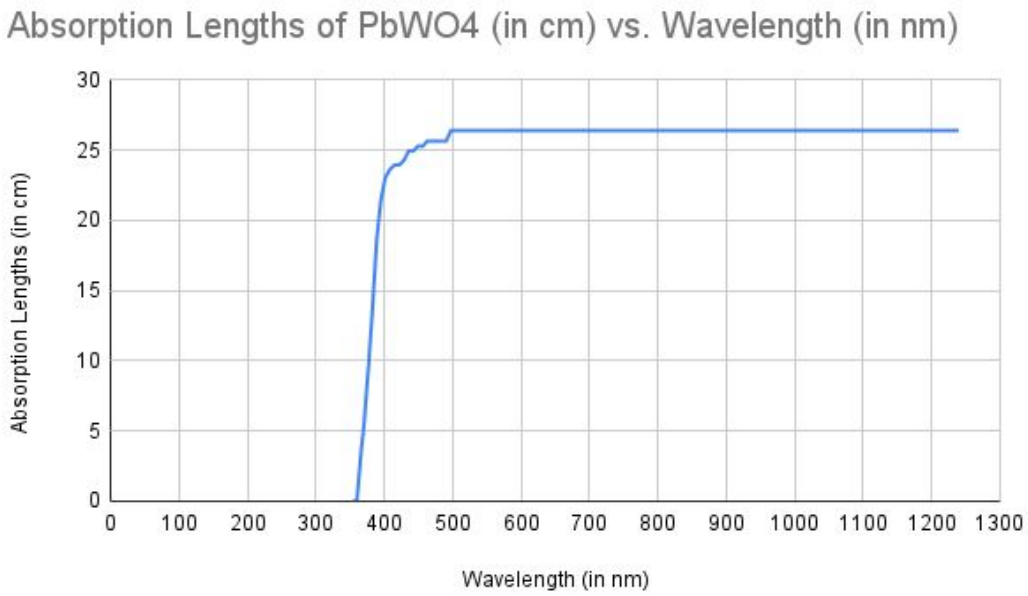
- To do
  - Implement the transmission efficiencies of the selected filters in the post processing code
  - Buy the filters and check whether the efficiency is indeed independent of the angle of incidence of the photons

