5 Years Neutrino Physics with Super-Kamiokande

XXXVII Rencontres de Moriond
March 2002

Michael Smy, UC Irvine
Neutrino Sources and Oscillations

- **Atm. Neutrinos:** (high energy)
  - e- and µ-type
  - Probe oscill. for $\Delta m^2 = 0.001 \text{eV}^2$
  - Varying L (zenith angle) and E
  - Probe matter effects

- **Solar Neutrinos:** (low energy)
  - Only e-type
  - Probe oscill. for $\Delta m^2 = 10^{-11} \text{eV}^2$
  - Varying L (season) and E
  - Probe matter effects (solar zenith angle)

**Mixing Matrix:**

\[
U = \begin{pmatrix}
  c_{12}c_{13} & s_{12}c_{13} \\
  -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} \\
  s_{12}s_{23} - c_{12}c_{23}s_{13} & c_{12}s_{23} - s_{12}c_{23}s_{13}
\end{pmatrix}
\]

\[
c_{ij} = \cos \theta_{ij} \quad s_{ij} = \sin \theta_{ij}
\]

\[
P_{\text{vac}}(\alpha \rightarrow \beta) = \delta_{\alpha\beta} - 4 \sum_{\substack{j \neq k}} U_{\alpha j} U_{\beta j} U_{\alpha k} U_{\beta k} \sin^2 \left( \frac{\Delta m^2_{jk} L}{4E} \right)
\]

\[
(\Delta m^2_{\text{mat}})^2 = (\Delta m^2)^2 \times \left[ \frac{2EV}{\Delta m^2} - \cos(2\theta) \right]^2 + \sin^2(2\theta)
\]

\[
\sin^2(2\theta_{\text{mat}}) = \sin^2(2\theta) \frac{\Delta m^2}{\Delta m^2_{\text{mat}}}
\]

Matter-Effects

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Super-K Collaboration

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Solar Neutrinos
Experimental Thresholds

Neutrino Spectrum

Recoil Electron Spectrum

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Standard Solar Model BP2001

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Super-K Solar Neutrinos

- 1496 Live Days between May 31st, 1996 and July 15th, 2001
- High Statistics
- Measures $^8$B, limits hep flux
- $^8$B flux time variations
- Studies energy spectrum
- Some sensitivity to other than $e$-type neutrinos

Oscillation Signatures

- Suppression of $^8$B flux
- Appearance of other active flavors (with SNO)
- Spectral Distortion
- Daily variations of $^8$B flux
- Anomalous yearly variations of $^8$B flux
Solar Peak above 5 MeV

SK-I 1496day 5.0-20MeV 22.5kt
(Preliminary)
Super-K Solar Neutrino Rate

1496 Day Final Sample:

• 287,000 events
• 22,400 solar neutrino events

Expect:

• 48,200 solar neutrinos (from SSM)
• 16,700 $e$-type solar neutrinos (from SNO)
• About 5,700 $\mu/\tau$-type solar neutrinos

flux is

$2.35 \pm 0.02 \text{(stat.)} \pm 0.08 \text{(sys.)} \times 10^6 / \text{cm}^2 \cdot \text{s}$

or

$0.465 \pm 0.005 \text{(stat.)} ^{+0.016}_{-0.015} \text{(sys.)} \times \text{SSM}$
Time Variation of SK Rate

Time-Dependence of ν Flux

- **New S_{17}**
- **SSM**
- **SK**
- **SNO**

Flux in $10^6$/cm$^2$s

Days since Analysis Start

Yearly Variation of SK Rate
Seasonal Dependence of $\nu$ Flux

Flux in $10^6$/cm$^2$s

Corrected data points

Flux at 1 AU

$\chi^2 = 4.7$ (69% C.L.)

(Flat $\chi^2 = 10.3$ or 17% C.L.)

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Large Mixing Angle (LMA)

Small Mixing Angle (SMA)

LOW

Vacuum

allowed (Ga, Cl & SNO rates+SSM pred.)

