Low Energy Neutrinos in Super-Kamiokande

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for the Super-K Collaboration
Super-Kamiokande

- 50kton pure water Cherenkov detector
- 1km (2.7km w.e) underground in Kamioka
- 11129 50cm PMTs in Inner Detector
- 1885 20cm PMTs in Outer Detector

Physics targets of Super-Kamiokande

- Atmospheric $\nu$
- $\sim 100$ GeV

This talk
- Solar $\nu$
- Relic SN $\nu$
- $\sim 3.5$ MeV $\sim 20$
- Proton decay
- WIMPs
- $\sim 1$ GeV
- Atmospheric $\nu$
- TeV
Solar neutrinos observation
SK ⁸B Solar neutrino observation

- SK has observed solar neutrino for 18 years (~1.5 solar cycle)
  - ~77000 solar ν interactions

SK I-IV combined flux
2.341±0.044(stat.+syst.) x 10⁶ cm⁻² sec⁻¹

<table>
<thead>
<tr>
<th>Phase</th>
<th>Energy threshold MeV(kin.)</th>
<th>Live time (say)</th>
<th>⁸B Flux x 10⁶/cm²/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>SK-I</td>
<td>4.5</td>
<td>1496</td>
<td>2.38±0.02±0.08</td>
</tr>
<tr>
<td>SK-II</td>
<td>6.5</td>
<td>791</td>
<td>2.41±0.05+0.16-0.15</td>
</tr>
<tr>
<td>SK-III</td>
<td>4.0</td>
<td>548</td>
<td>2.40±0.04±0.05</td>
</tr>
<tr>
<td>SK-IV</td>
<td>3.5</td>
<td>2034</td>
<td>2.31±0.02±0.04</td>
</tr>
</tbody>
</table>

DATA/MC = 0.4459±0.0084(stat.+syst.)
Time variation of $^8$B solar neutrino flux

- No correlation with the 11 years solar activity is observed.
- Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.
  - $\chi^2 = 13.10/18$ (dof)

Sun spot number was obtained by the web page of NASA
http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt
Oscillation analysis: Solar global fit

- This SK update and other latest results are combined.

Combined solar fit with KamLAND

Without reactor $\theta_{13}$ constraint

~2σ tension in $\Delta m_{21}^2$

between solar and KamLAND

Non-zero $\theta_{13}$ at 2σ from solar+KamLAND

Good agreement with Daya Bay, RENO & DC
Search for the direct MSW signal

- Current main motivation of SK $^8$B $\nu$ observation

Energy spectrum distortion

Neutrino survival probability

Vacuum oscillation dominant

Solar + KamLAND
$\sin^2 \theta_{12} = 0.308$
$\Delta m_{21}^2 = 7.50 \times 10^{-5} \text{eV}^2$

Matter oscillation dominant

Solar
$\sin^2 \theta_{12} = 0.311$
$\Delta m_{21}^2 = 4.85 \times 10^{-5} \text{eV}^2$

Flux day-night asymmetry

"Nighttime regeneration" of $\nu_e$ by earth matter effect

$P_{\nu_e} = 1 - \frac{1}{2} \sin^2 2\theta_{13}$
SK I-IV combined recoil spectrum

- Test of “spectrum upturn”
  - MSW is slightly disfavored by
    - ~1.7 \( \sigma \) using the Solar + KamLAND best fit parameters
    - ~1.0 \( \sigma \) using the Solar Global best fit parameters.

<table>
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<tr>
<th>Total # of bins of SK I-IV is 83</th>
<th>( \chi^2 )</th>
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<tr>
<td>Solar + KamLAND</td>
<td>70.13</td>
</tr>
<tr>
<td>Solar global</td>
<td>68.14</td>
</tr>
<tr>
<td>Quadratic fit</td>
<td>67.67</td>
</tr>
<tr>
<td>Exponential</td>
<td>67.54</td>
</tr>
</tbody>
</table>

Neutrino energy spectrum is convoluted in the electron recoil spectrum. For de-convolution, generic functions are used as a survival probability;

\[
P_{\text{ev}}(E) = c_0 + c_1 \left( \frac{E}{\text{MeV}} \right)^{-10} + c_2 \left( \frac{E}{\text{MeV}} \right)^{-10}^2 \quad \text{(quadratic)}
\]

\[
P_{\text{ev}}(E) = e_0 + \frac{e_1}{e_2} \left( \exp \left( e_2 \left( \frac{E}{\text{MeV}} \right)^{-10} \right) - 1 \right) \quad \text{(exponential)}
\]
Day-Night flux asymmetry

This is the "direct" indication for matter enhanced neutrino oscillation.