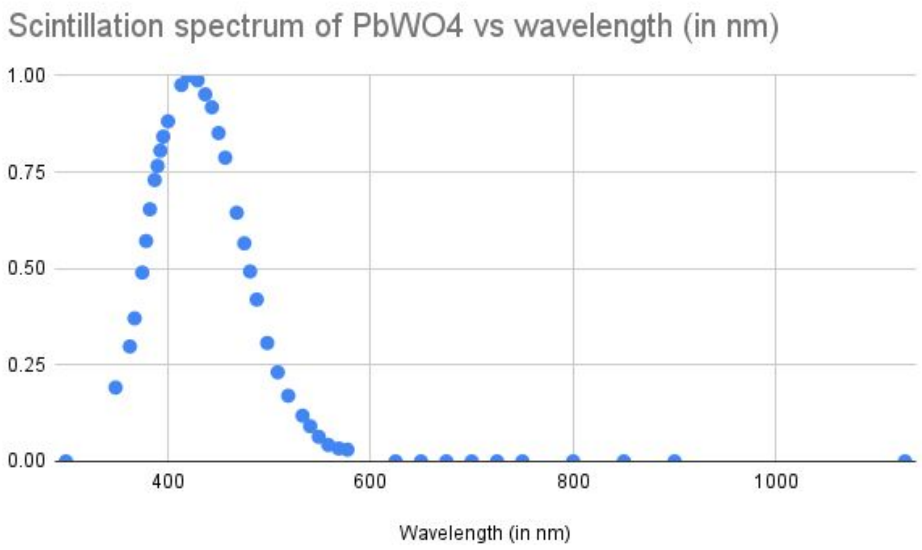
Backup

Material Properties for PbWO4

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

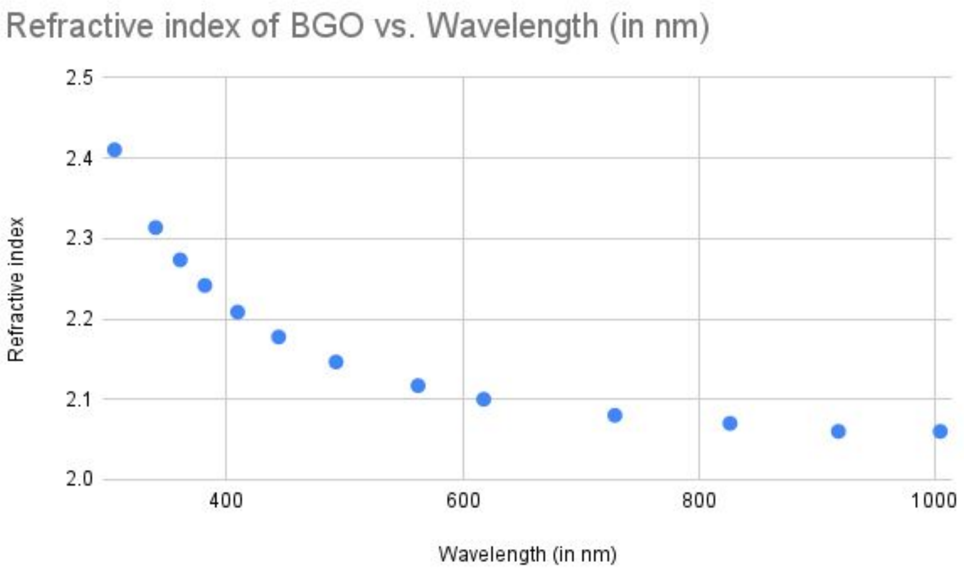


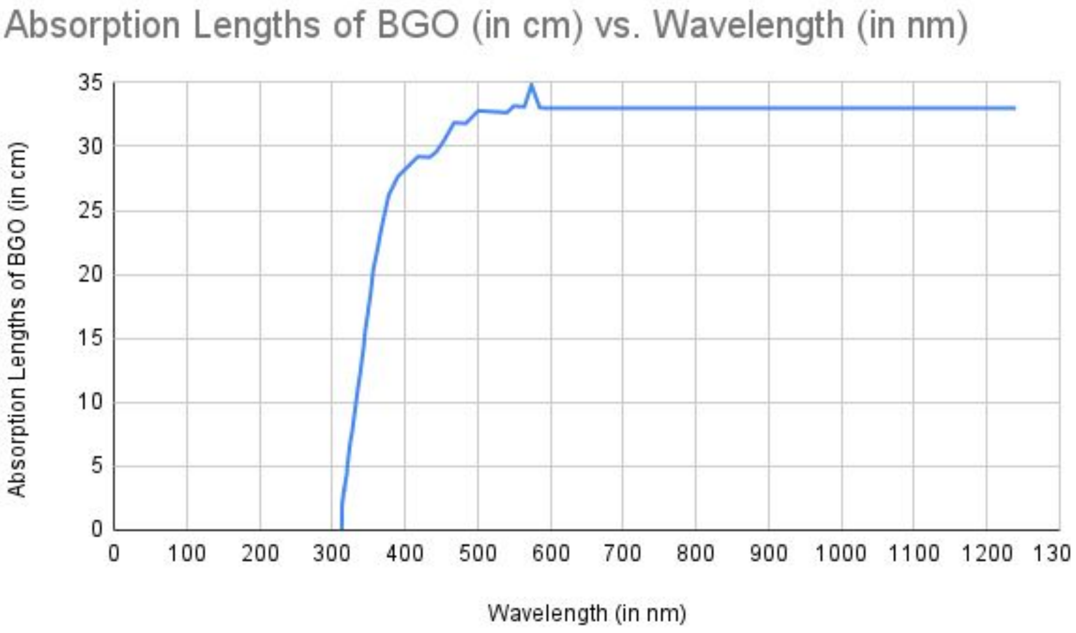


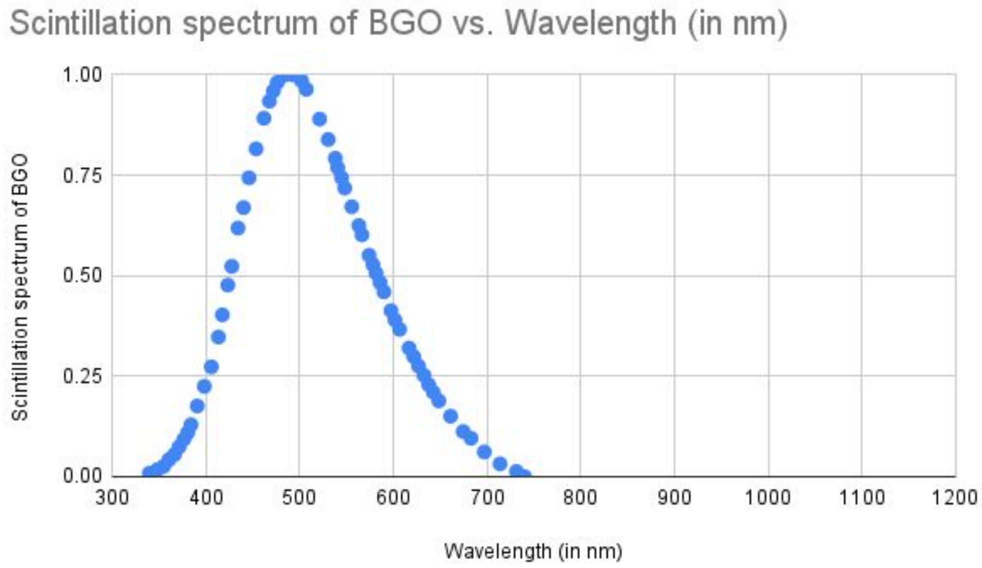