$\nu_e \rightarrow \nu_{\mu/\tau}$ (95% C.L.)
Zenith Angle Spectrum

Tested Oscillation Signatures:

<table>
<thead>
<tr>
<th>Tested Signatures</th>
<th>Verdict</th>
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</thead>
<tbody>
<tr>
<td>Suppression of $^8$B flux</td>
<td>✔️</td>
</tr>
<tr>
<td>Appearance of other active flavors (with SNO)</td>
<td>✔️</td>
</tr>
<tr>
<td>Spectral Distortion</td>
<td>✔️</td>
</tr>
<tr>
<td>Daily variation of $^8$B flux</td>
<td>✔️</td>
</tr>
<tr>
<td>Anomalous yearly variations of $^8$B flux</td>
<td>✗</td>
</tr>
</tbody>
</table>

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Zenith Spec: Data & Solutions

- $\tan^2 \theta = 0.26/3.8$
- $\Delta m^2 = 7.85 \times 10^{-4} \text{eV}^2$
- $\tan^2 \theta = 0.0016$
- $\Delta m^2 = 6.9 \times 10^{-6} \text{eV}^2$
- $\tan^2 \theta = 0.34$
- $\Delta m^2 = 2.2 \times 10^{-5} \text{eV}^2$
- $\tan^2 \theta = 0.65$
- $\Delta m^2 = 10^{-7} \text{eV}^2$

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$\nu_e \rightarrow \nu_\mu$ (95, 68, 99.73% C.L.)

Zenith Spectrum+Rates ($^{8}_B$, hep free)

$\Delta m^2$ in eV$^2$

$\tan^2(\theta)$
Zenith Spec. & Rates: Best Fits

- $\tan^2 \theta = 2.1$
  - $\Delta m^2 = 4.57 \times 10^{-10} \text{eV}^2$
- $\tan^2 \theta = 0.00044$
  - $\Delta m^2 = 4.8 \times 10^{-6} \text{eV}^2$
- $\tan^2 \theta = 0.34$
  - $\Delta m^2 = 6 \times 10^{-5} \text{eV}^2$
- $\tan^2 \theta = 0.83$
  - $\Delta m^2 = 5 \times 10^{-8} \text{eV}^2$

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## Best-fit Points

<table>
<thead>
<tr>
<th>Solution</th>
<th>Large Mixing Angle (LMA)</th>
<th>Quasi-Vacuum (Quasi-VAC)</th>
<th>Low $\Delta m^2$ (LOW)</th>
<th>Small Mixing Angle (SMA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2$</td>
<td>$6.0 \times 10^{-5}$</td>
<td>$4.57 \times 10^{-10}$</td>
<td>$5.0 \times 10^{-8}$</td>
<td>$4.8 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\tan^2 \theta$</td>
<td>0.35</td>
<td>2.1</td>
<td>0.83</td>
<td>0.00044</td>
</tr>
<tr>
<td>$\chi^2$ (45 dof; $p_{\chi^2}$ [%])</td>
<td>43.4 (53.9)</td>
<td>48.5 (33.4)</td>
<td>51.2 (24.3)</td>
<td>54.2 (16.2)</td>
</tr>
<tr>
<td>$\Delta \chi^2$ (2 dof; $p_{\Delta \chi^2}$ [%])</td>
<td>0.0 (100.0)</td>
<td>5.1 (7.9)</td>
<td>7.8 (2.0)</td>
<td>10.8 (0.5)</td>
</tr>
<tr>
<td>$\Delta \chi^2_{SK}$ ($p_{\Delta \chi^2}$ [$\sigma$])</td>
<td>3.4 (1.3$\sigma$)</td>
<td>3.1 (1.3$\sigma$)</td>
<td>3.9 (1.5$\sigma$)</td>
<td>5.0 (1.7$\sigma$)</td>
</tr>
<tr>
<td>Ga Rate [SNU]</td>
<td>73.2 (−0.3$\sigma$)</td>
<td>69.6 (−1.0$\sigma$)</td>
<td>68.2 (−1.3$\sigma$)</td>
<td>75.1 (+0.1$\sigma$)</td>
</tr>
<tr>
<td>Cl Rate [SNU]</td>
<td>2.97 (+1.8$\sigma$)</td>
<td>3.18 (+2.8$\sigma$)</td>
<td>3.13 (+2.5$\sigma$)</td>
<td>2.67 (+0.5$\sigma$)</td>
</tr>
<tr>
<td>SK Rate [%SSM]</td>
<td>46.4 (−0.1$\sigma$)</td>
<td>44.7 (−1.4$\sigma$)</td>
<td>44.9 (−1.2$\sigma$)</td>
<td>44.1 (−1.9$\sigma$)</td>
</tr>
<tr>
<td>SNO Rate [%SSM]</td>
<td>32.8 (−0.7$\sigma$)</td>
<td>37.1 (+0.8$\sigma$)</td>
<td>38.5 (+1.3$\sigma$)</td>
<td>43.8 (+3.1$\sigma$)</td>
</tr>
<tr>
<td>$\phi_{8B}$ [$10^6/(\text{cm}^2\text{s})$]</td>
<td>5.62 (+0.6$\sigma$)</td>
<td>3.71 (−1.7$\sigma$)</td>
<td>4.04 (−1.2$\sigma$)</td>
<td>2.71 (−2.9$\sigma$)</td>
</tr>
<tr>
<td>$\phi_{\text{hep}}$ [$10^3/(\text{cm}^2\text{s})$]</td>
<td>40</td>
<td>0</td>
<td>21</td>
<td>8</td>
</tr>
<tr>
<td>$^8B$ Spectrum Shape SK E-scale/resol.</td>
<td>−0.3$\sigma$</td>
<td>−0.7$\sigma$</td>
<td>−0.1$\sigma$</td>
<td>+0.1$\sigma$</td>
</tr>
</tbody>
</table>
What does it mean?

