

Nuclear Reactor Antineutrino Directionality via Elastic Electron Scattering in a Gd-doped Water Cherenkov Detector



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Introduction

- Research is being done on using large (kiloton scale) Gd-doped water Cherenkov antineutrino detectors (WCDs) for long range (> 10 km) remote monitoring of nuclear reactors [1].
- Detection via inverse beta decay (IBD) ($\bar{\nu}_e + p \rightarrow n + e^+$) can determine operational status, power level, and fuel burnup [2].
- Directional detection of the antineutrino source can reduce backgrounds from nearby reactors and can help search for clandestine reactors.
- We look to determine if directionality is possible with antineutrino-electron scattering (ES) ($\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$) → ES is forward peaked (see Fig. 1), but the reaction rate is ~ 5.4 times smaller than IBD in water.

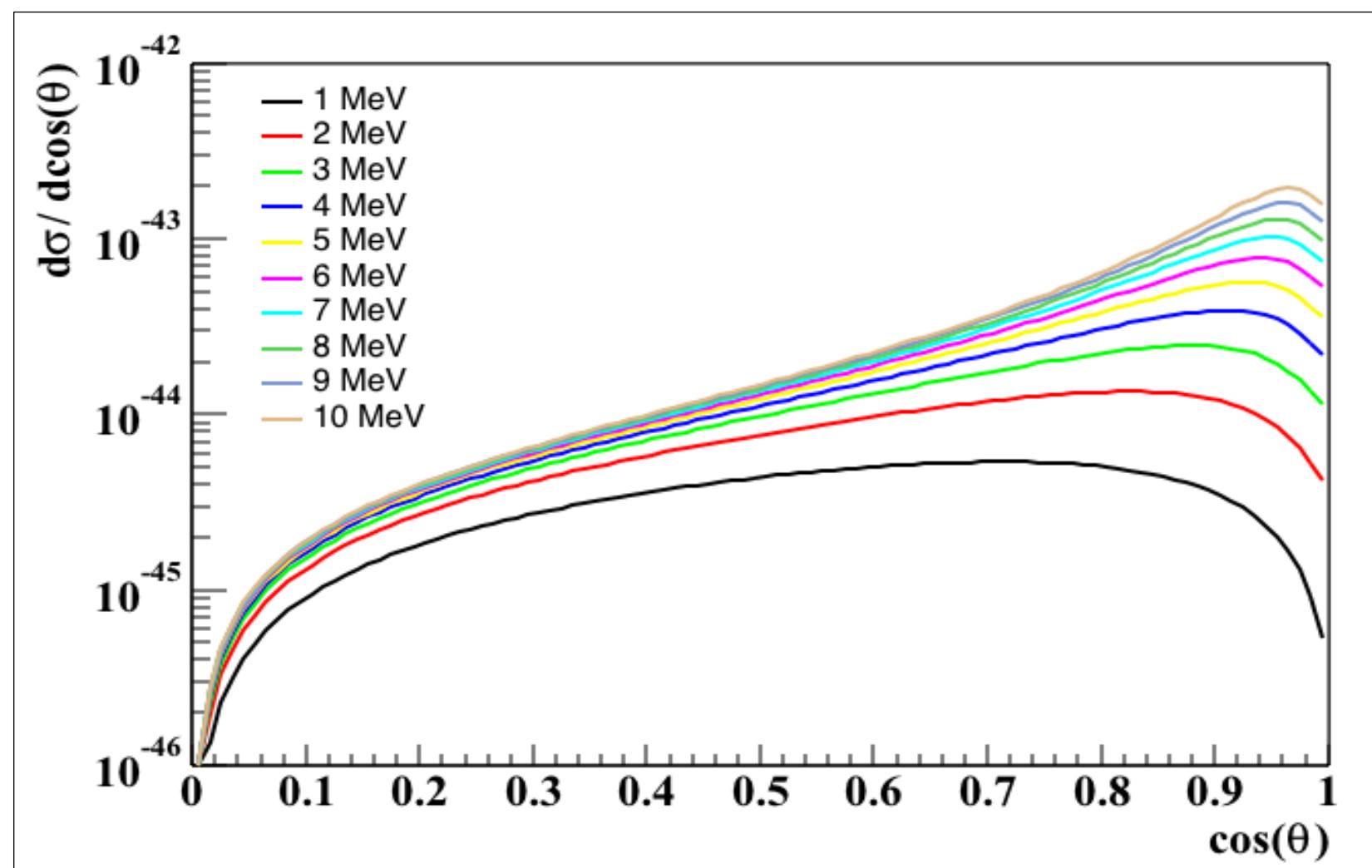
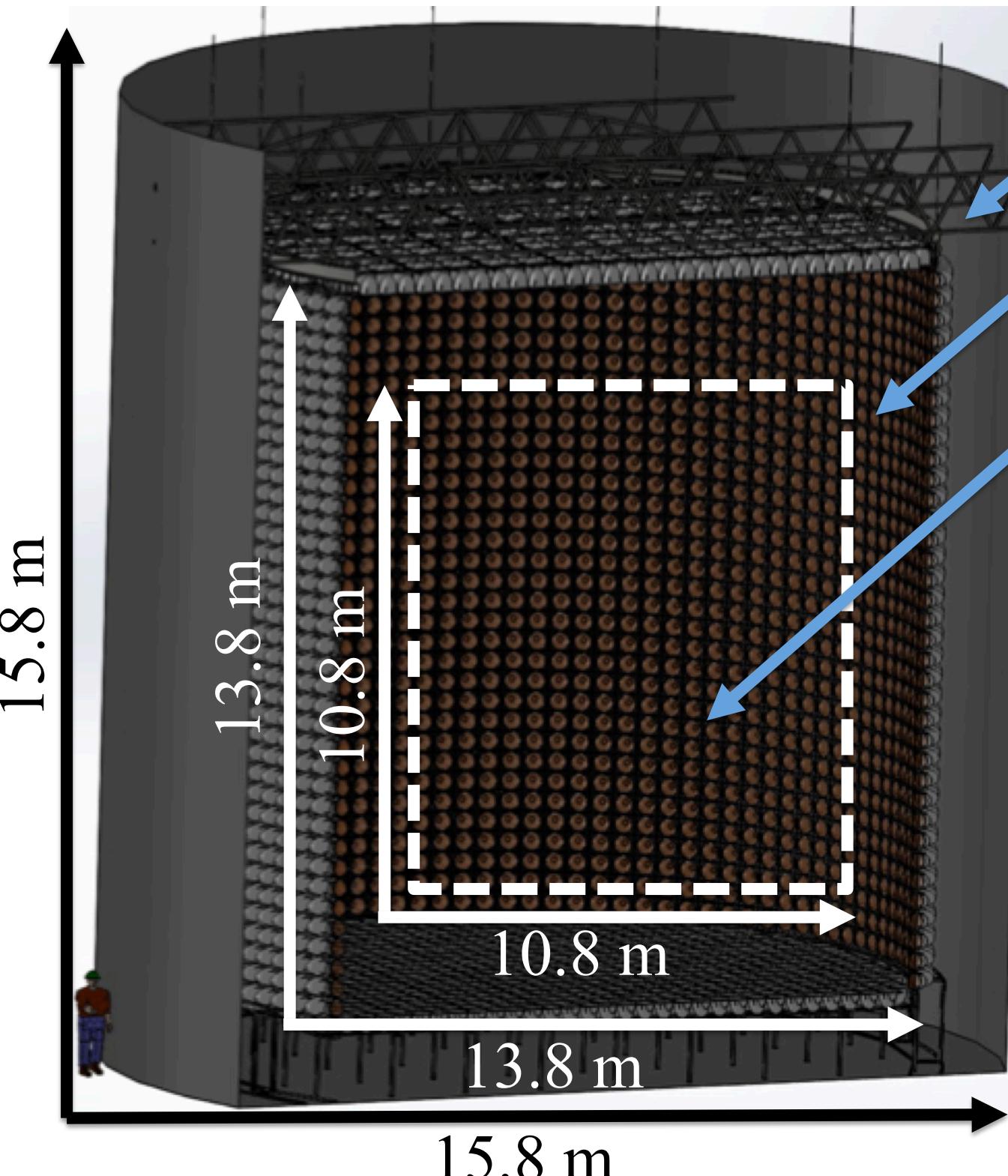


Fig. 1. Differential ES cross-section with respect to the cosine of the scattering angle, θ , for various antineutrino energies [3].

- This work serves as an introductory investigation into reactor directionality via ES in large WCDs → we aim to estimate the expected ES signal and background, and propose several strategies to reduce background.

