Atmospheric Neutrino Experiments

Part-I

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Kyoto University
CCEPP Summer School on Neutrino Physics
Daya Bay

2017.07.06

Introductory Remarks

- Lecture organization
  - History of Atmospheric Neutrino Measurements
  - Discovery of Oscillations
  - Systematic Errors for Atmospheric Neutrinos
  - Other Types of Oscillation Physics
  - Future for atmospheric neutrino oscillations

- Intrinsic bias(es)
  - I will mostly discuss the Super-Kamiokande and IceCube
  - (With some mention of other experiments)

Main Messages:

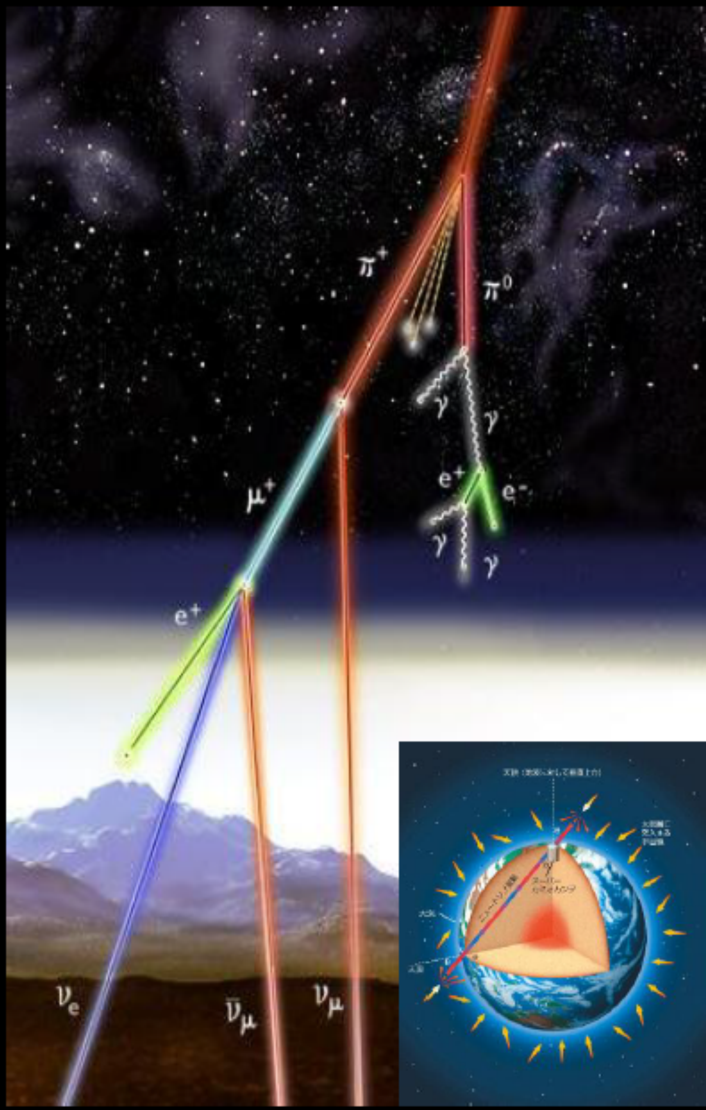
- Atmospheric neutrinos are a useful probe many interesting (potential) phenomena because:
  - Wide range of energies
  - Wide variety of their baselines
  - Constant source

- But precision measurements are challenging because:
  - Wide range of energies
  - True neutrino direction is unknown
  - Constant source
    - Form a background for many other interesting phenomena

	Large lAr or H_2O Cherenkov	Iron Calorimeter	ν Telescope
"Atmospheric" and Neutrino Oscillations			
Δm^2	■	■	■
$\sin^2\theta_{23}$, octant	■	■	
$\sin^2\theta_{13}$	■	■	■
δ_{cp}	■		
Mass Hierarchy	■	■	■
Exotic Scenarios	■	■	■
τ Appearance	■	■	■
Earth Radiography	■		■
Resolution of Parameter Degeneracy (+ beam)	■	■	■
Measurement of prompt flux			■

Flux Reminders

Reminders about the Atmospheric Neutrino Flux



- Cosmic rays strike air nuclei and the decays of the out-going hadrons produce neutrinos

$$P + A \rightarrow N + \pi^+ + x$$

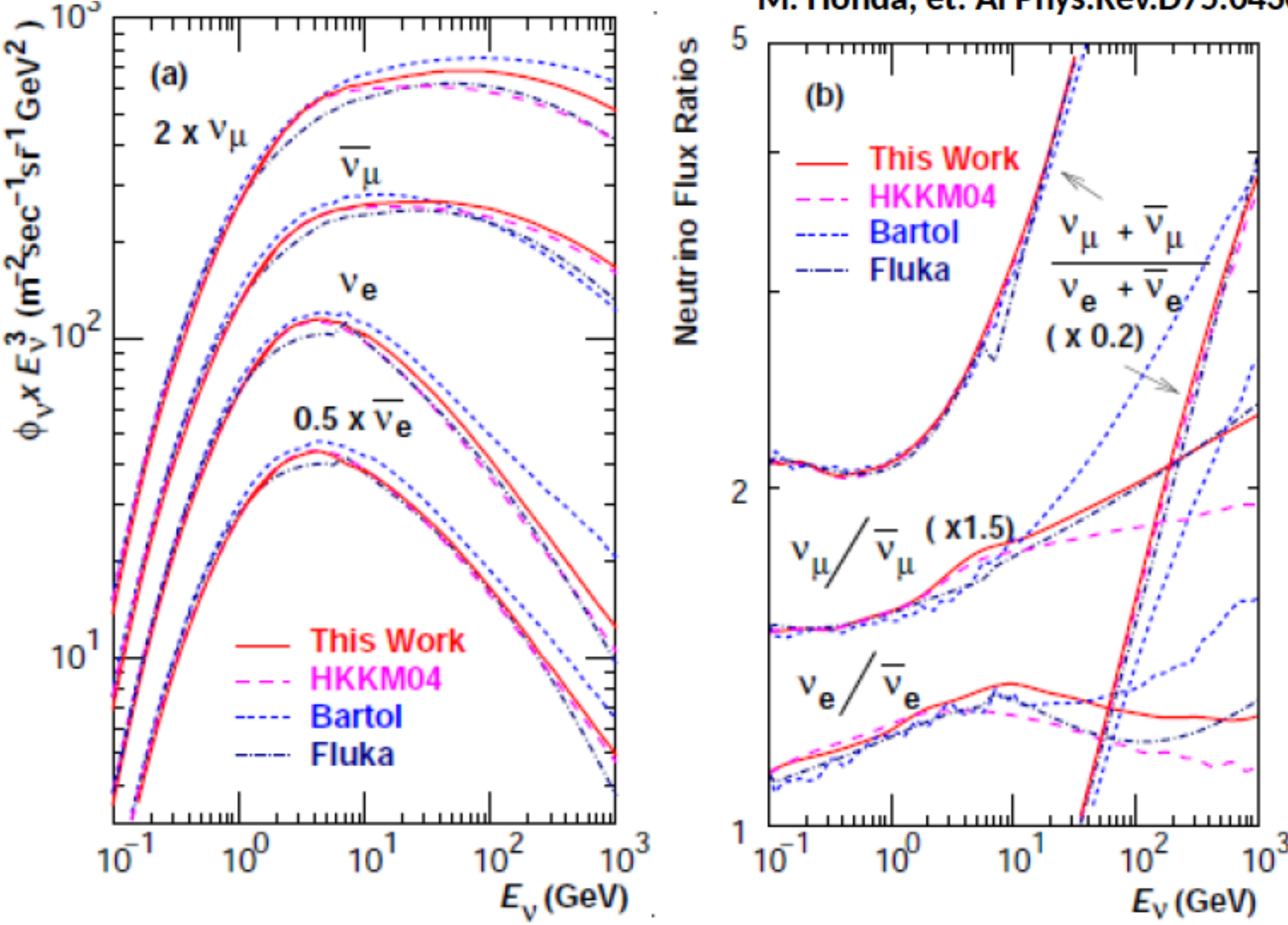
$$\hookrightarrow \mu^+ + \boxed{\nu_\mu} \rightarrow e^+ + \boxed{\nu_e} + \boxed{\bar{\nu}_\mu}$$

- Isotropic about the Earth
  - Path length to the detector spans 10 – 10,000 km

- Spans many decades in energy ~100 MeV – PeV+

Reminders about the Atmospheric Neutrino Flux

M. Honda, et. Al Phys.Rev.D75:043006,2007

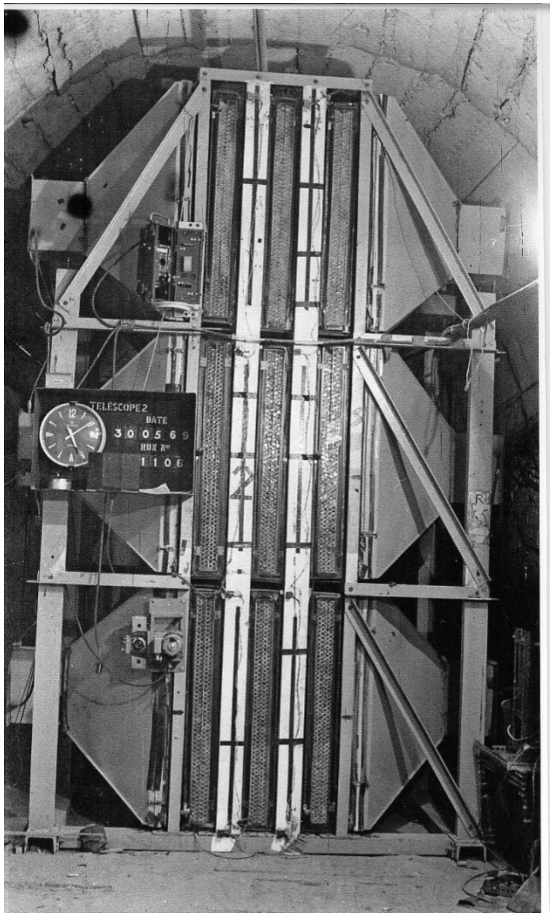


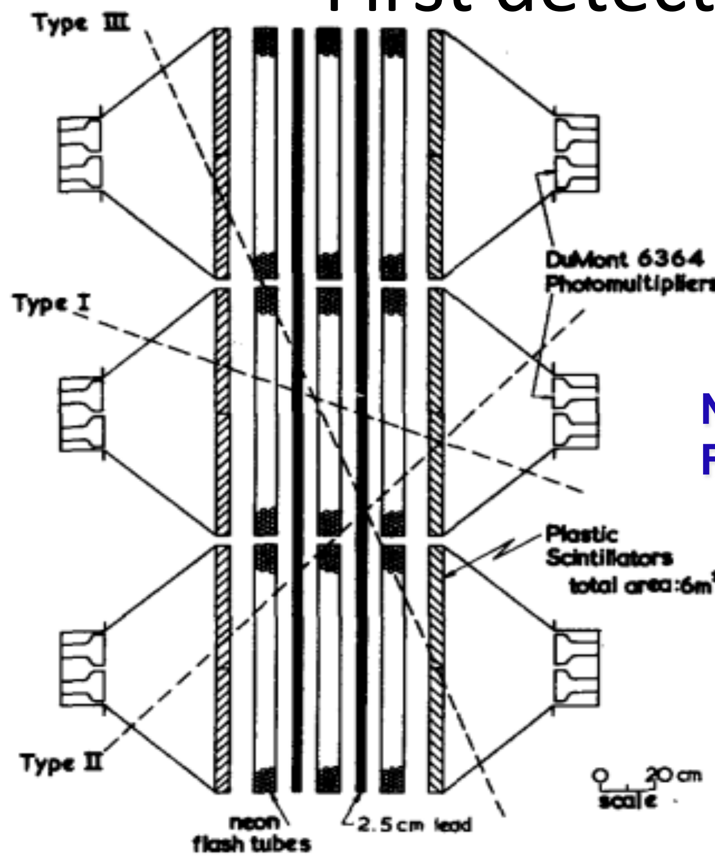
$$p + A \rightarrow N + \pi^+ + x$$

$$\Rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

History

First detection of atmospheric neutrinos in 1965





Neutrino telescope at Kolar Gold Fields, India –1965

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Physics Letters 18, (1965) 196, dated 15 Aug 1965

At a depth of 2400 meters (7500 meters water equivalent) in India

EVIDENCE FOR HIGH-ENERGY COSMIC-RAY NEUTRINO INTERACTIONS*

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith
Case Institute of Technology, Cleveland, Ohio
and
J. P. F. Sellschop and B. Meyer
University of the Witwatersrand, Johannesburg, Republic of South Africa
(Received 26 July 1965)

Neutrino detector at East Rand Proprietary Mine, South Africa –1965

At a depth of 3200 meters (8800 meters water equivalent)

PRL 15, (1965) 429, dated 30 Aug. 1965

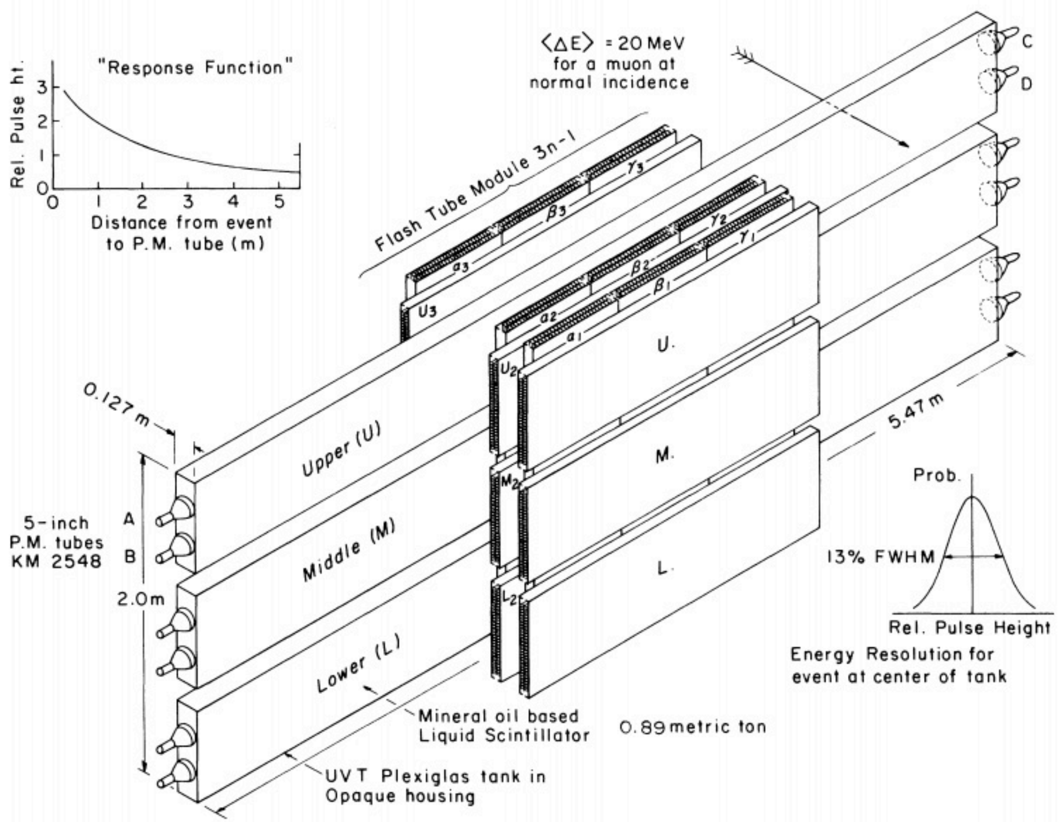
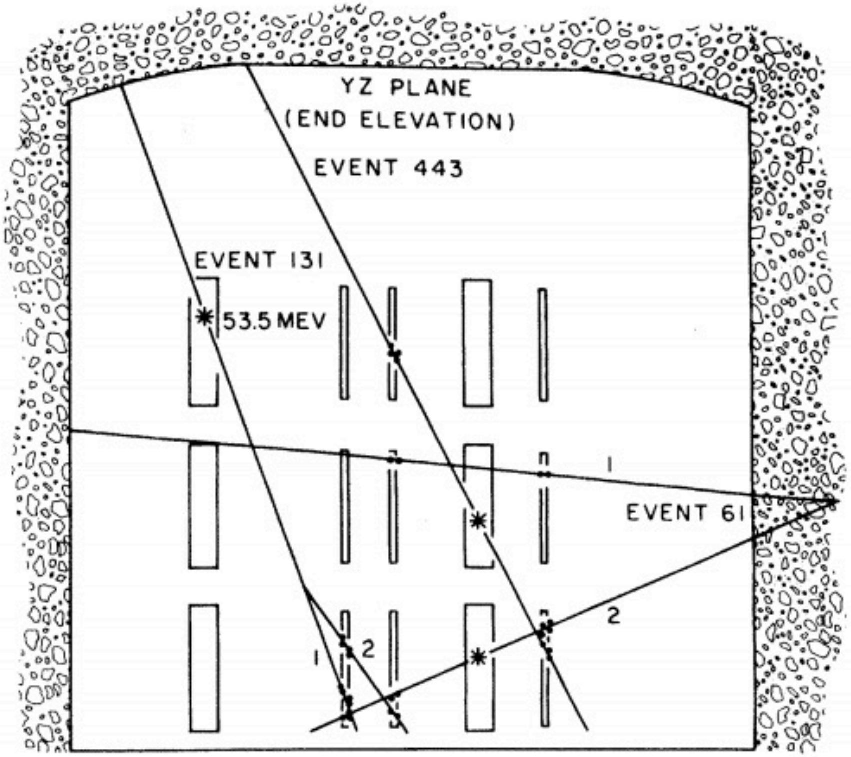


FIG. 2. Details of the nth scintillator bay and the (3n − 1)st flash-tube module.

East-Rand Property Experiment Results (1978)

PRL 18, (1978) 2239



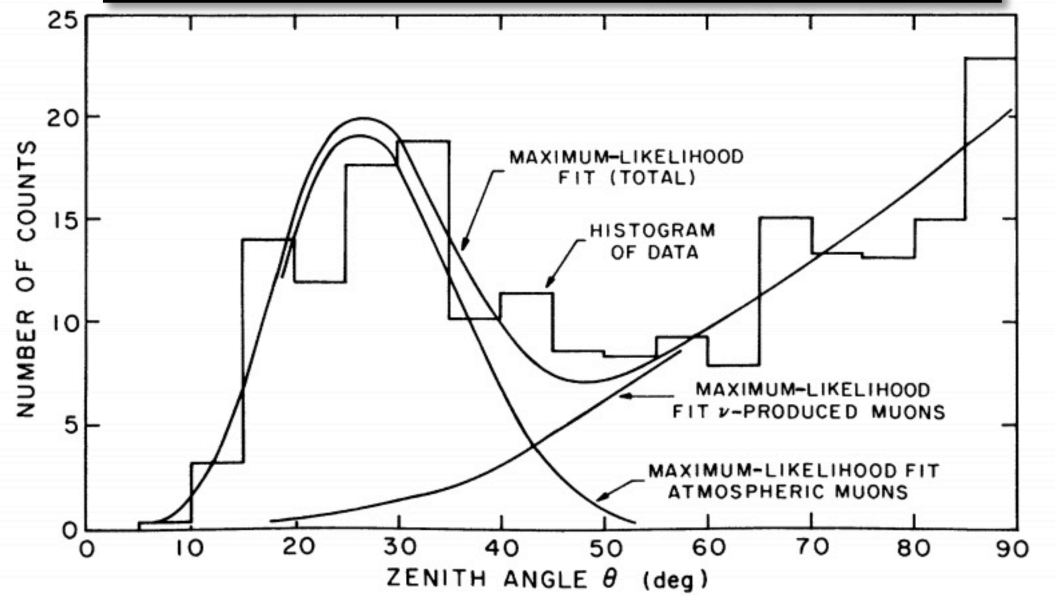
Cosmic-ray muon fluxes deep underground: Intensity vs depth, and the neutrino-induced component

M. F. Crouch
Department of Physics, Case Western Reserve University, Cleveland, Ohio 44106

P. B. Landecker,* J. F. Lathrop,† F. Reines, W. G. Sandie,‡ and H. W. Sobel
Department of Physics, University of California, Irvine, California 92717

H. Coxell** and J. P. F. Sellschop
Nuclear Physics Research Unit, University of the Witwatersrand, Johannesburg, Transvaal, Republic of South Africa

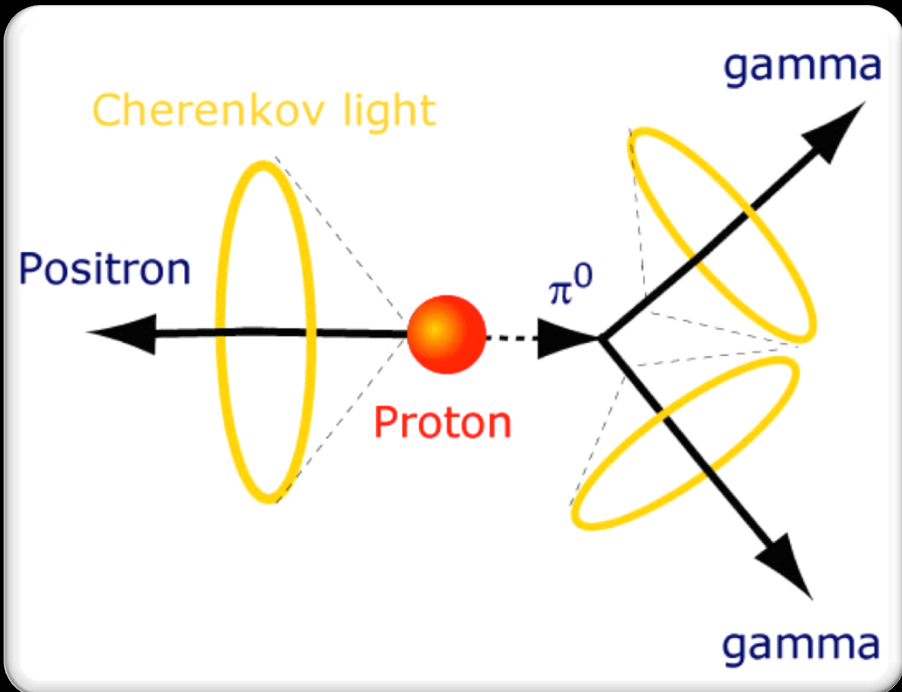
(Received 3 March 1978; revised manuscript received 12 September 1978)

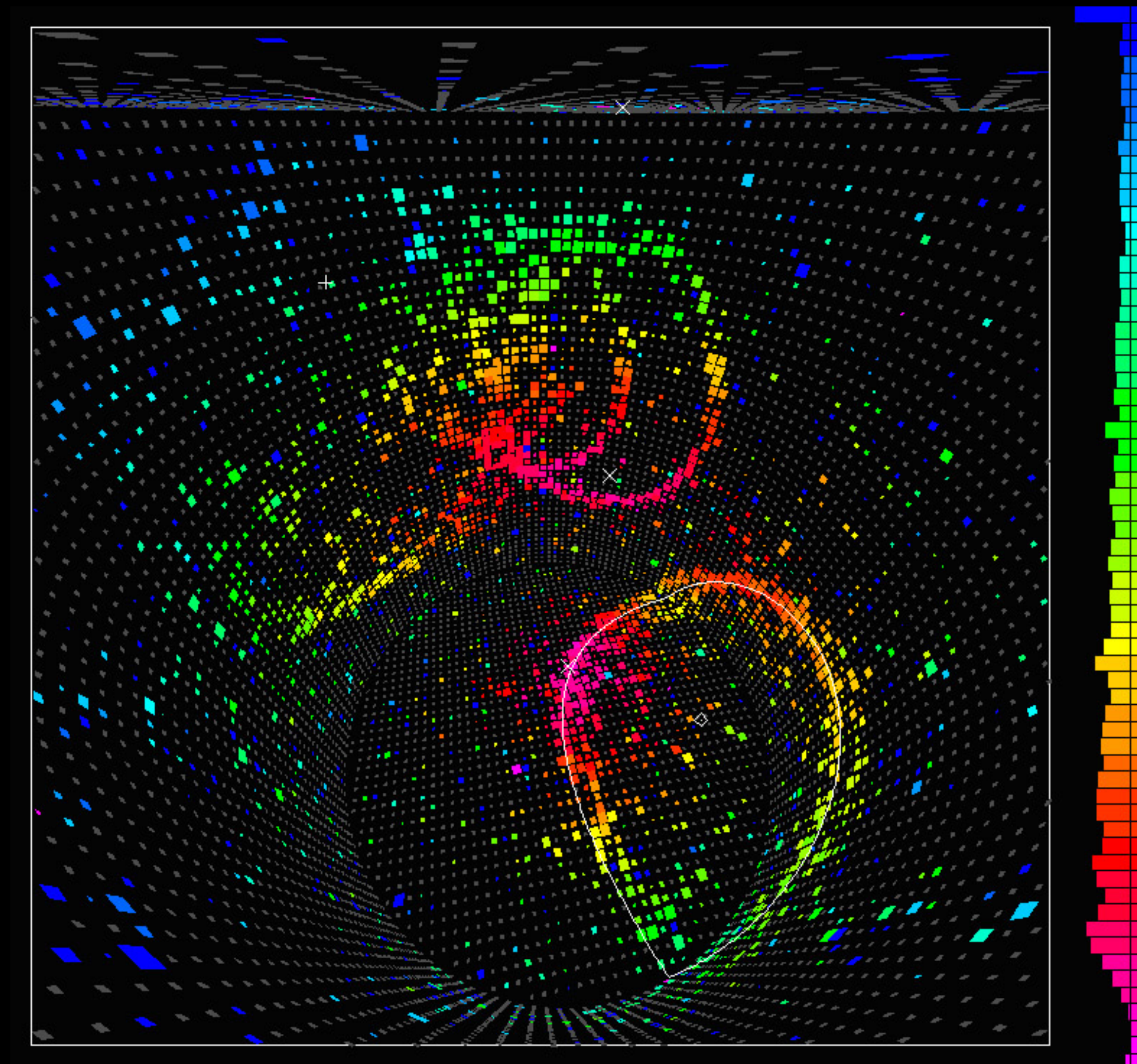


We conclude that there is fair agreement between the total observed and expected neutrino-induced muon flux (Table II), i.e.,

$$\frac{I_{h\mu}^{(\nu)}(\text{predicted})}{I_{h\mu}^{(\nu)}(\text{observed})} = 1.6 \pm 0.4\ .$$

It all begins with the search for proton decay





Theories of grand unification (unifying the strong, weak, and EM forces) were proposed in the late 1970's

- Prediction: protons and neutrons (nucleons) should decay with lifetimes ~10^{28} – 10^{31} years
- Experiments built to test this prediction in the early 1980's

Proposal for the Kamiokande Experiment

Kamioka, Japan

…to test theories of grand unification by direct direction of their predicted nucleon decay phenomena…

研 究 目 的

Research Objective

本研究の目的は、素粒子の大統一理論が予言する核子崩壊現象を直接実験することにより検証すること、その崩壊モードを詳しく調べることを主要課題とし、更に理論的研究と協力しつつ、より究極的統一理論が左右対称か否かを検定するため、ニュートリノ振動現象の有無を実験的に探索すること、また大統一理論が必然的に予言する磁気単極子など質量の大きい粒子を探索することにある。

昭和56年 9 月

September 1981

Proposal for the Kamiokande Experiment

Kamioka, Japan

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…experimentally search for the existence, or lack thereof, of neutrino oscillation phenomena …

昭和56年９月

September 1981

Proposal for the IMB Experiment

A PROPOSAL

TO TEST FOR BARYON STABILITY

TO A LIFETIME OF 10^{33} YEARS

Abstract

We have studied the properties of, and the expected backgrounds in, a totally active, 10,000 ton water Cerenkov detector located deep underground and sensitive to many of the conjectured decay modes of the nucleons in it. Sensitivity to π, μ and γ secondaries, good energy resolution, and good angular resolution provide sufficient background rejection in the proposed device and will permit us to obtain significant information about several decay channels, should they be observe

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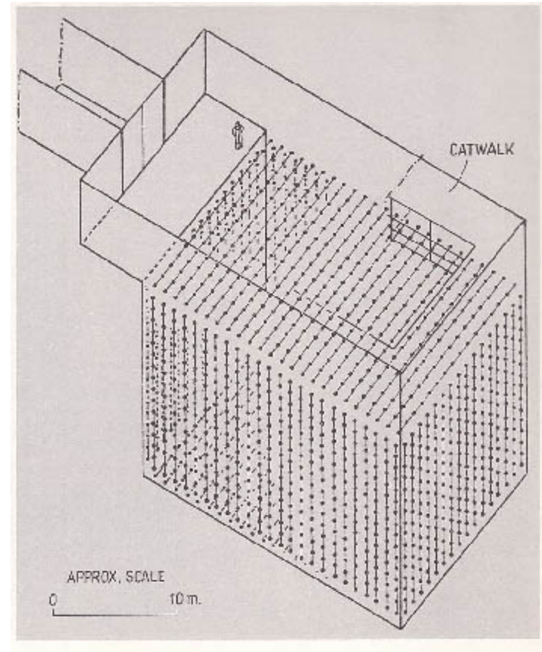
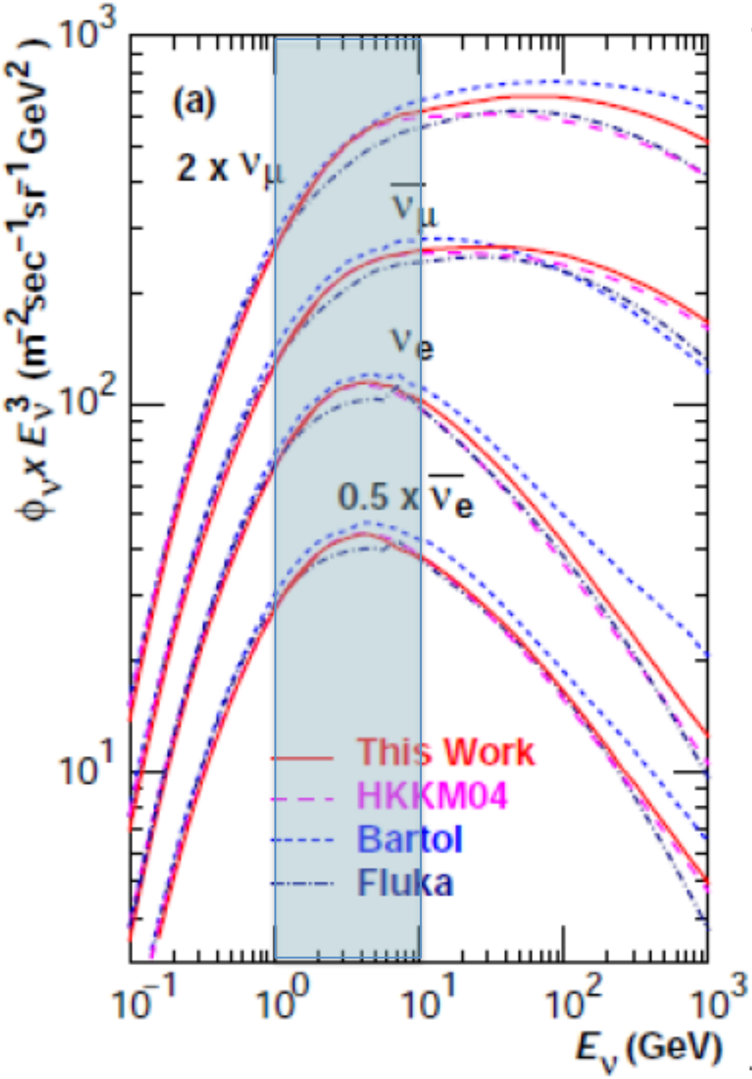
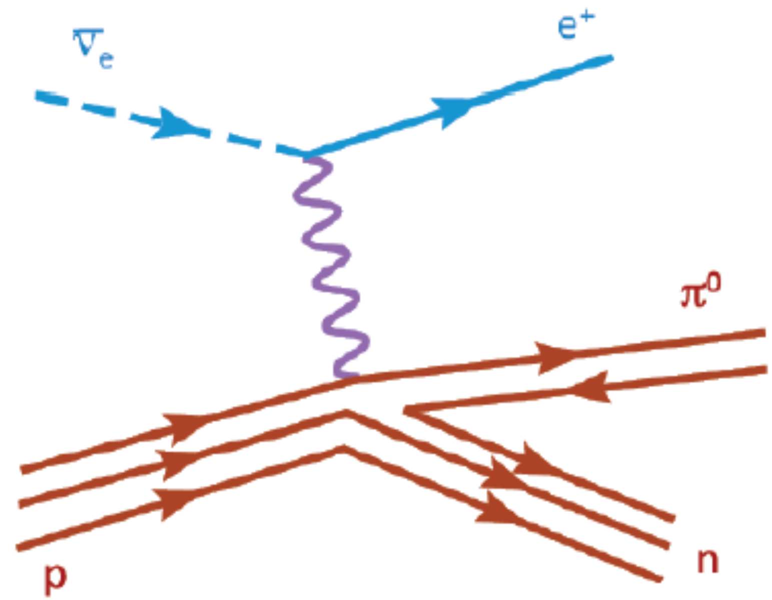


beyond the level suggested by many unifying theories. The sensitivity predicted for this instrument is within an order of magnitude of that achievable in an arbitrarily large detector of this general type, since known background from atmospheric neutrinos imposes an inherent limit.

Atmospheric Neutrino Flux

M. Honda, et. Al Phys.Rev.D75:043006,2007





$$p + A \rightarrow N + \pi + \; + x$$

$$\Rightarrow \mu^+ + \nu_\mu \;\rightarrow\; e^+ + \nu_e + \overline{\nu}_\mu$$

A Simple Nucleon Decay rate calculation

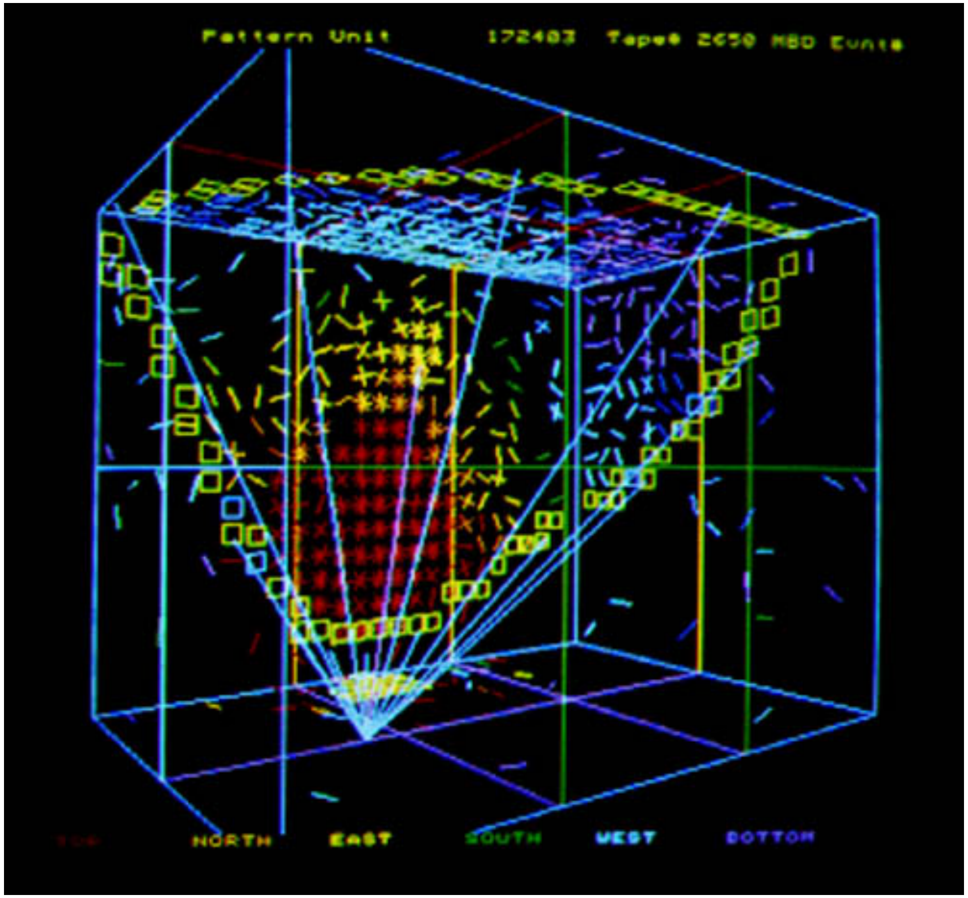
- Assume SU(5) lifetime is $10^{28} < \tau < 10^{31}$ years
- Number of targets $\lambda = 3.34 \times 10^{35}$ [$p \bullet Mton^{-1}$]
- For a 10 kton detector (3.3 kton fiducial)

- $N = T \times \lambda \times \varepsilon \times (1/\tau)$
- Efficiency $\varepsilon = 45\%$ (at best) for $p \to e^{+}\pi^{0}$ in water Cherenkov

- Therefore
  - $150 < N < 150{,}000$ $ev \bullet year^{-1}$

- *Expect about 0.5 atm. ν ev/kton/day*

Example Event From the IMB Experiment



- Each colored mark represents a hit PMT
- The color indicates the hit timing
  - Red: early
  - Late: blue
- Size of the marks indicates the collected charge

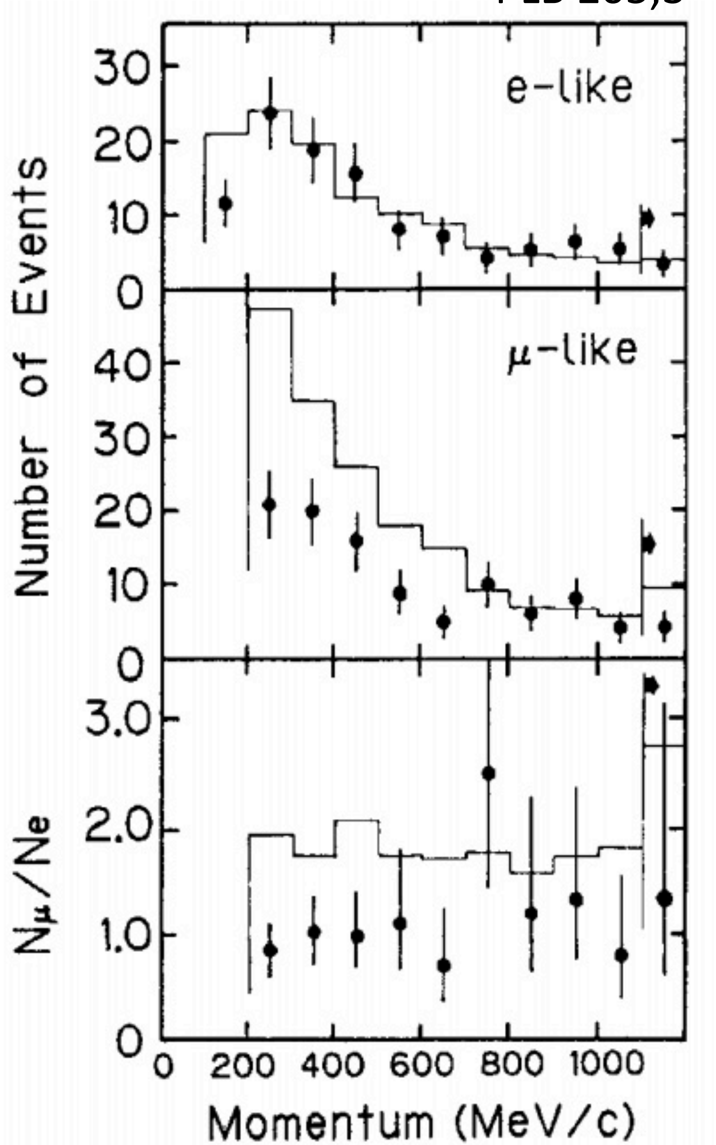
Very clearly an upward-going event!
Must be neutrino-induced

www-personal.umich.edu/~jcv/imb/imb.html

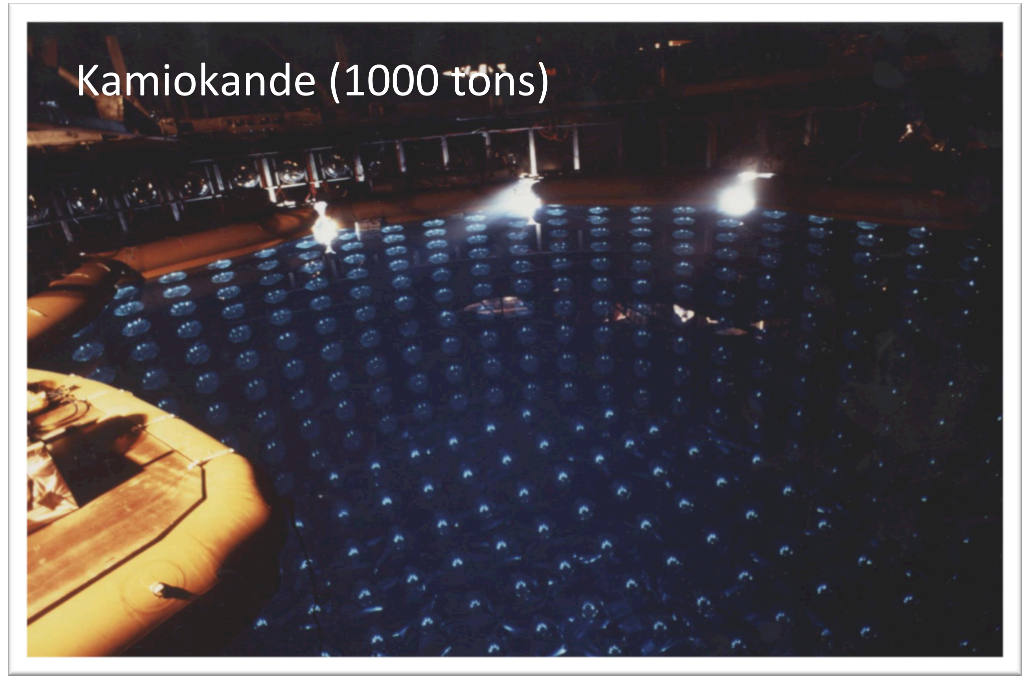
Atmospheric Neutrinos in Water Cherenkov Detectors

Kamiokande

PLB 205,3



https://inspirehep.net/record/302075



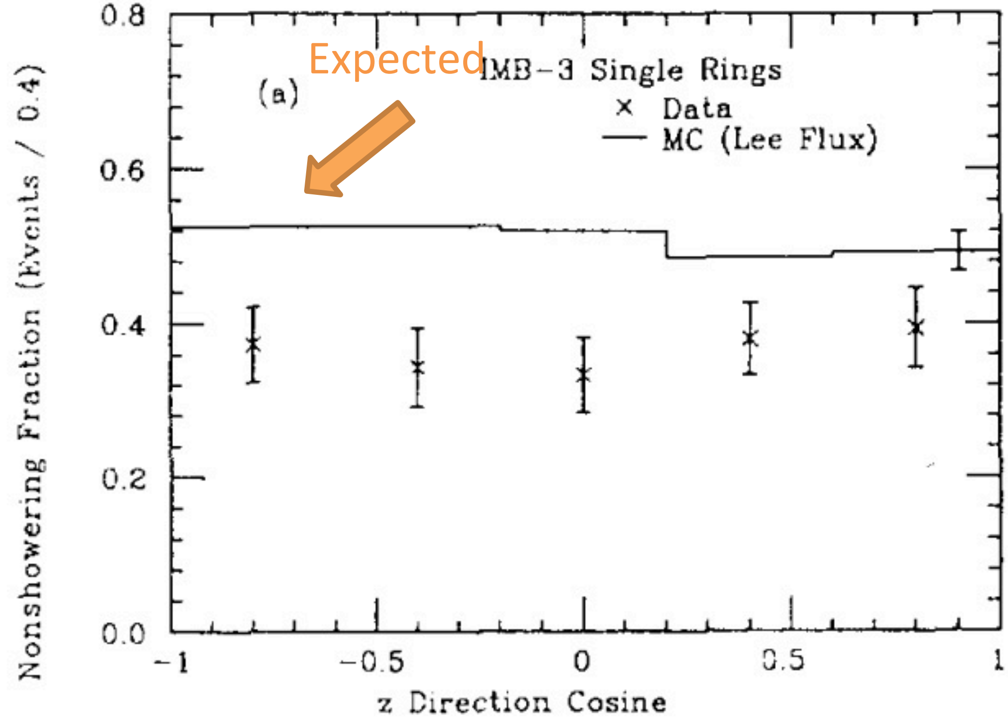
Expected`

Observed

Ratio ν_μ:ν_e smaller than expected

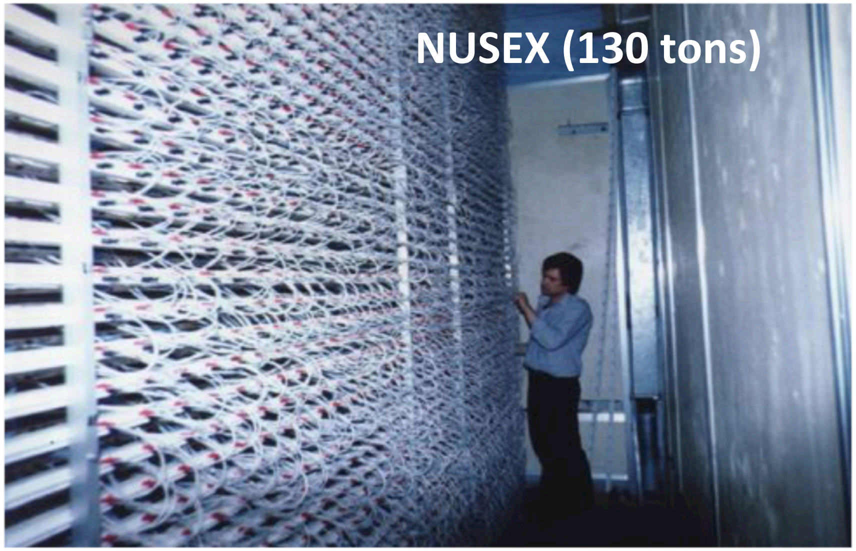
IMB Atmospheric Neutrino Results

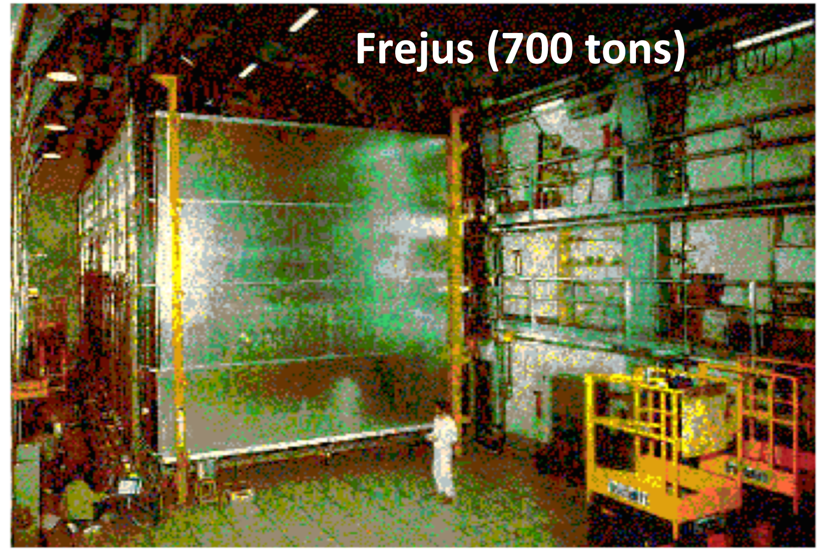
IMB (3300 tons)

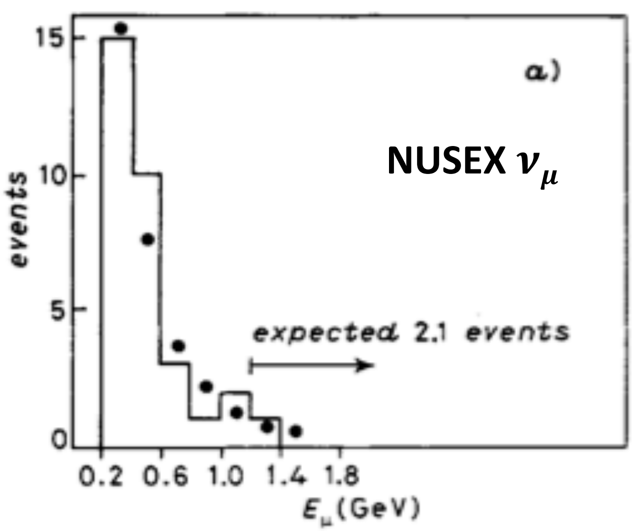


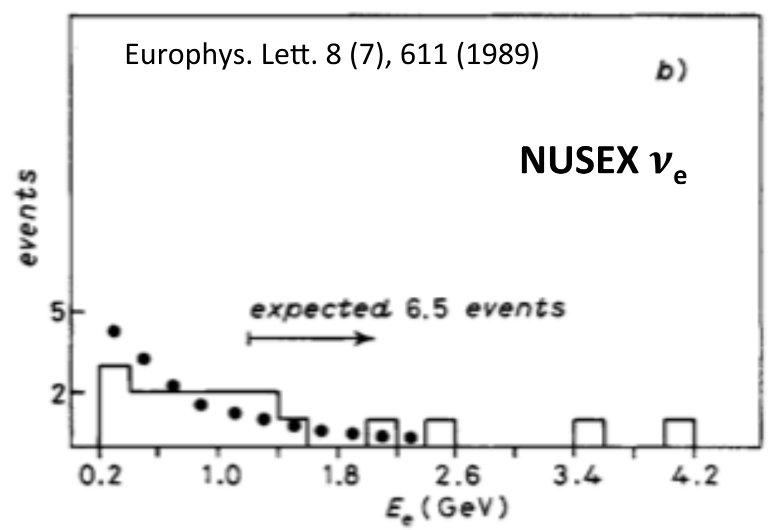
Nuclear Physics B (Proc. Suppl.) 38 (1995) 331–336

