

Solar neutrino results with the full data period until Super-Kamiokande-IV

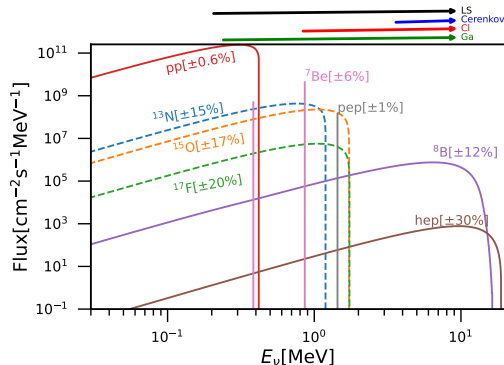
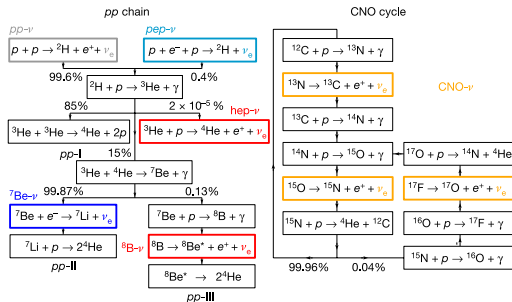
Yiyang Wu on behalf of Super-KamiokaNDE Collaboration

2025-08-26 TUAP @ Xichang



Solar Neutrinos at SuperK

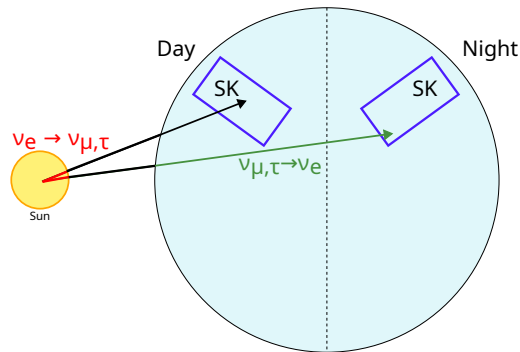
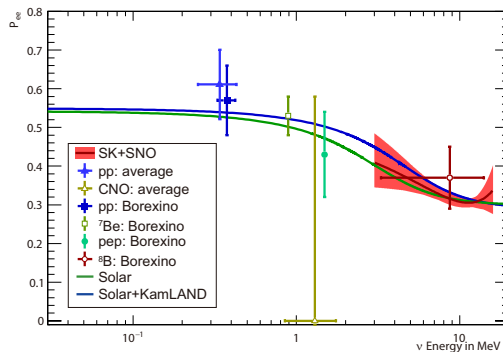
Nuclear fusion (pp chain and CNO cycle) in core of the Sun produce solar neutrinos



SuperK is sensitive to ${}^8\text{B}$ and hep neutrinos via elastic scattering on electrons

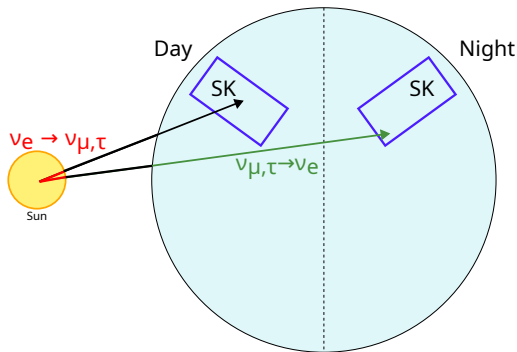
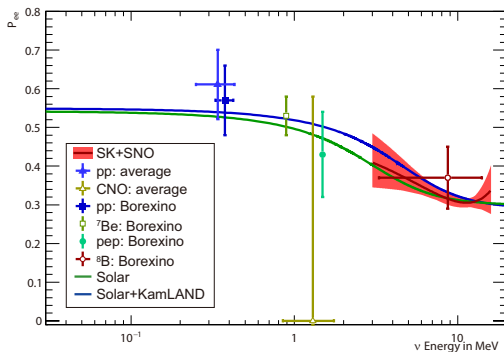
Neutrino Oscillation with Matter Effect

- MSW upturn in survival $P_{ee}(E_\nu)$



Neutrino Oscillation with Matter Effect

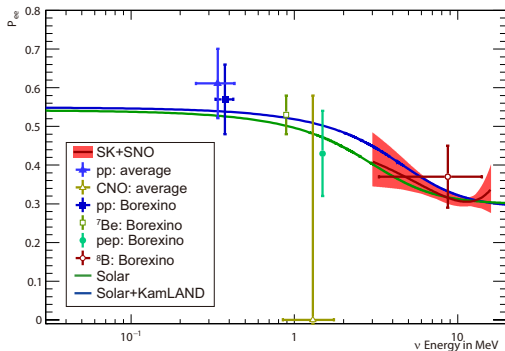
- MSW upturn in survival $P_{ee}(E_\nu)$



