Atmospheric Neutrinos
in the Age of Long Baseline Experiments

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- role of atmospheric neutrinos in revealing neutrino oscillation and motivating long baseline experiments
- detailed studies with current data (mostly Super-K)
- outlook for future impact as long baseline experiments take shape
Atmospheric Neutrinos

- mixed beam of $\nu_\mu$ $\bar{\nu}_\mu$ $\nu_e$ $\bar{\nu}_e$
- wide energy band 200 MeV - 1 TeV
- continuous flux - free
- multiple baselines 10 km - 13000 km
- neutrino direction unknown

Long Baseline Neutrinos

- nearly pure beam of $\nu_\mu$
- narrow energy band, adjustable
- pulsed flux - expensive
- fixed baseline 250 / 750 km so far
- neutrino direction known

first solid evidence for neutrino oscillation ...

motivates and suggests design for long baseline experiments
Flux Ratio of $\nu_\mu$ to $\nu_e$

- $\Phi(\nu_\mu)/\Phi(\nu_e) \sim 2$ below a few GeV
- Predicted to $\sim 5\%$ over wide range

Isotropic flux of cosmic rays

Zenith

neutrino direction 10000 km

atmosphere

Super-K

• above a few GeV - no geomagnetic effect
• enhancement at horizon due to pion survival

Zenith

θ

25 km

cosine of zenith angle

-1 -0.5 0 0.5 1

Eν, dN/dEυ

1 GeV

10 GeV

100 GeV

Atmospheric Neutrino Experiments

and Long Baseline Neutrino Beams

IMB
Kamiokande
MACRO
Soudan 2
Super-K
Super-K (SK-1, SK-2, SK-3)
MINOS
MINOS (NuMI, NuMI-1, NuMI-2)
ICARUS
ICARUS (NuMI, NuMI-1, NuMI-2)

1980 1990 2000 2010

μ/e, zenith, PC
μ/e
up μ
Fe ≠ H₂O
high statistics
νμ / ¯νμ
detailed events

others: NUSEX, Frejus, Baksan, SNO
Super-Kamiokande

SK-1  1996 - 2001
- 22.5 kton fiducial mass (2m from wall)
- 11134 50-cm photomultiplier tubes
- 40% photocathode coverage
- 1885 20-cm pmts in outer detector

SK-2  2003 - 2006 (estimated)
- 5183 PMTs, mostly recovered from accident
- ~20% coverage
  with acrylic shields →
- outer detector
  fully restored
- K2K beam resumed

SK-3  2006
- original coverage
  to be restored
- JHF ν off-axis beam
Super-K Reconstruction

thank you for your support
Super-Kamiokande

Run 21703 Sub 26 Ev 1030957
03-02-08:19:24:46 00b7 d02d 55af
Inner: 1289 hits, 8528 pE
Outer: 2 hits, 0 pE (in-time)
Trigger ID: 0x03
D wall: 945.2 cm

Charge(pe)
- >34.3
- 30.0-34.3
- 26.0-30.0
- 22.3-26.0
- 18.9-22.3
- 15.7-18.9
- 12.9-15.7
- 10.3-12.9
- 8.0-10.3
- 6.0-8.0
- 4.3-6.0
- 2.9-4.3
- 1.7-2.9
- 0.9-1.7
- 0.3-0.9
- <0.3

Rebuilt Super-K
Example Event
(from K2K beam)
Super-Kamiokande

Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5747 pE

Resid(ns)
- > 68
- 60–68
- 51–60
- 42–51
- 34–42
- 25–34
- 17–25
- 8–17
- 0–8
- -8–0
- -17–-8
- -25–-17
- -34–-25
- -42–-34
- -51–-42
- < -51

~620 MeV/c

for comparison
SK-1
e-like
PMT time view
Measured Double Ratio

\[
\frac{(N_{\mu}/N_e)_{\text{DATA}}}{(N_{\mu}/N_e)_{\text{M.C.}}}
\]

**SK sub-GeV:**

0.638 ± 0.016 ± 0.050

stat.  sys.