Atmospheric Neutrinos in Iron Calorimeters

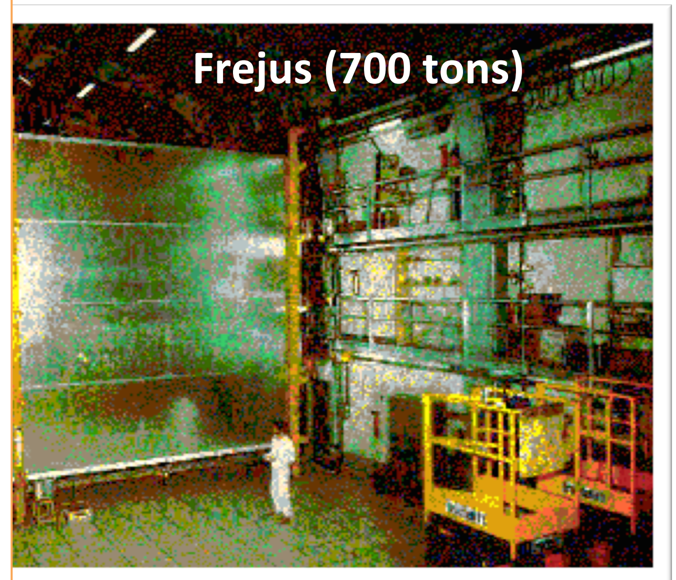


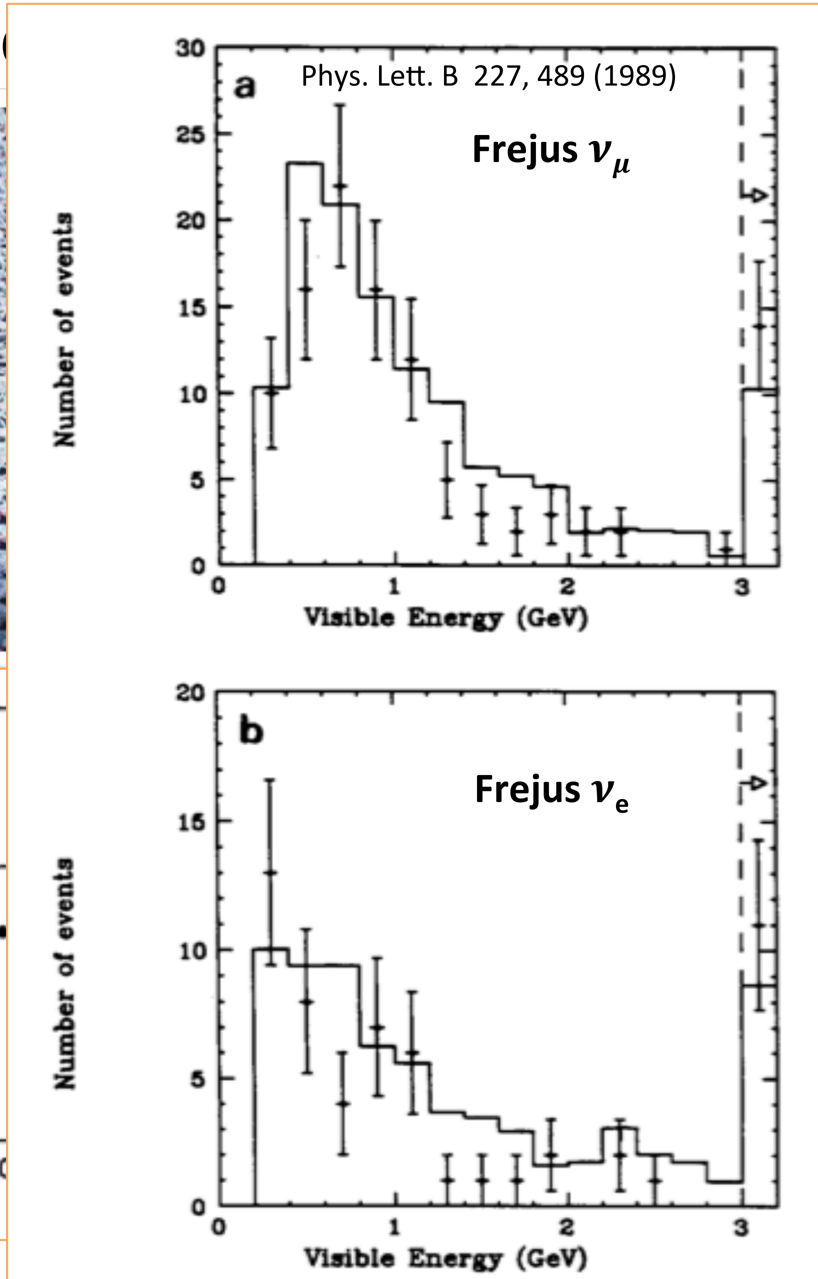


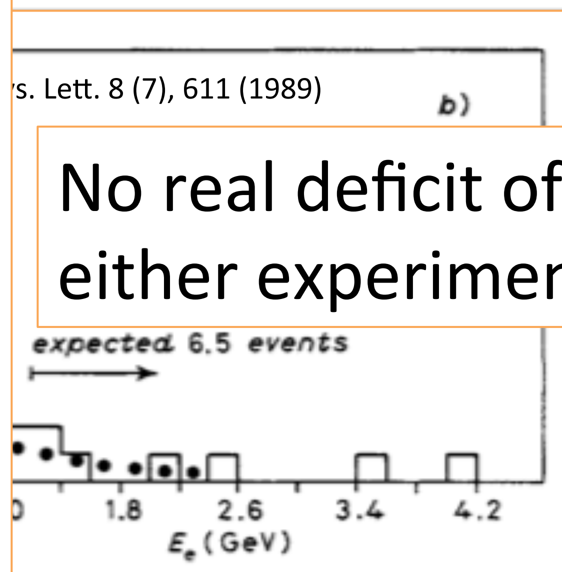




Atm on Calorimeters

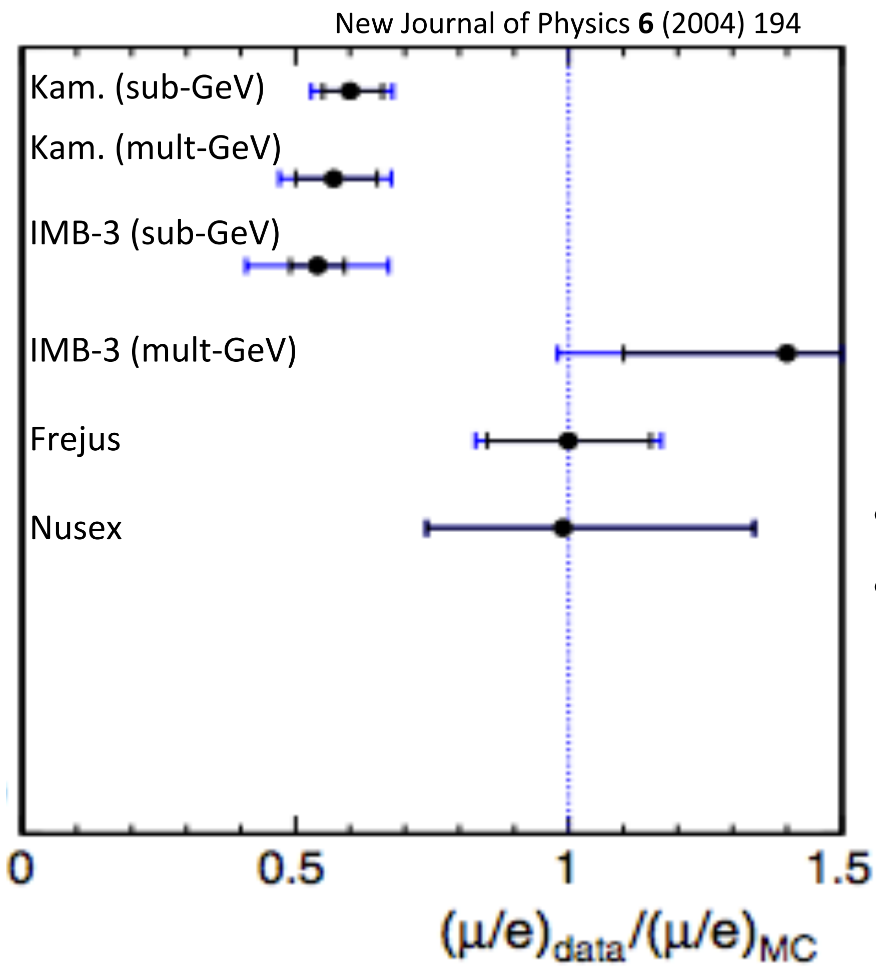






No real deficit of ν_μ in either experiment

Atmospheric Neutrino Anomaly



Measured flavor ratio in atmospheric neutrino flux:

$$\frac{[(\nu_\mu + \bar{\nu_\mu})/(\nu_e + \bar{\nu_e})]_{observed}}{[(\nu_\mu + \bar{\nu_\mu})/(\nu_e + \bar{\nu_e})]_{predicted}}$$

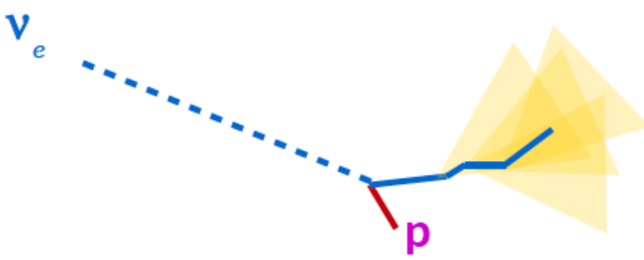
Double ratio:

- Many systematic uncertainties cancel
- If no neutrino oscillations, expect this ratio to be consistent with 1

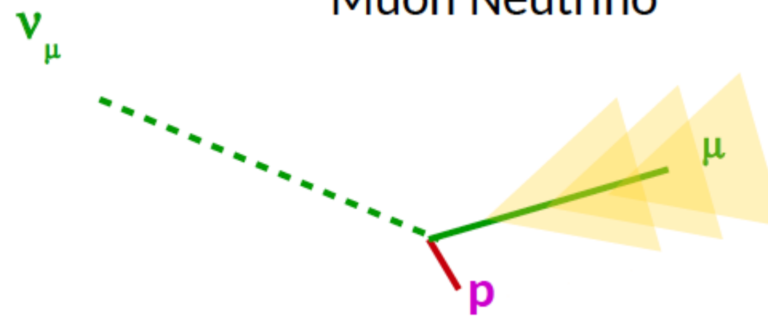
Anomaly

- Simulations wrong?
- Flux prediction of 2:1 wrong?
- PID incorrect?

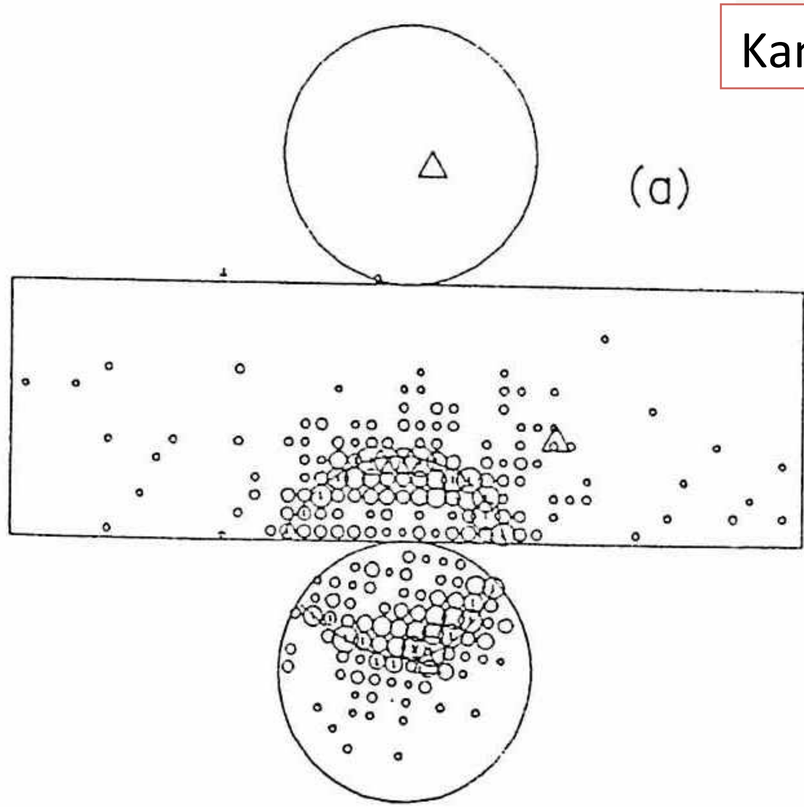
Electron Neutrino

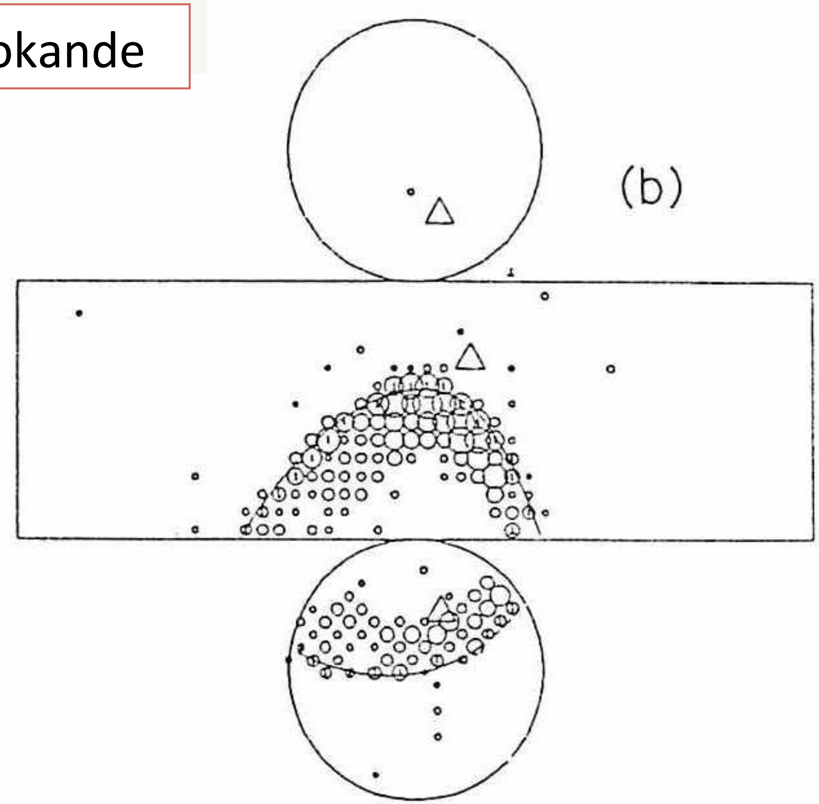


Muon Neutrino



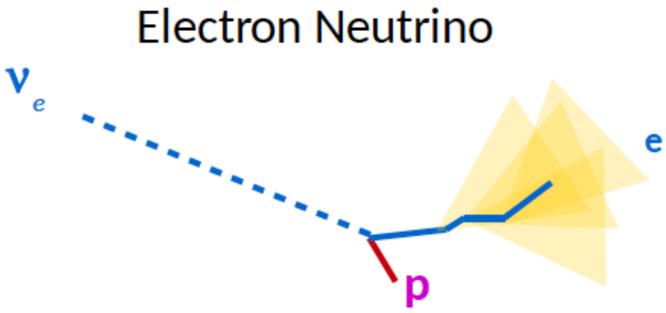
Kamiokande

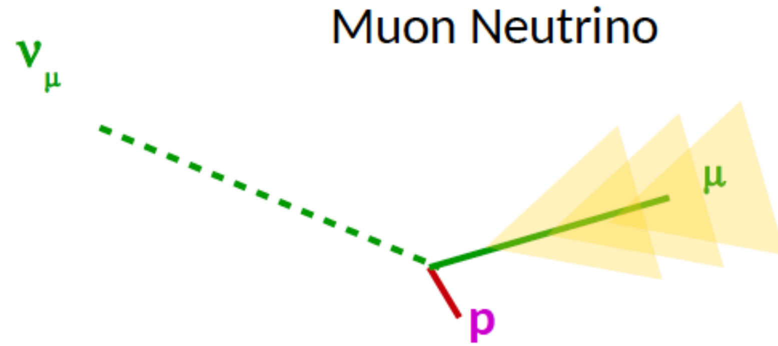




e: electromagnetic shower, multiple Coulomb scattering

μ: straight-line propagation, loose energy by ionization loss



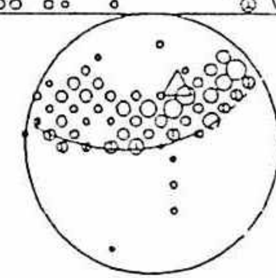


Kamiokande

The probability of misidentifying the particle species of single-ring events was estimated to be 2.2±0.9% and 1.4±0.7% for KAM-I and KAM-II, respectively, using Monte Carlo simulated neutrino events [#1]. The method was checked empirically by means of cosmic ray muons which were stopped in the detector. The analysis of stopping muons showed that the misidentification probability of muon-like events was 2% [#1], and therefore consistent with the Monte Carlo result. Accordingly it is unlikely that the particle identification program gives substantially incorrect assignments to the real fully contained events.

IMB

	ν_μ	ν_e	NC
ν_μ-like	0.95	0.07	0.34
ν_e-like	0.02	0.85	0.35
NC-like	0.03	0.08	0.31



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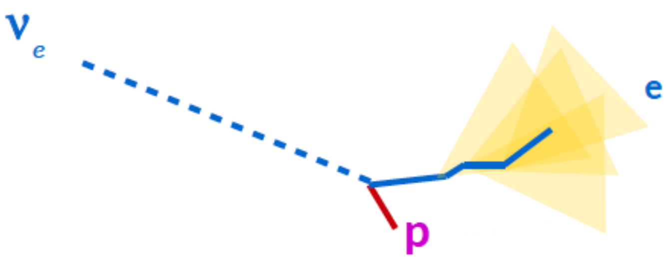
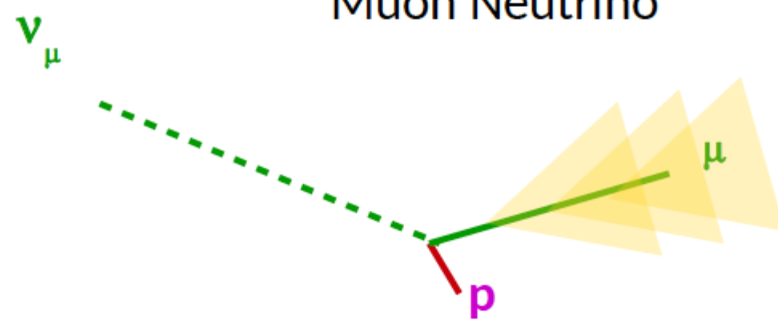
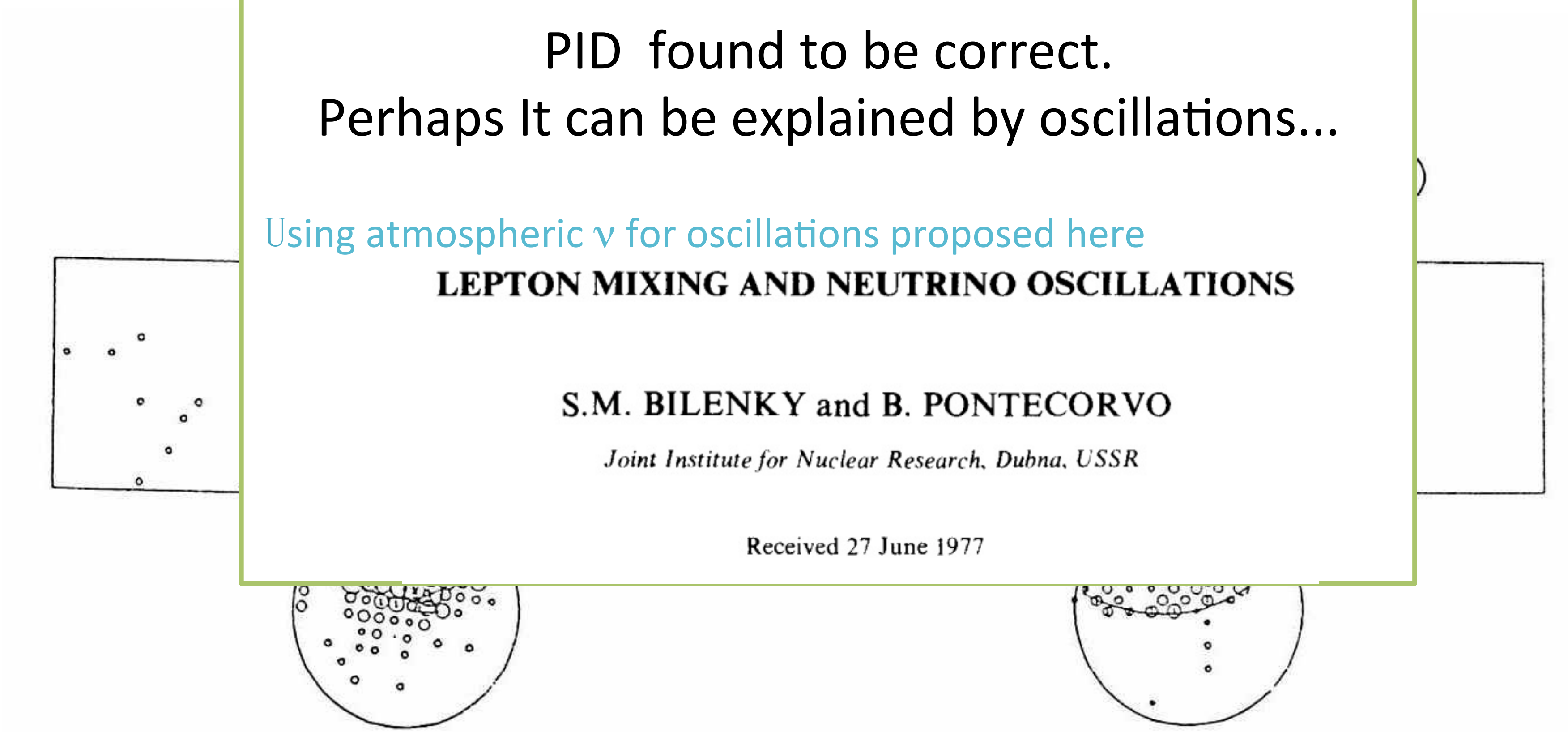
Electron Neutrino



Muon Neutrino





PID found to be correct.
Perhaps It can be explained by oscillations...

Using atmospheric ν for oscillations proposed here

LEPTON MIXING AND NEUTRINO OSCILLATIONS

S.M. BILENKY and B. PONTECORVO

Joint Institute for Nuclear Research, Dubna, USSR

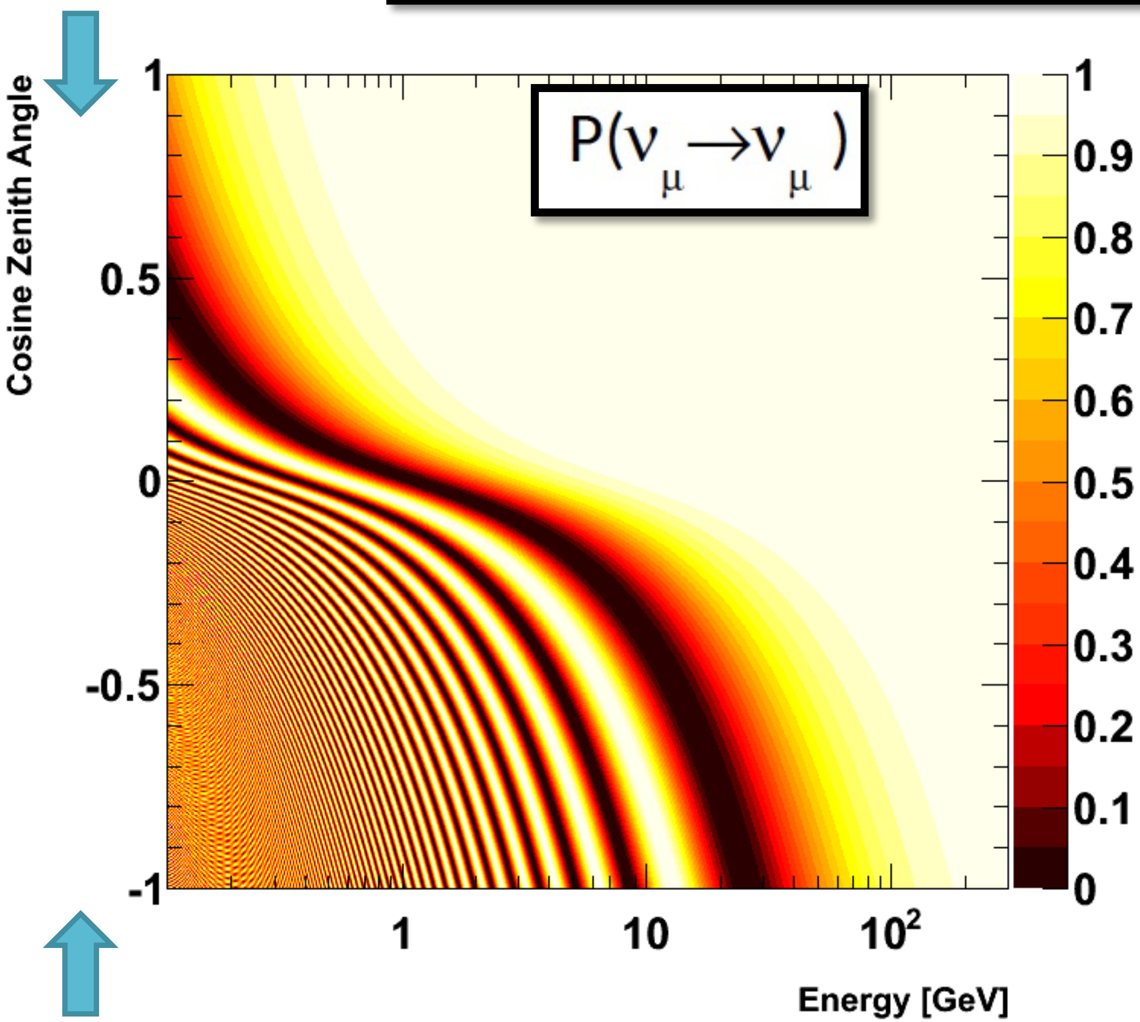
Received 27 June 1977

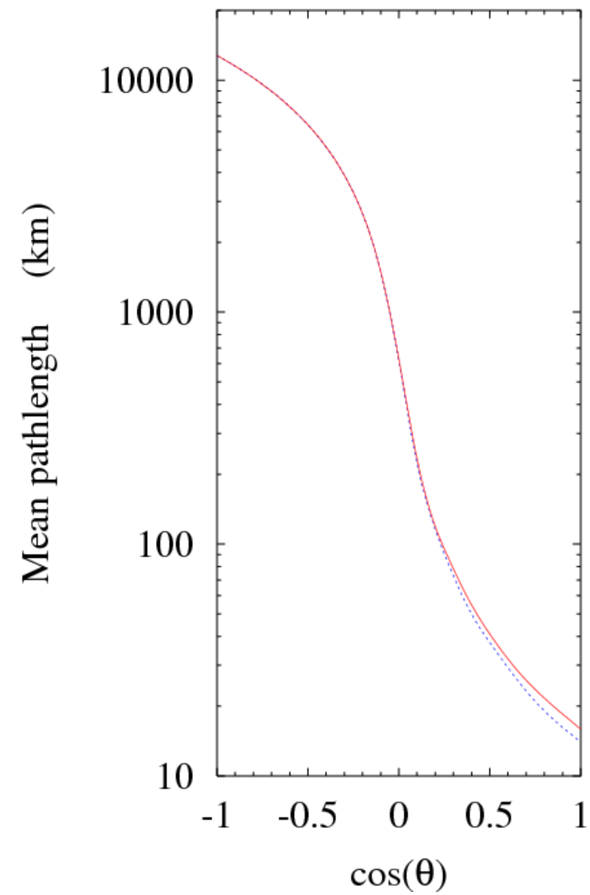
e: electromagnetic shower, multiple Coulomb scattering

μ: straight-line propagation, loose energy by ionization loss

Atmospheric Neutrino Oscillations (Two-Flavors)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$





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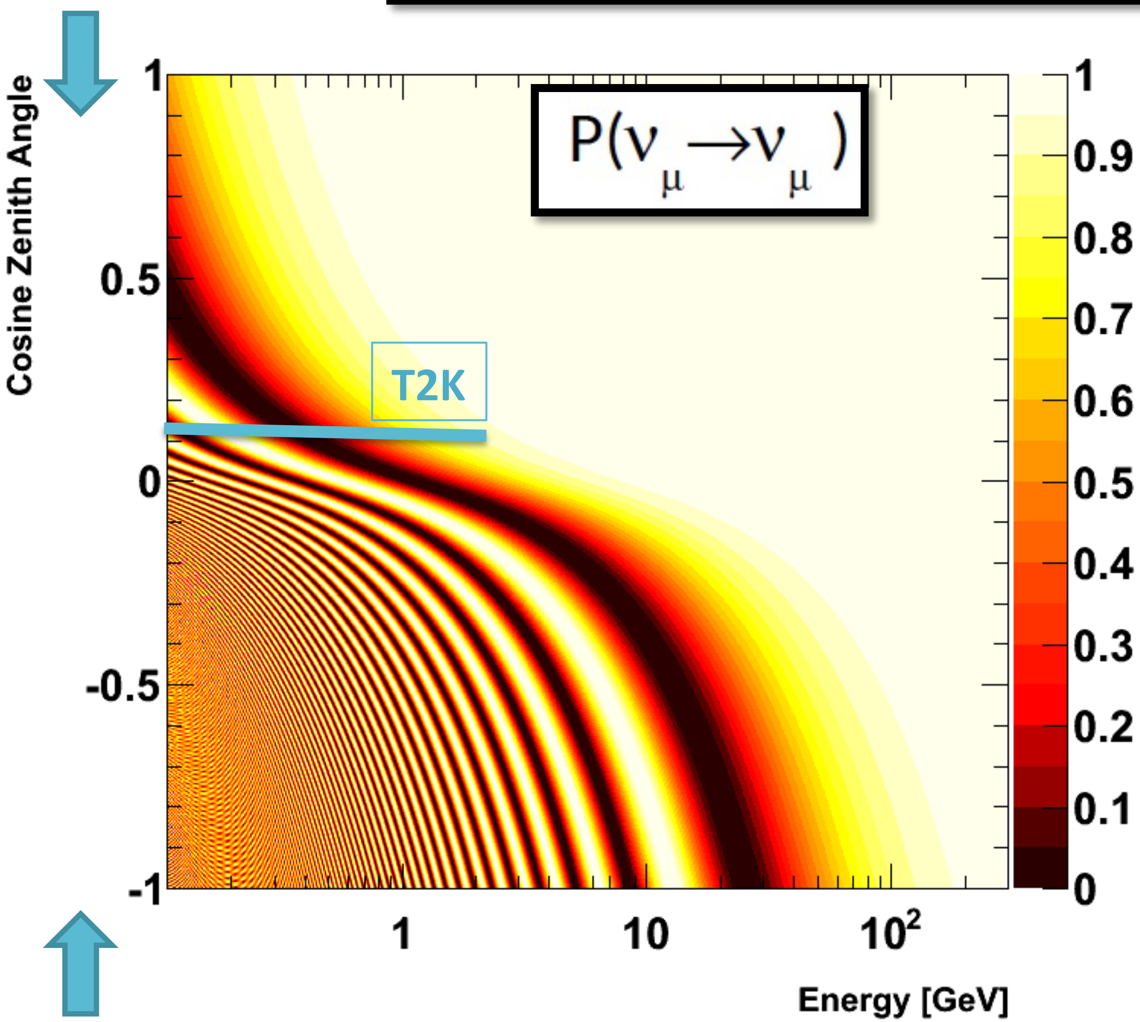
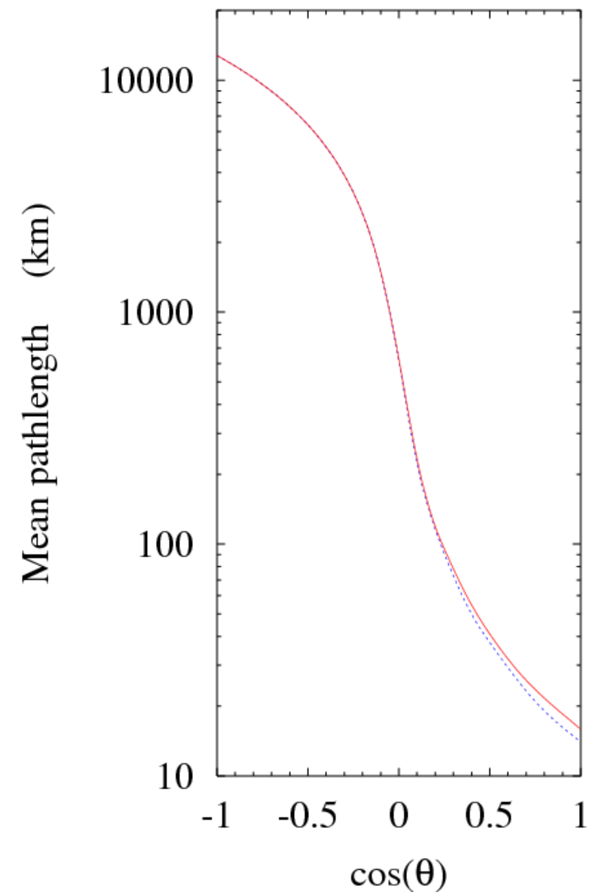
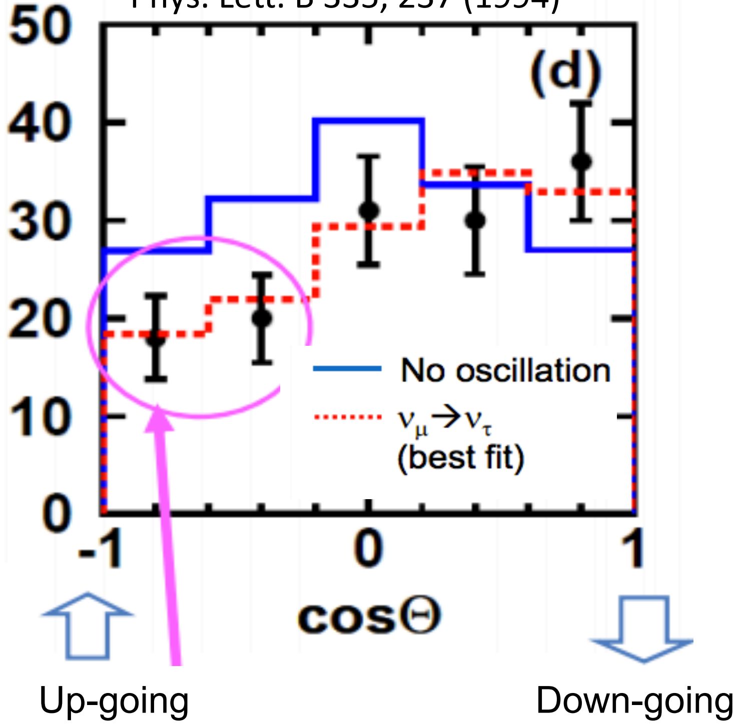




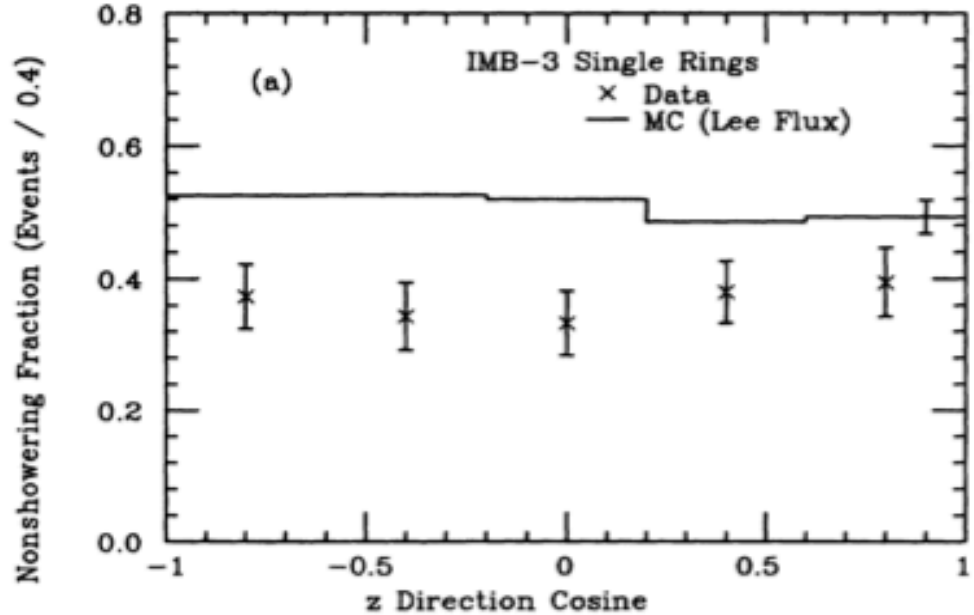
Results from Kamioka and IMB Experiments

Phys. Lett. B 335, 237 (1994)



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

Phys. Rev. Lett. 66, 2561 (1991)
Phys. Rev. D 46, 3720 (1992)

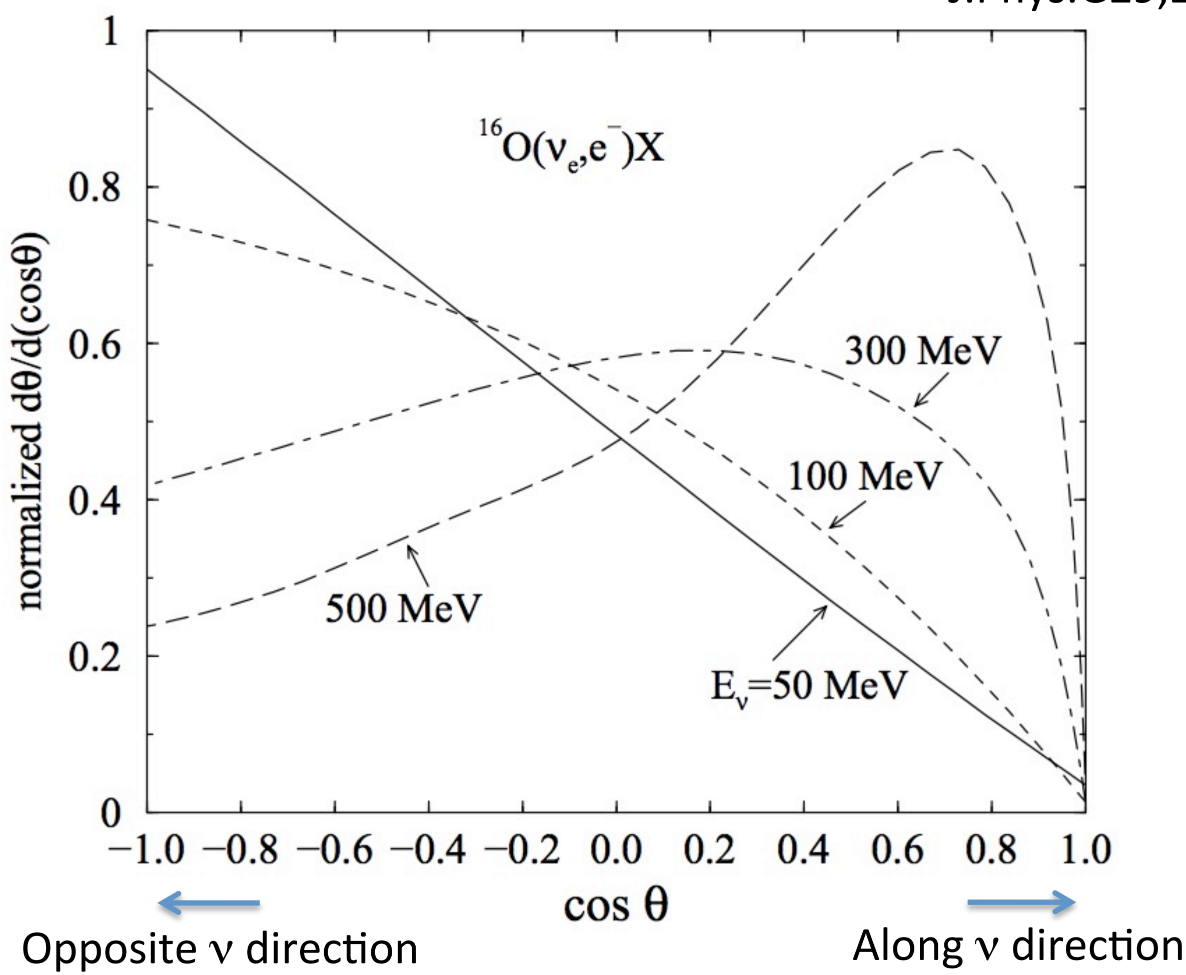


Up/Down = 0.54 ± 0.05 ± 0.11

Hints of oscillation, but not conclusive E < 1330.0 MeV

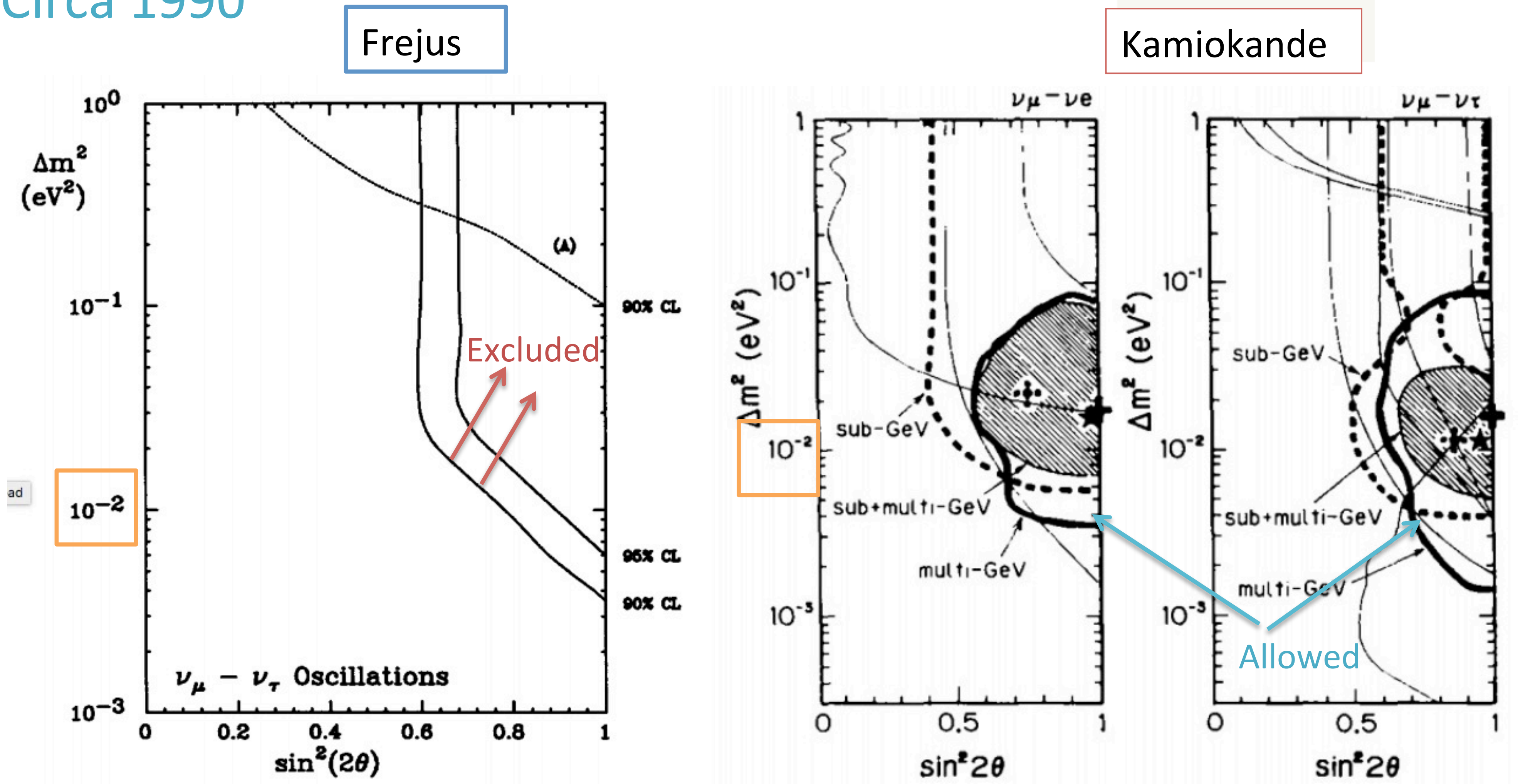
Angular Correlation Between ν and Lepton At Low Energies

J.Phys.G29,2569,2003



Need higher energy events to better study zenith angle dependence

Circa 1990

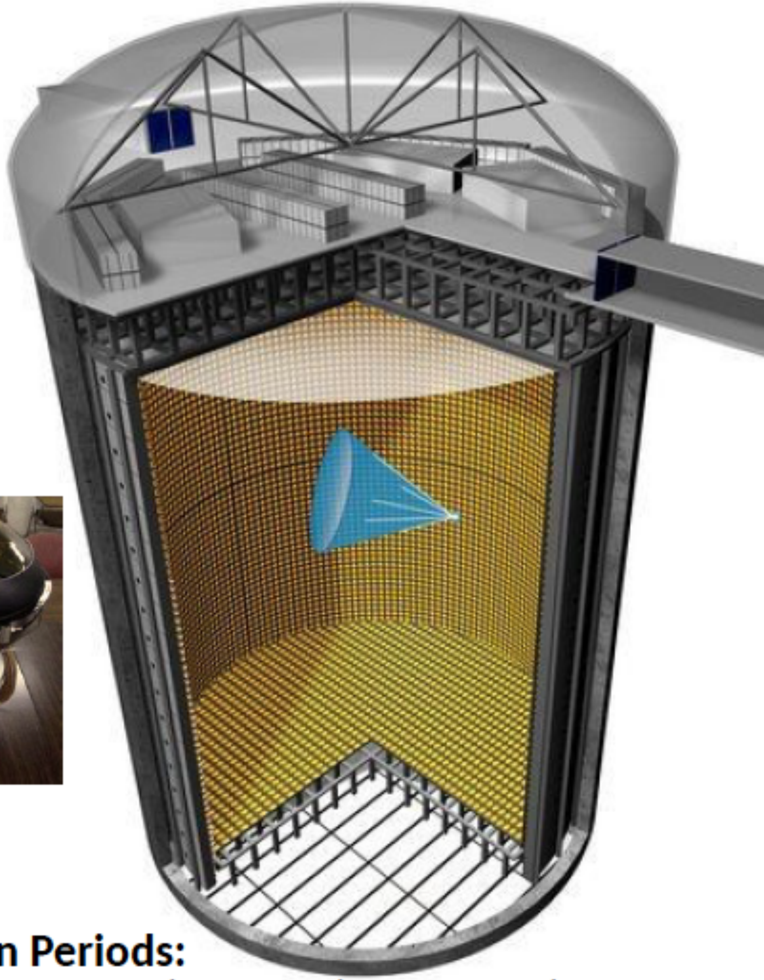


- Incidentally, no signs of proton decay
- SU(5) is dead
  - Limit for p -> $e^+\pi^0$: τ < 2.6 x 10^{32} years (90%C.L)

Discovery of Oscillations

In order to resolve the atmospheric neutrino anomaly definitively a larger experiment was needed...