- Measure $(\sin \theta_{12}, \Delta m_{21}^2)$

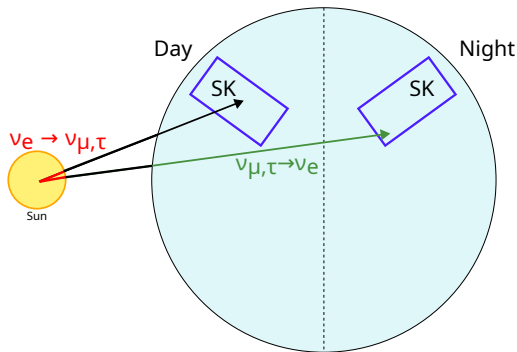
Neutrino Oscillation with Matter Effect

- MSW upturn in survival $P_{ee}(E_\nu)$



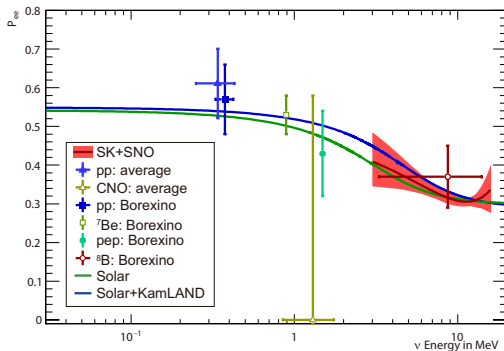
- Measure $(\sin \theta_{12}, \Delta m_{21}^2)$

- Earth MSW: day-night asymmetry



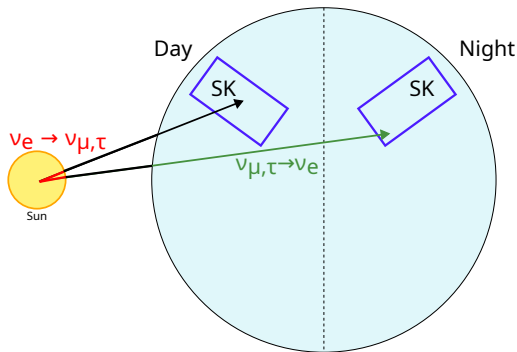
Neutrino Oscillation with Matter Effect

- MSW upturn in survival $P_{ee}(E_\nu)$



- Measure $(\sin \theta_{12}, \Delta m_{21}^2)$

- Earth MSW: day-night asymmetry



- Other topics: periodic modulation; search for *hep* neutrino

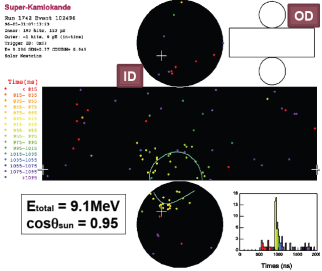
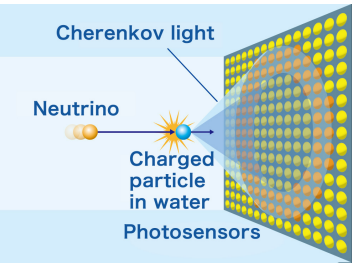
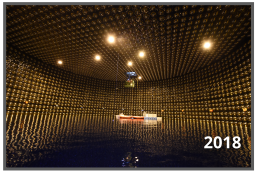
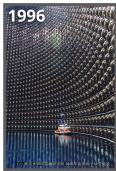
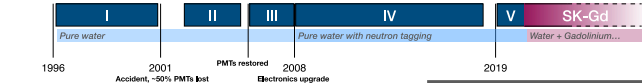
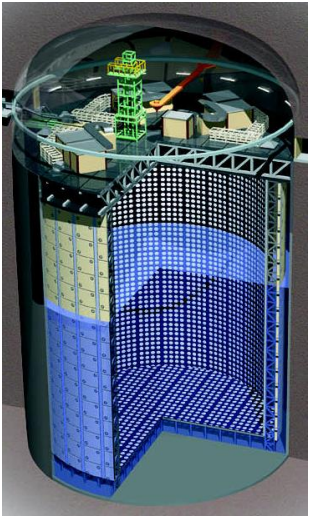
Solar neutrino results with the full data period until Super-Kamiokande-IV

Super-KamiokaNDE

Solar Neutrinos at SuperK

Solar Neutrino Analysis and Results

Backup

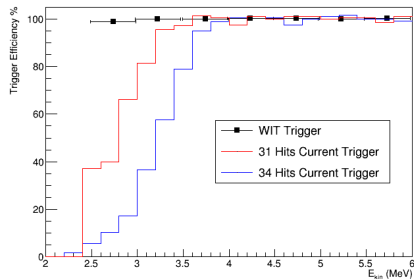


Progress made in SuperK solar neutrino analysis

- Full SK-IV solar neutrino measurements arXiv:2312.12907
 - Updated $(\sin \theta_{12}, \Delta m_{21}^2)$ measurements
 - Evidence of solar neutrino earth matter effect approaches 3σ

Progress made in SuperK solar neutrino analysis

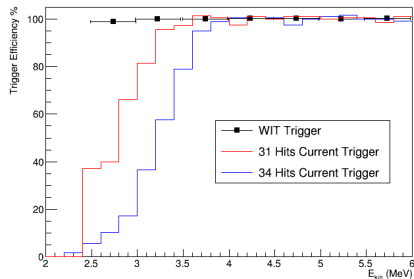
- Full SK-IV solar neutrino measurements arXiv:2312.12907
 - Updated $(\sin \theta_{12}, \Delta m_{21}^2)$ measurements
 - Evidence of solar neutrino earth matter effect approaches 3σ
- MSW upturn at < 4 MeV
 - Lower energy threshold: down to 2.5 MeV with Wideband Intelligent Trigger (WIT)
 - Machine learning to reduce background and find evidence of solar neutrino



