Atmospheric Neutrino Oscillations & Super-Kamiokande

Ryan Terri (QMUL)
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Queen Mary, University of London Seminar
Outline

• Neutrino oscillations
• Super-Kamiokande
  – Detector, simulation, & reconstruction
• The atmospheric neutrino anomaly
• Various Super-Kamiokande results
  – 2 flavour zenith angle analysis
  – 3 flavour analysis
  – Tau neutrino appearance
  – (anti-)neutrino oscillations (CPT invariance)
• Other experiments
In Standard Model, neutrinos are massless.

Individual and global lepton flavour # $(L_e, L_\mu, L_\tau)$ is conserved in interactions, e.g.:

- $e$ interacts with $\nu_e$ via a $W$ boson.
Neutrino Oscillations

\[ |\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \]

\[ P(\nu_\alpha \rightarrow \nu_\beta) \approx \sin^2(2\theta)\sin^2\left(1.267 \frac{\Delta m^2 L}{E}\right) \]

\[ P(\nu_\alpha \rightarrow \nu_\alpha) \approx 1 - \sin^2(2\theta)\sin^2\left(1.267 \frac{\Delta m^2 L}{E}\right) \]

\[ \Delta m^2 = m_i^2 - m_j^2 \]

Individual lepton flavour # conservation is violated

Total lepton # is still conserved

L [km]
E [GeV]
\(\Delta m^2 [\text{eV}^2]\)
Neutrino Oscillations

\[ |\nu_\alpha\rangle = \sum_i U^*_{ai} |\nu_i\rangle \]

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix} \begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
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2 flavour approximation:

\[ P(\nu^\alpha \rightarrow \nu^\beta) \approx \sin^2(2\theta)\sin^2 \left( 1.267 \frac{\Delta m^2 L}{E} \right) \]

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atmospheric \ \nu

solar \ \nu

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atmospheric $\nu$

\[
sin^22\theta_{23} \approx 1.0 \\
|\Delta m^2_{23}| \approx 0.0023 \text{ eV}^2
\]

From atm. $\nu$ & long-baseline experiments

2 flavour approximation:

\[ P(\nu_\alpha \rightarrow \nu_\beta) \approx \sin^2(2\theta)\sin^2 \left( 1.267 \frac{\Delta m^2 L}{E} \right) \]

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Is $\theta_{23}$ maximal?

\[ \Delta m^2 = m_i^2 - m_j^2 \]

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\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \]

**Neutrino Oscillations**

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atmospheric \(\nu\)

\[
\sin^2 2\theta_{23} \approx 1.0 \\
|\Delta m^2_{23}| \approx \text{0.0023 eV}^2 \\
\text{From atm. } \nu \text{ & long-baseline experiments}
\]

2 flavour approximation:

\[
P\left(\nu_\alpha \rightarrow \nu_\beta\right) \approx \sin^2 (2\theta)\sin^2 \left(1.267 \frac{\Delta m^2 L}{E}\right)
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\[
\Delta m^2 = m_i^2 - m_j^2
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Is \(\theta_{23}\) maximal?

What is the value of \(\theta_{13}\)?

What is the value of \(\delta_{\text{CP}}\)?
Neutrino Oscillations

\[ \left| \nu_\alpha \right> = \sum_i U^*_{\alpha i} \left| \nu_i \right> \]

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atmospheric $\nu$

solar $\nu$

\[ \sin^2 2\theta_{23} \approx 1.0 \]
\[ |\Delta m^2_{23}| \approx 0.0023 \text{ eV}^2 \]
From atm. $\nu$ & long-baseline experiments

Is $\theta_{23}$ maximal?
What is the value of $\theta_{13}$?
What is the value of $\delta_{\text{CP}}$?
Which mass hierarchy exists?
Do neutrinos & anti-neutrinos have the same oscillation parameters (i.e. is CPT violated)?