<table>
<thead>
<tr>
<th></th>
<th>SK-I</th>
<th>SK-II</th>
<th>SK-III</th>
<th>SK-IV</th>
<th>combined</th>
<th>non-zero significance</th>
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<tbody>
<tr>
<td>Fitted asymmetry amplitude</td>
<td>$\Delta m^2_{21}=4.84\times10^{-5}$ eV$^2$</td>
<td>$\Delta m^2_{21}=7.50\times10^{-5}$ eV$^2$</td>
<td>$-2.0\pm1.8\pm1.0%$</td>
<td>$-1.9\pm1.7\pm1.0%$</td>
<td>$-3.3\pm1.0\pm0.5%$</td>
<td>$3.0\sigma$</td>
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<td>$-4.4\pm3.8\pm1.0%$</td>
<td>$-4.4\pm3.6\pm1.0%$</td>
<td>$-3.3\pm1.0\pm0.5%$</td>
<td>$2.8\sigma$</td>
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<td>$\sin^2\theta_{12}=0.311$</td>
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<td>$-4.2\pm2.7\pm0.7%$</td>
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Solar best fit
$\sin^2\theta_{12}=0.311$
$\Delta m^2_{21}=4.85\times10^{-5}$ eV$^2$

Solar+KamLAND
$\sin^2\theta_{12}=0.308$
$\Delta m^2_{21}=7.50\times10^{-5}$ eV$^2$

- This is the "direct" indication for matter enhanced neutrino oscillation.
DSNB (SRN)

- $10^{10}$ stellar/galaxy $\times 10^{10}$ galaxies $\times 0.3\%$ (become SNe) $\sim O(10^{17})$ SNe

Neutrinos from past SNe

Theoretical flux prediction: $0.3\sim1.5$ /cm$^2$/s (17.3MeV threshold)

Super-K should be most sensitive to $\bar{\nu}_e$
Status of DSNB search

- Search window for SRN at SK: From \( \sim 10\text{MeV} \) to \( \sim 30\text{MeV} \)
- Limited by BG. More than 1 order reduction is needed.
  - n tagging efficiency (by proton) is low...

Comparison with Expected \( \bar{\nu}_e \) spectra
PRD 79 08013(2009)

Search window for SRN at SK: From \( \sim 10\text{MeV} \) to \( \sim 30\text{MeV} \)
- Limited by BG. More than 1 order reduction is needed.
  - n tagging efficiency (by proton) is low...
SK-Gd project

- Identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.
- Large cross section for thermal neutron (48.89kb)
- Neutron captured Gd emits 3-4 $\gamma$s in total 8 MeV
- $\text{Gd}_2(\text{SO}_4)_3$ was selected to dissolve.


Captures on Gd

- $0.1\%$ Gd ($0.2\%$ in $\text{Gd}_2(\text{SO}_4)_3$) gives $\sim 90\%$ efficiency for n capture

In Super-K this requires dissolving $\sim 100$ tons of $\text{Gd}_2(\text{SO}_4)_3$
Hiroyuki Sekiya

Expected signal with SK-Gd 10 years

SRN flux from Horiuchi et al.

Assumption
• n capture efficiency: 90%
• Gd $\gamma$ detection efficiency: 74%.
• 35% of the SK-IV invisible muon BG
  ◦ By n-tagging

Min/nominal/Max are due to uncertainties in astronomy.

Expect number of events in 10 years
in $E_{\text{total}} = 10$-30 MeV
  • Teff 6MeV case: 26-34 events
  • Teff 4MeV case: 13-16 events

Background: ~18 events

Aiming at “discovery” of SRN
EGADS
Evaluating Gadolinium’s Action on Detector Systems
- To study the Gd water quality with actual detector materials.
- The detector fully mimic Super-K detector.
  : SUS frame, PMT and PMT case, black sheets, etc.

