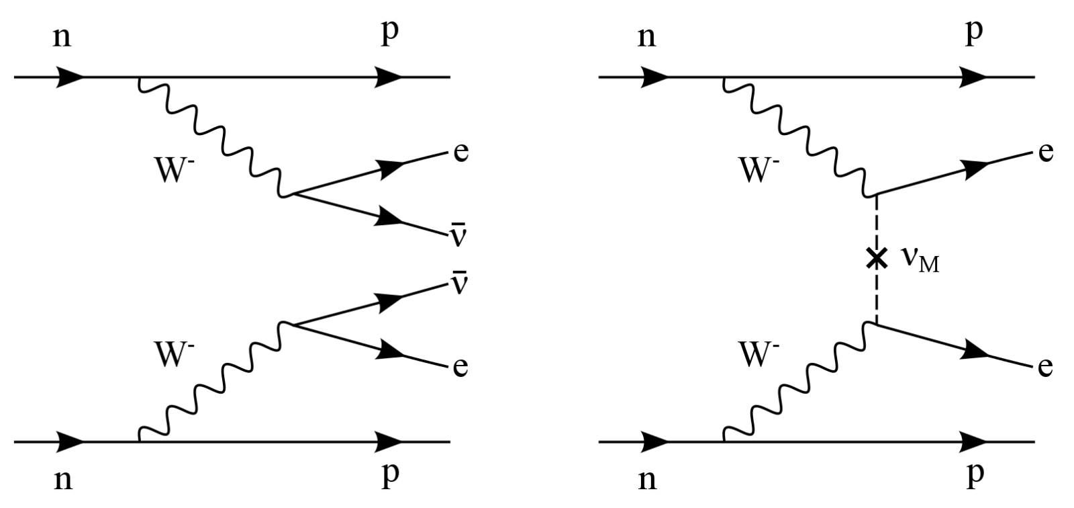
Identification of Double-Beta Decay Events in a Liquid Scintillator Detector

Andrey Elagin
Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA

Abstract

In a liquid scintillator detector electrons from double-beta decay ($\beta\beta$-decay) often exceed Cherenkov threshold. Selection of early photons using fast photo-detectors separates prompt directional Cherenkov light from delayed isotropic scintillation light. This leads to the possibility of reconstructing the event topology of $\beta\beta$-decay candidate events by analyzing spatial and timing distribution of early photons. Using a simulation of a 6.5 m radius ^{130}Te-doped liquid scintillator surrounded by photo-detectors with 100 ps resolution, reconstruction techniques for separating two-track $\beta\beta$-decay events from background due to one-track ^{8}B solar neutrino interactions as well as from other backgrounds with more complex event topologies are discussed.

