Measurement of below 3.49 MeV solar neutrinos at Super-Kamiokande

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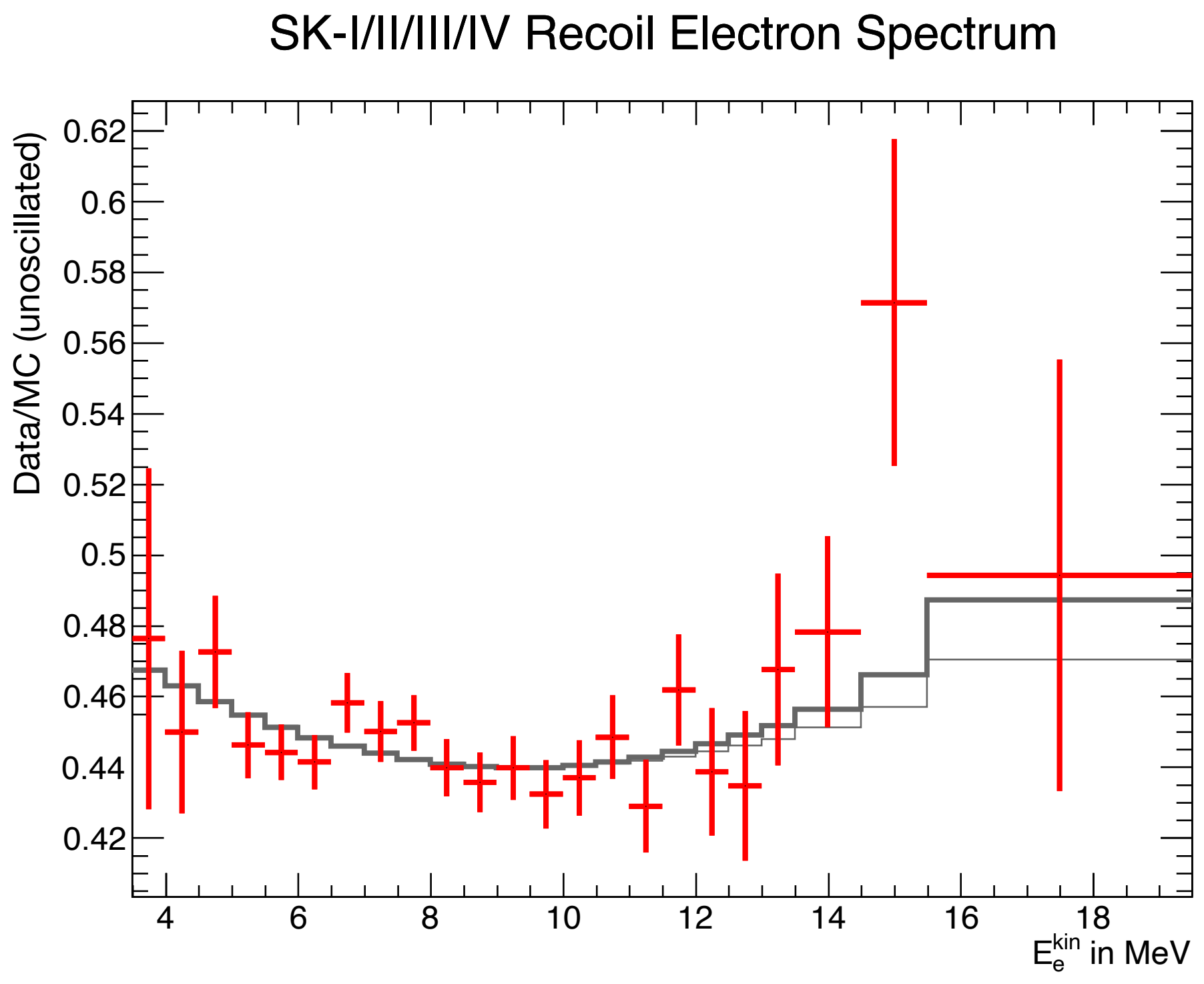
1. Mikheyev–Smirnov–Wolfenstein Effect

