Neutrino oscillations
Discovery, status and future directions

Takaaki Kajita
ICRR, Univ. of Tokyo
• Introduction
• Neutrino masses and neutrino oscillations
• Discovery of neutrino oscillations: Part I
• Discovery of neutrino oscillations: Part II
• Future prospects
• Summary
Introduction
In early 20th century, people observed that a certain kind of nucleus spontaneously change to a different nucleus by emitting β ray (electron).

This phenomena had serious mysteries, since it apparently did not to conserve energy, momentum and spin.
W. Pauli, in his letter to “Radioactive Ladies and Gentleman” at Tubingen, in Dec. 1930, pointed out that there could exist neutral particles which have spin 1/2 (neutrino).
Neutrinos are difficult to observe

If one wants to observe a single neutrino of a certain energy (for example, 1GeV), one typically needs 1,000,000 Earth equivalent matter (i.e., $10^{10}$ km of matter with the typical earth density).

⇒ One has to “observe” many neutrinos. If 1,000,000 neutrinos propagate in the Earth, one of them may interact somewhere in the Earth...
Discovery of electron-(anti-)neutrino (1950’s)

F. Reines (right, Nobel Prize, 1995) and C. Cowan Jr.
Discovery of electron-(anti-)neutrino (1950’)

Savanna River reactor

\[ \bar{\nu}_e \rightarrow p \rightarrow e^+ \rightarrow n \]

followed by neutron capture by Gd, which results in gamma ray emission.
From the left to right: J. Steinberger, M. Schwartz and L. Lederman (Nobel Prize, 1988)
Discovery of muon-neutrino (1962)

Neutrino production:

\[ \pi^+ \ \text{\(\rightarrow\)} \ \mu^+ + \nu_\mu \]

Neutrino detector:

\[ \nu_\mu + n \ \text{\(\rightarrow\)} \ \mu^- + p \]

One of the observed events
### Matter elementary particles

<table>
<thead>
<tr>
<th>第一世代 (first)</th>
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<tbody>
<tr>
<td>電子ニュートリノ</td>
<td>ミューニュートリノ</td>
<td>タウニュートリノ</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>muon neutrino</td>
<td>tau neutrino</td>
</tr>
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</tr>
<tr>
<td>ダウン</td>
<td>ストレンジ</td>
<td>ボトム</td>
</tr>
<tr>
<td>down</td>
<td>strange</td>
<td>bottom</td>
</tr>
<tr>
<td>アップ</td>
<td>チャーム</td>
<td>トップ</td>
</tr>
<tr>
<td>up</td>
<td>charm</td>
<td>top</td>
</tr>
</tbody>
</table>

#### Categories

- **Strong**
- **Electro magnetic**
- **Weak**
Neutrino masses and neutrino oscillations
Neutrinos are special

- There used to be no evidence for mass. Therefore, it has been assumed that neutrinos are massless in the Standard Model of particle physics.
- They have no electric charge.
- They only “feel” weak force.
- ...

Monday, June 20, 2011
Neutrinos are special

• There used to be no evidence for mass. Therefore, it has been assumed that neutrinos are massless in the Standard Model of particle physics.
• They have no electric charge.
• They only “feel” weak force.
• ...

However,

Maki  Nakagawa  Sakata  Pontecorvo

What will happen if neutrinos have masses....?
Neutrinos can be massive. However, according to Quantum mechanics, it is generally not required that a certain type of neutrino (for example, $\nu_\mu$) to have a unique mass value. Instead;
If neutrinos have masses, neutrinos change their type while propagating in the vacuum (or in a medium).
Neutrino masses and neutrino oscillations

\[ P(\nu_\mu \otimes \nu_\mu) = 1 - \sin^2 2\theta \times \sin^2 \left( \frac{1.27 \Delta m^2 \times L(km)}{E_\nu(GeV)} \right) \]

where \( (\Delta m^2 = |m_{\nu_3}^2 - m_{\nu_2}^2| eV^2) \).

\[ P(\nu_\mu \otimes \nu_\tau) + P(\nu_\mu \otimes \nu_\mu) = 1 \]

Used in most part of this talk.

