

*History of Neutrinos,
Paris, Sep. 6, 2018*

*Atmospheric Neutrinos:
the anomaly becomes the discovery*

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Institute for Cosmic Ray Research, The Univ. of Tokyo

- *Introduction*
- *Super-Kamiokande*
- *Discovery of atmospheric neutrino oscillations*
- *Further confirmation of $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations*
- *Summary*

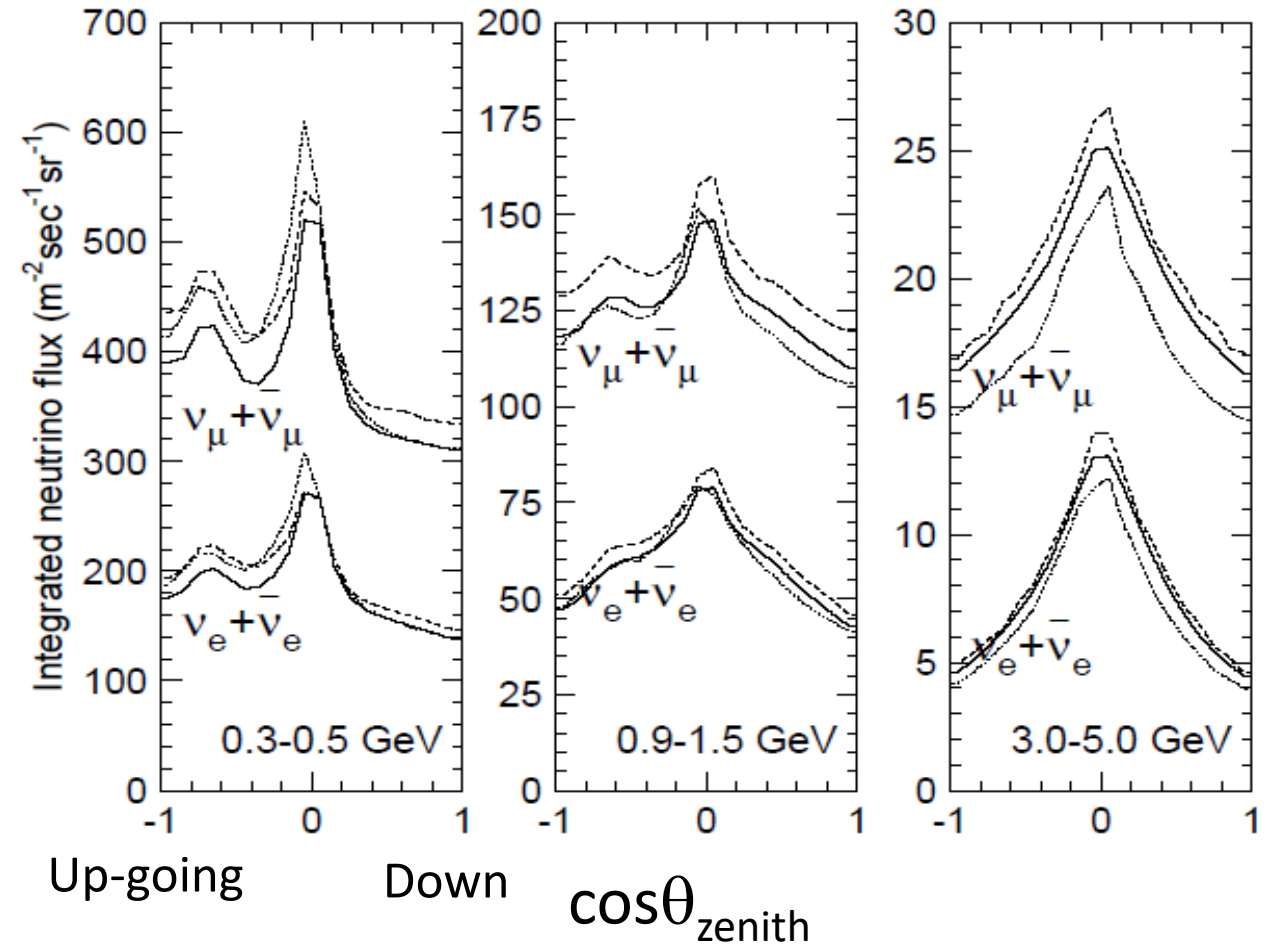
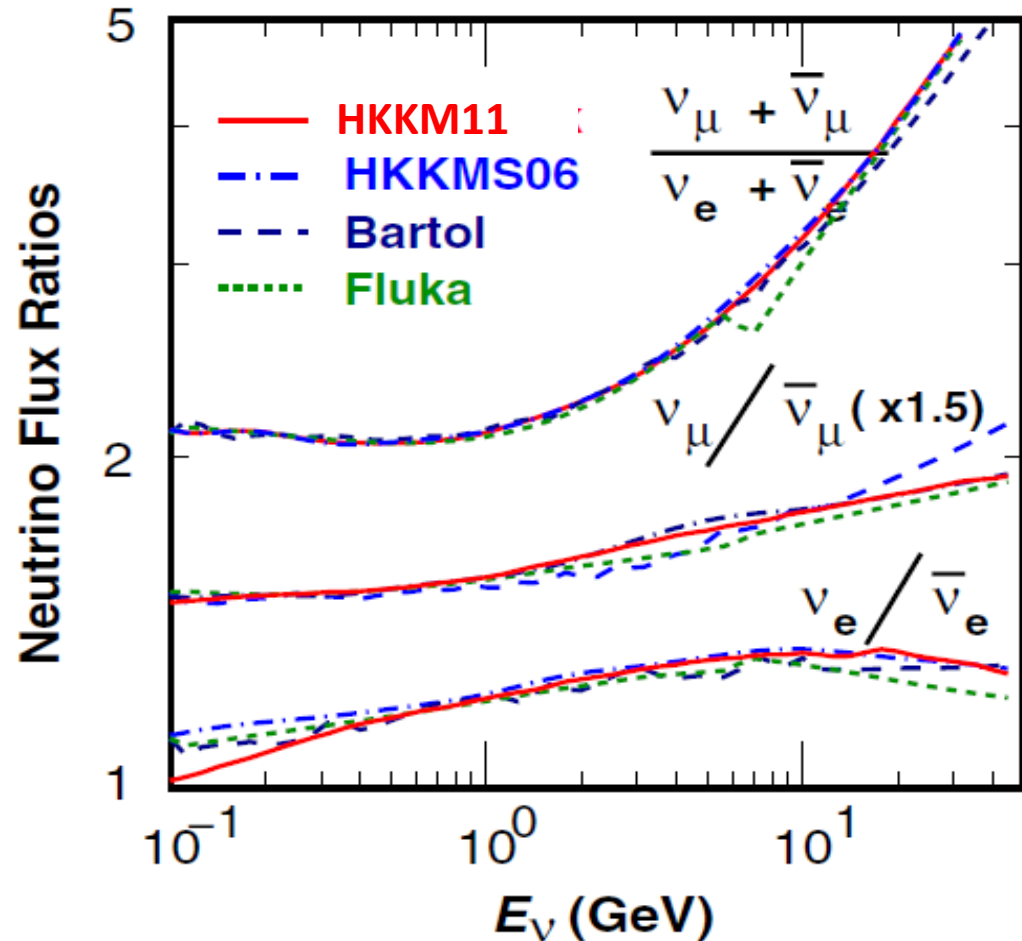
I will discuss only $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations and related studies.

Introduction

Key features of the atmospheric neutrino beam

M. Honda et al., PRD 83, 123001 (2011)

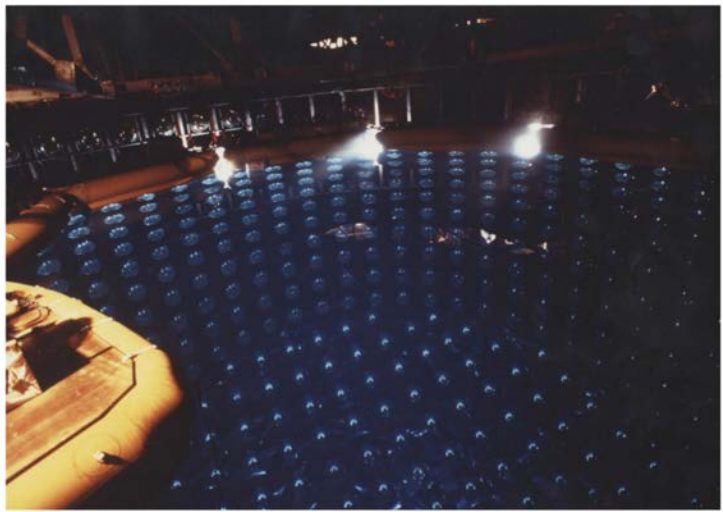
@Kamioka (Japan)



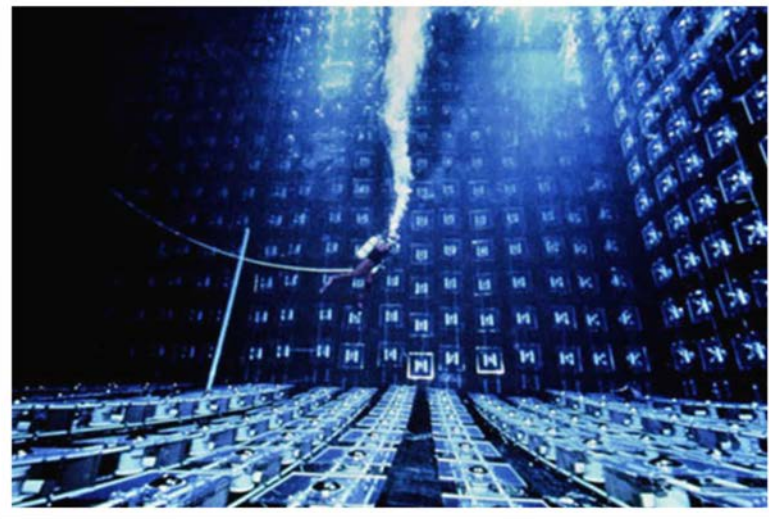
ν_μ/ν_e ratio is calculated to an accuracy of about 2% below $\sim 5\text{GeV}$.

Up/down flux ratio is very close to 1.0 and accurately calculated (1% or better) above a few GeV.

Atmospheric ν_μ/ν_e flux ratio (1980's to 90's)

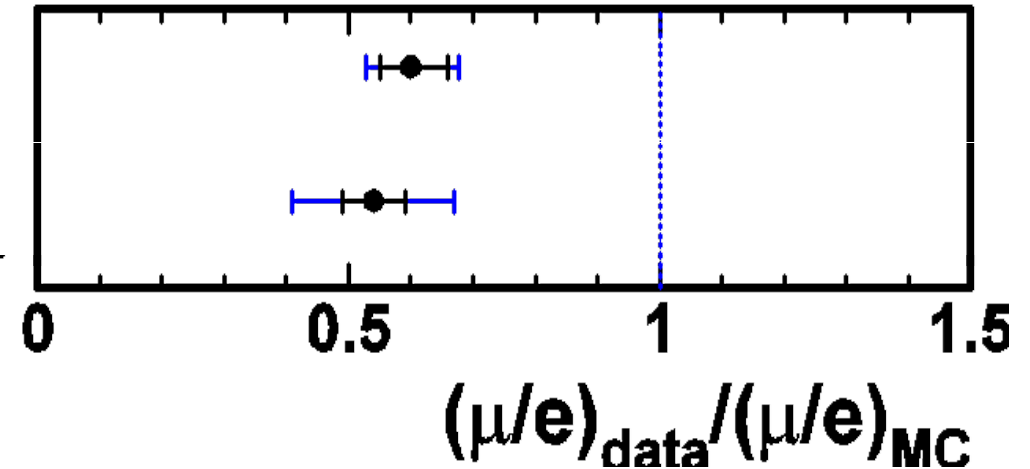


Kamiokande (1988, 92, 94)



IMB (1991, 92)

