Comparing Spherical Harmonics Analysis and Machine Learning Techniques for Double-Beta Decay Identification in a Large Liquid Scintillator Detector

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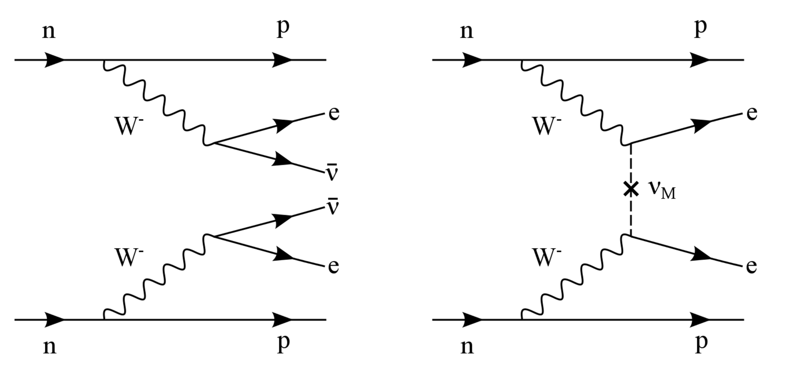
Abstract

In a liquid scintillator detector electrons from double-beta decay ($\beta\beta$-decay) often exceed Cherenkov threshold. These Cherenkov photons carry information about event topology of the two-track single-vertex $\beta\beta$-decay. Event topologies of background events are distinctly different by number of tracks and/or by number of verticies. Therefore signal/background separation can be achieved by analyzing spatial and timing distribution of photons in a liquid scintillator detector. Using a simulation of a 6.5 m radius liquid scintillator surrounded by photo-detectors with 100 ps resolution we compare performance of the spherical harmonics analysis with machine learning (ML) techniques. Even with currently similar performance of the two methods we emphasize an advantage of the ML methods since they do not depend explicitly on vertex reconstruction. Therefore a dedicated effort in further development of the ML methods is needed.

Signal and Backgrounds



$2\nu\beta\beta$- and $0\nu\beta\beta$-decay diagrams

$0\nu\beta\beta$-decay

- Very large detector mass is required to search for $0\nu\beta\beta$-decay
- Liquid scintillator detectors offer good scalability
- Efficient background suppression is critical
- Event topology: two electrons

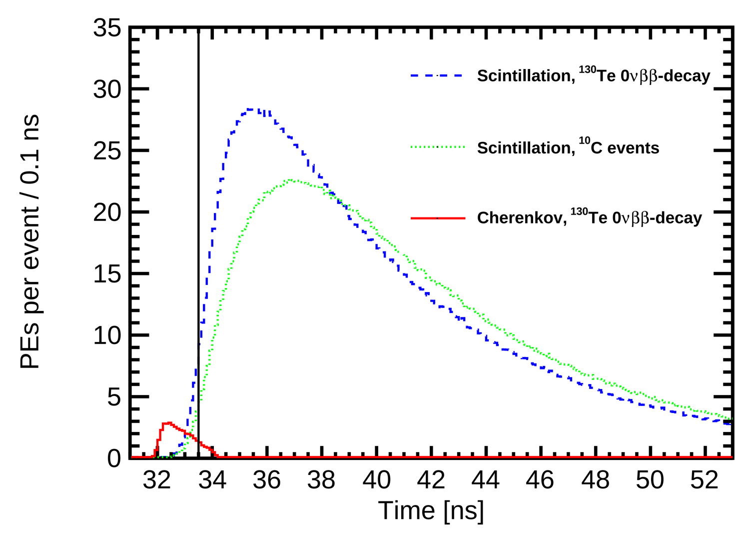
^{10}C background

- May become significant at a shallow detector depth
- Event topology: positron accompanied by gamma(s)
- 98% of ^{10}C decays through a long-lived ($\sim$1 ns) excited state
- e^+ has $\sim$50% chance to form ortho-positronium with a life-time of $\sim$3 ns

^{8}B background

- Becomes dominant at large detector masses
- ^{8}B background is traditionally viewed as irreducible
- Event topology: single electron

Cherenkov/Scintillation Light Separation



PE arrival times (R=6.5 m, TTS=100 ps). Central events.