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Discovery of neutrino oscillations: Part I

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Neutrino production by cosmic ray interactions in the atmosphere (atmospheric neutrinos)

Cosmic ray \((p, \text{He}, ..)\)

Nucleus in the atmosphere \((O, N, ..)\)

\[
\pi^+ \, \mu^+ \, + \nu_\mu \\
\mu^+ \, e^+ \, + \nu_\mu \, + \nu_e
\]
Proton decay experiments (1980’s)

Grand Unified Theories (in the 1970’s) \( \Rightarrow \tau_p = 10^{30 \pm 2} \) years

Kamiokande (1000 ton)

IMB (3300 ton)

NUSEX (130 ton)

Frejus (700 ton)

These experiments observed many contained atmospheric neutrino events (background for proton decay).
Kamiokande

1983 (Kamiokande construction)
Detecting Cherenkov photons

\[ \cos \theta = \frac{1}{n \beta} \]

Cherenkov radiation

\( n \) (refractive index) = 1.34 in water

\( \Rightarrow \theta = 42 \text{deg. for } \beta = 1 \)

M. Koshiba (2002 Nobel Prize)
Cherenkov rings by electrons and muons

electron-like events
\((\nu_e N \rightarrow e N')\)

muon-like events
\((\nu_\mu N \rightarrow \mu N')\)

Particle Identification; \(\varepsilon = 99\% @\text{Super-K}\) (98\% @ Kamiokande)
### First result on the $\mu/e$ ratio (1988)

The Kamiokande experiment reported on the first measurement of the $\mu/e$ ratio, which is a fundamental test of neutrino oscillations. The table below summarizes the data and MC predictions for $e$-like and $\mu$-like events:

<table>
<thead>
<tr>
<th>Type</th>
<th>Data</th>
<th>MC Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$-like ($\sim$CC $\nu_e$)</td>
<td>93</td>
<td>88.5</td>
</tr>
<tr>
<td>$\mu$-like ($\sim$CC $\nu_\mu$)</td>
<td>85</td>
<td>144.0</td>
</tr>
</tbody>
</table>

```
We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics such as neutrino oscillations might explain the data.
```

First supporting result on small $\mu/e$

IMB experiment also reported smaller ($\mu/e$) in 1991 and 1992.
What will happen if the moun deficit is due to neutrino oscillations

Detector

Cosmic ray

Detect down-going and up-going \( \nu \)

\(\nu_{\mu} \rightarrow \nu_{\tau}\) oscillation

Cosmic ray

Atmosphere

Down-going

Up-going

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What will happen if the muon deficit is due to neutrino oscillations

\[ \nu_\mu \rightarrow \nu_\tau \]

oscillation

One should observe a deficit of upward going \( \nu_\mu \)'s (=muons)!

(A demonstration that quantum mechanics works even at the scale of the Earth!)
Zenith angle distribution (multi-GeV)

multi-GeV μ-like events

Kamiokande PLB 335, 237 (1994)

No oscillation

ν_μ → ν_τ (best fit)

Up-going

Deficit of upward-going μ-like events

Up/Down=0.58 \(\pm 0.13\) \(-0.11\) (2.9 σ)

Down-going
Zenith angle distribution (multi-GeV)

multi-GeV μ-like events

Kamiokande PLB 335, 237 (1994)

No oscillation

\( \nu_\mu \rightarrow \nu_\tau \) (best fit)

Up-going

Down-going

Deficit of upward-going μ-like events

Up/Down=0.58 \text{ +0.13 } \text{ -0.11 } (2.9 \sigma)

Not high enough statistics to conclude ...

