History of Neutrinos,
Paris, Sep. 6, 2018

Atmospheric Neutrinos: the anomaly becomes the discovery

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Outline

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

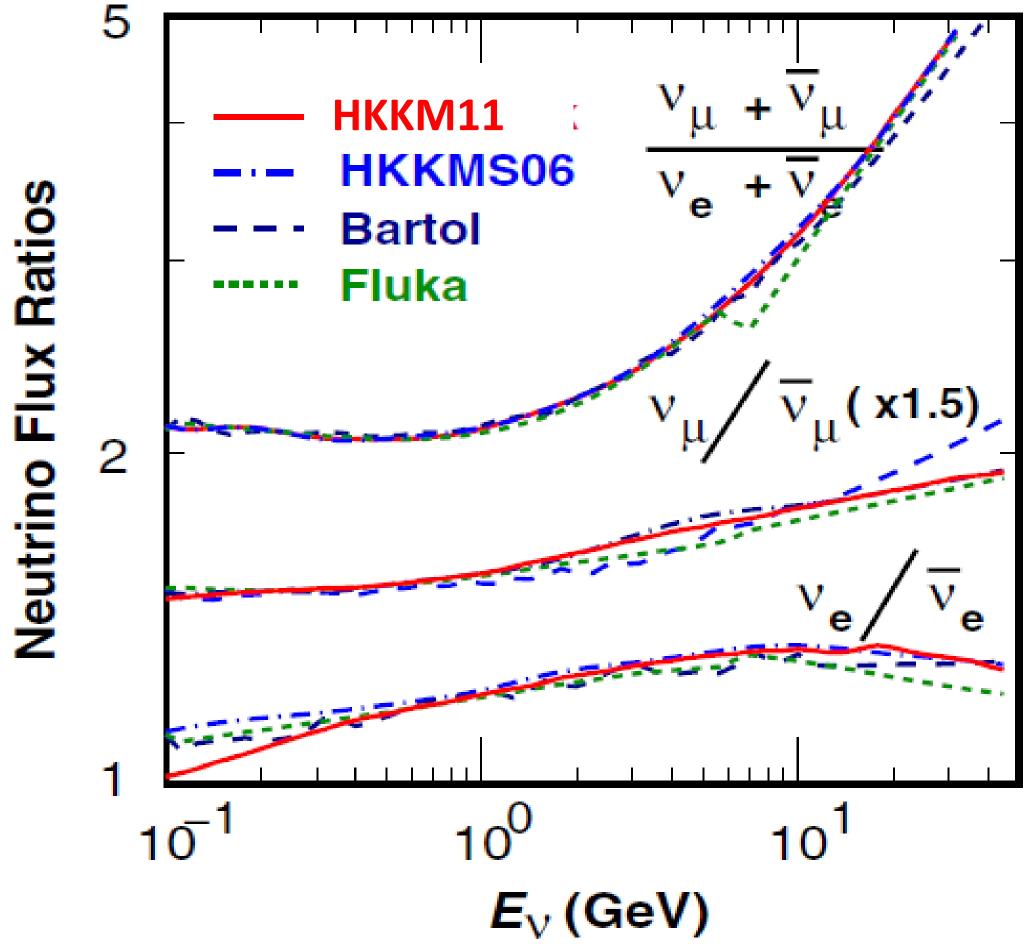
I will discuss only $\nu_\mu \rightarrow \nu_\tau$ oscillations and related studies.

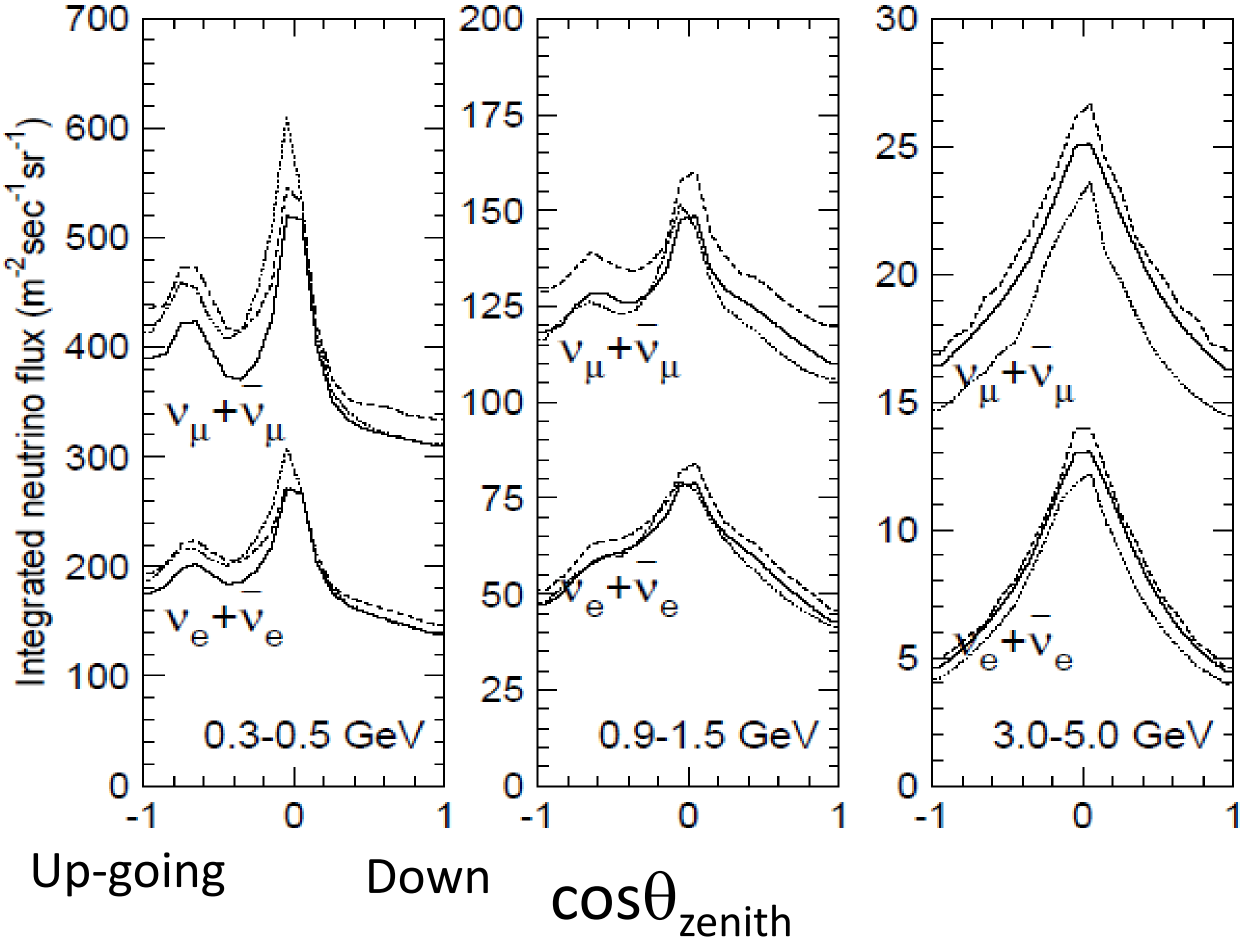
Introduction

Key features of the atmospheric neutrino beam

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

@Kamioka (Japan)

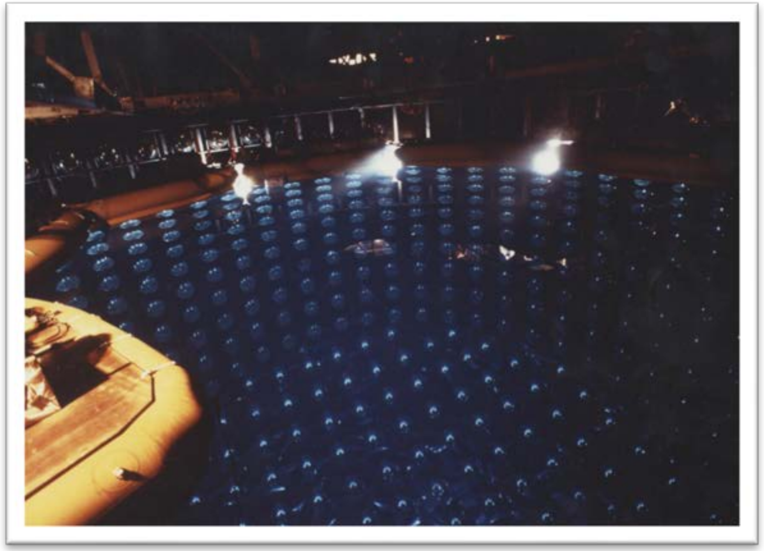




ν_μ/ν_e ratio is calculated to an accuracy of about 2% below ～5GeV.

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

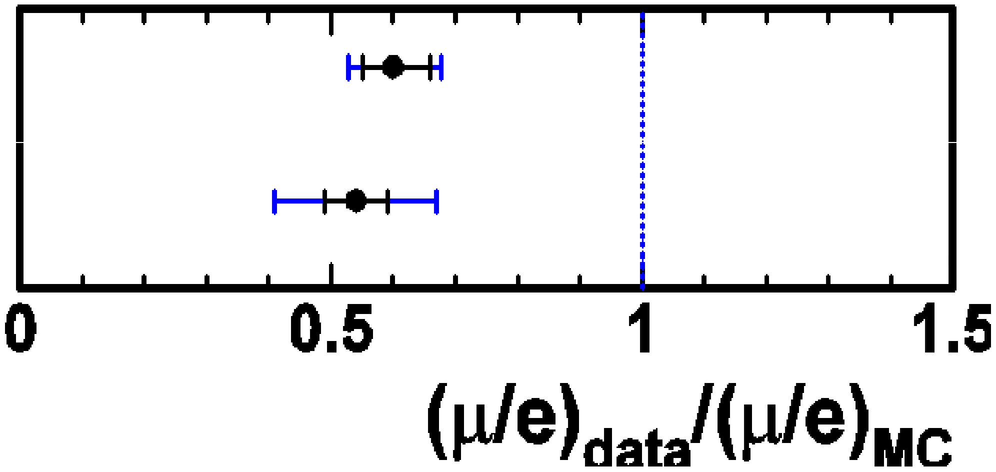
Atmospheric ν_μ / ν_e flux ratio (1980's to 90's)

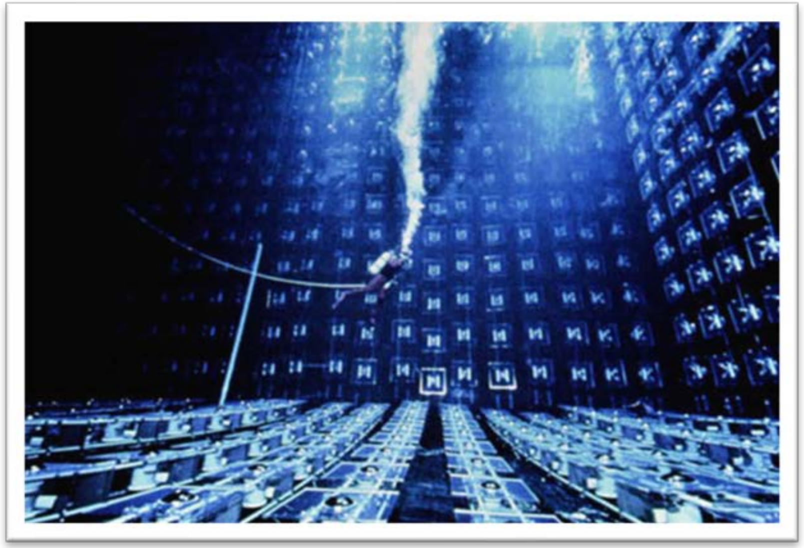


K. Hirata et al, Phys. Lett. B 205 (1988) 416-420.
K. S. Hirata, et al., Phys. Lett. B 280 (1992) 146-152.
Y. Fukuda, et al., Phys. Lett. B 335 (1994) 237-245.
D. Casper, et al., Phys. Rev. Lett. 66 (1991) 2561-2564.
R. Becker-Szendy, et al., Phys. Rev. D 46 (1992) 3720-3724.