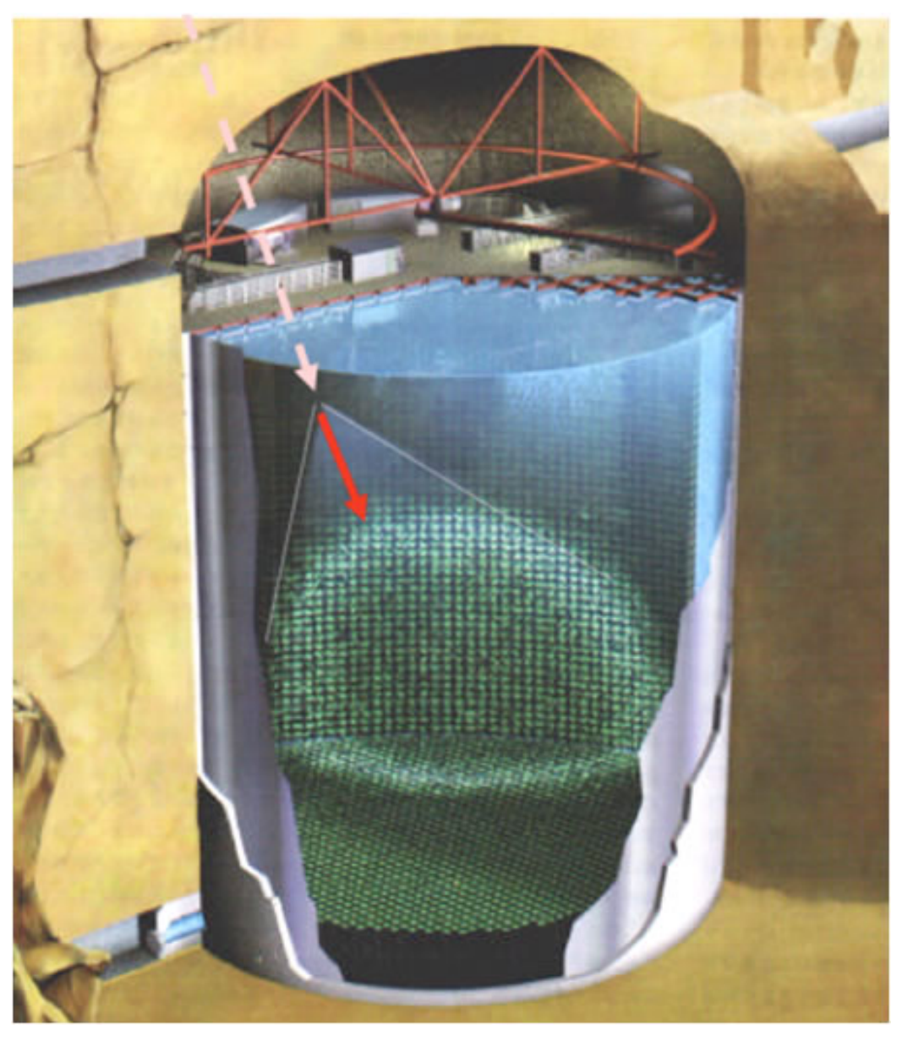
- ν_e produced in the core of the sun through ^{8}B decay at ~10 MeV adiabatically convert to mass state ν_2 via the MSW effect [1] as they pass through a resonant mass density region.
- ~1 MeV ν_e do not undergo this conversion.
- The transition from MSW-dominant to vacuum-dominant flavor conversions would lead to an upturn in the ν_e survival probability at lower energies.

SK-I/II/III/IV Recoil Electron Spectrum



Energy spectrum of ratio of selected ν_e solar events divided by the expected event rate assuming no neutrino oscillation for combined SK I-IV periods [2]. The thin grey line shows the quadratic best fit. The thick grey line accounts for energy scale, energy resolution, and neutrino spectrum systematic shifts.

