The Neutrino Physics Summer School
Fermilab, July 2007

The Evidence for Flavor Change and Oscillations I

Takaaki Kajita (ICRR, U.of Tokyo)

Overall Outline

Lecture 1:

Discovery of atmospheric neutrino oscillations

Lecture 2:

Solving the Solar Neutrino Problem with Solar neutrino oscillations

Lecture 3:

Studies of neutrino oscillations with accelerator and reactor neutrinos

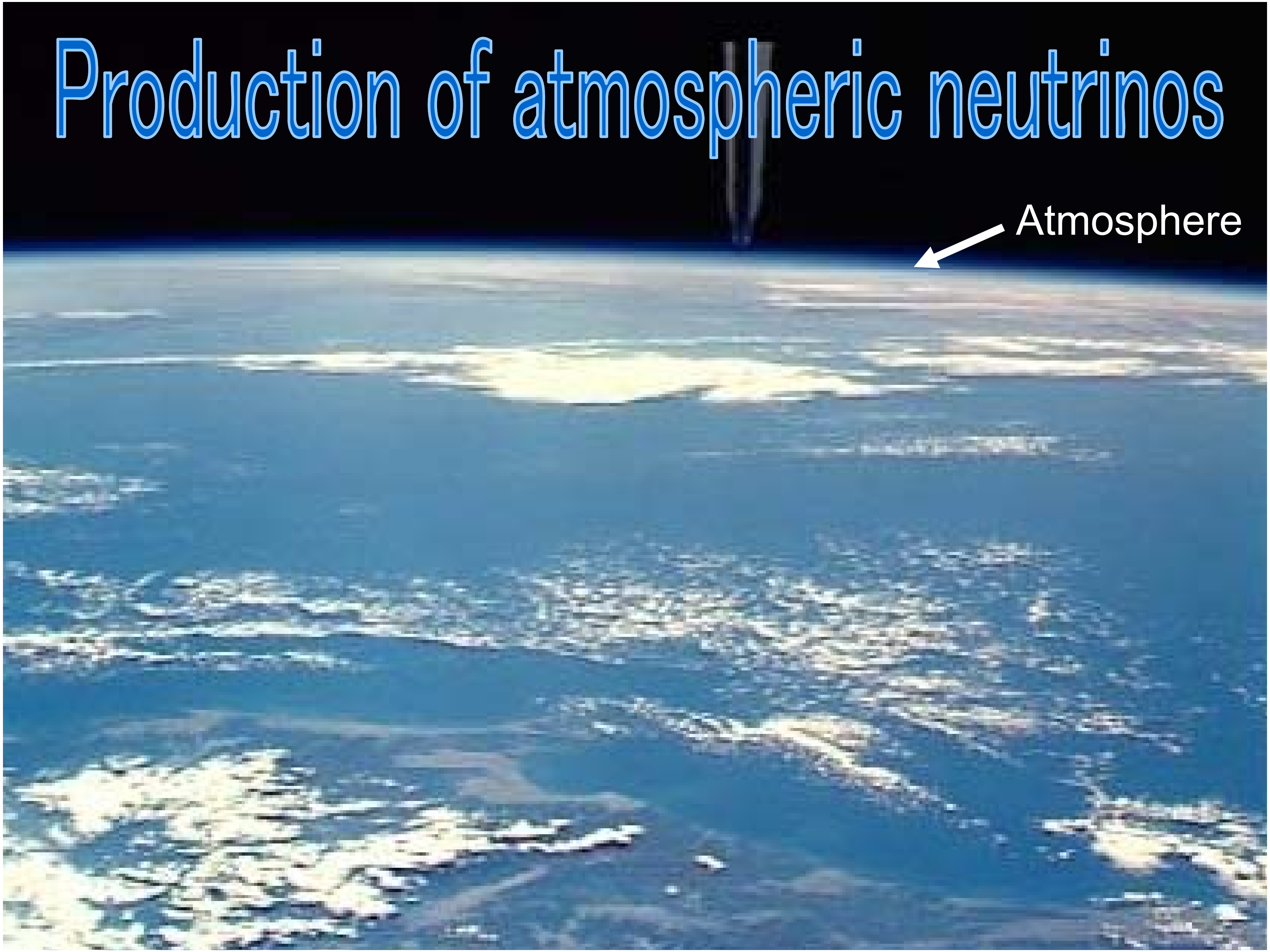
Outline - Lecture 1 -

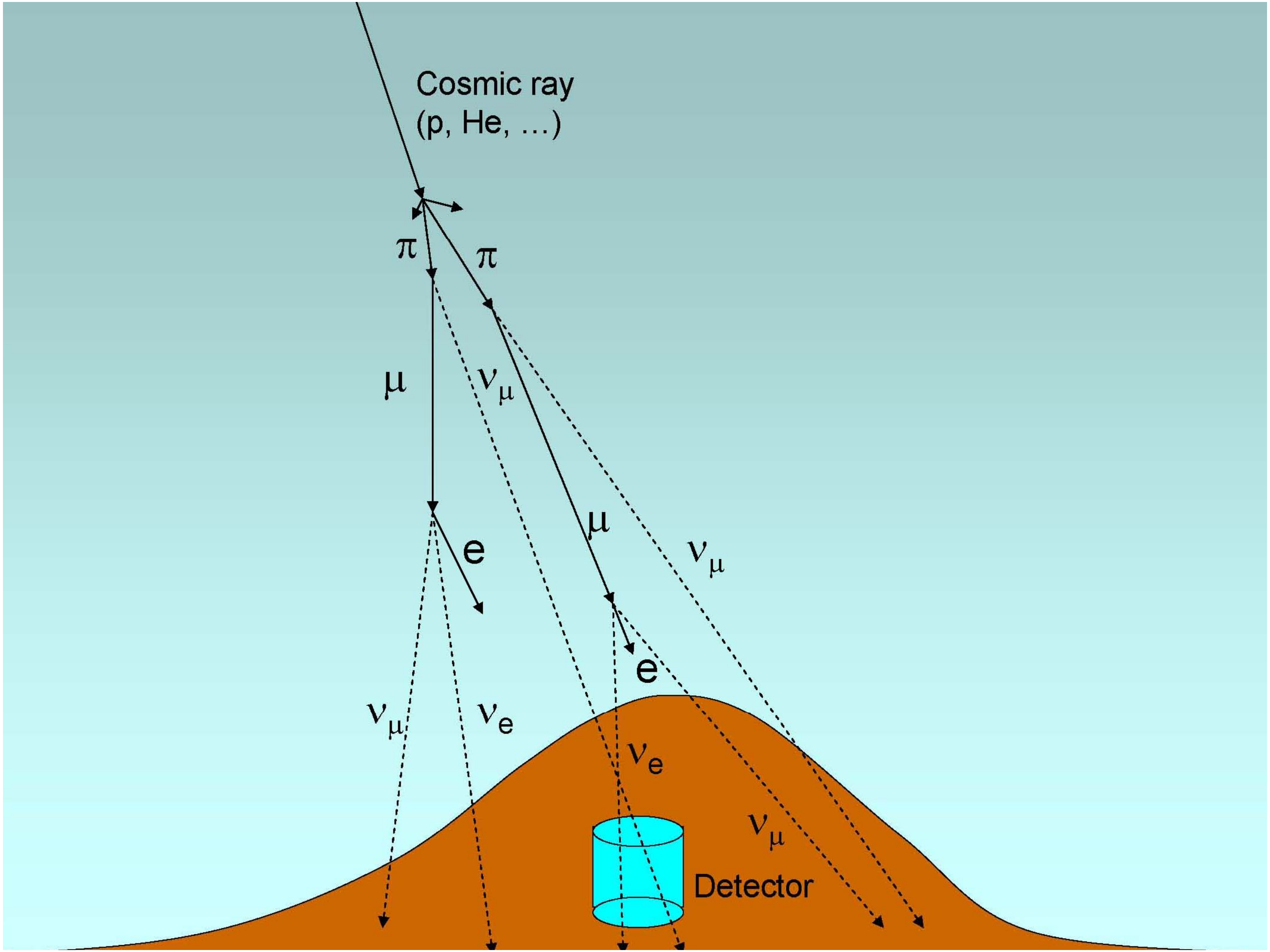
- Production of atmospheric neutrinos
- Some early history (Discovery of atmospheric neutrinos, Atmospheric neutrino anomaly)
- Discovery of neutrino oscillations
- Studies of atmospheric neutrino oscillations
- Summary of Lecture 1

In these lectures, we only discuss 2-flavor oscillations:

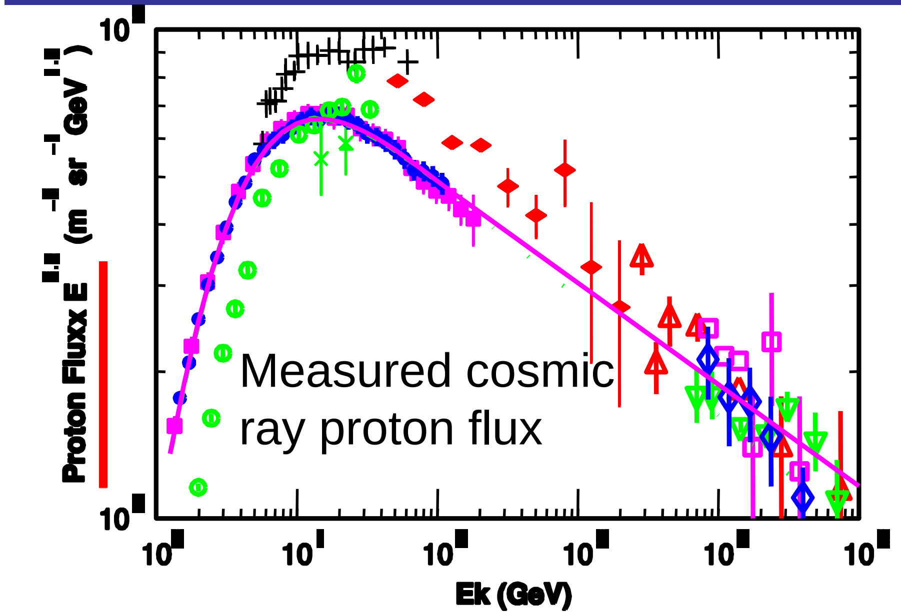
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L_\nu}{E_\nu}\right)$$

Production of atmospheric neutrinos

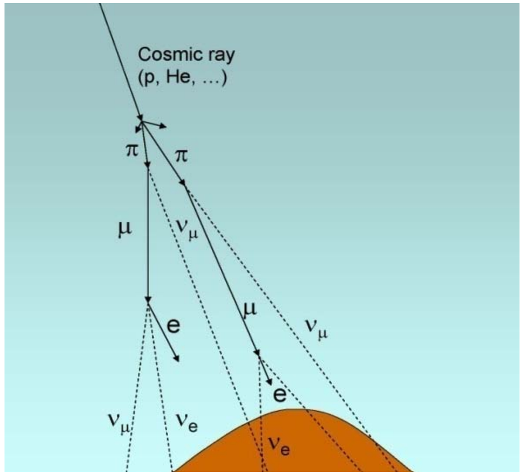


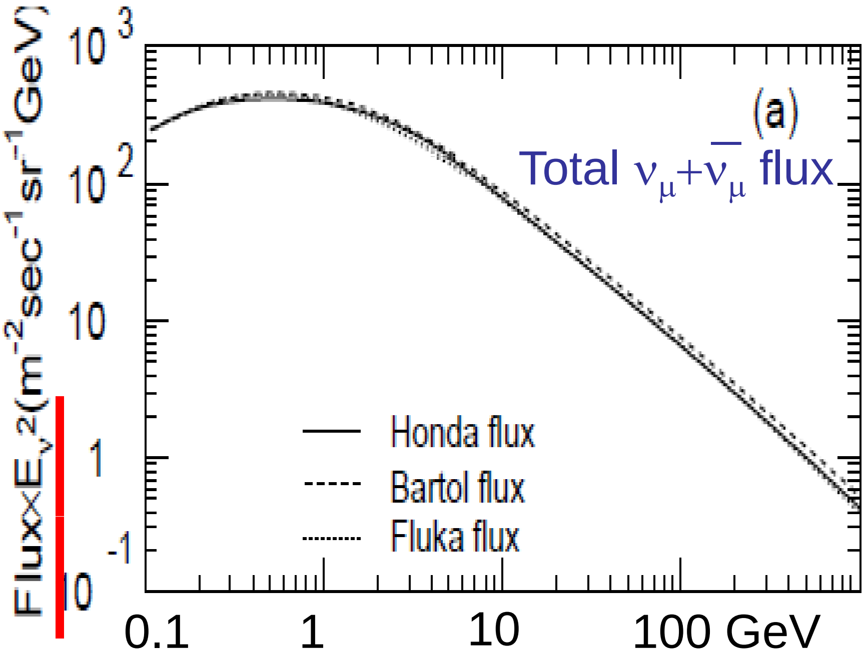
Cosmic ray
(p, He, …)
π
π
μ
ν_μ
μ
e
ν_μ
e
ν_μ
ν_e
ν_e
ν_μ
Detector

Calculating the atmospheric neutrino beam



Measured cosmic ray proton flux





Total $\nu_\mu + \overline{\nu}_\mu$ flux

Do the calculation all over the Earth

+ geomagnetic field

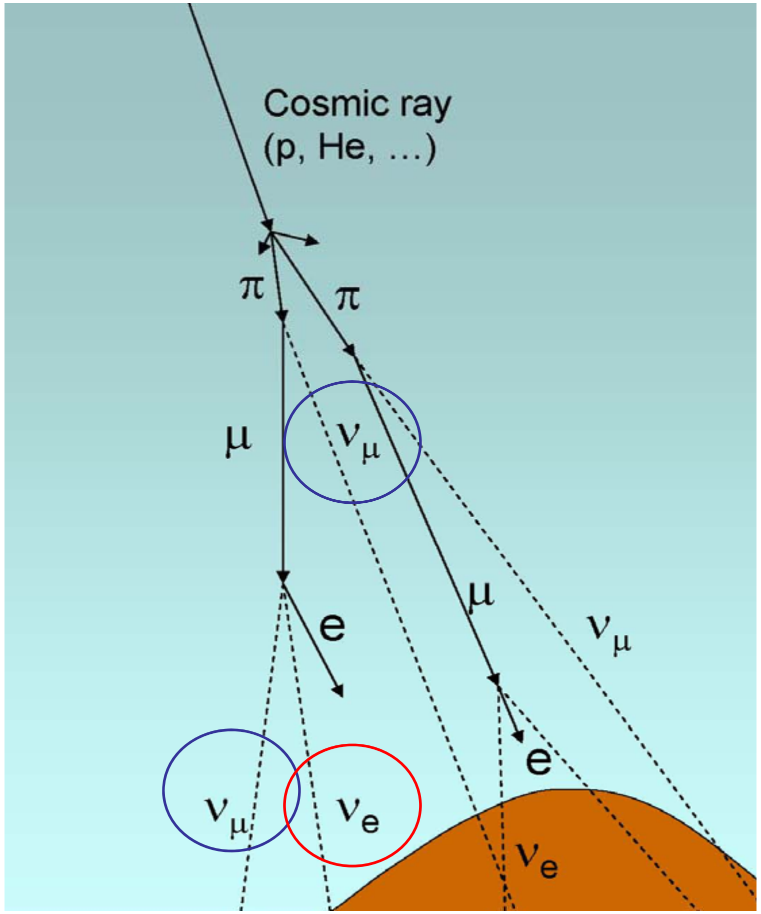
+ (p+Nucleon) int.

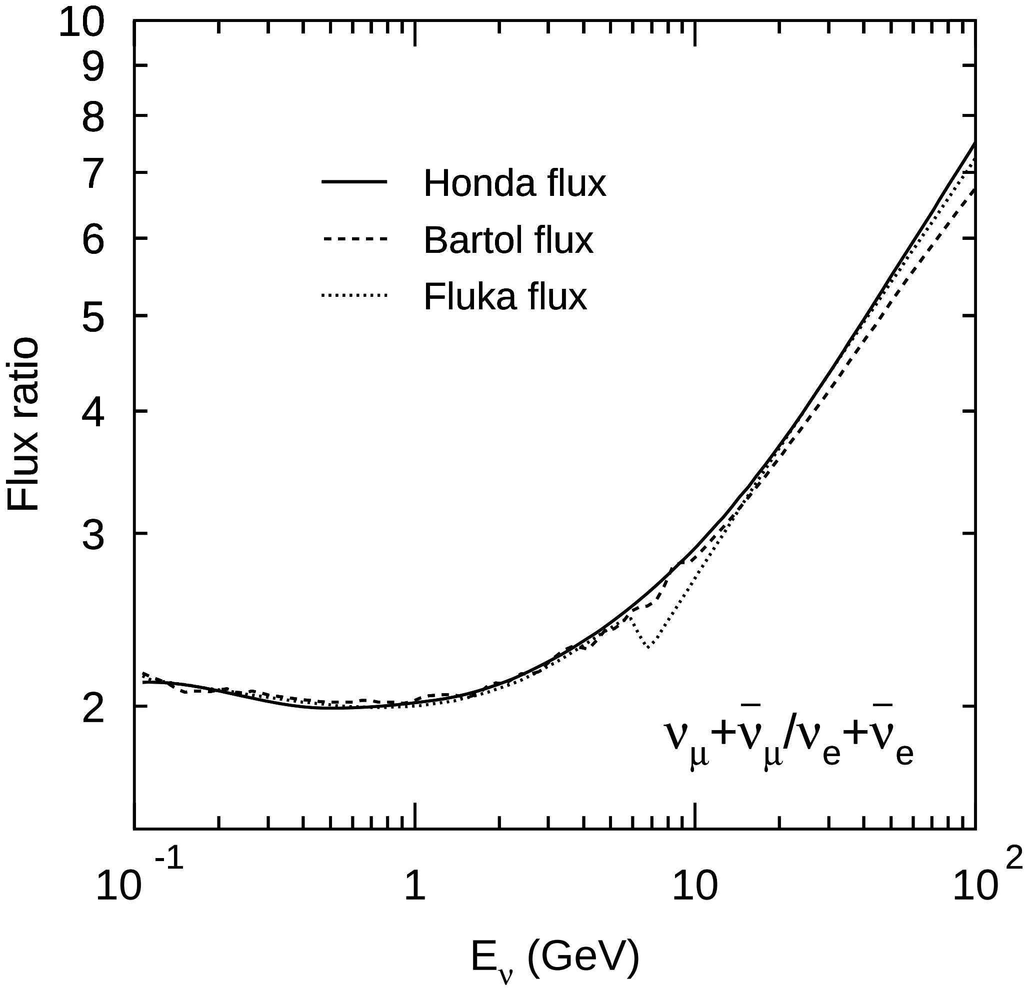
+ decay of π or K

+ ……

Some features of the beam (1)

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

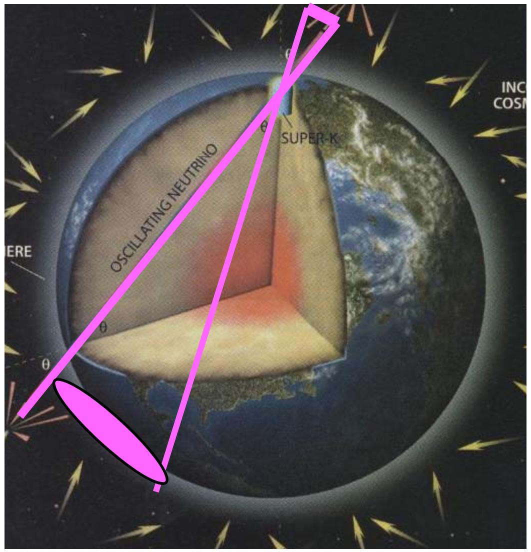




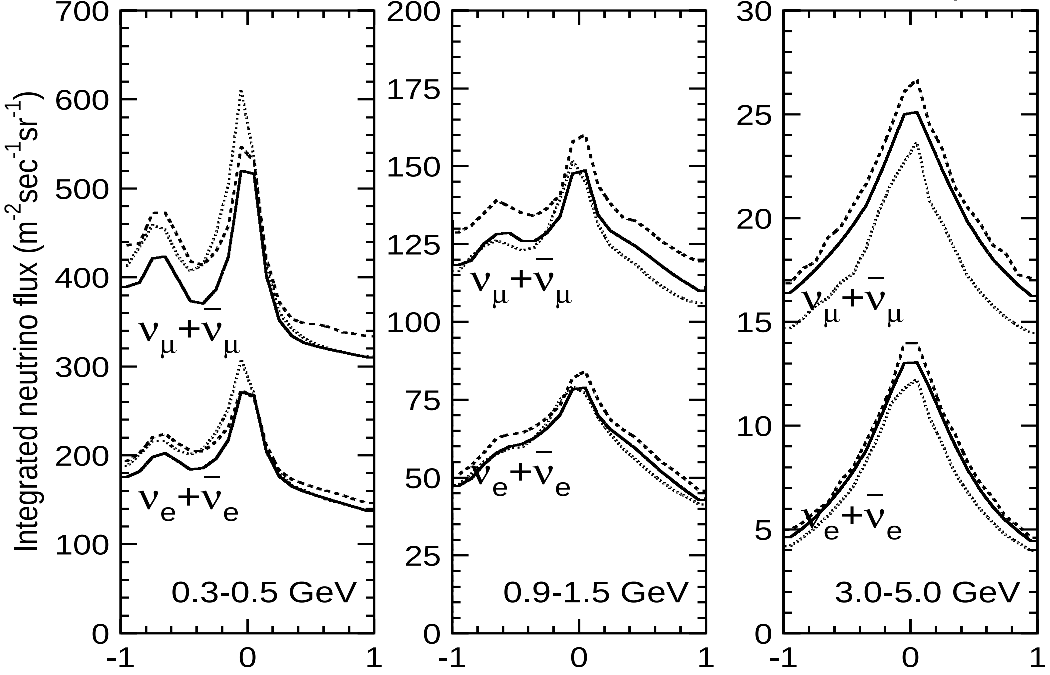
ν_μ/ν_e ratio is calculated to an accuracy of better than 3% below ～5GeV.

