

Crystal scintillation and Cherenkov studies

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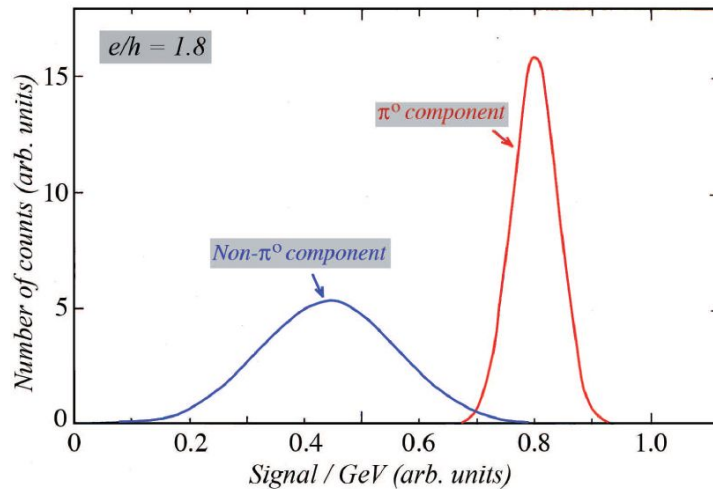
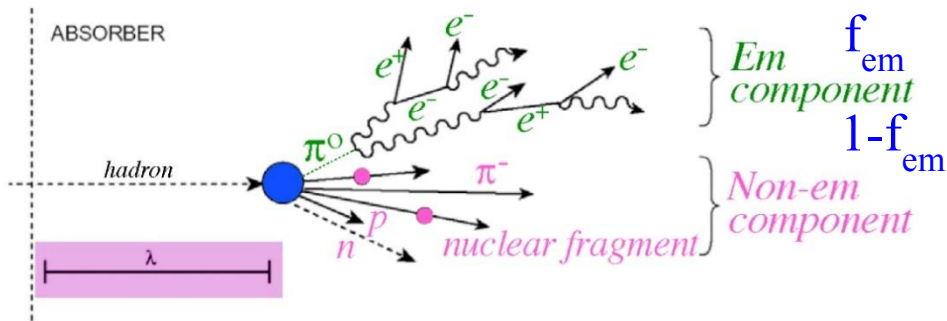
1. University of Michigan

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On behalf of the CALVISION team

Introduction

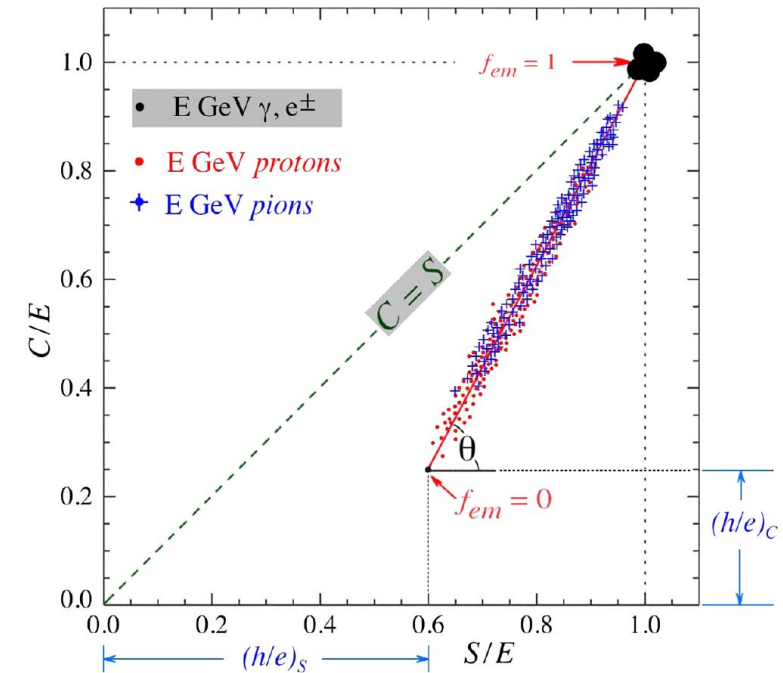
- Jet energy resolution is a key benchmark of the e^+e^- detector performance
- Important to build calorimeters that can achieve $\Delta E/E \sim 3\text{-}4\%$ for jets at 100 GeV to separate hadronically-decayed W and Z bosons
- Read out both scintillation and Cherenkov (relativistic charged particles, mostly electrons) photons to disentangle EM and hadronic components event-by-event



$$\chi = \frac{1 - \left(\frac{h}{e}\right)_S}{1 - \left(\frac{h}{e}\right)_C} = \cot \theta$$

$$E = \frac{S - \chi C}{1 - \chi}$$

f_{em} fluctuations dominate the hadronic energy resolution

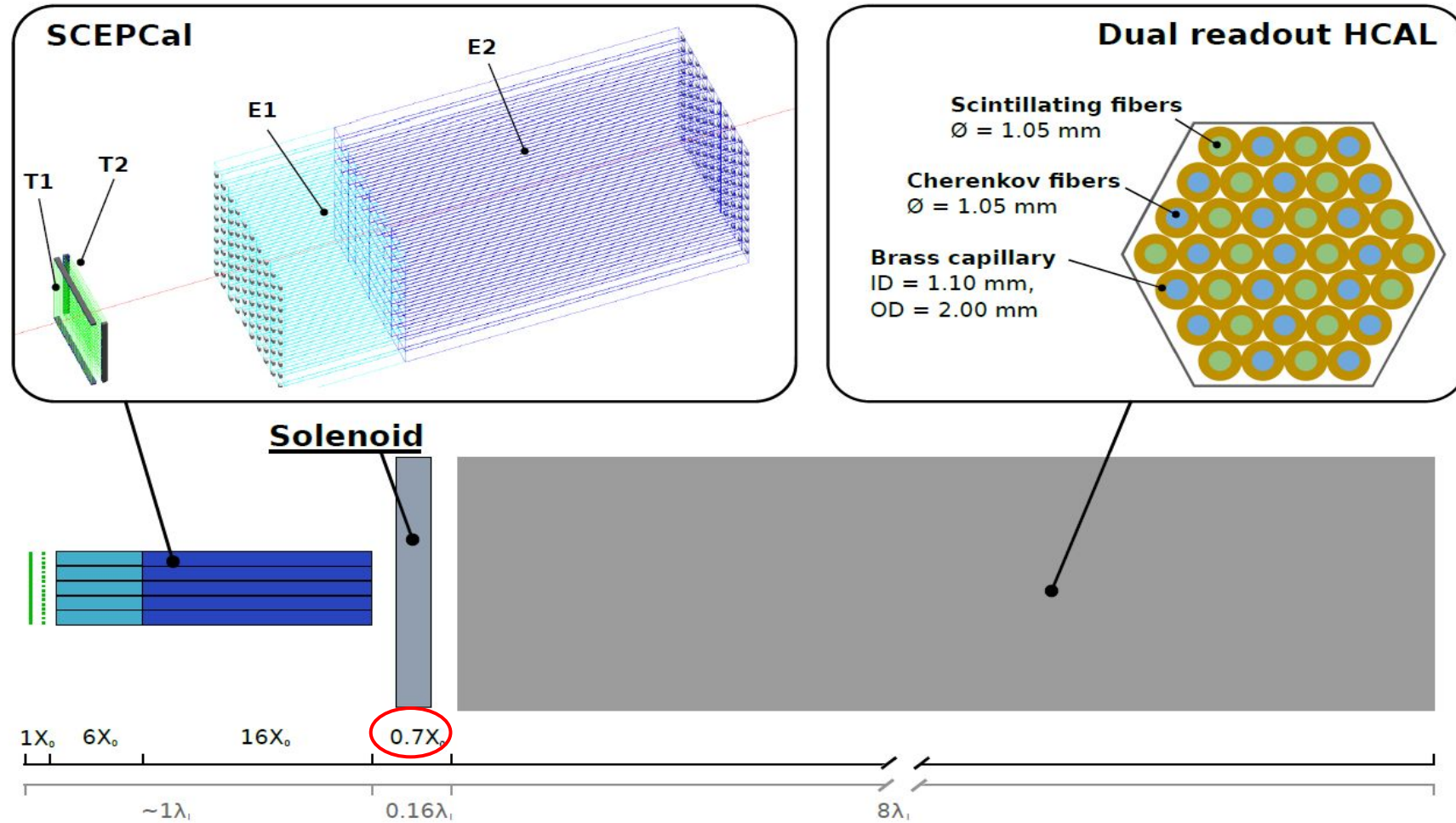


DRO calorimetry relies on the fact that e/h is different For Cerenkov and Scintillation readout

χ is independent of the incident hadron's energy

A Segmented DRO Crystal ECAL with a DRO Fiber HCAL

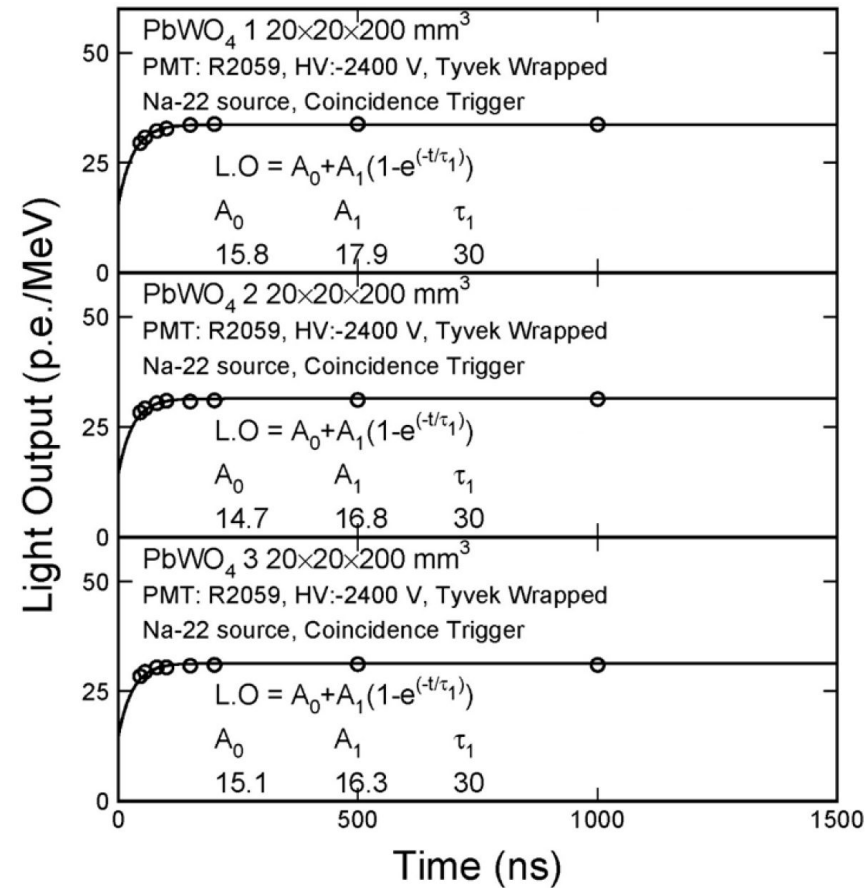
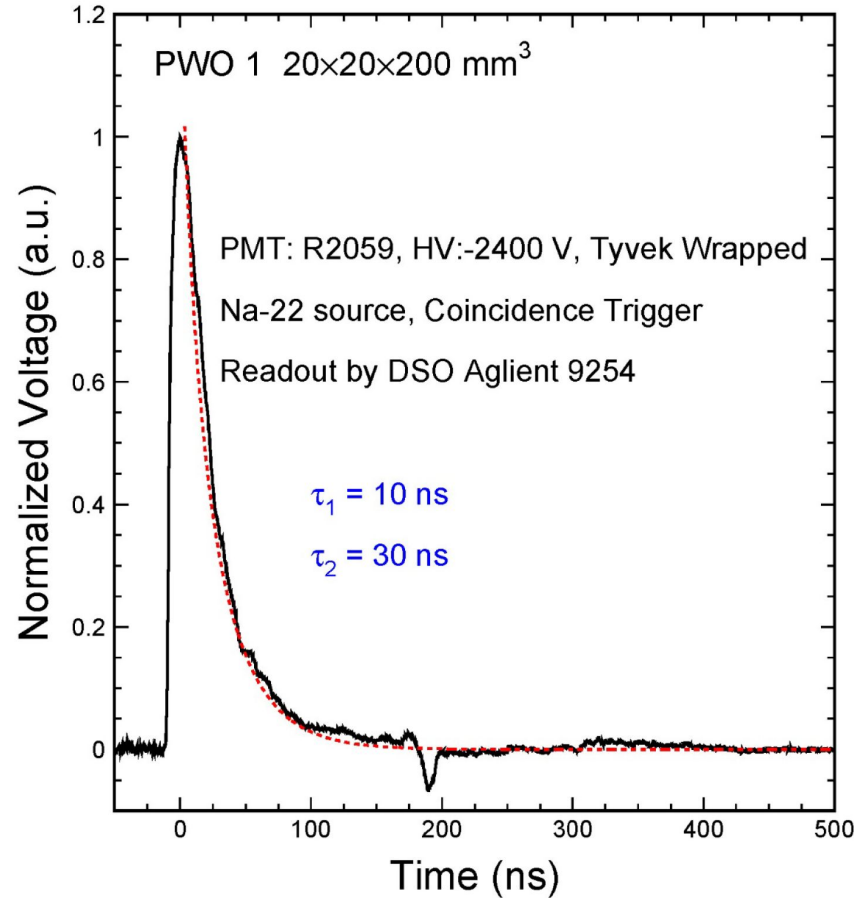
arXiv:2008.00338