Super-Kamiokande:

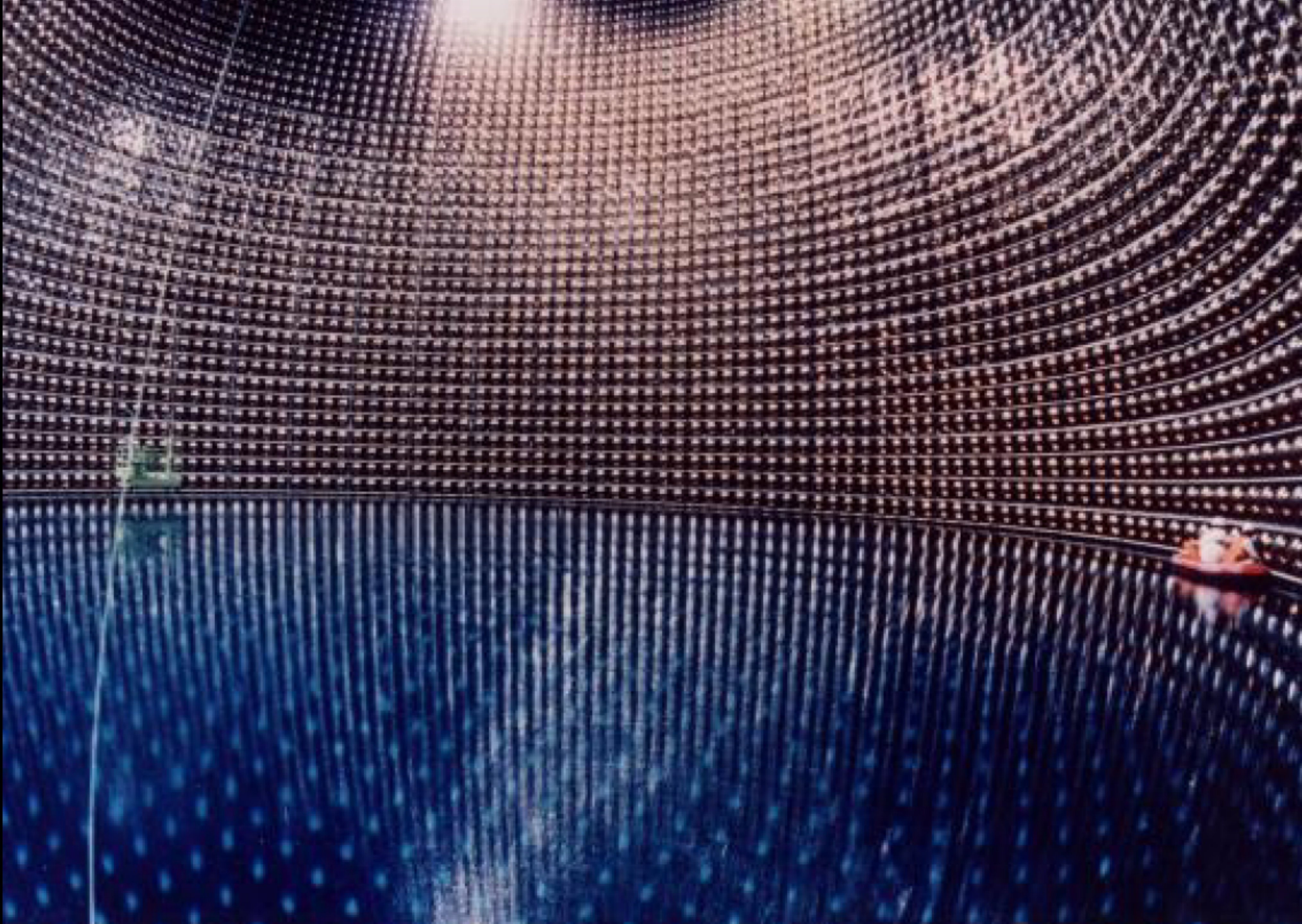


Four Run Periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III (2005-2008) SK-IV (2008-Present)

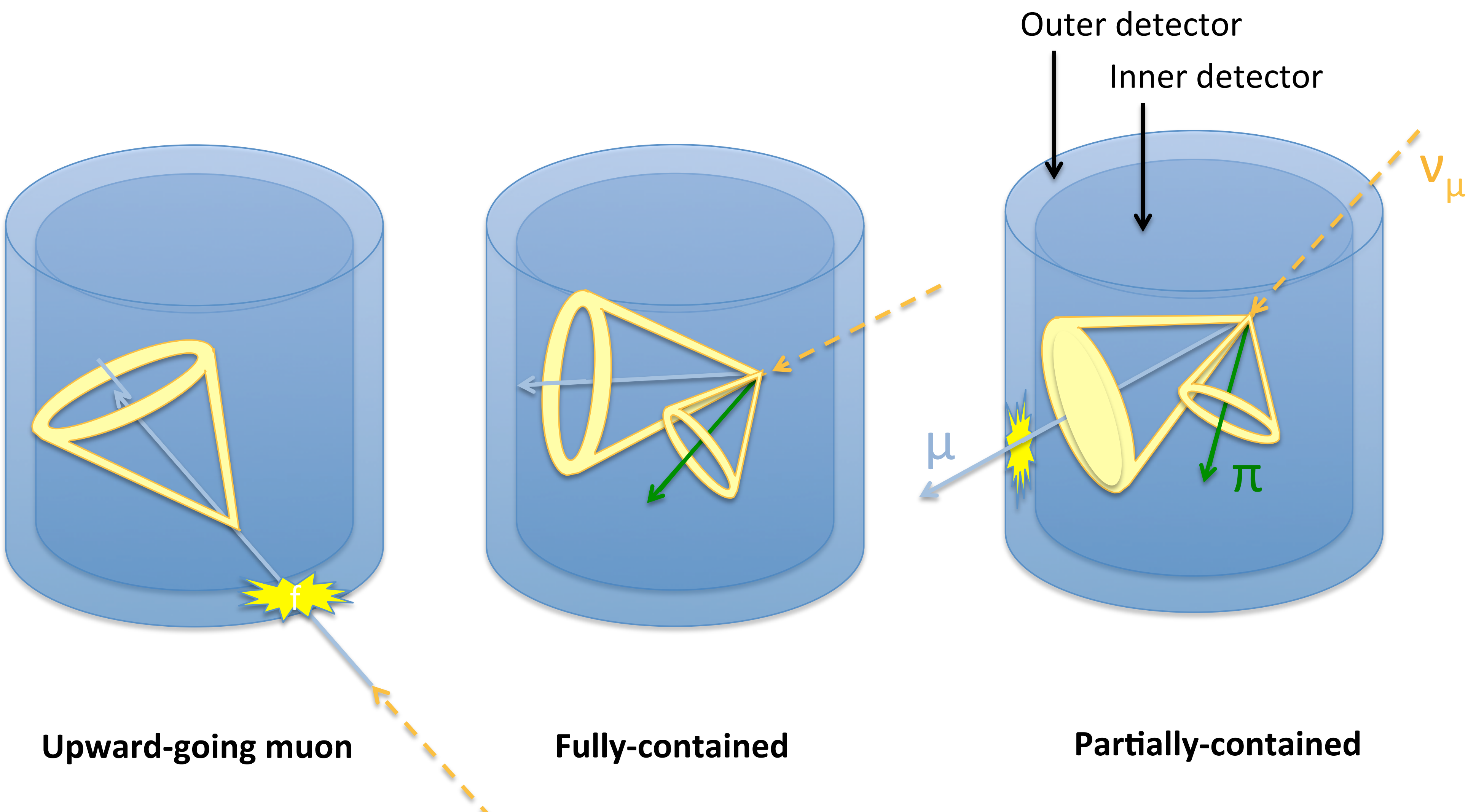
- 22.5 kton fiducial volume
- Optically separated into
  - Inner Detector 11,146 20" PMTs
  - Outer Detector 1885 8" PMTs

- No net electric or magnetic fields
- Neutrino direction and energy are unknown
  - Hard to reconstruct directly
- Excellent PID between showering (e-like) and non-showering (m-like)
  - ~ 1% MIS ID at 1 GeV

- As of Today: 4972 days of data
  - 51,000 Events
- Multipurpose machine
  - Solar and Supernova Neutrinos
  - Atmospheric Neutrinos (this talk)
  - Nucleon Decay
  - Far detector for T2K

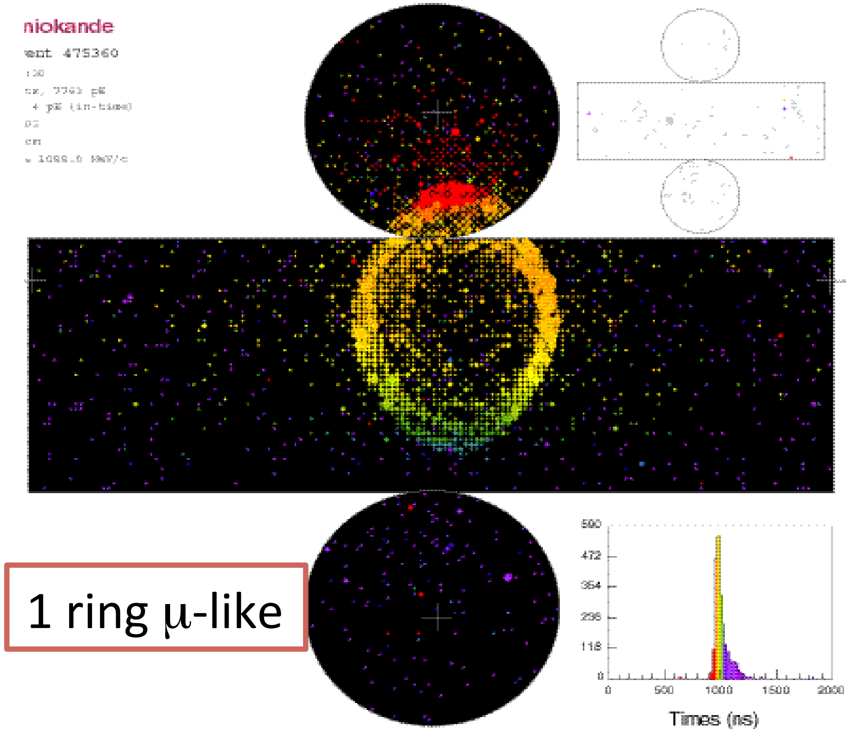


Basic Neutrino Event Classification in Super-K

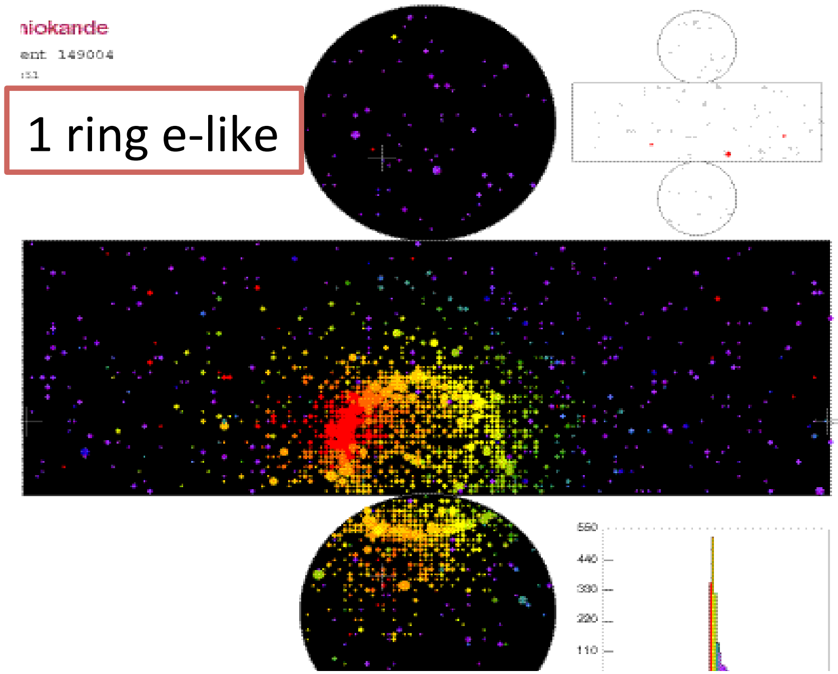


All of these (and more) are used in Super-K analyses

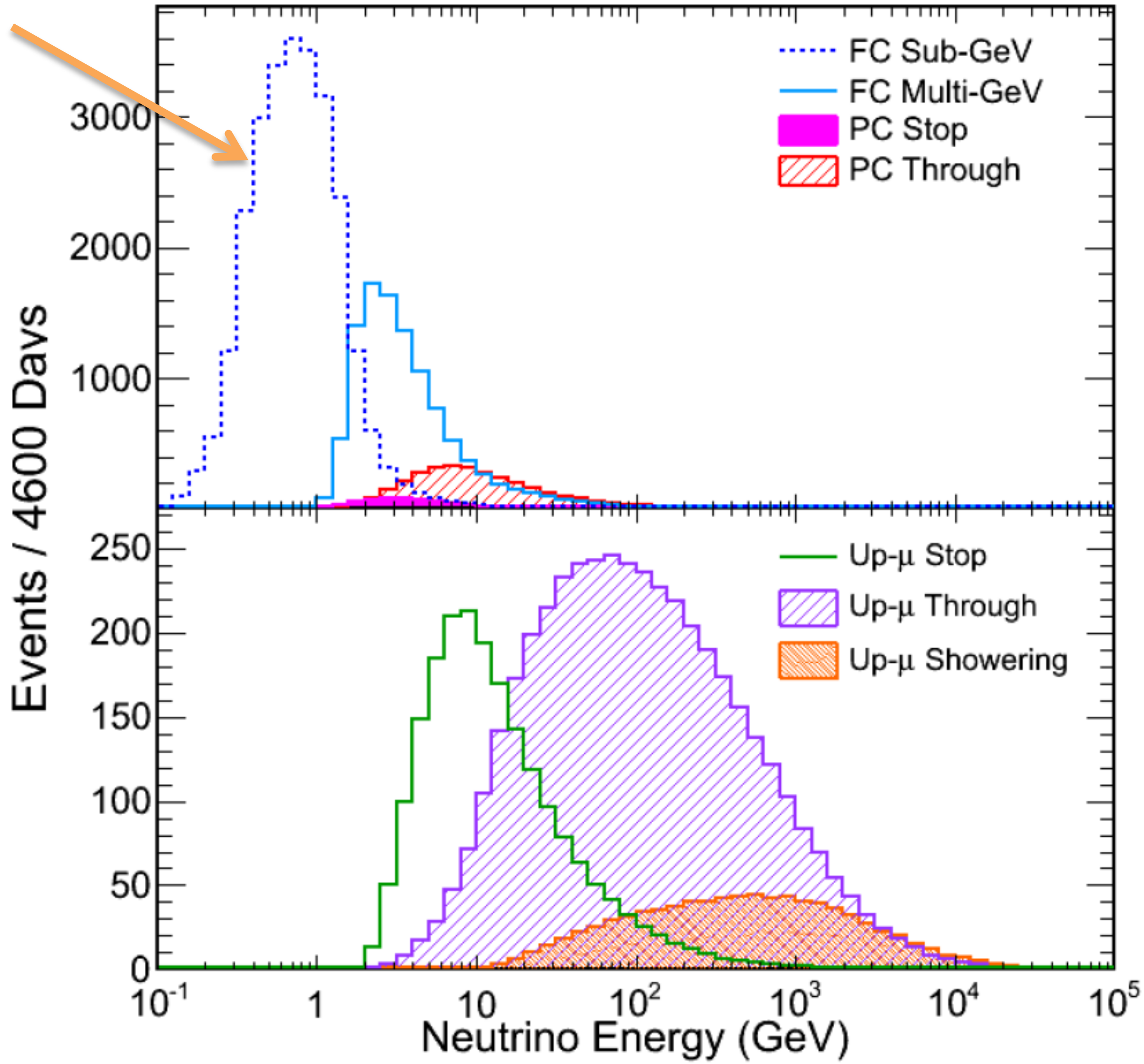
Super-K Event Types



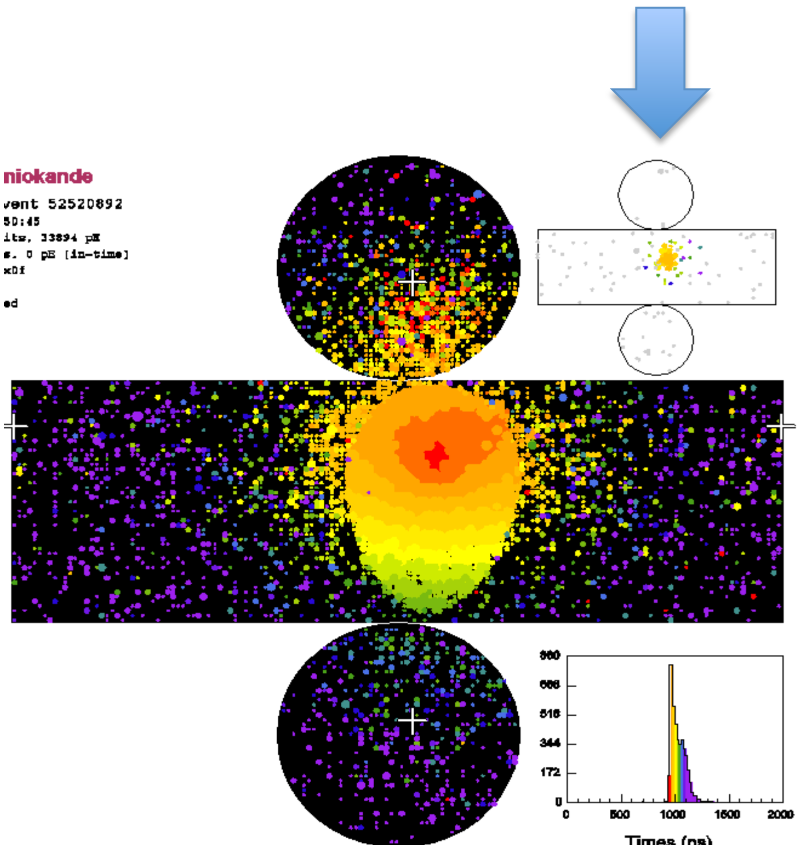
1 ring μ-like



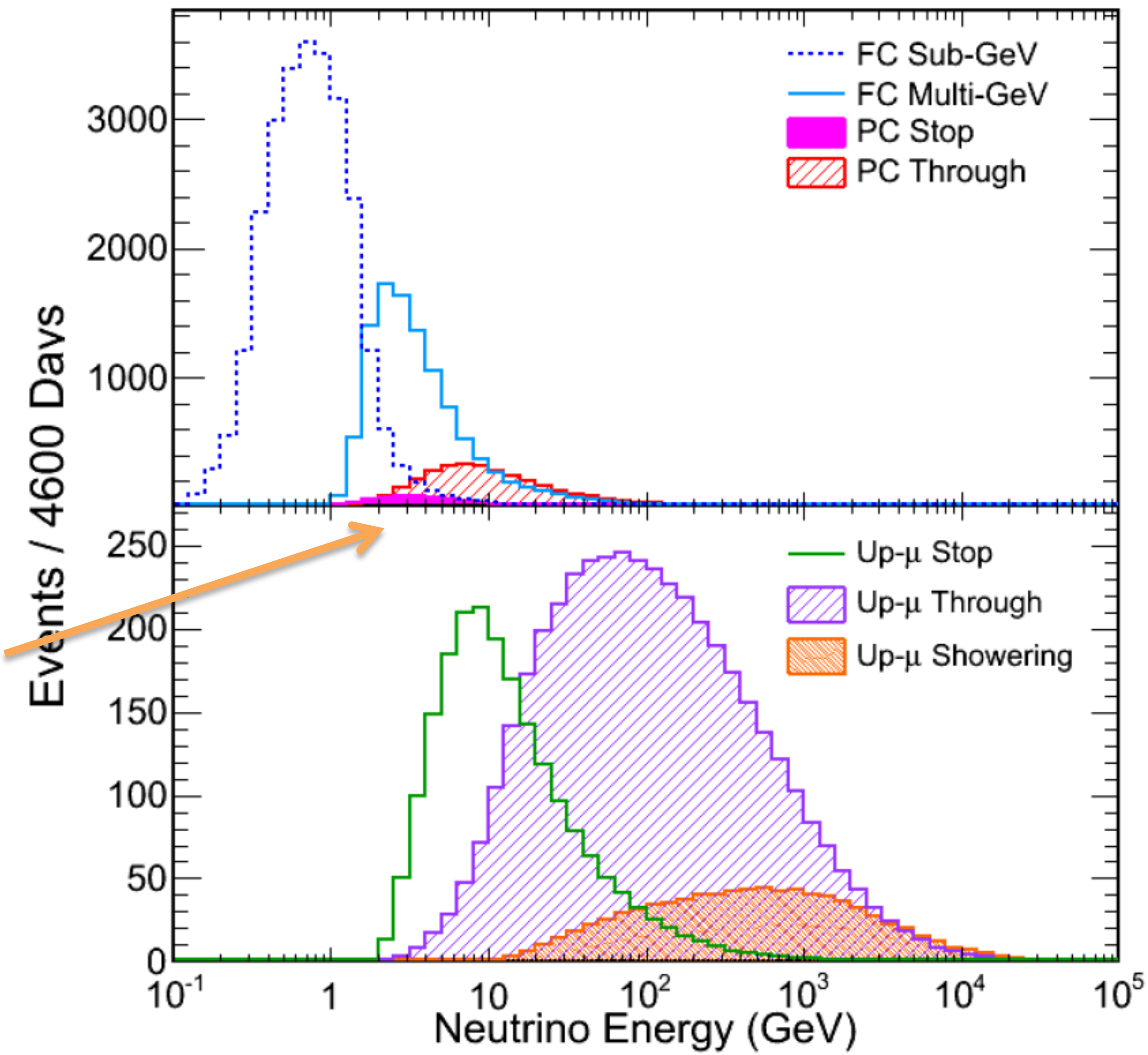
1 ring e-like



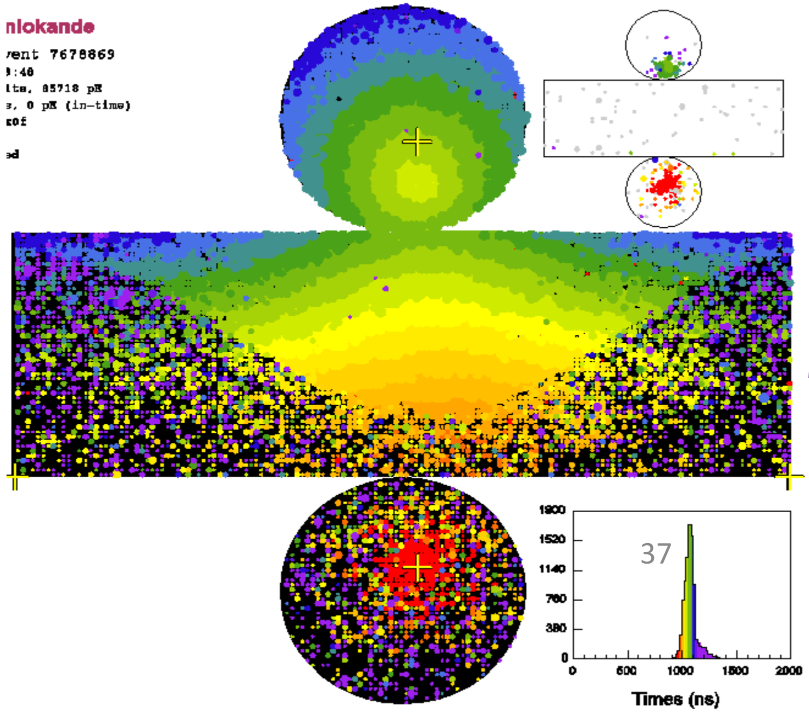
Super-K Event Types

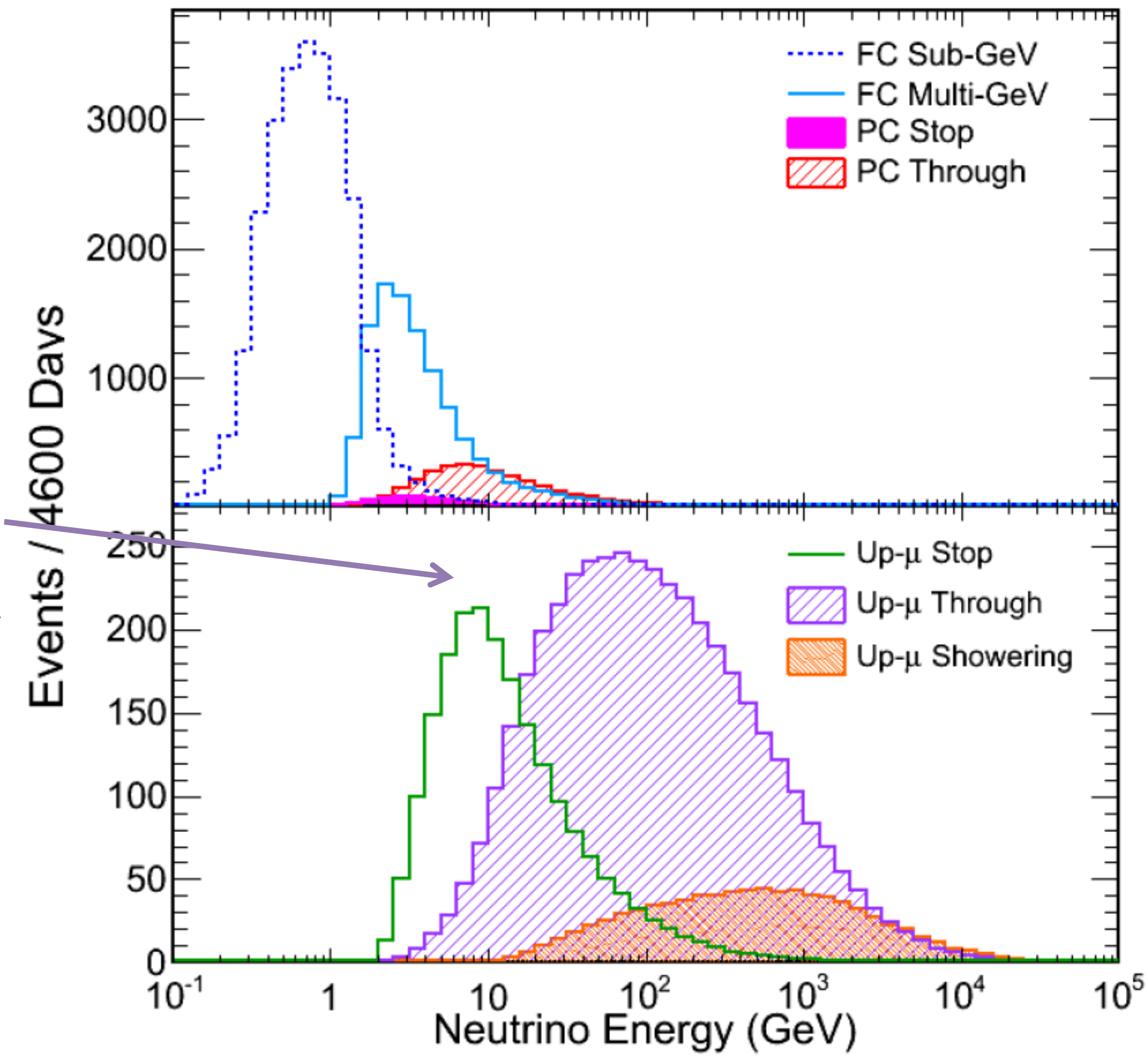


Partially contained



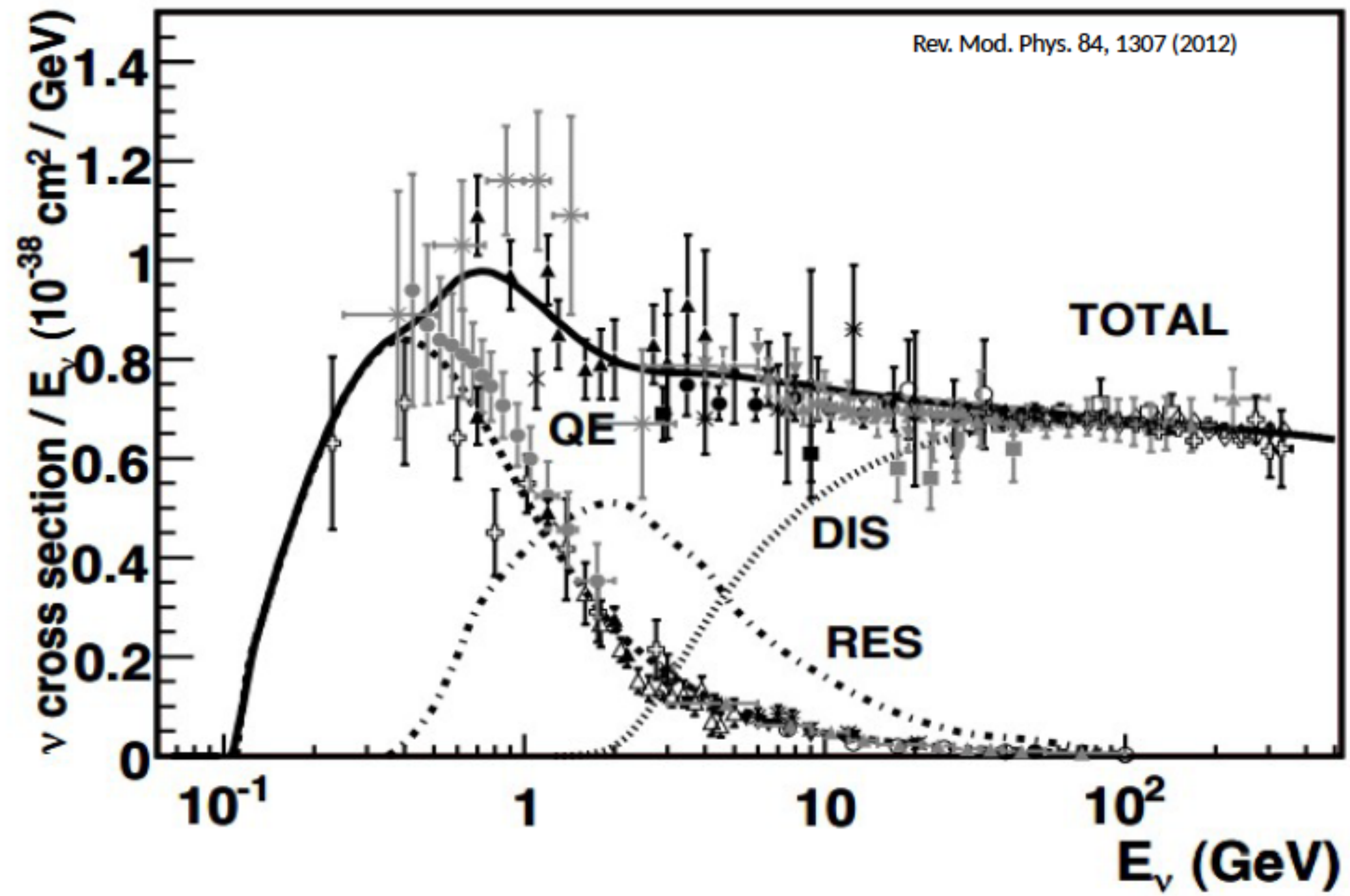
Super-K Event Types





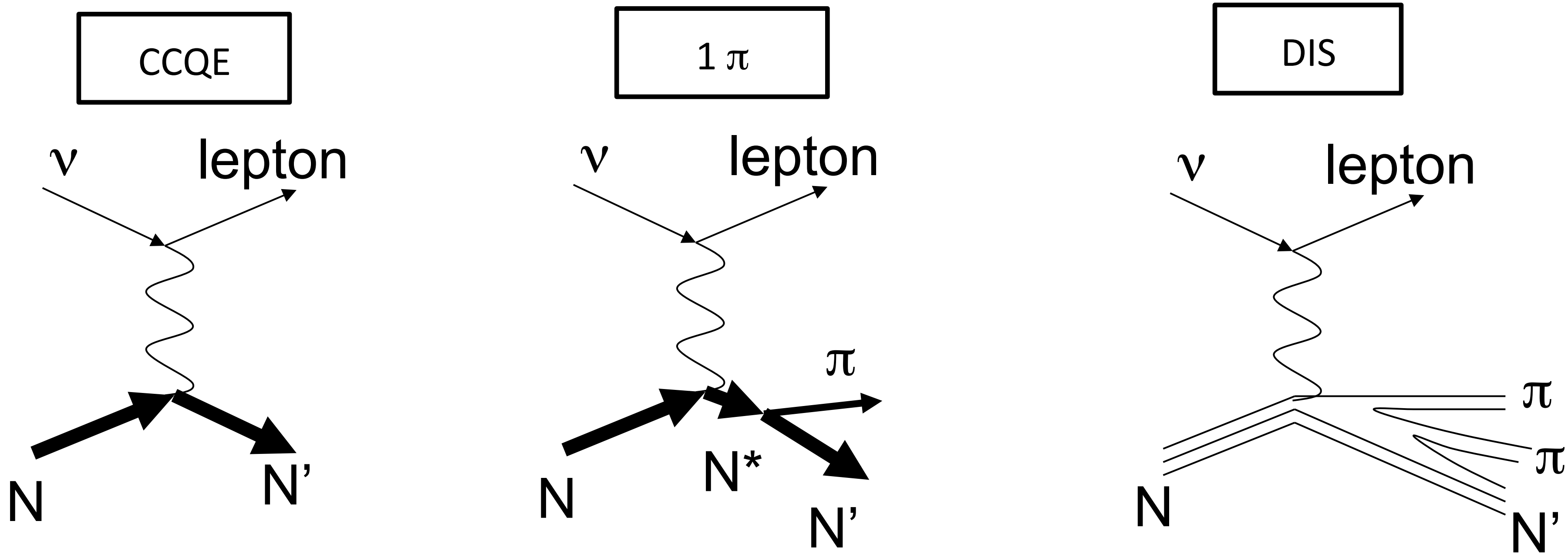
Upward going μ

Atmospheric Neutrino Interactions



- The flux spans 100 MeV to 100 GeV, so each of these processes are important

Atmospheric Neutrino Interactions



1 Cherenkov Ring

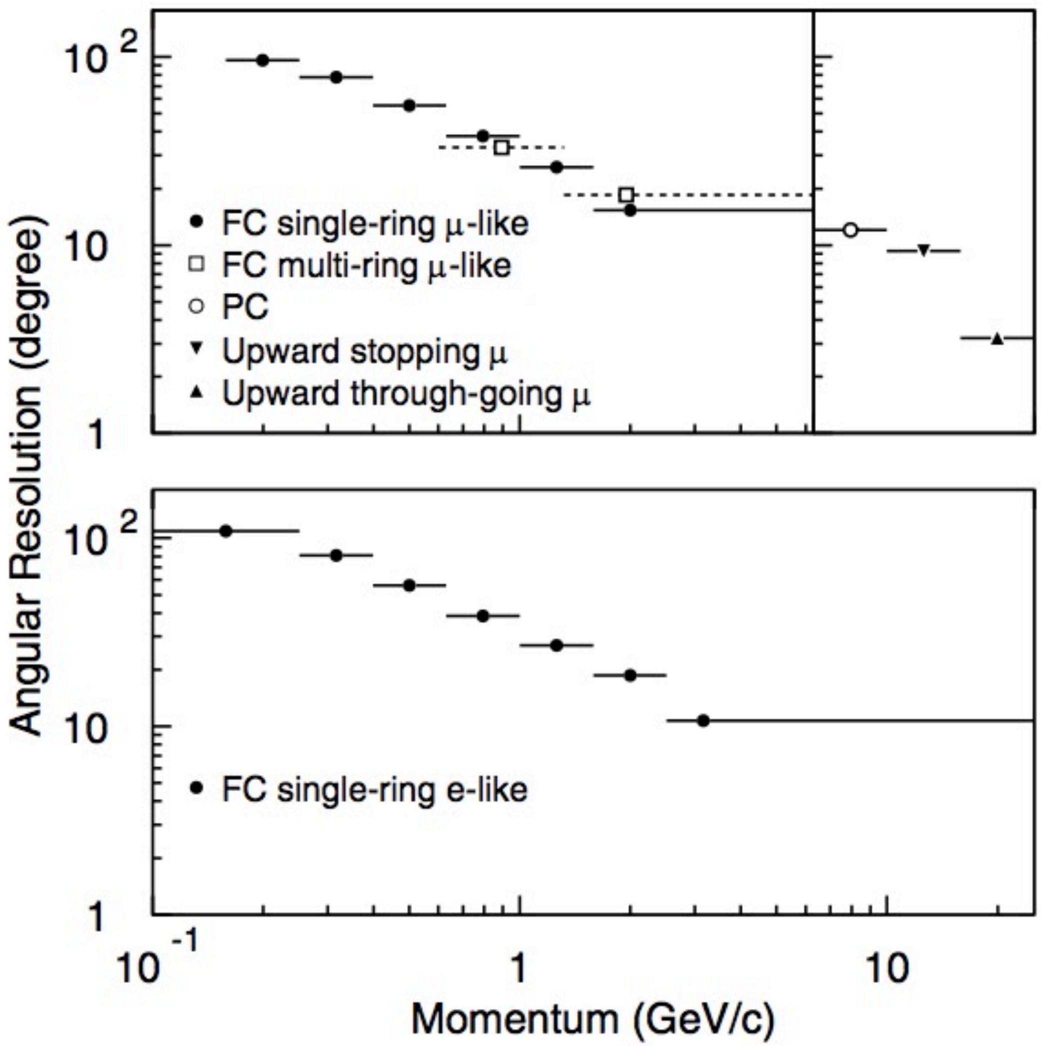
More than 1 Cherenkov Ring

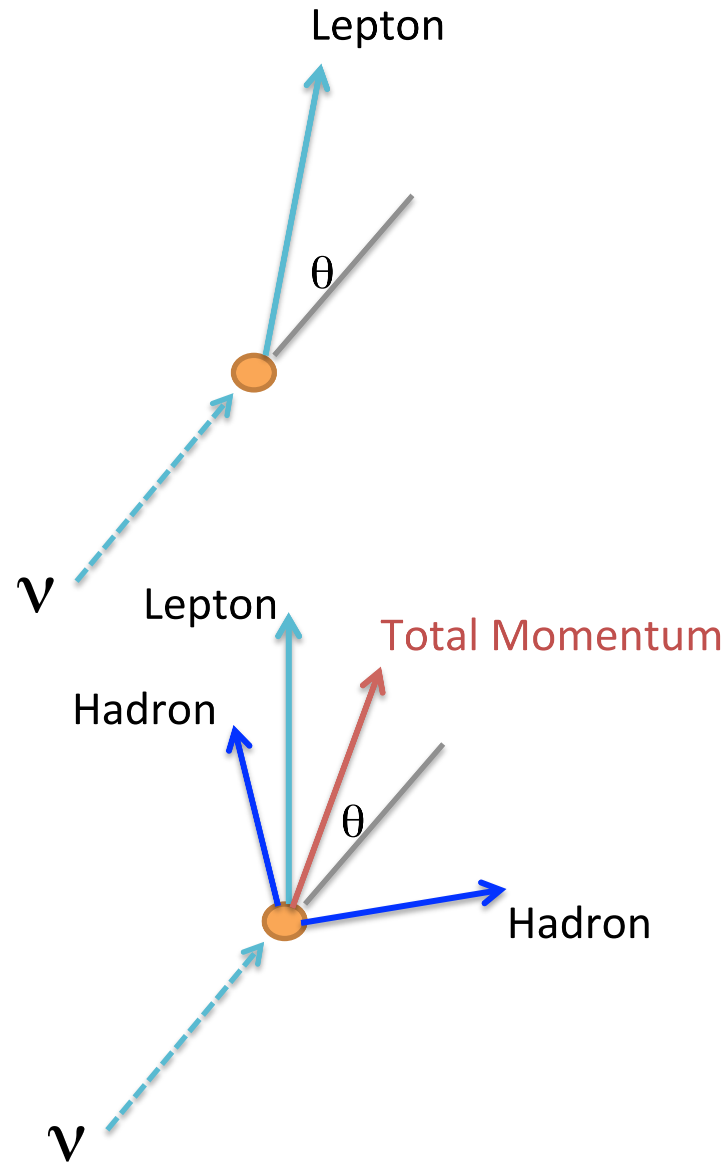
More than 1 Cherenkov ring

- Basic strategy is to divide data up by number of rings and PID of leading ring (~lepton)
  - Further divide by energy, decay electrons, etc
- Caution: These pictures are not necessarily the final visible state in the detector

Angular Resolution of the Neutrino

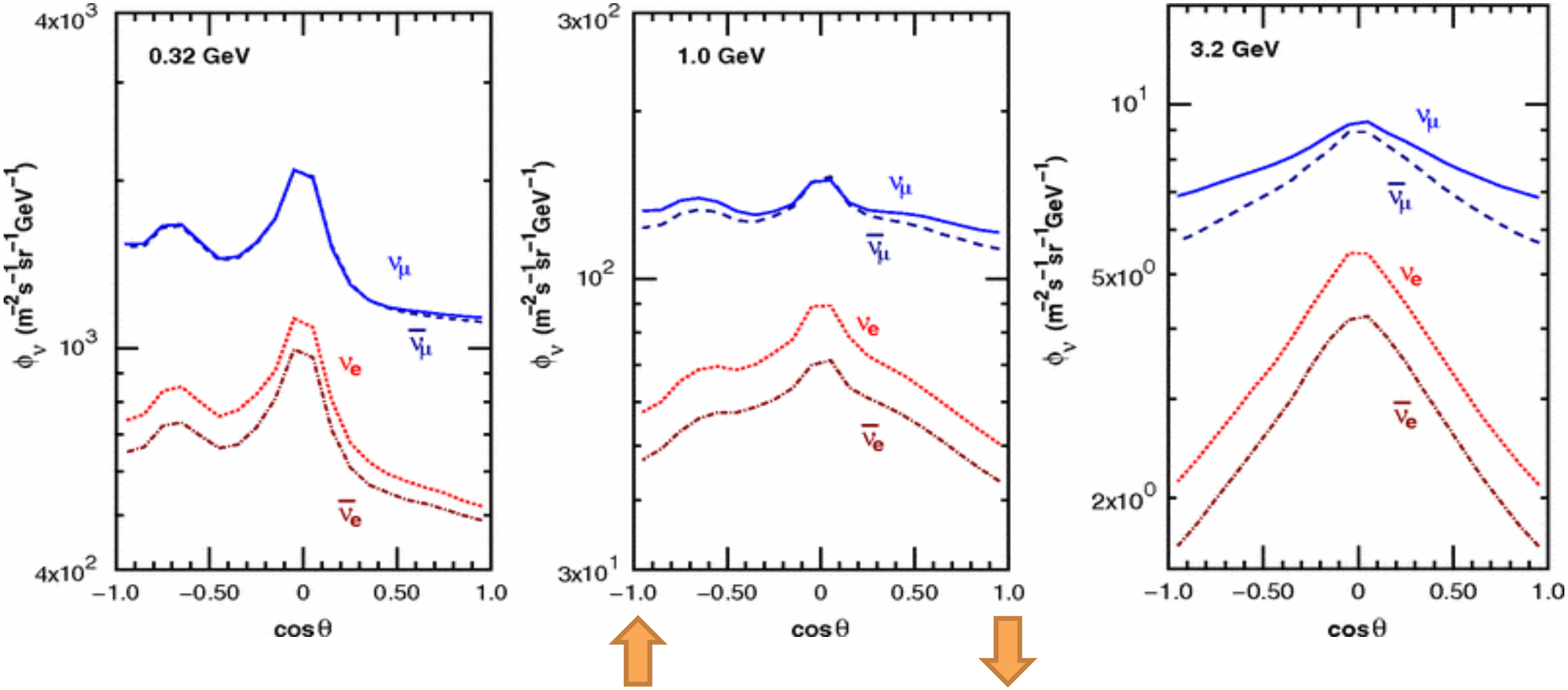
PRD D 71, 112005 (2005)





Basic Analysis Strategy

Phys. Rev. D 83 (2011) 123001



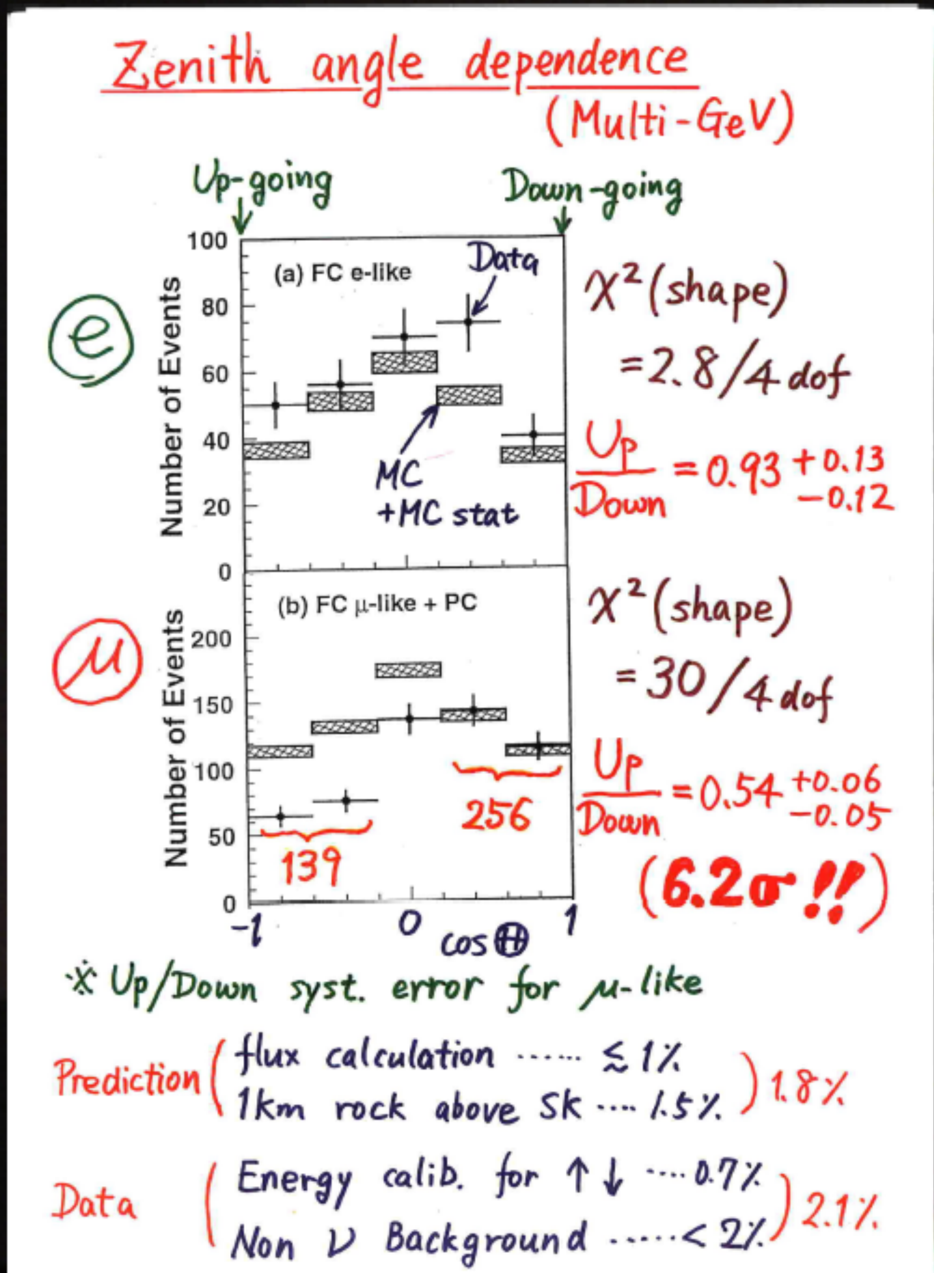
Upward-going
(~13000km pathlength)

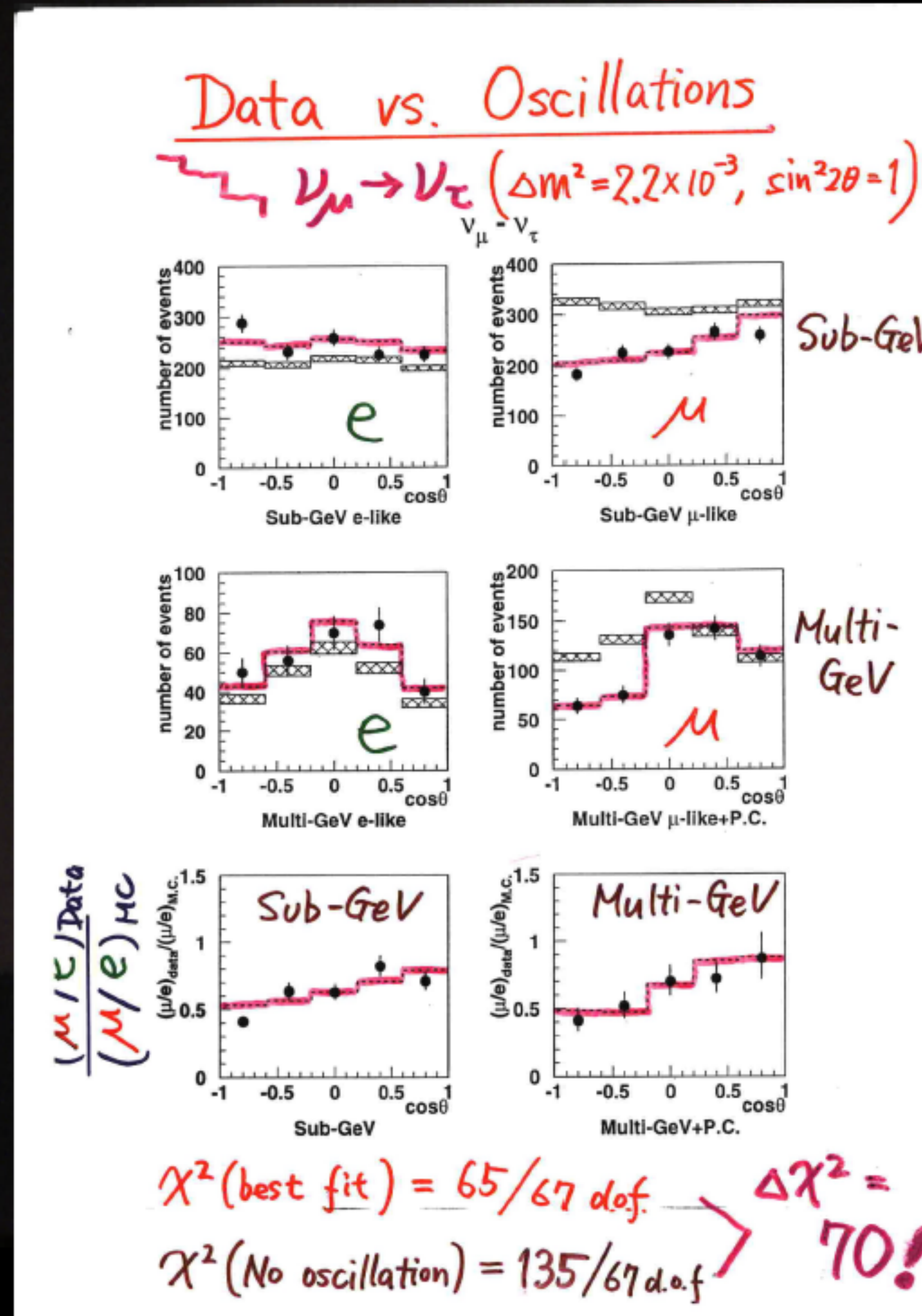
Downward-going
(~15km pathlength)

- The Flux is Up/Down Symmetric above a few GeV
- Choose Up/Down Symmetric Binning
- Event Samples binned in several momentum ranges

