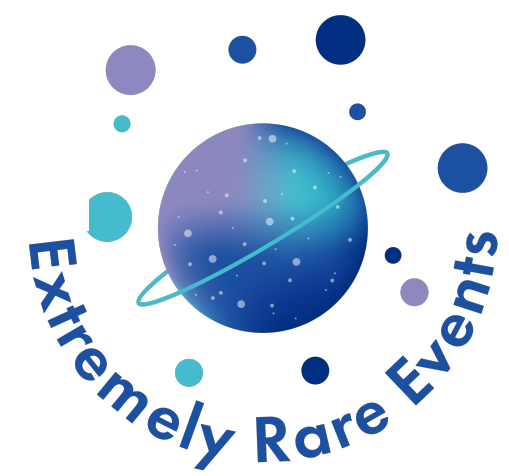




UGRP 2026



Solar Neutrino Interaction Rate



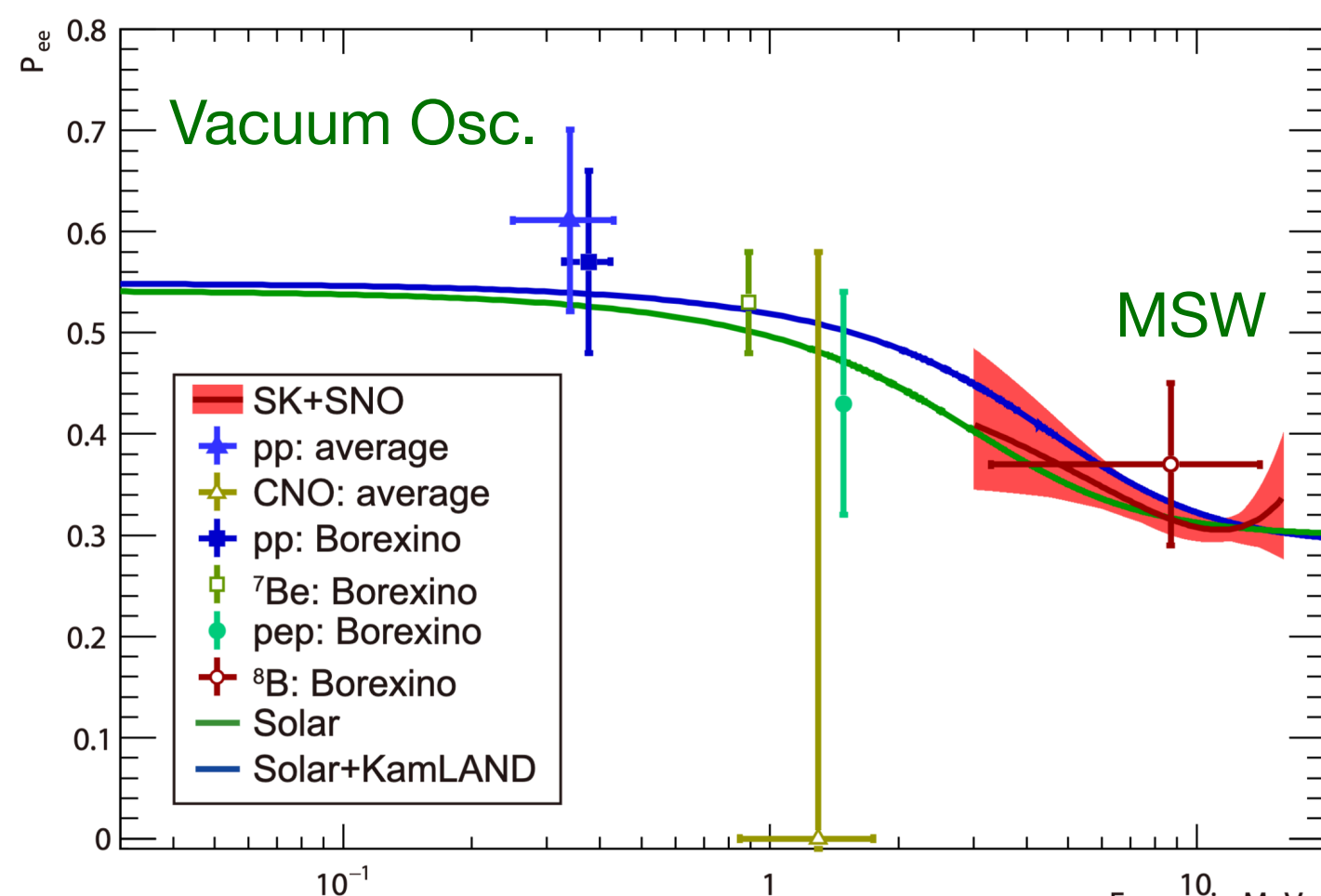
<3.49 MeV solar in Super-Kamiokande-IV

Alejandro Yankelevich for the Super-Kamiokande collaboration



1. The Solar Upturn

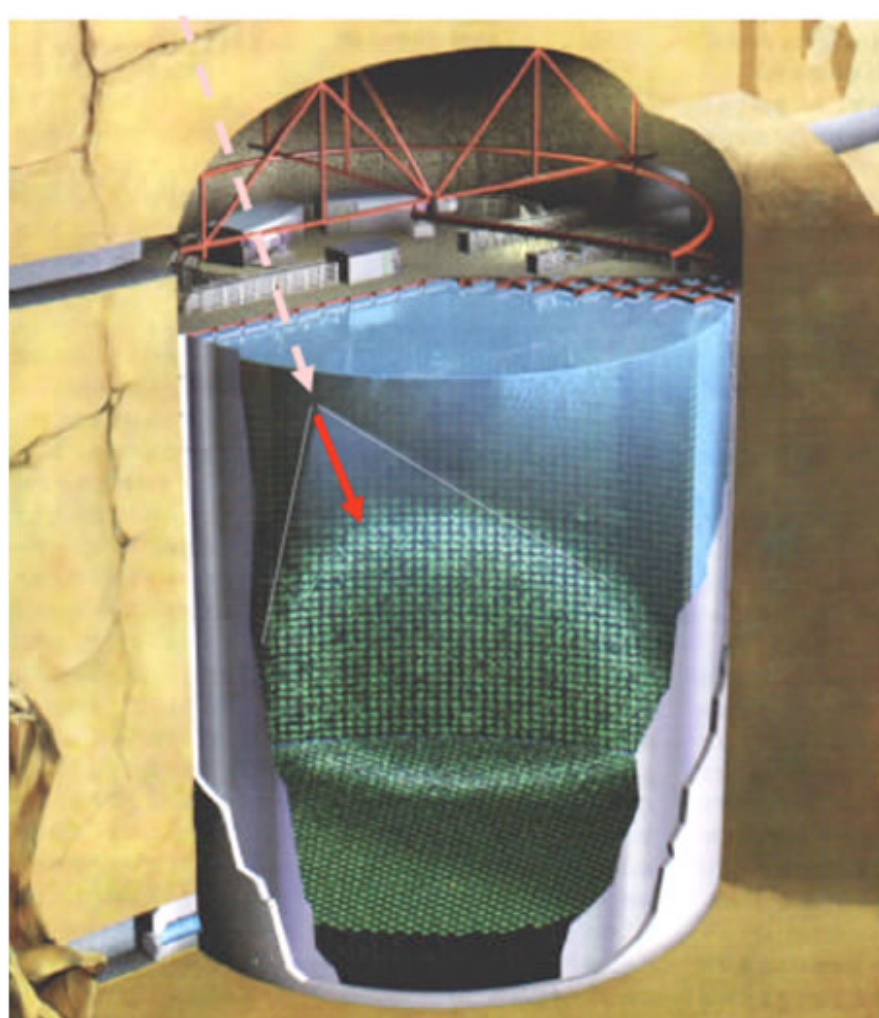
- Mikheyev–Smirnov–Wolfenstein (MSW) effect causes all ν_e to adiabatically convert to ν_2 [1].
- Required density increases with decreasing energy, so only vacuum oscillations below ≈ 1 MeV.
- “Upturn” in ν_e survival probability (P_{ee}) has not been observed due to high radioactive background.



P_{ee} as a function of neutrino energy with measurements from various experiments. The green (blue) lines show the expected P_{ee} based on the solar (solar+KamLAND) oscillation parameters. The red band shows the SK+SNO 1σ region based on a quadratic fit to their electron energy spectra [2].