- Plan to study various crystals and measure Cherenkov and Scintillation photons and compare with simulation
- Lots of ongoing work to prepare and understand the readout electronics and experimental setup for cosmic ray and test beam studies

Crystal measurements

- Three PWO crystals (20x20x200 mm³) and also three BGO (25x25x180 mm³) tested for **scintillation photon** properties at Caltech



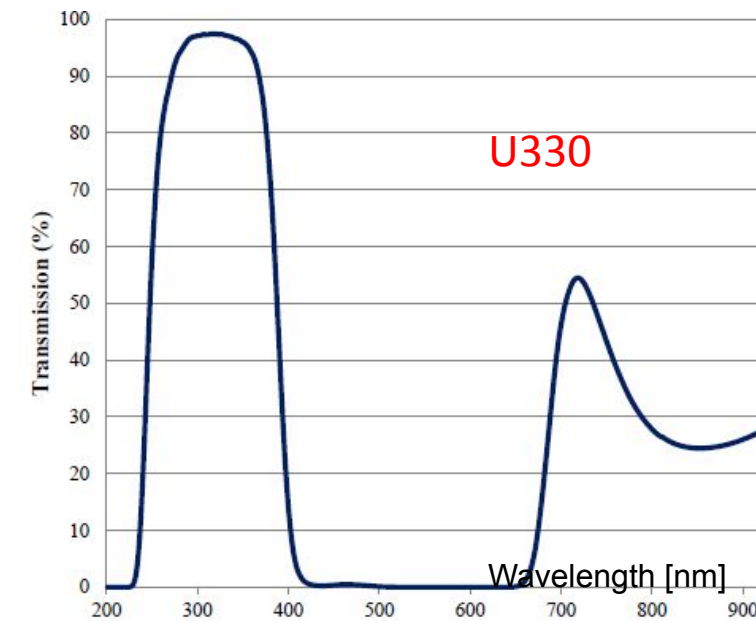
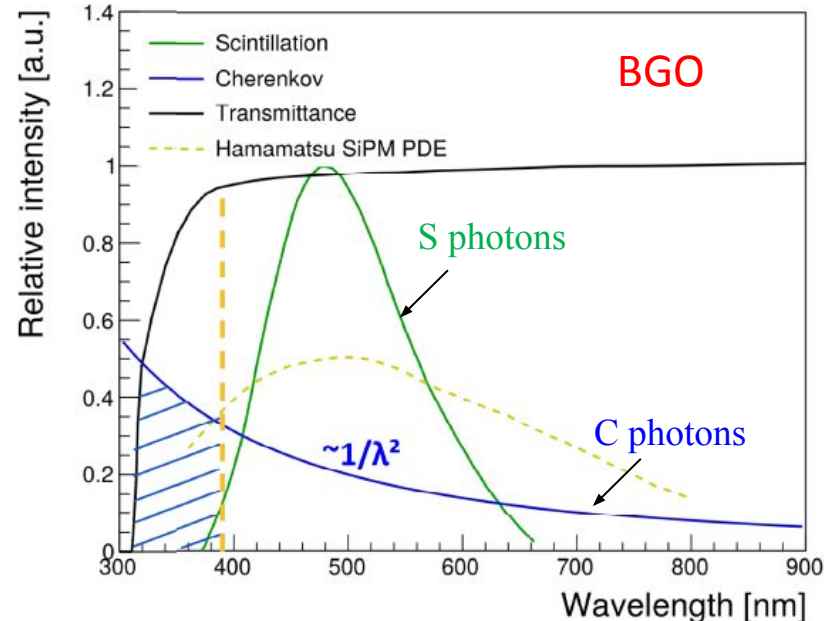
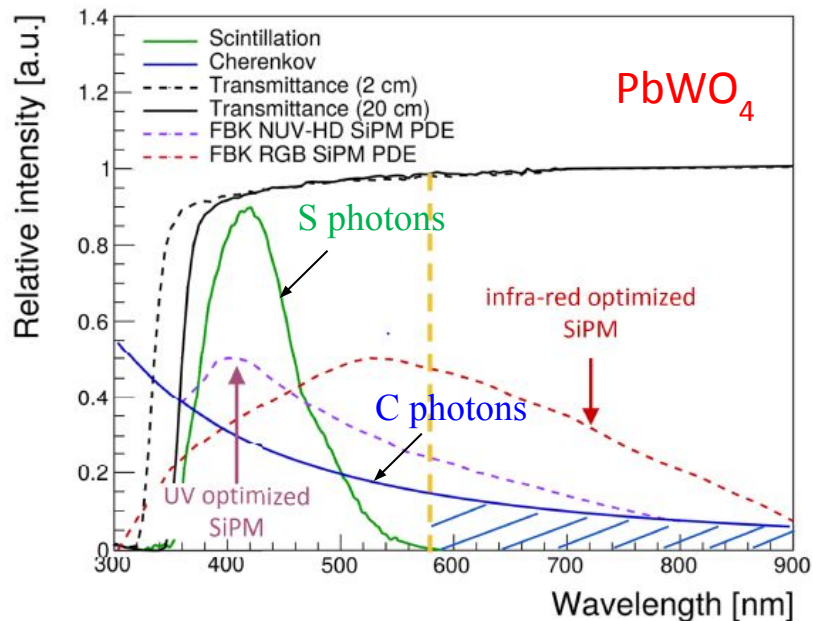
- PWO: 10 ns (fast) and 30 ns (slow) with Light Output of 32.2 p.e./MeV and Light Yield of 168 ph/MeV
- BGO: 314 ns decay time with Light Output of 775 p.e./MeV and Light Yield of 4,940 ph/MeV

Crystals and filters

Crystal	Density g/cm ²	X ₀ cm	λ _I cm	R _M cm	Relative Yield	Decay time ns	Refractive index
PbWO ₄	8.3	0.89	20.9	2.00	1.0	10	2.20
BGO	7.1	1.12	22.7	2.23	70	300	2.15
Glass	2.2	Only produce Cherenkov light					1.5

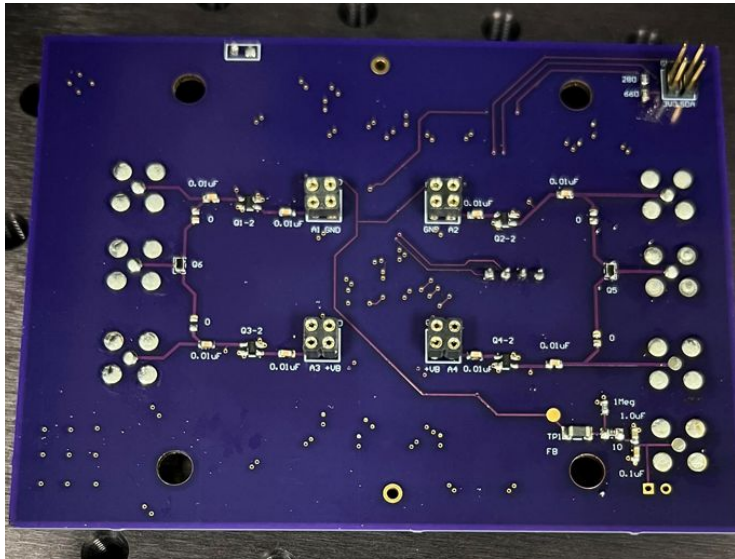
Filter	material	type	Density g/cm ²	cut-on wavelength h (nm)
U330	colored glass	band pass	2.78	-
#15-226	hard coated	long pass	-	600
R60	colored glass	long pass	2.69	600
UG11	colored glass	band pass	2.92	-
GG420	colored glass	long pass	2.55	420

Rely on optical filters to reduce contaminations from scintillation light
Will use Hoya R60 longpass optical filter for PWO studies in the future

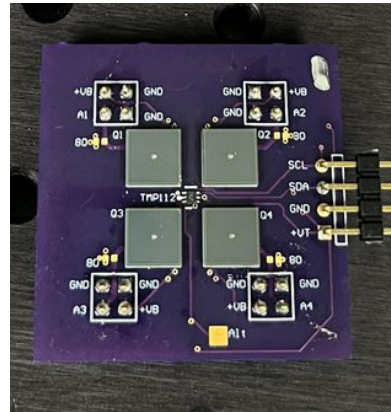


SiPM readout

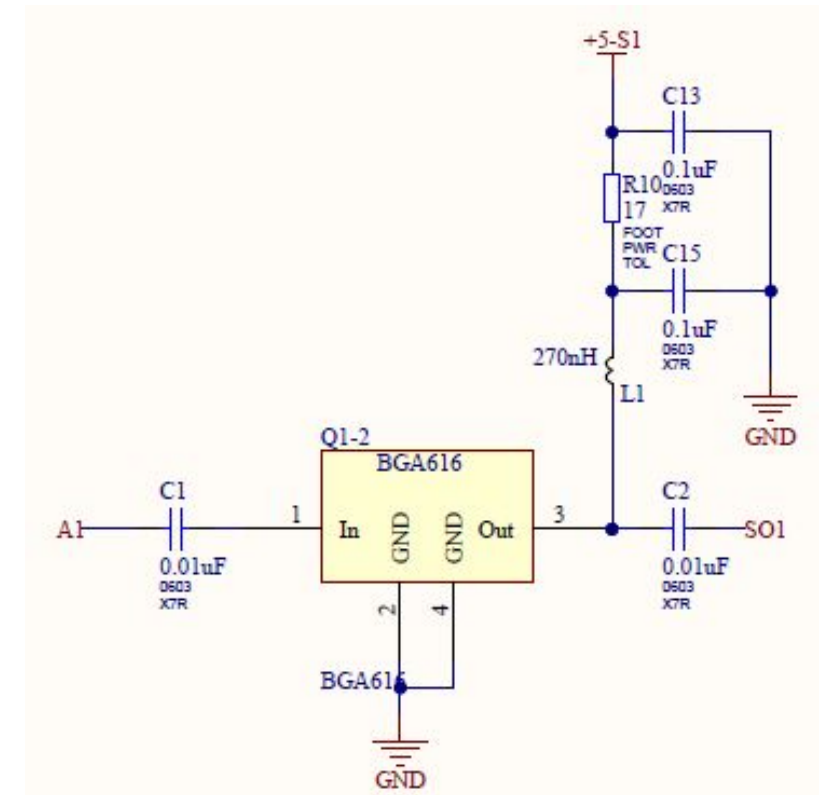
- Boards designed by the UVa group
- Four S14160-6050HS (6 x 6 mm²) SiPMs on board
- Single-stage RF amplifier for each channel
- Noise level when SiPM bias voltage is off: 220 μ V (RMS) (SiPM dark count amplitude \sim 2 mV)



4-channel amplifier board



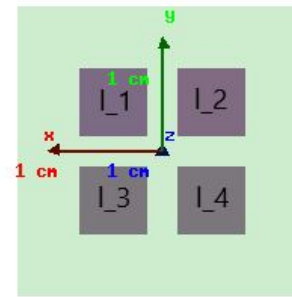
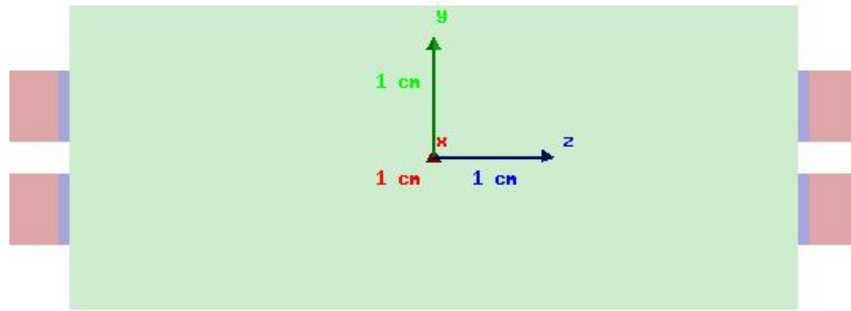
SiPM board