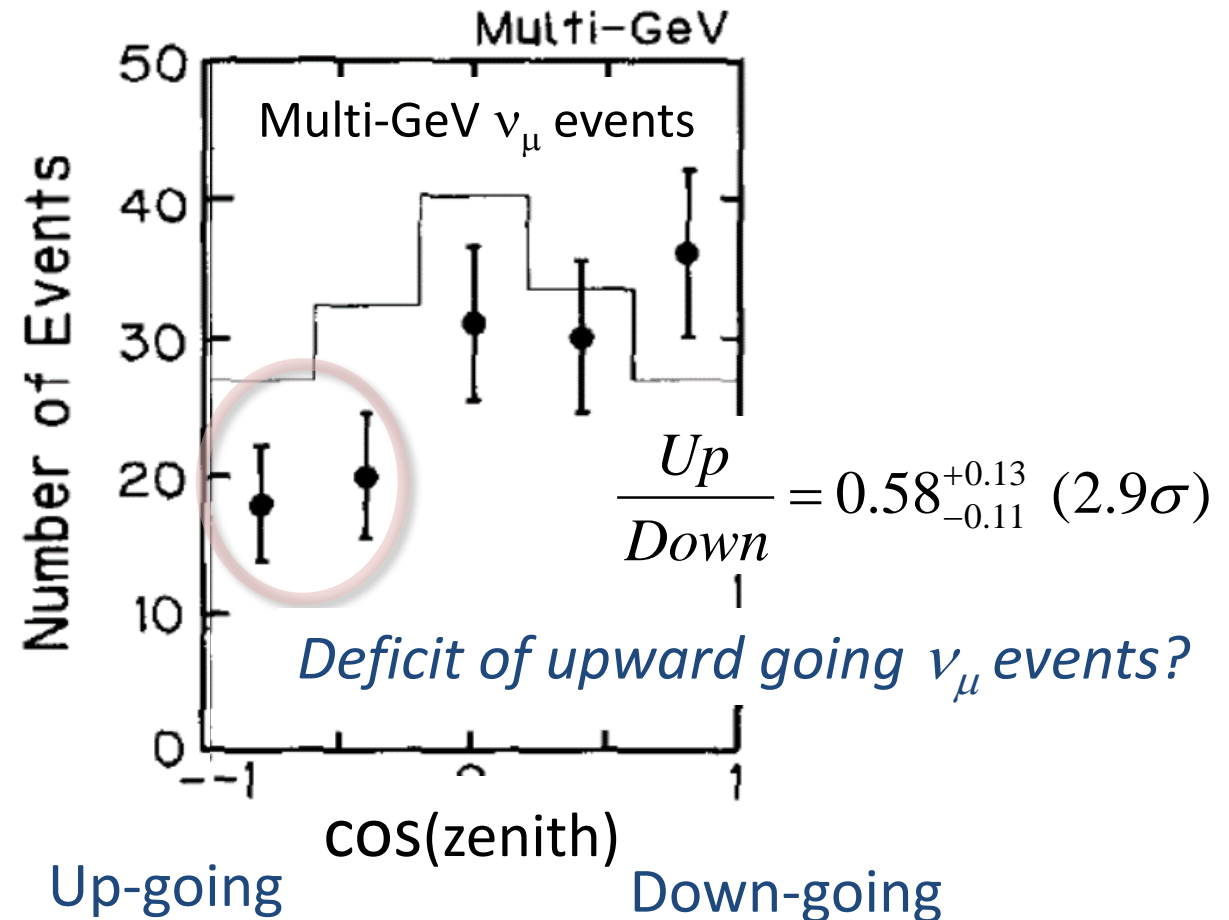
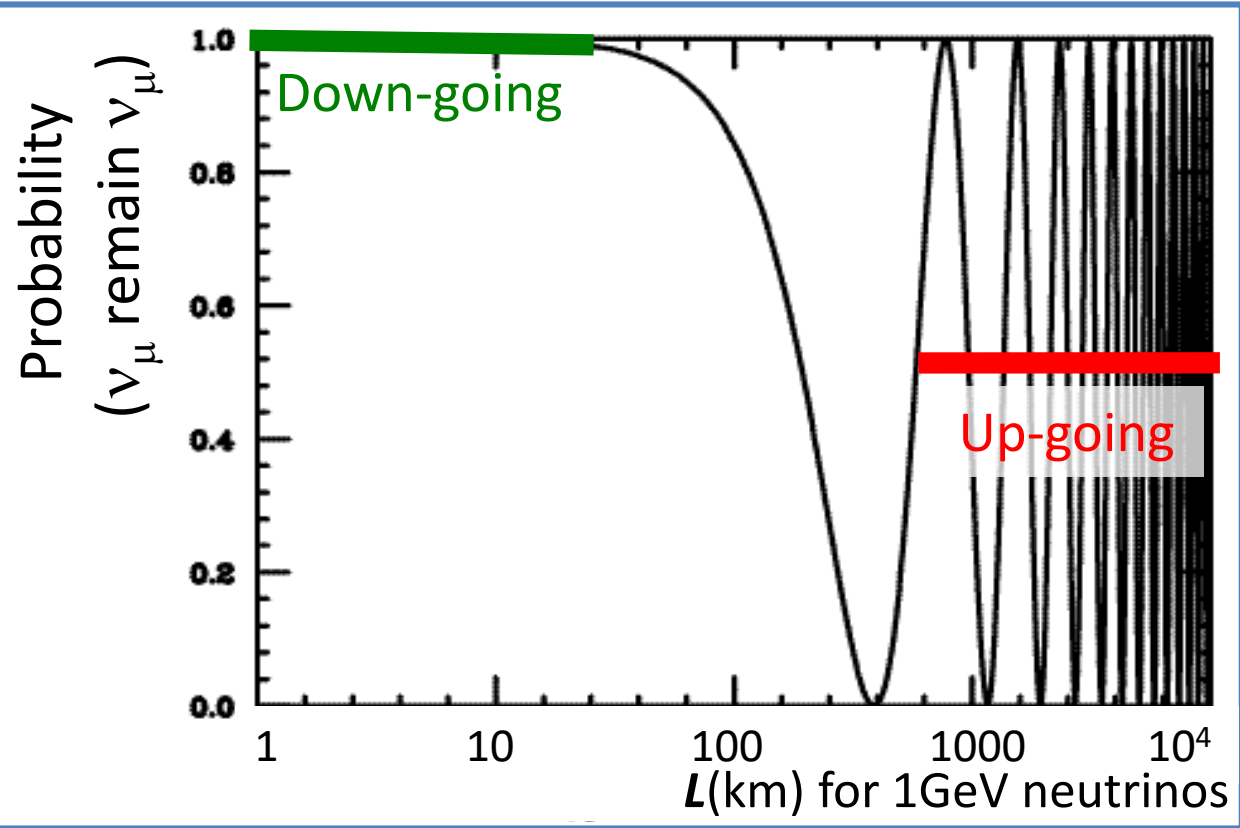
- K. Hirata et al, Phys. Lett. B 205 (1988) 416-420.
- K. S. Hirata, et al., Phys. Lett. B 280 (1992) 146-152.
- Y. Fukuda, et al., Phys. Lett. B 335 (1994) 237-245.
- D. Casper, et al., Phys. Rev. Lett. 66 (1991) 2561-2564.
- R. Becker-Szendy, et al., Phys. Rev. D 46 (1992) 3720-3724.



→ Paolo Lipari and John Learned

Zenith angle distribution from Kamiokande (1994)

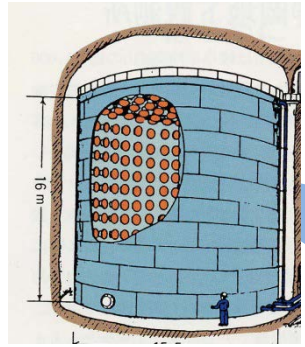
Kamiokande Phys. Lett. B 335, 237 (1994)



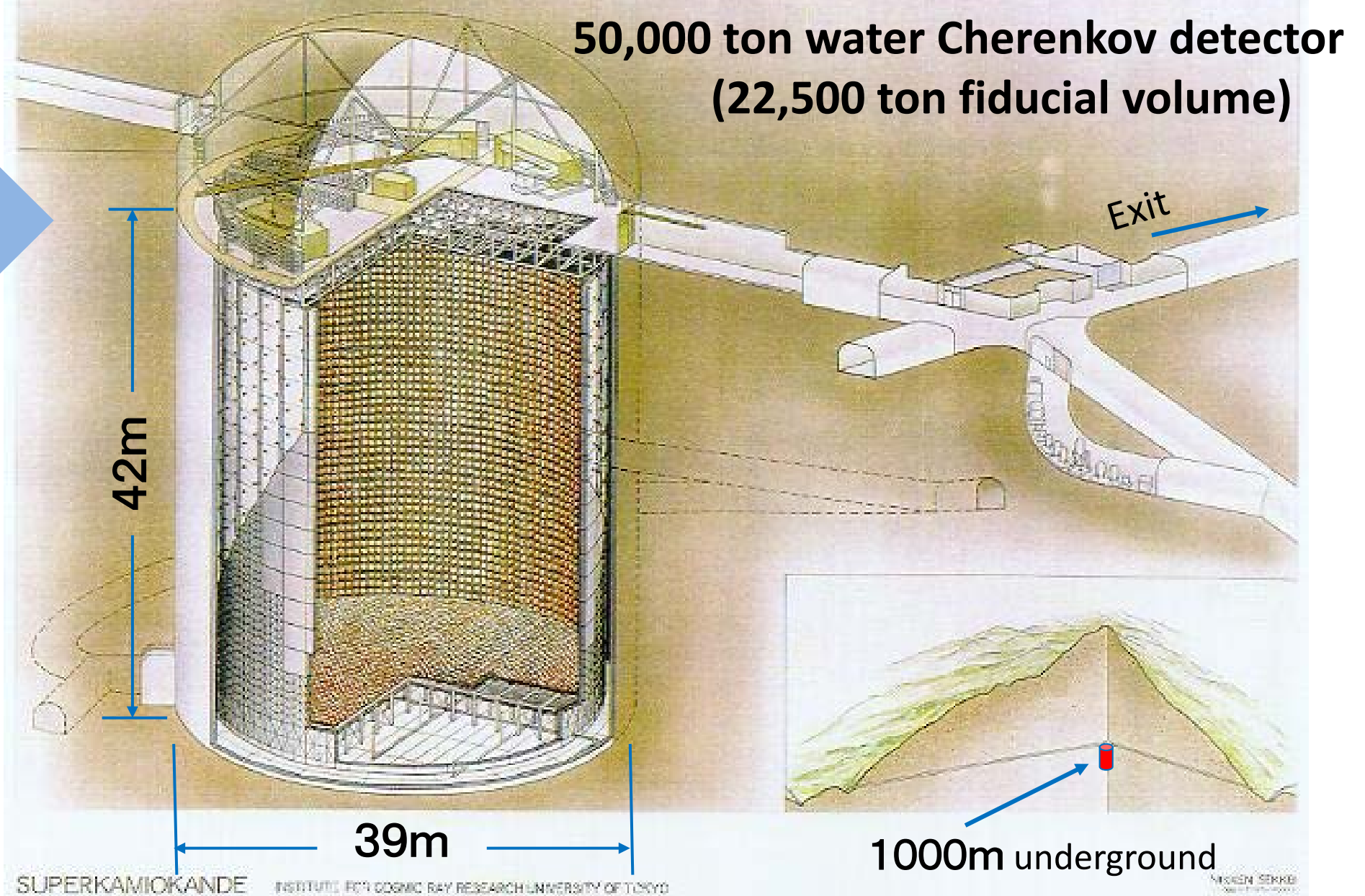
The data suggested something interesting. But the statistics of the data are not large enough. Much larger detector needed. → Super-Kamiokande

Super-Kamiokande

Super-Kamiokande detector



~20 times
larger mass



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

Exit

42m

39m

1000m underground

SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

ANDRÉ SENKÉ

Initial idea of Super-Kamiokande



KEK Report 84-12
September 1984
H

PROCEEDINGS OF
WORKSHOP ON GRAND UNIFIED THEORIES
AND COSMOLOGY

KEK, Tsukuba, Japan
December, 7-10, 1983

Edited by
K. ODAKA and A. SUGAMOTO

32 Kton Water Cerenkov Detector(JACK)

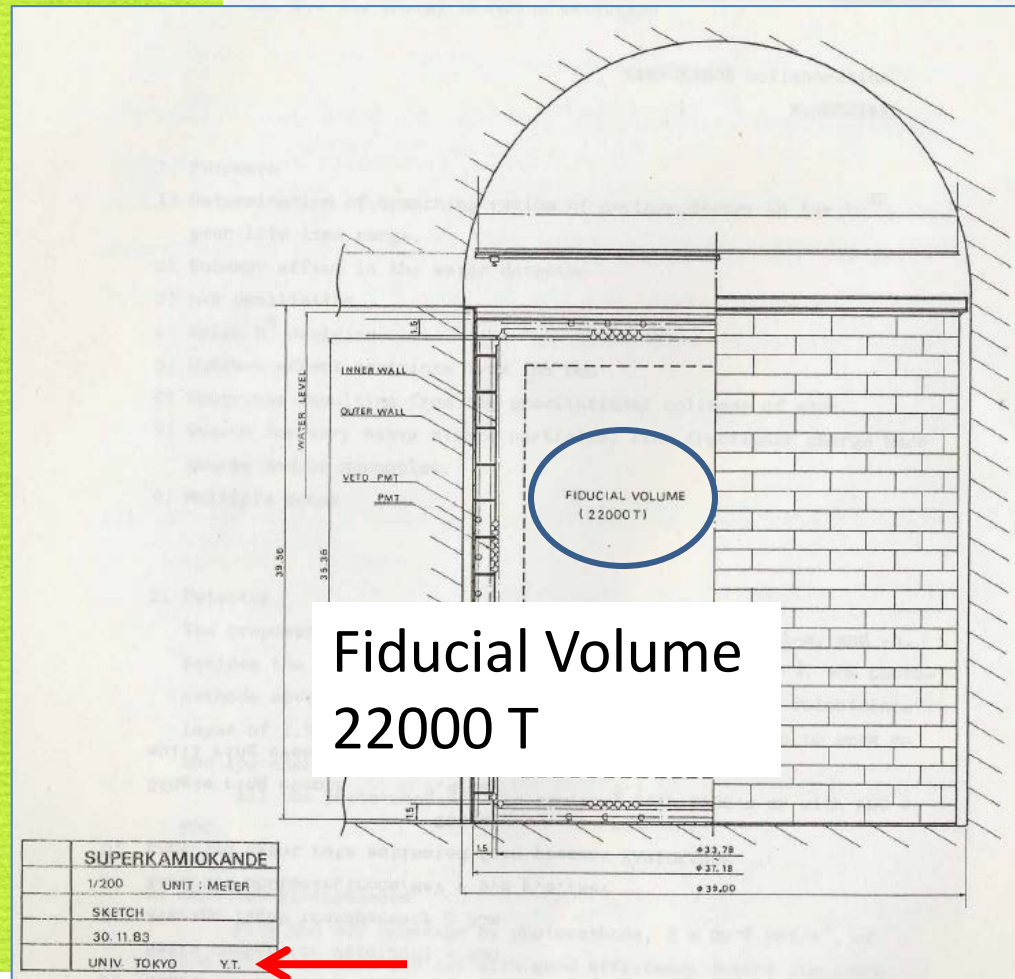
A proposal for detailed studies of nucleon decays
and for low energy neutrino detection

KAMIOKANDE collaboration

M. KOSHIBA

In the fall of 1983, Prof. Koshiba proposed Super-Kamiokande to study solar neutrinos in detail (and to search for p-decays).

