Probing the Universe with Neutrinos

ISAPP2008 Valencia
July 2008

Results from Neutrino Oscillation Experiments

Lecture 1

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Overall Outline

Lecture 1:

Atmospheric neutrino oscillations

Long baseline neutrino oscillation experiments

Lecture 2:

Solving the Solar Neutrino Problem with neutrino oscillations

Status of the 3 flavor effects

Outline - Lecture 1 -

- Production of atmospheric neutrinos
- Atmospheric neutrino anomaly
- Discovery of neutrino oscillations
- Long baseline neutrino oscillation experiments
- Oscillation to ν_τ or $\nu_{sterile}$?
- Tau neutrino appearance? (brief)
- Summary of Lecture-1

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

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

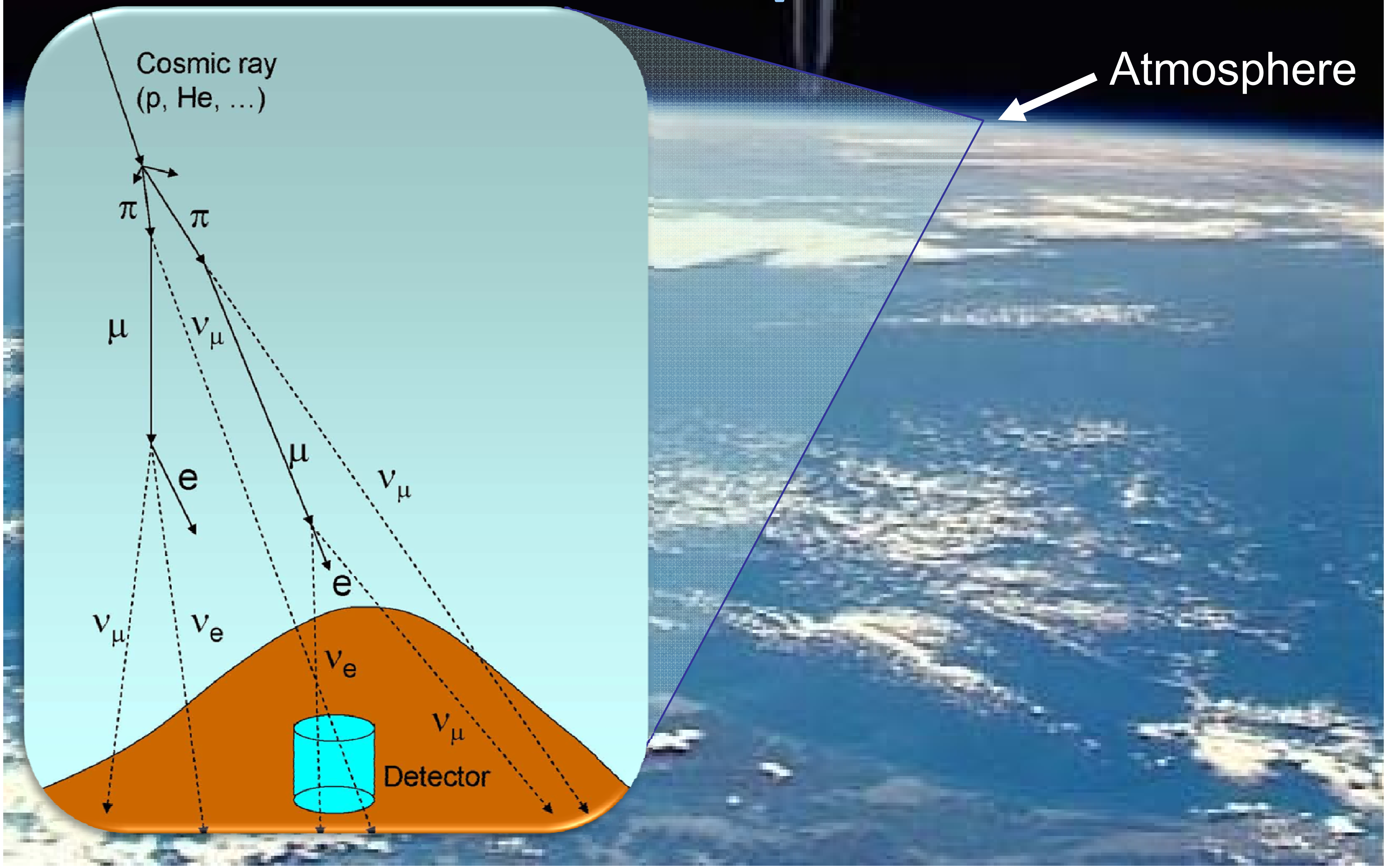
Introduction - motivation -

Reasons for neutrino experiments in 1 page:

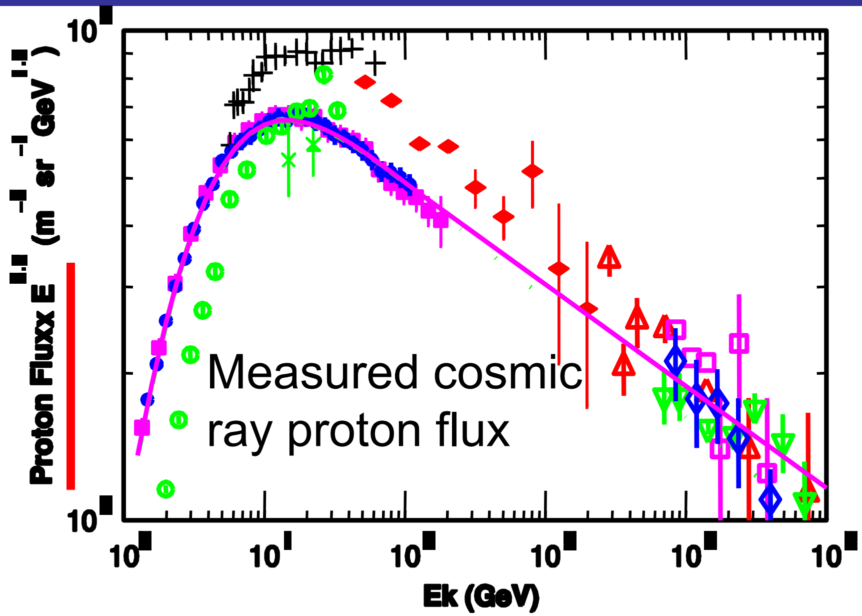
- Small but finite neutrino masses are believed to be related to the physics at the very high energy scale (Seesaw mechanism).
- At present, information from neutrino oscillation experiments gives one of a few experimental evidence for physics "beyond the standard model".
- The observed large neutrino 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).

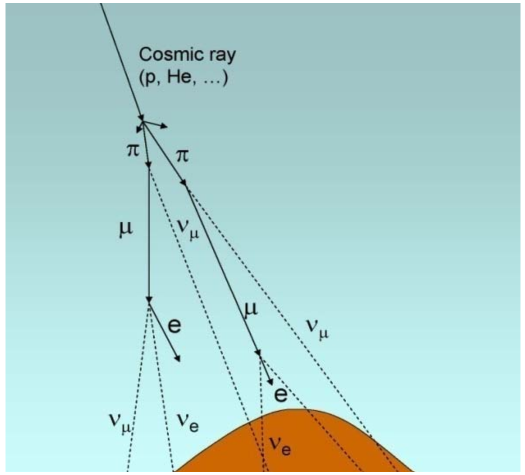
$\leftarrow$ "Probing the Universe with Neutrinos".

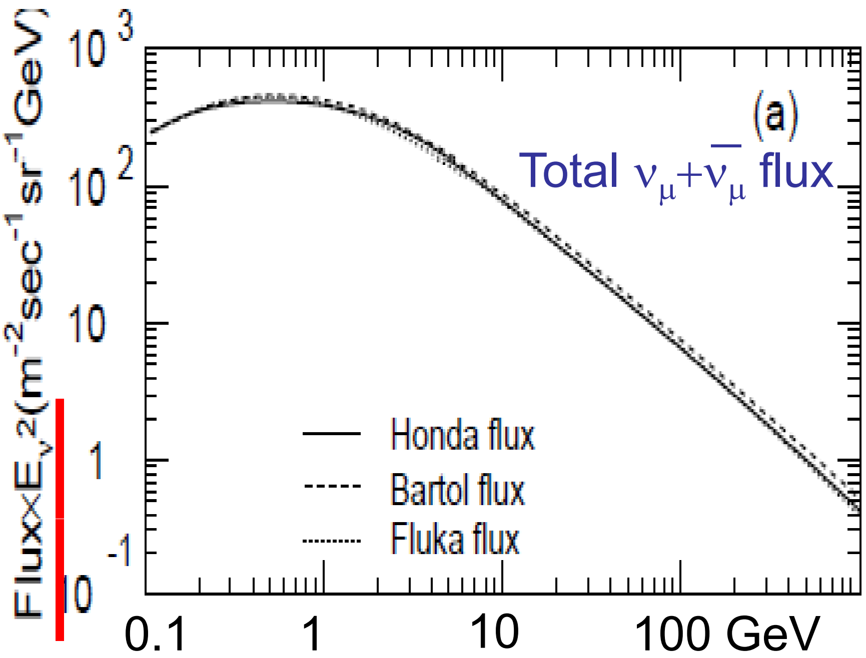
Production of atmospheric neutrinos



Calculating the atmospheric neutrino beam







Do the calculation all over the Earth

+ geomagnetic field

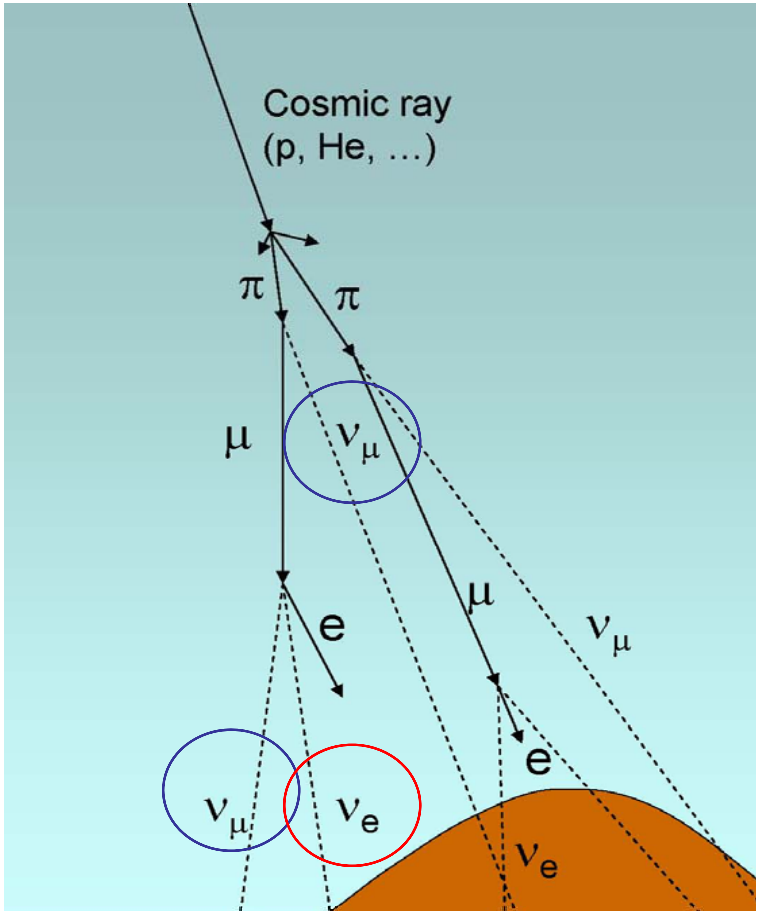
+ (p+(O or N)) int.

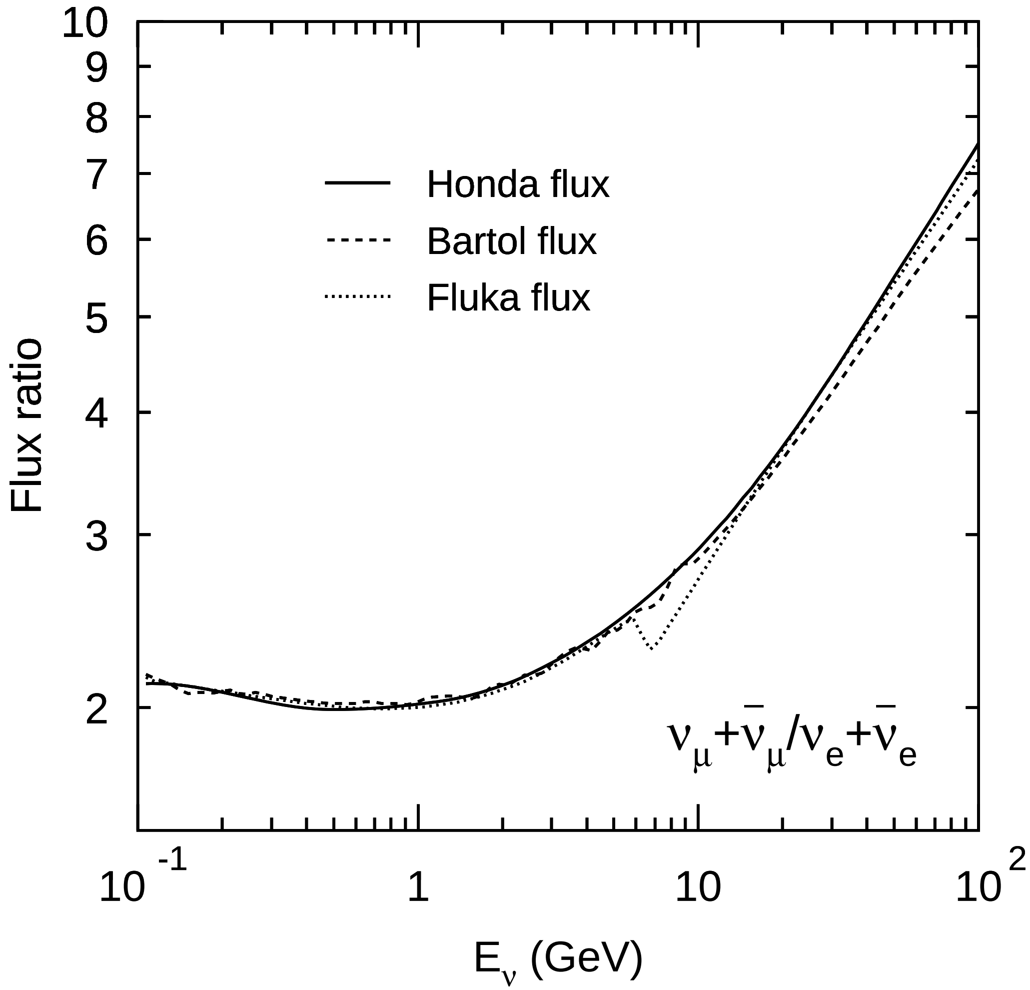
+ decay of π or K

+ ……

Some features of the beam (1)

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

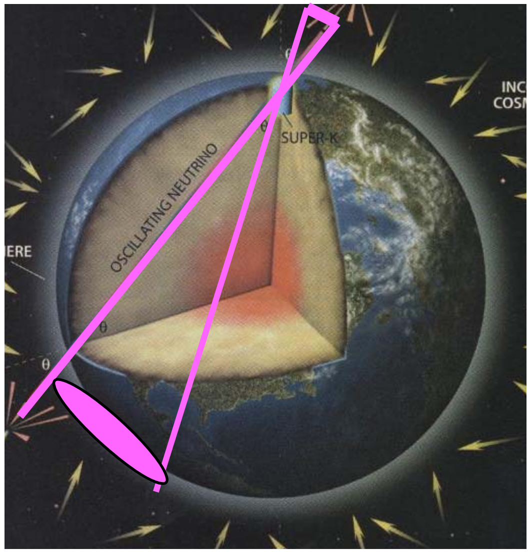




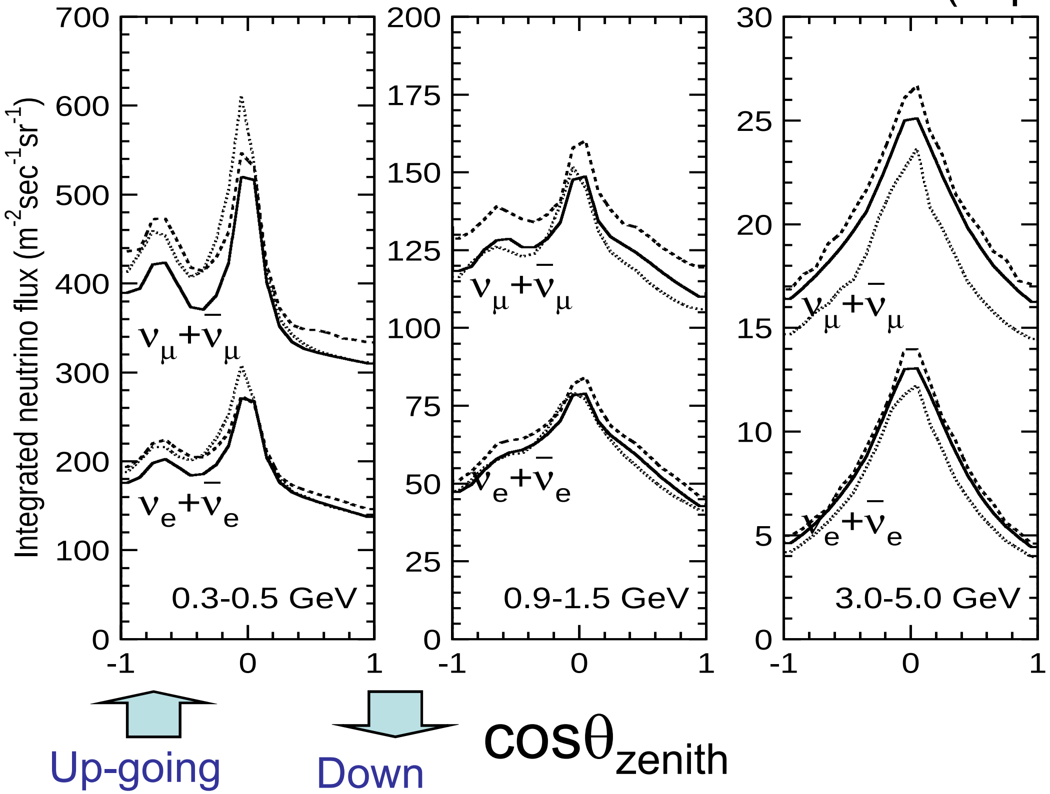
ν_μ/ν_e ratio is calculated to an accuracy of better than 3% below ∼5GeV.

Some features of the beam (2)

Zenith angle



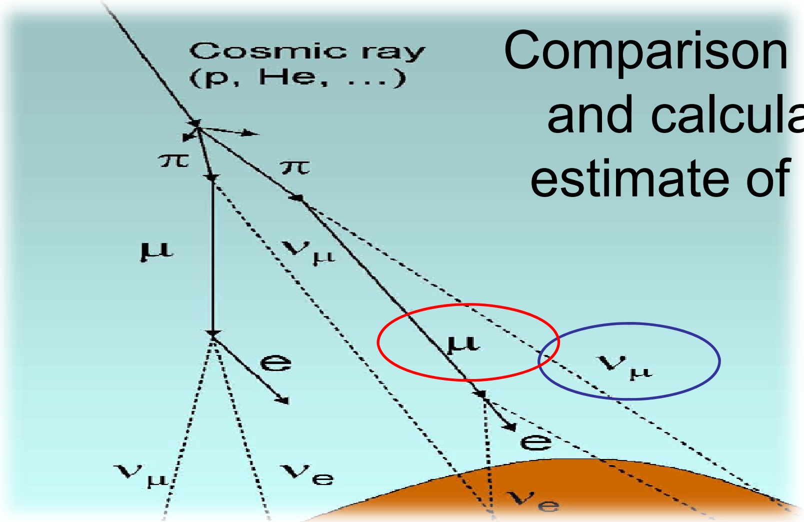
@Kamioka (Japan)



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

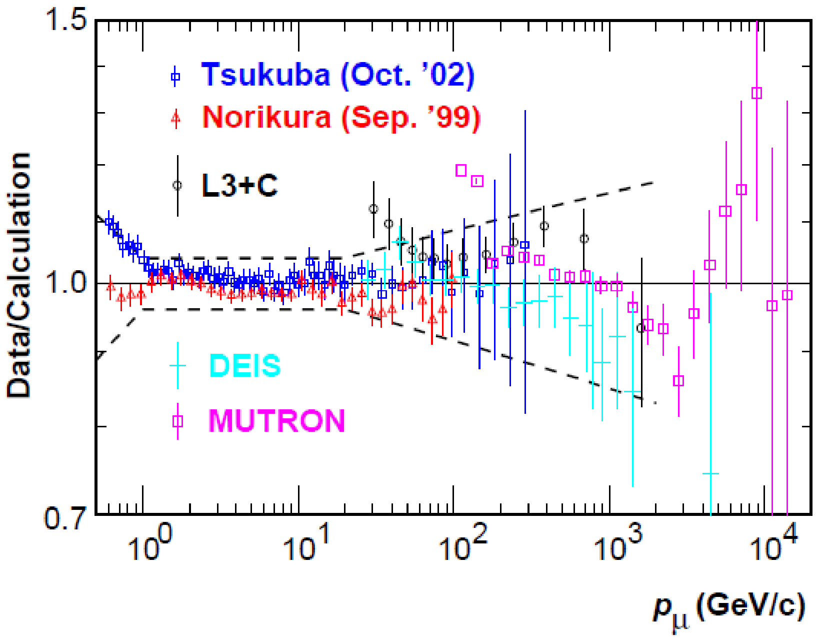
Comment: How accurate is the absolute normalization of the flux ?

astro-ph/0611201
astro-ph/0611418

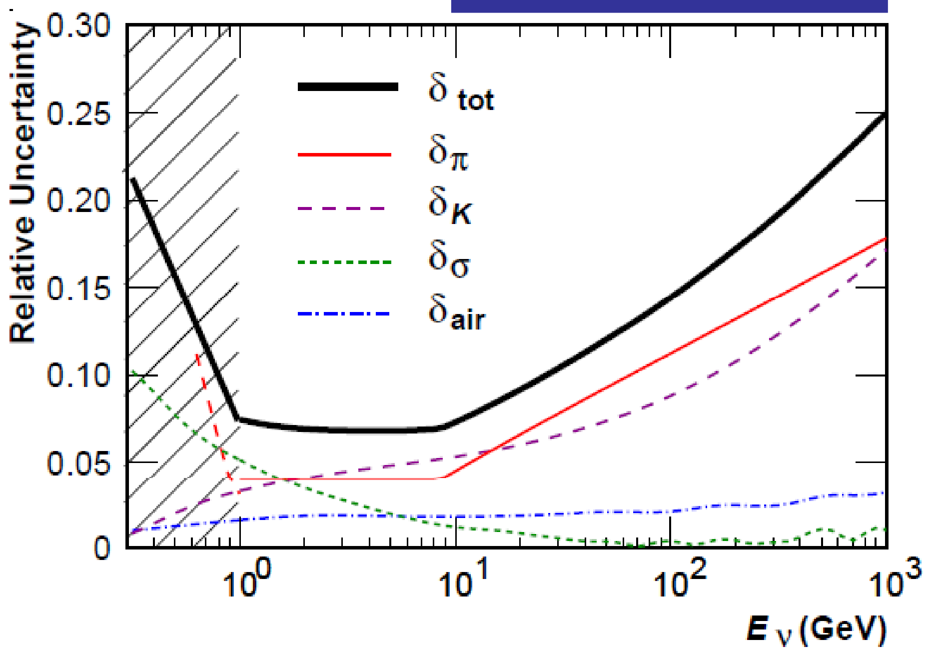


Comparison of the muon flux data and calculation results gives the estimate of the absolute neutrino flux uncertainty.

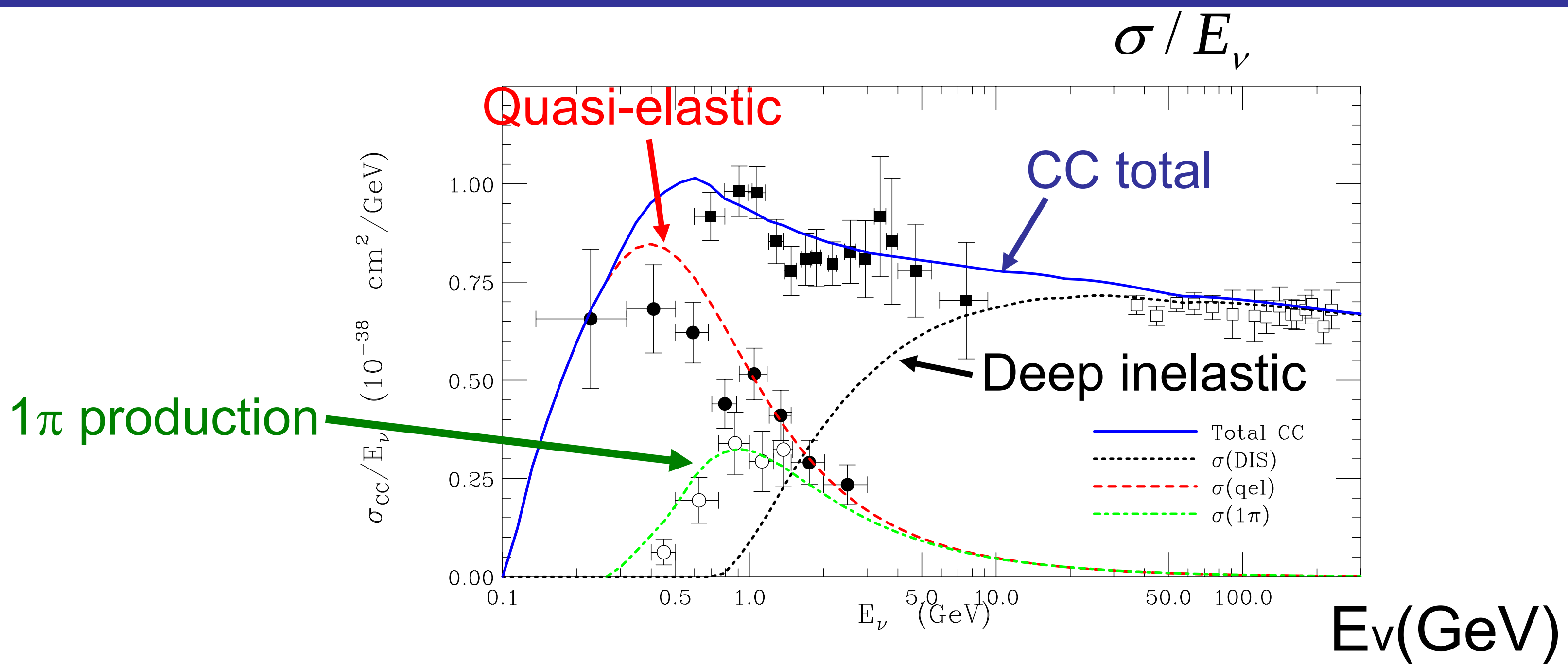
Data/Calculation (muon flux)

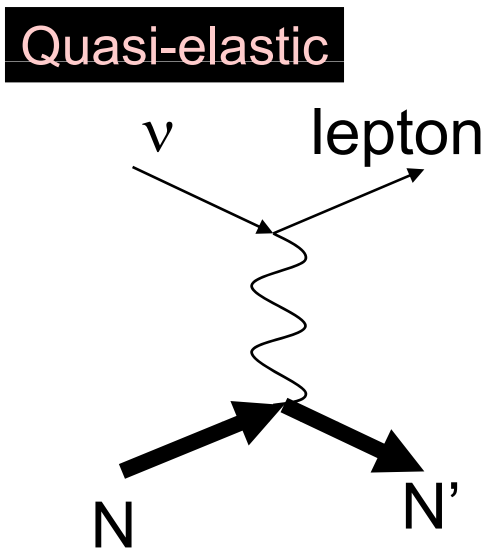


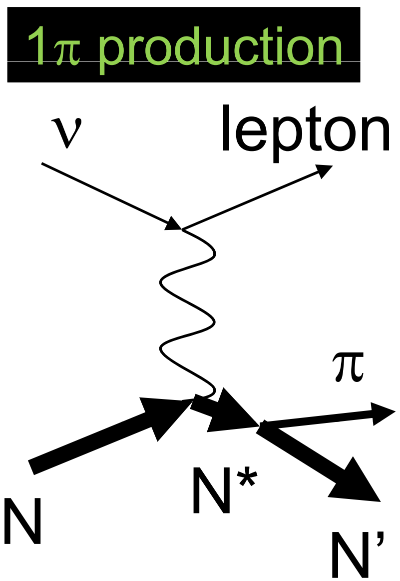
Systematic error for the absolute neutrino flux