Gd water circulation system (purify water with keeping Gd)

200 m³ tank with 240 PMTs

15m³ tank to dissolve Gd

2014
Water transparency during adding Gd

- Gd had been dissolved from Nov. 2014 to May. 2015

Cherenkov light left at 15 m for EGADS detector

Blue band: SK-III and SK-IV values.

Sampling position:
- Bottom
- Centre
- Top
- 0.02% Gd$_2$(SO$_4$)$_3$
- 0.10% Gd$_2$(SO$_4$)$_3$
- 0.15% Gd$_2$(SO$_4$)$_3$
- 0.20% Gd$_2$(SO$_4$)$_3$
The light left at 15 m in the 200m³ tank was very stable and ~75% for 0.2% Gd₂(SO₄)₃, which corresponds to ~92% of SK-IV pure water average.
Neutron capture signal in EGADS

- Using Am/Be + BGO

Gd concentration dependence was confirmed.

<table>
<thead>
<tr>
<th>Gd Concentration</th>
<th>Data</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2178±76ppm</td>
<td>1055±37ppm</td>
<td>225±8ppm</td>
</tr>
<tr>
<td>Data</td>
<td>29.89±0.33</td>
<td>51.48±0.52</td>
</tr>
<tr>
<td>MC</td>
<td>30.05±1.14</td>
<td>53.47±1.77</td>
</tr>
</tbody>
</table>
Official statement from SK collaboration

On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water. The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.
Summary

Solar $\nu$ observation

- SK has observed $\sim 77000$ $^8$B $\nu$ interactions over 18 years, by far the largest sample of solar neutrino events in the world.
  - No correlation with the solar activity cycle.
- SK recoil electron energy spectrum slightly disfavors “MSW upturn”
- SK data provide the first indication (at 2.8~3.0 $\sigma$) of terrestrial matter effects on $^8$B solar $\nu$ oscillation.

For DSNB detection

- Gd project in SK (was known as GADZOOKS!) started in 2002.
- EGADS started in 2009 to evaluate Gd effect to SK.
- In 2015, 0.2% of Gd sulfate was dissolved in EGADS and it was confirmed that there is no showstopper for putting Gd into SK. SK-Gd was accepted by Super-K in June 2015.

Stay tuned for low energy SK neutrino
Extra Slides
History of Gd project in Super-K

2002 Nov. Started to discuss as “GADZOOKS!”

2006 May. Gd Advisory Committee was formed.

List up R&D items and specifications

2007 Nov. collaboration council

It was suggested to make a test tank and study feasibility.

2009 “EGADS” was started.

A 200 ton test tank was constructed.

2013 0.2% Gd$_2$(SO$_4$)$_3$ was dissolved before mounting PMTs and transparency was measured.

2013 summer 240 PMTs were mounted in the EGADS tank.

2014 Oct. – 2015 May Dissolved 0.2% Gd$_2$(SO$_4$)$_3$ again and checked water transparency.

2015 Jun. collaboration council

GADZOOKS! was approved as “Super Kamiokande Gd”
## Timeline of SK-Gd

<table>
<thead>
<tr>
<th>201X</th>
<th>201X</th>
<th>201X</th>
<th>20XX</th>
<th>20XX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T₀ = Start leak stop work (~3.5)</strong>&lt;br&gt;Fill water (~2)&lt;br&gt;Pure water circulation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>T₁ = Load first Gd₂(SO₄)₃ 1t = 0.002% (~1)</strong>&lt;br&gt;Load Gd₂(SO₄)₃ 10t (~1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>T₂ = Load full Gd₂(SO₄)₃ 100t = 0.2% (~2)</strong>&lt;br&gt;Observation&lt;br&gt;Stabilize water transparency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- In order to set T₀, T₁, & T₂, T2K schedule will be also taken into account.

Numbers in parentheses are months to be taken for the work.
Why Gd (not 2.2MeV $\gamma$) for neutron tagging

Vertex reconstruction is possible.