Super-Kamiokande was approved by the Japanese government in 1991.



Beginning of the Super-Kamiokande collaboration between Japan and USA (1992)



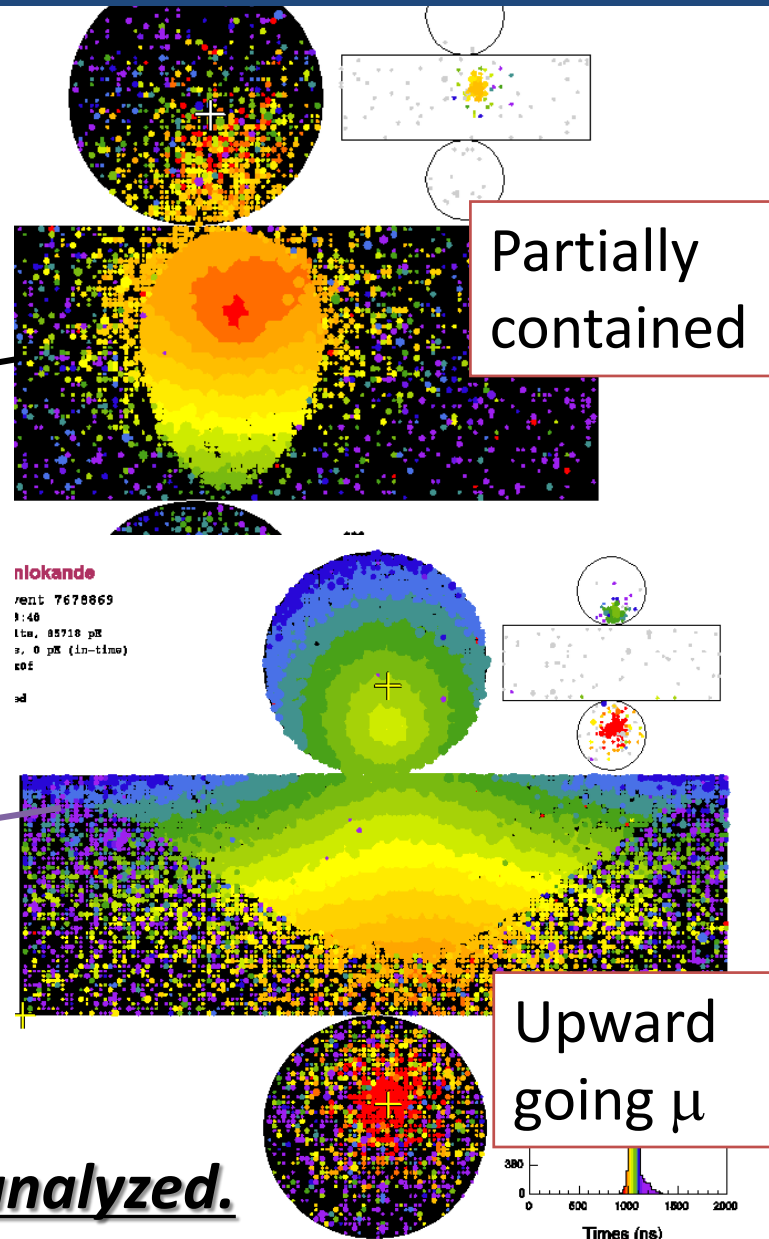
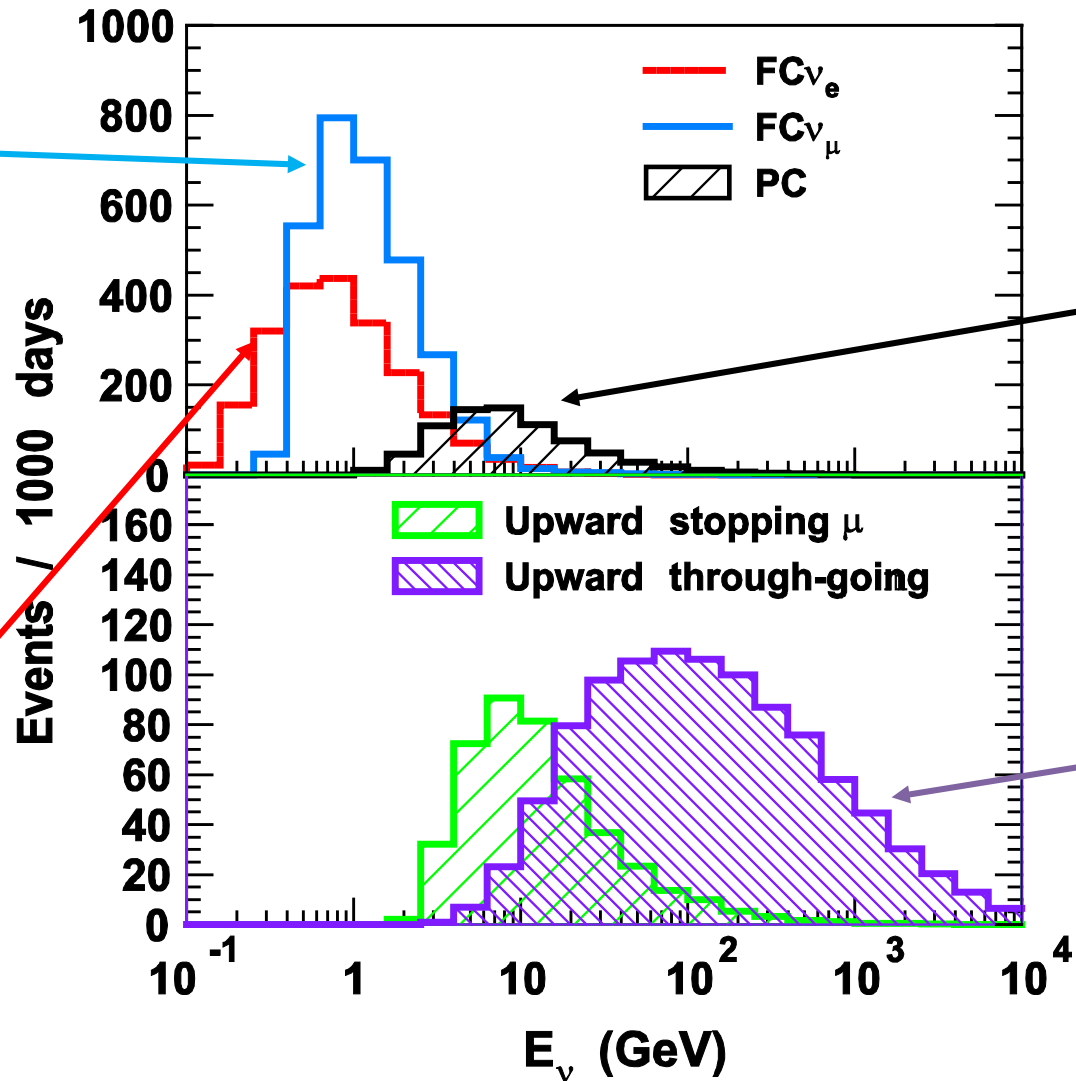
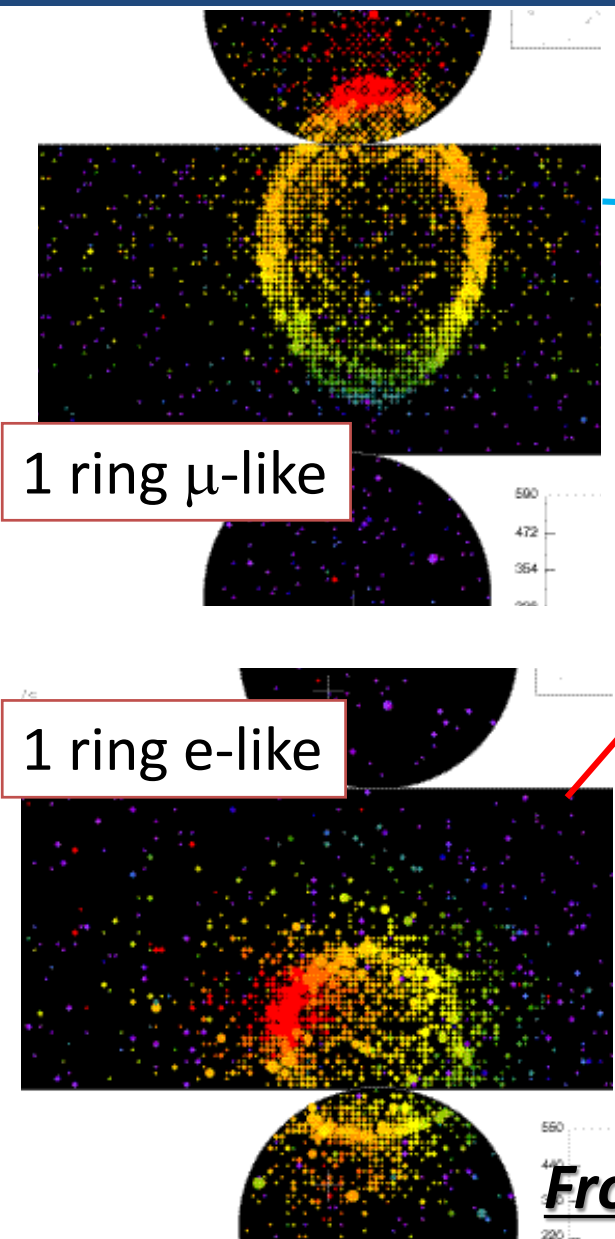
@ Institute for
Cosmic Ray
Research, 1992

Starting the Super-Kamiokande experiment



The experiment began at
0:00 on April 1, 1996

Event type and neutrino energy

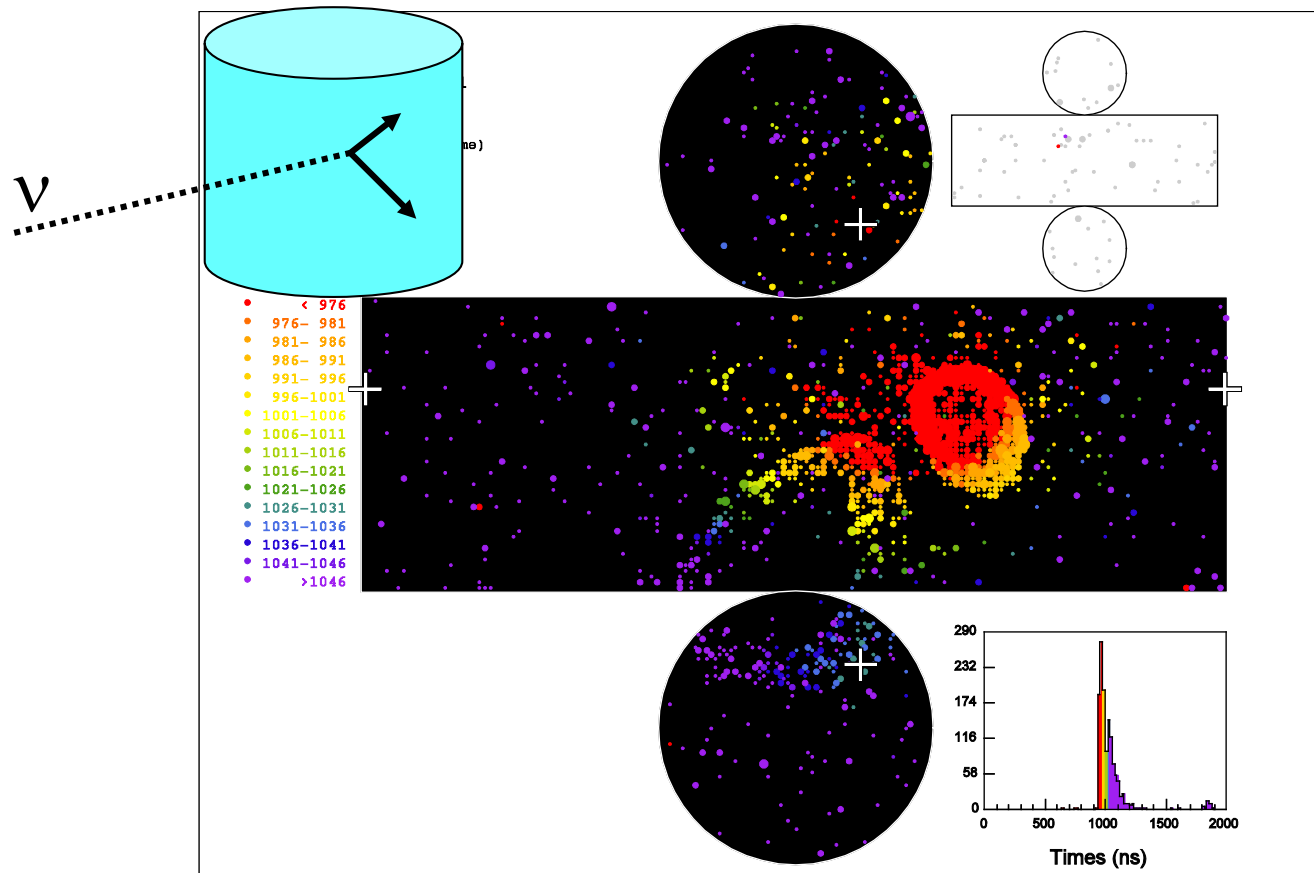


From the beginning, all these events were analyzed.