Kamiokande (1988, 92, 94)

IMB (1991, 92)

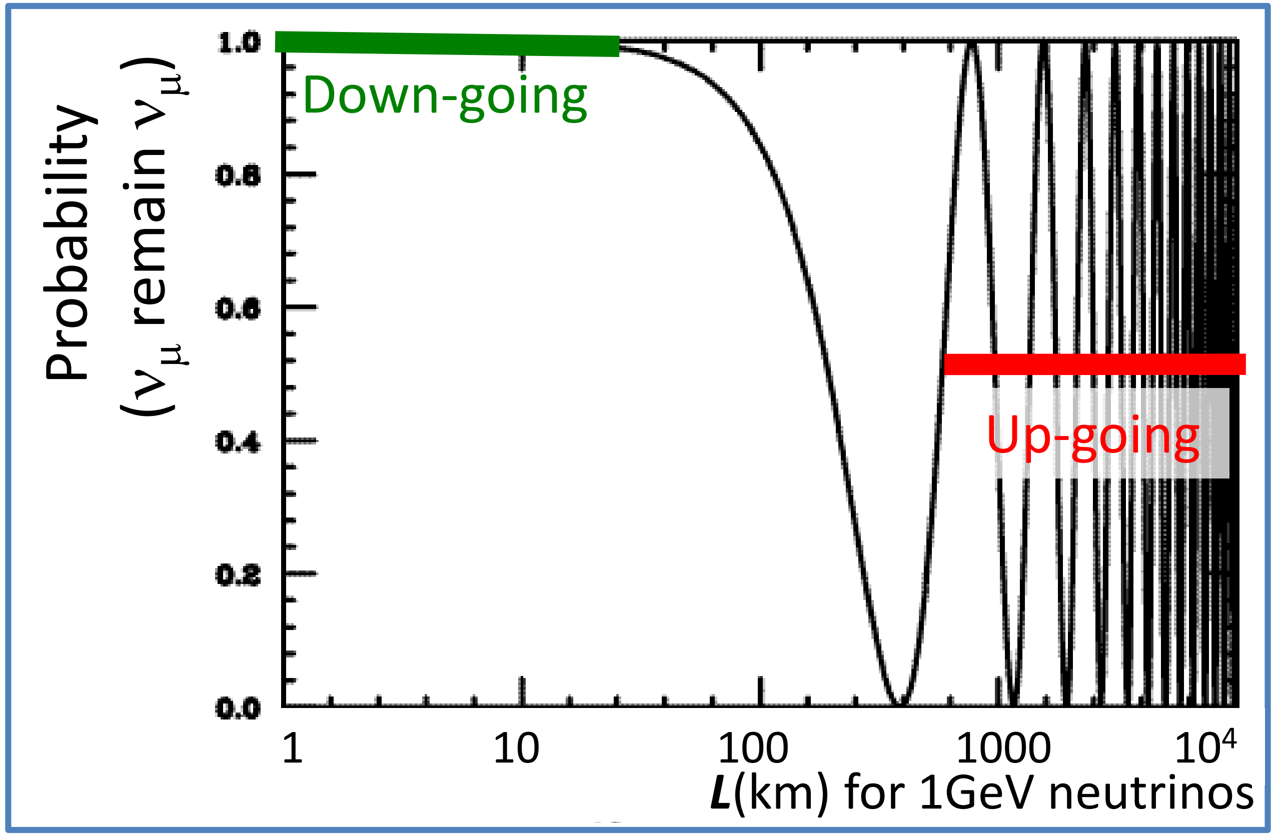


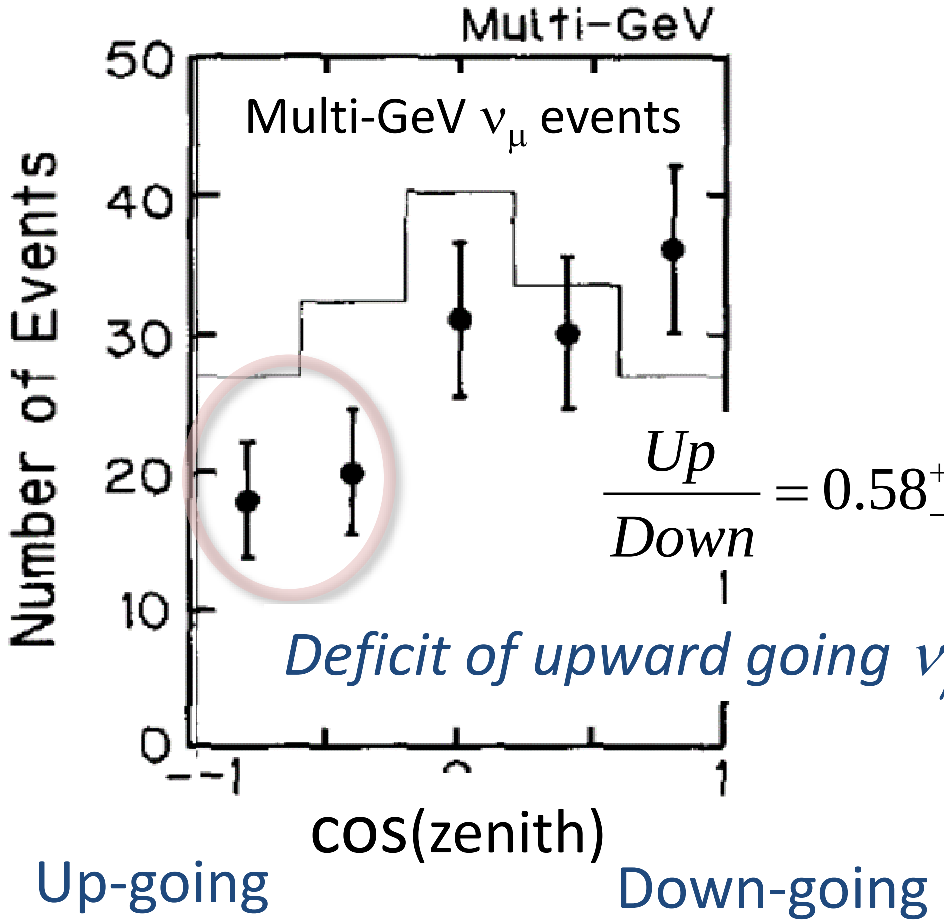


➔ Paolo Lipari and John Learned

Zenith angle distribution from Kamiokande (1994)

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





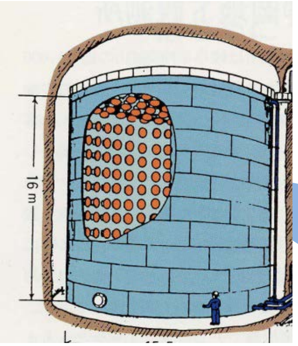
$$\frac{Up}{Down} = 0.58^{+0.13}_{-0.11} \ (2.9\sigma)$$

Deficit of upward going ν_μ events?

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

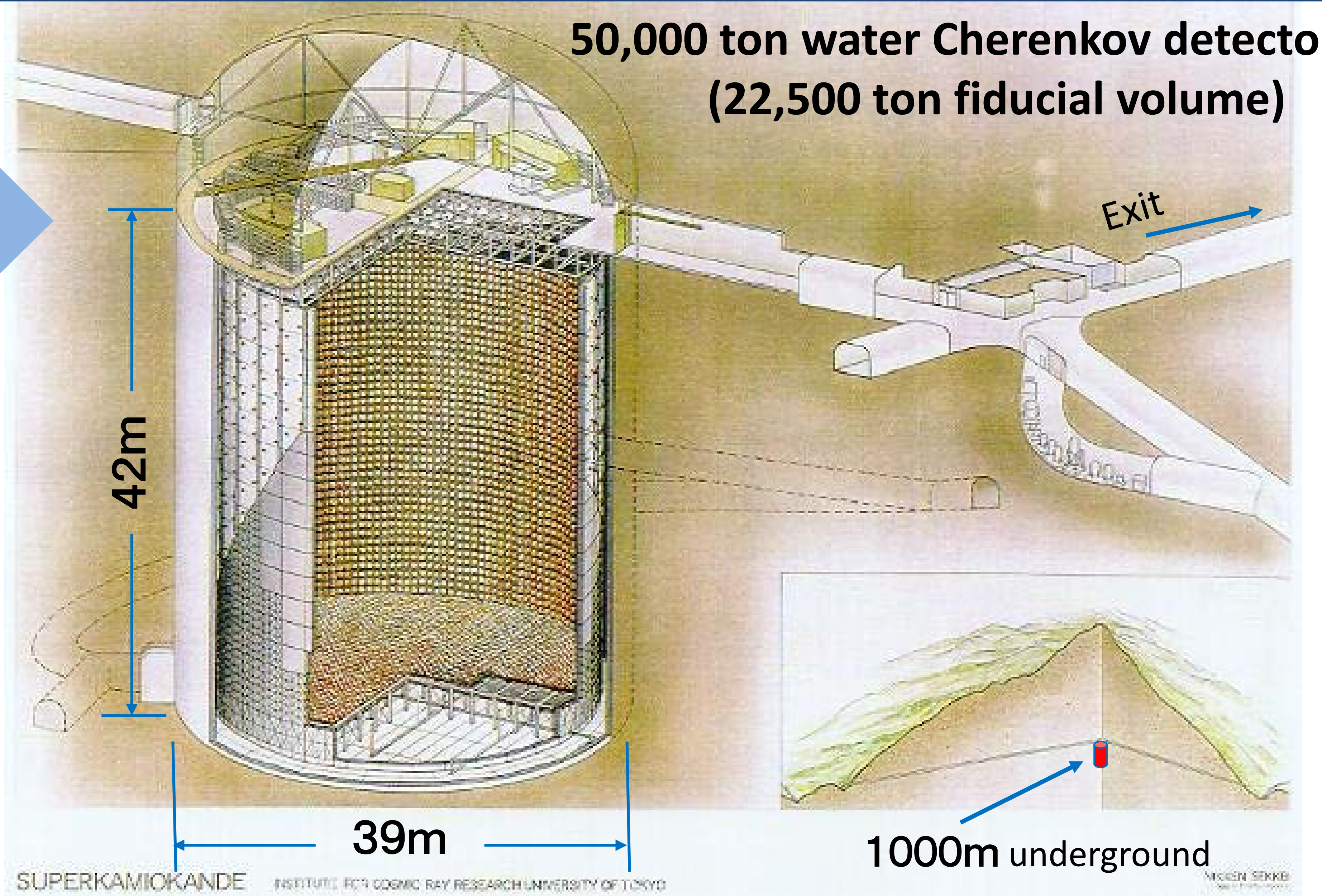
Super-Kamiokande

Super-Kamiokande detector



~20 times larger mass

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



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

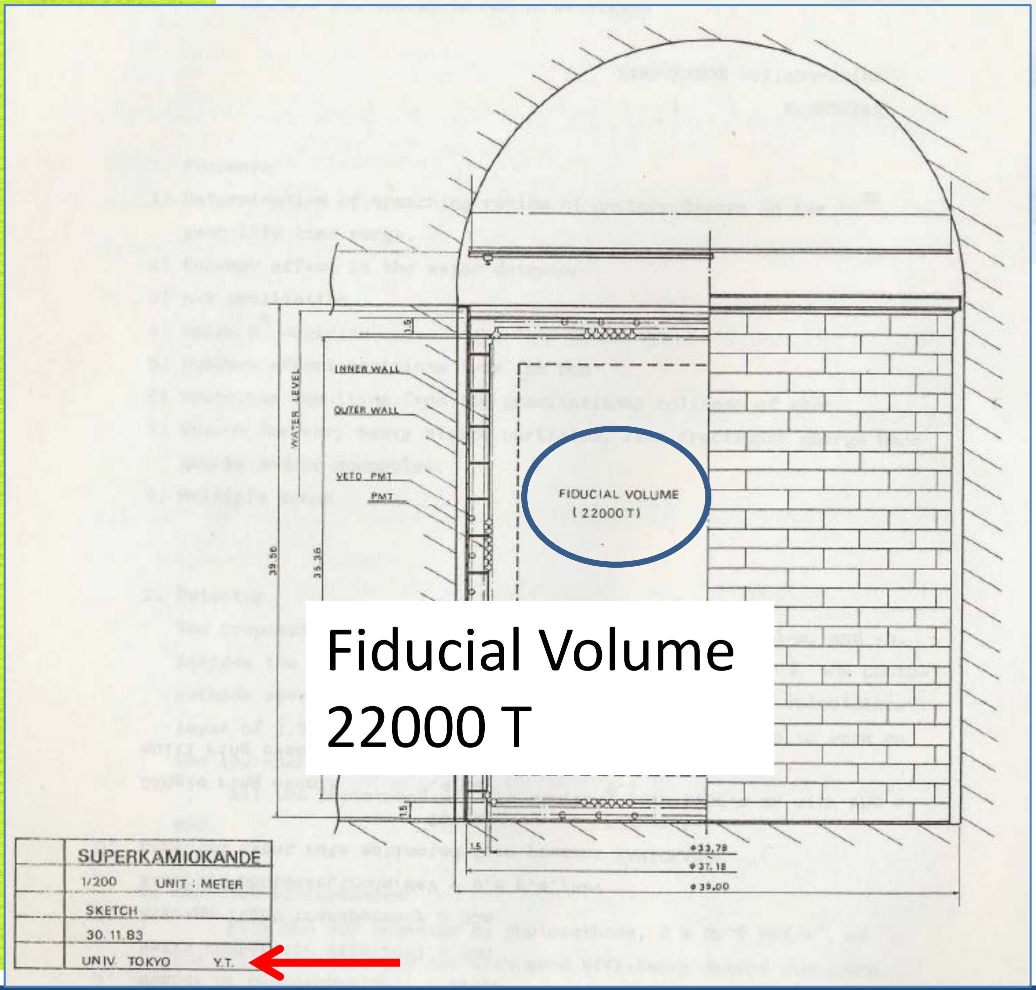
32 Kton Water Cerenkov Detector(JACK)

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.