Material Properties for BGO

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

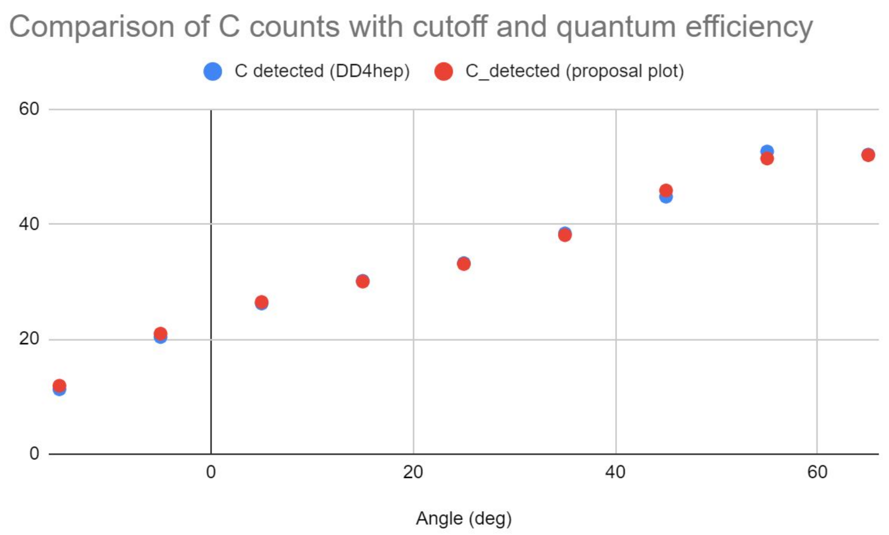




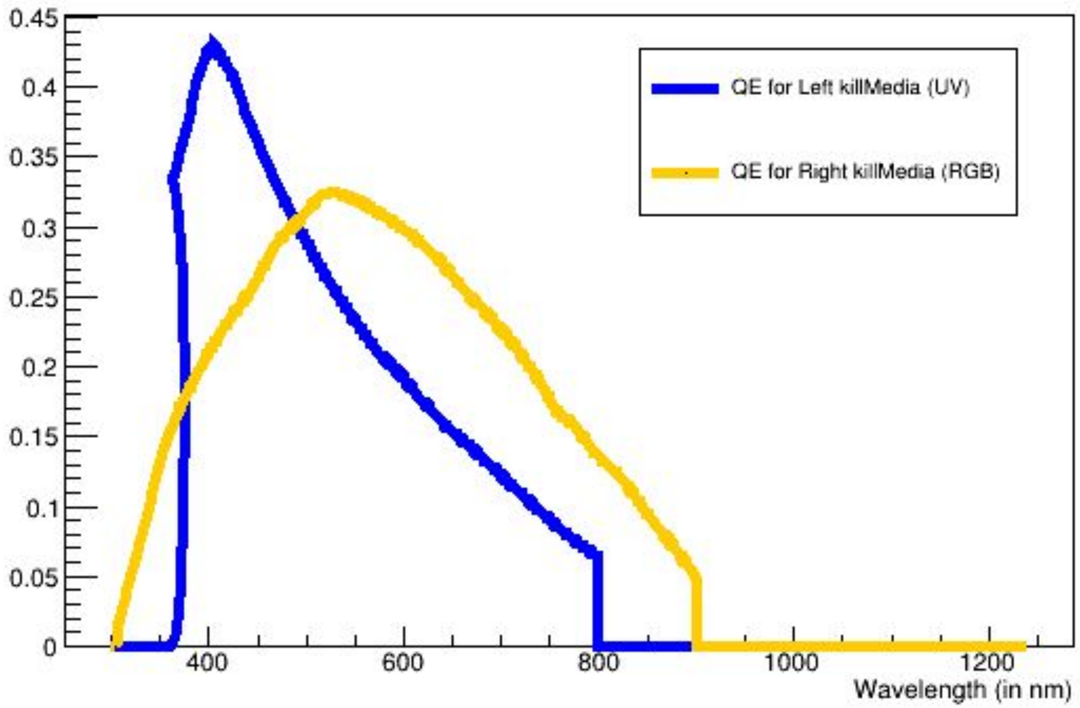


C counts (with cutoff) for PbWO4

- Also with a hard lower cutoff of 550 nm for the Cerenkov end (this is with the cutoff as well as the quantum efficiency of the SiPMs) the plots show good agreement
  - This was originally chosen is because the scintillation counts are negligible above 550 nm

