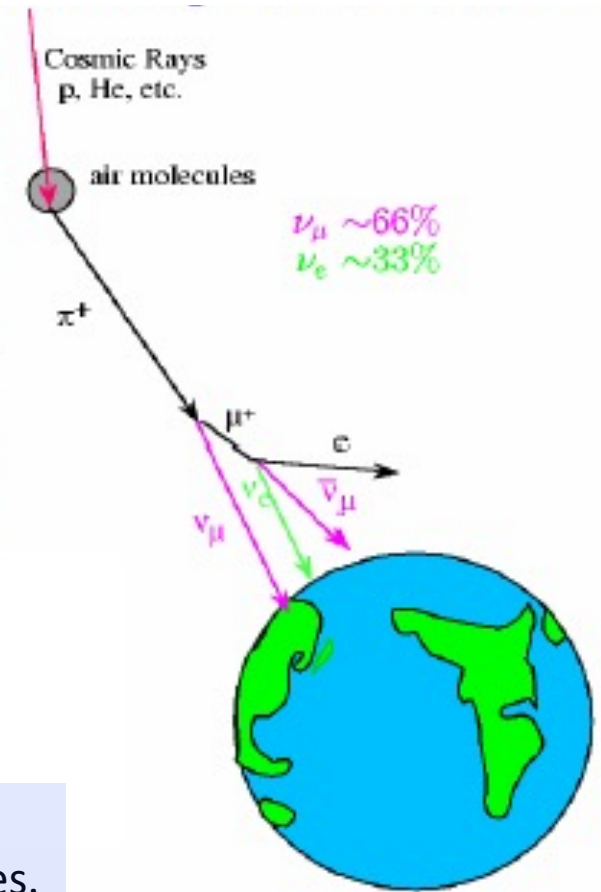


# Atmospheric Neutrinos

- Another evidence for  $\nu$  oscillations
- First atm.  $\nu$  observations:
  - Kamiokande
  - Soudan
  - IMB

and then:

- MACRO LNGS
- SUPERKAMIOKANDE



Neutrinos have non-zero masses.

Mass eigenstates are distinct from weak interaction eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

# The first observations of Atmospheric Neutrinos made in Kolar Gold Fields near Bangalore, and in South Africa in 1965.

- The Indian team was led by M. G. K. Menon et al
- The South African team was led by F. Reines et al.

# KGF – The 1<sup>st</sup> reported Atmospheric

ν

Several detectors in KGF mine at various depths.

3 ν evts published 15 Aug 65

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*

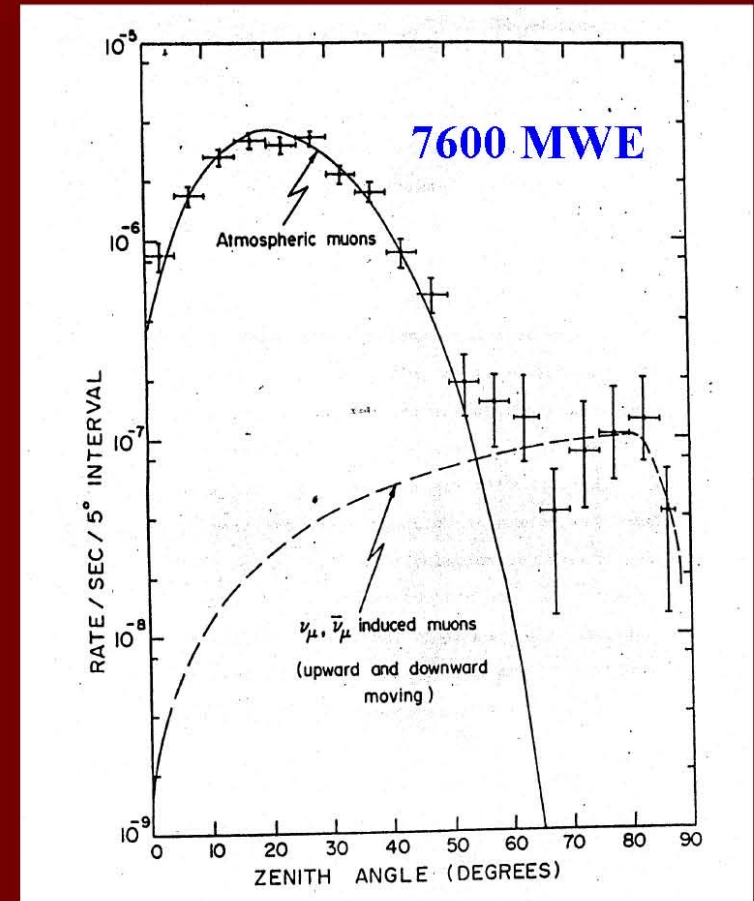
K. HINOTANI and S. MIYAKE,  
*Osaka City University, Osaka, Japan*

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

Received 12 July 1965

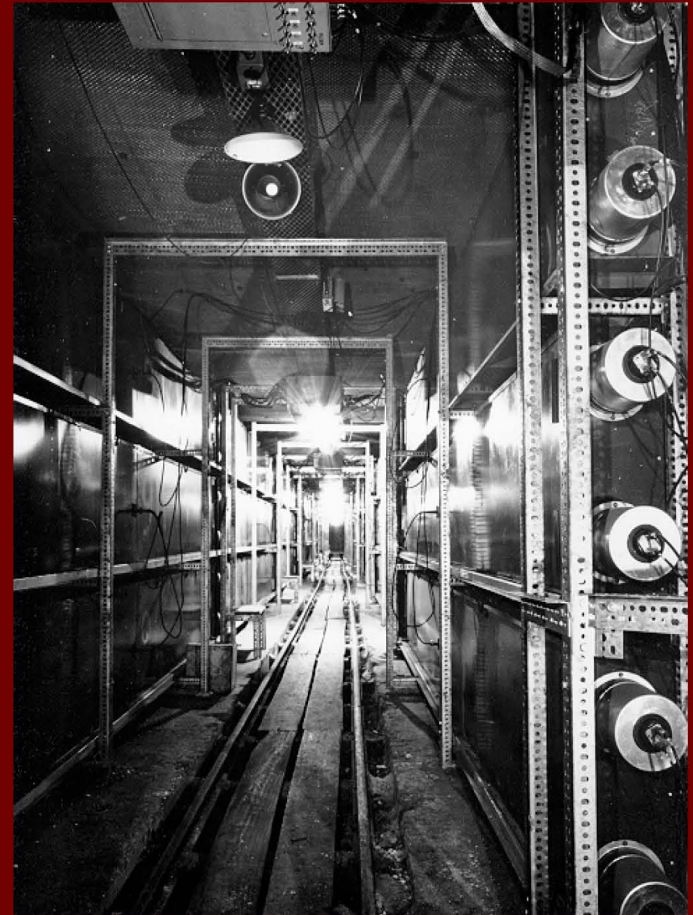
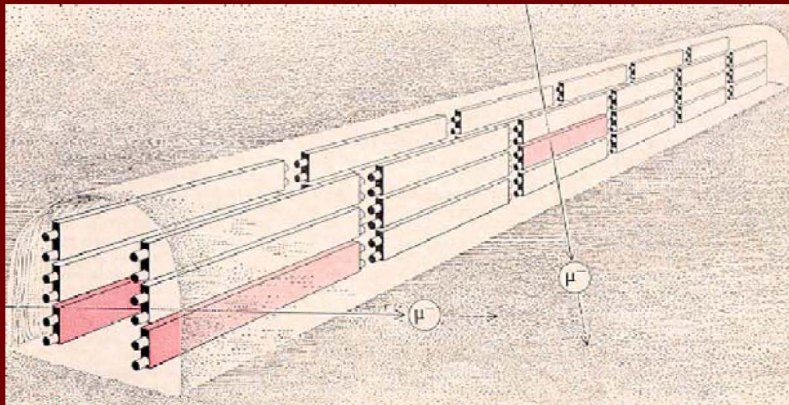
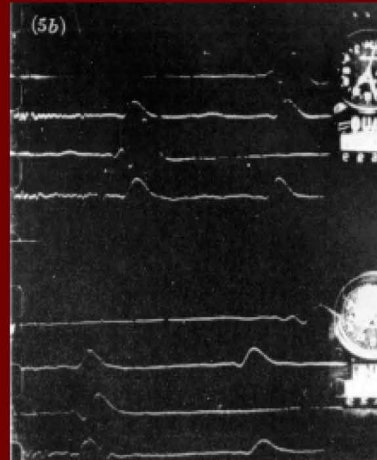
Table 1

Event number	Type of coincidence	Projected zenith angle	Date	Time
1	TEL. 2 N <sub>4</sub> + S <sub>4</sub>	37°	30.3	20.04
2	TEL. 1 N <sub>1</sub> + S <sub>1</sub>	48 ± 1°	27.4	18.26
3	TEL. 2 N <sub>6</sub> + S <sub>6</sub>	75 ± 10°	25.5	20.03



# CWI – The 1<sup>st</sup> recorded Atmospheric $\nu$

First  $\nu$   
February 29, 1965  
Recorded 100 (1/month)





CASE



E. R. P. M.

WITS



DETECTION OF THE FIRST NEUTRINO IN NATURE  
 ON  
 23<sup>RD</sup> FEBRUARY 1965  
 IN  
 EAST RAND PROPRIETARY MINE

THIS DISCOVERY TOOK PLACE IN A LABORATORY SITUATED  
 TWO MILES BELOW THE SURFACE OF THE EARTH ON  
 76 LEVEL OF EAST RAND PROPRIETARY MINE, MANNED  
 BY A GROUP OF PHYSICISTS FROM THE CASE INSTITUTE OF TECHNOLOGY U.S.  
 AND THE UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG.

THE PROJECT WAS SPONSORED BY :-  
 UNITED STATES ATOMIC ENERGY COMMISSION  
 E.R.P.M. AND RAND MINES GROUP  
 CASE INSTITUTE OF TECHNOLOGY  
 UNIVERSITY OF THE WITWATERSRAND  
 TVL. & O.F.S. CHAMBER OF MINES  
 AND CONVERTED FROM PROPOSAL TO REALITY  
 WITH THE HELP OF THE OFFICIALS AND MEN  
 OF THE HERCULES SHAFT OF E.R.P.M.

6<sup>TH</sup> DECEMBER 1967

SCIENTIFIC TEAM : E. REINES, J. P. E. SELLSCHOP, M. E. CROUCH  
 AND L. J. JENKINS, W. R. KRÖPP, H. S. GURR, B. MEYER, A. A. HRUSCHKA, B. M. SHOFNER

# “Atmospheric” neutrinos

## Main sources of atmospheric neutrinos

$$\pi^\pm, K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$\downarrow \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

For energies  $E < 2 \text{ GeV}$  most pions and muons decay before reaching the Earth:

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

At higher energies, most muons reach the Earth before decaying:

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} > 2$$

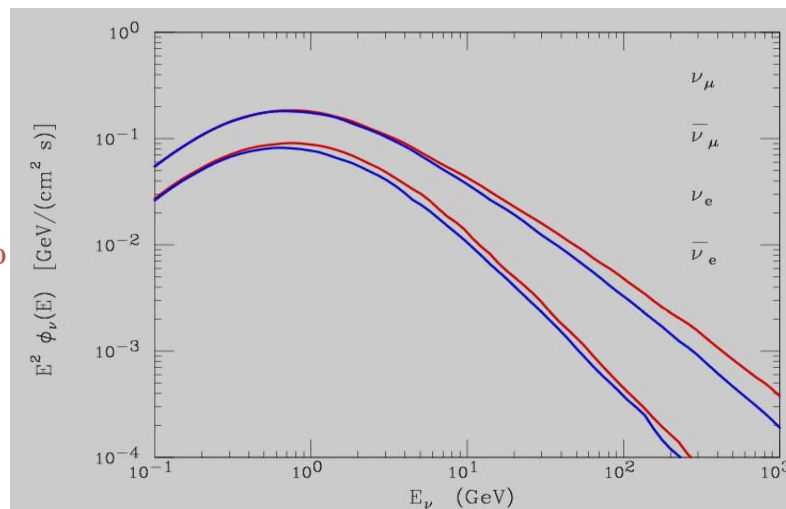
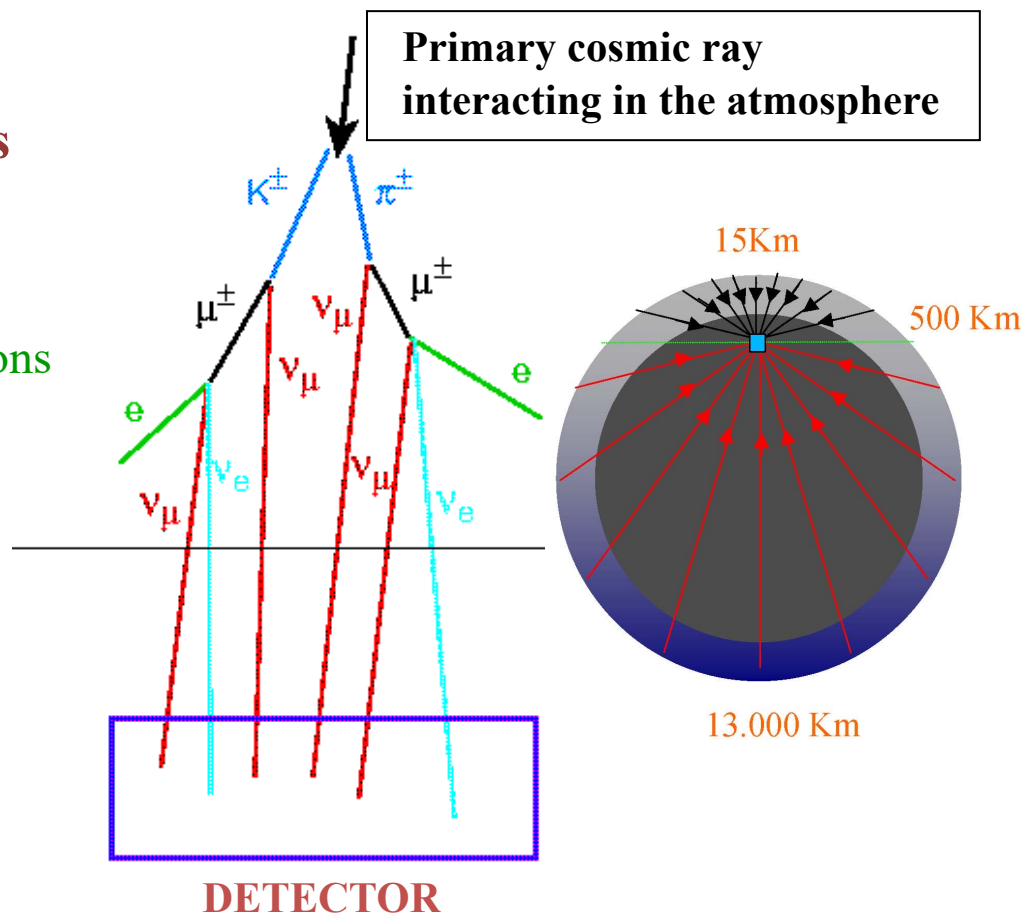
(increasing with  $E$ )