Slides from T.Kajita Neutrino 1998

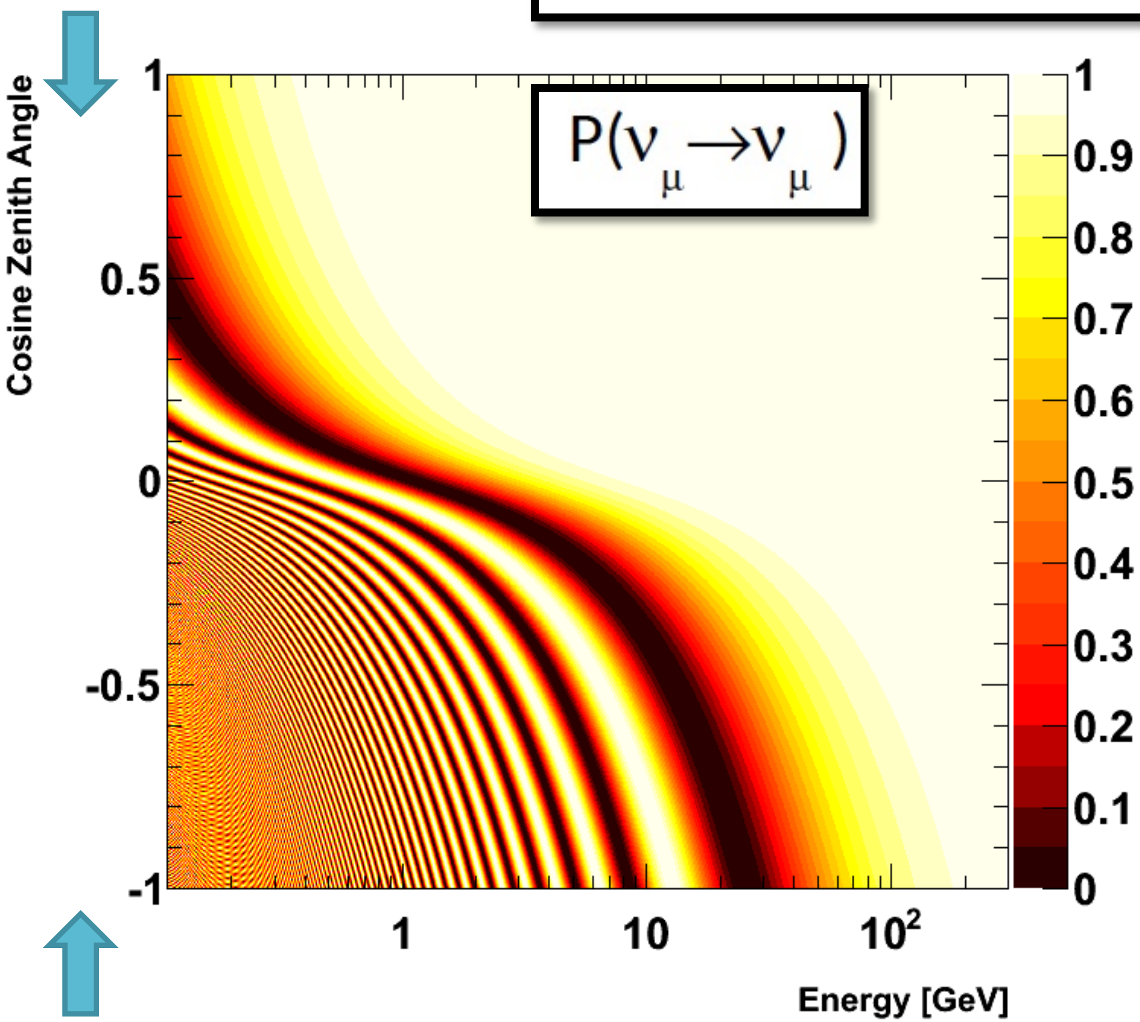
1998





Atmospheric Neutrino Oscillations (Two-Flavors)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$



$\Delta m^2 = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2 2\theta = 1.0$

Atmospheric Neutrino Oscillations (Two-Flavors)

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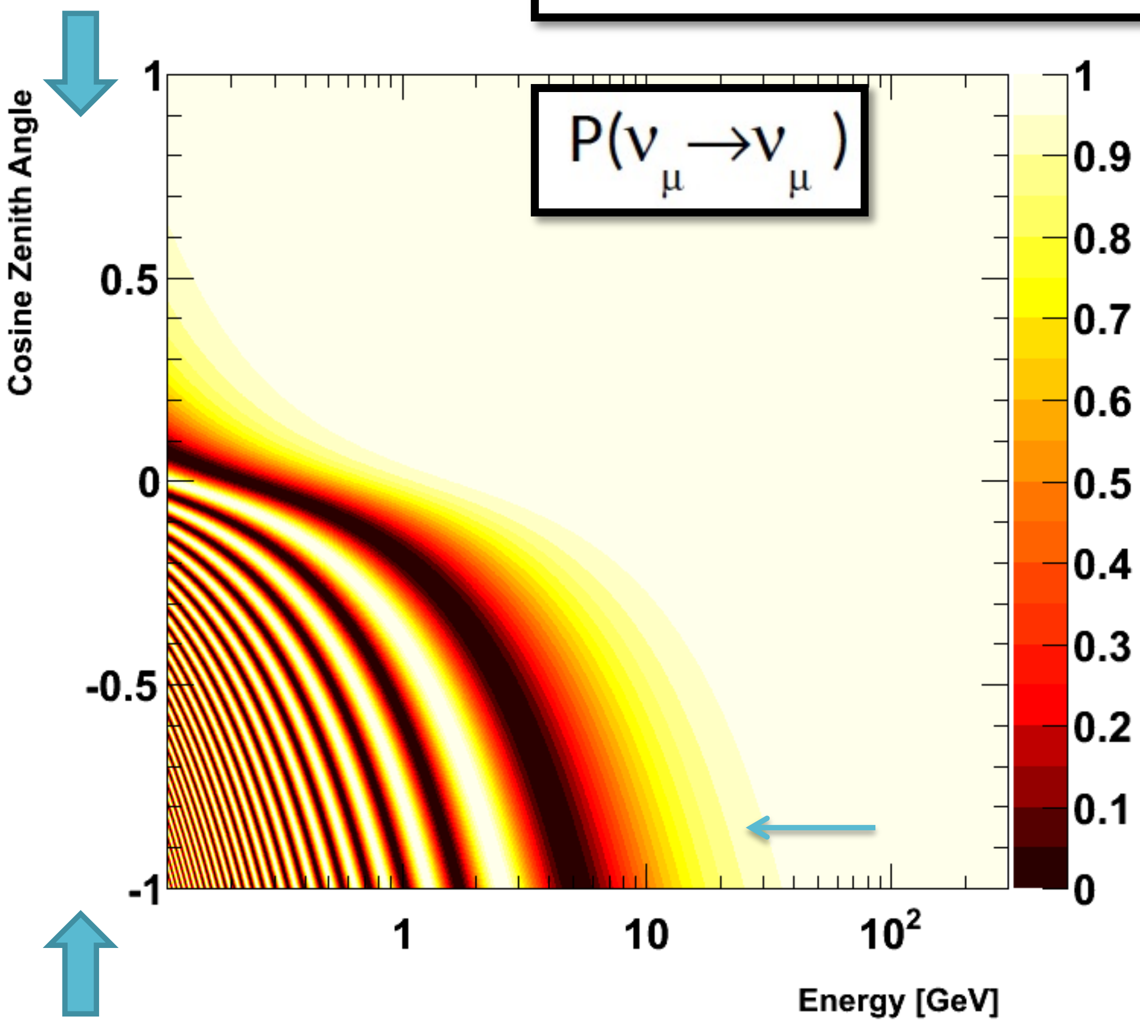
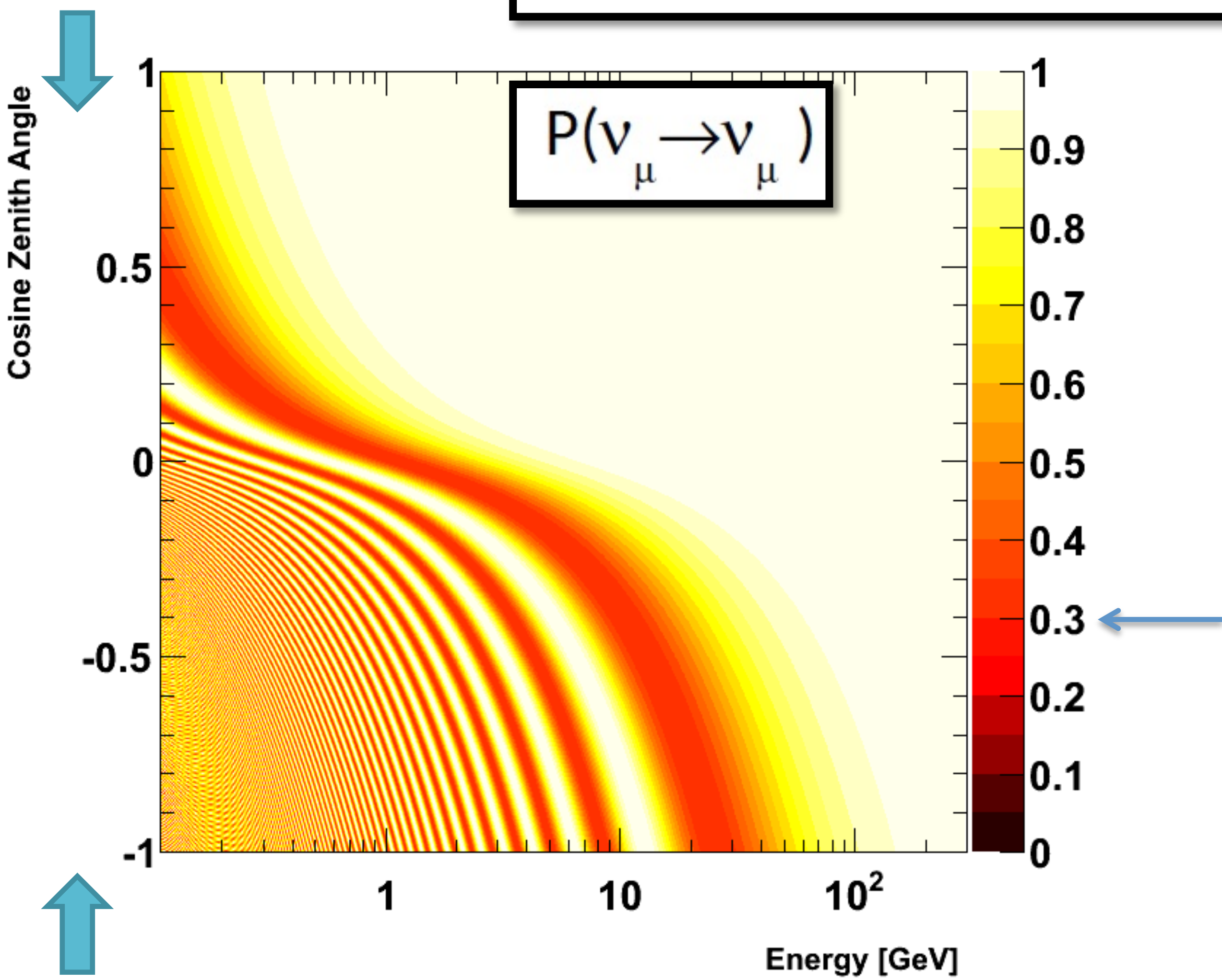


$\Delta m^2 = 0.5 \times 10^{-3}\ \text{eV}^2$

$\sin^2 2\theta = 1.0$

Atmospheric Neutrino Oscillations (Two-Flavors)

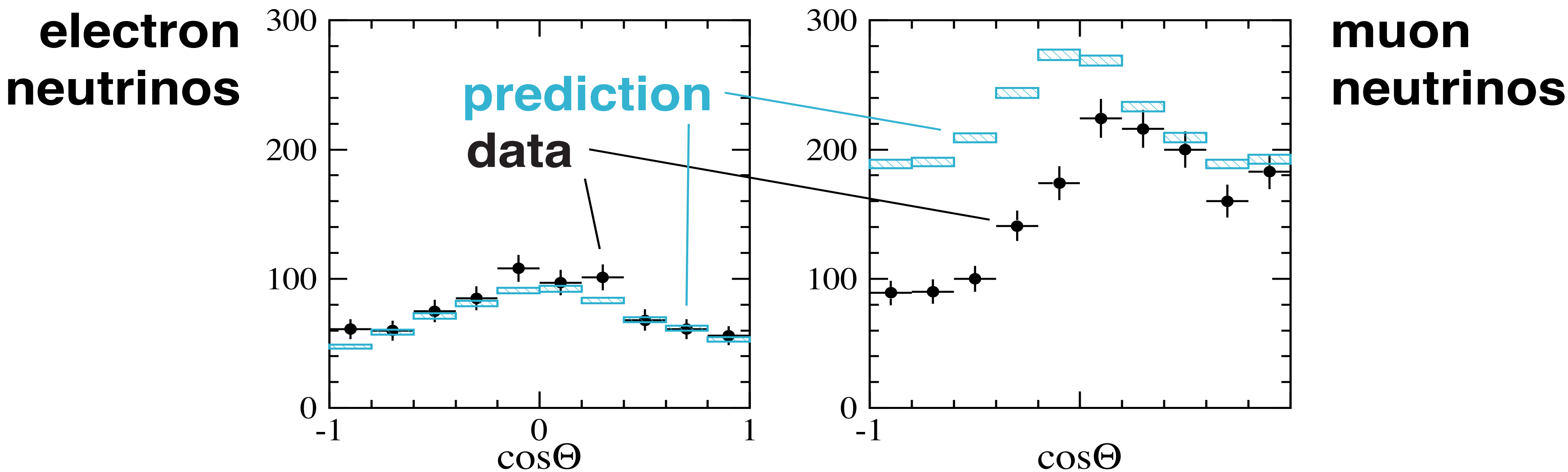
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$



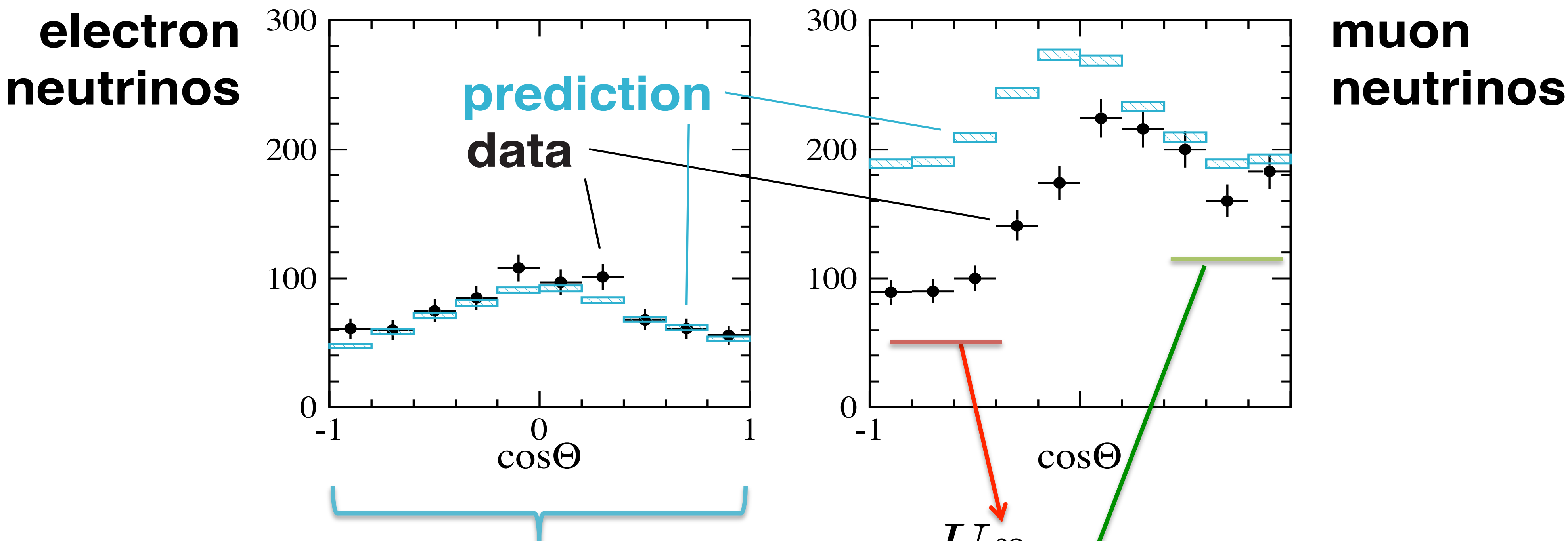
$\Delta m^2 = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2 2\theta = 0.7$

Neutrino Oscillation?



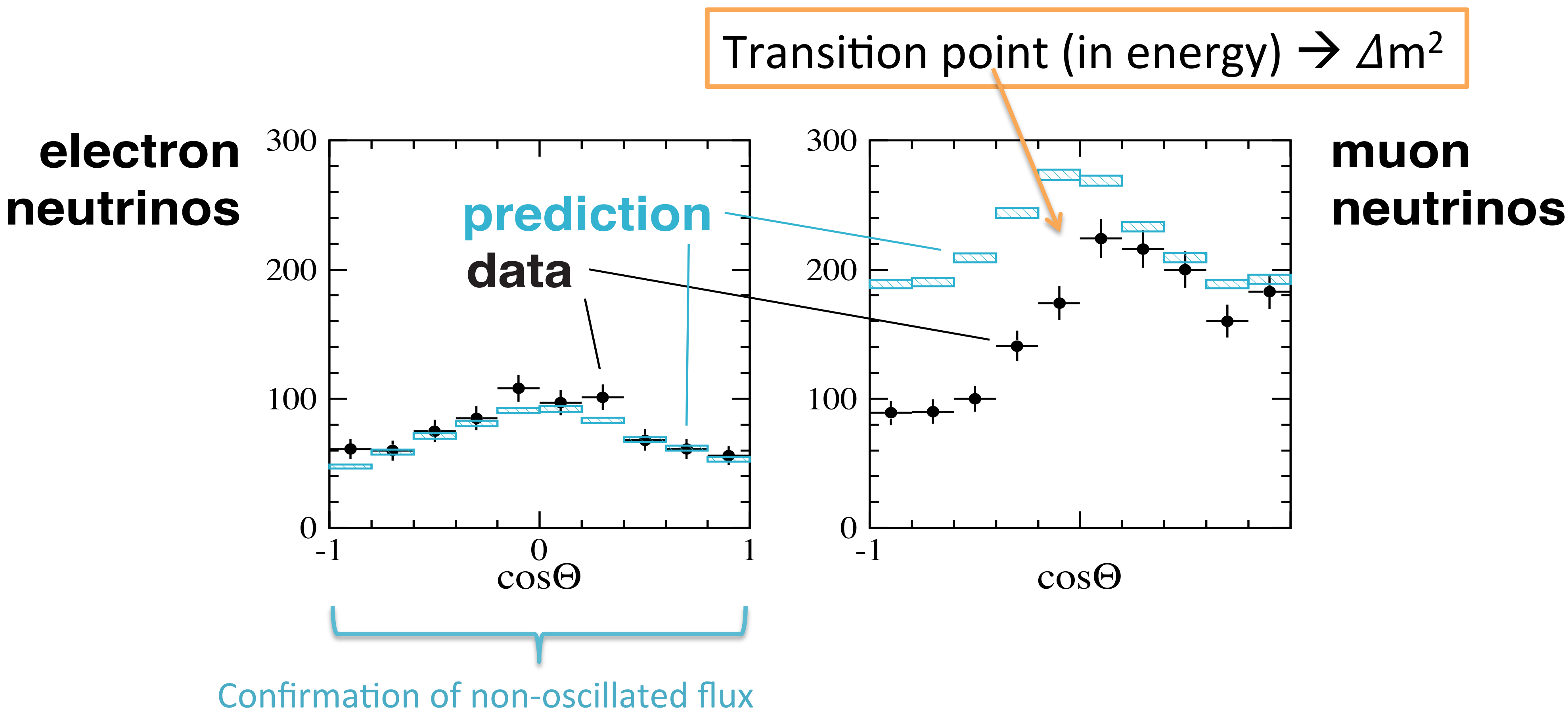
Estimating the Oscillation Parameters



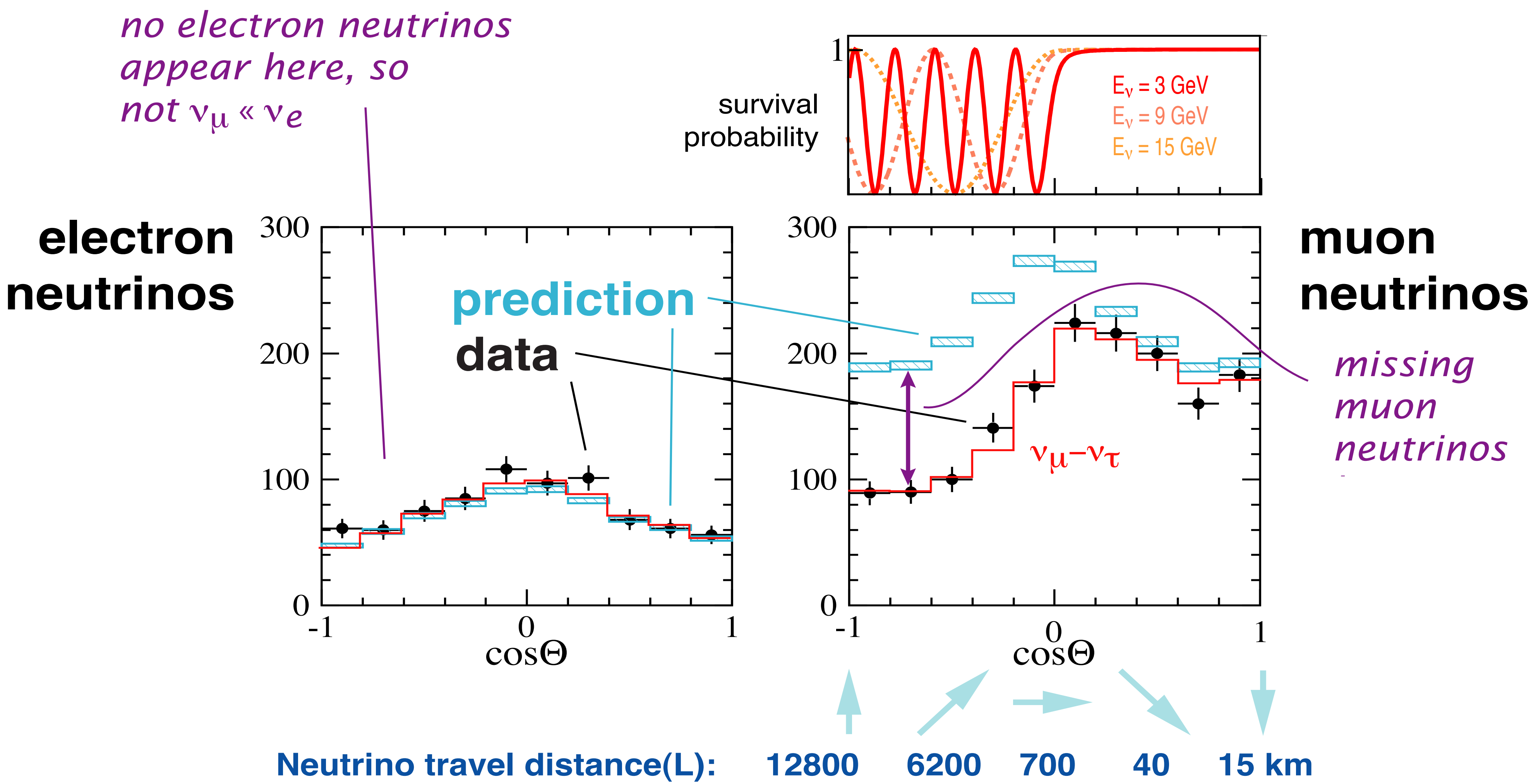
Confirmation of non-oscillated flux

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

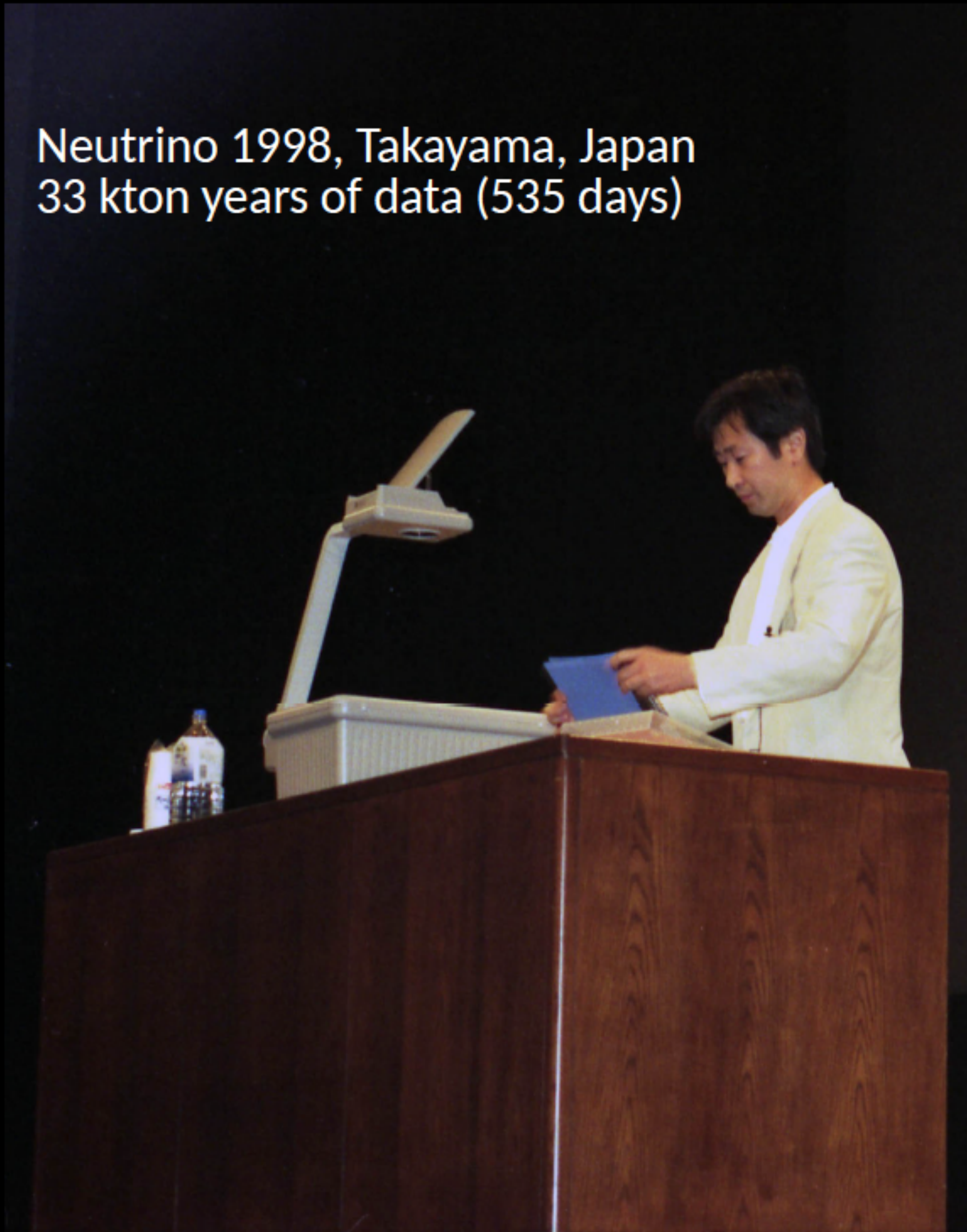
Estimating the Oscillation Parameters

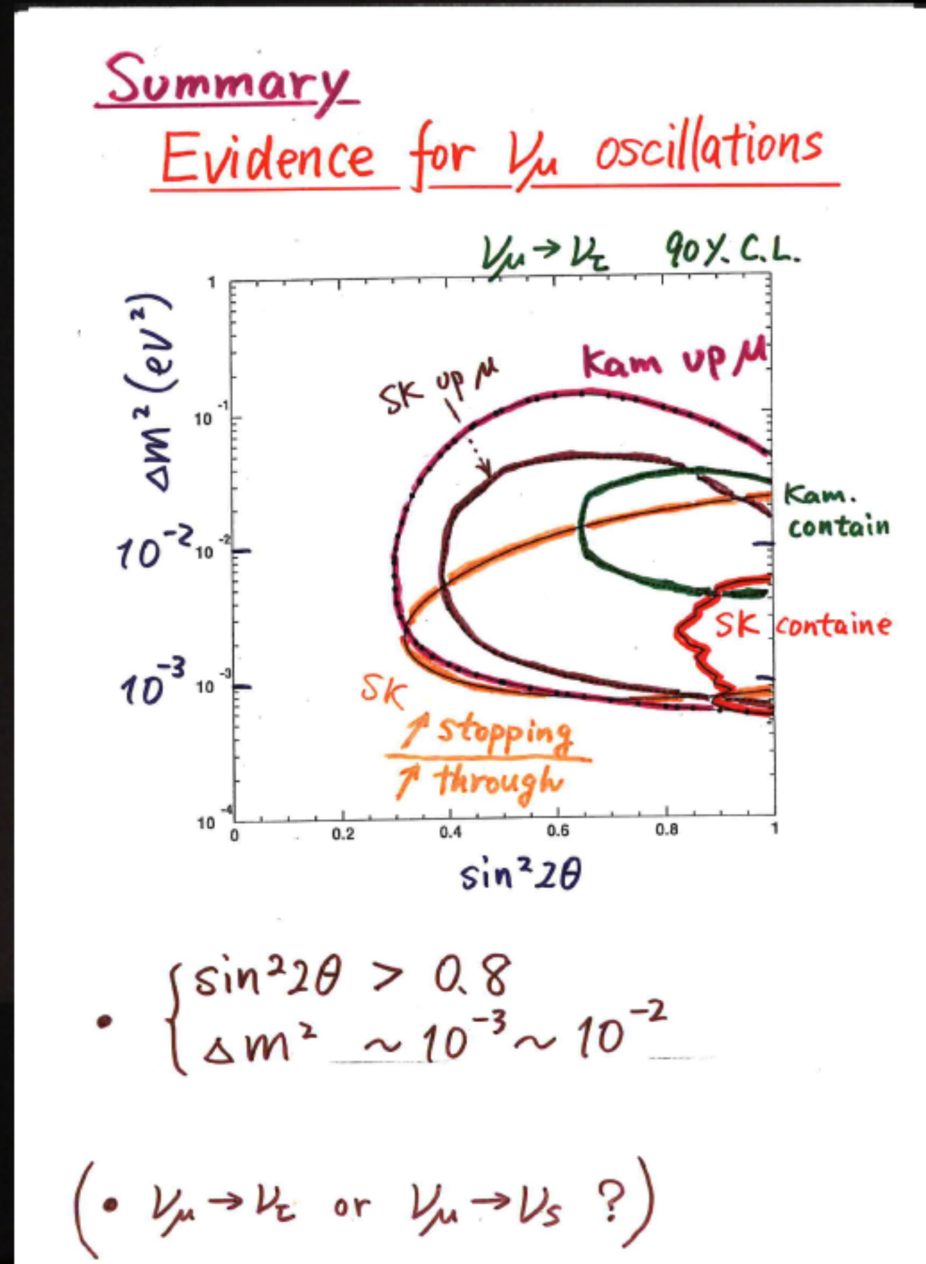


Neutrino Oscillation



Neutrino 1998, Takayama, Japan
33 kton years of data (535 days)





After Neutrino 1998

- Super-K saw definitive evidence for the disappearance of atmospheric muon neutrinos
  - No distortion seen in the electron samples

- Data are well fit by $\nu_\mu \rightarrow \nu_\tau$ oscillations

Atmospheric

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

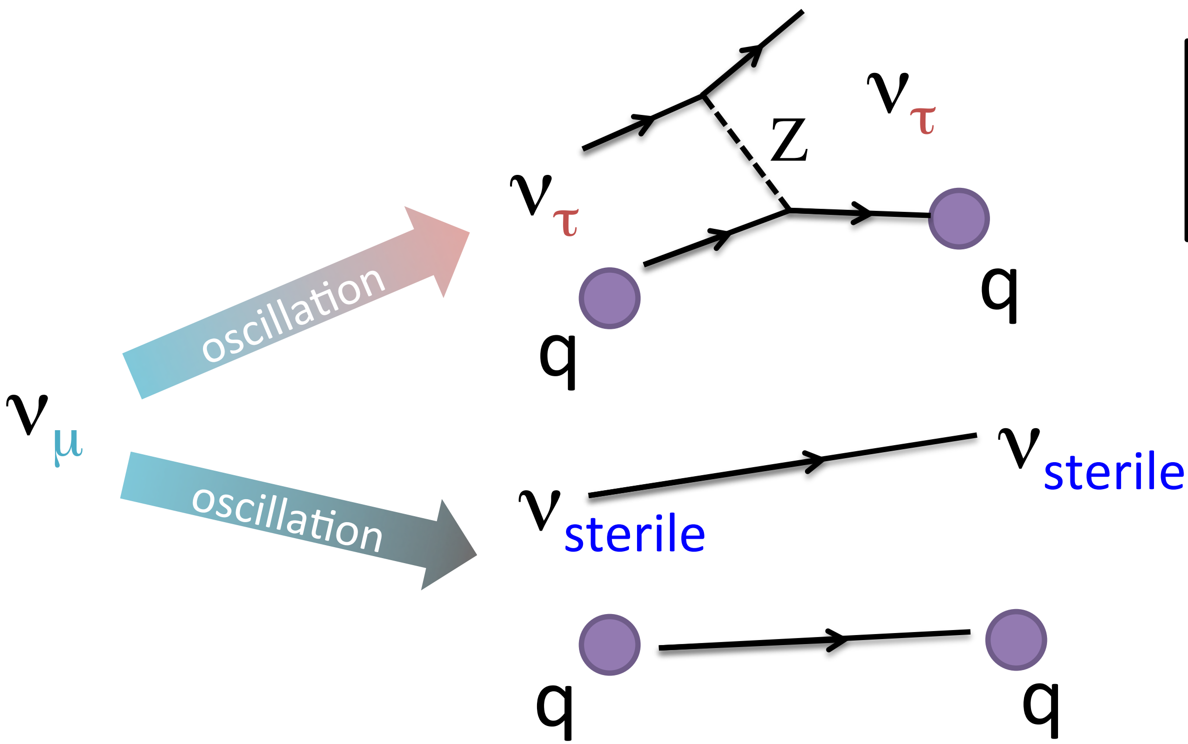
- But there are other possibilities

- Oscillations into a sterile state?
- Neutrino Decoherence?
- Neutrino Decay?
- Can we find the tau neutrinos?
- Need to fully test oscillation hypothesis:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

Sterile Oscillations, Hard to Enrich in NC

- Oscillations into a sterile neutrino would also decrease the number of observed μ-like events



Has both Charged and Neutral Current Interactions

No Interactions!

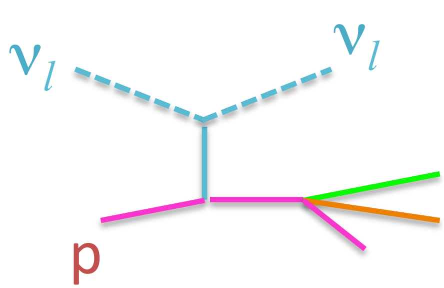
Look for a decrease in NC interactions...

Sterile Oscillations, Hard to Enrich in NC

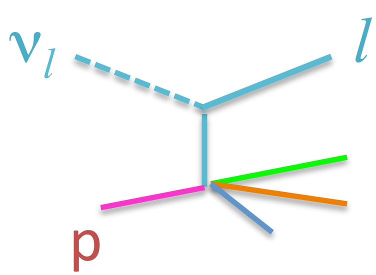
- Event Selection
  - Fiducial Volume
  - Multiple rings
  - Most energetic ring is showering
  - Visible energy greater than 400 MeV

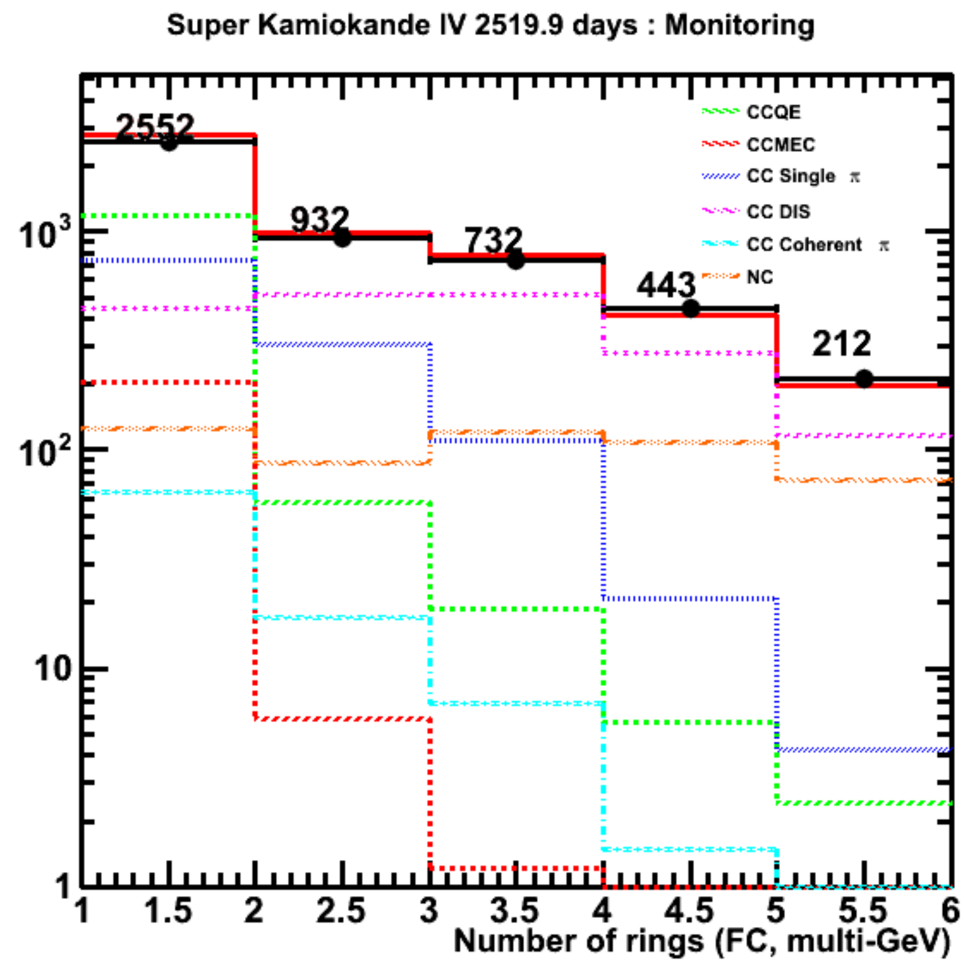
Hard to enrich in NC interactions

NC



CC

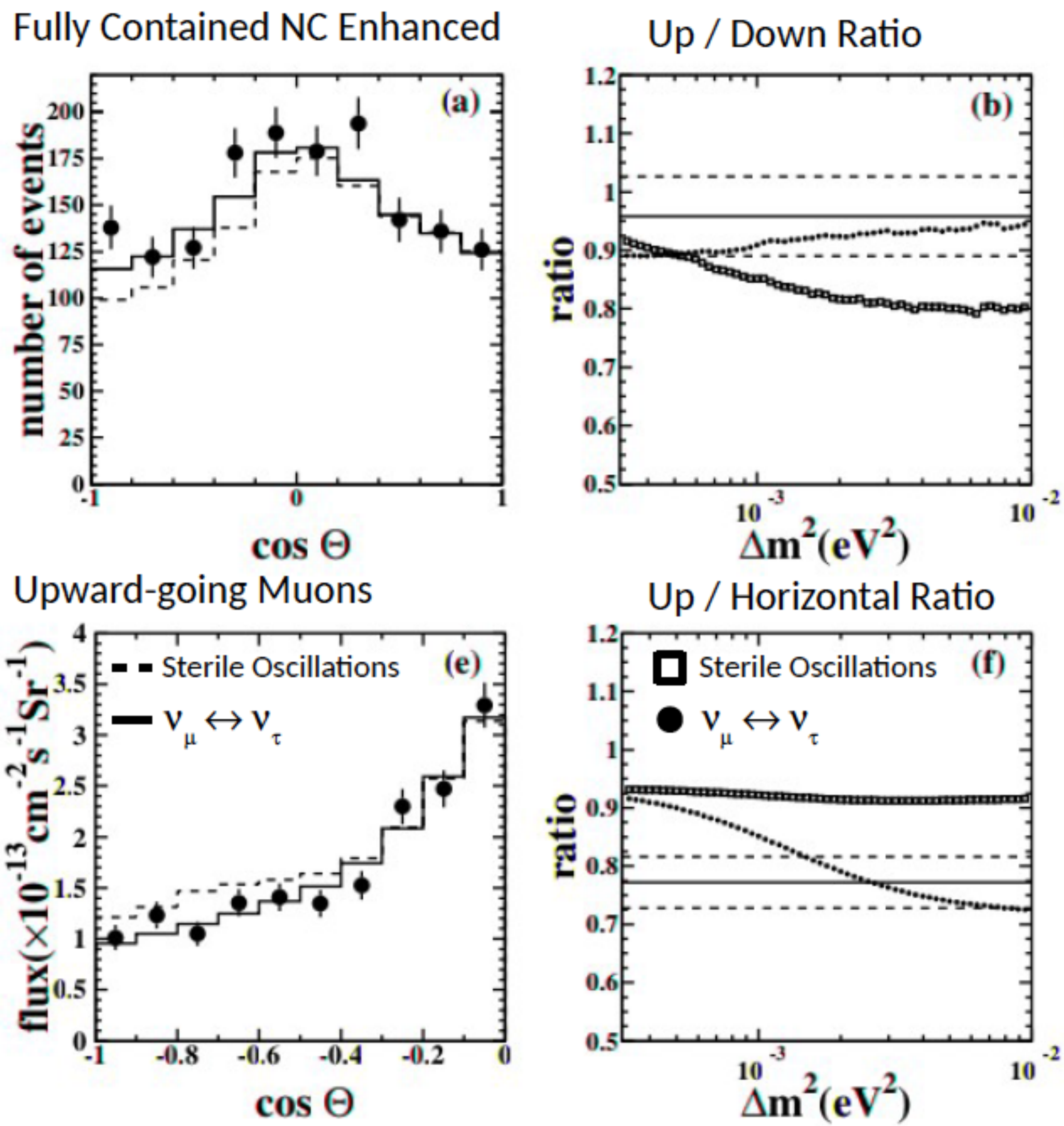




Phys. Rev. Lett. 85 (2000) 3999

Rejecting Oscillations into a Sterile State

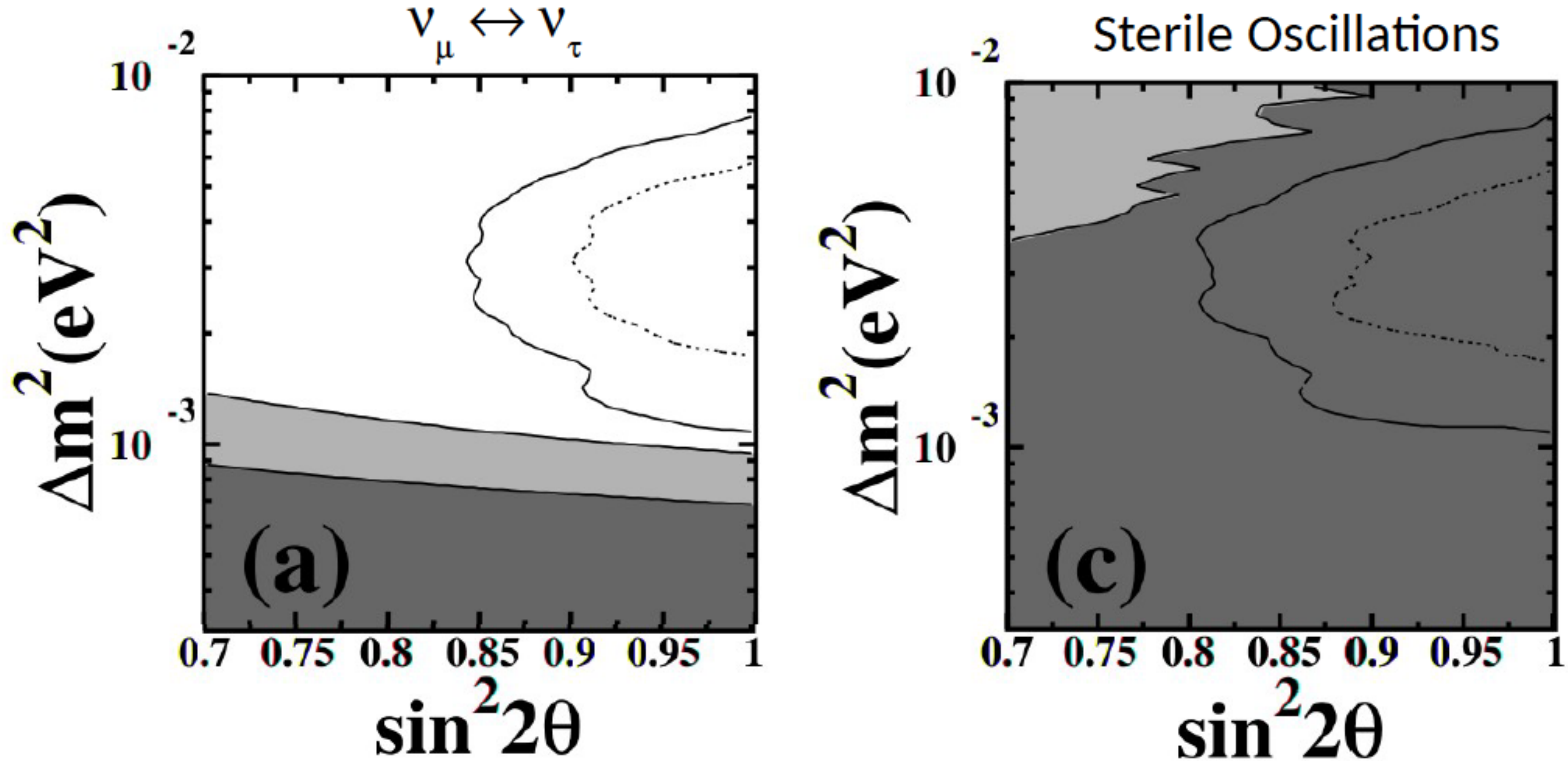
2000



- For sterile oscillation expect
  - Fewer NC interactions relative to $\nu\mu \leftrightarrow \nu\tau$
  - Oscillation suppression at high energies due to sterile "matter effect"
- Select NC enhanced sample
  - (Multi-ring e-like)
  - NC : 29%
  - CC νe : 46%
  - CC $\nu\mu$: 25%
- Test hypothesis using ratio measurement
  - NC: Up/Down
  - Up-μ : Up/Horizontal

Constraints on (100%) Sterile Oscillations

2000



Excluded at 99% C.L.

Excluded at 90% C.L.