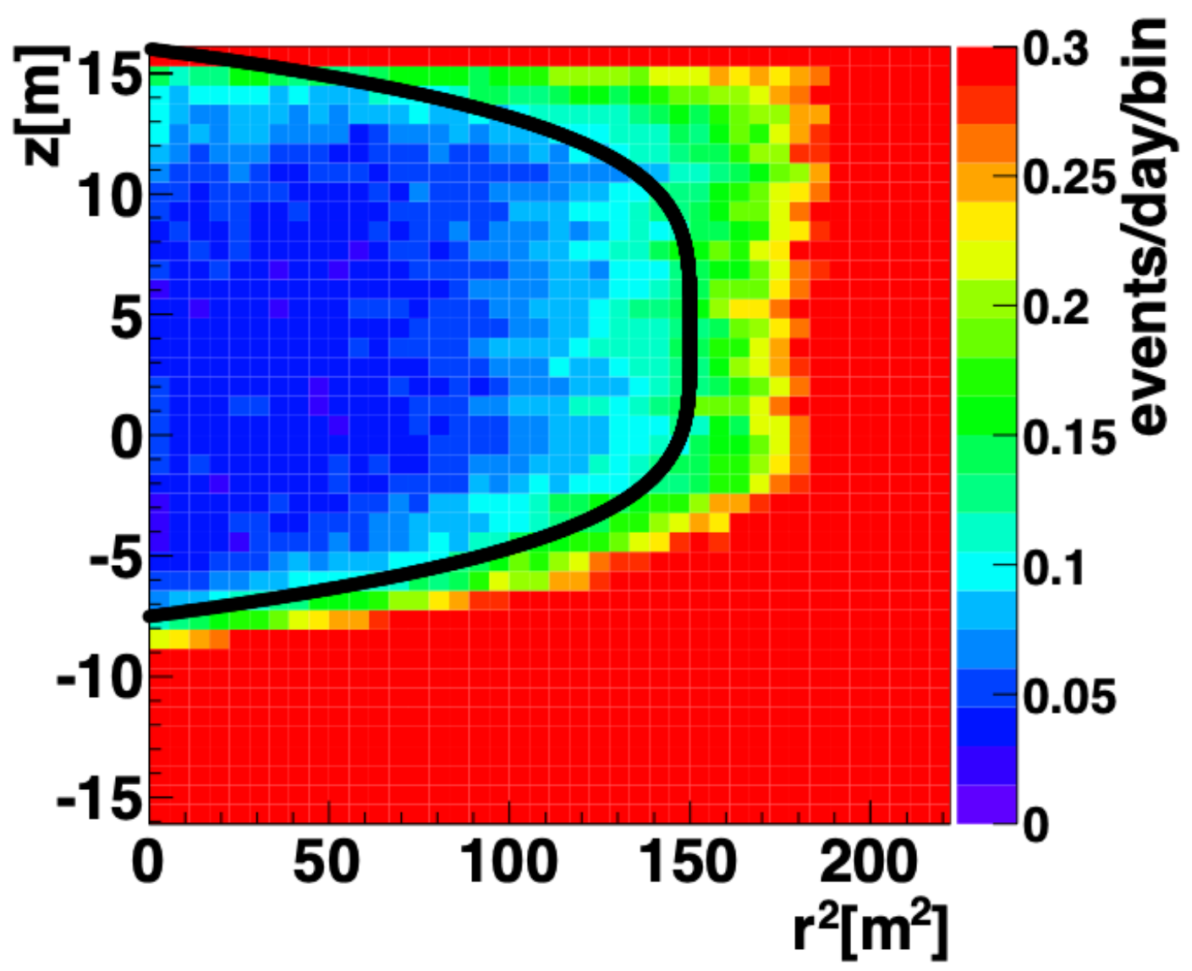
2. About Super-Kamiokande



- 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. Sources of Background

- ^{214}Bi beta decay from radon gas near the walls and the bottom half of the detector [4]
- ^{208}Tl beta decay followed by gamma decay from PMT glass



SK-IV event distribution in 3.49 MeV to 3.99 MeV [5].