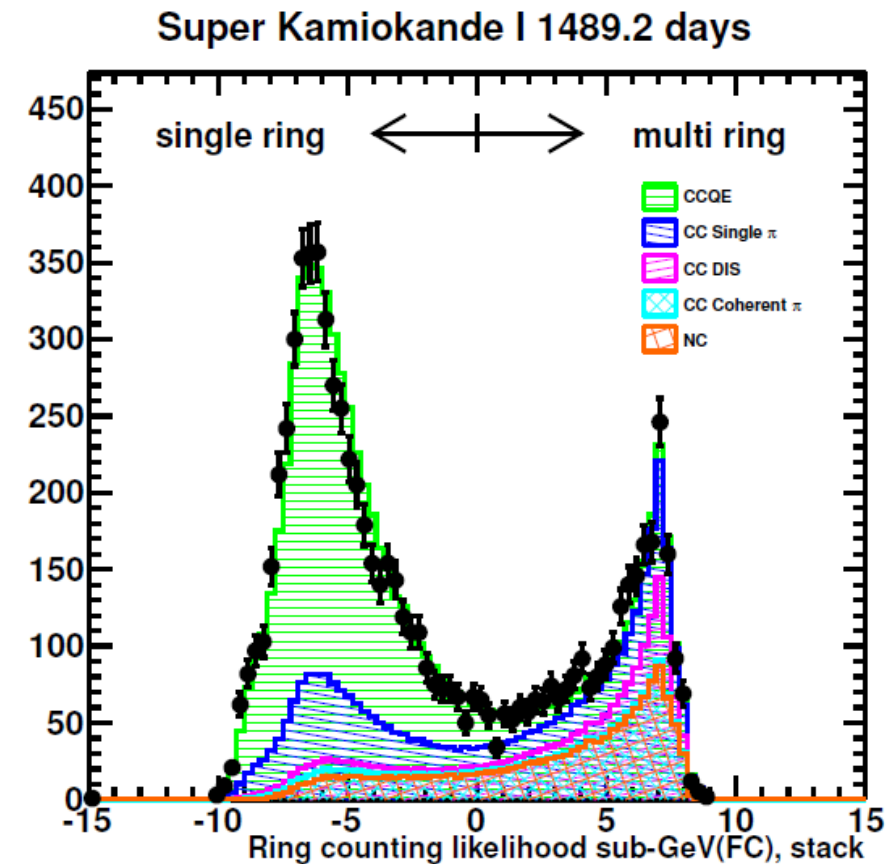
Fully automated analysis

- One of the limitations of the Kamiokande's analysis was the necessity of the event scanning for all data and Monte Carlo events, due to no satisfactory ring identification software.

Multi Cherenkov ring event



Hough transformation + maximum likelihood



Discovery of atmospheric neutrino oscillations

June 5

* Session 6: Atmospheric neutrinos I

- Contained events and Soudan-2
 - E.Peterson(Minesota)
- Upward-going muons and MACRO
 - F.Ronga(Frascati)
- Results from Super-Kamiokande & Kamiokande
 - T.Kajita(ICRR)

* Session 7: Atmospheric neutrinos II

NEUTRINO'98

**XVIII INTERNATIONAL CONFERENCE
ON
NEUTRINO PHYSICS AND ASTROPHYSICS**
Takayama, Japan - June 4-9, 1998

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- T.Yanagida (Tokyo)

Attendance by Invitation

Further information:

URL: <http://www-sk.icrr.u-tokyo.ac.jp/nu98/>
E-mail: nu98@suketto.icrr.u-tokyo.ac.jp

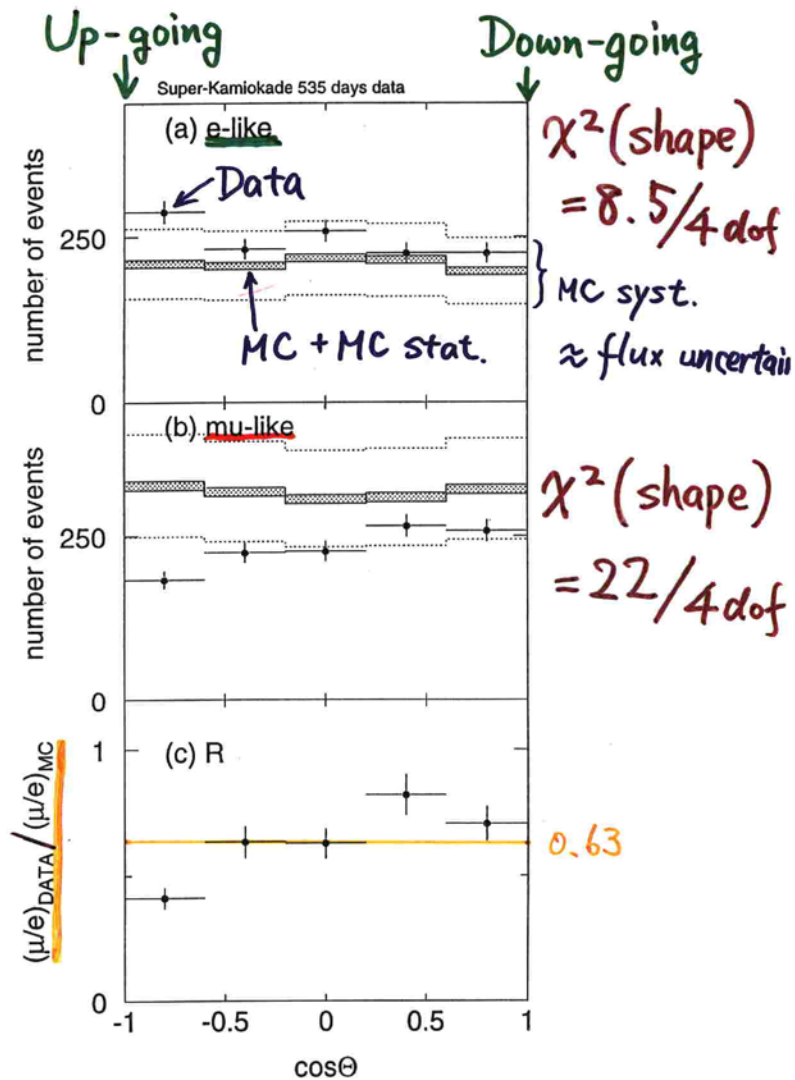
Supported by

- International Union of Pure and Applied Physics (IUPAP)
- Japan National Committee for Physics, Science Council of Japan

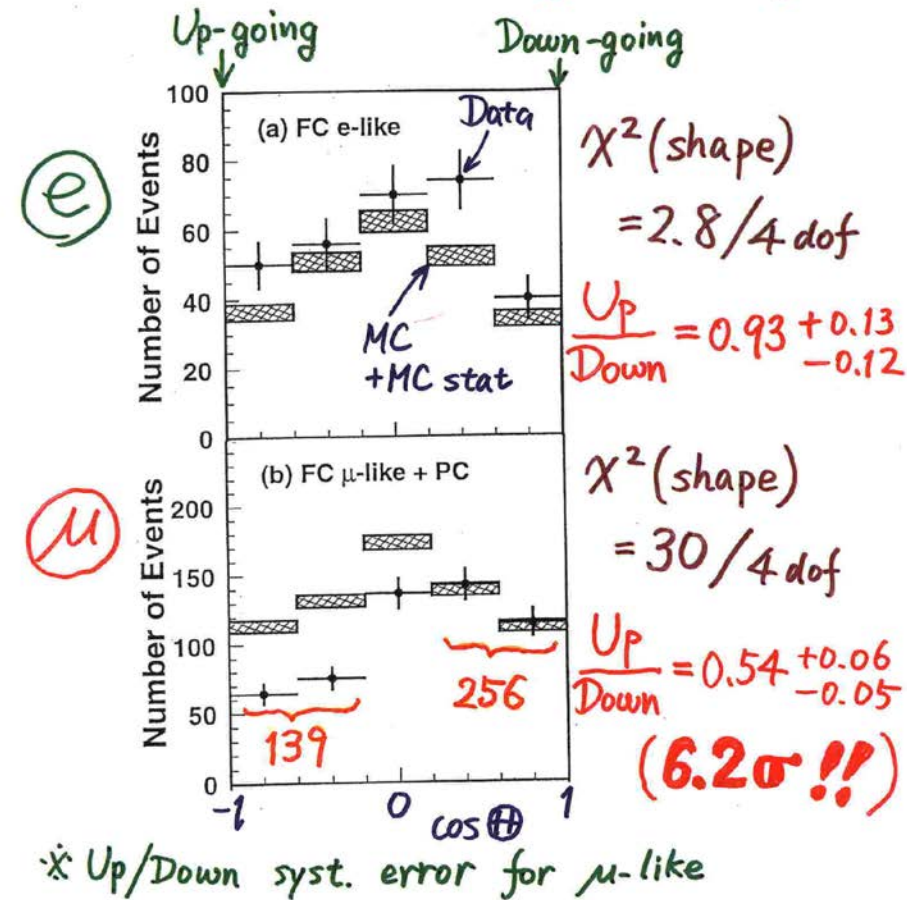
Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

Super-K, Neutrino 98,
 Super-K, PLB 433, 9-18 (1998)
 Super-K, PLB 436, 33-41 (1998)

Zenith angle dependence (Sub-GeV)



Zenith angle dependence (Multi-GeV)



Prediction (flux calculation $\dots \lesssim 1\%$, 1km rock above SK $\dots 1.5\%$) 1.8%

Data (Energy calib. for $\uparrow\downarrow \dots 0.7\%$, Non ν Background $\dots < 2\%$) 2.1%

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

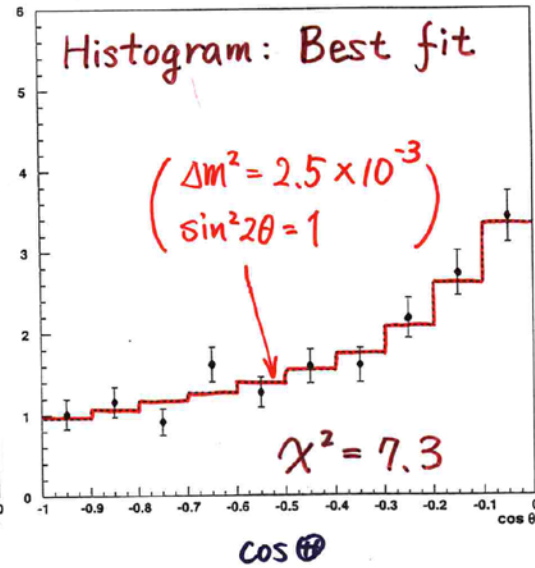
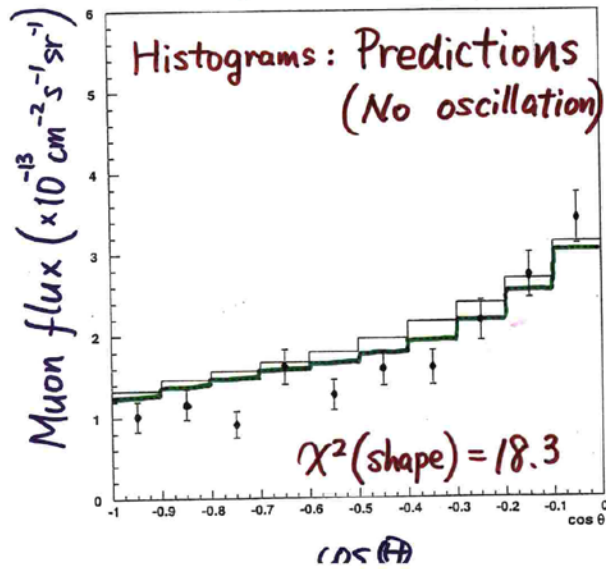
Super-K, Neutrino 98,
Super-K, PRL, 82, 2644 (1999)
Super-K, PLB 467, 185-193 (1999)