- Solar problem is due to neutrino flavor oscillation
- e-type neutrinos oscillate predominantly into μ/τ-type neutrinos, no sterile neutrino needed
- Indications of appearance of μ-type neutrinos
- LMA solution is most likely, but quasi-VAC is still a (remote) possibility
- The mixing is large, but not quite maximal
- The $\Delta m^2$ is 3 to 23 times $10^{-5}$eV$^2$
Atmospheric Neutrinos
Particle Identification

- **Showering ring (e-like)**
- **Electron or photon (e.g. from $\pi^0$)**

- **Non-Showering ring (μ-like)**
- **Sometimes decay electron**

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Data Samples

- **Fully contained** (FC) events have determined energy and PID: no OD activity allowed
- **Multi-ring** (fully contained) events: μ-like or neutral-current (e.g. $\pi^0$s) enhanced (NC)
- **Partially contained** (PC) events are assumed μs, no precise energy: only exiting particles allowed
- **Upward-going muons** (from rock): stopping (lower energy) or through-going (higher energy)
Data and Oscillation Best Fit (ν_μ−ν_τ)
Atmospheric Allowed Region

- Disappearance of \( \mu \)-type, no appearance of e-type: \( \nu_\mu - \nu_\tau \)
- Uses all Super-K data sets (1290d) FC, PC, up \( \mu \) and multi-ring
- Very good \( \chi^2 \) (175.0/190)
- Maximal mixing

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### Nature of atmospheric Oscillation

<table>
<thead>
<tr>
<th>Mode</th>
<th>Best fit</th>
<th>$\Delta\chi^2$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu - \nu_\tau$</td>
<td>$\sin^2 2\theta = 1.00; \Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2$</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$\nu_\mu - \nu_e$</td>
<td>$\sin^2 2\theta = 0.97; \Delta m^2 = 5.0 \times 10^{-3} \text{eV}^2$</td>
<td>79.3</td>
<td>8.9</td>
</tr>
<tr>
<td>$\nu_\mu - \nu_s$</td>
<td>$\sin^2 2\theta = 0.96; \Delta m^2 = 3.6 \times 10^{-3} \text{eV}^2$</td>
<td>19.0</td>
<td>4.4</td>
</tr>
<tr>
<td>LxE</td>
<td>$\sin^2 2\theta = 0.90; \alpha = 5.3 \times 10^{-4}$</td>
<td>67.1</td>
<td>8.2</td>
</tr>
<tr>
<td>$\nu_\mu$ Decay</td>
<td>$\cos^2 \theta = 0.47; \alpha = 3.0 \times 10^{-3} \text{eV}^2$</td>
<td>81.1</td>
<td>9.0</td>
</tr>
<tr>
<td>$\nu_\mu$ Decay to $\nu_s$</td>
<td>$\cos^2 \theta = 0.33; \alpha = 1.1 \times 10^{-2} \text{eV}^2$</td>
<td>14.1</td>
<td>3.8</td>
</tr>
</tbody>
</table>
• Maximal mixing in the dominant mode ($\nu_\mu - \nu_\tau$)
• Zero mixing in the subdominant mode ($\nu_\mu - \nu_e$)
• About 30 to 40% e-type fraction (90% C.L.) allowed
Limits on $\theta_{13}$