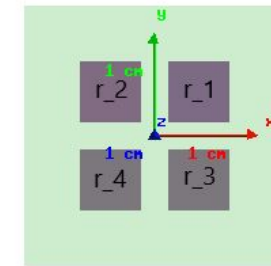
Amplification stage

Cosmic muon setup - 2 GeV muons

- The crystal dimensions (green) are $2.5\text{cm} \times 2.5\text{cm} \times 6\text{cm}$ (PbWO₄)
 - The cosmic ray setup has 4 SiPMs (in red) each of size $6\text{ mm} \times 6\text{ mm}$ 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)

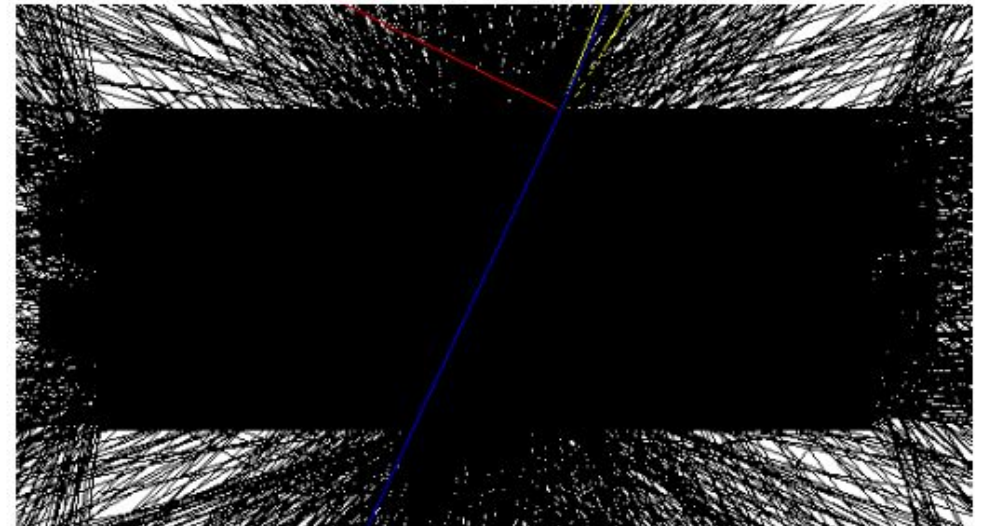


Viewed from the left side



Viewed from the right side

- Sample event display (with optical photons, muon in blue)
 - Angle of incidence in the crystal has been measured from the normal to the longest side (25 deg)

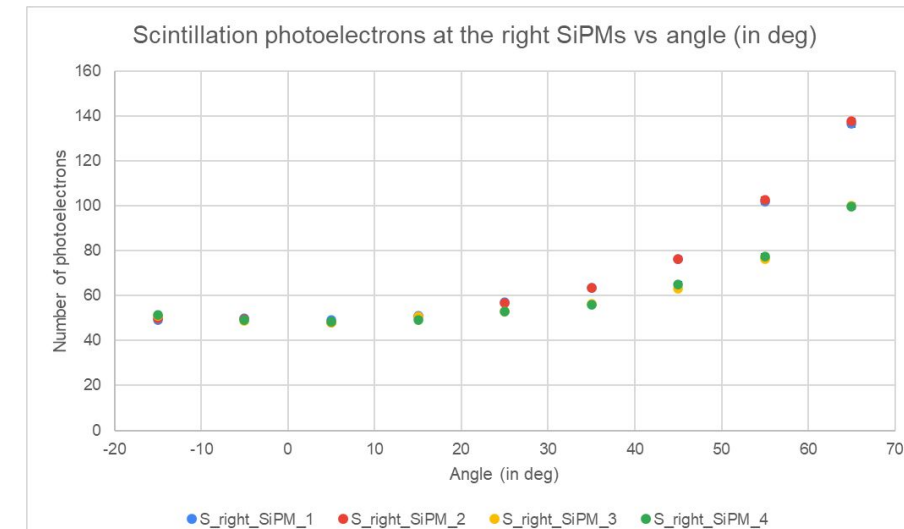
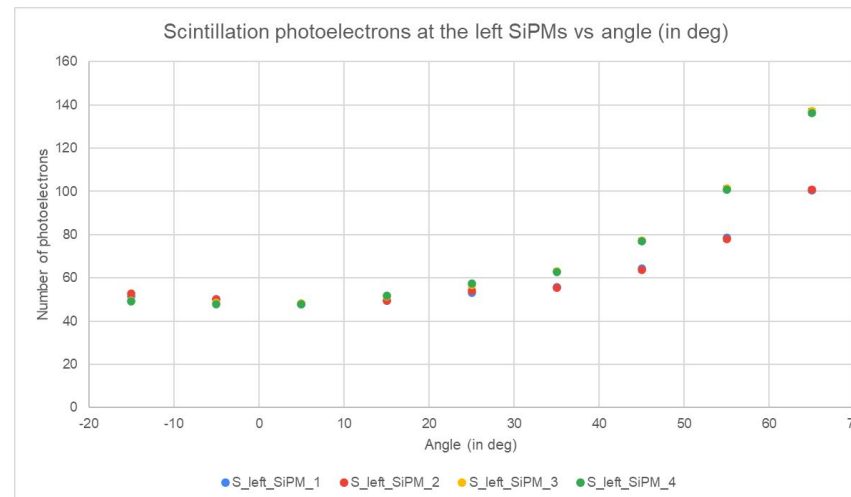
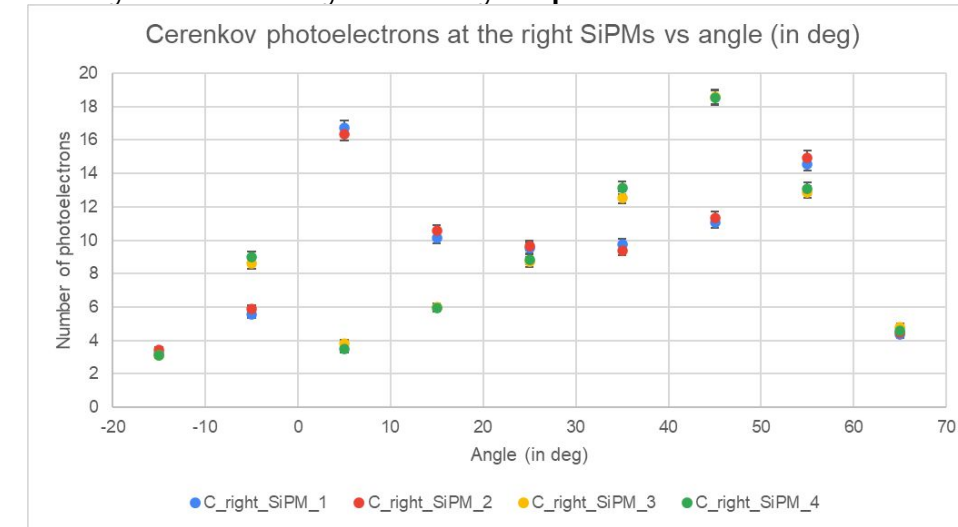
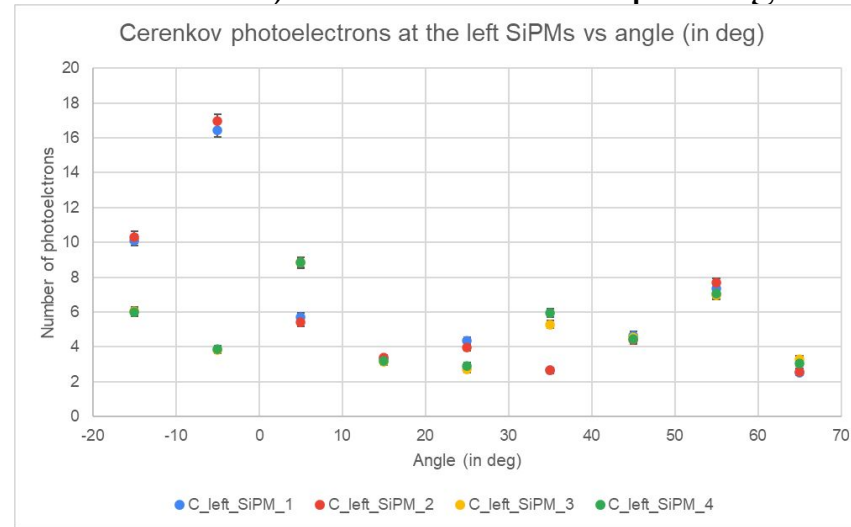


Cosmic muon setup - 2 GeV muons

- The CRY (cosmic ray simulation) library is not fully setup so currently using 2 GeV muons with specific angles of incidence (photon counts averaged over 100 events) - the beam while passing through the crystal is fully in the y-z plane

- For pairs of SiPMs (1,2) and (3,4) for both Cherenkov and scintillation, the counts match, which is expected considering the beam orientation

- There is also a difference between the two pairs of SiPMs for scintillation counts for higher angles, given that the pair with the higher number of counts is closer to the muon trajectory for both ends

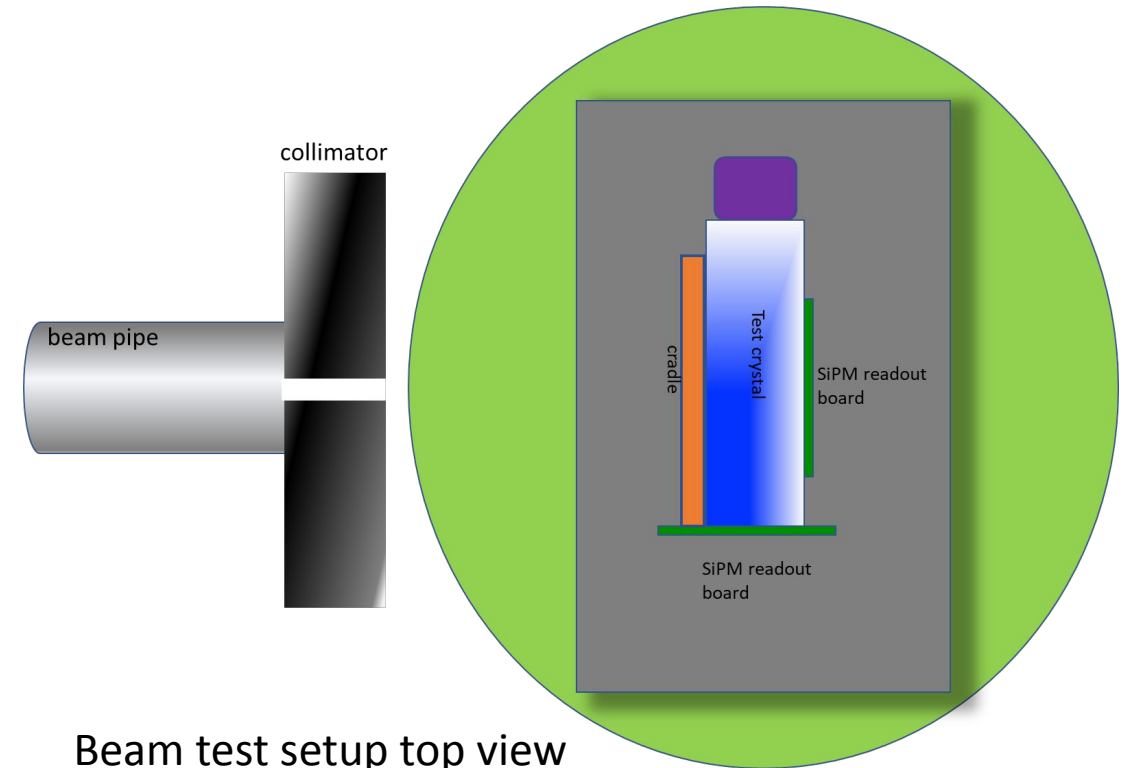


- The plots above are without the use of wavelength filters to separate the Cherenkov and scintillation components

Beam test at University of Notre Dame

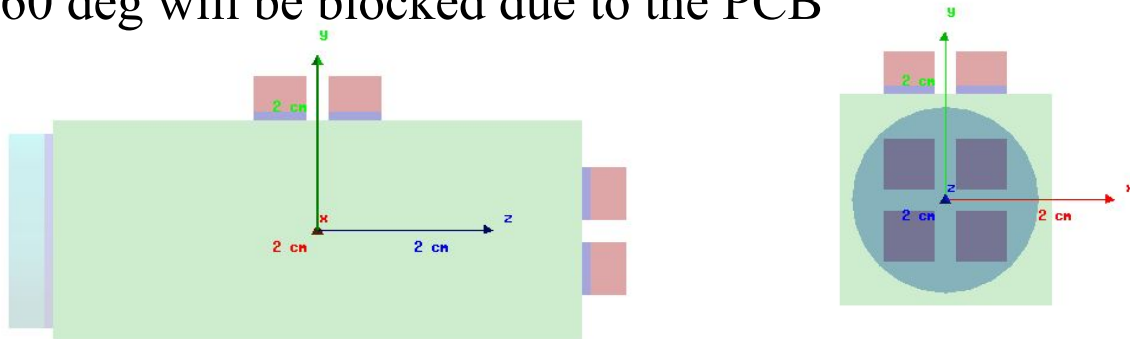


- Last week we had an opportunity to perform tests with electron beams at U of Notre Dame, finished data taking this past Friday
- Linear particle accelerator: 8 MeV electrons
- Pulsed beam with injector: width = 1 ns (FWHM)
- Pulse repeating rate: 30 Hz
- Charge per pulse: minimum measurable 0.09 nC, defocused to a few hundred electrons at receiving end.