Detector Design



- Outer (veto) region
- Inner (target) region
- Fiducial volume
- 3.1 kilotons of 0.1% Gd-doped water in total.
- 4300 10-inch photomultiplier tubes (PMTs).
- 1 kiloton fiducial volume.**

- 1500 meters of water equivalent (m.w.e.) underground.
- 13 km from a 3.8 GWt light water reactor.
- Roughly consistent with the WATCHMAN project [1].

Detection and Reconstruction

- Following an ES event, the scattered electron will produce a Cherenkov light cone (see Fig. 2).
- The direction and interaction vertex of the scattered electron is reconstructed via the light pattern detected by the PMTs.

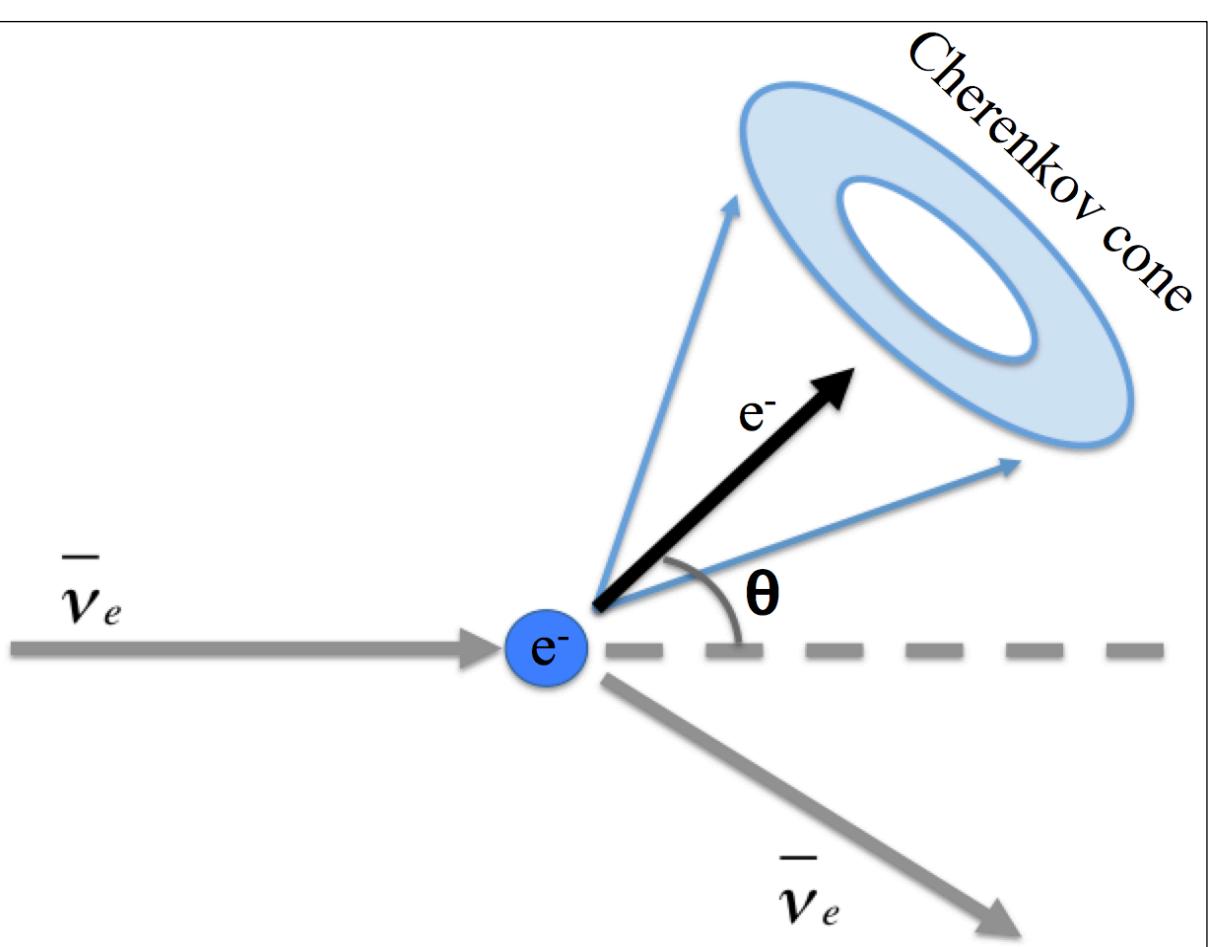


Fig. 2. Diagram of the ES interaction.