- Fast timing enables new background suppresion techniques in liquid scintillator detectors
- Cherenkov light arrives first
- Early light contains directionality and event topology information
- Two-track event topology of $\beta\beta$-decay is distinct from one-track ^{8}B events and from complex topology of ^{10}C events
- Directionality of the single track from ^{8}B events is correlated with position of the Sun, thus providing extra handle on $\beta\beta$-decay vs ^{8}B separation

Spherical Harmonics Analysis

$$f(\theta,\phi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} f_{lm} Y_{lm}(\theta,\phi), \quad (1)$$

$$Y_{lm} = \begin{cases} \sqrt{2} N_{lm} P_l^m(cos\theta) cos\, m\phi, & \text{if } m>0 \\ N_{lm} = \sqrt{\frac{(2l+1)}{4\pi}\frac{(l-m)!}{(l+m)!}}, & \text{if } m=0 \\ \sqrt{2} N_{l|m|} P_l^{|m|}(cos\theta) sin\, |m|\phi, & \text{if } m<0 \end{cases} \quad (2)$$

$$f_{lm} = \int_0^{2\pi} d\phi \int_0^{\pi} d\theta sin\theta f(\theta,\phi) Y_{lm}(\theta,\phi). \quad (3)$$

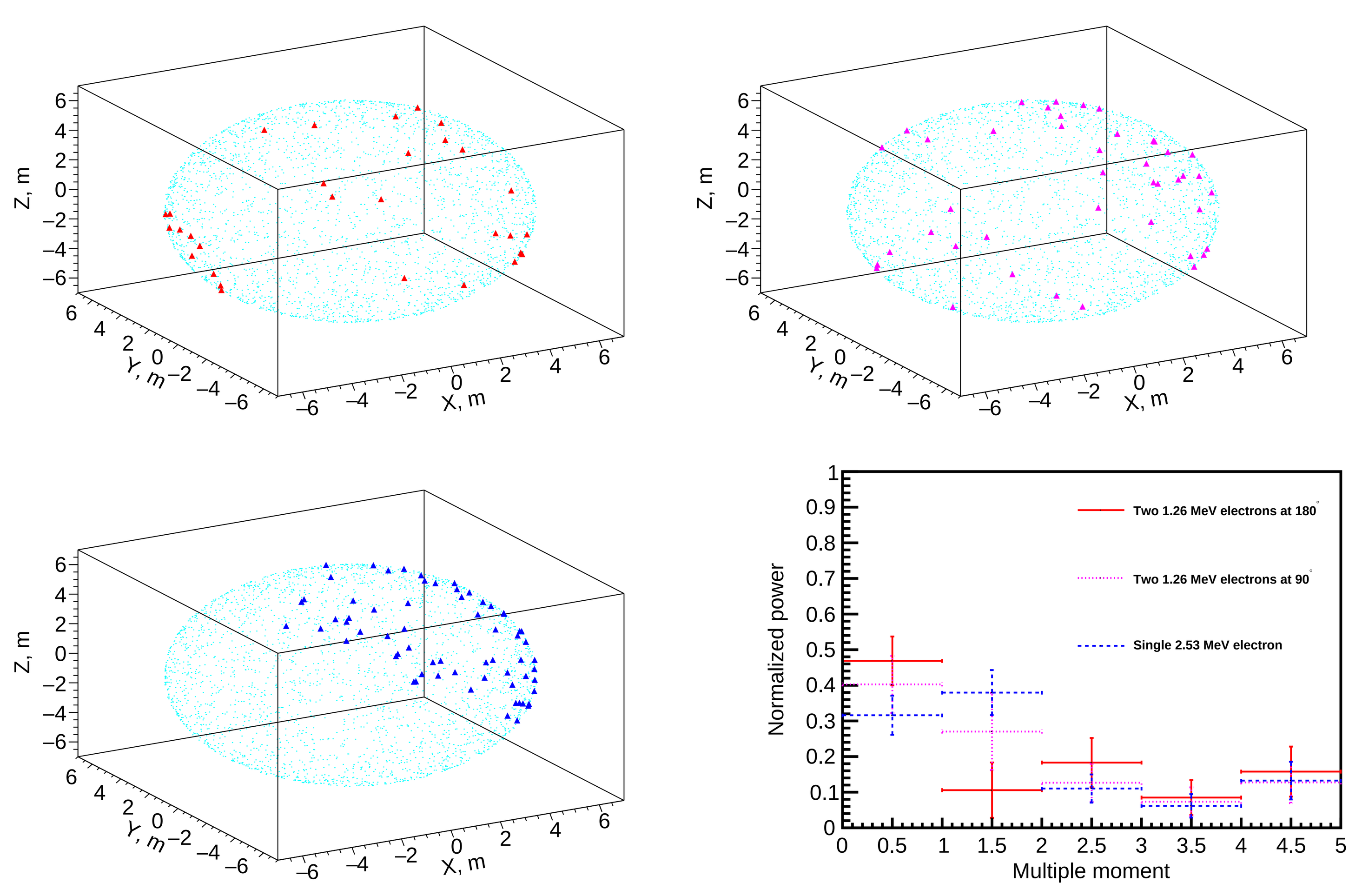
Power spectrum, $s_l = \sum_{m=-l}^{m=l} |f_{lm}|^2$, is invariant under rotation. Normalized power spectrum is defined by an event topology:

$$S_l = \frac{s_l}{\sum_{l=0}^{\infty} s_l} = \frac{s_l}{\int_\Omega |f(\theta,\phi)|^2 d\Omega}, \quad (4)$$