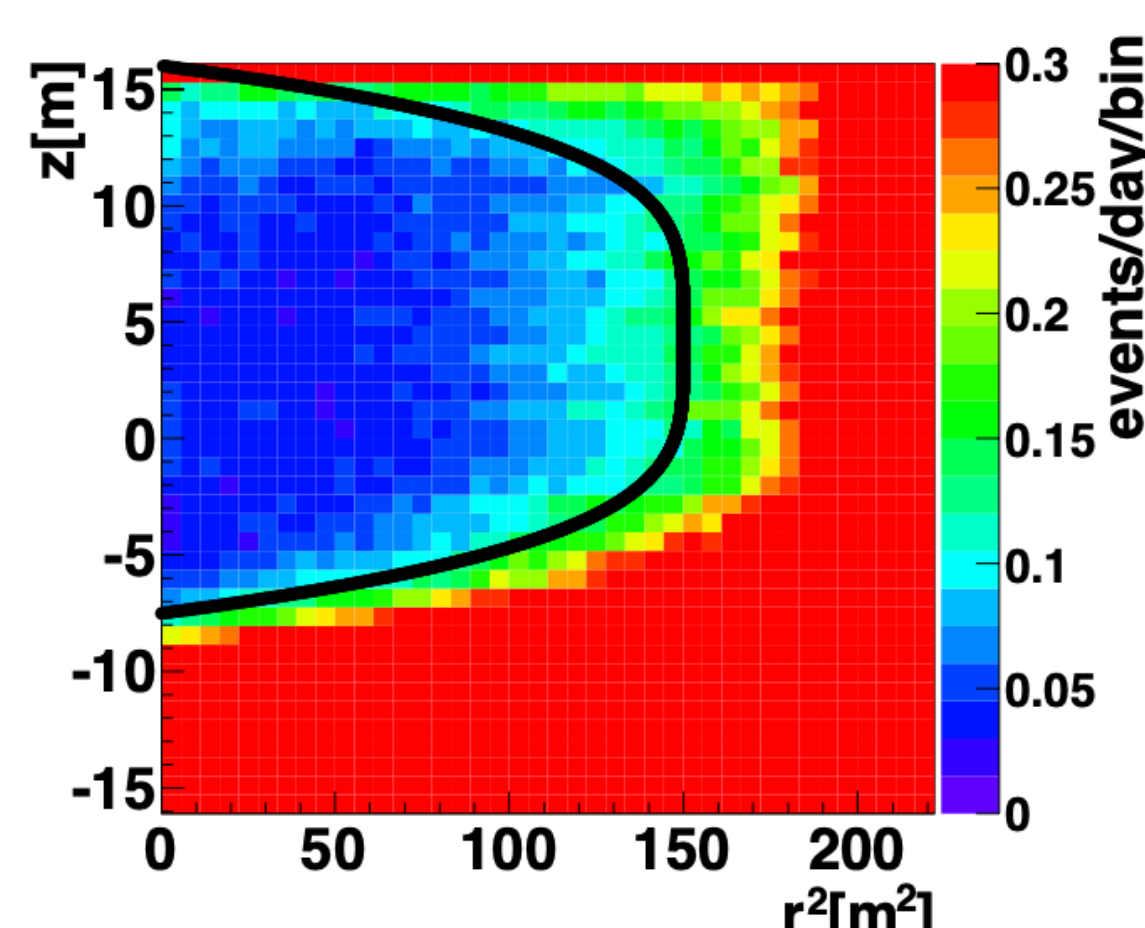
2. Super-Kamiokande

- 50 kton water Cherenkov detector [3].
- 1 km under Mt. Ikeno, Japan.
- 39 m diameter x 41 m height.
- 11,129 20” photomultiplier tubes (PMTs) in inner detector.
- SK-IV (Oct. 2008 - May 2018) is the longest phase of the experiment with the lowest energy threshold.



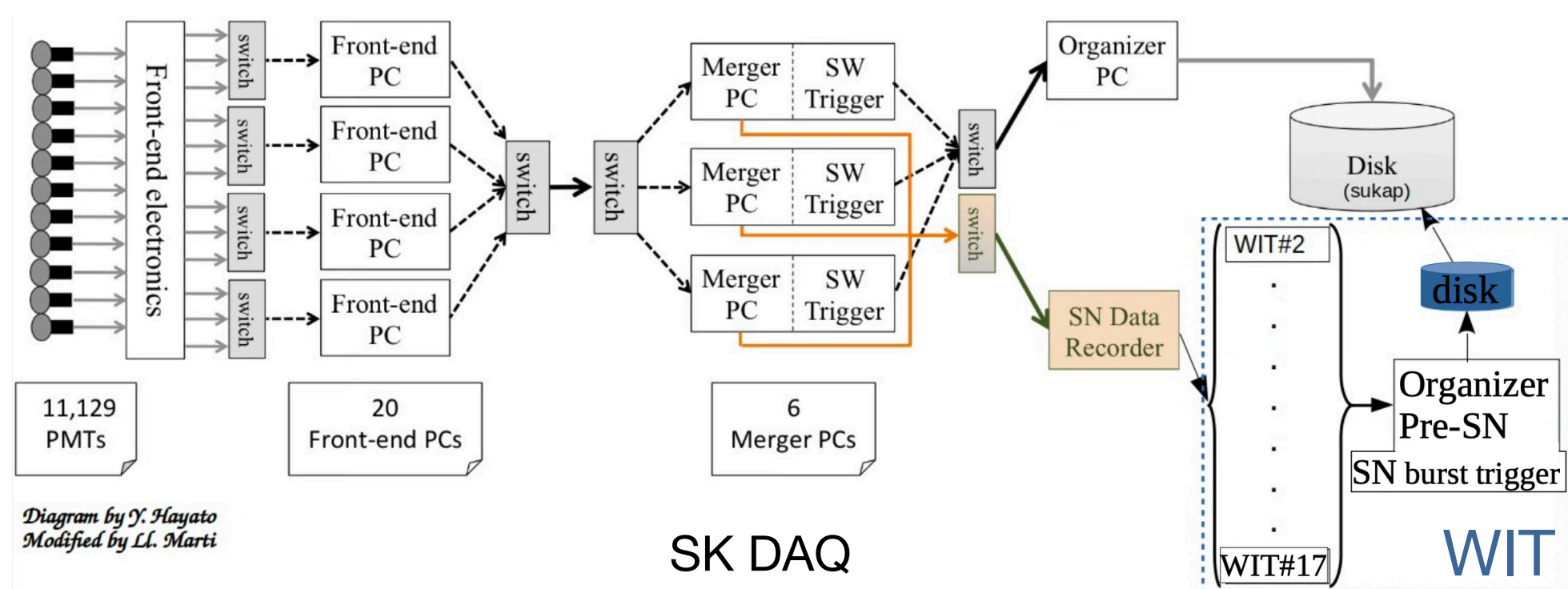
3. Radioactive Background

- Radon gas from mine enters detector. ^{214}Bi β -decay (3.3 MeV Q-value) [4].
- PMT glass ^{208}Tl $\beta\gamma$ -decay (5.0 MeV Q-value, 2.2 MeV γ).
- Cosmic ray muon spallation and resulting hadronic showers on ^{16}O produce ^{16}N , β -decay seconds later, meters away from track [6].



SK-IV event distribution in 3.49 MeV to 3.99 MeV [5]. Water currents are designed to keep a still, clean region in the center-top.