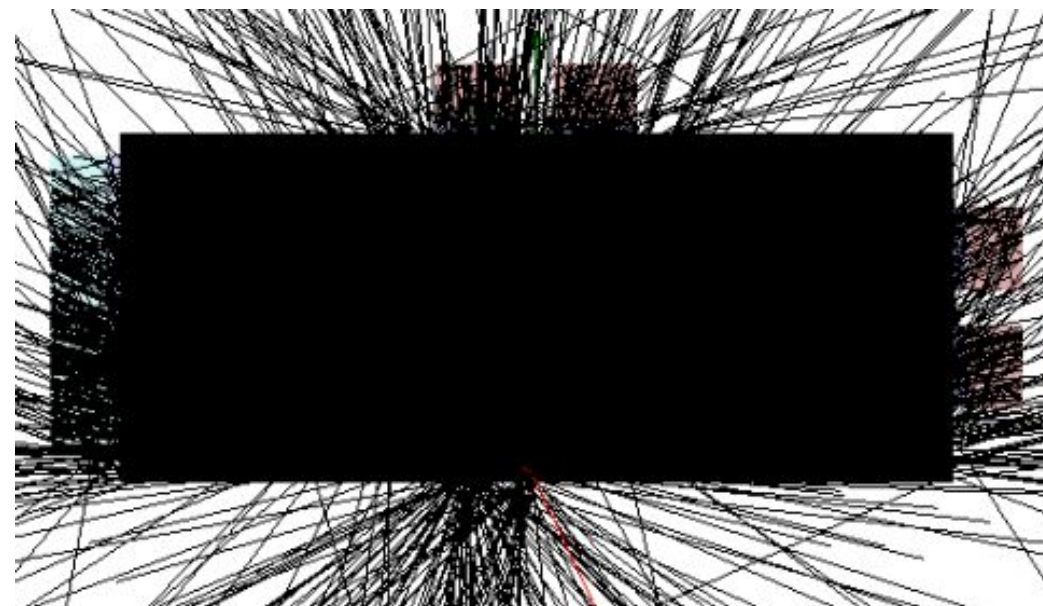
Simulation of beam test setup - 8 MeV electrons (Geometry)

- 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 attached to the other square face]
- 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



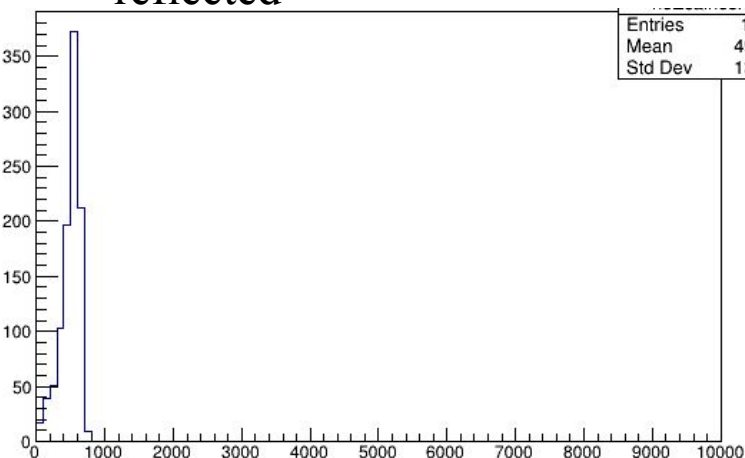
- At this energy, the electron penetrates barely 1-1.5 mm inside the crystal

- Sample event display (with optical photons, electron at the bottom in red)
 - Angle of incidence in the crystal has been measured from the normal to the longest side (-25 deg)

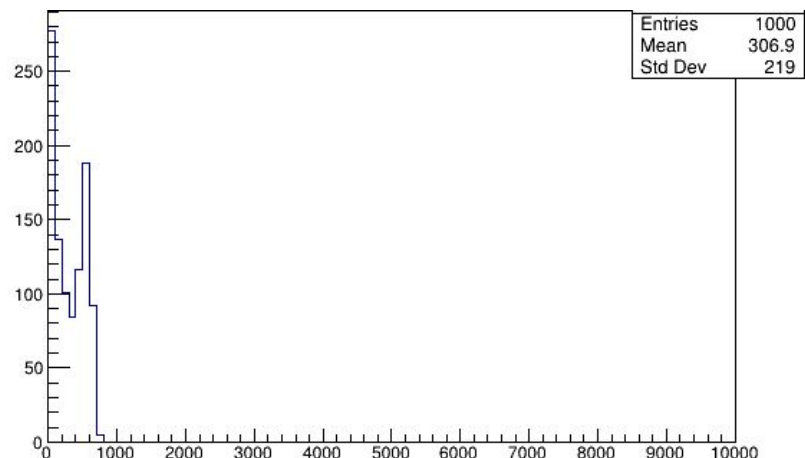


Simulation of beam test setup - 8 MeV electrons (Generated counts)

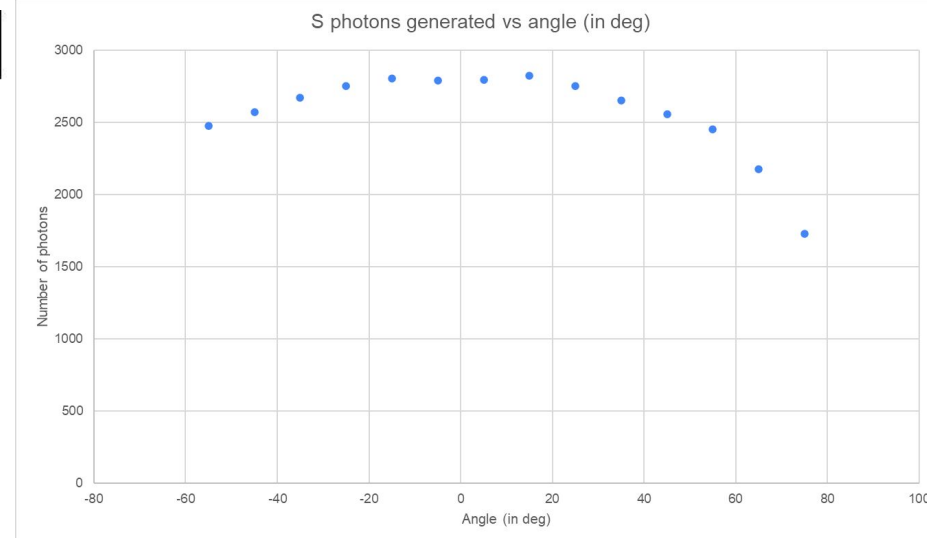
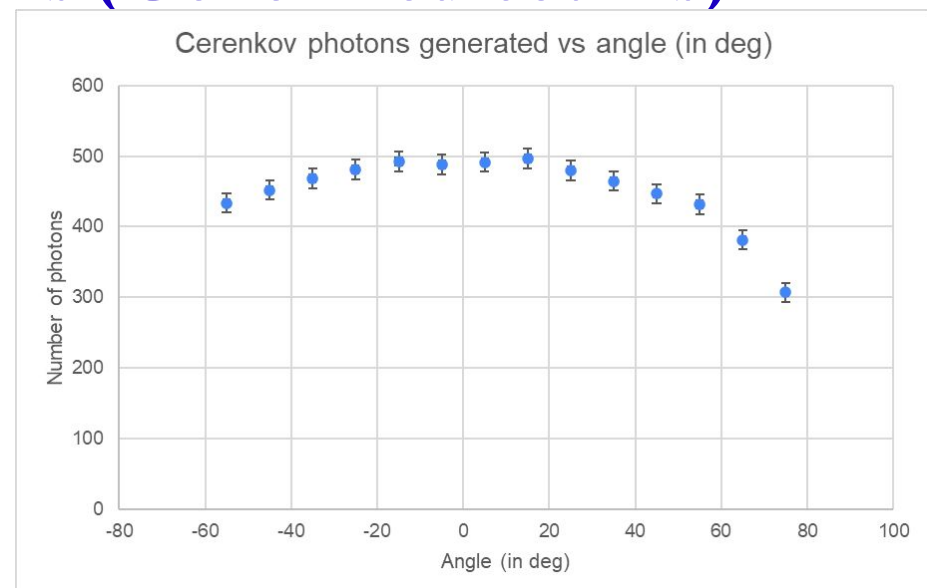
- The electron does not pass fully through the crystal and there is no well defined path length, so we do not observe the $1/\cos$ dependence for the generated photons, that was seen in case of the 2 GeV muons
- If it is assumed that the electron deposits its **full 8 MeV** inside the crystal, the plots of generated photons would have been constant with angle
- But at the higher angles of incidence, the component of momentum normal to the interface is **not enough to penetrate through** the crystal, so for a large portion of the events, the beam grazes the surface and gets partially reflected