Some features of the beam (2)

Zenith angle



@Kamioka (Japan)



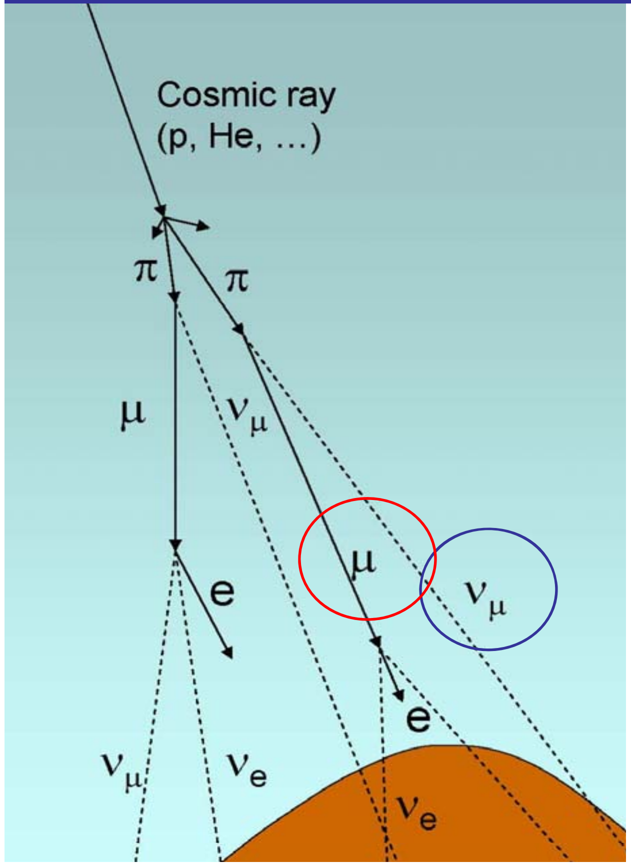
Up-going

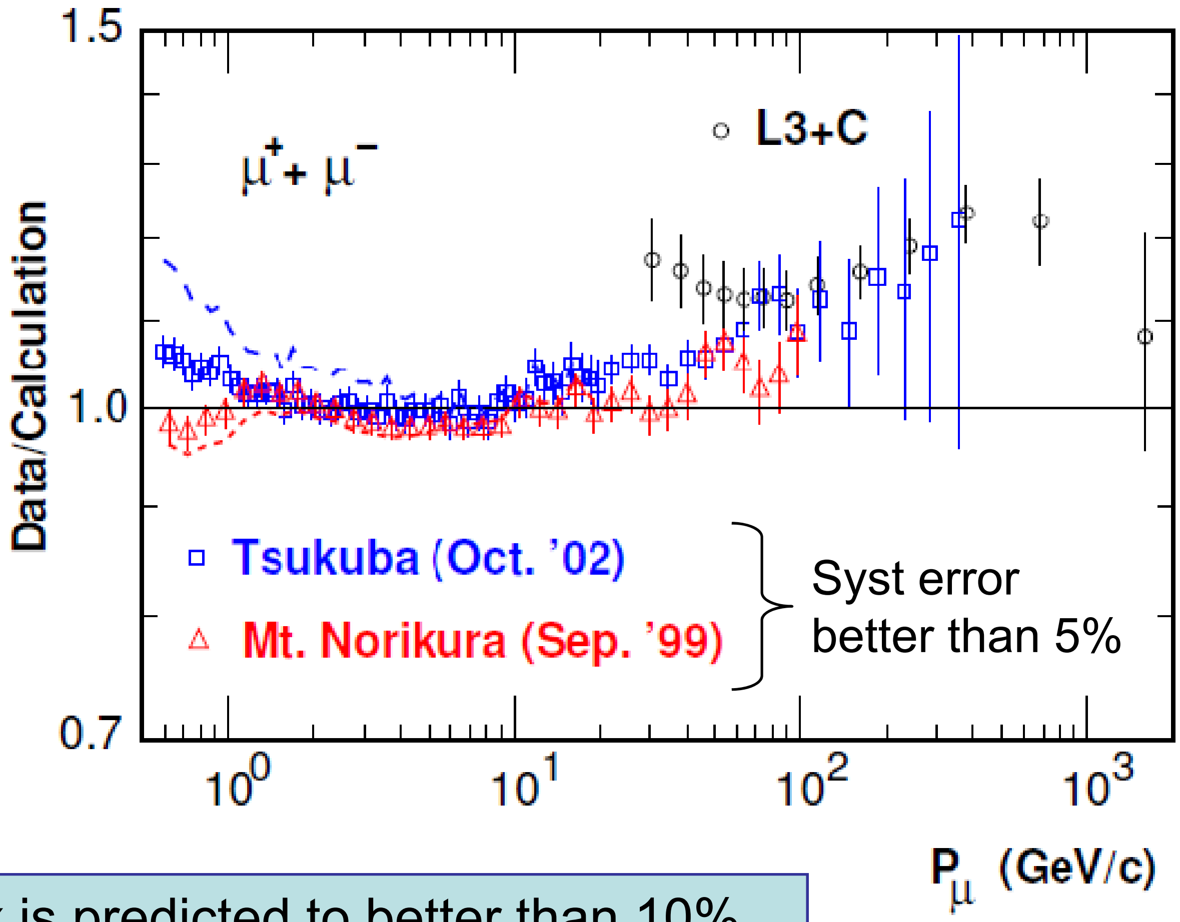
Down

$\cos\theta_{zenith}$

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

How accurate is the absolute normalization of the flux ?

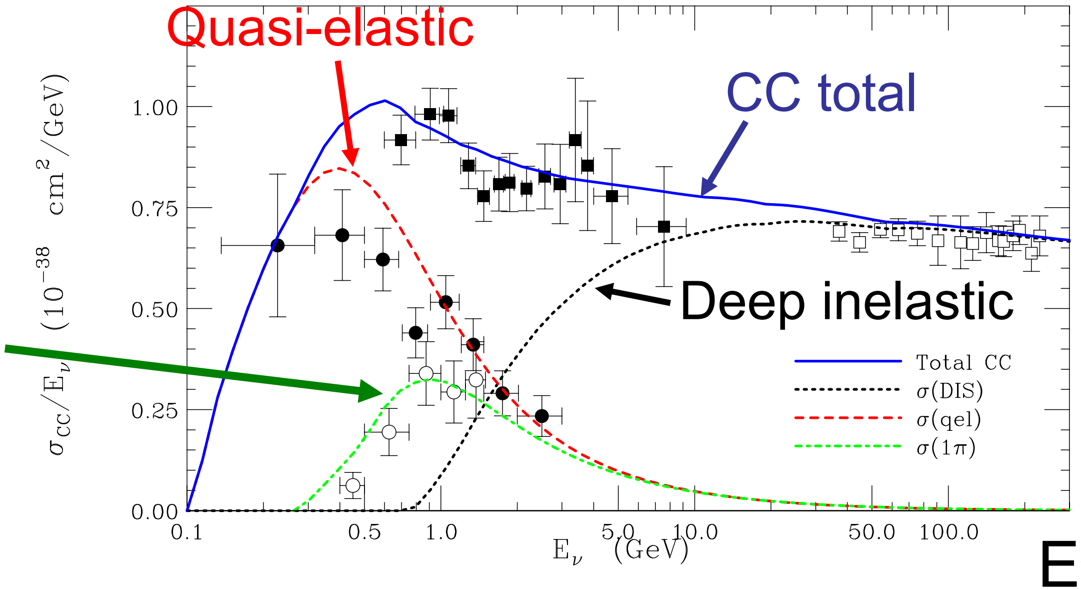




Below 10GeV, the flux is predicted to better than 10%.
Above 10GeV the flux calculation must be improved.
(This statement is for Honda04 flux.)

Neutrino interactions

σ / E_ν



Quasi-elastic

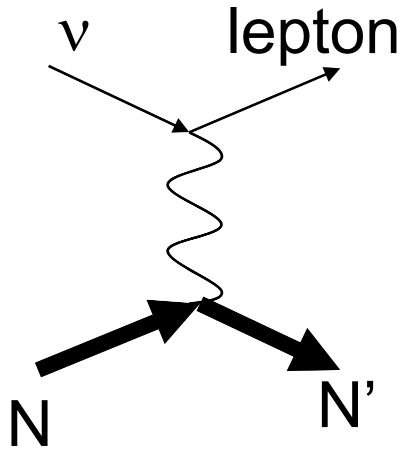
CC total

Deep inelastic

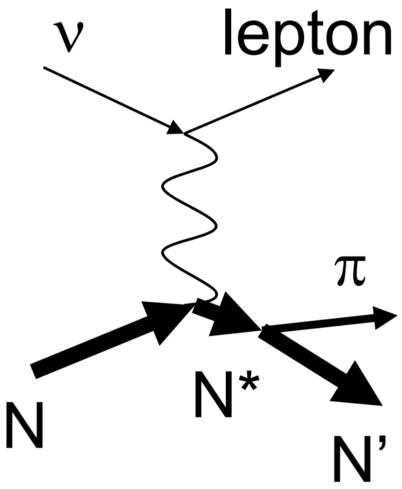
1π production

Eν(GeV)

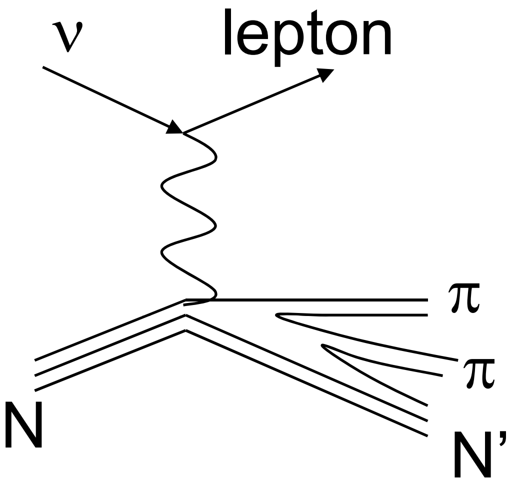
Quasi-elastic



1π production

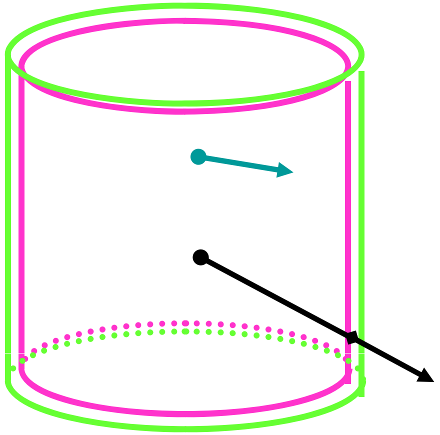


Deep inelastic

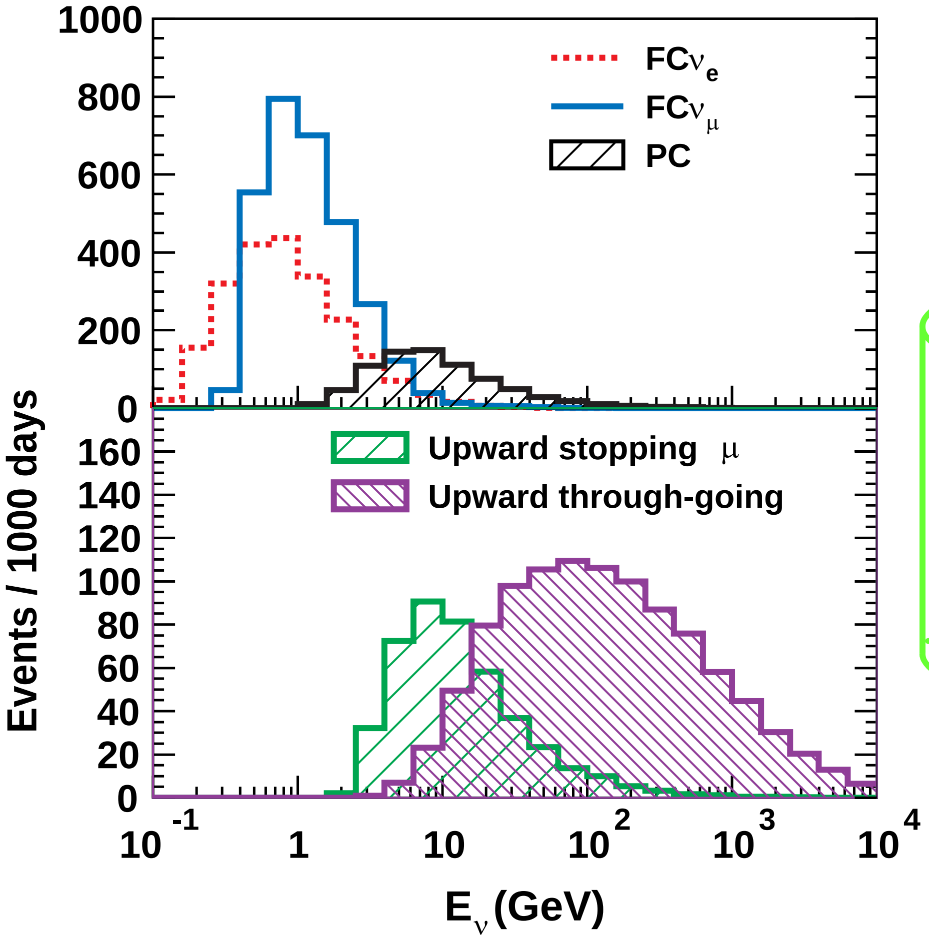


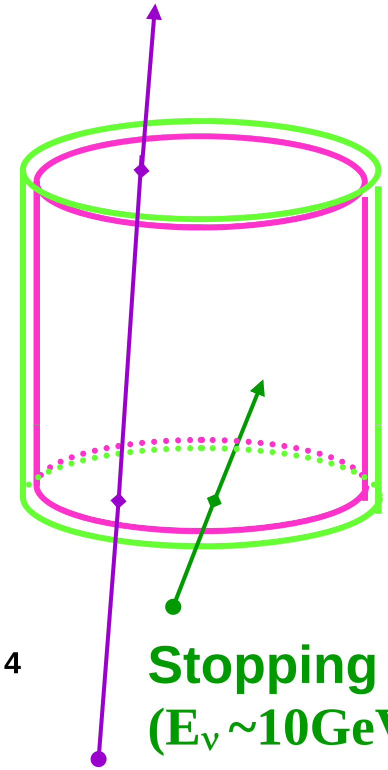
Event type and neutrino energy

Fully Contained (FC) (E_ν ~1GeV)



Partially Contained (PC) (E_ν ~10GeV)

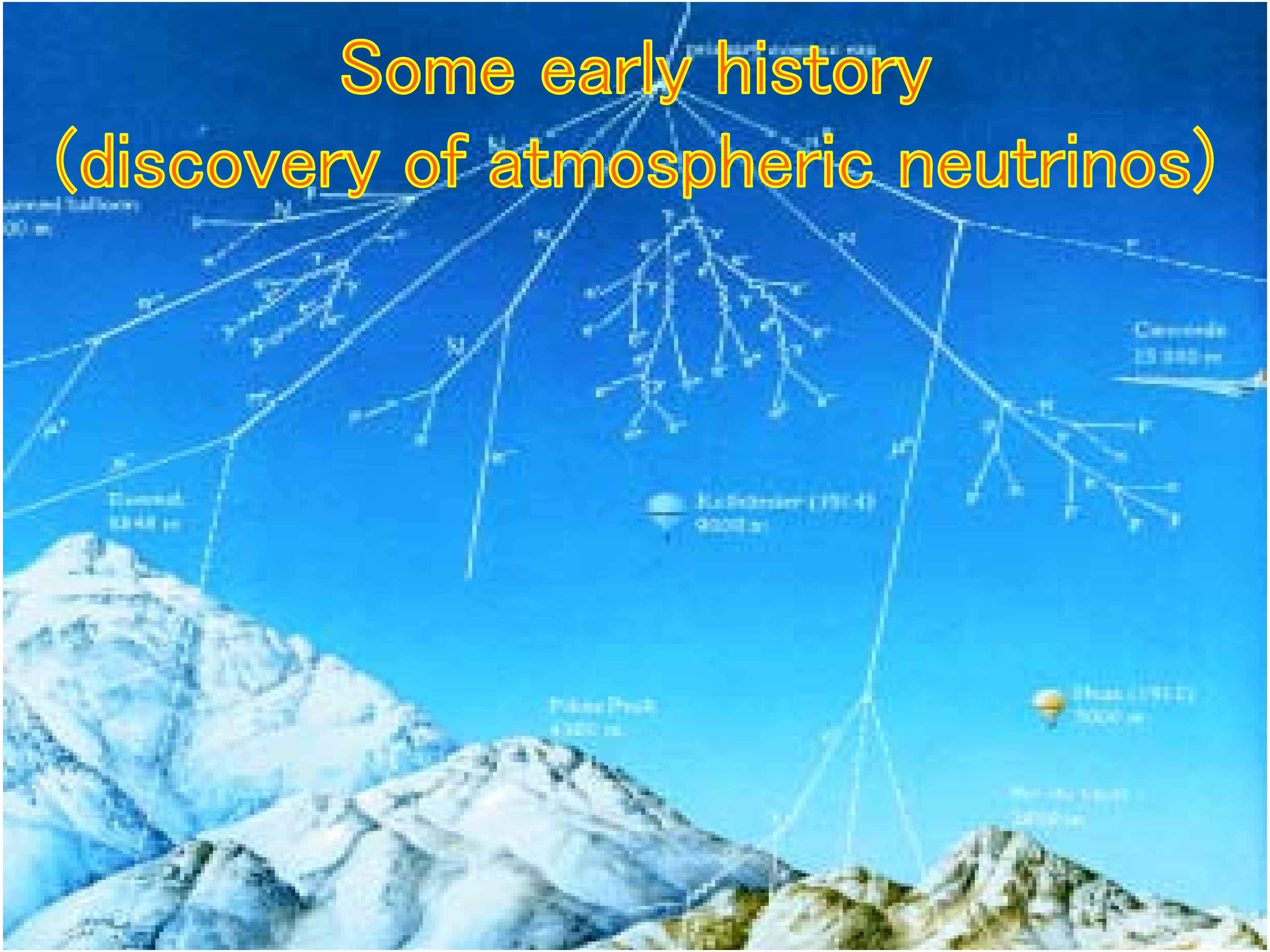




Stopping μ (E_ν ~10GeV)

Through-going μ (E_ν ~100GeV)

Some early history (discovery of atmospheric neutrinos)



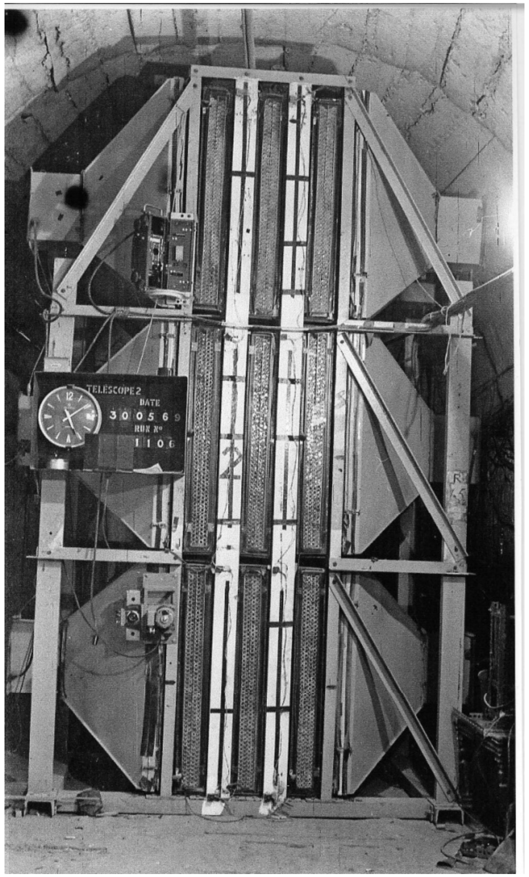
Discovery of atmospheric neutrinos

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.

photo of the South Africa experiment

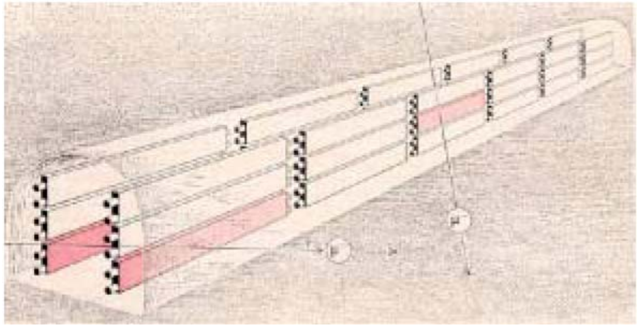
$(\nu_\mu N \rightarrow \mu X)$

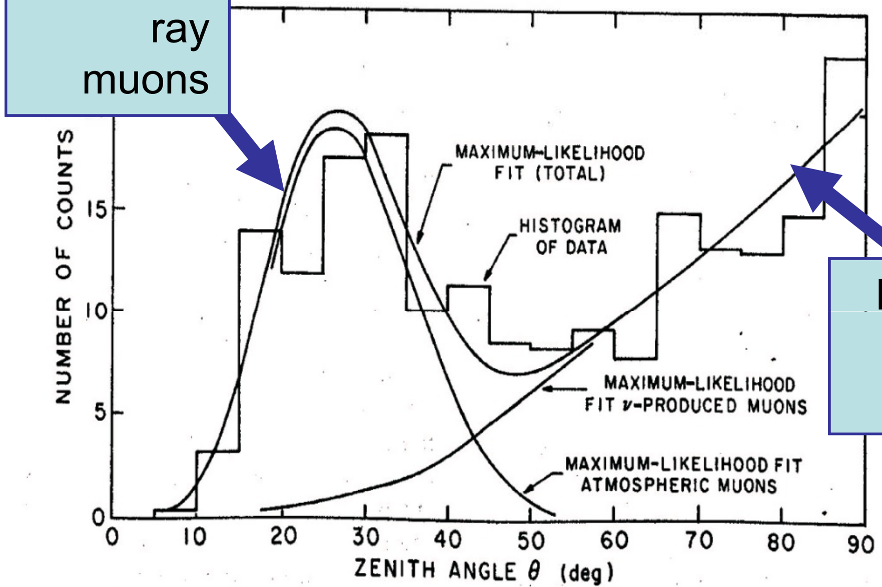


Detector for the KGF experiment

Zenith angle distribution
(updated data from the South Africa experiment)

PRD18, 2239 (1978)





Cosmic ray muons

Neutrino induced muons

Vertical (going up or down)