FC Single-Ring Allowed 99%

Clear preference for standard oscillations

After Neutrino 1998

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Atmospheric

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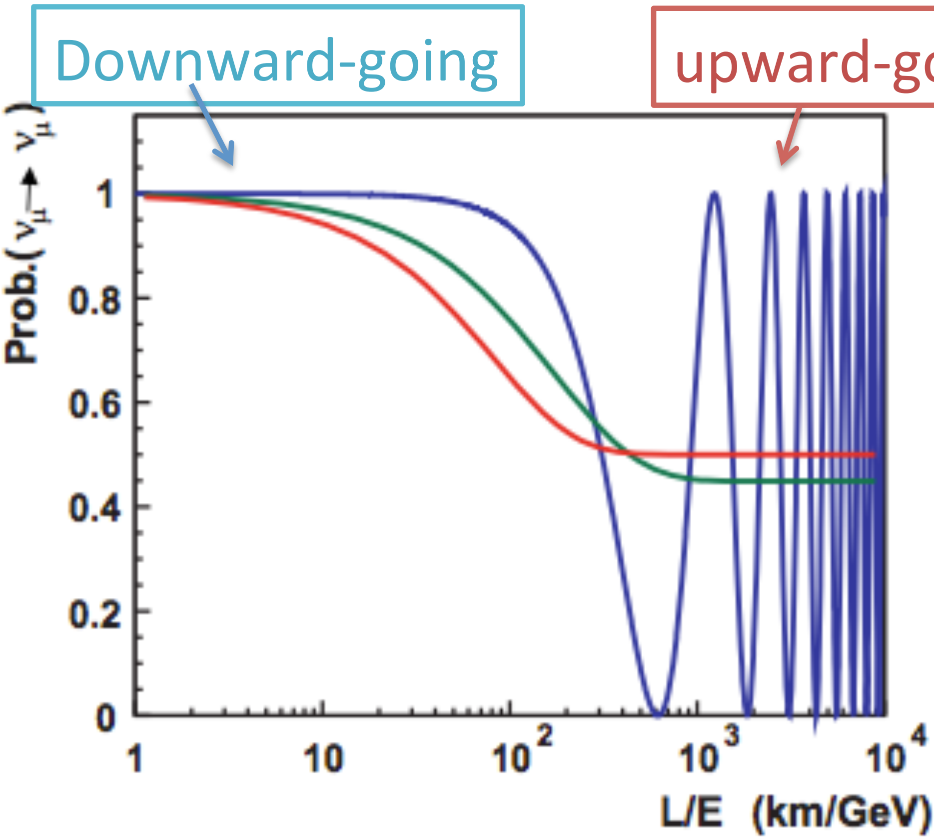
Searching for An Oscillatory Signature



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

Decoherence:

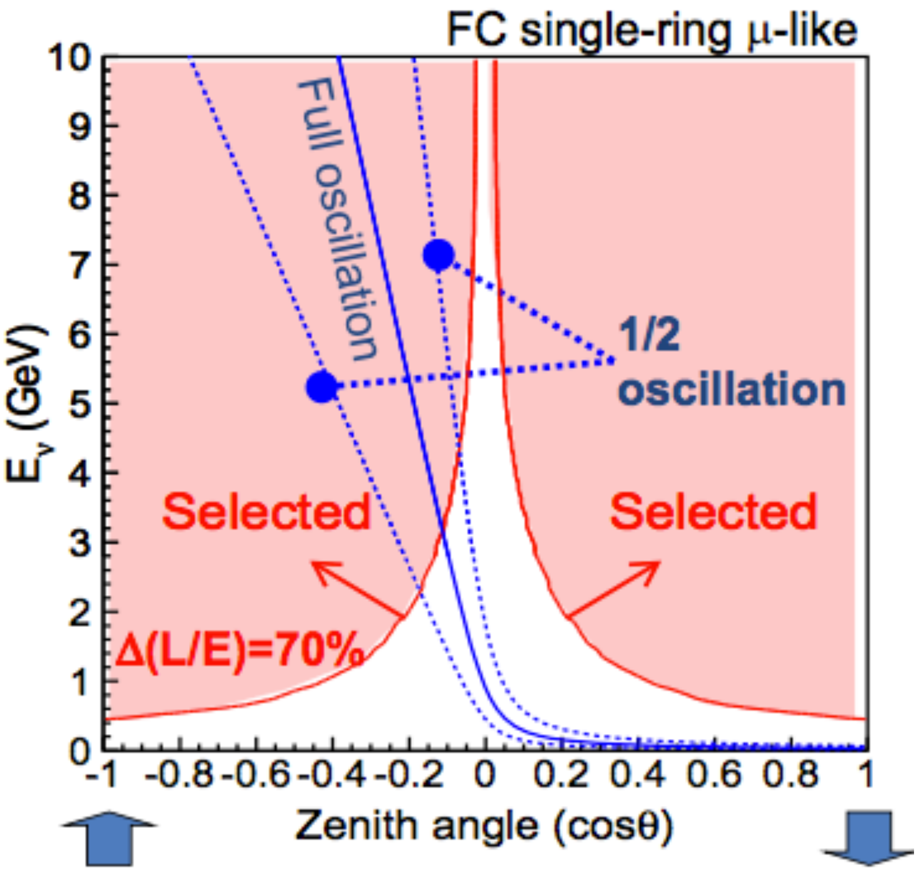
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \frac{1}{2}\sin^2 2\theta \cdot (1 - \exp(-\gamma_0 \frac{L}{E}))$$

Decay:

$$P(\nu_\mu \rightarrow \nu_\mu) = (\cos^2\theta + \sin^2\theta \cdot exp(-\frac{m}{2\tau}\frac{L}{E}))^2$$

- To strengthen evidence for oscillations search of the "L/E" oscillation shape
- (This technique will be used in other modern experiments)

Searching for An Oscillatory Signature

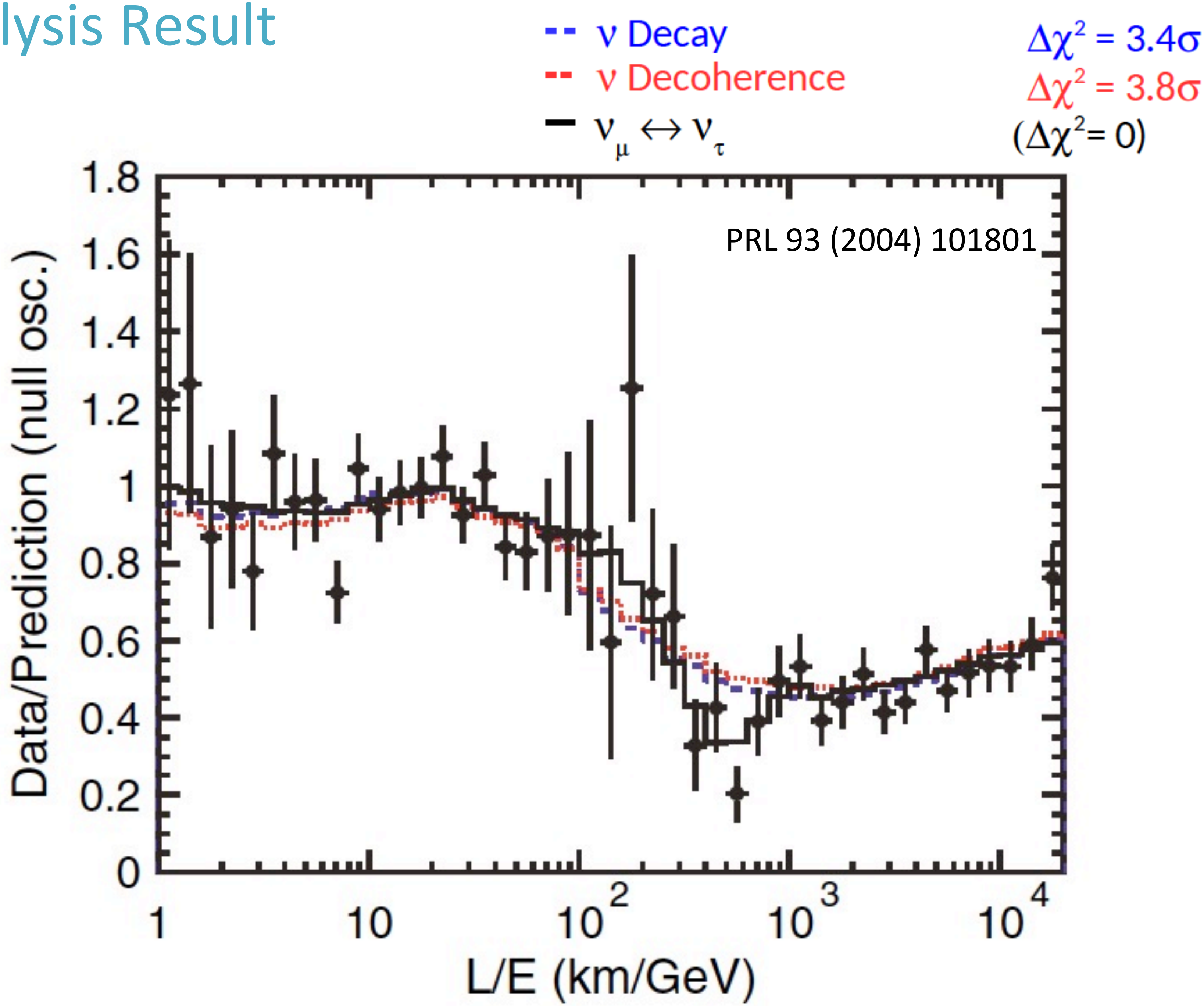


$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

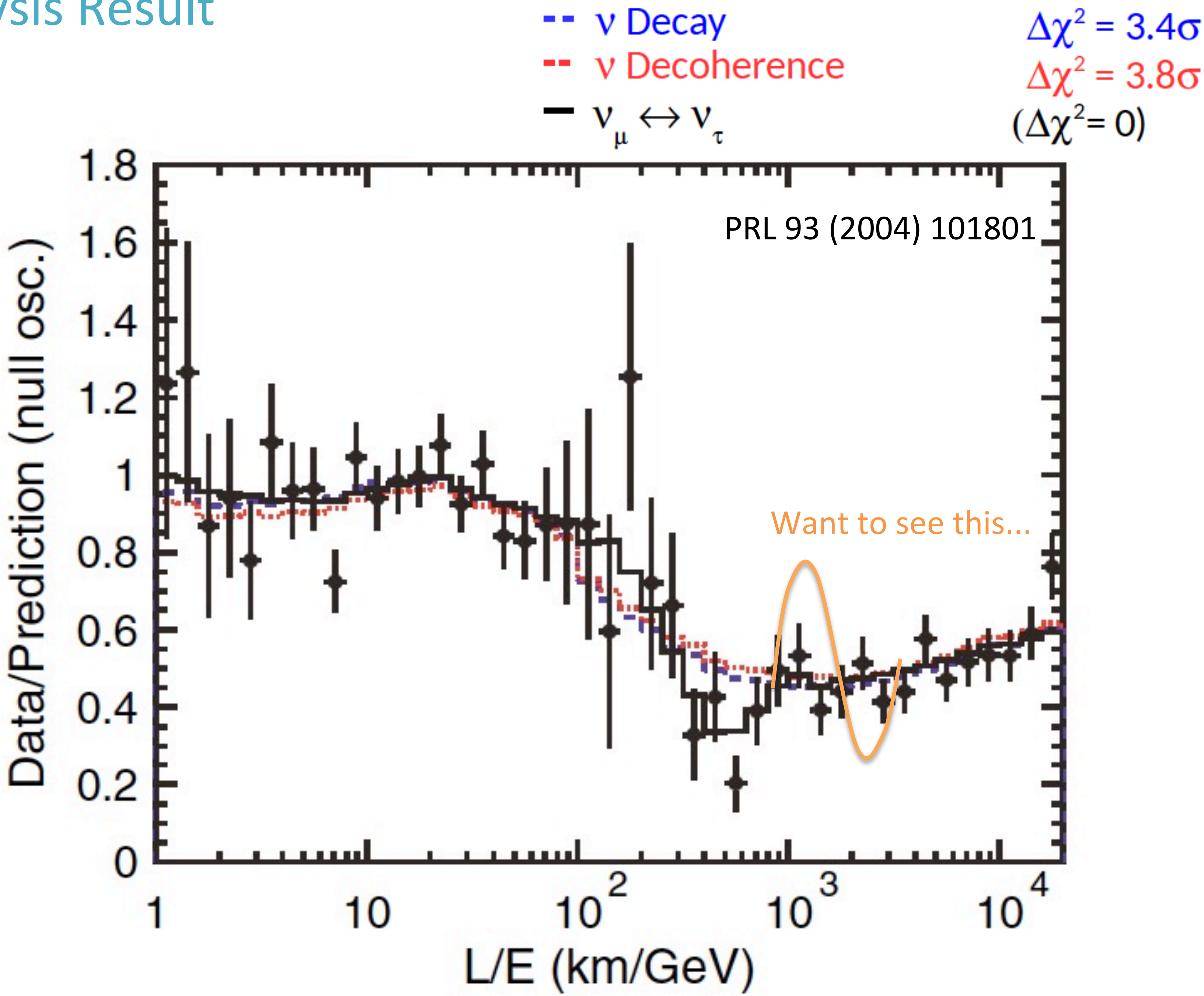
- To strengthen evidence for oscillations search of the "L/E" oscillation shape
- Select event with good resolution in L/E
  - *Remove* low energy events
  - *Remove* events near the horizon

L/E Analysis Result

2004



L/E Analysis Result



After Neutrino 1998

- Super-K saw definitive evidence for the disappearance of atmospheric muon neutrinos
  - No distortion seen in the electron samples

- Data are well fit by $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - By the way, where did the ν_τ go?

Atmospheric

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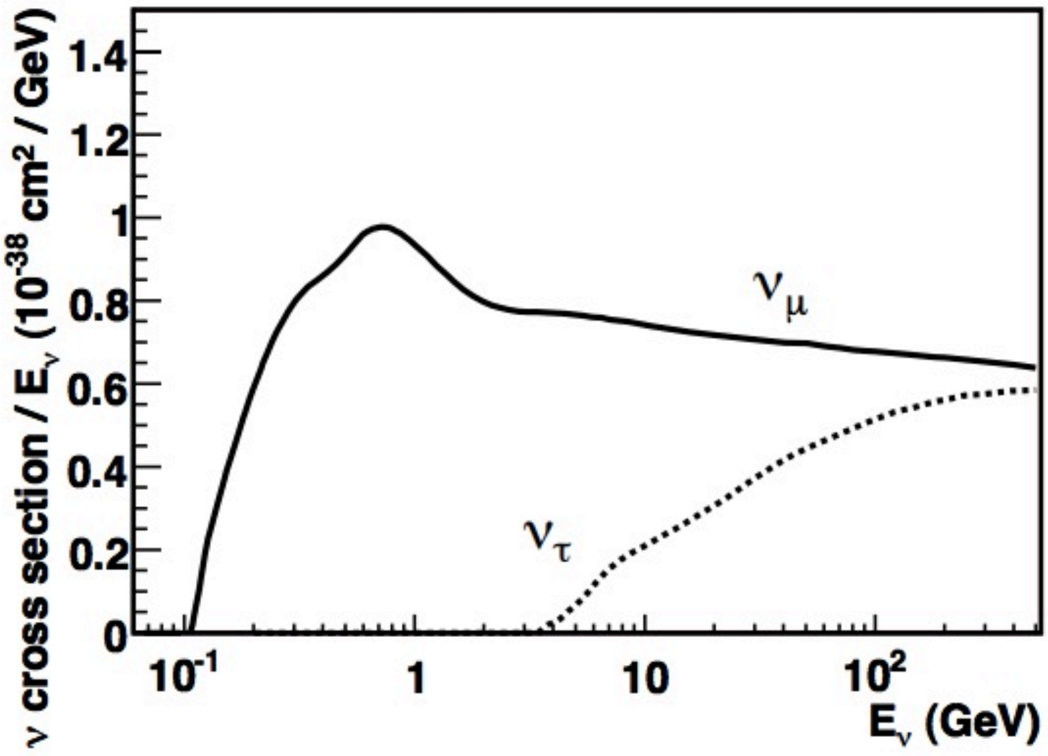
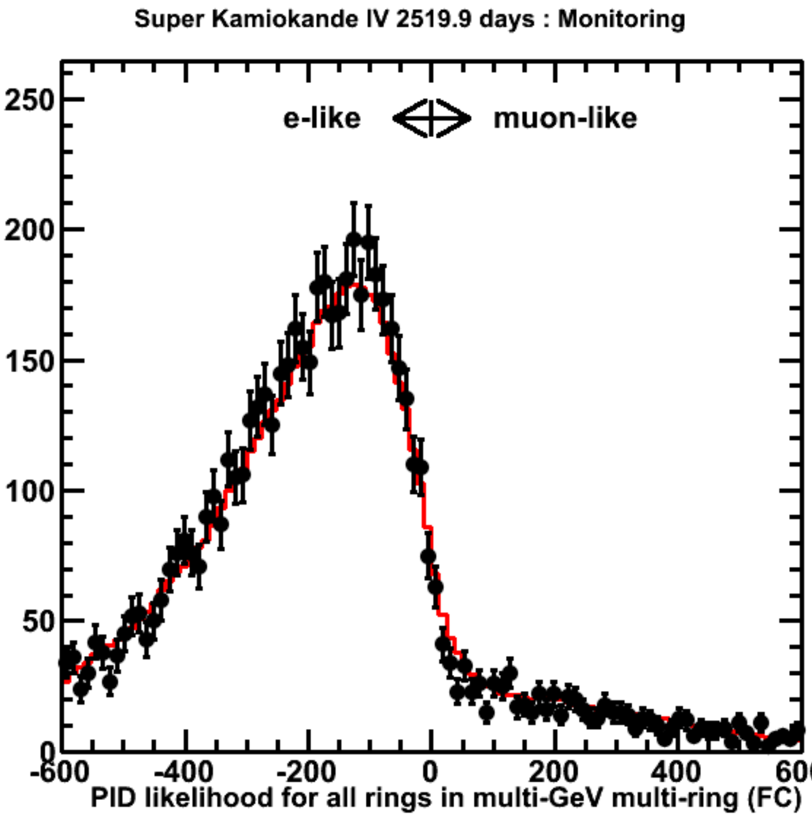
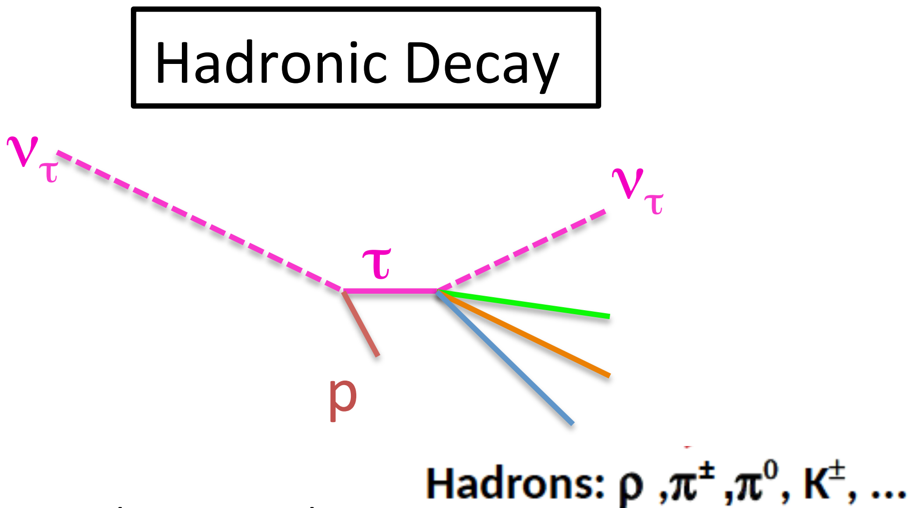
Tau Neutrino Cross Section



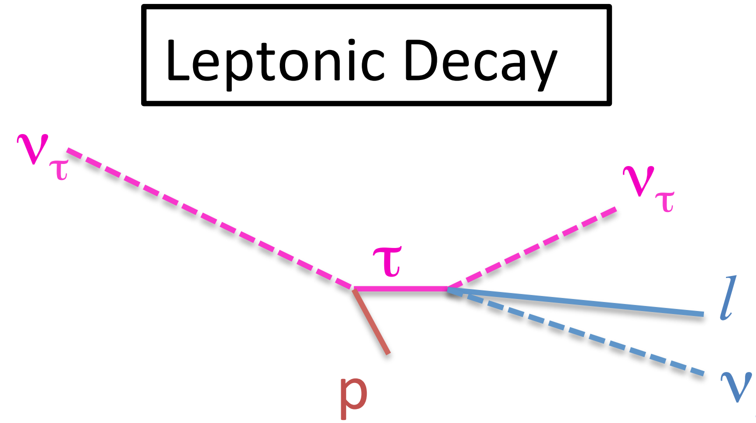


- In order to make a tau neutrino in the first place, you need around 3.4 GeV of energy
- Expect on average about 1 ev/kton/year in Super-K, usually look e-like

Searching for Tau Neutrinos



(BR: ~65%)



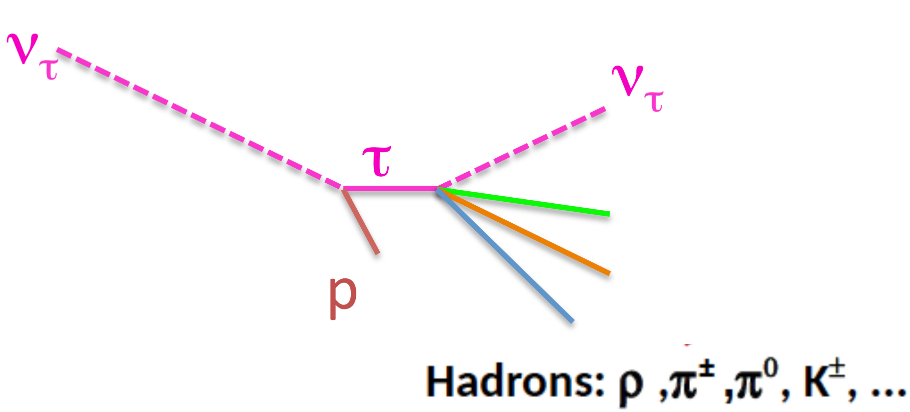
(BR: ~34%)

- A 10 GeV τ will travel about 0.5 mm
- Leptonic decay is swamped by backgrounds from ν_l CC interactions
- Focus on hadronic decay modes

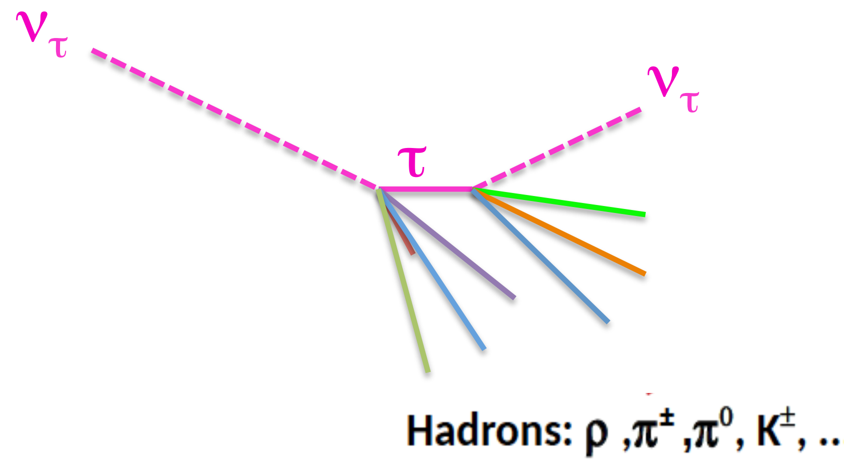
- Due to production threshold, many tau neutrino interactions are DIS
  - So *even more* hadrons

Searching for Tau Neutrinos

CCQE + Hadronic



CC DIS + Hadronic



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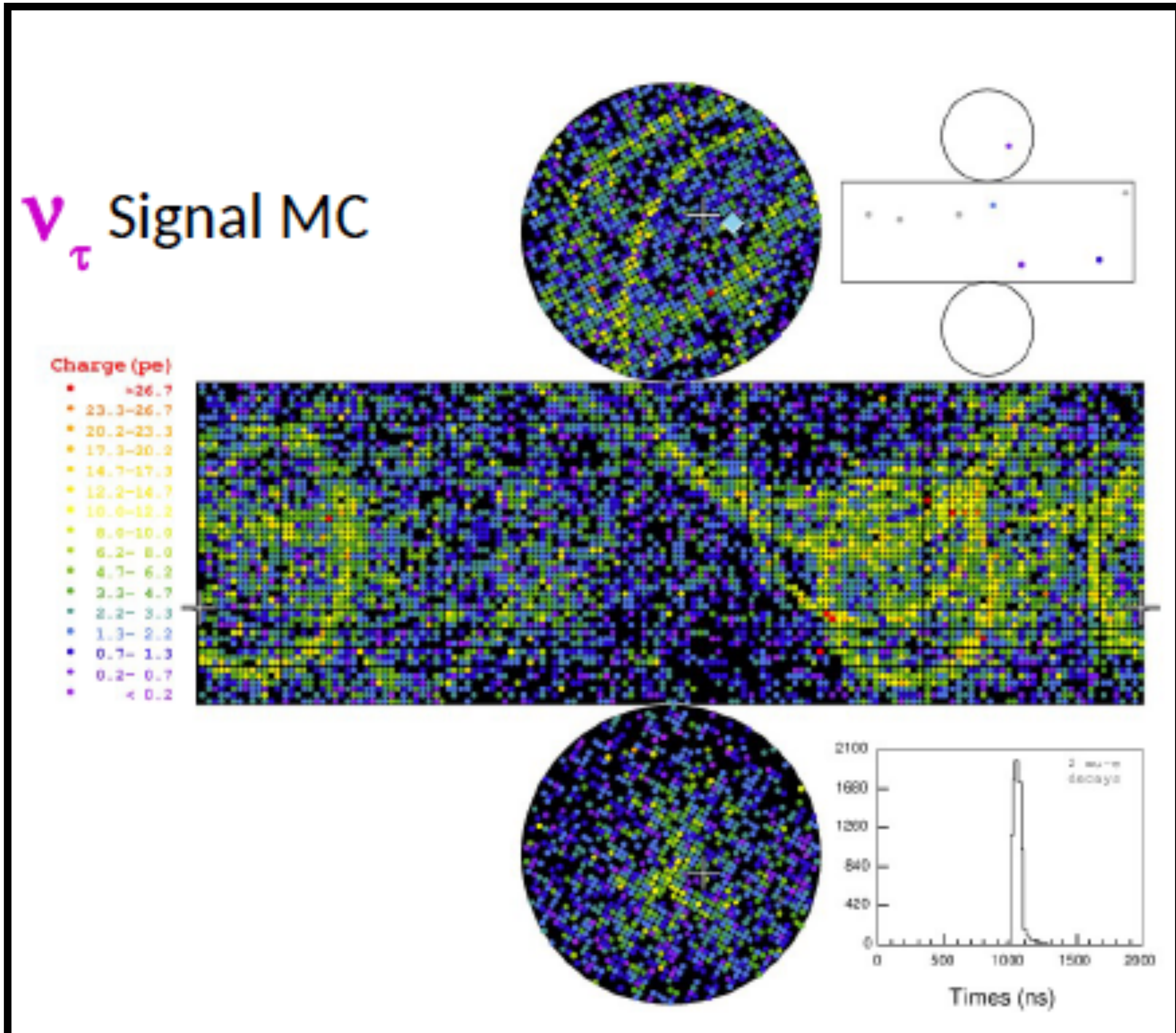
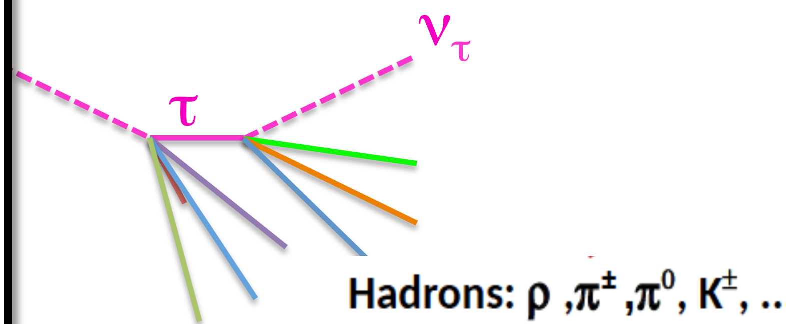
Searching for Tau Neutrinos



C DIS + Hadronic



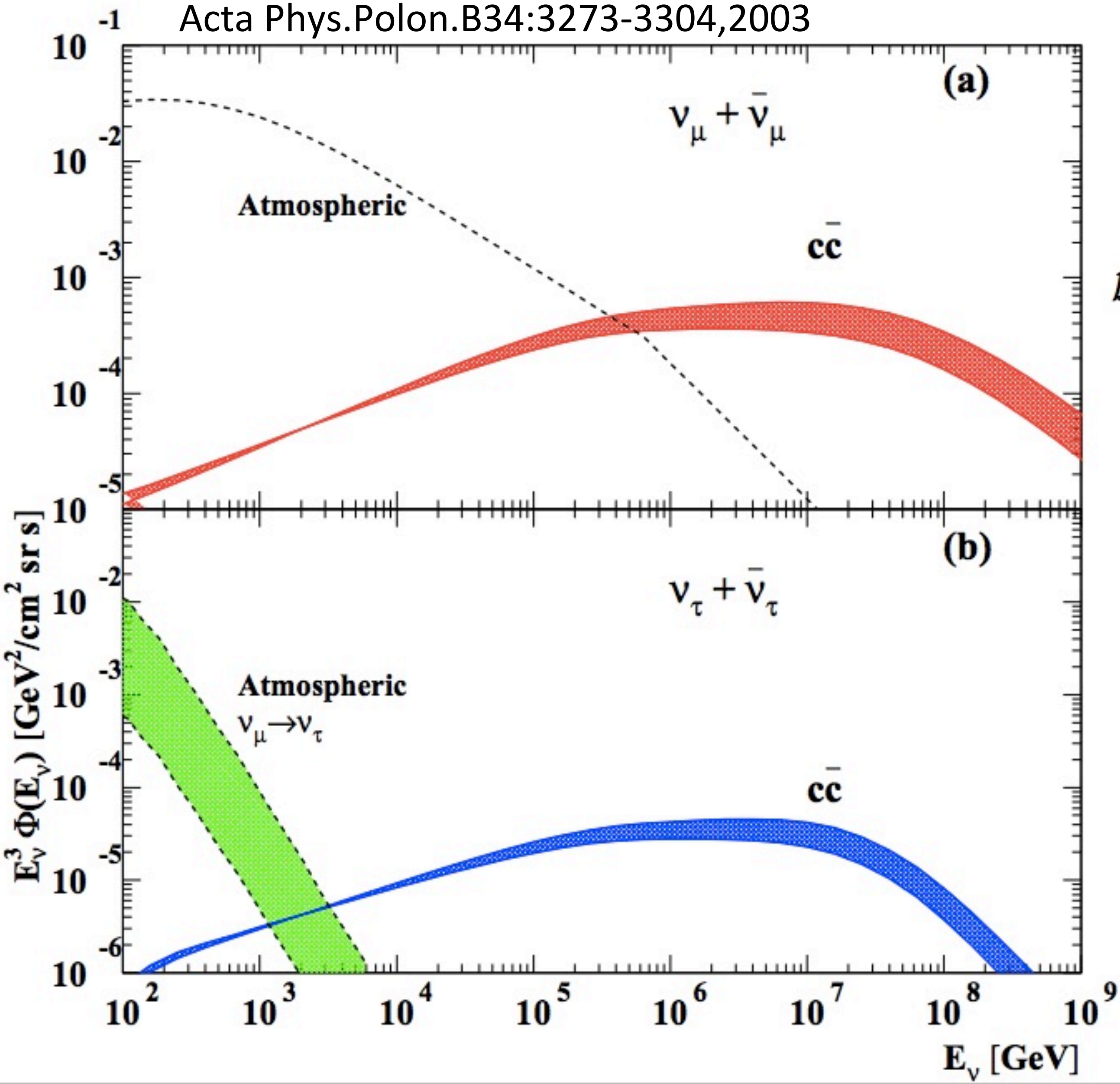
from ν_l CC interactions

utrino interactions are DIS

Identifying tau interactions is a challenge

Background Tau Neutrinos and the "Prompt" Flux

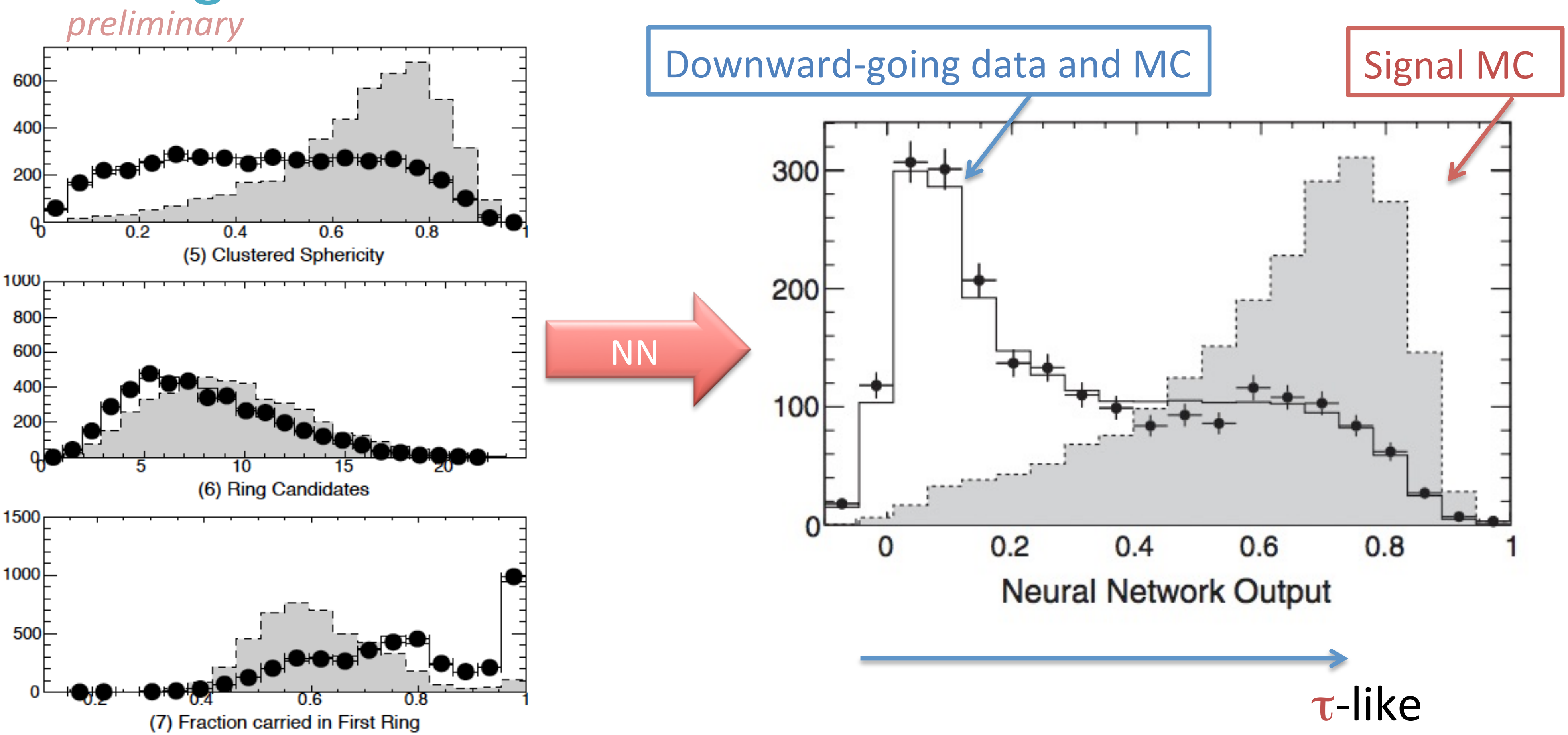
Acta Phys.Polon.B34:3273-3304,2003



$$\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau) = (6.6 \pm 0.6) \times 10^{-2}$$

- Tau neutrinos from charmed particle decays
- Only important at high energies

Searching for Tau Neutrinos



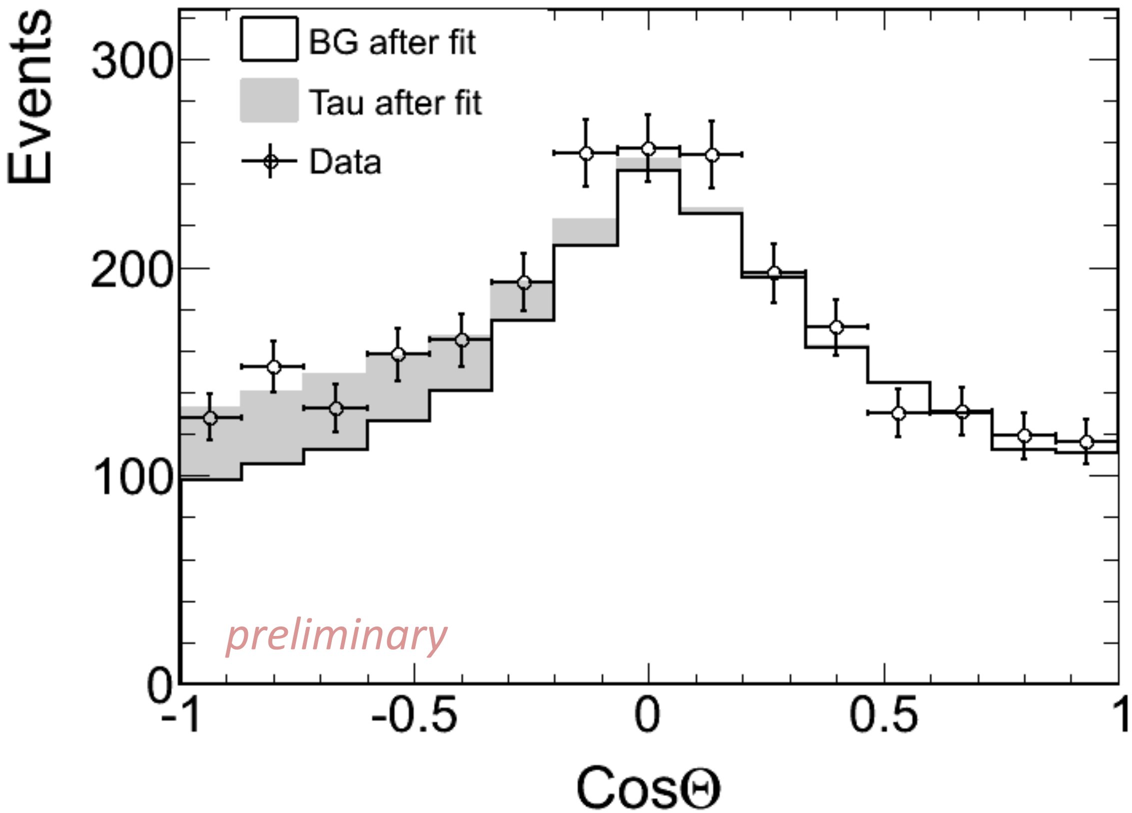
- Use a multi-variate approach to try and identify
- Expect tau events only in upward-going data
  - Ie, where the muon events disappeared
- Downward-going data can be used to train and test

Evidence for ν_τ Appearance at Super-K

2013-16

$\alpha = 0$, no ν_τ

$$Data = PDF_{BG} + \alpha \times PDF_{tau} + \sum \epsilon_i \times PDF_i$$



Best fit α = 1.47 ± 0.32 (tot.)

This corresponds to a significance of 4.6σ for rejecting the no-tau hypothesis

Tau neutrinos have been seen in the atmospheric data

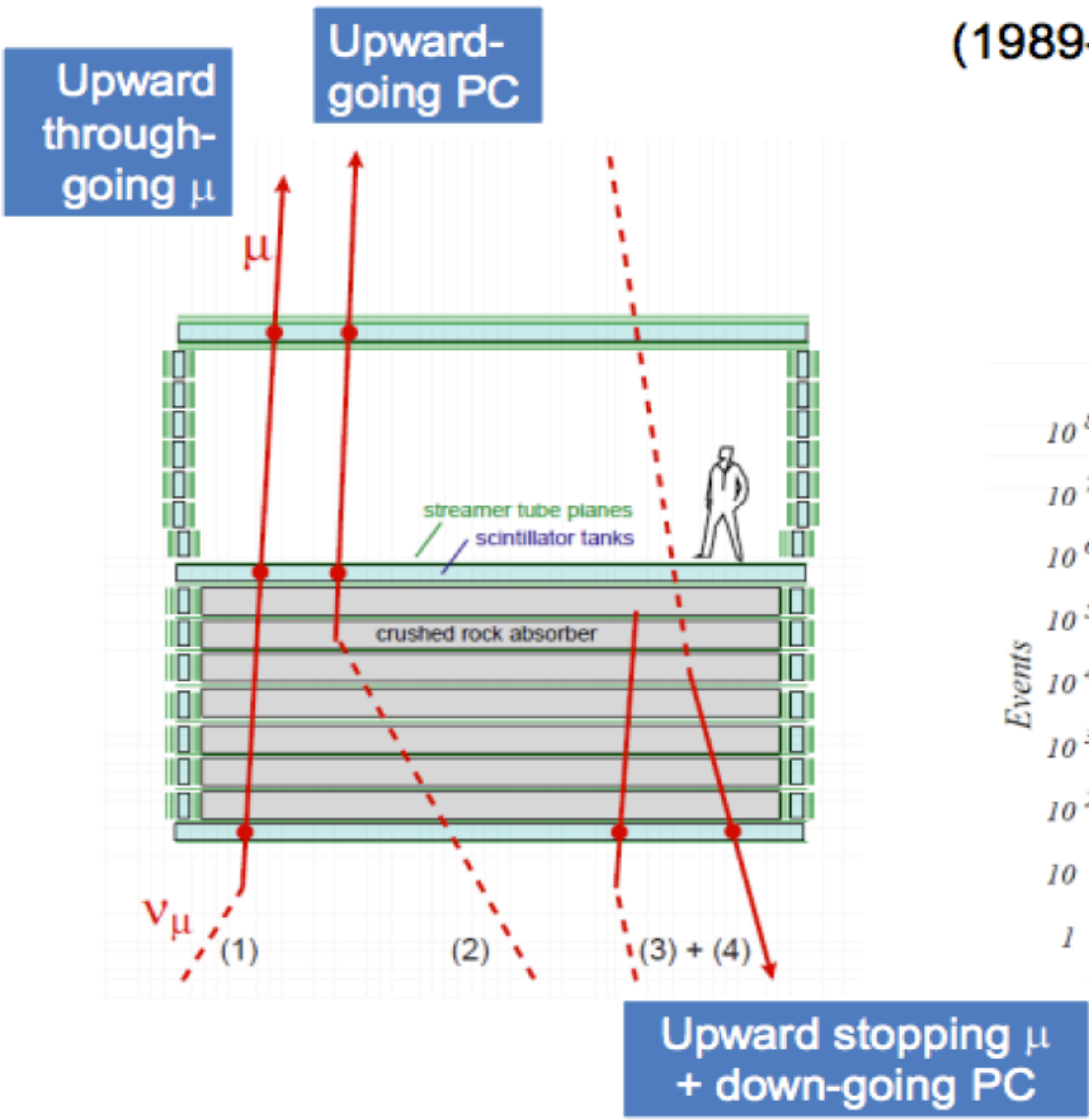
Other Experiments From Around the Same Time

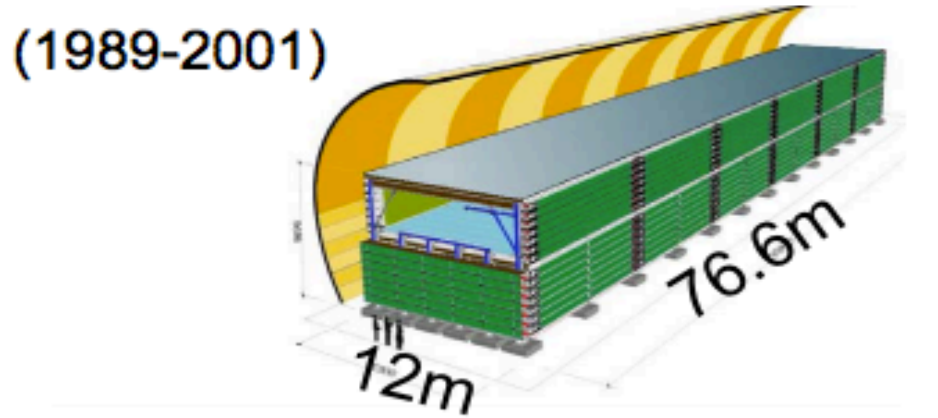
- Many other experiments saw oscillations, in several channels
- Several of those experiments have also tested the sterile oscillation hypotheses and other types of disappearance to verify PMNS mixing
- Opera experiment has also observed $\nu\tau$ appearance (more cleanly)

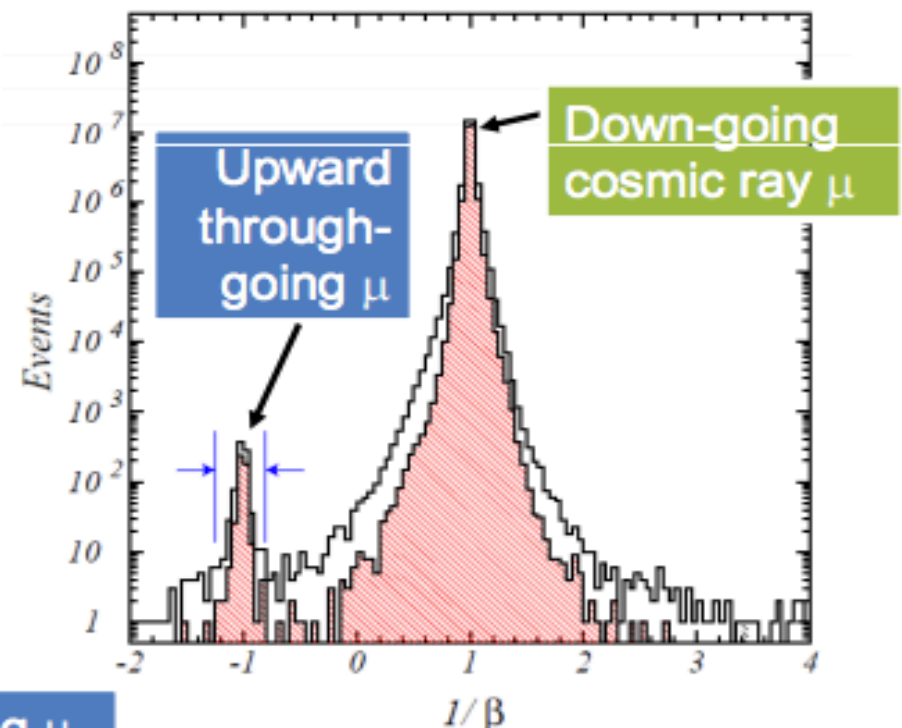
MACRO (Monopole Astrophysics Cosmic Ray Observatory)

Operated from 1989-2000 (LGNS)
5300 tons
Streamer tubes & scintillator planes

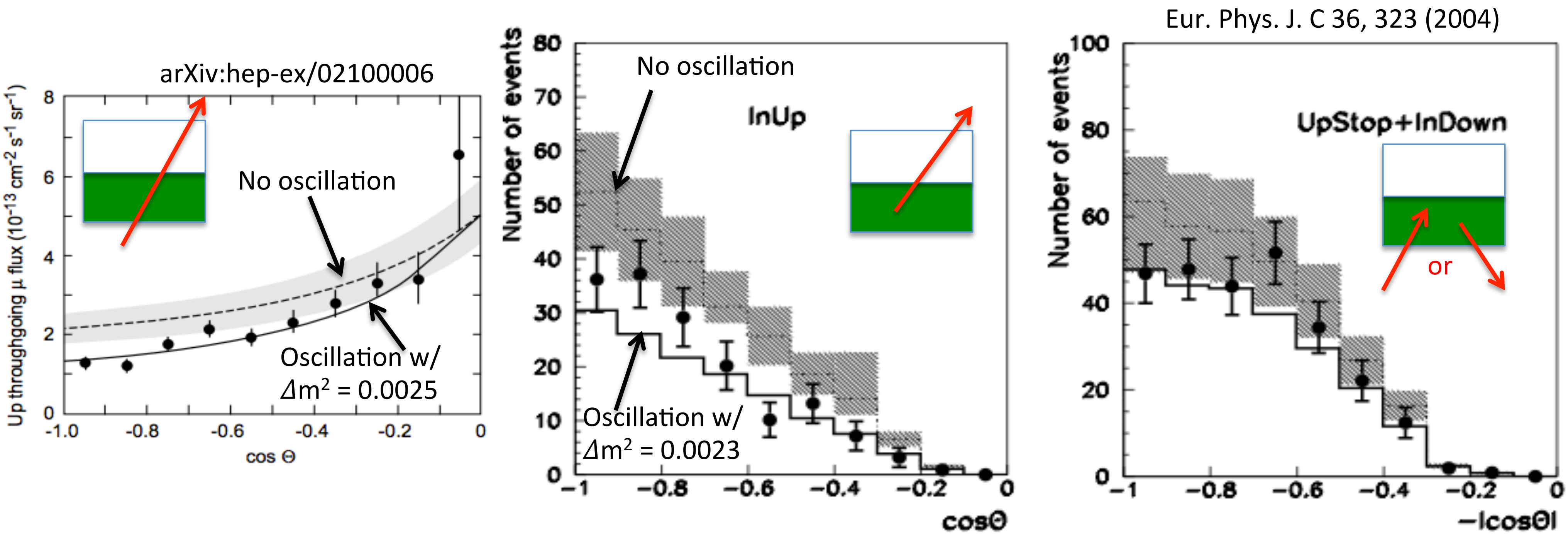
Event Classification in MACRO







MACRO Results

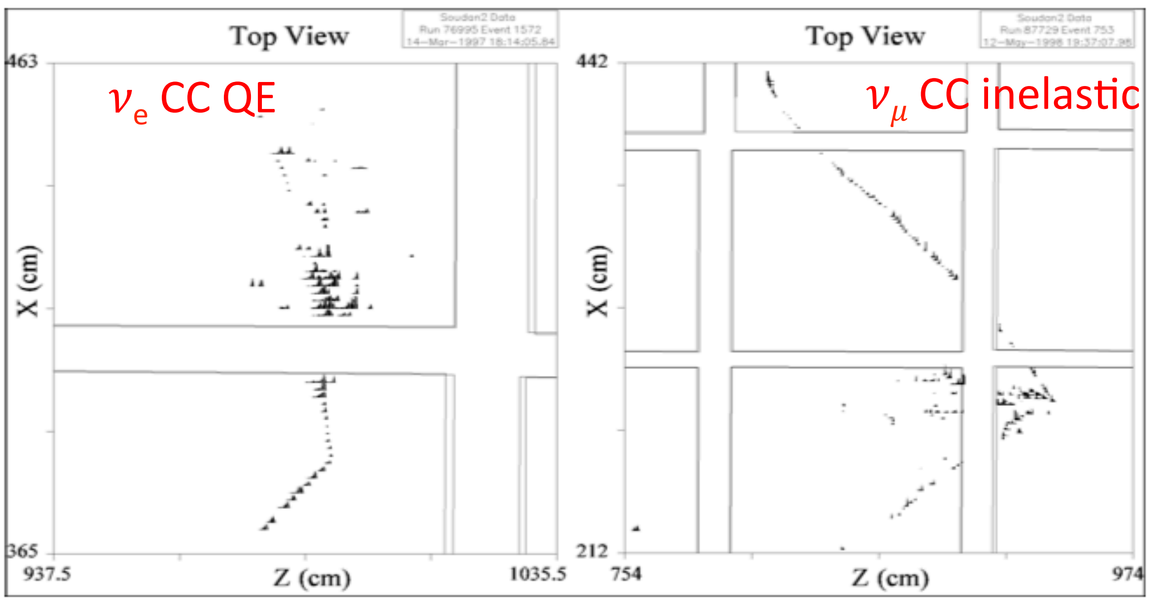


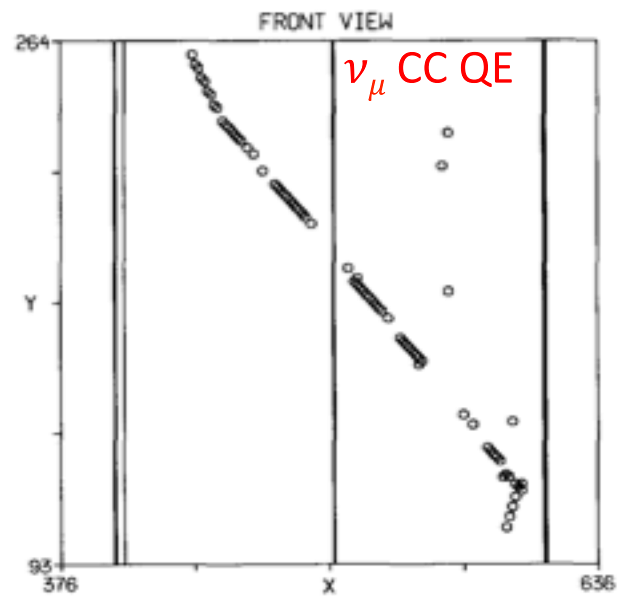
- Also saw zenith distortion of upward-going muons
- First experiment to independently confirm Super-K's atmospheric ν oscillation signal