- Cosmic ray muon spallation and resulting neutron clouds [6]

4. Wideband Intelligent Trigger

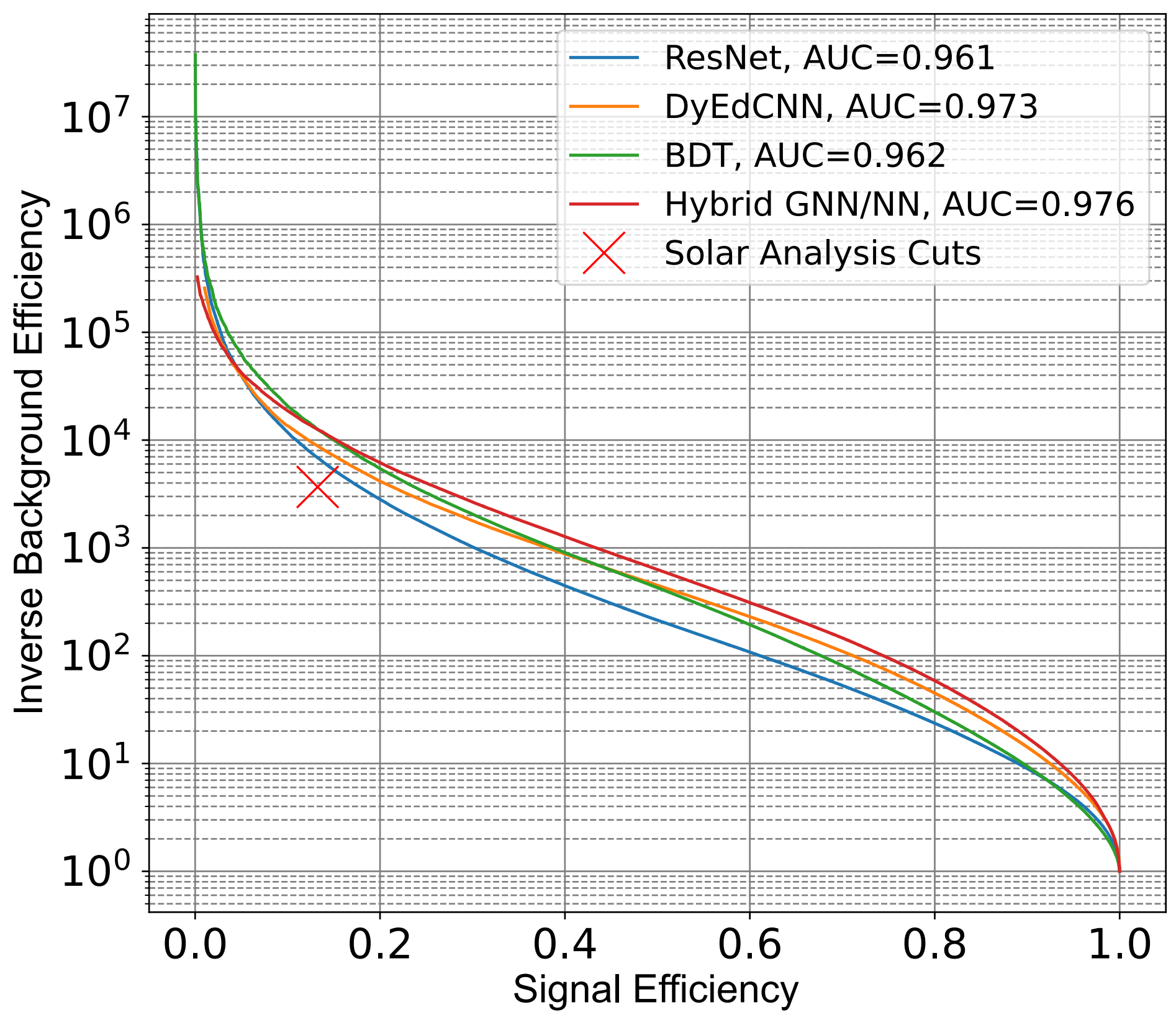
- Alternative WIT DAQ conducts simultaneous online event reconstruction and triggering to preserve lower energy events [7].
- Began July 2015 during SK-IV with up to 196 reconstruction processes on 7 computers, now 796 processes on 16 computers.
- >90% triggering efficiency down to 2.99 MeV.