Progress made in SuperK solar neutrino analysis

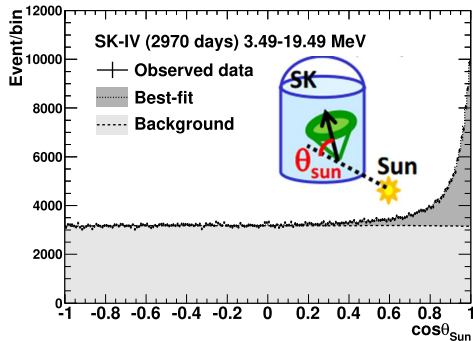
- Full SK-IV solar neutrino measurements arXiv:2312.12907
 - Updated $(\sin \theta_{12}, \Delta m_{21}^2)$ measurements
 - Evidence of solar neutrino earth matter effect approaches 3σ

- MSW upturn at < 4 MeV
 - Lower energy threshold: down to 2.5 MeV with Wideband Intelligent Trigger (WIT)
 - Machine learning to reduce background and find evidence of solar neutrino



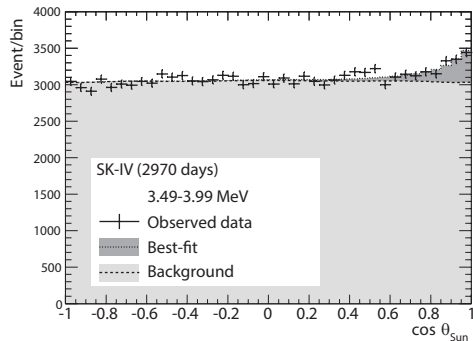
- Periodic modulation arXiv:2311.01159
 - Earth elliptic orbit modulation detected.
 - No other modulation found, stable $^8\text{B}-\nu$ flux from solar core.

Solar Neutrino Analysis and Results



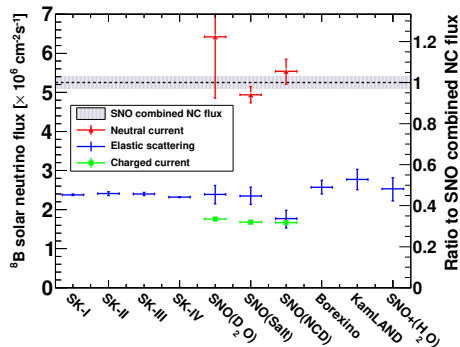
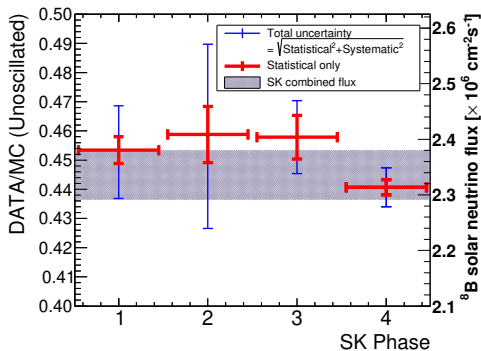
$$65443_{-388}^{+390}(\text{stat.}) \pm 925(\text{syst.})$$

$$\Phi_{\text{B}} = (2.314 \pm 0.014 \pm 0.040) \times 10^6 \text{ cm/s}$$



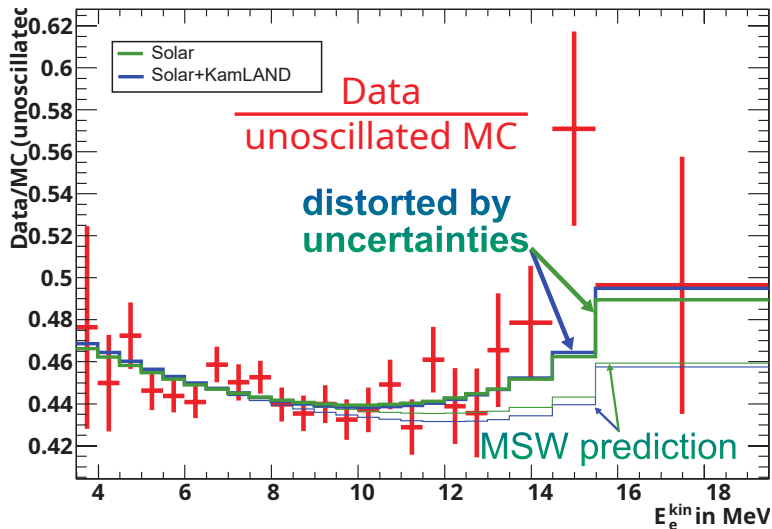
- Radioactive Rn backgrounds dominates MSW upturn region

^8B - ν measurements in each phase

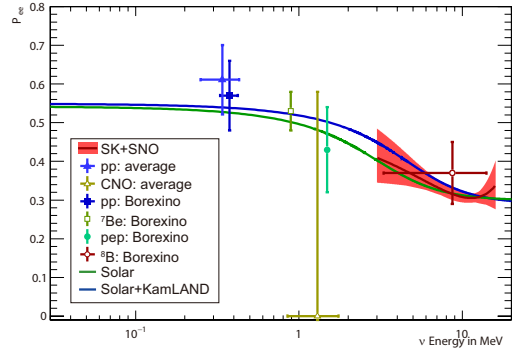
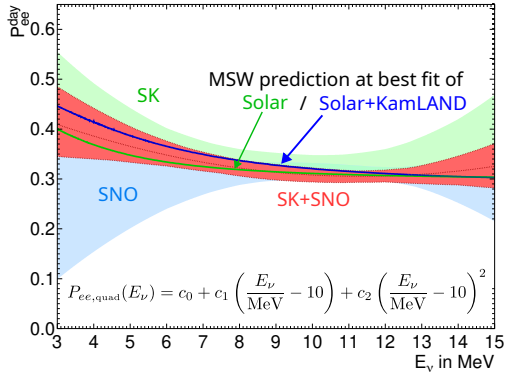