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Super-Kamiokande

50 kton water Cherenkov detector
22.5 kton fiducial volume

Depth of 2700 m.w.e
cosmic ray background ~3 Hz

Roughly ~10 Atmospheric $\nu$ per day

Inner detector (ID) 11,146 50 cm PMTs
~ 2 ns timing resolution
39% photo-coverage

Outer detector (OD) 1,885 20 cm PMTs

Multi-purpose detector: (this talk)
Nucleon decay
Solar neutrinos
Supernova neutrinos (Relic SN's)
Atmospheric neutrinos
Beam neutrinos: K2K, T2K
Exotic particles

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Cherenkov Radiation

Wave front created by charged particle going faster than the speed of light in a medium

Angle related to index of refraction of medium

\[ \cos \theta_C = \frac{1}{n(\lambda)\beta} \]

For SK, the maximum \( \theta_C \) is roughly 42 degrees
Super-Kamiokande: Generations

SK-I (1996-2001)
- 11,146 ID PMTs (40% coverage)
- 1,885 OD PMTs

SK-II (2003-2005)
- 5182 ID PMTs (19% coverage)
- Acrylic shields added

SK-III (2006-2008)
- 11,129 ID PMTs (40% cov.)
- OD segmentation (top/barrel/bottom)

SK-IV (2008-...)
- New front-end electronics (ID and OD)
- New DAQ
- Record-all-hit data-taking + software trigger

Still taking data!

Data Update

Analyses

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Atmospheric Neutrinos

Created by cosmic ray interactions with the atmosphere

Mainly pions produced

$\nu_\mu : \nu_e$ ratio is $\sim 2:1$

Anti-$\nu_\mu : \bar{\nu}_\mu : \nu_e \sim 1:1:1$
Atmospheric Neutrino Simulation:

Atmospheric neutrino flux model is from Honda et al. specifically at Super-Kamiokande

Uses changes in solar activity (minimum to maximum)

Cross checks from two other fluxes

Cosmic $\mu$ bkg uses mountain profile to determine background contributions

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In-house $\nu$ interaction MC
Valid from range 100 MeV~~TeV
Also used in K2K, SciBooNE, & T2K

Cross-sections

CCQE & NCEL: Smith-Moniz w/ RFG
Resonant/coherent interactions: Rein-Sehgal
DIS: GRV98 w/ Bodek-Yang correction

Includes base cross sections & nuclear effects, validated on external data sets
SK Event Reduction:

Events divided into different categories for analysis:
- Fully Contained (FC) – little to no OD activity
- Partially Contained (PC) – activity in OD & ID
- Up\(\mu\) – Muons coming from below the detector

Extract 10 events from a background of more than a million

FC:
- Total charge in 300 ns timing window >200 photoelectrons (p.e.)
- Less than half of the light is in any ID PMT
- Little OD activity
- >100 \(\mu\)s window between events
- Remove flashers
- Inside FV with at least 30 MeV visible energy
SK Event Reduction:

Events divided into different categories for analysis:
- **Fully Contained (FC)** – little to no OD activity
- **Partially Contained (PC)** – activity in OD & ID
- **$\mu$** – Muons coming from below the detector

Must extract 10 events from a background of more than a million

**PC:**
- $>3000$ p.e. & travels at least 2.5 m in ID
- $>100$ µs window between events
- Must have clusters in the OD
- Remove flashers
- At least 150 cm from corner
- Fail through-going muon cuts
- Must pass various goodness-of-fit cuts on reconstructed vertex & direction
SK Event Reduction:

Events divided into different categories for analysis:
- Fully Contained (FC) – little to no OD activity
- Partially Contained (PC) – activity in OD & ID
- $Up\mu$ – Muons coming from below the detector

Must extract 10 events from a background of more than a million

$Up\mu$:
- 10 OD PMT hits w/in 8 m of track entrance or exit point
- $8000<p.e.<1.75e6$ in ID
- Must be more than 7m in track length
- Various fitters applied (remove muons from top of tank)
- Eye scan applied by at least 2 physicists
- $\geq 10$ hits at exit point means through-going $\mu$
  Otherwise, stopping $\mu$
Event Reconstruction

Initial vertex fit based on PMT timing
Direction based on summed vector of weighted charge in each PMT
Cherenkov angle fitted

Ring counting (Hough transform + likelihood) up to 5 rings
PID applied (see next slide)
Momentum determined (corrected charge fraction in 70 degree half-angle cone)
Precise vertex for single ring events based on PID & Cherenkov angle