Abstract

Super-Kamiokande has observed ^{8}B solar neutrino elastic scattering on electrons with recoil electrons at kinetic energies as low as 3.49 MeV to study neutrino flavor conversion within the sun. At SK-observable energies, these conversions are dominated by the Mikheyev–Smirnov–Wolfenstein effect. An upturn in the electron survival probability in which vacuum neutrino oscillations become dominant is predicted to occur at lower energies, but radioactive background increases exponentially with decreasing energy. New machine learning approaches provide substantial background reduction below 3.49 MeV such that statistical extraction of solar neutrino interactions becomes feasible. Measurements of the solar neutrino flux in this energy region using a boosted decision tree for event selection are presented.

5. 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
  - 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
  - Train only on difficult-to-reject background
  - Loss functions for class-imbalanced datasets
- BDT for radioactive background rejection and existing cosmic ray muon spallation cut applied to 618 days SK-IV WIT data.



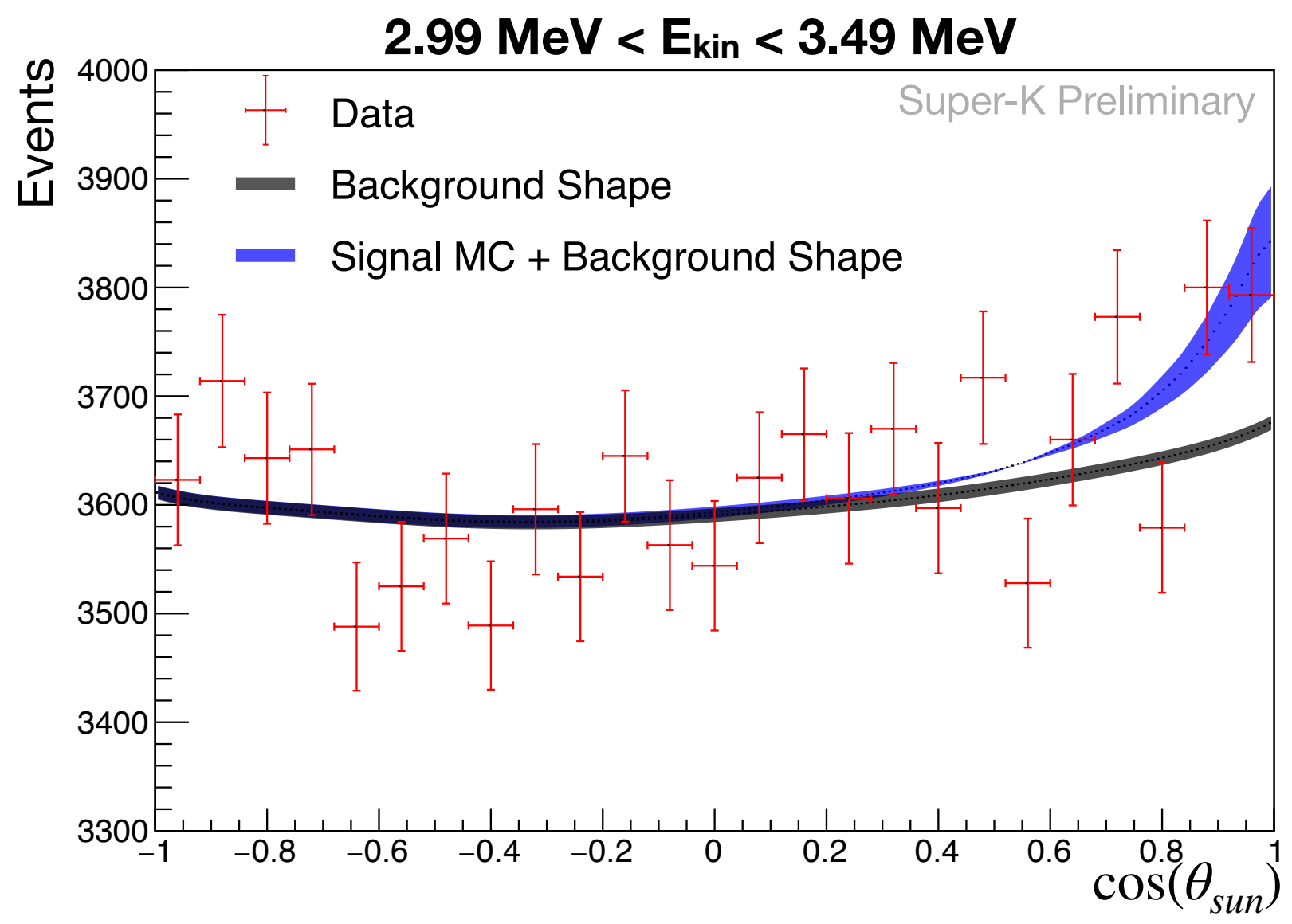
Rejection ROC curve for 2.49 MeV - 3.49 MeV. Legend shows area under the curve (AUC) values on a standard ROC curve.