- CHOOZ limit by far the best
- SK allowed area contributes in low $\Delta m^2$ region
- Favor for $\nu_\mu - \nu_\tau$, disfavor $\nu_\mu - \nu_e$
- No hint for electron appearance
Oscillation Best Fit ($\nu_\mu - \nu_{\text{sterile}}$)
Limit on Sterile Content

• Mass Hierarchy:
  \( \Delta m^2_{34} = 1 \text{eV}^2, \)
  \( \Delta m^2_{23} = 0.001 \text{eV}^2, \)
  \( \Delta m^2_{12} = 0.0001 \text{eV}^2 \)

• 3 Parameters:
  \( \sin^2 2\theta, \Delta m^2, \sin^2 \xi \) (sterile content)

• \( \sin^2 \xi \) controls size of matter effect

• \( \sin^2 \xi \) controls NC disappearance probability \( P_{NC} \)

\[
P_{NC} = \sin^2 \xi - \sin^2 \xi P_{CC}
\]
Limit on Sterile Content

- Consistent with pure $\nu_\mu - \nu_\tau$
- Sterile Content Limit of 25% (90% C.L.) is based on 2 d.o.f.
- Pure $\nu_\mu - \nu_{\text{sterile}}$ don’t fit well the NC multi-ring and the up-$\mu$ samples

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Limit on Sterile Content

Limit On $\nu_\mu - \nu_s$ Admixture

Best Fit $\chi^2 = 171.6/190$ (P=83%)

$\sin^2 \xi = 0.0$

$\sin^2 2\theta = 1$

$\Delta m^2 = 3.2 \times 10^{-3} \text{ eV}^2$

- Best fit very close to maximal mixing and pure $\nu_\mu - \nu_\tau$

- Consistent $\Delta m^2$

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τ-type Appearance
Three Different Analyses

- Different event reconstruction (energy flow, jet variables), Likelihood-function
- Standard ring reconstruction, Likelihood-function
- Standard ring reconstruction, Neural Net

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Zenith Angle Plot of enriched Sample

Fit of Zenith Angle Distribution is used to extract the $\tau$ signal

Energy flow Analysis

Ring Counting Likelihood

Neural Net
# τ-type Appearance Summary

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Number τ-events in fit</th>
<th>Efficiency $\varepsilon$</th>
<th>Significance</th>
<th>Expect significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy-flow Likelihood-function</td>
<td>$79^{+44}_{-40}$ (stat+sys)</td>
<td>32%</td>
<td>1.8$\sigma$</td>
<td>1.9$\sigma$</td>
</tr>
<tr>
<td>Ring-Counting Likelihood-function</td>
<td>$66^{+41}<em>{-35.3}$ (stat$^{+18}</em>{-18}$) (sys)</td>
<td>43%</td>
<td>1.5$\sigma$</td>
<td>2.0$\sigma$</td>
</tr>
<tr>
<td>Ring-Counting Neutral Net</td>
<td>$92^{+35.3}<em>{-35.3}$ (stat$^{+18}</em>{-18}$) (sys)</td>
<td>51%</td>
<td>2.2$\sigma$</td>
<td>2.0$\sigma$</td>
</tr>
</tbody>
</table>

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What does it mean?

- Atmospheric problem is due to neutrino flavor oscillation
- $\mu$-type neutrinos oscillate predominantly into $\tau$-type neutrinos, no sterile neutrino needed
- A hint of appearance of $\tau$-type neutrinos
- The mixing is large, possibly maximal
- The $\Delta m^2$ is a few times $10^{-3}\text{eV}^2$
- No hint of positive $\theta_{13}$, set limit
What does it all mean?

• Prefer large mixing
• 3 neutrinos are enough: no hint anywhere in SK for sterile neutrinos
• $\Delta m^2_{\text{atm}} = 0.0025 \text{eV}^2$
• $\Delta m^2_{\text{solar}} = 0.00006 \text{eV}^2$
• Mass scheme (right):
  – Assume $m_1 = 0$
  – Assume $\theta_{13} = 0$
  – Neglect CP phase
Super-Kamiokande Accident and Future Plans
Super-K after Collapse
Seismic Recording (2.3 km from SK)