Super-Kamiokande up-going muon results

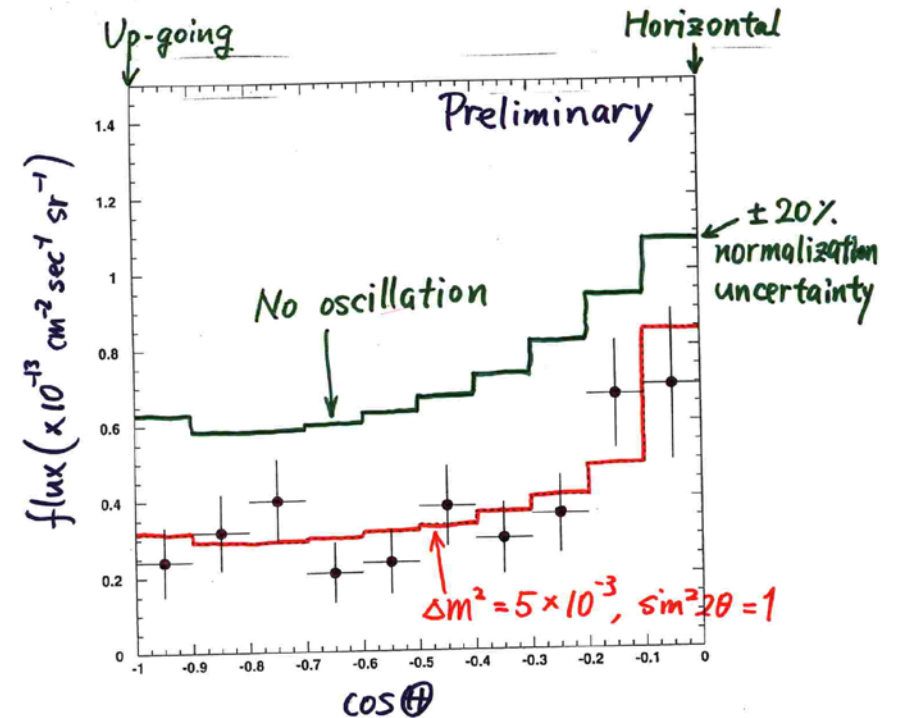
• 617 events / 534 days

Preliminary

• Average flux $(\times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1})$
 • Data: 1.75 ± 0.07 (stat) ± 0.09 (syst.)
 • Prediction: 2.02 ± 0.4
 1.88 ± 0.4



↑ stopping muon data Super-Kamiokande



$$\frac{\left(\begin{array}{l} \uparrow \text{Stopping } \mu \\ \uparrow \text{through } \mu \end{array} \right)_{\text{Data}}}{\left(\begin{array}{l} \uparrow \text{Stopping } \mu \\ \uparrow \text{through } \mu \end{array} \right)_{\text{Prediction}}} = \frac{0.22 \pm 0.023 \pm 0.014}{0.39 \pm 0.05}$$

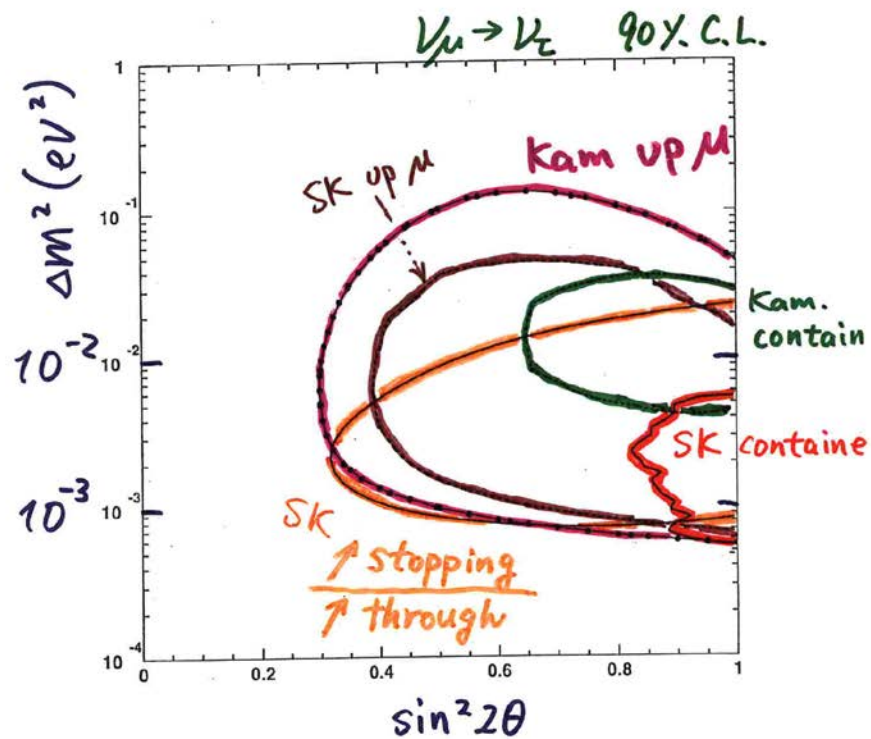
< 1

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

Super-K, Neutrino 98,
Super-K., PRL 81 (1998) 1562

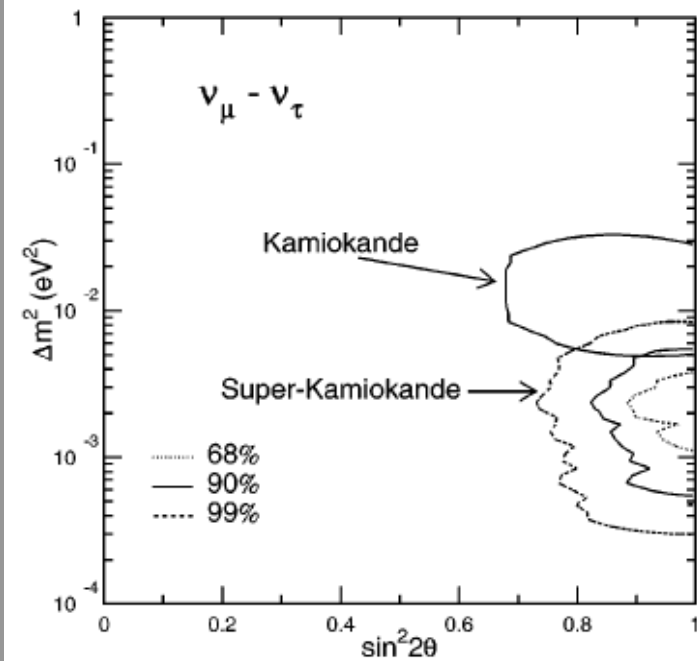
Super-Kamiokande concluded that the observed zenith angle dependent deficit and the other supporting data gave evidence for neutrino oscillations.

Summary Evidence for ν_μ oscillations



- $$\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$$

(• $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_s$?)

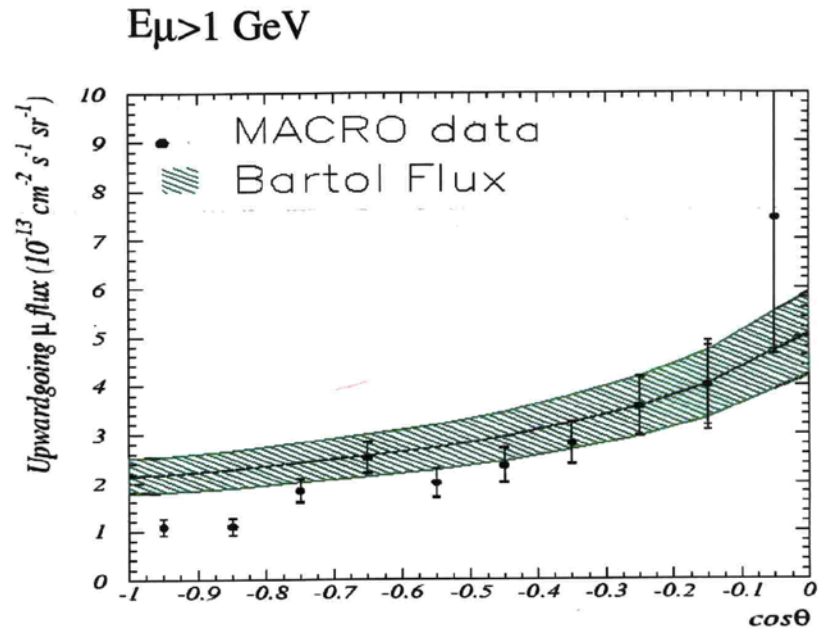
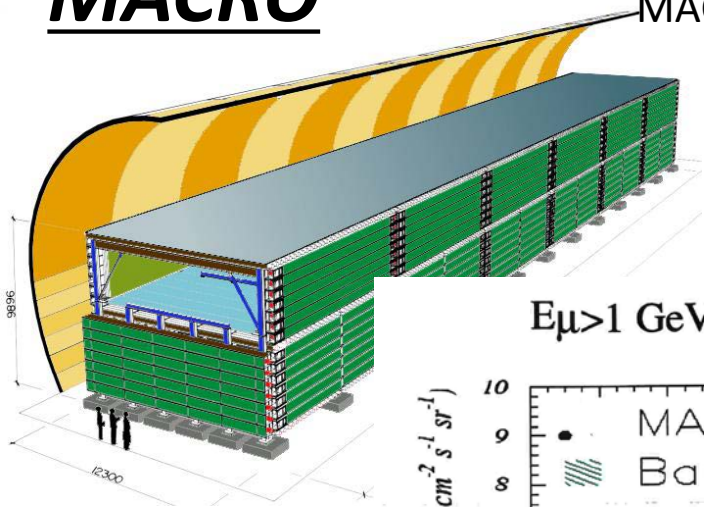


Published version
(without upward-going muons)

Results from the other atmospheric neutrino experiments

MACRO

MACRO, Neutrino 98
MACRO, PLB 434, 451-457 (1998)



Up-stop, In-down and In-up also mentioned.

Soudan-2

Soudan-2, Neutrino 98
Soudan-2 PLB 449, 137-144 (1999)



$$\begin{aligned} (\mu/e)_{\text{data}} / (\mu/e)_{\text{MC}} = \\ 0.64 \pm 0.11(\text{stat.}) \pm 0.06(\text{syst.}). \end{aligned}$$

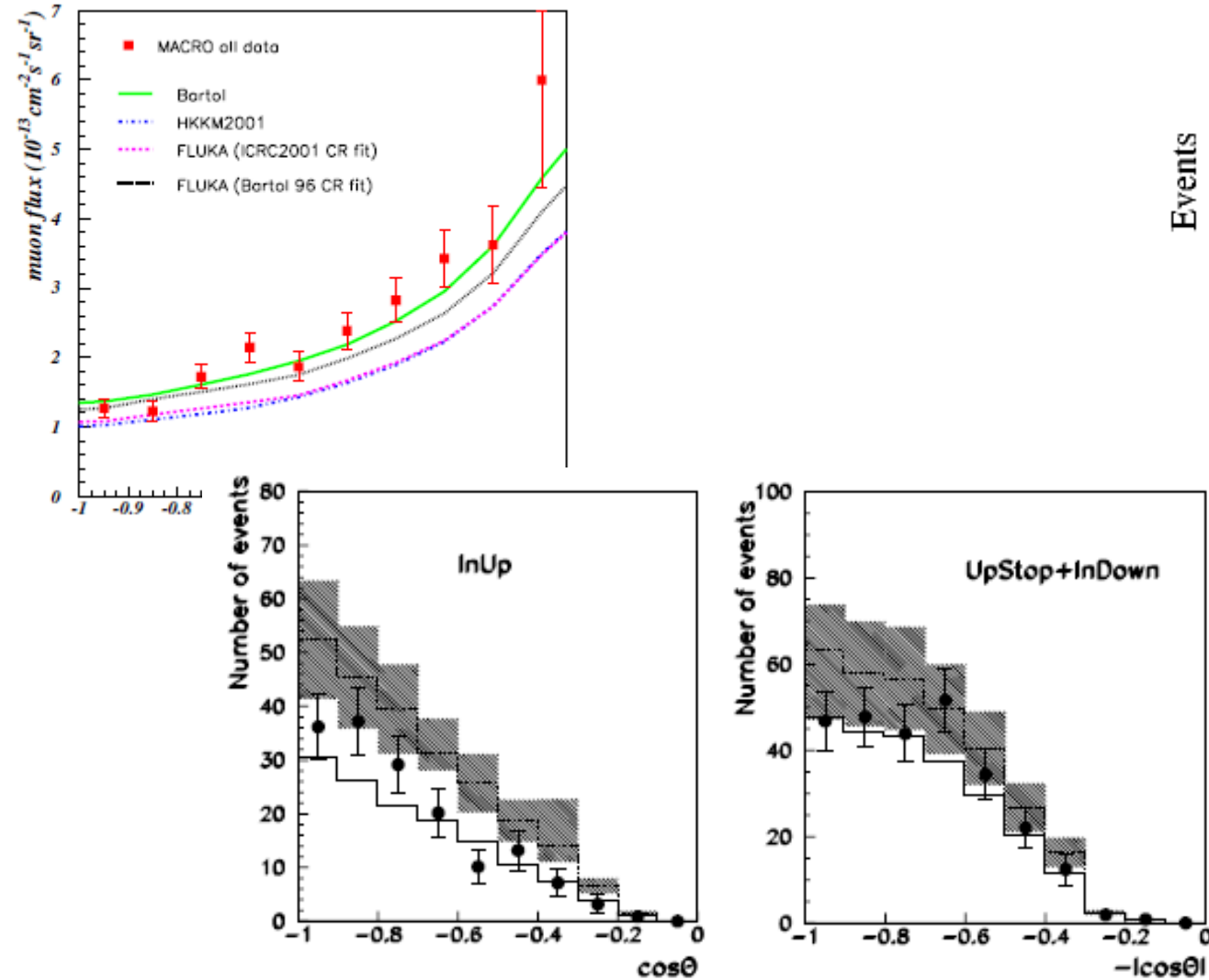
(the value is from the publication in 1999.)

Data from these experiments were also consistent with neutrinos oscillations.