**SK multi-GeV:**

0.658 ± 0.030 ± 0.078

stat.  sys.

**Soudan 2:**

0.68 ± 0.12

total
**SK multi-GeV:**

\[
\frac{N_{UP} - N_{DOWN}}{N_{UP} + N_{DOWN}} = -0.288 \pm 0.028 \pm 0.004 \quad \text{stat. \, sys.}
\]

> 10σ deviation!

*Measured Up-Down Asymmetry*

**Neutrino travel distance:** 12800 6200 700 40 15 km
Interpretation of Neutrino Oscillation

Atmospheric Neutrino Data

... is described by:

Two flavor neutrino oscillations

\[ P(\nu_\mu - \nu_\tau) = \sin^22\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

with oscillation parameters of

\[ \Delta m^2 \sim 3 \times 10^{-3} \text{ eV}^2 \quad \sin^2 2\theta \sim 1 \]
Upward-Going Muons

• neutrino interaction in the rock below the detector
• highest energy neutrinos
• large target mass (of rock) overcomes decreasing flux
• different detection techniques and systematics
• by definition- only zenith angles from nadir to horizon
• background subtraction often needed in most horizontal bin

• study zenith angle shape
• stopping-throughgoing ratio (energy dependence)
Upward-Going Muon Results from Super-K

\[ \langle E_\nu \rangle \approx 10 \text{ GeV} \]

\[ \langle E_\nu \rangle \approx 100 \text{ GeV} \]

**Stopping**

\[ \text{flux} \left( \times 10^{-13} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right) \]

\[ \cos \Theta \]

**Throughgoing**

\[ \text{flux} \left( \times 10^{-13} \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \right) \]

\[ \cos \Theta \]

\[ R = \text{stopping/throughgoing flux} \]

\[ R = 0.24 \pm 0.014 \pm 0.012 \text{ (data)} \]

\[ R = 0.37 \pm 0.05 \text{ (expected)} \]

\[ \text{no osc.} \]
Neutrino Oscillation also in Multi-Ring Events

- momentum > 600 MeV/c
- brightest ring μ-like

~98% CC ν_μ

when included for fitting, the normalization is allowed to float for these categories
Allowed Regions from Super-K Analyses

\[ \nu_\mu \leftrightarrow \nu_\tau \]
90\% C.L. contours

- **upmu zenith**
- **FC+PC**
- **stop/thru upmu**
- **combined FC+PC+upmu +multiring mu**

Best fit:
\[ \Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta = 1.03 \]
\[ \chi^2/\text{DOF} = 163/170 \]
Soudan 2 Experiment

Soudan Mine (Minnesota), 2100 m.w.e.
iron tracking calorimeter
high geomagnetic latitude
5.9 kt-yr, 661 contained interactions
~24% background subtraction using veto events

\[ R = \frac{(\mu/e)_{\text{DATA}}}{(\mu/e)_{\text{M.C.}}} = 0.68 \pm 0.12 \]
Soudan 2 High Resolution Sample

- quasi-elastic
  - $p > 150\ \text{MeV/c}$ if recoil present
  - $E_{\text{vis}} > 600\ \text{MeV}$ otherwise

- high energy multi-prongs

- $20-30^\circ$ pointing resolution

- log(L/E) resolution $\sim 0.5$

data shows suppression at lower L/E compared to Super-K:
will allow higher values of delta $m^2$
MACRO Experiment
upward-going muons

Throughgoing
Upward Muons

Throughgoing
Internal Upgoing

Internal Downgoing

Upward Stopping +
Internal Dowgoing

$\Delta m^2 = 0.0025$ eV$^2$, $\sin^2 2\theta = 1$

- $\pm$ MACRO all data
- $\pm$ Bartol flux

Muon flux ($10^{-13}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$) vs. cosine zenith angle
SNO Upward-Going Muons

Through-Going Muon Zenith Angle Distribution (PRELIMINARY)

- Atmospheric Muons
- $\nu_\mu$ Induced Flux (No oscillations)
- $\nu_\mu$ Induced Flux (SK$\nu_\mu \rightarrow \nu_e$)
- All Sky Data, 149 days