Soudan-2

Operated from 1989-2001
770 ton fiducial mass

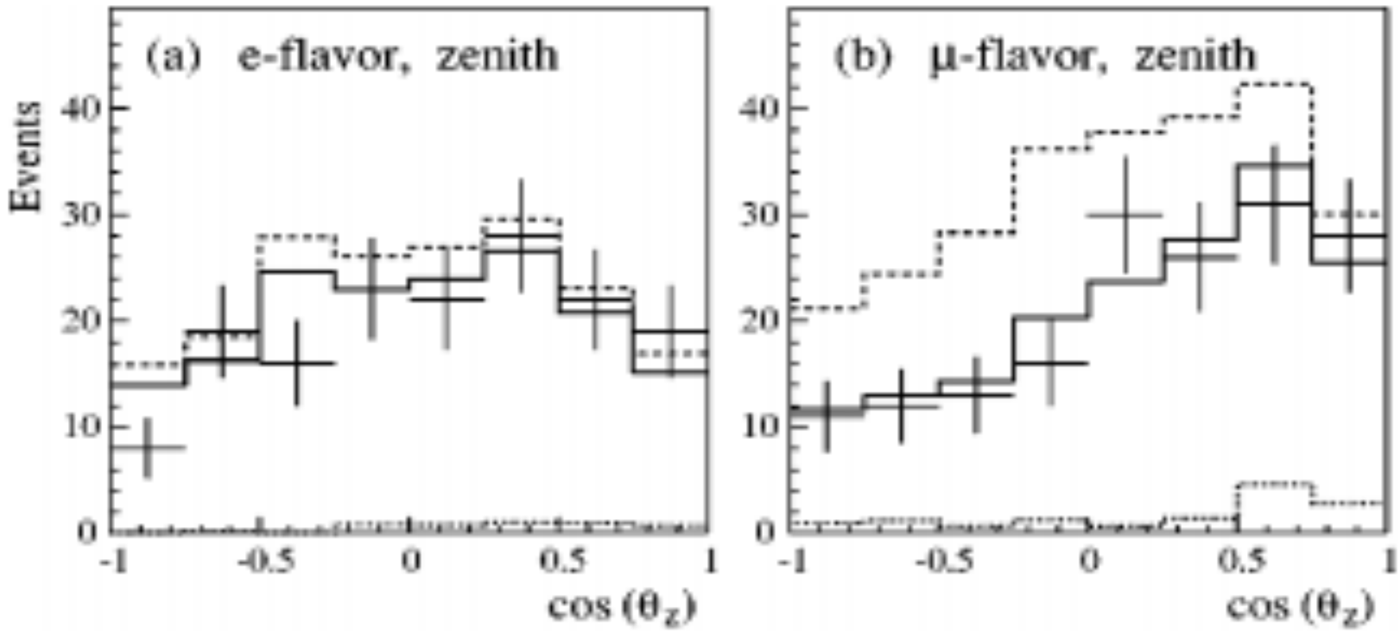
- Fine-grained iron tracking calorimeter
- Operated in Soudan (U.S.) from 1989-2001
- 770 ton fiducial mass
- Event classification:





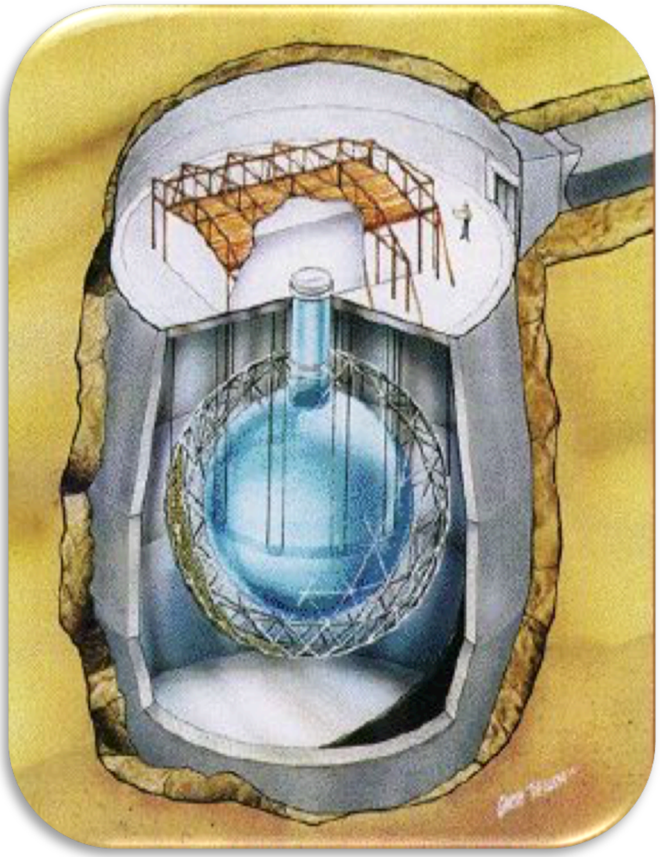
Soudan-2 results

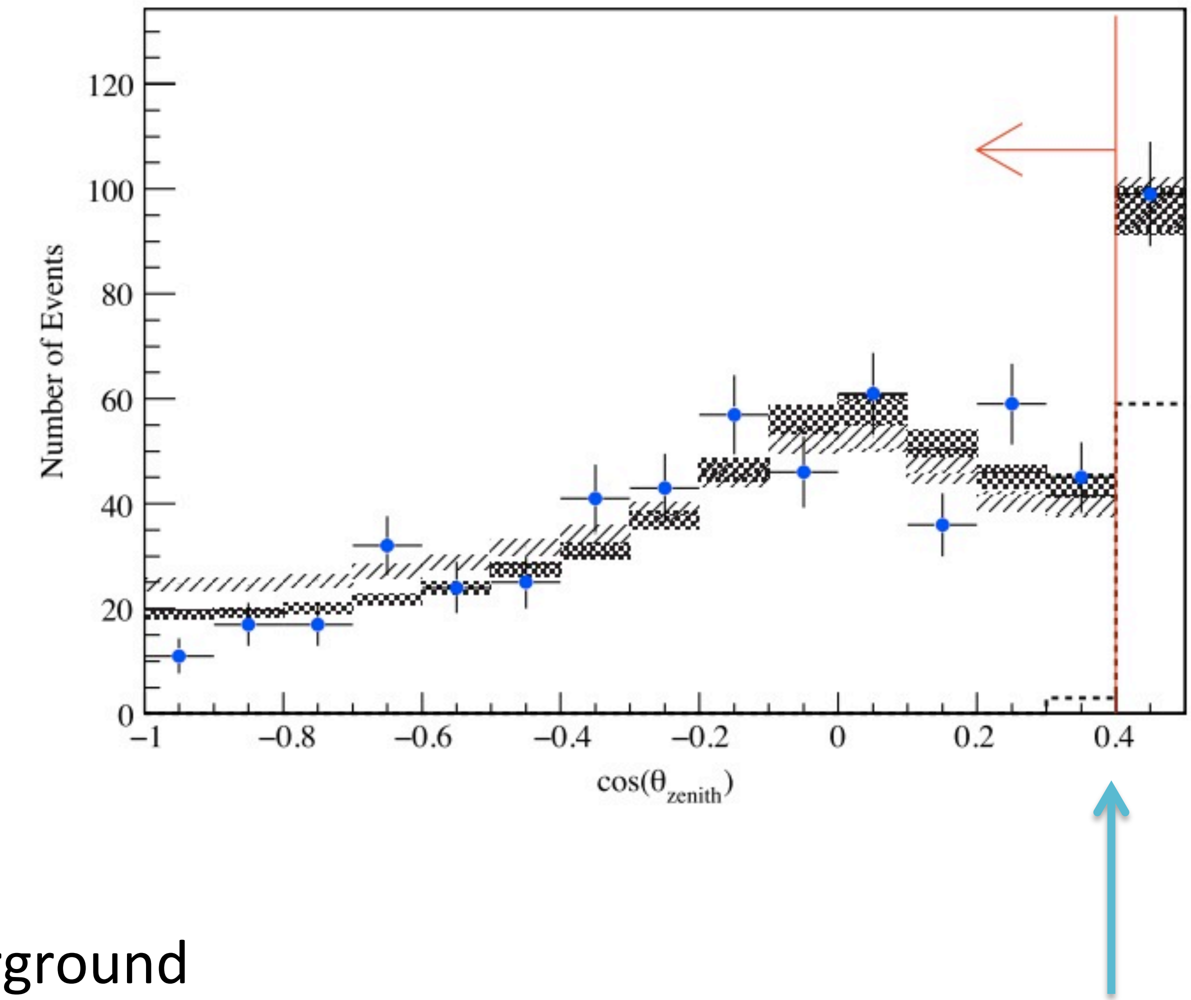
Phys. Rev. D 68, 113004 (2003)



Again, confirmed zenith distortion, consistent with oscillation of $\nu_\mu \longrightarrow \nu_\tau$

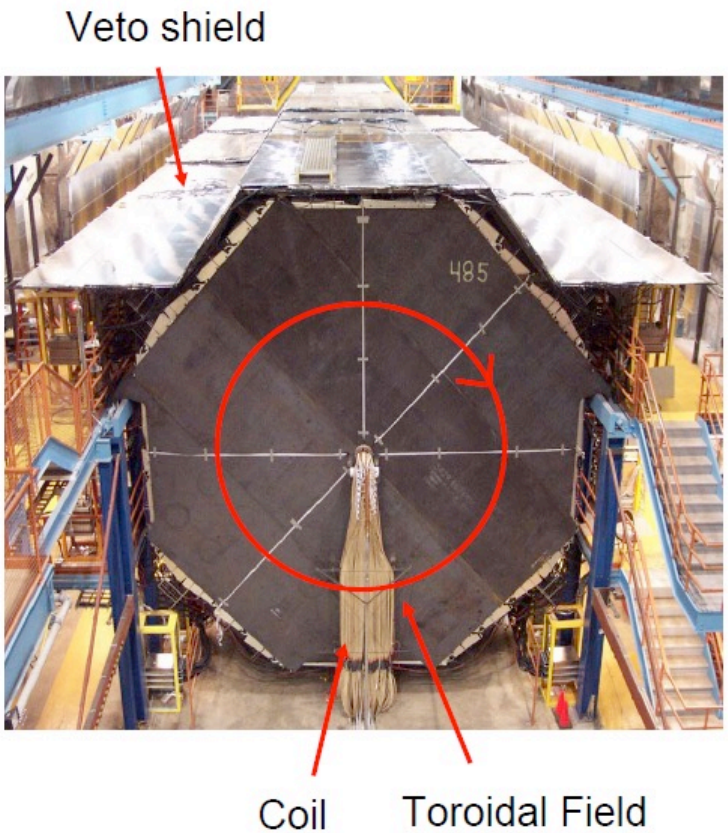
SNO, Not Just Solar Neutrinos



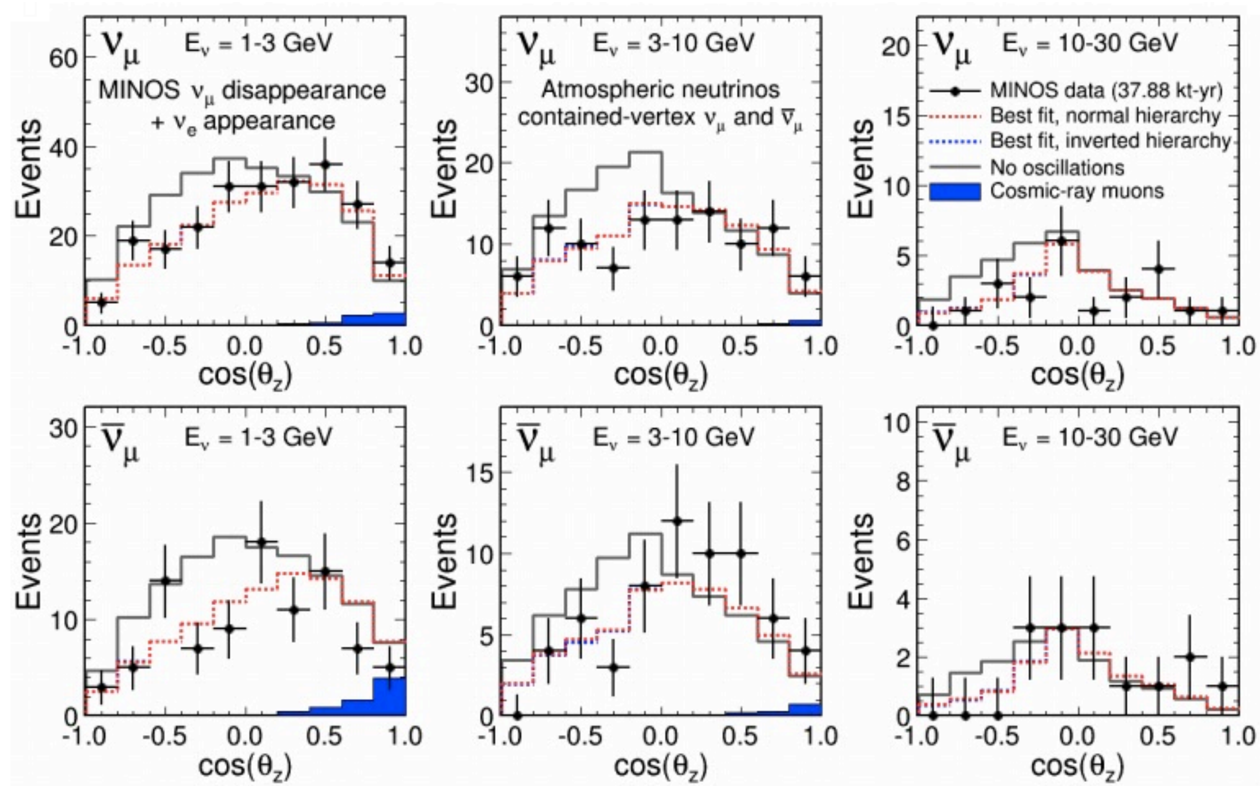


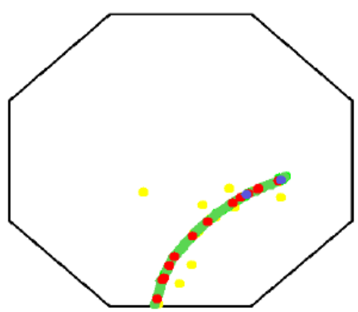
- Located 2.09 km underground
- 1 kton of $D_2 0$
- Sensitive to downward-going neutrino-induced muons from rock interactions due to depth

MINOS



Separation of ν_μ and anti-ν_μ



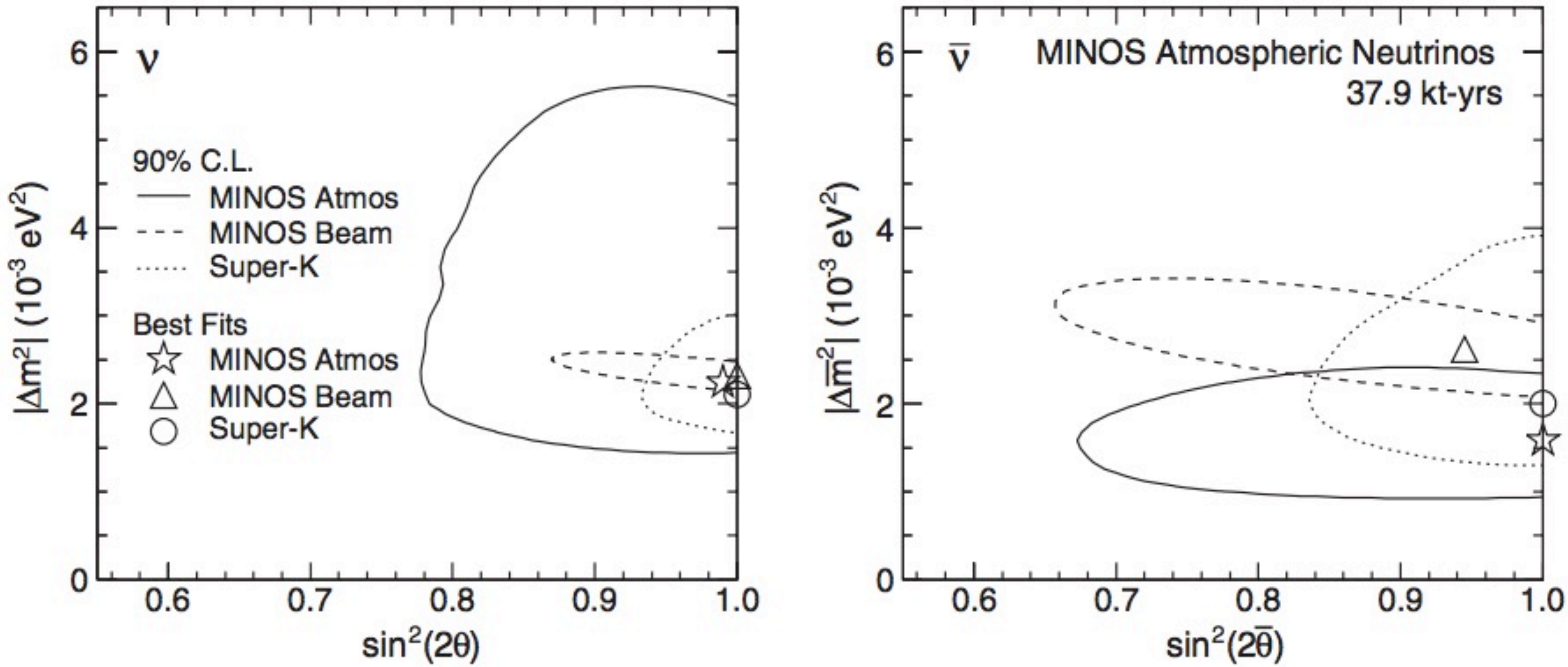


Downward going partially contained event

- Operated from 2005-2016 in Soundan Mine (U.S.)
- 5.4 kton mass, magnetized steel and plastic scintillator
- Allows separation of neutrinos and antineutrinos on an event-by-event basis!

MINOS Neutrino and Antineutrino Measurements

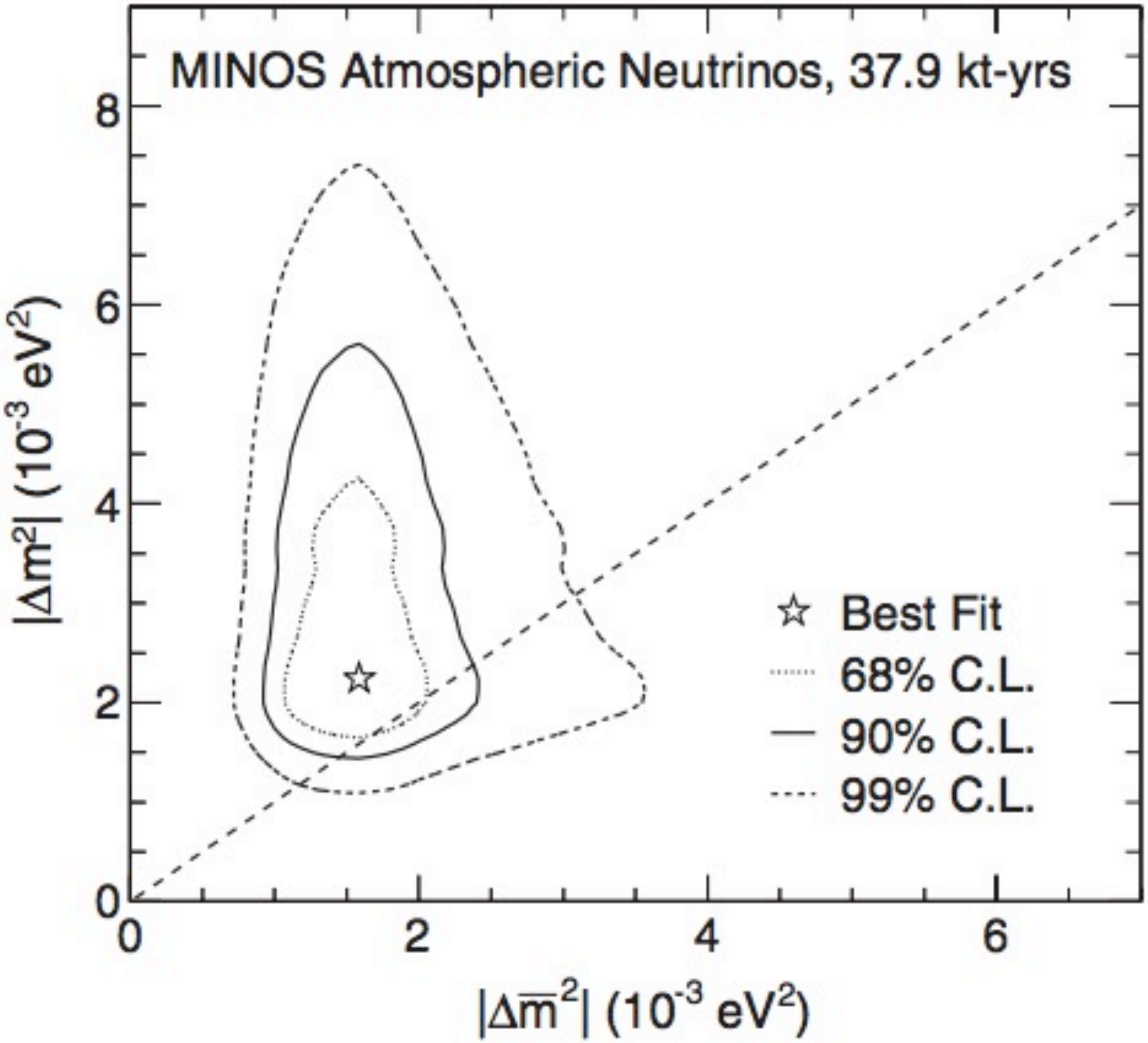
PHYSICAL REVIEW D 86, 052007 (2012)



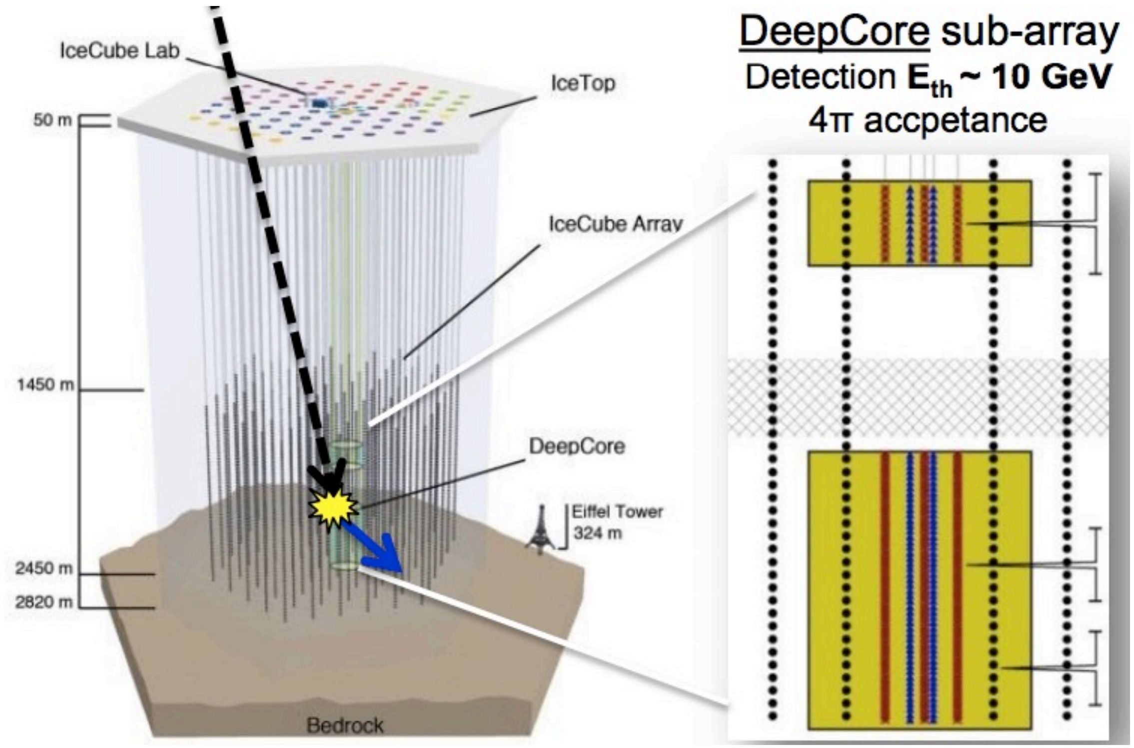
- Independent measurements of neutrino and antineutrino mixing
- Test for *ad hoc* CPT violation

MINOS ad hoc CPT Violation Constraints c

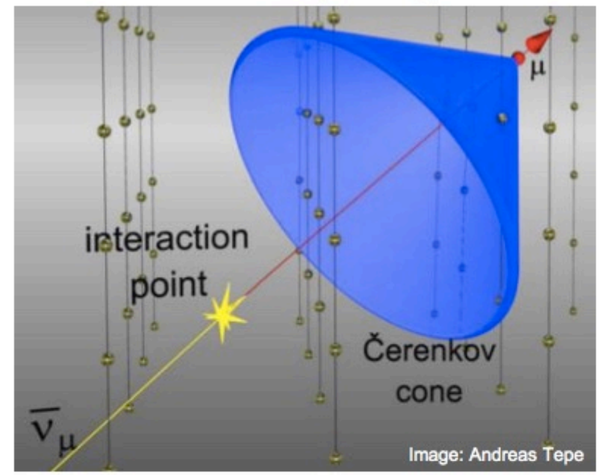
PHYSICAL REVIEW D 86, 052007 (2012)



IceCube Experement



Detection principle



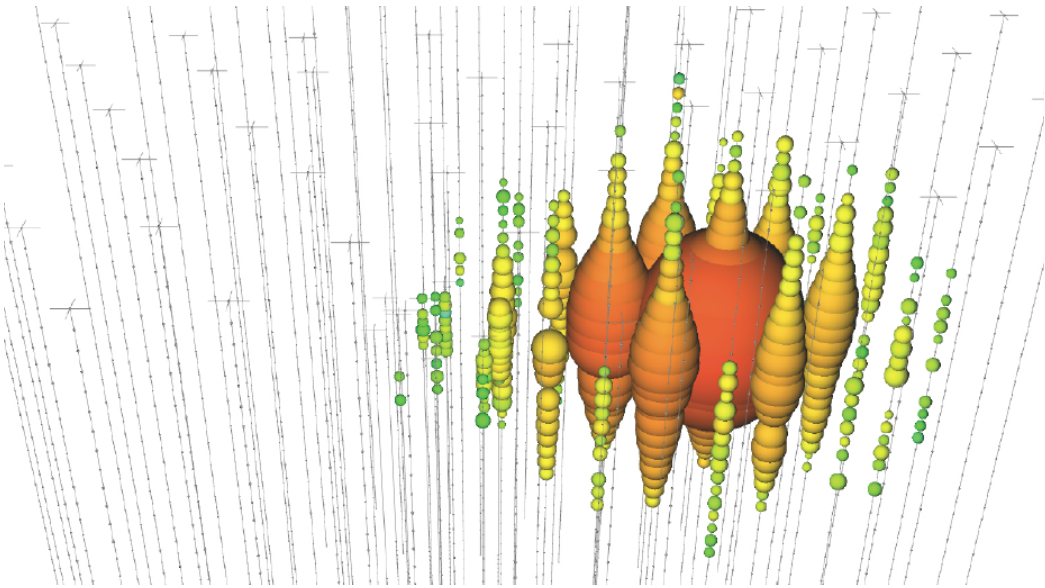
IceCube: 5,160 PMTs over ~ 1 km^3
DeepCore: ~ 600 PMTs over 0.02 km^3

- Cubic kilometer of instrumented ice near the south pole
- PMT spacing
  - IceCube : 125 m (x-y) , 17 m (z)
  - DeepCore: 40-70m (x-y), 7 m (z)

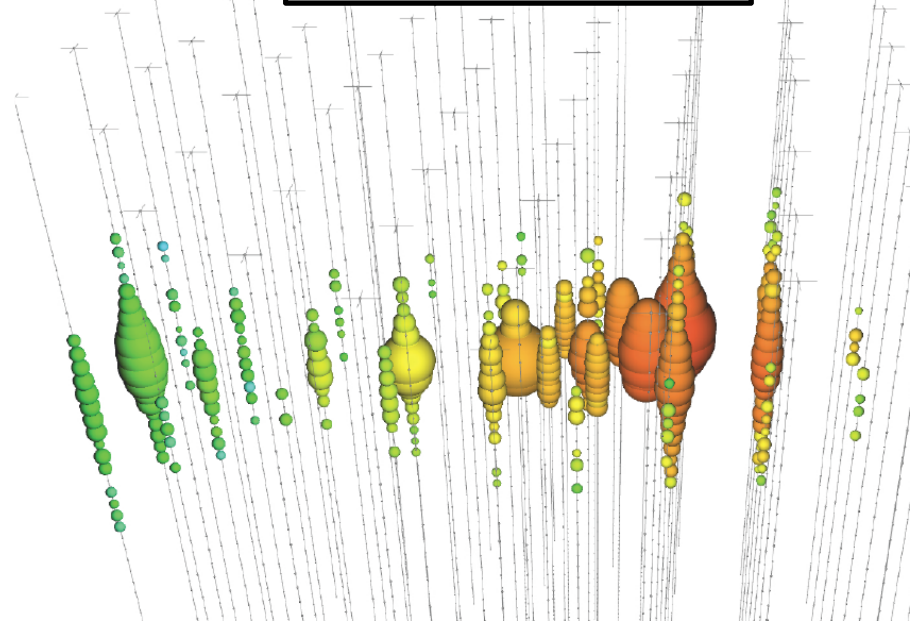
IceCube	DeepCore
PMT density	
Energy Threshold	
~100 GeV	~10 GeV

IceCube Event Topologies

Cascade Event

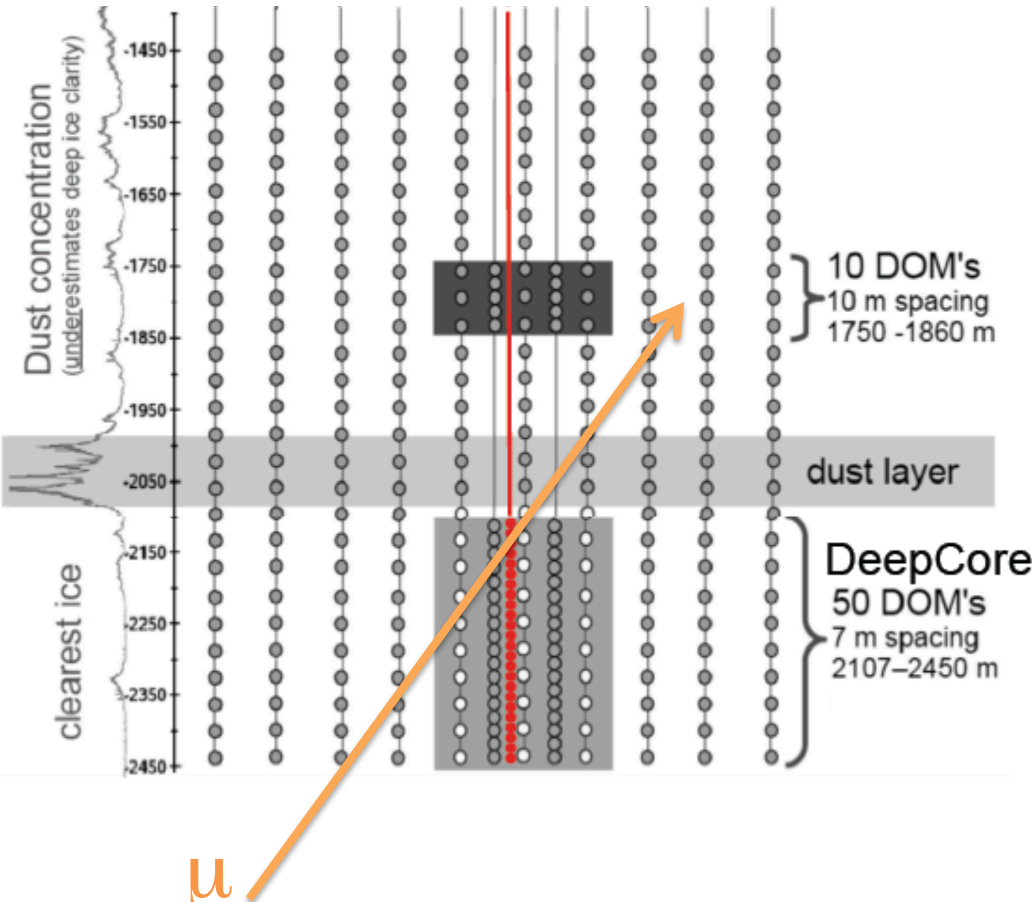


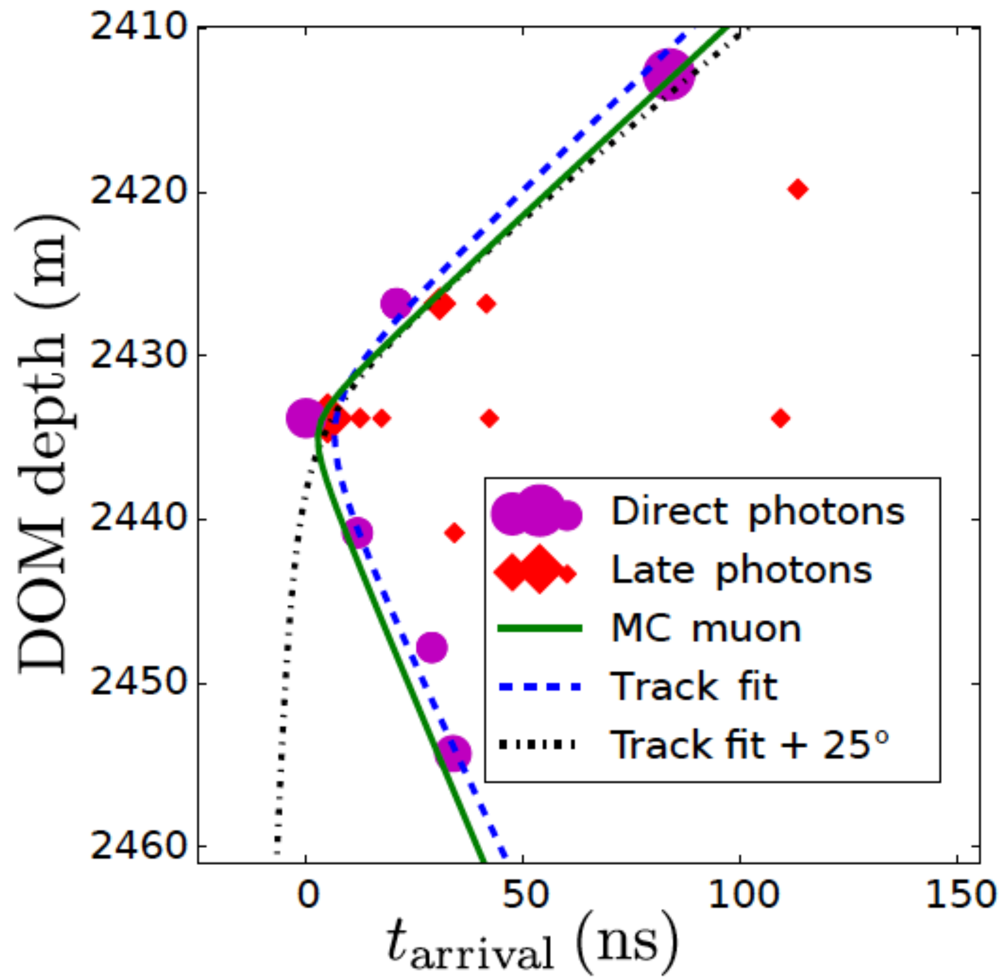
Track Event



- Cascade-like events are mostly CC νe, NC, and CC $\nu\tau$ interactions
  - Difficult to separate these!
- Track-like events are almost purely CC $\nu\mu$ interactions
- IceCube strings can be used as a veto for the DeepCore sub detector

IceCube Events

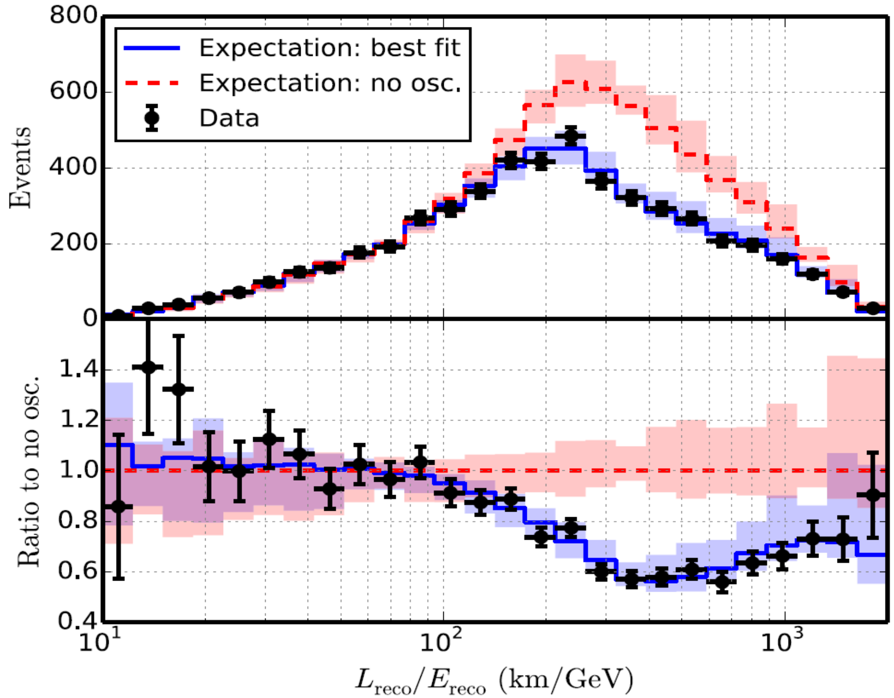


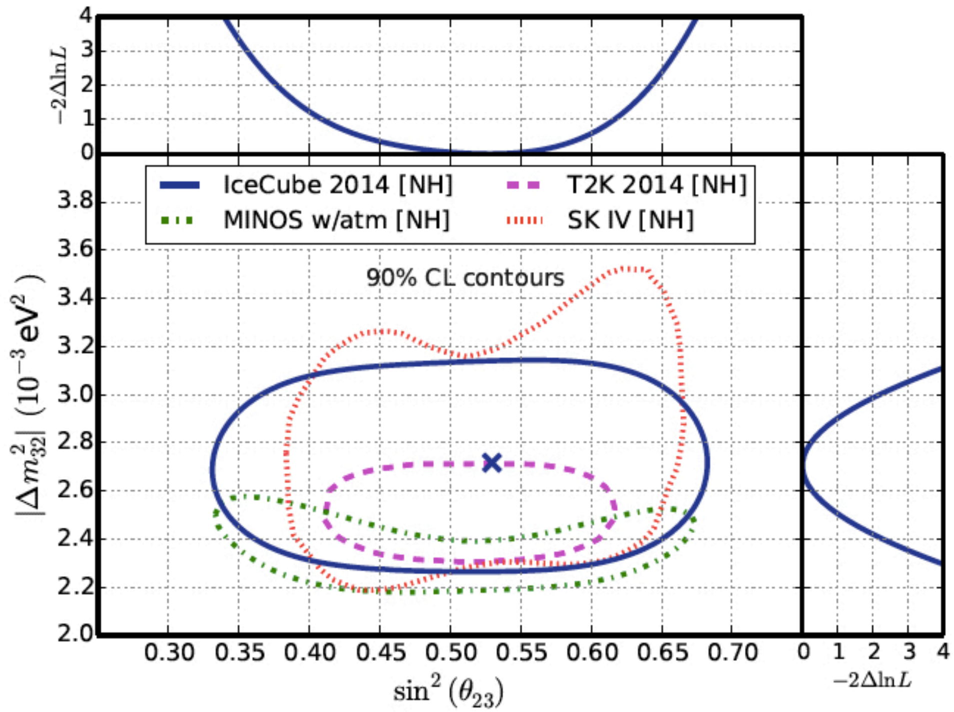


- Minimize the effects of scattering/absorption in ice by reconstructing tracks using "direct" (on-time) photons

IceCube Atmospheric ν Mixing

arXiv:1410.7227v2



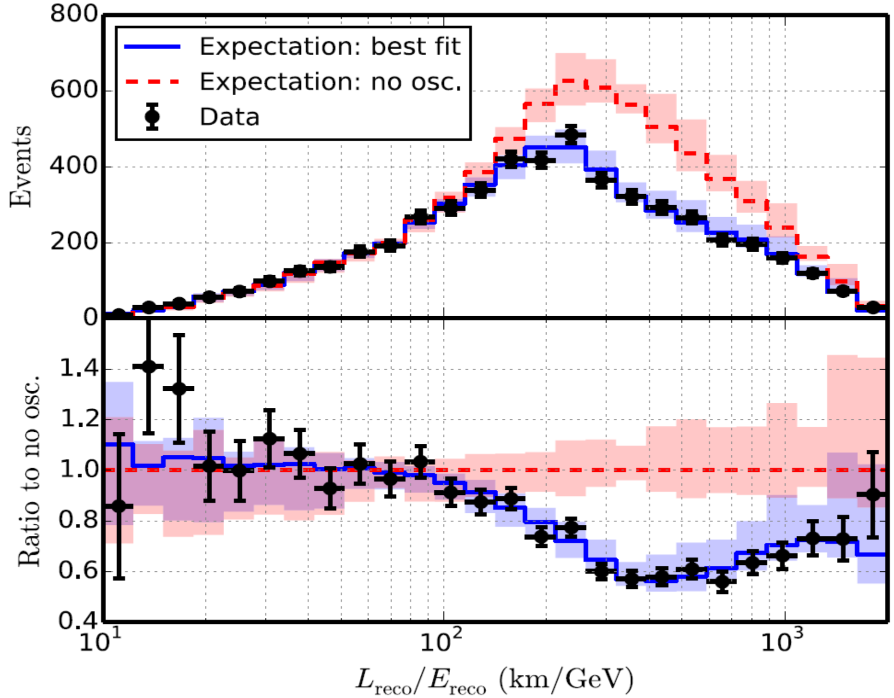


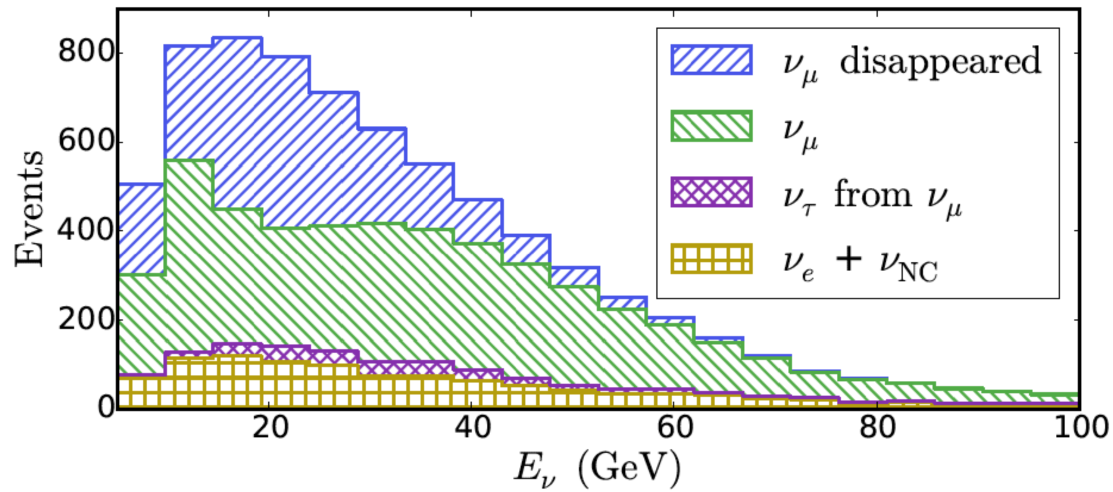
- Select clear muon tracks (no sign selection)
- Observe : 5174 events
- Without oscillations expect 6830

- “Atmospheric” oscillations are clearly seen using high threshold (10 GeV)

IceCube Atmospheric ν Mixing

arXiv:1410.7227v2

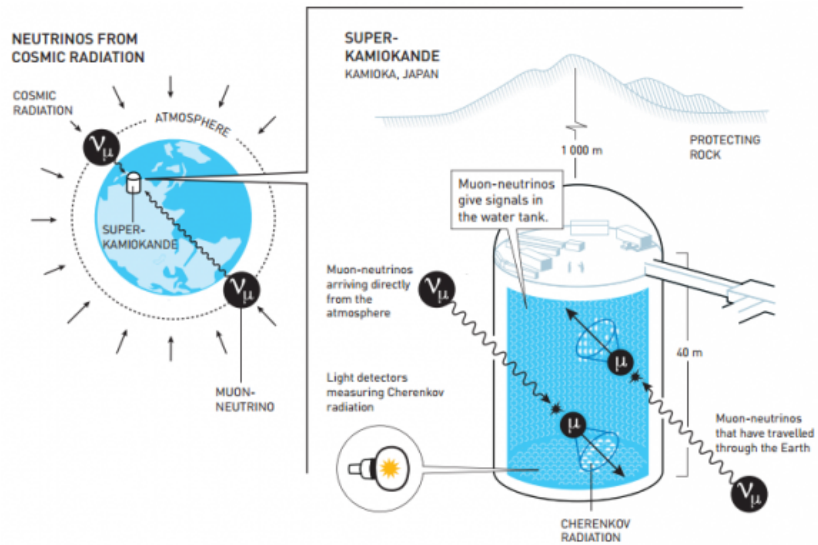




- Select clear muon tracks (no sign selection)
- Observe : 5174 events
- Without oscillations expect 6830

- “Atmospheric” oscillations are clearly seen using high threshold (10 GeV)

2015



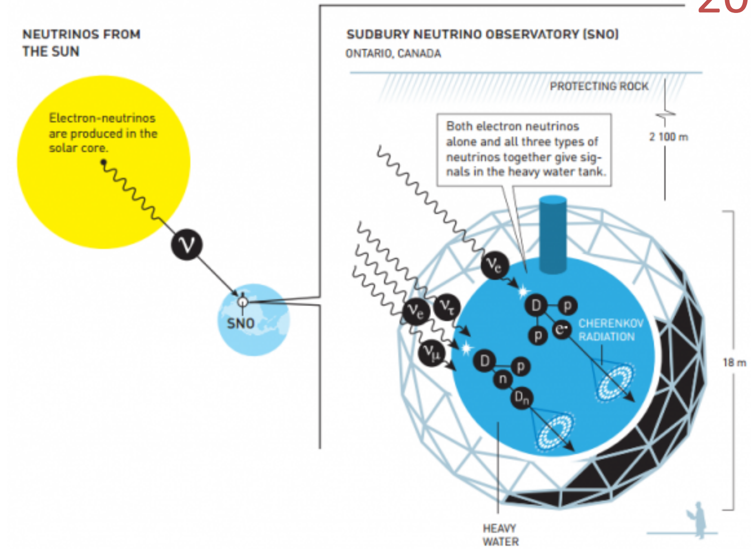


Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

Photo: A. Mahmoud

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Summary So Far

- Wide range of energies and pathlengths in the atmospheric neutrino flux make them a useful, but complicated tool

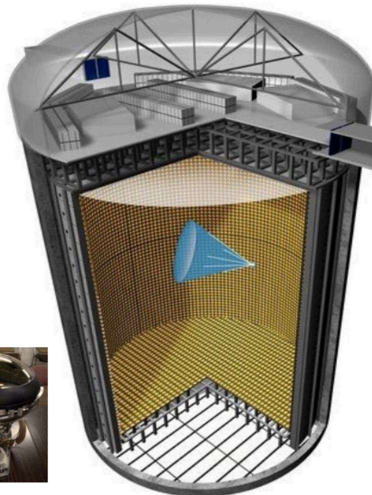
- Atmospheric neutrino measurements were the first place that oscillations were seen and since then oscillations, both atmospheric and man-made, have been seen in a variety of experiments

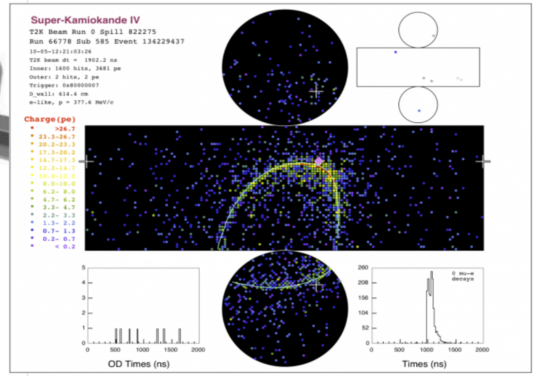
- The atmospheric neutrinos themselves have been used to verify that these oscillations are muon neutrinos into tau neutrinos
  - This has been verified (with better precision) in several experiments

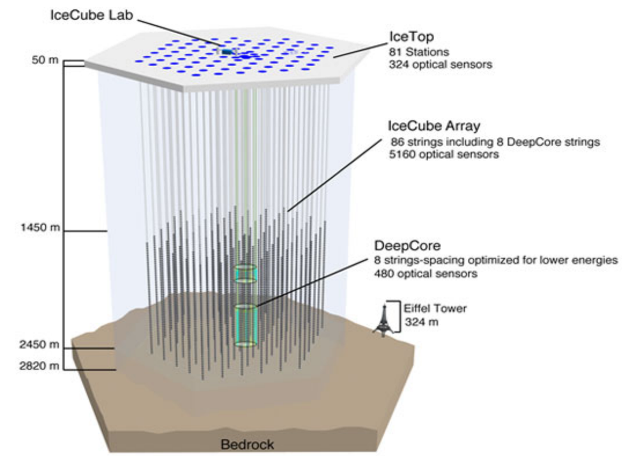
The Three Flavor Era

- Thanks to measurements of reactor neutrinos, θ_{13} is known to be non-zero and there is a connection between the ''solar'' and ''atmospheric'' mixing

Atmospheric Neutrino Experiments:







40m

ICECUBE

1 km

Super-Kamiokande	IceCube
50,000 Ton Ultrapure Water	1 km^3 of Antarctic *Ice*
11,000 20” PMTs (ID) 1885 8” (OD)	5100 Digital Optical Modules (DOM)
Ring-Imaging	“String” Imaging
40% Cathode Coverage	86 Strings, 17m / 7m DOM Spacing
0.1 ~ 10^3 GeV	10 ~ 10^5 GeV
Excellent e/μ PID, MIS PID 1%	Cascade (e/NC) and Track (μ)

Both are Cherenkov detectors without event-by-event $\nu/\bar{\nu}$ separation

Open Questions in Neutrino Physics

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

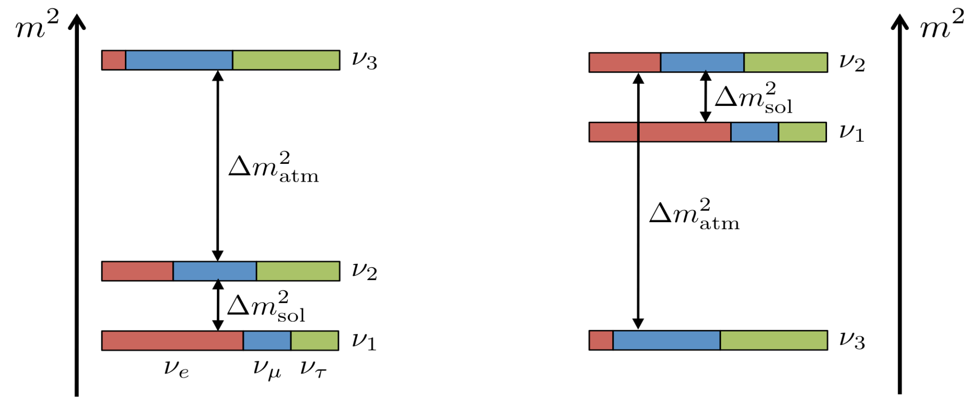
Atmospheric | Solar

- Three mixing angles, two independent mass differences (Δm^2_{21}, Δm^2_{32}), and a CP violating phase δ_{cp}

- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest
- However, several open questions remain
  - Neutrino Mass hierarchy

Mass Ordering is Unknown

normal hierarchy (NH) | **inverted hierarchy (IH)**



$\Delta m^2_{32} > 0$ | $\Delta m^2_{32} < 0$

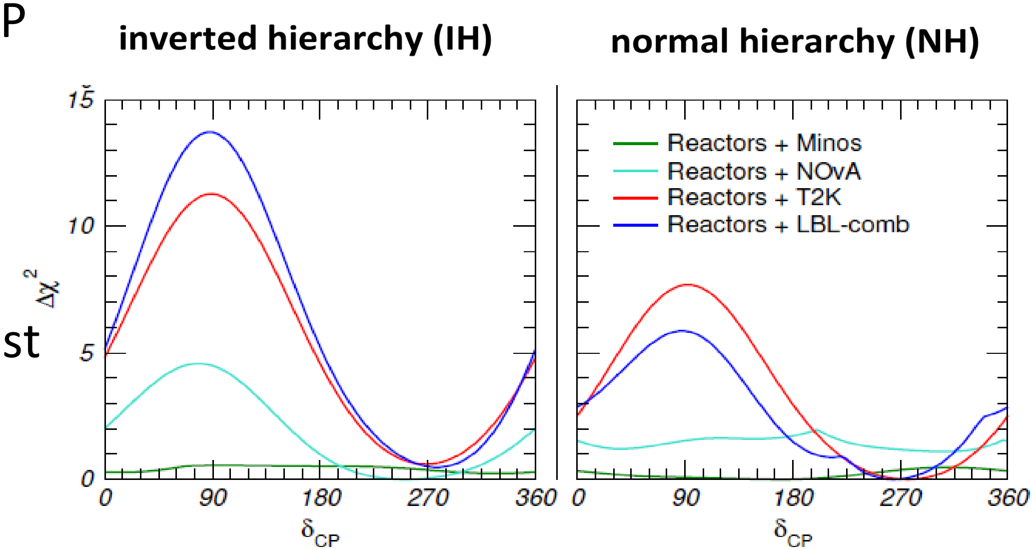
Open Questions in Neutrino Physics

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Solar

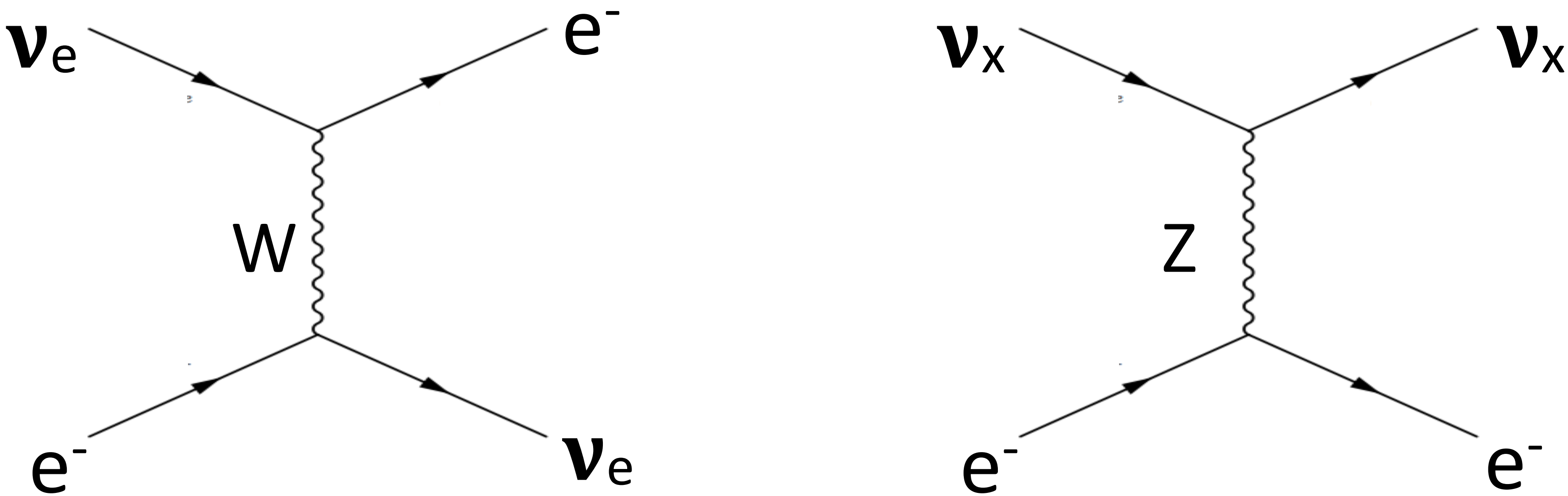
- Three mixing angles, two independent mass differences (Δm^2_{21} , Δm^2_{32}), and a CP violating phase δ_{cp}
- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest
- However, several open questions remain
  - Neutrino Mass hierarchy

Is CP Violated in Neutrino Mixing?