Updates from MACRO and Soudan-2

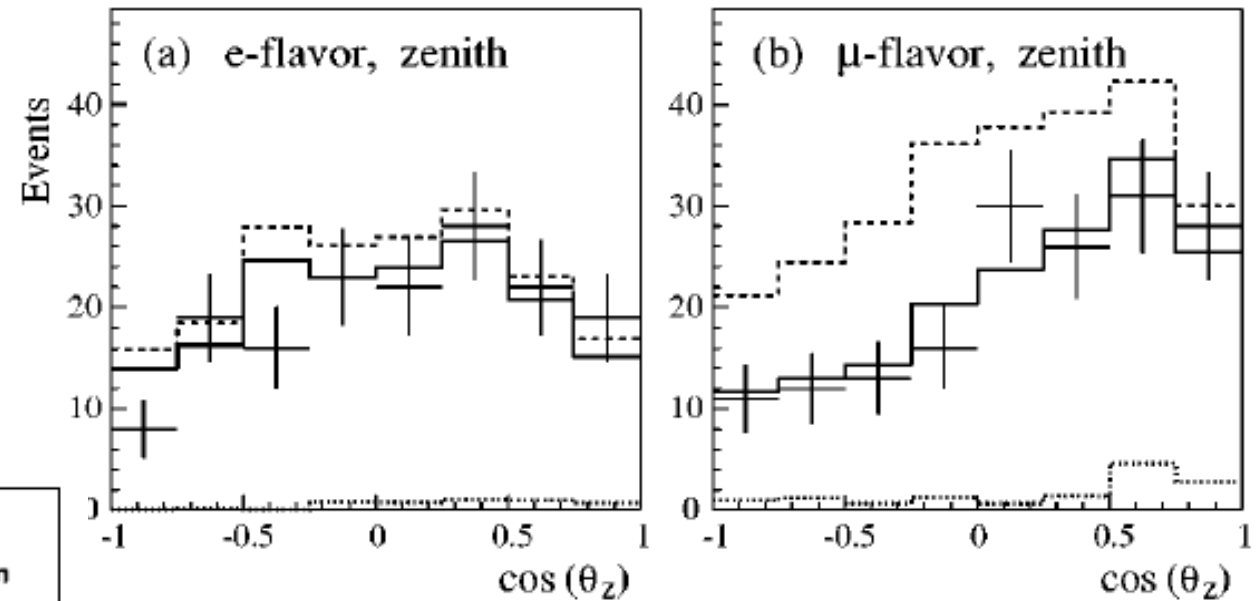
MACRO

MACRO, PLB 566, 35-44 (2003)
MACRO, Eur Phys J C36, 323-339 (2004)



Soudan-2

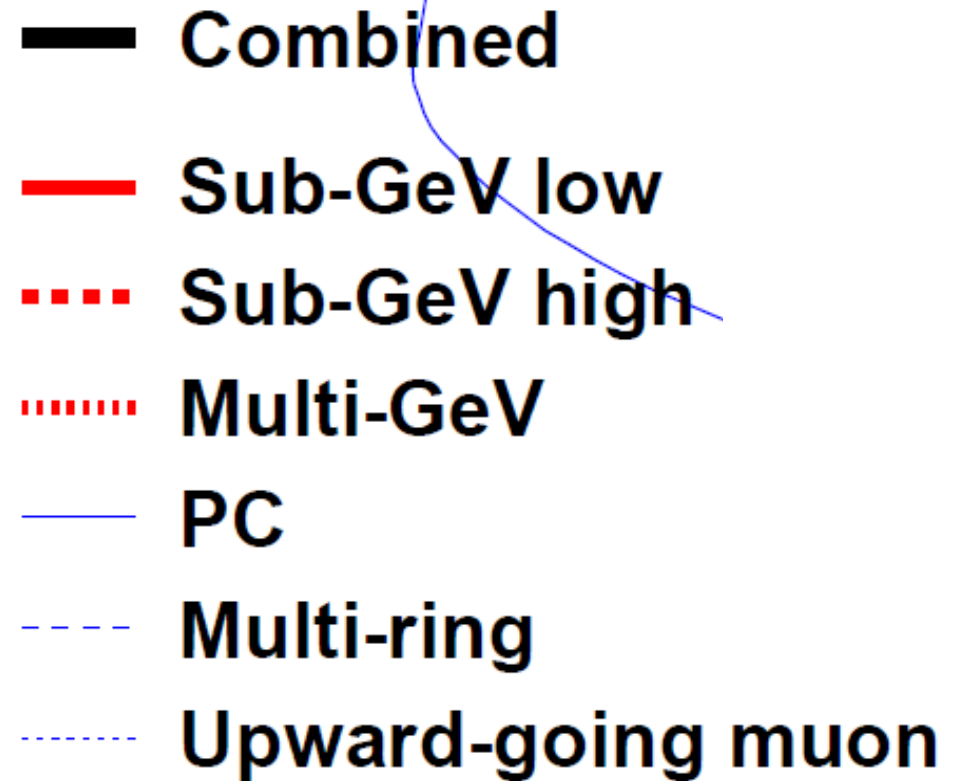
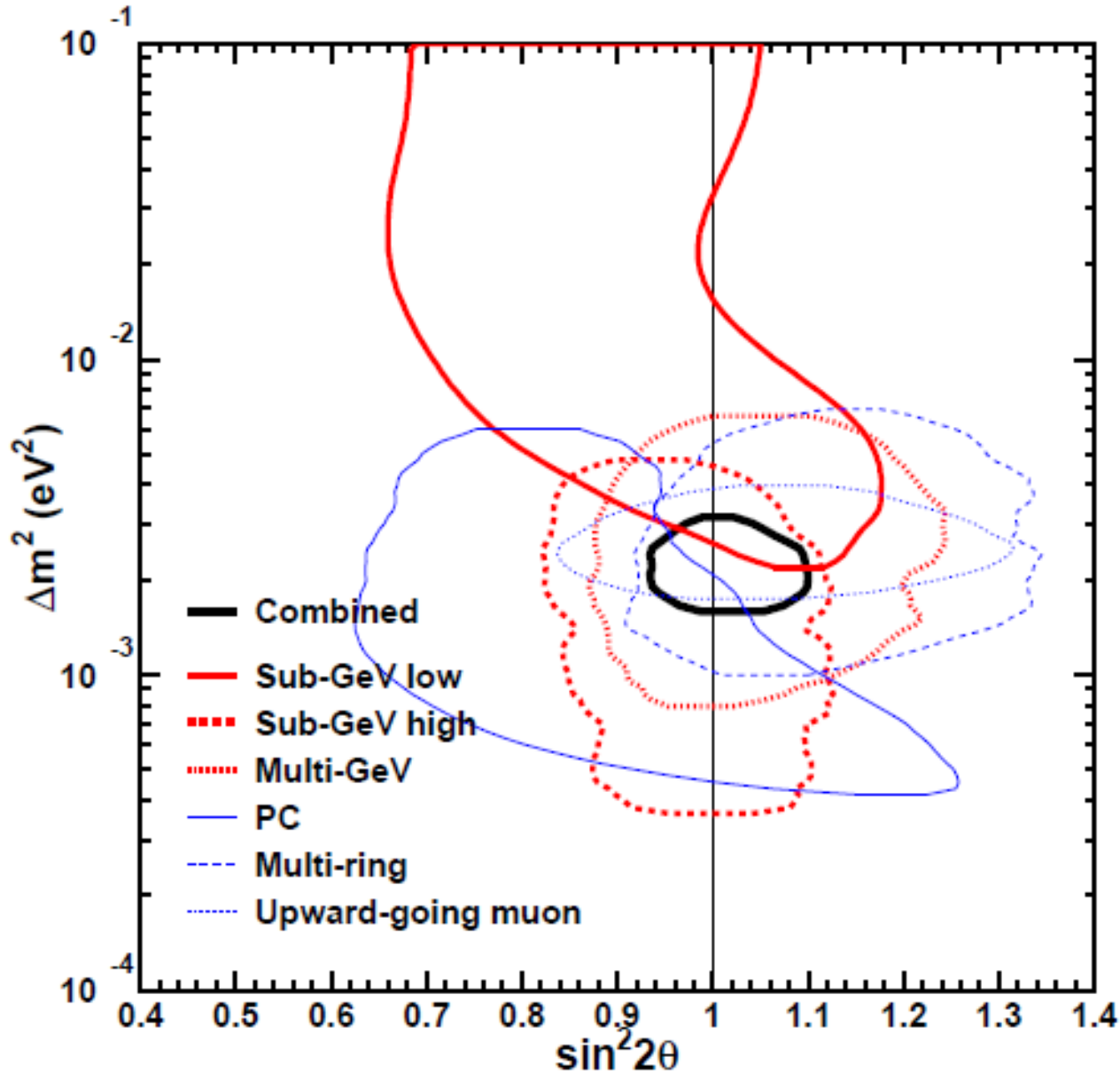
Soudan-2 PRD 68, 113004 (2003)



(See also more recent results from IceCube and ANTARES.)

Super-K oscillation parameter fit with various data samples (2005)

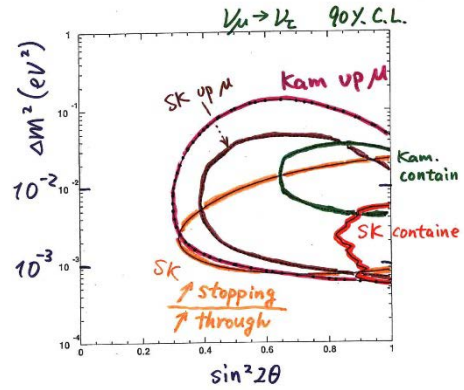
Super-K, PRD 71, 112005 (2005)



Further confirmation of $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations

Oscillation to ν_τ or $\nu_{sterile}$?

Summary Evidence for ν_μ oscillations



- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_s$?)

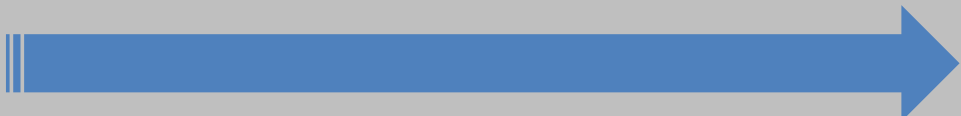
μ -like data show zenith-angle and energy dependent deficit of events, while e-like data show no such effect.

$$\nu_\mu \rightarrow \nu_\tau$$

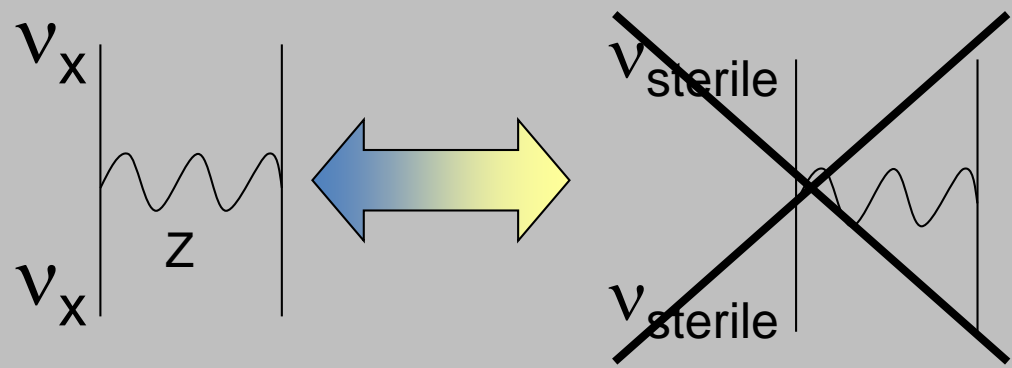
or

$$\nu_\mu \rightarrow \nu_{sterile}$$

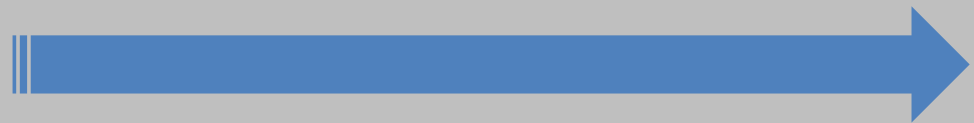
Propagation



Difference in $P(\nu_\mu \rightarrow \nu_\tau)$ and $P(\nu_\mu \rightarrow \nu_{sterile})$ due to matter effect