Efficiency and fake probability

2.2MeV $\gamma$: Efficiency: $10 \sim 20\%$, fake probability: $\sim 10^{-2}$

Gd(n,$\gamma$)Gd: Efficiency: $>80\%$, fake probability: $<10^{-4}$
Improvement for Proton decay

Neutron multiplicity for $P \rightarrow e^+\pi^-\nu^0$ MC

Atmospheric $\nu$ BG

Accompany many n

If one proton decay event is observed at Super-K after 10 years
Current background level: 0.58 events/10 years
Background with neutron anti-tag: 0.098 events/10 years

Background probability will be decreased from 44% (w/o n) to 9% (w/ n).
Improvement for T2K

Number of tagged neutrons in T2K energy range

Atmospheric neutrino
1-ring e-like sample
0.5 GeV < E_ν < 0.7 GeV

Assuming n-tag efficiency of 80%.
(capture eff.=90%, Gd-γ det.eff.=~90%)

Using n-tagging information, $\bar{\nu}_e$ ID ($\nu_e$ missID) eff. ~70%(30%)
$\bar{\nu}_e$ enhanced sample in anti mode appearance analysis

Signal $\bar{\nu}_e$, Signal $\nu_e$

$\bar{\nu}_e$, $\nu_e$, $\nu_\mu$ and $\bar{\nu}_\mu$

<table>
<thead>
<tr>
<th>Erec [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events @ $3.9 \times 10^{21}$ POT</td>
</tr>
</tbody>
</table>

Osc parameters: $\sin^2 \theta_{13} = 0.1$, $\delta_{CP} = -90^\circ$, $\Delta m^2 = 0.0024 \text{eV}^2$, $\sin^2 \theta_{23} = 0.5$, NH

$\bar{\nu}_e$ ID ($\nu_e$ missID) eff. = 70% (30%) is assumed w/o energy dependence

Note: Directional information of $e/e+$ is not used
Anti mode $3.9 \times 10^{21}$ Appearance Contour

True parameters: $\sin^2 2\theta_{13} = 0.1, \delta_{CP} = -90^\circ$

$\Delta m_{32}^2 = 0.0024\text{eV}^2$ (Fixed), $\sin^2 \theta_{23} = 0.5$ (Fixed), NH (Fixed)
**e/π**

**0 separation**

\[ \text{e MC} \quad \text{(ex. 500MeV/c)} \]

\[ \text{π}^0 \text{MC} \]

<table>
<thead>
<tr>
<th>pure</th>
<th>Gd water</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>92.9±2.1</td>
</tr>
<tr>
<td>500</td>
<td>89.3±2.0</td>
</tr>
<tr>
<td>1000</td>
<td>75.7±1.8</td>
</tr>
</tbody>
</table>

True (MeV/c)

**π**

**0 mass**

\[ \text{π}^0 \text{MC, remain } \varepsilon \text{ (\%)} \]

<table>
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<th>true (MeV/c)</th>
<th>pure</th>
<th>Gd water</th>
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<tr>
<td>250</td>
<td>1.7±0.2</td>
<td>1.9±0.2</td>
</tr>
<tr>
<td>500</td>
<td>4.7±0.3</td>
<td>6.1±0.4</td>
</tr>
<tr>
<td>1000</td>
<td>15.8±0.7</td>
<td>16.7±0.7</td>
</tr>
</tbody>
</table>

**e MC, det.**

\[ \text{fiTQun } L_{\pi^0/Le} \]

\[ \text{fiTQun } \pi^0 \text{ mass (MeV/c^2)} \]
Improvements in SK-IV

- Reduced $^{222}$Rn BG
- New analysis in low energy bins
  Remaining BG-electrons from $^{214}$Bi should have more multiple-scatterings than signal-electrons have: MSG
  \[\text{MSG < 0.35} \quad \text{0.35 < MSG < 0.45} \quad \text{0.45 < MSG}\]

- Reduced systematic error
  1.7% for flux  cf. SK-I: 3.2%  SK-III: 2.1%

Achieved 3.5 MeV(kin.) energy threshold
$8.6\sigma$ signal is observed with MSG
Recoil electron spectra

SK-I Energy Spectrum

SK-II Energy Spectrum

SK-III Energy Spectrum

SK-IV Energy Spectrum

MC: $5.25 \times 10^6$/cm$^2$/sec

Preliminary

SK-IV

1669 days

Hiroyuki Sekiya

TAUP2015 Torino

September 7 2015
SK-I+II+III+IV spectrum

N.B. All SK phase are combined without regard to energy resolution or systematics in this figure.