Much higher statics required (= much larger detector required)

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Super-Kamiokande detector

50,000 ton water Cherenkov detector (22,500 ton fiducial volume)

11,200 PMTs (Inner detector)

1,900 PMTs (Outer detector)

1,000 m underground

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Water filling in Super-Kamiokande

Kamiokande

Jan. 1996

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Evidence for neutrino oscillations
(Super-Kamiokande @Neutrino ’98)

Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.
First, we must help you to ensure that America continues to lead the revolution in science and technology. Growth is a prerequisite for opportunity, and scientific research is a basic prerequisite for growth. Just yesterday in Japan, physicists announced a discovery that tiny neutrinos have mass. Now, that may not mean much to most Americans, but it may change our most fundamental theories -- from the nature of the smallest subatomic particles to how the universe itself works, and indeed how it expands.
Why very small neutrino masses are important?

\[
\left( \frac{m(\nu_3)}{m(\text{top quark})} \right) \approx \left( \frac{1}{3 \times 10^{12}} \right)
\]

\[
m_\nu \approx \frac{m_q^2}{m_N}
\]
Why very small neutrino masses are important?

Minkowsky, Yanagida, Gell-mann, Lamond, Slansky

If we input $m_{\nu_3}$ and $m_q$ ($m_{\text{top}}$ is used), we get $m_N=10^{15}\text{GeV}$

$\left(\frac{m(\nu_3)}{m(\text{top quark})}\right) \approx \left(\frac{1}{3 \times 10^{12}}\right)$
Mass scales of neutrino physics and Unification

In the 1970’s

Present Unification model

Unification model

(Coupling constant)$^{-1}$

$\alpha_1^{-1}$

$\alpha_2^{-1}$

$\alpha_3^{-1}$

$\log_{10}(Q/1 \text{ GeV})$
Mass scales of neutrino physics and Unification

In the 1970's Unification model

Present Unification model

(Coupling constant)\(^{-1}\)

Log\(_{10}(Q/1 \text{ GeV})\)

Unification

Neutrino Phys.
Mass scales of neutrino physics and Unification

This suggests that physics of neutrino mass could be related to physics of Grand Unification!
Super-Kamiokande data now

@Neutrino98
(535 day)

@2010
(2806 day)

No oscillation

\(\nu_\mu \rightarrow \nu_\tau\) oscillation

Up-going

Down-going
Future direction

Atmospheric neutrinos

→ Very wide neutrino flight length
→ Wide neutrino energy
→ Mixture of $\nu_\mu$, anti-$\nu_\mu$, $\nu_e$ and anti-$\nu_e$

Long baseline Experiments

→ Single flight length
→ Controlled neutrino energy
→ almost pure $\nu_\mu$ (or anti-$\nu_\mu$)

Initial discovery

(However, there are still topics that atmospheric neutrinos can contribute ...)

Precise studies

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K2K experiment (1999-2004)  
MINOS experiment (2005- )

MC normalization: number of events (58)

No oscillation  
Oscillation best fit

reconstructed $E_{\nu}$ (GeV)  
Events (GeV)

Reconstructed neutrino energy (GeV)

1986 events
Allowed parameter region from atmospheric and long baseline experiments

\[ |\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3} \text{eV}^2 \]

\( \nu_3 \) might be as heave as 0.05 eV.

(MINOS)

Consistent with maximal mixing!
Discovery of neutrino oscillations: Part II
Observing the Interior of the Sun with

J.N. Bahcall “Solar neutrinos I: Theoretical” P.R.L. 12, 300 (1964)
R. Davis Jr. “Solar neutrinos II: Experimental”, P.R.L. 12, 303 (1964)
Search for Neutrinos from the Sun
R. Davis Jr., D.S. Harmer, and K.C. Hoffman, PRL 20, 1205 (1968)

The Ar production rate by $\nu_e^{37}\text{Cl} \rightarrow e^-^{37}\text{Ar}$ was substantially smaller than the prediction by the Standard Solar Model.
Solar Neutrino Problem

Search for Neutrinos from the Sun
R. Davis Jr., D.S. Harmer, and K.C. Hoffman, PRL 20, 1205 (1968)
The Ar production rate by $\nu_e^{37}\text{Cl} \rightarrow e^-^{37}\text{Ar}$ was substantially smaller than the prediction by the Standard Solar Model.