Interaction



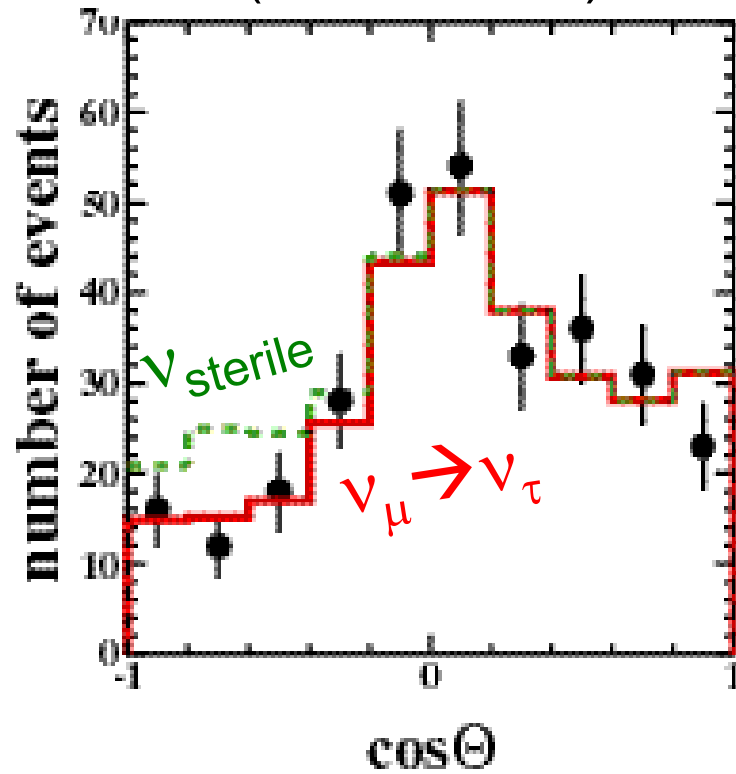
Neutral current interaction

Testing $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_{sterile}$

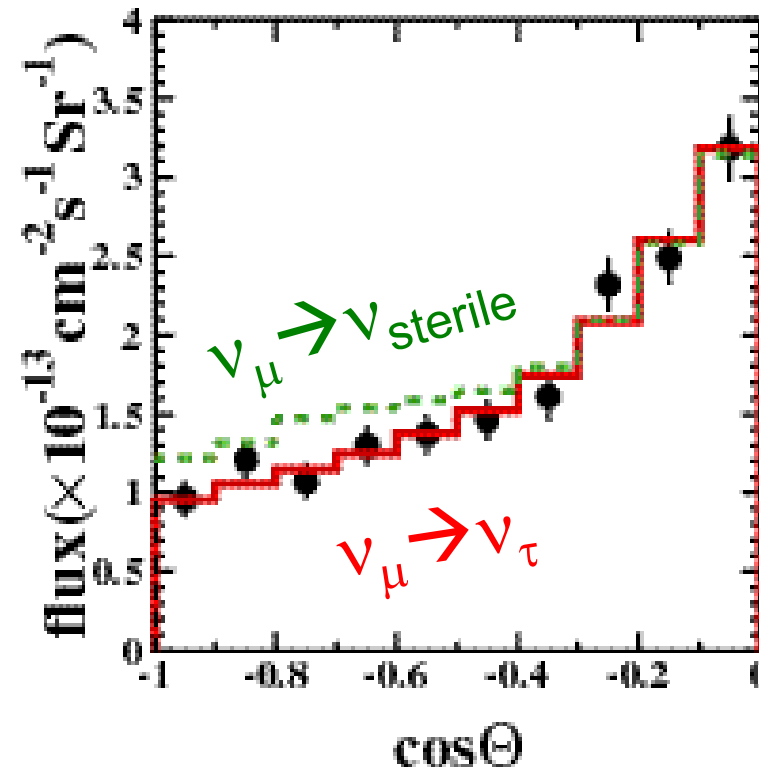
Super-K PRL85,3999 (2000)

Matter effect

High-E PC events
(Evis > 5 GeV)

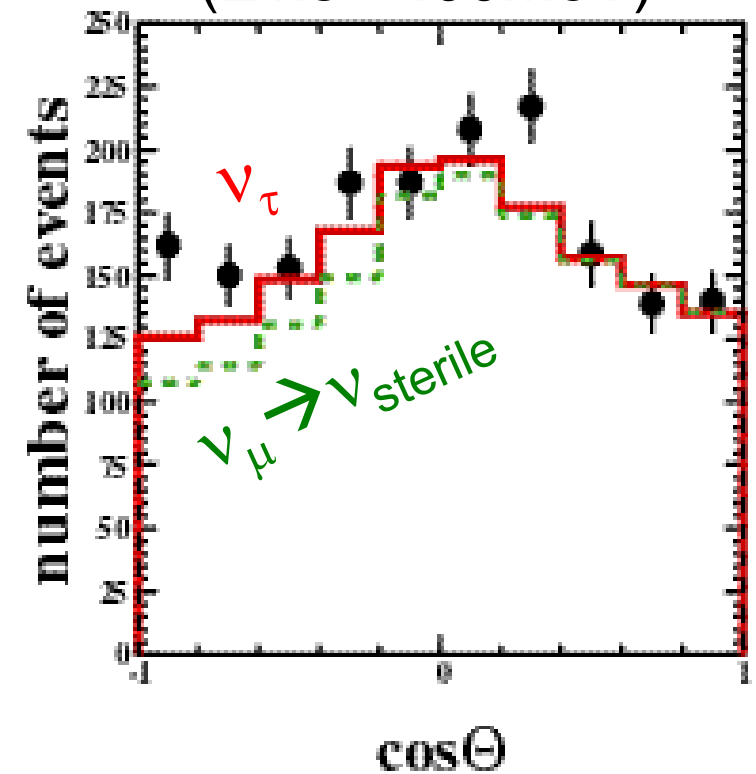


Up through muons



Neutral current

Multi-ring e-like
(Evis > 400 MeV)

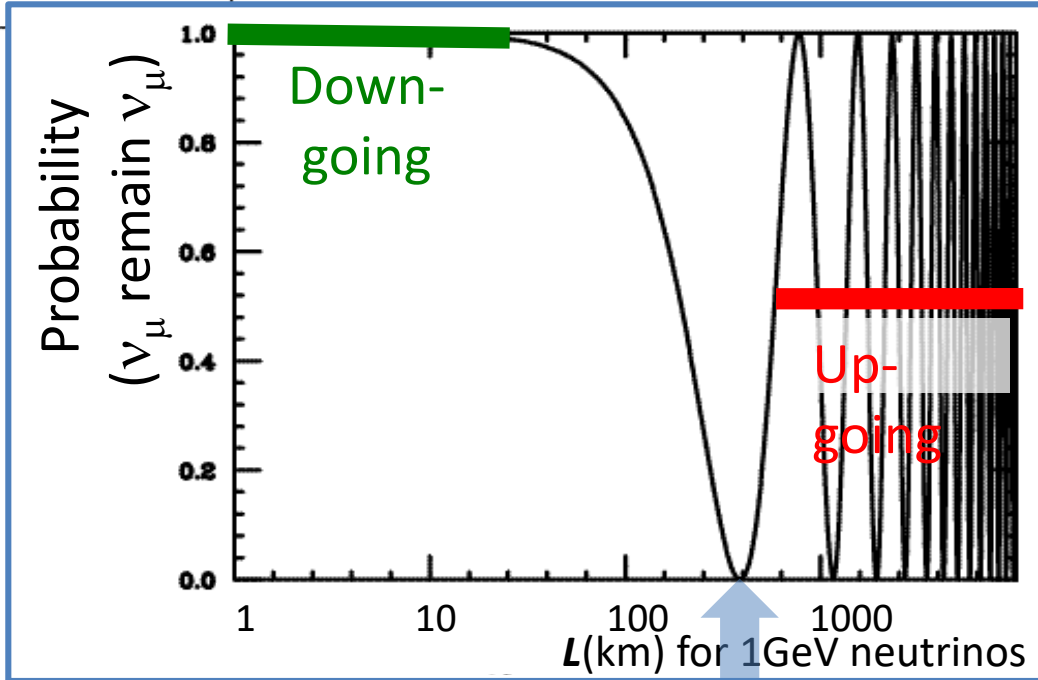
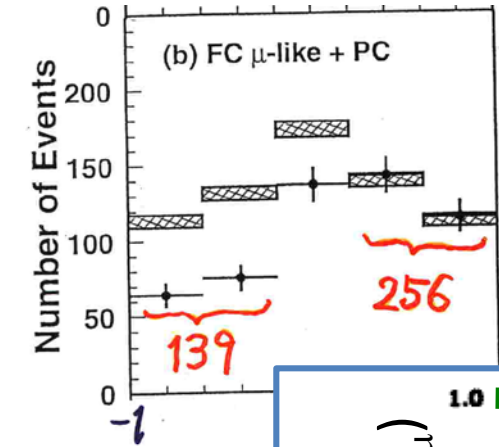


Pure $\nu_\mu \rightarrow \nu_\tau$ fit all of the data samples presented, without any inconsistency.

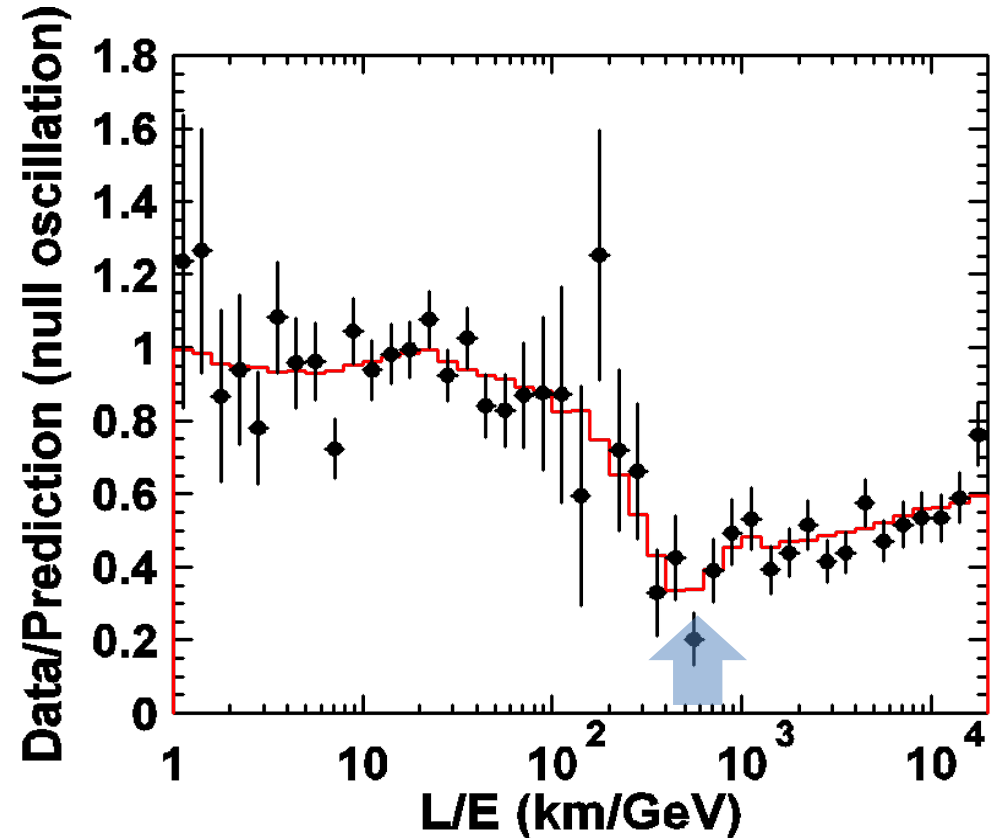
Really oscillations

Super-K, PRL 93, 101801 (2004)

It was very nice to see that approximately half of the long traveling ν_μ 's disappear. However, we wanted to really confirm neutrino "oscillations".



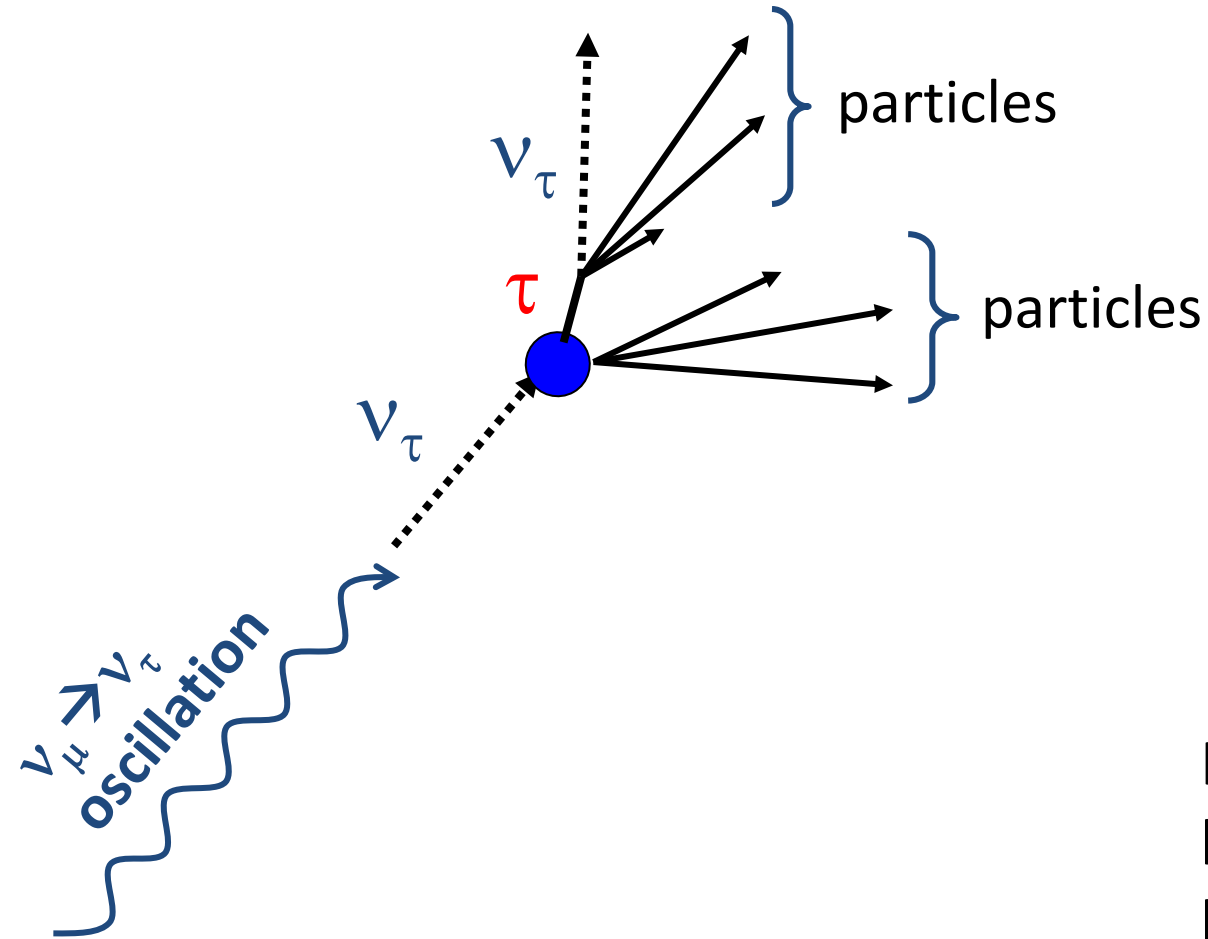
We wanted to observe this dip to confirm neutrino "oscillations".