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Ring Types & Particle ID

muons leave rings with sharp edges
electrons undergo pair production, producing a fuzzy ring

non-showering

multi-ring

showering

muon, charged pion, proton

μ-like

PID verified @ KEK test
beam w/ 1kton detector

electron, photon
e-like
SK Event Types

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Sub-GeV ($E_{\text{visible}} < 1.33$ GeV):
- One ring (R)

Multi-GeV ($E_{\text{visible}} > 1.33$ GeV):
- 1R or multi-R

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SK Event Types

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**Sub-GeV (E_{visible}<1.33 GeV):**
- One ring (R) e-like
- 1R μ-like

**Multi-GeV (E_{visible}>1.33 GeV):**
- 1R or multi-R, e- or μ-like
- PID applied to most energetic ring

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SK Event Types

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**Sub-GeV (E\text{\_visible} < 1.33 \, \text{GeV})**:
- One ring (R) e-like: 0 or 1 decay electron or π₀-like
- 1R μ-like: 0, 1, or 2, decay electron
- 2R π₀-like

**Multi-GeV (E\text{\_visible} > 1.33 \, \text{GeV})**:
- 1R or multi-R, e- or μ-like
- PID applied to most energetic ring

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Multi-GeV ($E_{\text{visible}} > 1.33$ GeV):
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Stopping – stops in OD
Though-going – exits OD

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SK Event Types

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Multi-GeV \((E_{\text{visible}} > 1.33 \text{ GeV})\):
- 1R or multi-R, e- or \(\mu\)-like
- PID applied to most energetic ring

- **Stopping** – stops in OD
- **Though-going** – exits OD
- **Stopping** – stops in ID
- **non-showering**
- **showering**

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Atmospheric Neutrino Anomaly

- Double ratio of flavours
  \[ R = \frac{N_{\text{Data}}(\mu/e)}{N_{\text{MC}}(\mu/e)} \]

- Early experiments show considerable difference in R
  - Thought to be problem of water Cherenkov detectors since they were a new technology

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Method</th>
<th>Exposure (kt-year)</th>
<th>Flavor Ratio $R(\mu/e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMB</td>
<td>Water Cherenkov</td>
<td>7.7</td>
<td>$0.54 \pm 0.05 \pm 0.012$ (Sub-GeV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.1</td>
<td>$1.40 \pm 0.30 \pm 0.05$ (Multi-GeV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.7</td>
<td>$0.60 \pm 0.05 \pm 0.05$ (Sub-GeV)</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>Water Cherenkov</td>
<td>8.2</td>
<td>$0.57 \pm 0.08 \pm 0.07$ (Multi-GeV)</td>
</tr>
<tr>
<td>NUSEX</td>
<td>Iron Calorimeter</td>
<td>0.74</td>
<td>$0.96 \pm 0.32$</td>
</tr>
<tr>
<td>Fréjus</td>
<td>Iron Calorimeter</td>
<td>1.56</td>
<td>$1.00 \pm 0.15 \pm 0.08$</td>
</tr>
<tr>
<td>Soudan-2</td>
<td>Iron Calorimeter</td>
<td>5.1</td>
<td>$0.68 \pm 0.11 \pm 0.06$</td>
</tr>
<tr>
<td>Super-K</td>
<td>Water Cherenkov</td>
<td>92</td>
<td>$0.658 \pm 0.016 \pm 0.05$ (Sub-GeV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>92</td>
<td>$0.702 \pm 0.032 \pm 0.010$ (Multi-GeV)</td>
</tr>
</tbody>
</table>
Zenith Angle Distributions

• Way to check to see if the atmospheric neutrino ratios are similar based on where in the atmosphere neutrino was created

• Neutrino production should be the same regardless of direction
  – See if systematically different or directionally dependent
Zenith angle & lepton momentum distributions: SK-I+II+III

- $\nu_\mu - \nu_\tau$ oscillation (best fit)
- null oscillation

**$\mu$-like**

- $\mu$-like samples show large deficits in the upward-going bins that are well described by oscillations

**e-like**

**momentum**

Live time:
- SK-I
  - 1489d (FCPC)
  - 1646d (Upmu)
- SK-II
  - 799d (FCPC)
  - 828d (Upmu)
- SK-III
  - 518d (FCPC)
  - 635d (Upmu)
Global Picture of Atm. ν Osc. Parameters