4. DAQ Trigger Systems

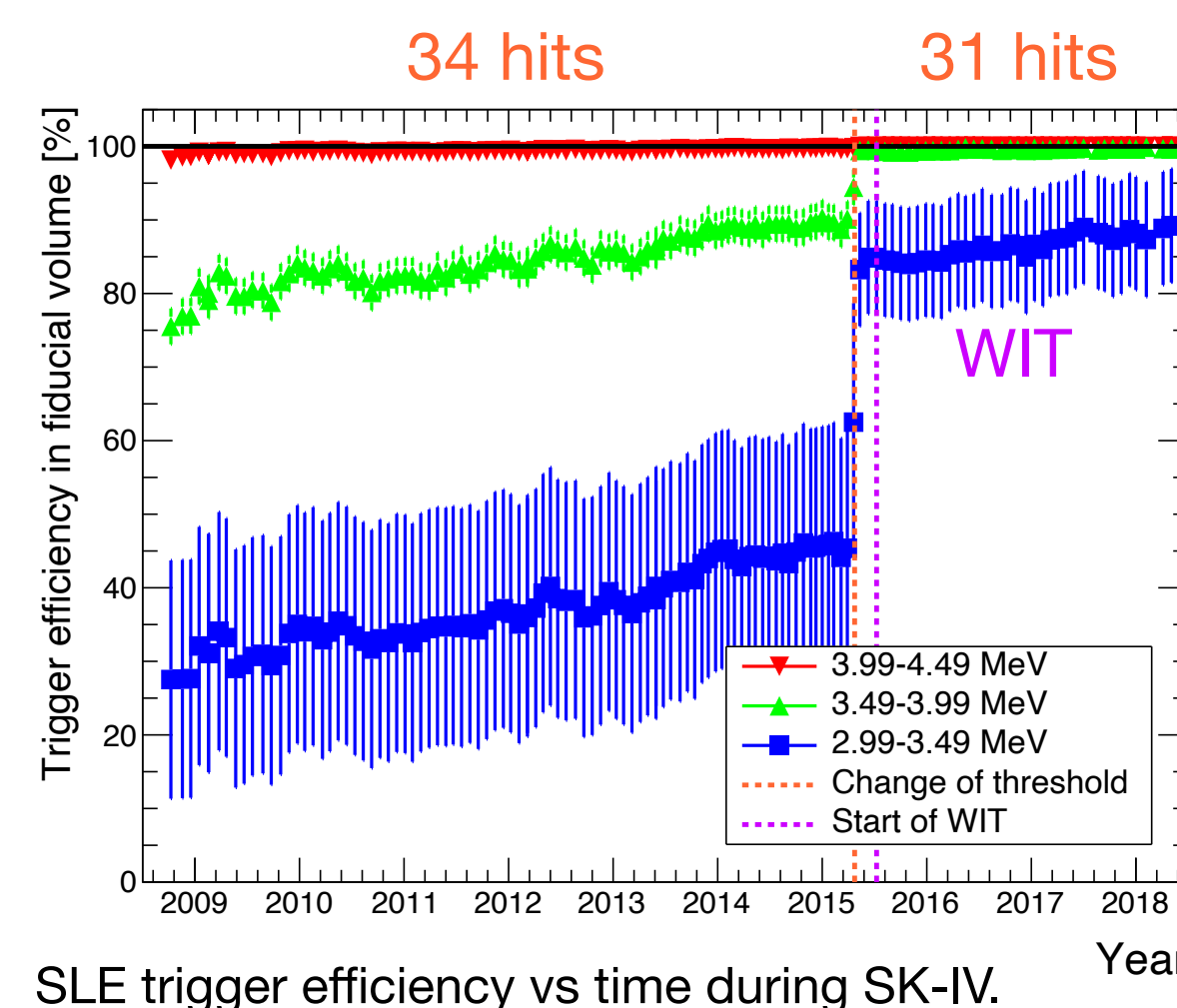


- Two independent triggers in DAQ: software trigger and wideband intelligent trigger (WIT).
- Software trigger uses simple hit coincidence.
- WIT is system of CPUs that, after looser hit pre-trigger, conduct simultaneous online event reconstruction to increase background rejection and preserve lower energy events [7].

5. Lowering Trigger Threshold

- Several efforts to lower trigger threshold near end of SK-IV.