Atmospheric neutrino energies: 0.1 — 100 GeV

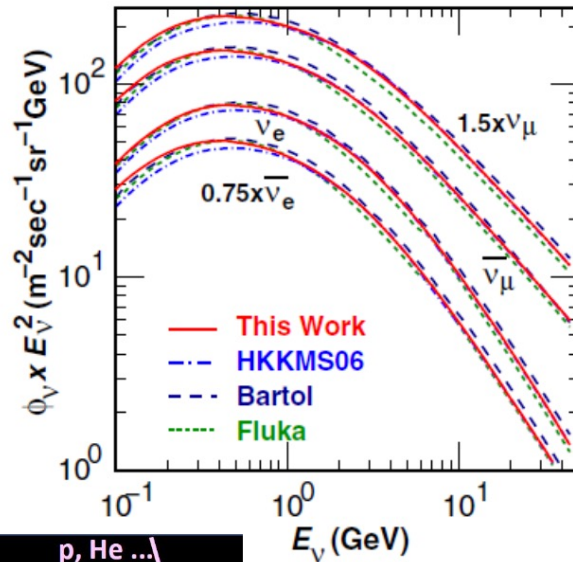
Very low event rates:  $\sim 100$  /year for a 1000-ton detector

Typical uncertainty on the atmospheric neutrino fluxes:  $\pm 30\%$   
(from uncertainties on the primary cosmic ray spectrum, on hadron production, etc.)

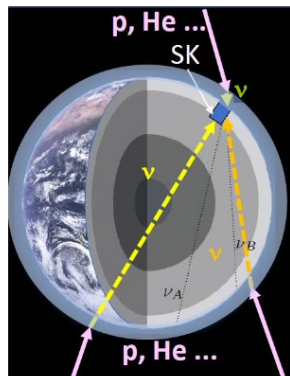
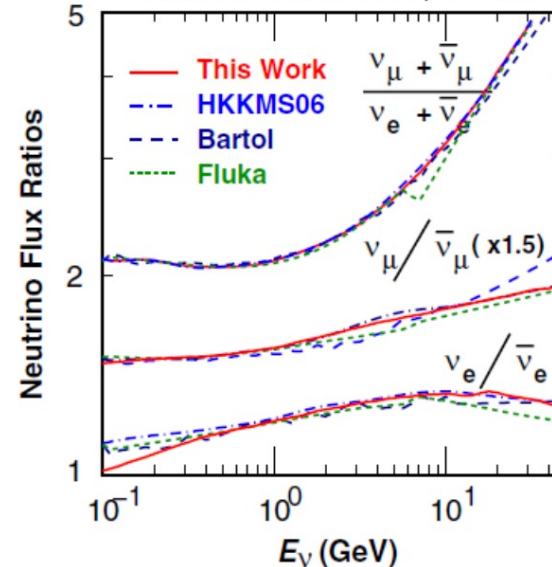
Uncertainty on the  $\nu_\mu/\nu_e$  ratio :  $\pm 5\%$



# Atmospheric neutrinos



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



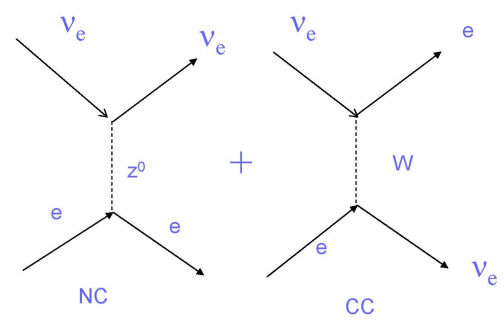
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu; \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\Rightarrow (\bar{\nu}_\mu + \nu_\mu) / (\bar{\nu}_e + \nu_e) \approx 2$$

Baseline:  $L \sim L(\cos\theta_{zenith})$

Neutrinos travel 10~12000 km

# Neutrino scattering on electrons



$$\sigma(CC)/\sigma(NC) = 6$$

Remember for  $\nu_\mu$  and  $\nu_\tau$  only NC

## Neutrino cross section at low energy

$$\sigma/E = 10^{-38} \text{ cm}^2/\text{GeV}$$

Ad alte energie  $E > 10\text{GeV}$

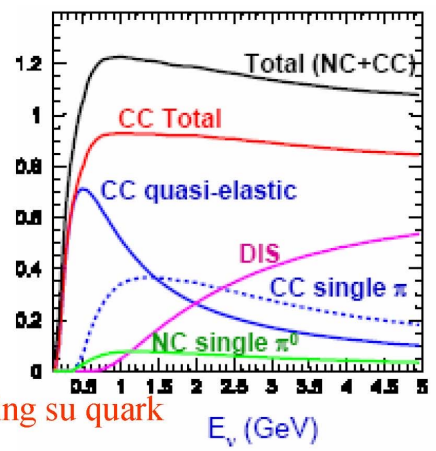
Deep inelastic scattering :scattering su quark

$$\nu + d = \mu^- + u$$

$$\text{anti}\nu + u = \mu^+ + d$$

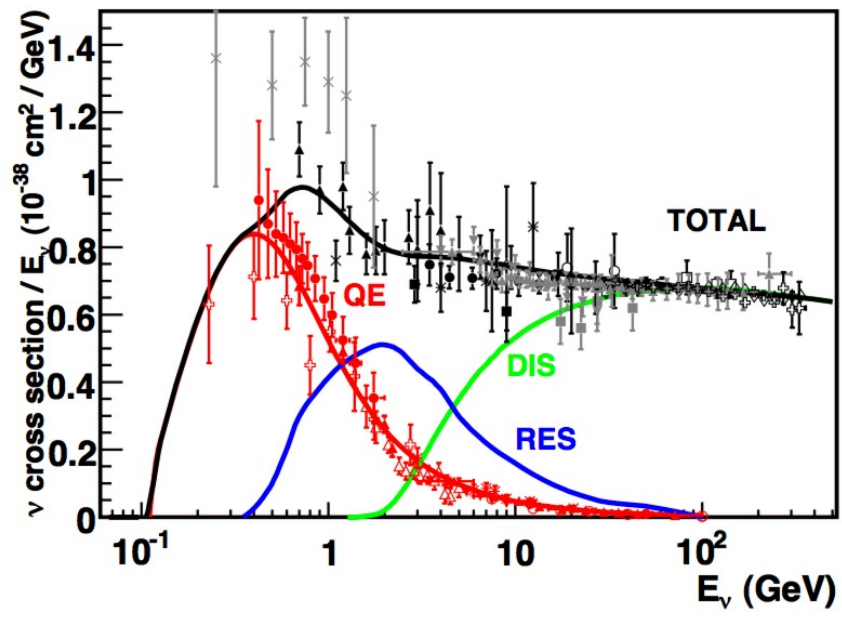
$$\sigma(CC)/E = 0.67 \times 10^{-38} \text{ cm}^2/\text{GeV} \text{ [neutrini]}$$

$$\sigma(CC)/E = 0.34 \times 10^{-38} \text{ cm}^2/\text{GeV} \text{ [antineutrini]}$$



## OSSERVAZIONI

- 1) Le sezioni d'urto dei neutrini (interazioni deboli) sono molto piccole a 1 GeV:  
 $\sigma(\nu p)/\sigma(p p) = 10^{-38}/10^{-26}$   
 Questo richiede rivelatori massivi
- 2) Il tipo di un neutrino che abbia interagito viene rivelato se esso abbia subito una interazione di corrente carica
- 3) Le sezioni d'urto su elettrone sono un fattore  $m_e/m_p$  più piccole



# Atmospheric neutrino detection

$\nu_\mu + \text{nucleon} \rightarrow \mu + \text{hadrons}$ : presence of a long, minimum-ionizing track (the muon)

$\nu_e + n \rightarrow e^- + p$ ,  $\bar{\nu}_e + p \rightarrow e^+ + n \Rightarrow$  presence of an electromagnetic shower

( $\nu_e$  interactions with multiple hadron production cannot be easily distinguished from Neutral Current interactions  $\nu + N \rightarrow \nu + \text{hadrons}$ )

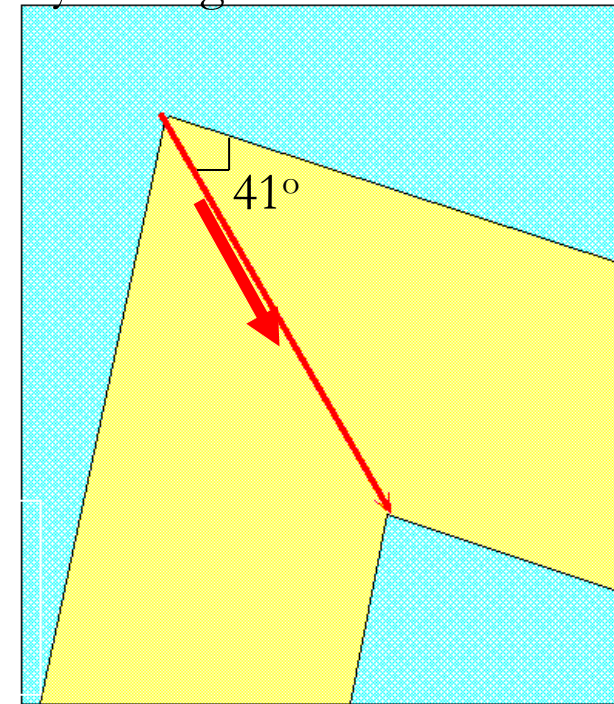
## Event identification in water Čerenkov detectors

- Muon track:  $dE/dx$  consistent with ionization minimum; well defined edges of Čerenkov light ring
- **Electromagnetic shower**: high  $dE/dx$  (many secondary electrons); fuzzy edges of Čerenkov light ring (from the shower angular aperture)

Direct measurement by exposing a 1000-ton water Čerenkov detector to electron and muon beams from a proton accelerator.

Measured probability of wrong identification  $\sim 2\%$

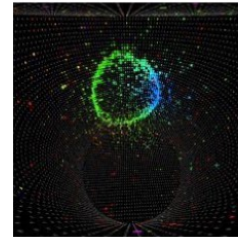
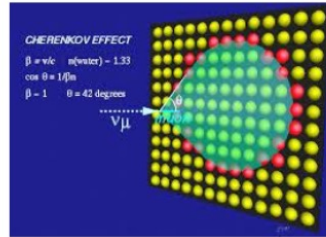
Measurement of the  $\nu_\mu/\nu_e$  ratio: first hints for a new phenomenon in water Čerenkov detectors: Kamiokande (1988), IMB (1991), Super-K (1998) Conventional calorimeters (iron plates + proportional tubes): Soudan2 (1997)



$$R = \frac{(\nu_\mu/\nu_e)_{\text{measured}}}{(\nu_\mu/\nu_e)_{\text{predicted}}} = 0.65 \pm 0.08$$

# Atmospheric neutrino

## IMB detector: indication of muon neutrino oscillations



Reconstruction of muon trajectory and energy

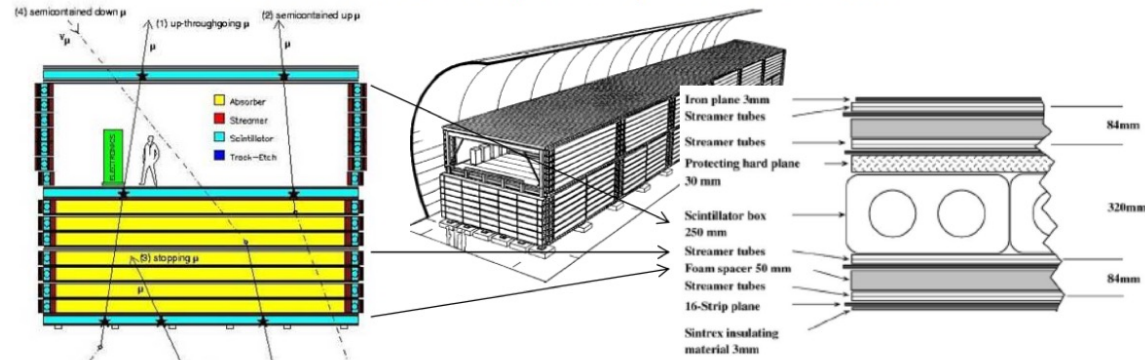
First hints of atmospheric  $\nu$  oscillations

Nonshowering events comprise  $[41 \pm 3(\text{stat}) \pm 2(\text{syst})]\%$ .  
While the expected fraction is  $[51 \pm 5(\text{syst})]\%$ .