Horizontal going

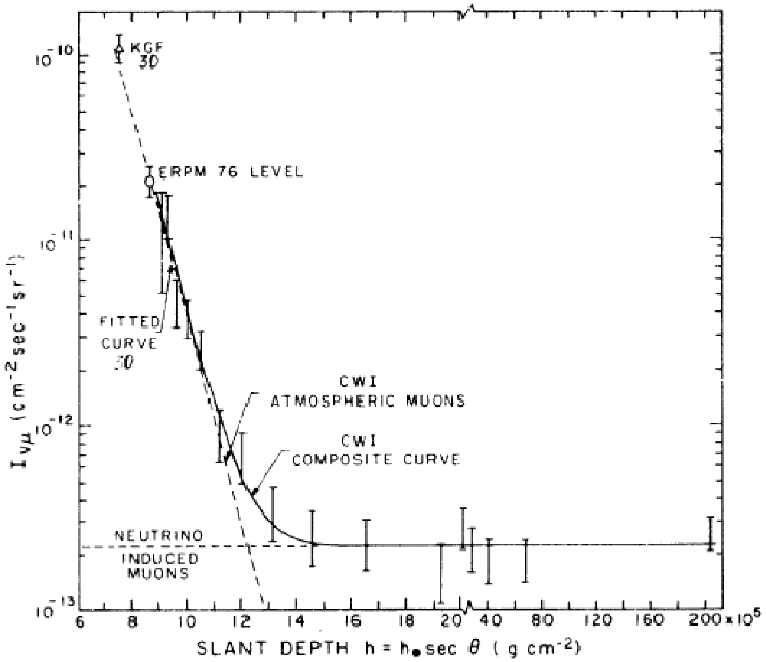
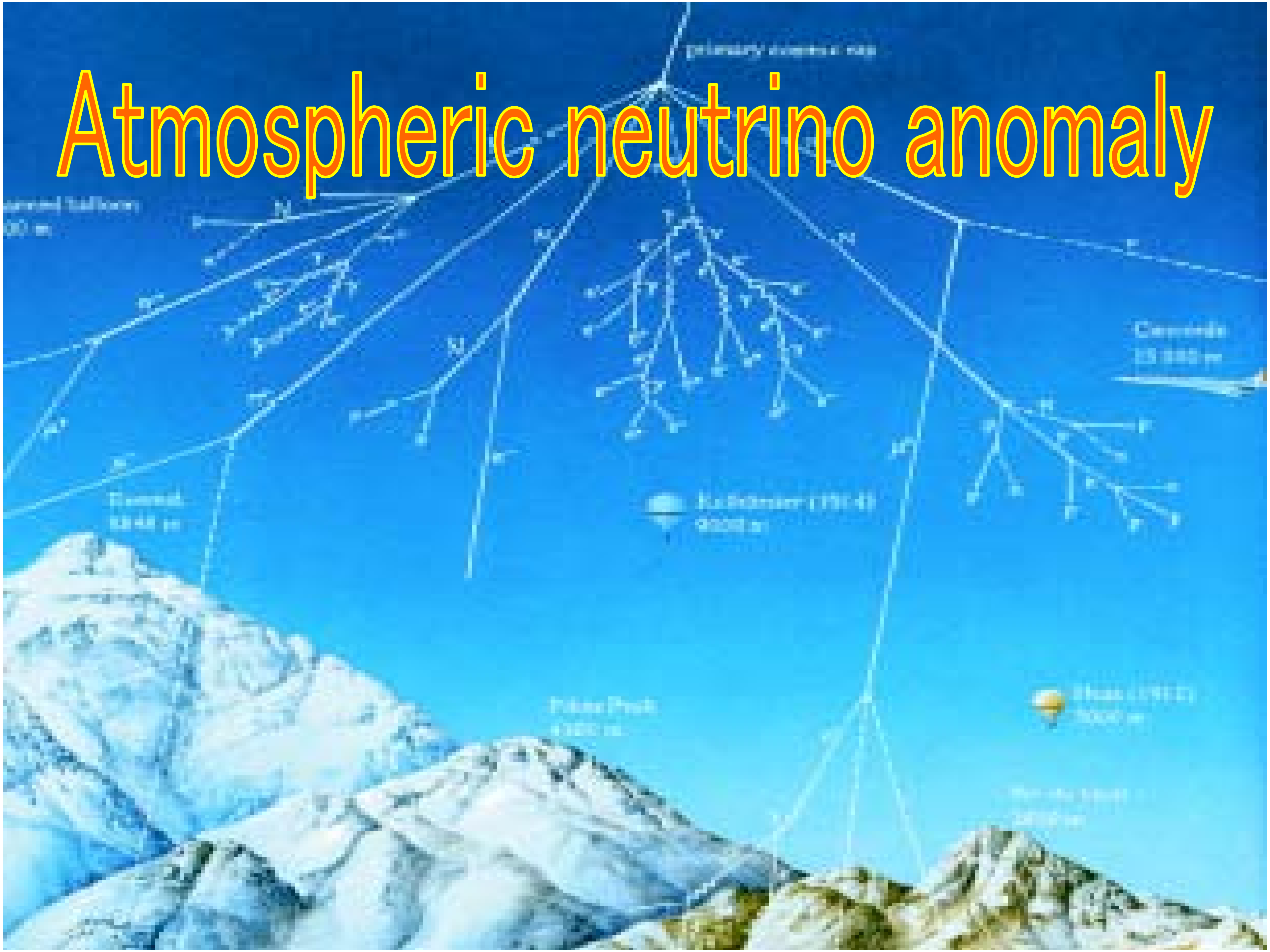


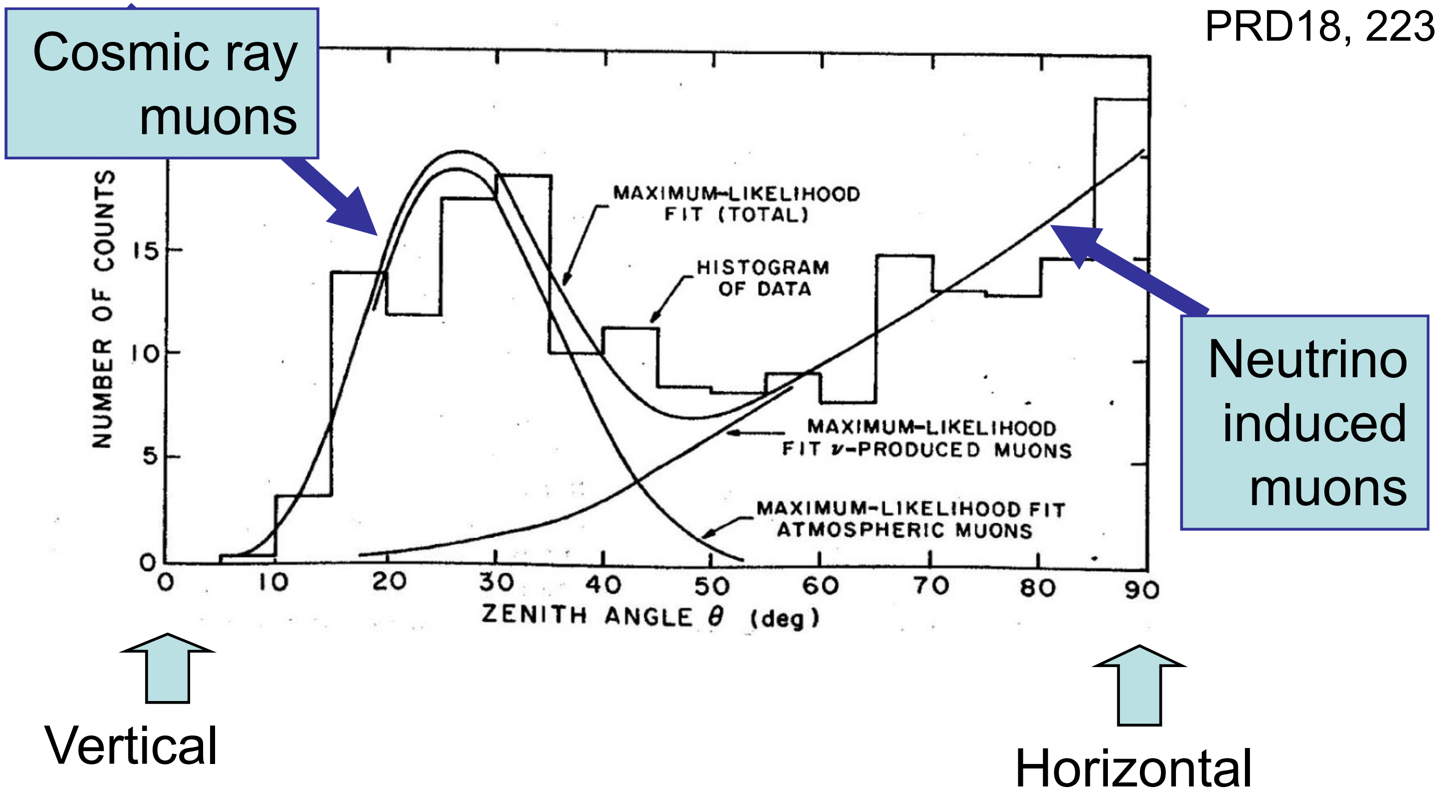
FIG. 9. Vertical intensity $I_{\nu\mu}$ of muons vs slant depth h, deduced from muon angular distribution at $h_0 = 8.89 \times 10^5$ g cm^{-2}. Fitted curve is from Ref. 30.

Atmospheric neutrino anomaly



The first hint ?
(South Africa experiment, 1978)

PRD18, 2239 (1978)



Cosmic ray muons

Neutrino induced muons

Vertical

Horizontal

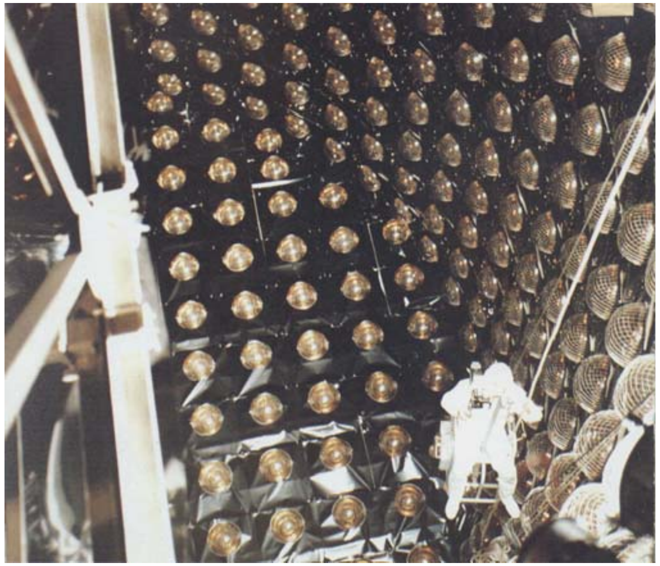
$$\left(\frac{Monte\ Carlo}{Data}\right) = 1.6 \pm 0.4$$

Deficit of muon data

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

Proton decay experiments

Grand Unified Theories ➔ $\tau_p = 10^{30\pm 2}$ years

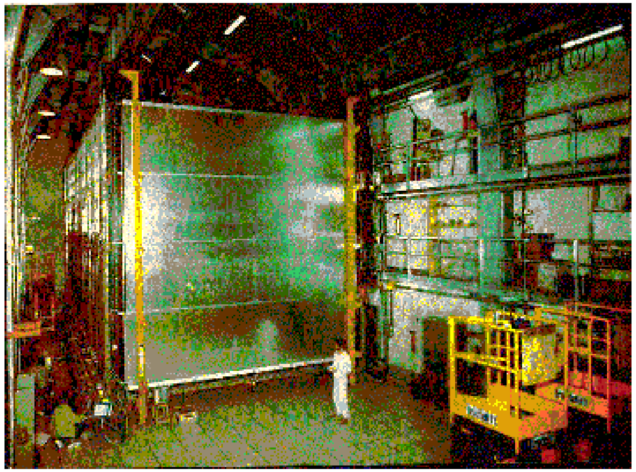


Kamiokande
(1000ton)

IMB
(3300ton)

NUSEX
(130ton)

Frejus
(700ton)



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

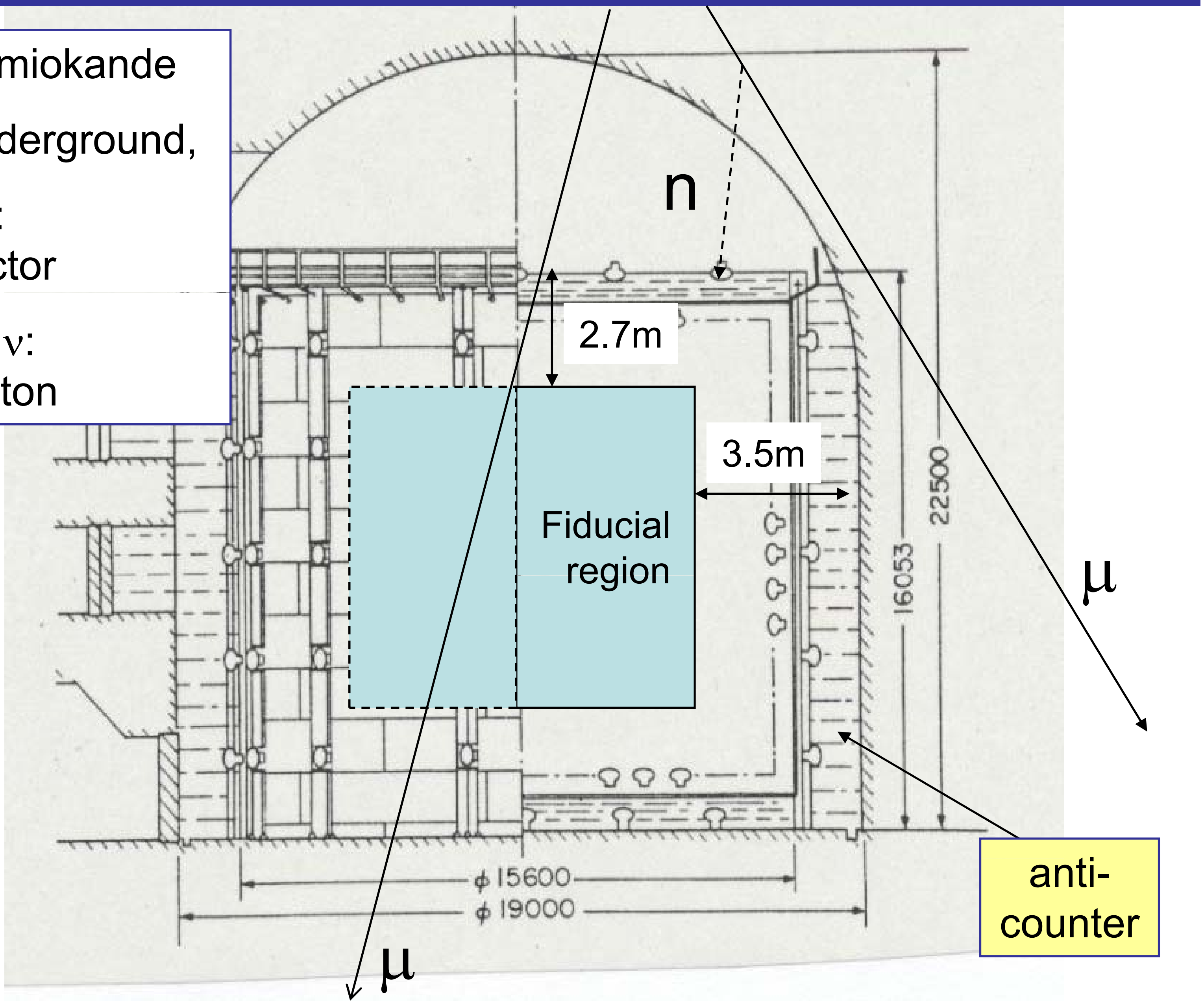
Selection of atmospheric neutrinos

Example: Kamiokande

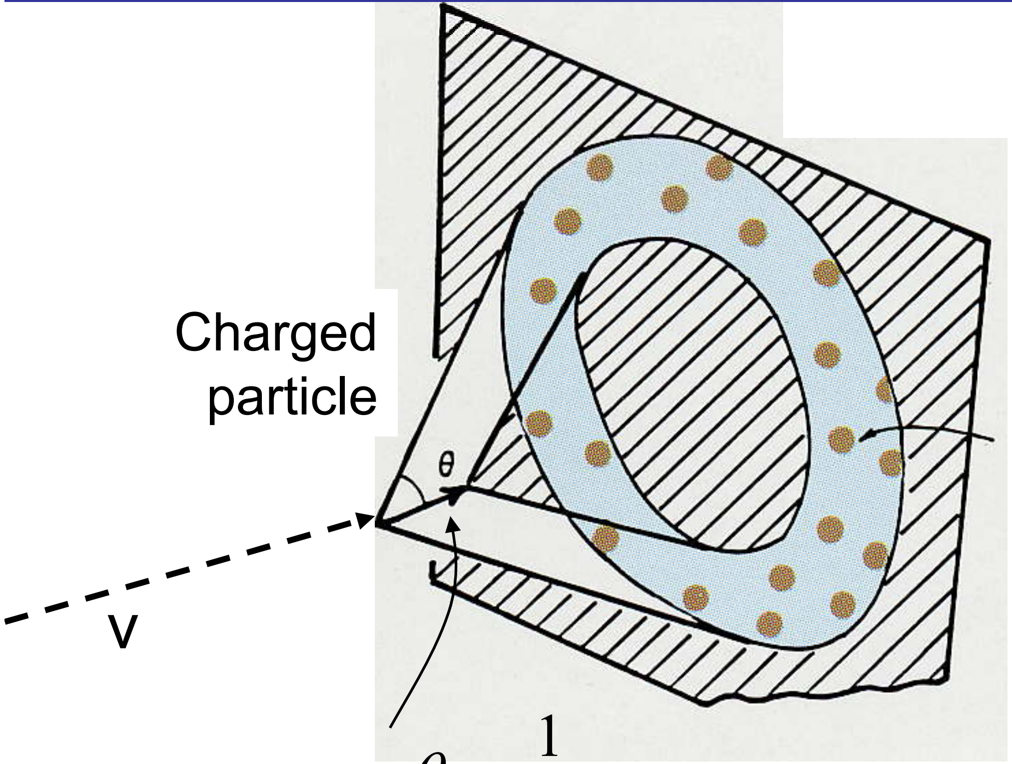
At 1000m underground,

cosmic ray μ: 0.3/sec/detector

Atmospheric ν: 0.3/day/1000ton



Detecting Cherenkov photons



Charged particle

ν

Photomultiplier tube (PMT)

$$\cos\theta = \frac{1}{n\beta}$$

n (refractive index)=1.34 in water

⇨ θ=42deg. for β=1

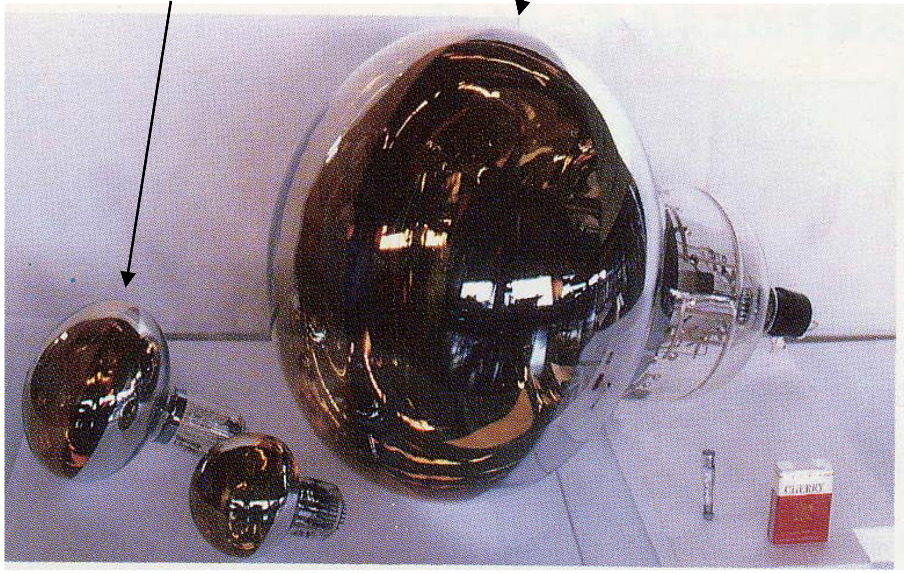
Time: vertex position

⇨ direction

Pulse height (number of pe’s): energy

50cm φ (Super-K)

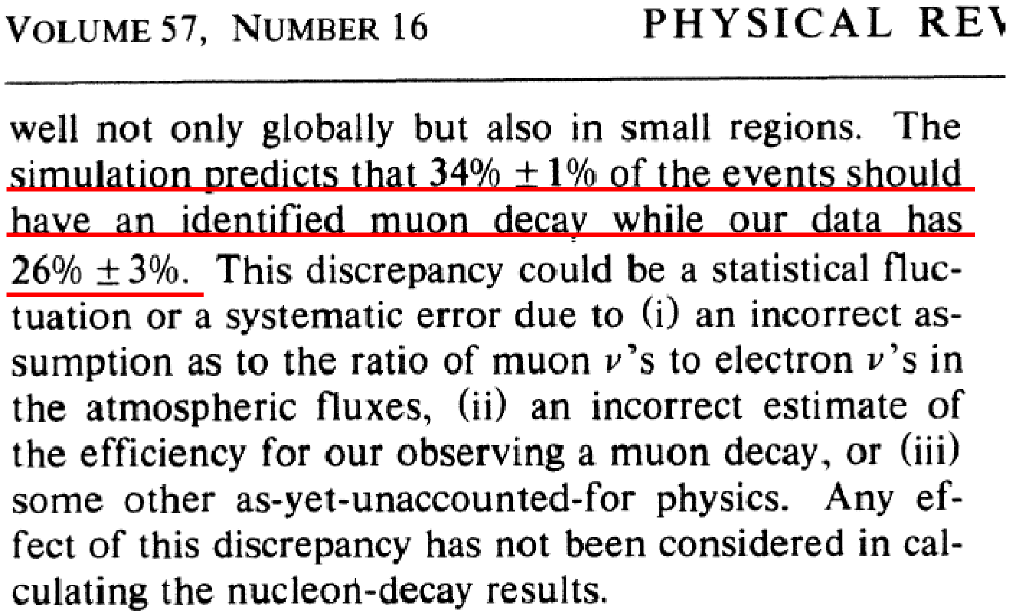
20cm φ



Too few muon decays

Proton decay background papers:

IMB:
PRL57, 1986 (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.