- Best ^8B - ν flux precision
- $\Phi_B = (2.336 \pm 0.011 \pm 0.043) \times 10^6 \text{ cm}^2/\text{s}$ combining SK I-IV

SK I-IV combined recoil electron spectrum

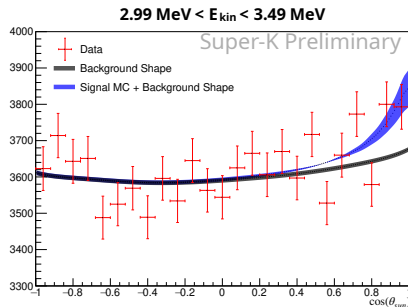
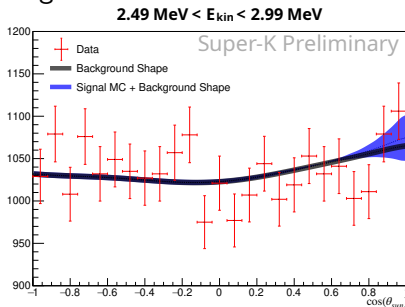


Solar ν_e survival probability spectrum



- Strongest constraints on survival probability spectrum in upturn region.

- 618 days livetime in SK-IV. Machine learning (BDT) further suppress background



1σ statistical error bands

Observed: 25^{+83}_{-81}

$457^{+159}_{-157} \pm 69$ **2.6σ**

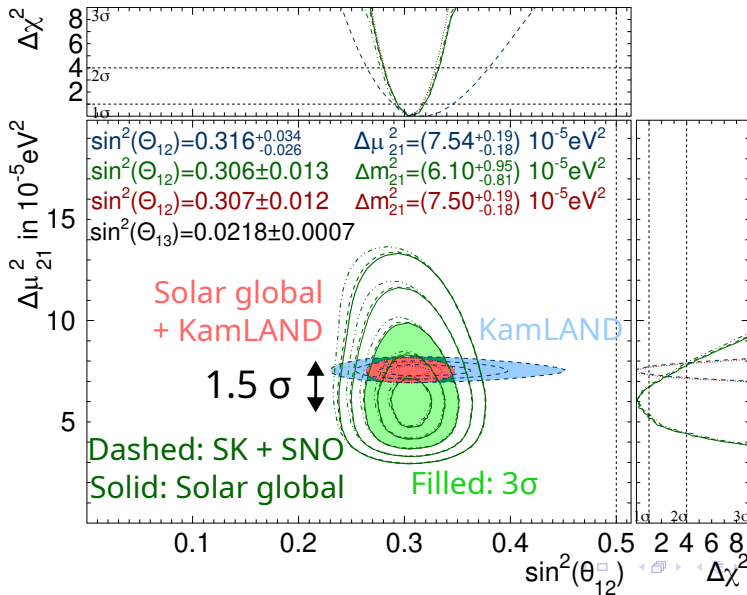
Observed/Expected: $0.11^{+0.37}_{-0.36}$