IMB-3 is a large (3.3-kt fiducial mass, 2048 8-in. photomultiplier tubes) water Cherenkov detector. Using the ringimaging ability of the IMB-3 detector to separate events induced by  $\nu_e$  and  $\nu_{\mu}$ , the neutrino flavor content at the detector was compared to calculated production rates in the atmosphere.

# Atmospheric neutrino

## MACRO detector, atmospheric $\nu$ deficit

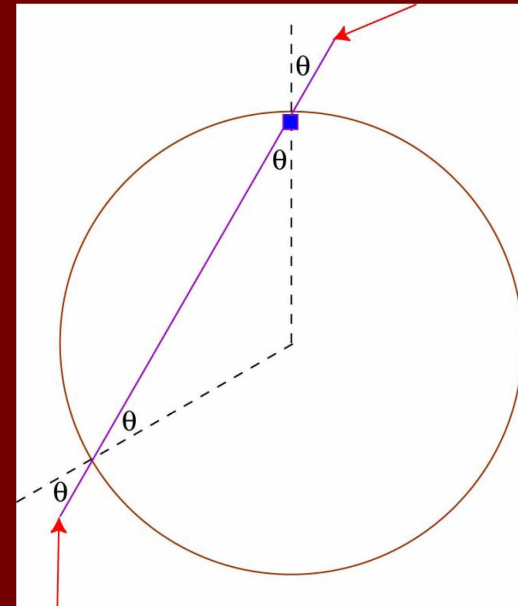
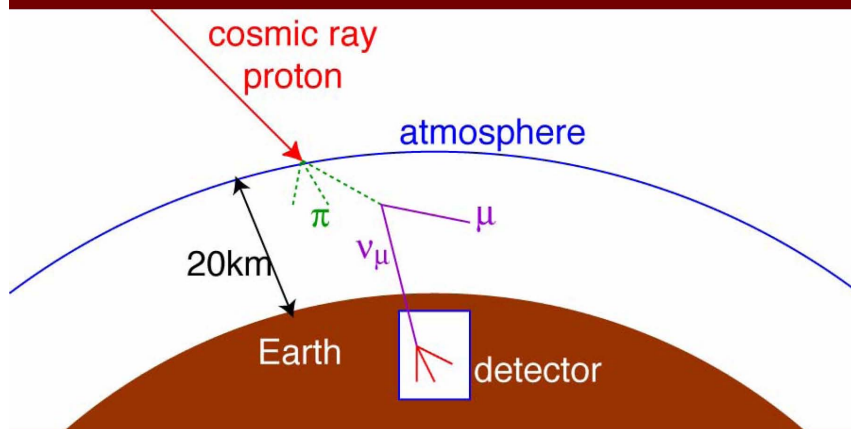


The principal goal of MACRO was to search for magnetic monopoles. The detector was also searching for WIMP annihilations in the Earth and the Sun, neutrino bursts from stellar collapses, and measurements of the flux of up-going muons showing evidence for neutrino oscillations. The apparatus consisted of: liquid scintillator counters, limited streamer tubes, and nuclear track etch detectors. The ratio of the number of observed to expected events integrated over all zenith angles is  $0.74 \pm 0.036(\text{stat}) \pm 0.046(\text{systematic}) \pm 0.13(\text{theoretical}) \Rightarrow$  these data favor a neutrino oscillation hypothesis.

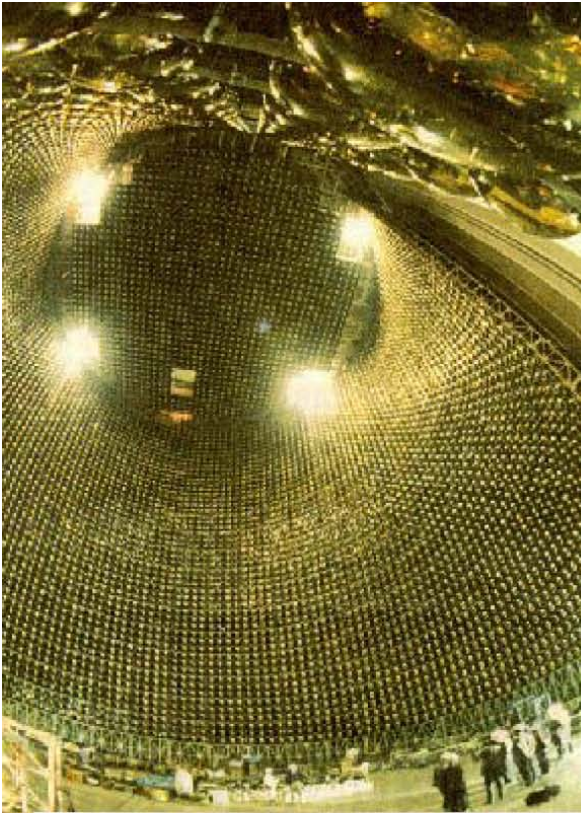
# 1998: Super-Kamiokande announces observation of Neutrino oscillations

## Super-Kamiokande Nucleon Decay Experiment

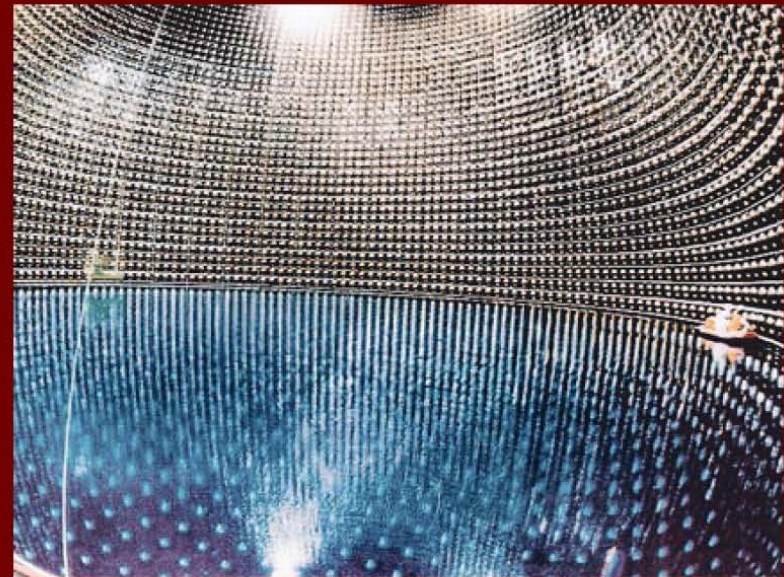
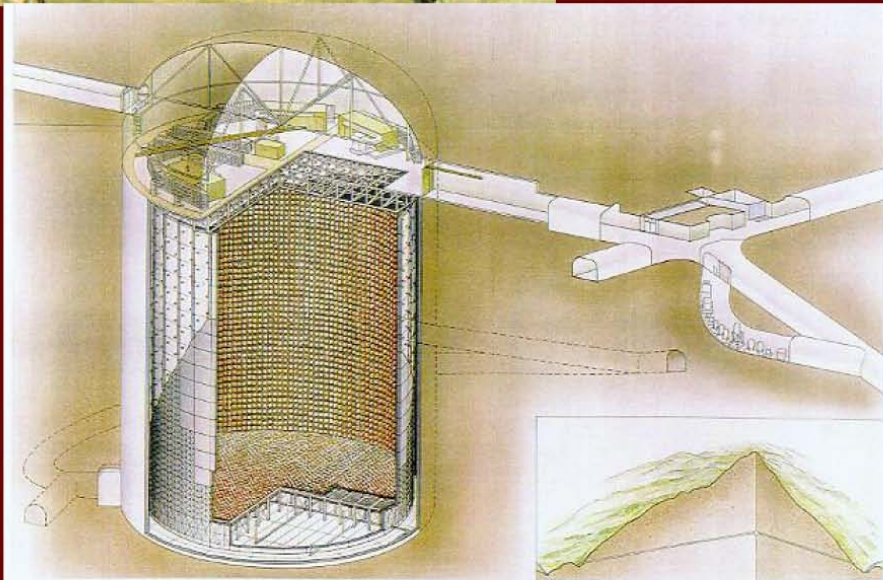
- $p \rightarrow e^+ \pi^0, K^+ \nu,$  etc
  - So far not seen
  - Atmospheric neutrino main background
- Cosmic rays isotropic
  - Atmospheric neutrino up-down symmetric



# Super-Kamiokande



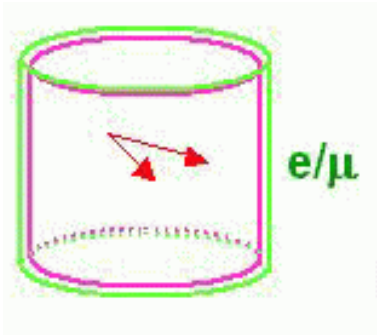
- 11 stories high
- 1,000 meters underground
- 50,000 tons of water
- 22,500 tons fiducial volume
- 11,200 photomultipliers
- 0.5 meter photomultiplier diameter  
(old copper and zinc mine)



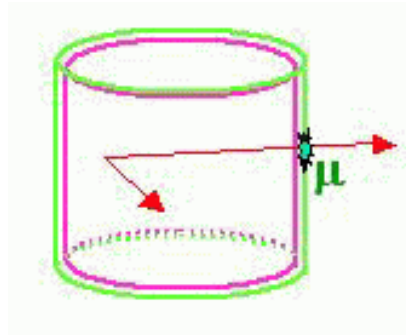
# Different typologies of events in SK

Contained events (Sub-GeV and Multi-GeV samples)

Fully contained (FC)



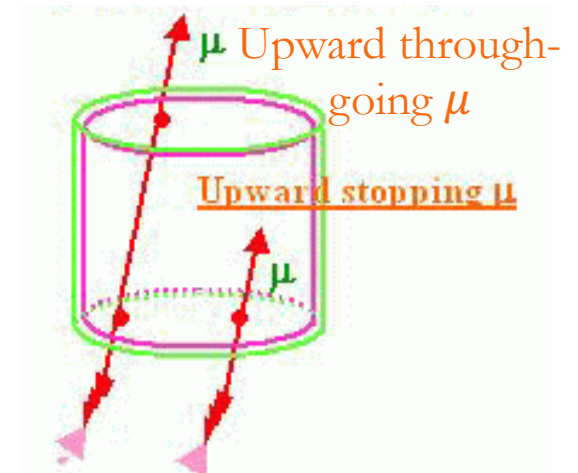
Partially contained (PC)



H<sub>2</sub>O radiation length  $\approx 36$  cm

→ energetic electrons are totally absorbed in  $\sim 8$  m of water

Up-going muons from  $\nu_\mu$  interactions in the rock



Note: down-going muons are mainly due to  $\pi \rightarrow \mu$  decays in the atmosphere

# Measurement of the zenith angle distribution

Definition of the zenith angle  $\theta$ :

Polar axis along the local vertical axis,  
pointing downwards

Down-going :  $\theta = 0^\circ$

Horizontal :  $\theta = 90^\circ$

Earth atmosphere

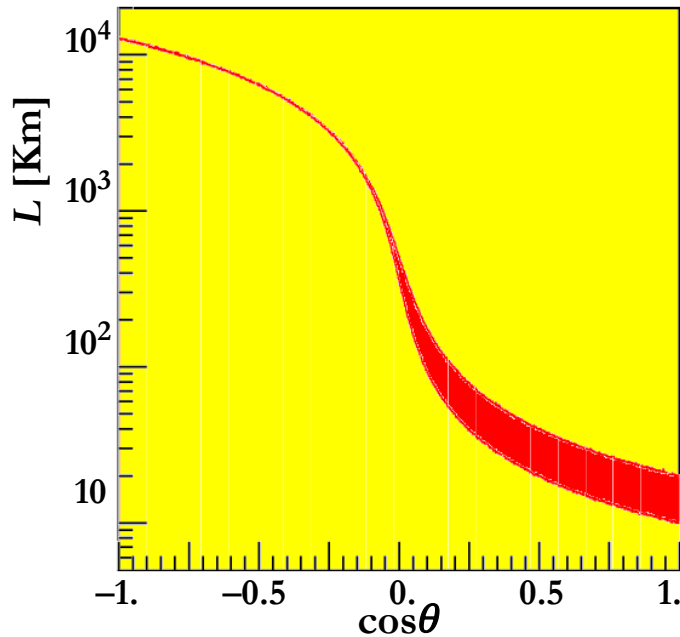
detector

Up-going :  $\theta = 180^\circ$

Earth

Local vertical axis

$L$  (distance between neutrino  
production point and detector)  
depends on zenith angle



