The International Neutrino Summer School

INSS2013

August 6-16, 2013, Beijing, China

Solar, Reactor and Atmospheric Neutrinos

Lecture 1

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In my original plan….

Lecture 1: Solar neutrino experiments.
Starting from the historical Homestake experiment and the solar neutrino problem, I will explain how the problem was solved.

Lecture 2: Reactor neutrino experiments
I will discuss the KamLAND experiment that played a very important role in the understanding of the solar oscillation paramters, and reactor theta_13 experiments (Daya-Bay, RENO and Double-CHOOZ). Also mentioned will be possible future reactor experiments.

Lecture 3: Atmospheric neutrino experiments.
Starting from the historical role of atmospheric neutrino expriments (i.e., neutrino Oscillation discovery), I will discuss the present and future atmospheric neutrino experiments.

However, it might be better to arrange my lectures based on physics (Δm_{ij}^2's and θ_{ij}'s)

Overall Outline

Lecture 1:

Δm_{23}^2 and θ_{23}:

Atmospheric neutrino experiments

Lecture 2:

Δm_{12}^2 and θ_{12}:

Solar neutrino and reactor experiments

Lecture 3:

θ_{13} and beyond:

Reactor and atmospheric neutrino exps

Outline - Lecture 1 -

- Introduction
- Production of atmospheric neutrinos
- History
- Neutrino oscillation studies with atmospheric neutrinos
- L/E analysis
- Oscillation to ν_τ or $\nu_{sterile}$?
- Tau neutrino appearance
- Summary of Lecture-1

In today's lecture, we essentially discuss 2-flavor vacuum oscillations:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L_\nu}{E_\nu}\right)$$

Introduction - motivation -

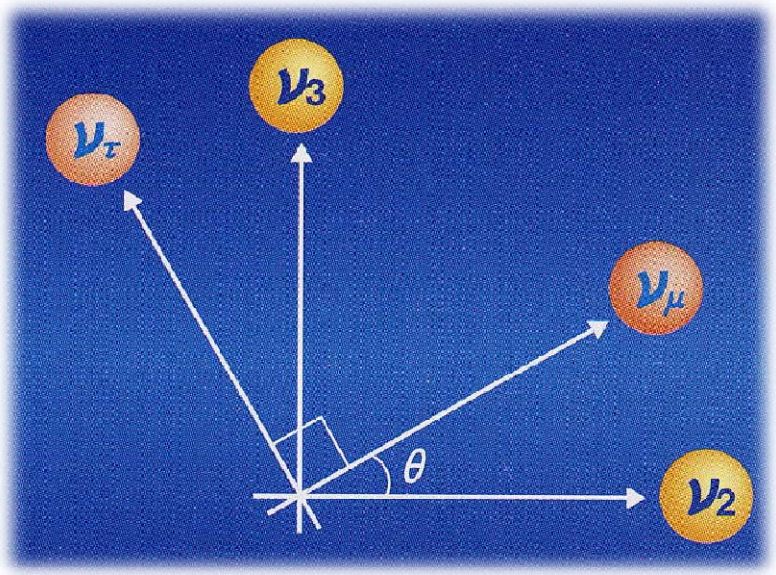
Reasons for neutrino experiments in 1 page:

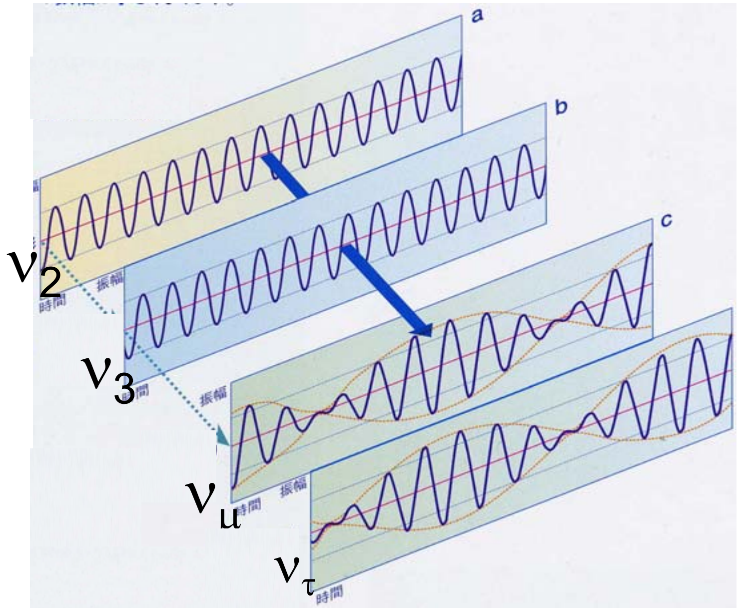
- Small but finite neutrino masses are believed to be related to the physics at the very high energy scale (Seesaw mechanism).
- At present, information from neutrino oscillation experiments gives one of a few experimental evidence for physics “beyond the standard model”.
- The observed large neutrino mixing angles might also suggest some hints for understanding physics at the very high energies.
- Furthermore, the physics of neutrino masses might be related to the baryon asymmetry of the Universe (Leptogenesis).

➔ other lectures

Neutrino masses and neutrino oscillations

Let us assume that there are only 2 types of neutrinos, and consider propagation of a neutrino (for example, initially ν_μ).





$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 \cdot L(km)}{E_\nu(GeV)}\right)$$

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

Used in most part of today's lecture.

$$P(\nu_\mu \to \nu_\tau) + P(\nu_\mu \to \nu_\mu) = 1$$

3 flavor neutrino oscillations

We know that there are 3 (active) neutrino flavors.

2 flavor → 3 flavor

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = U \cdot \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix} \quad \Longrightarrow \quad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

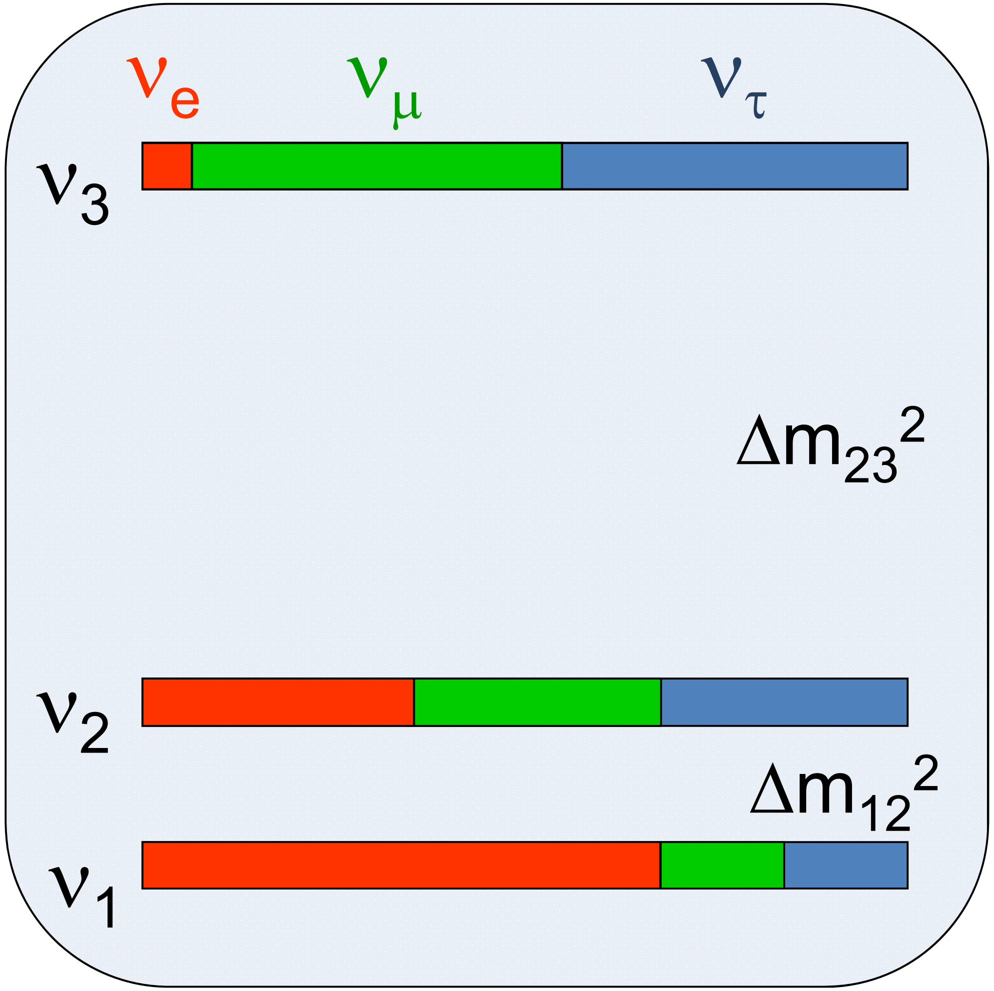
$$U = \begin{pmatrix} c_{23}, & s_{23} \\ -s_{23}, & c_{23} \end{pmatrix} \quad \Longrightarrow \quad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Δm^2, $\sin^2 2\theta$ → Δm_{12}^2, Δm_{23}^2 ($\sim\Delta m_{13}^2$), θ_{12}, θ_{23}, θ_{13}, δ_{CP}

Can we approximate with 2 flavor oscillations in some cases?

3 flavor neutrino oscillations

Neutrino flavor content for each mass state (normal mass hierarchy assumed)



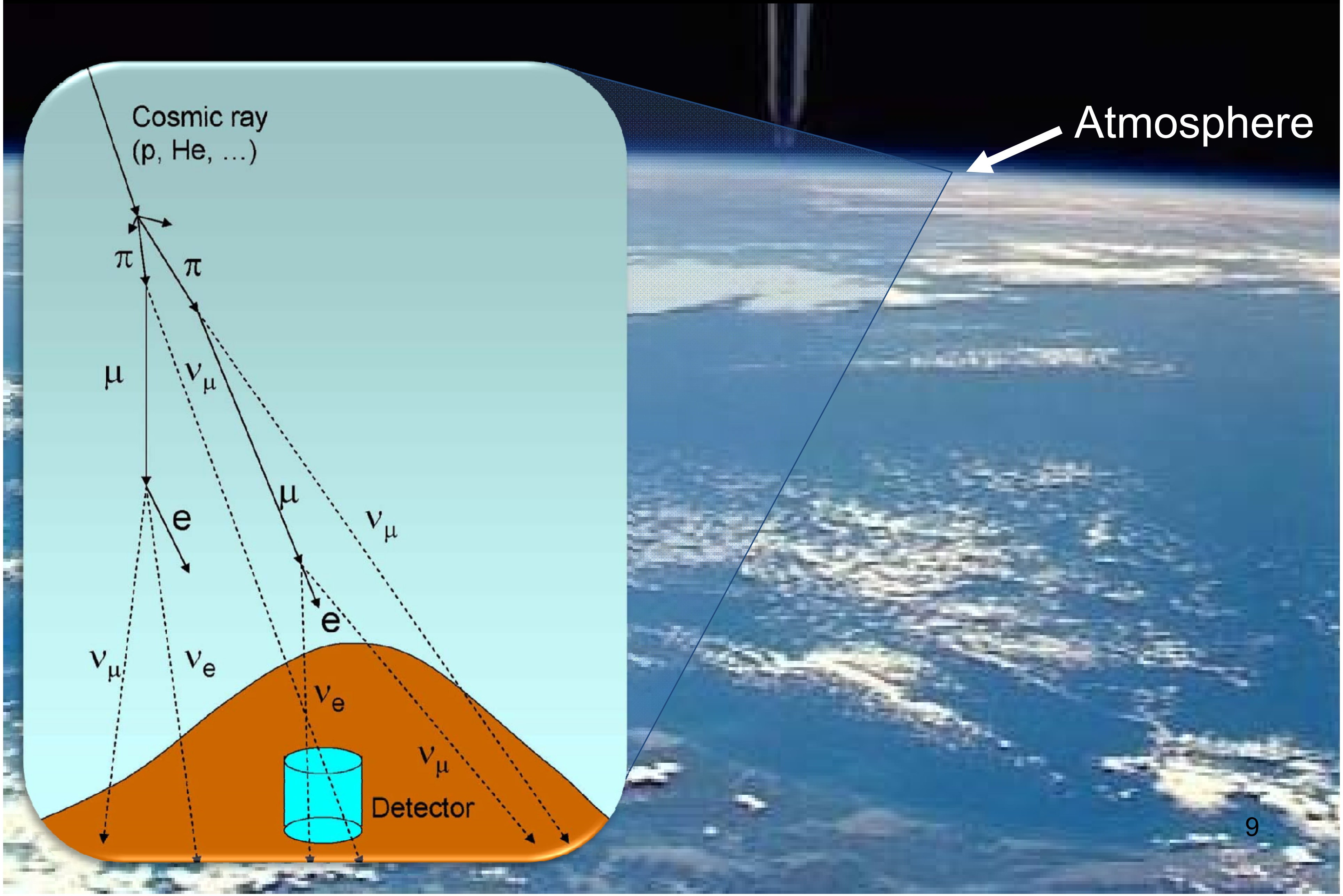
There are 2 small numbers:

1) $\Delta m_{12}^2 << \Delta m_{23}^2$
2) The ν_e content in ν_3 is small (i.e., θ_{13} is small)

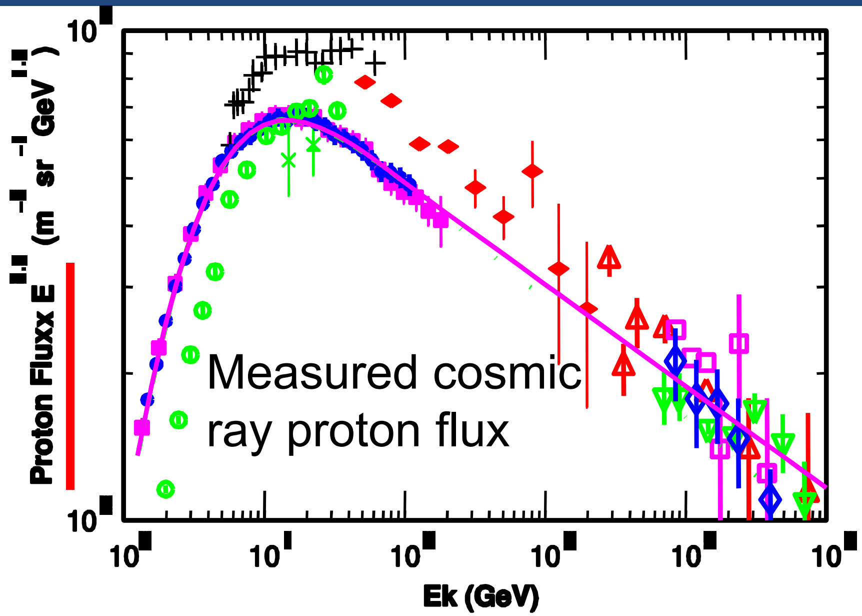
As the first approximation, it is possible to assume 2 flavor oscillations.

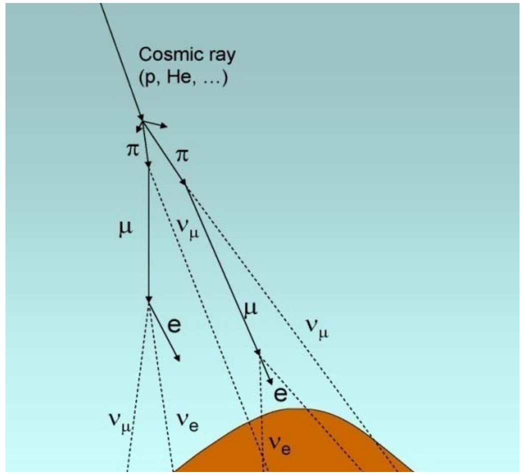
In many part of my lecture, 2 flavor oscillations are assumed. Later 3 flavor oscillations will be discussed. (In most part, we do not discuss, sterile neutrinos, and other non-standard assumptions.)

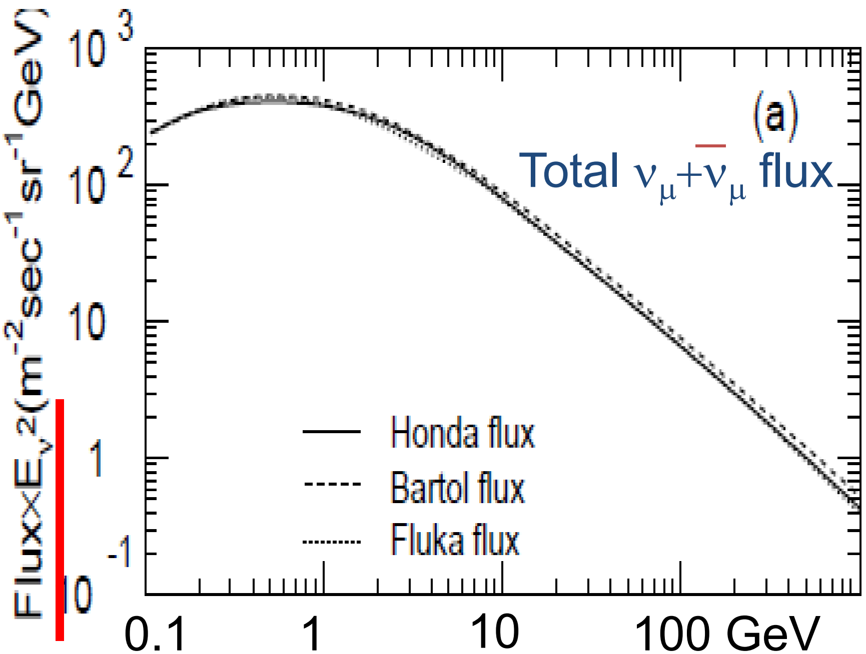
Production of atmospheric neutrinos



Calculating the atmospheric neutrino beam







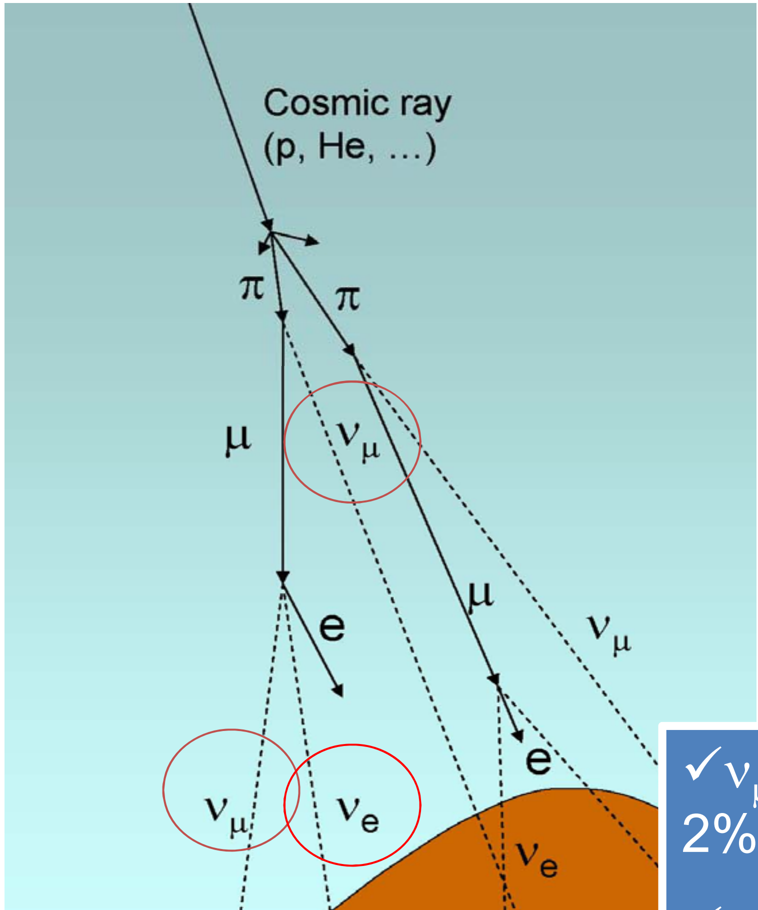
Carrying out the calculation all over the Earth

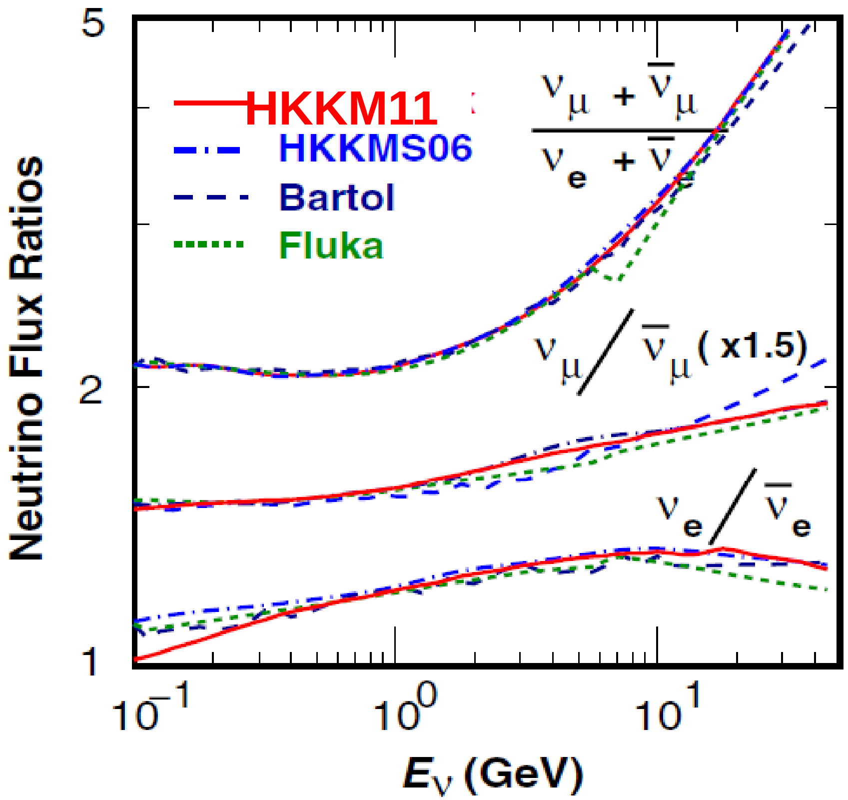
+ solar activity
+ geomagnetic field
+ (p+Nucleon) int.
+ decay of π or K
+ ……

Some features of the beam (1)

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

$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$



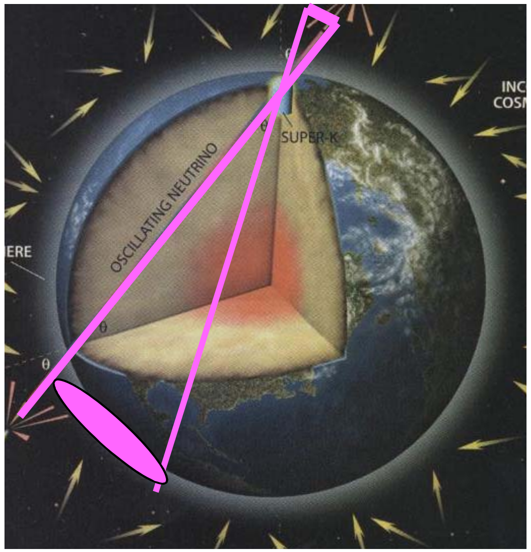


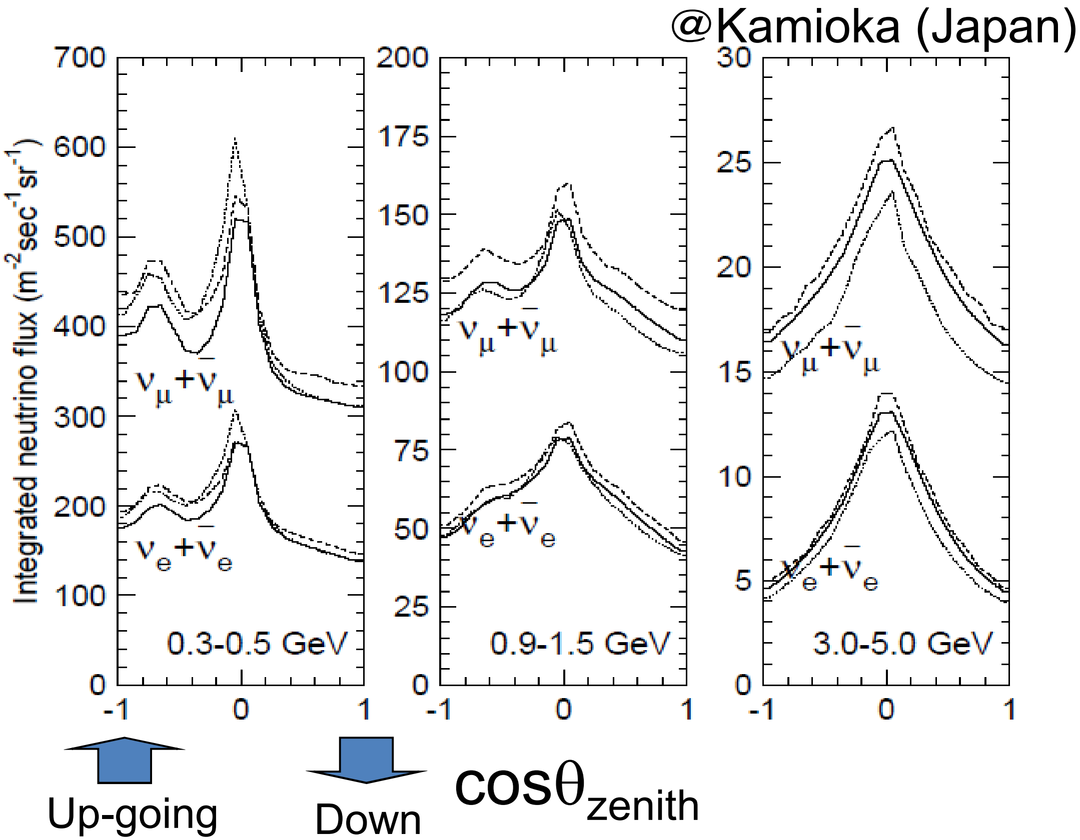
✓ν_μ/ν_e ratio is calculated to an accuracy of about 2% below ∼5GeV.