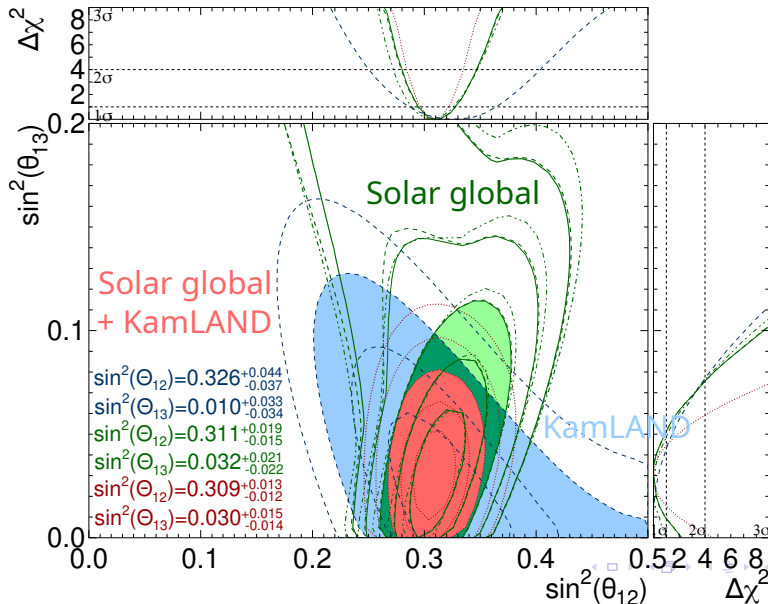
$0.425^{+0.148}_{-0.146} \pm 0.064$

Measurement $\pm$ stat

Measurement $\pm$ stat $\pm$ syst

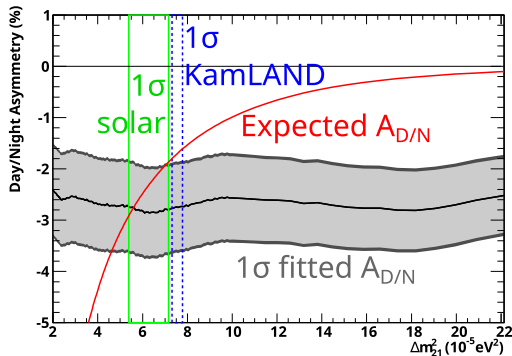
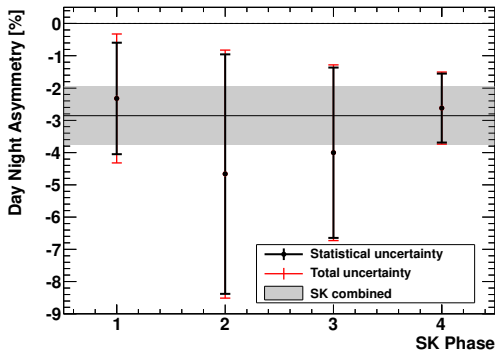
Oscillation: solar global vs KamLAND





Rate variation $r(\cos \theta_{Z,\text{solar}}) = A_{\text{D/N}}^{\text{SK-IV, fit}} \times \text{calculated shape}$

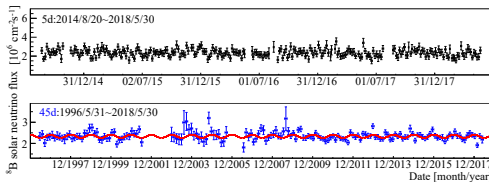
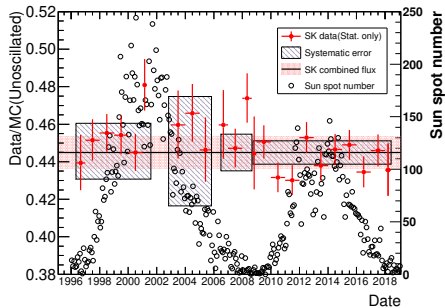
$$A_{\text{D/N}}^{\text{SK-IV, fit}} = \frac{\Phi^{\text{Day}} - \Phi^{\text{Night}}}{(\Phi^{\text{Day}} + \Phi^{\text{Night}})/2} = -0.0286 \pm 0.0085 (\text{stat.}) \pm 0.0032 (\text{syst.})$$



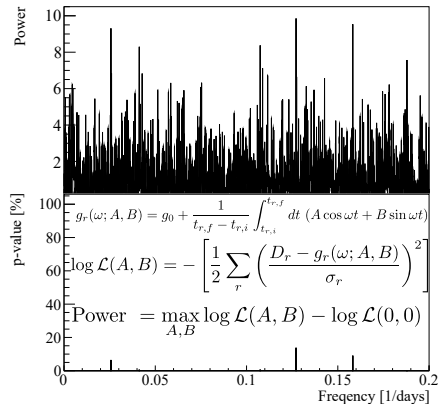
- 3.2 σ evidence of earth matter effects on solar neutrino oscillation!

^8B - ν flux variations in 22 years

- The only modulation for ^8B - ν is due to Earth elliptic orbit



- Agree with constant solar neutrino flux emitted by the Sun



- With full SK-IV data, ^8B - ν flux is measured with the best precision.

- With full SK-IV data, ^8B - ν flux is measured with the best precision.
- Solar neutrino oscillation with MSW effect
 - Observed recoil electron energy spectrum is consistent with no distortions.
 - Preliminary result of recoil electron in 2.49-3.49 MeV
 - 2.6σ significance of solar signal in 2.99-3.49 MeV.
- Updated oscillation analysis results of SK, solar, solar + KamLAND:
 - $\sin \theta_{12,\text{SK}} = 0.324^{+0.027}_{-0.023}, \Delta m_{21,\text{SK}}^2 = (6.10^{+1.26}_{-0.86}) \times 10^{-5} \text{ eV}^2$
 - $\sin \theta_{12,\text{solar}} = 0.306 \pm 0.013, \Delta m_{21,\text{solar}}^2 = (6.10^{+0.95}_{-0.81}) \times 10^{-5} \text{ eV}^2$
 - $\sin \theta_{12,\text{global}} = 0.307 \pm 0.012, \Delta m_{21,\text{global}}^2 = (7.50^{+0.19}_{-0.18}) \times 10^{-5} \text{ eV}^2$

- With full SK-IV data, ^8B - ν flux is measured with the best precision.
- Solar neutrino oscillation with MSW effect
 - Observed recoil electron energy spectrum is consistent with no distortions.
 - Preliminary result of recoil electron in 2.49-3.49 MeV
 - 2.6σ significance of solar signal in 2.99-3.49 MeV.
- Updated oscillation analysis results of SK, solar, solar + KamLAND:
 - $\sin \theta_{12,\text{SK}} = 0.324^{+0.027}_{-0.023}$, $\Delta m_{21,\text{SK}}^2 = (6.10^{+1.26}_{-0.86}) \times 10^{-5} \text{ eV}^2$
 - $\sin \theta_{12,\text{solar}} = 0.306 \pm 0.013$, $\Delta m_{21,\text{solar}}^2 = (6.10^{+0.95}_{-0.81}) \times 10^{-5} \text{ eV}^2$
 - $\sin \theta_{12,\text{global}} = 0.307 \pm 0.012$, $\Delta m_{21,\text{global}}^2 = (7.50^{+0.19}_{-0.18}) \times 10^{-5} \text{ eV}^2$
- Day/Night asymmetry evidence at 3.2σ