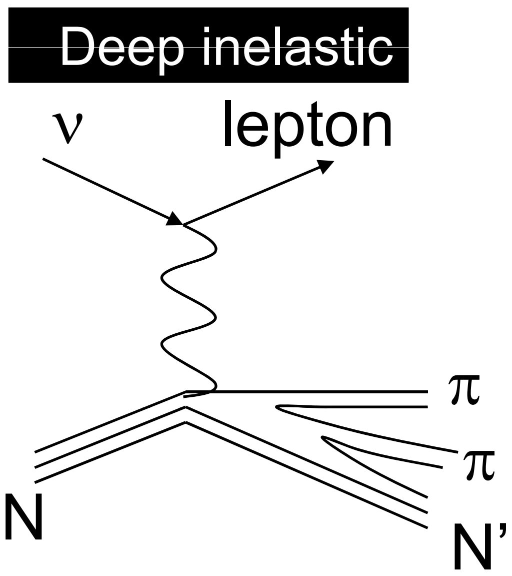


Neutrino interactions

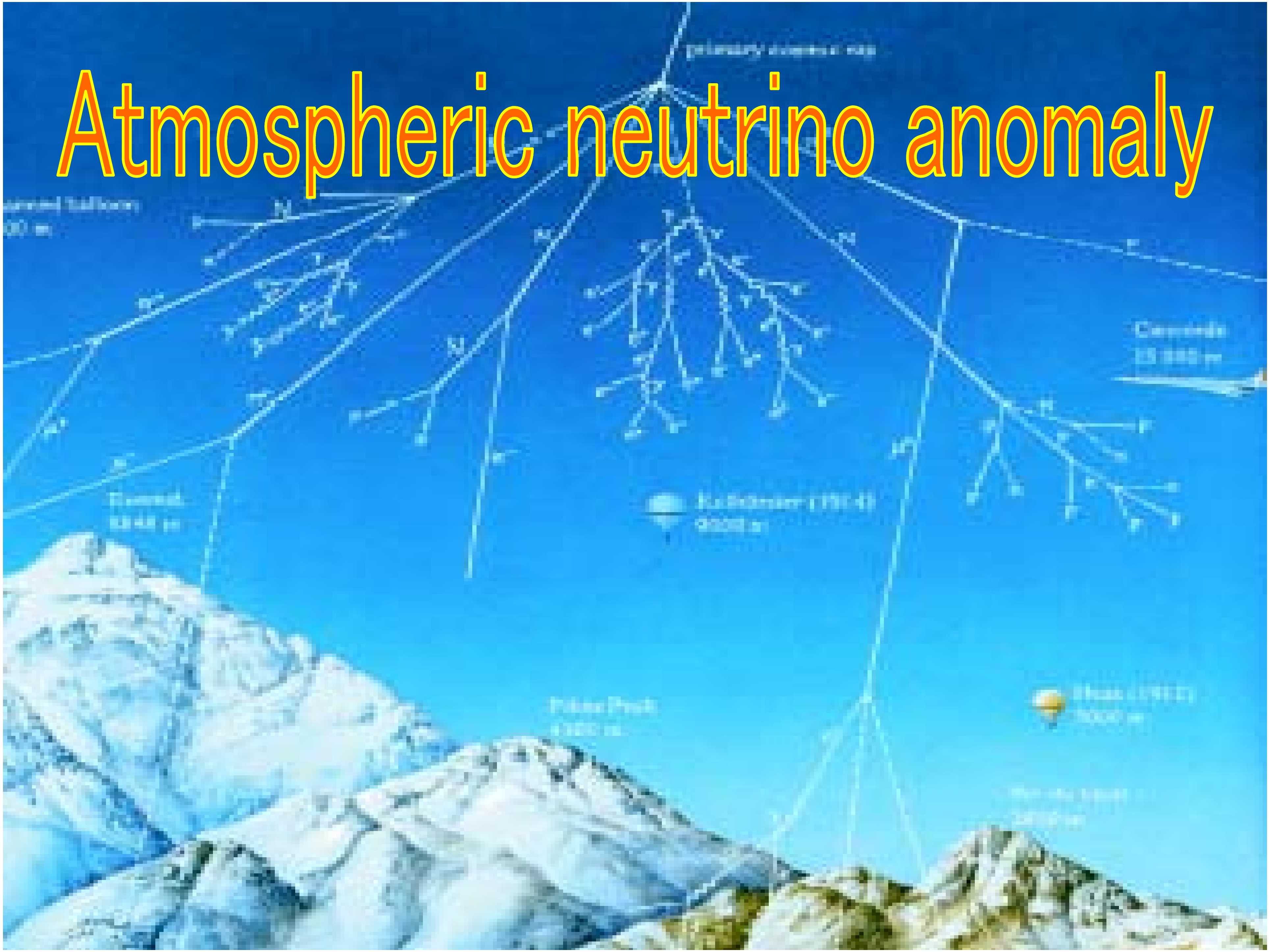






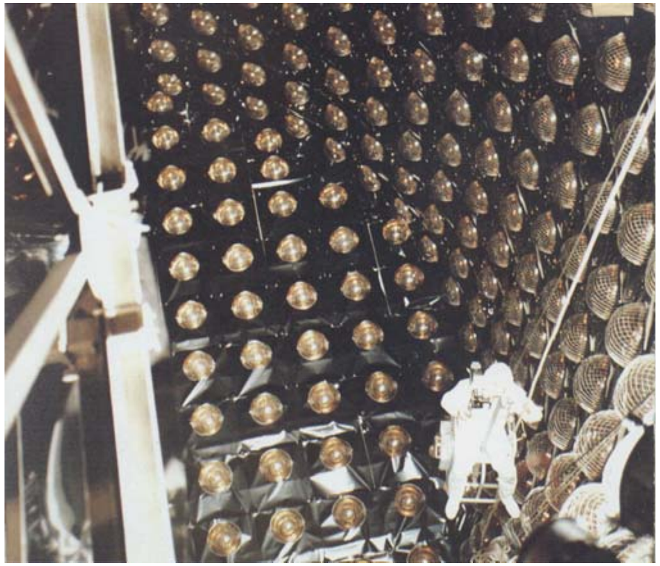


Atmospheric neutrino anomaly



“Proton decay” experiments

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

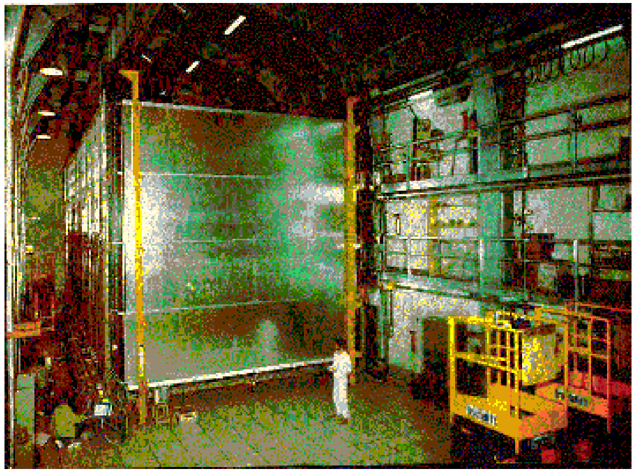


Kamiokande (1000ton)

IMB (3300ton)

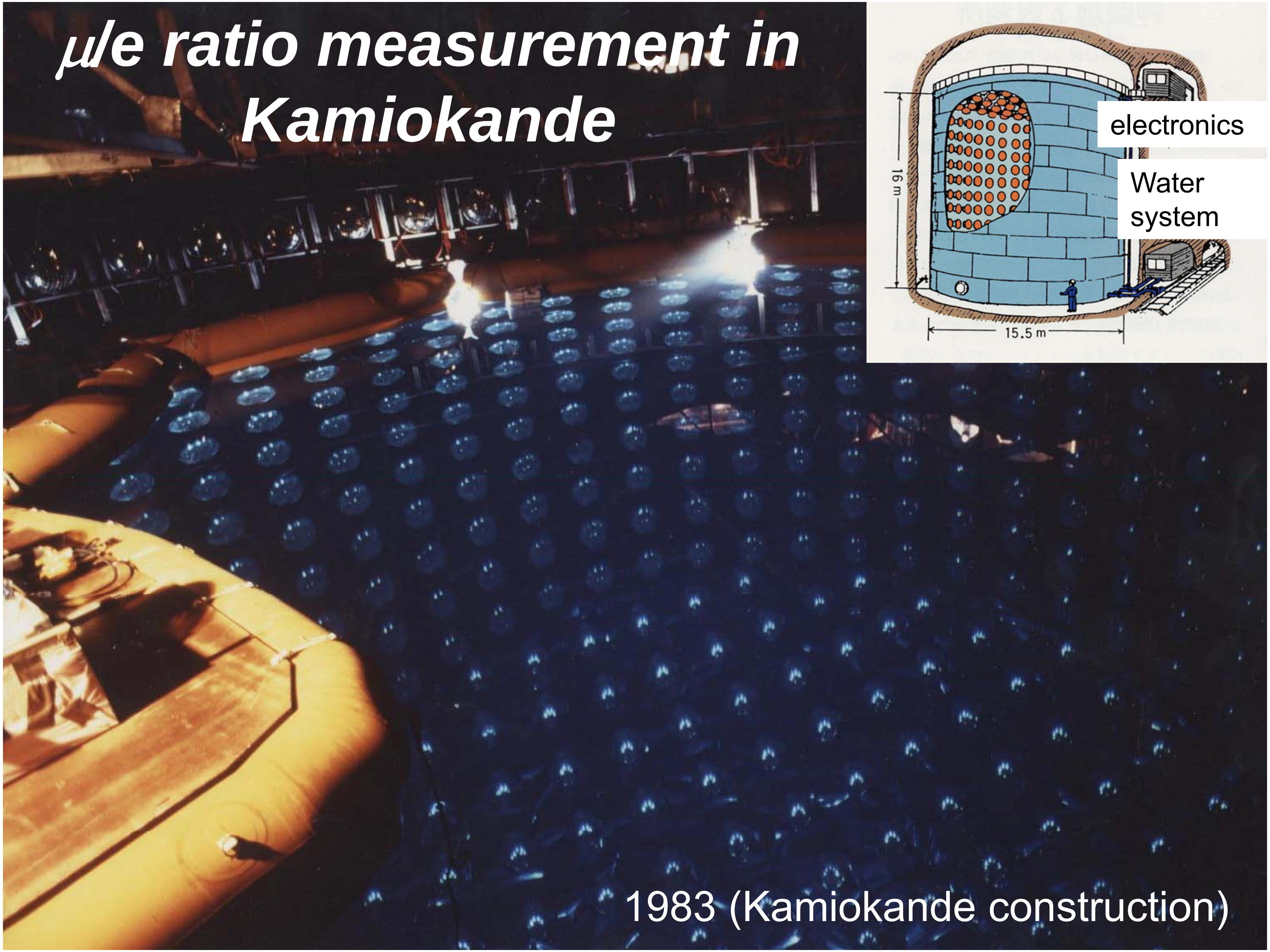
NUSEX (130ton)

Frejus (700ton)



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

μ/e ratio measurement in Kamiokande



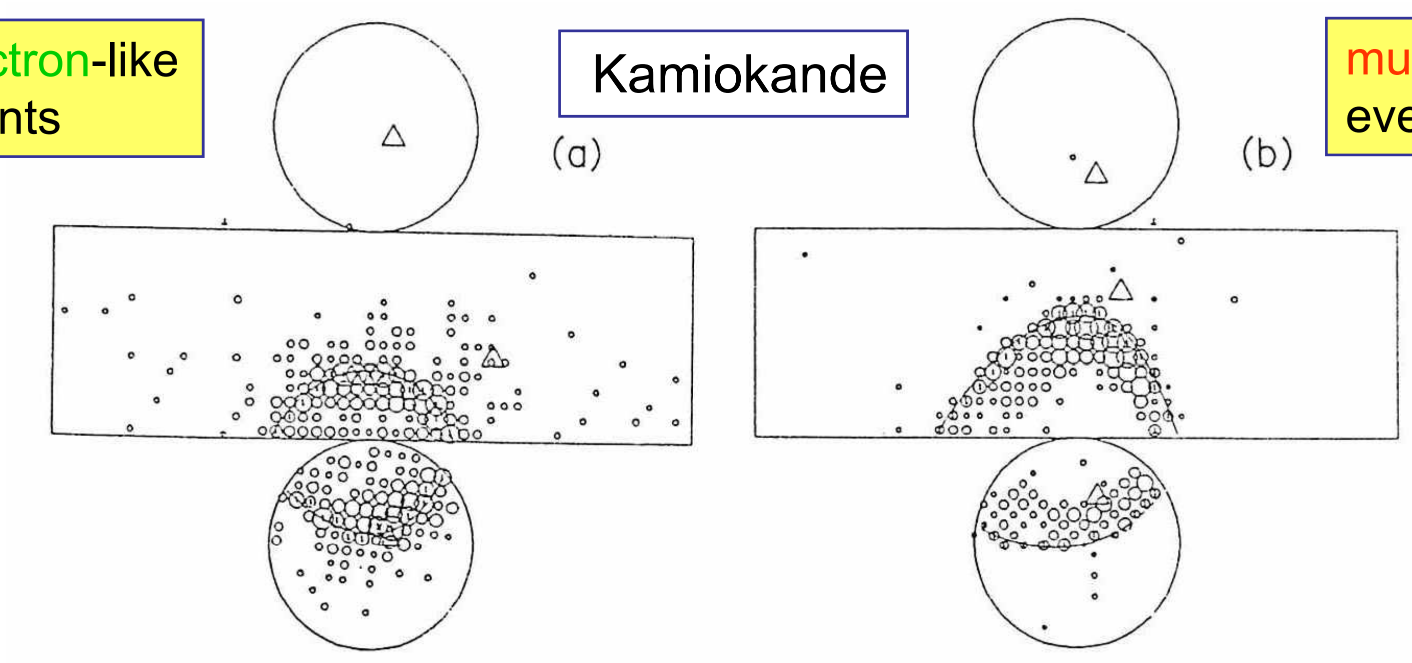
1983 (Kamiokande construction)

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

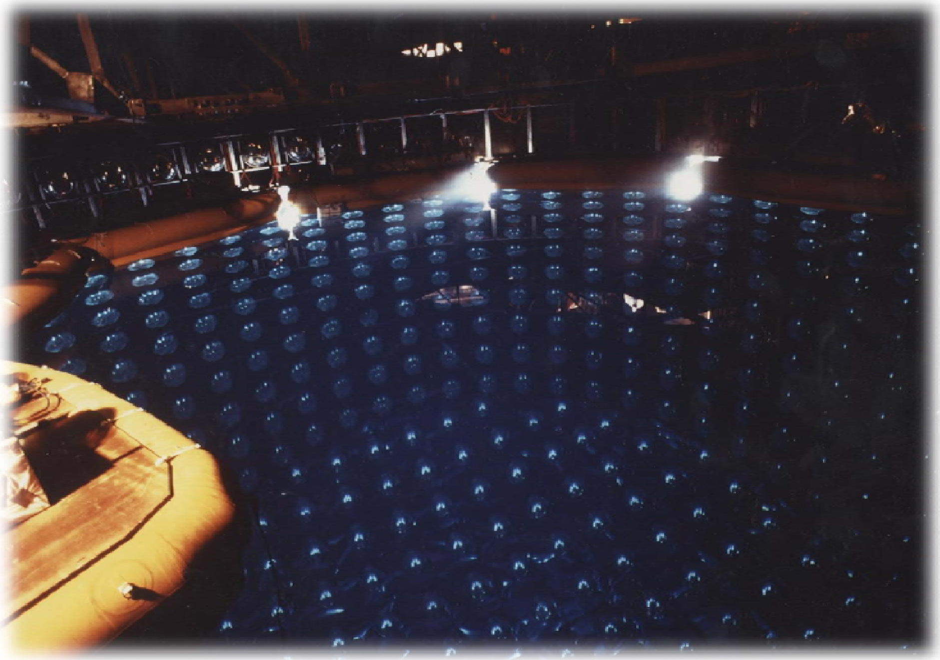
Difference in the event pattern

Particle ID

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

98% efficiency

First result on the μ/e ratio (1988)



Kamiokande

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

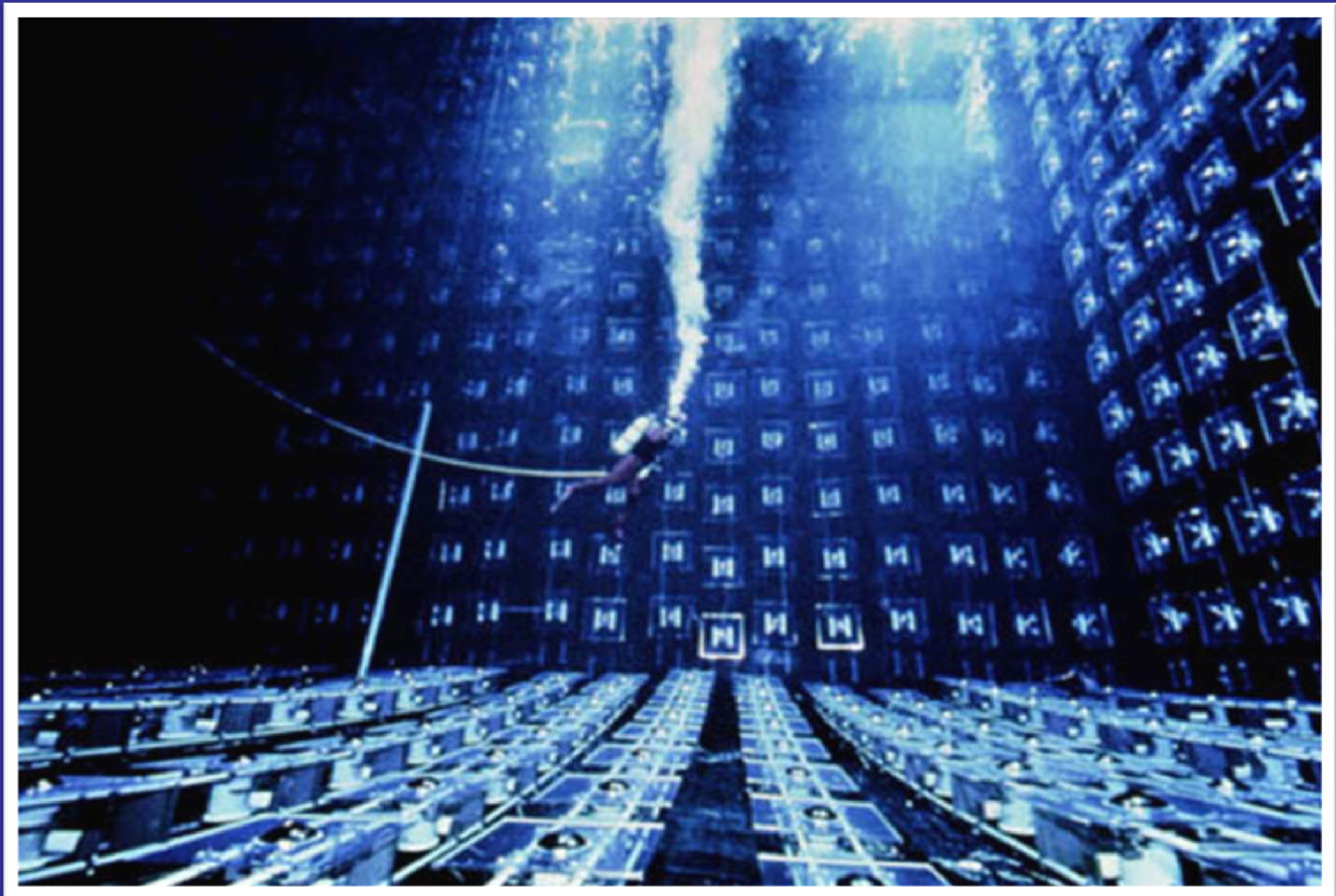
2.87 kton・year

	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."

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

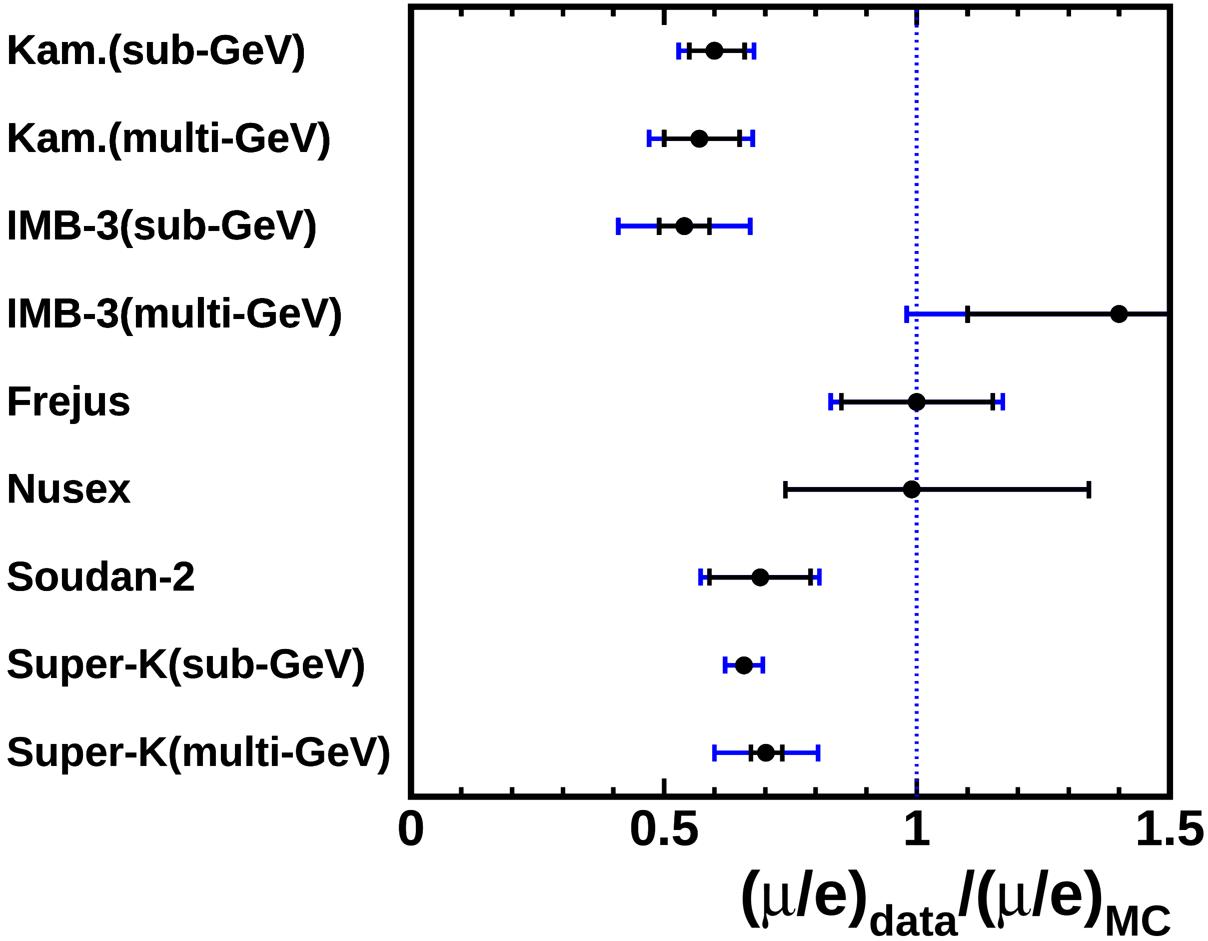
First supporting evidence for small μ/e



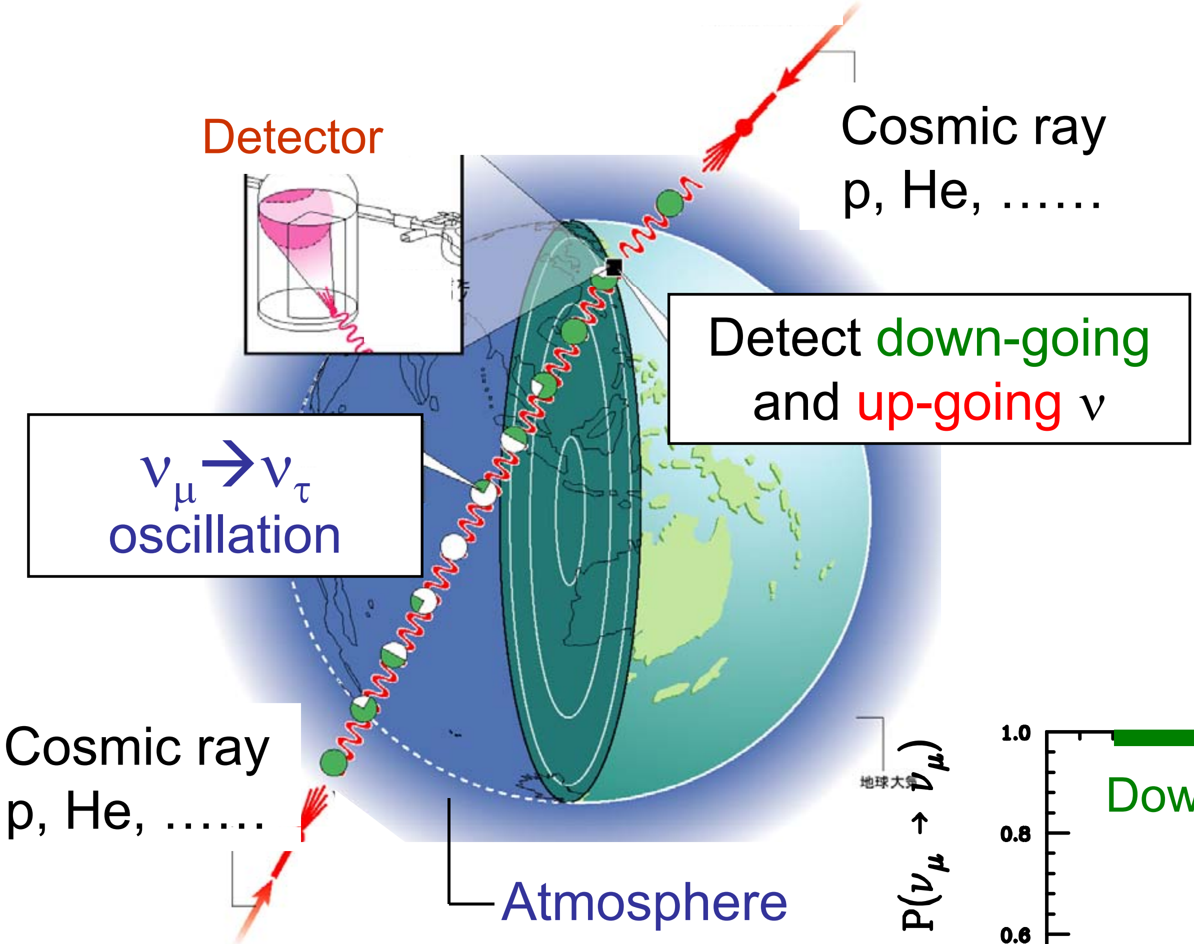
IMB experiment also observed smaller (μ/e) in 1991 and 1992.