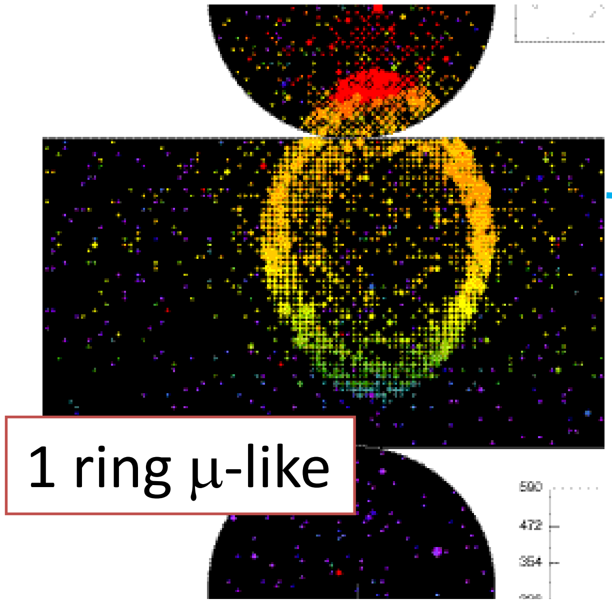
Beginning of the Super-Kamiokande collaboration between Japan and USA (1992)

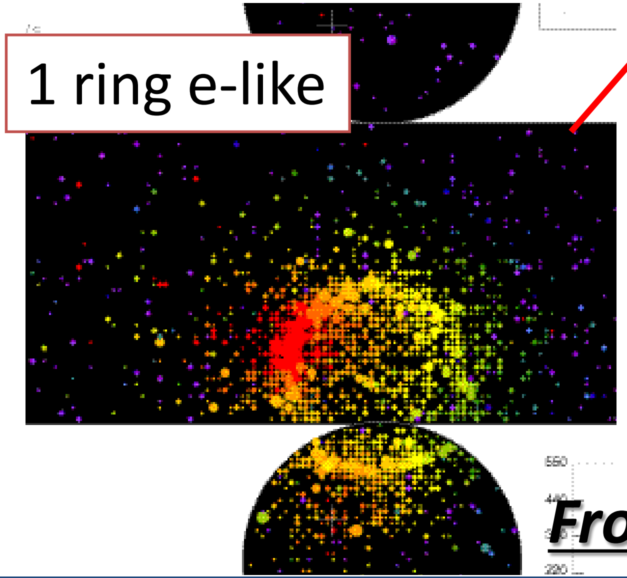
@ Institute for Cosmic Ray Research, 1992

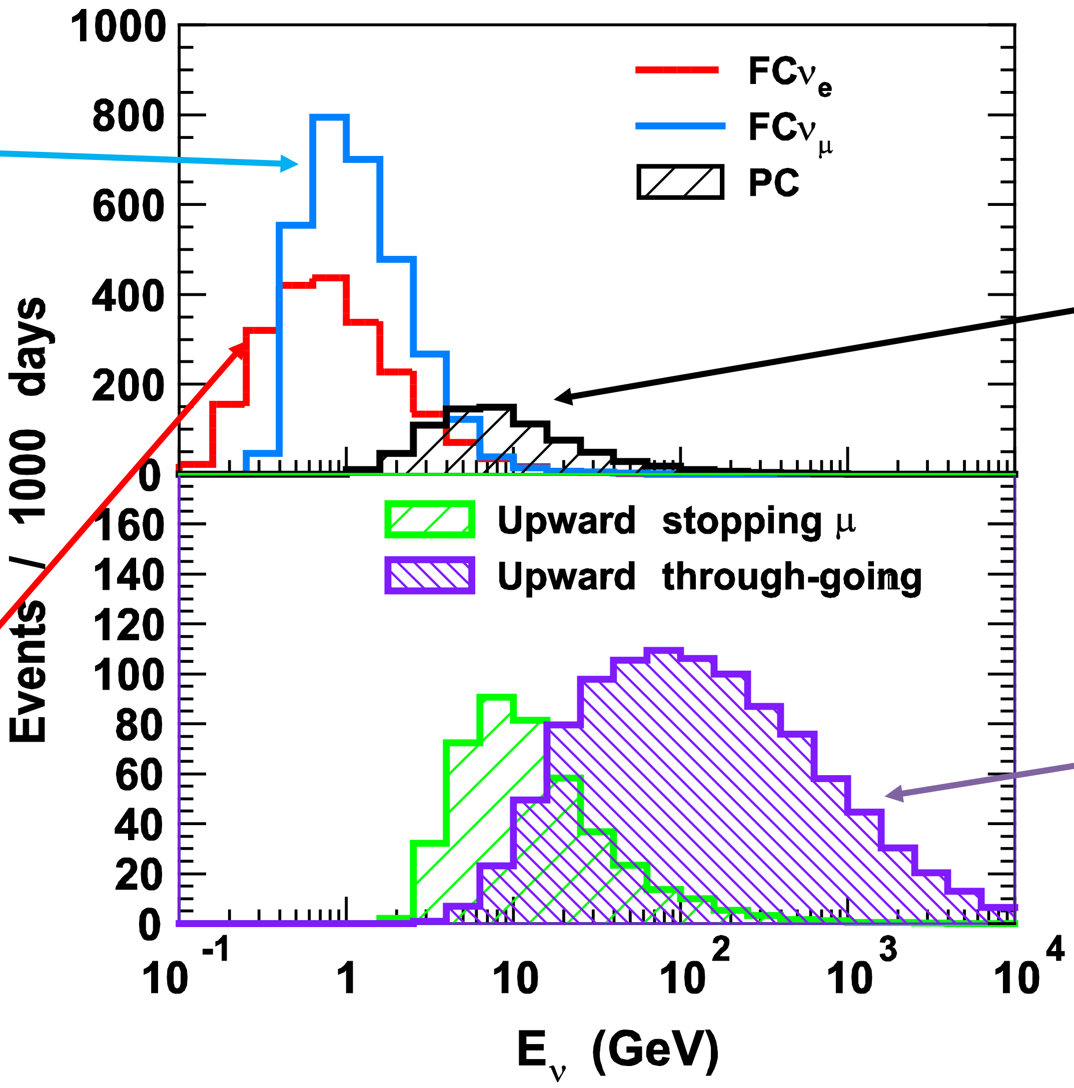
Starting the Super-Kamiokande experiment

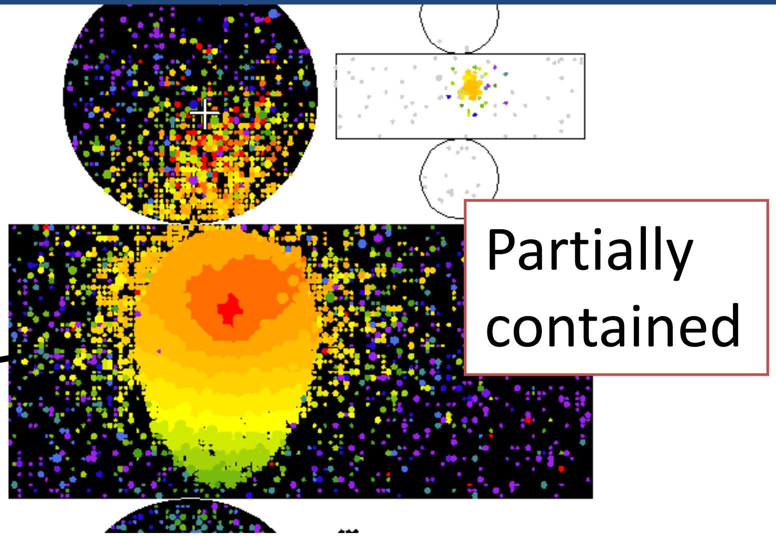
The experiment began at 0:00 on April 1, 1996

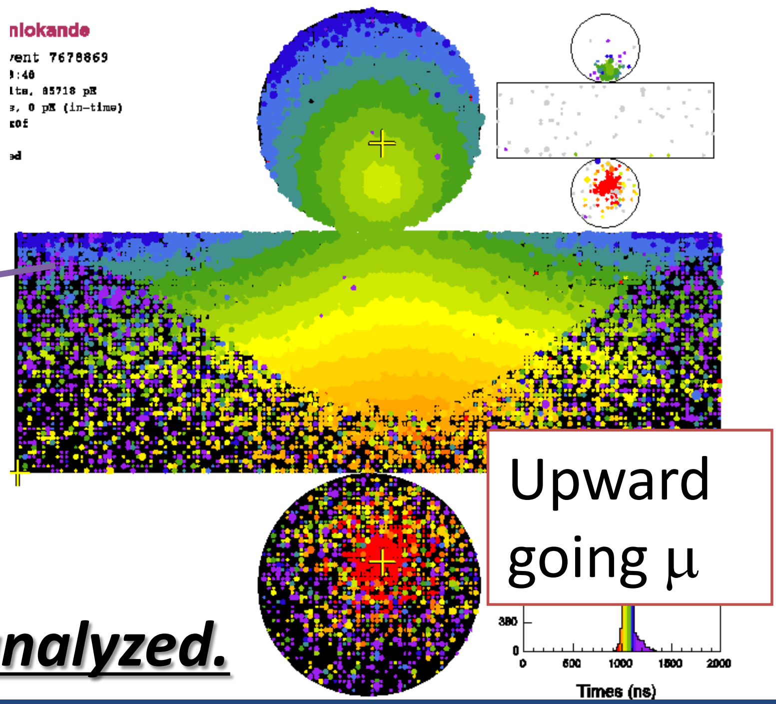
Event type and neutrino energy









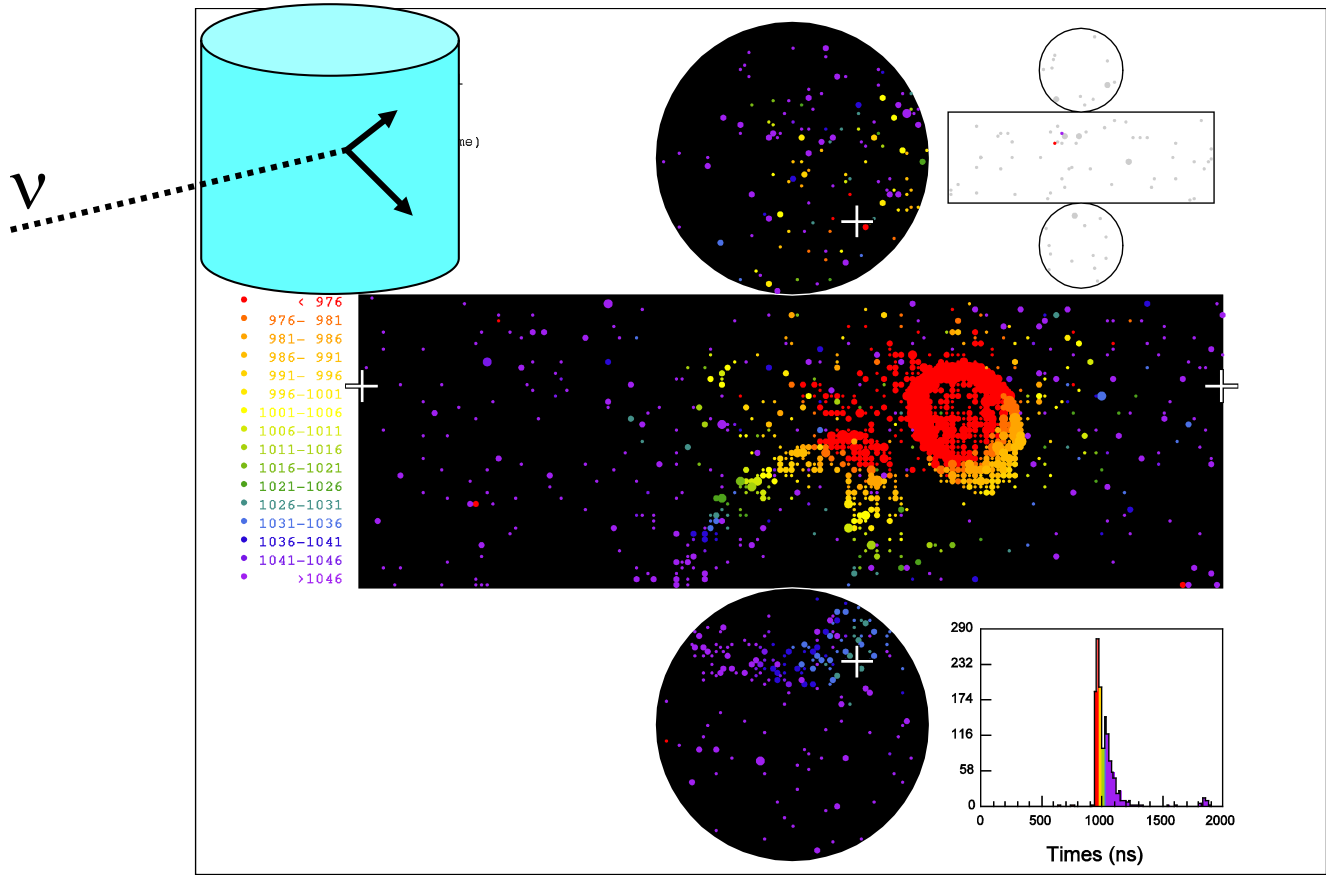


From the beginning, all these events were analyzed.