We choose normalization using only $l = 0, 1, 2, 3$:

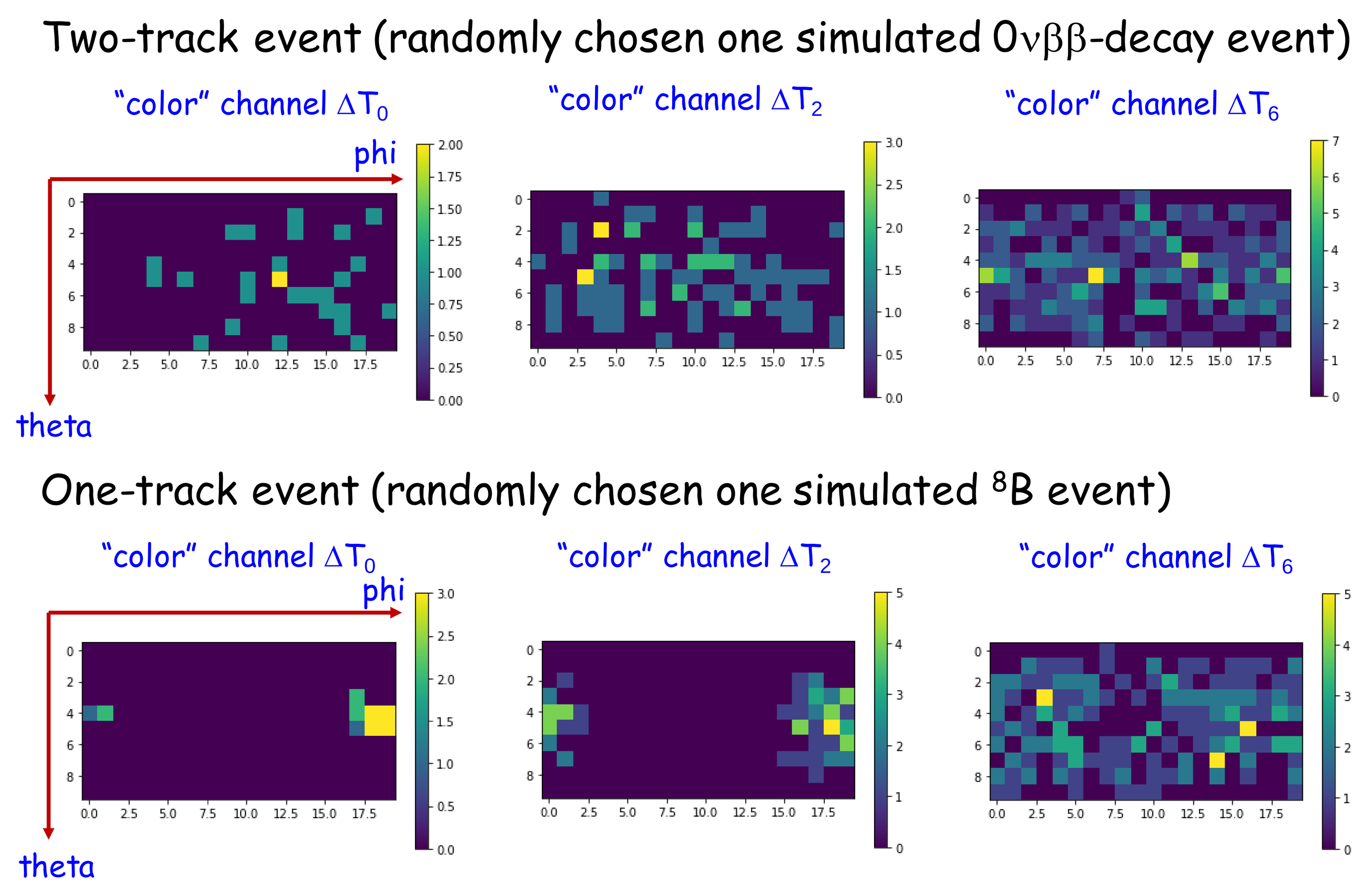
$$S_l = \frac{s_l}{\sum_{l=0}^{3} s_l} \quad (5)$$