✓ν and anti–ν ratios are also accurately calculated.

Some features of the beam (2)

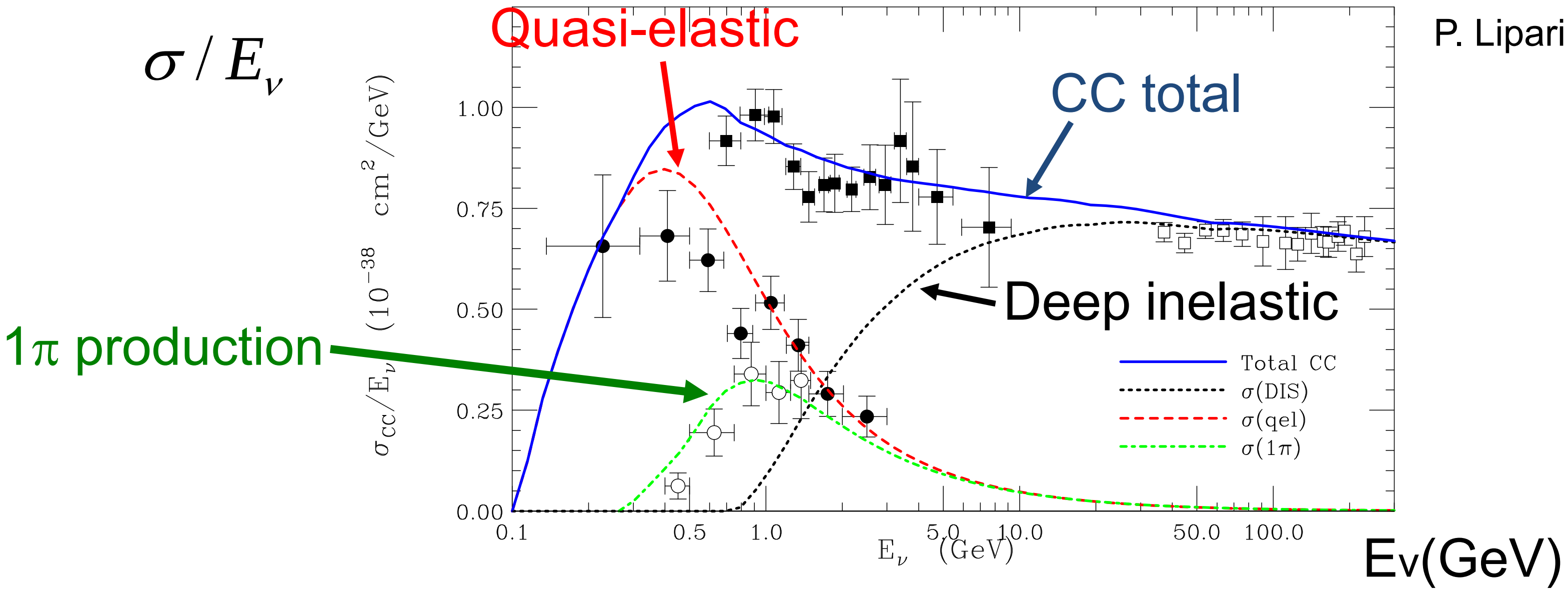
Zenith angle



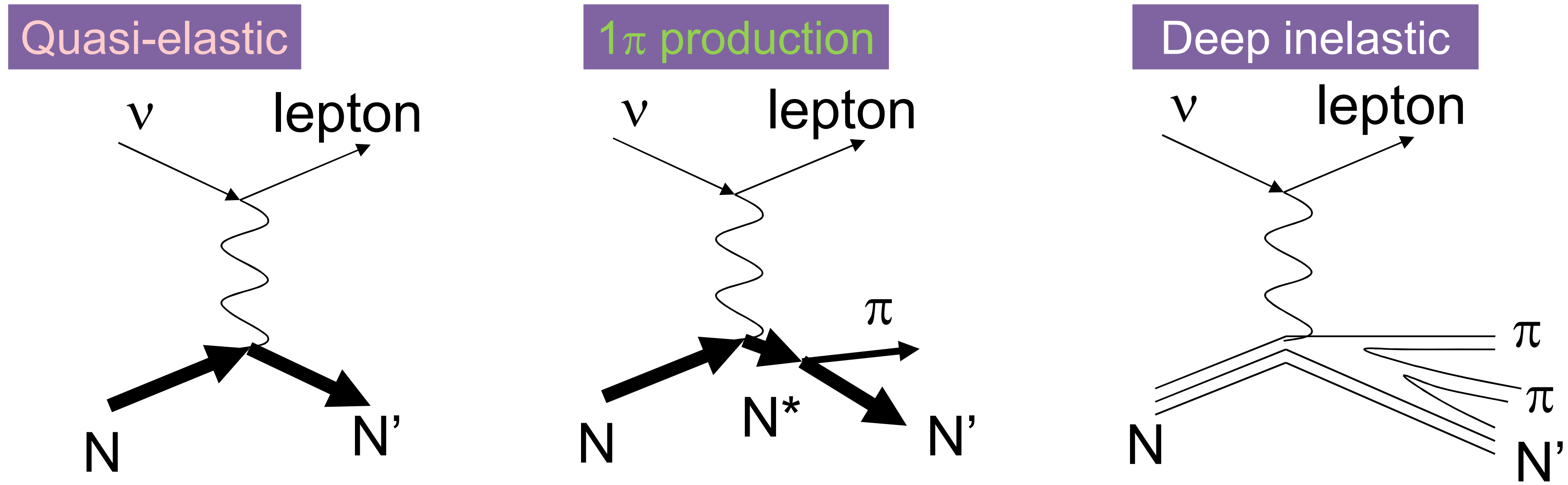


Up/down ratio very close to 1.0 and accurately calculated (1% or better) above a few GeV.

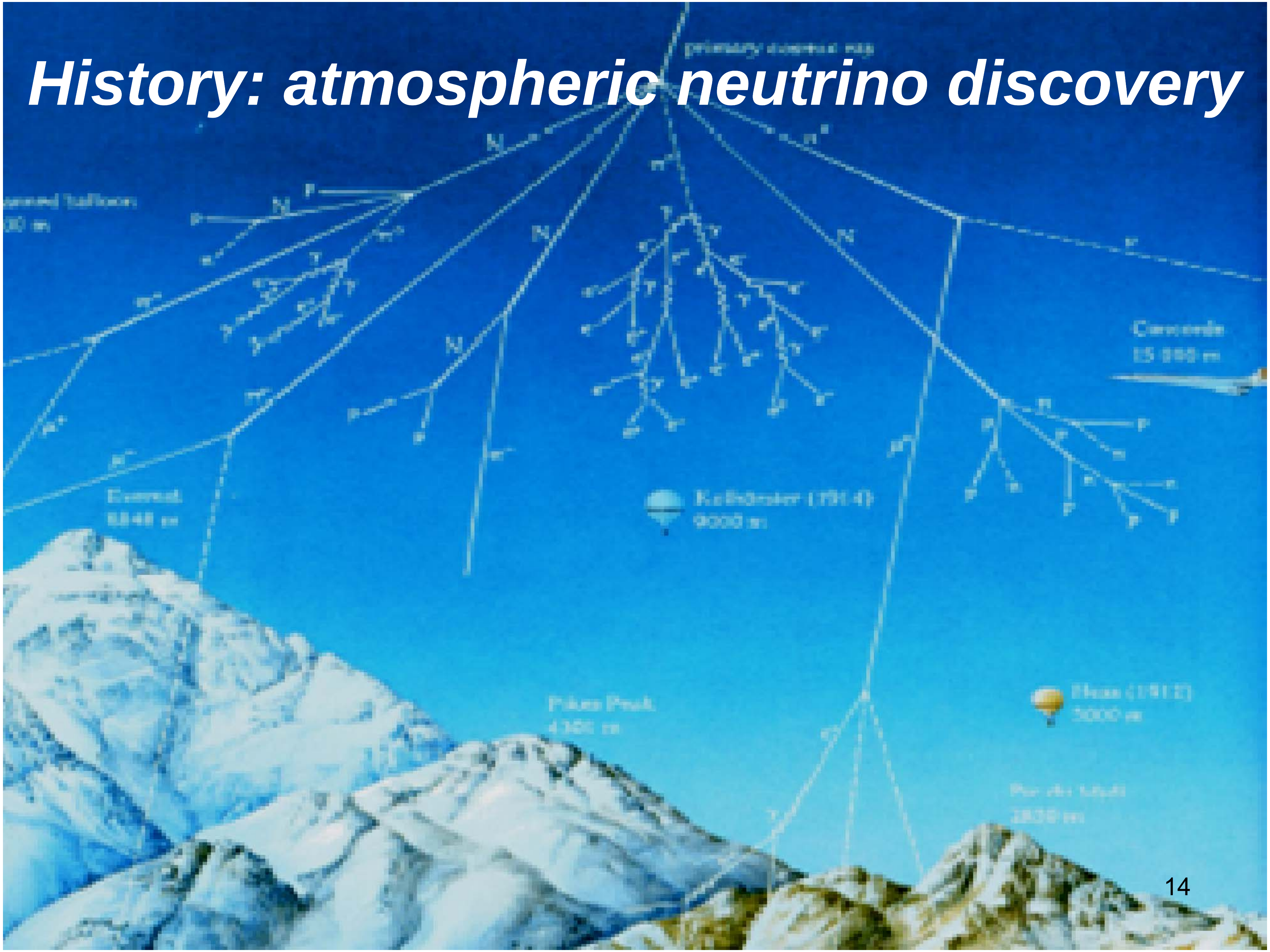
Neutrino interactions



P. Lipari



History: atmospheric neutrino discovery



Discovery of atmospheric neutrinos

At the depth of 3200 meters (8800 meters water equivalent) in South Africa
1st event observed on Feb. 23, 1965
Published on Aug.30, 1965
F.Reines et al. PRL 15, 429 (1965)

At the depth of 2400 meters (7500 meters water equivalent) in India (Kolar Gold Field)
1st event observed on March 30, 1965
Published on Aug. 15, 1965
C.V. Achar et al. Phys.Lett. 18, 196 (1965)

photo of the South Africa experiment

($\nu_\mu N \rightarrow \mu X$)

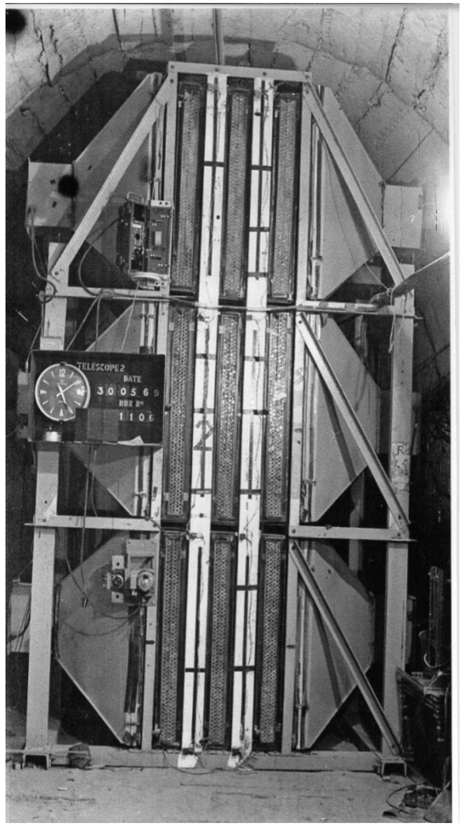
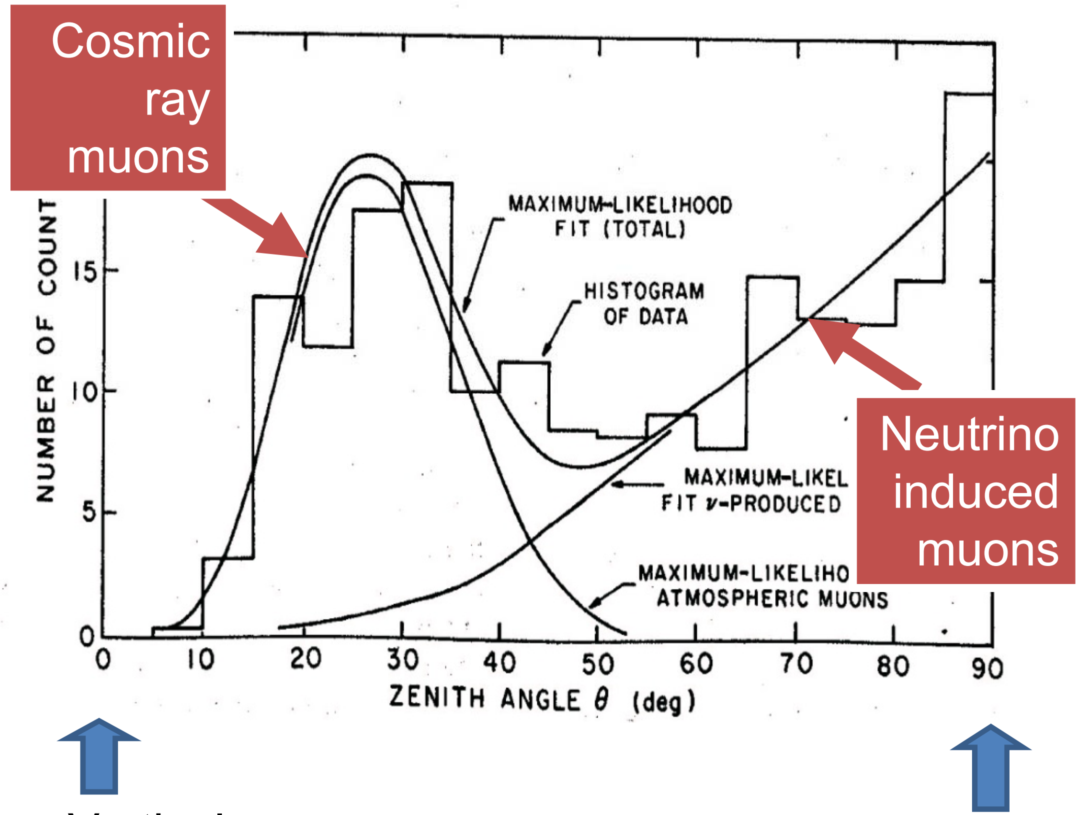


Photo of the KGF experiment

Zenith angle distribution and…

South Africa experiment (1978)

PRD18, 2239 (1978)



Vertical (up-going or down-going)

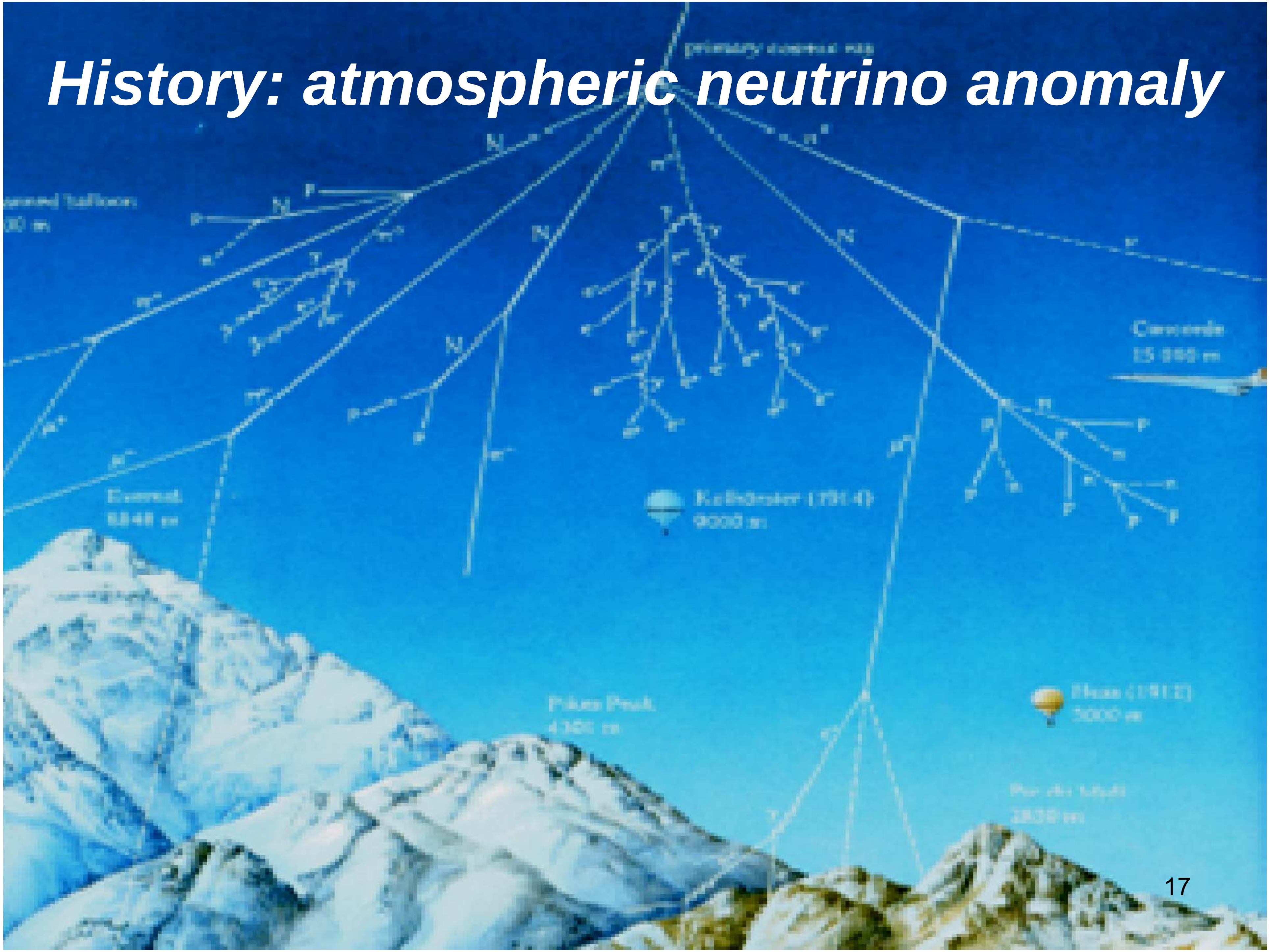
Horizontal going

$$\left(\frac{\mathit{Monte\ Carlo}}{\mathit{Data}}\right) = 1.6 \pm 0.4$$

Deficit of muon data

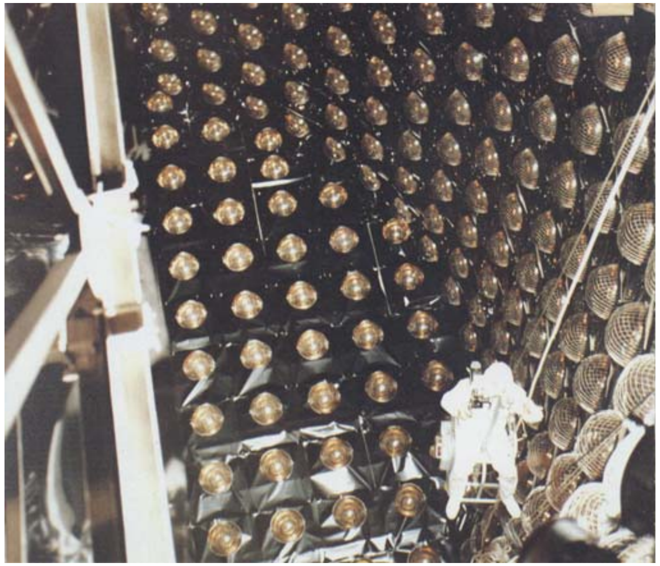
"We conclude that there is fair agreement between the total observed and expected neutrino induced muon flux …"

History: atmospheric neutrino anomaly



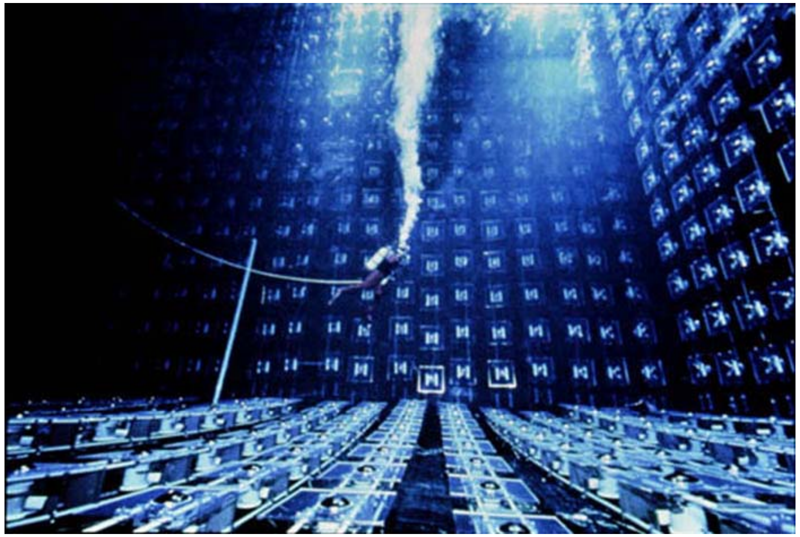
"Proton decay" experiments in the 1980's

Grand Unified Theories → $\tau_p = 10^{30\pm2}$ years



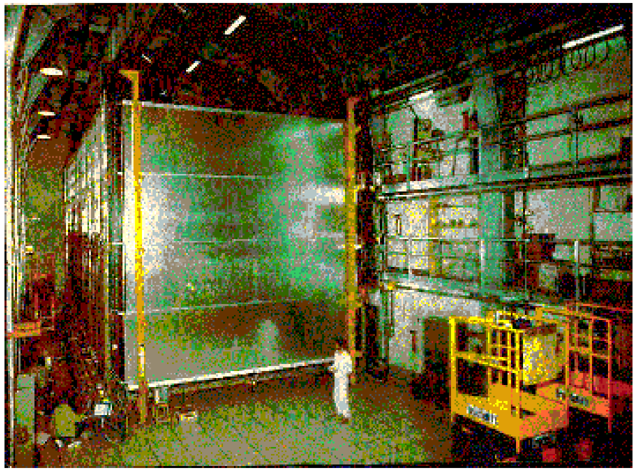
Kamiokande
(1000ton)

IMB
(3300ton)



NUSEX
(130ton)

Frejus
(700ton)



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

Fewer muon decays than expected

IMB

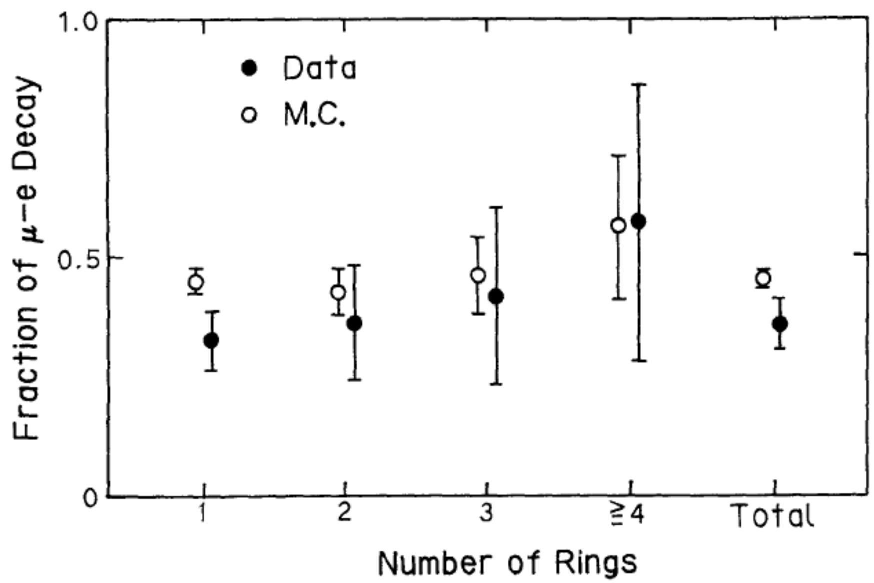
Kamiokande

IMB: PRL57, 1986 (1986)

Kamiokande J.Phys.Soc.Jpn 55, 3786 (1986)

VOLUME 57, NUMBER 16 PHYSICAL REV

well not only globally but also in small regions. The simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.



$\nu_\mu N \rightarrow \mu X$, $\mu \rightarrow e\nu\nu$

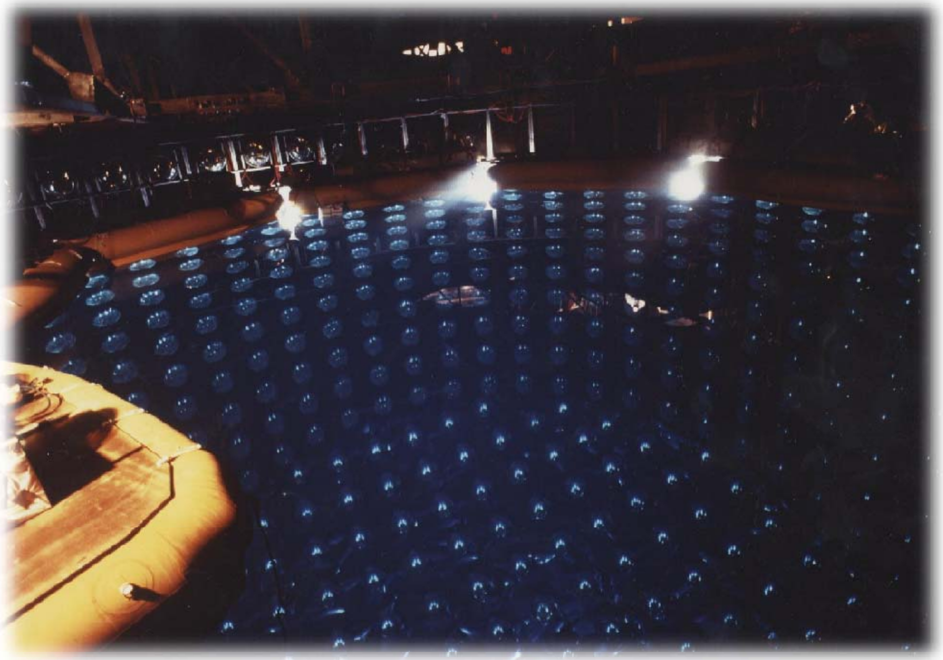
or

$\nu N \rightarrow$ lepton$+\pi^+ + X$, $\pi^+ \rightarrow \mu^+\nu$, $\mu^+ \rightarrow e^+\nu\nu$

No idea what was wrong…

First result on the μ/e ratio (1988)

K. Hirata et al (Kamiokande) Phys.Lett.B 205 (1988) 416.



Kamiokande

(3000ton Water Ch.
～1000ton fid. Vol.)