Intensity ($\mu$/cm$^2$/s/sr)

$\cos \theta$

$depth = 2000 \, m$

neutrino induced events above the horizon
Allowed Regions from Several Experiments

\[ \nu_\mu \leftrightarrow \nu_\tau \]
90\% C.L. contours

- Kamiokande
- Soudan 2
- MACRO
- MACRO Low Energy
- SK combined FC+PC+upmu +multiring mu

\[ \Delta m^2, \sin^2 2\theta \]
First Comparison of Atmospheric Neutrino with Long Baseline

Combined with Total Events:

predicted = 80.1 +6.2
−5.4

measured = 56 events

confirmation at 
≈99% C.L.
Purpose of Atm. $\nu +$ Long Baseline Comparison

*in my humble opinion!*

No: Combine into a smaller contour to know $\Delta m^2$ better?
(other than for practical guidance for future off-axis experiments)

Yes: Test oscillation scenario with very different system.
(See first slide).
If they disagree, we may learn something new.

For this comparison, we must understand systematic effects

- neutrino production
  - cosmic ray flux
  - hadronic interaction
  - shower model
- neutrino interaction
  - cross section
  - nuclear effects
- detector response
  - detailed MC simulation

*emphasis of current Super-K studies ...*

*the easy part is over with*
New Precise Data on Primary Cosmic Ray Flux

Honda et al. PRD64(2001)053011

most important for atmospheric $\nu$

Note: Honda and Bartol neutrino fluxes generally agreed with each other (despite primary flux difference) due to different hadronic models.
1D versus 3D Flux Calculations

until recently, all atmospheric neutrino flux calculations have used the
1D approximation (ignoring $p_T$, magnetic deflection of secondaries etc.):

- primary proton
- pion
- muon
- electron

First attempts at 3D calculation (P.Battistoni et al. hep-ph/9907408)
uncovered geometric effect (P.Lipari hep-ph/0002282)

Effect: enhancement at horizon

but effect is strong only at lower energy
and at low energy, lepton-neutrino
angular correlation is poor and washes it out

recent 3D flux calculations:
Honda et al. PRD64 (2001) 053011
Tserkovnyak et al. Proc. 27th ICRC (2001)1196
Wentz et al. hep-ph/0301199
1D and 3D Flux versus Zenith Angle

- **0.1-0.3 GeV**
- **0.3-1.0 GeV**
- **1.0-3.2 GeV**
- **>3.2 GeV**

- Honda 1D 1995
- Honda 3D 2001
- Fluka 3D

**Geomagnetic Effect**

- $\nu^+ + \nu^-$
- $\nu_e + \bar{\nu}_e$
Super-K Fit using 3D Flux Calculations

3D enhancement at horizon is washed out by neutrino-lepton angle

1D and 3D calculations yield similar results for oscillation fit further studies in progress
Hadronic Interaction Model

\( p + \text{Air} \) interactions → \( \pi, K \)

- multiplicity
- momentum
- \( \pi/K \)

... as a function of primary energy

**HARP Experiment at CERN**

- \( p, \pi \) beams on thin low-Z targets including O, N
- beam energy 2-15 GeV
- also study horn targets
- goal: 2% precision in secondary particle production

Other similar experiments planned
Neutrino Cross Sections

Long baseline near detector data (K2K) influence atm ν Monte Carlo:

\[ M_{\text{A}(\text{QE})} = 1.11 \text{ GeV} \quad M_{\text{A}(1p)} = 1.21 \text{ GeV} \]

K2K oscillation analysis insensitive
atmospheric neutrino analysis under study

Recent workshops (NuInt) dedicated to this topic:
http://nuint.ps.uci.edu/
http://neutrino.kek.jp/nuint01/

Quasi-Elastic
\[ \nu_\mu N \rightarrow \mu^- N' \quad \text{V-A} \]
Llewellyn-Smith 1972

Single Pion
\[ \nu_\mu N \rightarrow \mu^- N' \pi \quad \text{resonance production} \]
Rein & Seghal 1981

Coherent Pion (not shown)
\[ \nu_\mu ^{16}O \rightarrow \mu^- X \pi \]
Marteau et al.