Histogram of generated Cherenkov photons for angle of incidence = -15 deg

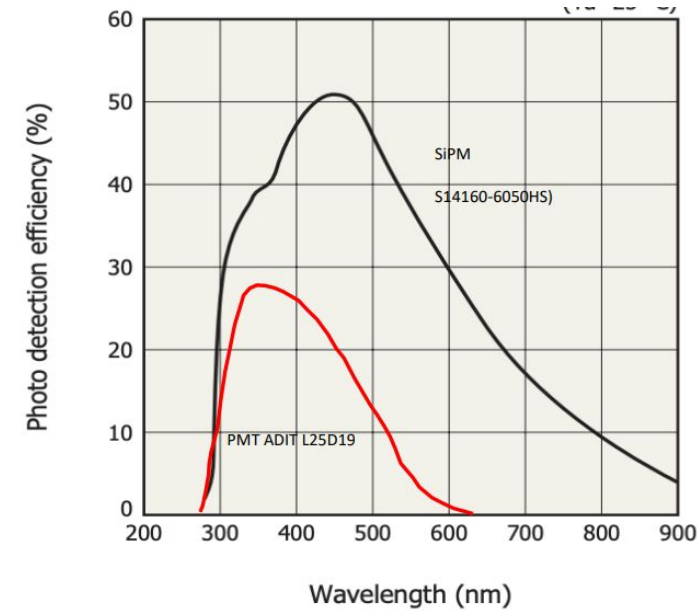


Histogram of generated Cherenkov photons for angle of incidence = 75 deg

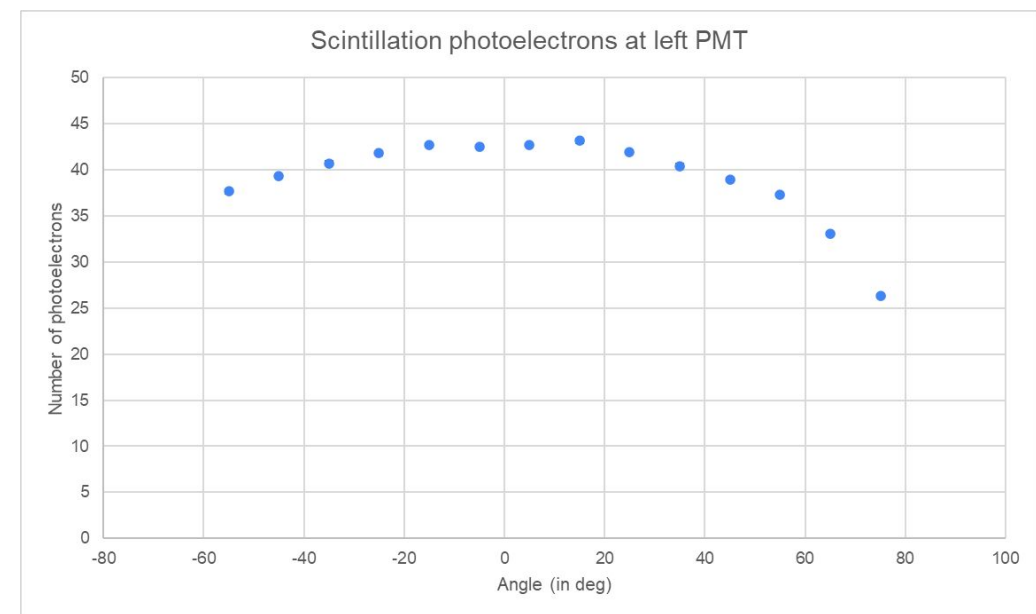
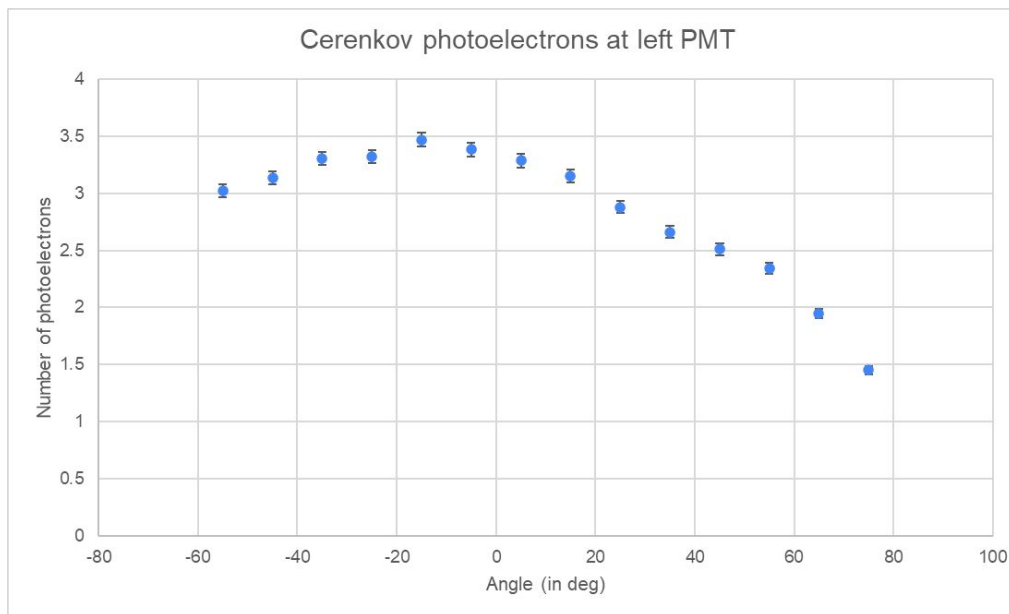


Simulation - 8 MeV electrons

Photo detection Efficiency of the SiPMs and PMT

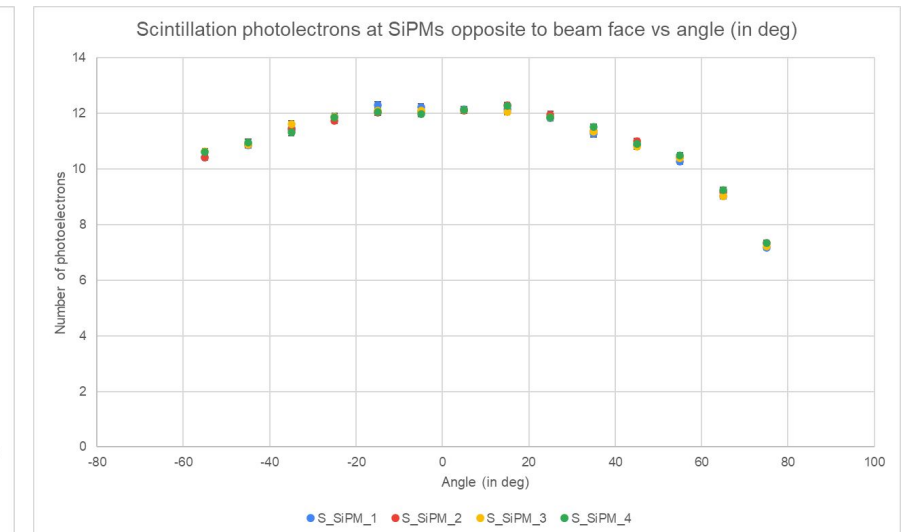
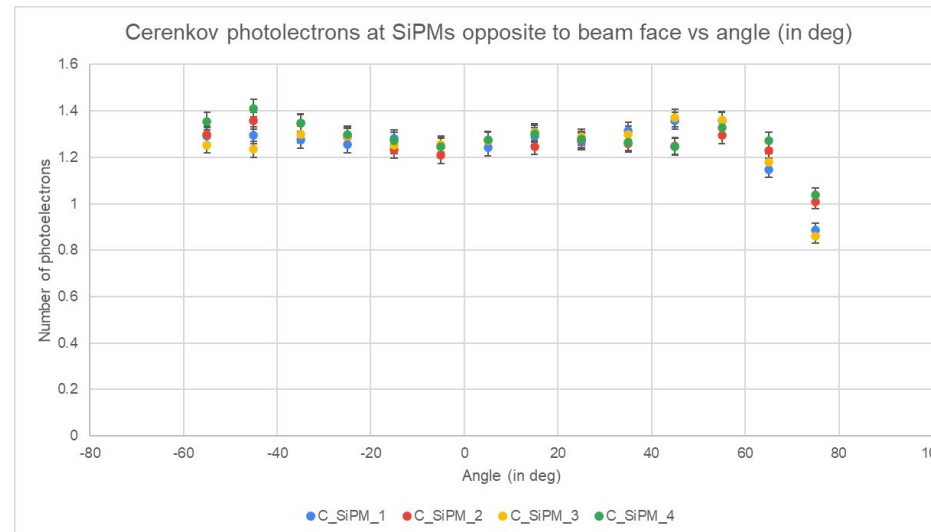
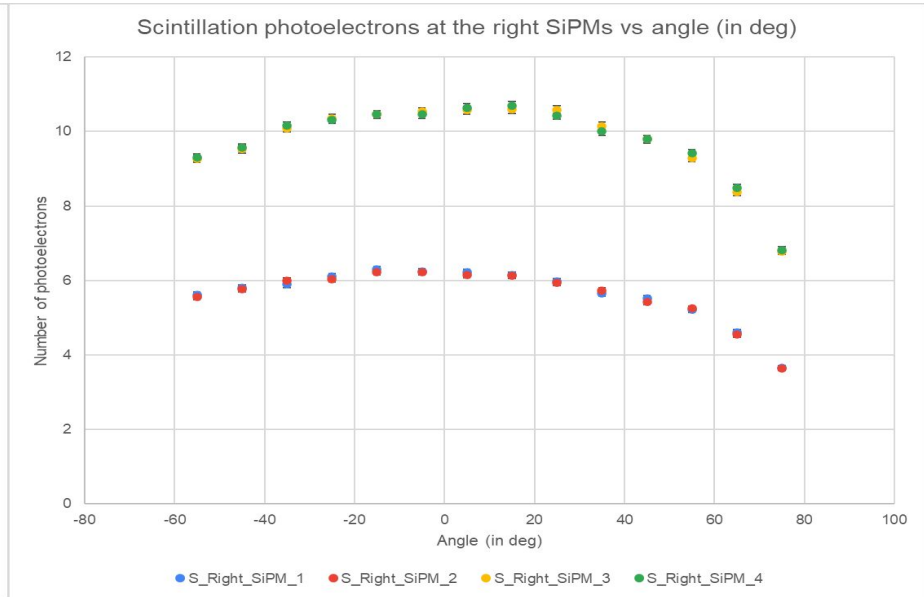
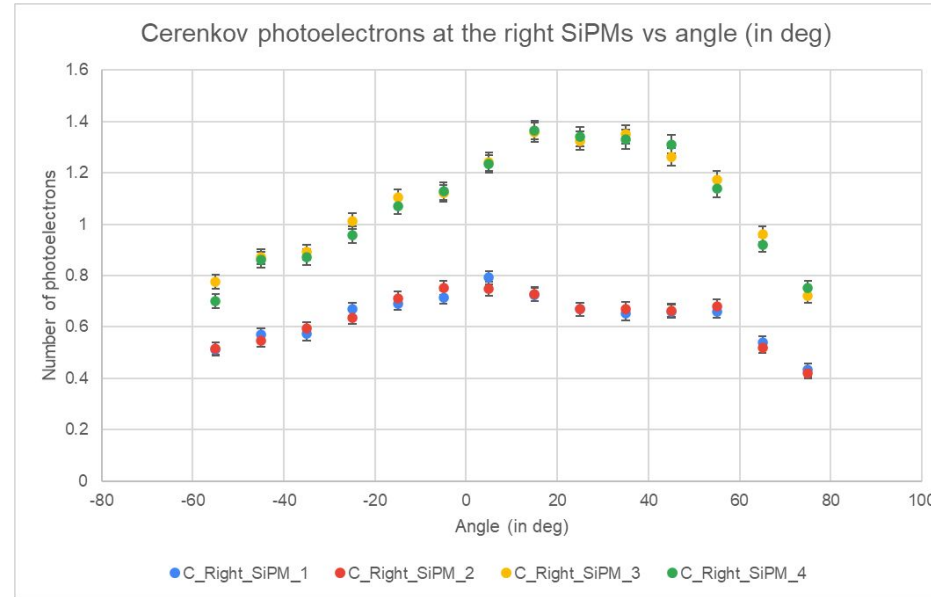


- Again these plots (and the ones in the next slide) are without the use of wavelength filters



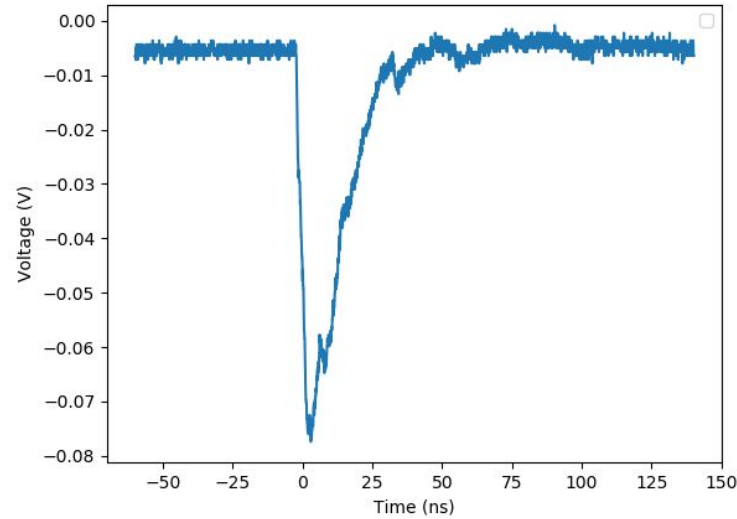
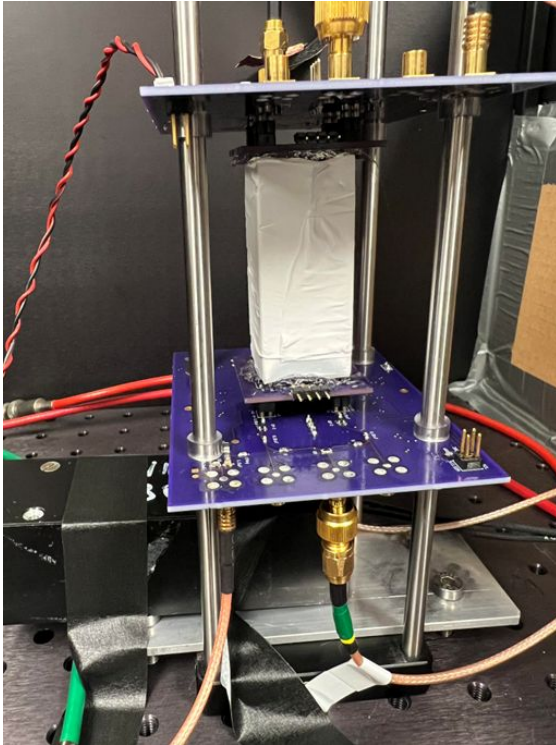
Simulation - 8 MeV electrons

Difference of counts
between pairs of SiPMs
on the right side due to
orientation of the beam