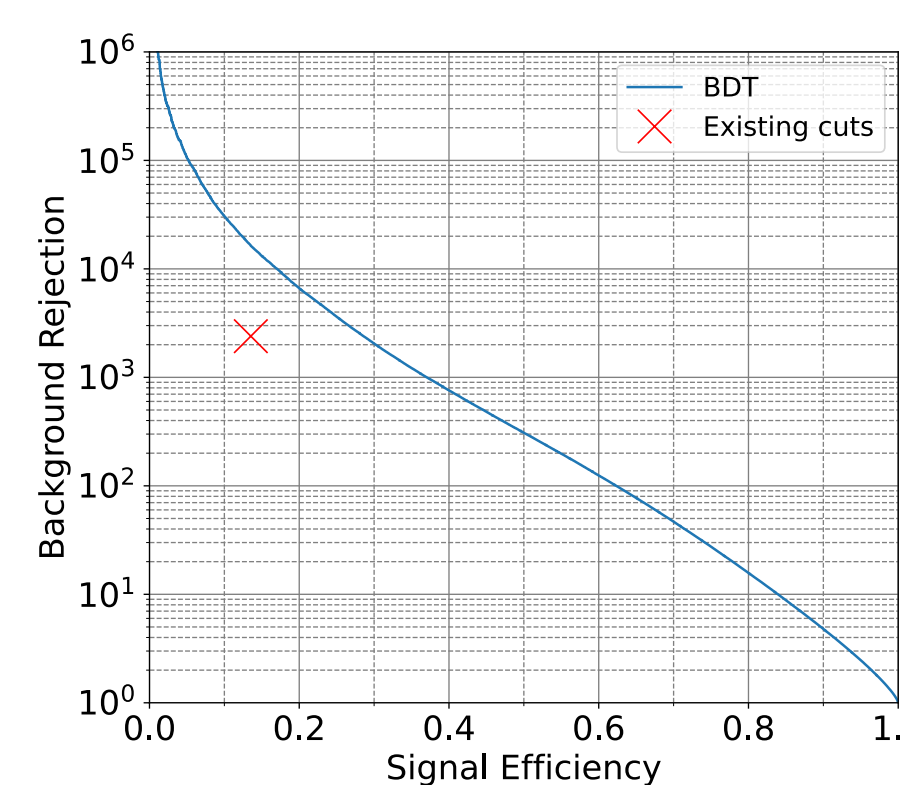
- Software trigger “SLE” (super lower energy) threshold lowered from 34 hits to 31 hits in 230 ns [2].



- WIT introduced shortly after with >95% pre-trigger efficiency down to 2.49 MeV [8].