Esteban, I et al: 1611.01514

Matter Effects Matter



$$V_{cc}^{\nu_e} = \pm\sqrt{2}G_F N_e = \pm 7.56 \times 10^{-14}\left(\frac{\rho}{g/cm^3}\right) Y_e eV$$

G_F is Fermi Constant, N_e is electron density

$\boldsymbol{\rho}$ is matter density

Y_e is electron to nucleon ratio (≈0.5 in Earth)

+ for ν_e, - for $\bar{\nu}_e$

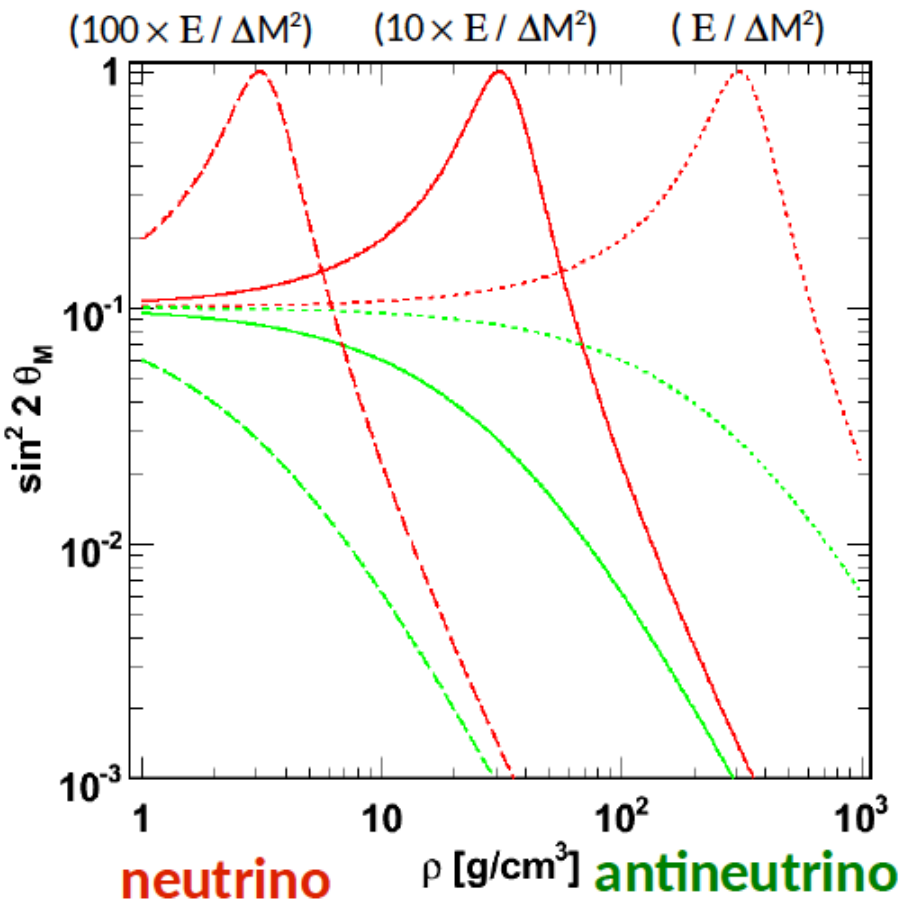
- Hamiltonian of neutrino passing through matter affected by coherent $\boldsymbol{\nu}_e$ CC scattering

Matter Effects Matter

$$P(\nu_e \to \nu_\alpha) = \frac{\sin^2 2\theta}{\sin^2 2\theta - (\pm\sqrt{2} G_F n_e E / \Delta m^2 - \cos 2\theta)^2} \sin^2\left(\frac{1.27 \Delta M^2 L}{E}\right)$$

neutrino (+)
antineutrino (-)

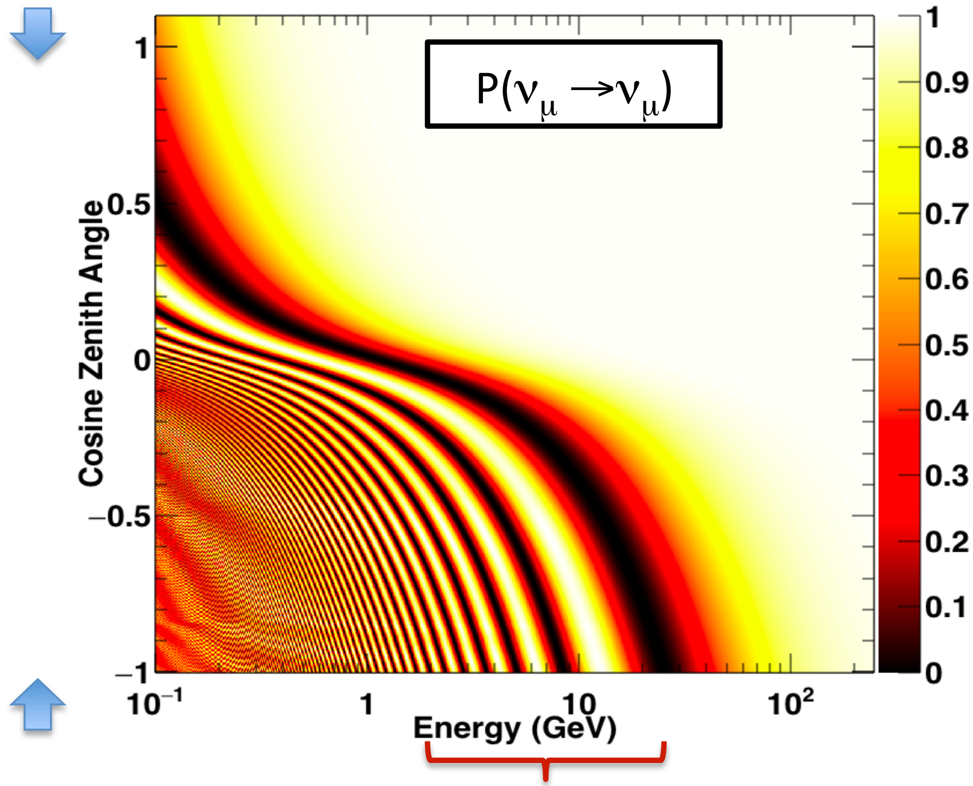
Sign of Δm^2 matters
Ie, hierarchy

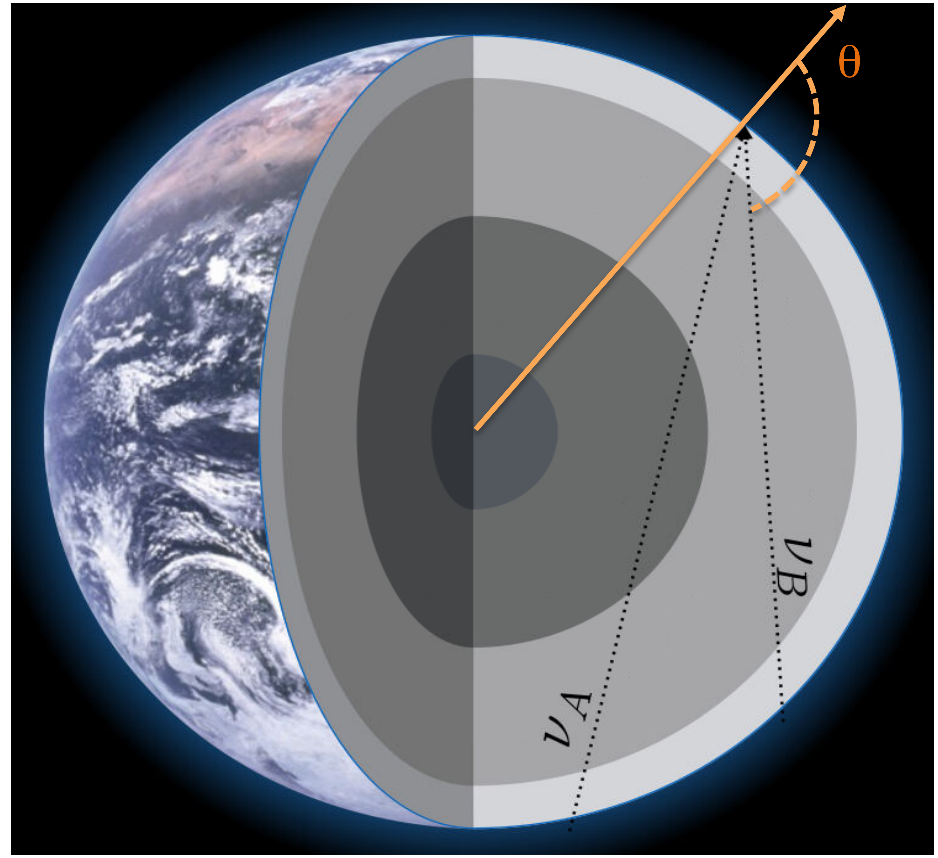


- Additional matter potential gives rise to resonantly enhanced oscillations
- Resonance is for either neutrinos or antineutrinos – not both!
- Depends on the sign of the mass hierarchy
  - Look for this resonance to determine the mass hierarchy!

Mass Hierarchy Determination: Matter-Effects

Normal Hierarchy

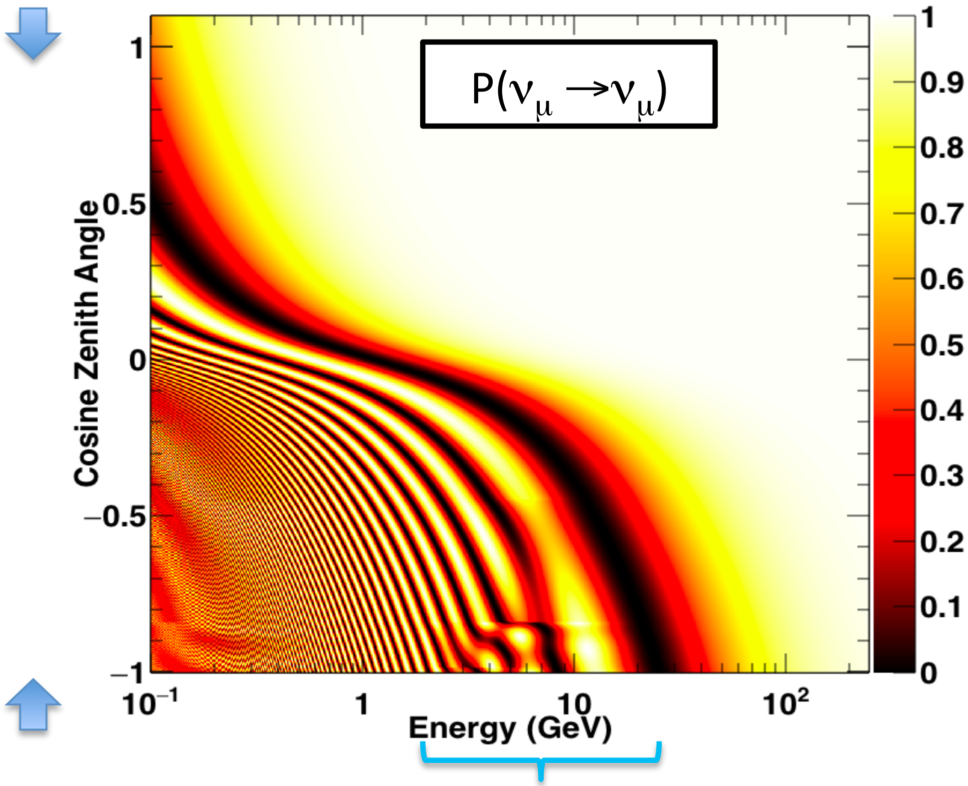




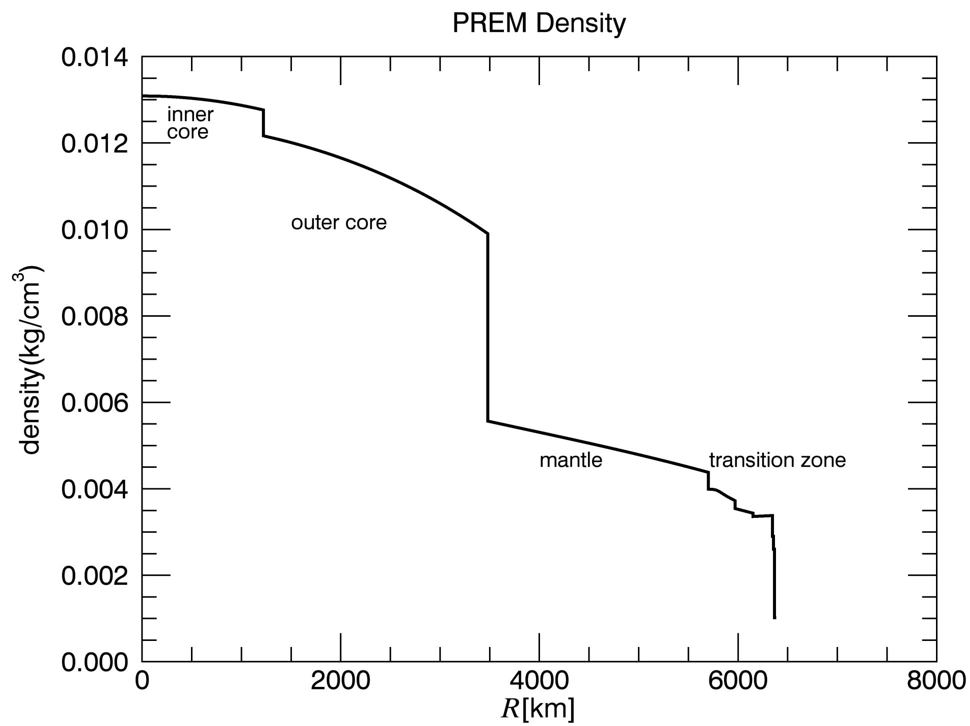
- Presence of electrons (as opposed to muons) induces asymmetric oscillations between electron-type neutrinos and antineutrinos

Mass Hierarchy Determination: Matter-Effects

Normal Hierarchy



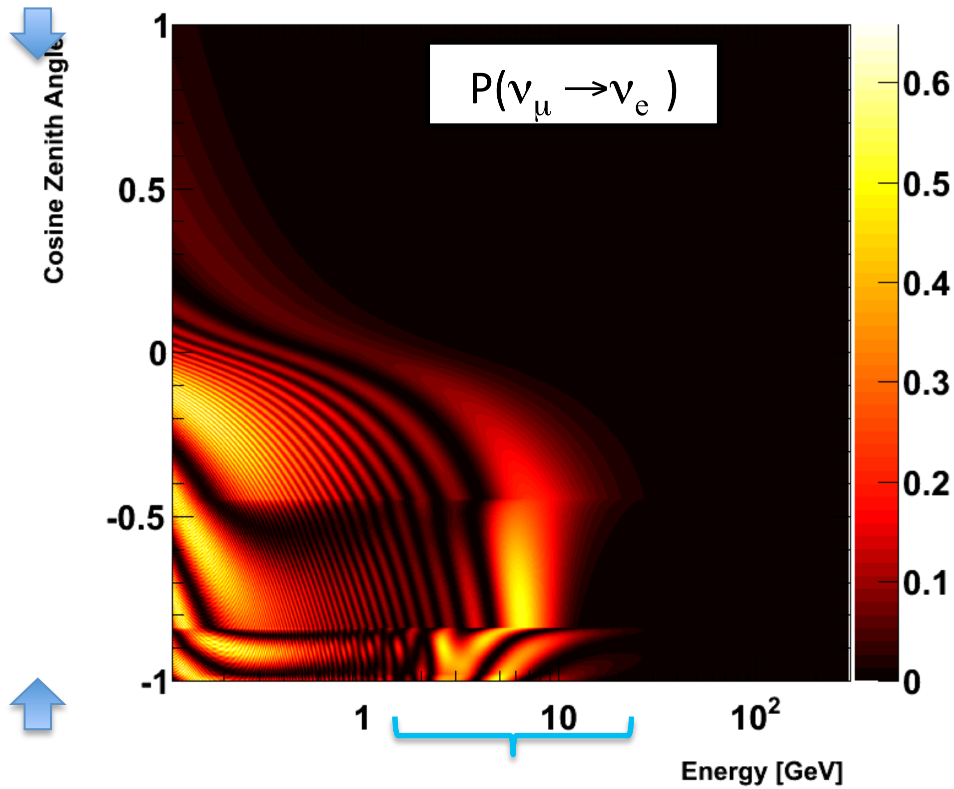
Astrophys.J. 814 (2015) no.2, 122



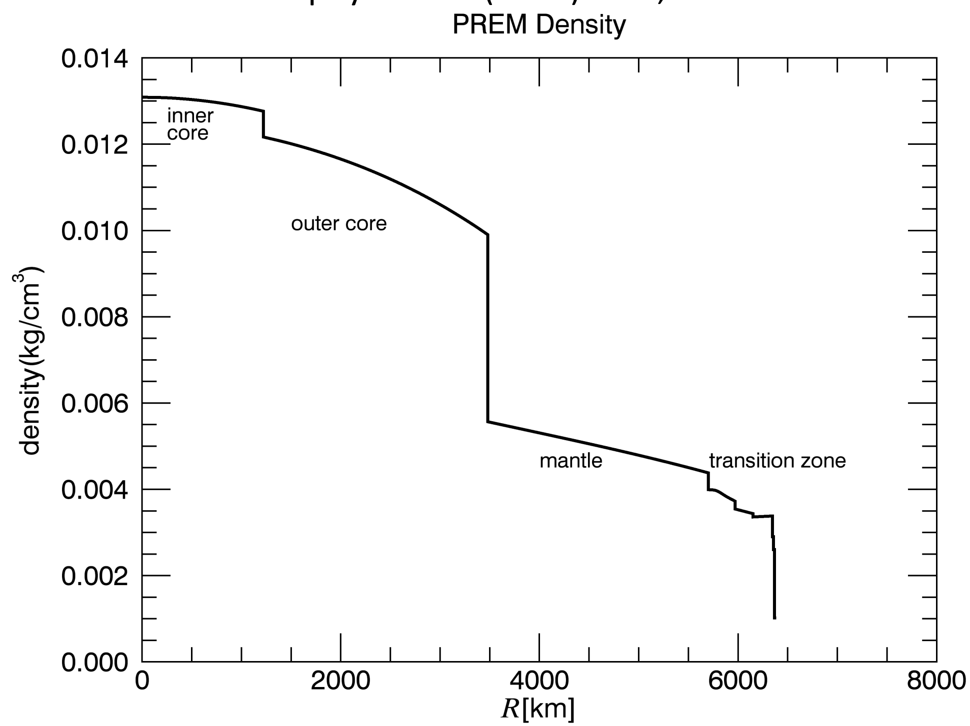
- Expect slightly *more* muon neutrino disappearance for neutrinos travelling through the core of the earth

Mass Hierarchy Determination: Matter-Effects

Normal Hierarchy



Astrophys.J. 814 (2015) no.2, 122

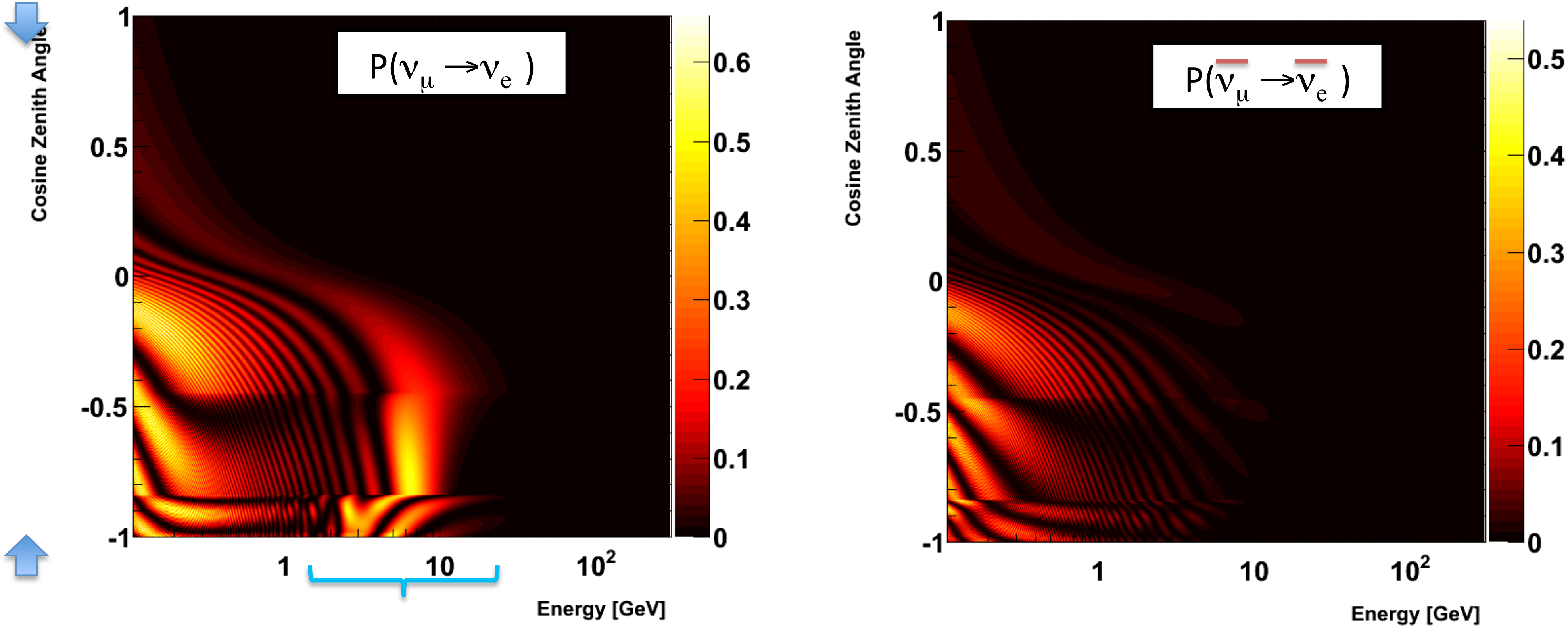


- Resonance effects are expected to enhance the number of upward-going electron neutrinos

- Size of the effect depends on θ_{13}, which has been measured precisely by reactor experiments

Mass Hierarchy Determination: Matter-Effects

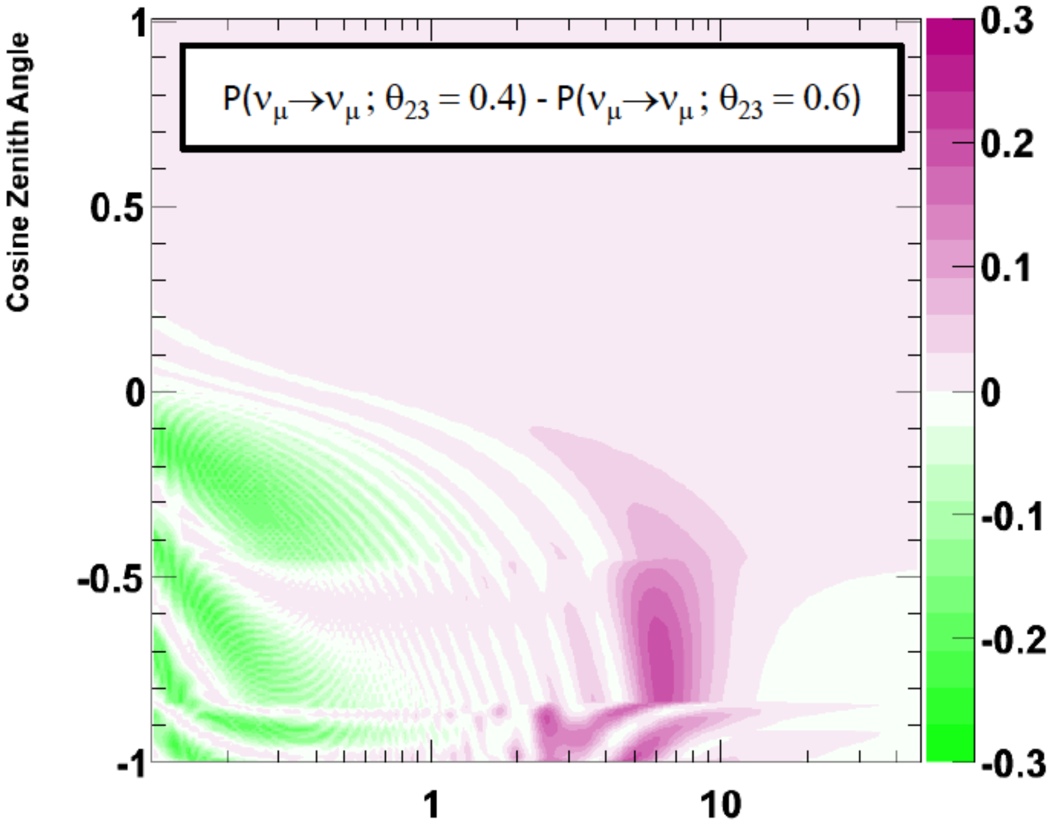
Normal Hierarchy

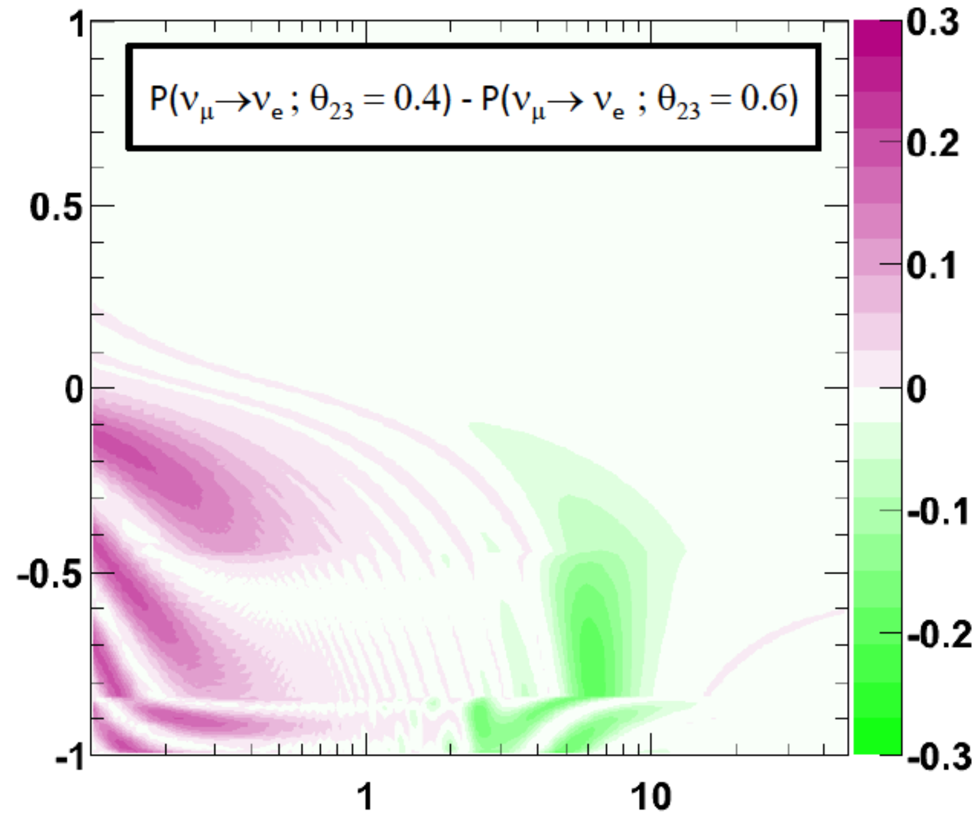


- Resonance effects are expected to enhance the number of upward-going electron neutrinos
- Enhancement expected for antineutrinos if the hierarchy is *inverted*

- *Muon nuetrinos also sensitive (ICAL-INO)*

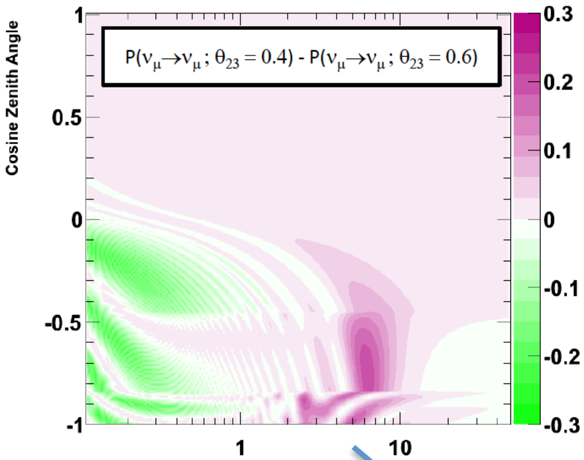
P(1st Octant) - P(2nd Octant)

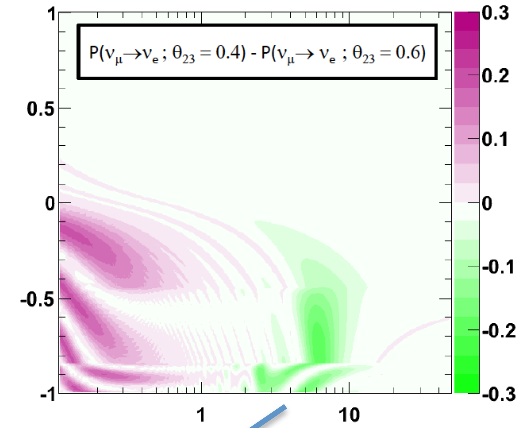


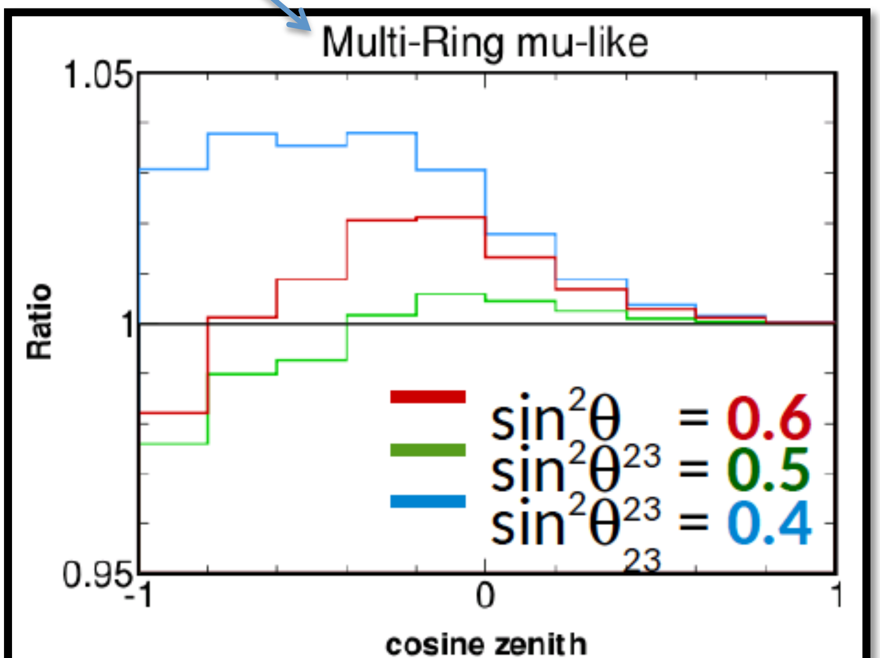


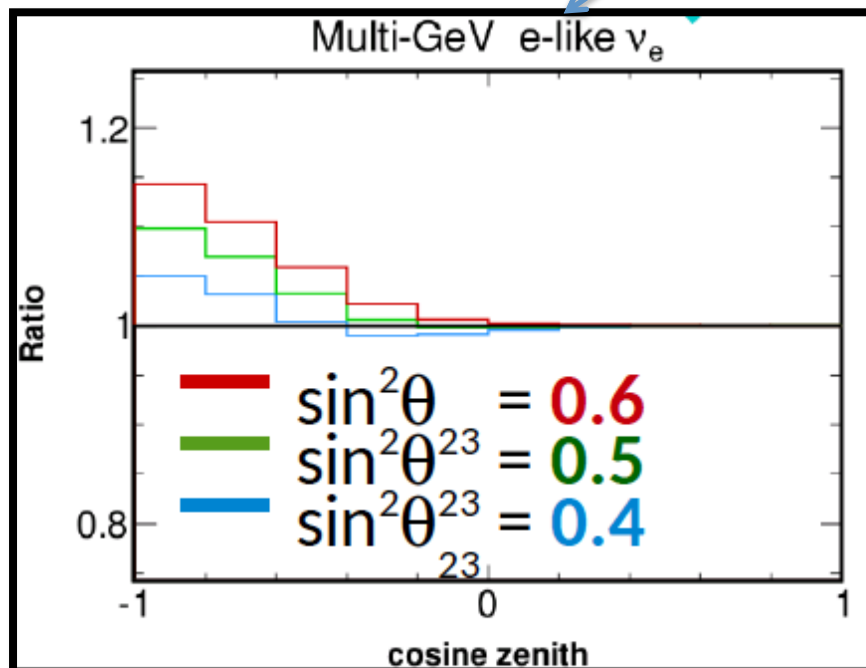
$\sin^2\theta_{23}$ = 0.4 vs 0.6	$P(\nu_\mu \to \nu_\mu)$	$P(\nu_\mu \to \nu_e)$
E ~ Sub-GeV	More disappearance	More appearance
E ~ **Multi**-GeV	Less disappearance	Less appearance

P(1st Octant) - P(2nd Octant)

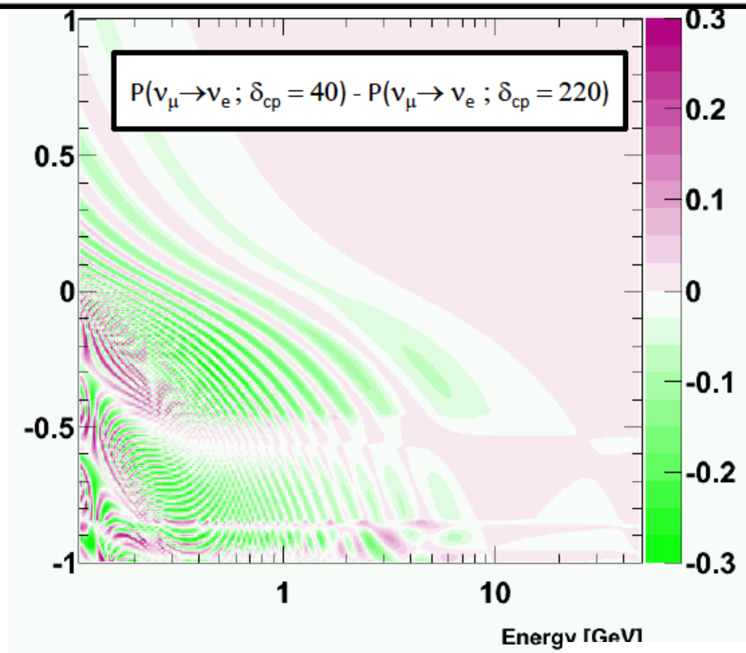


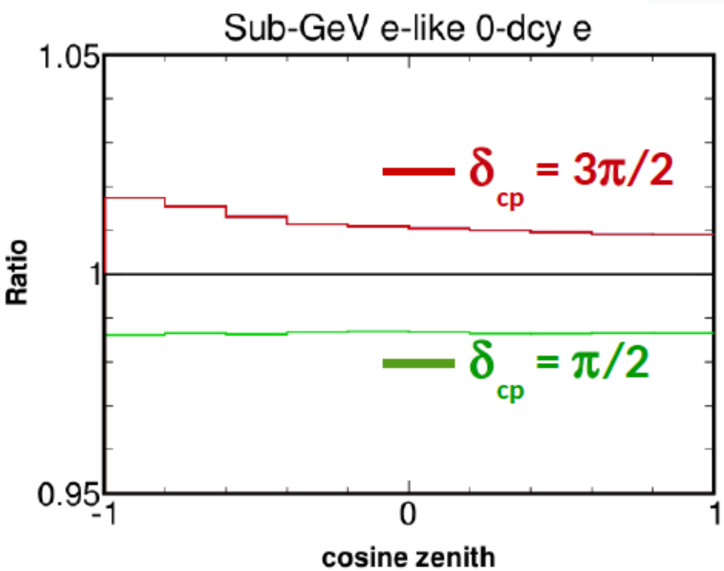


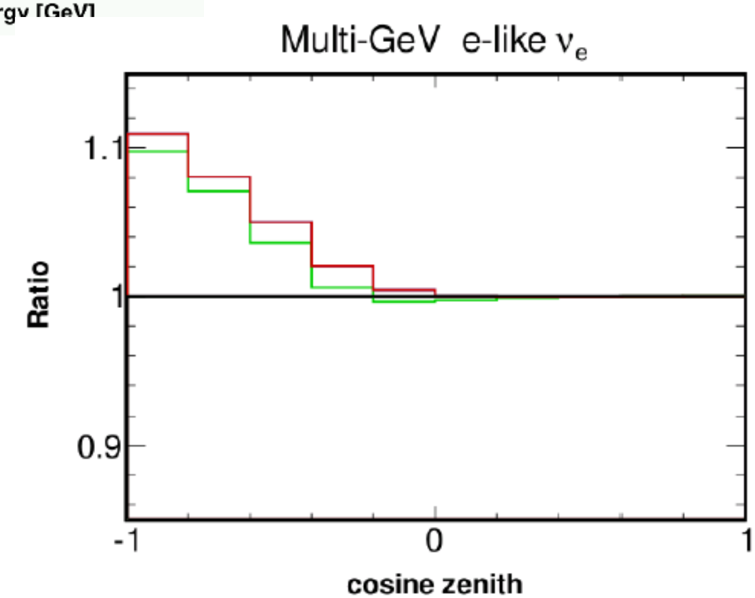




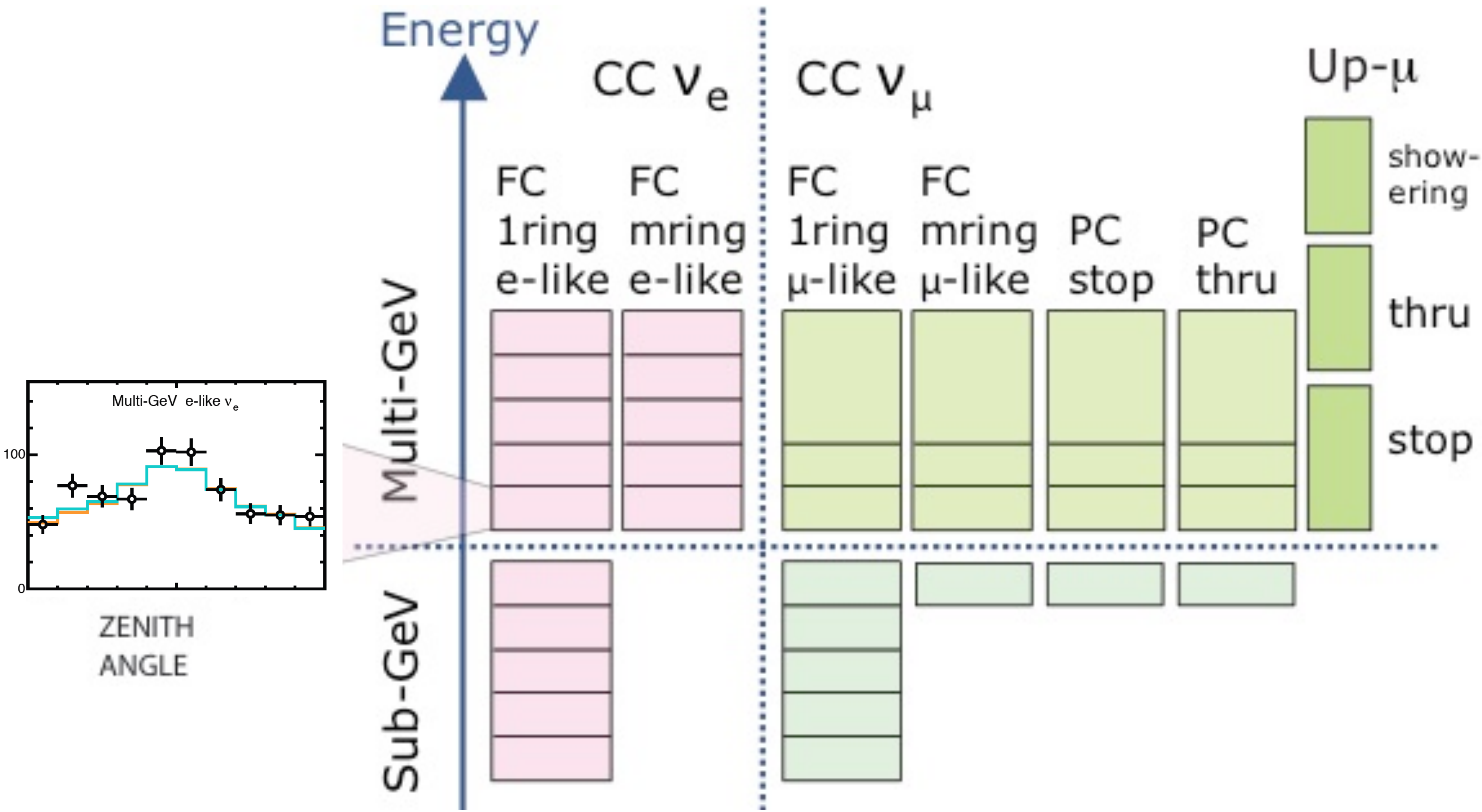
P(40 degrees) - P(220 degrees)