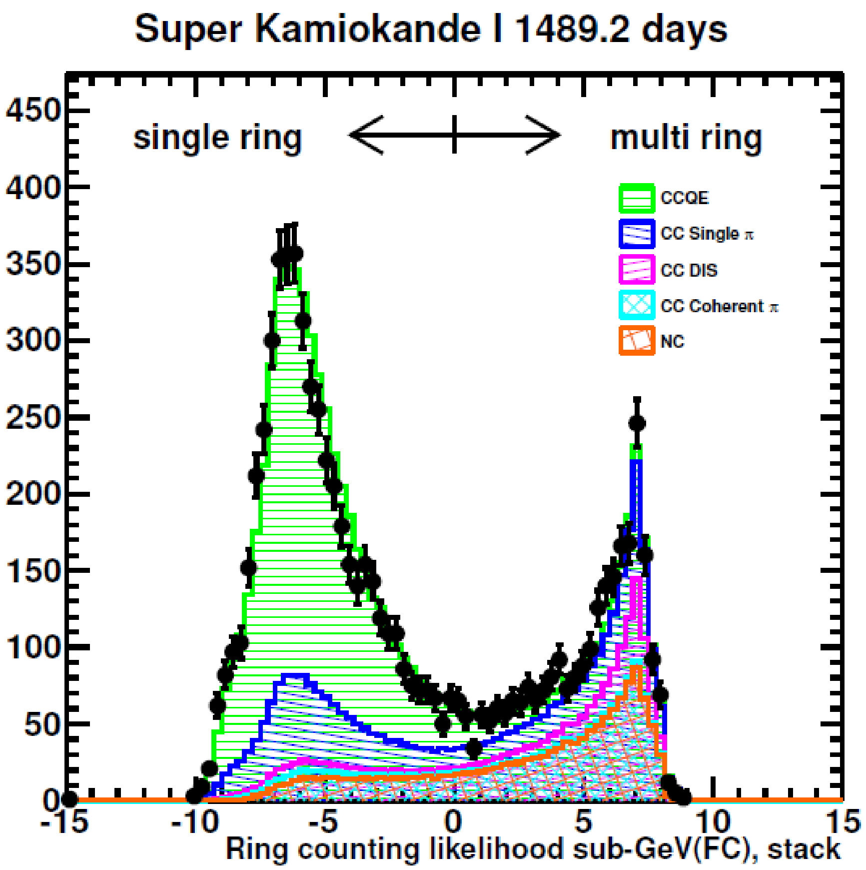
Fully automated analysis

- One of the limitation 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

Neutrino '98 (Takayama, June 4-9, 1998)

June 5

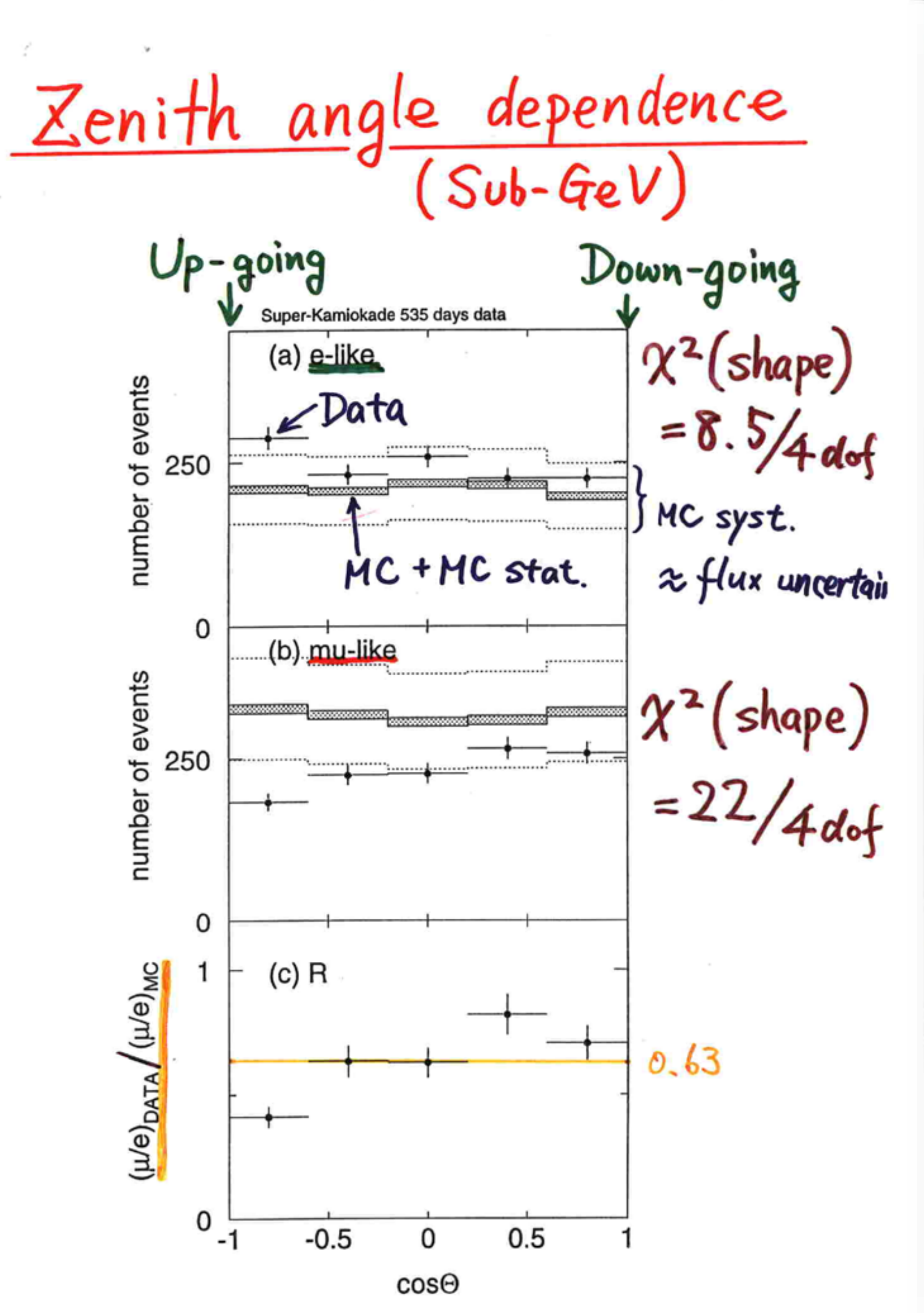
* Session 6: Atmospheric neutrinos I

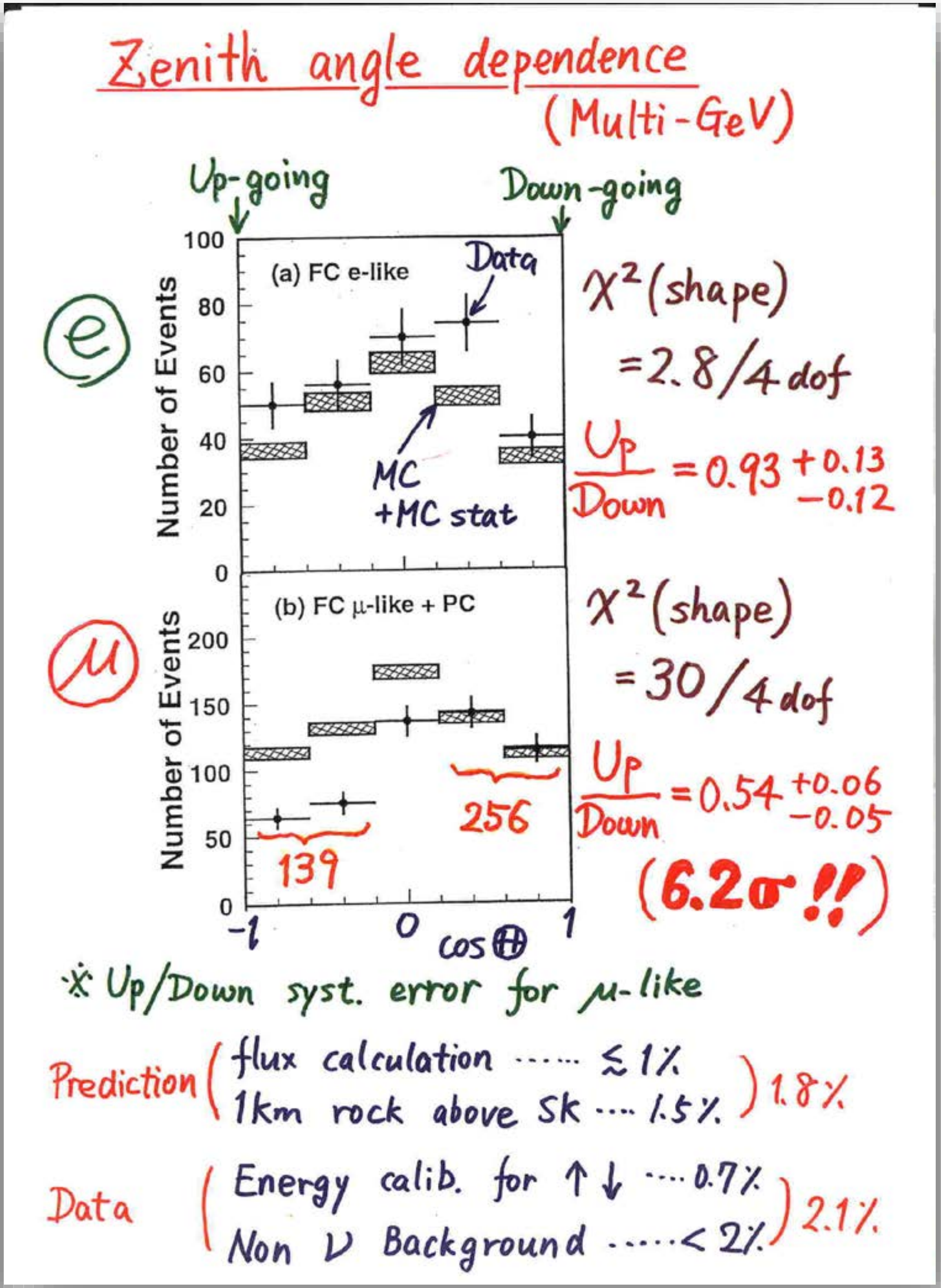
- Contained events and Soudan-2
  - E.Peterson(Minesota)
- Upward-going muons and MACRO
  - F.Ronga(Frascati)
- Results from Super-Kamiokande & Kamiokande
  - T.Kajita(ICRR)

* Session 7: Atmospheric neutrinos II

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

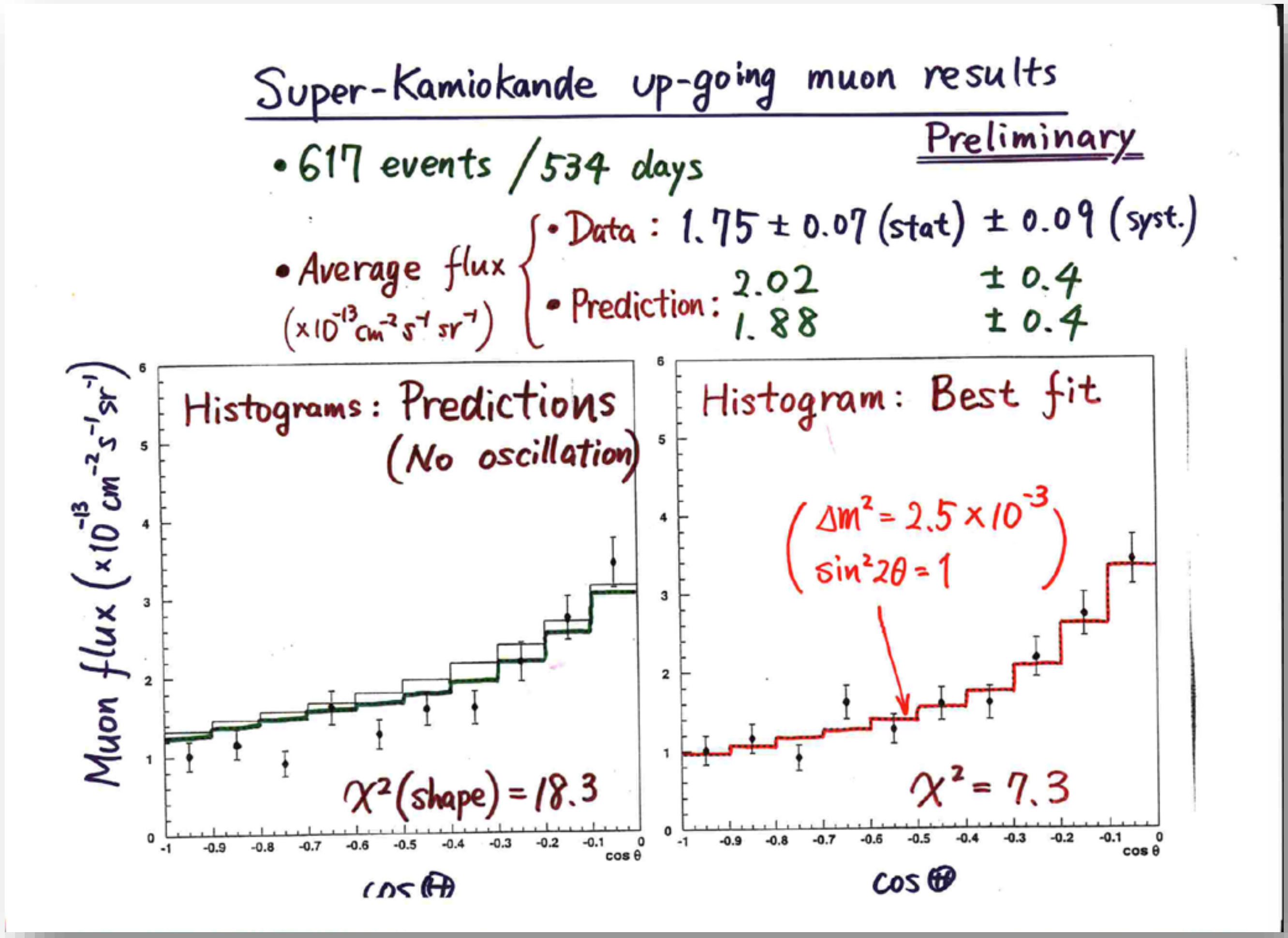
Super-K, Neutrino 98,
Super-K, PLB 433, 9-18 (1998)
Super-K, PLB 436, 33-41 (1998)