2.87 kton･year

	Data	MC prediction
e-like (～CC ν_e)	93	88.5
μ-like (～CC ν_μ)	85	144.0

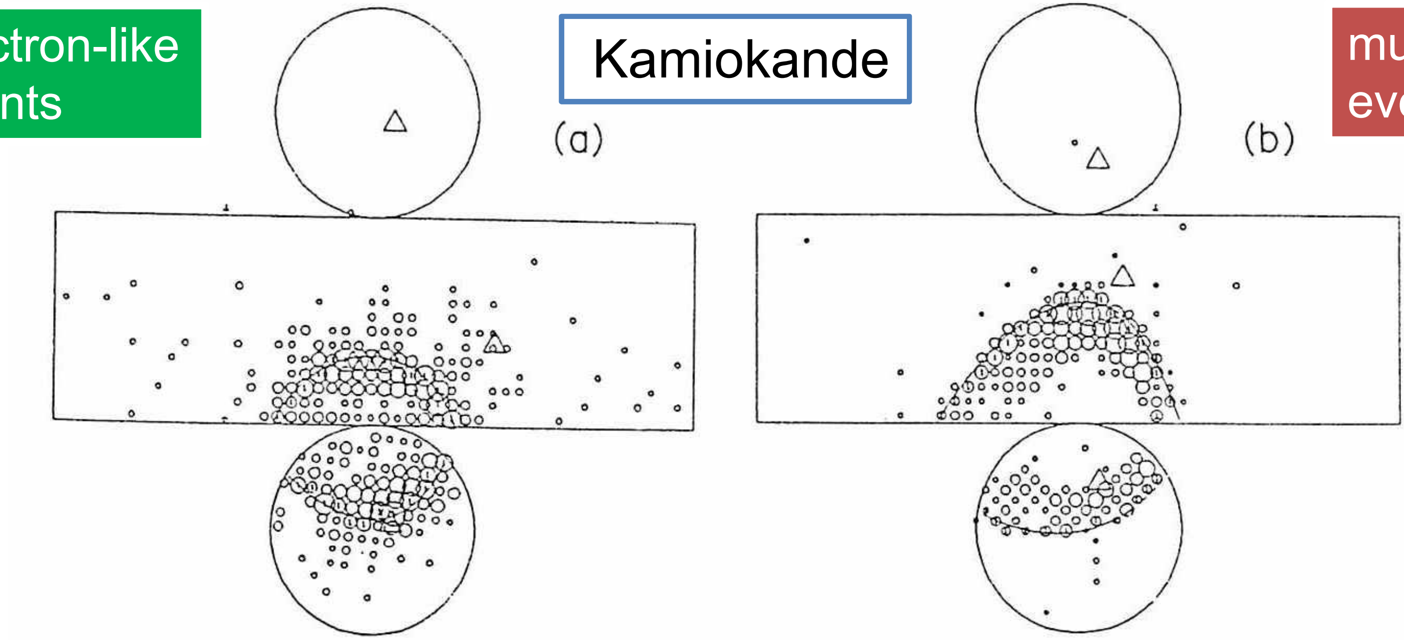
"We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccoundted-for physics such as neutrino oscillations might explain the data."

Particle identification: electron or muon ?

electron-like events

Kamiokande

muon-like events



e: electromagnetic shower, multiple Coulomb scattering

μ: propagate almost straightly, loose energy by ionization loss

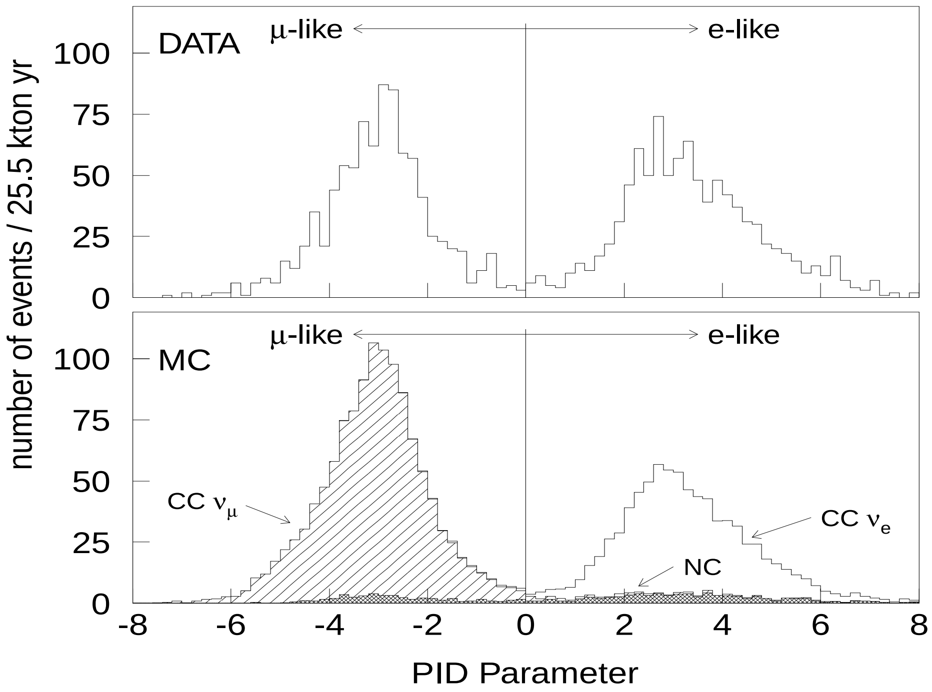
Difference in the event pattern

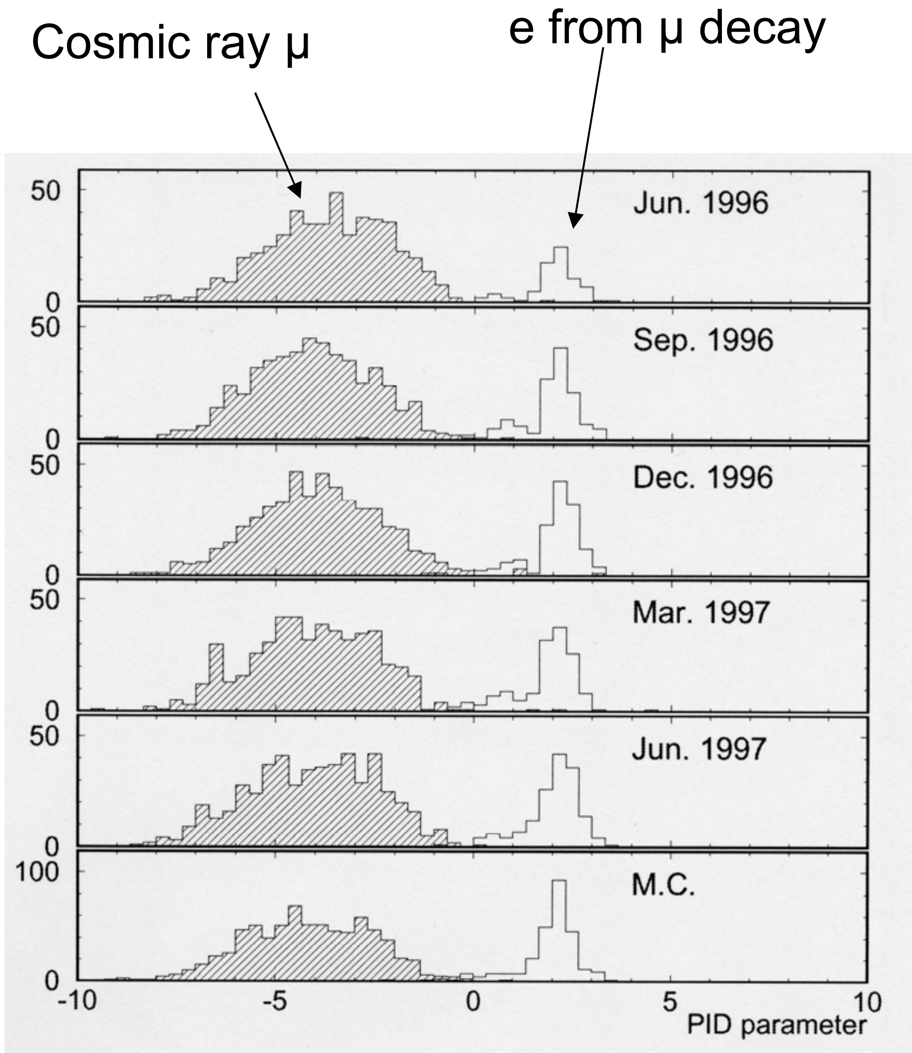
Particle ID

$$\chi^2 = \sum_{\theta<70\deg} \left(\frac{p.e.(obs'd) - p.e._{e \text{ or } \mu}(expected)}{\sigma_{p.e.}} \right)^2$$

Particle identification

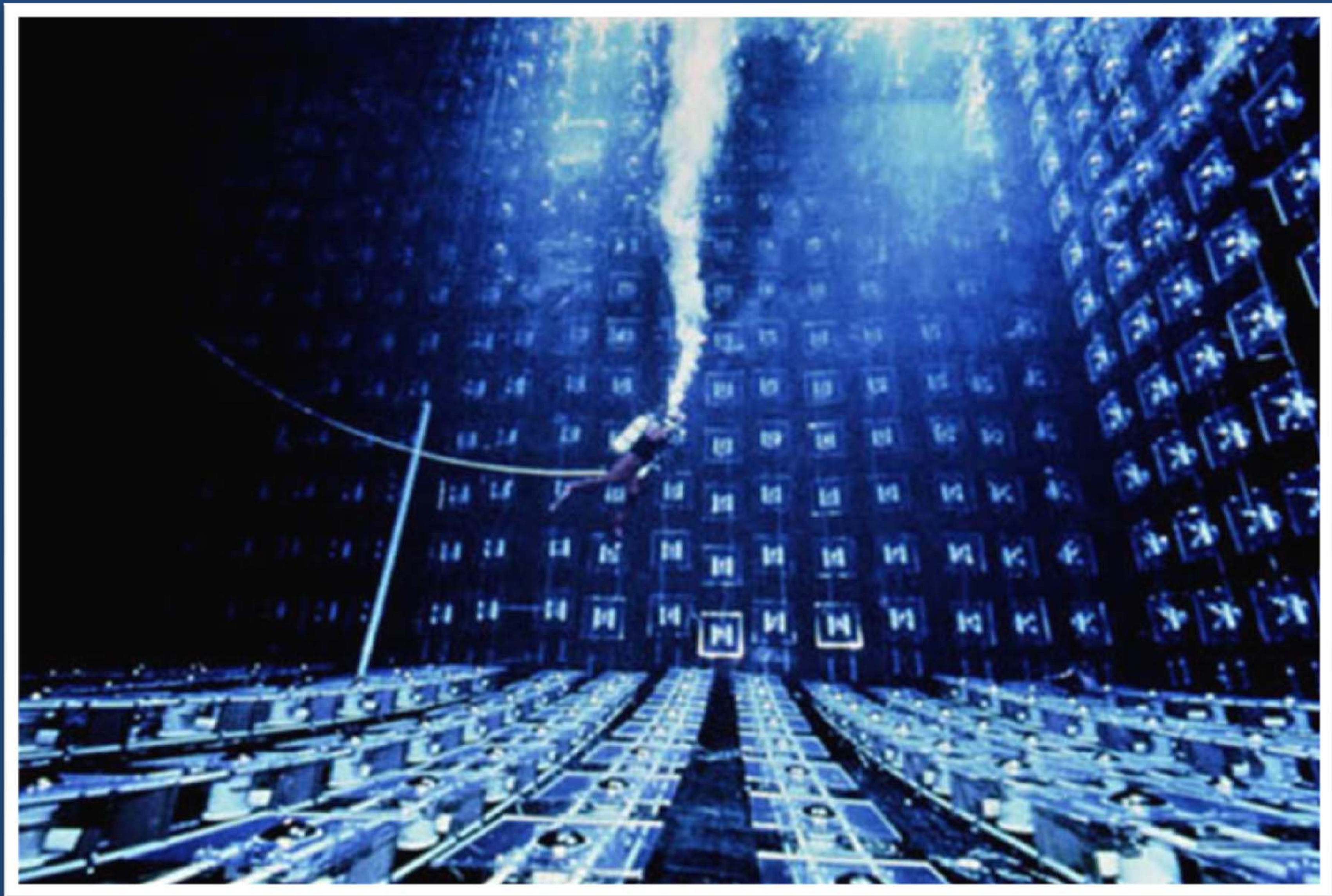
(figures from Super-K)





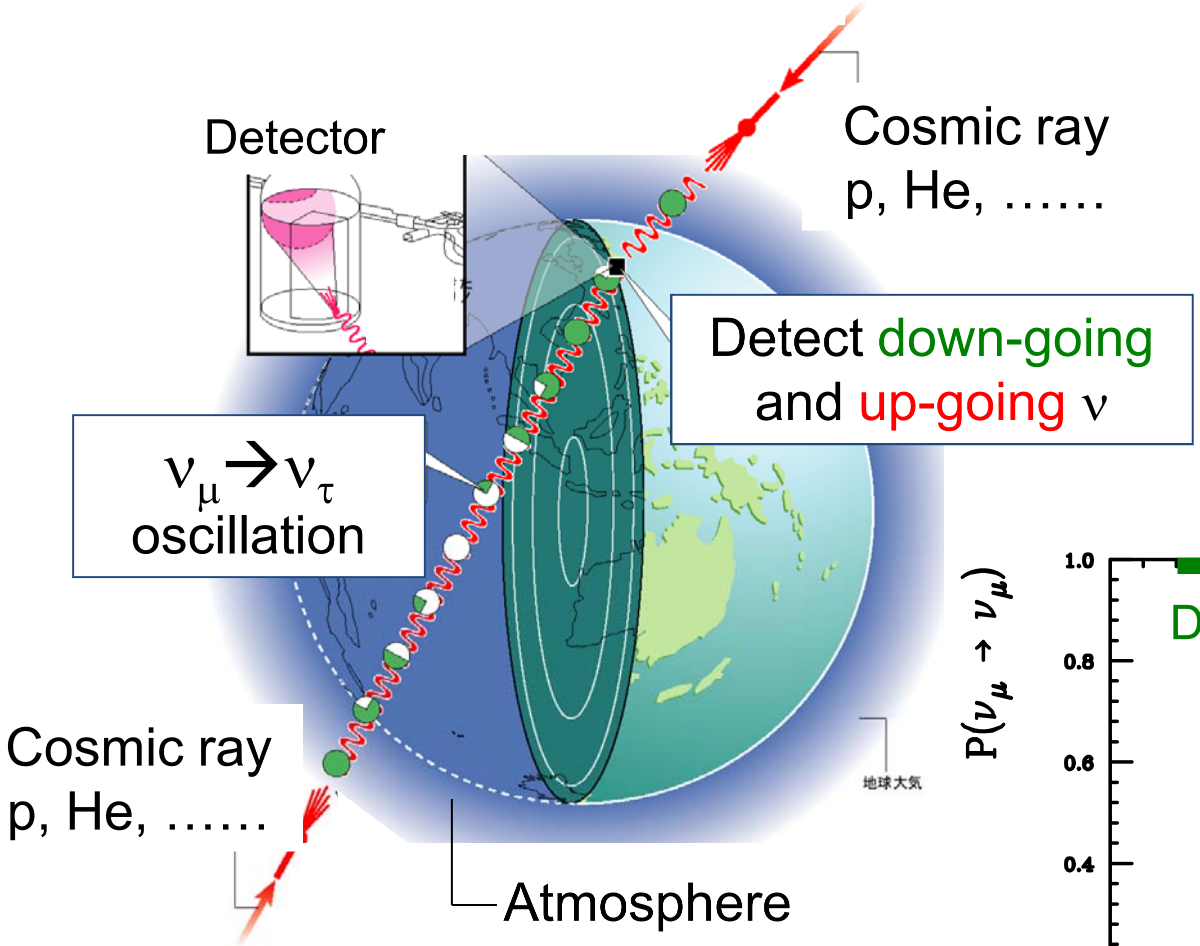
ε=99%@Super-K (98% @Kamiokande)

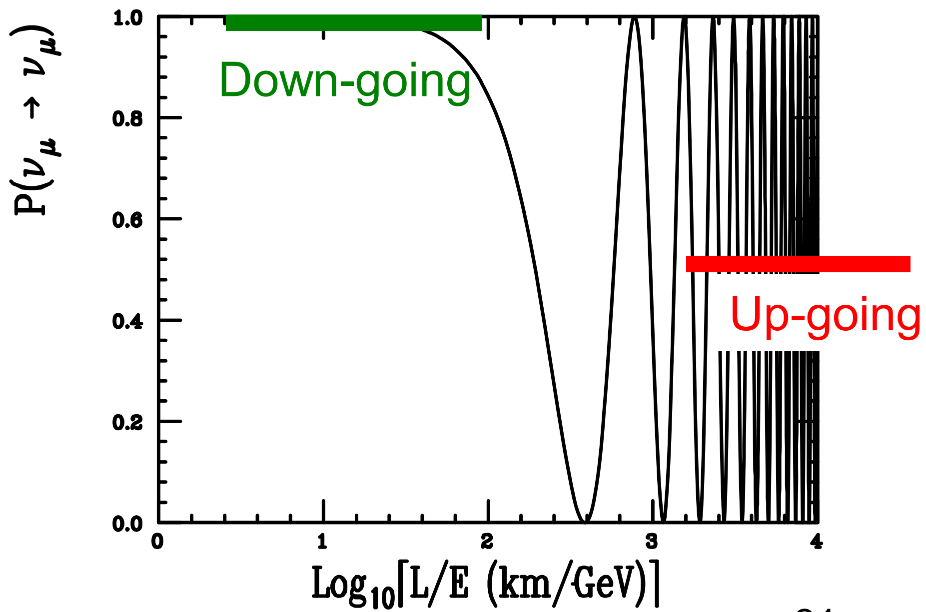
Supporting evidence for small μ/e



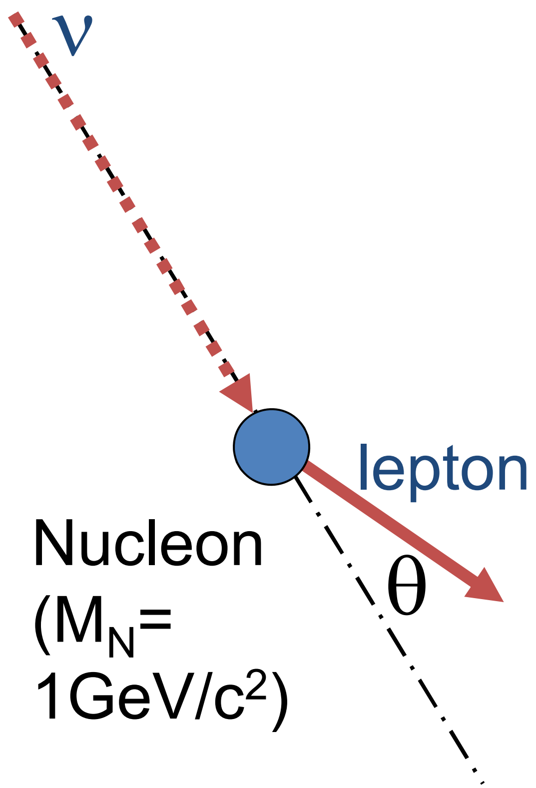
IMB experiment also published smaller (μ/e) in 1991 and 1992.

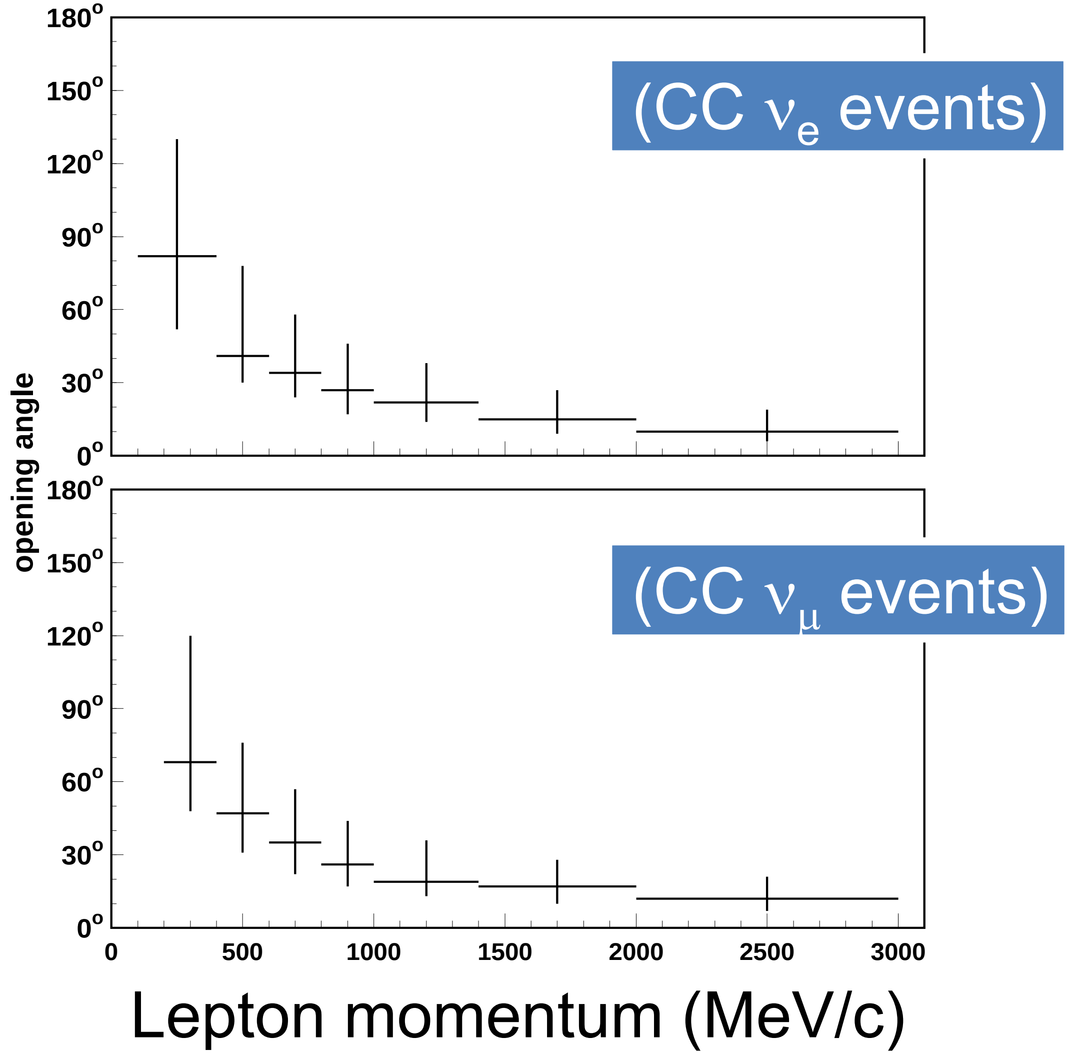
Atmospheric neutrino oscillations ?