MOZ-V (8418) 01/11/12 0.07 mkine/cm

10 s

Nov. 12
11:01:29

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## Super-K Damage Summary

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damaged PMT’s</td>
<td>6777 (out of 11146 20” tubes)</td>
</tr>
<tr>
<td></td>
<td>1149 (out of 1885 8” tubes)</td>
</tr>
<tr>
<td>Electronics damage</td>
<td>none</td>
</tr>
<tr>
<td>High voltage damage</td>
<td>negligible</td>
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<tr>
<td>Wavelength shifting plates</td>
<td>700 (out of 1885 damaged)</td>
</tr>
<tr>
<td>Plastic, Tyvek sheeting</td>
<td>Needs total replacement</td>
</tr>
<tr>
<td>Cables</td>
<td>Still undetermined</td>
</tr>
<tr>
<td>Tube frames/housings</td>
<td>Extensive damage</td>
</tr>
<tr>
<td>Small water leak</td>
<td>4.2 tons/hr</td>
</tr>
<tr>
<td>Damage to detector structure</td>
<td>none</td>
</tr>
</tbody>
</table>

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First Imploding PMTs

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Observed pressure pulse at 0.45m from tube center is about **5.6 MPa**. Idealized simulation predicts about **13 MPa**.

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Rebuilding Super-Kamiokande

- It takes several years to rebuild 20” PMTs
- Take existing 20” PMTs and redo ID with about 50% coverage in one year
- Design PMT enclosures to prevent chain reaction
- Rebuild OD with full coverage in one year
- Rebuild ID with full coverage in 4-5 years
- Old Super-K back in time for JHF turn-on

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PMT Enclosure Designs

Acrylic (10 mm; front) and Fiberglass (5mm; back) Design

All-Acrylic Design

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Test at 30m Depth

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Super-K Rebuilt Schedule

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Fe</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>PMT Implosion Tests</td>
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<td>2</td>
<td>Remove ID PMTs SM 11 to 17</td>
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<td>3</td>
<td>Raise Water to Mid SM 17</td>
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<tr>
<td>4</td>
<td>Install OD Floating Floor</td>
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<td>5</td>
<td>40 Meter Implosion Tests</td>
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<tr>
<td>6</td>
<td>Barrel Demolition</td>
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<tr>
<td>7</td>
<td>Drain Remaining Water from Tank</td>
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<td>8</td>
<td>Clean PMT Support Structure</td>
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<tr>
<td>9</td>
<td>Remove OD Floating floor</td>
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<td>Bottom Demolition</td>
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<td>11</td>
<td>Remove Debris from Detector Floor</td>
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<td>Inspect tank Floor for Leaks</td>
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<td>Detector Top Reconstruction</td>
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<td>Install wall Tyvek</td>
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<td>Detector Bottom Reconstruction</td>
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<td>Bottom Tyvek</td>
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<td>Fill detector</td>
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Preliminary S-K Reconstruction Schedule

William Kropp, UC Irvine
Real K2K Event

1.3 GeV Single Ring $\mu$

As recorded

50% of PMTs masked

Momentum and angle from beam should be measurable with negligible loss of accuracy

Hank Sobel, UC Irvine
Proton Decay

Proton Decay to $K^+ \nu$: $K^+ \rightarrow \mu \nu$ with prompt tag from $^{16}N^* \rightarrow ^{16}N + \gamma$

8 or more hits in 12 ns sliding window preceding muon ($K^+$ is below Cherenkov threshold)

M.C. direction of 6 MeV gamma

PMT hits from 6 MeV gamma

Hank Sobel, UC Irvine
Threshold with 50% Coverage

Michael Smy, UC Irvine
Further Impact of SK Solar Data

• Continue to watch the long-term time stability of $^8$B flux
• Search for anomalous yearly variation to limit quasi-vacuum oscillation possibilities
• Improve high-energy spectrum shape precision to limit quasi-vacuum oscillation possibilities
• Improve day-night asymmetry precision at high energy and limit LMA oscillation possibilities
• Increase precision of high-energy flux (to test if large hep neutrino flux of LMA is really there)
• Increase the solar neutrino $\mu/\tau$ appearance sample; do spectral analysis (with SNO)

Michael Smy, UC Irvine
Further Impact of SK High-E Data

• Confirm oscillation of \(\mu\)-type into \(\tau\)-type by K2K beam spectrum
• Increase significance of \(\tau\)-type appearance
• Maybe observe oscillation pattern
• Push limits for nucleon decay
• Search for positive \(\theta_{13}\) using JHF beam

Michael Smy, UC Irvine