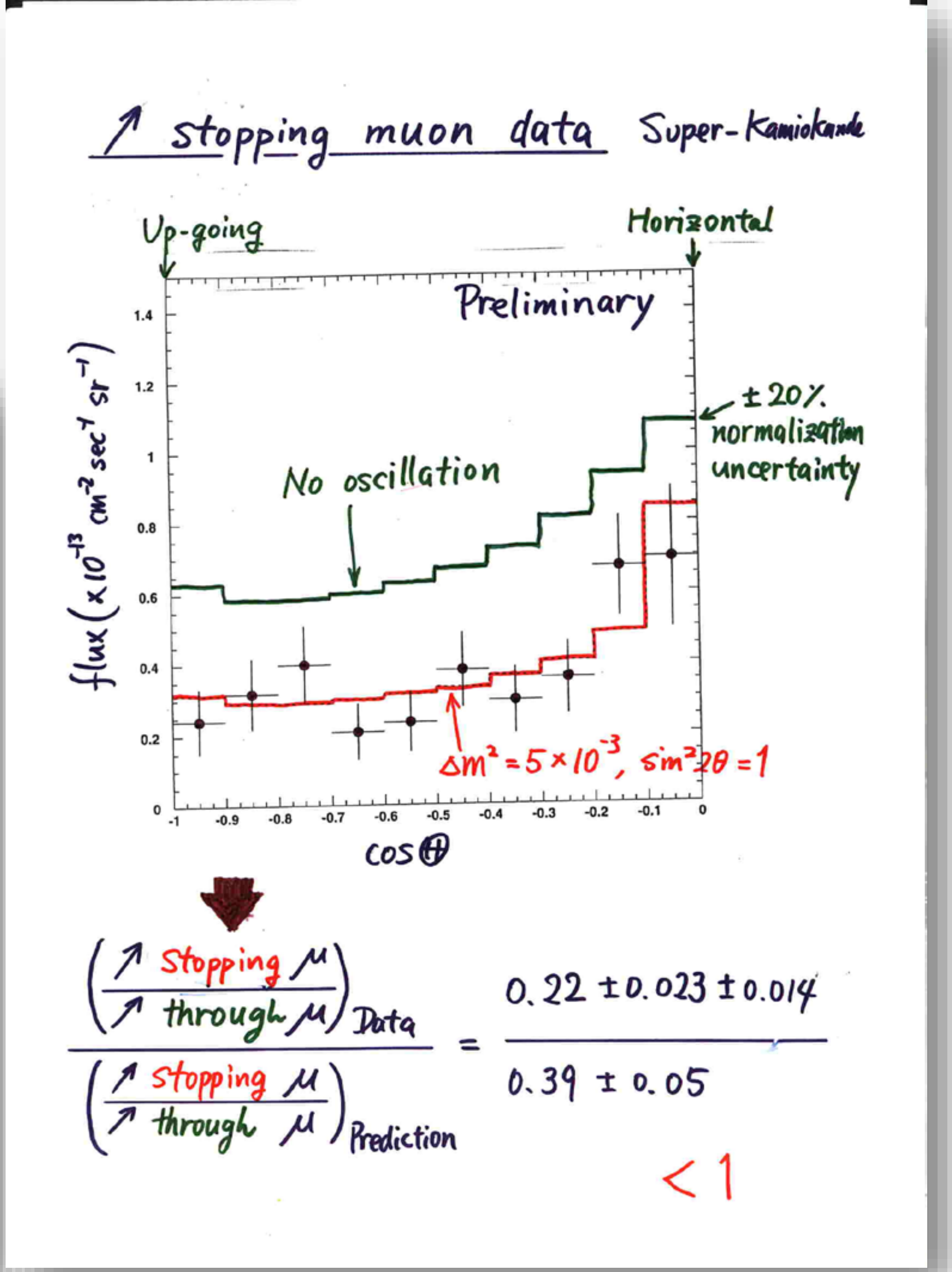




Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

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

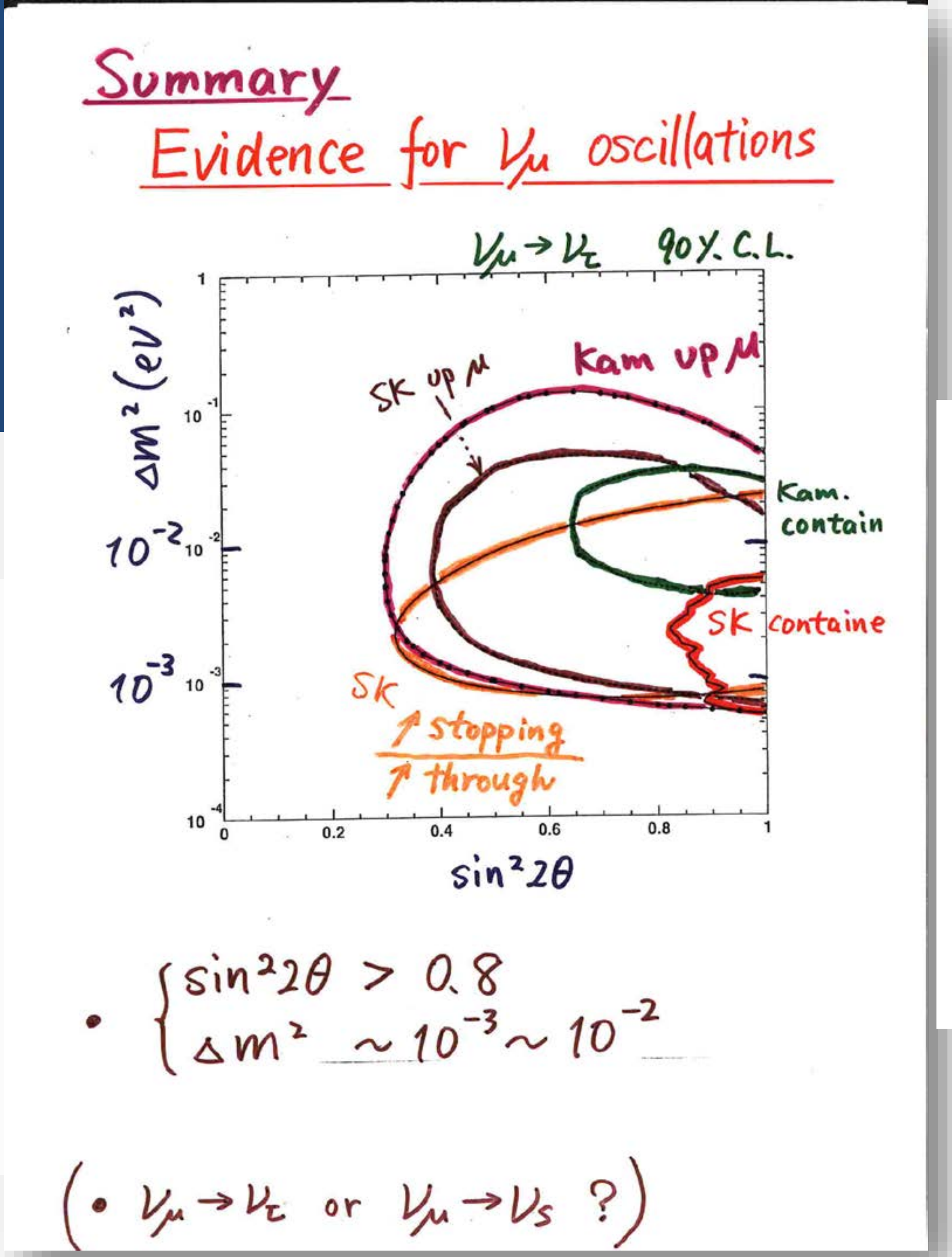


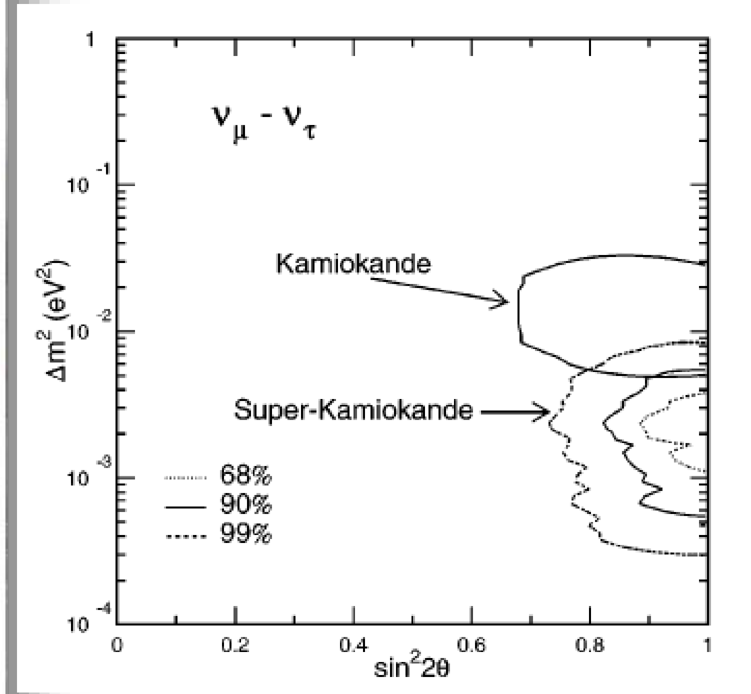


Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

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.



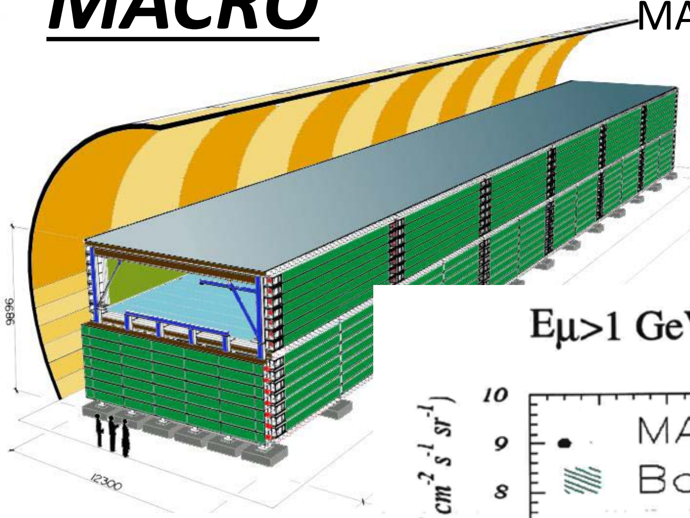


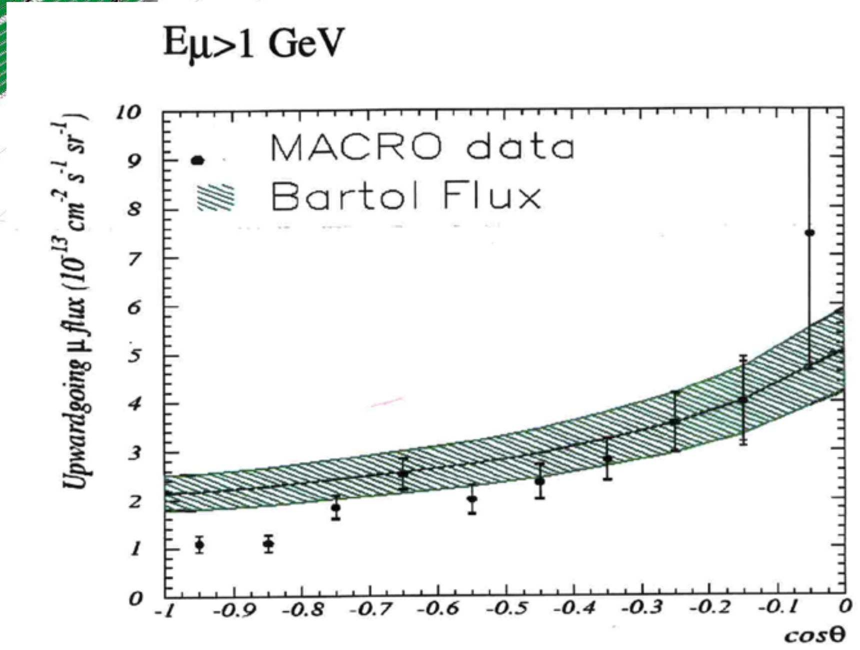
Published version (without upward-going muons)

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)

$$(\mu/e)_{data}/(\mu/e)_{MC} =$$

$$0.64 \pm 0.11(\text{stat.}) \pm 0.06(\text{syst.}).$$

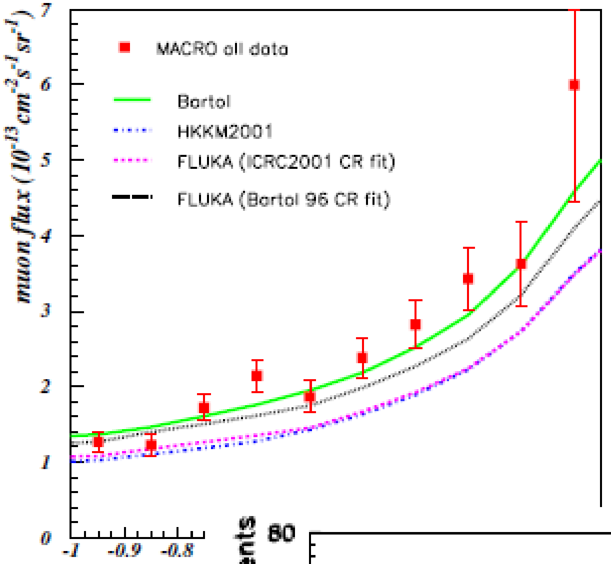
(the value is from the publication in 1999.)