Signal and Background

- Signal:** estimate using the number of antineutrinos produced per fission [4-5], the reactor power level, the detector distance and size, and the cross-section.
→ ~ 1850 ES events per year.
- Background:** gamma rays from steel, rock, and PMTs, solar neutrinos, misidentified IBD events, cosmogenic radionuclides, and radon → estimate by independent simulations and scaling from other experiments (Super-K, KamLAND, and SNO) [6-11].

Results

- Backgrounds are dominated by the PMTs, radon, and cosmogenic radionuclides.

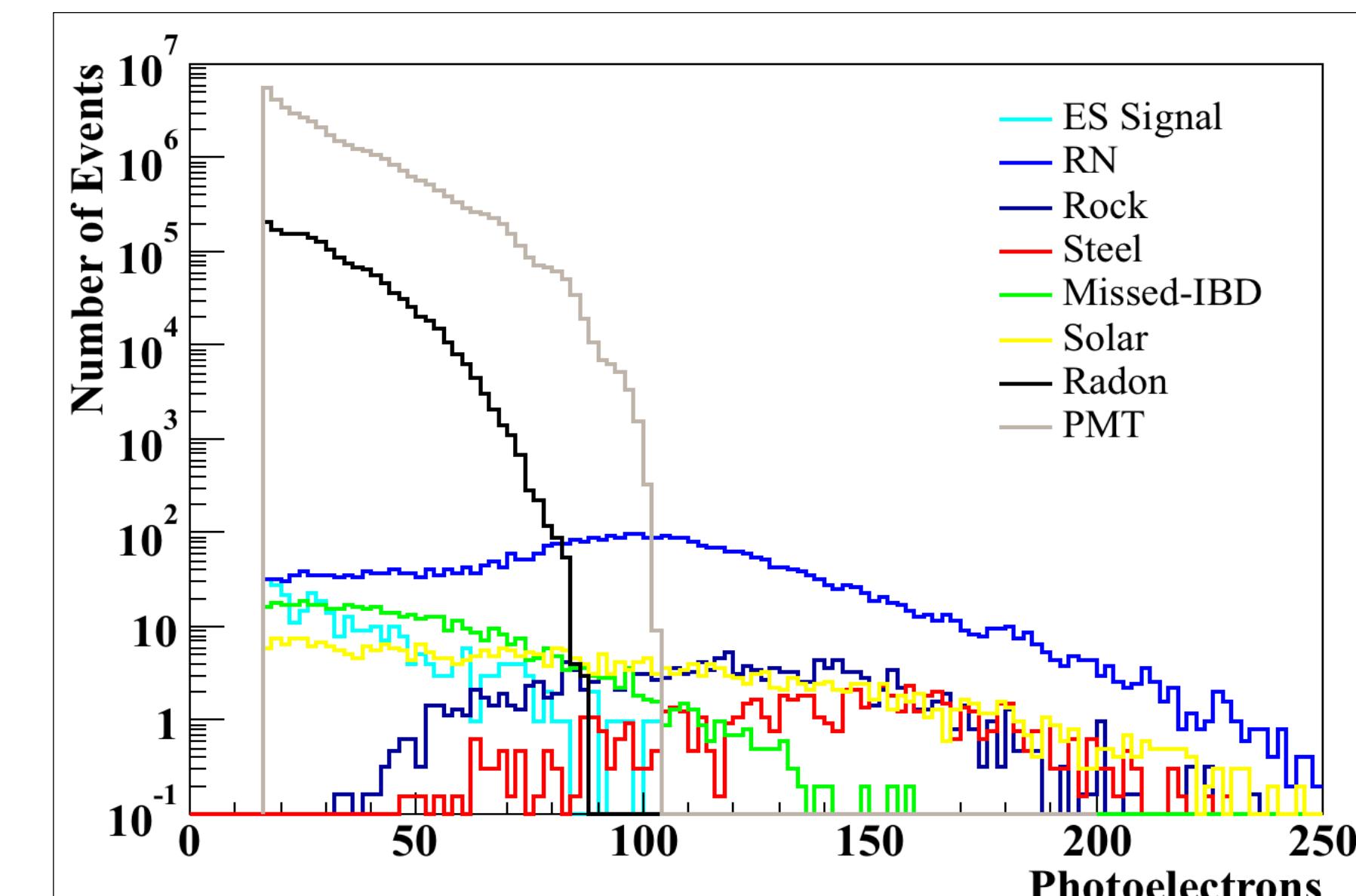


Fig. 4. One year PE spectra of signal and backgrounds in the kiloton fiducial volume.