$$\theta = 0^\circ \text{ — } 180^\circ$$

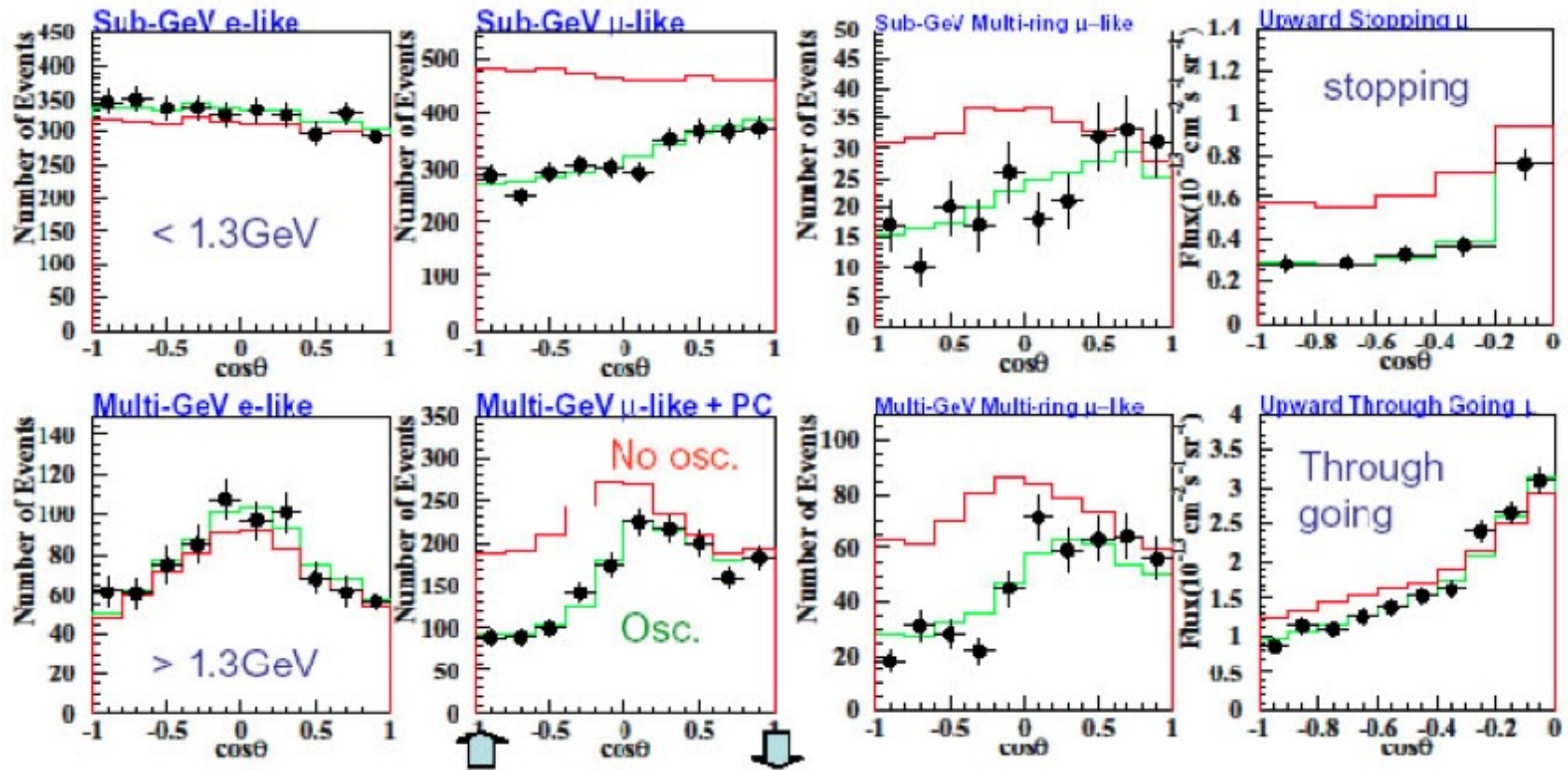
$$L = \sim 10 \text{ — } \sim 12800 \text{ km}$$

- Search for oscillations with variable distance  $L$
- Strong angular correlation between incident neutrino and produced electron/muon for  $E > 1$  GeV:



Uncertainty on neutrino  
production point  $\pm 5$  km

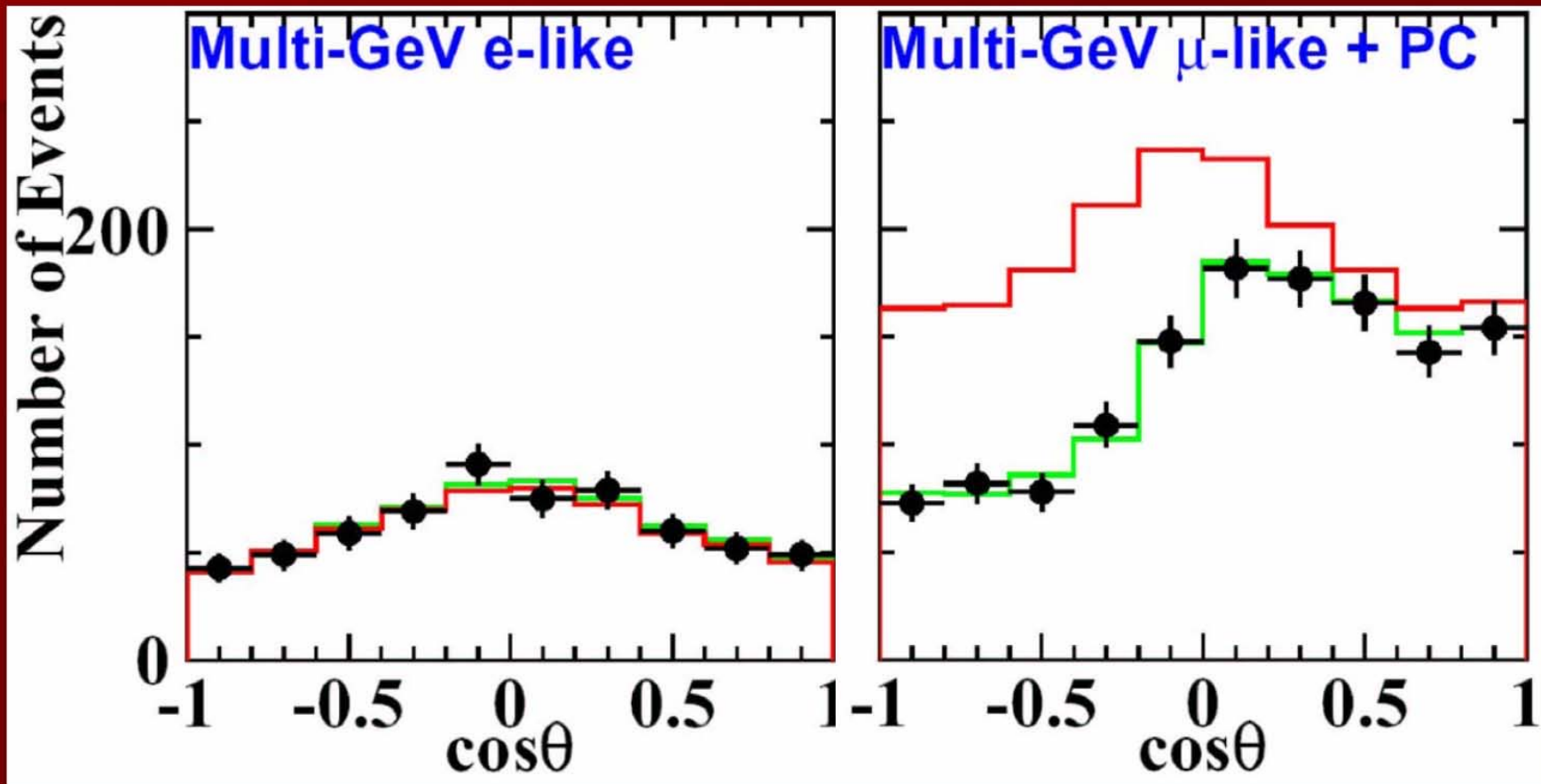
# The up-ward going $\nu_\mu$ flux is depleted in SK



— No oscillation ( $\chi^2 = 456.5 / 172$  degrees of freedom)

—  $\nu_\mu - \nu_\tau$  oscillation (best fit):  $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$ ,  $\sin^2 2\theta = 1.0$   
 $\chi^2 = 163.2 / 170$  degrees of freedom

# Half of $\nu_\mu$ lost!



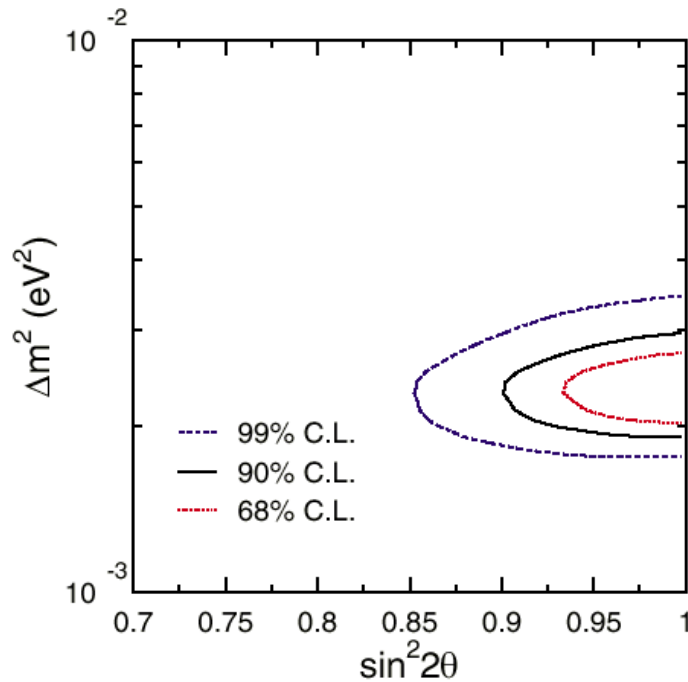
SUPERKAMIOKANDE

# SK showed that at L/E of atmospheric neutrinos

1)  $\nu_\mu$  DO oscillate

2)  $\nu_e$  DO NOT oscillate

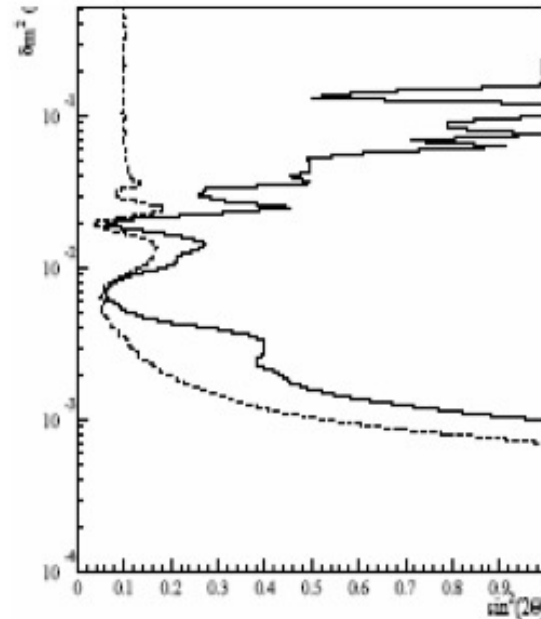
This is confirmed by CHOOZ



Region of oscillation parameters  
(confidence level 90%):

$$1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta > 0.90$$



$\nu_\tau + N \rightarrow \tau + X$  requires  $E(\nu_\tau) > 3.5 \text{ GeV}$ ;  
fraction of  $\tau \rightarrow \mu$  decays  $\approx 18\%$

- Atmospheric  $\nu_\mu$  do oscillate, but not to  $\nu_e$
- In a scenario with three neutrinos,  $\nu_\mu$  do oscillate to  $\nu_\tau$
- Sterile neutrinos?
- Direct evidence of oscillation to  $\nu_\tau$  is from OPERA at LNGS (5  $\nu_\tau$  observed)

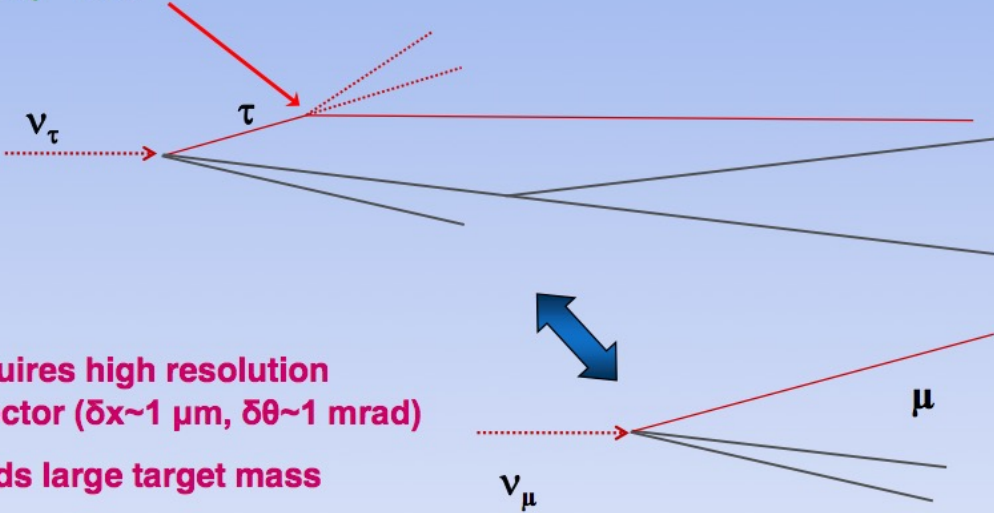
# OPERA: Oscillation Project with Emulsion tRacking Apparatus



- High-energy long baseline  $\nu_\mu$  beam
- Direct search for  $\nu_\mu \rightarrow \nu_\tau$  oscillations by looking at the **appearance** of  $\nu_\tau$  in a pure  $\nu_\mu$  beam
- Search for the sub-dominant  $\nu_\mu \rightarrow \nu_e$  oscillations for  $\theta_{13}$  measurement

# Direct observation of $\tau$ decay topologies in $\nu_\tau$ CC events

Decay "kink"