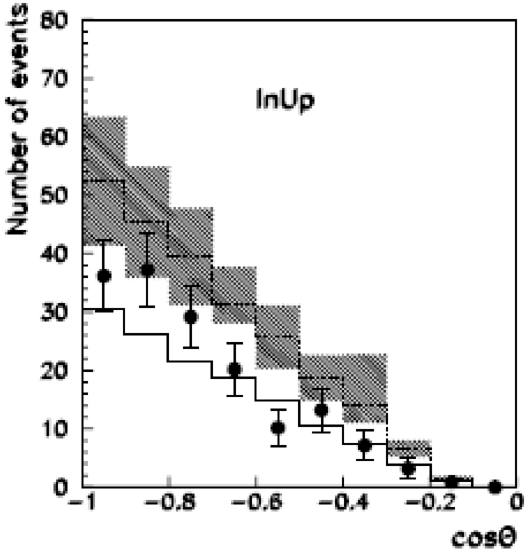
Data from these experiments were also consistent with neutrinos oscillations.

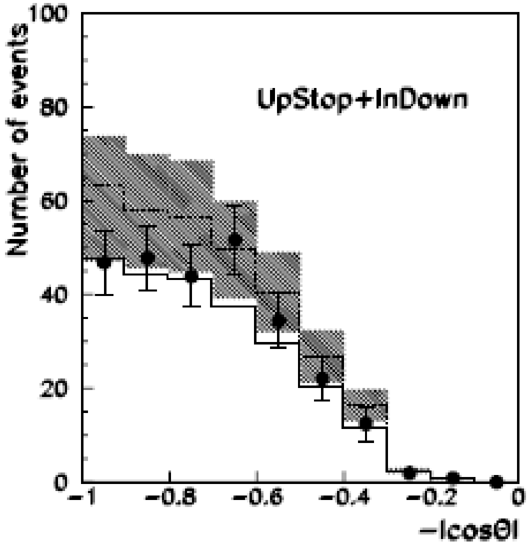
Updates from MACRO and Soudan-2

MACRO

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

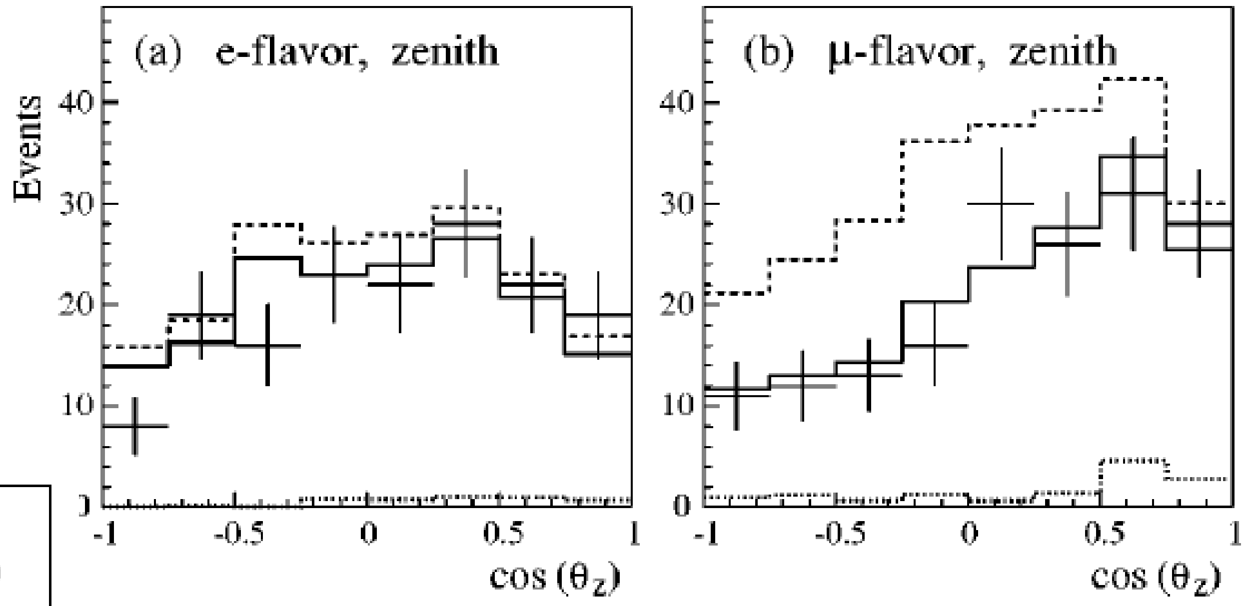






Soudan-2

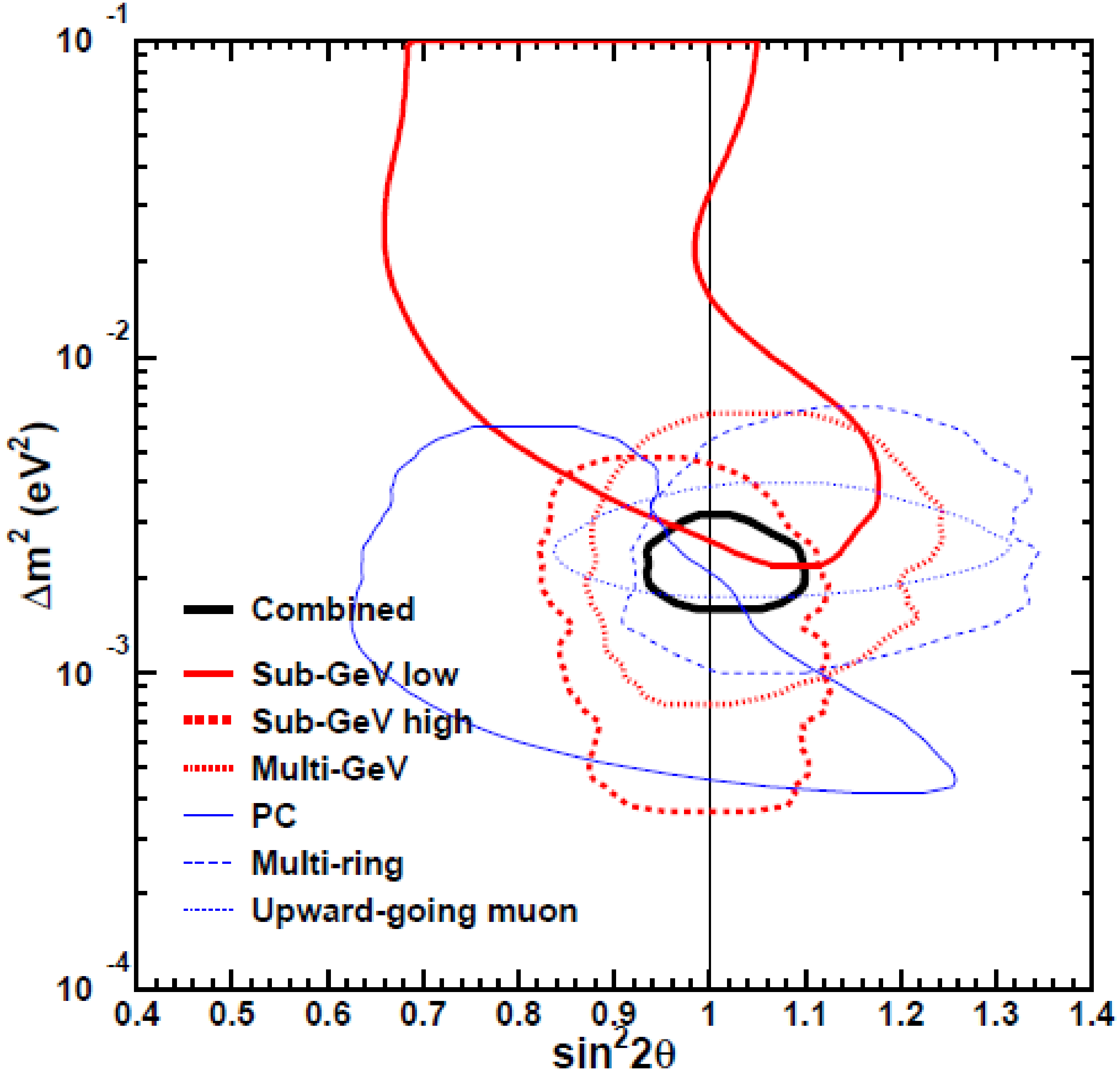
Soudan-2 PRD 68, 113004 (2003)

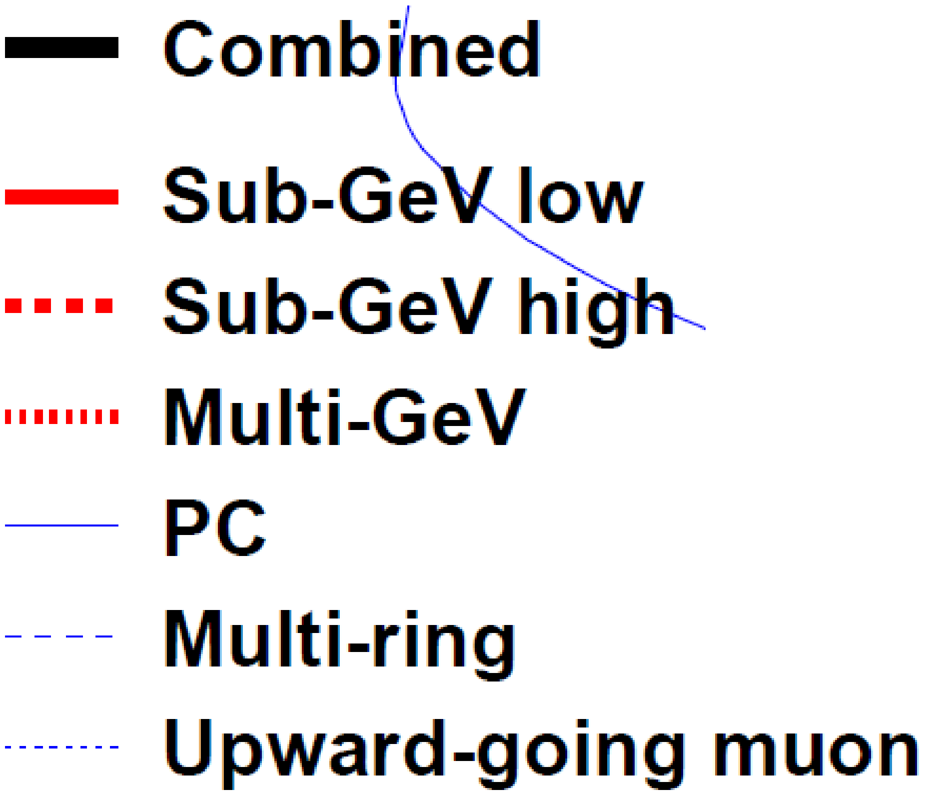


(See also more recent results from IceCube and ANTARES.)

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

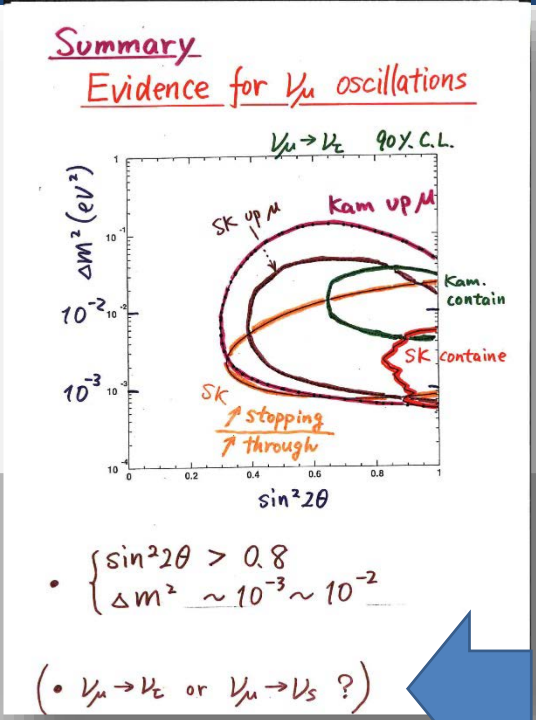
Super-K, PRD 71, 112005 (2005)





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

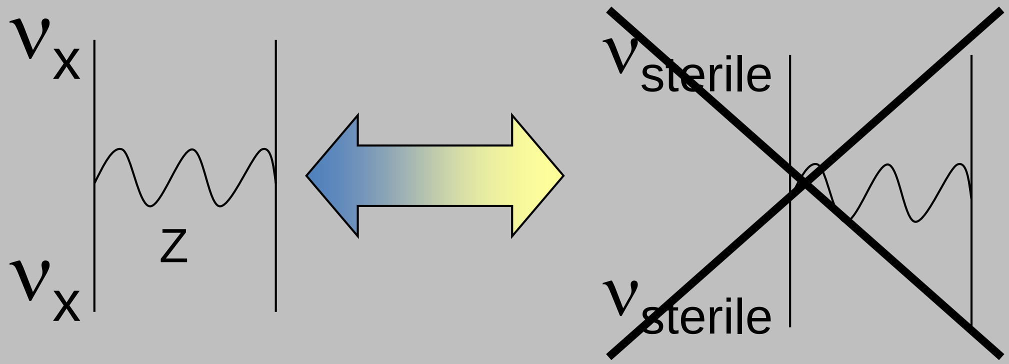
Oscillation to ν_τ or $\nu_{sterile}$?