Kamiokande:
J.Phys.Soc.Jpn 55, 711 (1986)

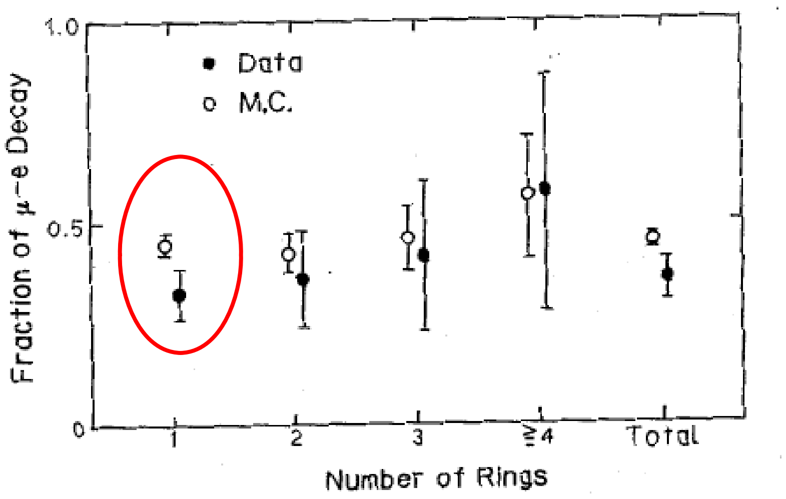


Fig. 13

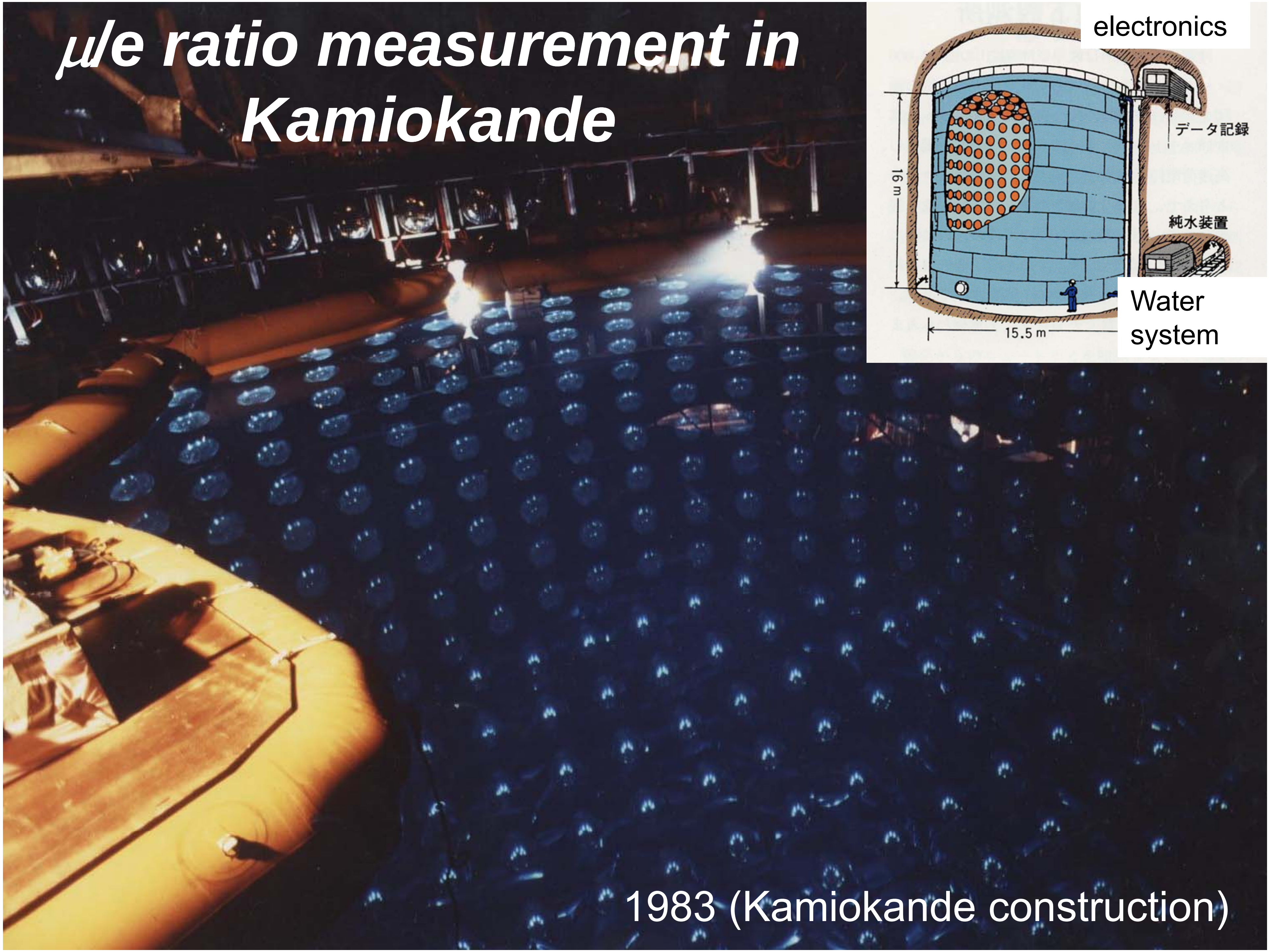
$\nu_\mu N \rightarrow \mu X$, $\mu(\tau=2.2\mu\text{sec}) \rightarrow e\nu\nu$

or

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

But, it was not understood what was happening…

μ/e ratio measurement in Kamiokande



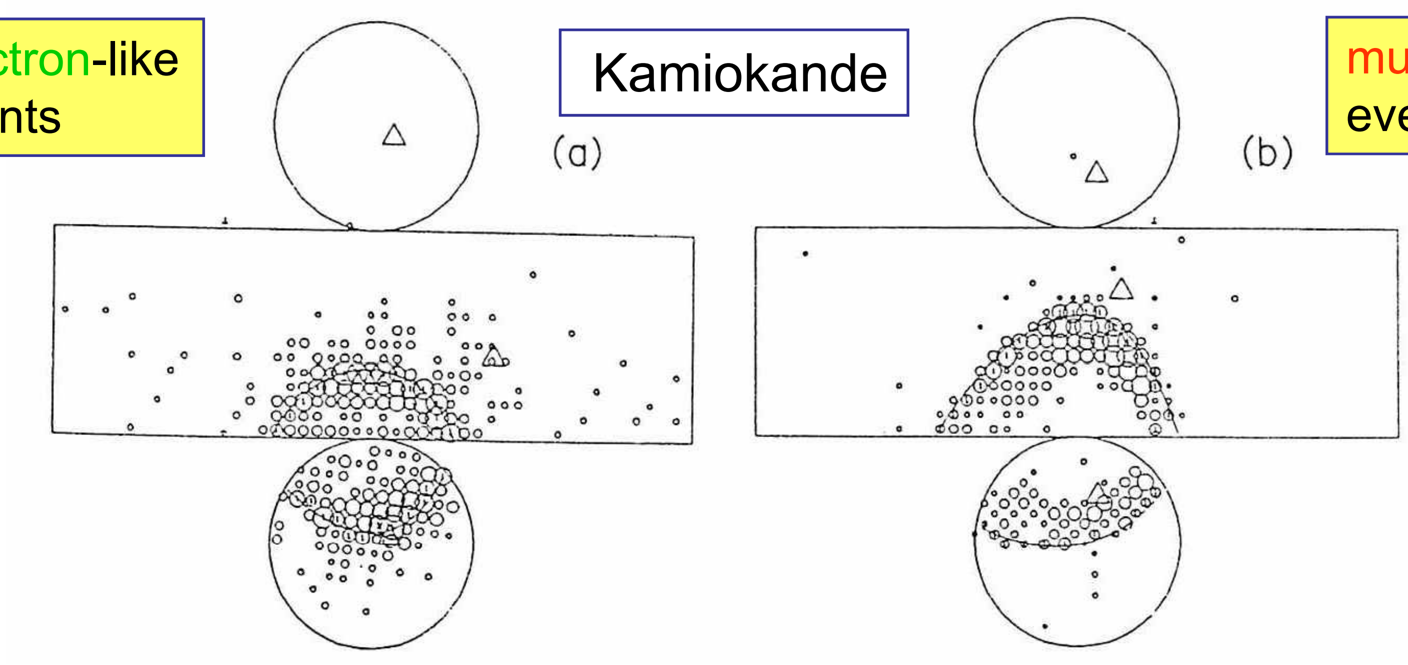
1983 (Kamiokande construction)

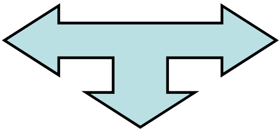
Electrons, muons and particle identification

electron-like events

Kamiokande

muon-like events





e: electromagnetic shower, multiple Coulomb scattering

μ: propagate almost straightly, loose energy by ionization loss

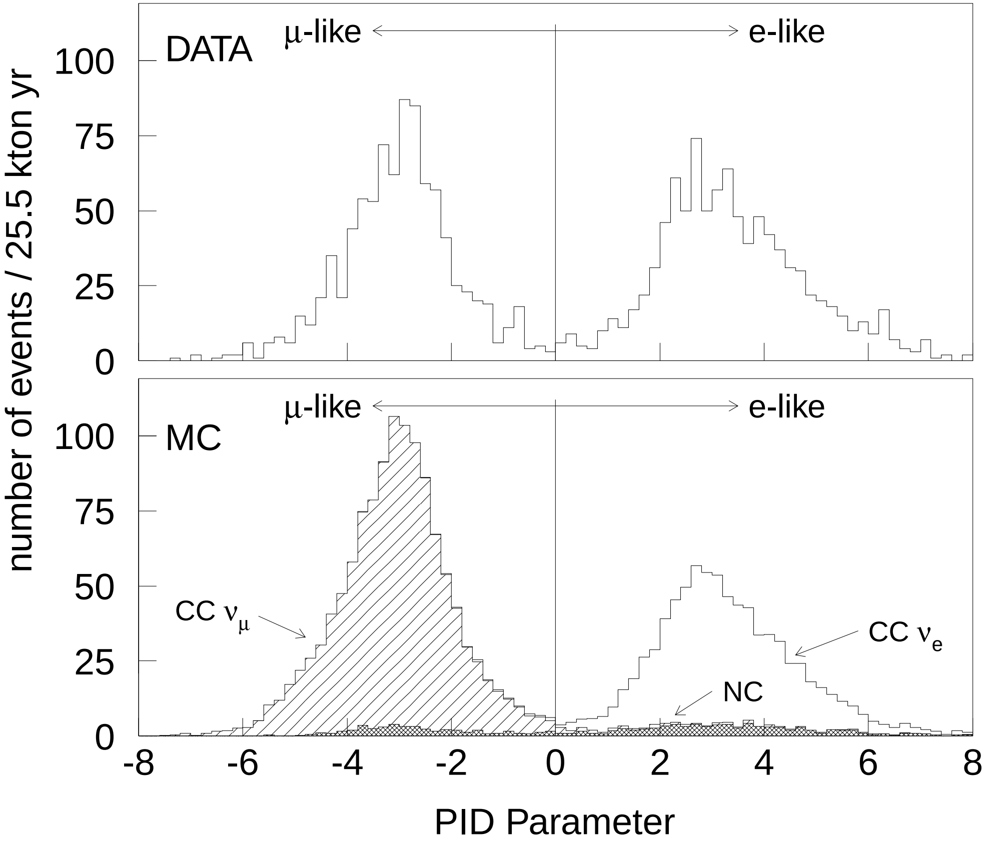
Difference in the event pattern

Particle ID

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

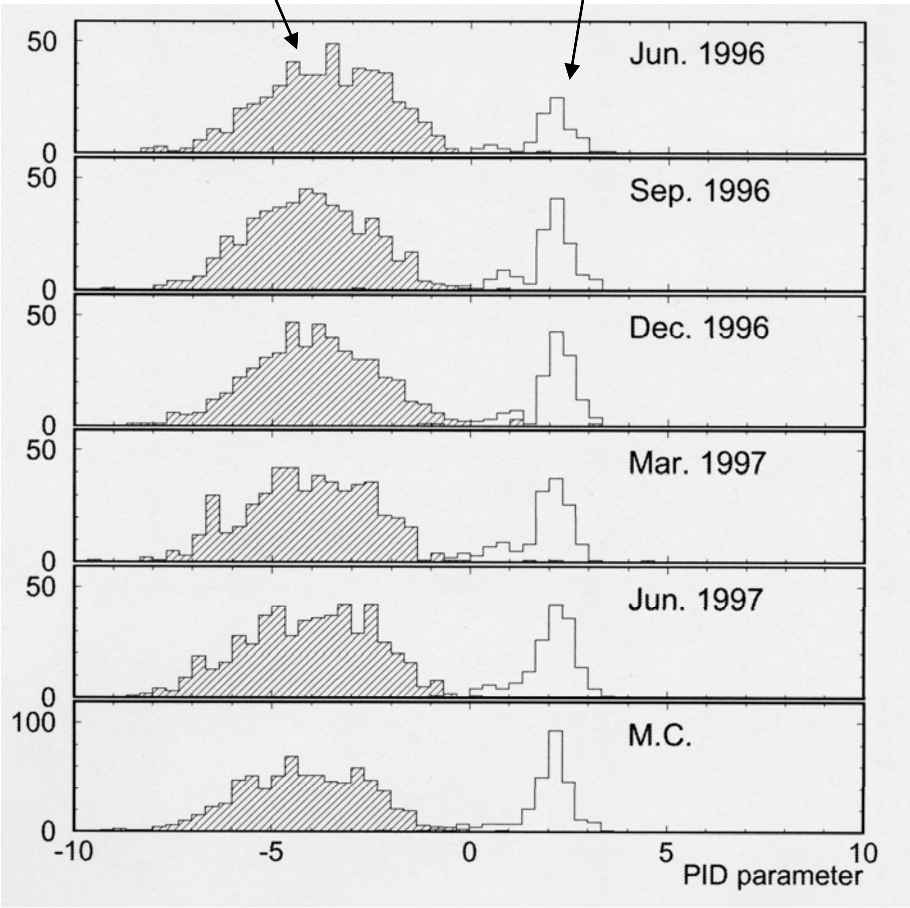
Particle ID performance

(figures from Super-K)



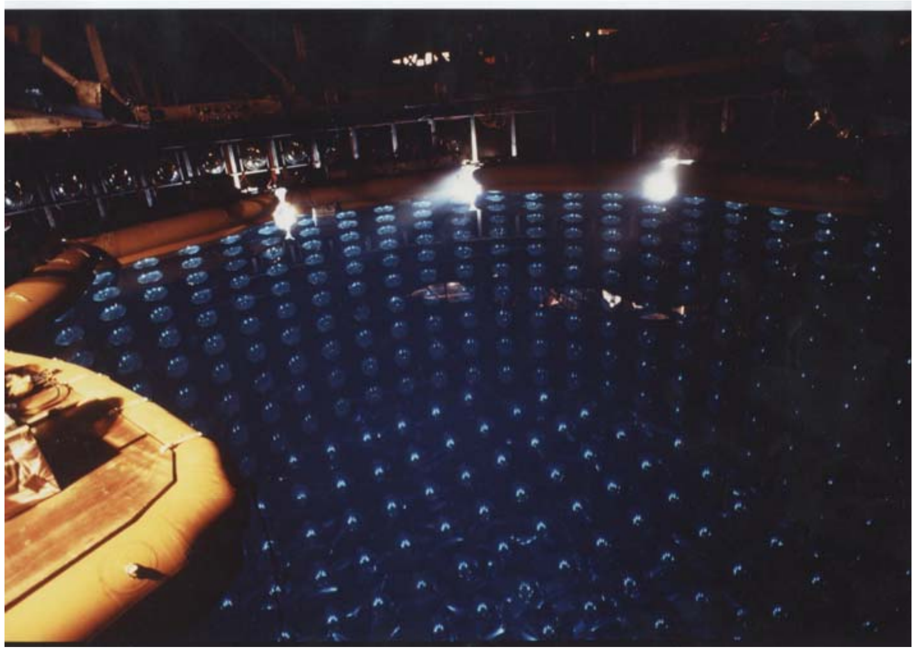
Cosmic ray μ

e from μ decay



ε=99%@Super-K (98% @Kamiokande)

First result on the μ/e ratio (1988)



Kamiokande

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

2.87 kton･year

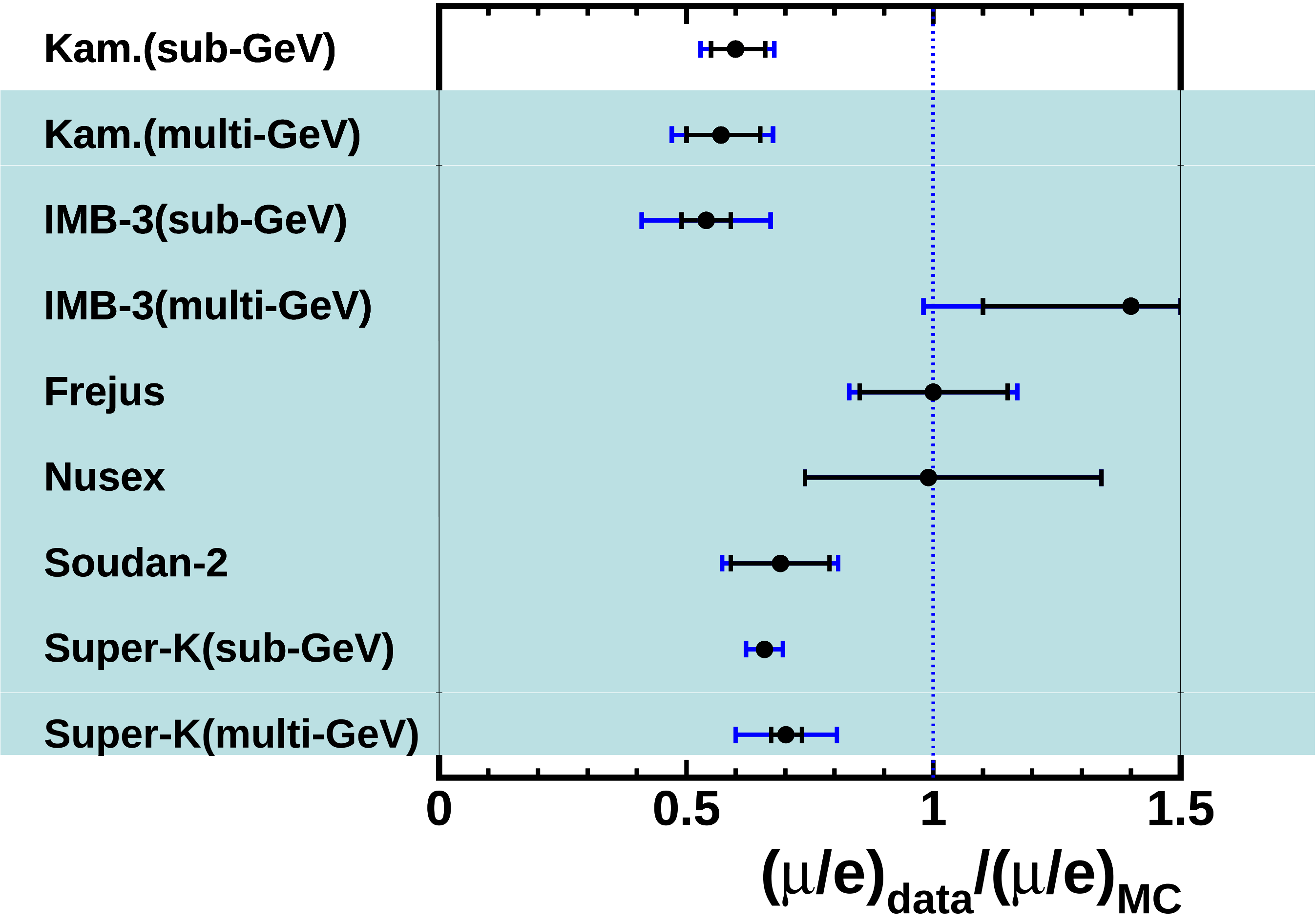
	Data	MC prediction
e-like ($\sim$CC ν_e)	93	88.5
μ-like ($\sim$CC ν_μ)	85	144.0

"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."

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

However, …

Let's write the atmospheric ν_μ deficit by $(\mu/e)_{data}/(\mu/e)_{MC}$

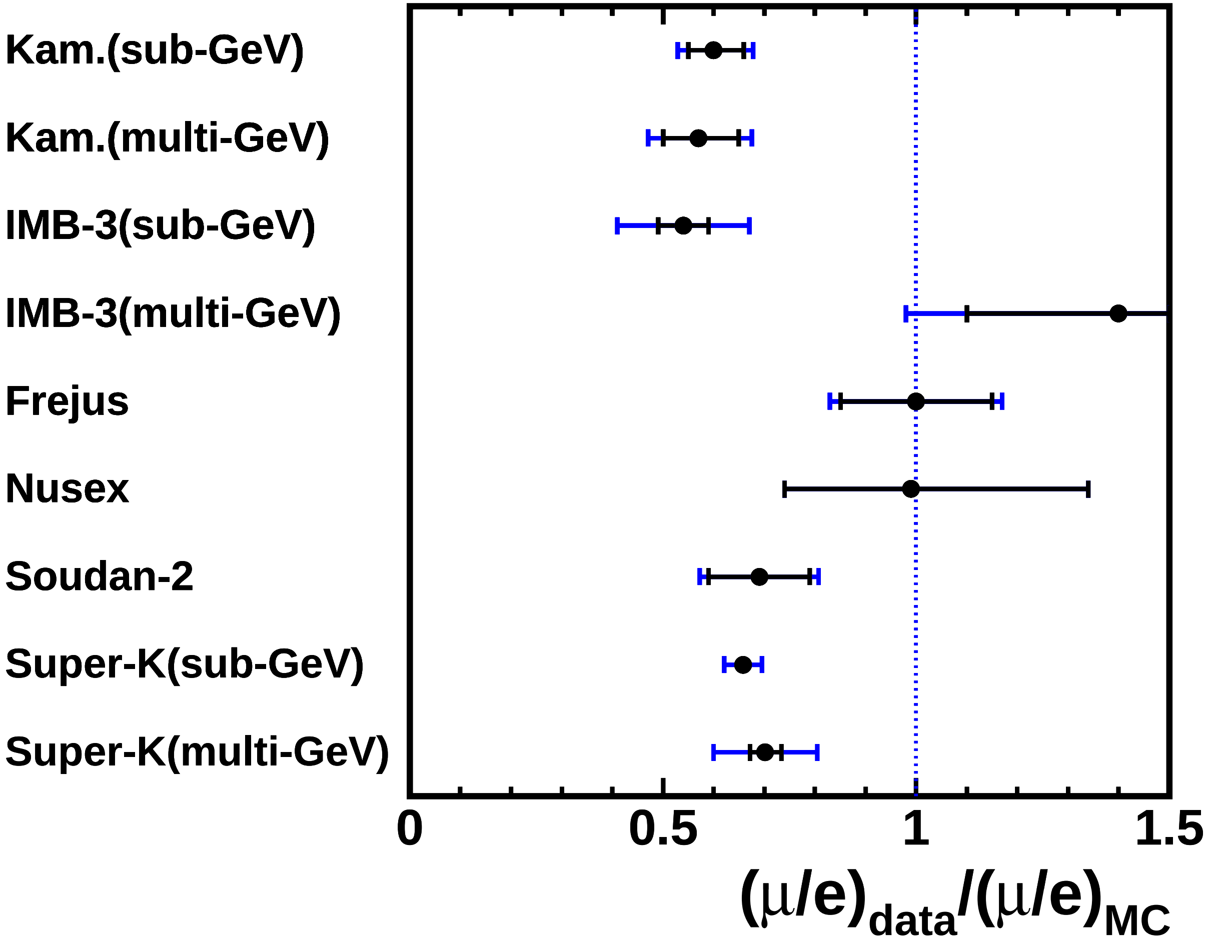


First supporting evidence for small μ/e

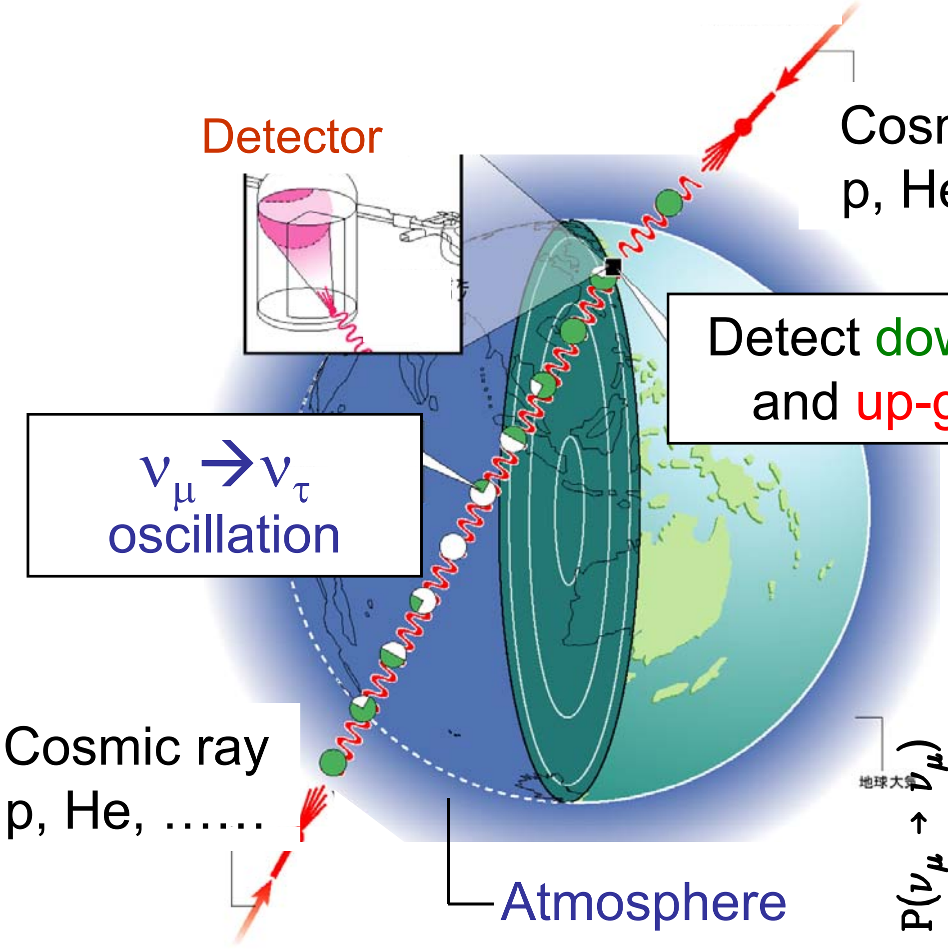
IMB experiment also observed smaller (μ/e) in 1991 and 1992.