Spherical Harmonics Analysis



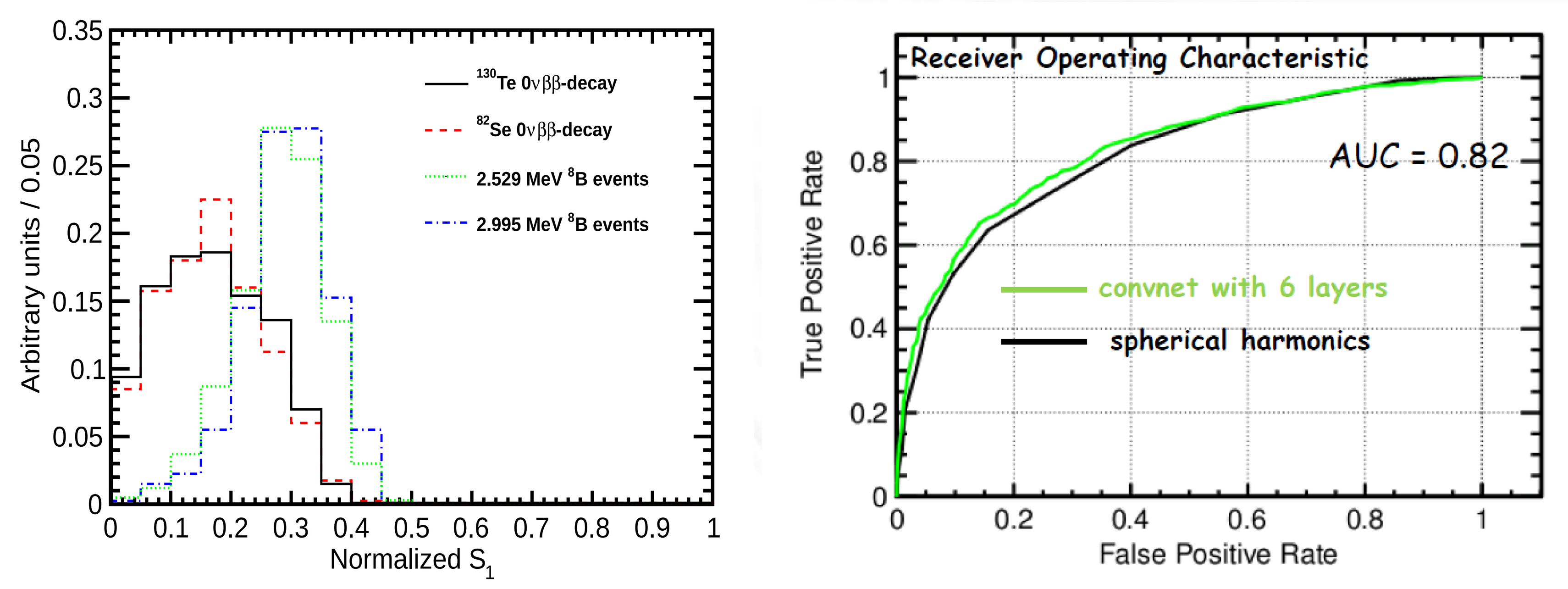
Event displays for three distinct topologies: two back-to-back electrons (*top left*), two electrons at 90° (*top right*), and a single electrons (*bottom left*). (*Bottom right:*) Normalized power spectrum for these three event topologies. Cherenkov photons are shown as triangles.

Convolutional Neural Network



ConvNet receives as input 'photos' of theta-phi plane. Each photo is binned in time intervals so that each timing bin can be treated as a 'color' channel in the ConvNet. Current implemenation uses 0.5 ns binning in time.