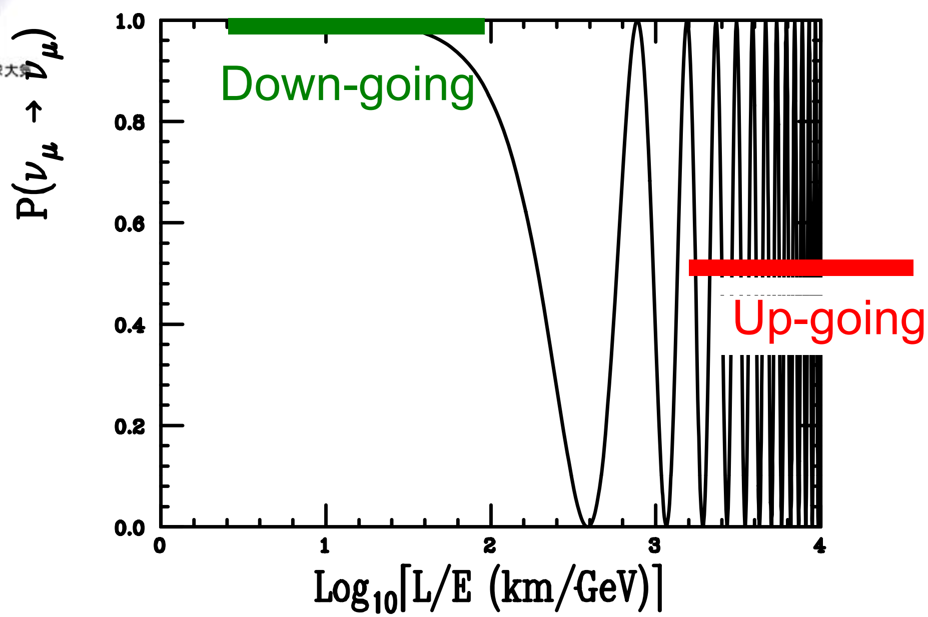
μ/e ratio measurement: summary

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

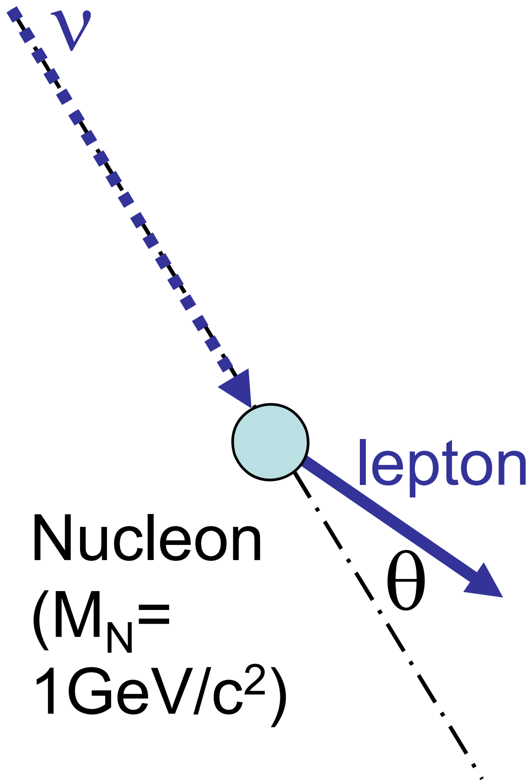


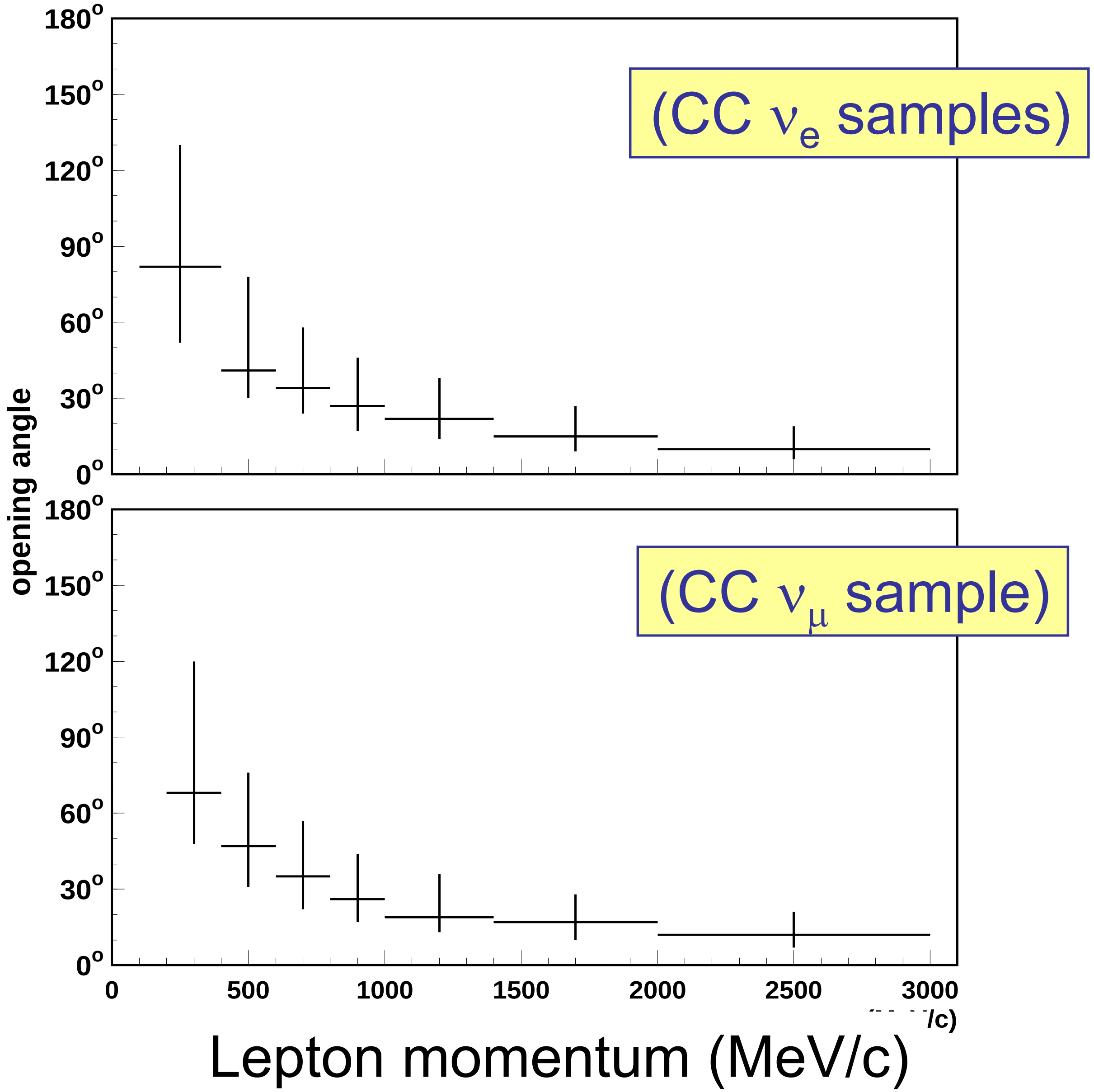
Atmospheric neutrinos and neutrino oscillations





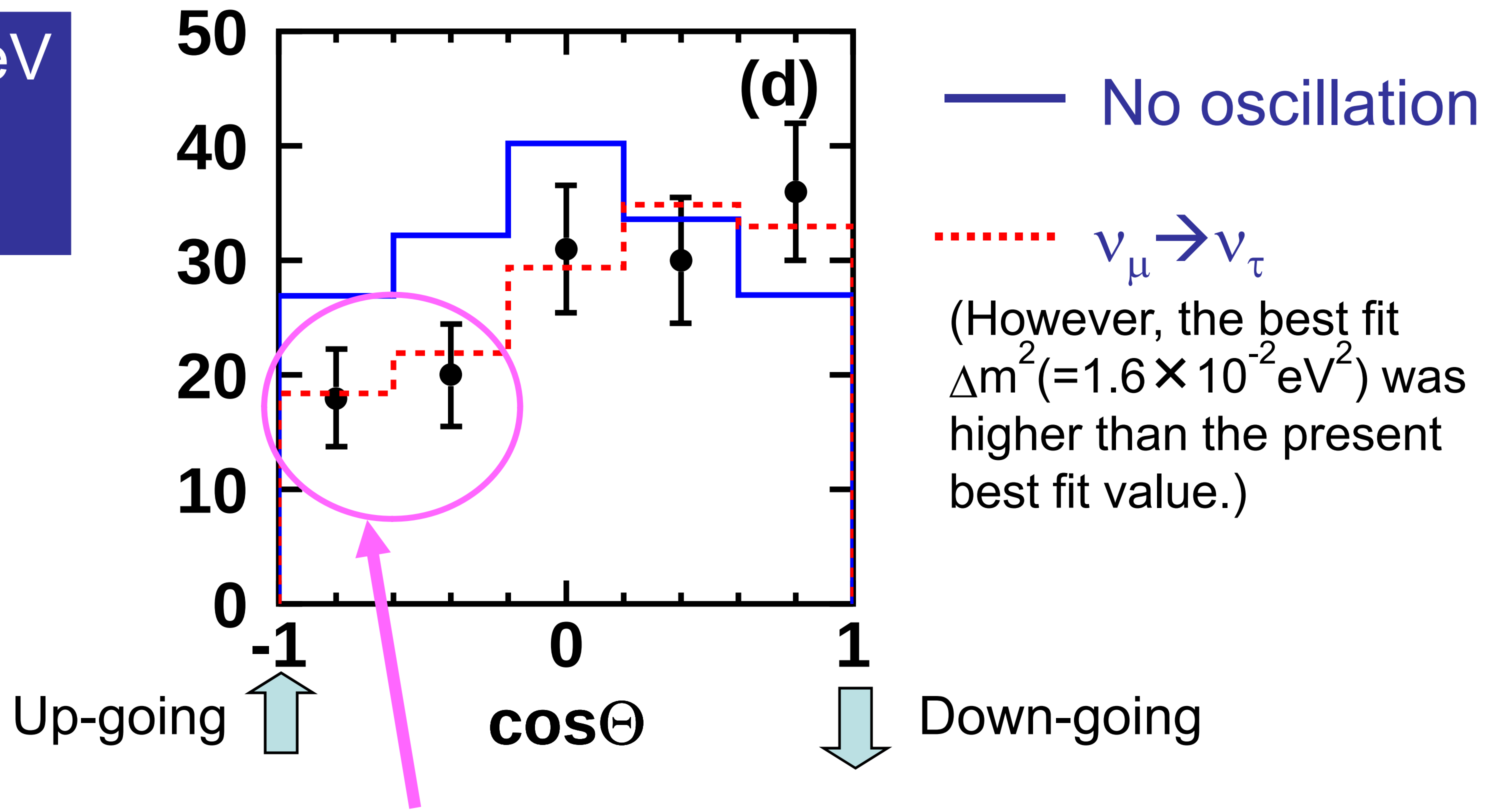
Angular correlation





Next: zenith angle…(Kamiokande,1994)

multi-GeV
μ-like
events



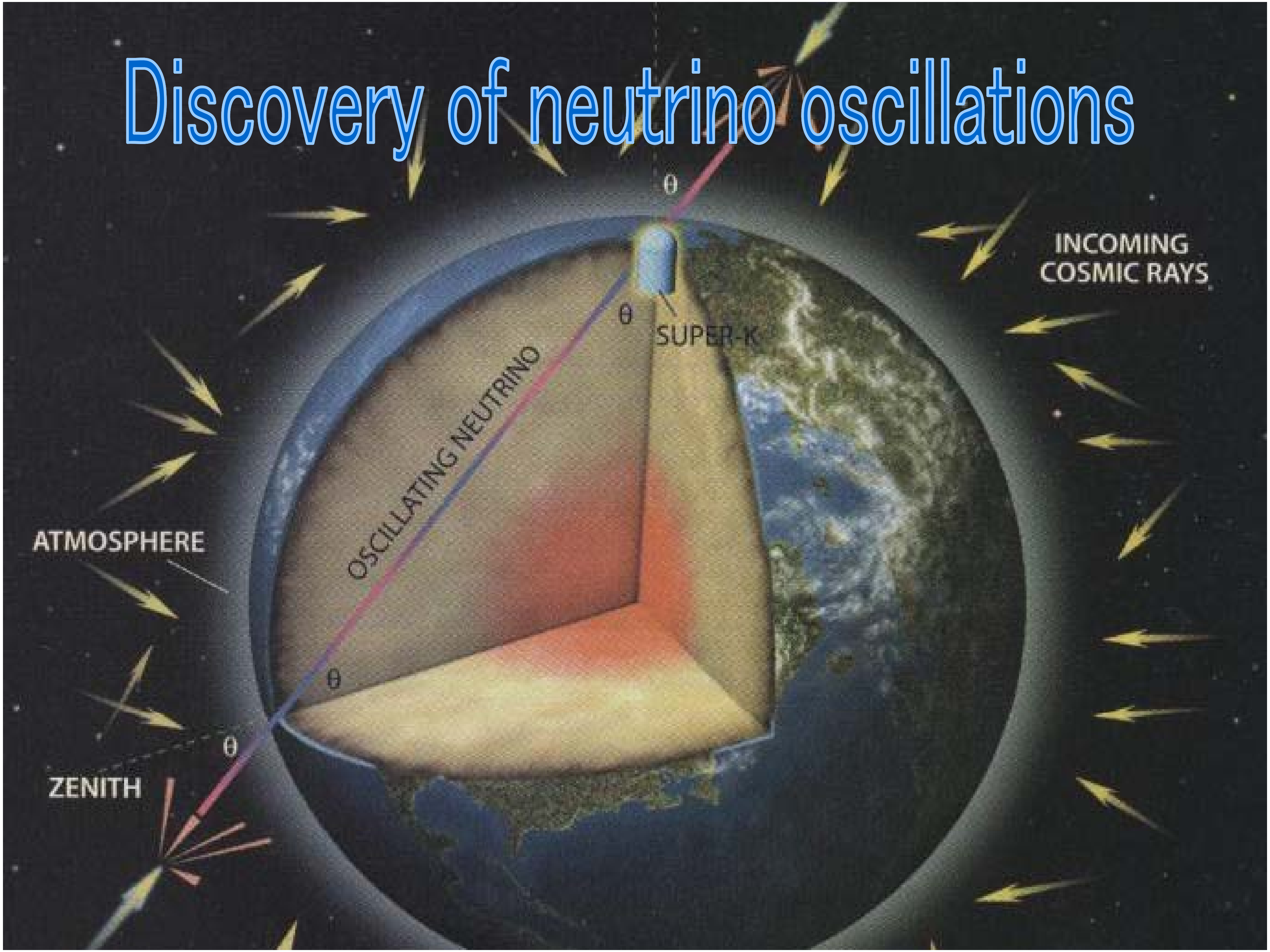
(However, the best fit Δm^2(=1.6×10^{-2}eV^2) was higher than the present best fit value.)

Deficit of upward-going μ-like events

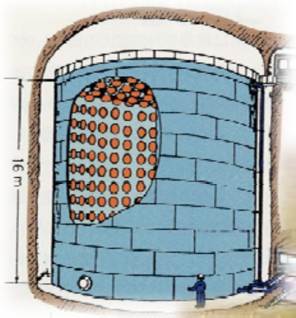
Up/Down=$0.58^{+0.13}_{-0.11}$ (2.9 σ)

Not high enough statistics to conclude …

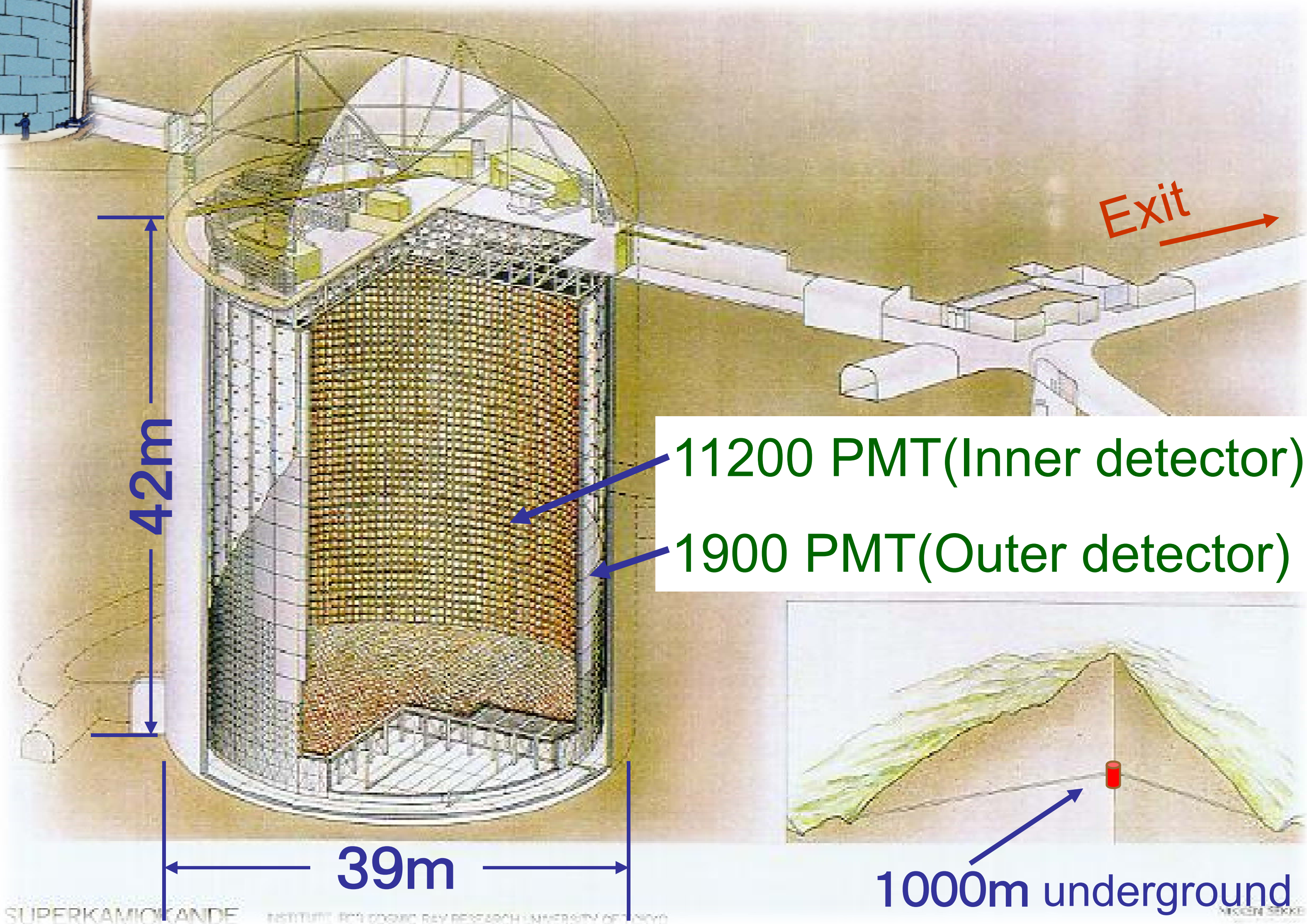
Discovery of neutrino oscillations



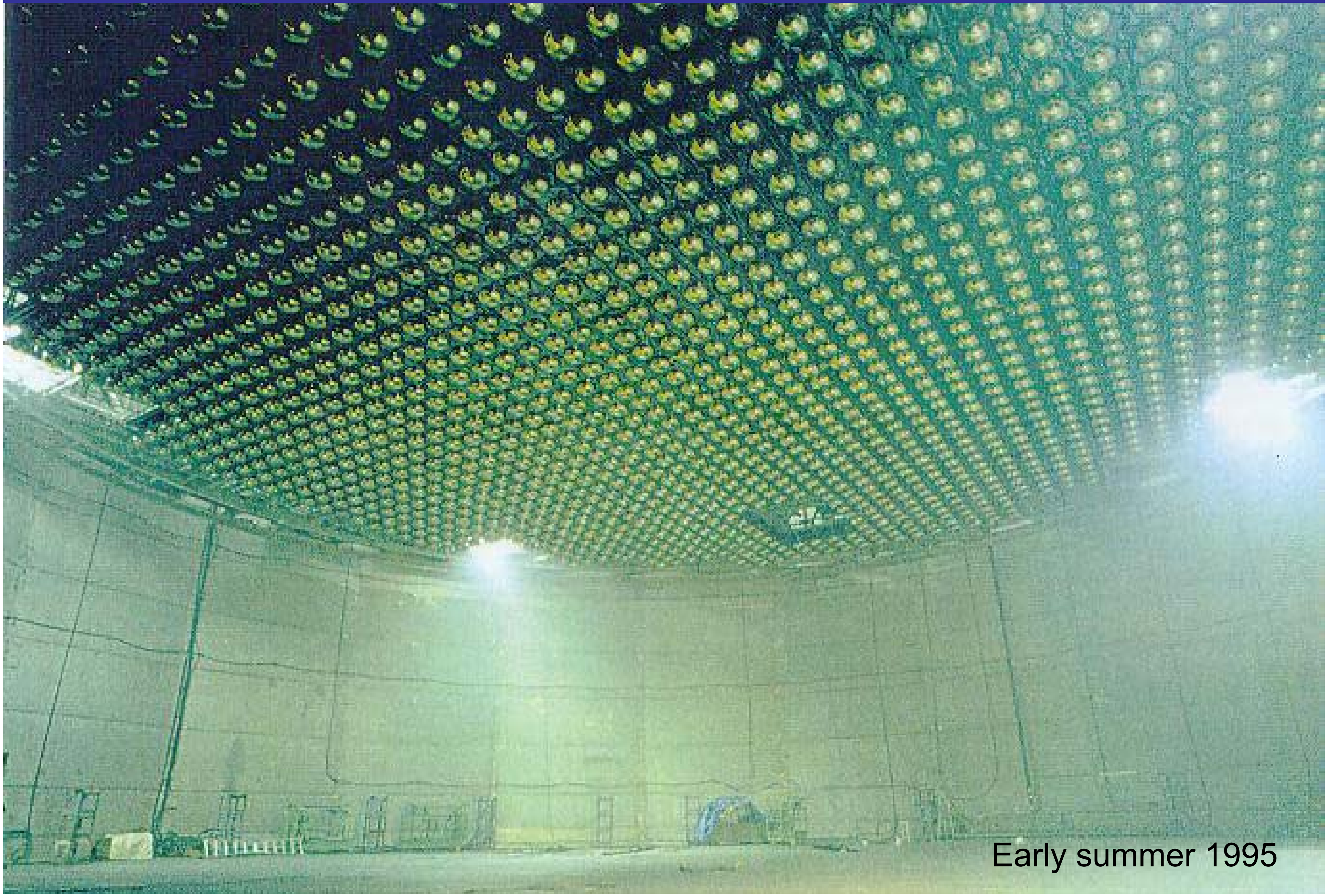
Super-Kamiokade detector

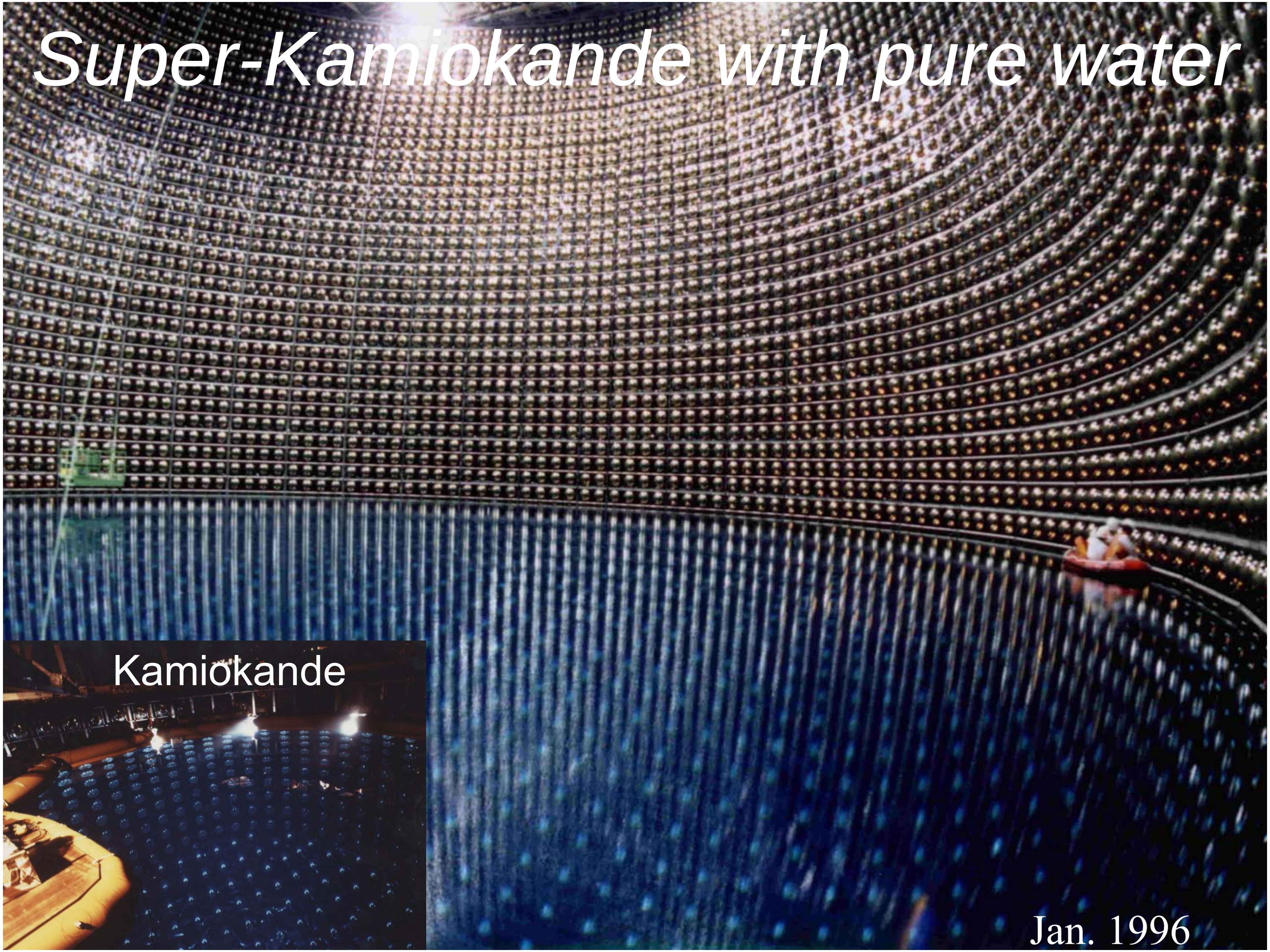


50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)



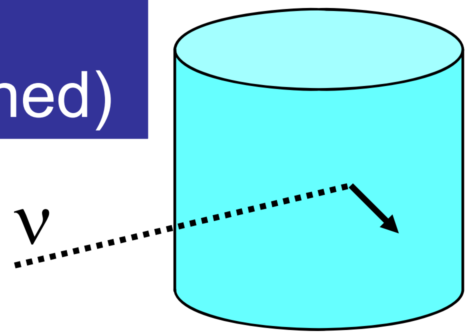
Super-Kamiokande detector under construction




Super-Kamiokande with pure water
Kamiokande
Jan. 1996

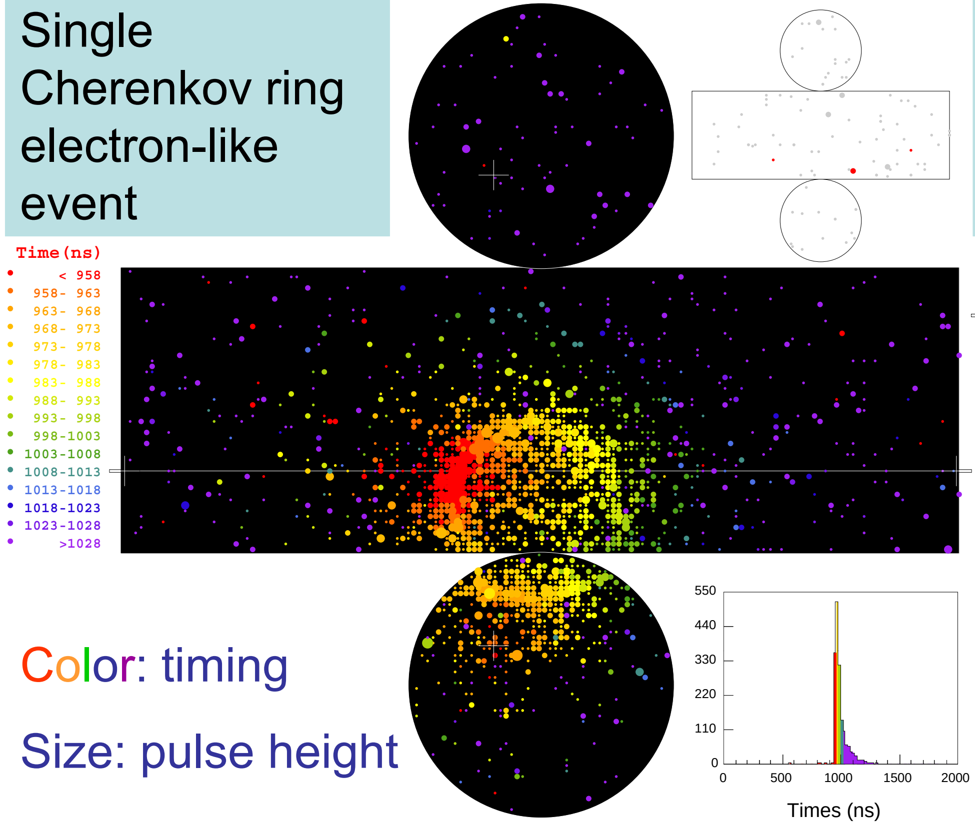
Various types of atmospheric ν events (1)

FC (fully contained)

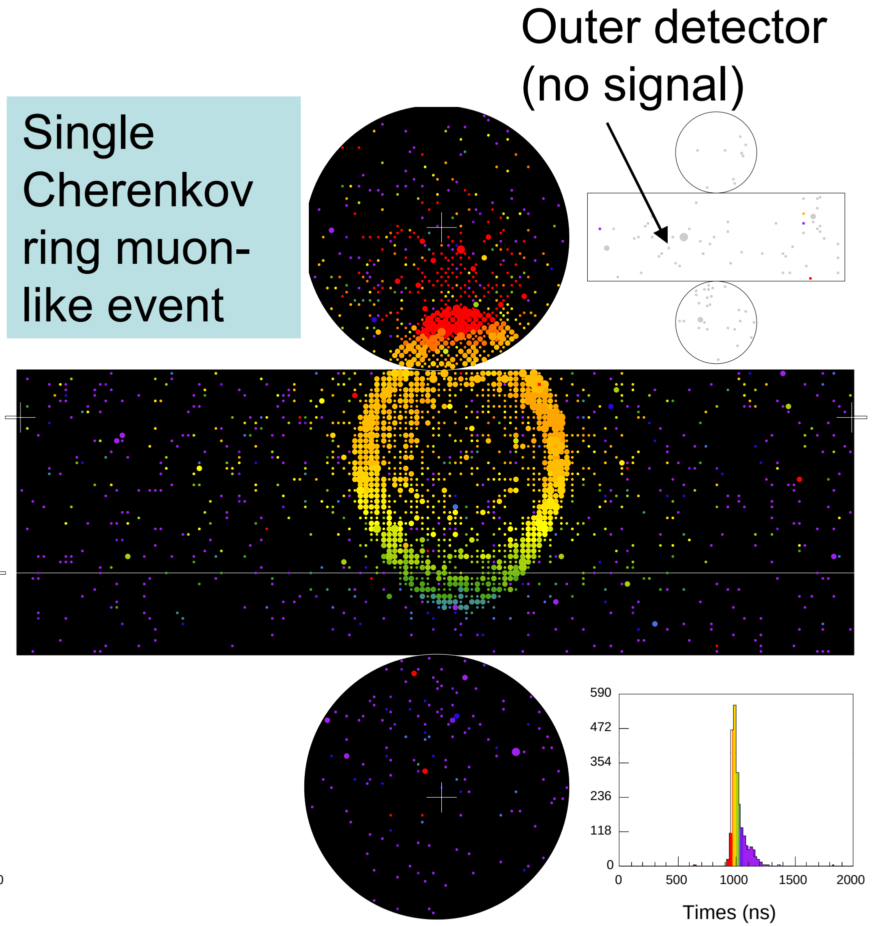


- Both CC ν_e and ν_μ (+NC)
- Particle identification separates electrons and muons with ε=99%.