SK Zenith Analysis (1σ) (2 flavour)
\[ \Delta m_{23}^2 = 2.11^{+0.11}_{-0.19} \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta_{23} > 0.96 \ (90\% \ C.L.) \]

SK L/E Analysis (1σ) (2 flavour)
\[ \Delta m_{23}^2 = 2.19^{+0.14}_{-0.13} \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta_{23} > 0.96 \ (90\% \ C.L.) \]

Experiments are in good agreement about these oscillation parameters
SK Data disfavour other types of disappearance strongly, sterile ν ~7σ
Three-Flavour Oscillations in Matter

- Presence of electrons in the Earth alter the neutrino interaction potential and induce additional $\nu_\mu \rightarrow \nu_e$ oscillations.

- Higher energy, 2-10 GeV, (anti-)neutrinos experience resonant enhanced transitions, for normal (inverted) hierarchy.

- Lower energy oscillations, $< 1\text{GeV}$, are moderated by octant of $\theta_{23}$.

\[
\Delta_\theta \equiv \frac{N_\theta}{N_\theta^0} \approx \Delta_1(\theta_{13}) + \Delta_2(\Delta m^2_{12}) + \Delta_3(\theta_{13}, \Delta m^2_{12}, \delta)
\]

Simultaneously considering all of these effects gives sensitivity to many of the remaining questions on oscillation physics...
No strong preference for either hierarchy ($\Delta \chi^2 = 1.6$)
No preference for $\theta_{23}$ octant or $\delta_{CP}$
$\nu_\tau$ Appearance at Super-K

Many Cherenkov light producing particles
Most events are DIS interactions

Energy Threshold: 3.5 GeV

Negligible primary flux
$\rightarrow$ Observed tau events would be oscillation induced

Complicated event topology complicate identification of the leading lepton

How inconsistent is the “no appearance” hypothesis?
SK $\tau$ Appearance Fit Results (Updated)


Fit corresponds to 213.6 $\tau$ events

SK data is inconsistent with no $\tau$ appearance at 3.8$\sigma$

Expected significance: 2.6$\sigma$
Previous result: inconsistent at 2.4$\sigma$

One of two experiments so far to observe some signal of $\nu_\tau$ appearance (OPERA being the other)
ν/Anti-ν oscillations

Motivated from recent MINOS indications of different osc. parameters of ν & anti-ν

SK applies an ad hoc 2 flavour model, fit osc. parameters individually for ν & anti-ν

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^22\theta\sin \left(\frac{\Delta m^2 L}{4E}\right)
\]

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \sin^22\bar{\theta}\sin \left(\frac{\Delta m^2 L}{4E}\right)
\]

Divide into samples same as with normal 2 flavour oscillation fit

MC histogram is best fit, w/ blue region anti-ν contribution

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### $\nu$/Anti-$\nu$ Osc. Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Fit</th>
<th>90% C.L.</th>
<th>Three-Flavour</th>
<th>MINOS Best Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2/1 eV^2$</td>
<td>2.1</td>
<td>1.7-3.0</td>
<td>1.7-3.3</td>
<td>2.32$^{+0.12}_{-0.08}$</td>
</tr>
<tr>
<td>Anti-$\Delta m^2/1 eV^2$</td>
<td>2.0</td>
<td>1.3-4.0</td>
<td>1.2-4.0</td>
<td>2.62$^{+0.32}_{-0.29}$</td>
</tr>
<tr>
<td>$\sin^2 2\theta$</td>
<td>1.0</td>
<td>.93-1.0</td>
<td>.93-1.0</td>
<td>&gt;0.90 (90% C.L.)</td>
</tr>
<tr>
<td>Anti-$\sin^2 2\theta$</td>
<td>1.0</td>
<td>.83-1.0</td>
<td>.78-1.0</td>
<td>&gt;0.75 (90% C.L.)</td>
</tr>
</tbody>
</table>

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Do $\nu$ & Anti-$\nu$ Have Same Oscillation Parameters?

Short answer: yes!