Angular correlation



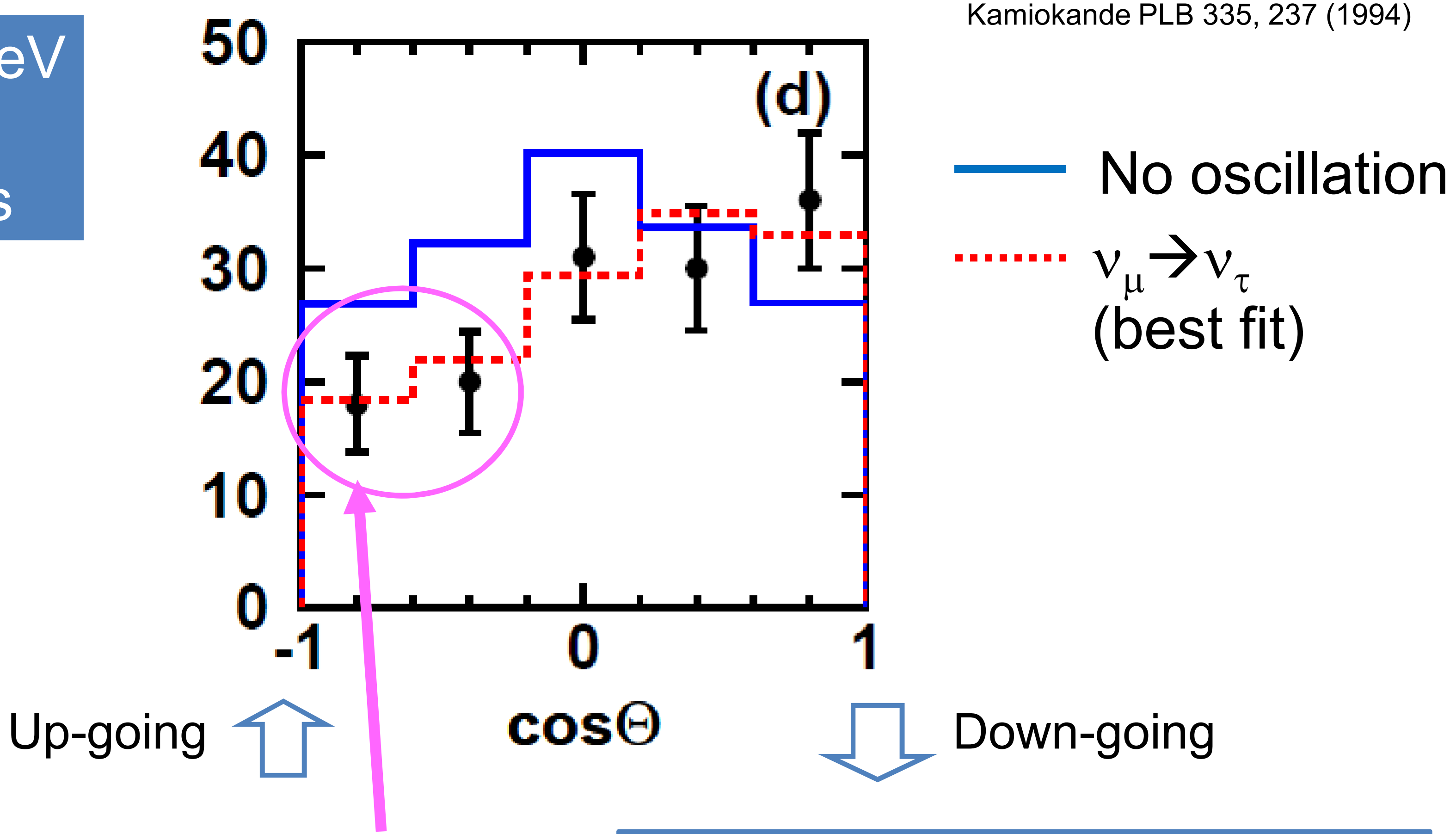


>GeV events need to be observed to study the zenith angle dependence

Zenith angle distribution (multi-GeV)

multi-GeV
μ-like
events

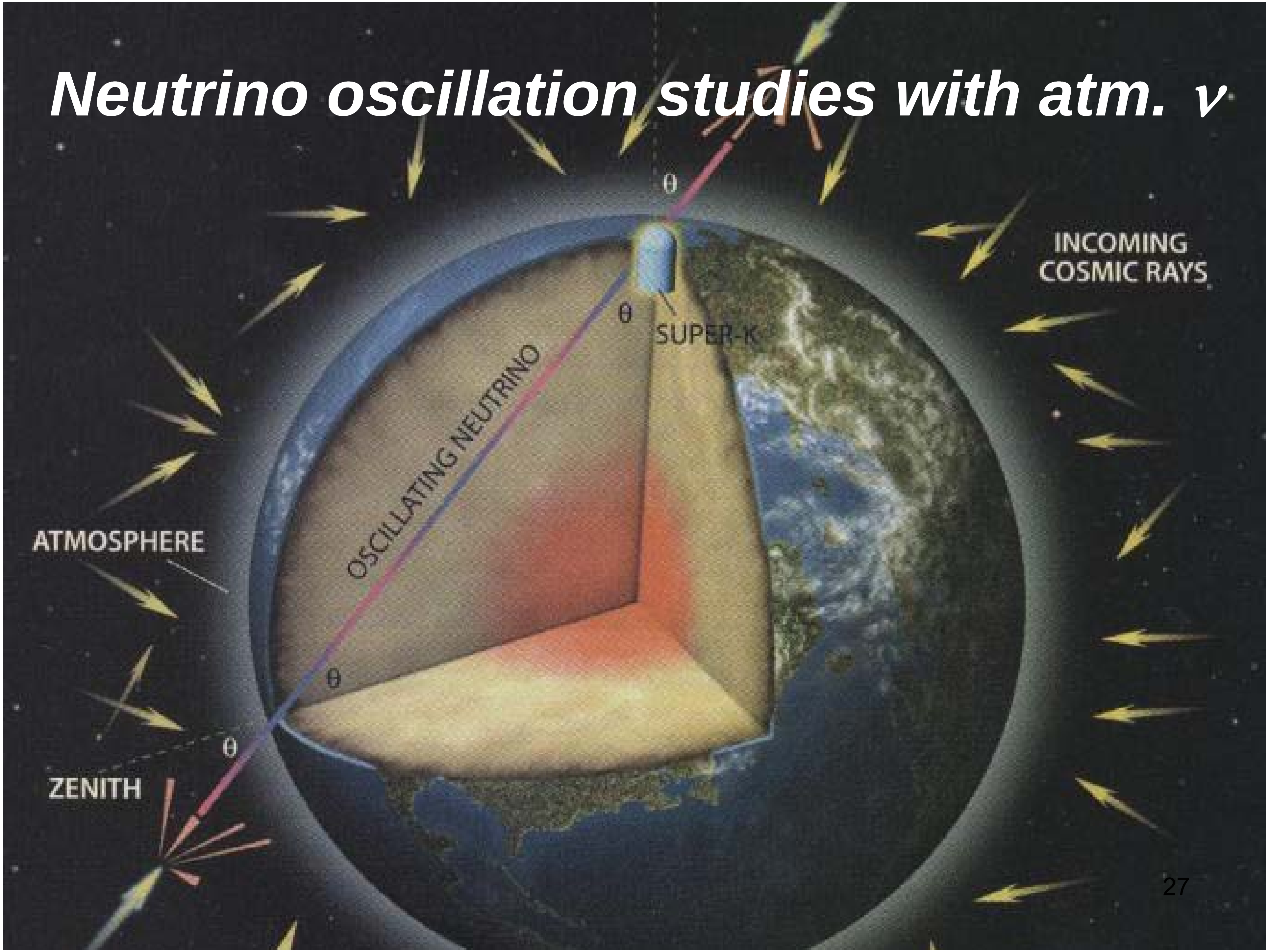
Kamiokande PLB 335, 237 (1994)



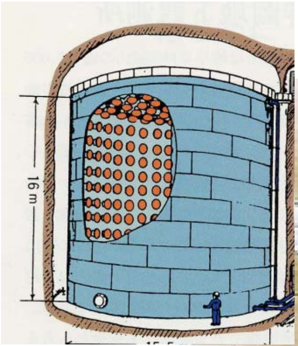
$Up/Down=0.58^{+0.13}_{-0.11}$ (2.9 σ)

Not high enough statistics to conclude …
Much higher statics required (= much larger detector required)

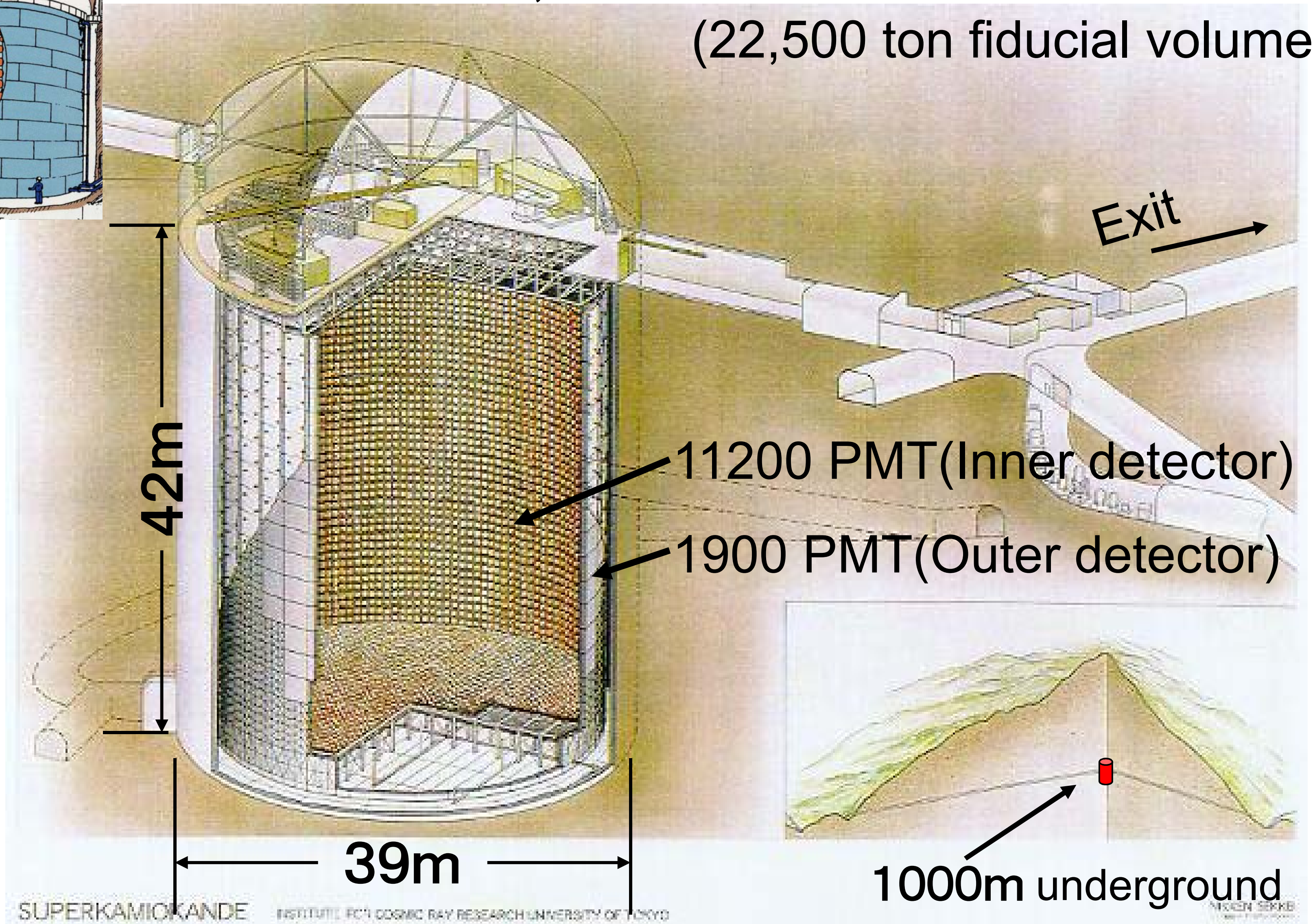
Neutrino oscillation studies with atm. ν

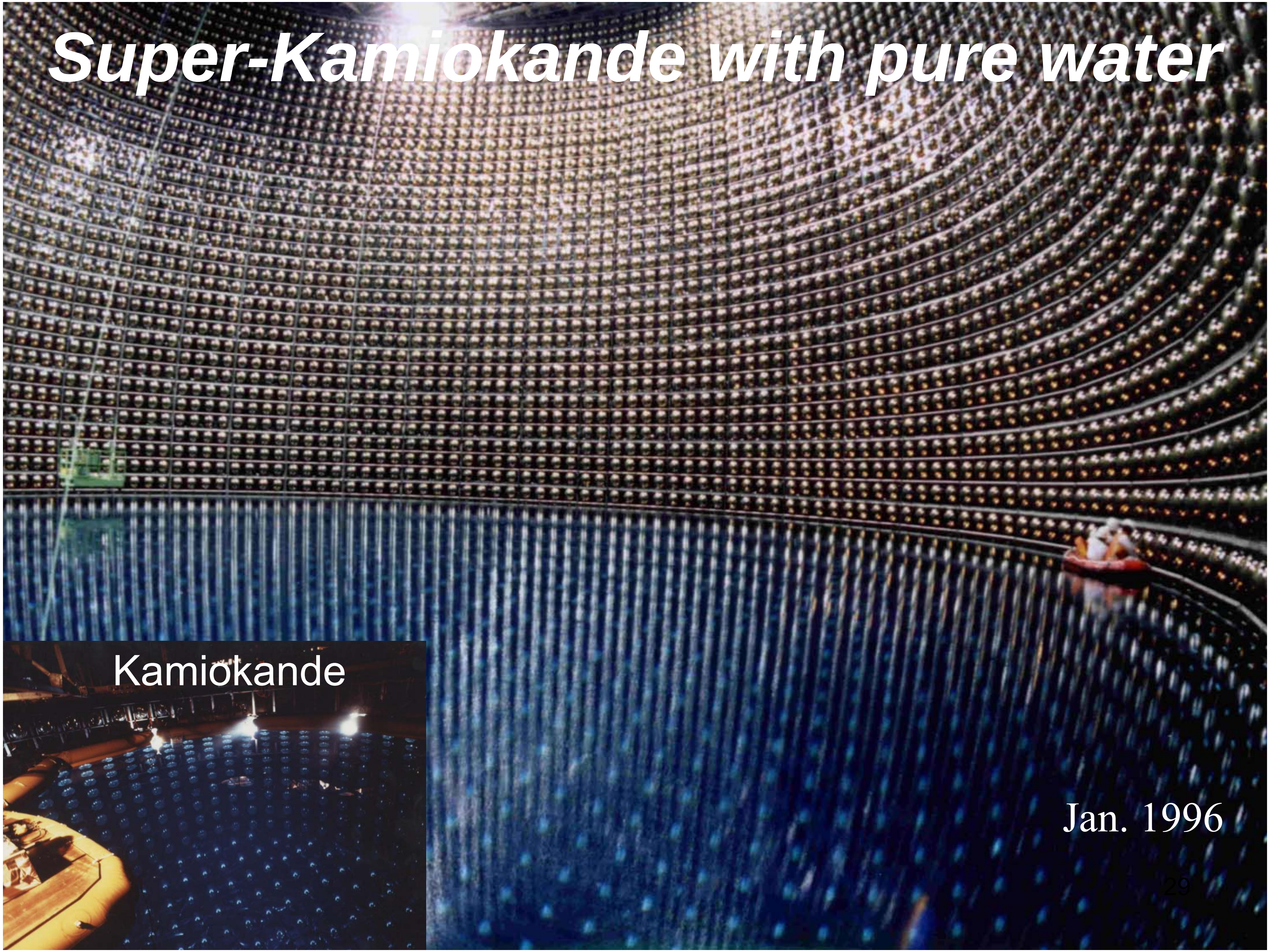


Super-Kamiokade detector



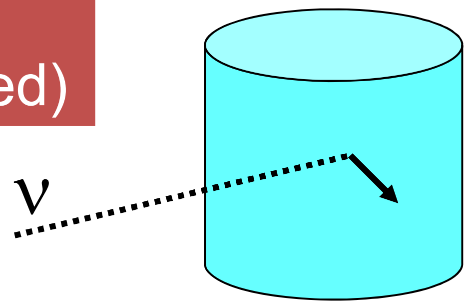
50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)




Super-Kamiokande with pure water
Kamiokande
Jan. 1996

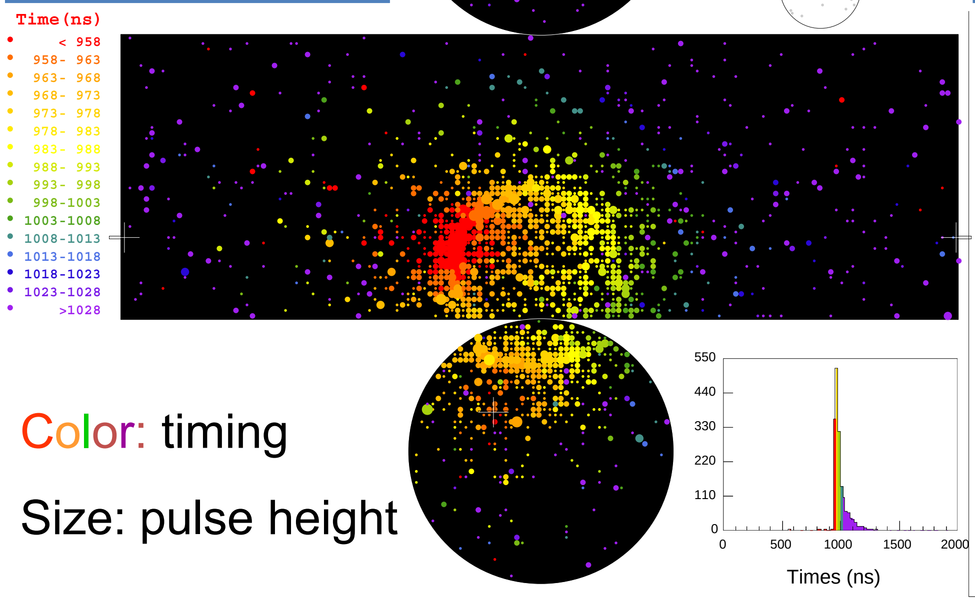
Various types of atmospheric ν events (1)

FC
(fully contained)



- Both CC ν_e and ν_μ (+NC)
- Particle identification separates electrons and muons with ε=99%.

Single Cherenkov ring electron-like event

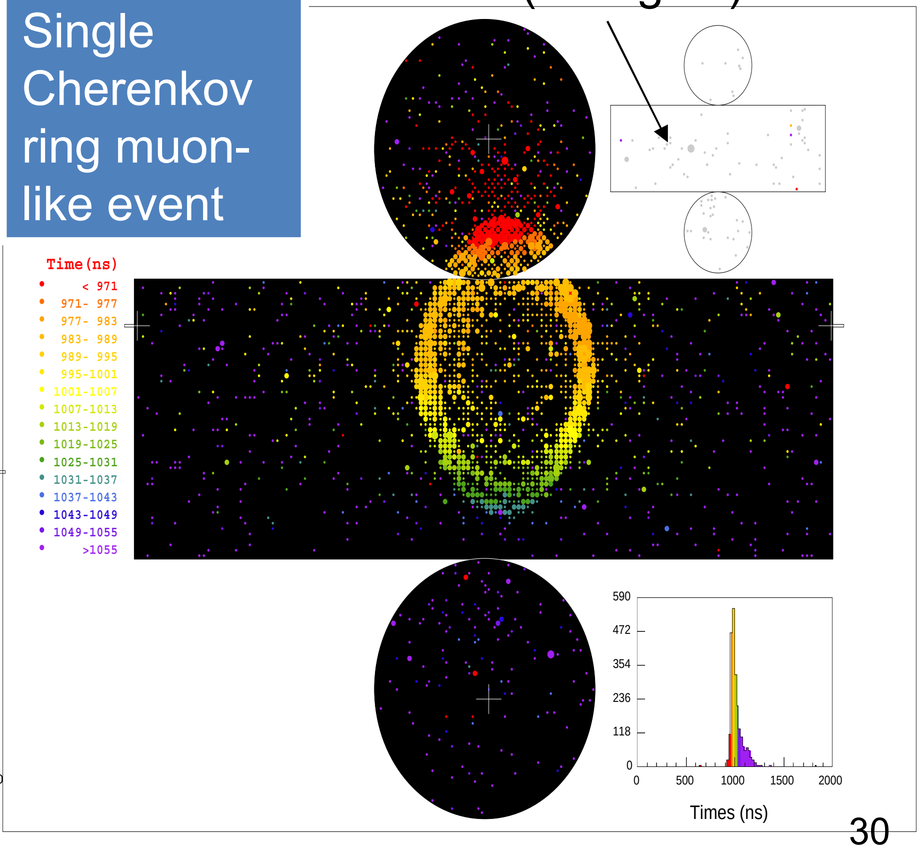


Color: timing

Size: pulse height

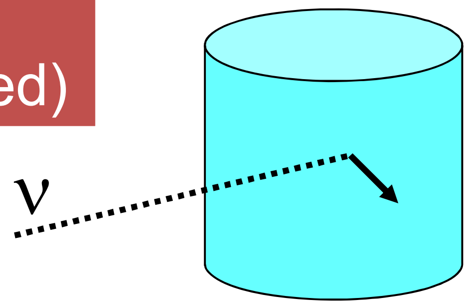
Single Cherenkov ring muon-like event

Outer detector (no signal)



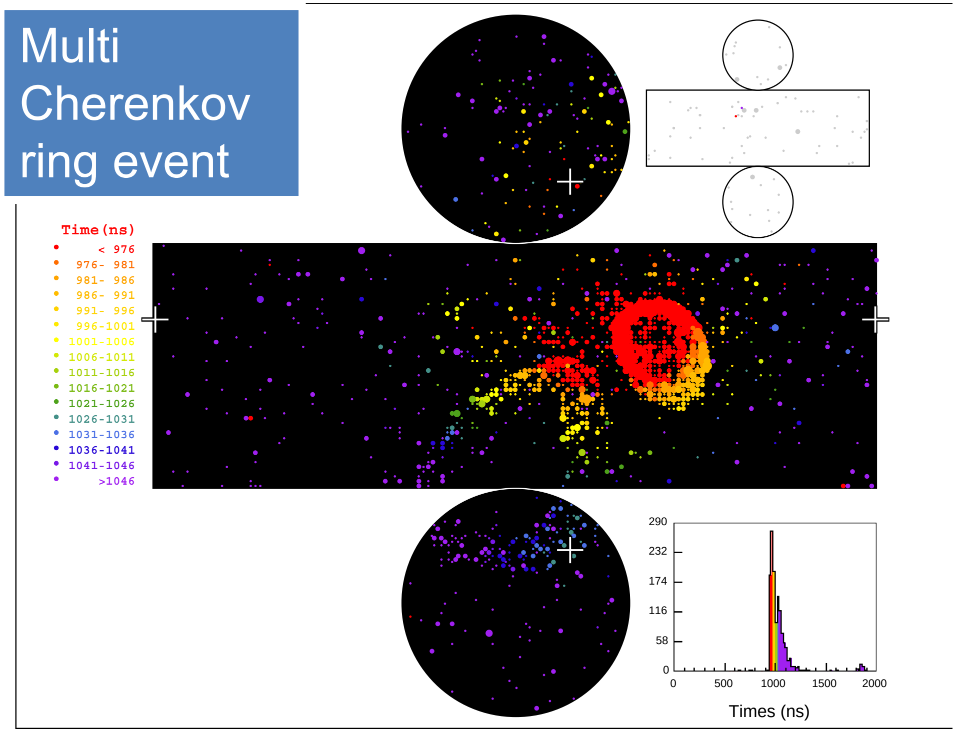
Various types of atmospheric ν events (2)

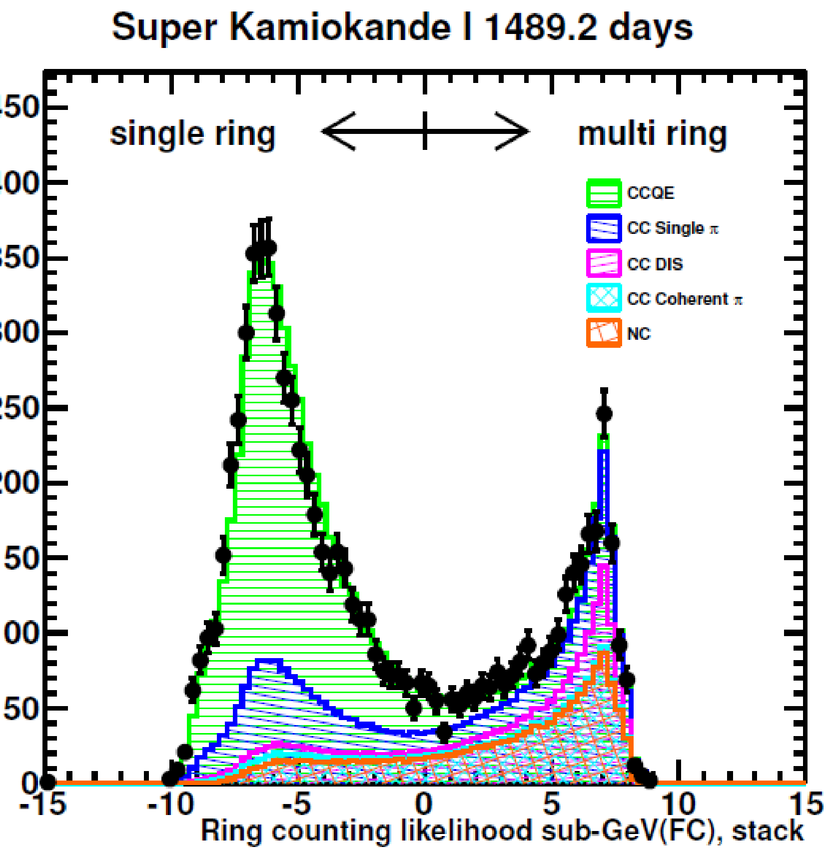
FC
(fully contained)



- Both CC ν_e and ν_μ (+NC)
- multi-ring events are also used in the oscillation analysis if the event is identified as e-like or mu-like.