Neutrino energy spectrum is convoluted in the electron recoil spectrum. For de-convolution, generic functions are used as a survival probability:

$$P_{ee}(E_{\nu}) = c_0 + c_1 \left( \frac{E_{\nu}}{MeV} - 10 \right) + c_2 \left( \frac{E_{\nu}}{MeV} - 10 \right)^2$$

$$P_{ee}(E_{\nu}) = e_0 + \frac{e_1}{e_2} \exp \left( e_2 \left( \frac{E_{\nu}}{MeV} - 10 \right) - 1 \right)$$

SK recoil electron spectrum constrain the fit parameters ($c_i, e_i$) of the function and the allowed $P_{ee}(E_{\nu})$ is derived using the allowed ($c_i, e_i$).

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<th>(total # of bins of SKI - IV is 83)</th>
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Allowed $P_{ee}(E_\nu)$ for SK

$P_{ee}(E_\nu) = c_0 + c_1 \left( \frac{E_\nu}{\text{MeV}} - 10 \right) + c_2 \left( \frac{E_\nu}{\text{MeV}} - 10 \right)^2$

- MSW (solar+KamLAND) is consistent at ~1.6$\sigma$
- MSW (solar) fits better (at ~0.7$\sigma$)

- Solar+KamLAND:
  - $\sin^2\theta_{12}=0.308$
  - $\Delta m^2_{21}=7.50\times10^{-5}\text{eV}^2$

- Solar:
  - $\sin^2\theta_{12}=0.311$
  - $\Delta m^2_{21}=4.85\times10^{-5}\text{eV}^2$

$\sqrt{\text{MSW (solar+KamLAND)}}$ is consistent at ~1.6$\sigma$
$\sqrt{\text{MSW (solar)}}$ fits better (at ~0.7$\sigma$)
Allowed $P_{ee}(E_{\nu})$ for SK+SNO

\[ P_{ee}(E_{\nu}) = c_0 + c_1 \left( \frac{E_{\nu}}{\text{MeV}} - 10 \right) + c_2 \left( \frac{E_{\nu}}{\text{MeV}} - 10 \right)^2 \]

- SK and SNO are complementary for the shape constraint
- MSW is consistent at 1\(\sigma\)

Solar+KamLAND
- \(\sin^2 \theta_{12} = 0.308\)
- \(\Delta m^2_{21} = 7.50 \times 10^{-5} \text{eV}^2\)

SK
- \(\sin^2 \theta_{12} = 0.311\)
- \(\Delta m^2_{21} = 4.85 \times 10^{-5} \text{eV}^2\)

SNO
- √SK and SNO are complementary for the shape constraint
- √MSW is consistent at 1\(\sigma\)
Global view of $P_{ee}(E_{\nu})$

![Graph showing the global view of $P_{ee}(E_{\nu})$ with data points from various sources including all solar (pp), Borexino (pep), Borexino ($^7$Be), Homestake + SK+SNO (CNO), and SK+SNO.]
$\Delta m_{21}^2$ dependence

Solar region
differ from zero
by $2.9$~$3.0\sigma$
agree with expect
by $1.0\sigma$

KamLAND region
differ from zero
by more than $2.8\sigma$
agree with expect
by $1.3\sigma$

$\sin^2 \theta_{12} = 0.311, \sin^2 \theta_{13} = 0.025$
History of lowered BG and threshold

- Solar angle distributions
  - BG SK-I/SK-IV = 1/4, $E_{th}$ SK-I – SK-IV = 1MeV

4.5MeV-5.0MeV bin

3.5MeV-4.0MeV bin

SK-I
SK-III
SK-IV
SK-IV
How it was achieved?

- It’s easy! Just tightening the FV to reject Rn rich region.

- Keeping the FV (boarder) is not easy at all!