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

$\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_{sterile}$

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



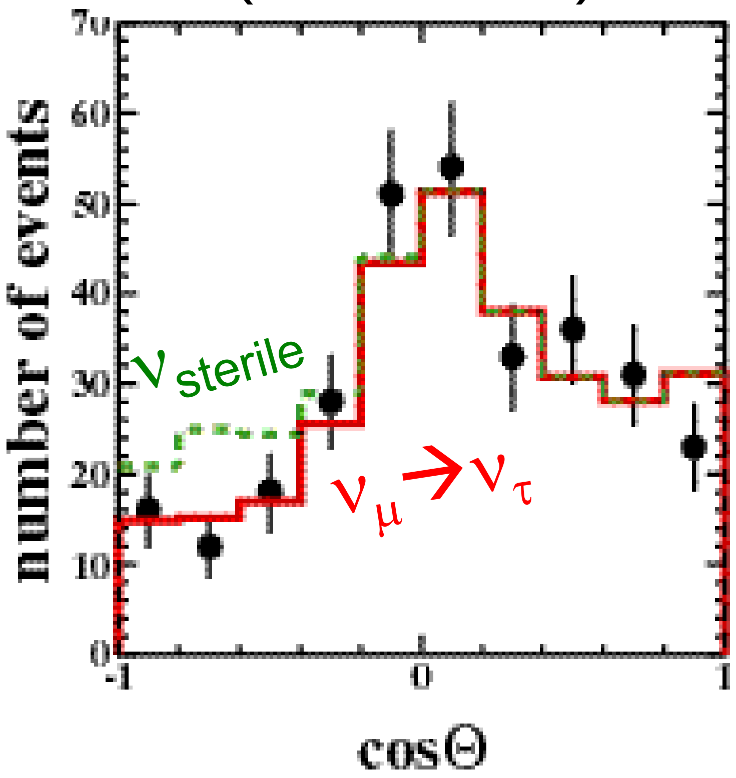
Interaction → Neutral current interaction

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

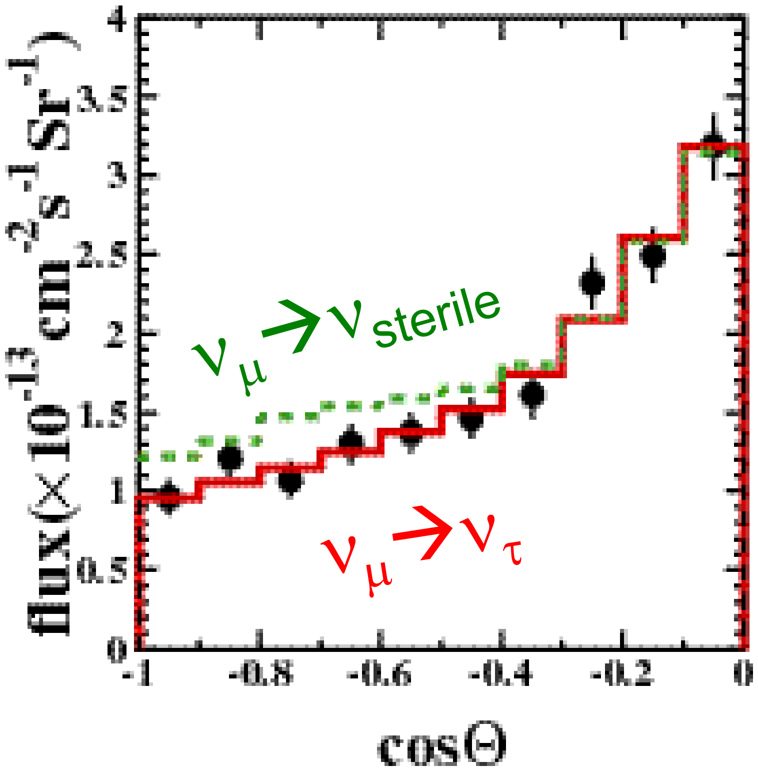
Super-K PRL85,3999 (2000)

Matter effect

High-E PC events
(Evis>5GeV)

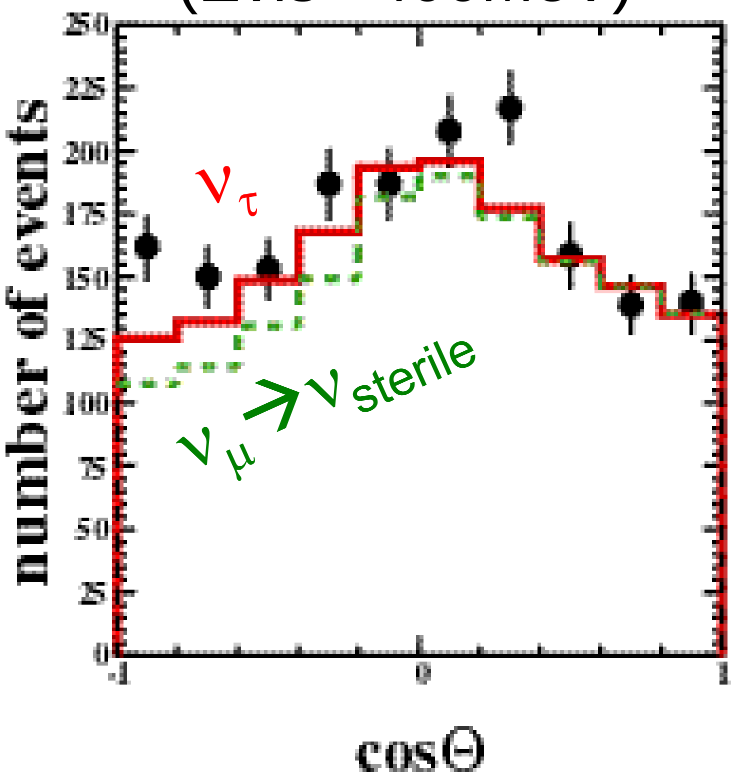


Up through muons



Neutral current

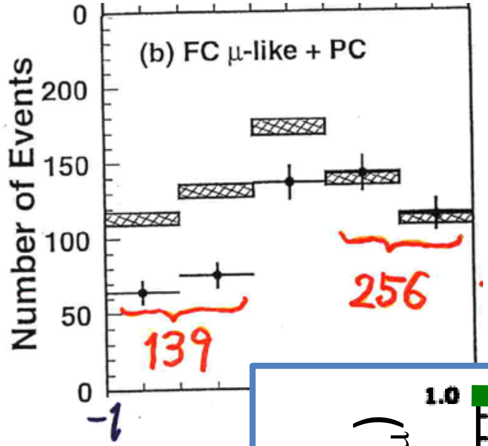
Multi-ring e-like
(Evis >400MeV)



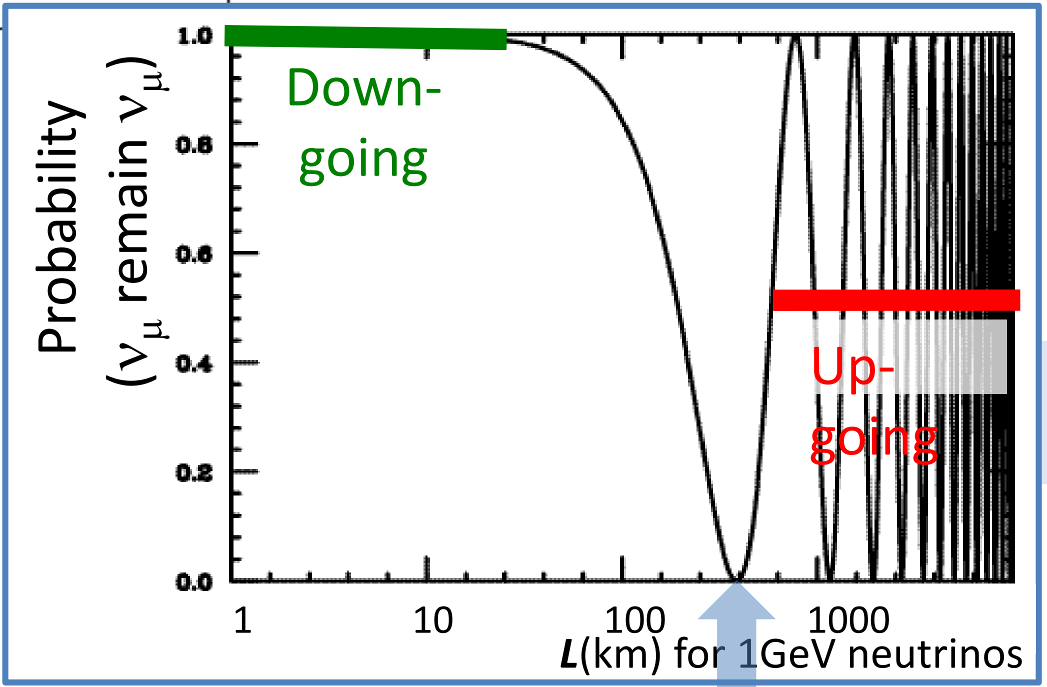
Pure $\nu_\mu \rightarrow \nu_\tau$ fit all of the data samples presented, without any inconsistency.

Really oscillations

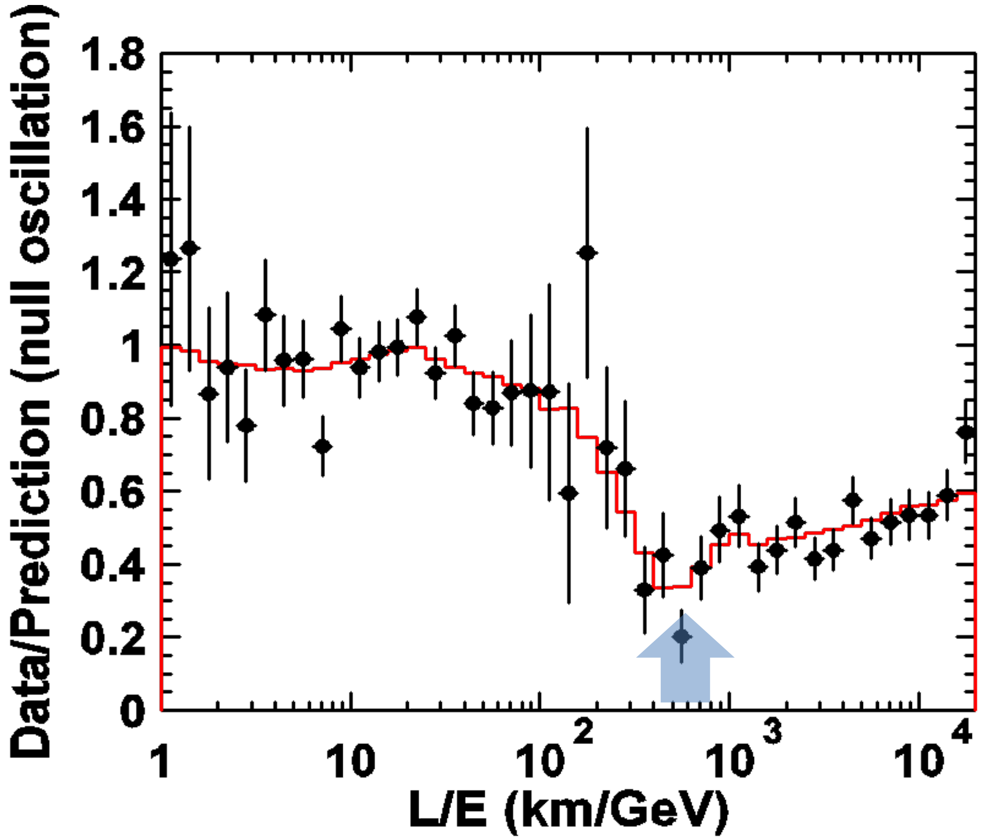
Super-K, PRL 93, 101801 (2004)



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".