- If we increase the buffer thickness (the region between the fiducial volume and PMTs), we can essentially reduce the PMT background to zero (see Fig. 5).

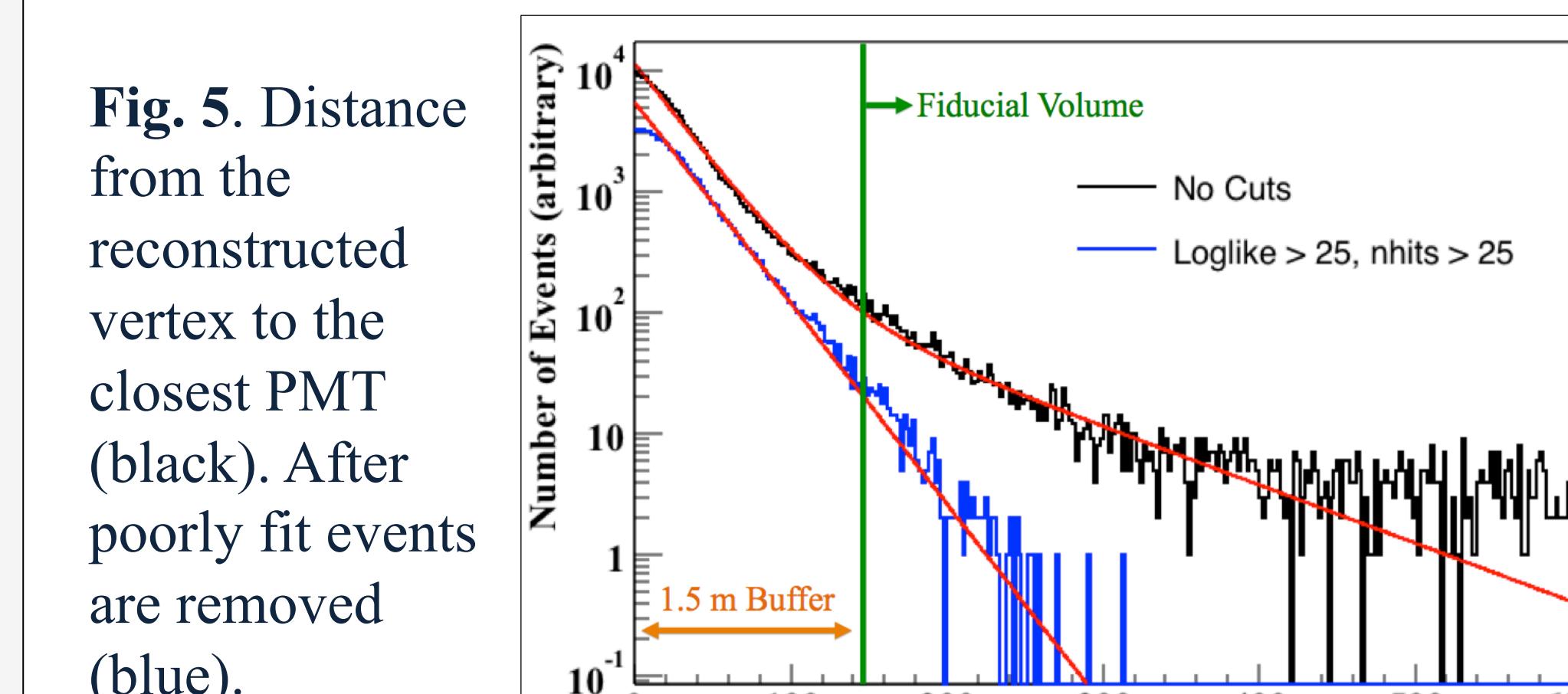


Fig. 5. Distance from the reconstructed vertex to the closest PMT (black). After poorly fit events are removed (blue).

GEANT4 Simulation

- Simulate one year of signal and background using GEANT4, sampling position, energy, and direction (see Fig. 3 for a visualization).