Deep Inelastic Scattering
\[ \nu_\mu N \rightarrow \mu^- N' \text{hadrons} \]
GRV94 parton distribution with Bodek 2001

Nuclear Effects
Fermi motion
Pauli blocking
Nuclear rescattering
ICARUS Experiment at Gran Sasso

Liquid Argon TPC
- mm resolution
- 300 t module tested on surface
- 600 t module to be installed underground this year
- final proposed size 3 kt (relatively small mass but...)

Fine grained reconstruction of neutrino interactions (atmospheric or CNGS beam)

~100 evts/yr/600t from atmospheric $\nu$
~280 CC $\nu_\tau$ in 3 kt, CNGS beam (5 yr)

will detailed events reveal anything new?
Liquid Argon TPC in near site of beams may provide valuable exclusive cross section data
Treatment of Systematic Uncertainty

\[ \chi^2 = \sum_{\text{bins}} \frac{(N_{\text{data}} - N_{\text{MC}})}{\sigma^2} + \sum \frac{\varepsilon^2}{\sigma^2} \]

systematic uncertainty terms

\[ \alpha \]
- Absolute Normalization Uncertainty
  - Free
  - best fit: 4.1 %

\[ \alpha_L \]
- SubGeV Multi-ring Absolute Normalization Uncertainty
  - Free
  - best fit: -10.9 %

\[ \alpha_H \]
- MultiGeV Multi-ring Absolute Normalization Uncertainty
  - Free
  - best fit: -17.9 %

\[ \delta \]
- E\nu Spectrum Index
  - best fit: 0.05
  - best fit: 0.001

\[ \beta_L \]
- SubGeV \( \mu/e \) Ratio
  - best fit: 8 %
  - best fit: -6.5 %

\[ \beta_H \]
- MultiGeV \( \mu/e \) Ratio
  - best fit: 12 %
  - best fit: -13.8 %

\[ \rho \]
- FC/PC Relative Normalization
  - best fit: 8 %
  - best fit: 0.6 %

\[ \eta_L \]
- SubGeV Up/Down Asymmetry
  - best fit: 2.4 %
  - best fit: -1.9 %

\[ \eta_H \]
- MultiGeV Up/Down Asymmetry
  - best fit: 2.7 %
  - best fit: -1.1 %

\[ \beta_1 \]
- FC+PC/Stop \( \uparrow \mu \) Relative Normalization
  - best fit: 7 %
  - best fit: -1.2 %

\[ \beta_2 \]
- Through \( \uparrow \mu \)/Stop \( \uparrow \mu \) Relative Normalization
  - best fit: 7 %
  - best fit: 1.8 %

\[ \text{FC+PC Horizontal/Vertical Uncertainty} \]
- best fit: 4 %
  - best fit: 1.4 %

\[ \uparrow \mu \text{ Horizontal/Vertical Uncertainty} \]
- best fit: 3 %
  - best fit: 1.1 %

\[ \text{L/E Uncertainty} \]
- best fit: 15 %
  - best fit: -3.0 %

90% C.L. contours

2x systematic

\( \frac{\varepsilon^2}{\sigma^2} \)

\( \frac{N_{\text{data}} - N_{\text{MC}}}{\sigma^2} \)

\( \sum \)

\( \sum \)

\( \chi^2 \)

\( \sin^2 2\theta \)

\( \sigma_i \)

\( \text{standard} \)

\( \frac{\varepsilon^2}{\sigma^2} \)

\( \frac{N_{\text{data}} - N_{\text{MC}}}{\sigma^2} \)

\( \sum \)

\( \sum \)

\( \chi^2 \)

\( \sin^2 2\theta \)

\( \sigma_i \)

\( \text{standard} \)

\( \frac{\varepsilon^2}{\sigma^2} \)

\( \frac{N_{\text{data}} - N_{\text{MC}}}{\sigma^2} \)

\( \sum \)

\( \sum \)
Atmospheric Neutrinos + Long Baseline Neutrinos

Goal: Good Comparison

Atmospheric neutrino studies will provide as good a target as possible.