Single Cherenkov ring electron-like event



Single Cherenkov ring muon-like event

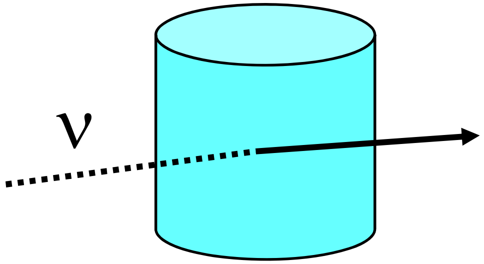


Color: timing

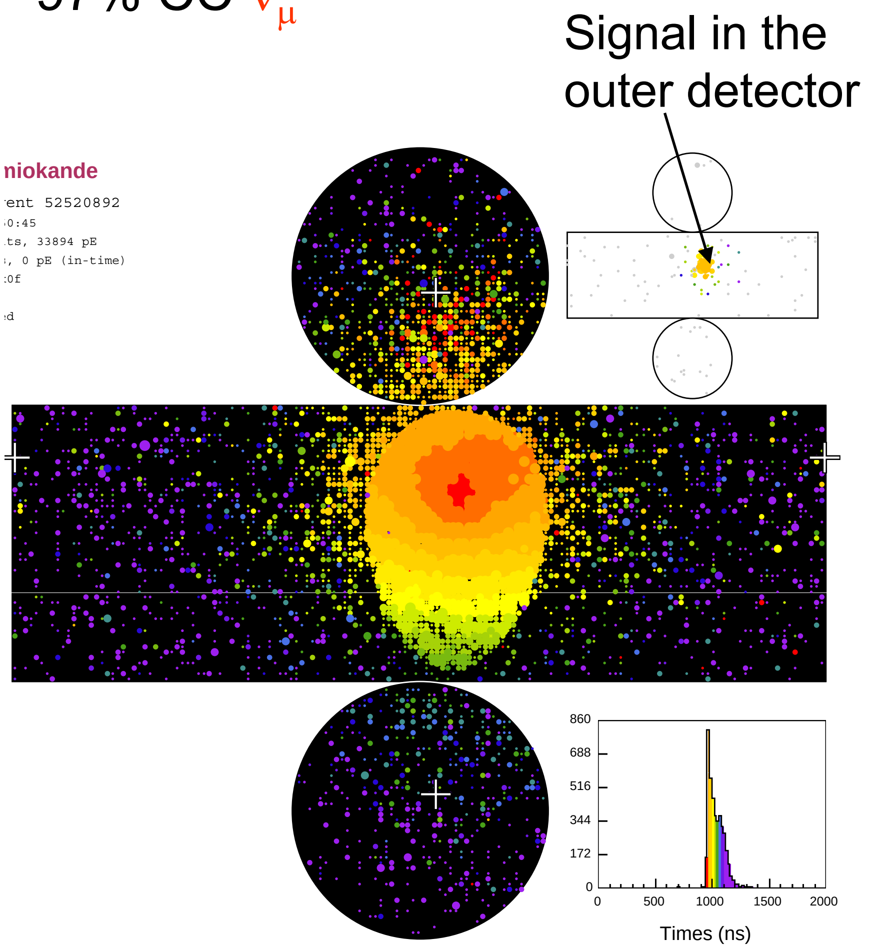
Size: pulse height

Various types of atmospheric ν events (2)

PC (partially contained)

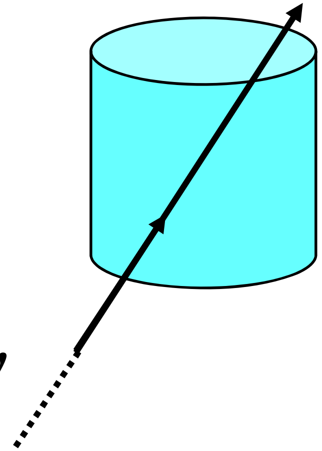


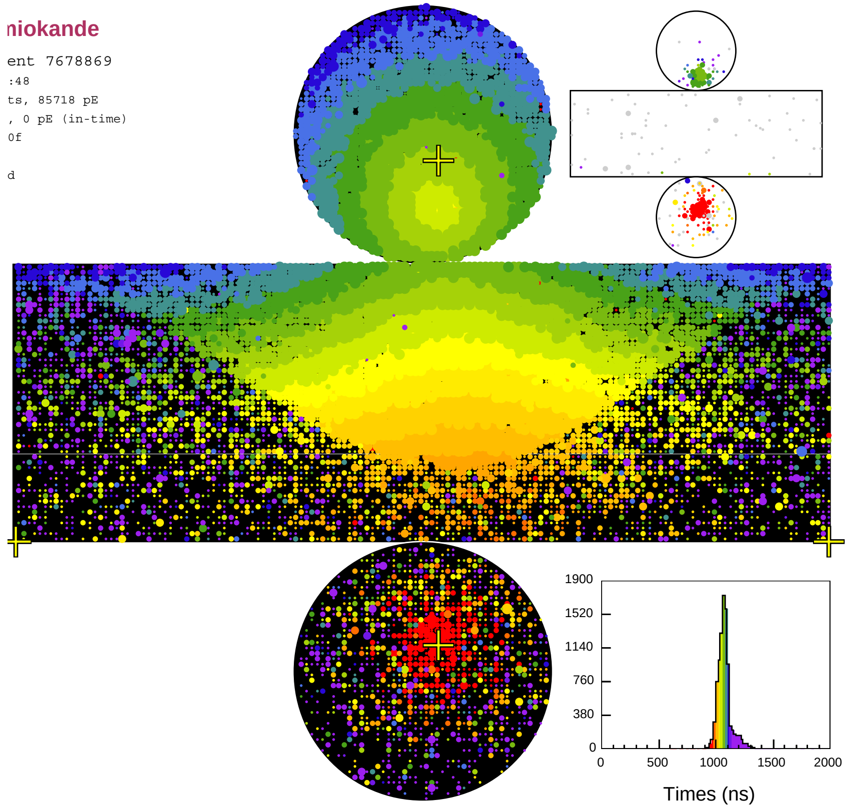
- 97% CC ν_μ



Upward going muon

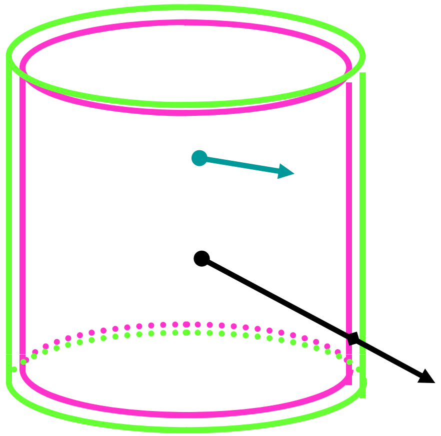
- almost pure CC ν_μ



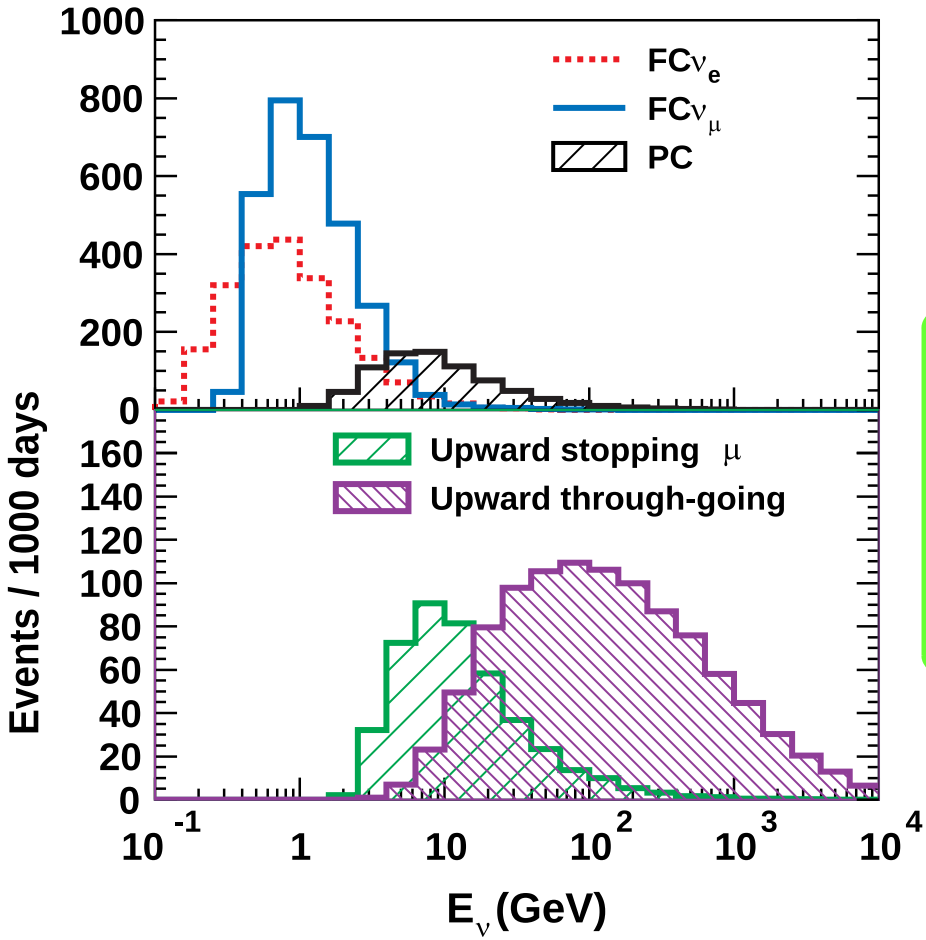


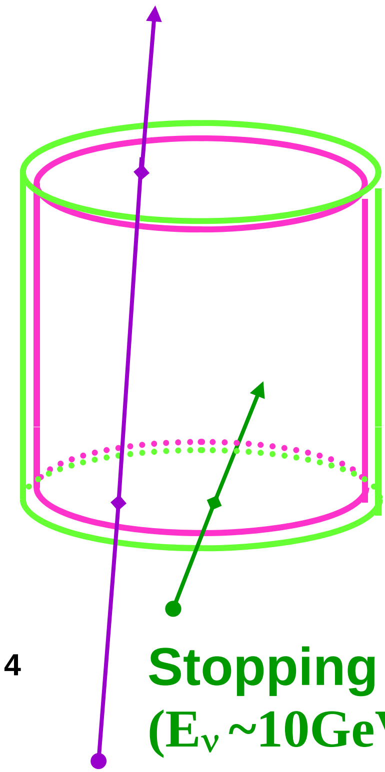
Event type and neutrino energy

Fully Contained (FC) (E_ν ~1GeV)



Partially Contained (PC) (E_ν ~10GeV)





Stopping μ (E_ν ~10GeV)

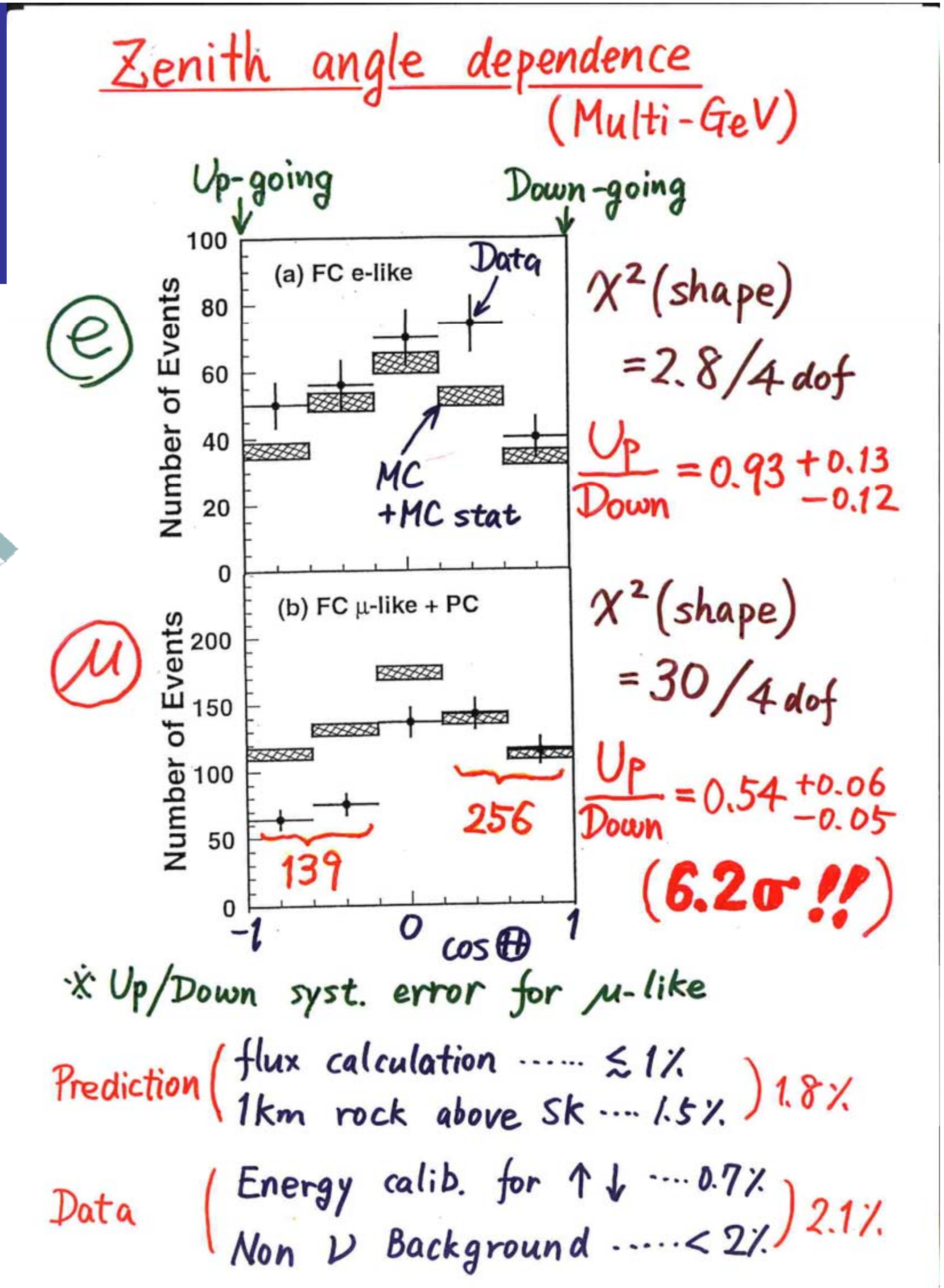
Through-going μ (E_ν ~100GeV)

Super-K @Neutrino98

Fully contained, 1-ring events

with Evis > 1.33GeV

plus partially contained events



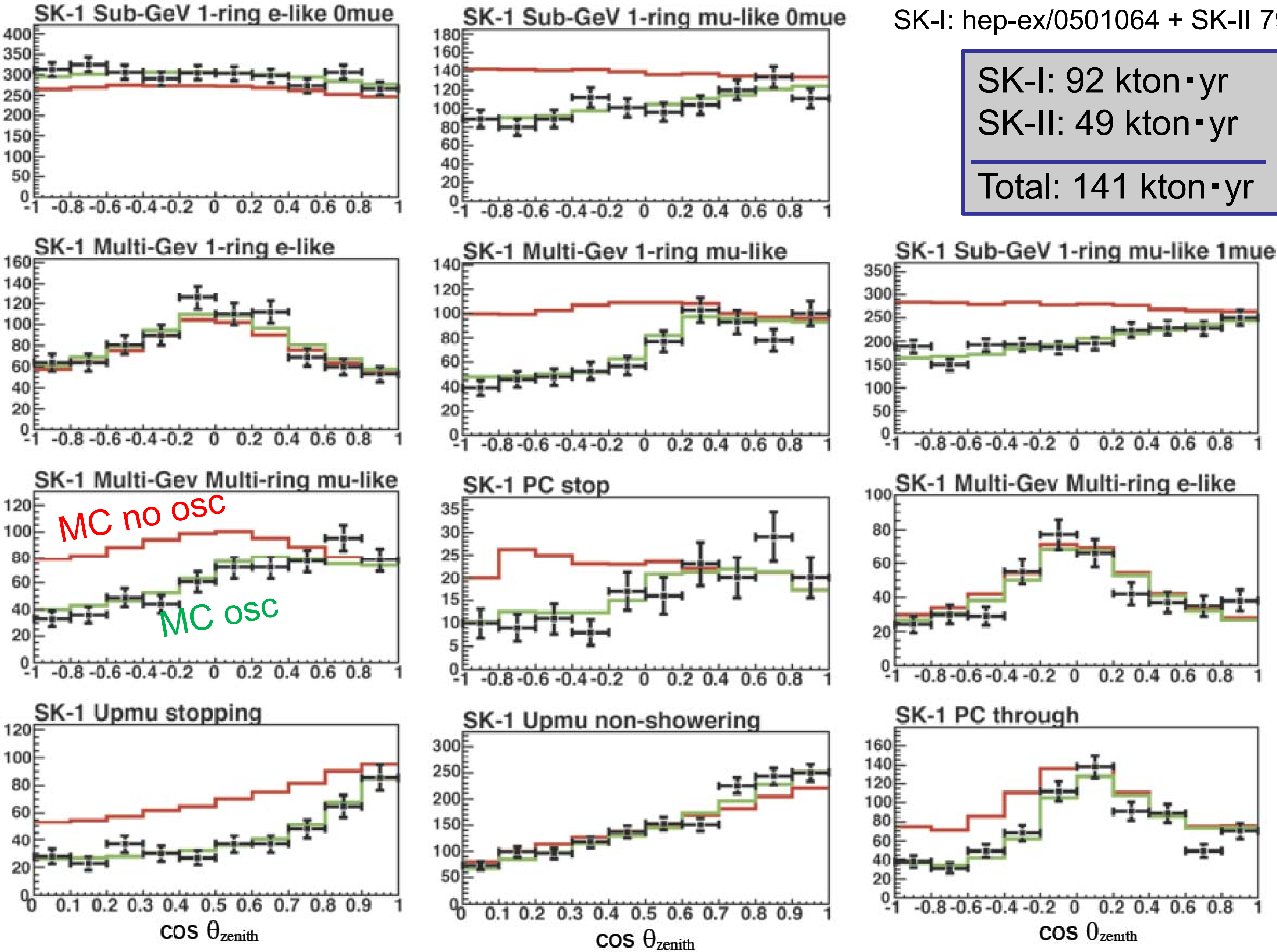
SK concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

Atmospheric neutrino data now (SK-I)

SK-I: hep-ex/0501064 + SK-II 799 day

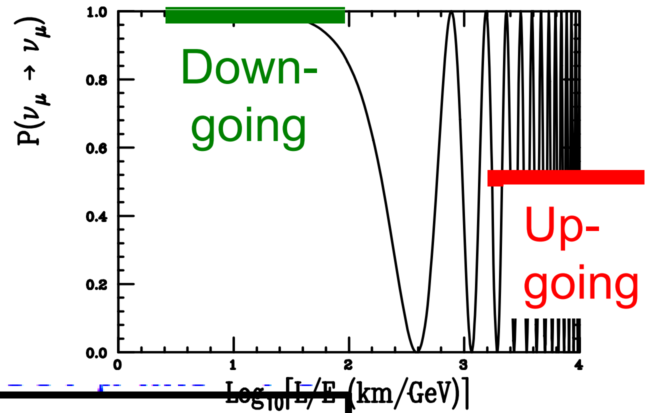
SK-I: 92 kton･yr
SK-II: 49 kton･yr

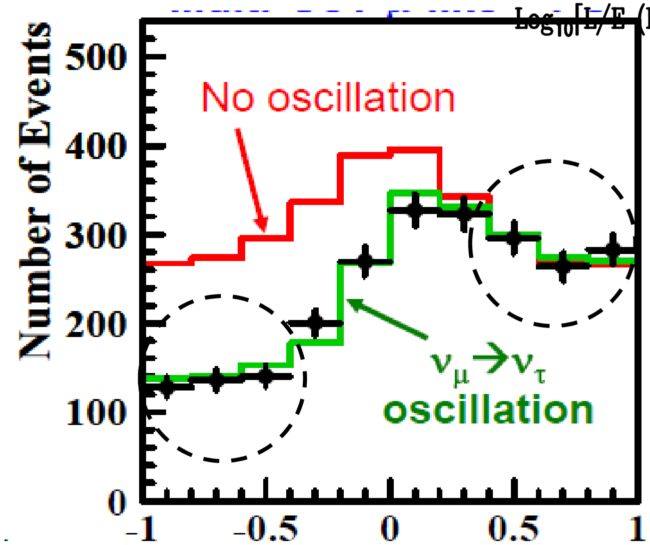
Total: 141 kton･yr



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

J. Raaf, talk @Nu2008

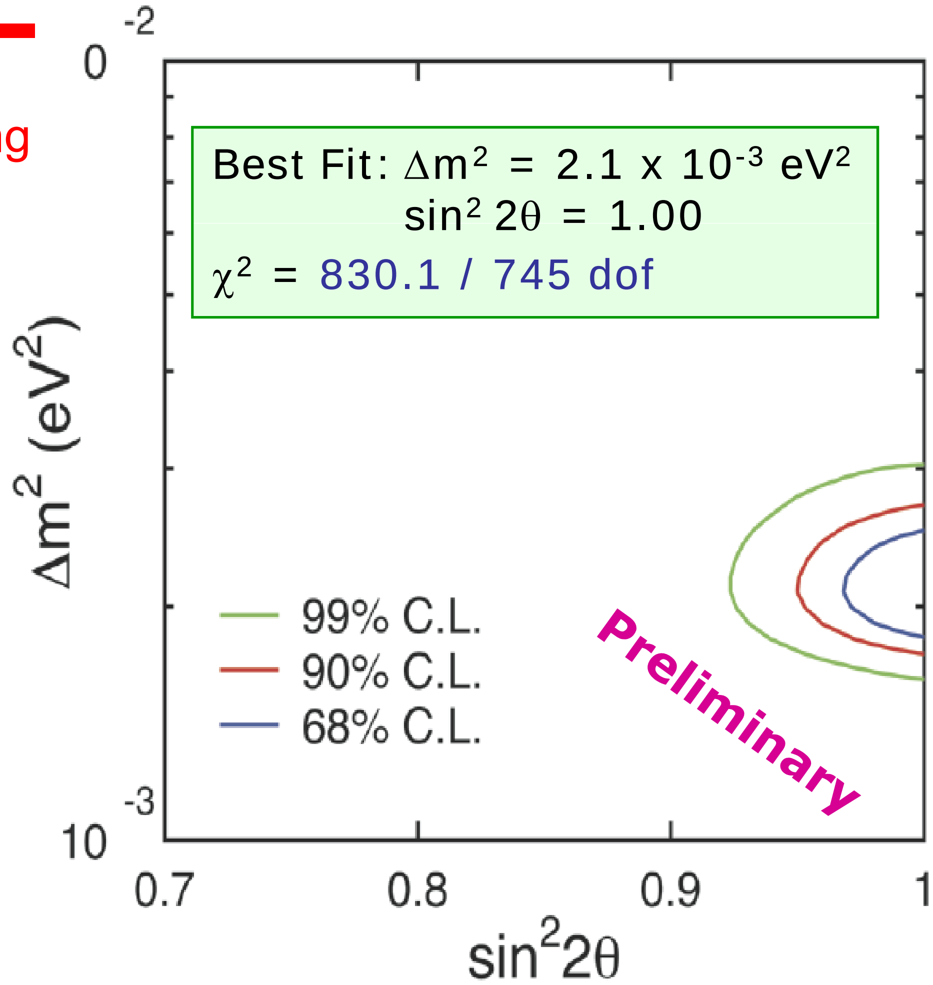




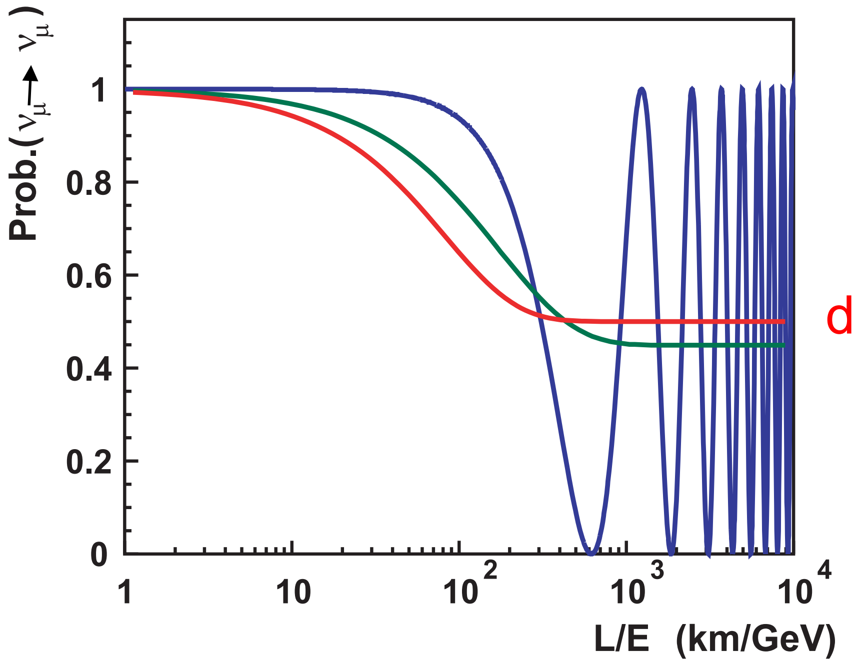
$$\frac{Up}{Down} = 1 - \sin^2 2\theta$$

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

1489 days (SK-1)+ 799 days (SK-II)



Really oscillation?