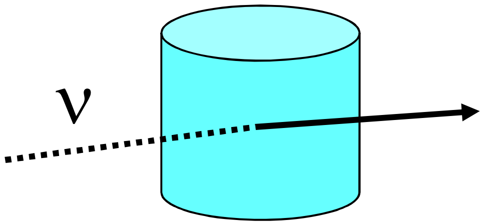
Multi Cherenkov ring event





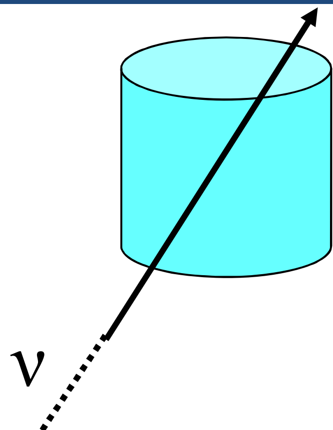
Various types of atmospheric ν events (3)

PC (partially contained)



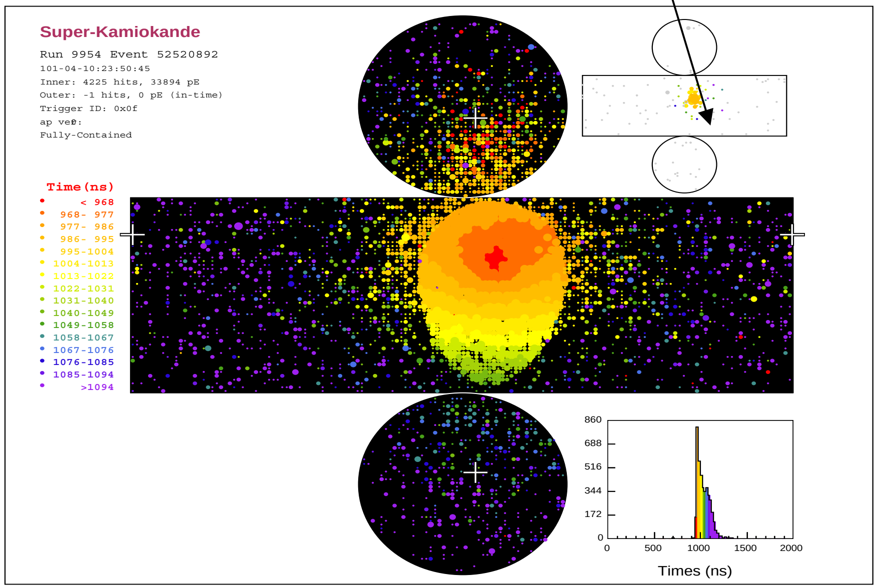
- 97% CC ν_μ

Upward going muon

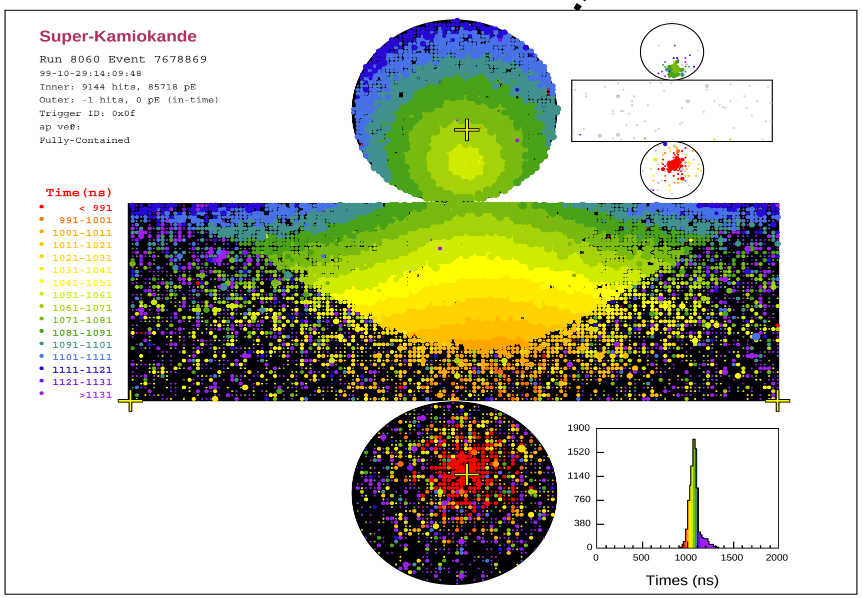


- almost pure CC ν_μ

Signal in the outer detector



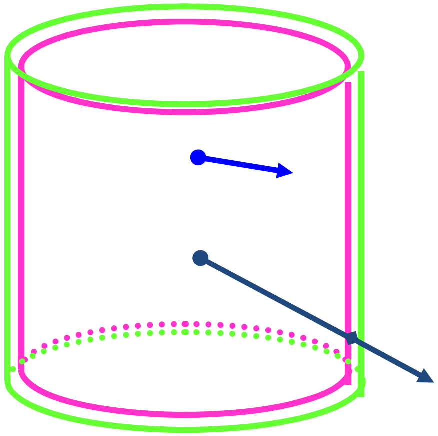
superscan[saji] Wed Mar 5 15:40:01 2003



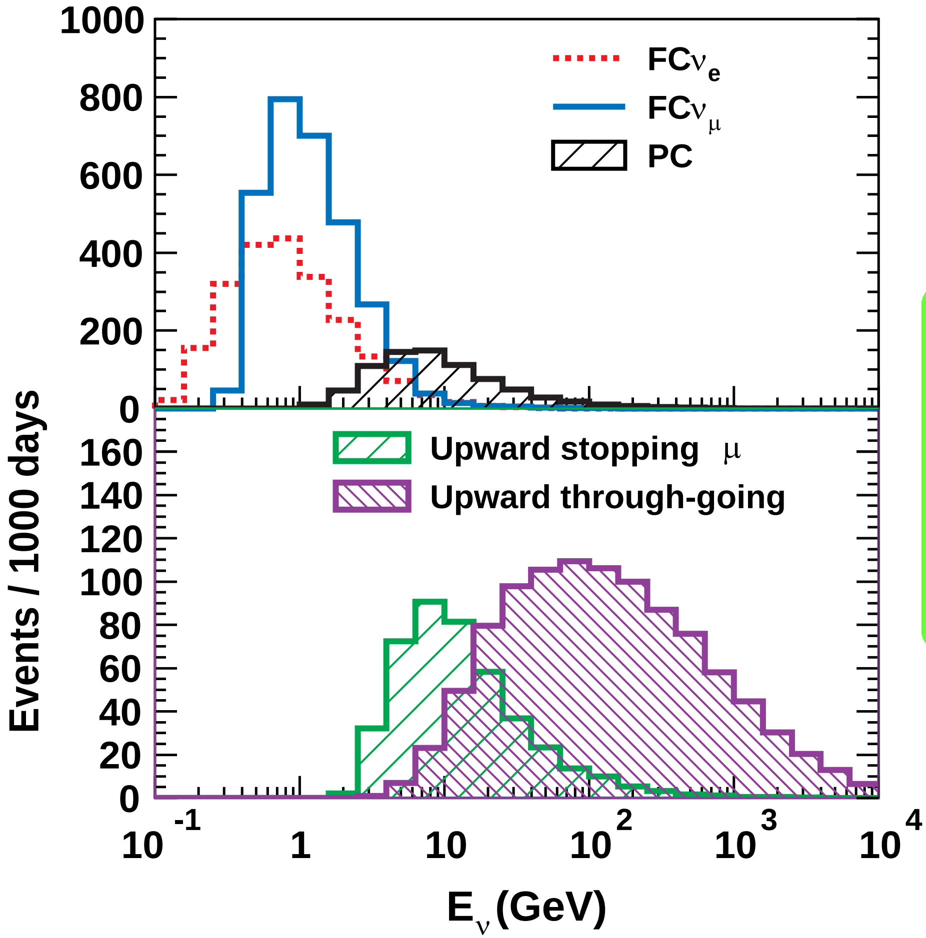
superscan[saji] Wed Mar 5 14:06:03 2003

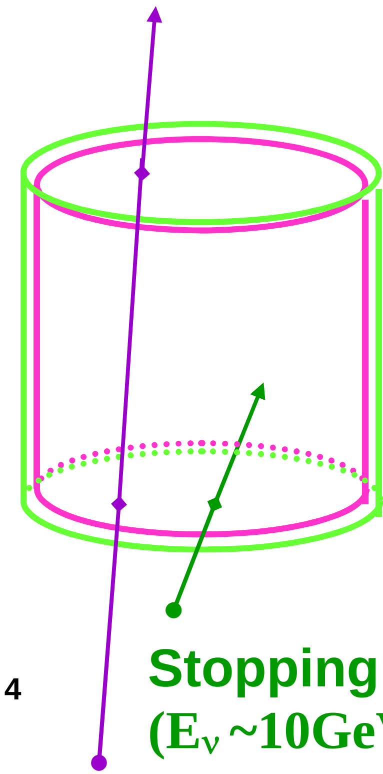
Event type and neutrino energy

Fully Contained (FC) (E_ν ~1GeV)



Partially Contained (PC) (E_ν ~10GeV)



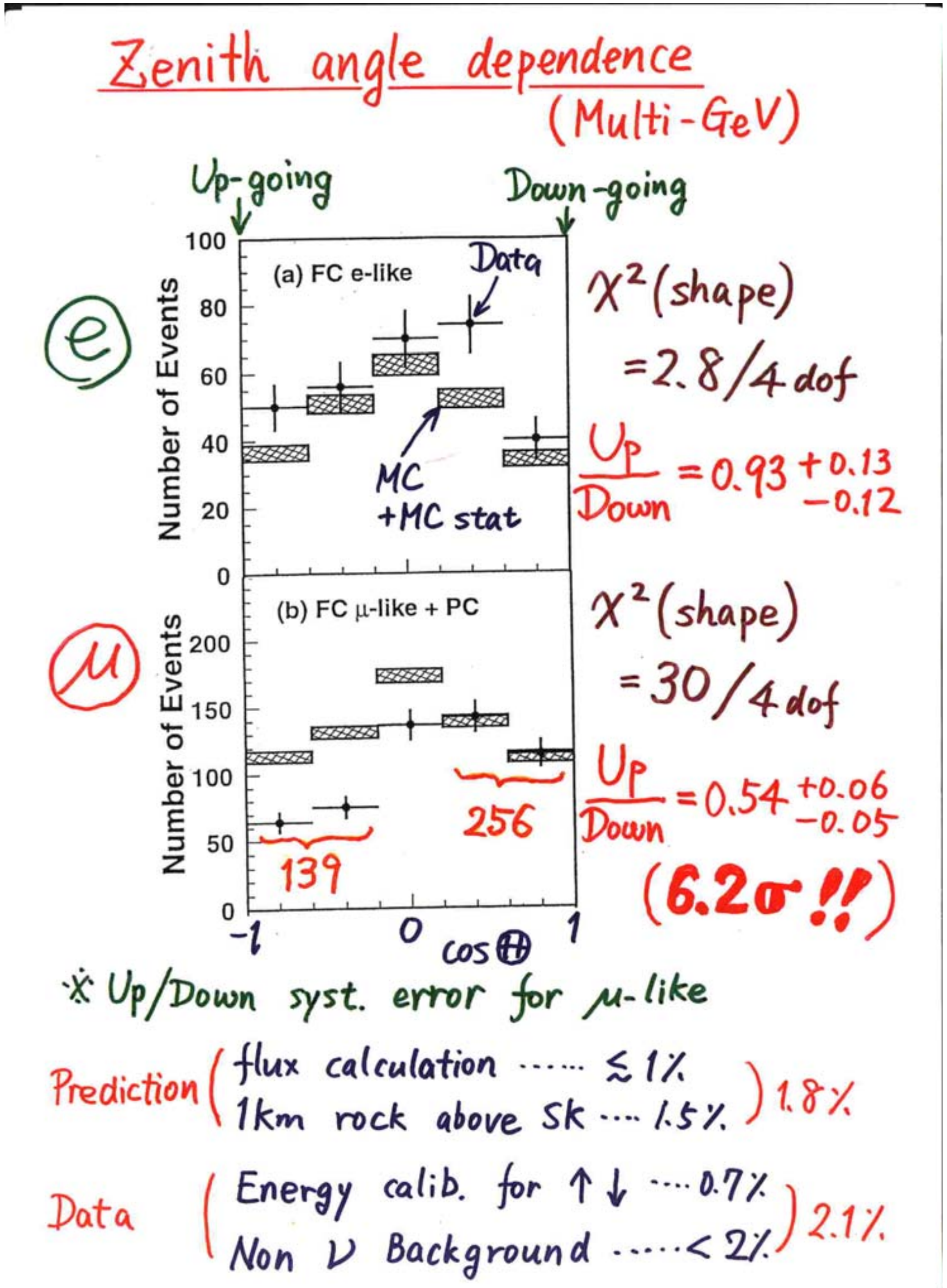


Stopping μ (E_ν ~10GeV)

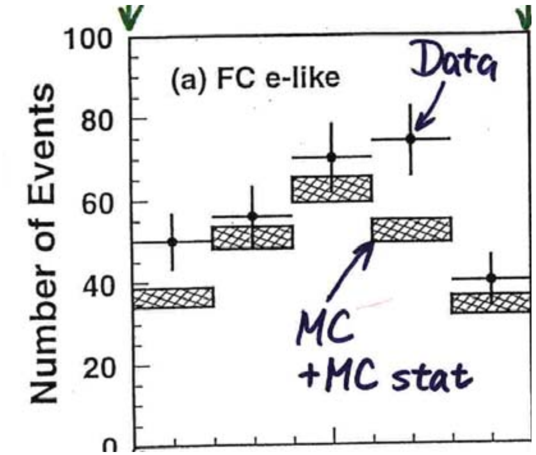
Through-going μ (E_ν ~100GeV)

Super-K @Neutrino98

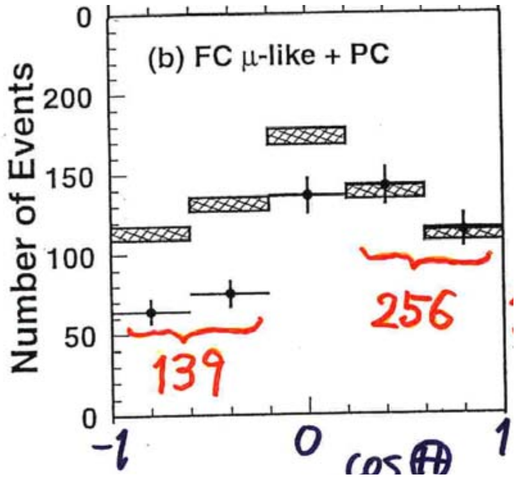
SK concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.



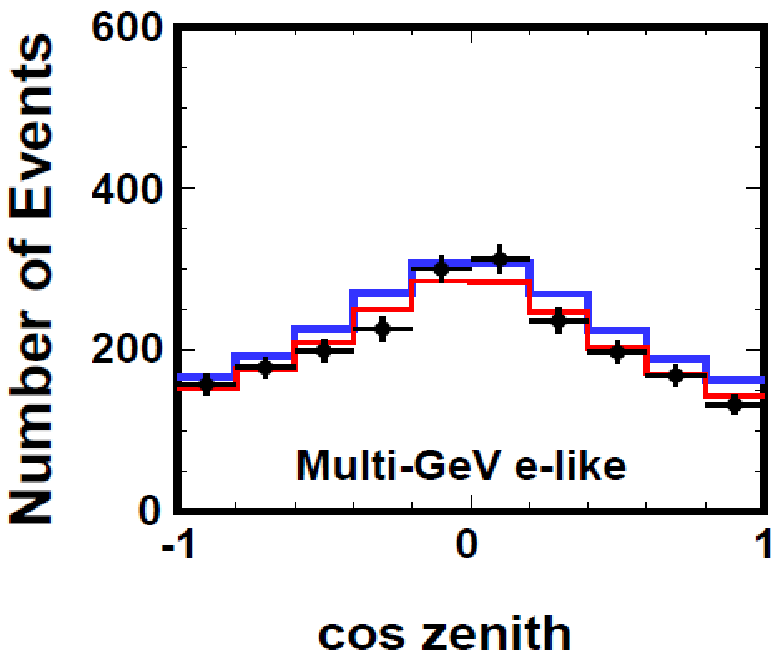
Super-Kamiokande data update

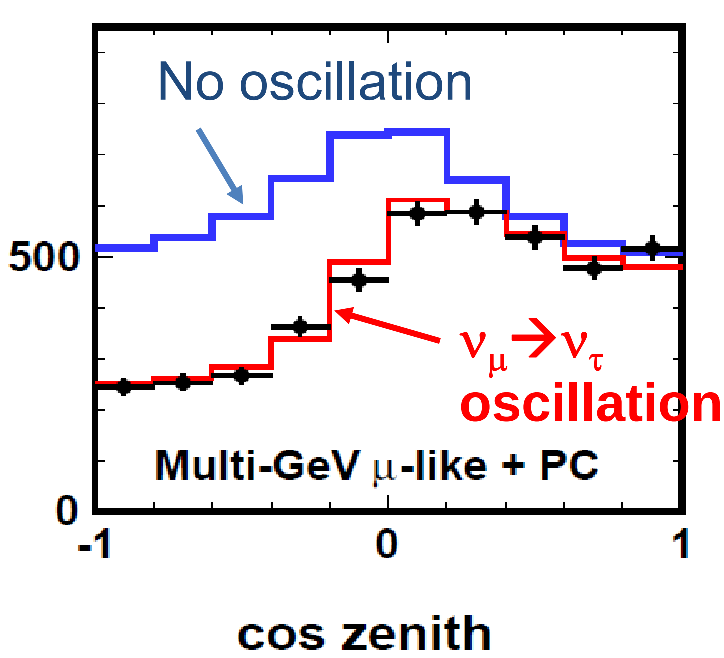


@Neutrino98
(535 day)

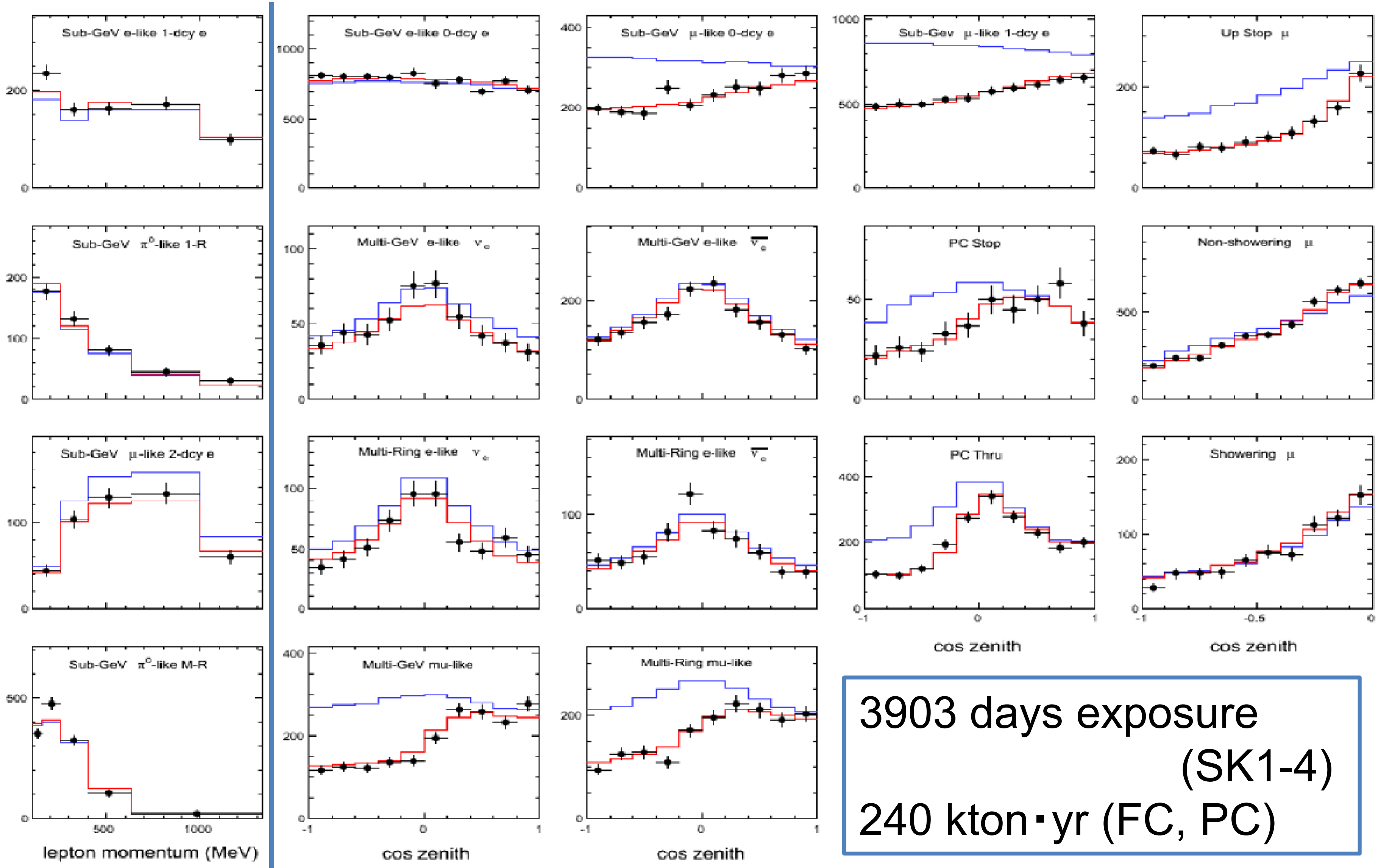


@2012
(3903 day)





Present Super-K atmospheric neutrino data



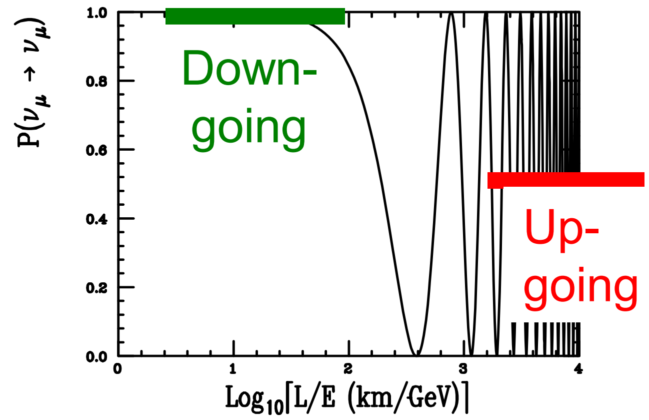
3903 days exposure (SK1-4)

240 kton・yr (FC, PC)

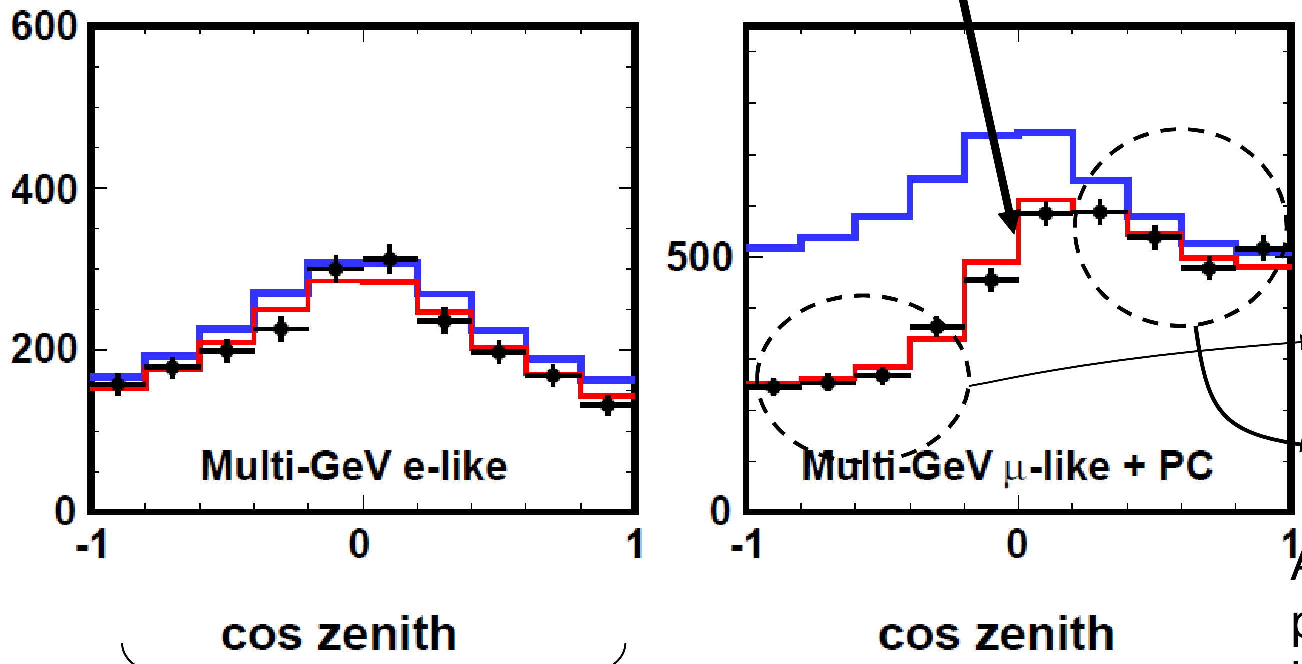
Mom. dist.

Zenith angle dist.