Physics goal: measure non-maximal mixing (if it is true)
Up-Down symmetry is very powerful

up/down = 1 - $\frac{\sin^2 2\theta}{2}$ + $\varepsilon$

systematic term includes mountain overburden
detector response

atmospheric neutrinos can be competitive in measure mixing angle
If we are interested in testing the oscillation scenario, what about other specific alternatives?

- neutrino decay?
- sterile neutrinos?
- Lorentz invariance violation?
- decoherence?
- flavor changing neutral currents?

*atmospheric neutrinos have essentially ruled these out ⇒ long baseline experiments should focus on neutrino oscillation*
(Nearly) All Super-K Atmospheric Neutrinos

actually binned finer than this in momentum ...

add important subsample for discriminating hypotheses

nring > 1
brightest ring e-like
p > 400 MeV/c

29% NC
45% $\nu_e$ CC
26% $\nu_\mu$ CC

up-down symmetric
Neutral Current and Matter Effects as Tools

1. **Neutral Current**: missing for \( \nu_\mu \rightarrow \nu_{\text{sterile}} \) and for \( \nu \)-decay etc.

\[
\nu_\mu, \nu_\tau \xrightarrow{Z^0} \text{pions, eg: } \pi^0 \rightarrow \gamma\gamma
\]

2. **Matter effects**: suppress \( \nu_\mu \rightarrow \nu_{\text{sterile}} \)

\[
\nu_\mu + \nu_\tau \rightarrow Z^0 \quad \text{(identical (no matter effect))}
\]
\[
\nu_\mu + \nu_{\text{sterile}} \rightarrow Z^0 \quad \text{(different (matter effect))}
\]

\[
sin^2 2\theta = 1, \quad \Delta m^2 = 5 \times 10^{-3} \text{ eV}^2
\]

\[
E_V = 5 \text{ GeV}
\]
\[
E_V = 10 \text{ GeV}
\]
\[
E_V = 50 \text{ GeV}
\]
\[
E_V = 100 \text{ GeV}
\]

\[
\sin^2 2\theta \rightarrow \frac{\sin^2 2\theta}{(A - \cos 2\theta)^2 + \sin^2 2\theta}
\]
\[
\Delta m^2 \rightarrow \frac{\Delta m^2}{\sqrt{(A - \cos 2\theta)^2 + \sin^2 2\theta}}
\]

\[
A = \pm \frac{\sqrt{2} E_V G_F n}{\Delta m^2}
\]

large \( E_V, |A| >> 1 \) oscillation is suppressed

small \( E_V, |A| << 1 \) no matter effects → vacuum oscillation

\(|A| \sim 1 \text{ in earth for } E_V = 5 \text{ GeV} \times \Delta m^2(10^{-3} \text{ eV}^2)\)
Check SK data against alternatives to $\nu_\mu - \nu_\tau$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Best Fit</th>
<th>$\chi^2$</th>
<th>$P(\chi^2)$</th>
<th>$\Delta \chi^2$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu - \nu_\tau$</td>
<td>$\sin^2 2\theta = 1.00$</td>
<td>173.8</td>
<td>79%</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>$\nu_\mu - \nu_e$</td>
<td>$\sin^2 2\theta = 0.97$</td>
<td>284.3</td>
<td>0.001%</td>
<td>110.5</td>
<td>10.5$\sigma$</td>
</tr>
<tr>
<td>$\nu_\mu - \nu_e$</td>
<td>$\sin^2 2\theta = 0.98$</td>
<td>222.7</td>
<td>5%</td>
<td>48.9</td>
<td>7.0$\sigma$</td>
</tr>
<tr>
<td>$\nu_\mu$ Decay</td>
<td>$\cos^2 \theta = 0.50$</td>
<td>279.4</td>
<td>0.003%</td>
<td>105.6</td>
<td>10.3$\sigma$</td>
</tr>
<tr>
<td>$\nu_\mu$ Decay</td>
<td>$\cos^2 \theta = 0.33$</td>
<td>194.0</td>
<td>41%</td>
<td>20.2</td>
<td>4.5$\sigma$</td>
</tr>
<tr>
<td>$\nu_\mu$ Decoherence</td>
<td>$\sin^2 2\theta = 0.98$</td>
<td>184.3</td>
<td>64%</td>
<td>10.5</td>
<td>3.2$\sigma$</td>
</tr>
<tr>
<td>No Oscillations</td>
<td>-</td>
<td>427.4</td>
<td>0%</td>
<td>252.4</td>
<td>15.9$\sigma$</td>
</tr>
</tbody>
</table>