**Event rates**

- SK IV
- SK III

**Vertex distributions**

- SK-IV vertex distributions

**Graphs**

- 3.5 - 4.0 MeV
- 4.0 - 4.5 MeV
- 4.5 - 5.0 MeV
Convection suppression in SK-IV

- Very precisely temperature-controlled (±0.01°C) water must be supplied to the bottom.

3.5MeV-4.5MeV Event distribution

Temperature in Z direction
The difference is only 0.2 °C
Wide-band Intelligent Trigger

- Reconstruction and Reduction just after Front-end

100% trigger efficiency above 2.5MeV(kin.)

Just started
Oscillation parameter

SK and SNO

\[
\sin^2(\theta_{12}) = 0.317^{+0.017}_{-0.027}, \\
m^2_{21} = (5.4^{+1.7}_{-1.3}) \times 10^{-5} \text{eV}^2
\]

\[
\sin^2(\theta_{12}) = 0.339^{+0.027}_{-0.024}, \\
m^2_{21} = (4.74^{+1.96}_{-0.79}) \times 10^{-5} \text{eV}^2
\]

\[
\sin^2(\theta_{12}) = 0.313 \pm 0.014, \\
m^2_{21} = (4.86^{+1.10}_{-0.42}) \times 10^{-5} \text{eV}^2
\]

Spectral distortion expected

Day/night asymmetry expected
Probing the Unknown

Non-standard physics effects can alter the shape / position of the “MSW rise”

Non-standard interactions (flavour changing NC)

Sterile Neutrinos

Mass varying neutrinos (MaVaNs)


Holanda & Smirnov PRD 83 (2011) 113011

M.C. Gonzalez-Garcia, M. Maltoni
SK+SNO $^8$B total flux

- For each oscillation parameter set there is a minimum chi2 and a $^8$B error term describing the parabolic increase of the chi2 with deviations from the best chi2. The reduced chi2 vs. $^8$B flux is below. The jump is due to the relatively coarse grid in theta12.

- $5.30 \pm 0.17 - 0.11 \times 10^6/(\text{cm}^2 \text{ sec})$, which is a (+3%,-2%) error on the total $^8$B for SK+SNO compared to the 1.5% error of SK’s ES flux by itself.
### Systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>SK-IV flux (3.5-19.5MeV)</th>
<th>SK-III flux (4.5-19.5MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy scale</td>
<td>+1.14, -1.16%</td>
<td>± 1.4%</td>
</tr>
<tr>
<td>energy resolution</td>
<td>+0.14, -0.08%</td>
<td>± 0.2%</td>
</tr>
<tr>
<td>B8 spectrum</td>
<td>+0.33, -0.37%</td>
<td>± 0.2%</td>
</tr>
<tr>
<td>trigger efficiency</td>
<td>± 0.1%</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>angular resolution</td>
<td>+0.32, -0.25%</td>
<td>± 0.67%</td>
</tr>
<tr>
<td>vertex shift</td>
<td>± 0.18%</td>
<td>± 0.54%</td>
</tr>
<tr>
<td>BG event cut</td>
<td>± 0.36%</td>
<td>± 0.4%</td>
</tr>
<tr>
<td>hit pattern cut</td>
<td>± 0.27%</td>
<td>± 0.25%</td>
</tr>
<tr>
<td>another vertex cut</td>
<td>removed</td>
<td>± 0.45%</td>
</tr>
<tr>
<td>spallation cut</td>
<td>± 0.2%</td>
<td>± 0.2%</td>
</tr>
<tr>
<td>gamma cut</td>
<td>± 0.26%</td>
<td>± 0.25%</td>
</tr>
<tr>
<td>cluster hit cut</td>
<td>+0.45, -0.44%</td>
<td>± 0.5%</td>
</tr>
<tr>
<td>BG shape</td>
<td>± 0.1%</td>
<td>± 0.1%</td>
</tr>
<tr>
<td>signal extraction</td>
<td>± 0.7%</td>
<td>± 0.7%</td>
</tr>
<tr>
<td>cross section</td>
<td>± 0.5%</td>
<td>± 0.5%</td>
</tr>
</tbody>
</table>