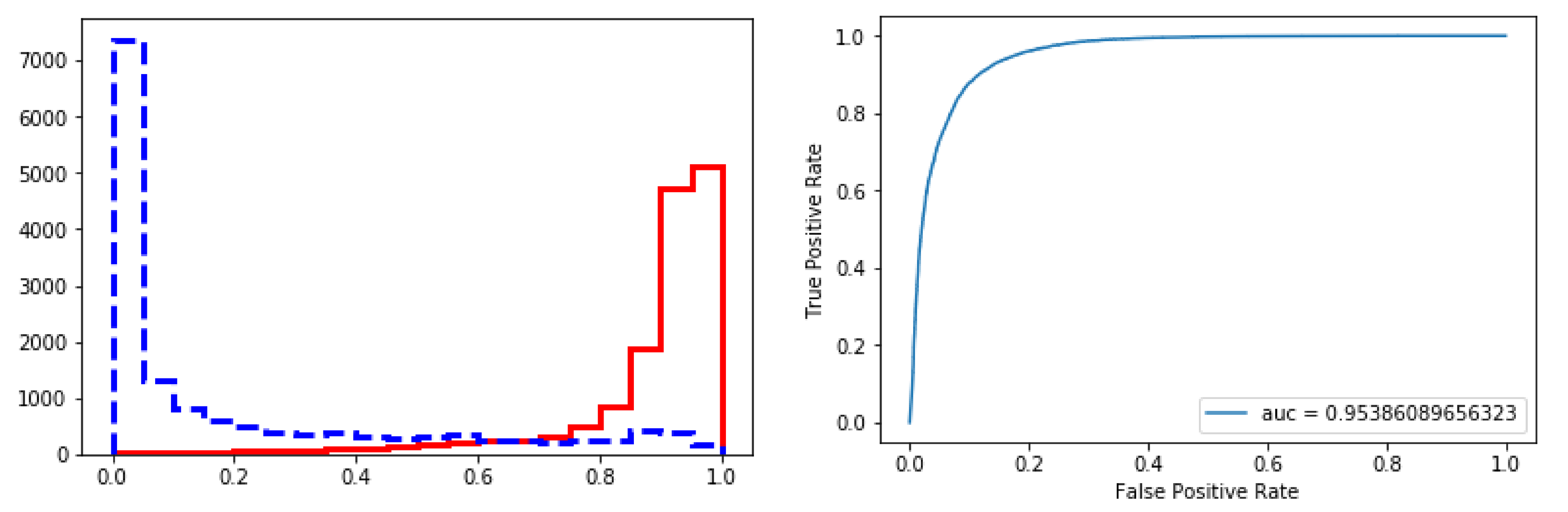
Separation between $0\nu\beta\beta$-decay and ^{8}B Events



(*Left:*) Spherical harmonics power spectrum component S_1. (*Right:*) Receiver Operating Characteristic (ROC) curve comparing accuracy of spherical harmonics analysis and a machine learning reconstruction based on a 6-layer convolutional neural network. True positive rate is a fraction of correctly identified $0\nu\beta\beta$-decay signal events. False positive rate is a fraction ^{8}B background events misidentified as $0\nu\beta\beta$-decay. Area under the curve (AUC) is a figure of merit characterizing performance of a classification algorithm: an ideal classifier has AUC=1, a completely random classifier has AUC=0.5

Central events only. Time cut of 33.5 ns on the PE arrival time is applied to select early light sample. QE$_{che}$=12%, QE$_{sci}$=23%. Photo-coverage is 100%. Scintillation rise time constant is τ_r =1 ns. Spherical harmonics analysis requires reconstructed vertex. Perfect vertex reconsruction is assumed for events shown here. ConvNet does not use any vertex information.

Separation between $0\nu\beta\beta$-decay and ^{10}C Events



(*Left:*) ConvNet classifier output comparing $0\nu\beta\beta$-decay signal events (red) and ^{10}C backgroung events (blue). (*Right:*) ROC curve showing ConvNet $0\nu\beta\beta$-decay vs ^{10}C separation power: AUC=0.95. Ortho-positronium formation is not included in the simulation of ^{10}C events.

Events uniformly distributed within the fiducial volume of R<3 m. QE$_{che}$=12%, QE$_{sci}$=23%. Photo-coverage is 100%. Scintillation rise time constant is τ_r =1 ns. No explicit vertex reconstruction is used.

Conclusions

- Fast timing can be used for Cherenkov/scintillation light separation to reconstruct event topology and suppress backgrounds in searches for $0\nu\beta\beta$-decay with large liquid scintillator detectors
- Spherical harmonics analysis and machine learning techniques provide handles on various backgrounds including the 'irreducible' ^{8}B background
- Machine learning techniques do not explicitly depend on vertex reconstruction

References and Acknowledgments

Neutrino 2018 Posters: 1) J. Gruszko 'NuDot: Double-Beta Decay with Direction Reconstruction in Liquid Scintillator', Monday Session #53; 2) S. Fraker 'Deep Learning for Liquid-Scintillator-Based Double-Beta Decay Searches', Monday Session #70.

References: JINST 7 (2012) P07010; PRD87 (2013) 071301; JINST 9 (2014) 06012; arXiv:1409.5864; NIMA 849 (2017) 102; NIMA 830 (2016) 303; PRC95 (2017) 055801; Eur.Phys.J. C77 (2017) no.12, 811.

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