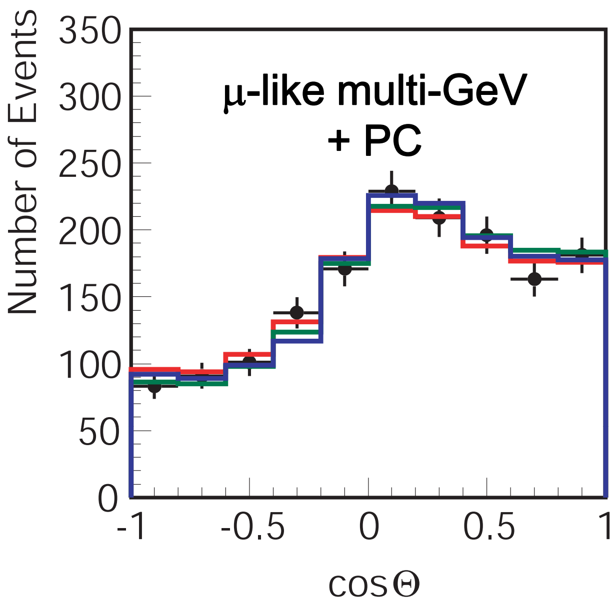
oscillation

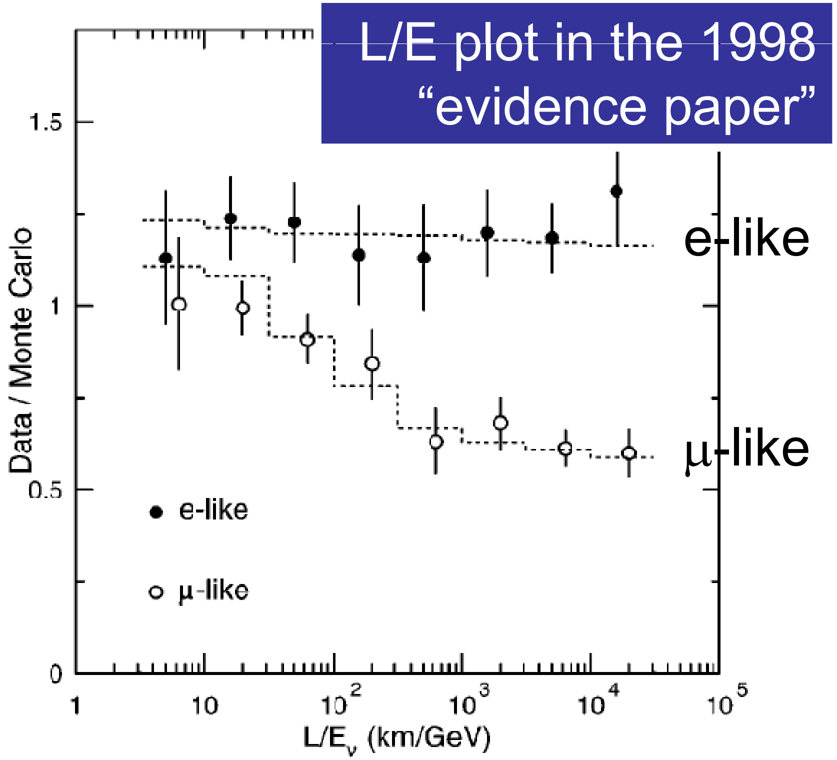
$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \cdot \left(1 - \exp\left(-\gamma_0 \frac{L}{E}\right)\right)$$

decoherence

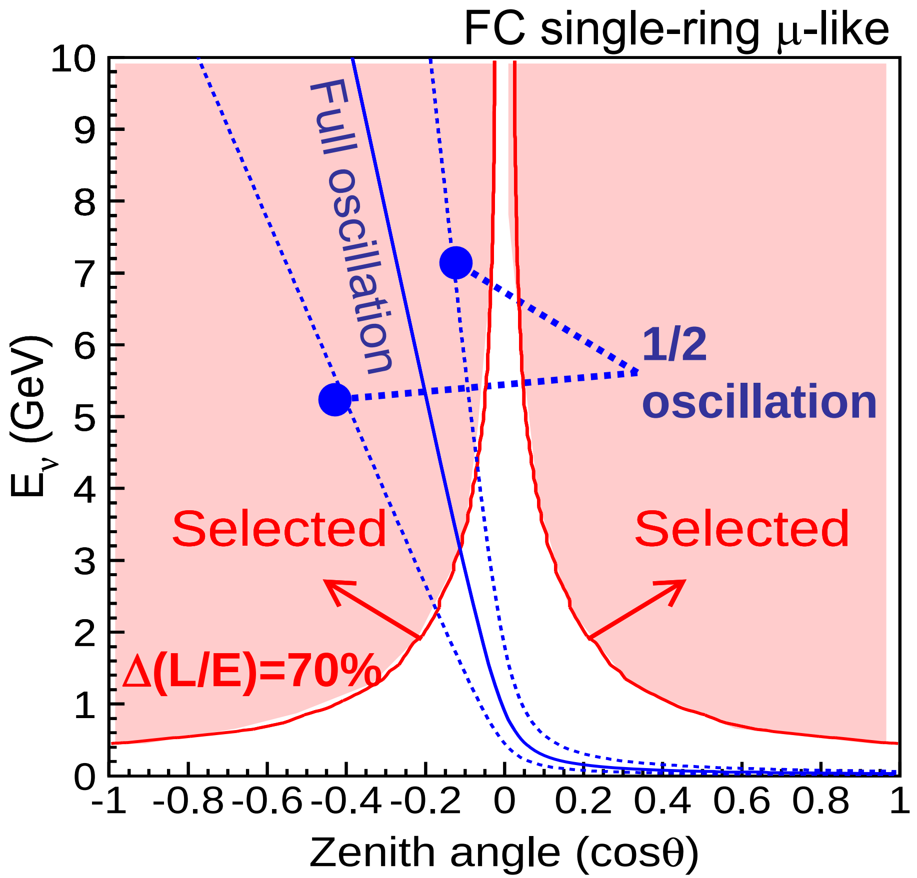
decay

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





L/E: Selection criteria



Select events with high L/E resolution

(Δ(L/E) < 70%)

Events are not used, if:

★horizontally going events

★low energy events

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

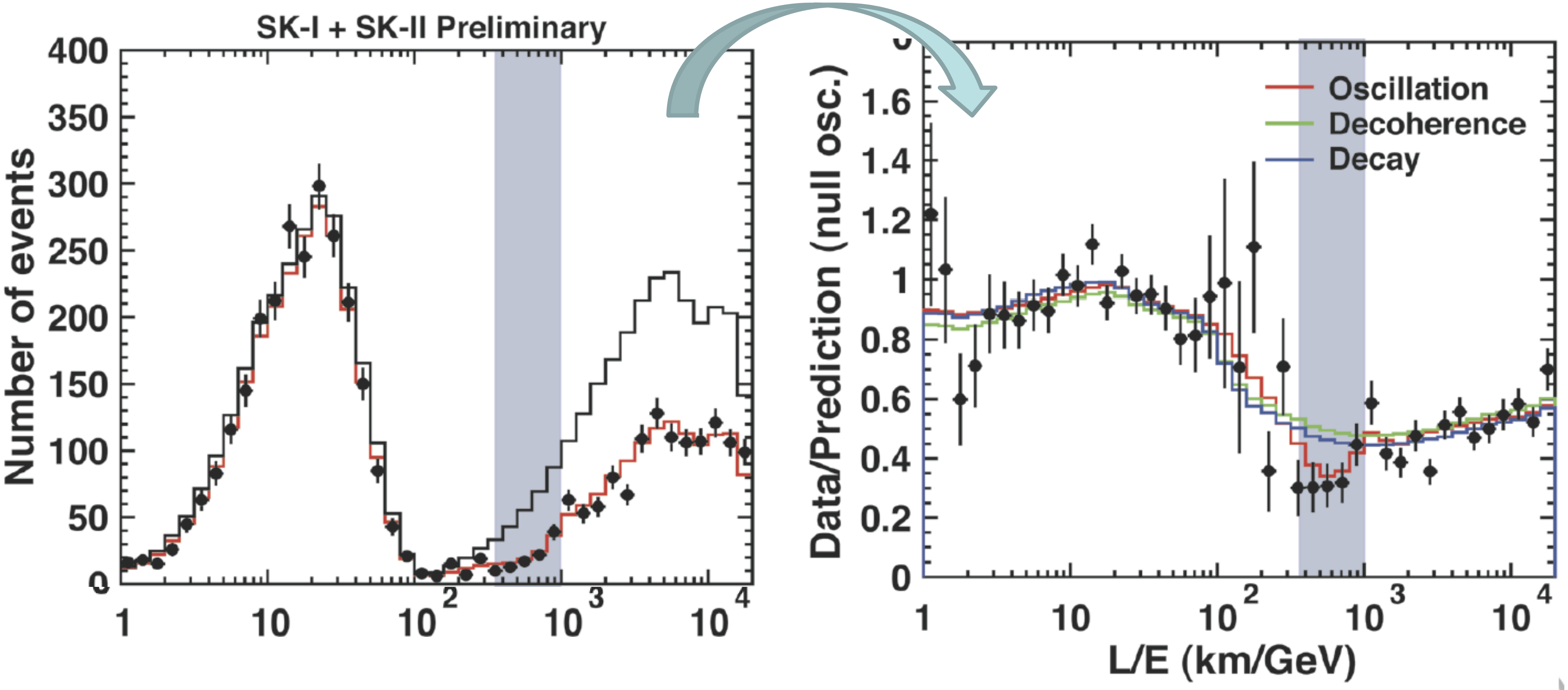
OD stopping PC, and

OD through-going PC

L/E analysis: Really oscillation!

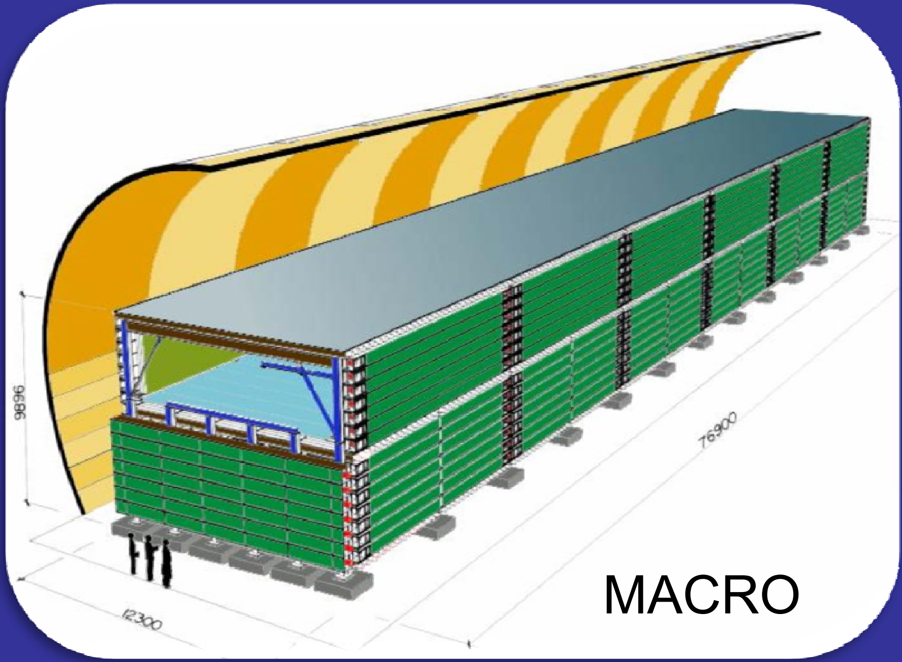
Special analysis with high L/E resolution events.
(σ(L/E)<70%)

Initial results hep-ex/0404034,
J. Raaf, talk @Nu2008

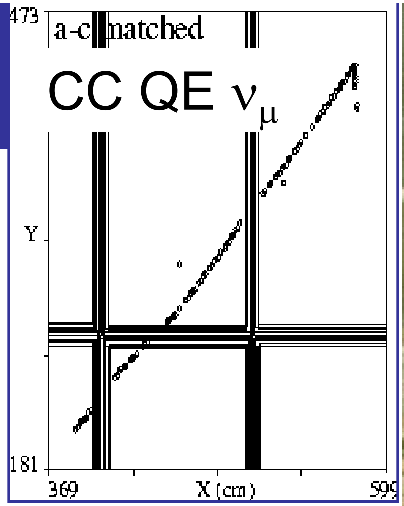


A dip is seem around L/E = 500 km/GeV (first oscillation minimum).
Oscillation gives the best fit to the data.
Decay and decoherence models disfavored at 4.1 and 5.0 σ, resp.

Other atmospheric ν experiments



Soudan2

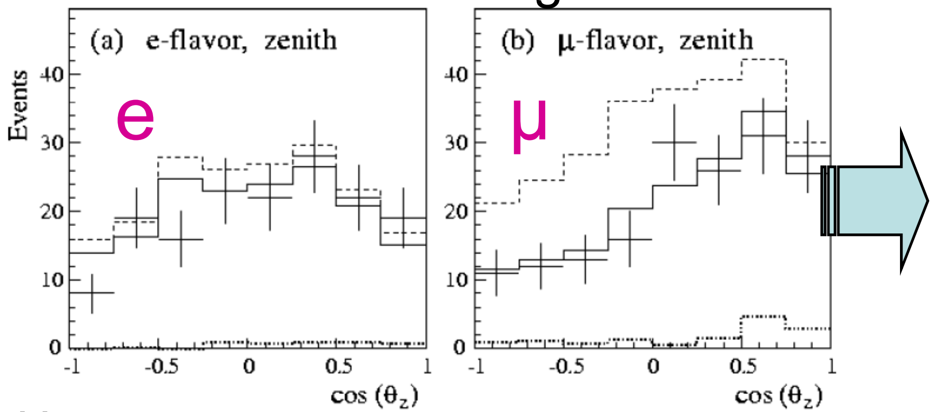


1 kton fine grain tracking calorimeter

5.9 kton･yr exposure
(Experiment: finished)

Phys.Rev. D68 (2003) 113004

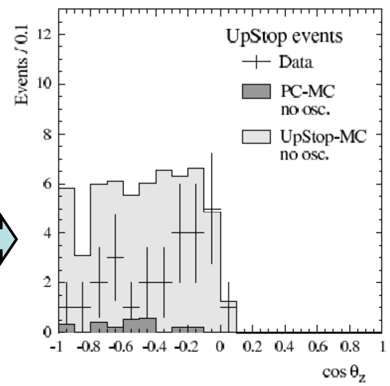
Zenith angle



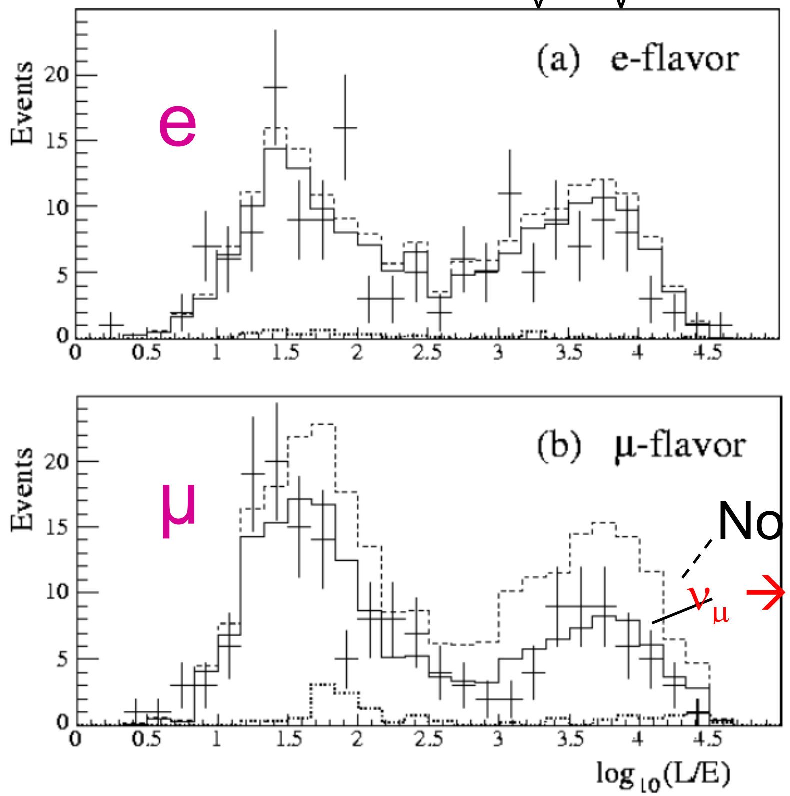
Up-going

Down-going

Upward stopping muons



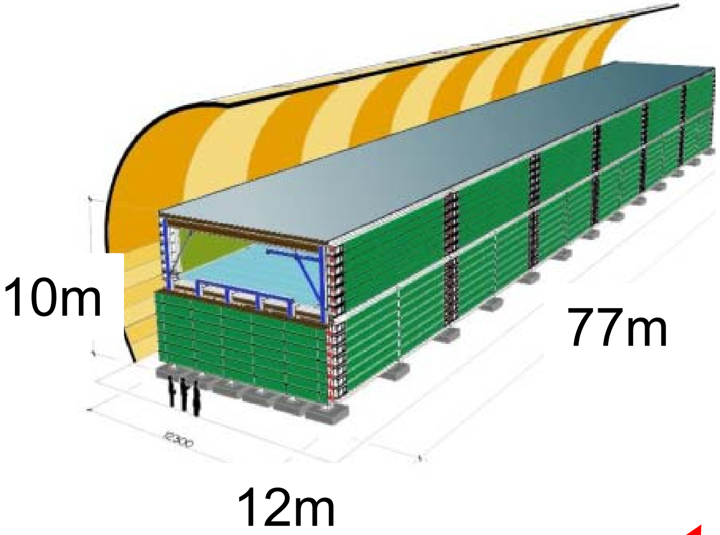
Reconstructed L_ν/ E_ν dist.

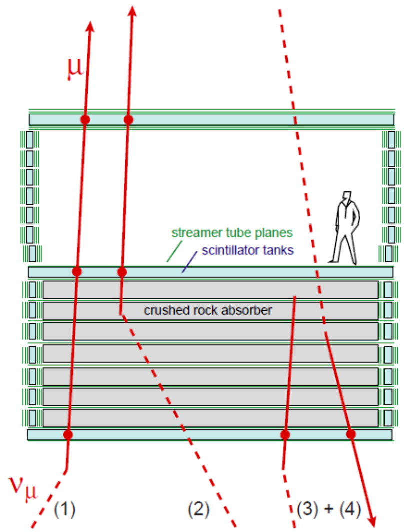


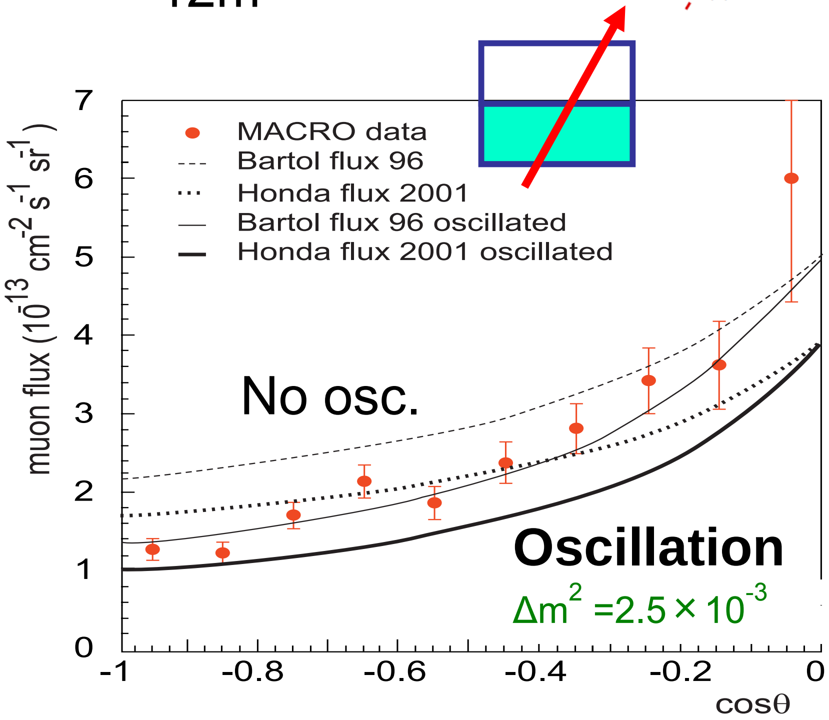
MACRO

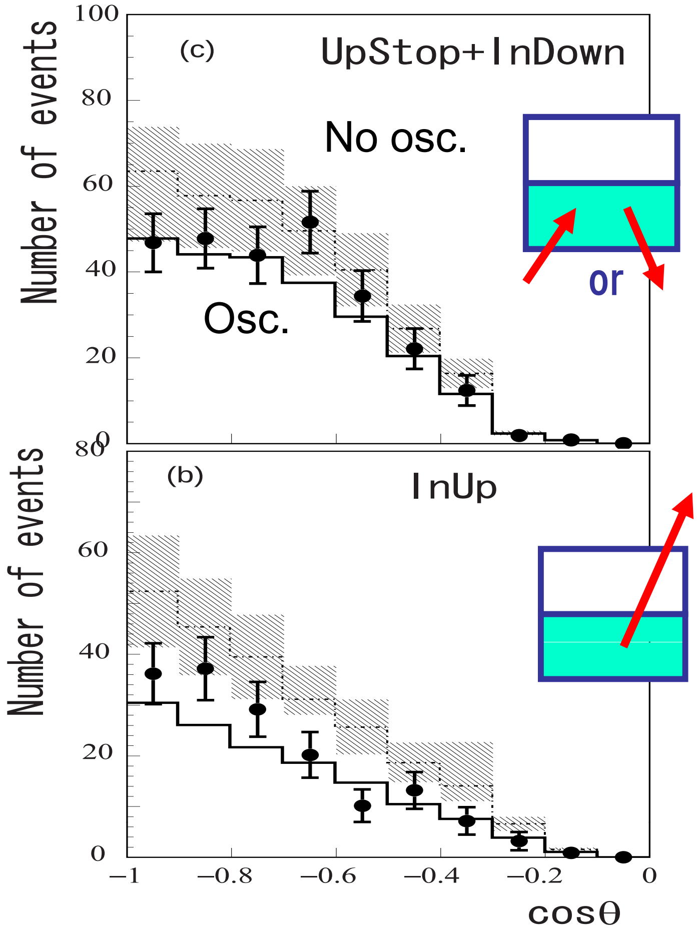
PLB 566 (2003) 35
EPJ C36(2004)323

(Experiment; finished)







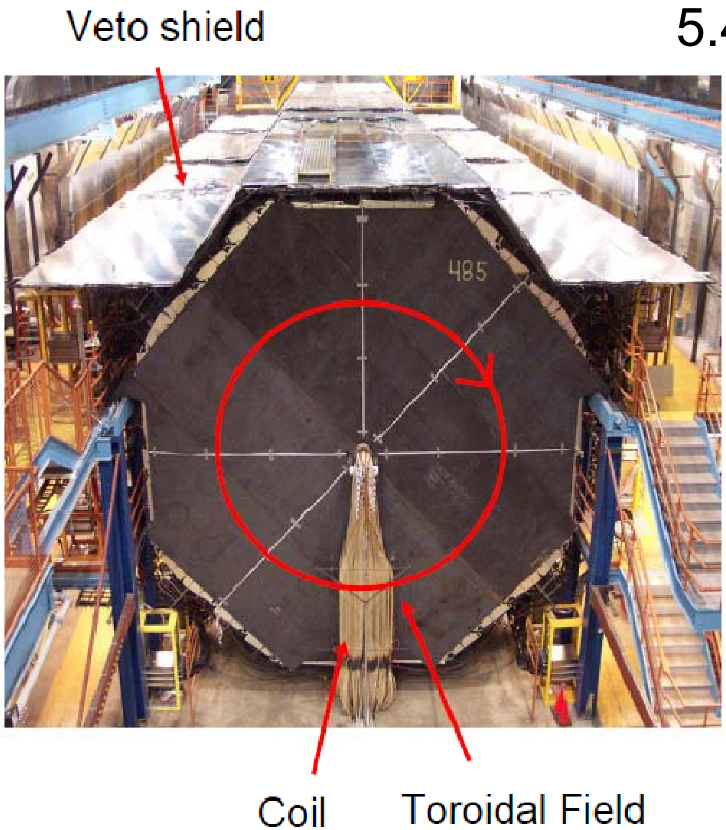


Upward horizontal

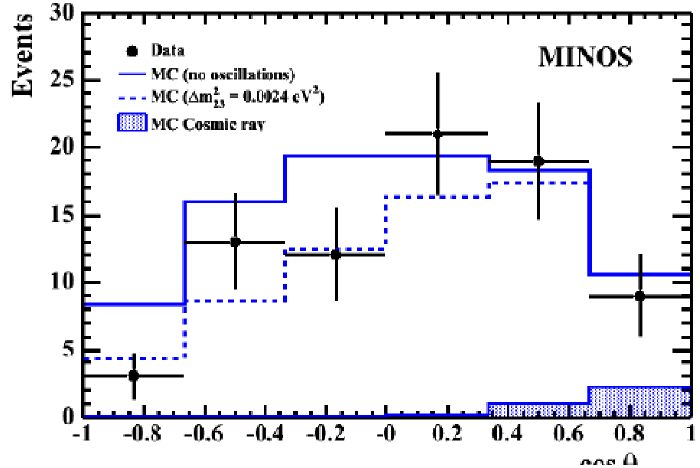
MINOS (atmospheric)

5.4 kton tracking detector with magnetic field

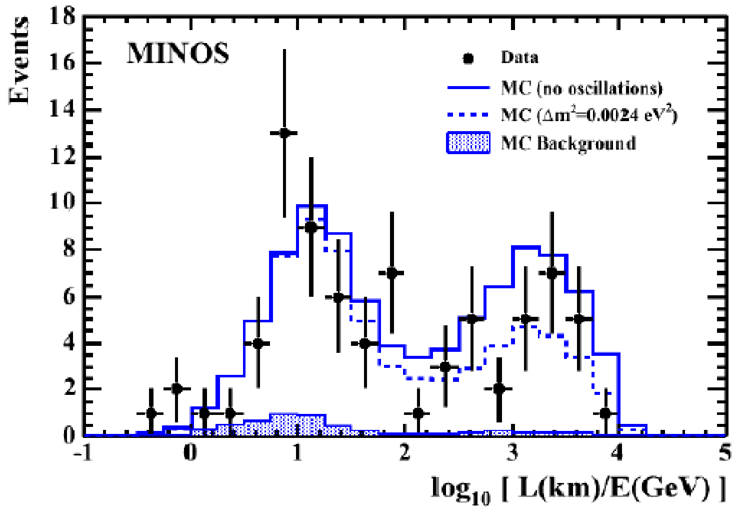
PRD73, 072002 (2006)
6.18 kton・yr (418days)

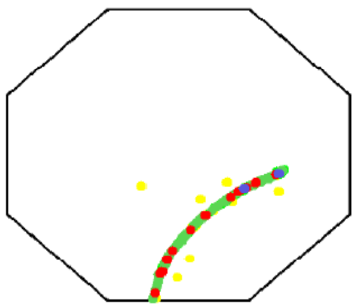


ν_μ zenith-angle



L/E



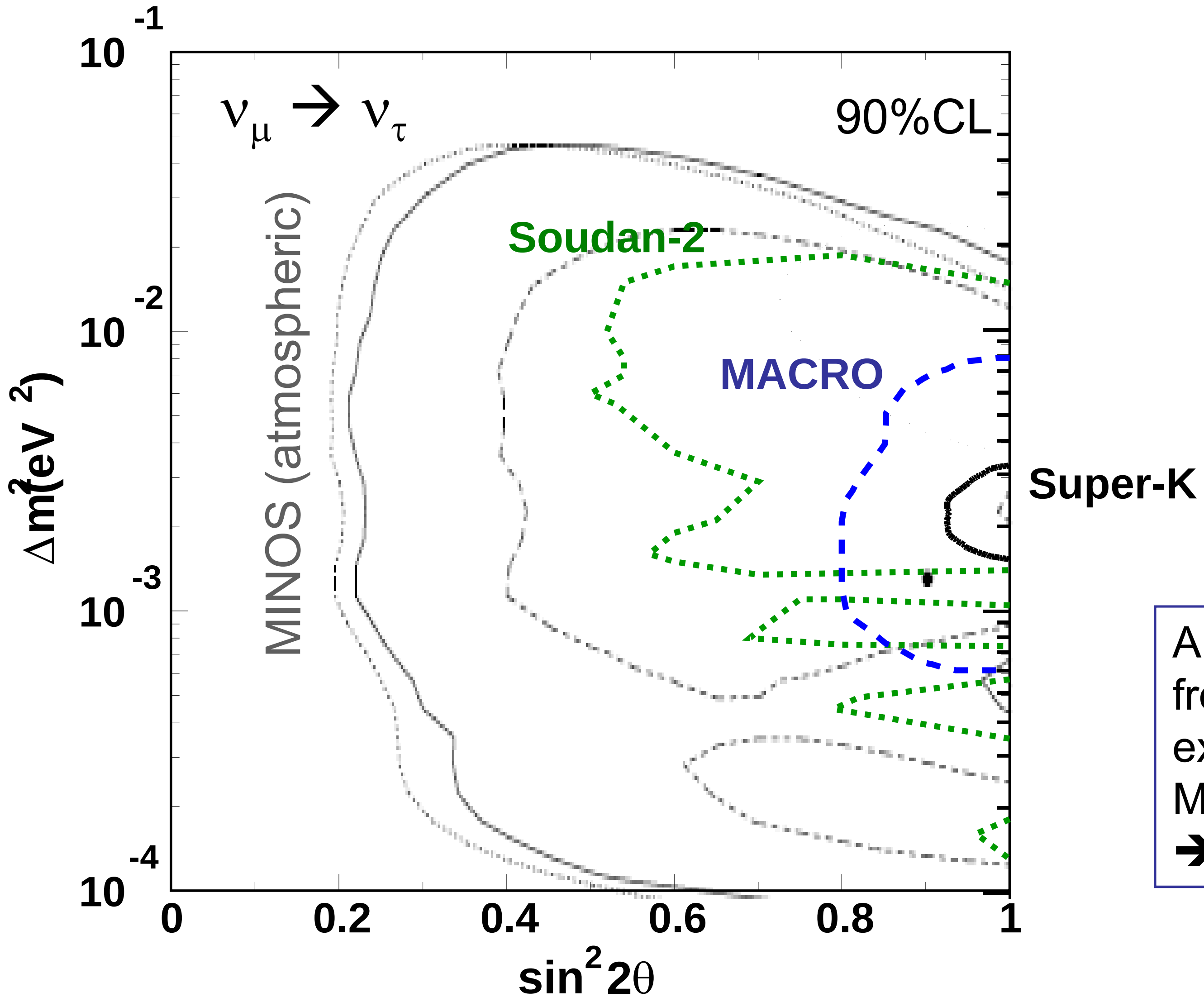


Downward going partially contained event

Separation of ν_μ and anti-ν_μ

hep-ex/0701045

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



Atmospheric neutrino results after 2000.

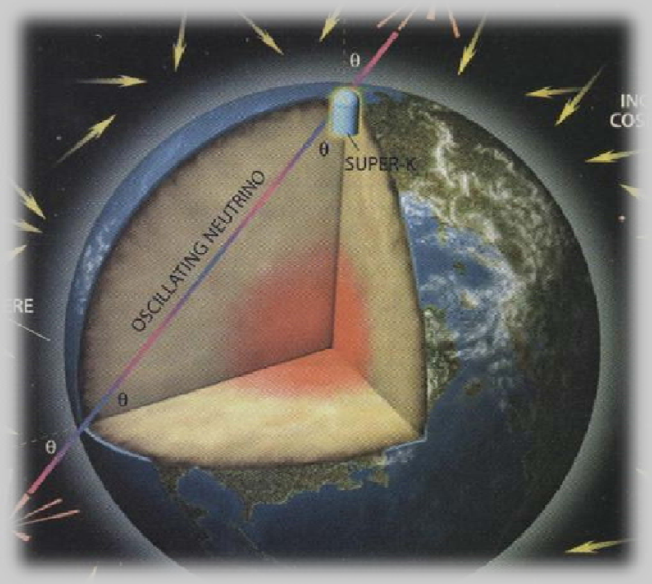
Allowed regions in this page might be slightly old…

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

Long baseline neutrino oscillation experiments

Why long baseline experiments?