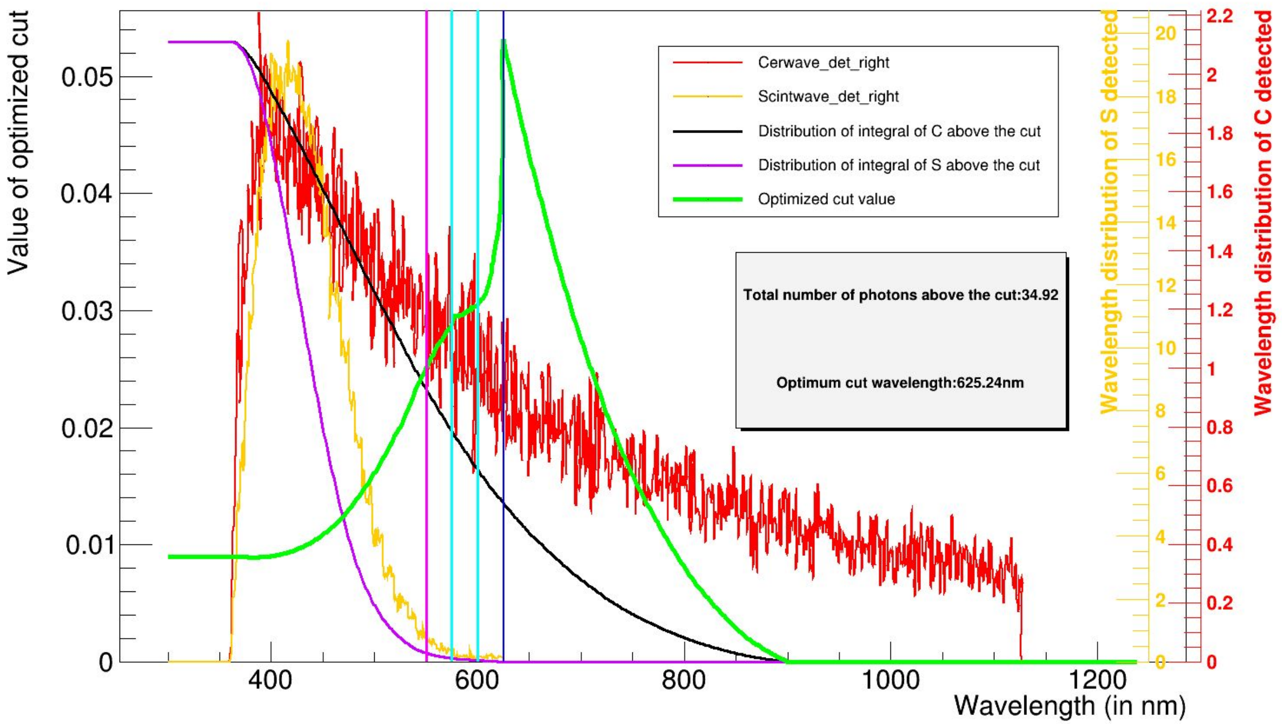


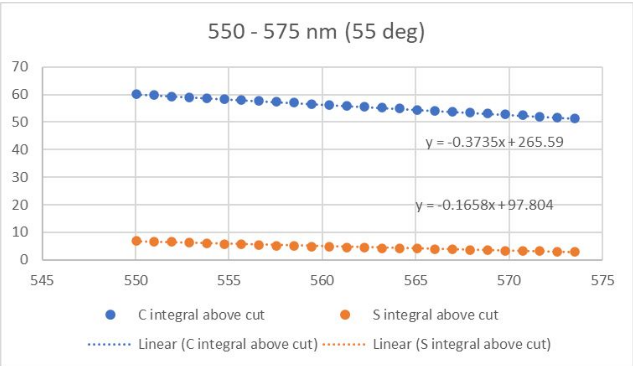
- Plots of the quantum efficiency for both SiPMs as a function of photon wavelength are shown to the right

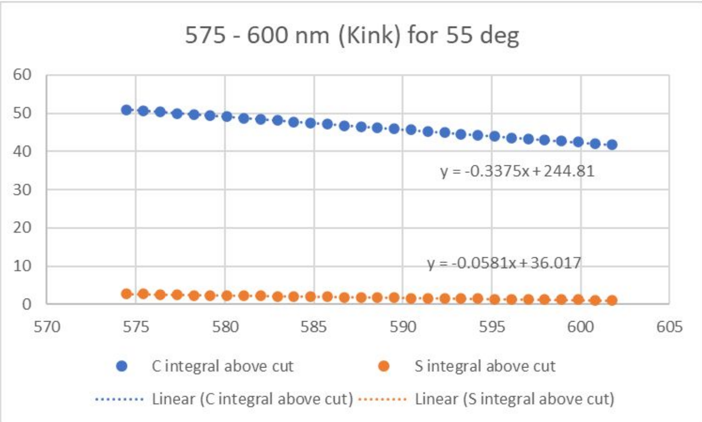


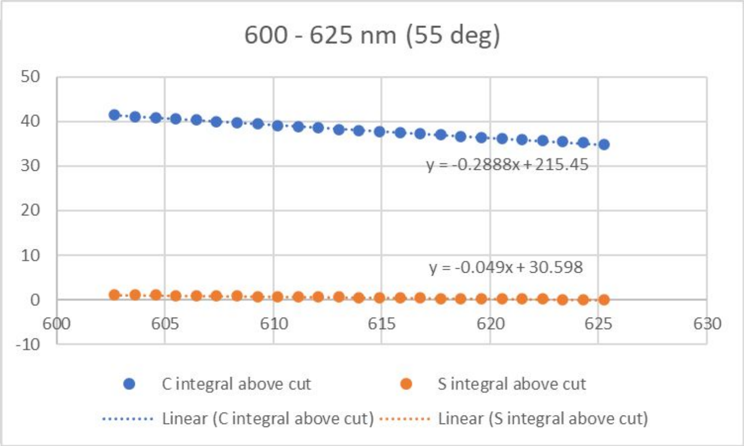
Investigation of the kink in the PbWO4 optimization

- Did a piecewise linear fit for the 'integral of C above the cut' (black) and 'integral of S above the cut' (violet) in the 3 relevant wavelength regions i.e. 550 to 575 nm, 575 to 600 nm and 600 to 625 nm
- This particular set of values is for the angle of incidence of the muon = 55 degrees and 'a' = 2









Investigation of the kink in the PbWO4 optimization

- We note that the slope of B (integral of S photons above the cut) increases quite a bit (i.e. magnitude decreases) from region 1 to region 2
- If we look at the derivative of the optimization curve $(aC'\sqrt{B} + 2C'B - CB')/(2C_{det}\sqrt{B}(a/2 + \sqrt{B})^2)$, the denominator is always positive
- For the numerator, both C' and B' are negative for all the three wavelength regions, but from region 1 to region 2, the B' decreases in magnitude in the 3rd term, so the slope of the net optimization function decreases
- It is possible that this effect is seen in PbWO4 and not as prominently in BGO, since in BGO, for these analogous wavelength regions, even if the 3rd term becomes less positive, B' is large enough to produce little noticeable difference in slope (due to the very high scintillation yield)
- The kink also becomes more pronounced when 'a' increases because that contributes to the first term in the numerator and becomes more negative