Finally, …

Let’s write the atmospheric ν_μ deficit by $(\mu/e)_{data}/(\mu/e)_{MC}$



Atmospheric neutrinos and neutrino oscillations



Detector

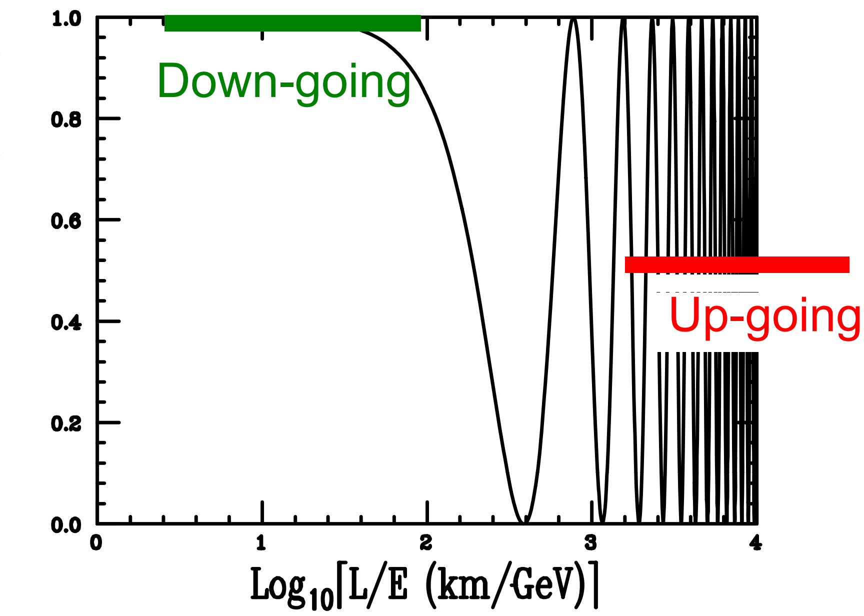
Cosmic ray
p, He, ……

Detect down-going and up-going ν

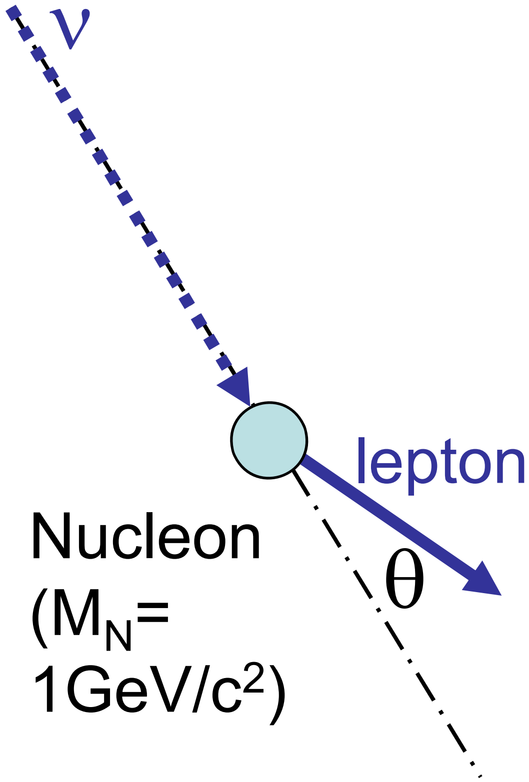
$\nu_\mu \rightarrow \nu_\tau$
oscillation

Cosmic ray
p, He, ……

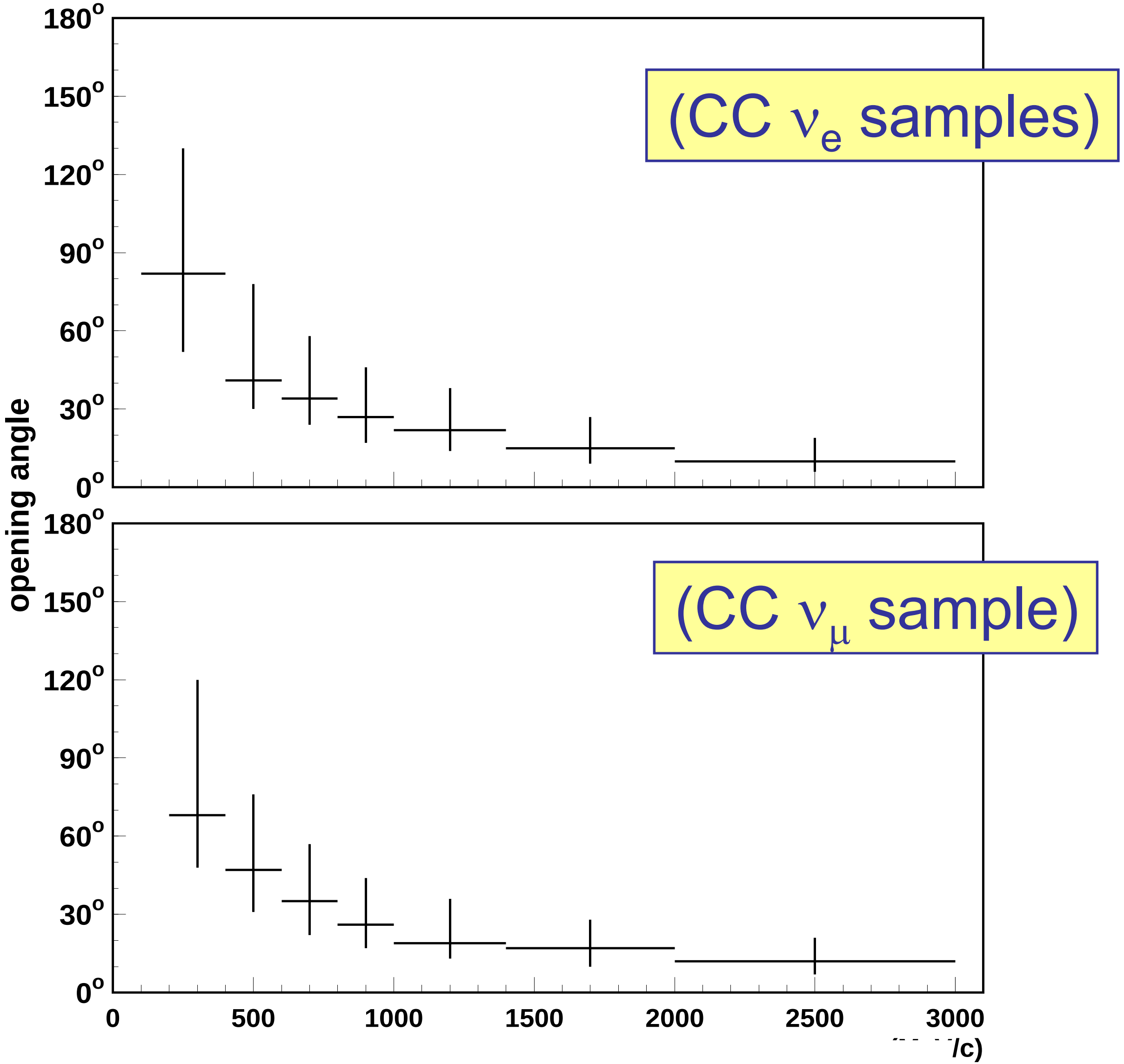
Atmosphere



Angular correlation



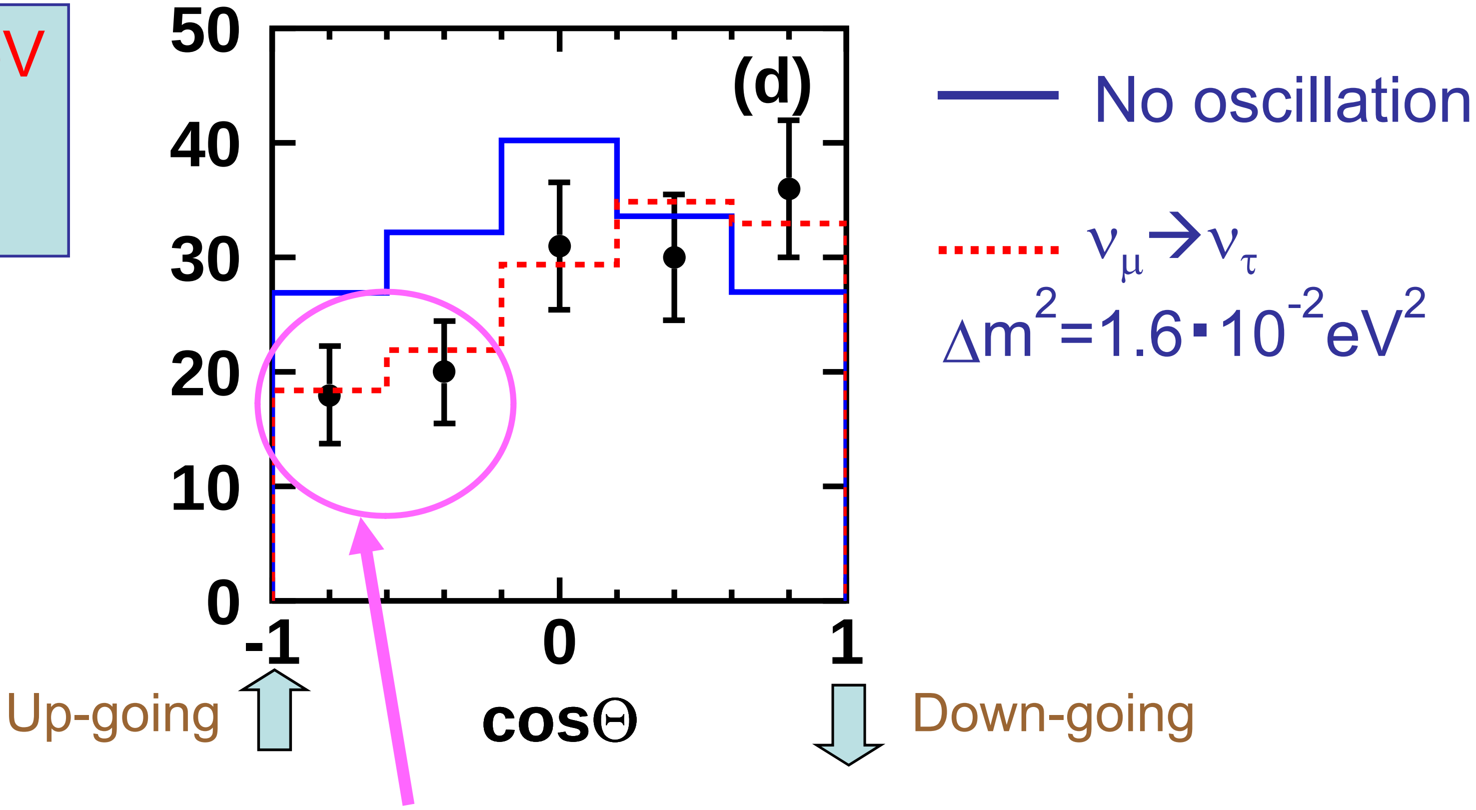
Nucleon
(M_N=
1GeV/c^2)



Lepton momentum (MeV/c)

Next: zenith angle…(Kamiokande,1994)

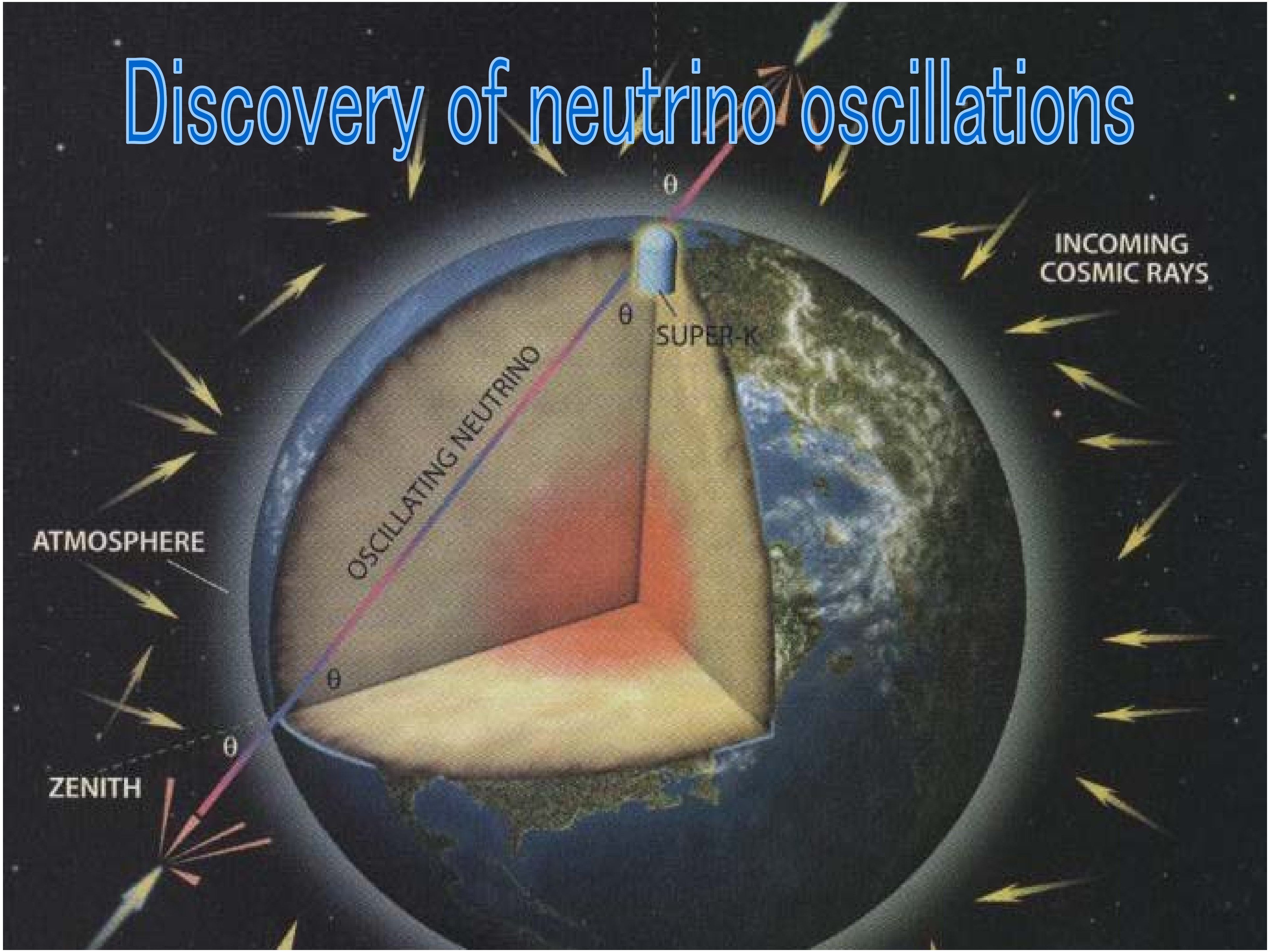
multi-GeV
μ-like
events



Deficit of upward-going
μ-like events

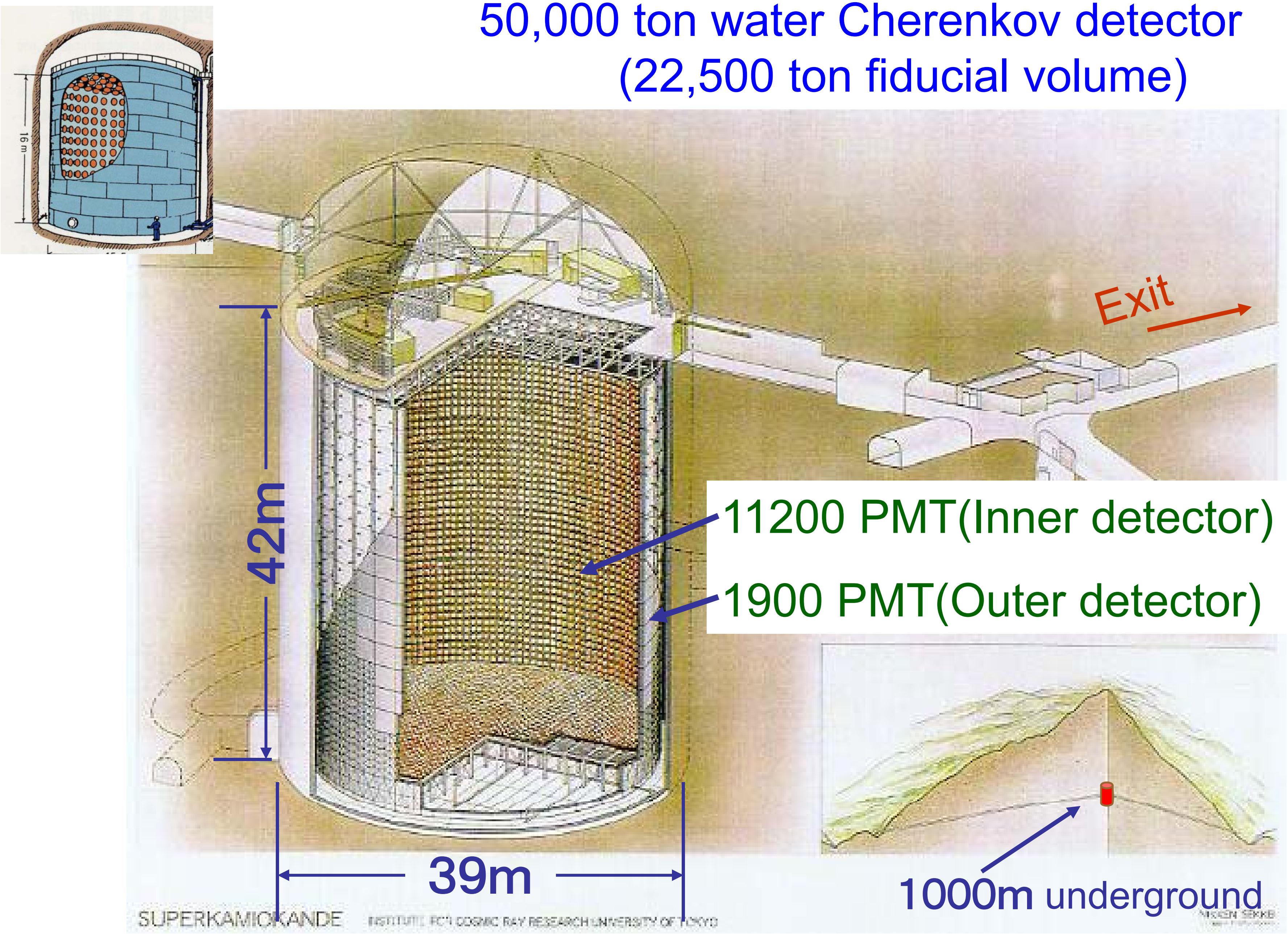
Up/Down=$0.58^{+0.13}_{-0.11}$ (2.9 σ)