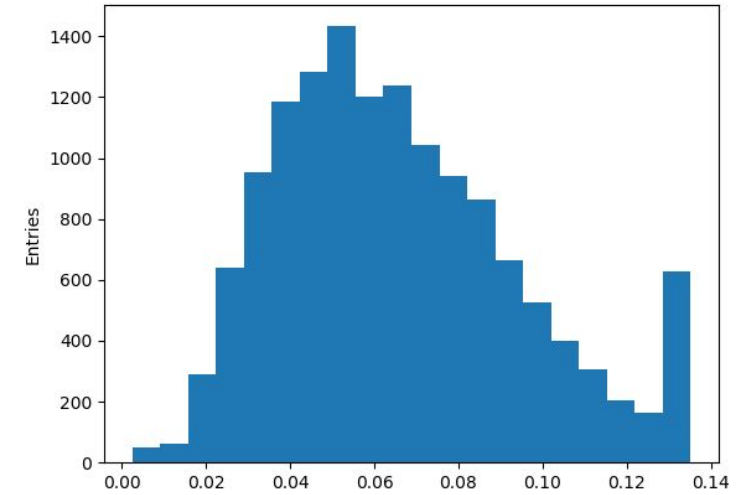


Cosmic muon test setup

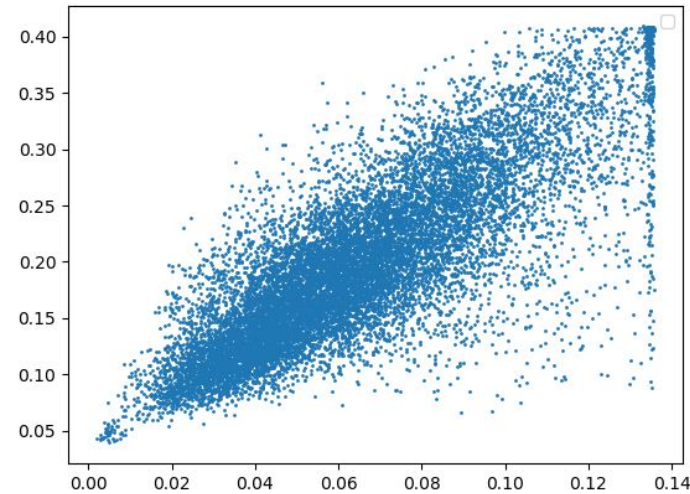
- A PWO crystal (25x25x60 mm³) is used for cosmic muon test
- Crystal side wrapped with teflon tape
- Event rate: 5.5 s/event
- Readout using Lecroy waverunner 8404M 8-bit oscilloscope
- filter not arrived at the test time



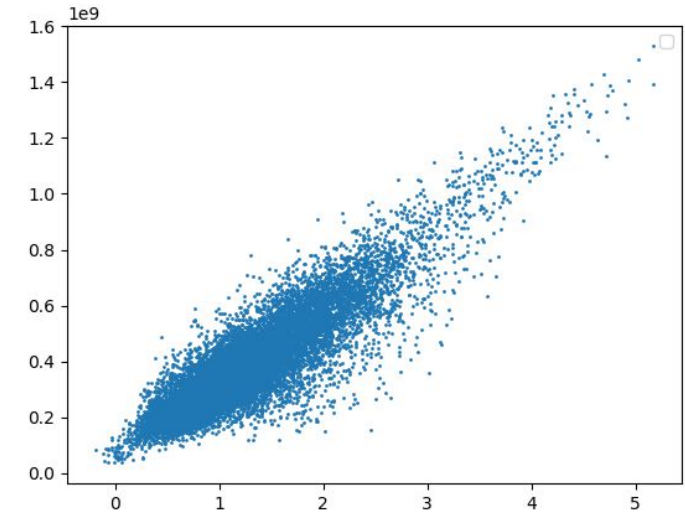
Waveform of a single SiPM (most are scintillation photons)



Amplitude (pulse height) histogram (V)



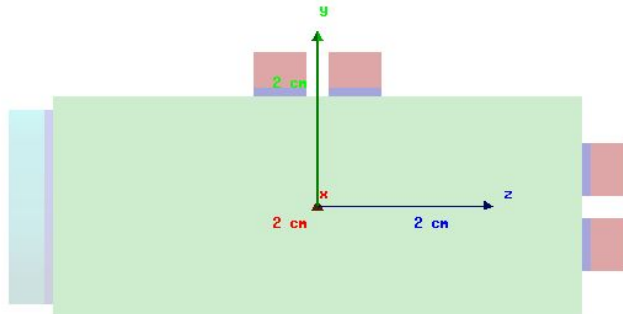
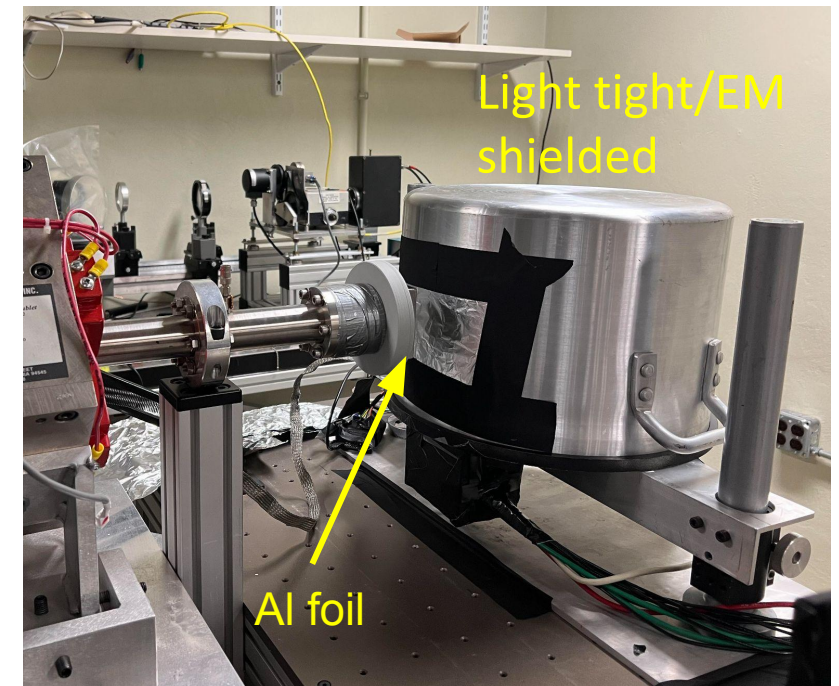
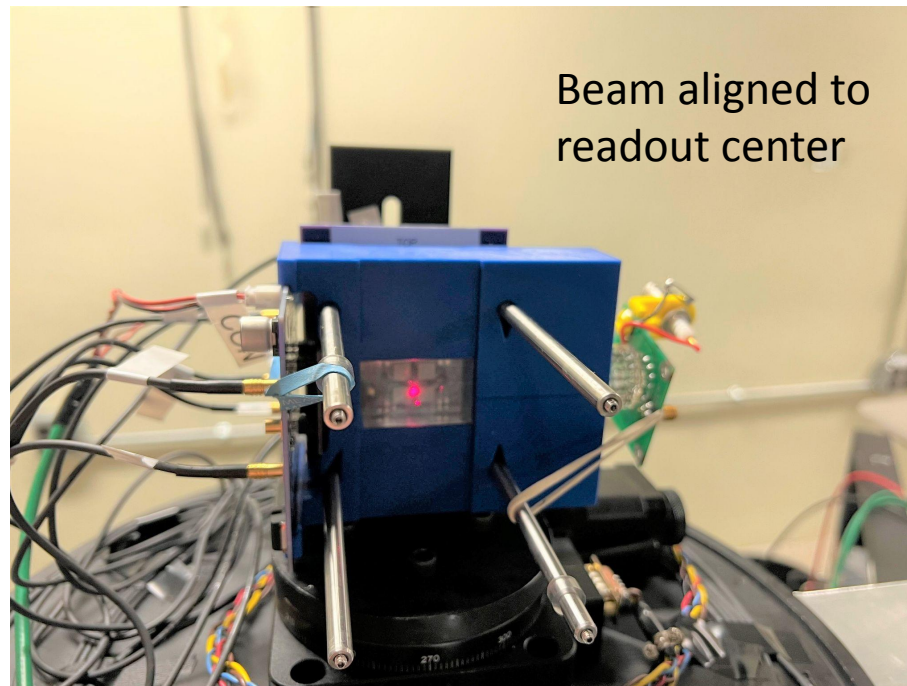
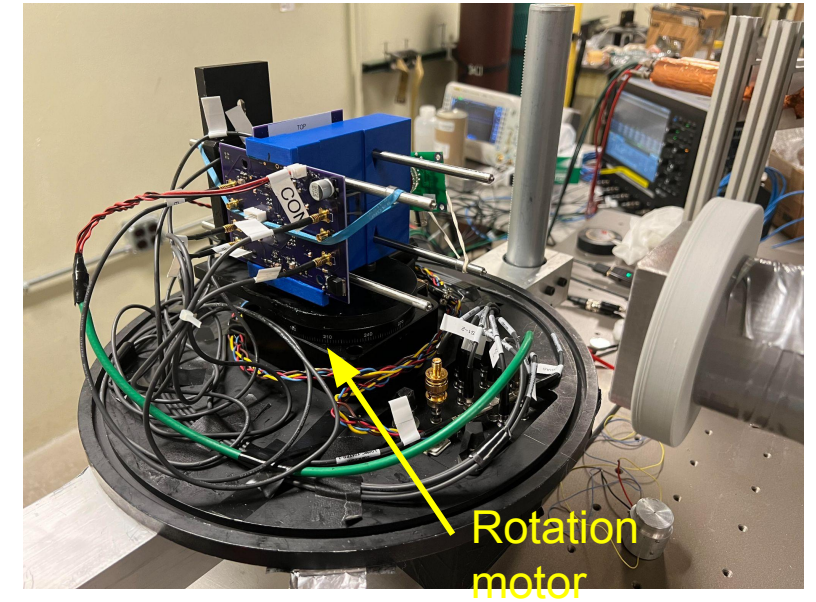
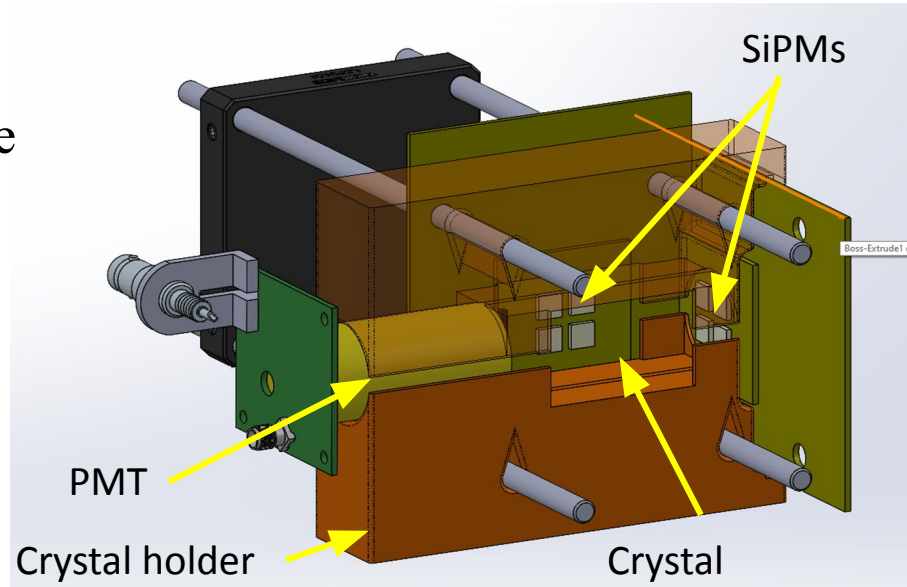
Correlation between amplitude of one SiPM and sum of the other 3 SiPMs



Correlation between pulse integration of one SiPM and sum of the other 3 SiPMs

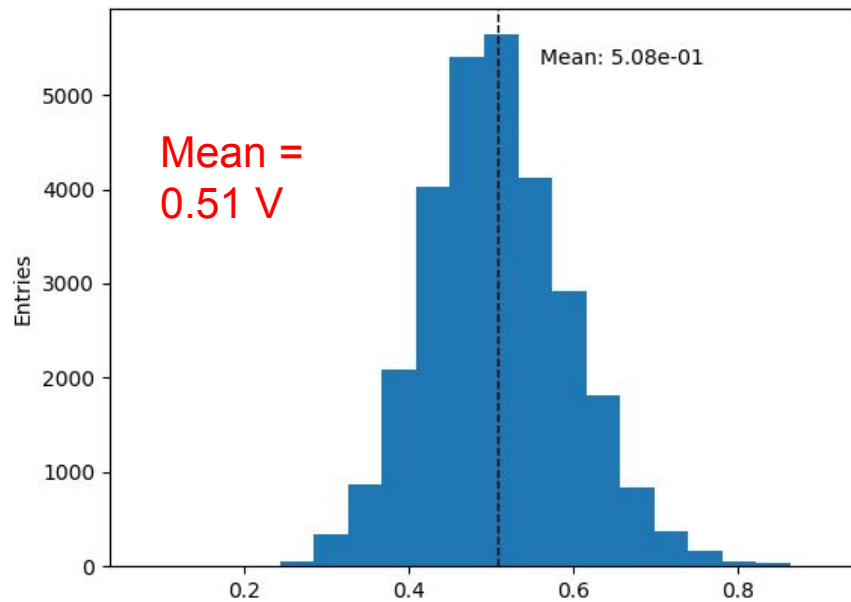
Beam test setup

- Crystal long side facing the beam
- SiPMs are at crystal one rectangle side and one square end
- PMT placed at one end, but not used due to big RF noise found at the beam
- Rotation motor used for angle dependence study
- Data taking finished last Friday, ongoing analysis