Requires high resolution detector ( $\delta x \sim 1 \mu\text{m}$ ,  $\delta \theta \sim 1 \text{ mrad}$ )

Needs large target mass

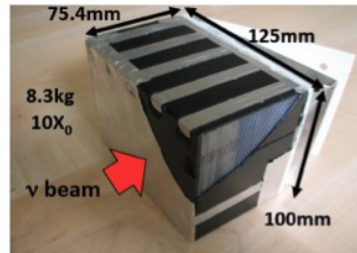
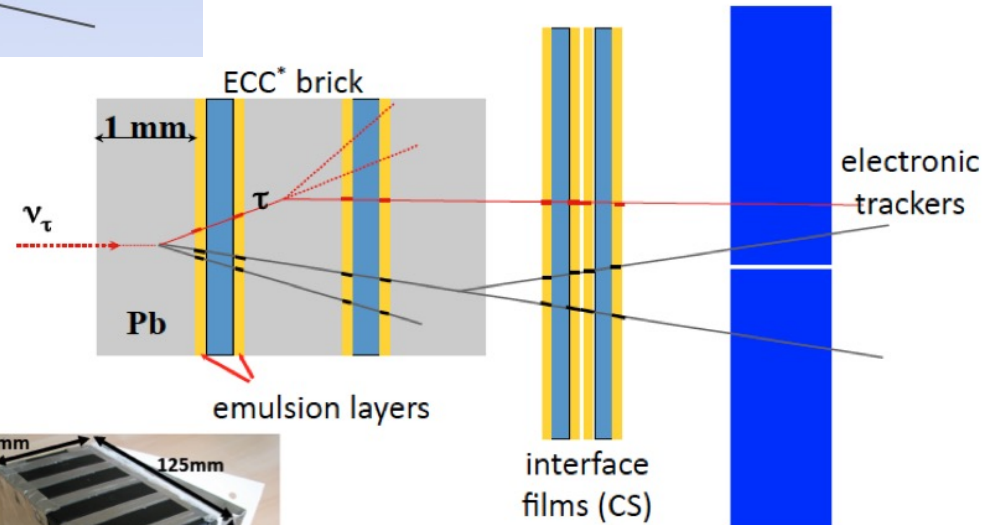
# OPERA @ LNGS

Tau lifetime = 0.29 ps ( $\approx 100 \mu\text{m}$ )

Tau decays:

- 64.79% hadronically
- 17.82% into a  $\nu_\tau$ , e and  $\nu_e$
- 17.39% into a  $\nu_\tau$ ,  $\mu$  and  $\nu_\mu$

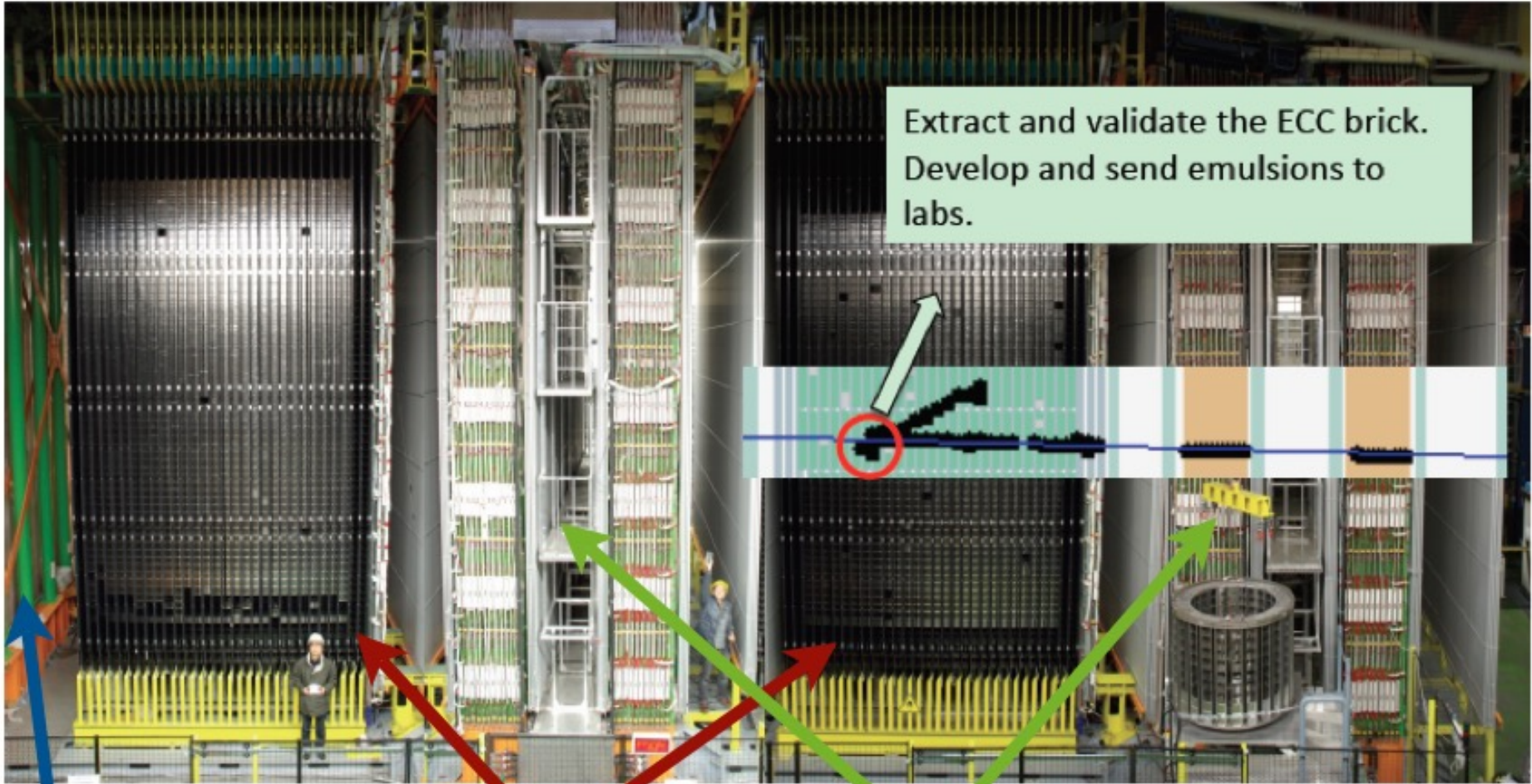
## How to detect tau vertex



ECC: Emulsion Cloud Chamber

# OPERA

## How to detect tau vertex



Extract and validate the ECC brick.  
Develop and send emulsions to  
labs.

**Veto**

**Target:**

- Trackers (scintillators)
- Lead/Emulsion bricks

**Spectrometers**

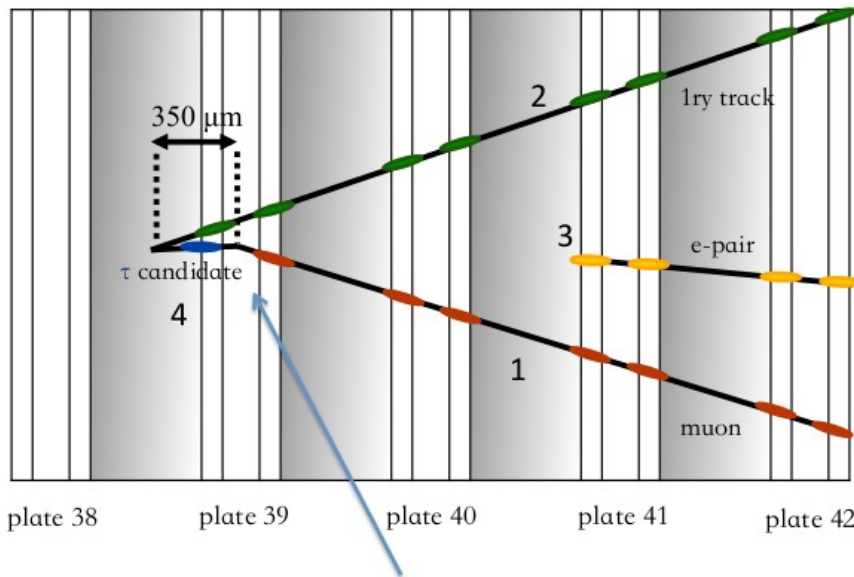
- Iron & RPC chambers
- 6 planes of drift tubes for  
precision tracking

# Five $\nu_\tau$ candidates observed until 2015

Examples:

PRL 115 (2015) 121802.

Third candidate (muon decay)

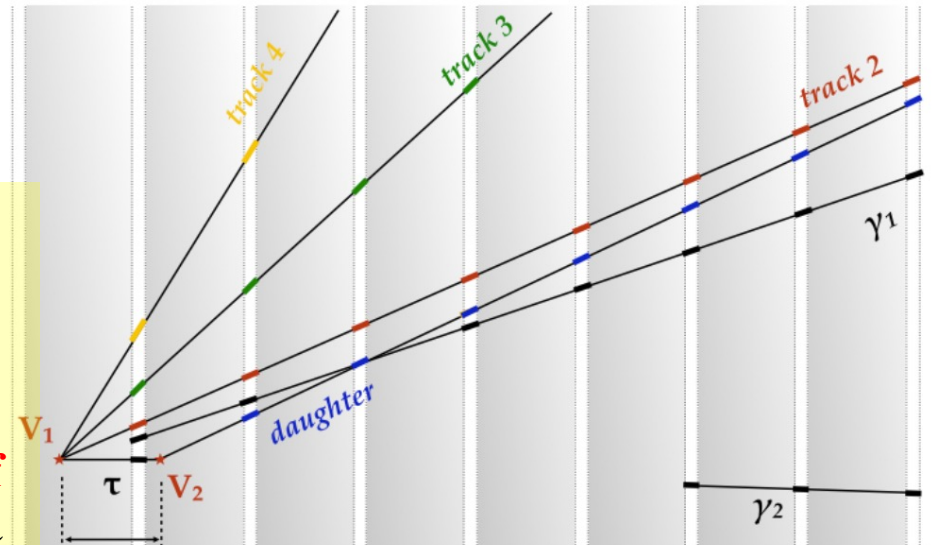


Decay in the plastic base

- OPERA was designed to search for  $\nu_\mu \rightarrow \nu_\tau$  oscillations in **appearance** mode, i.e. by detecting the  $\tau$  leptons produced in charged current  $\nu_\tau$  interactions.

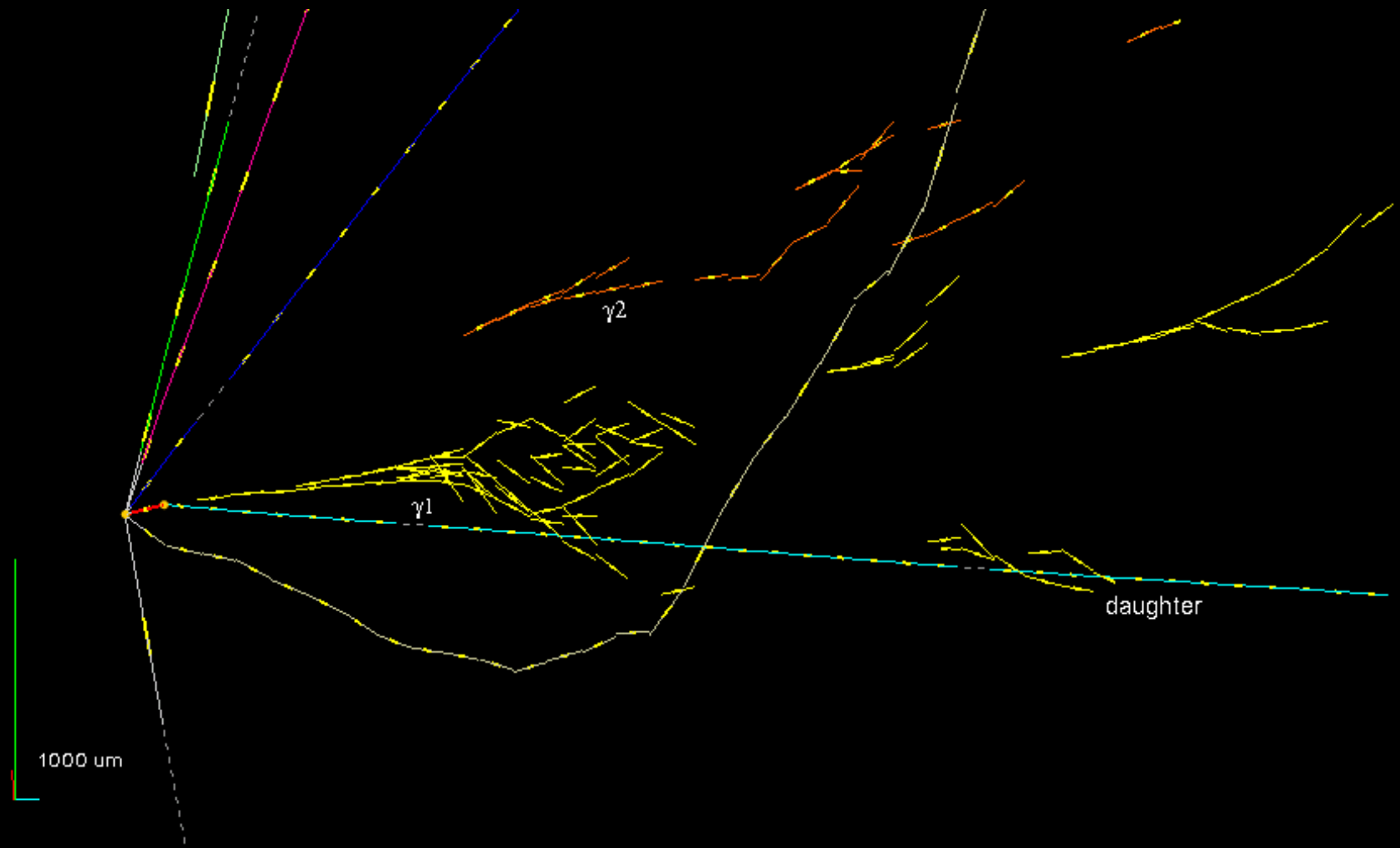
Final result (2018) 10  $\nu_\tau$  candidates observed, with less stringent selection of events