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

---

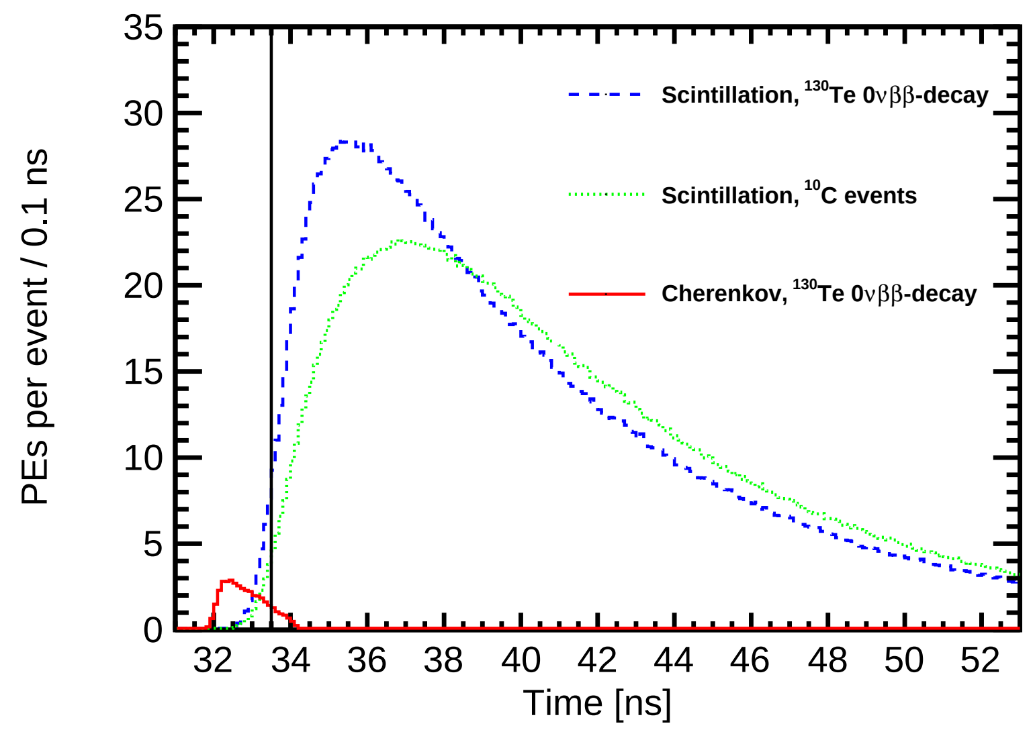
^{10}C background

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

- Fast timing enables new background suppression techniques
- Cherenkov light arrives first
- Early light contains directionality and event topology information
- Cherenkov light is a handle on ^{8}B
- Time profile of the scintillation light provides an extra handle on ^{10}C

Spherical Harmonics Analysis

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

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

where the coefficients f_{lm} are defined as

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

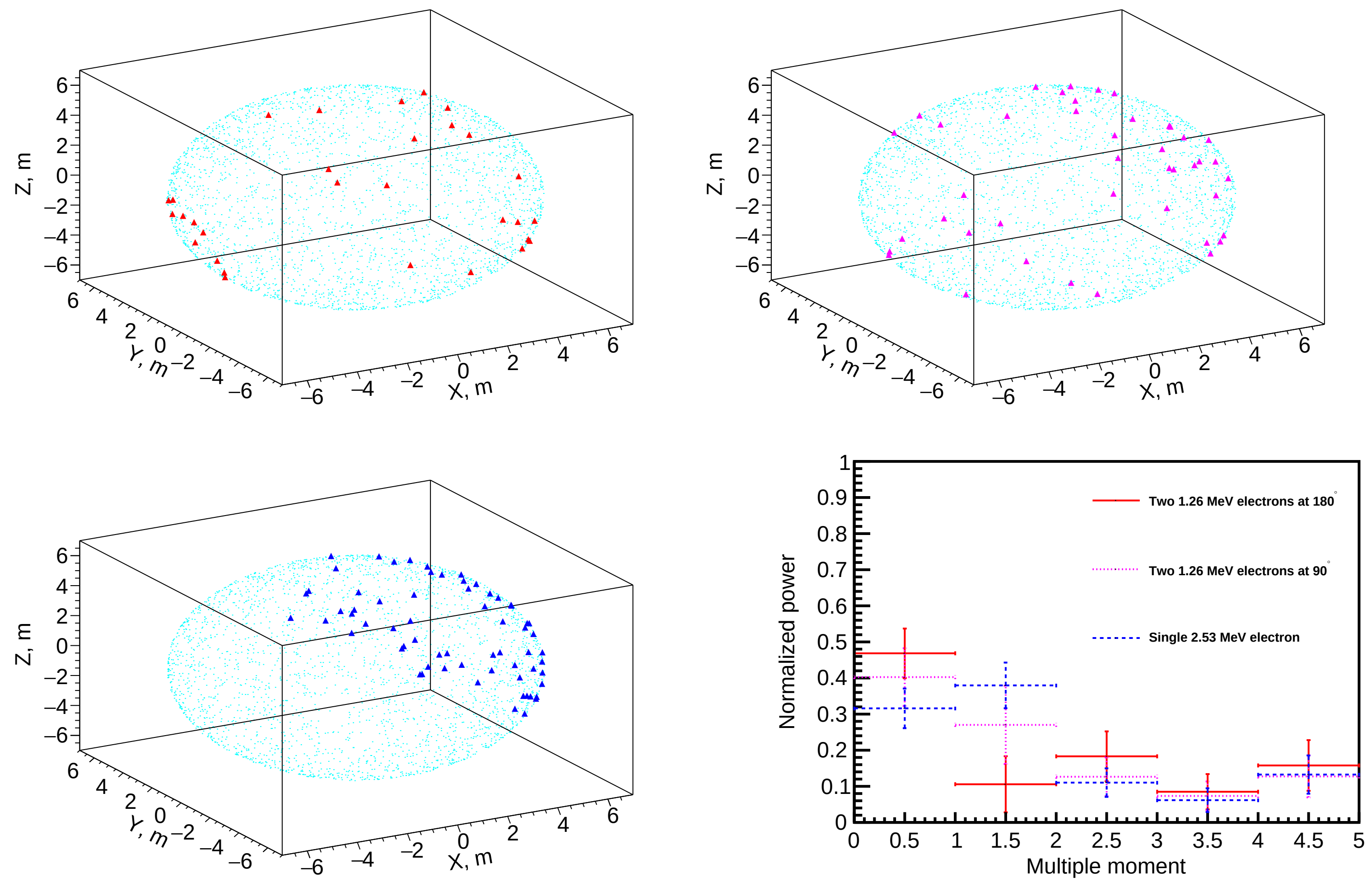
Power spectrum, $s_l=\sum_{m=-l}^{m=l}|f_{lm}|^2$, is invariant under rotation. Normalized power spectrum is defined by an event topology:

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

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

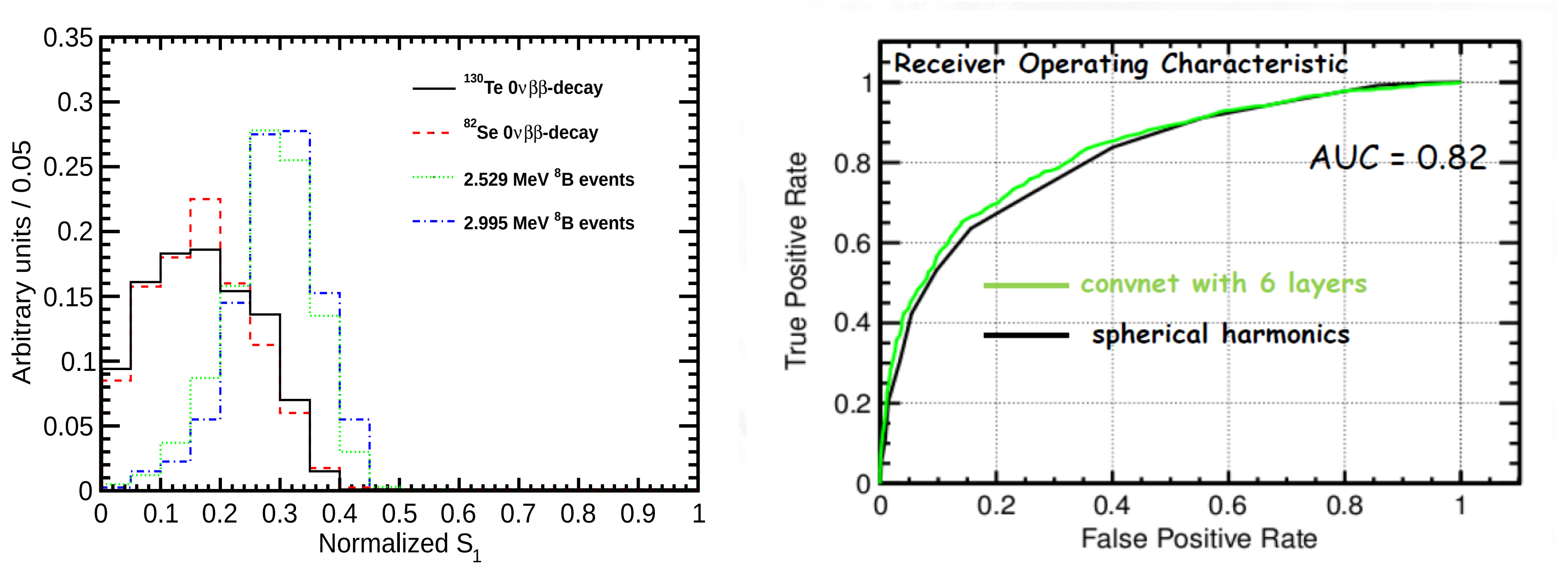
$$S_l=\frac{s_l}{\sum_{l=0}^{3}s_l} \tag{5}$$

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.

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 assuming perfect reconstruction of vertex position. 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 (τ_r =5 ns may be required for more efficient signal/background separation, especially in the case of off-center events).

Conclusions

There are handles on the "irreducible" ^{8}B background in liquid scintillator detectors for $0\nu\beta\beta$-decay searches. Detector requirements for signal/background separation:

- Photo-detectors with TTS~100 ps
- Liquid scintillator with rise time constant as high as τ_r ~5 ns

References and Acknowledgments

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

Acknowledgements: C. Aberle (UCLA), E. Angelico (Chicago), J. Flusser (IITA, CAS), S. Fraker (MIT), H. Frisch (Chicago), C. Grant (Boston), R.Jiang (Chicago), A. Li(Boston), B. Naranjo (UCLA), J. Ouellet (MIT), G. Orebi Gann (UC Berkeley), C. Pilcher (Chicago), E. Toropov (Carnegie Mellon), E. Spieglan (Chicago), . Vukotic (Chicago), M. Wetstein (Iowa State), L. Winslow (MIT), T. Wongjirad (MIT), M. Yeh (BNL).
This work supported by U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences and Offices of High Energy Physics and Nuclear Physics under contracts DE-SC0008172 and DE-SC0015367; the National Science Foundation under grant PHY-1066014; and the Physical Sciences Division of the University of Chicago.

Andrey Elagin • May 28, 2018 • Pisa Meeting • Isola d'Elba