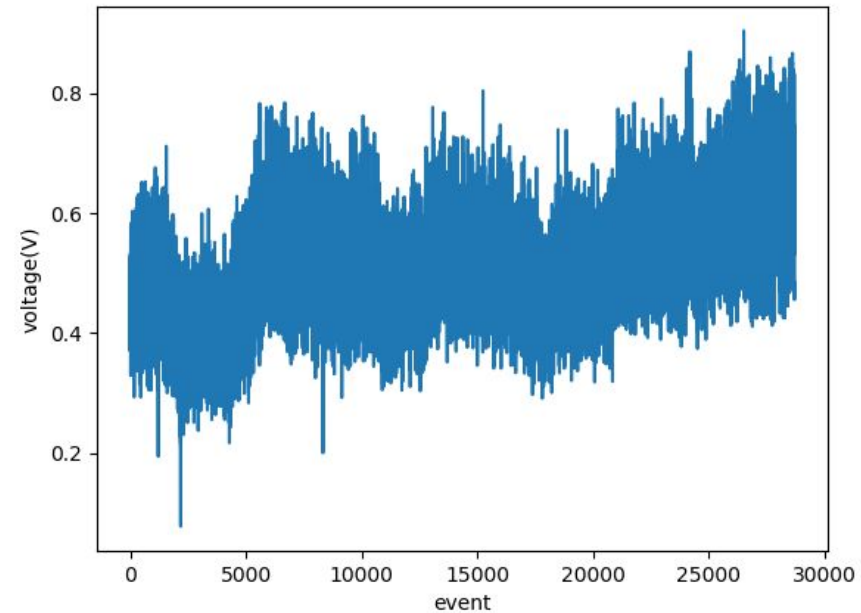


Beam intensity tuning and stability

- Using minimum measurable charge per pulse: 0.09 nC, and defocused to a few hundred electrons at receiving end
- Cannot directly measure the beam property with in-house instrumentation due to very low intensity
- Estimate pulse intensity using the known average pulse charge from cosmic ray muons in PWO
- Beam fluctuates $\pm 30\%$ in 15 minutes



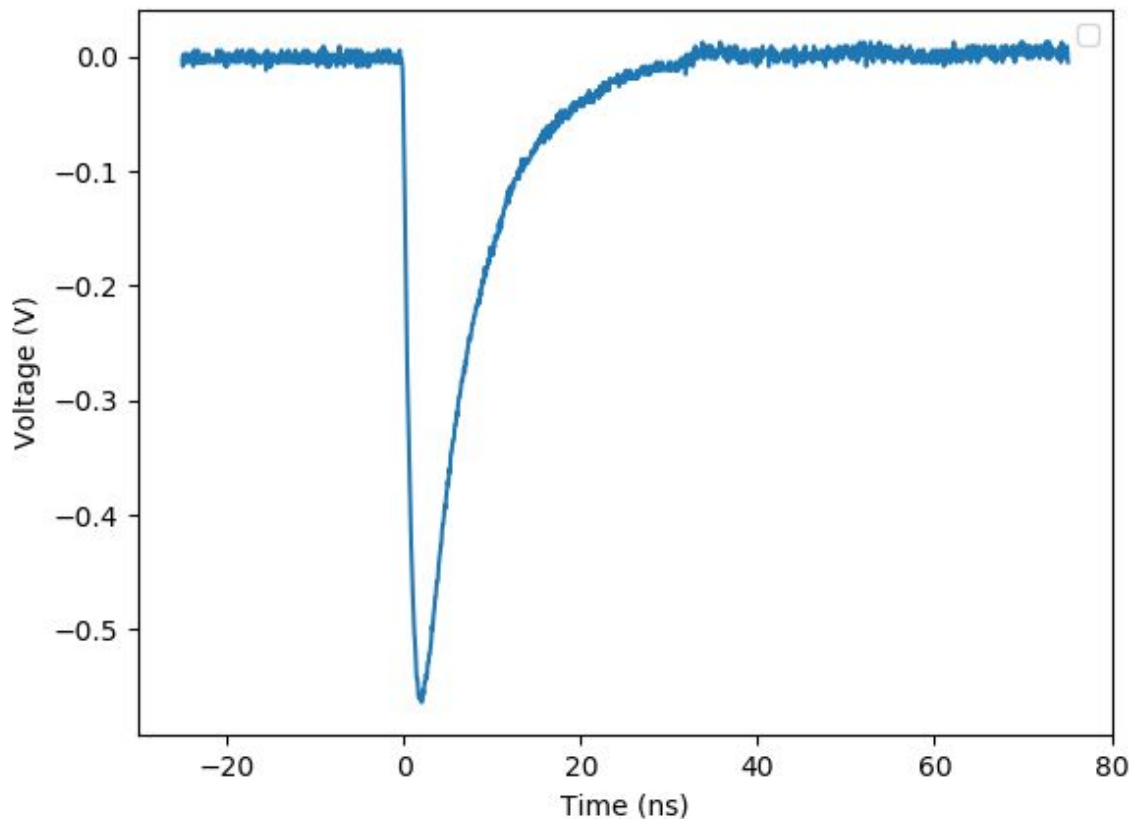
Side SiPM pulse height histogram for 28k events



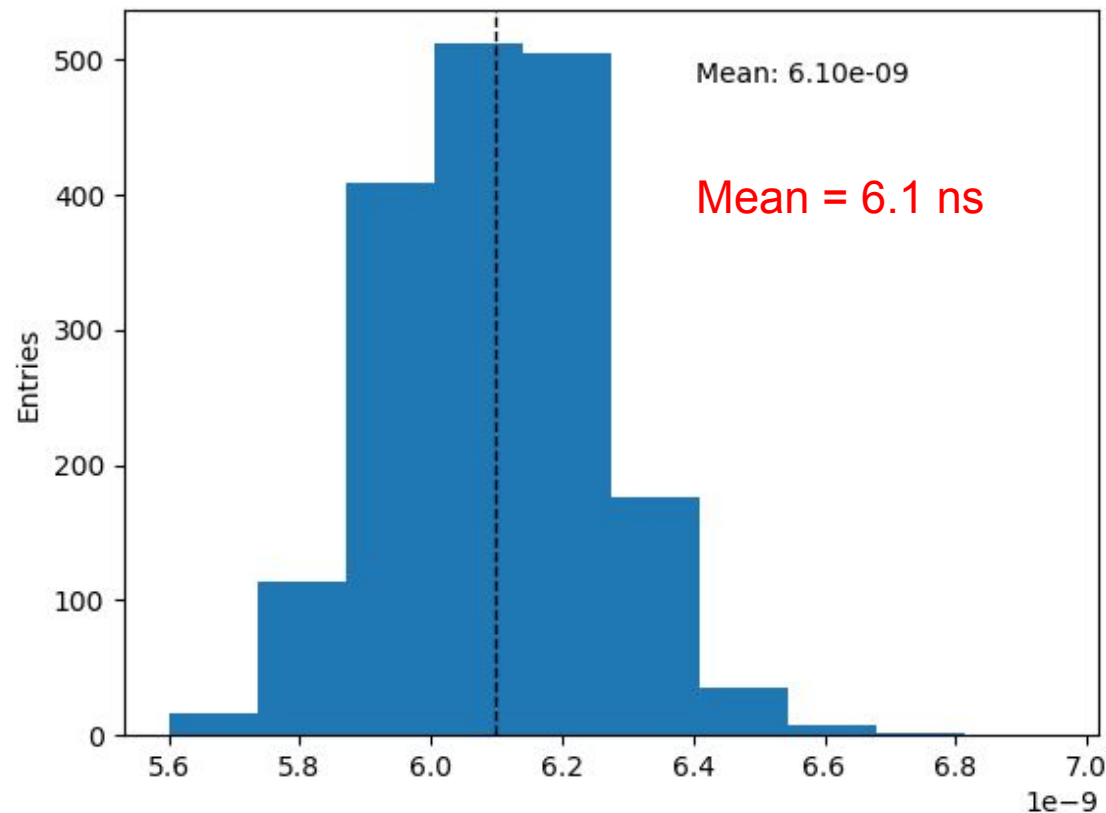
Side SiPM pulse height by event

Optical glass end SiPM response

- Optical glass only generates Cherenkov light, waveform shows how fast the SiPM is
- Fast pulse shape with pulse width (FWHM) = 6.1 ns

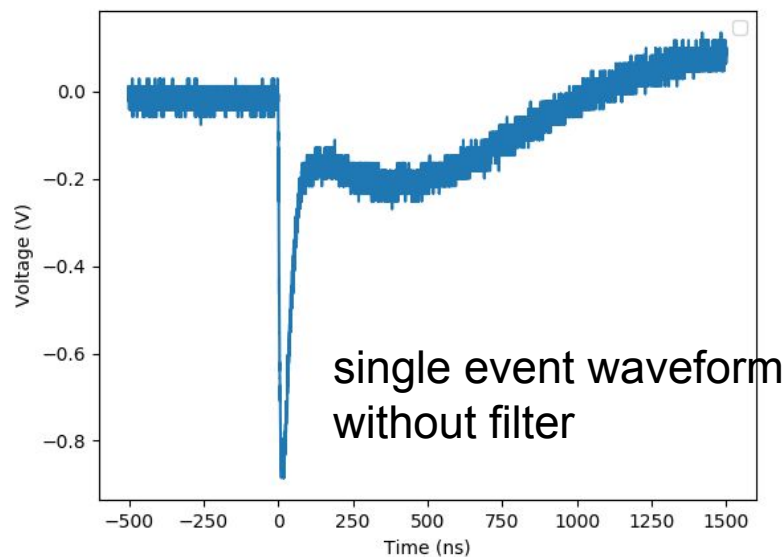


Single event waveform of the optical glass

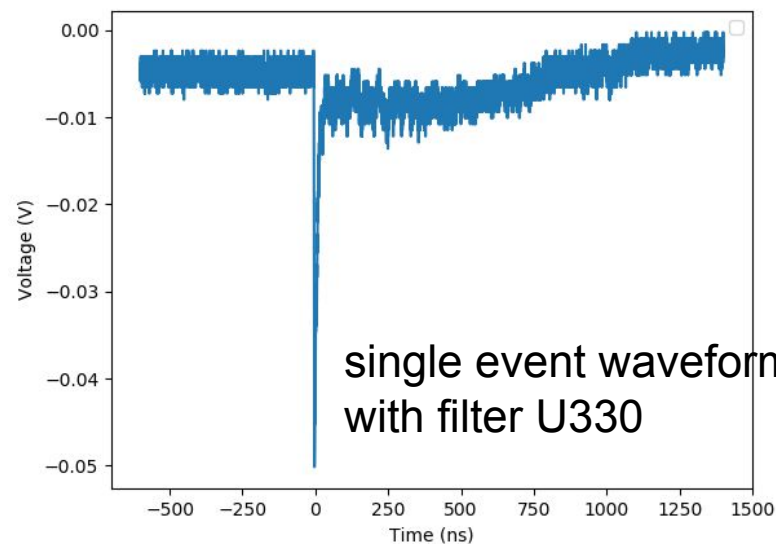
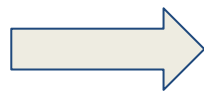


1800 events pulse width histogram (FWHM)

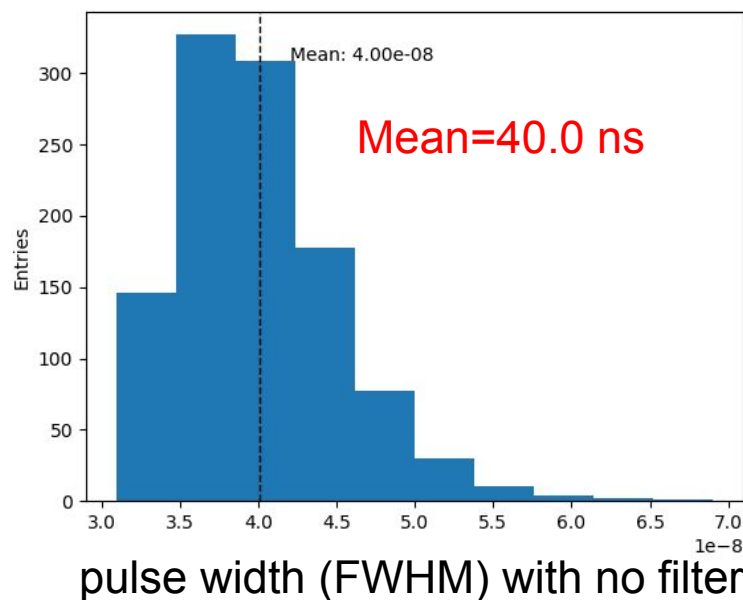
BGO end SiPM response w/wo optical filter