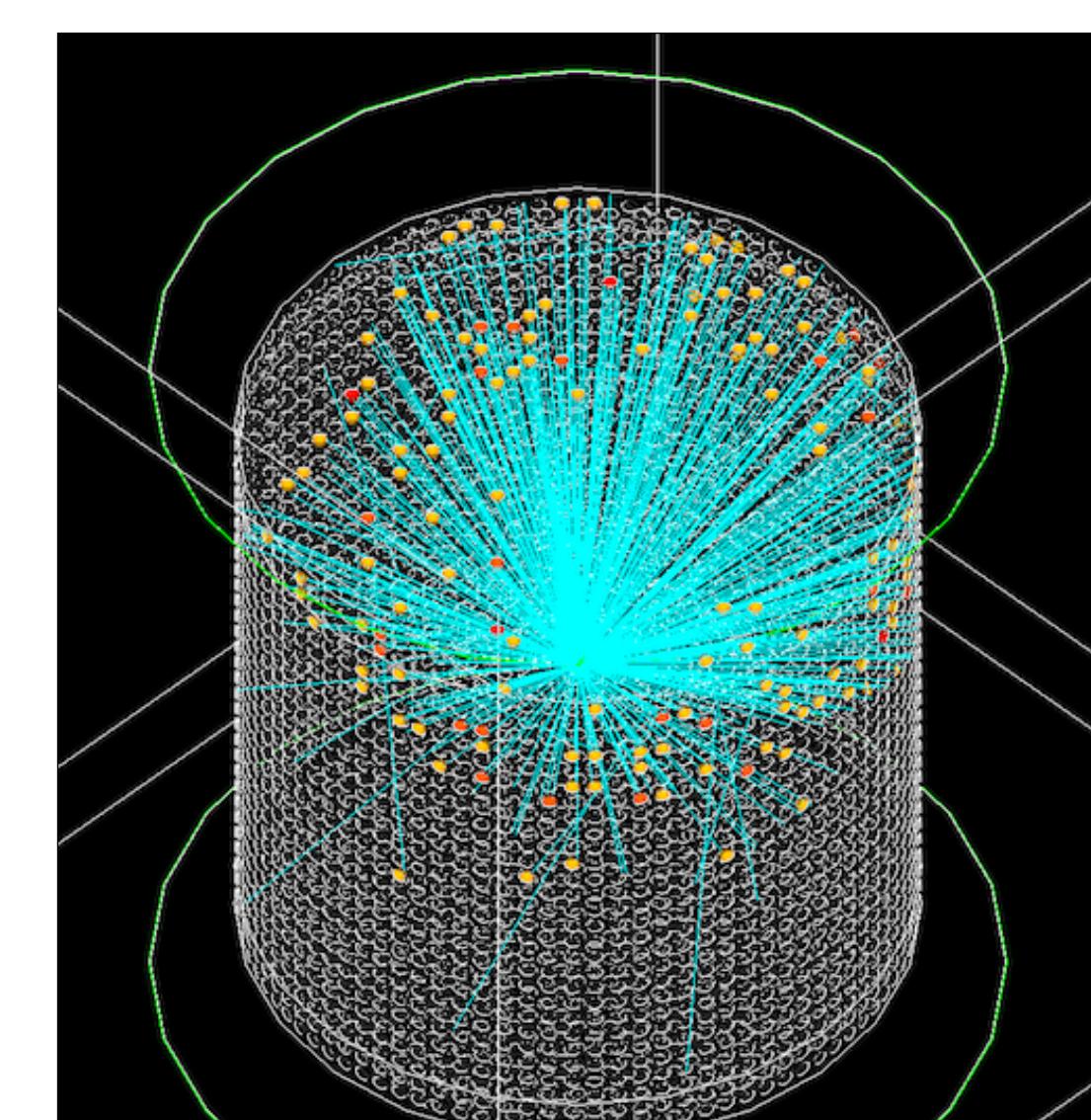


Fig. 3. Visualization of an ES event simulated in GEANT4.

- Analyze the photoelectron (PE) distributions for each source individually (see Fig. 4).

Conclusions

- PMT backgrounds can be suppressed with a sufficiently large buffer thickness, leaving radon and cosmogenic radionuclides to dominate background.
- Radionuclide background can be reduced with more overburden and radon background can be removed using a high PE threshold.
- A larger detector will be needed to accommodate both the larger buffer and to increase the ES signal detection rate.