Problem: We did not know the solar neutrino flux very well. People were afraid that the problem might be solved by finding out that the calculated flux was too high...
Heavy water experiment

H. Chen PRL 55, 1534 (1985)
“Direct Approach to Resolve the Solar-neutrino Problem”

\[
\frac{CC}{NC} = P(\nu_e \rightarrow \nu_e)
\]

**Charged-Current (CC)**

(= \(\nu_e\) flux)

**Neutral-Current (NC)**

(= total flux)
Solving the solar neutrino problem

Only about 30% of the neutrinos from the Sun are electron-neutrinos! (2001, 2002)
Long baseline reactor exp: KamLAND

\[ \langle L_\nu \rangle = 180 \text{km} \]
\[ \langle E_\nu \rangle = \text{a few MeV} \]

Sensitive to \( \Delta m^2 > 10^{-5} \text{eV}^2 \)

KamLAND

1000 ton liquid scintillator

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KamLAND and neutrino oscillation

Really, really oscillation!

KamLAND arXiv: 1009.4771
Future prospects
Present and future

Present

2 flavor neutrino oscillation:
- $\nu_\mu \Leftrightarrow \nu_\tau$: atmospheric $\nu$
- $\nu_e \Leftrightarrow \nu_x$: solar $\nu$

Future

3 flavor neutrino oscillation:
- measure 3 mixing angles (2 are known)
- $\nabla$ measure all the parameters relevant to osc.
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<tr>
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<td>アップ up</td>
<td>チャーム charm</td>
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</table>
Matter elementary particles

Grand Unification: Unification of forces
Grand Unification: Unification of forces
Unification of quarks and leptons

MaDer
elementary
classes

Grand Unification:
Unification of forces
Unification of quarks and leptons

Monday, June 20, 2011
Relation between quarks and leptons?

Quark mixing

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= V_{CKM} \times
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

3×3 mixing matrix

Neutrino mixing

\[
\begin{pmatrix}
  \nu_e \\
  \nu_\mu \\
  \nu_\tau
\end{pmatrix}
= U_{MNSP} \times
\begin{pmatrix}
  \nu_1 \\
  \nu_2 \\
  \nu_3
\end{pmatrix}
\]

3×3 mixing matrix

\[V_{CKM} \approx U_{MNSP}\]
Rela.on between quarks and leptons?

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3×3 mixing matrix

\[ V_{CKM} \approx U_{MNS} \]

Neutrino mixing

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3×3 mixing matrix

\[ \theta_{12} = 34 \pm 1^\circ \\
\theta_{23} = 45 \pm 6^\circ \\
\theta_{13} < 11^\circ \]

Very different!

For quarks

\[ \theta_{12} = 13^\circ \\
\theta_{23} = 2.4^\circ \\
\theta_{13} = 0.21^\circ \]
Relation between quarks and leptons?

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3×3 mixing matrix

For neutrinos

\[ \theta_{12} = 34 \pm 1^\circ \]
\[ \theta_{23} = 45 \pm 6^\circ \]
\[ \theta_{13} < 11^\circ \]

Is \( \theta_{23} \) maximal?

Monday, June 20, 2011
Relation between quarks and leptons?

**Quark mixing**

$$
\begin{pmatrix}
\frac{d'}{s'} \\
\frac{b'}{j}
\end{pmatrix}
= V_{CKM}
\begin{pmatrix}
\frac{d}{s} \\
\frac{b}{j}
\end{pmatrix}
$$

3x3 mixing matrix

**Neutrino mixing**

$$
\begin{pmatrix}
\frac{\nu_e}{j} \\
\frac{\nu_\mu}{j} \\
\frac{\nu_\tau}{j}
\end{pmatrix}
= U_{MNSP}
\begin{pmatrix}
\frac{\nu_1}{j} \\
\frac{\nu_2}{j} \\
\frac{\nu_3}{j}
\end{pmatrix}
$$

3x3 mixing matrix

For quarks

$$
\begin{align*}
\theta_{12} &= 13^\circ \\
\theta_{23} &= 2.4^\circ \\
\theta_{13} &= 0.21^\circ
\end{align*}
$$

For neutrinos

$$
\begin{align*}
\theta_{12} &= 34\pm1^\circ \\
\theta_{23} &= 45\pm6^\circ \\
\theta_{13} &< 11^\circ
\end{align*}
$$

Very different!