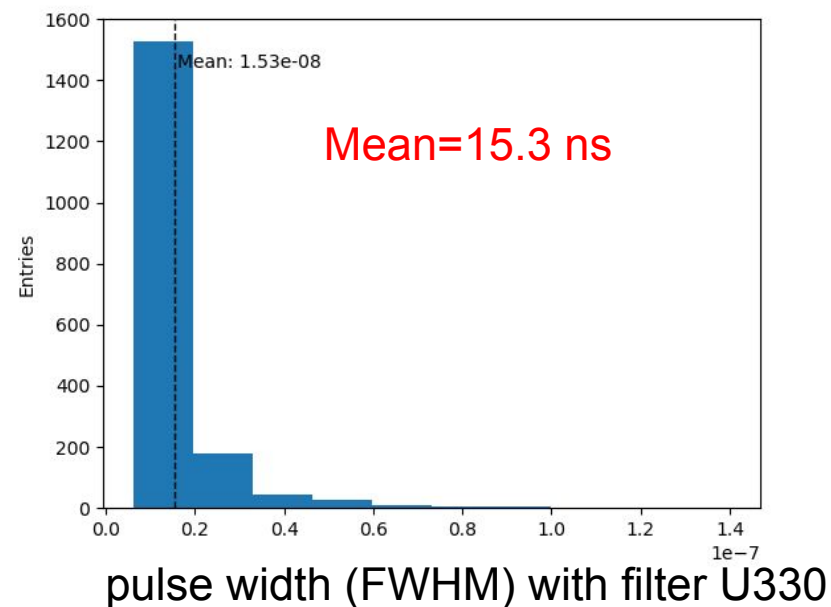
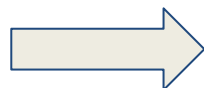
add filter



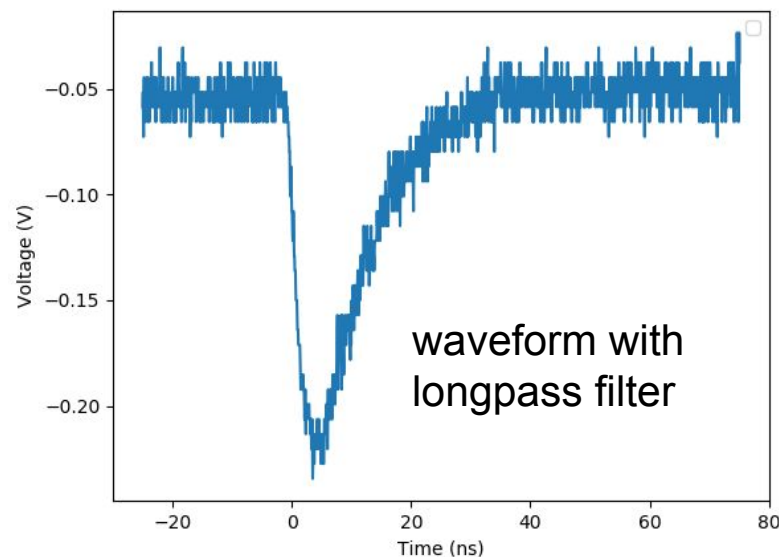
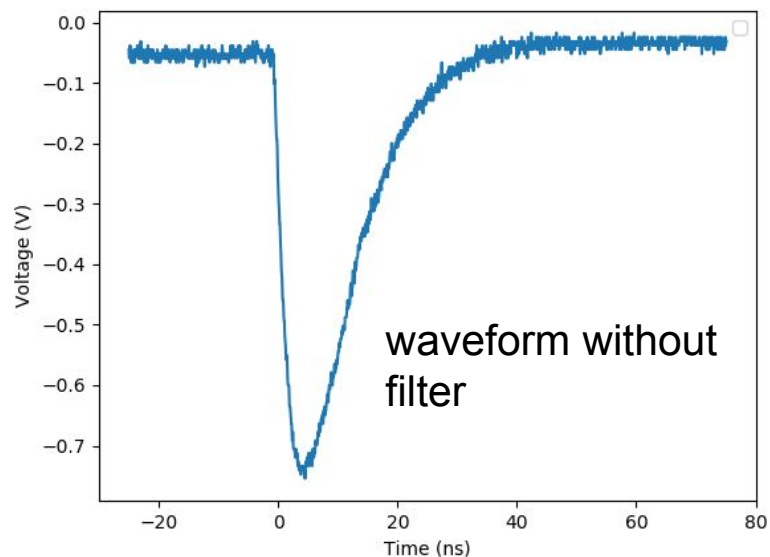
With optical filter U330 added to the end SiPMs, the BGO pulses width become much narrower.



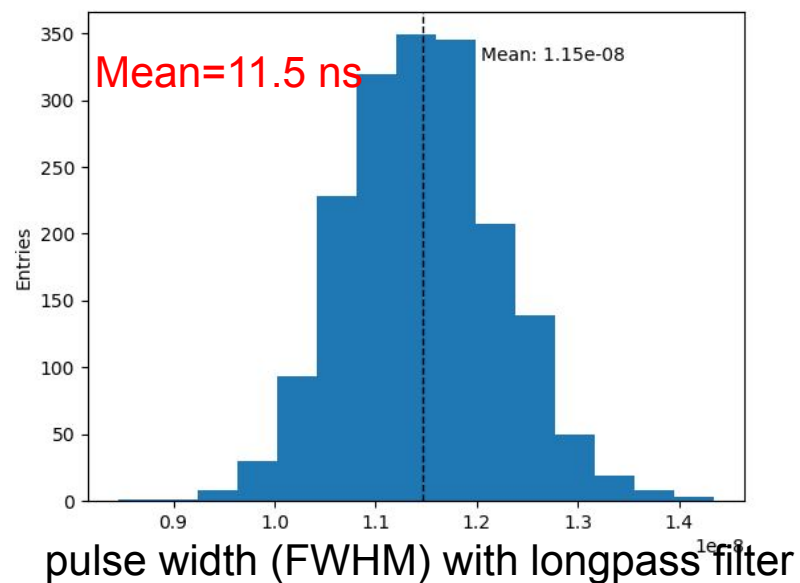
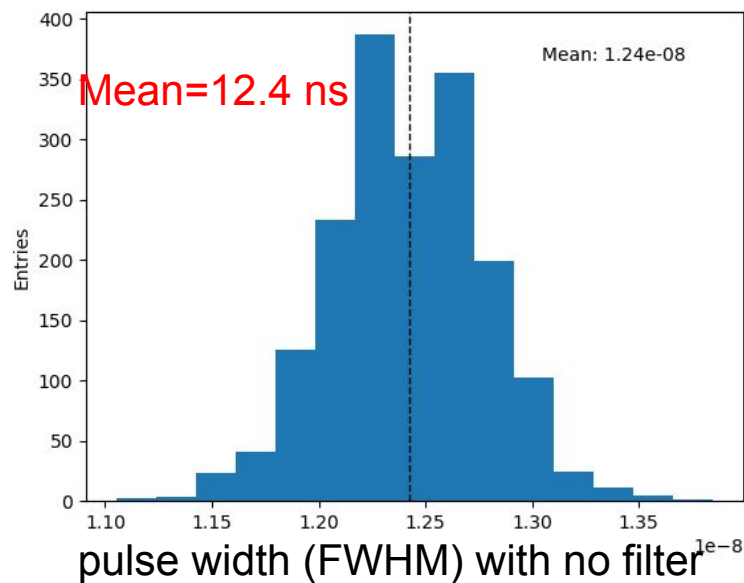
add filter



PWO end SiPM response w/wo 600 nm longpass filter

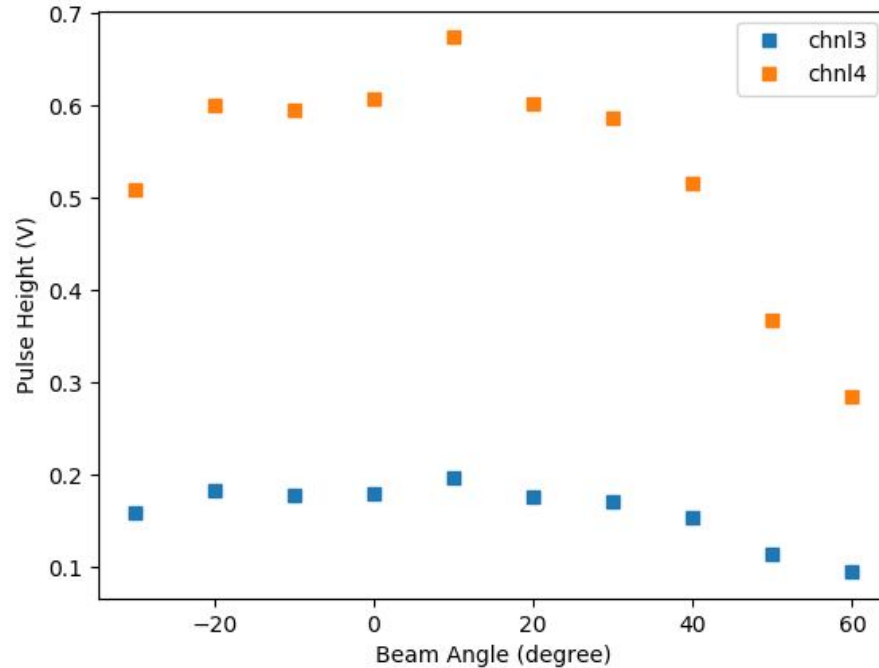


- The longpass filter used here is an interference one, not great to remove all scintillation photons.
- Will try Hoya R60 (600 nm colored glass longpass filter) in the future.



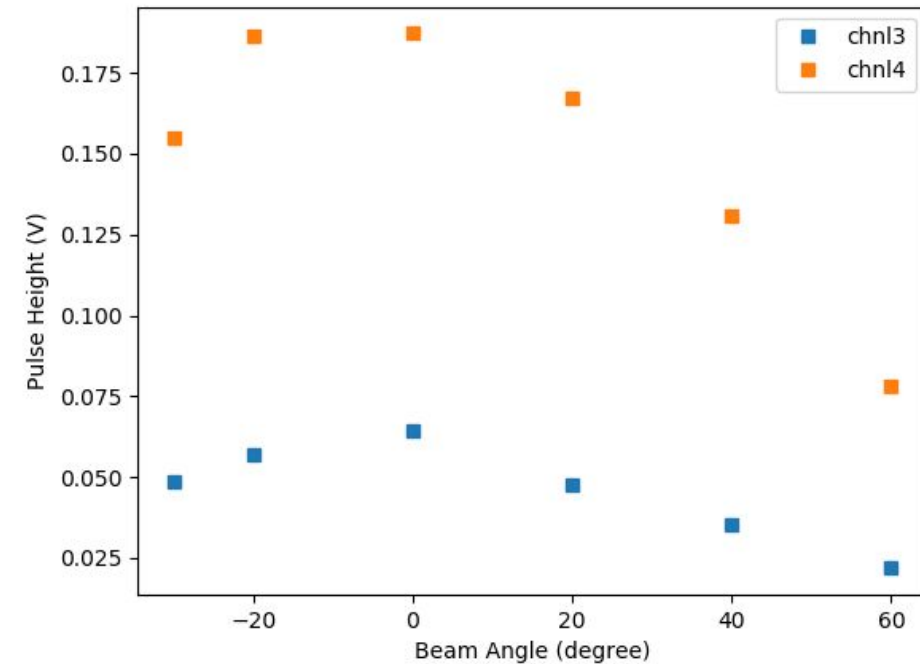
PWO pulse height beam angle dependence

- Pulse height angle dependence corresponds to simulation, but pending further analysis



Pulse height vs beam angle (without filter)

add filter



Pulse height vs beam angle (with longpass filter)

Conclusions

- The CalVision collaboration proposes to use inorganic crystals and dual-readout technique to improve both EM and hadronic energy resolutions
- Simulation framework ready for single crystal simulation with different configurations and optical filters/grease
- Crystals, electronics boards, and experimental setup prepared for cosmic ray and test beam studies, still working on improvements, for example, adding telescope to determine the direction of the incident charged particle, adding temperature control etc
- Data taken with 8 MeV electron beam at U of Notre Dame last week, data analysis still ongoing
- Plan to perform cosmic muon studies in the next few weeks and compare with simulation
- Plan to perform muon test beam at Fermilab this summer