FC: 10 zenith angle×7 momentum bins
PC: 10 zenith angle bins
upStop 5 zenith angle bins 195 Bins
upThru 10 zenith angle bins 190 DOF
multi-Ring $\mu$-like 10 zenith angle bins×2 momentum bins
multi-Ring NC-like 10 zenith angle bins

For example

matter effects suppress high energy $\nu_\mu - \nu_{\text{sterile}}$ oscillation
neutral current should disappear for $\nu_{\text{sterile}}$ oscillation
Consider Sterile Admixture

\[
\begin{bmatrix}
    v_e \\
v_\mu \\
v_\tau \\
v_s
\end{bmatrix} = U \begin{bmatrix}
    v_1 \\
v_2 \\
v_3 \\
v_4
\end{bmatrix}
\]

\(\delta m^2\) - Solar Neutrinos (\(< 10^{-4}\ eV^2\))
\(\Delta m^2\) - Atmospheric Neutrinos (\(= 10^{-3}-10^{-2}\ eV^2\))
\(\Delta M^2\) - LSND (\(= 1\ eV^2\))

If \(\delta m^2 \ll \Delta m^2 \ll \Delta M^2\)
then this simplifies to 3 parameters,
\(\sin^2(2\theta), \Delta m^2\), and \(\sin^2\xi\)

Best Fit \(\chi^2 = 172.6/190\ (P=81\%)\)
\(\sin^2\xi = 0.0\)
\(\sin^22\theta = 1\)
\(\Delta m^2 = 2.1 \times 10^{-3}\ eV^2\)

following Fogli, Lisi & Marrone PRD63-053008
CPT tests

\[ \nu \quad \bar{\nu} \quad \delta \equiv \Delta m^2(\nu) - \Delta m^2(\bar{\nu}) \]

\[ \Delta m^2 \]

\[ 1 - \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E \pm 0.5 b L) \]

no singular evidence to support violation

(other than compound scenarios explaining multiple experiments)
No evidence for anything unusual, (other than massive neutrino oscillation)

Can we see other effects that should be there?

\( \nu_\tau \) appearance
- *goal of longbaseline CNGS - Opera*

\( \nu_e \) appearance
- *goal of long baseline JHF-SK and NuMI Off-Axis*

Oscillation pattern
- *goal of ~ every long baseline experiment especially NuMI-MINOS*
for $\sin^22\theta = 1$ and $\Delta m^2 = 3 \times 10^{-3}$ eV$^2$, we expect ~85 events in the 1489 day SK sample.

Events have large visible energy (> 2 GeV)

Multiple rings (not all may be reconstructed)

Over threshold, only upward-going neutrinos have sufficient oscillation length

Generally speaking... rather difficult events to exclusively identify
Enhanced Tau Sample Selection

Event Classification Input Variables

Neural network weighting

input variables
nonlinear function

non-tau-like ← tau? → tau-like

Atm. ν MC
νμ CC

τ MC  Atm. ν MC  Down-going Data

other SK analyses use some of the same and some different variables and use different techniques (Likelihood) to weight them
**Tau Sample: Downward and Upward Events**

**downgoing bins:** oscillation length for $E_{\nu} \gg$ threshold predicts no CC tau present

**upgoing bins:** CC tau appearance should be at larger values of the neural network output

---

**downgoing events**

- $\cos \text{ zenith} > 0.2$
- 1489 days SK prelim.