Discovery of neutrino oscillations



Super-Kamiokade detector

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

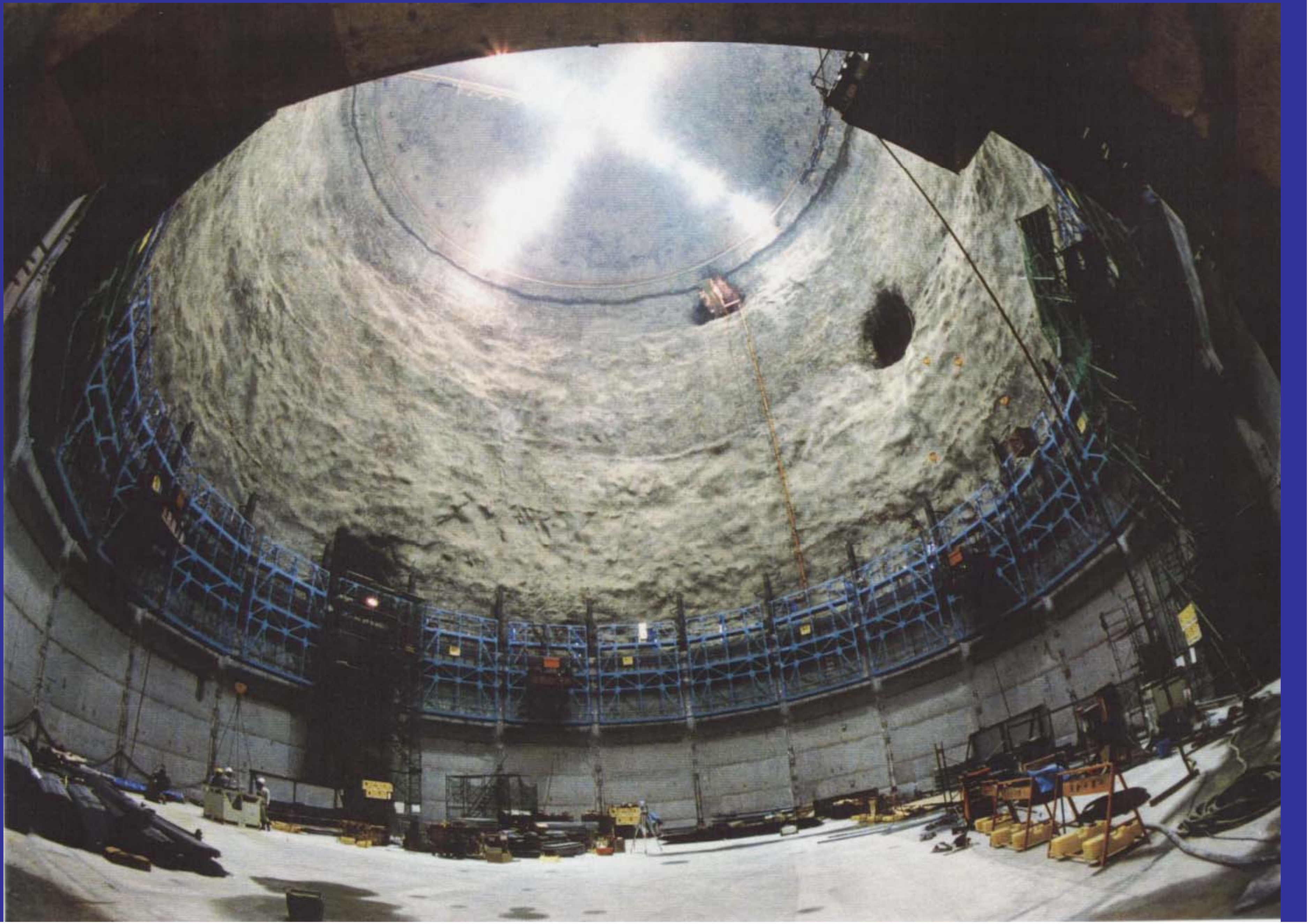


11200 PMT(Inner detector)

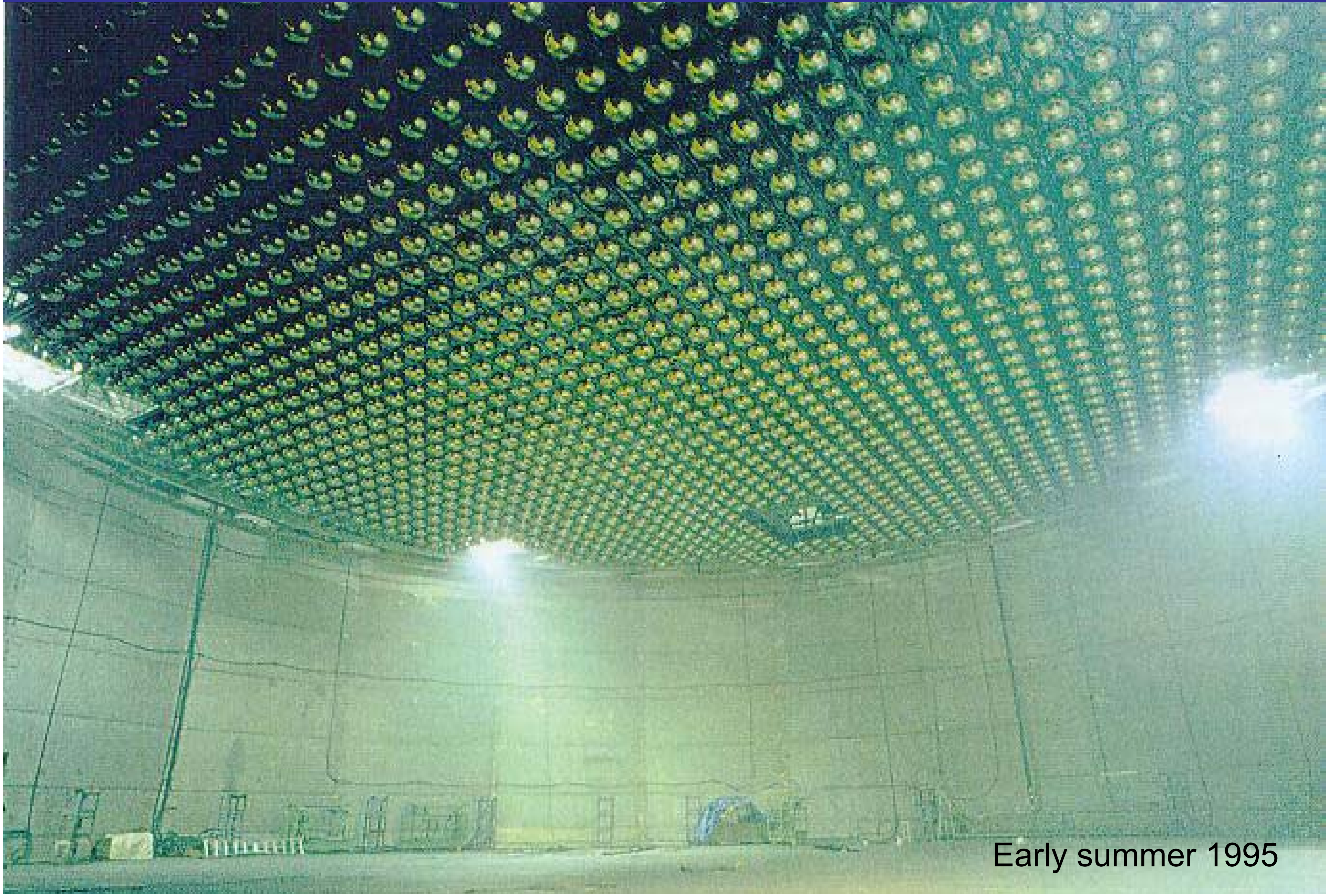
1900 PMT(Outer detector)

1000m underground

Super-Kamiokande *(under construction, Dec. 1994)*

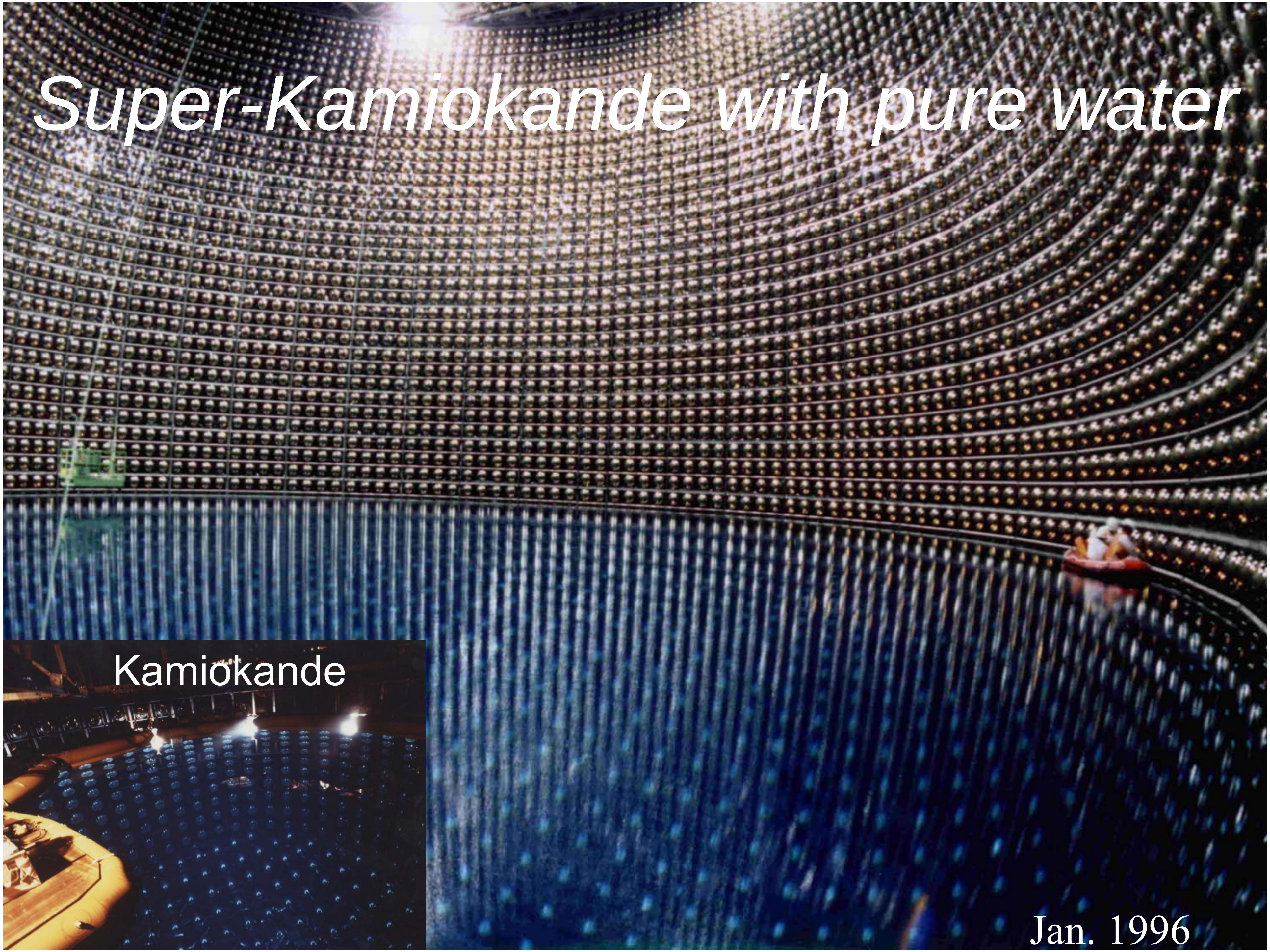


Super-Kamiokande detector ***under construction***



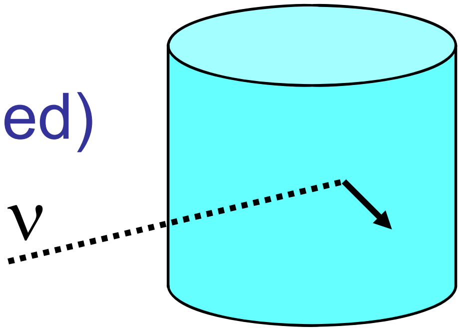
Early summer 1995

Super-Kamiokande with pure water



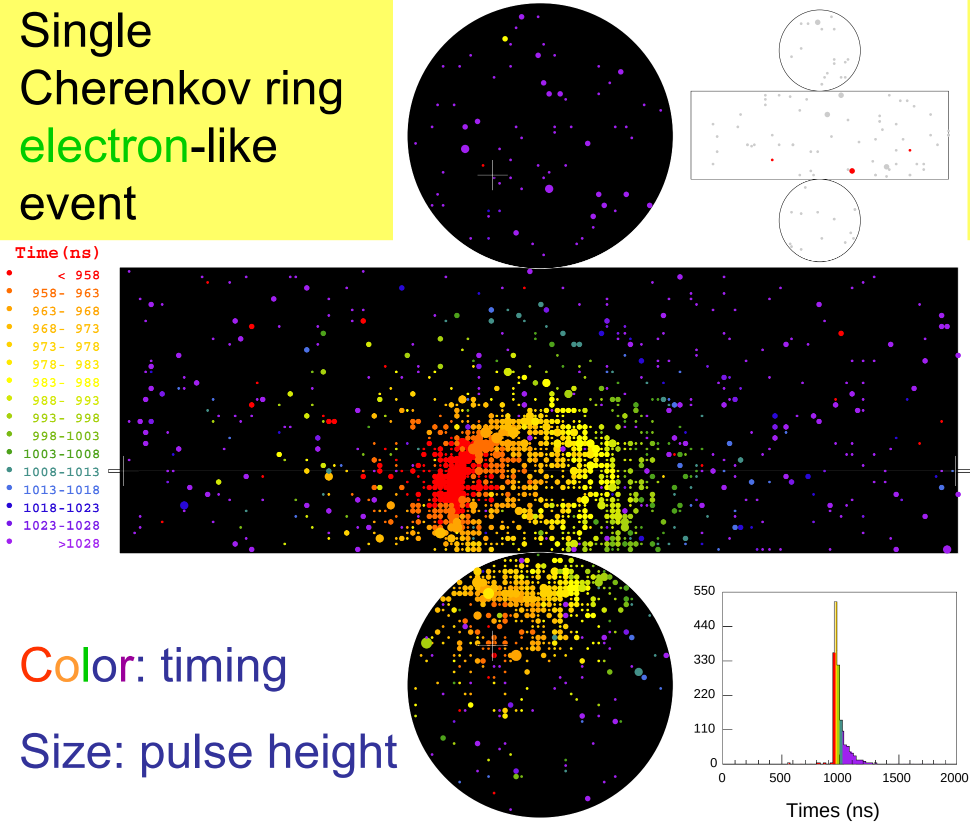
Various types of atmospheric neutrino events (1)

FC
(fully contained)

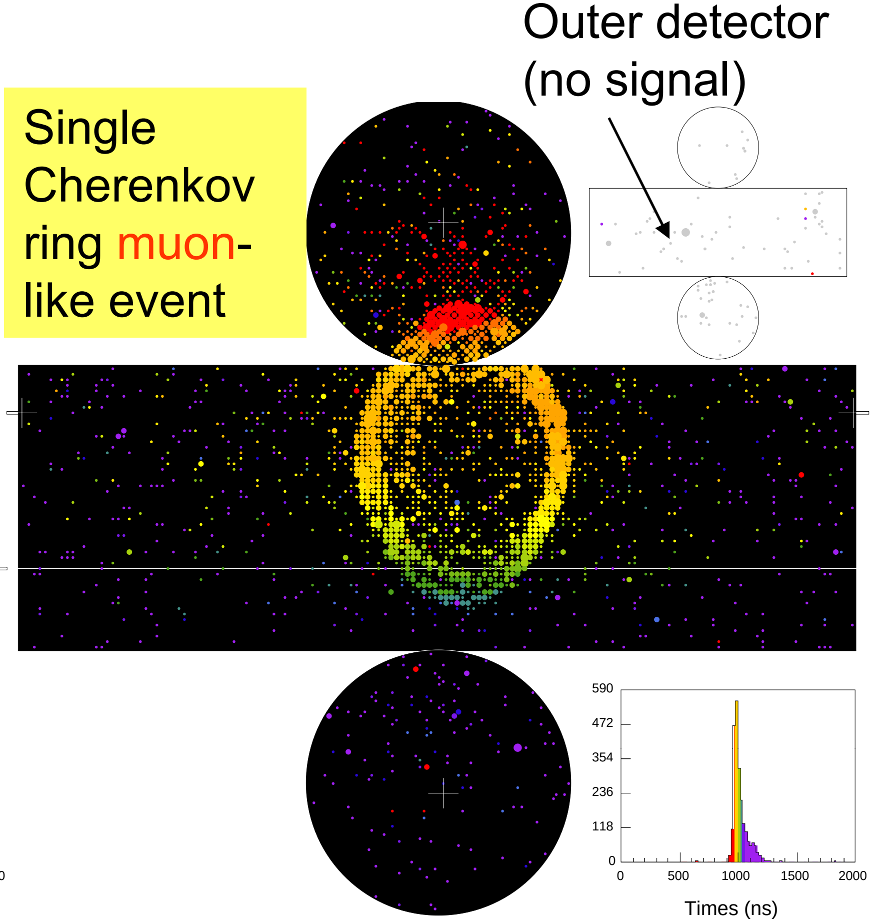


- Both CC ν_e and ν_μ (+NC)
- Particle identification separates electrons and muons with ε=99%.

Single Cherenkov ring electron-like event



Single Cherenkov ring muon-like event



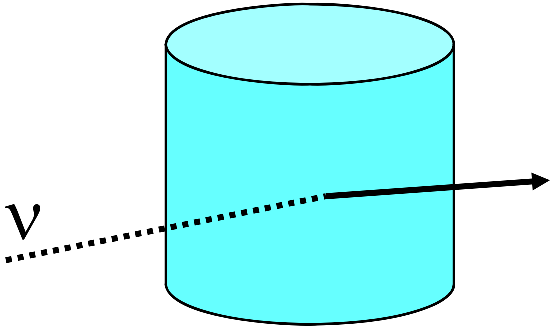
Outer detector
(no signal)

Color: timing

Size: pulse height

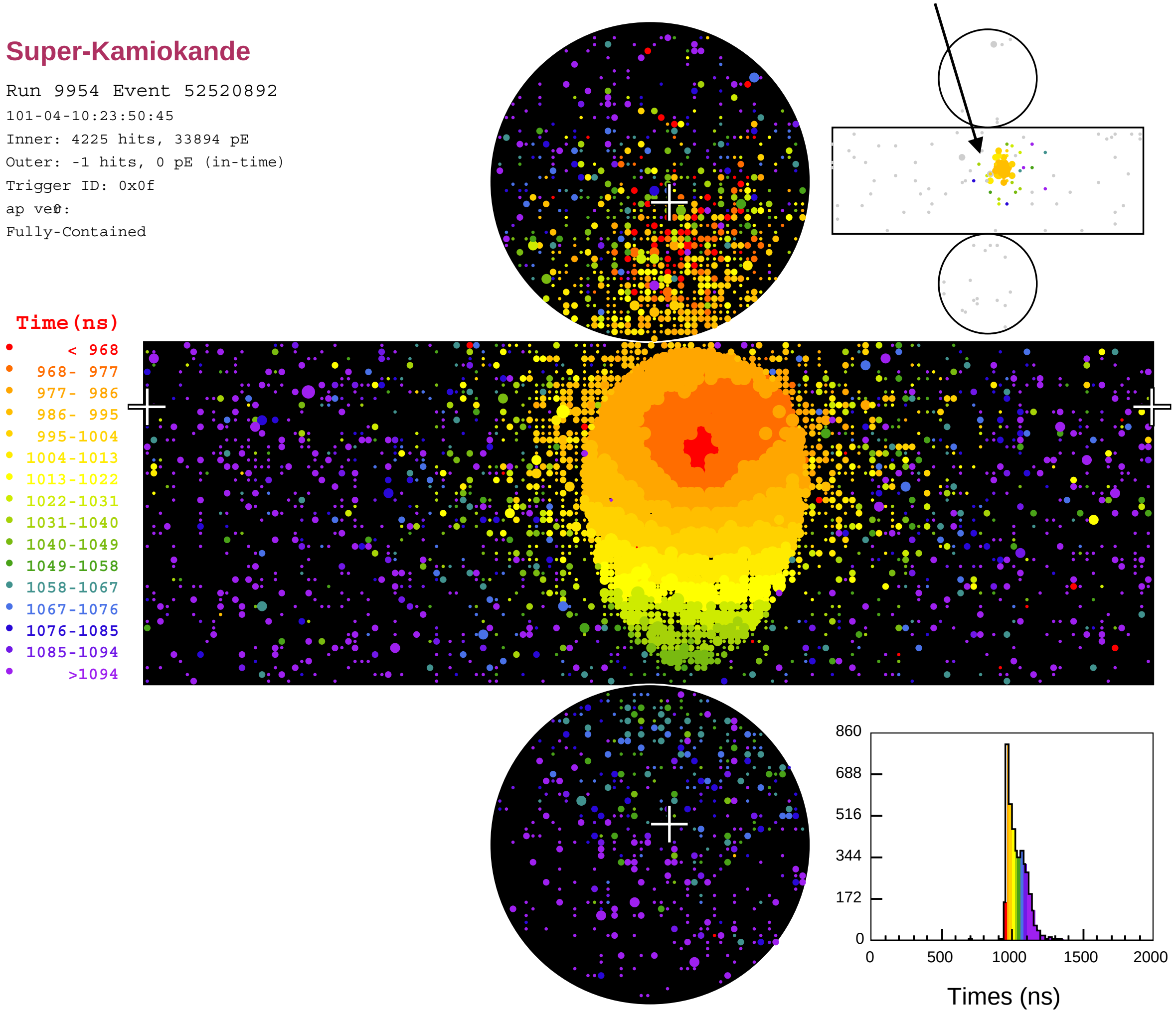
Various types of atmospheric neutrino events (2)

PC
(partially contained)



- 97% CC ν_μ

Signal in the outer detector

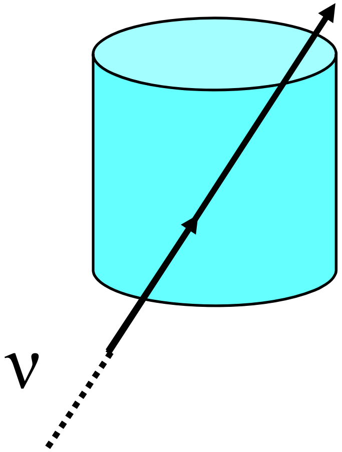


Super-Kamiokande

```
Run 9954 Event 52520892
101-04-10:23:50:45
Inner: 4225 hits, 33894 pE
Outer: -1 hits, 0 pE (in-time)
Trigger ID: 0x0f
ap ve0:
Fully-Contained
```

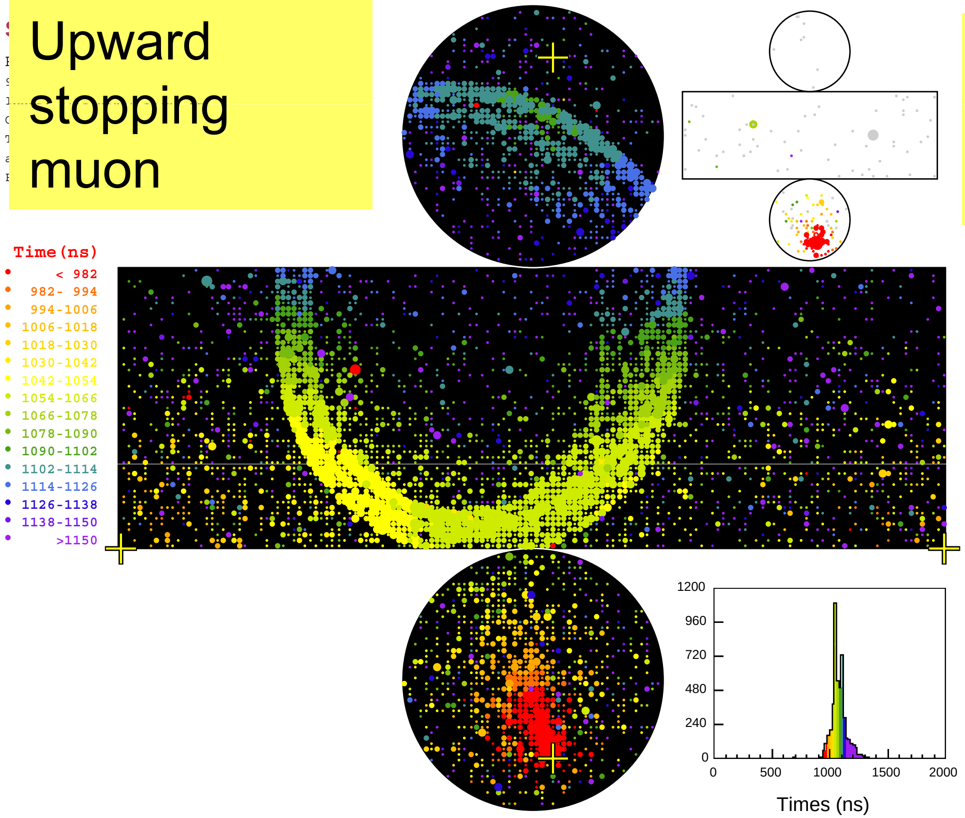
Various types of atmospheric neutrino events (3)