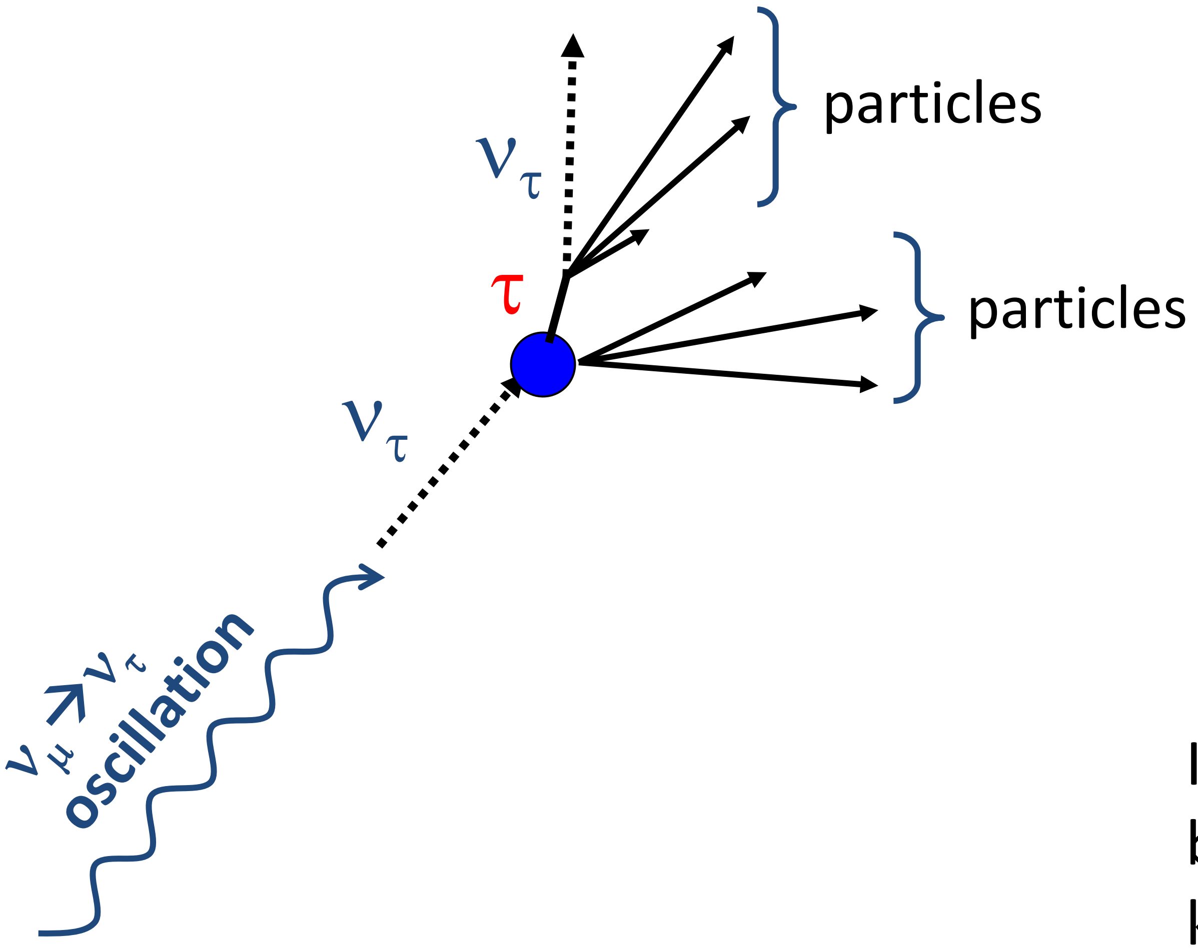
We wanted to observe this dip to confirm neutrino "oscillations".



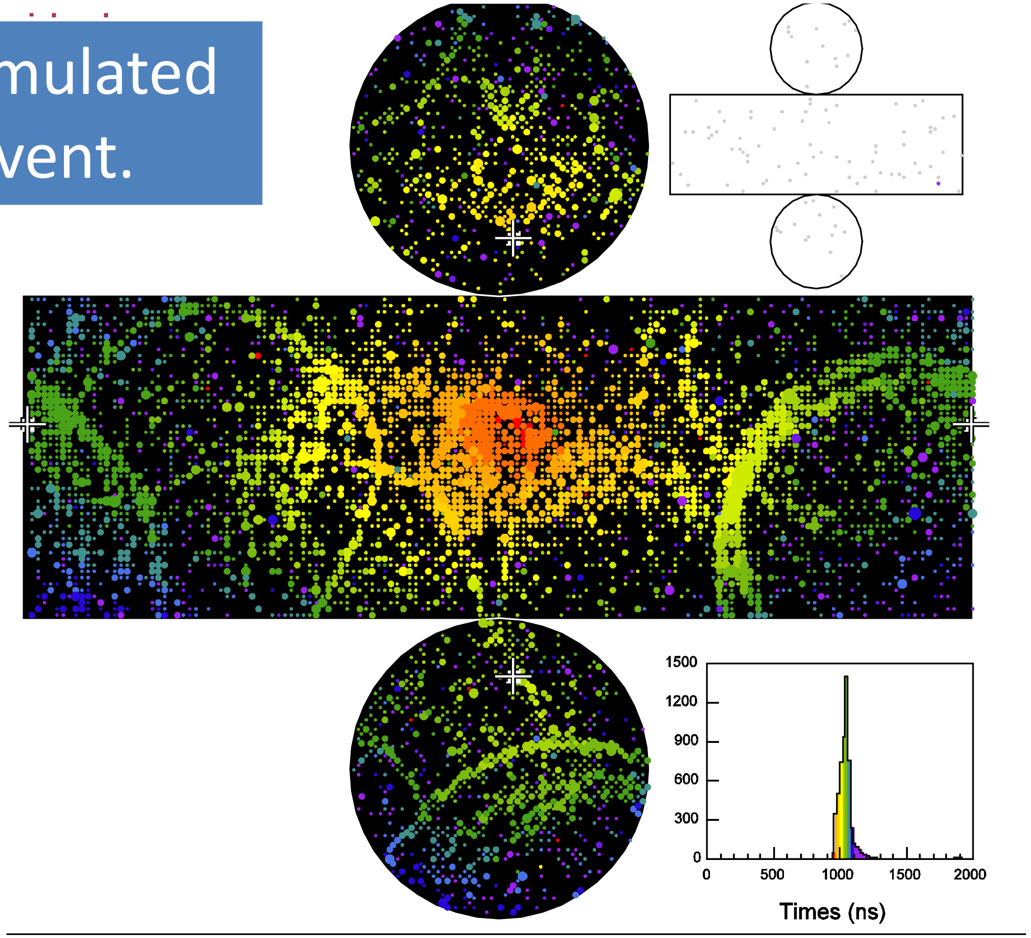
Paper title: Evidence for an Oscillatory Signature in Atmospheric Neutrino Oscillations

tau neutrino appearance?

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



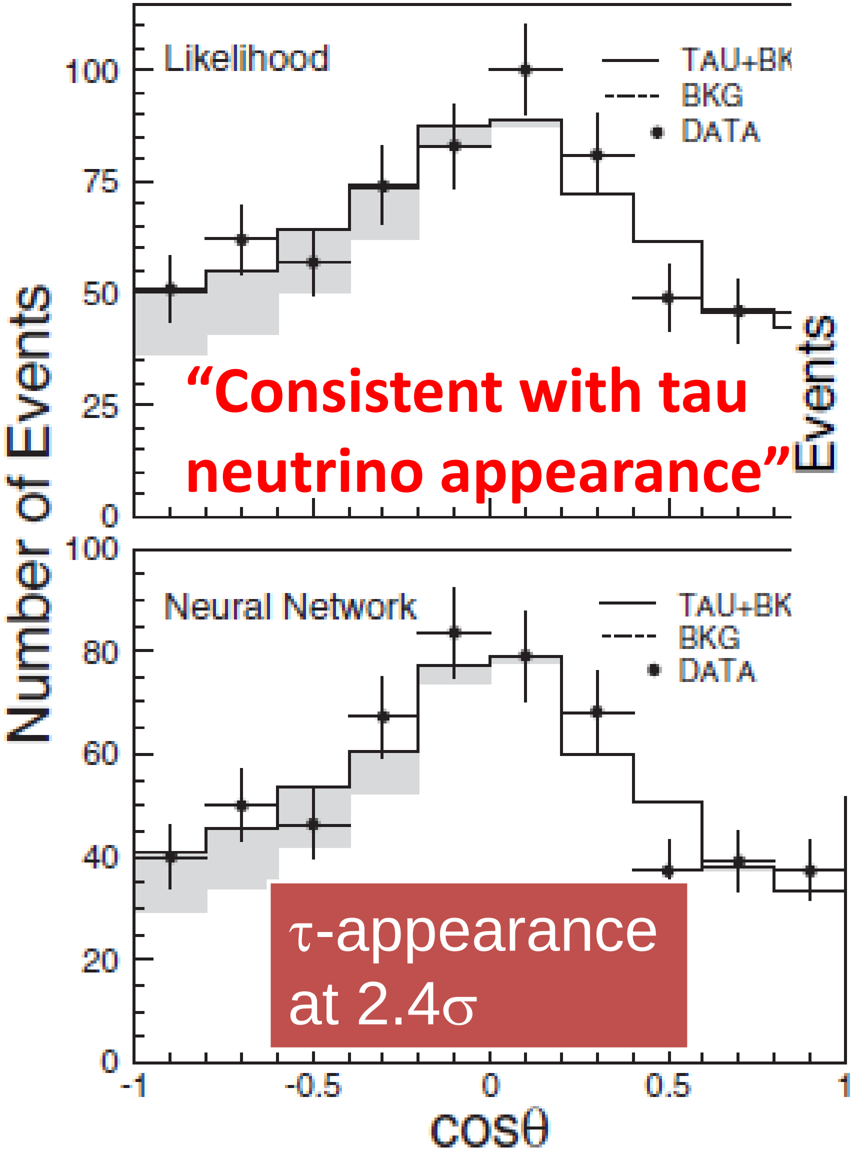
A simulated ν_τ event.



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

ν_τ appearance history in Super-K

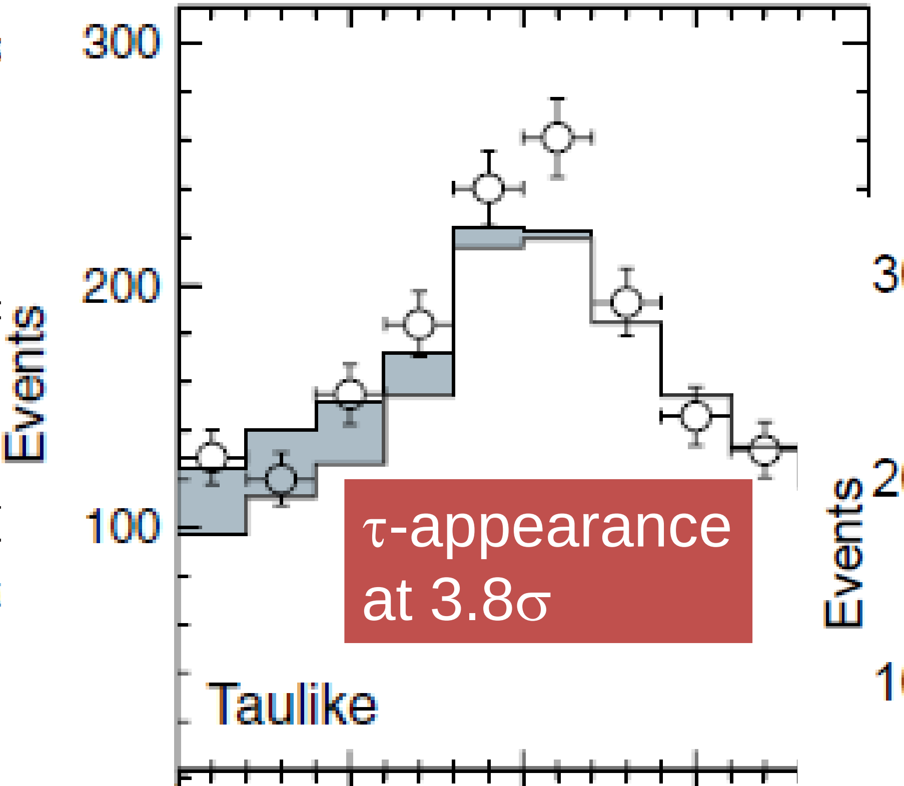
Super-K, PRL 97, 171801 (2006)



"Consistent with tau neutrino appearance"

τ-appearance at 2.4σ

Super-K, PRL 110, 181802 (2013)

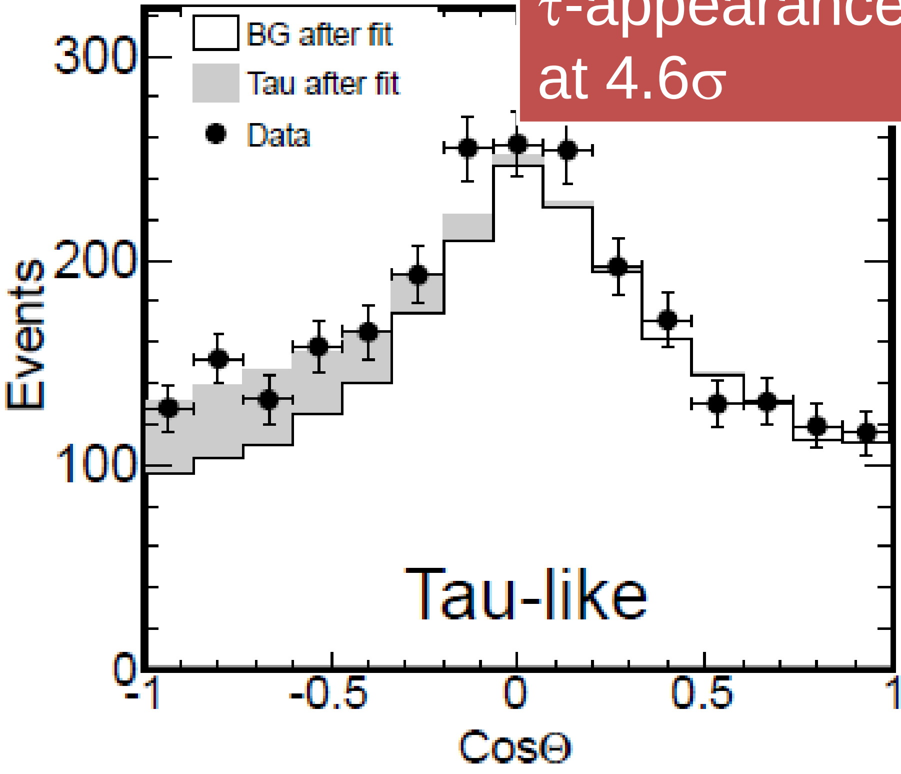


τ-appearance at 3.8σ

"Evidence for the appearance of atmospheric ν_τ"

Super-K,arXiv:1711.09436

"Measurement of the ν_τ cross section"



τ-appearance at 4.6σ

(Also consistent with OPERA. IceCube also measured $\sigma_{\nu\tau}$.)

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.