Estimating the oscillation parameters



Transition point
(as a function of energy)
➔ Δm^2

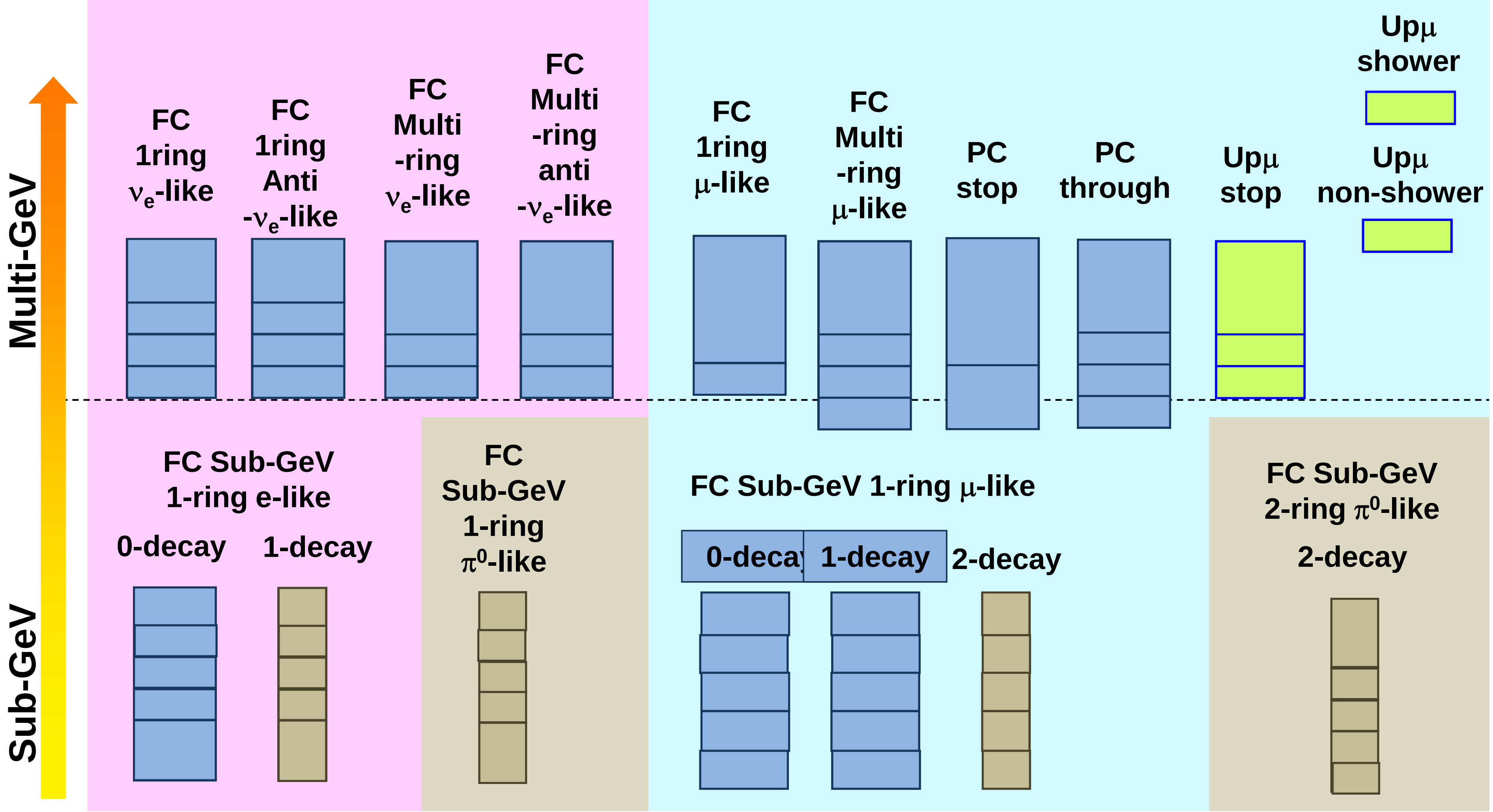


$$\frac{Up}{Down} = 1 - \sin^2 2\theta$$

Accurate measurement possible due to small syst. in up/down (2% or less)

Confirmation of non-oscillated flux

Oscillation analysis: zenith angle bins



- 10 bins ($-1 < \cos\theta < 1$)
- 10 bins ($-1 < \cos\theta < 0$)
- 1 bin

- e like
- μ like
- NC like

χ^2

Data are compared with MC by using a pull χ^2 method based on Poisson probability distribution.

$$\chi^2 \equiv 2\sum_i [(N_i^{\exp}(1+\sum_j f_j^i \varepsilon_j) - N_i^{obs}) + N_i^{obs} \ln(\frac{N_i^{obs}}{N_i^{\exp}(1+\sum_j f_j^i \varepsilon_j)})] + \sum_j (\frac{\varepsilon_j}{\sigma_j^{sys}})^2$$

where N_i^{obs} = number of observed events

N_i^{exp} = expected number of events

ε_j = systematic error parameters (j = systematic error index)

f^i_j = fractional change in the predicted MC events in the i-th bin due to 1σ change of the j-th systematic error

σ_j^{sys} = 1σ value of the systematic error

Syst. error parameters;

19: neutrino flux uncertainties

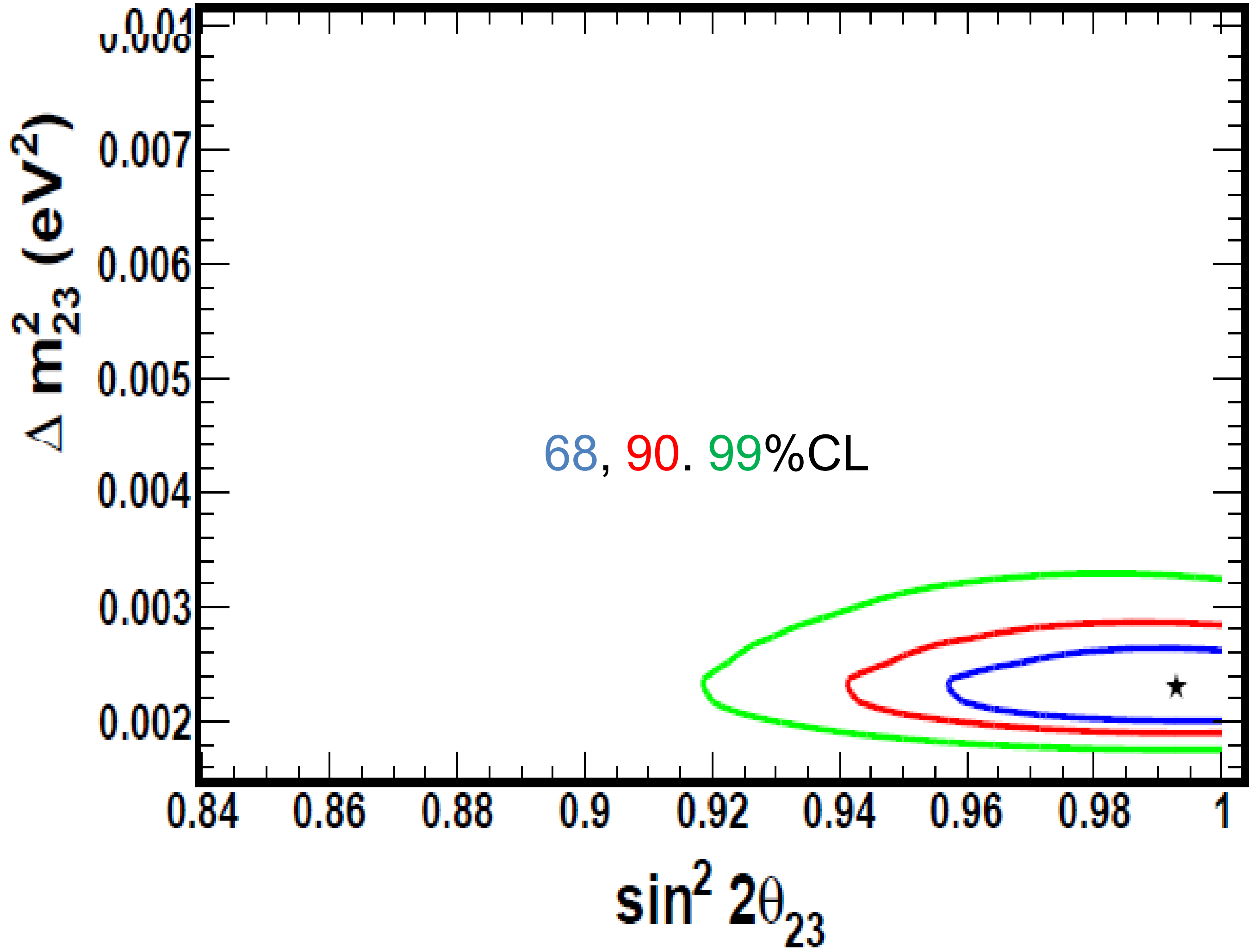
20: neutrino interactions

28×4: event reduction and reconstruction (SK-1 to 4)

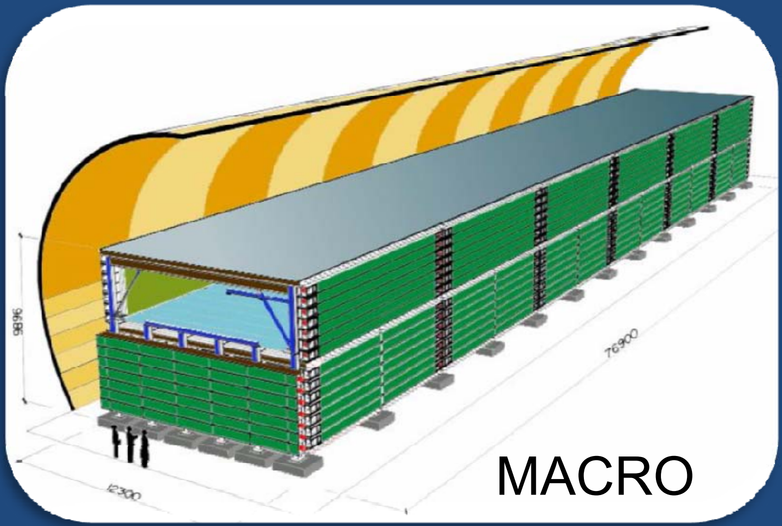
<u>Total: 151</u>

$\nu_\mu \rightarrow \nu_\tau$ allowed parameter region

Y. Itow (SK) nu2012



various atmospheric ν experiments



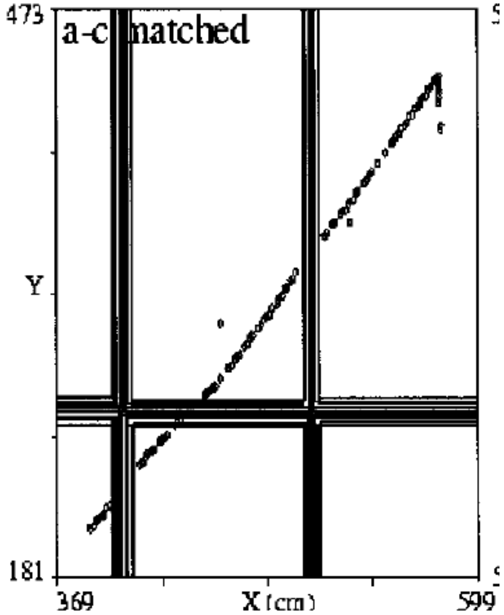
Soudan-2

MINOS
(atmospheric ν)

Soudan-2

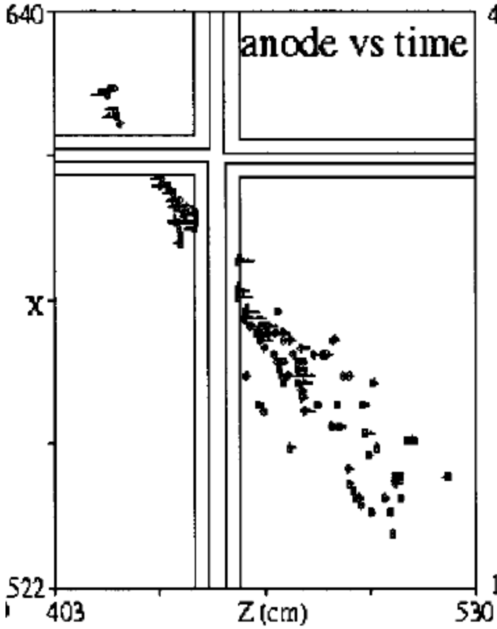
(1989-2001)

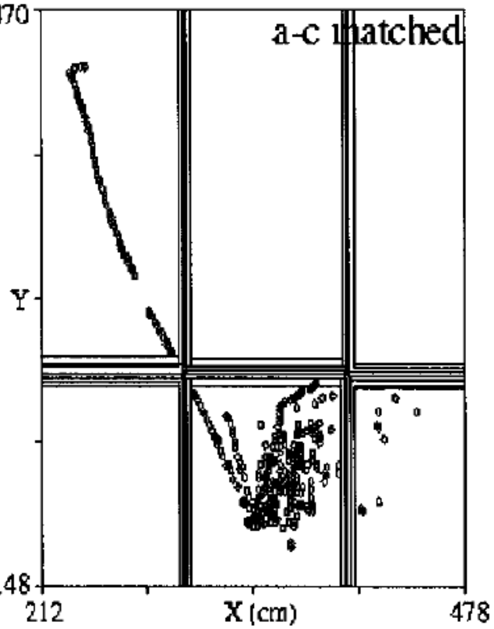
ν_μ CC
quasi-elastic



770 ton fiducial mass

ν_e CC



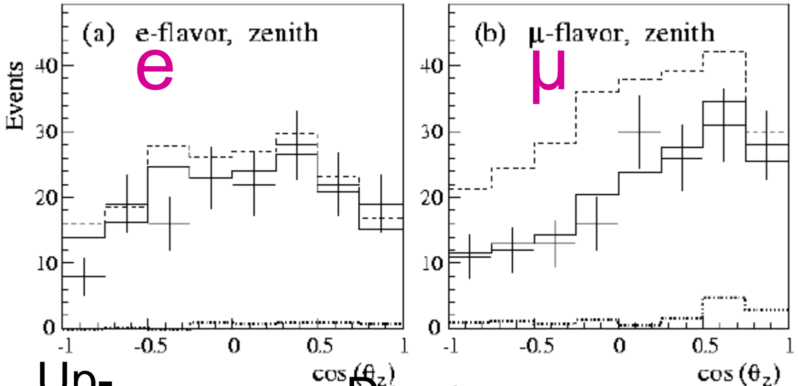


ν_μ CC
deep inelastic

Soudan-2 data

Phys.Rev. D68 (2003) 113004

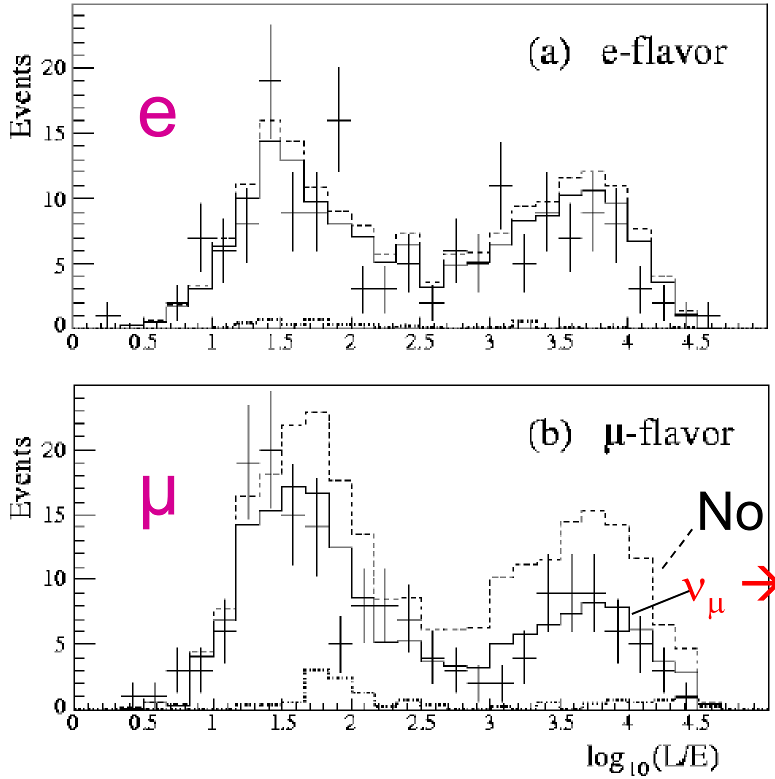
Zenith angle



Up-going

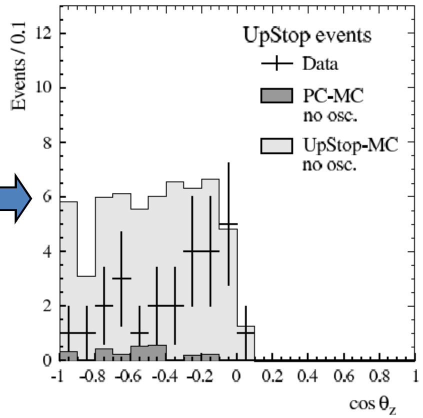
Down-going

Reconstructed L_ν / E_ν dist.

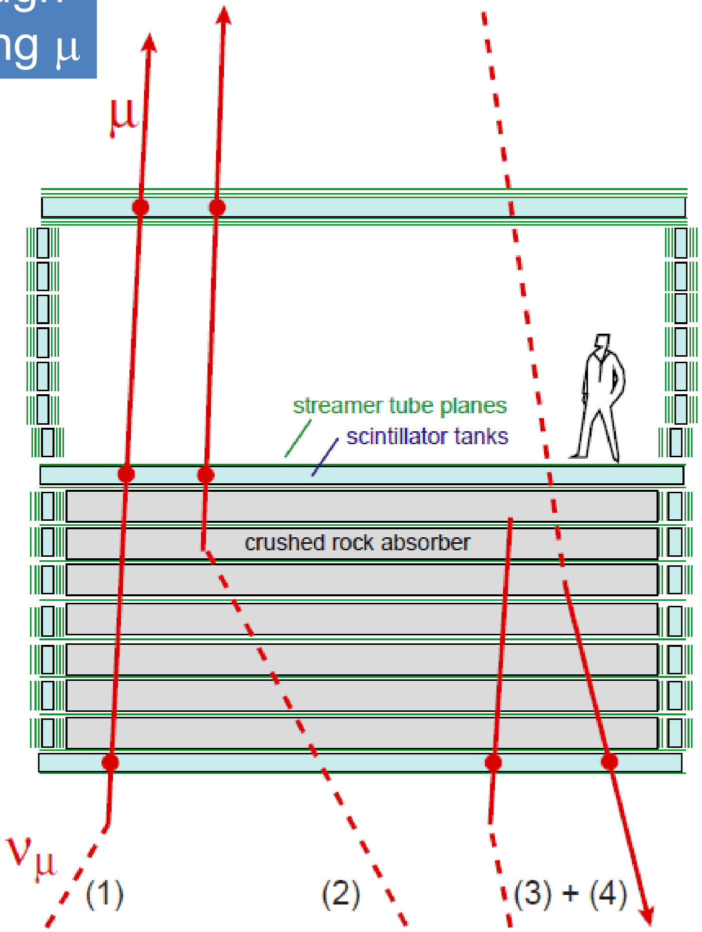


hep-ex/0507068

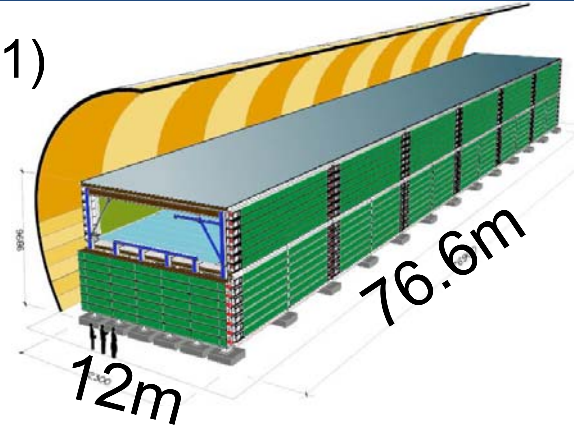
Upward stopping muons

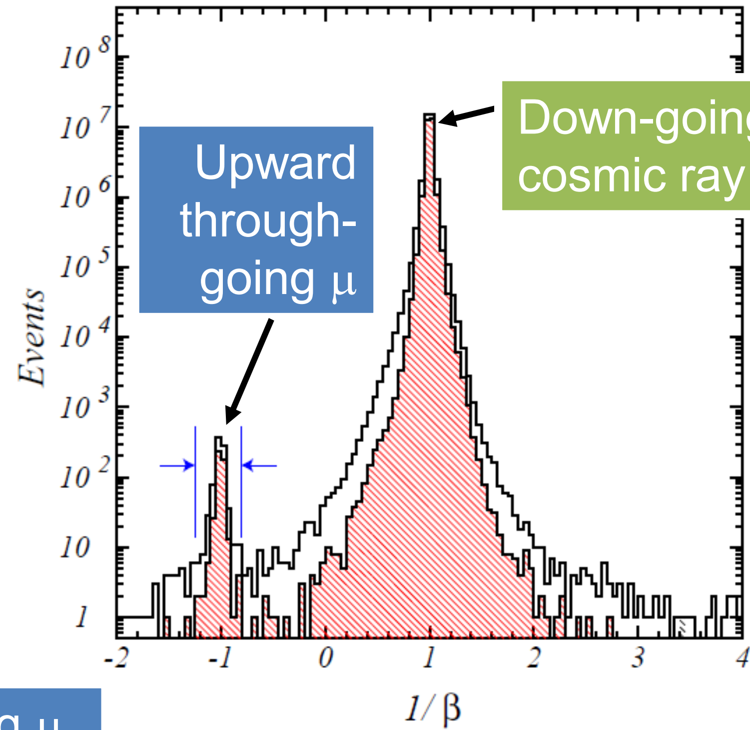


MACRO



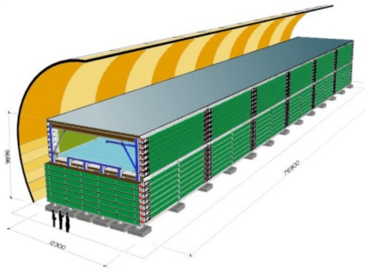
(1989-2001)