Future Work

- Determine pointing ability by analyzing the directional reconstructions of the signal and background.
- Investigate directional significance as a function of radon contamination, detector depth, and detector size.
- The results will outline a list of conditions that will enable a WCD to determine the direction of nuclear reactor antineutrinos.

References

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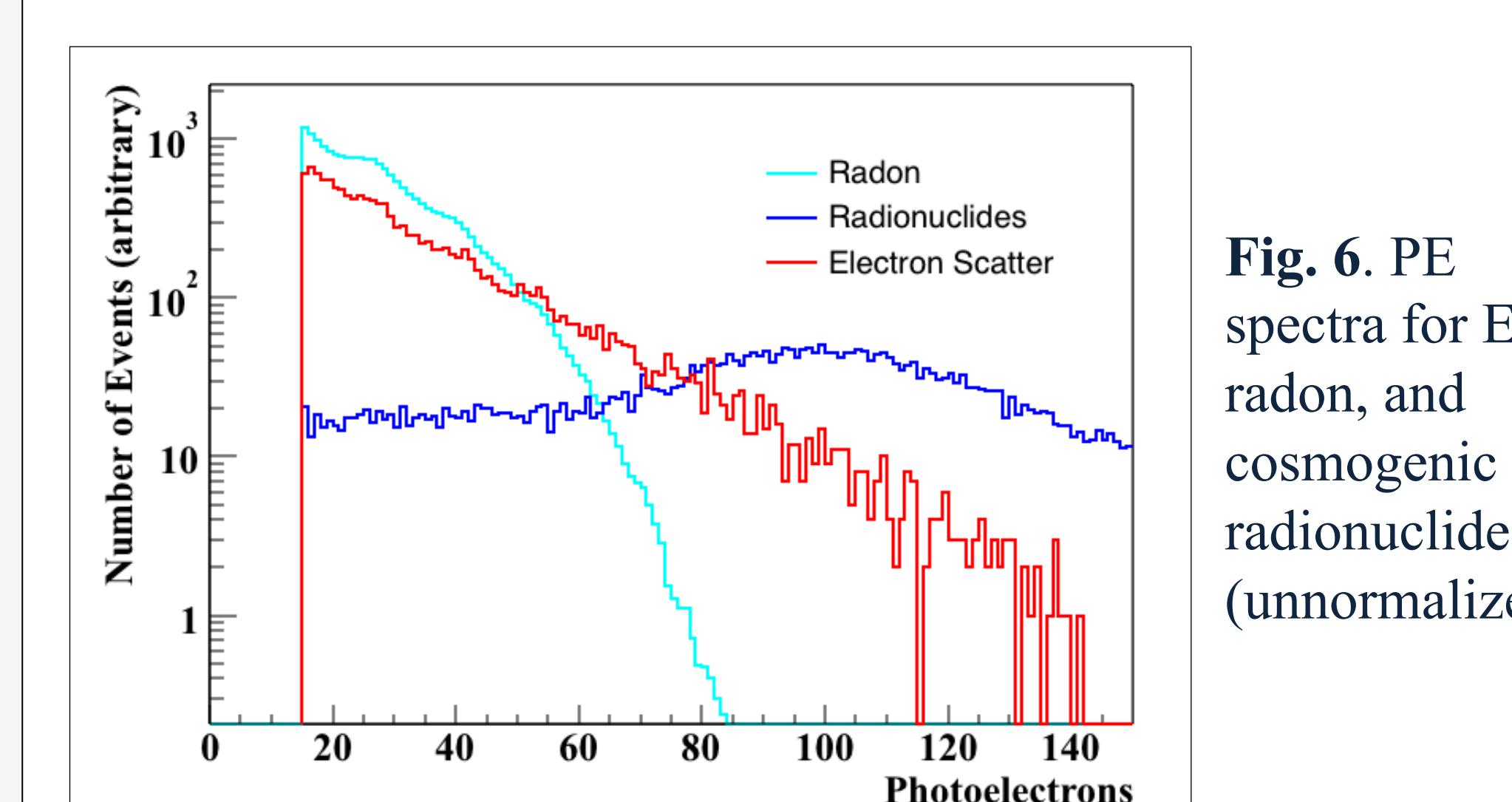


Fig. 6. PE spectra for ES, radon, and cosmogenic radionuclides (unnormalized).