- **Total 1.7%**
Data set for global solar analysis

The most up-to-date data are used

- **SK:**
  - SK-I 1496 days, spectrum 4.5-19.5 MeV(kin.)+D/N: Ekin>4.5 MeV
  - SK-II 791 days, spectrum 6.5-19.5 MeV(kin.)+D/N: Ekin>7.0 MeV
  - SK-III 548 days, spectrum 4.0-19.5 MeV(kin.)+D/N: Ekin>4.5 MeV
  - SK-IV 1669 days, spectrum 3.5-19.5 MeV(kin.)+D/N: Ekin>4.5 MeV

- **SNO:**
  - Parameterized analysis (c0, c1, c2, a0, a1) of all SNO phased. (PRC88, 025501 (2013))
  - Same method is applied to both SK and SNO with a0 and a1 to LMA expectation

- **Radiochemical:** Cl, Ga

- **Borexino:** Latest 7Be flux (PRL 107, 141302 (2011)) Does NOT include Borexino pp 2014
- **KamLAND reactor:** Latest (3-flavor) analysis (PRD88, 3, 033001 (2013))
- **8B spectrum:** Winter 2006 (PRC73, 73, 025503 (2006))
- **8B and hep flux**
  \[
  \phi_8 = 5.25 \times 10^9/(cm^2\cdot sec) \\
  \phi_{hep} = 7.88 \times 10^3/(cm^2\cdot sec)
  \]
Day/Night

<table>
<thead>
<tr>
<th></th>
<th>Amplitude fit</th>
<th>Straight calc. (D-N)/((D+N)/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta m_{21}^{2}=4.84\times10^{-5},\text{eV}^2$</td>
<td>$\Delta m_{21}^{2}=7.50\times10^{-5},\text{eV}^2$</td>
</tr>
<tr>
<td>SK-I</td>
<td>$-2.0\pm1.8\pm1.0%$</td>
<td>$-1.9\pm1.7\pm1.0%$</td>
</tr>
<tr>
<td>SK-II</td>
<td>$-4.4\pm3.8\pm1.0%$</td>
<td>$-4.4\pm3.6\pm1.0%$</td>
</tr>
<tr>
<td>SK-III</td>
<td>$-4.2\pm2.7\pm0.7%$</td>
<td>$-3.8\pm2.6\pm0.7%$</td>
</tr>
<tr>
<td>SK-IV</td>
<td>$-3.6\pm1.6\pm0.6%$</td>
<td>$-3.3\pm1.5\pm0.6%$</td>
</tr>
<tr>
<td>combined</td>
<td>$-3.3\pm1.0\pm0.5%$</td>
<td>$-3.1\pm1.0\pm0.5%$</td>
</tr>
</tbody>
</table>

non-zero significance: $3.0\sigma$, $2.8\sigma$, $2.8\sigma$

expected time variation as a function of $\cos\theta_z$

\[ L = e^{\sum B_i S_i} \prod_{i=1}^{N_{str}} \prod_{v=1}^{N_{run}} (\beta_i (c_v) B_i + \sigma_i (c_v) \times z_i (t_v) m_i S_i) \]

\[ z_i (t_v) = z_i (\alpha, t) = \frac{1 + \alpha ((1 + a_i) r_i (t) / r_i^{av} - 1) \times z_{\exp} (t)}{1 + \alpha a_i} \]

$\alpha$ : day-night asym. scaling factor

(sin$^2\theta_{12}=0.311$, sin$^2\theta_{13}=0.025$)
exponential parameterization

\[ P_{ee}(E_\nu) = e_0 + \frac{e_1}{e_2} \left( \exp \left( e_2 \left( \frac{E_\nu}{MeV} - 10 \right) \right) - 1 \right) \]

**Solar+KamLAND**
- \( \sin^2 \theta_{12} = 0.308 \)
- \( \Delta m^2_{21} = 7.50 \times 10^{-5} eV^2 \)

**Solar**
- \( \sin^2 \theta_{12} = 0.311 \)
- \( \Delta m^2_{21} = 4.85 \times 10^{-5} eV^2 \)

\( \sqrt{SK} \) spectrum, red: exponential, green: quadratic

-preliminary-
Comparison with others

Comparison of 8B Elastic Scattering Data

- BOREXINO
- SNO
- KamLAND
- Super-K

Super-K spectrum is the most precise!