Fourth candidate (hadronic decay, single prong)



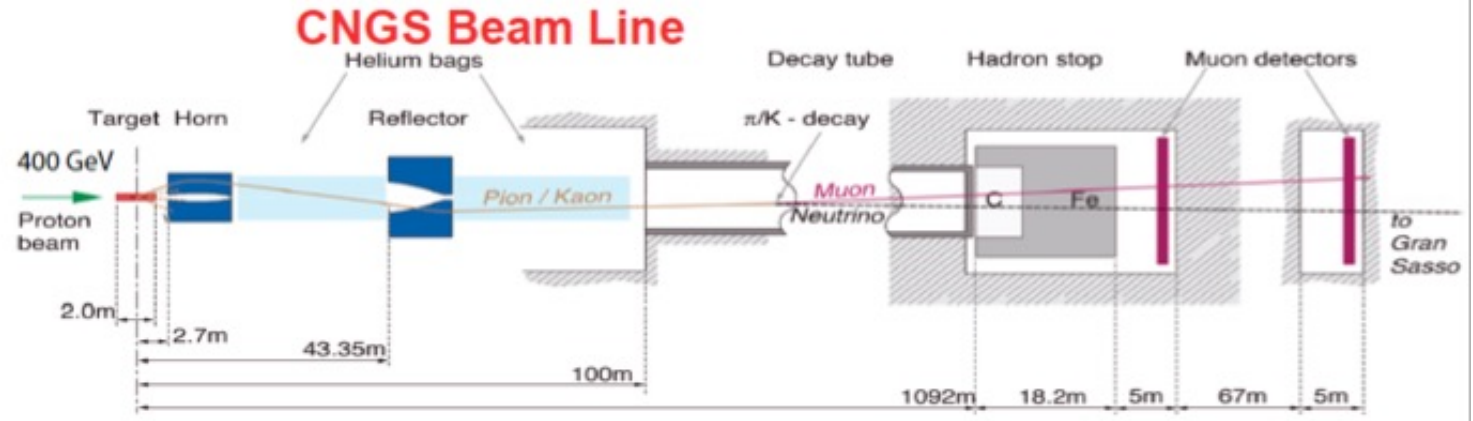
- Observation of the  $\nu_\mu \rightarrow \nu_\tau$  appearance, achieved with **five** candidate events.
- Together with a further reduction of the expected background, the candidate events detected so far allow to assess the **discovery of  $\nu_\mu \rightarrow \nu_\tau$  oscillations** in appearance mode with a significance larger than  **$5\sigma$**

# Event reconstruction (1)

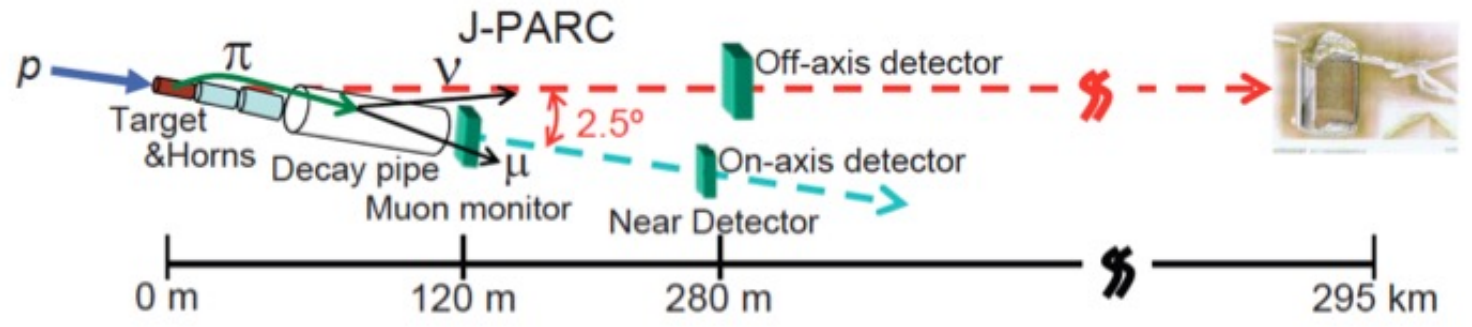


SK results for atmospheric neutrinos have been confirmed by “Long Baseline” expts  
 - neutrino beams in the world (at the end of their projects)

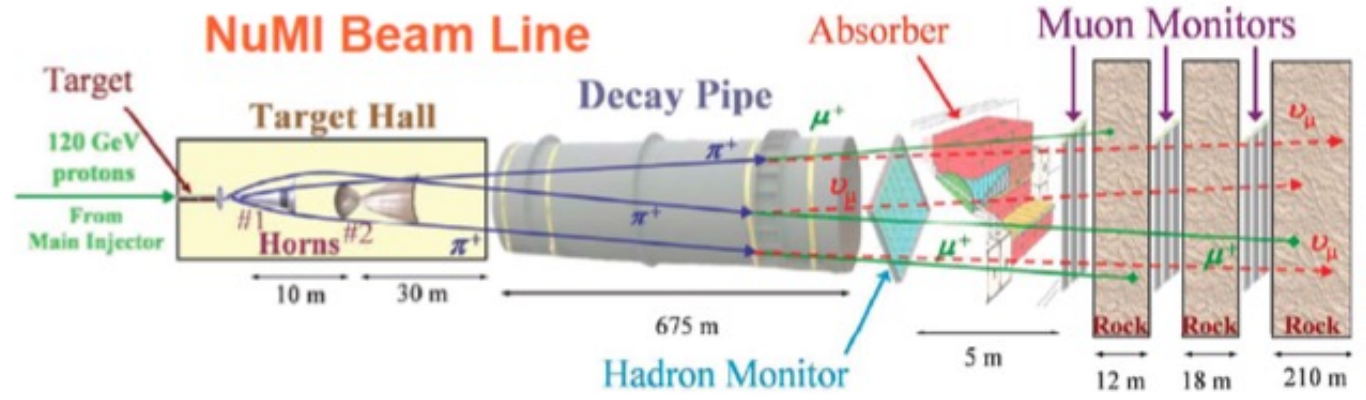
**CERN-  
 Gran Sasso**  
 ~730 km  
 $\nu_\tau$  appearance



**KEK-  
 SuperK**  
 ~295 km  
 $\theta_{13}$



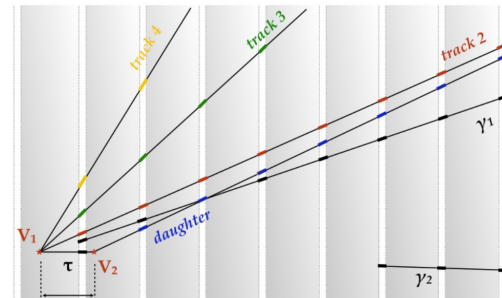
**Fermilab-  
 Minnesota**  
 ~730 km  
 $\nu_\mu$  disappearance



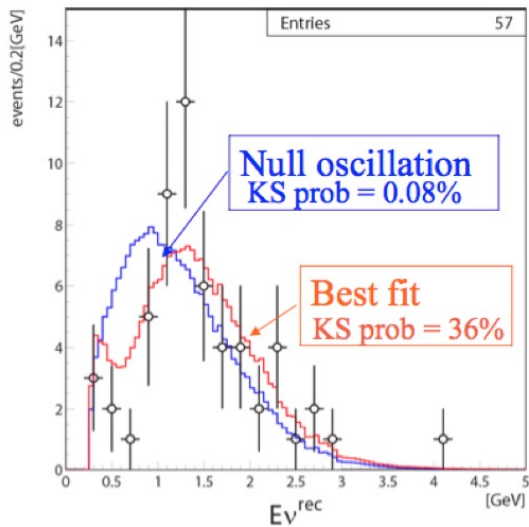
SK results for atmospheric neutrinos have been confirmed by “Long Baseline” expts  
 - neutrino beams in the world (at the end of their projects)

**CERN-  
 Gran Sasso**  
 ~730 km  
 $\nu_\tau$  appearance

- Five  $\nu_\tau$  candidates observed
- Discovery of  $\nu_\tau$  appearance



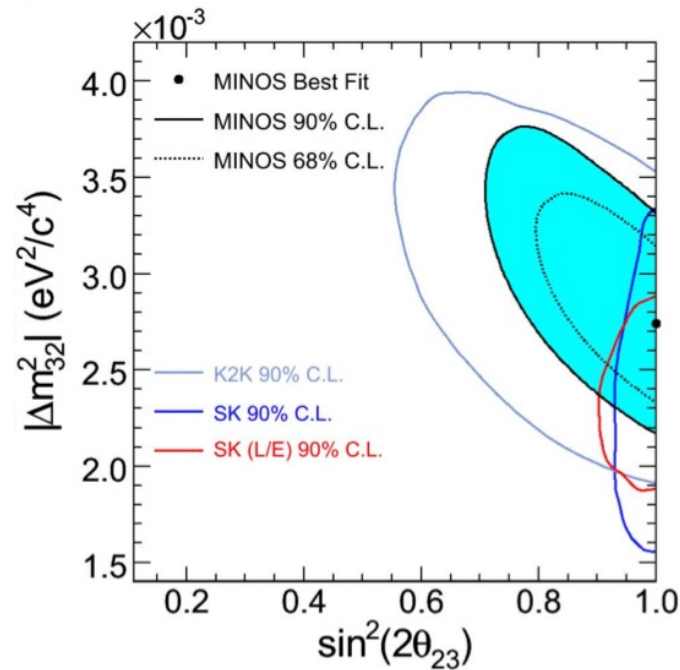
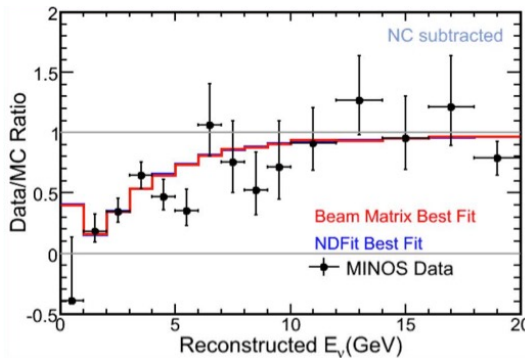
**KEK-  
 SuperK**  
 ~295 km  
 $\theta_{13}$



- Expected  $\nu$  interactions with osc. is 104 (107 observed), 151 w/out.

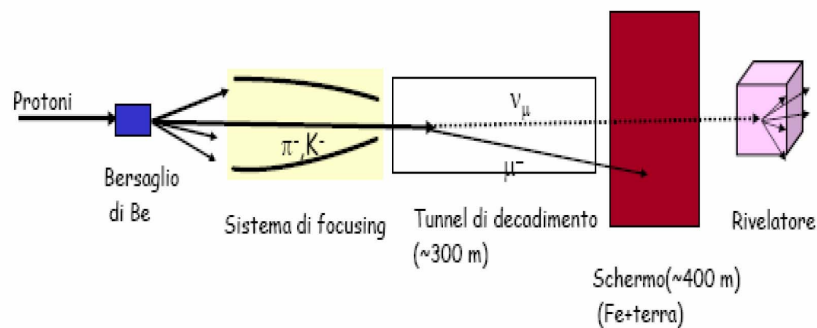
**Fermilab-  
 Minnesota**  
 ~730 km  
 $\nu_\mu$  disappearance

- MINOS





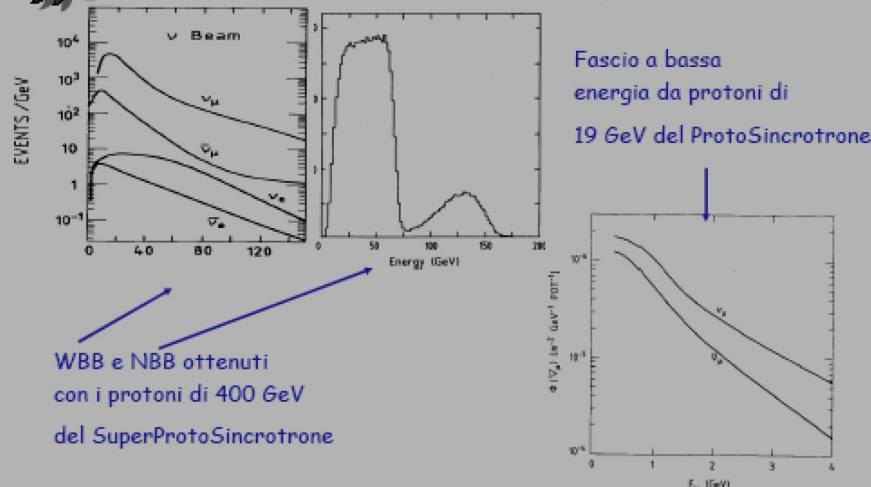
## Fasci di neutrini:schema generale



WBB (Wide Band Beam) :  $\pi, K^-$  focalizzati  $\rightarrow$  fascio intenso di  $\nu_\mu$   
 NBB (Narrow Band Beam) :  $\pi, K^-$  focalizzati e selezionati in momento  $\rightarrow$  fascio meno intenso di  $\nu_\mu$  ma con energia maggiormente definita