Is \( \theta_{23} \) maximal?

How small is \( \theta_{13} \)?

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$\theta_{13}$ experiments

Reactor experiments
- Double Chooz (France)
- Daya Bay (China)
- RENO (Korea)

Atmospheric neutrino exp.
- Super-K
- T2K (Japan)
- NO$\nu$A (USA)

Long baseline experiments
Expected non-zero $\theta_{13}$ signals

Reactor experiments

Signal : $\nu_e$ (= electron) disappearance

Long baseline experiments

Assume: $\sin^2 2\theta_{13} = 0.01$

(about 1/15 of the present limit)

Example: T2K

Signal : $\nu_e$ (= electron) appearance

- exp’d signal+BG
- NC BG
- Beam $\nu_e$ BG

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J-PARC and the T2K beam line

Neutrino Beam to Super-K

30 GeV Main ring
750 kW (design value)

181 (400) MeV Linac

3 GeV Synchrotron

North

(KEK/JAEA)
Initial T2K results on electron appearance

Data until the 2010 summer shutdown were analyzed. \((3.23 \times 10^{19} \text{ POT})\)

1 electron candidate

<table>
<thead>
<tr>
<th>Expected background</th>
<th>(\nu\mu)</th>
<th>0.13</th>
<th>NC 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\text{anti-}\nu\mu)</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\nu e)</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>(0.30 \pm 0.07) (syst)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Signal + background \((\sin^2 2\theta_{13} = 0.1)\)**

| Total               | \(1.20 \pm 0.22\) (syst) |      |        |

**A. Feldman-Cousins**

**B. Classical one-sided limit**

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>Upper Limit</th>
<th>Sensitivity</th>
</tr>
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<tbody>
<tr>
<td>Normal ((\Delta m^2_{23} &gt; 0))</td>
<td>0.50</td>
<td>0.35</td>
</tr>
<tr>
<td>Inverted ((\Delta m^2_{23} &lt; 0))</td>
<td>0.59</td>
<td>0.42</td>
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**A. Feldman-Cousins**

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<td>0.32</td>
</tr>
<tr>
<td>Inverted ((\Delta m^2_{23} &lt; 0))</td>
<td>0.53</td>
<td>0.39</td>
</tr>
</tbody>
</table>

\((at (\Delta m^2_{23}, \sin^2 2\theta_{23}, \delta_{cp}) = (2.4 \times 10^{-3} \text{eV}^2, 1.0, 0.0))\)
Earthquake on March 11

- Super-K and KamLAND were OK.
- People in Tohoku University were OK.
- J-PARC was damaged.

“Master Plan for J-PARC Recovery” will be released in

Monday, June 20, 2011
A big question:
Why is our Universe made by matter (not by anti-matter)?
A big question: Why is our Universe made by matter (not by anti-matter)?

It has been discussed that the origin of matter may come from the particle-anti-particle asymmetric decay of the heavy neutral particle of the See-Saw mechanism.

Fukugita Yanagida PLB 1986
A big question: Why is our Universe made by matter (not by anti-matter)?

It has been discussed that the origin of matter may come from the particle-anti-particle asymmetric decay of the heavy neutral particle of the See-Saw mechanism.

This idea should be tested.