**upgoing events**

- $\cos \text{ zenith} < -0.2$
- 1489 days SK prelim.

---

**Neural Network Output**

- Oscillated MC with tau
- Oscillated MC without tau
- SK data

---

**Event Counts**

- Not tau-like
- Tau-like

---

**Neural Network Output**

- Not tau-like
- Tau-like

---

**Cut here for zenith distribution**
Super-K Tau Appearance Result:

Expected τ-neutrino CC events in SK data sample = 85

Fit to:  
\[ A \times \text{tau appearance} + B \times \text{tau no-appearance} \]

(as a function of \( \cos \Theta \))

Result (tau events in SK data):  
\[ 99 \pm 39 \pm 13^{+0}_{-16} \]

\( \Delta m^2 \) uncertainty  
3-flavor uncertainty

other independent SK analyses give consistent results

SK data is consistent with presence of CC tau neutrino interactions
Strategy: bin data very finely and look for enhancement at certain energies and angles due to electron neutrino resonance in earth

Active 3-Flavor Oscillation ($\nu_e - \nu_\mu - \nu_\tau$)

- $P_{e\mu} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 1.27 \Delta m^2 L/E$
- $P_{\mu\tau} = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 1.27 \Delta m^2 L/E$
- $P_{\tau e} = \sin^2 2\theta_{13} \cos^2 \theta_{23} \sin^2 1.27 \Delta m^2 L/E$

Only 3 parameters

at Chooz limit: {$\Delta m^2 = 0.003 \text{ eV}^2$, $\sin^2 \theta_{23} = 0.5$, $\sin^2 \theta_{13} = 0.024$}
Super-K e-like Data

No sign of deviation from expectation ...
Allowed Regions for 3-Flavor Oscillation

\((\nu_e - \nu_\mu - \nu_\tau)\)

Heirarchical non-inverted mass scale

Limits from Reactor Experiments

- SK 90\% C.L.
- SK 99\% C.L.
- CHOOZ 90\% CL exclude
- PALO VERDE 90\% CL exclude

pure \(\nu_\mu - \nu_\tau\)
Principle of Fixed Long Baseline Experiment

\[ \Delta m^2 = 5 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m^2 = 3 \times 10^{-3} \text{ eV}^2 \]
\[ \Delta m^2 = 1.5 \times 10^{-3} \text{ eV}^2 \]

low statistics: energy spectrum distortion
high statistics: resolve oscillation shape

\( \Delta m^2 \) must also cooperate with respect to the energy spectrum and baseline

long baseline experiments should see it...
MONOLITH (proposed)

measure atmospheric neutrinos

very massive  ~35 kton
magnetized iron  B ~ 1.3 Tesla
$\sigma_{p/p} \sim 15\%$
58000 m$^2$ of detector
e.g. glass spark counters

measure momentum of exiting muons
to obtain good L and E resolution

not approved at LNGS
Future Large Water Cherenkov

Hyper-K

Can contain high energy muons because of large size ... allowing good L and E measurement

UNO
Super-K can try this analysis too...

4 years simulated SK data

Probability

log_{10}(L/E(km/GeV))

oscillation vs decoherence

SK-1 may say something at ~2σ continued running with SK-2 will help.
Conclusions

Atmospheric neutrinos have revealed neutrino oscillation and provide the impetus and design choices for long baseline experiments.

*Thank to large statistics, Super-K has made statistically definitive statements preferring $\nu_\mu - \nu_\tau$ oscillation and giving a fairly narrow range of mixing parameters. Detailed studies are underway to evaluate the ingredients of the oscillation measurement.*

Meanwhile...

*There is nothing in the data to suggest anything exotic*

*There is weak evidence for tau appearance*

*There is no evidence for mixing with electron neutrinos*

*The oscillation pattern is washed out in atmospheric neutrinos but we can try hard and see what is possible*

*$\Delta m^2$ is clearly better measured using beams, but $\sin^2 2\theta$ may be competitive with atmospheric neutrinos*

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