Updated MINOS beam results indicate same answer (hep-ex 1202.2772)
Far Detector Description and Event Types

Far detector (5.4 kton):
In Soudan Mine, 2070 m.w.e.
486 2.54 cm thick steel planes
484 scintillator planes, 1 cm thick

Magnetic field average ~1.3 T
Can separate differently charged tracks

Cosmic Ray μ:

Select muon tracks:
• Single track only
• Vertex starts inside fiducial volume
• Good timing & track quality cuts
• Separate by charge (+/-)
• Separate by momentum:
  p<10 GeV, 10 GeV<p<100 GeV, Unknown

Event selection taken from hep-ex/0701045v2
Atm. $\nu$ results (NEUTRINO 2010)

- Atmospheric neutrino results based on 1657 live-days of far detector data (24.6 kt-yrs).
- Observe 1128 candidate events:
  - 572 contained vertex muons.
  - 292 contained vertex showers.
  - 264 $\nu$-induced rock muons.
- MINOS detector is magnetised, enabling direct separation of neutrinos and anti-neutrinos. Measuring charge ratio:
  \[ \frac{R_{\text{data}}}{R_{\text{MC}}} = 1.04^{+0.11}_{-0.10} \pm 0.10 \]
- Fit oscillations separately for neutrinos and anti-neutrinos. Testing CPT symmetry:
  \[ |\Delta m^2| - |\Delta \bar{m}^2| = 0.4^{+2.5}_{-1.2} \times 10^{-3} \text{eV}^2 \]
  90% C.L. at maximal mixing.

From MINOS Collaboration
IceCube
Detector Setup

Neutrino astronomy experiment located at South Pole

~1 km³ volume

Searching for HE & UHE neutrinos from various astrophysical sources e.g. Supernova, γ-ray bursts, black holes, dark matter

Years installed:
- 04-05
- 05-06
- 06-07
- 07-08
- 08-09
- 09-10
- 10-11
Possible Atmospheric $\nu$ Measurements

- Atm. $\nu$ one of two backgrounds to $\nu$ astronomy
  - Needs to be well-measured
- Future measurements may include:
  - Atm. $\nu$ oscillation parameter measurement
    - 10 GeV threshold
  - $\nu_\tau$ appearance searches
  - Mass hierarchy

**Preliminary**

1yr. DeepCore data (Simulated)
- $\cos \phi < 0.6$
- $\cos \phi < 0.6$ (osc)

Expected IceCube 40-string Sensitivity (no background)

Non-DeepCore based analysis
- 40 strings, no bkg., no syst.
Summary

• Super-Kamiokande holds the world’s best oscillation measurements from atmospheric neutrinos
  – Still competitive w/ MINOS’s long-baseline measurements in the 23 sector
  – One of two experiments to see $\tau$ appearance
  – Confirms $\nu$ & anti-$\nu$ oscillation atmospheric neutrino oscillation parameters are statistically consistent
  – Now also searching for $\theta_{13}$, $\delta_{CP}$, and mass hierarchy

• MINOS able to measure CPT using atmospheric neutrino sample
  – No violations yet observed

• Possible contributions by other experiments anticipated
Backup
Selected/Biased Neutrino History

• First proposed in 1930 by Pauli to explain beta decay energy spectrum
• First observed by Reines and Cowan in 1956
  – Savannah River experiment records inverse beta decay signal
• Homestake Experiment begins in 1968, Solar Neutrino Problem
  – Followed later by the Atmospheric Neutrino Anomaly
• Early 1980s, IMB becomes the first water Cherenkov experiment
  – Followed soon by the Kamiokande detector
  – Built to look for proton decay
• In 1998 Super-Kamiokande reports that neutrinos have mass
  – First physics beyond the Standard Model
3 event classes

**FC Reduction:**
Little to no OD activity (less than 25 hit PMTs) w/in +/-400 ns window around trigger
Must have at least 200 photoelectrons in 300 ns window
No PMT may have more than ½ the light
At least 30 MeV in visible energy
Separated by at least 100 us
Remove events w/ at least 10 hit PMTs w/in 8m of where a particle could enter
Remove “flasher” PMTs
Remove stopping muons & invisible muons based on hits in various sliding windows

**PC Reduction:**
Travel at least 2.5 m into ID
Have at least 3000 p.e. In ID
Separated by at least 100 us
Have large cluster of p.e. in OD 8m around entrance point w/ Cherenkov ring having high angle WRT entrance proposed entrance point
Eye scan by 2 physicists

**Umpu:**
Between 8000 & 1.75e6 p.e.
At least 7m track length