Atmospheric neutrinos



➔ Very wide neutrino flight length

➔ Wide neutrino energy

➔ Mixture of ν_μ, anti-ν_μ, ν_e and anti-ν_e

Long baseline Experiments

➔ Single flight length

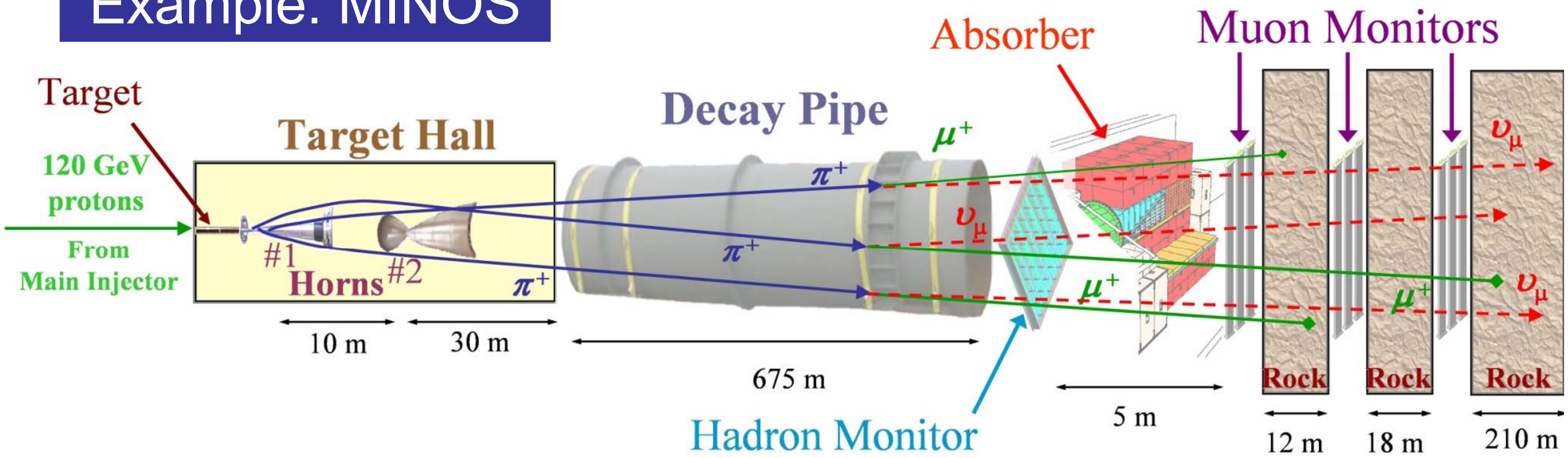
➔ Controlled neutrino energy

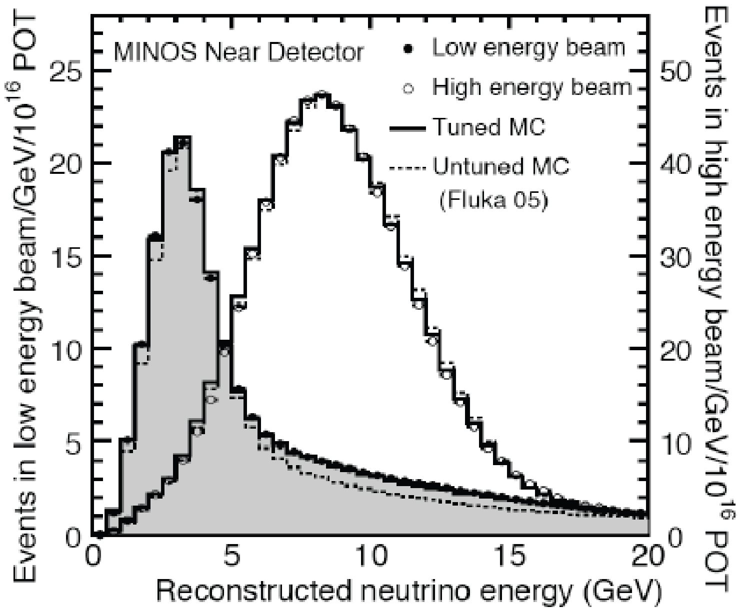
➔ almost pure ν_μ (or anti-ν_μ)

Initial discovery ➔ *Precise studies*

Producing the neutrino beam

Example: MINOS





In the LE configuration, interactions are:

$$92.9\%\ \nu_\mu,\ \underline{5.8\%\ \bar{\nu}_\mu},\ \underline{1.3\%\ \nu_e + \bar{\nu}_e}$$

π^-'s not focused

μ's not decay

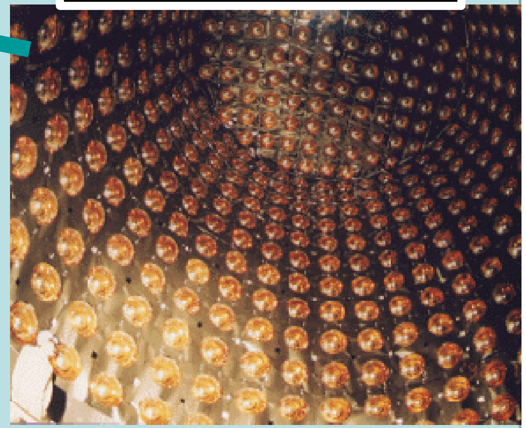
Beam line

Example: K2K

To Super-Kamiokande

250km

Near ν detector



12GeV proton
accelerator

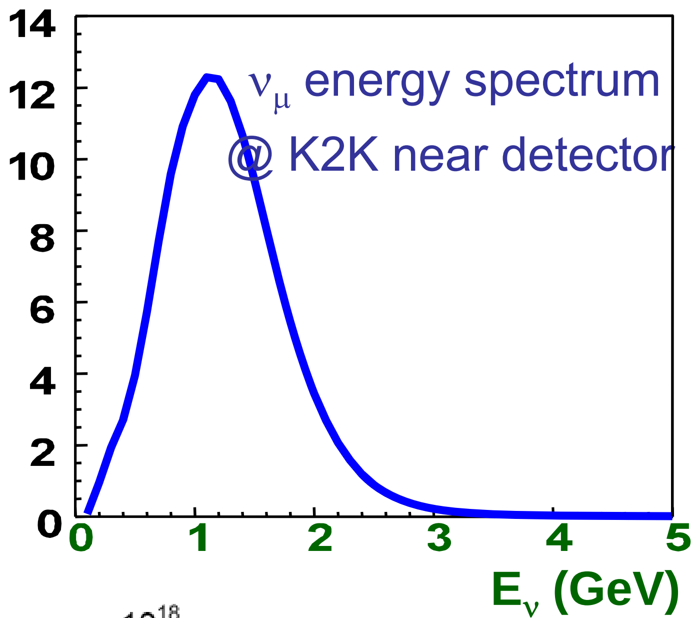
KEK

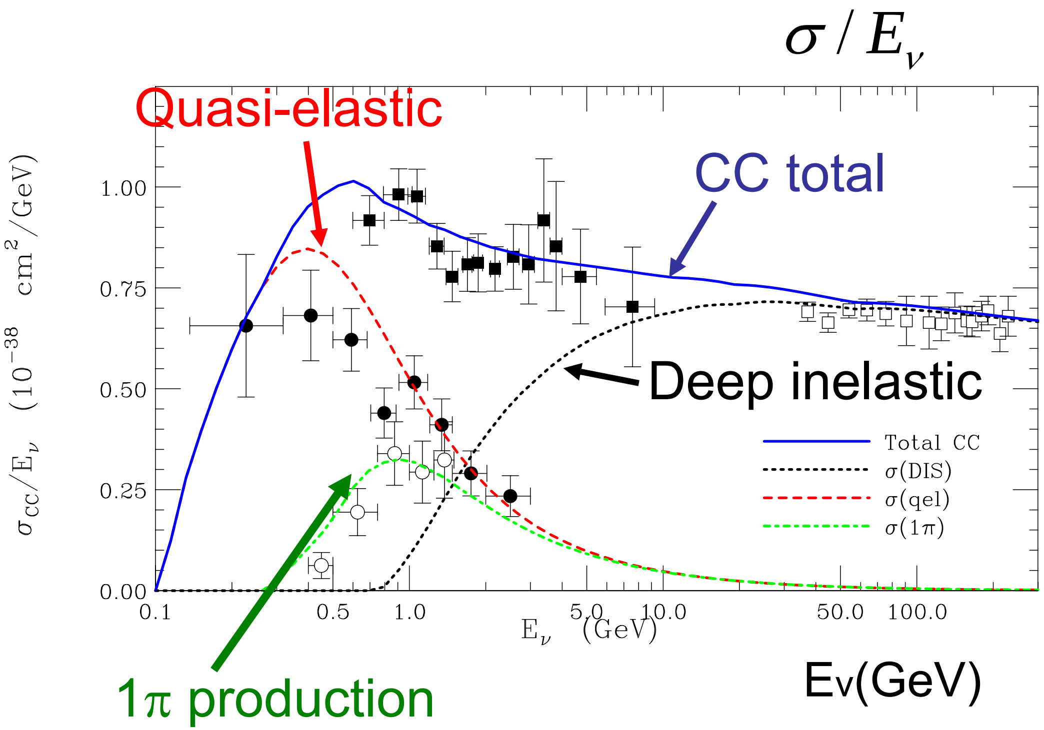
Target region (Horn)

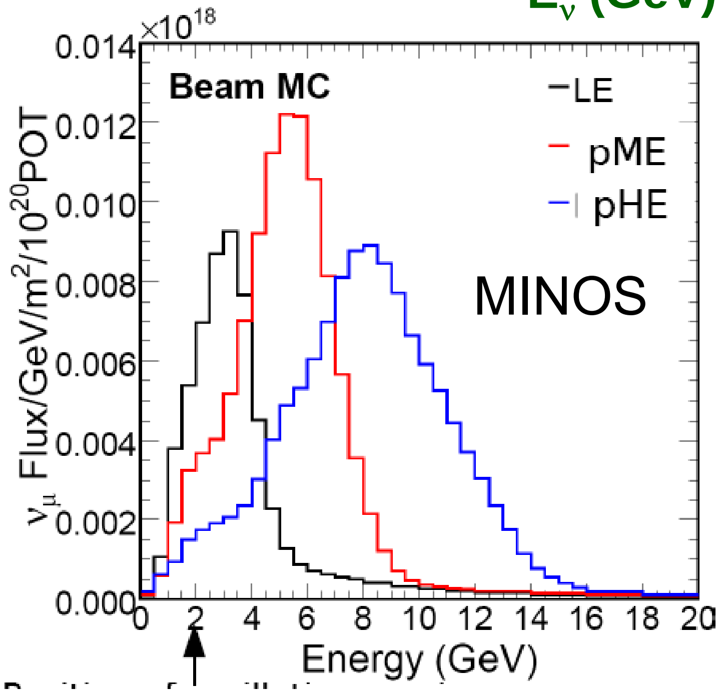
(about 30 years old,
already shut down)

Proton beam line

Neutrino spectrum and neutrino interactions

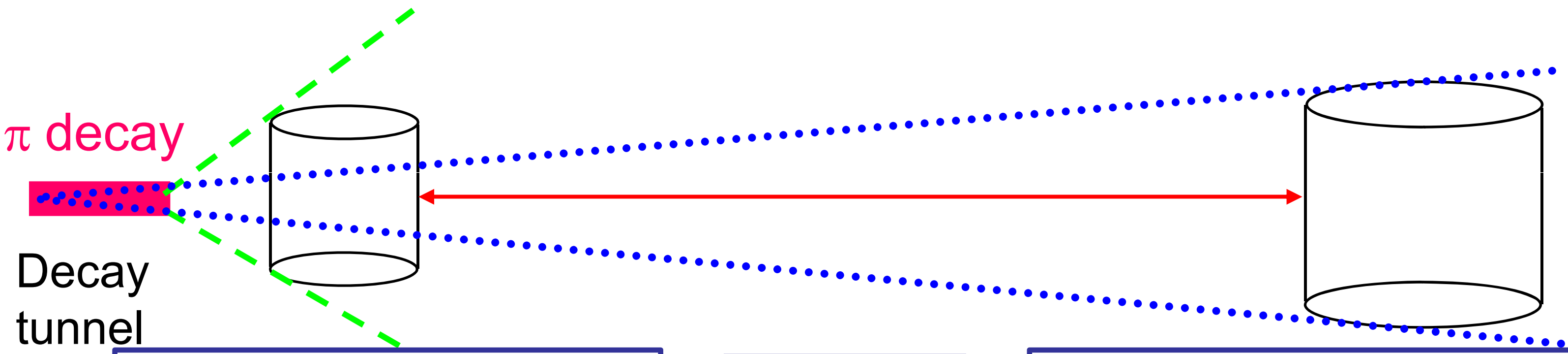






Various neutrino interaction modes are important.
➔ Good understanding of the neutrino interactions necessary.

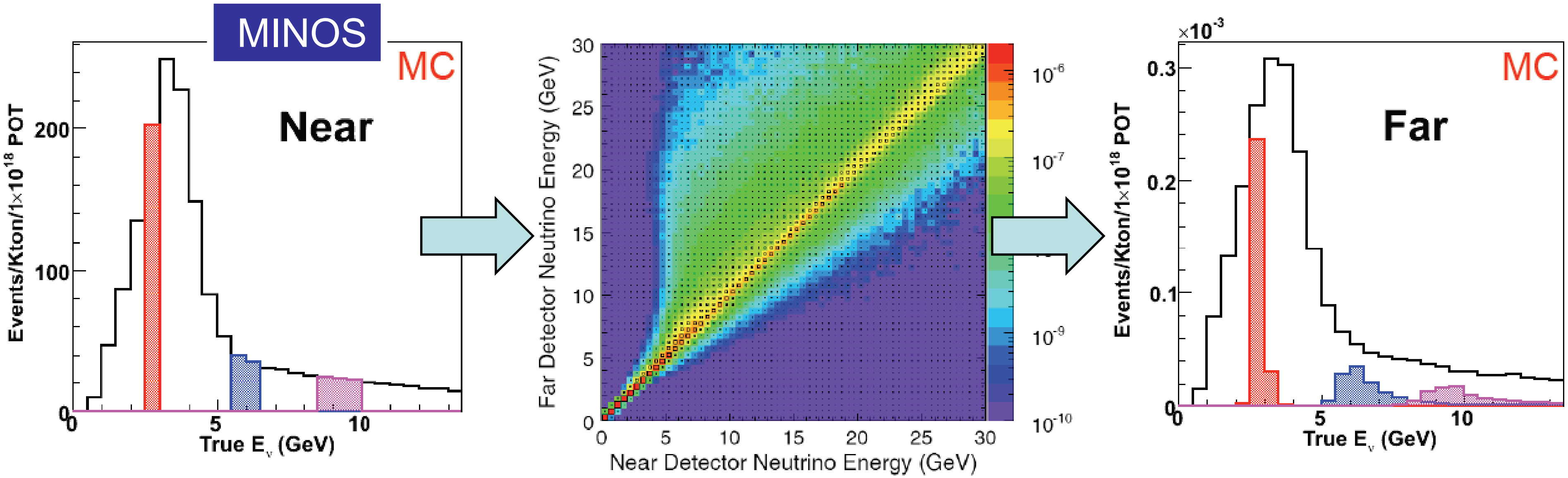
Neutrino spectrum and the far/near ratio



Near detector:
Neutrinos are produced from a line source.

different

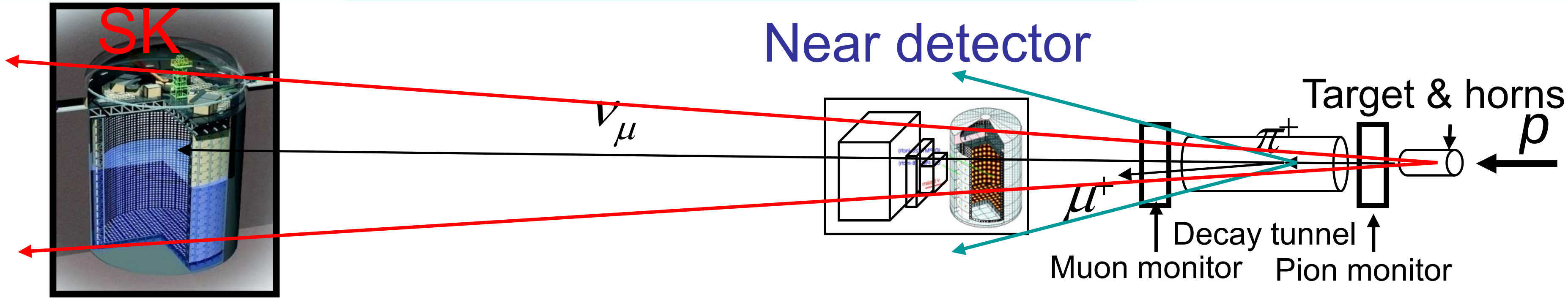
Far detector:
Neutrinos are produced from an approximate point source.



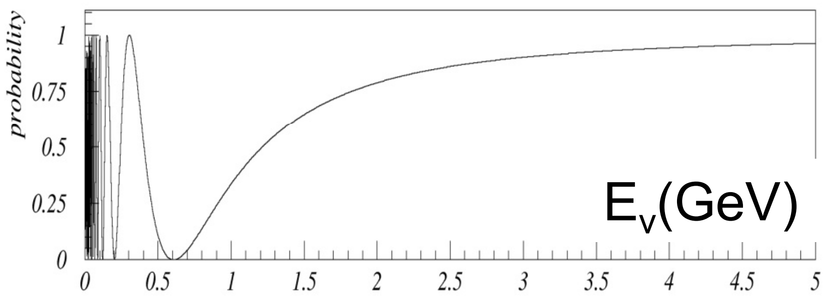
Near spectrum ➔ ➔ ➔ Matrix ➔ ➔ ➔ Far spectrum

K2K experiment and its results

hep-ex/0606032



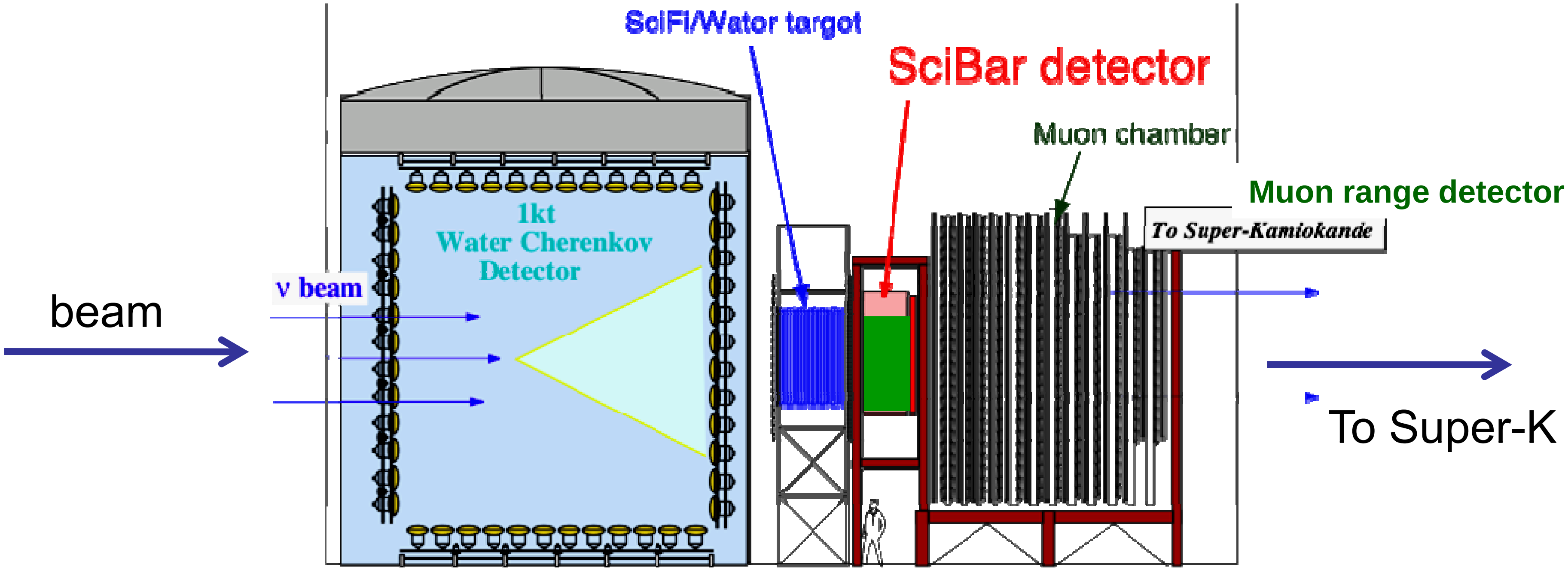
Neutrino oscillation probability for Δm^2=0.003eV^2 and at 250km.



Near detector measurements

- 1KT Water Cherenkov Detector (1KT)
- Scintillating-fiber/Water sandwich Detector (SciFi)
- Lead Glass calorimeter (LG) before 2002
- Scintillator Bar Detector (SciBar) after 2003
- Muon Range Detector (MRD)

They predict the event rate and spectrum @ Super-K



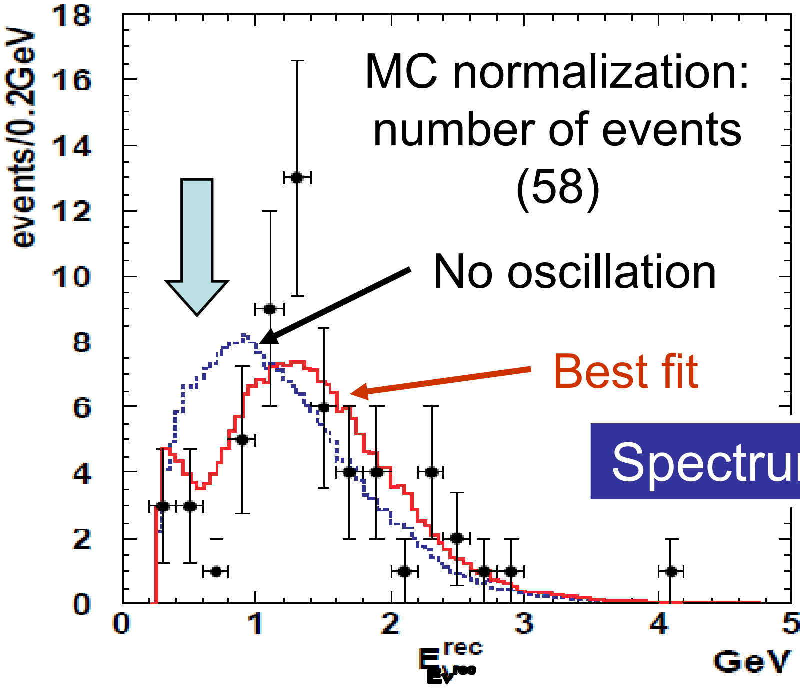
K2K events in Super-Kamiokande

K2K-I + II	DATA	MC
FC 22.5kt	112	$158.1^{+9.2}_{-8.6}$
1ring	67	
μ-like	58	
e-like	9	
Multi Ring	45	

Number

Event deficit

Energy spectrum

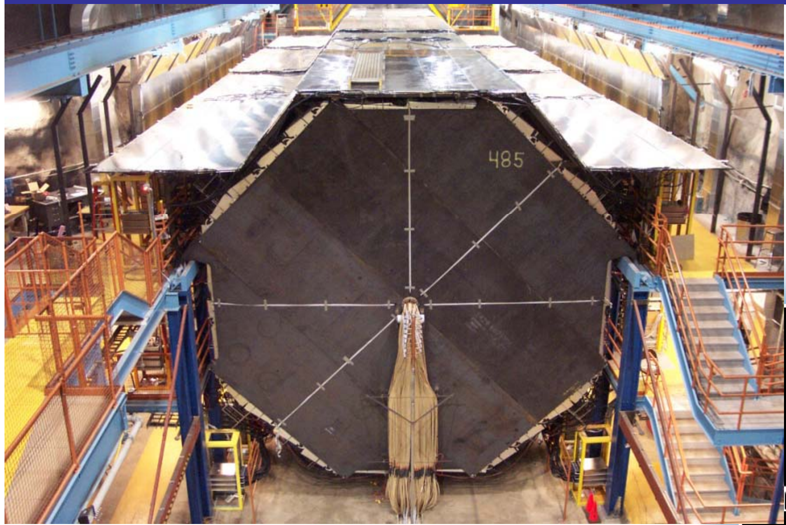


Spectrum distortion

reconstructed Eν (GeV)

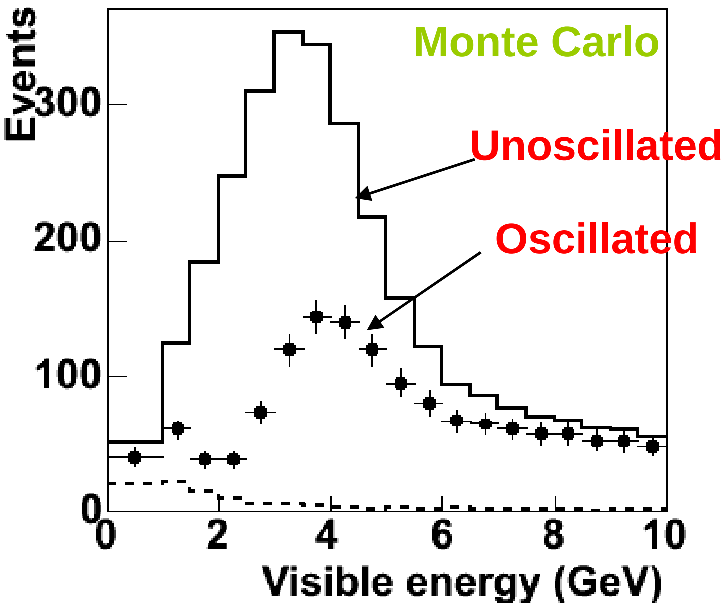
Osc. analysis

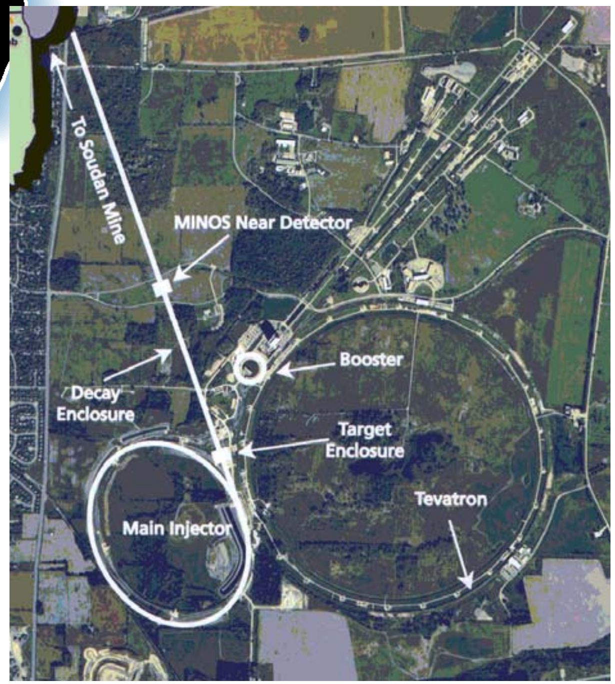
The MINOS experiment and its results



5.4 kton MINOS far detector

1 kton near detector



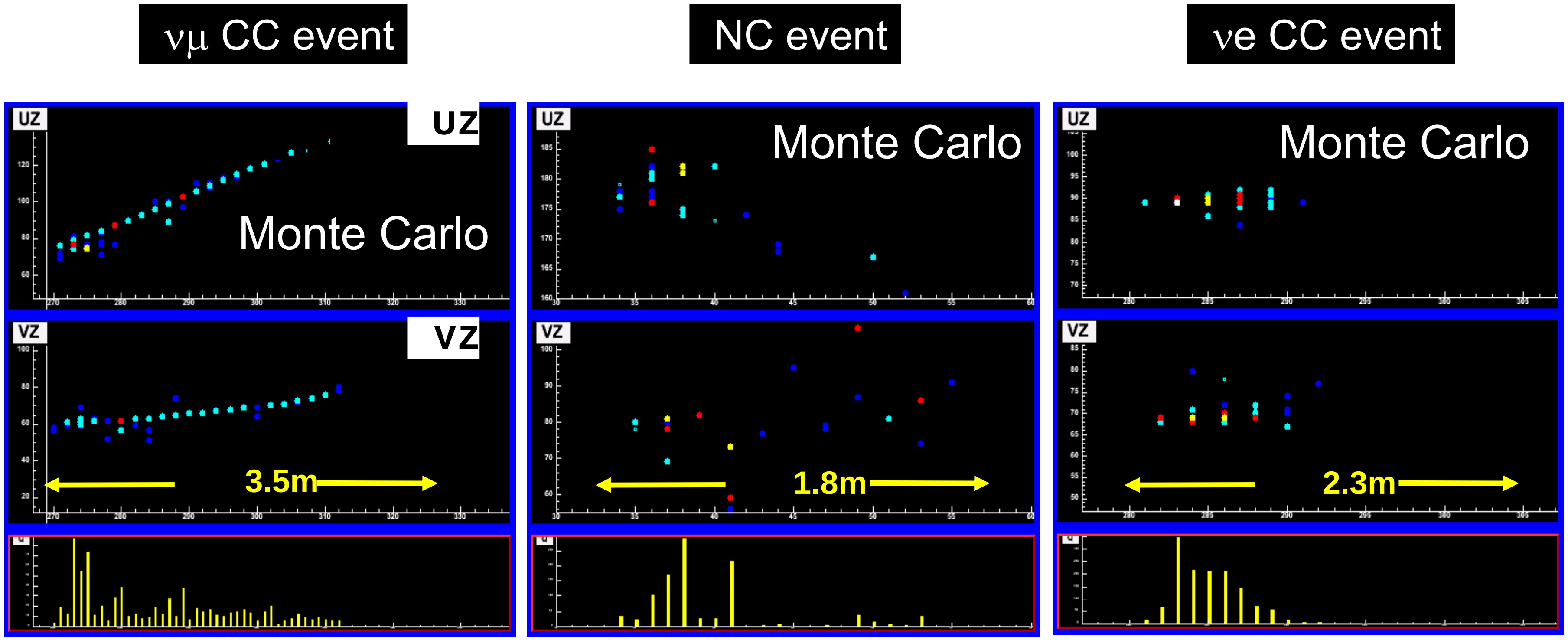


NuMI beam line

MINOS near and far detectors

1	mass (kt)	5.4
3.8x4.8	plane size (m^2)	8x8
282/153	# steel/scint pl.	486/484
front: all pl. instrumented back: 1/5 pl. instrumented fast QIE electronics	specifics	veto shield for cosmics 8x optical multiplexing