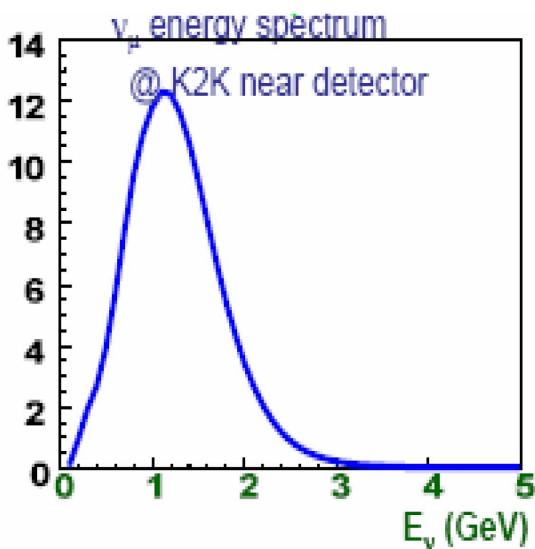
## Fasci di neutrini:esempi



## Note sui fasci di neutrini

- I fasci di neutrini da acceleratori sono fasci di  $\nu_\mu$  con piccola contaminazione  $\nu_e$  e  $\nu_\tau$
- Per questo motivo solo recentemente le interazioni dei  $\nu_\tau$  sono state osservate: esperimento Donuts a Fermilab

## Low energy beam



## Off-Axis Neutrino Beams



$$F = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

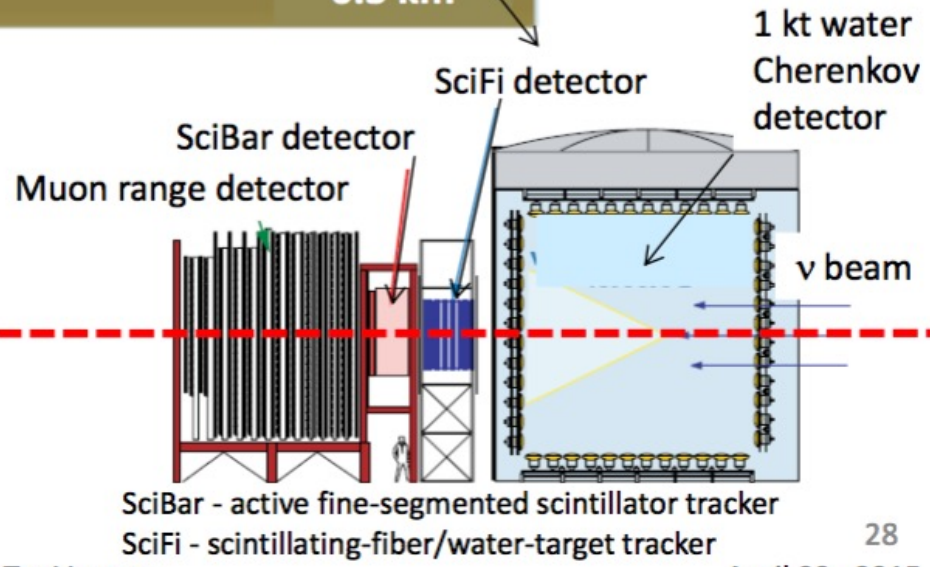
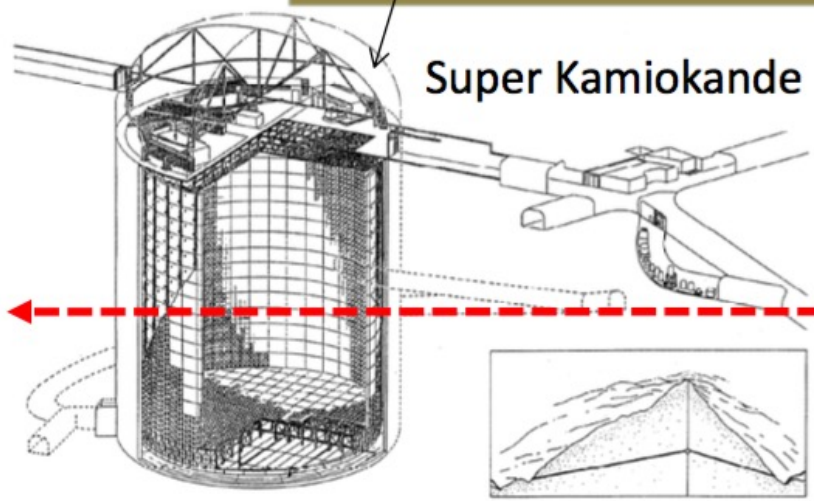
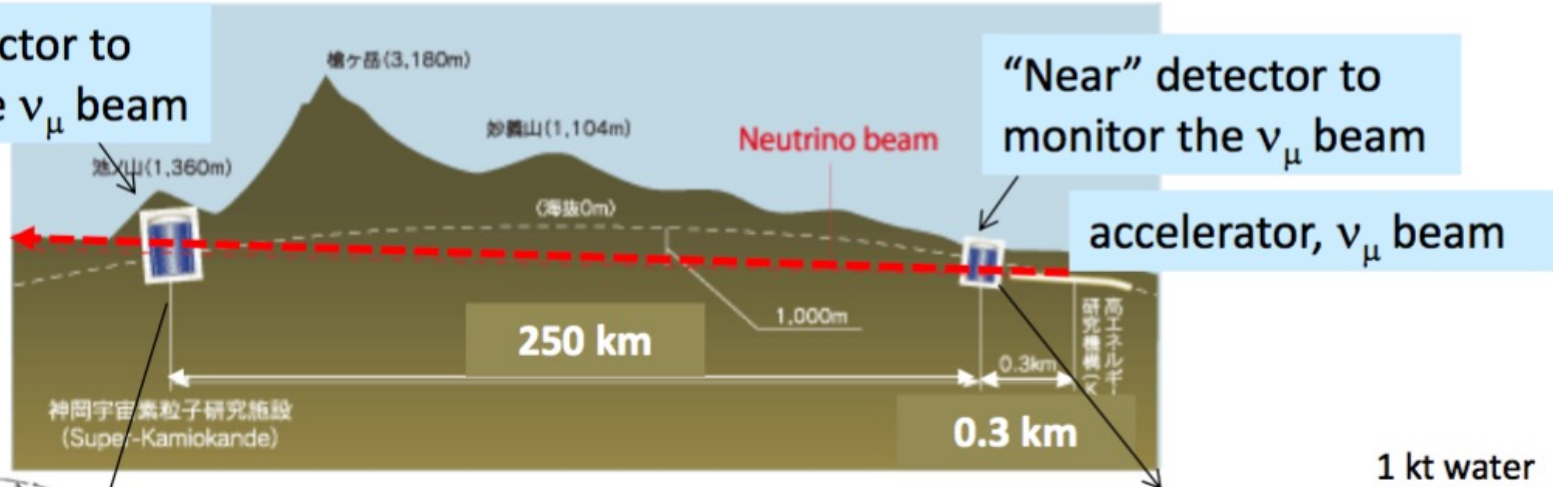
# Long-baseline oscillation experiments

K2K (the KEK to Kamioka long-baseline neutrino oscillation experiment)

An accelerator based experiment to study the neutrino oscillations discovered by the study of atmospheric neutrinos. The neutrinos are artificially generated by using the proton accelerator at KEK and observed in the Super-Kamiokande detector located 250 km away from KEK

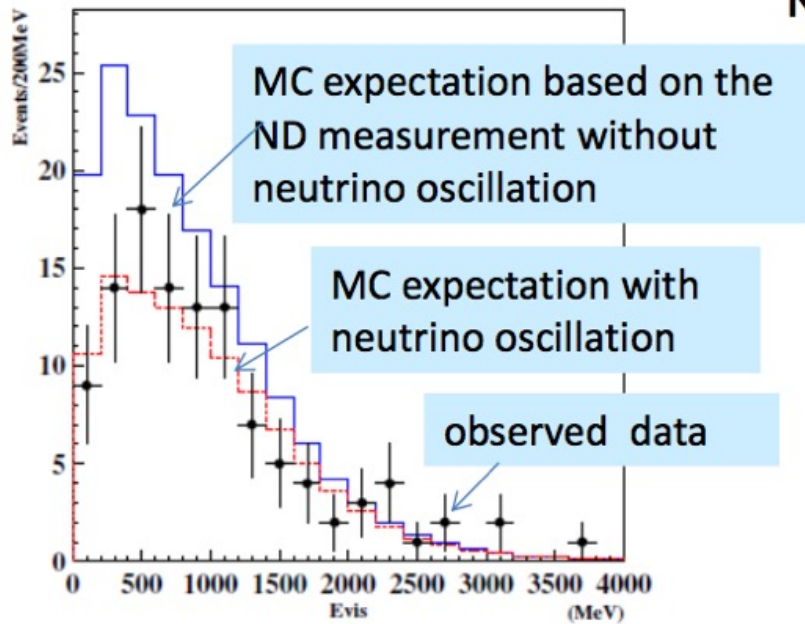
“Far” detector to measure the  $\nu_\mu$  beam

“Near” detector to monitor the  $\nu_\mu$  beam

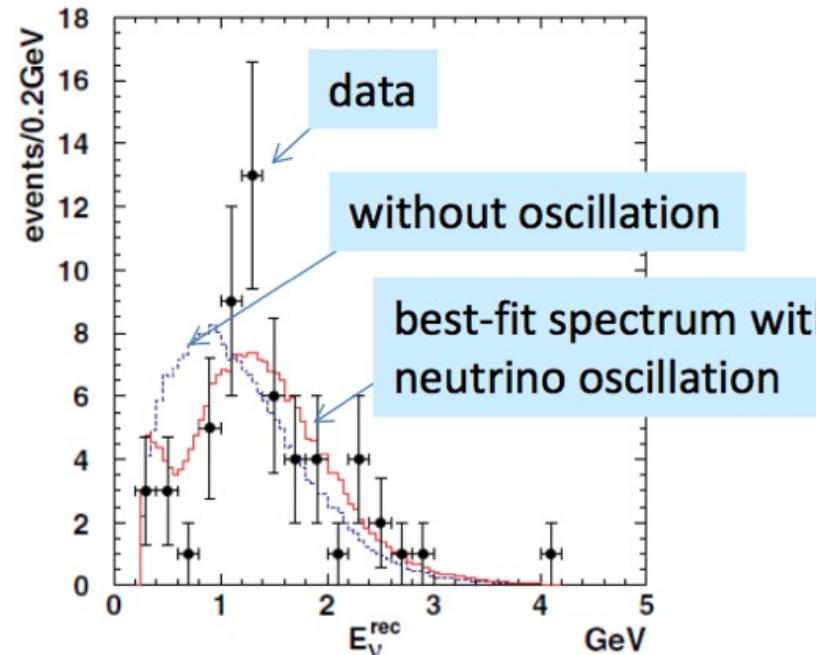


# Long-baseline oscillation experiments

## K2K results



Energy distribution for 112 fully contained fiducial-volume events in SK. The data can be explained by neutrino oscillation with  $\sin^2 2\theta = 1$  and  $\Delta m^2 = 2.8 \times 10^{-3} \text{ eV}_2^2$



Energy distribution for the 58 one-ring  $\mu$ -like events

This experiment was completed in Nov. 2004. As a result, 112 neutrino events are observed in Super-Kamiokande, while the expected number of events without oscillations is 158. The probability to observe the deficit without neutrino oscillations is estimated to be 0.0015% and this deficit confirms the prediction of the neutrino oscillation discovered by the observation of atmospheric neutrinos.

# Long-baseline oscillation experiments

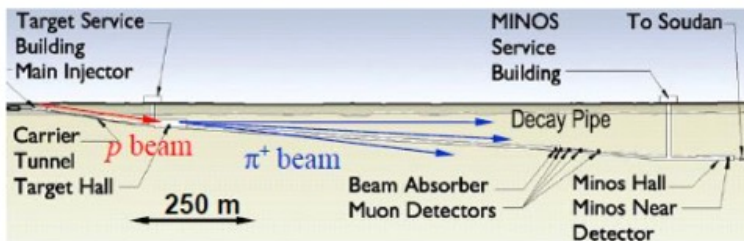
## MINOS



The MINOS far detector is an 8 m wide octagonal tracking calorimeter, consisting of 486 layers of 1-in.-thick steel interleaved with scintillator, giving a total mass of 5.4 kton. It has a toroidal magnetic field of strength approximately 1.3 T



735 km



The NuMI beam, indicating primary beam transport, target station, decay volume, beam absorber, muon detectors (Fermilab)

The near detector is similar to the far detector in design, but smaller in size with a mass of 0.98 ktons