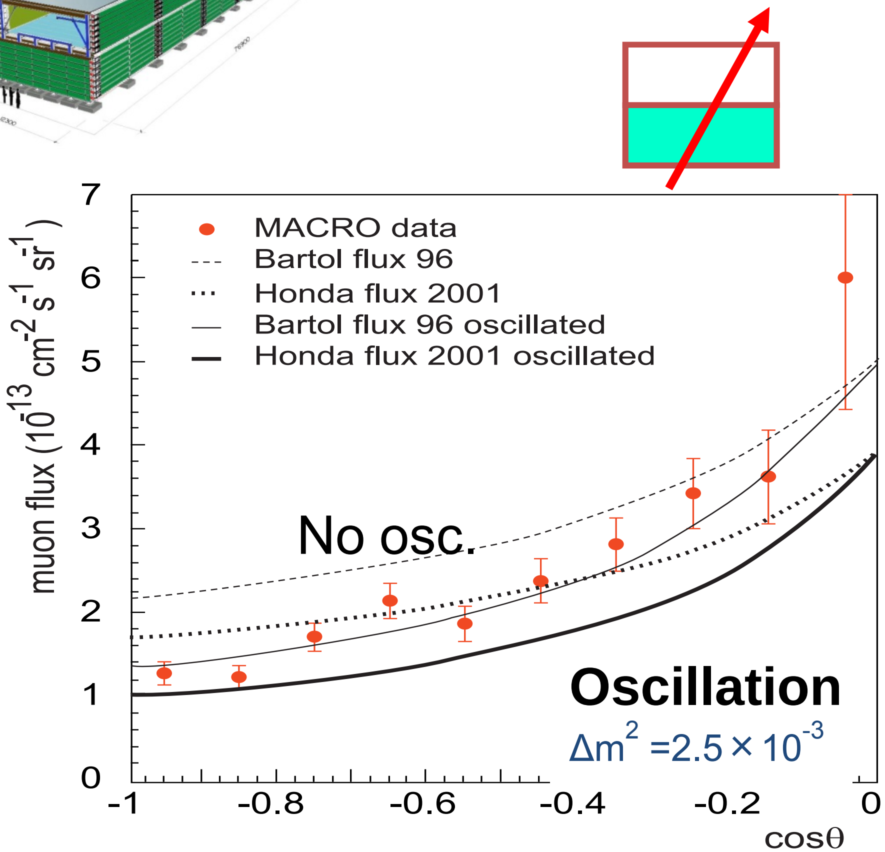


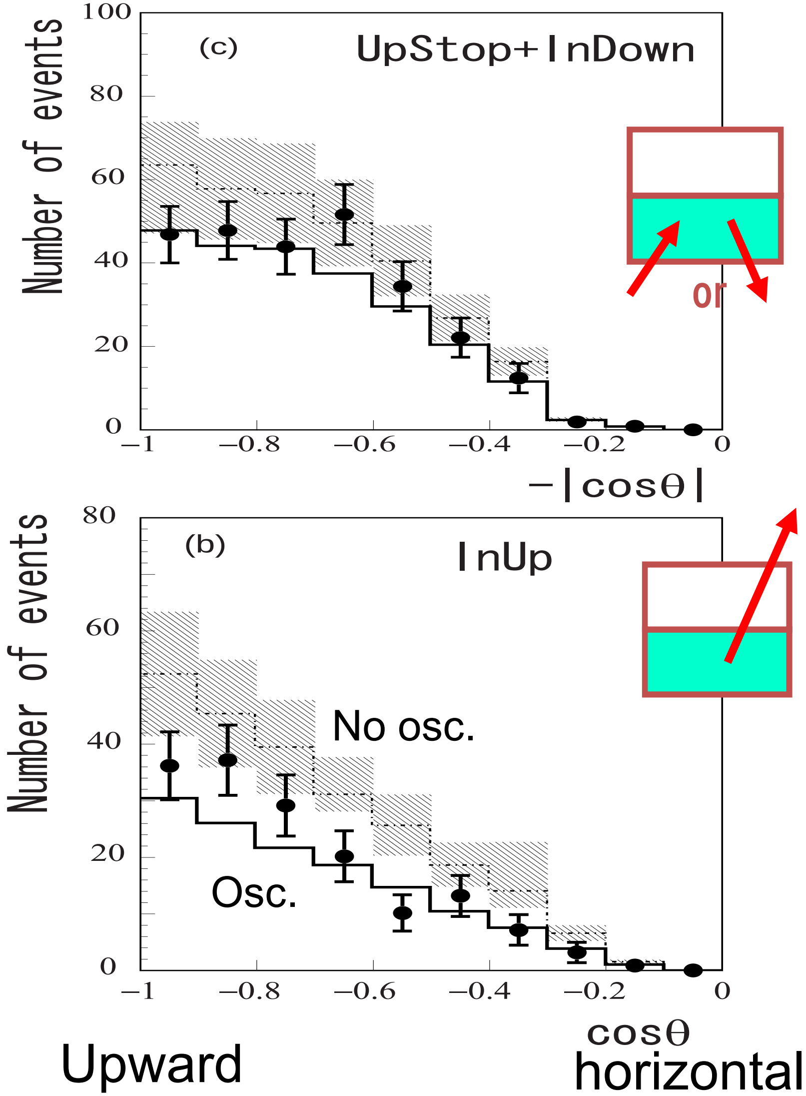


MACRO data

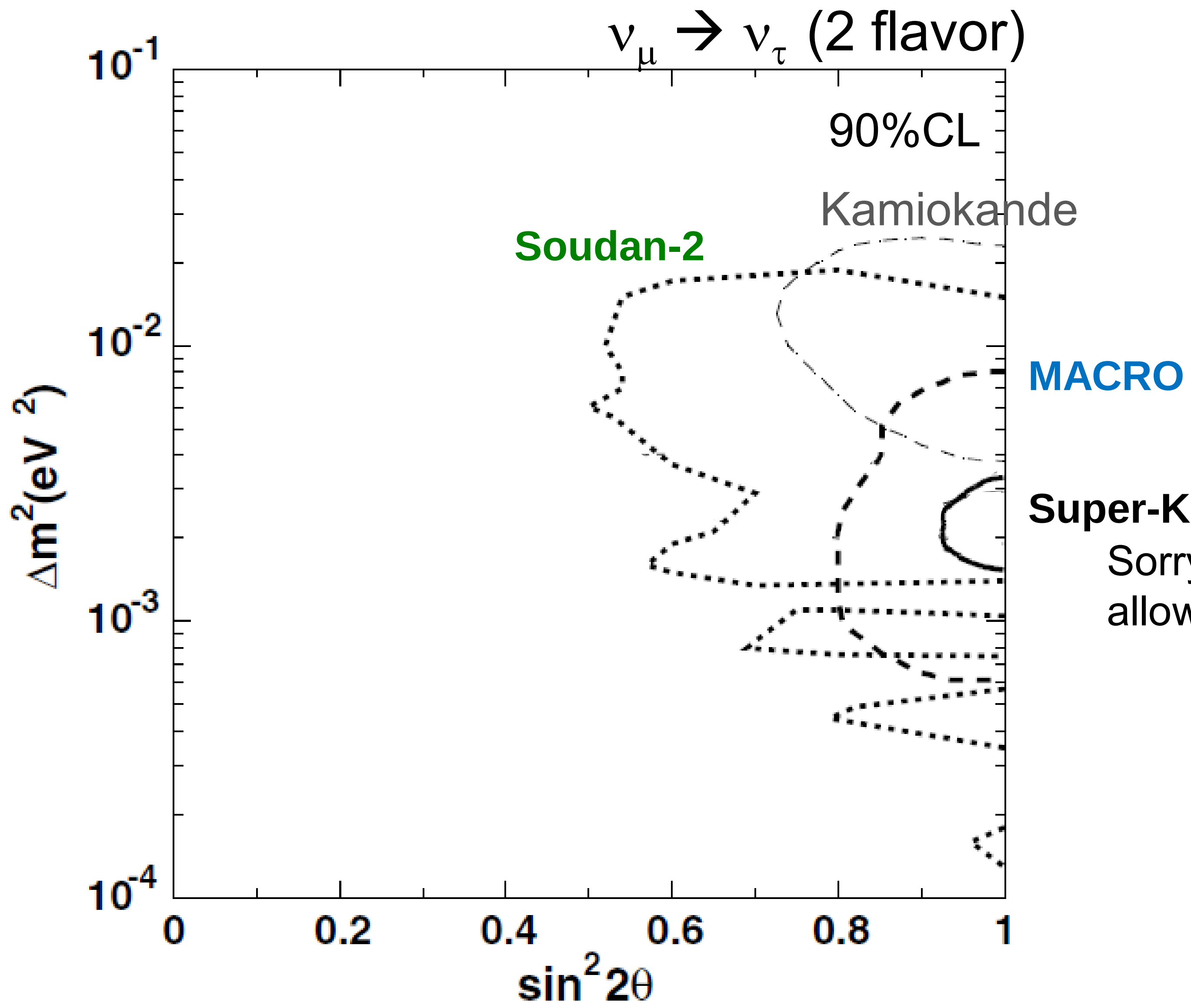
PLB 566 (2003) 35
EPJ C36(2004)323





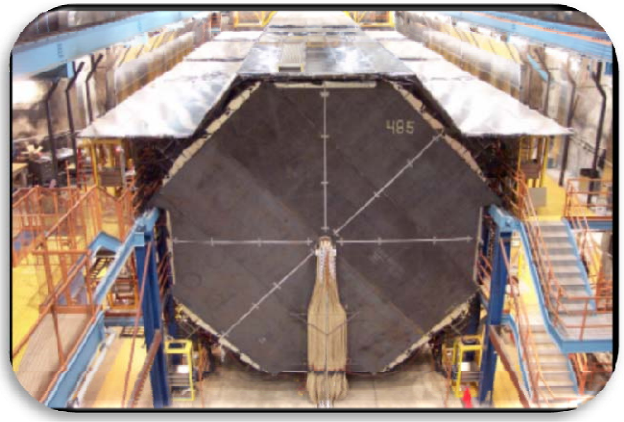


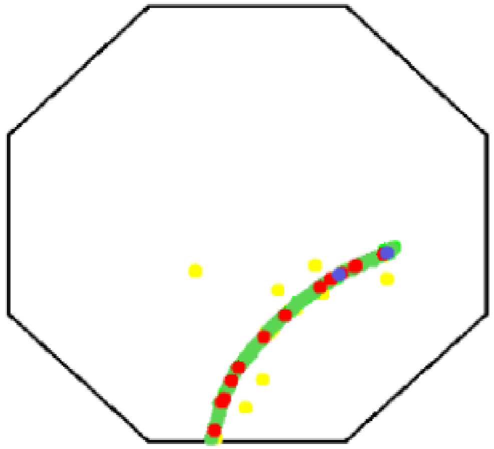
$\nu_\mu \rightarrow \nu_\tau$ oscillation parameters



Sorry, but the SK allowed region is old.

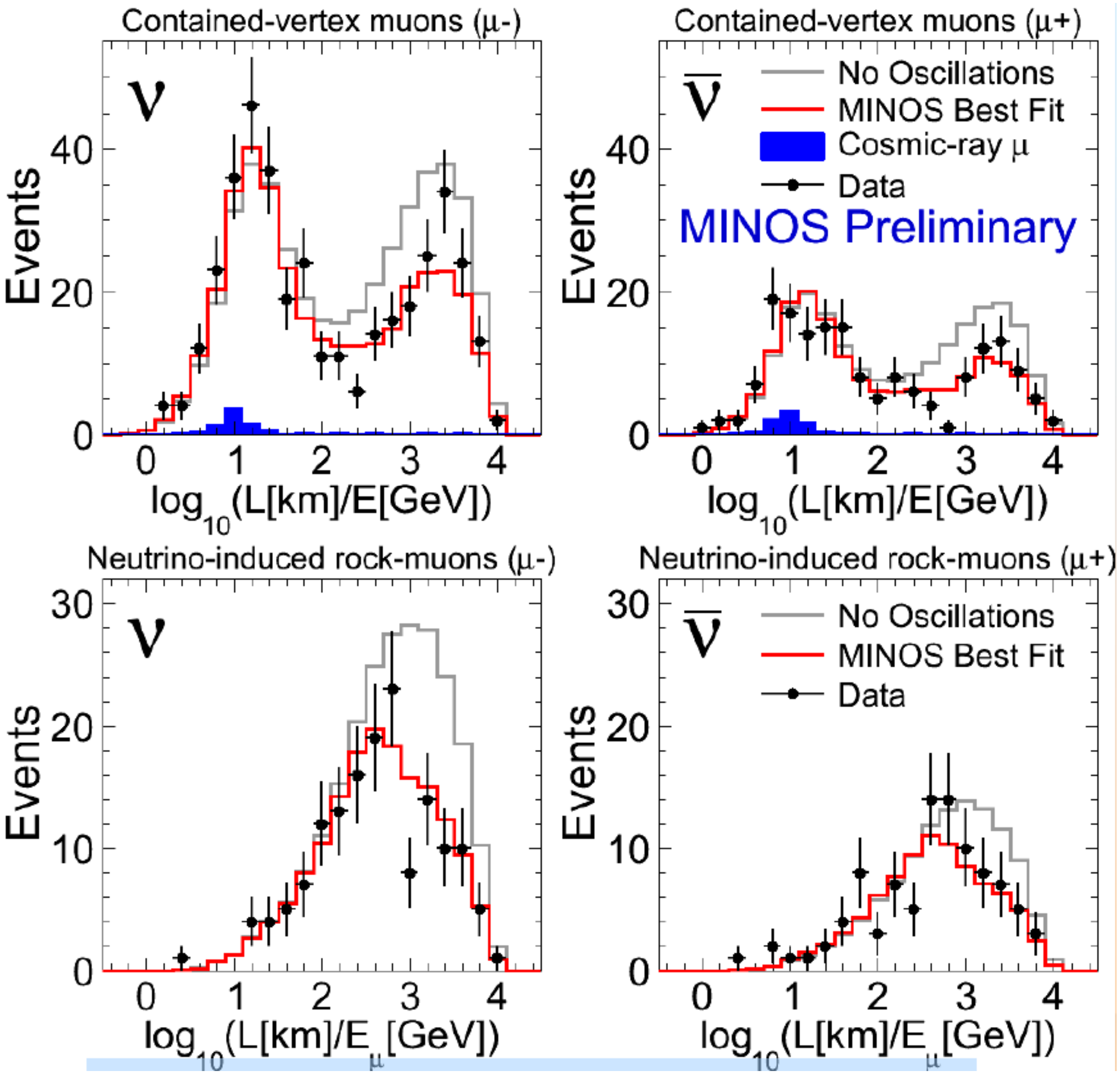
MINOS (atmospheric)



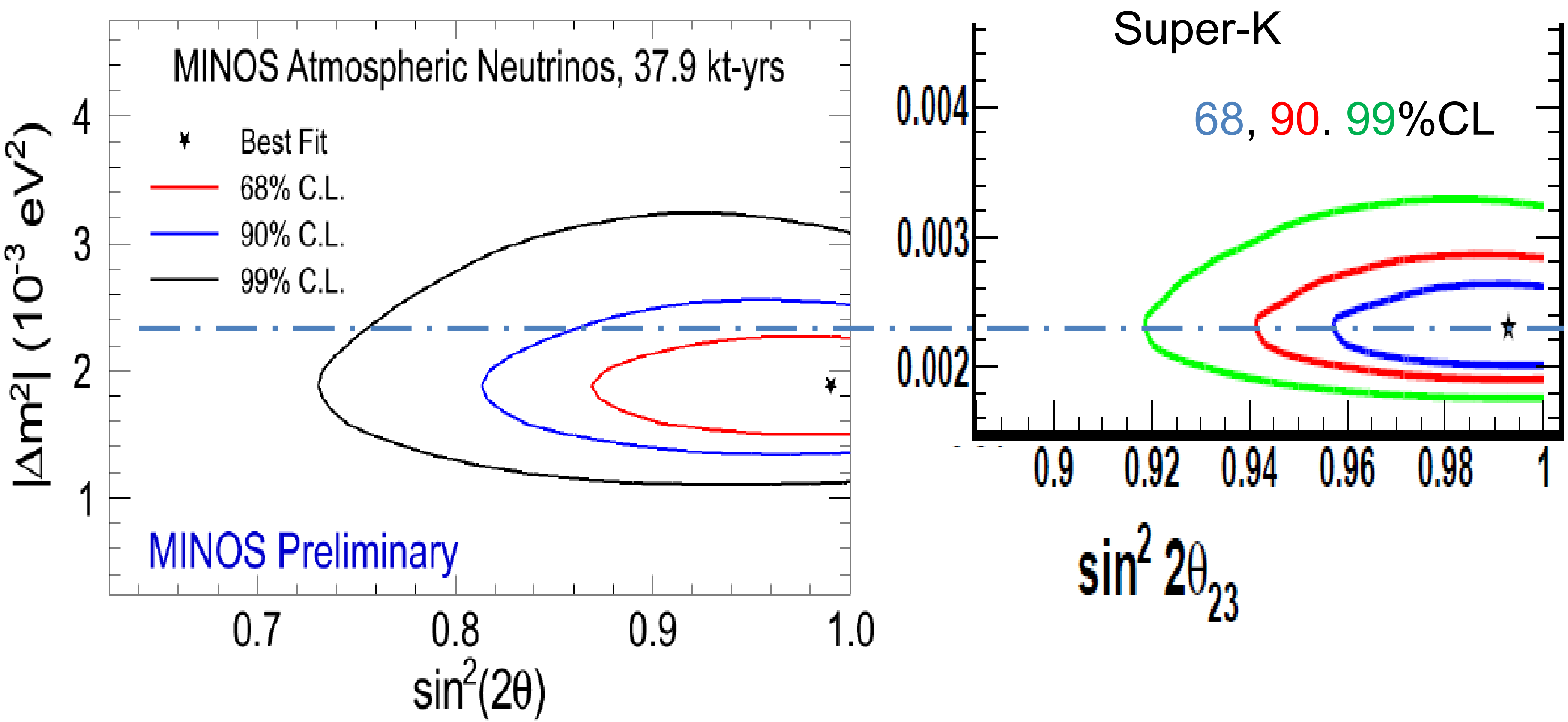


Separation of ν_μ and anti-ν_μ

MINOS nu2012 (37.9 kton・yr)



$\nu_\mu \rightarrow \nu_\tau$ oscillation parameters from atmospheric ν experiments

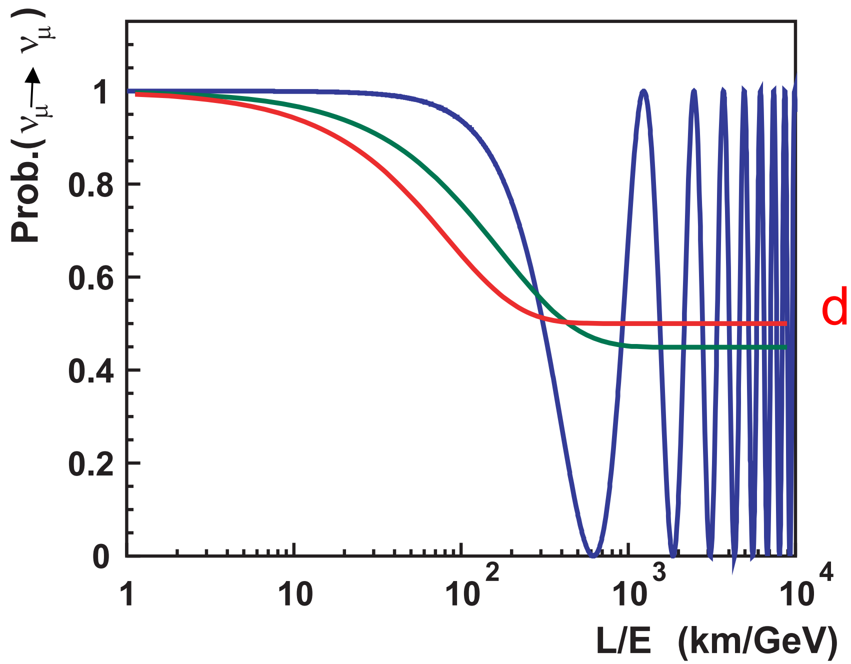


Allowed parameter regions from SK and MINOS, as well as those from Soudan-2 and MACRO (not shown in this page), are consistent.

L/E analysis

L/E analysis: Original motivation

SK PRL 93, 101801 (2004)



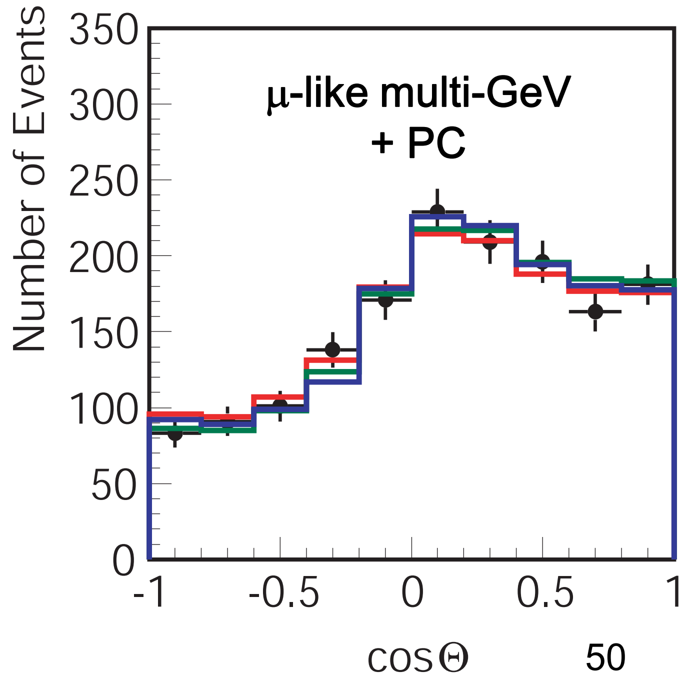
oscillation

decoherence

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \cdot \left(1 - \exp\left(-\gamma_0 \frac{L}{E}\right)\right)$$

decay

$$P_{\mu\mu} = \left(\cos^2\theta + \sin^2\theta \cdot \exp\left(-\frac{m}{2\tau}\frac{L}{E}\right)\right)^2$$

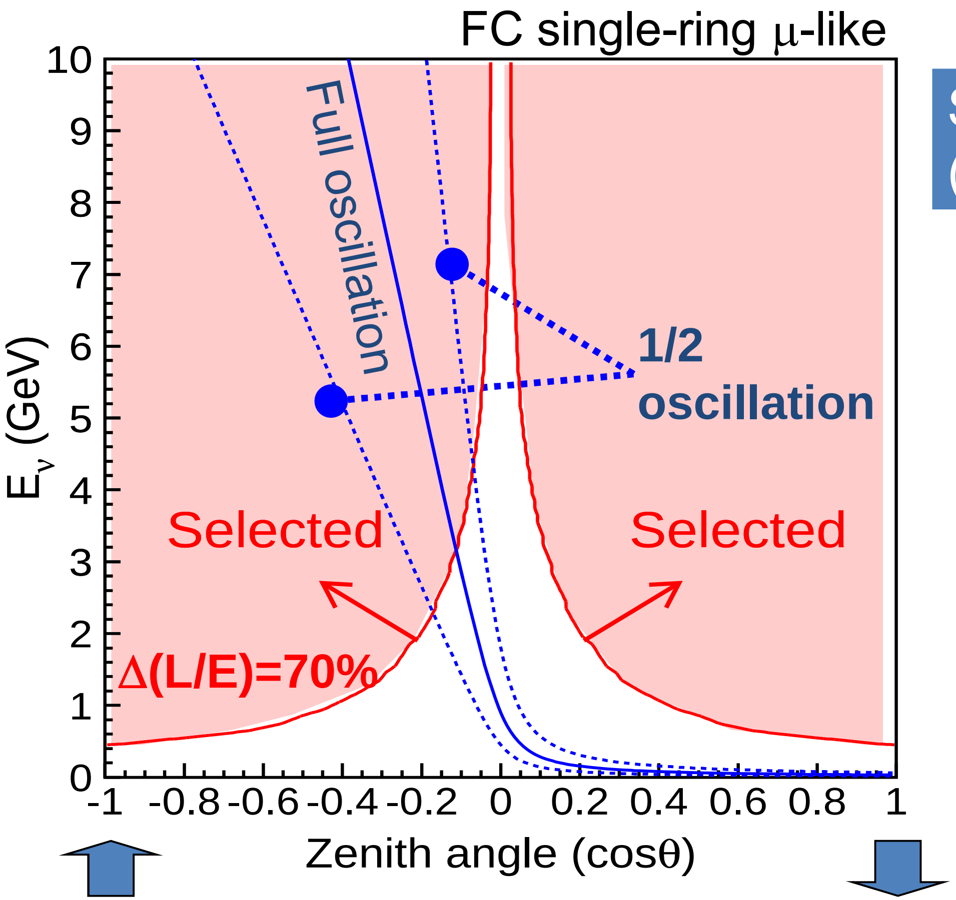


Should observe this dip!

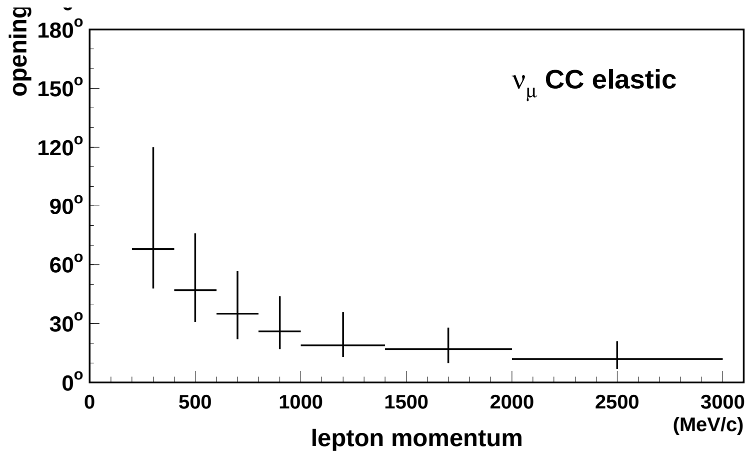
→ Further evidence for oscillation
→ Strong constraint on oscillation parameters, especially Δm^2

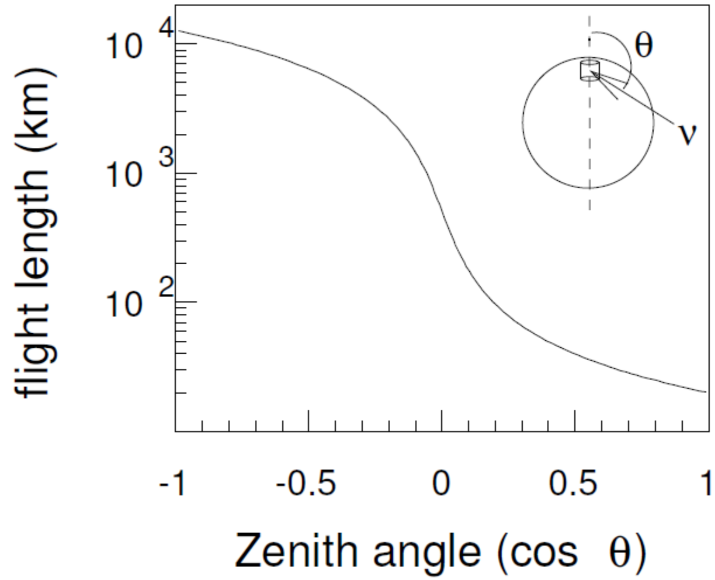
Selection criteria

SK PRL 93, 101801 (2004)



Select events with high L/E resolution:
(Δ(L/E) < 70%)





Similar cuts for: FC multi-ring μ-like,

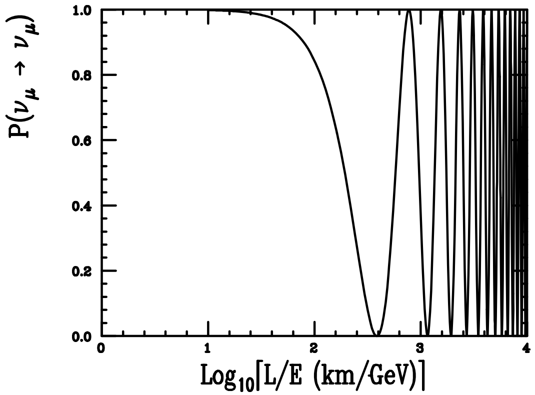
OD stopping PC, and

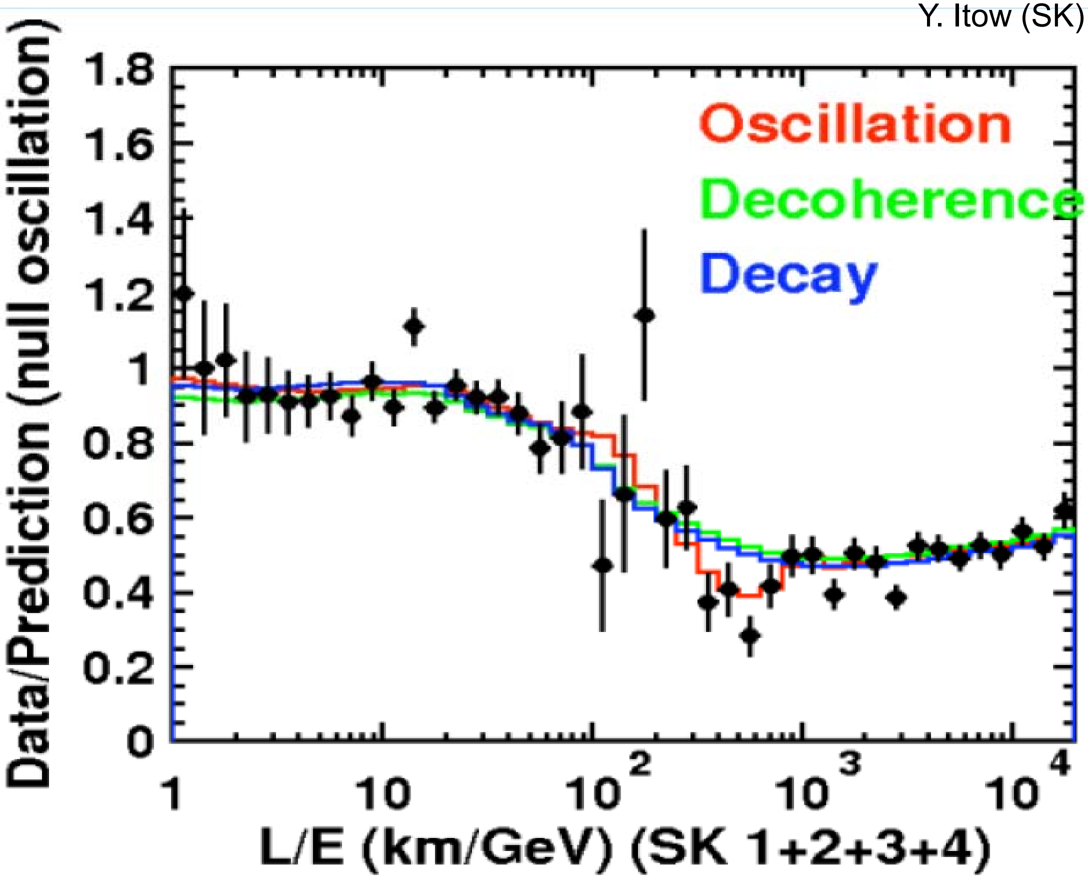
OD through-going PC

L/E analysis

Initial results PRL 93, 101801 (2004)
Y. Itow (SK) nu2012

“Perfect” experiment

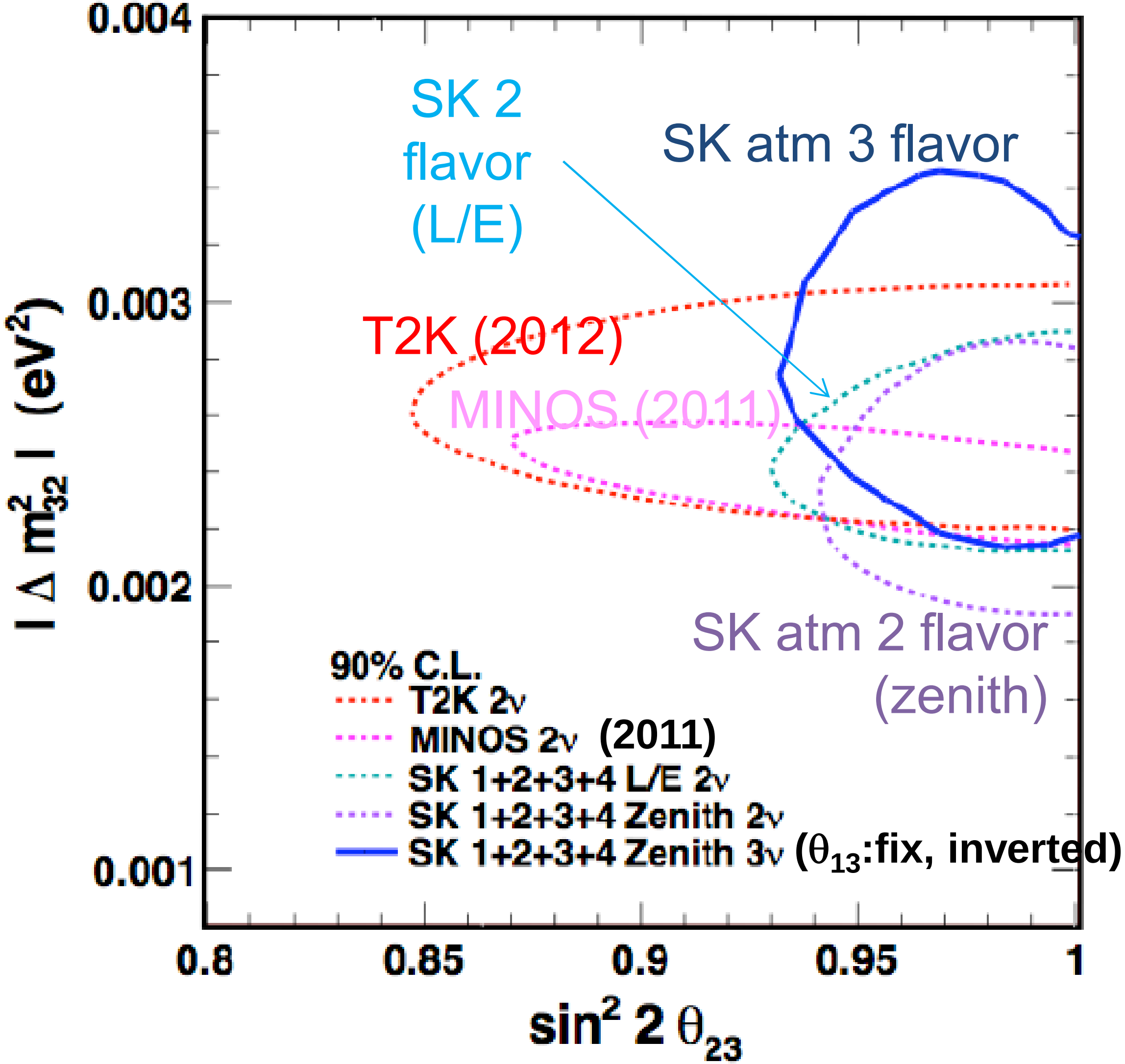




A dip is seem around L/E = 500 km/GeV (first oscillation minimum).
Oscillation gives the best fit to the data.
Decay and decoherence models disfavored by 4.0 and 4.8σ, resp.