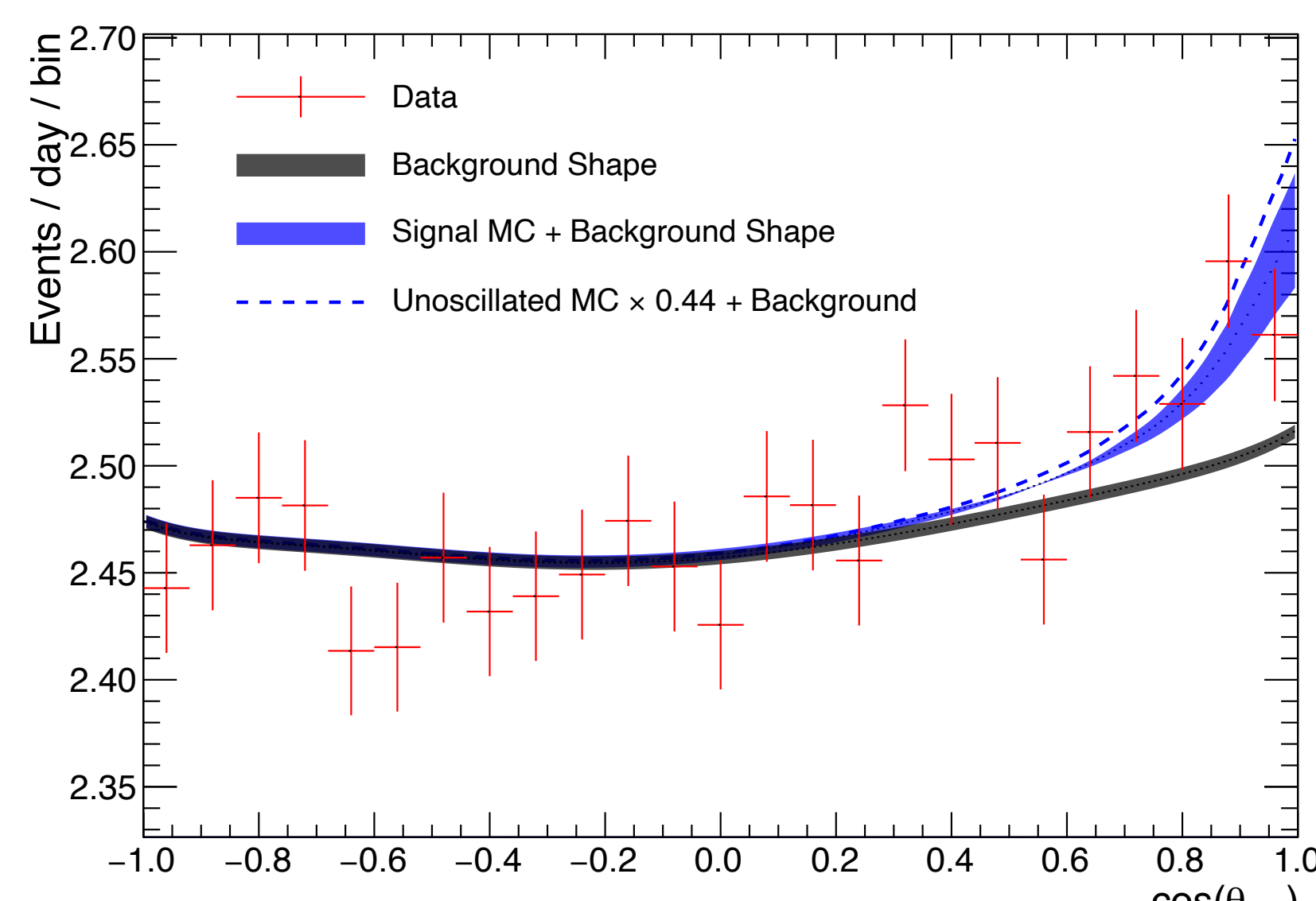
6. Event Selection

- Various machine learning methods studied to improve background rejection using reconstructed variables and/or PMT hit inputs.
- Convolutional neural network with event display images [9]
- Graph neural network with PMT hits
- Boosted decision tree (BDT) with reconstructed variables used in the cut-based solar analysis (e.g. position, direction, energy, distance to wall, goodness of fit, etc.)
- Hybrid input methods with both reconstructed variables and PMT hits
- BDT provides 6.8x background rejection vs previous selection cuts in 2.49–3.49 MeV E_{kin} .
- BDTs for radioactive background rejection and existing cosmic ray muon spallation cut applied to SK-IV WIT, SLE 34-hit, and SLE 31-hit (not overlapping with WIT) data.



Background rejection (inverse acceptance) vs signal efficiency ROC curve for 2.49–3.49 MeV WIT dataset.

7. Signal Extraction



Solar angle distribution in 2.99–3.49 MeV aggregated over the WIT and SLE 34-hit datasets for data selection (red), calculated background shape (black), and calculated signal shape added to background shape (blue) all with 1σ statistical error bands. The blue dashed line indicates the signal shape if the average interaction rate in 3.49–19.49 MeV measured in [2] is assumed.

- Following [2], create “shapes” in solar angle for signal and background.
- Data-driven background shape calculation. Two methods compared for background shape systematic uncertainty, which dominates systematics due to low signal to background ratio.
- “Solfit” maximum likelihood fitter determines number of signal and background events based on data and shapes.

References:

- [1] S.P. Mikheyev, A.Y. Smirnov. *Resonant amplification of ν oscillations in matter and solar-neutrino spectroscopy*. Il Nuovo Cimento C 9, 17–26 (1986).
- [2] K. Abe, et al. *Solar neutrino measurements using the full data period of Super-Kamiokande-IV*. Phys. Rev. D 109, 092001 (2024).
- [3] S. Fukuda, et al. *The Super-Kamiokande detector*. Nucl. Instr. and Meth. A 501, 418–462 (2003).
- [4] Y. Nakano, et al. *Measurement of the radon concentration in purified water in the Super-Kamiokande IV detector*. Nucl. Instr. and Meth. A 977, 164297 (2003).
- [5] K. Abe, et al. *Solar neutrino measurements in Super-Kamiokande-IV*. Phys. Rev. D 94, 052010 (2016).
- [6] Y. Zhang, et al. *First measurement of radioactive isotope production through cosmic-ray muon spallation in Super-Kamiokande IV*. Phys. Rev. D 93, 012004 (2016).
- [7] M. Elmir, et al. *Low Energy ^{18}O Solar Neutrinos with the Wideband Intelligent Trigger at Super-Kamiokande*. J. Phys.: Conf. Ser. 888, 012189 (2017).
- [8] A. Yankelevich, et al. *Measurement of the solar neutrino interaction rate below 3.49 MeV in Super-Kamiokande-IV*. Phys. Rev. D 113, 112001 (2026).
- [9] N. Prouse, P. de Perio, and W. Fedorko. *Machine Learning Techniques to Enhance Event Reconstruction in Water Cherenkov Detectors*. Phys. Sci. Forum 8, 63 (2023).