- With full SK-IV data, $^8\text{B}-\nu$ flux is measured with the best precision.
- Solar neutrino oscillation with MSW effect
 - Observed recoil electron energy spectrum is consistent with no distortions.
 - Preliminary result of recoil electron in 2.49-3.49 MeV
 - 2.6σ significance of solar signal in 2.99-3.49 MeV.
- Updated oscillation analysis results of SK, solar, solar + KamLAND:
 - $\sin \theta_{12,\text{SK}} = 0.324^{+0.027}_{-0.023}$, $\Delta m_{21,\text{SK}}^2 = (6.10^{+1.26}_{-0.86}) \times 10^{-5} \text{ eV}^2$
 - $\sin \theta_{12,\text{solar}} = 0.306 \pm 0.013$, $\Delta m_{21,\text{solar}}^2 = (6.10^{+0.95}_{-0.81}) \times 10^{-5} \text{ eV}^2$
 - $\sin \theta_{12,\text{global}} = 0.307 \pm 0.012$, $\Delta m_{21,\text{global}}^2 = (7.50^{+0.19}_{-0.18}) \times 10^{-5} \text{ eV}^2$
- Day/Night asymmetry evidence at 3.2σ
- 22 years of $^8\text{B}-\nu$ flux monitor agrees with constant solar neutrino emission.

- With full SK-IV data, ^8B - ν flux is measured with the best precision.
- Solar neutrino oscillation with MSW effect
 - Observed recoil electron energy spectrum is consistent with no distortions.
 - Preliminary result of recoil electron in 2.49-3.49 MeV
 - 2.6σ significance of solar signal in 2.99-3.49 MeV.
- Updated oscillation analysis results of SK, solar, solar + KamLAND:
 - $\sin \theta_{12,\text{SK}} = 0.324^{+0.027}_{-0.023}$, $\Delta m_{21,\text{SK}}^2 = (6.10^{+1.26}_{-0.86}) \times 10^{-5} \text{ eV}^2$
 - $\sin \theta_{12,\text{solar}} = 0.306 \pm 0.013$, $\Delta m_{21,\text{solar}}^2 = (6.10^{+0.95}_{-0.81}) \times 10^{-5} \text{ eV}^2$
 - $\sin \theta_{12,\text{global}} = 0.307 \pm 0.012$, $\Delta m_{21,\text{global}}^2 = (7.50^{+0.19}_{-0.18}) \times 10^{-5} \text{ eV}^2$
- Day/Night asymmetry evidence at 3.2σ
- 22 years of ^8B - ν flux monitor agrees with constant solar neutrino emission.
- Ongoing SK V-VII solar neutrino data analysis.
- SK I-VII hep neutrino update (last result SK-I in 2006) with various improvements is in progress.