Upward going muon

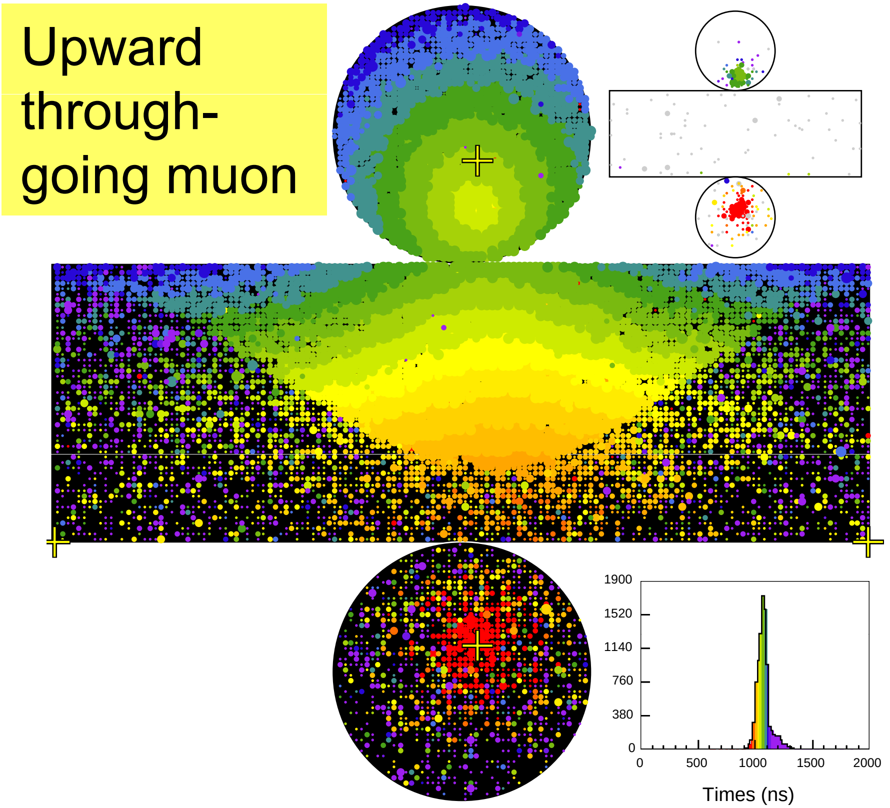


- almost pure CC ν_μ

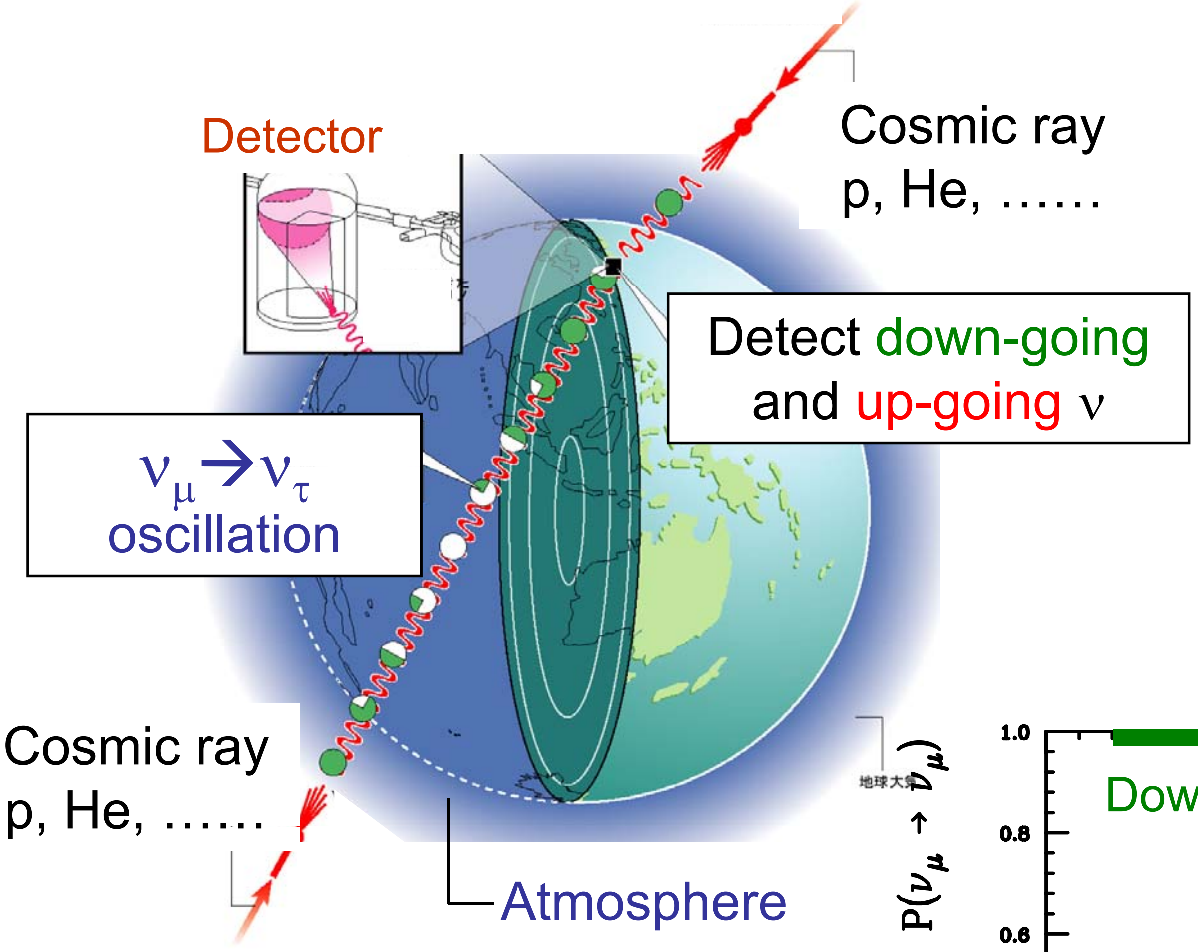
Upward stopping muon

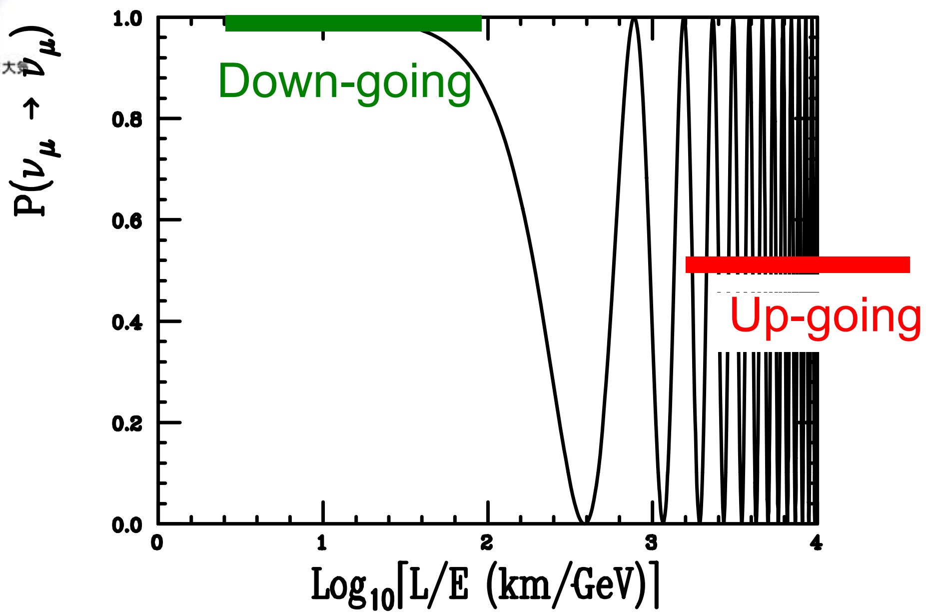


Upward through-going muon



Atmospheric neutrinos and neutrino oscillations





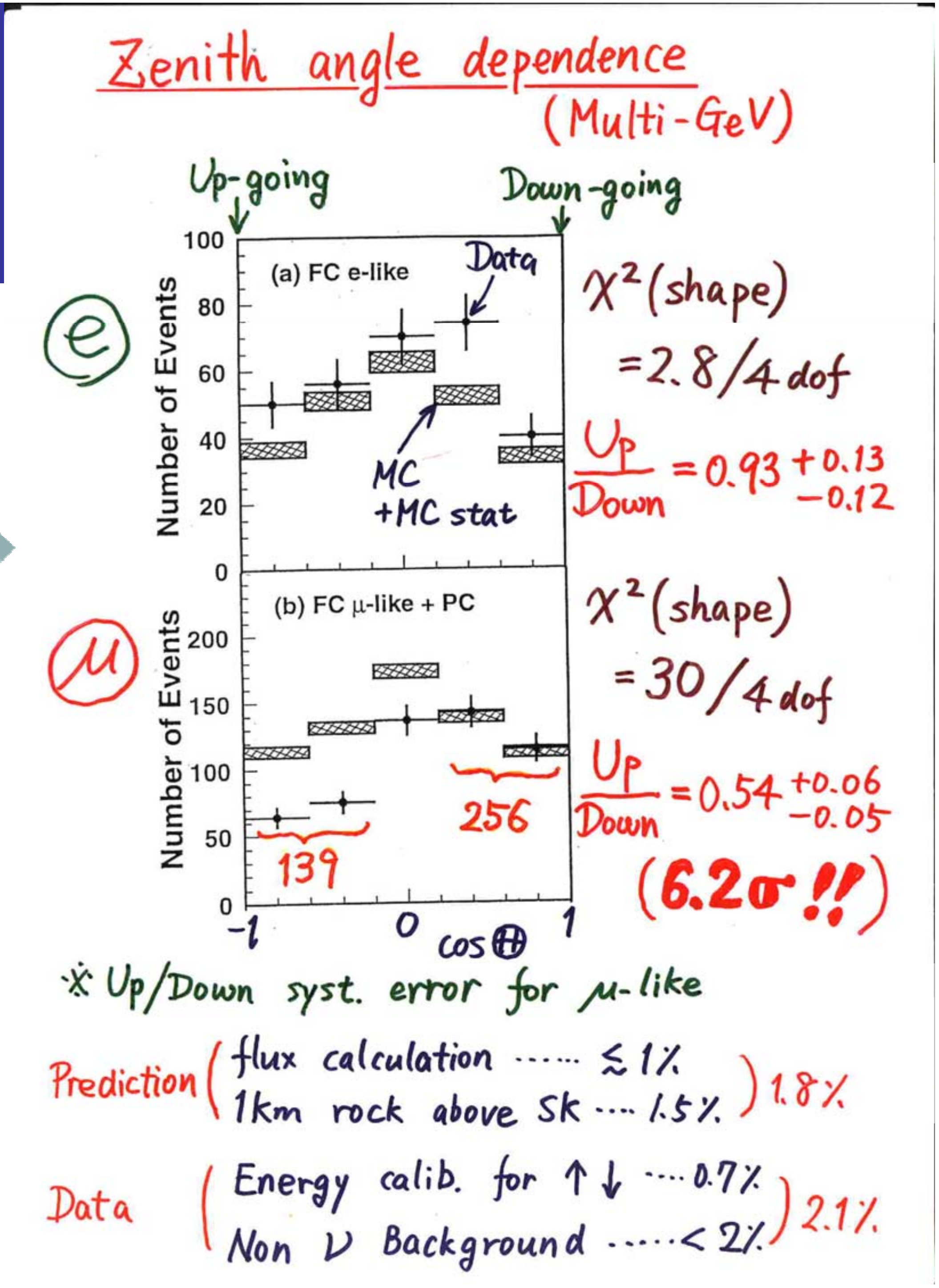
Super-K @Neutrino98

Fully contained, 1-ring events

with Evis > 1.33GeV

plus partially contained events

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



Zenith angle dependence
(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

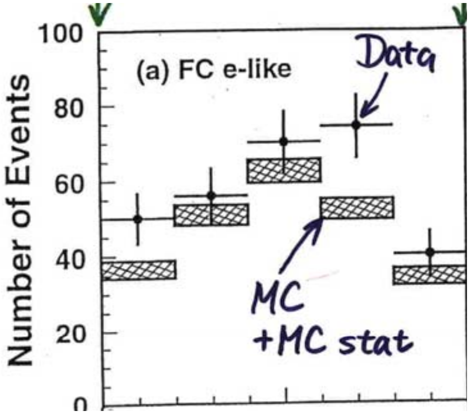
(6.2σ!!)

※ Up/Down syst. error for μ-like

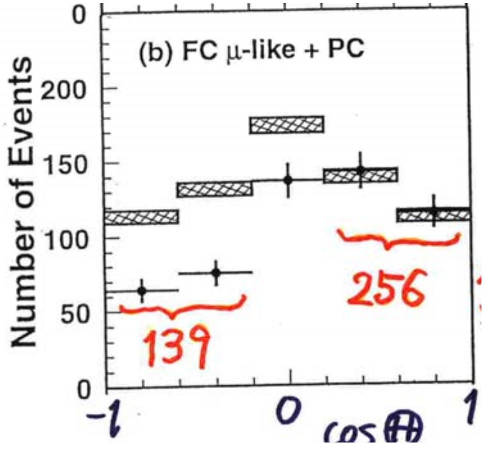
Prediction (flux calculation ······ ≲ 1% ; 1km rock above SK ···· 1.5%) 1.8%

Data (Energy calib. for ↑↓ ····0.7% ; Non ν Background ·····< 2%) 2.1%

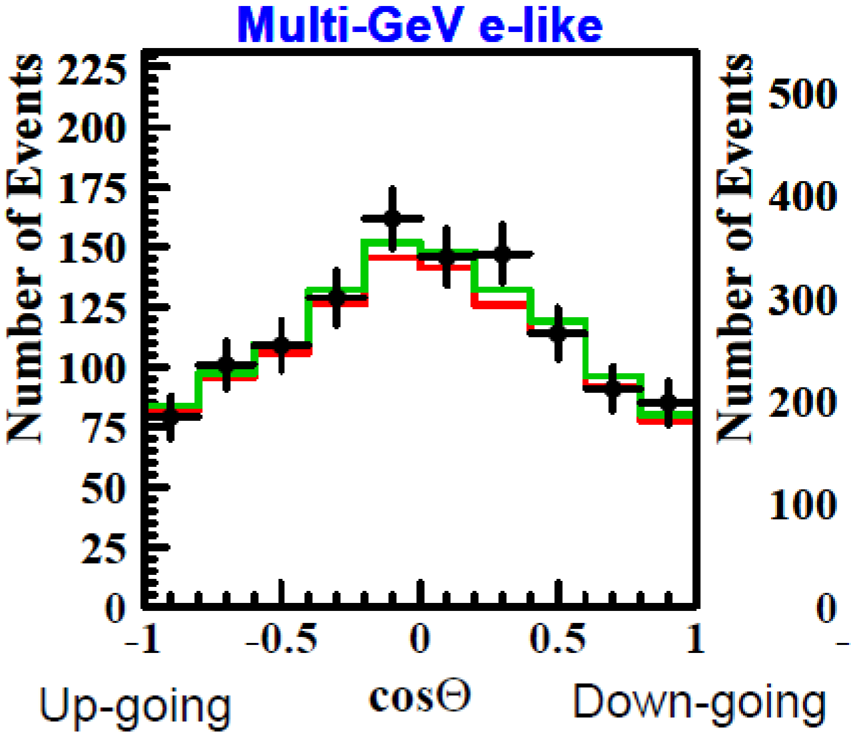
Super-K data now

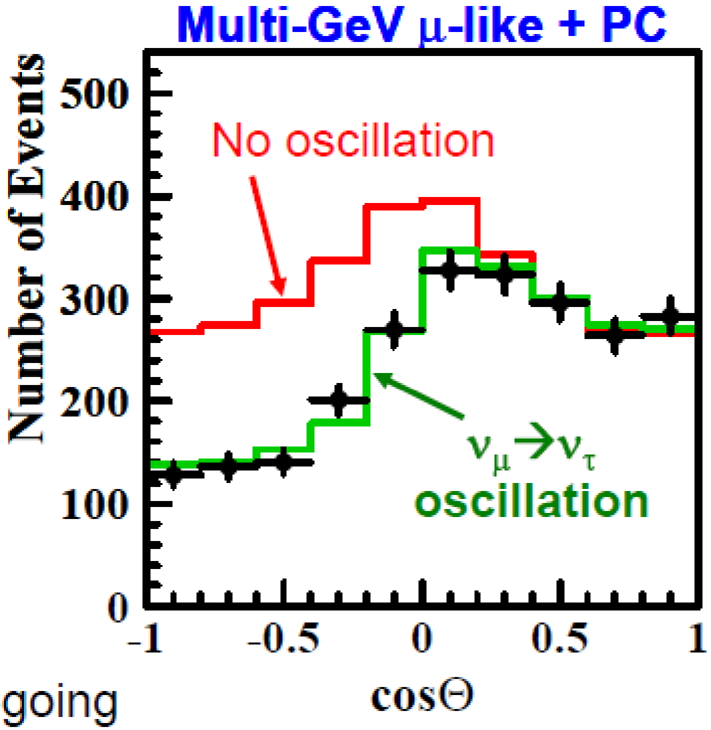


@Neutrino98
(535 day)

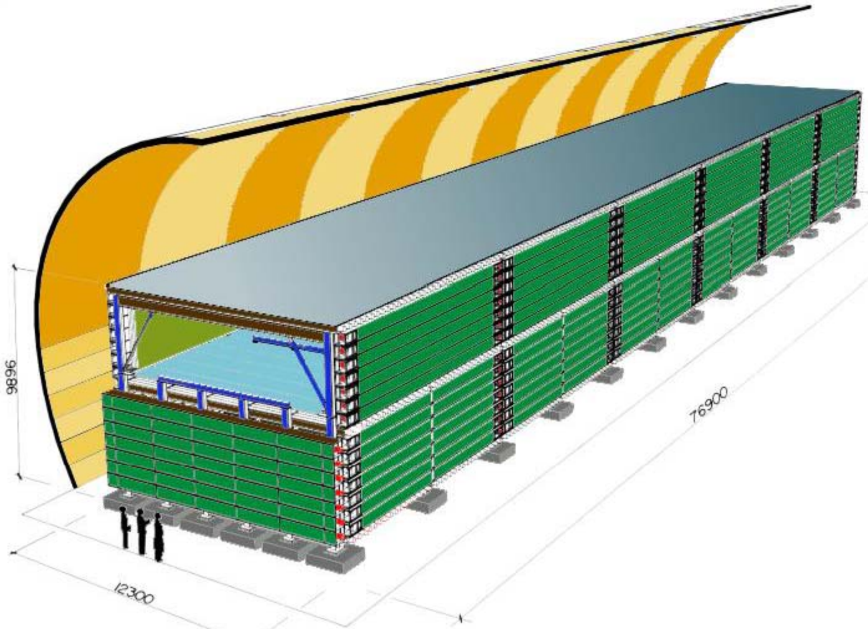


Now
(2293 day)





Results from the other atmospheric neutrino experiments



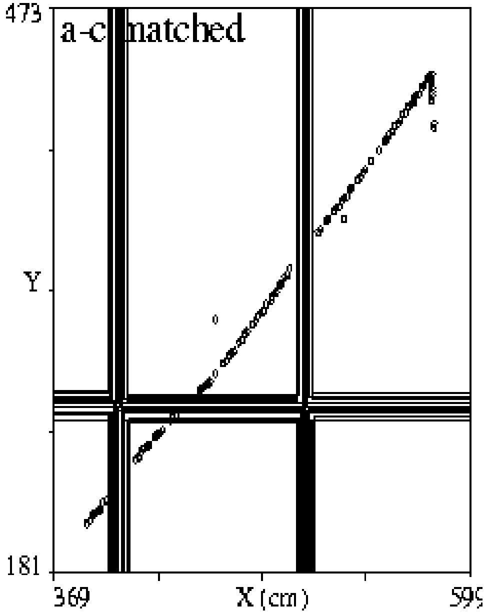
MACRO

Soudan-2

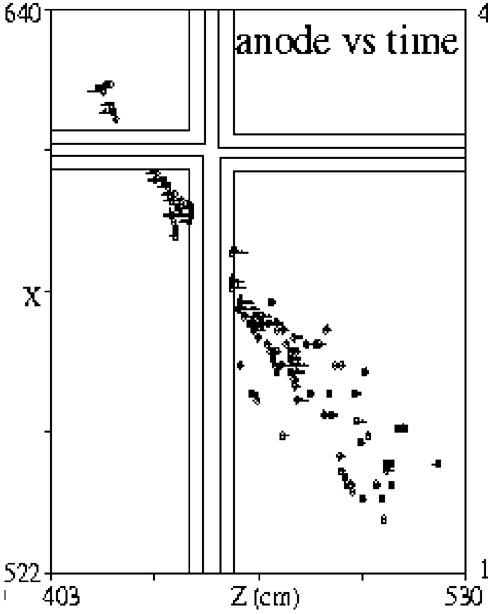
MINOS
(first data in 2005)