Allowed parameter regions from present experiments

Y. Itow (SK) nu2012



These results agree very well!

Central value:
$\Delta m^2 = 2.39 \times 10^{-3} eV^2$
(MINOS 2012)
$\sin^2 2\theta = 0.99$
(SK 2-flavor zenith)
(consistent with maximal mixing, within 1σ!)

Accuracy:
Δm^2: LBL,
$\sin^2 2\theta$: still atm.
(until 2012…)

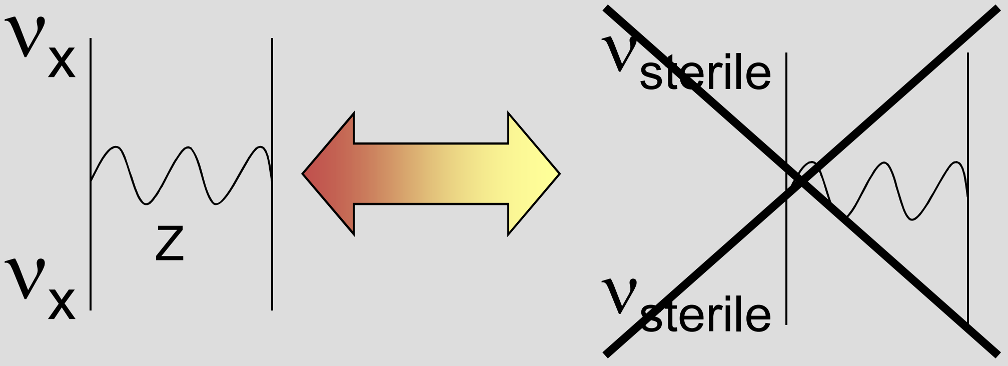
Oscillation to ν_τ or $\nu_{sterile}$?

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.

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

SK, PRL85,3999 (2000)

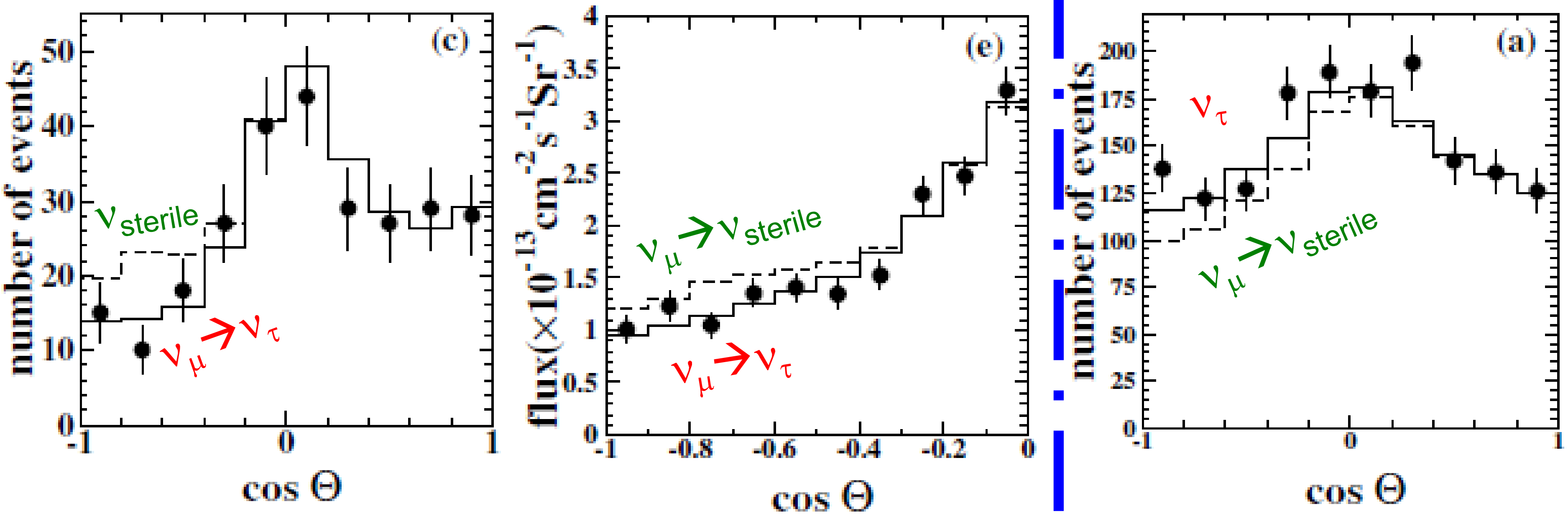
Matter effect

High E PC events (Evis>5GeV)

Up through muons

Neutral current

Multi-ring e-like, with Evis >400MeV



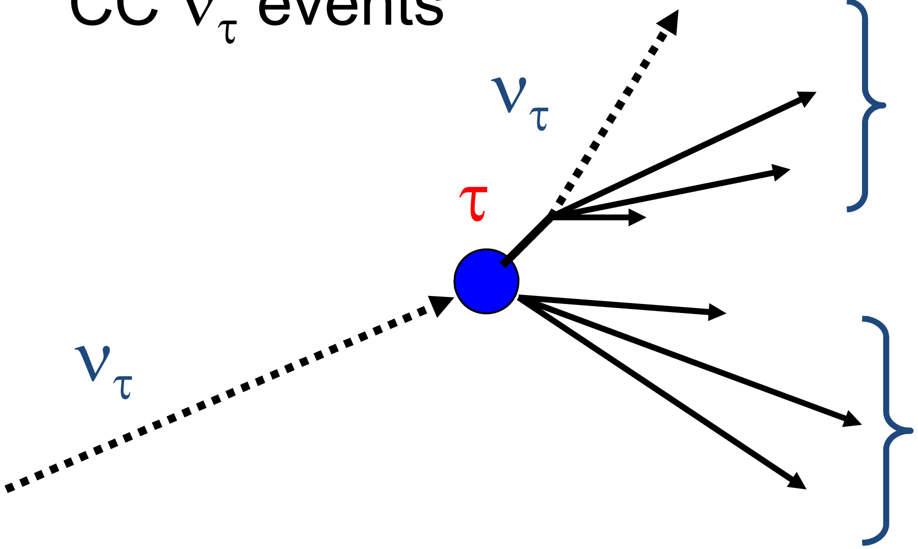
→ Pure $\nu_\mu \rightarrow \nu_{sterile}$ excluded (@99%CL)

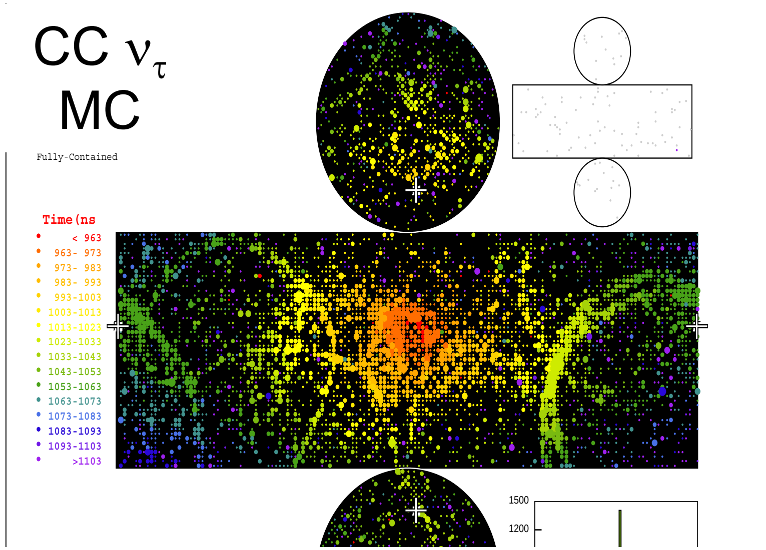
Tau neutrino appearance

We would like to confirm $\nu_\mu \rightarrow \nu_\tau$ by observing tau produced by ν_τ interactions.

Detecting CC ν_τ events (Super-K)

CC ν_τ events





✓ Many particles (hadrons) ….
(But no big difference with the other (NC) events.)

Neural Network (NN) analysis

✓ Upward going only

Zenith angle

Only ~ 1.0 CC ν_τ FC events/kton・yr

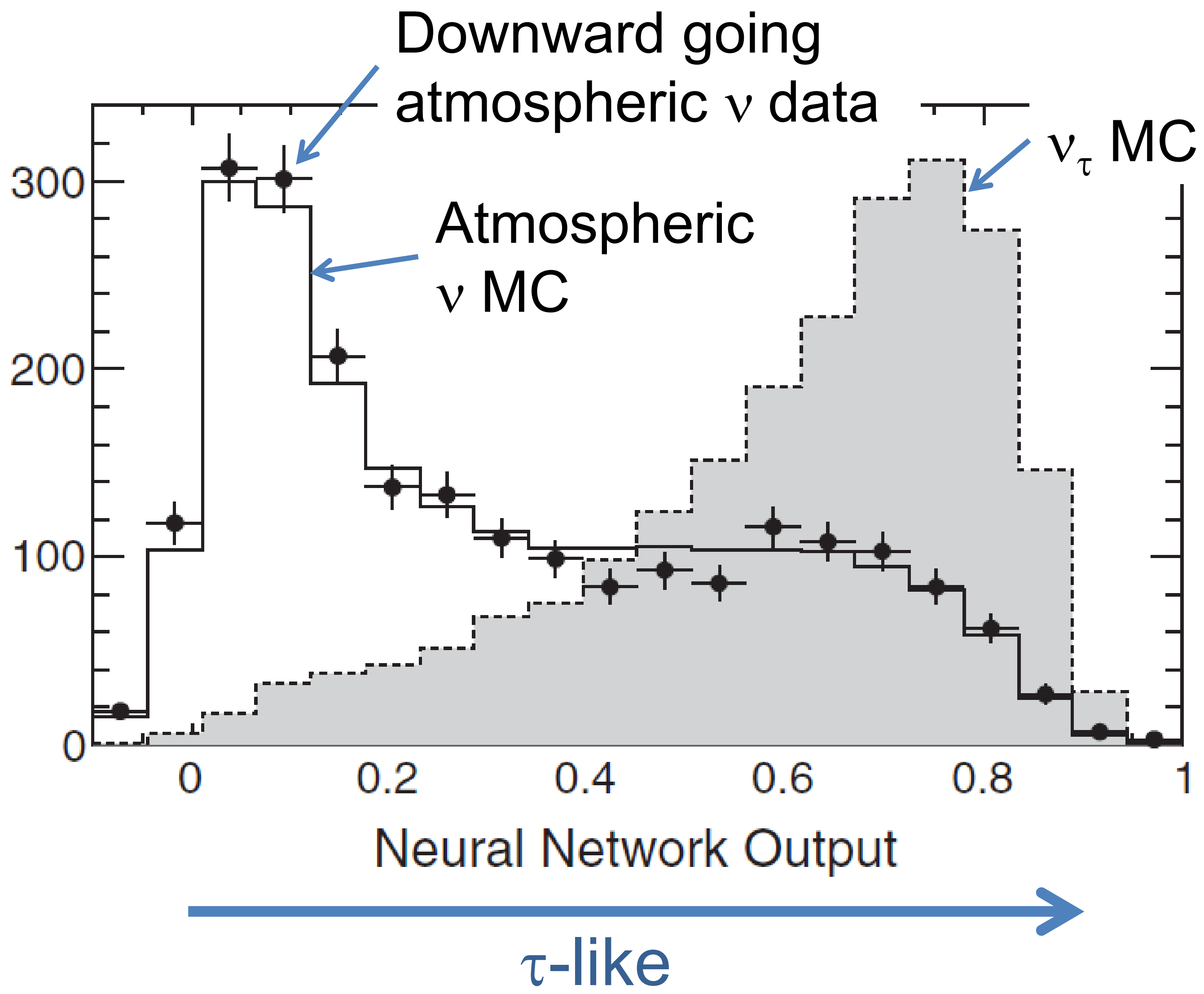
(BG (other ν events) ~ 130 ev./kton・yr)

Neural Network

SK PRL 110(2013)181802

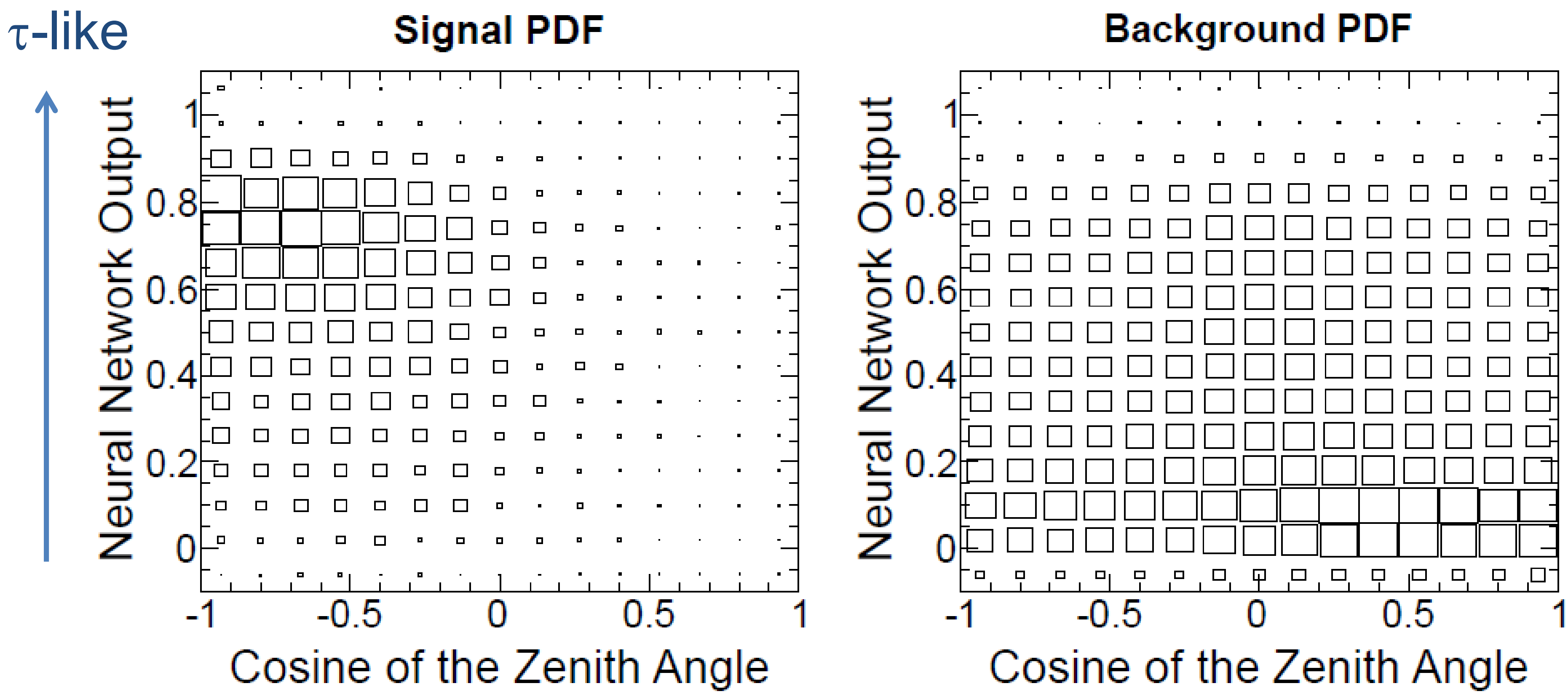
NN inputs:

- ✓$E_{visible}$
- ✓PID (highest E ring)
- ✓N($\mu \rightarrow e$)
- ✓Distance (vertex - e-vertex)
- ✓Sphericity
- ✓N (Ch. ring candidates)
- ✓$E_{visible}$ fraction of the 1st ring



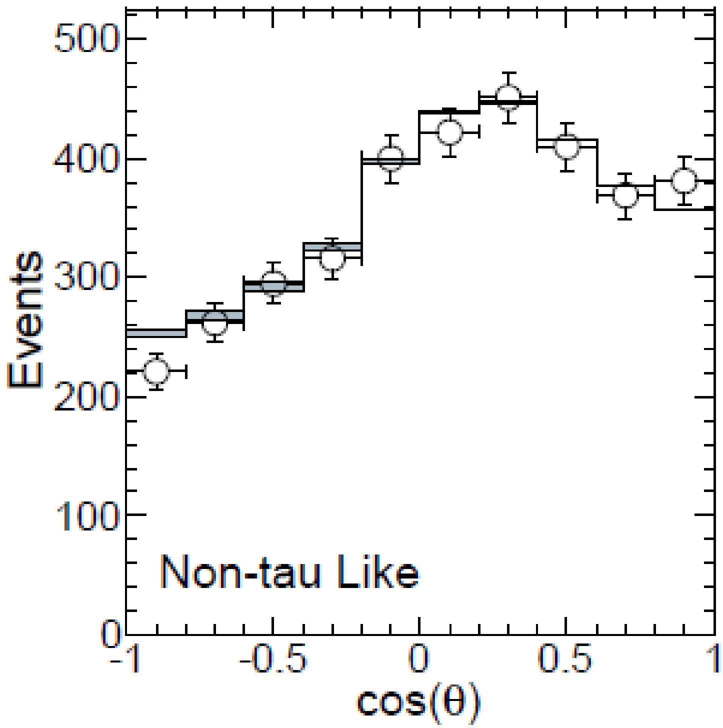
NN output vs. Zenith angle

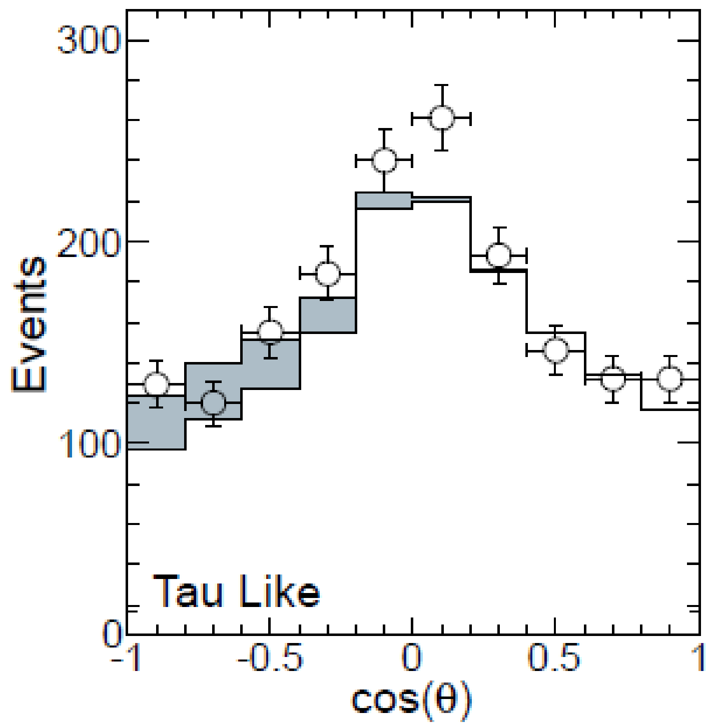
SK PRL 110(2013)181802



Zenith angle dist. and fit results

SK PRL 110(2013)181802





Fitted number of τ events	180.1±44.3(stat) +17.8 / -15.2(syst)
Exp'd number of τ events	120.2+34.2/-34.8(syst)

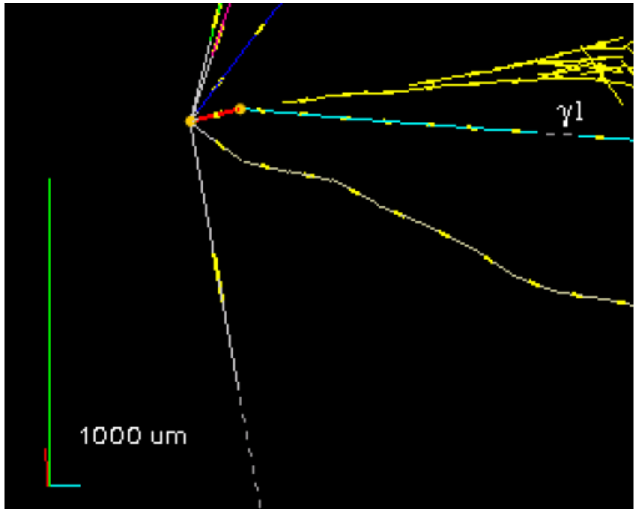
Compared with the previous results (2006), systematic error due to θ_{13} uncertainty was greatly reduced.

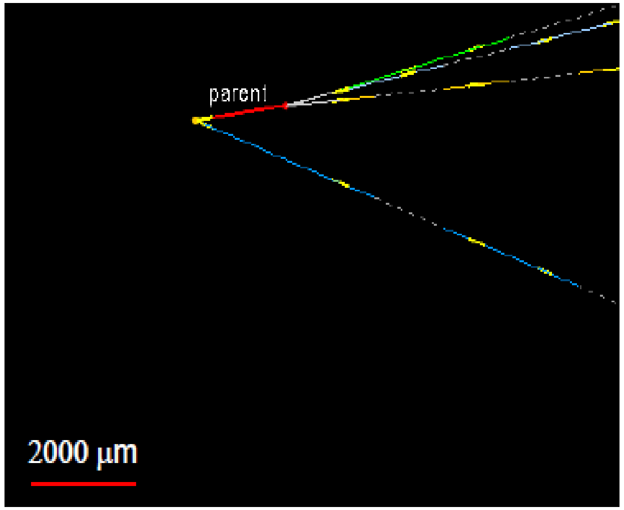
τ-appearance signal at 3.8σ.

Comparison: OPERA ν_τ events

M. Nakamura (OPERA) Nu2012

Years	Status	Number of ev.	Expected ν_τ (prelim)	Obs'd ν_τ candidates	Expected BG
2008 - 2009	Finished	2783		1	
2010 - 2011	In analysis	1343		1	
2012	Started				
Total		4126	2.1	**2**	0.2





(3rd event reported)

Results are consistent between atm. and acc. experiments

Summary of Leture-1

- Study of the background for proton decay found unexpected atmospheric ν_μ deficit.
- The ν_μ deficit was concluded as due to neutrino oscillations. Recent atmospheric neutrino data are consistently explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations.
- Results from long baseline accelerator experiments and atmospheric neutrino experiments are consistent.
- .Δm_{23}^2: LBL, $\sin^2 2\theta_{23}$: atm. (until 2012...)
- Tau appearance has been observed by atmospheric neutrino experiment.