6. Signal Extraction

- Using the “scramble” method, the *background shape* for the solar angle distribution is $\cos(\theta_{sun}^{ij}) = \hat{d}_i \cdot \hat{s}_j$ for all possible pairs of event direction $\hat{d}_i$ and solar direction and $\hat{s}_j$ in the sample. This isolates events with directions that have no correlations in detector coordinates.
- *Signal shape* is polynomial fit of solar MC $\cos(\theta_{sun})$.
- “solfit” [2] is a maximum likelihood fitter that calculates the number of solar neutrino signal events given the background and signal solar angle distribution 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. Elnimr, et al. *Low Energy ^{8}B Solar Neutrinos with the Wideband Intelligent Trigger at Super-Kamiokande*. J. Phys.: Conf. Ser. **888,** 012189 (2017).

7. Solar Angle Distribution



Solar angle distribution for BDT selection (red), background shape (black), and signal MC shape added to background shape (blue) all with 1σ statistical error bands.

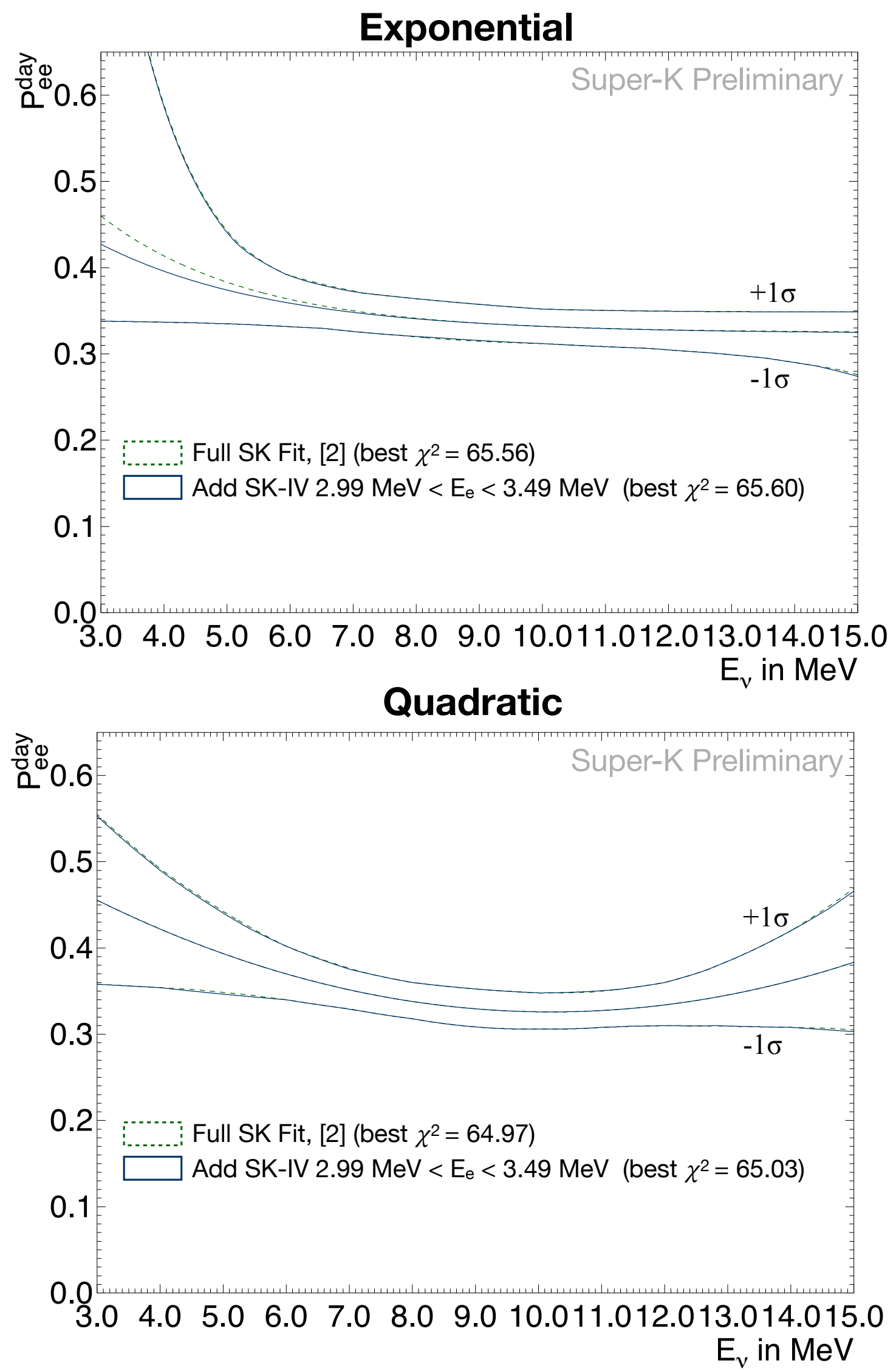
8. Solar Neutrino Flux

E_{kin} Bin Range	Signal	Data/MC (Unosc.)	Flux (10^6 cm^{-2} s^{-1})
2.99 MeV - 3.49 MeV	$457^{+159}_{-157} \pm 69$	$0.425^{+0.148}_{-0.146} \pm 0.064$	$2.23^{+0.78}_{-0.77} \pm 0.33$

Observed number of signal events and their implied ratio to expected unoscillated events and solar neutrino flux reported as measurement ± statistical ± systematic error.

- Solar signal observable in 2.99 MeV - 3.49 MeV bin.
- Due to large statistical error, DATA/MC is consistent with both no-upturn case (0.4268) and hint of upturn observed in published SK-IV lowest energy bins [2].

9. ν_e Survival Probability



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

- Combine this 2.99 MeV - 3.49 MeV bin measurement with full SK dataset and repeat fits to ν_e survival probability spectra.
- Low impact on fits due to better signal:background ratio and higher livetime in 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. Future Work

- Aim to reduce statistical error by applying BDT to following SK phases as well as traditional DAQ SK-IV data despite reduced trigger efficiency.
- Continue to research improvements in selection methods with both raw hit and reconstructed variable inputs.

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