MINOS event topologies



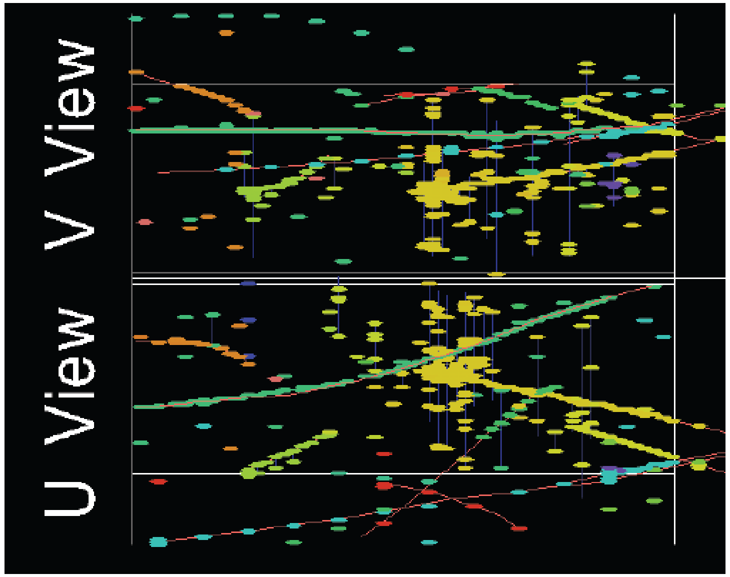
- Long muon track + hadronic activity at vertex
- Short showering event, often diffuse
- Short event with typical EM shower profile

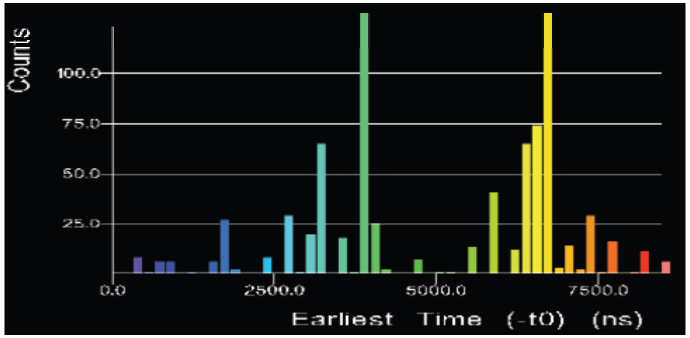
These events must be selected for the $\nu_\mu \rightarrow \nu_\mu$ studies

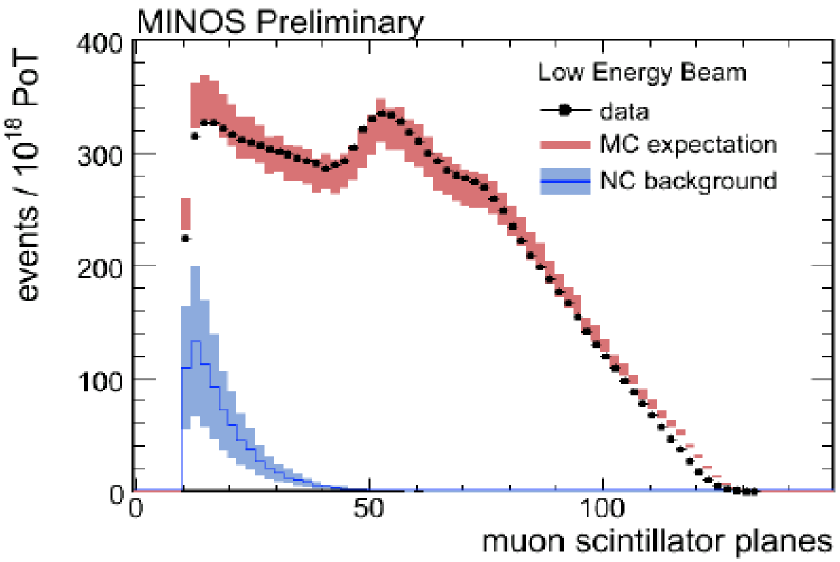
Checking neutrino events with the near detector data

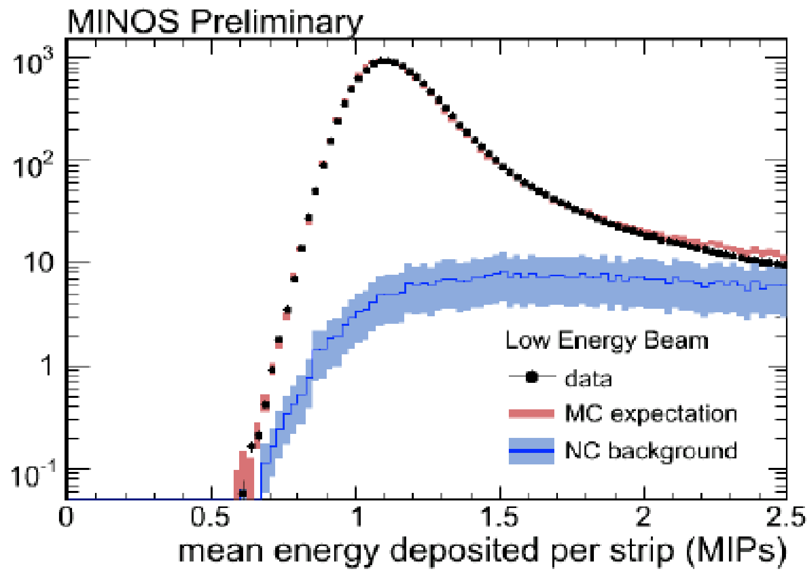
Typical near detector data.

(Multiple events per spill are separated based on topology and timing.)







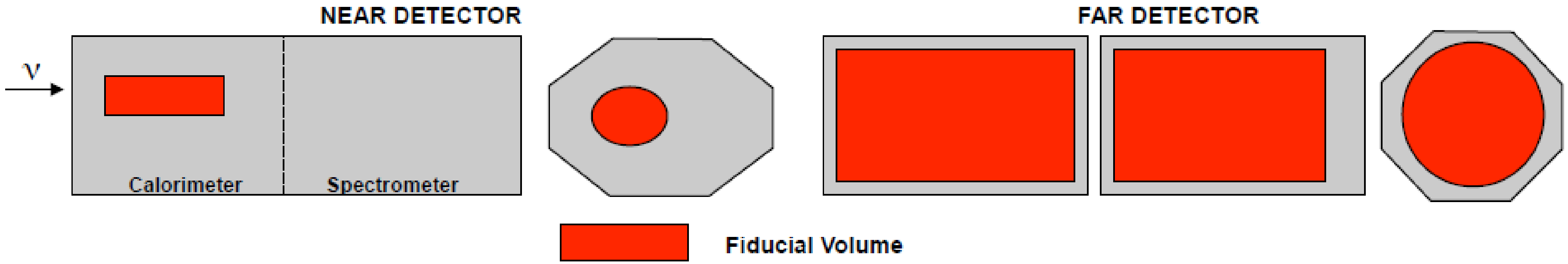


MINOS ν_μ event selection

ν_μ CC is selected by;

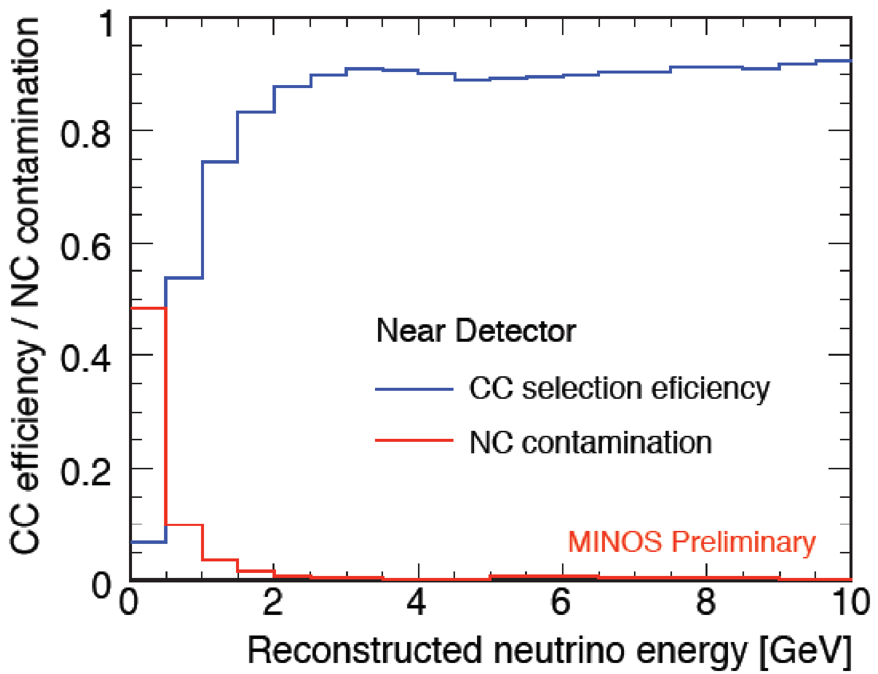
- >=1 track
- Fiducial volume

Total mass: 5.4kton
Fiducial mass: 3.9kton



- Negative charge (curvature)
- k-nearest neighbor (kNN) based on
  - Track length
  - Mean pulse height
  - Fluctuation in pulse height
  - Transverse track profile

CC efficiency and NC contamination

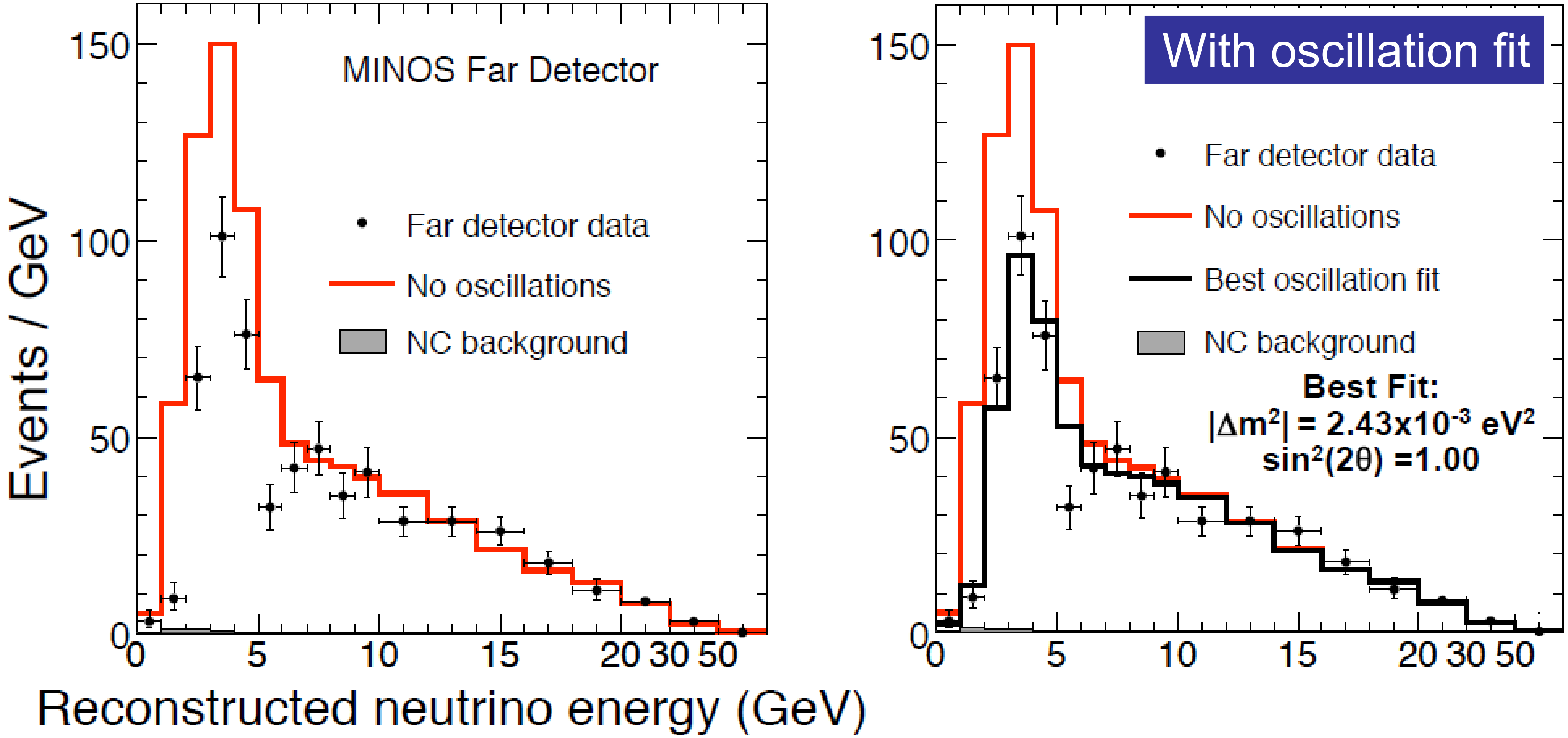


MINOS updated results

H. Gallagher(MINOS collab.) talk at Nu2008

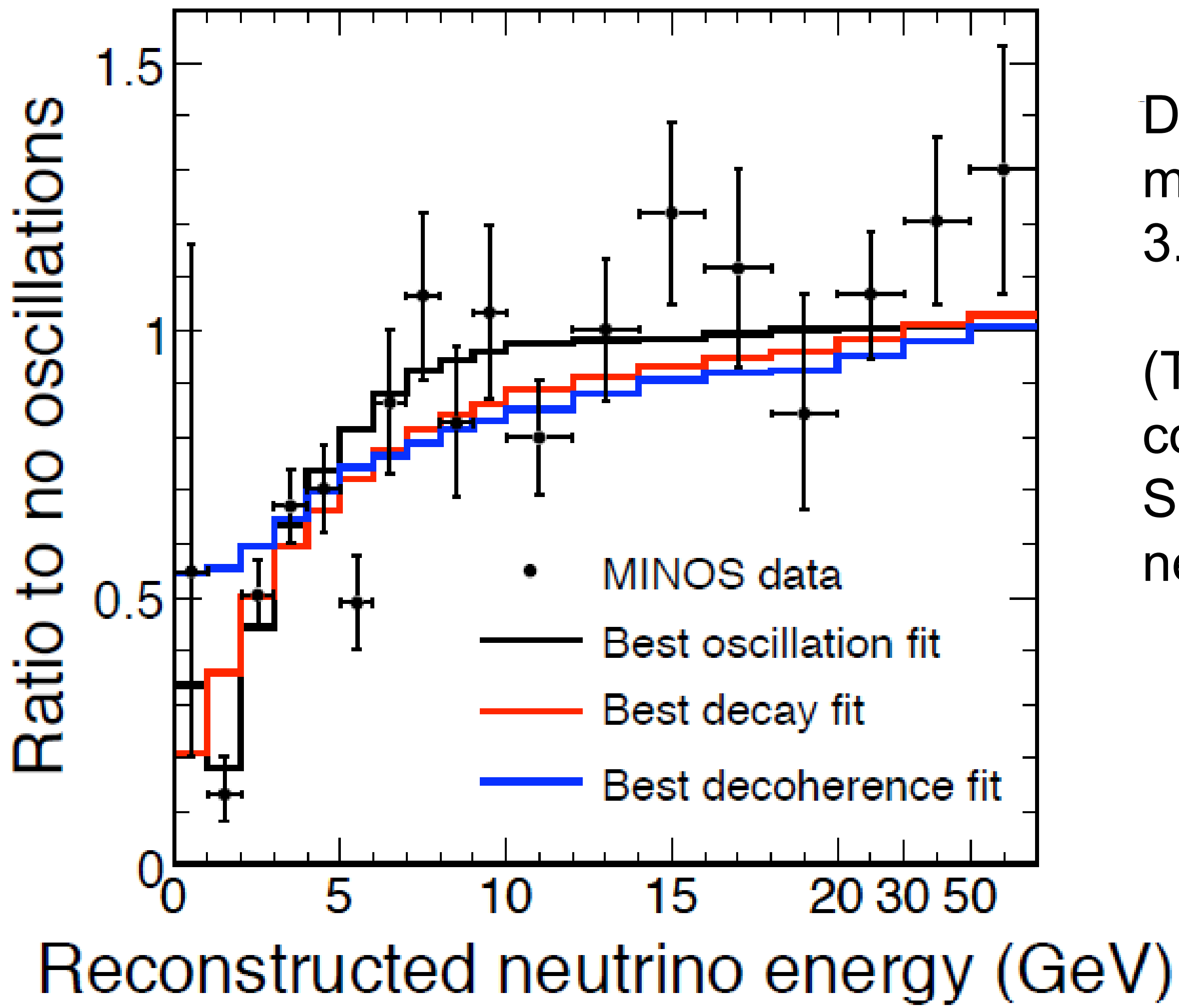
3.2×10^{20} pot (～Aug. 2007)

848 CC ν_μ candidates ←→ 1065±60(syst) no-osc. prediction



Clear energy dependent ν_μ deficit, which is completely consistent with $\nu_\mu \rightarrow \nu_\tau$.

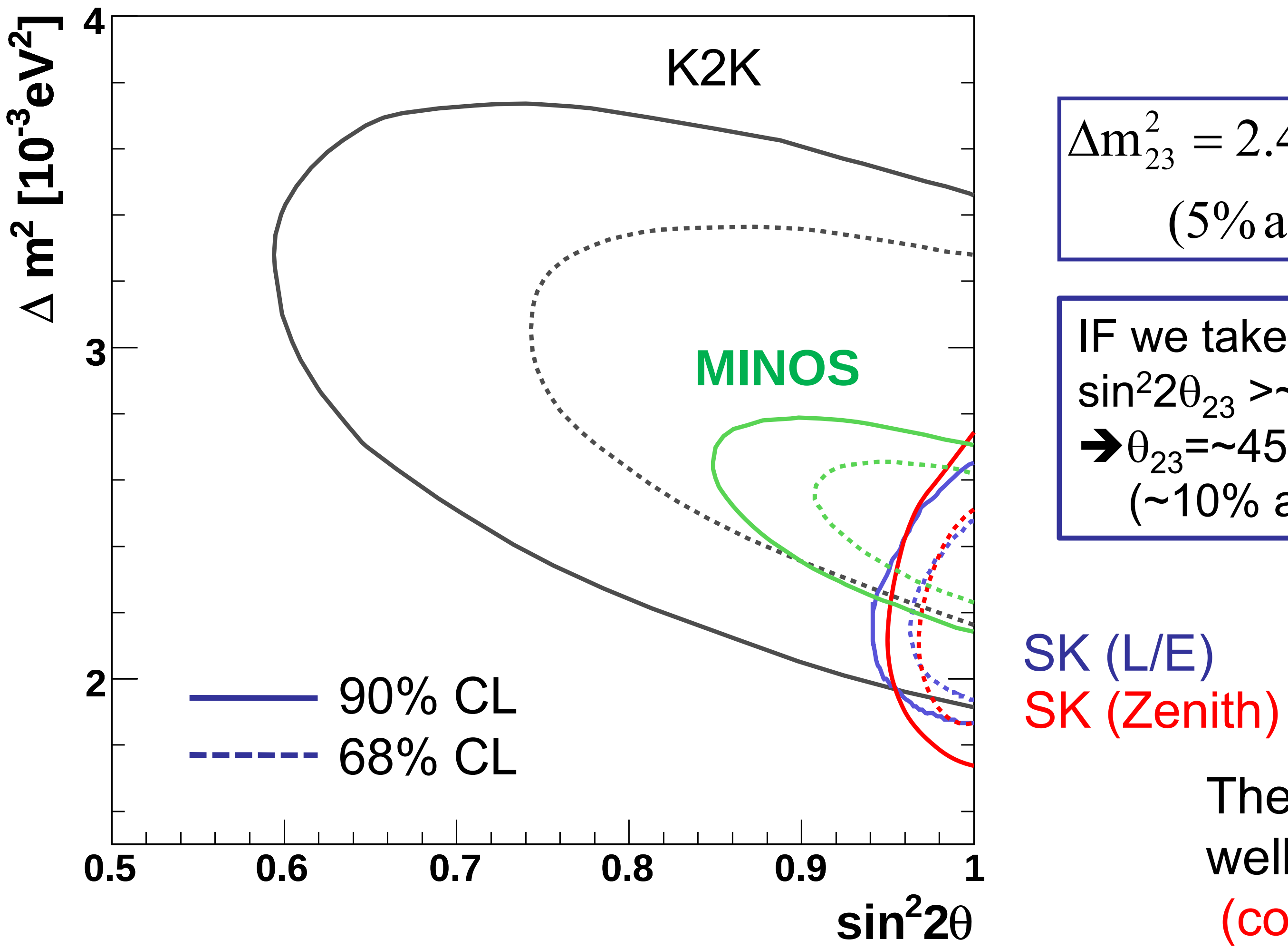
Testing alternative hypotheses @MINOS



Decay and decoherence models are disfavored at 3.7 and 5.7σ, resp.

(These results are consistent with those from Super-K atmospheric neutrino experiment.)

Allowed parameter space from present experiments



$$\Delta m^2_{23} = 2.43 \pm 0.13 \times 10^{-3}\, eV^2$$

(5% accuracy, MINOS)

IF we take $\Delta\chi^2 = 1$,
$\sin^2 2\theta_{23}$ >~ 0.98
➔ θ_{23}=~45±4
(~10% accuracy, Super-K)

These results agree well!
(consistent with maximal mixing!)

Accuracy: Δm^2: Atm → LBL, $\sin^2 2\theta$: still atm.

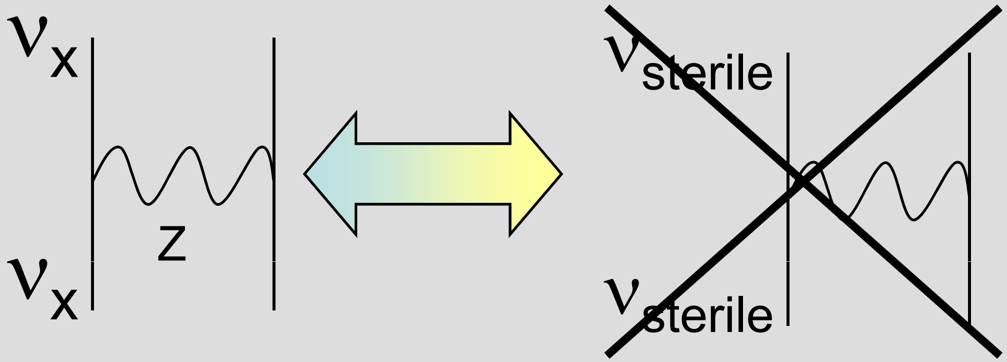
Oscillation to ν_τ or $\nu_{sterile}$?

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

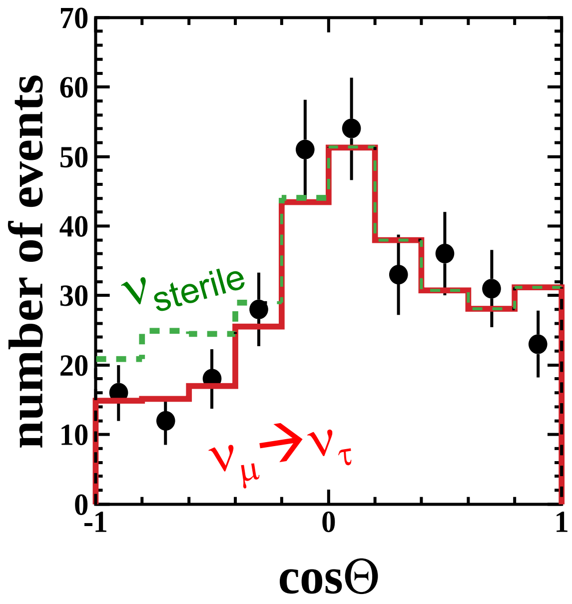


Interaction → Neutral current interaction

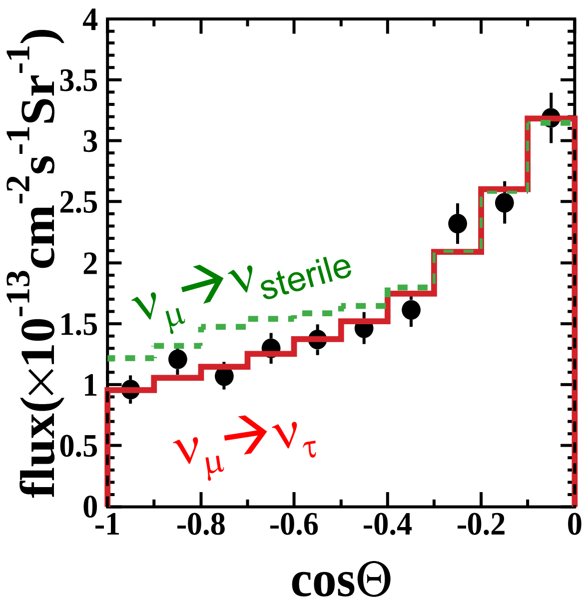
Testing $\nu_\mu \rightarrow \nu_\tau$ vs. $\nu_\mu \rightarrow \nu_{sterile}$

Matter effect

High E PC events (Evis>5GeV)