7. Interaction Rate

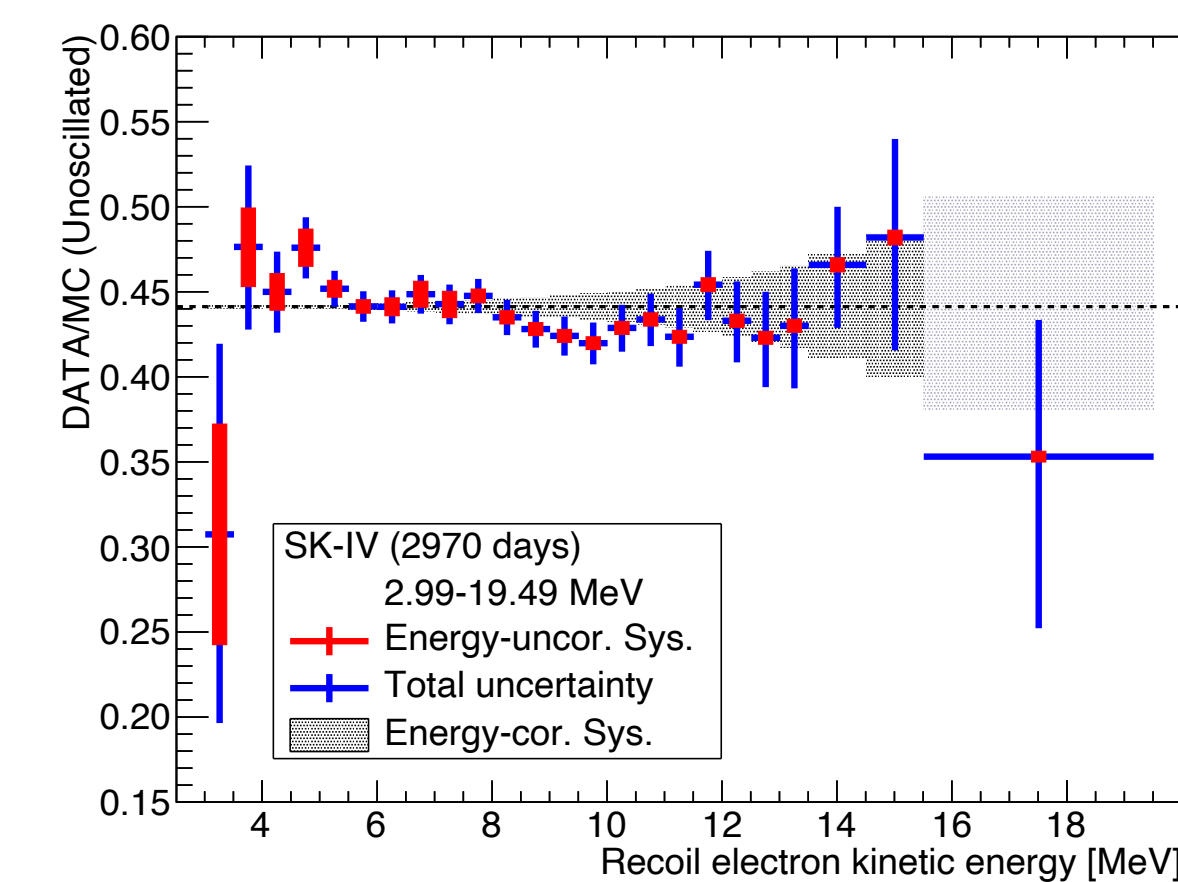
Dataset	E_{kin} Bin Range	Observed Signal	Data/MC (Unosc.)
WIT (618 days)	2.49–2.99 MeV	25^{+83}_{-81}	$0.11^{+0.37}_{-0.36}$
	2.99–3.49 MeV	$457^{+159}_{-157} \pm 69$	$0.425^{+0.148}_{-0.146} \pm 0.064$
SLE 34-hit (2047 days)	2.99–3.49 MeV	$213^{+141}_{-140} \pm 98$	$0.196^{+0.130}_{-0.128} \pm 0.090$
SLE 31-hit* (305 days)	2.99–3.49 MeV	23^{+77}_{-74}	$0.08^{+0.26}_{-0.26}$
WIT+SLE 34-hit	2.99–3.49 MeV	$667^{+198}_{-195} \pm 143$	$0.307^{+0.091}_{-0.090} \pm 0.066$

*Only when WIT not available.