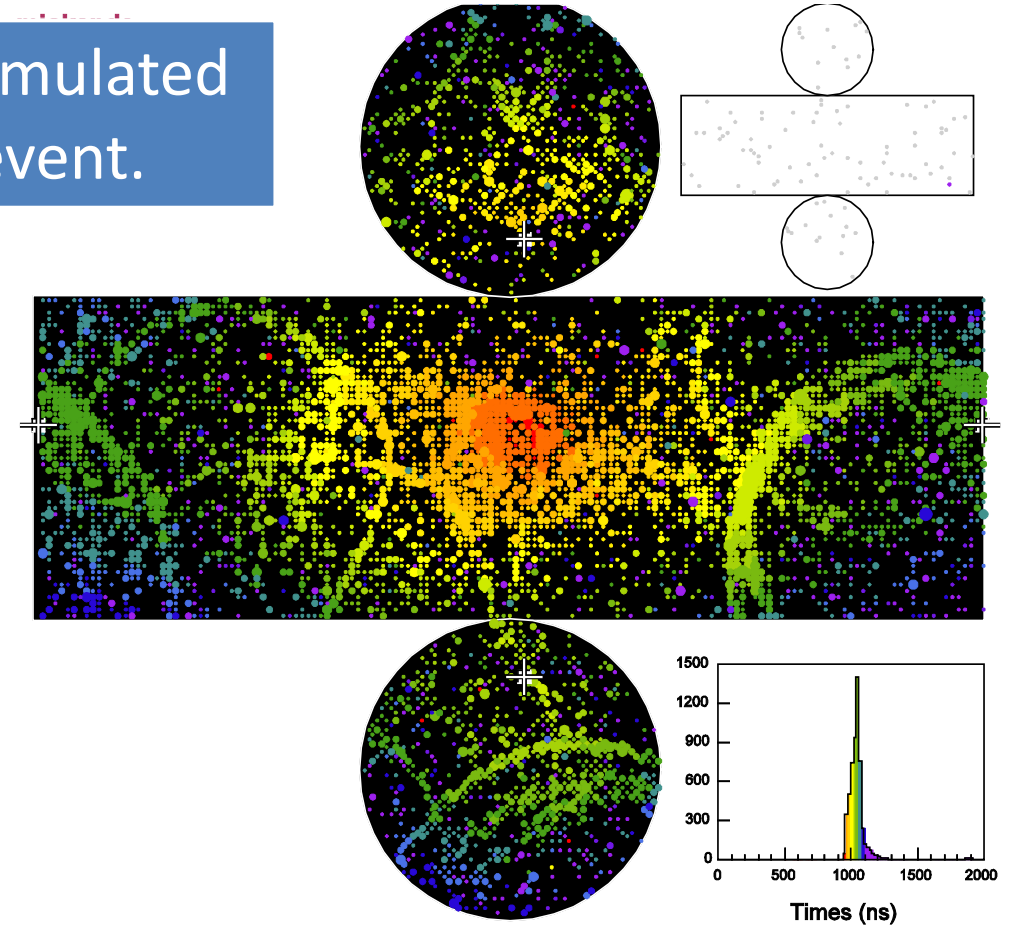
Paper title: Evidence for an Oscillatory Signature in Atmospheric Neutrino Oscillations

tau neutrino appearance?

If the oscillations are between ν_μ and ν_τ , one should be able to observe ν_τ interactions.



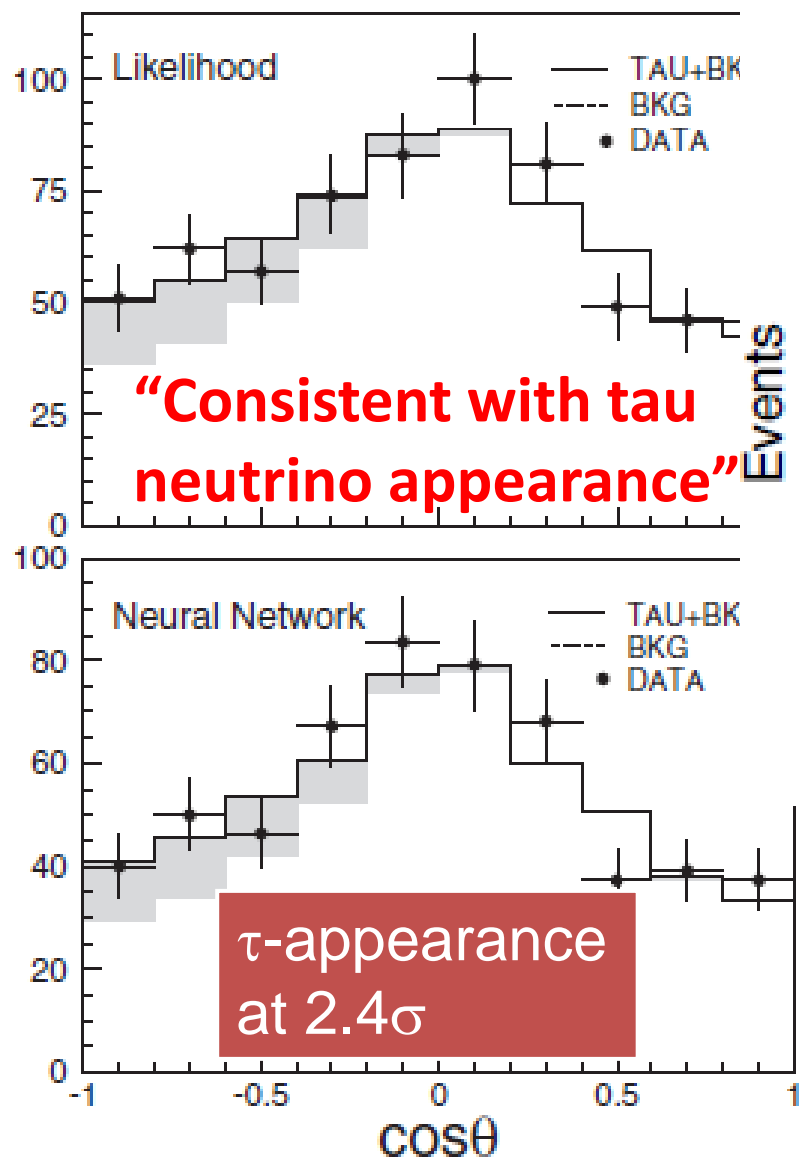
A simulated ν_τ event.



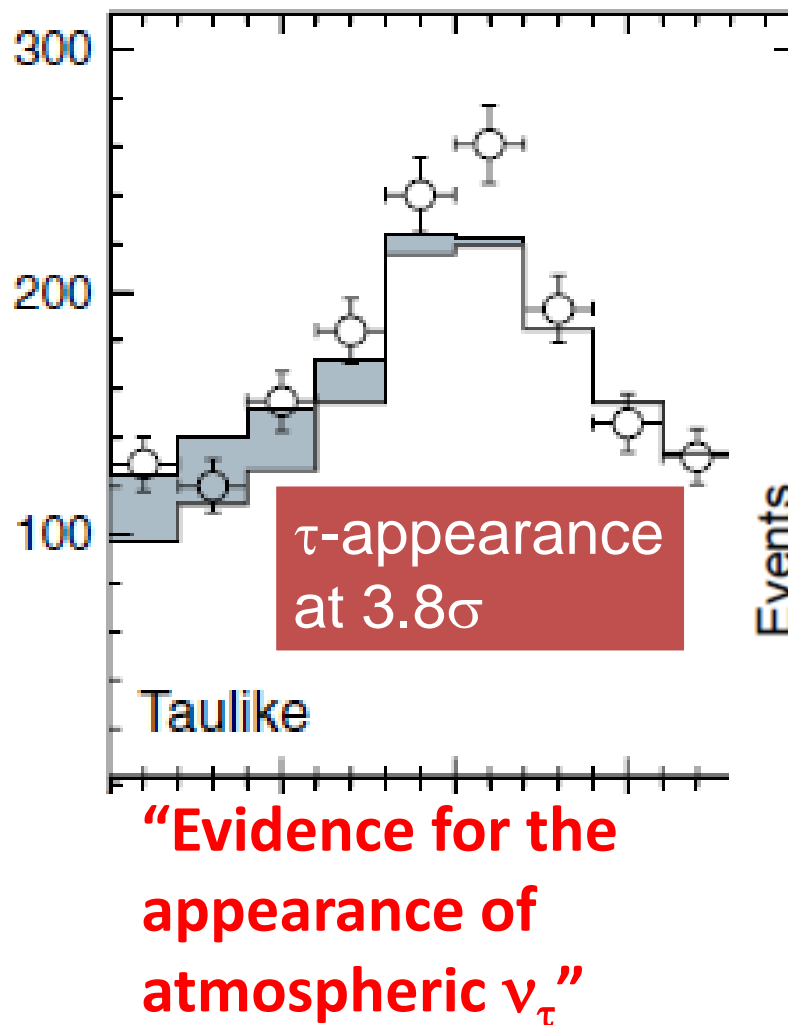
It is not possible for Super-K to identify ν_τ events by an event by event bases. \rightarrow Statistical analysis knowing that ν_τ 's are upward-going only.

ν_τ appearance history in Super-K

Super-K, PRL 97, 171801 (2006)

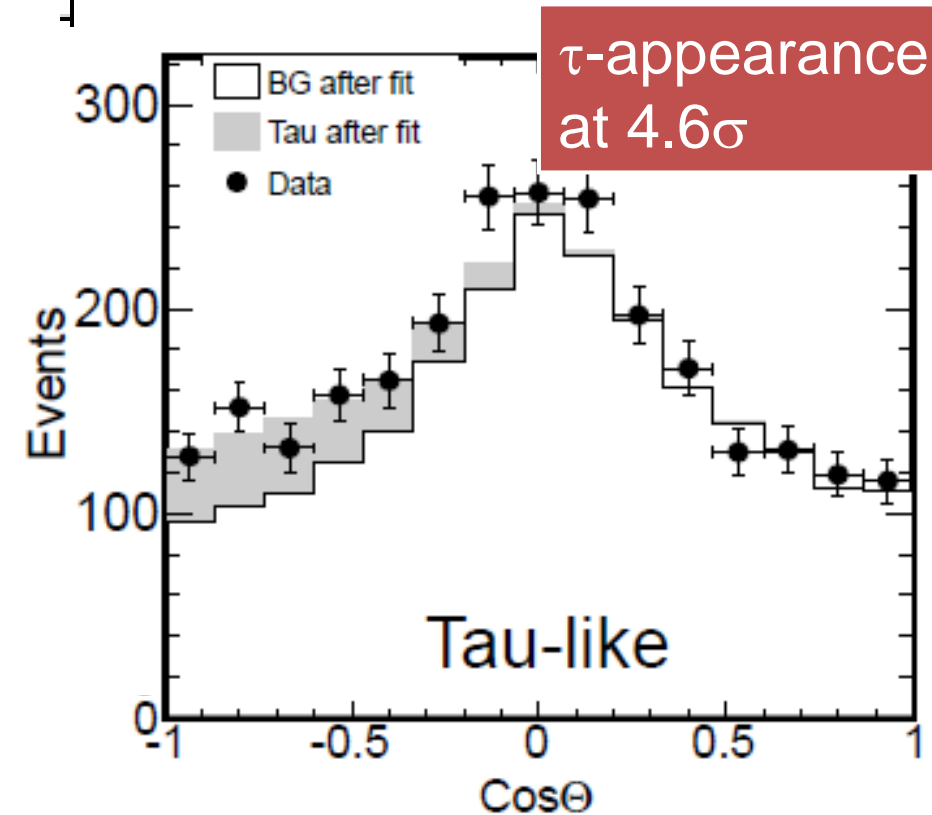


Super-K, PRL 110, 181802 (2013)



Super-K, arXiv:1711.09436

“Measurement of the ν_τ cross section”



(Also consistent with OPERA. IceCube also measured σ_{ν_τ} .)

Summary

- In 1998, neutrino oscillations were discovered by atmospheric neutrino experiments.
- After the discovery, atmospheric neutrino experiments have been studying oscillations, and contributed substantially to establish the $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations generated by neutrino masses and mixing angles.