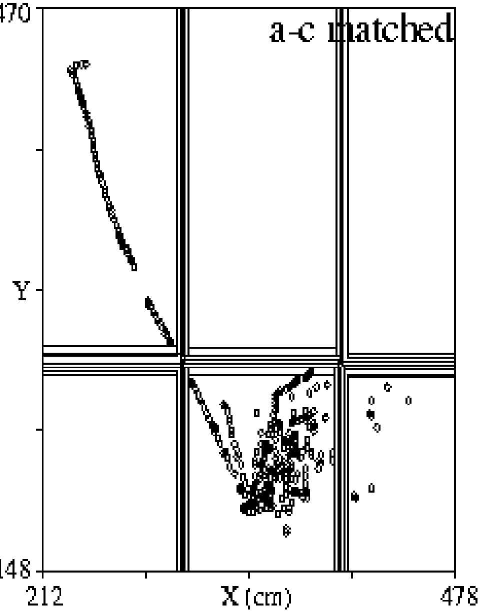
Soudan2

ν_μ CC
quasi-elastic



ν_e CC





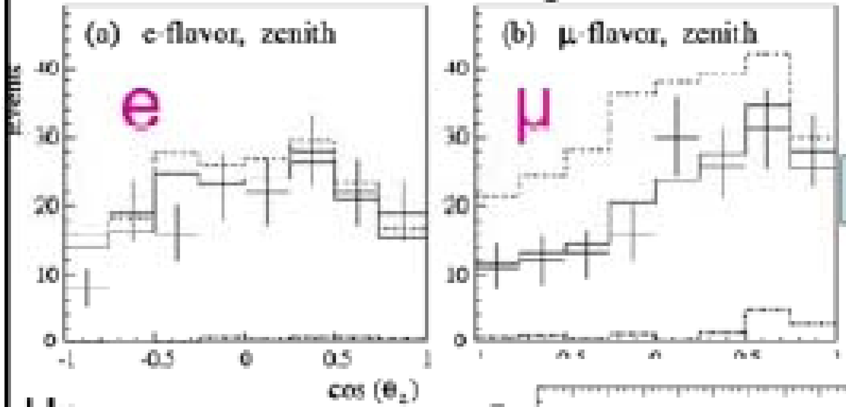
ν_μ CC
deep inelastic

Soudan2

- 5.9 kton・yr exposure
- Partially contained events included.
- L/E analysis with the "high resolution" sample
- Upward stopping muons included. hep-ex/0507068

Phys.Rev. D68 (2003) 113004

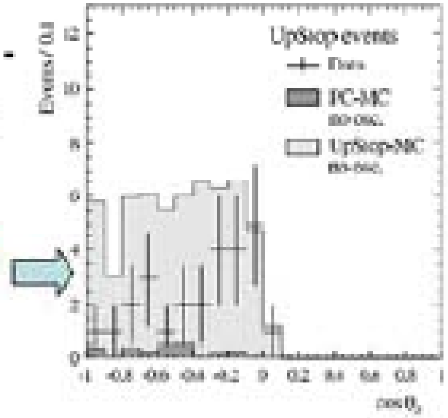
Zenith angle



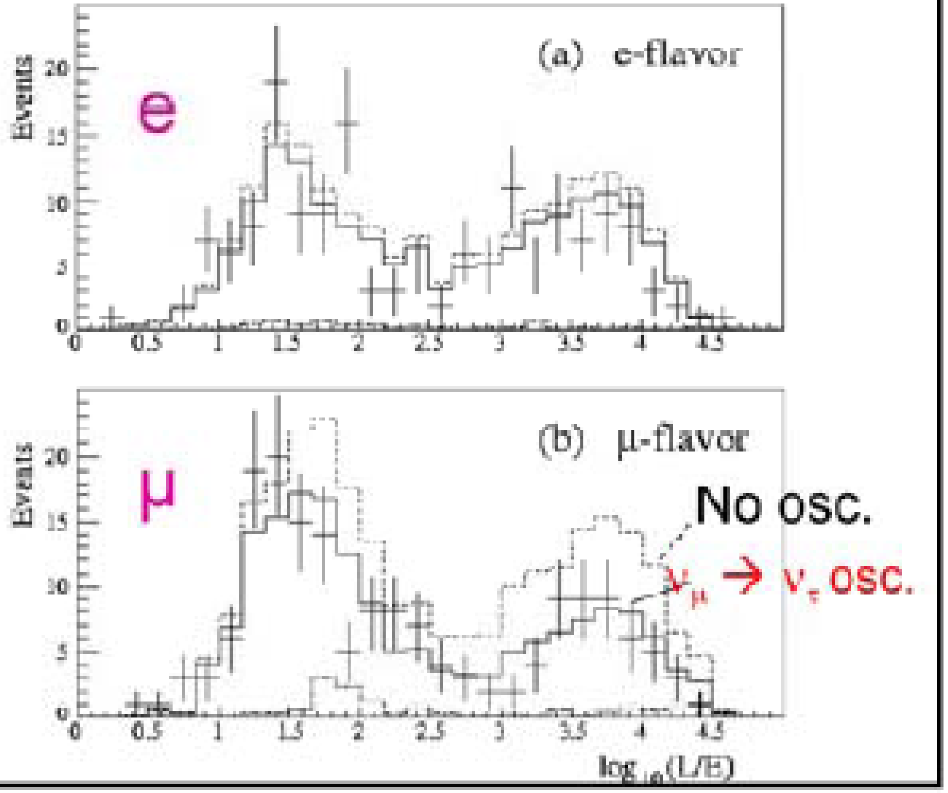
Up-going

Down-going

Upward stopping muons



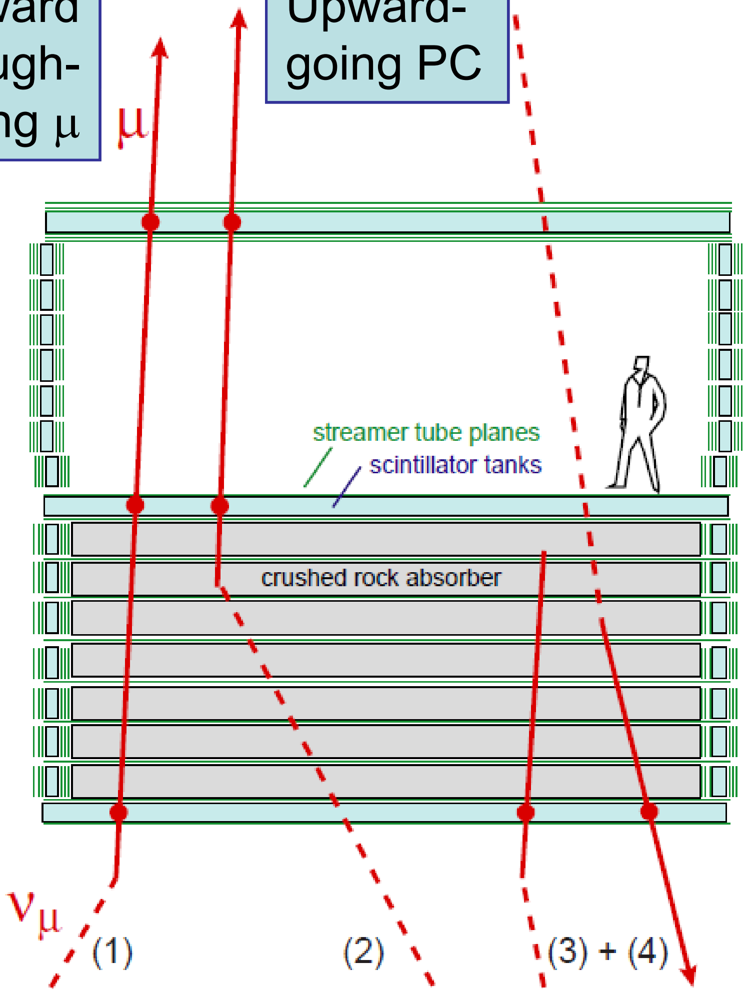
Reconstructed L_ν / E_ν dist.



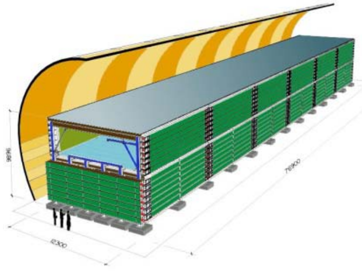
MACRO

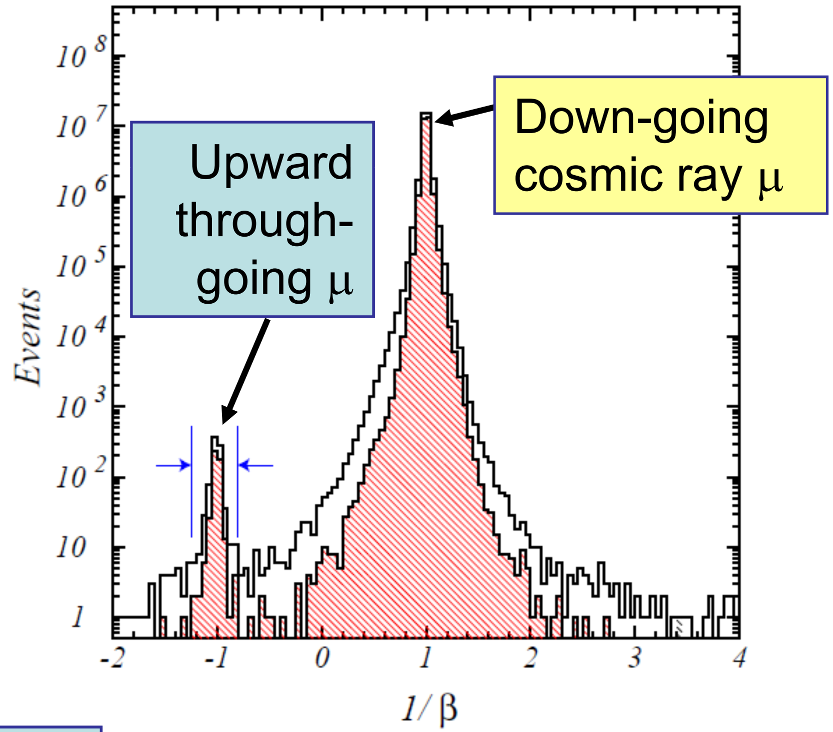
Upward through-going μ

Upward-going PC



Upward stopping μ + down-going PC



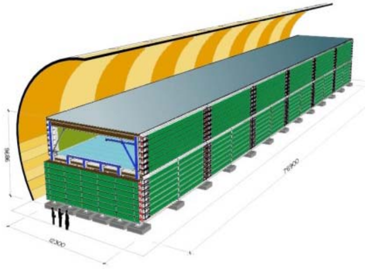


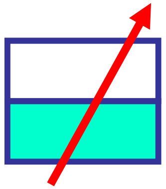
Upward through-going μ

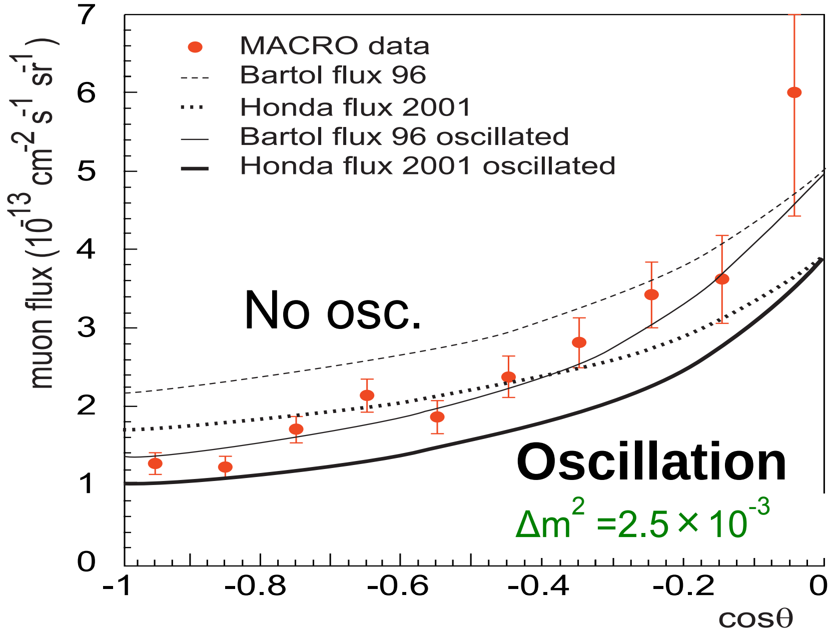
Down-going cosmic ray μ

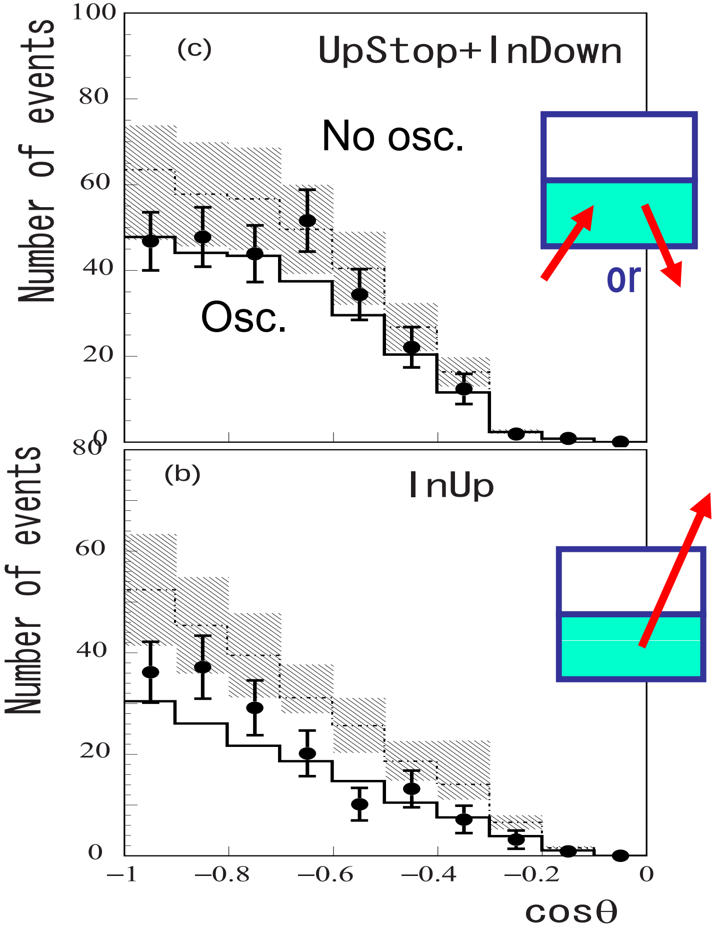
MACRO

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





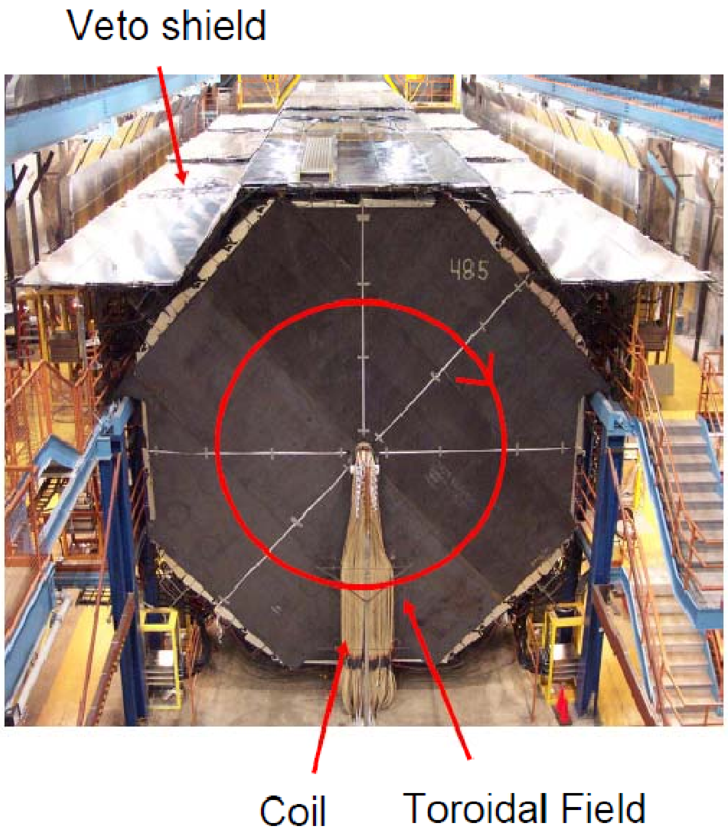




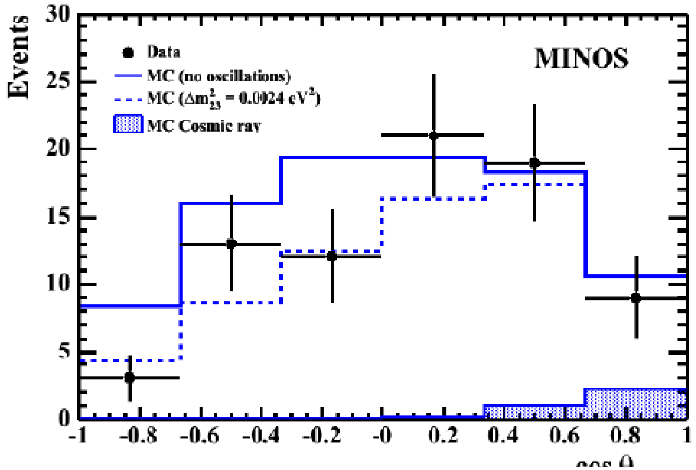
Upward horizontal

MINOS

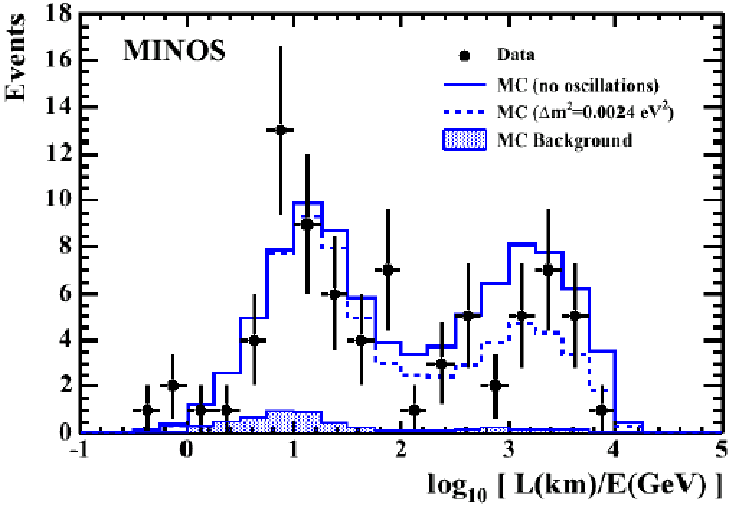
PRD73, 072002 (2006)
6.18 kton･yr (418days)

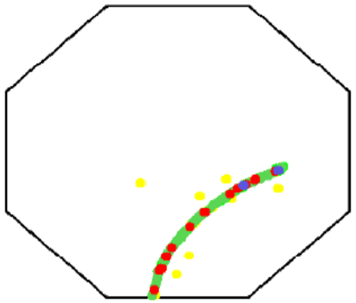


νμ zenith-angle



L/E

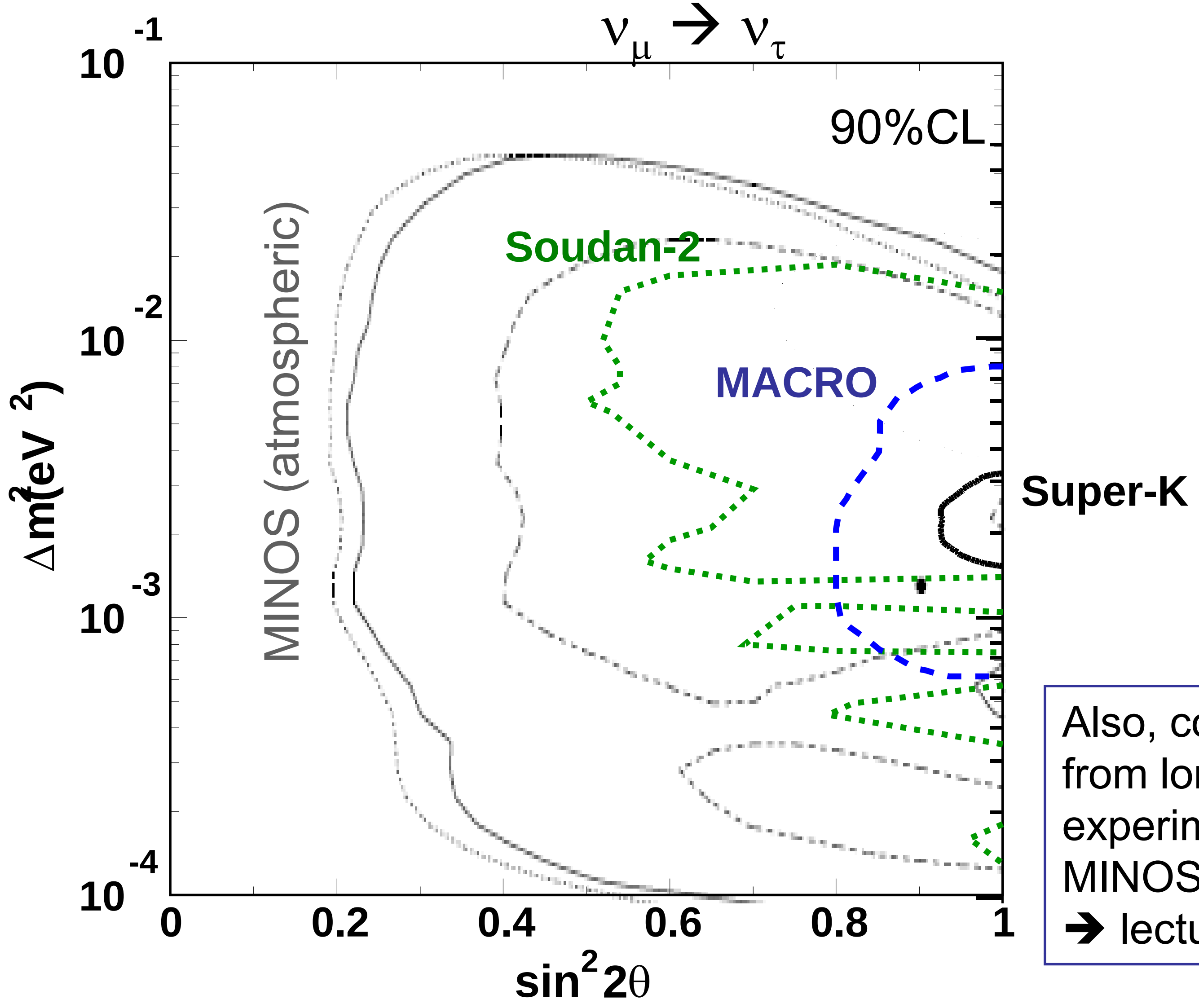




Downward going partially contained event

Separation of ν_μ and anti-ν_μ

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



Also, consistent results from long baseline experiments (K2K & MINOS)
➔ lecture 3

Summary of Leture-1

- Experimental studies of atmospheric neutrinos started in the mid. 1960's.
- Different type of atmospheric neutrino experiments started in the 1980's (proton decay experiments).
- Study of the background for proton decay found unexpected atmospheric ν_μ deficit.
- In 1998, the ν_μ deficit was concluded as evidence for neutrino oscillations.
- Recent atmospheric neutrino data are consistently explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations.

End