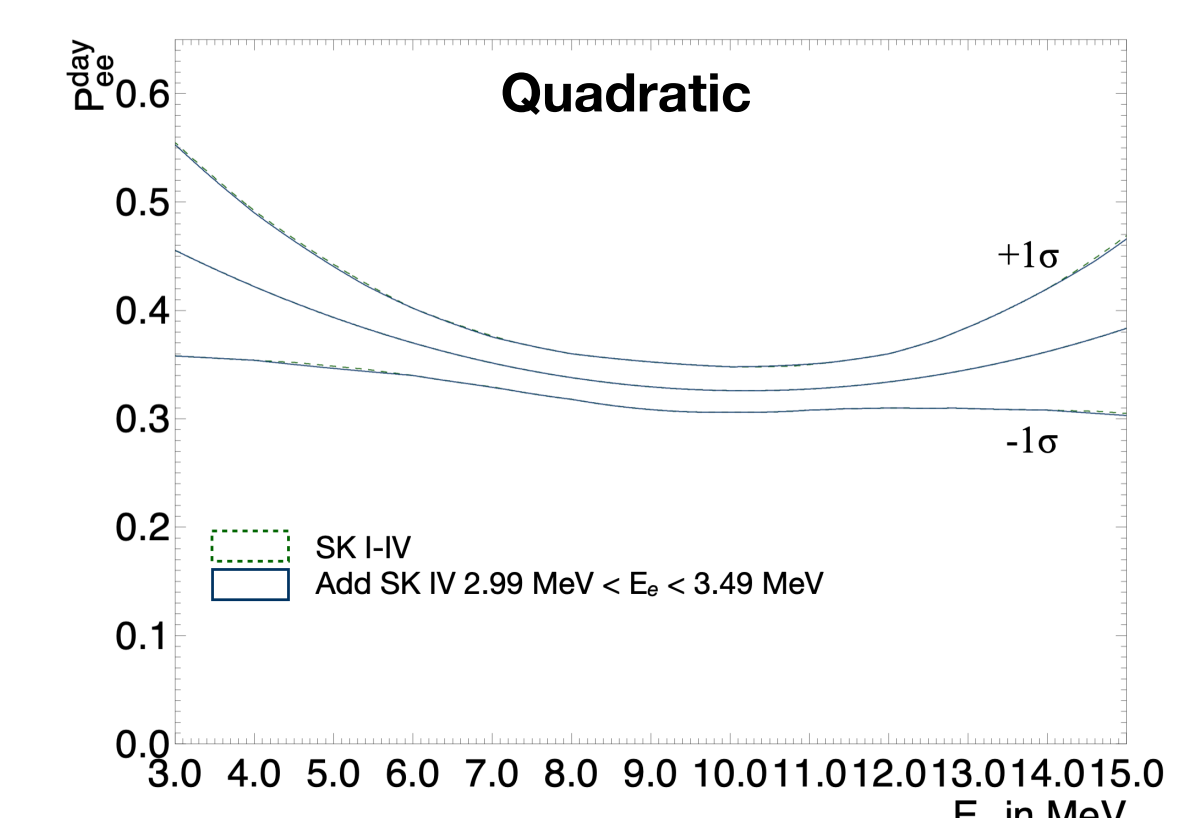
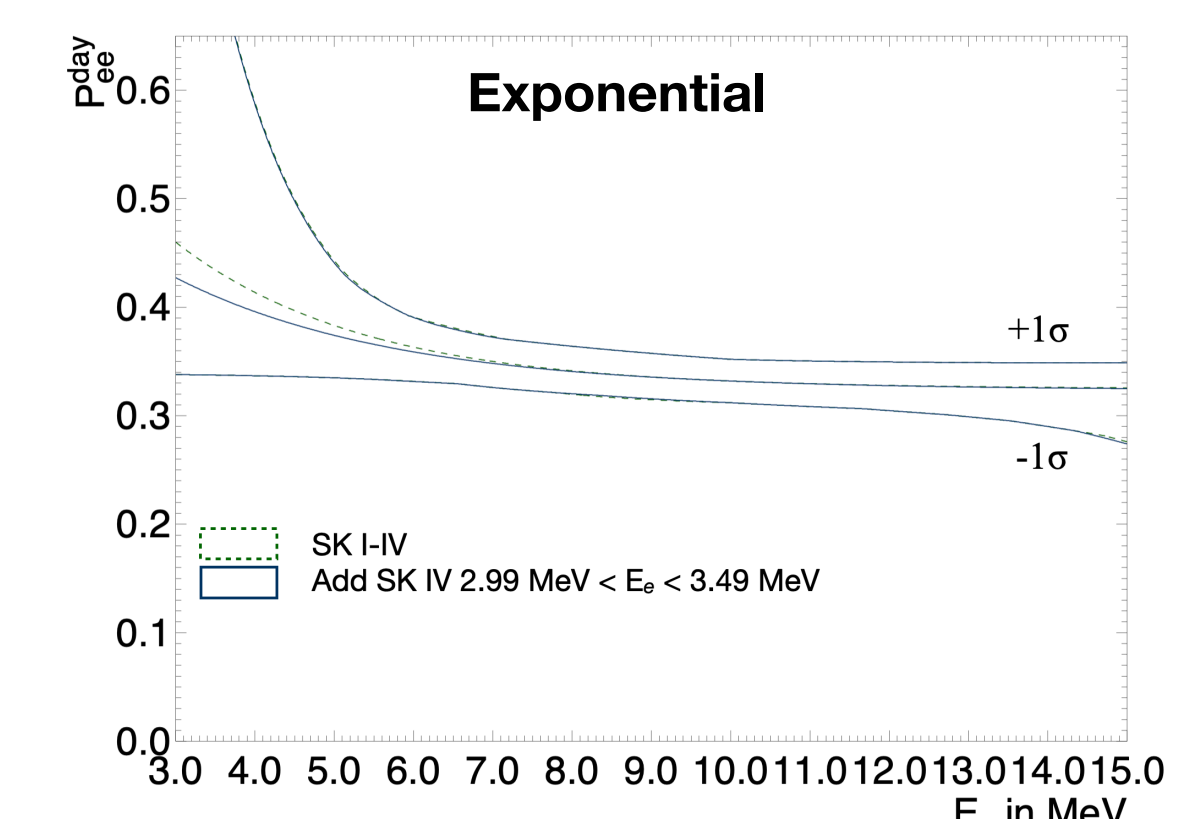
measurement $\pm$ stat. $\pm$ syst. (when signal observed)

- 2.76 σ** solar neutrino indication in combined 2.99–3.49 MeV measurement.
- 1.20 σ deficit compared to average Data/MC in 3.49–19.49 MeV (energy-independent / no upturn case) and 1.47 σ to prediction with upturn [2].
- Equivalent to solar neutrino flux of $1.61^{+0.48}_{-0.47} \pm 0.35 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$.
- Signal not observable in 2.49–2.99 MeV (high background) or SLE 31-hit (too little livetime).

8. Energy Spectra



- Combine this SK-IV 2.99–3.49 MeV measurement with full SK dataset and repeat fits to P_{ee} spectra.



P_{ee} as a function of neutrino energy obtained from the exponential (top) and quadratic (bottom) fits to SK recoil electron data. The green dashed lines use all SK-IV and earlier data from [2], and the blue solid lines adds the additional 2.99–3.49 MeV E_{kin} bin for SK-IV. The best fits and 1σ confidence intervals are shown.

- Low impact on fits due to better sensitivity of higher energy bins, but observe slight decrease in upper confidence interval at lower energies and noticeable shift in exponential best fit due to lower DATA/MC measurement compared to higher energy bins.

10. Summary and Future Sensitivity

- First indication of solar neutrino signal indication in radioactivity-dominated energy region <3.49 MeV, but uncertainty too large to improve upturn measurement.
- Will need higher energy threshold (≈ 3.99 MeV) during later SK phases.
- Primary goals of future SK solar analyses are day-night effect (currently 3.1σ) and *hep* neutrino search.

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