- Are neutrino and anti-neutrino oscillations different?
  - Is neutrino its own anti-particle?
Inflation

400,000 years after Big Bang

Size of the Universe

Present Universe (13.7 B years)
Future LBL possibilities
(assuming $\sin^2 2\theta_{13}$ is larger than 0.01)

Megawatt class super-beam +
Megaton class (water) detector
Summary

• Neutrinos have been playing major roles in the development of particle physics.
• Small but non-zero neutrino masses were discovered by studies of neutrinos produced in the Earth’s atmosphere and in the Sun.
• The discovery of non-zero neutrino masses opened a window to study physics at a very high energy scale, probably Grand Unification.
• Further studies of neutrinos might tell us the origin of the matter in the Universe.
Summary

• Neutrinos have been playing major roles in the development of particle physics.
• Small but non-zero neutrino masses were discovered by studies of neutrinos produced in the Earth’s atmosphere and in the Sun.
• The discovery of non-zero neutrino masses opened a window to study physics at a very high energy scale, probably Grand Unification.
• Further studies of neutrinos might tell us the origin of the matter in the Universe.

It is likely that future neutrino experiments will continue to be as exciting as those in the past!
backups
Studying massive neutrinos

Takaaki Kajita
ICRR and IPMU, Univ. of Tokyo
In the early 20th century, it was known that there existed natural radiation on the surface. It was assumed that they came from the earth.

Victor Hess carried out a balloon experiment in order to test this assumption. (The radiation should decrease in high altitudes.)

He observed that the radiation gets stronger in higher altitudes (of about 5km).

Discovery of cosmic rays (Nobel prize 1936)

Subsequent studies found that the majority of the cosmic rays are high energy protons, He, and heavier nuclei.
Development of the cosmic ray studies

• Subsequent studies found that the majority of the cosmic rays are high energy protons, He, and heavier nuclei.

• We knew that there are some cosmic accelerators that accelerate cosmic ray particles up to $10^{20}$ eV in the extreme case. (This is a very interesting scientific field. However, due to the limited time, I skip any details of the current cosmic ray studies.)
Observation of atmospheric neutrinos

At the depth of 3200 meters (8800 meters water equivalent) in South Africa
First observed on Feb. 23, 1965
By F. Reines et al.

At the depth of 2400 meters (7500 meters water equivalent) in India (Kolar Gold Field)
First published on Aug. 15, 1965
By C.V. Achar et al.

(ν_μ N → μ X)

Detector for the KGF experiment

photo of the South Africa experiment
Identifying electrons and muons

Atmospheric neutrino data & Monte Carlo simulation

Cosmic ray $\mu$ e from $\mu$ decay

$\varepsilon=99\% @\text{Super-K} \ (98\% @\text{Kamiokande})$

(figures from Super-K)

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The first hint for the problem?  
(South Africa experiment, 1978)

Cosmic ray muons

Neutrino induced muons

\[
\left( \frac{\text{Monte Carlo}}{\text{Data}} \right) = 1.6 \pm 0.4
\]
The first hint for the problem?
(South Africa experiment, 1978)

We conclude that there is fair agreement between the total observed and expected neutrino induced muon flux ...

\[
\left( \frac{\text{Monte Carlo}}{\text{Data}} \right) = 1.6 \pm 0.4
\]
Zenith angle distribution
(updated data from the original South Africa experiment)

PRD18, 2239 (1978)

Cosmic ray muons

Neutrino induced muons

(ν_μ N → μ X)

Horizontal going

Vertical up or down

(going up or down)
Results from the other atmospheric neutrino experiments observed atmospheric neutrinos and neutrino oscillations.
MINOS $\nu_\mu \rightarrow \nu_\tau$ result

7.2 $\times$ $10^{20}$ POT (about factor 2 improved statistics compared with the 2008 results)

No oscillation: 2451
Observation: 1986

Oscillation gives very good fit
(Decay model disfavored $> 6\sigma$)
(Decoherence model disfavored $> 8\sigma$)
T2K experiment started in 2009 (physics run in 2010).
2008 $\theta_{13}$ global fit

- SNO and KamLAND slight tension.
- CHOOZ: dominant contribution.

⇒ Still not clear....

Much higher sensitivity experiments required.
LBL $\theta_{13}$ experiments

NOvA

T2K

J-PARC

Super-Kamiokande

Will start in ~2013

Similar sensitivity

Started in 2009 (2010)