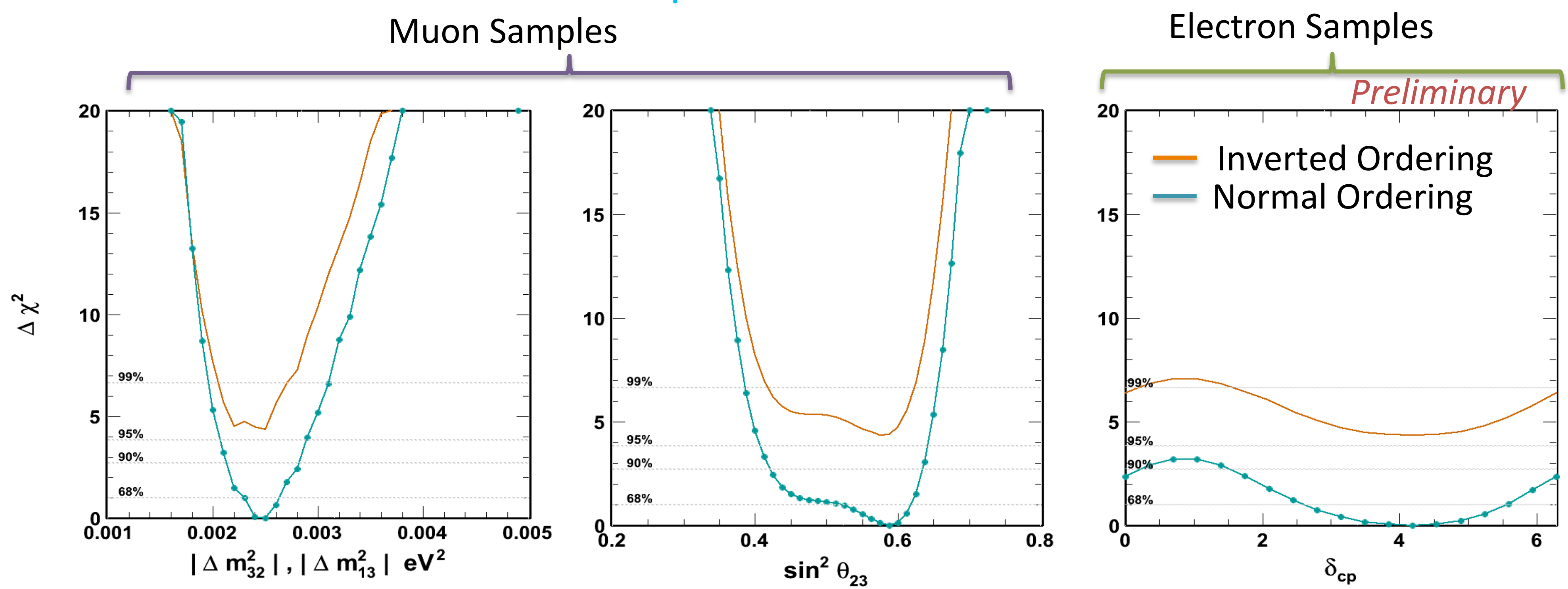




Super-Kamiokande Analysis Samples



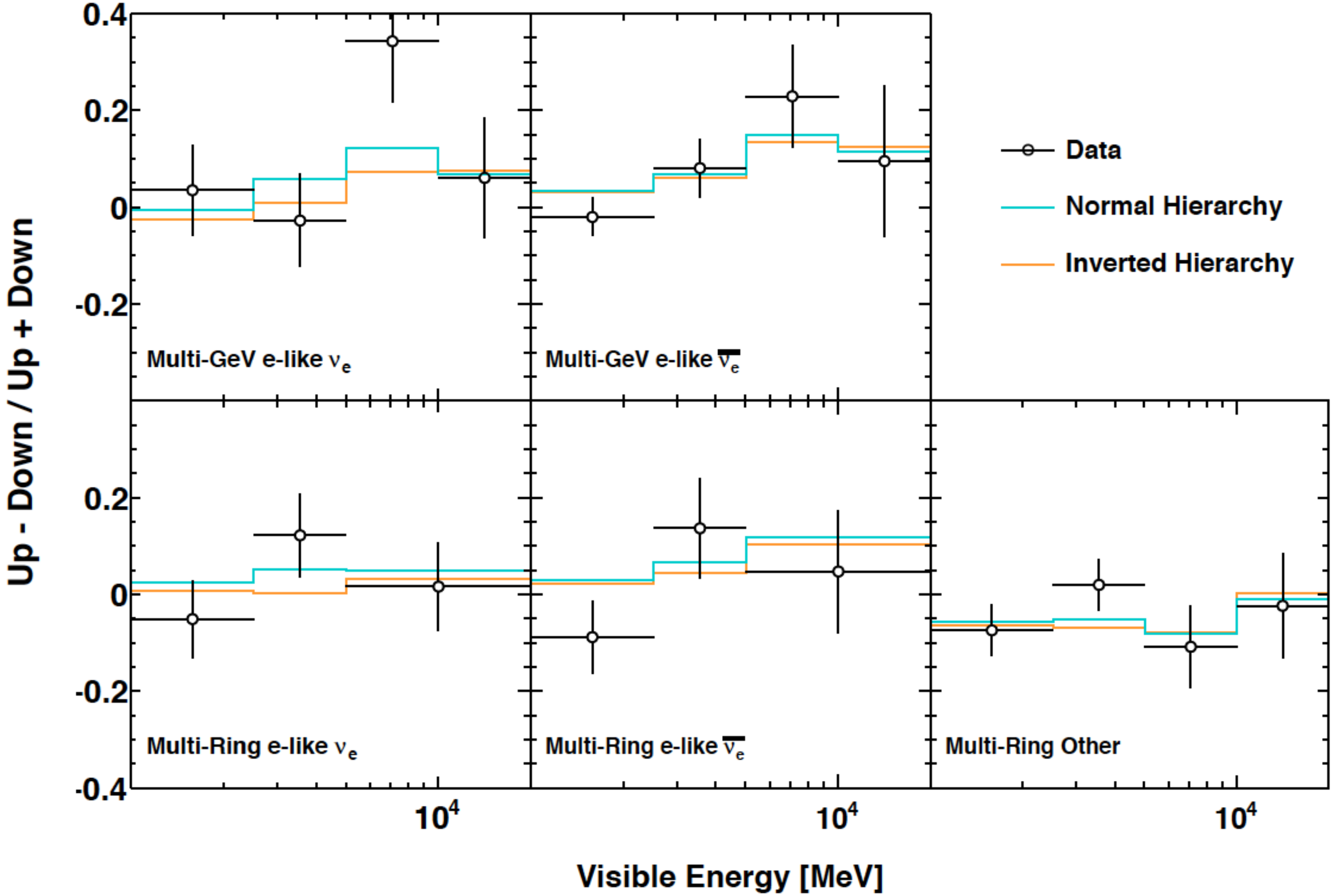
Atmospheric Mixing + δ_{cp}: Super-Kamiokande



- Comparatively weak constraint on atmospheric mixing
- Observe an excess of upward-going electron neutrino events weakly favoring the *normal hierarchy*
  - $\Delta\chi^2$ (NH – IH) = -4.3
  - P(NH|IH) : 3.1%
- Weak hint for δ_{cp} ~1.33π

Signature of the Mass hieararchy

Preliminary



- Some indication of expected upward-going electron neutrino appearance, but not conclusive

Summary So Far

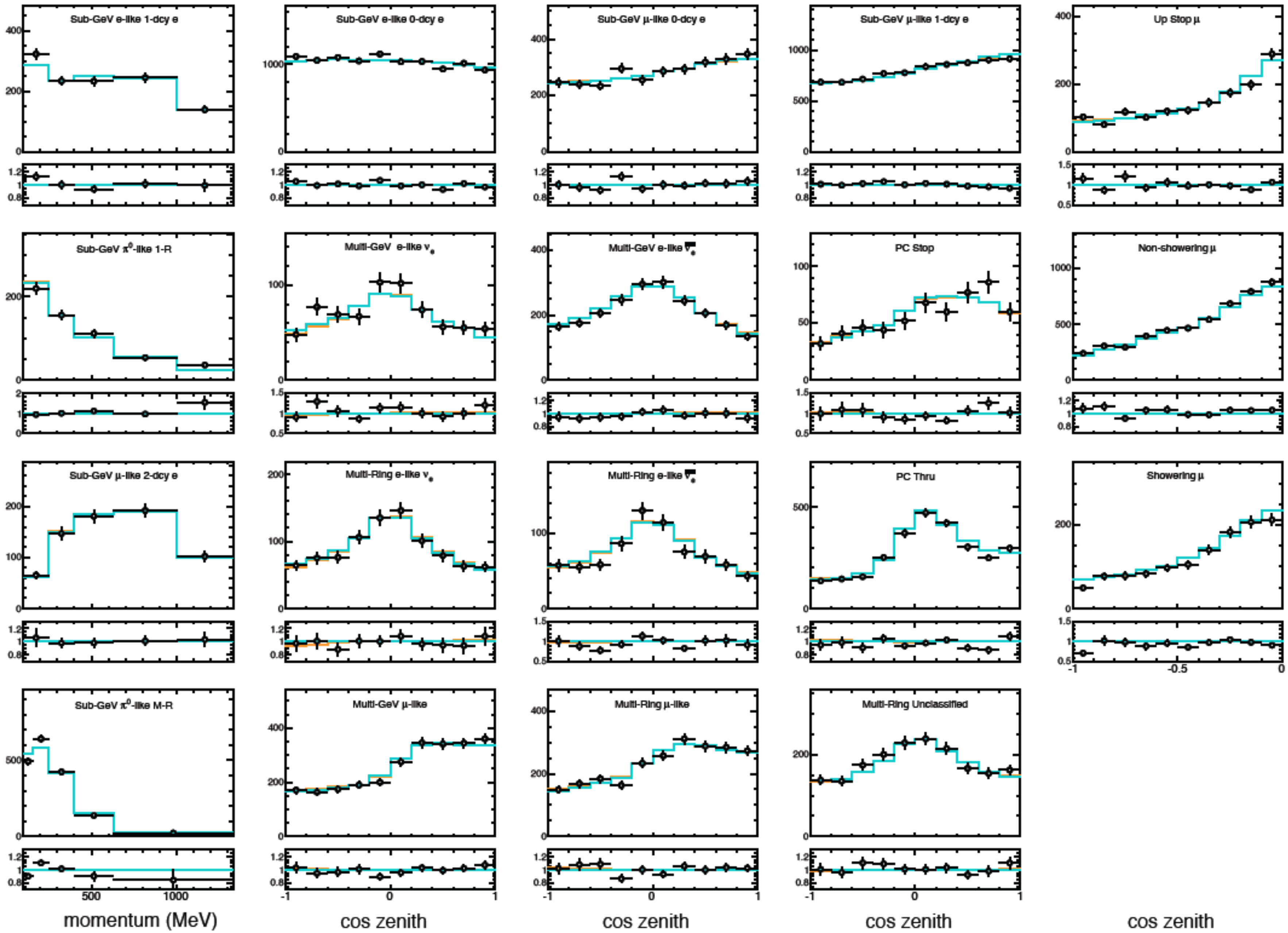
- Wide range of energies and pathlengths in the atmospheric neutrino flux make them a useful, but complicated tool

- Atmospheric neutrino measurements were the first place that oscillations were seen and since then oscillations, both atmospheric and man-made, have been seen in a variety of experiments

- The atmospheric neutrinos themselves have been used to verify that these oscillations are muon neutrinos into tau neutrinos
  - This has been verified (with better precision) in several experiments

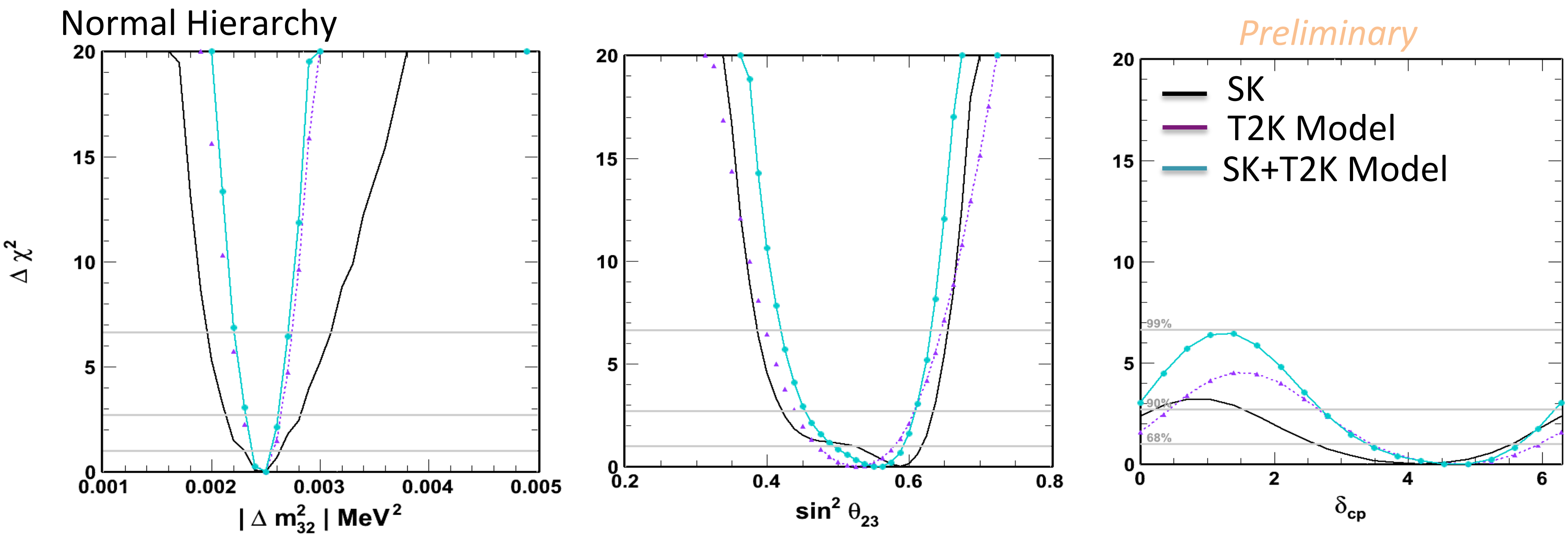
- Matter effects and a non-zero q13 allow for studies of the neutrino mass hierarchy and δ_{cp} with these neutrinos

Zenith Angle Distributions



Supplements

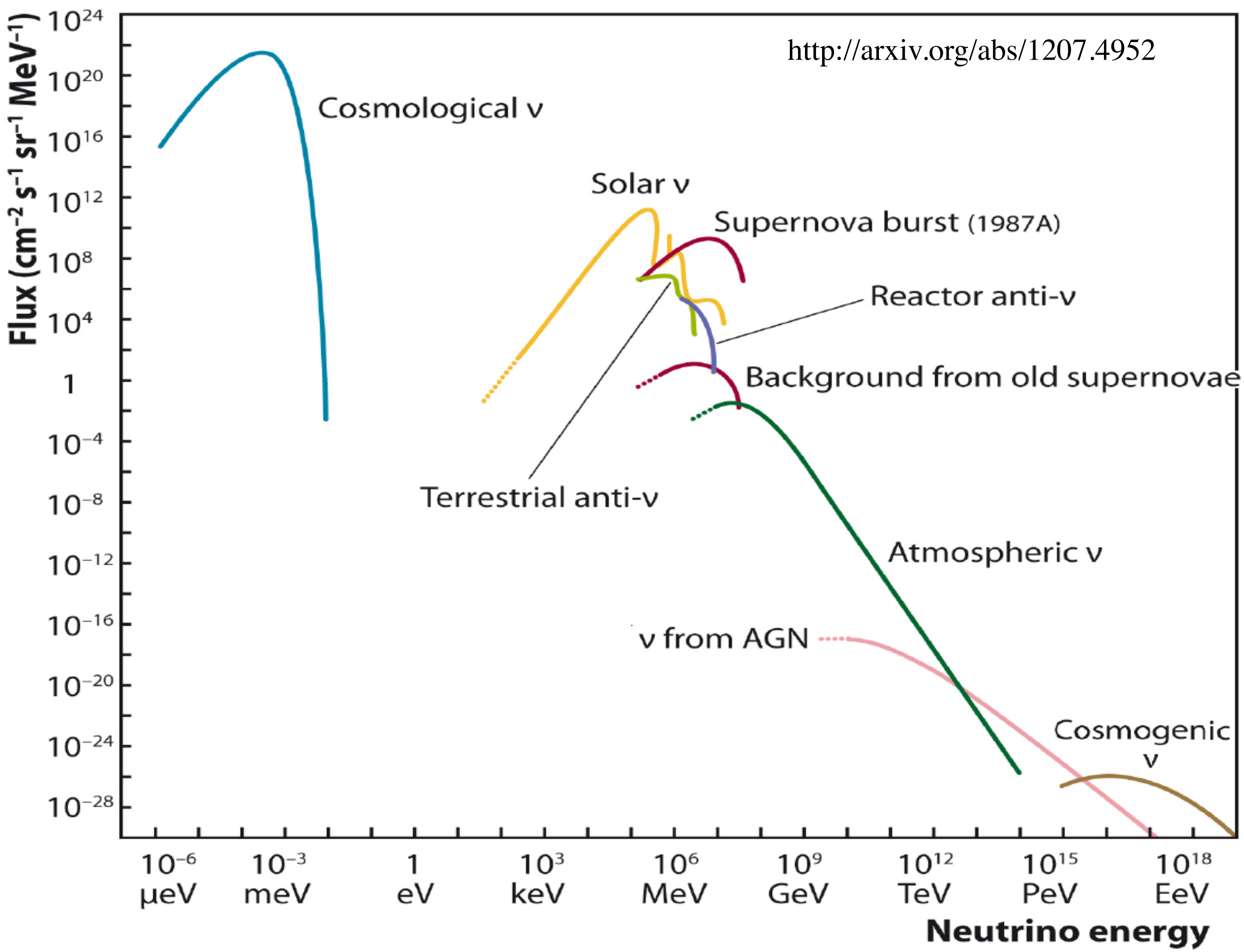
Into the Future: Combining T2K-SK?



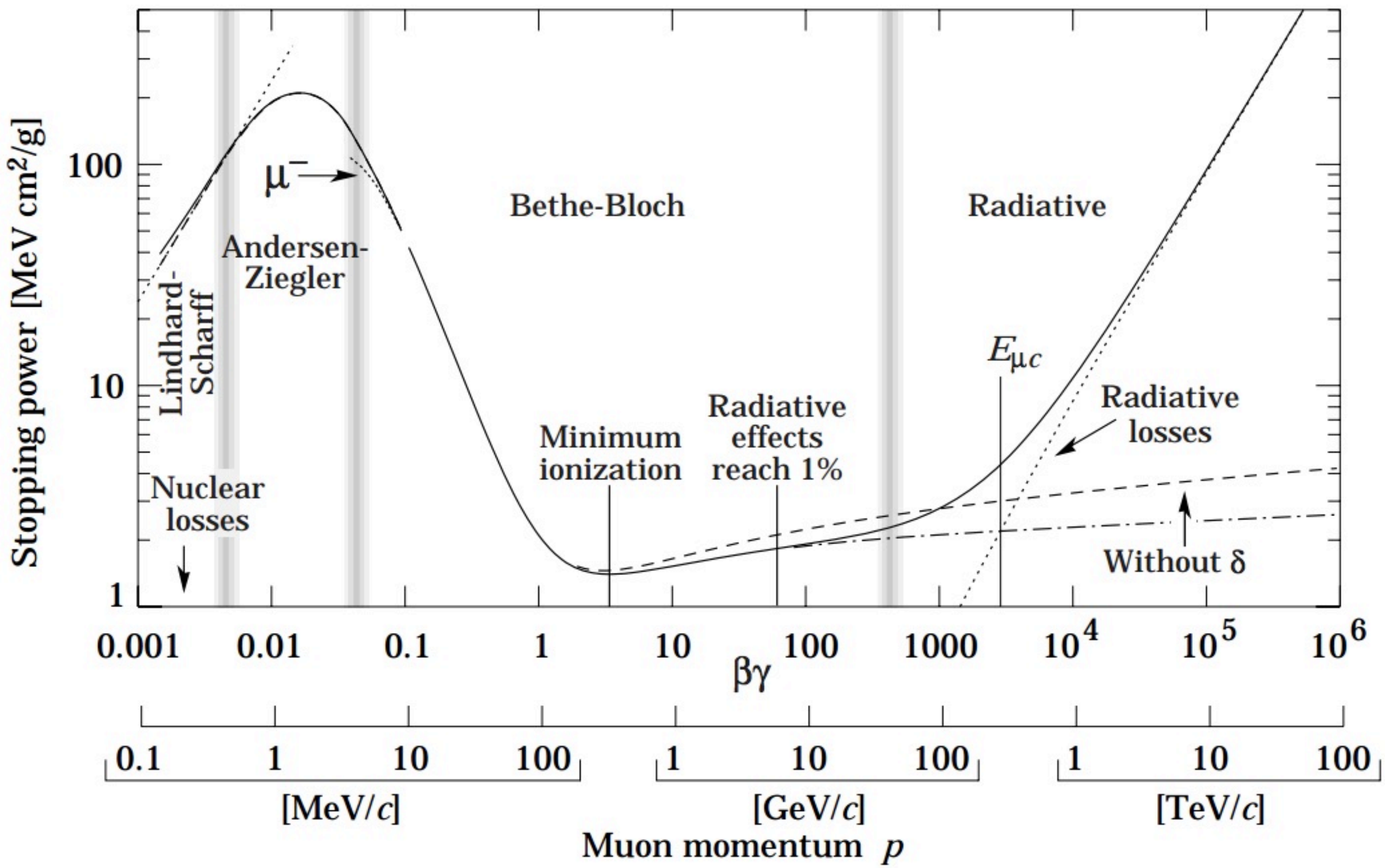
- Super-K collaboration has used *publicly available* information to model and fit the T2K experiment together with atmospheric neutrinos
- Atmospheric mixing constraint improves NH preference
  - $\Delta\chi^2$ (NH − IH) = -5.1 (-4.3 SK Only)
  - P(NH|IH) : 2.7%

- Better constraint with correlated systematics between experiments: future?!
- T2K + NOνA combination also in discussion

Sources of Neutrinos



A Sense of Scales

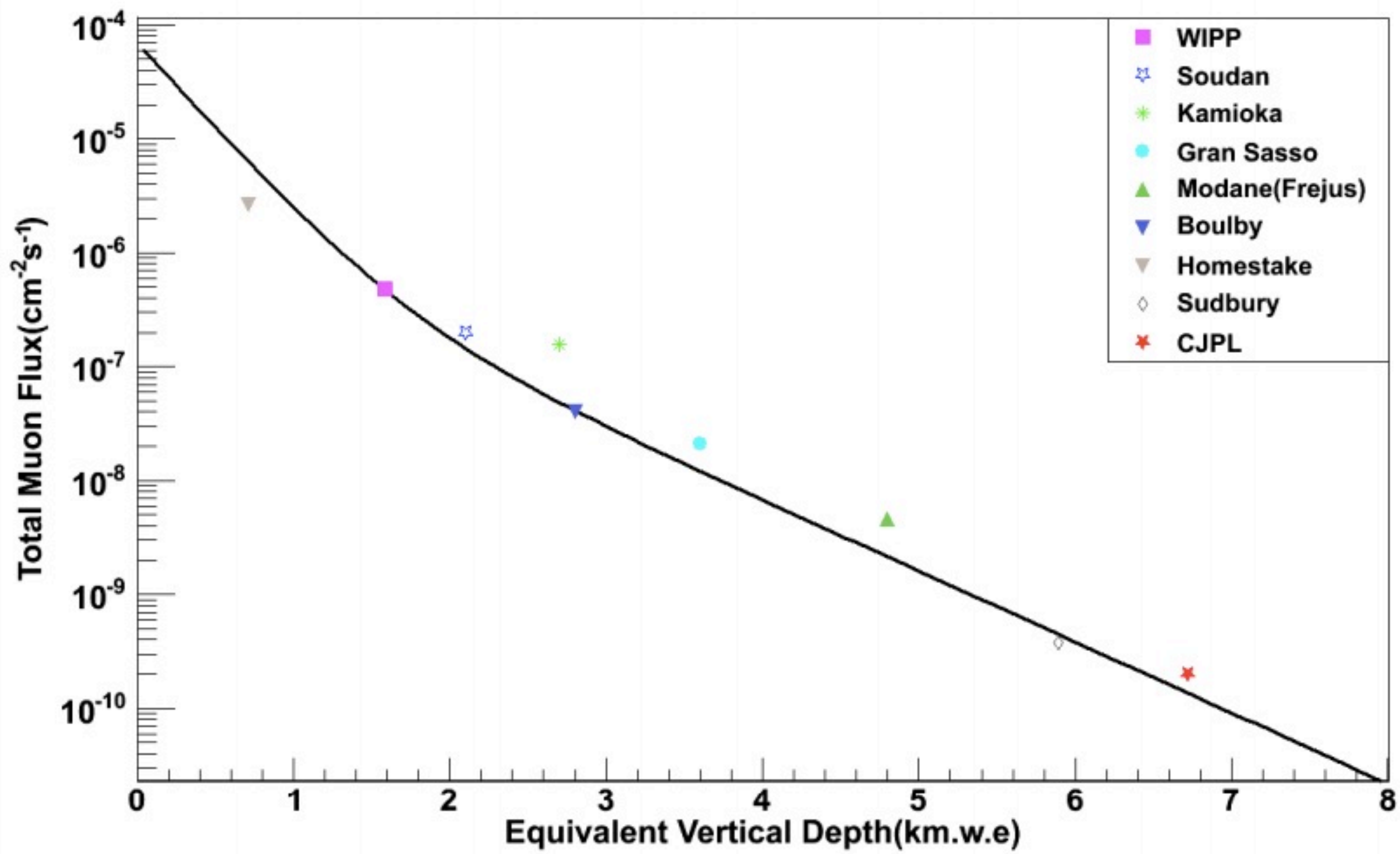


$\langle -dE/dx \rangle_{min}$ 1.688 MeV cm^2/g in “Standard Rock”

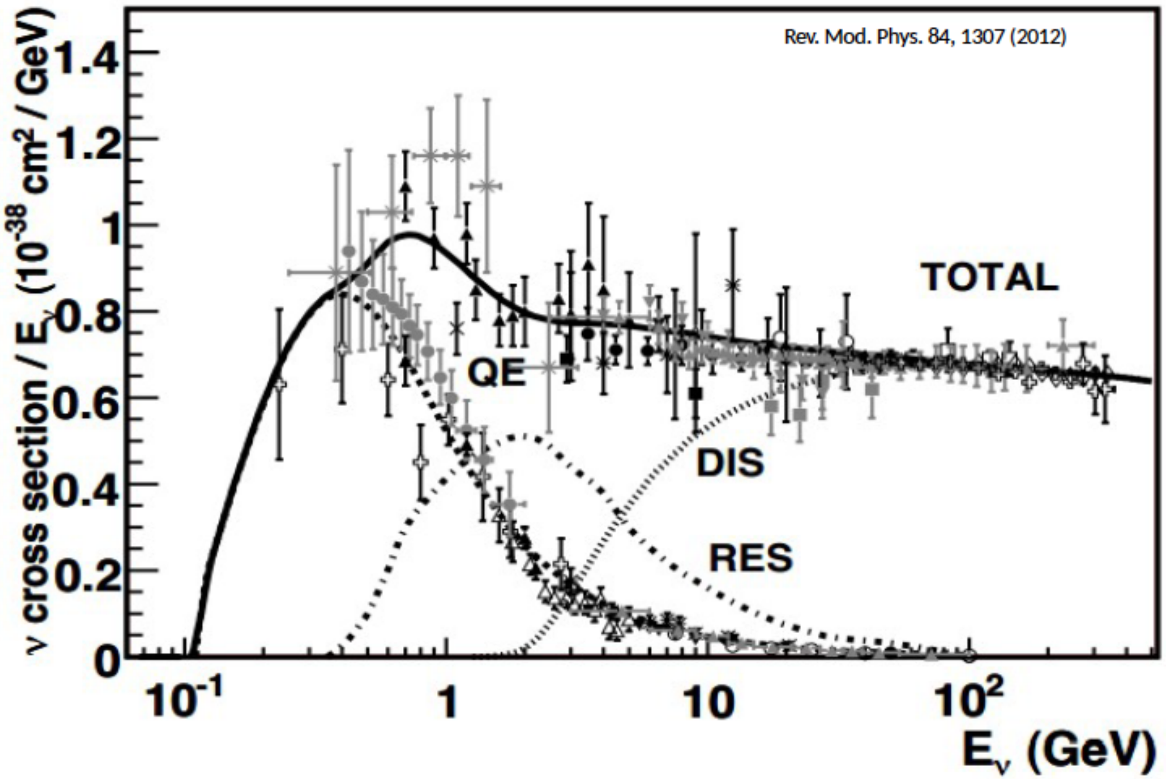
100 GeV μ travels O(1~km)

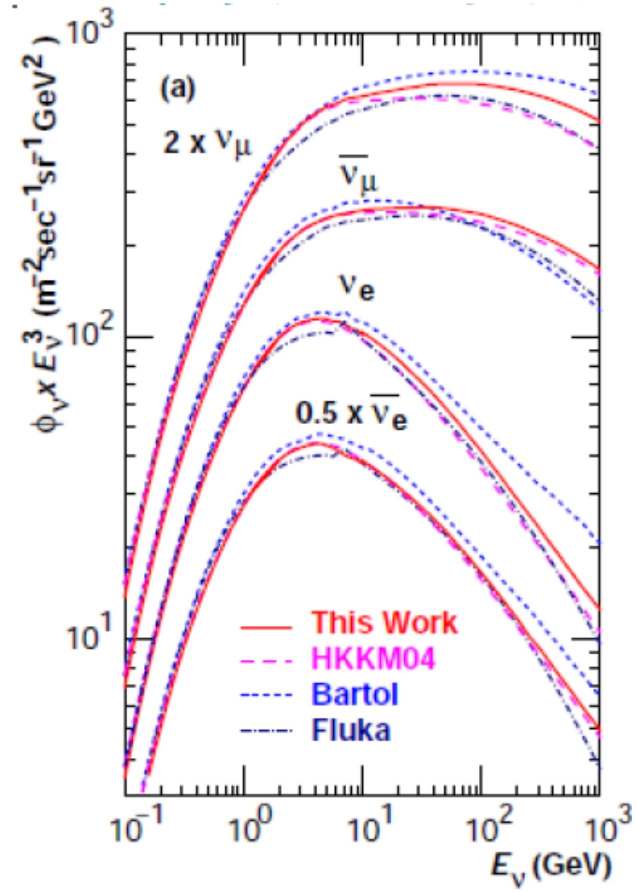
How do we know it's a neutrino

https://arxiv.org/pdf/1305.0899.pdf



How Many Atmospheric Neutrinos Are Expected

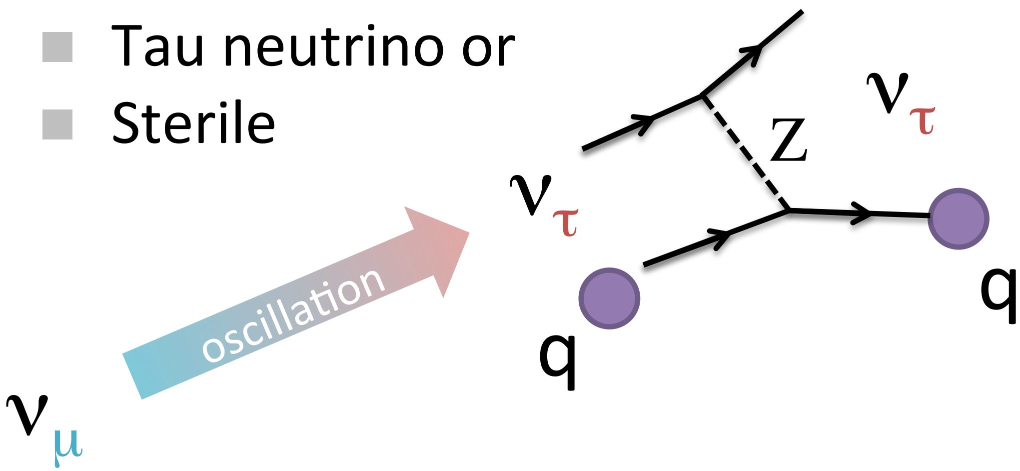


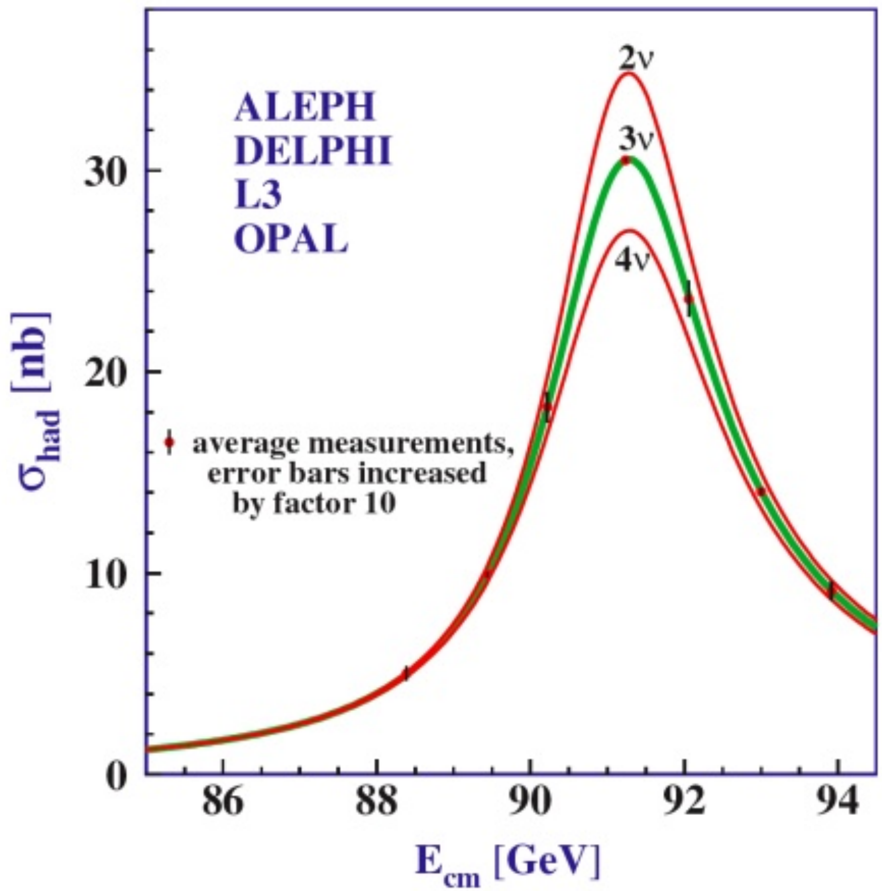


- IMB has diagonal length of 33m
- Kamioka is about 22m
- Most energetic muon that can be reconstructed is about 4 – 5 GeV
- F ϕ - $E_\nu^{-3.7}$
- Expect about 0.5 ν/kton/day
- $\sigma_{tot} \sim E_\nu$, 10^{-38} cm^2 at 1 GeV

Sterile Oscillations

- Muon neutrinos have oscillated into something
- Either
  - Tau neutrino or
  - Sterile

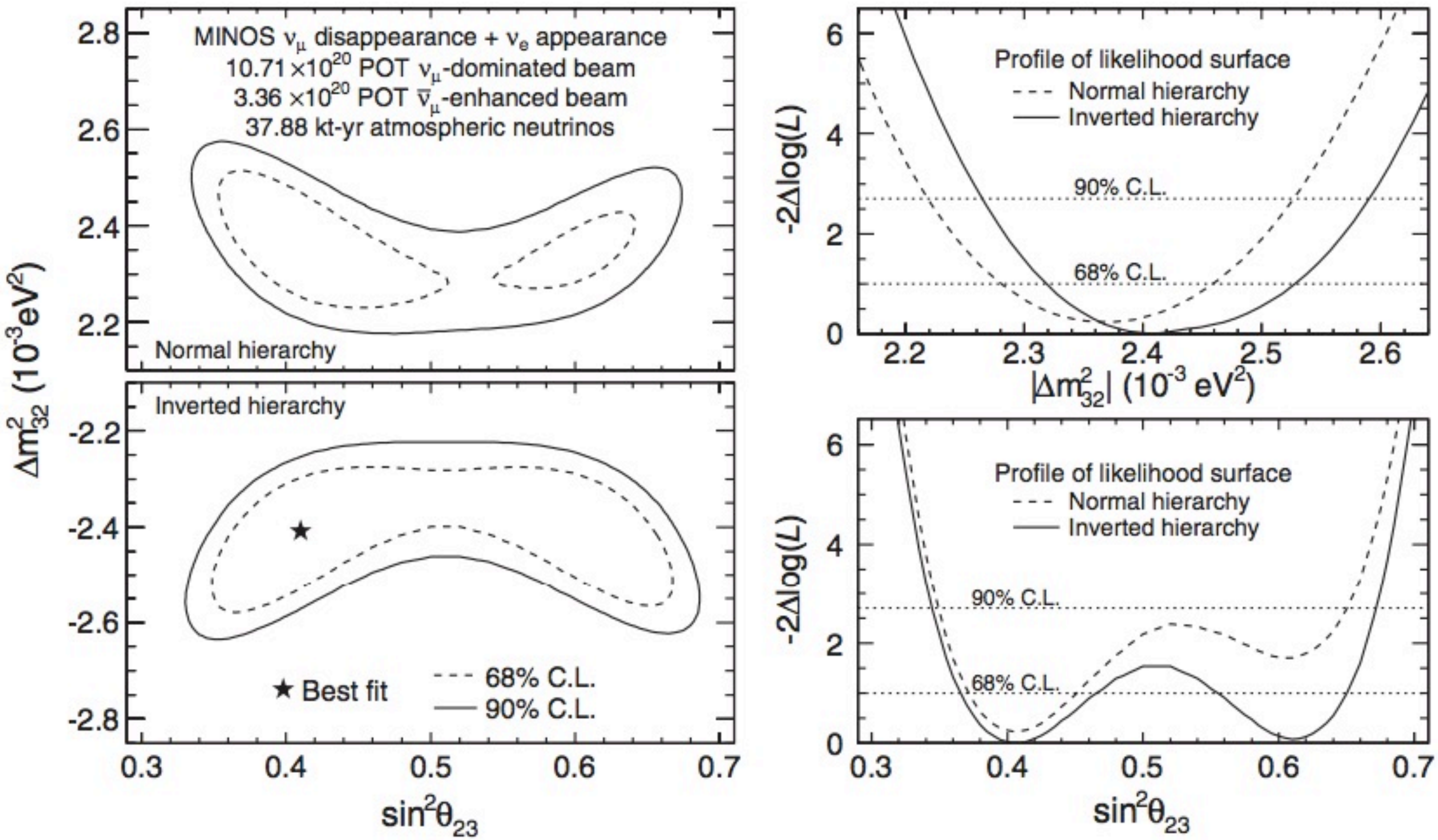




- Sterile neutrino will not participate in weak interactions

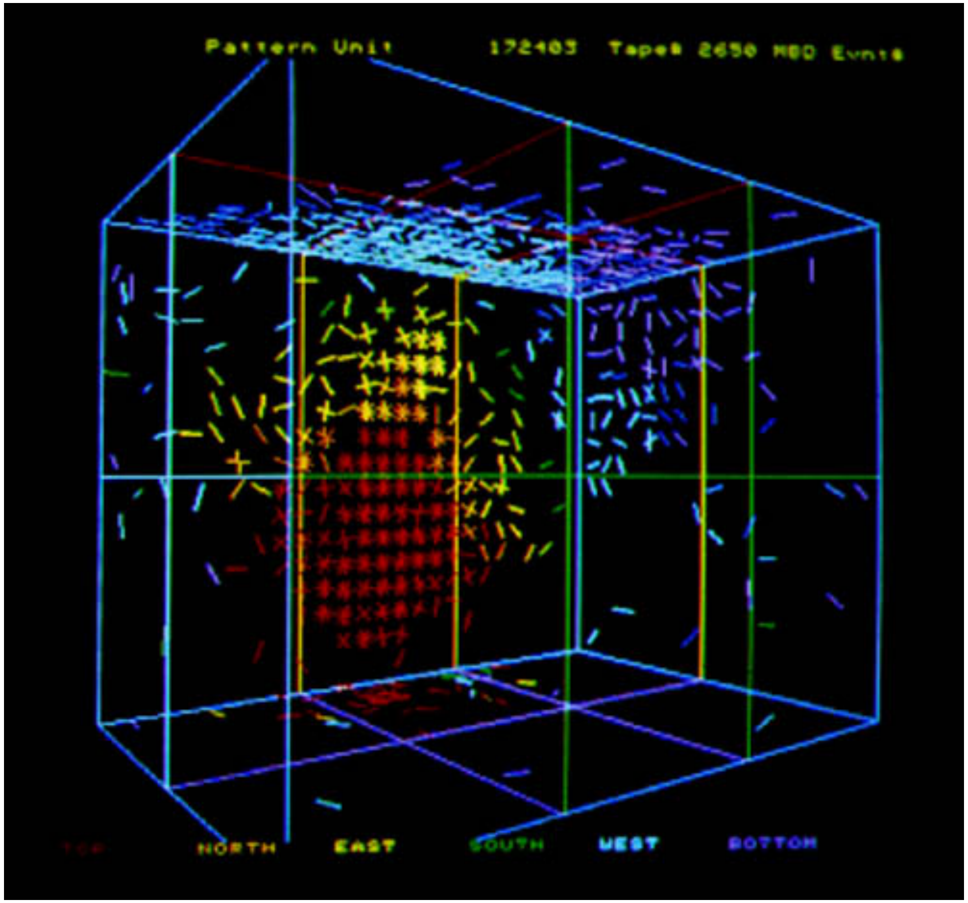
MINOS Combined Beam and Atmospheric ν Measurement

PRL 112, 191801 (2014)



- First experiment to combine atmospheric and beam neutrino data
- Improves hierarchy sensitivity (more later)
  - This result weakly favors the inverted hierarchy

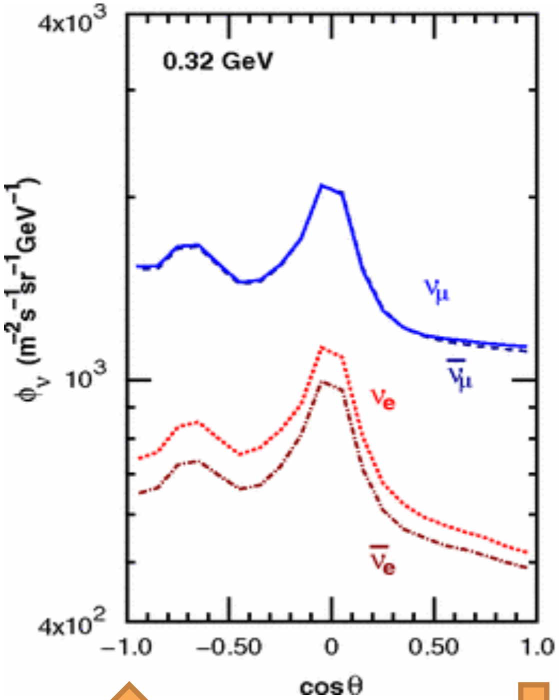
Example Event From the IMB Experiment



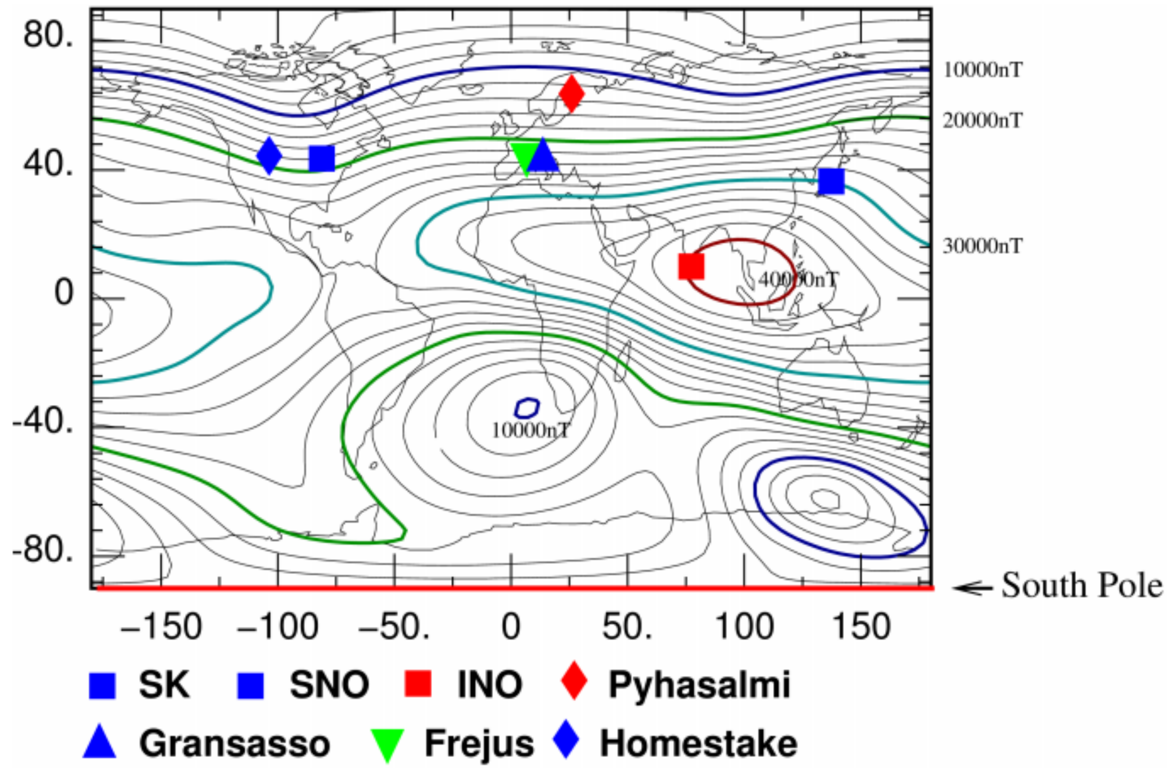
- Each colored mark represents a hit PMT
- The color indicates the hit timing
  - Red: early
  - Late: blue
- Size of the marks indicates the collected charge

www-personal.umich.edu/~jcv/imb/imb.html

Analysis Strategy



Phys. Rev. D 83 (2011) 123001



Upward-going (~13000km pathlength)

Downward-going (~15km pathlength)

- The Flux is Up/Down Symmetric above a few GeV
- Choose Up/Down Symmetric Binning
- Event Samples binned in several momentum ranges

Proposal for the IMB Experiment

A PROPOSAL

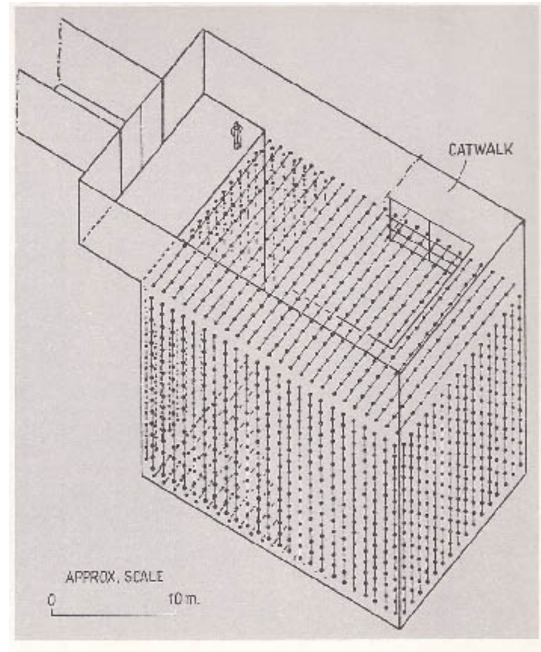
TO TEST FOR BARYON STABILITY

TO A LIFETIME OF 10^{33} YEARS

Abstract

We have studied the properties of, and the expected backgrounds in, a totally active, 10,000 ton water Cerenkov detector located deep underground and sensitive to many of the conjectured decay modes of the nucleons in it. Sensitivity to π, μ and γ secondaries, good energy resolution, and good angular resolution provide sufficient background rejection in the proposed device and will permit us to obtain significant information about several decay channels, should they b…

atmospheric neutrinos imposes an inherent limit.



We have studied the properties of, and the expected backgrounds in, a totally active, 10,000 ton water Cerenkov detector located deep underground and sensitive to many of the conjectured decay modes of the nucleons in it. Sensitivity

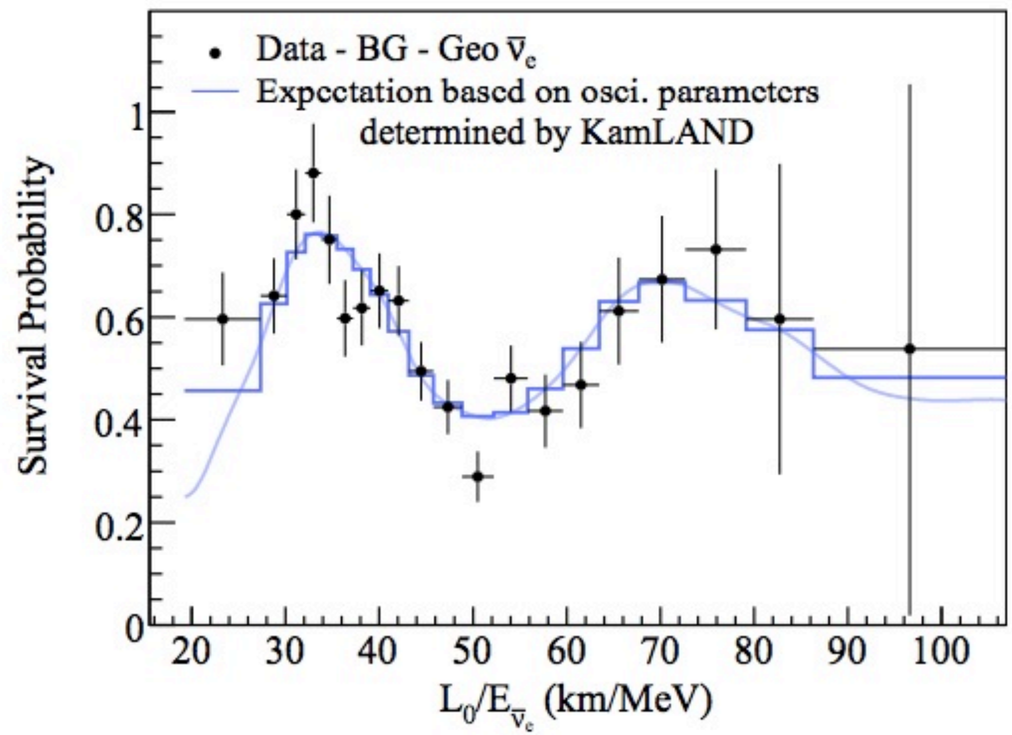
L/E Analysis Result

ν Decay $\Delta\chi^2 = 3.4\sigma$

ν Decoherence $\Delta\chi^2 = 3.8\sigma$

$\nu_\mu \leftrightarrow \nu_\tau$ $(\Delta\chi^2 = 0)$

PhysRevLett.100.221803



PRL 93 (2004) 101801