Solar
neutrino
results with
the full data
period until
Super-
Kamiokande-
IV

Super-
KamiokaNDE

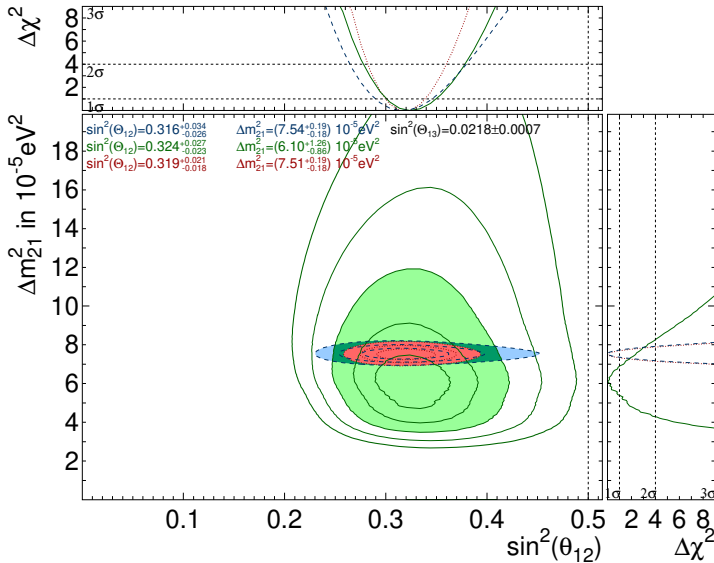
Solar
Neutrinos at
SuperK

Solar
Neutrino
Analysis and
Results

Backup

Backup

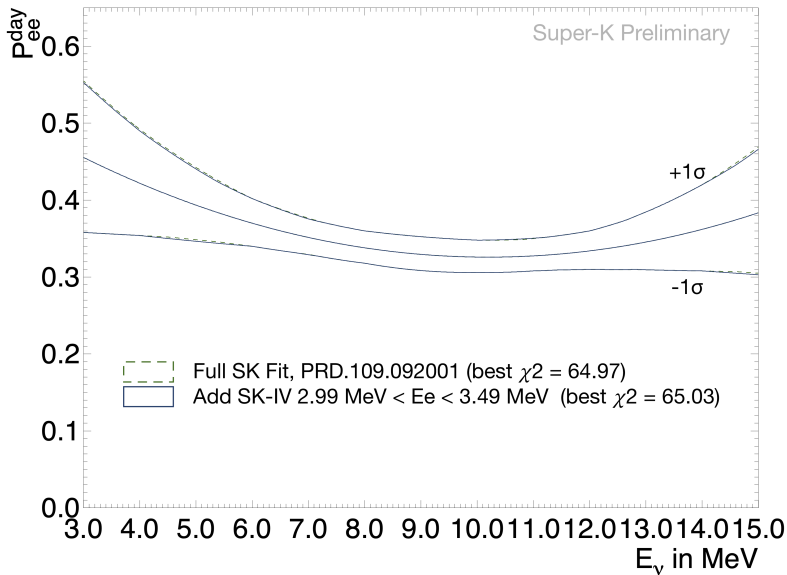
Oscillation analysis: SK vs KamLAND



Survival spectrum with WIT data, poly parametrization

Solar
neutrino
results with
the full data
period until
Super-
Kamiokande-
IV

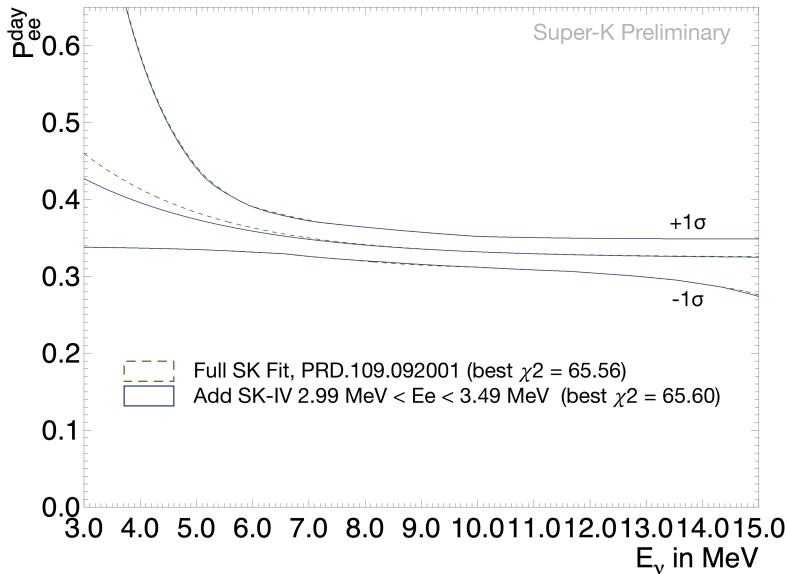
Super-
KamiokaNDE



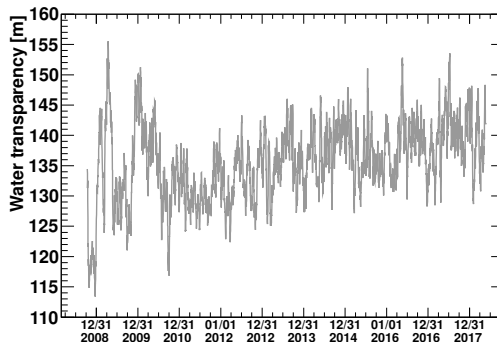
Survival spectrum with WIT data, exp parametrization

Solar
neutrino
results with
the full data
period until
Super-
Kamiokande-
IV

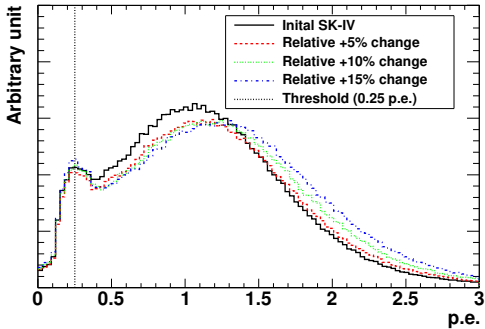
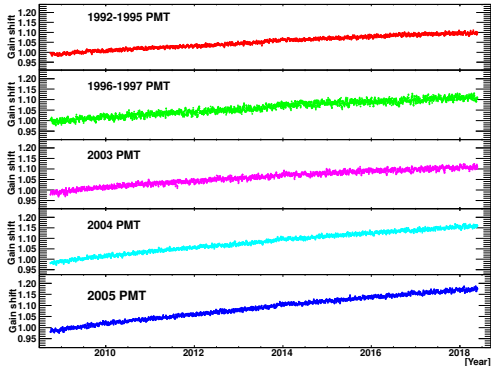
Super-
KamiokaNDE



- Water system: remove Rn + increase transparency
- Laser calibration system to measure absorption and scattering

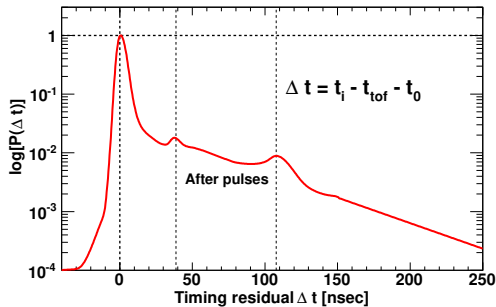


- PMT gain gradually increases for all kinds of PMTs

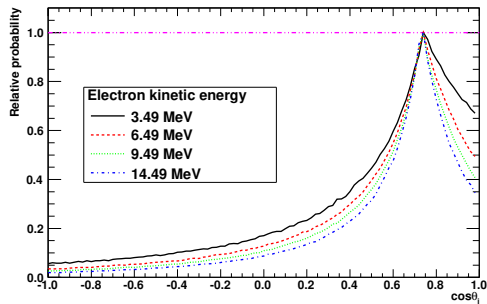


Vertex and Direction Reconstruction

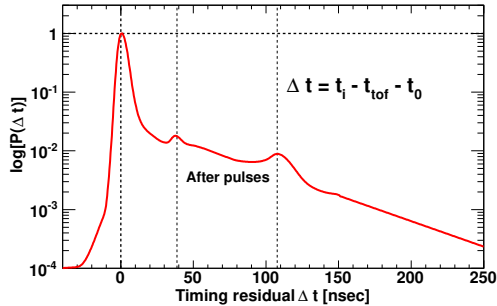
- Time-of-flight subtracted hit time PDF