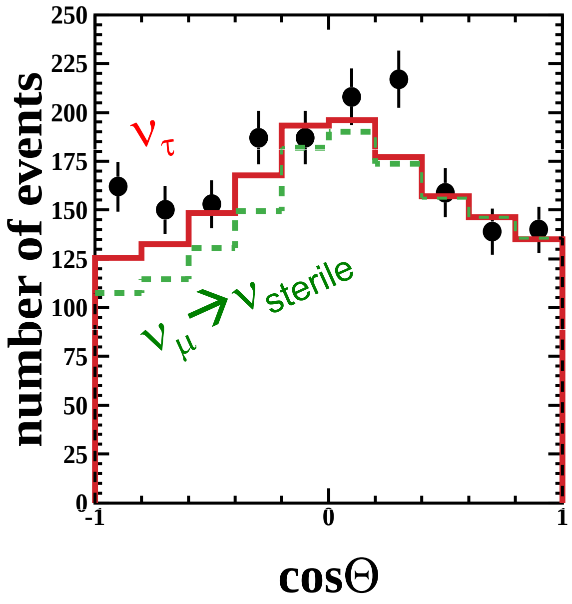


Up through muons



Neutral current

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



⇒ **Pure $\nu_\mu \rightarrow \nu_{sterile}$ excluded**

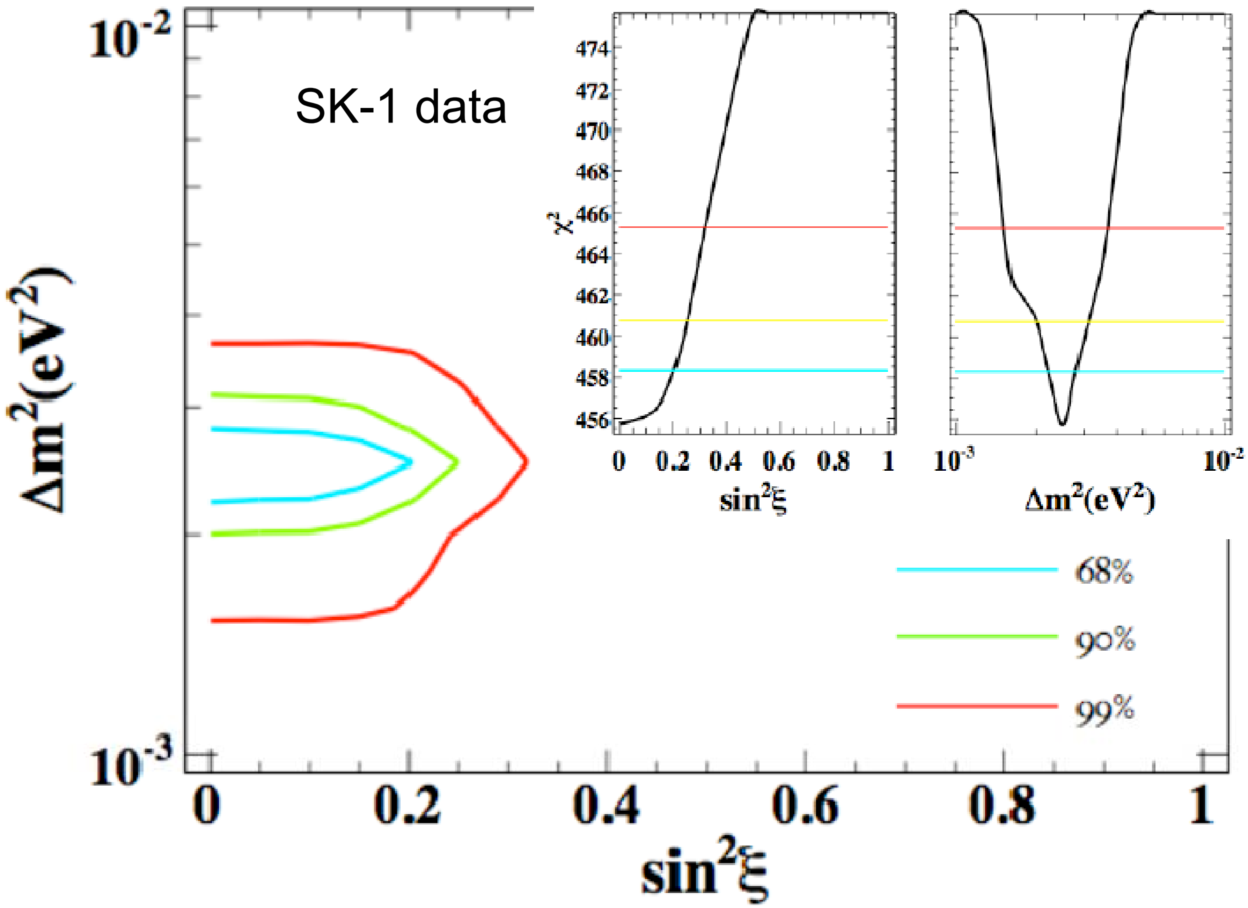
(PRL85,3999 (2000))

Limit on oscillations to $\nu_{sterile}$

$\nu_\mu \rightarrow (\sin\xi \cdot \nu_{sterile} + \cos\xi \cdot \nu_\tau)$

If pure $\nu_\mu \rightarrow \nu_\tau$, $\sin^2\xi=0$

If pure $\nu_\mu \rightarrow \nu_{sterile}$, $\sin^2\xi=1$



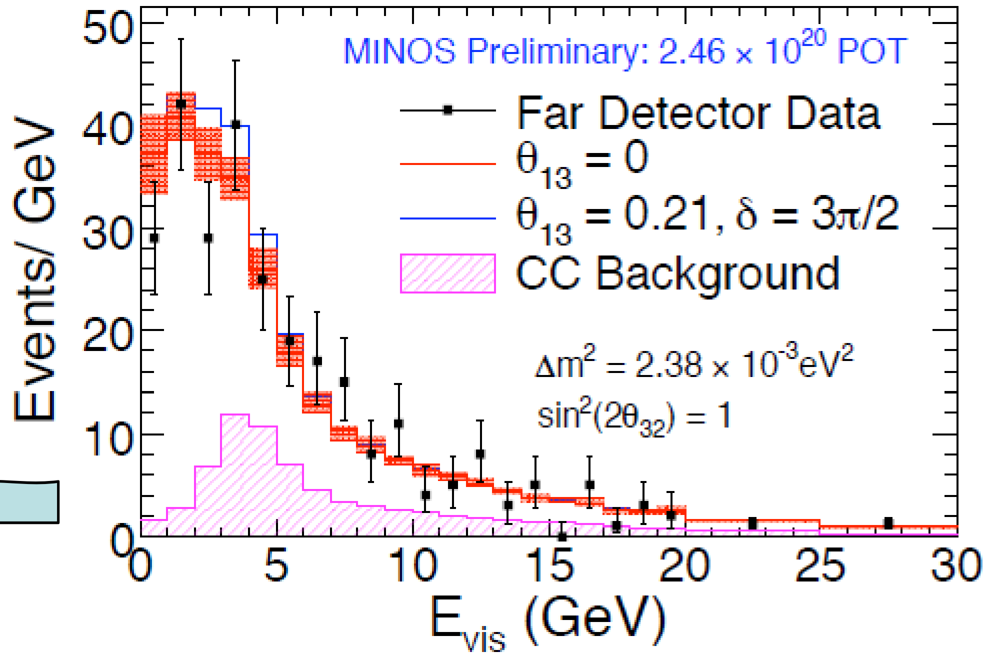
Consistent with pure $\nu_\mu \rightarrow \nu_\tau$

SK collab. draft in preparation

(This figure is slightly old)

MINOS NC analysis

Energy spectra for NC-like events



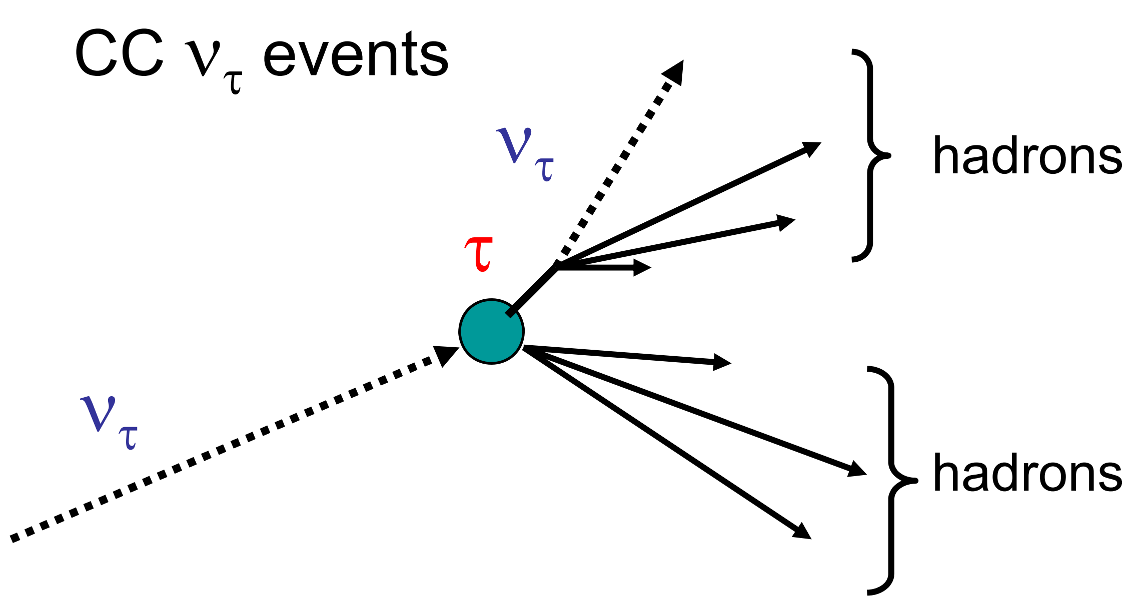
No evidence for NC disappearance

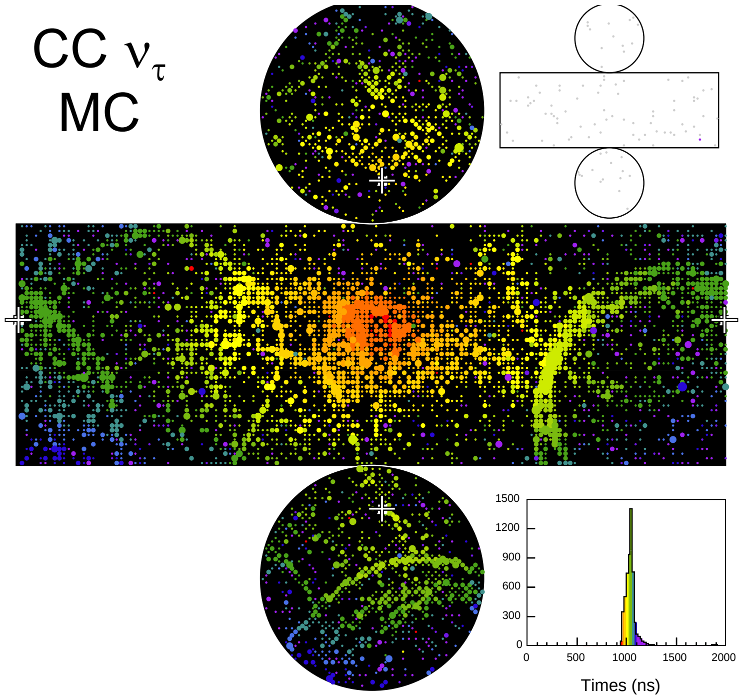
Energy Range (GeV)	Data	MC	Significance (σ)
0-3	100	115.16 ± 7.67	1.15
0-5	165	175.92 ± 10.42	0.65
0-120	291	292.63 ± 15.02	0.10

(Consistent with atmospheric neutrino data)

Tau neutrino appearance ?

Detecting CC ν_τ events (SK-I)





- Many particles (hadrons) ….

(But no big difference with the other (NC) events.)

→ τ-likelihood or 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)

Selecting ν_τ candidates

Pre-cuts: E(visible) >1,33GeV, most-energetic ring = e-like

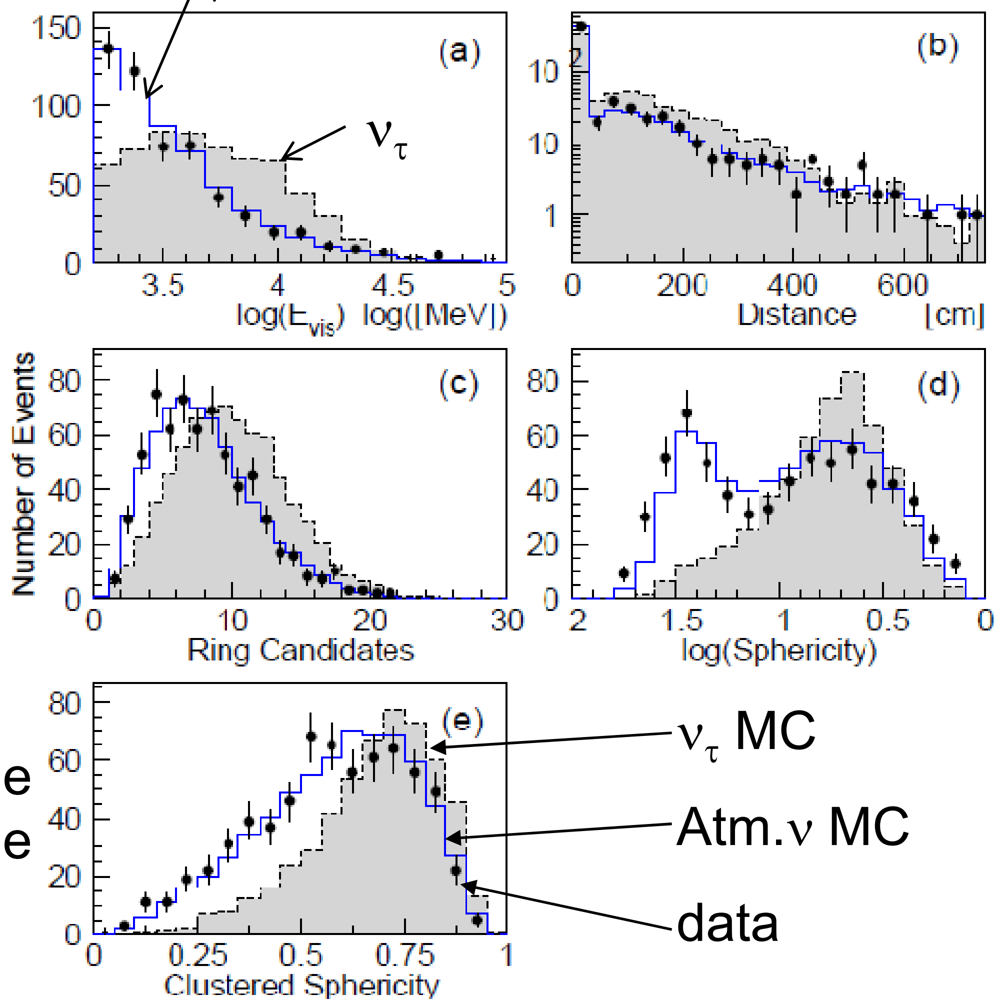
ν_μ+ν_e+NC

E(visible)

ν_τ

Number of ring candidates

Sphericity in the CM frame



Max. distance between primary vertex and the decay-electron vertex

Sphericity in the lab frame

ν_τ MC

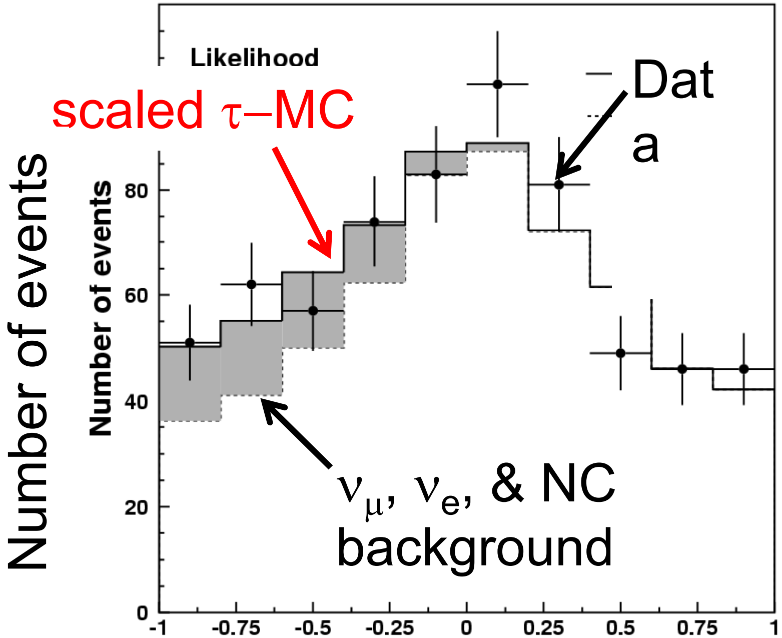
Atm.ν MC

data

Zenith angle dist. and fit results

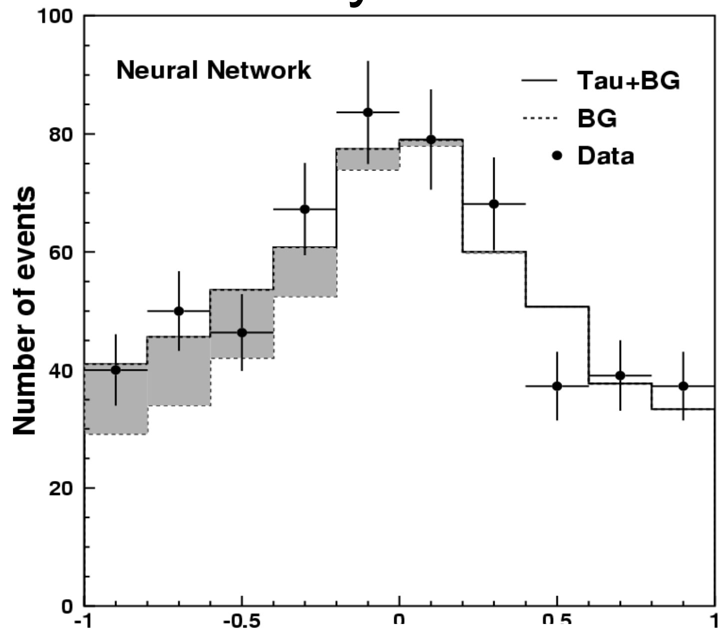
SK-collab. hep-ex/0607059

Likelihood analysis



$\cos\theta_{zenith}$

NN analysis



$\cos\theta_{zenith}$

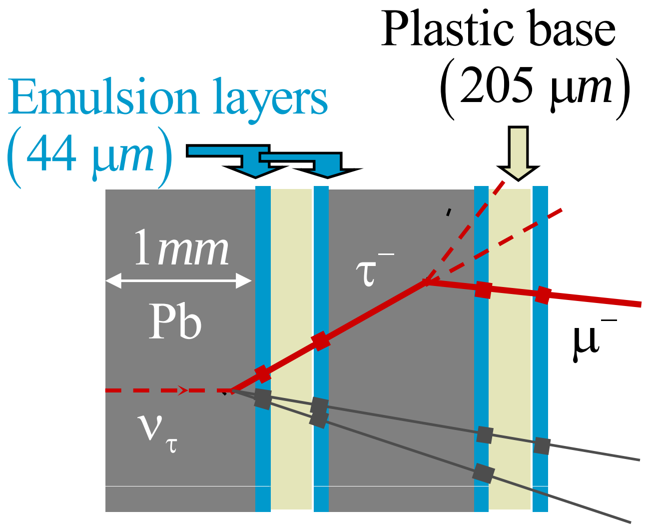
Fitted number of τ events	138±48(stat) +15 / -32(syst)	134±48(stat) +16 / -27(syst)
Exp'd number of τ events	78±26(syst)	78±27 (syst)

Zero tau neutrino interaction is disfavored at 2.4σ.

Future of ν_τ detection

G.Wilquet, EPS2007

OPERA



Channels	Signal Δm^2=0.0025	Signal Δm^2=0.0030	Background
$\tau \rightarrow \mu$	2.9	4.2	0.17
$\tau \rightarrow e$	3.5	5.0	0.17
$\tau \rightarrow h^-$	3.1	4.4	0.24
$\tau \rightarrow 3h$	0.9	1.3	0.17
All	**10.4**	15.0	**0.76**

- The 2008 run started.

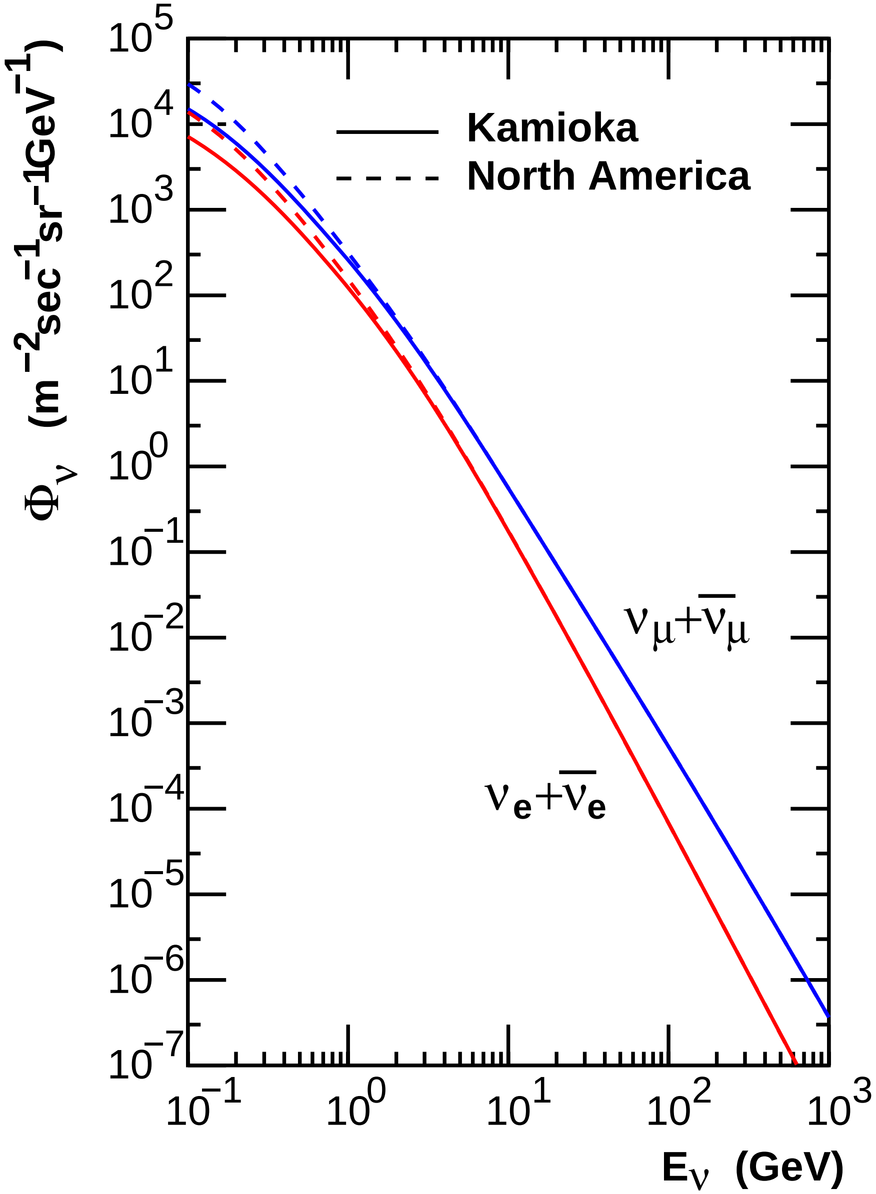
5 yrs with $4.5 \cdot 10^{19}$ p.o.t./yr

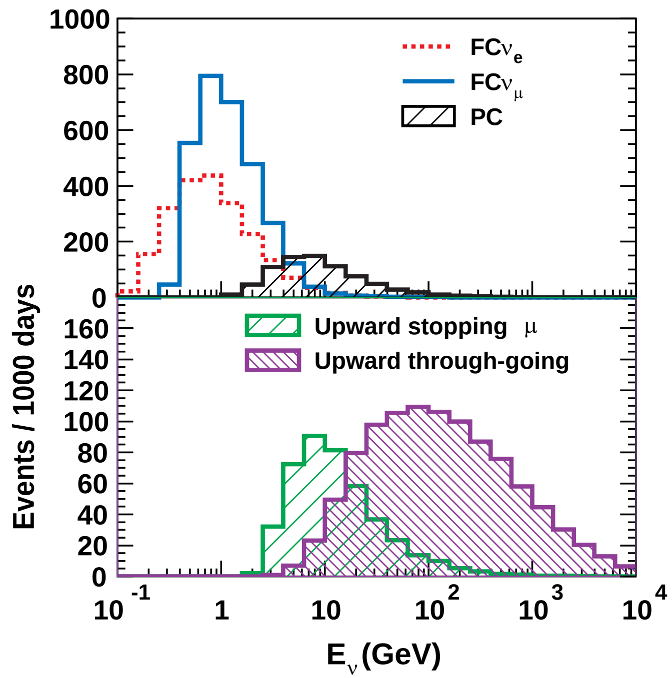
Summary of Leture-1

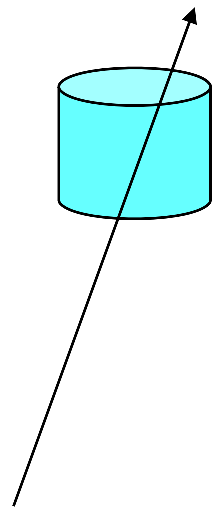
- Study of the background for proton decay found unexpected atmospheric ν_μ deficit.
- In 1998, the ν_μ deficit was concluded as evidence for neutrino oscillations.
- Recent atmospheric neutrino data are consistently explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations.
- Long baseline accelerator experiments clearly observed $\nu_\mu \rightarrow \nu_\tau$ oscillations.
- Next step in the $\nu_\mu \rightarrow \nu_\tau$ oscillation: unambiguous measurement of tau appearance.

End

Comment: upward-going muons







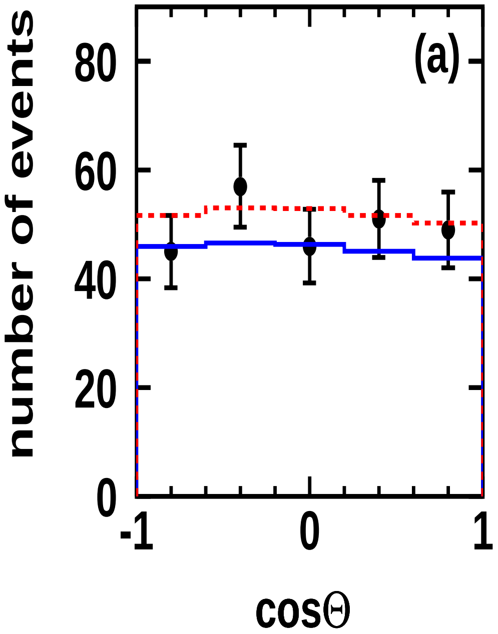
$\sigma(\nu N) \propto E_\nu$

Range E_μ, $\langle E_\mu \rangle$ E_ν

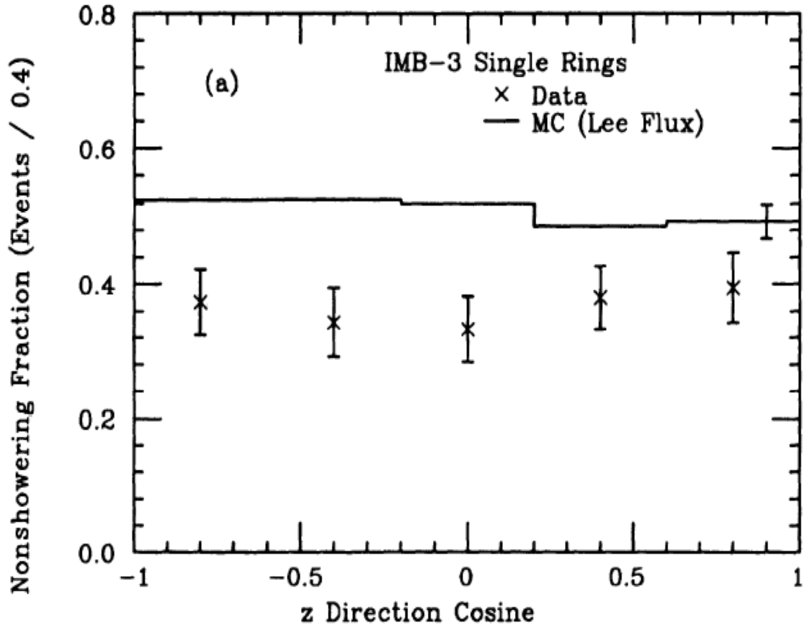
Wide energy range

Zenith angle distributions

Kamiokande (Evis <1.3 GeV)

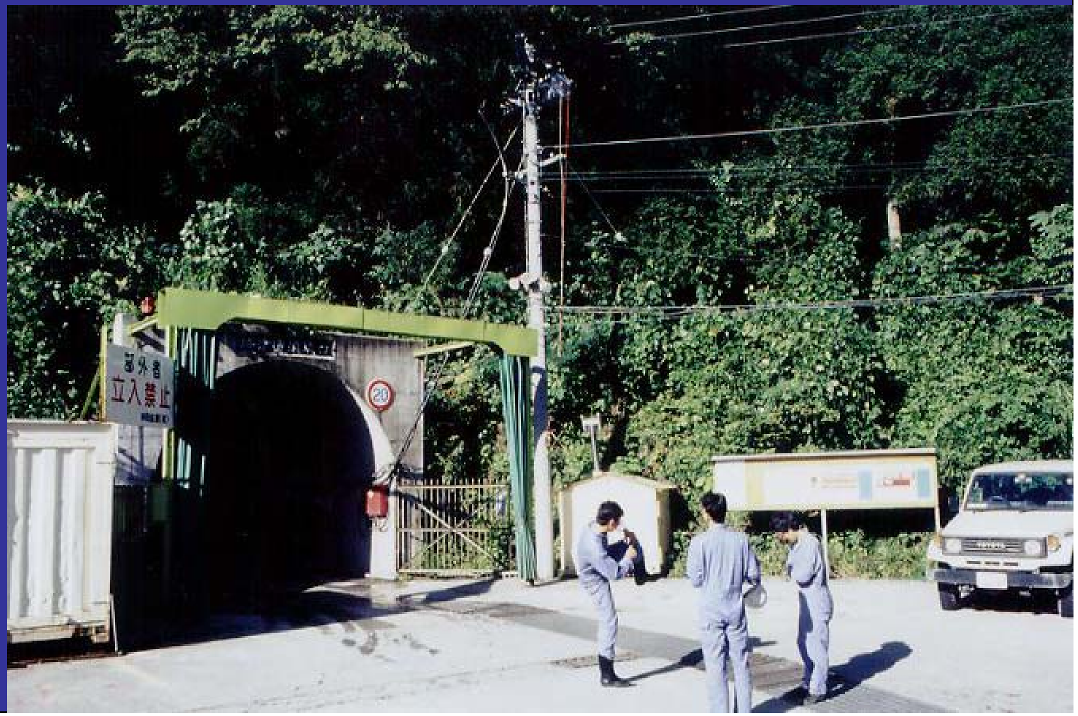


IMB (<1.5GeV)



Consistent with no zenith angle dependence...

Around Super-K



Entrance to the mine

χ^2's: Super-K atmospheric

zenith

L/E