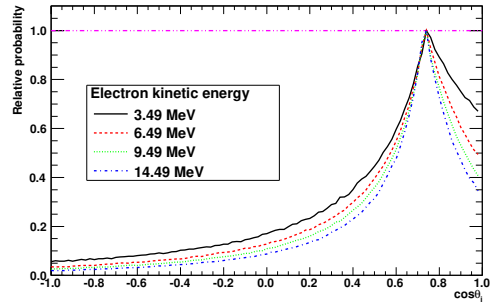
- Angular PDF of fired PMT



- Time-of-flight subtracted hit time PDF



- Angular PDF of fired PMT



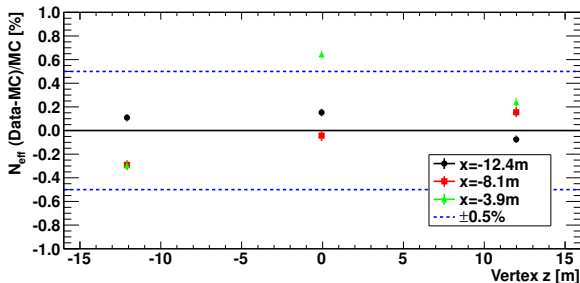
- Maximized likelihood estimation with successive annealing iterations

- Effective hit counting

$$N_{\text{eff}} = \sum_i^{N_{50}} \left[(X_i + \epsilon_{\text{tail}} - \epsilon_{\text{dark}}) C_i \times \frac{N_{\text{all}}}{N_{\text{alive}}} \times \frac{S(0,0)}{S(\theta_i, \phi_i)} \times \frac{1}{QE_i(t)} \times \frac{1}{P} \right]$$

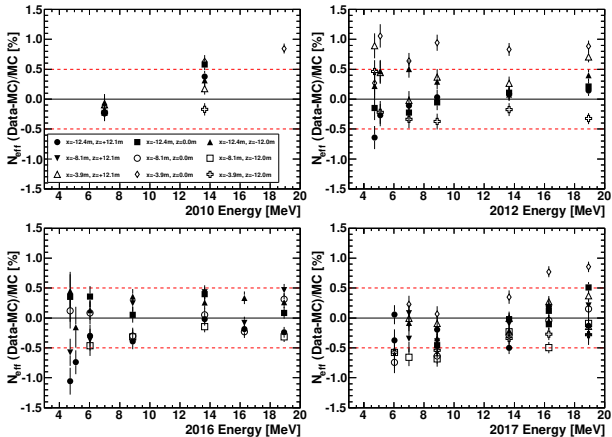
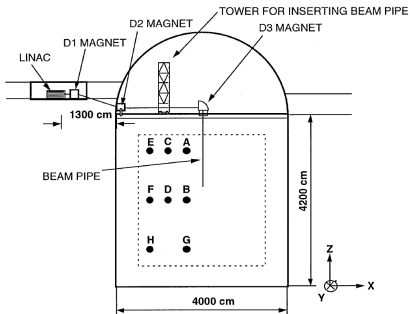
- N_{50} : hit count in 50ns window
- i : PMT index
- X_i : PMT occupancy
- ϵ_{dark} : dark noise
- ϵ_{tail} : hits outside 50ns
- C_i : gain corrections
- QE_i : QE corrections
- S : PMT incident angel response

- Energy non-uniformity < 0.5 %

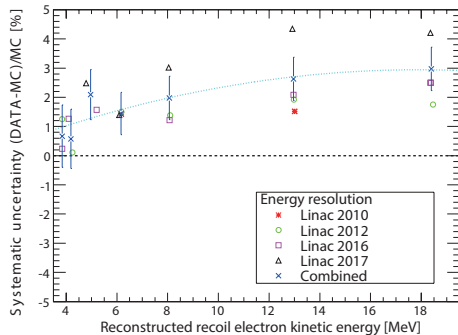
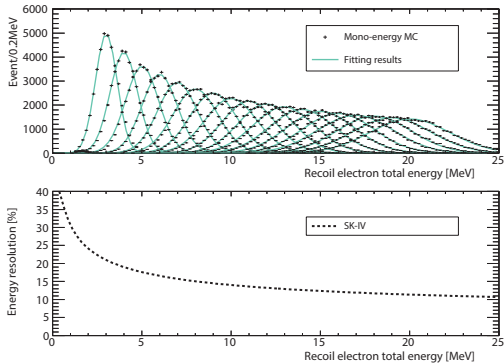


Electron kinetic energy range: 4.4 MeV to 18.9 MeV

- Energy scale



$$\sigma_E = -0.0525 + 0.3162\sqrt{E} + 0.04572E$$



- Recoil electron spectrum is the key to search rare events.