S. Kopp, The numi neutrino beam at fermilab, <http://arxiv.org/abs/hep-ex/0412052>

P. Adamson et al., The MINOS light-injection calibration system, Nucl. Instr. Meth. A 492 (2002) 325

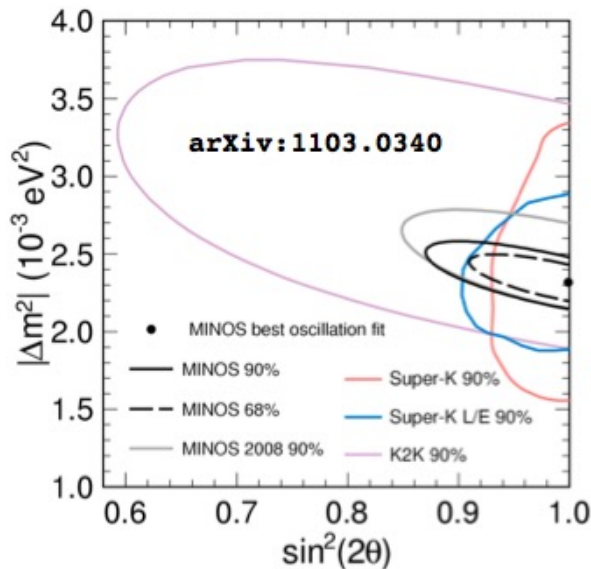
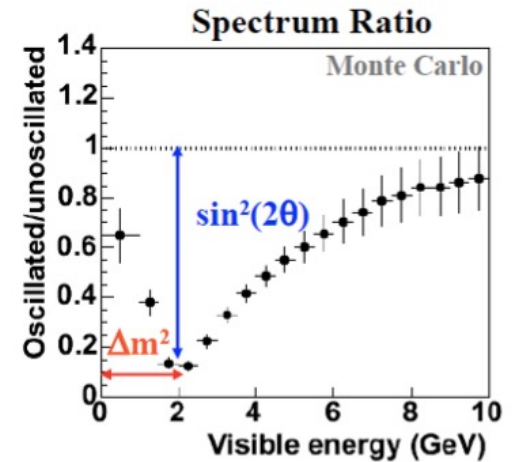
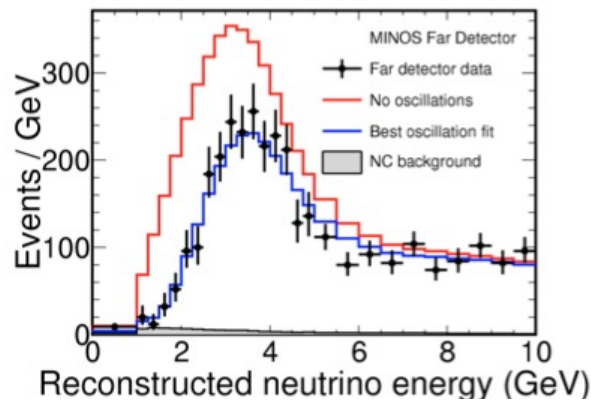
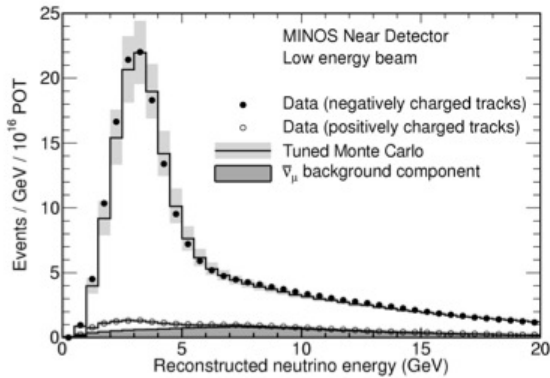
D.G. Michael et al., The magnetized steel and scintillator calorimeters of the MINOS experiment, Nucl. Instr.

Meth. A 596 (2008) 190

# Minos: $\nu_\mu$ disappearance

- By counting CC events at the far detector, the residual  $\nu_\mu$  flux is obtained, and the survival probability is measured:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left( \frac{1.27 \Delta m_{23}^2 L}{E} \right)$$

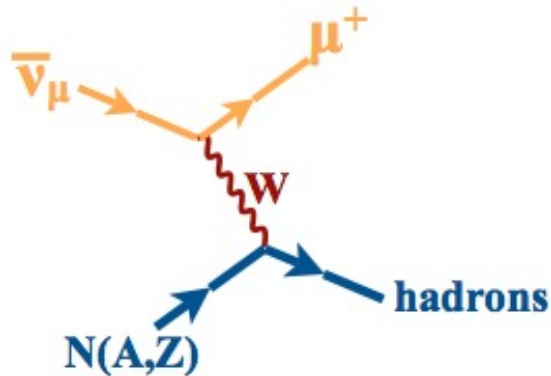


## MINOS vs atmospheric neutrinos

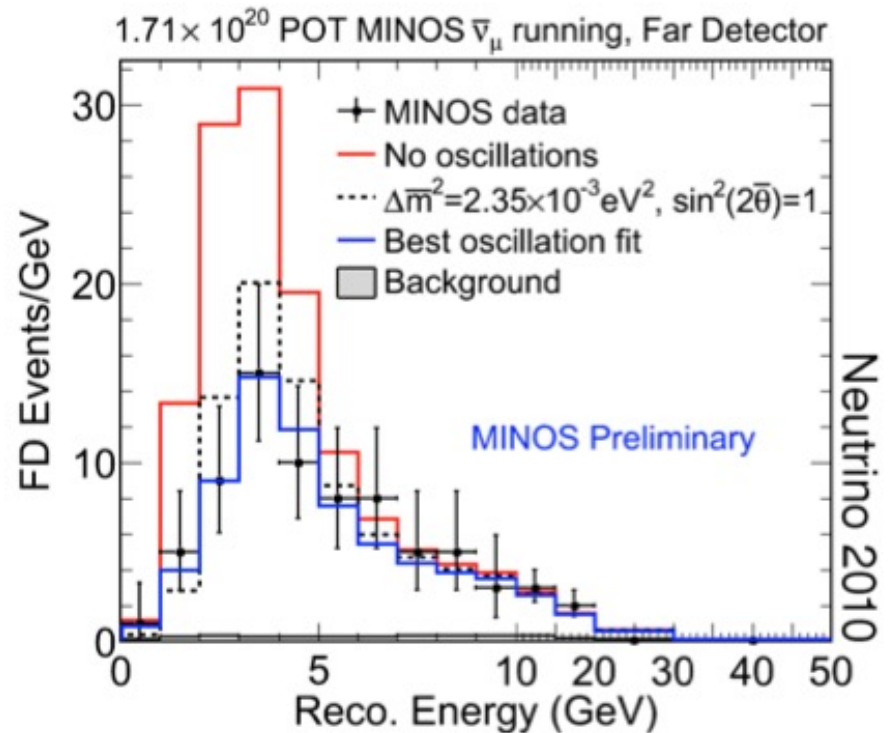
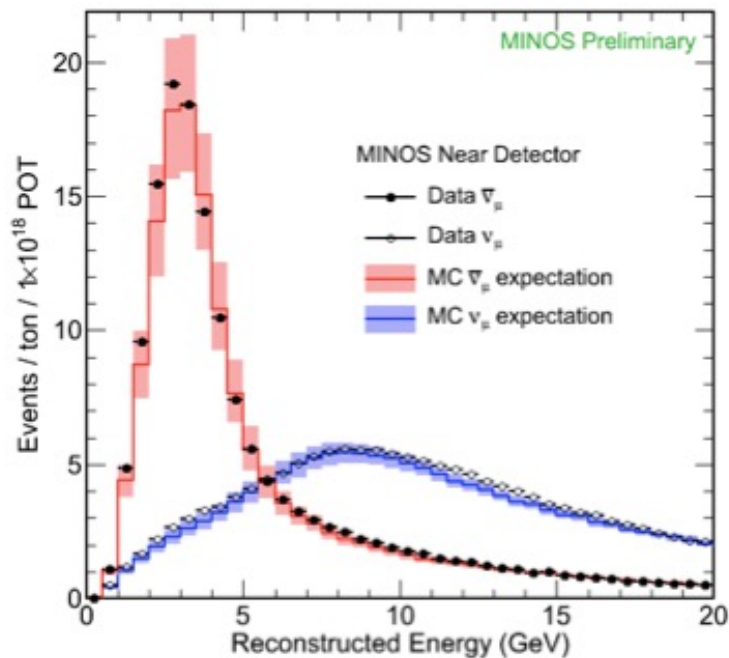
$$|\Delta m^2| = 2.32_{-0.08}^{+0.12} 10^{-3} eV^2$$

$$\sin^2(2\theta_{23}) > 0.90 \quad 90\% \text{ c.l.}$$

# Minos: $\bar{\nu}_\mu$ oscillation parameters

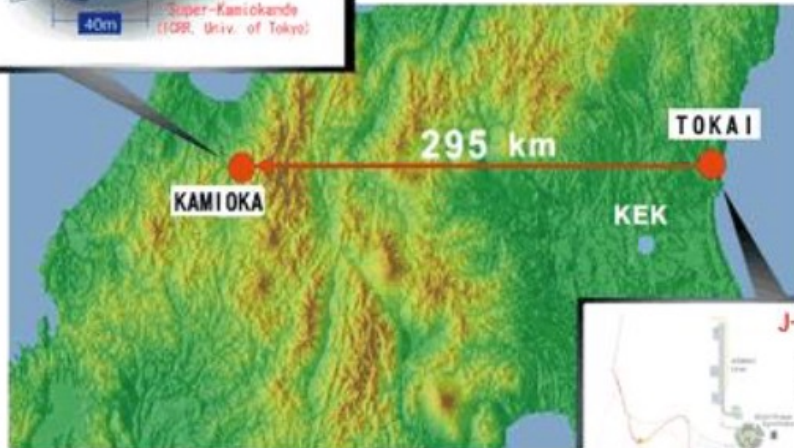
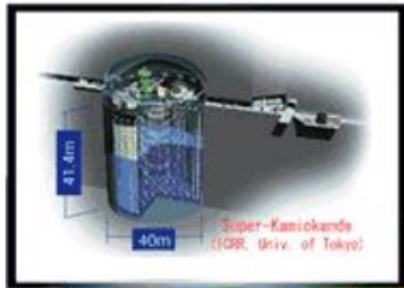


- Very similar analysis with respect to  $\nu_\mu$  but reversed horn current to select  $\pi^-$  instead of  $\pi^+$
- Background:
  - Neutral current at low energy
  - Wrong muon sign in CC events

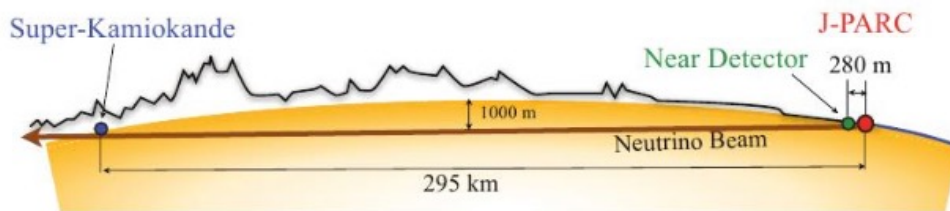


# Long-baseline oscillation experiments

## T2K: running experiment



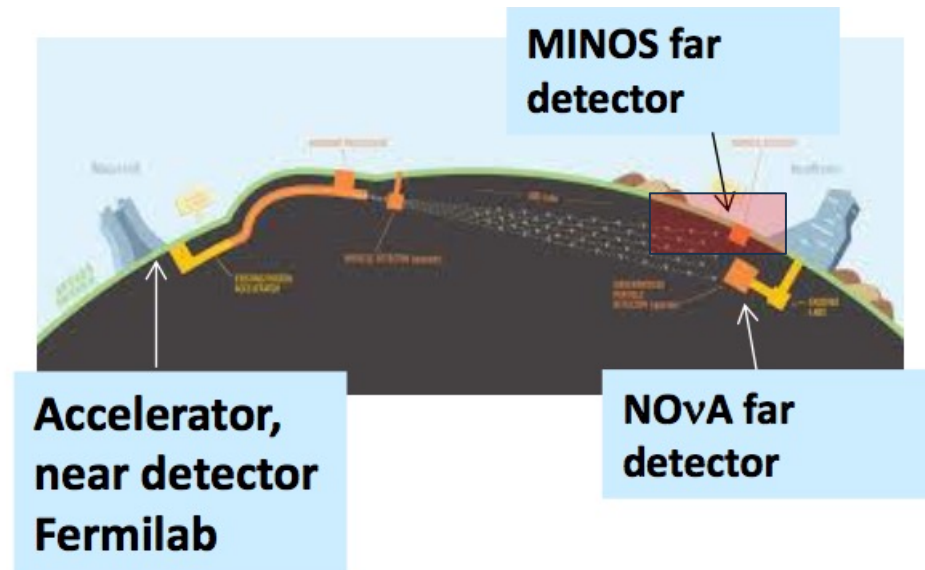
T2K is a neutrino experiment designed to investigate how neutrinos change from one flavour to another as they travel (neutrino oscillations). An intense beam of muon neutrinos is generated at the J-PARC nuclear physics site on the East coast of Japan and directed across the country to the Super-Kamiokande neutrino detector in the mountains of western Japan. The beam is measured once before it leaves the J-PARC site, using the near detector ND280, and again at Super-K: the change in the measured intensity and composition of the beam is used to provide information on the properties of neutrinos.



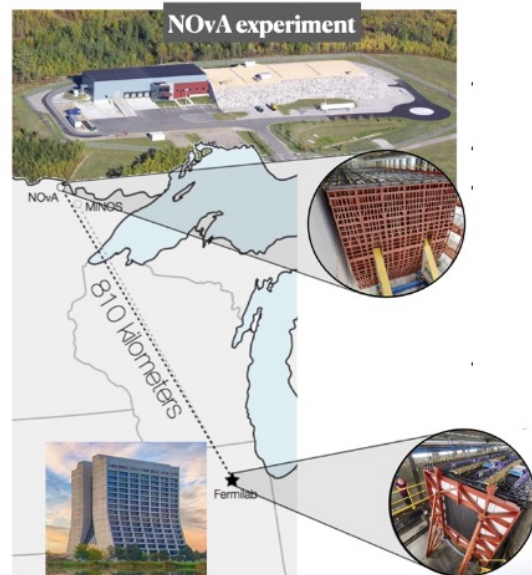
# Long-baseline oscillation experiments

## NOvA

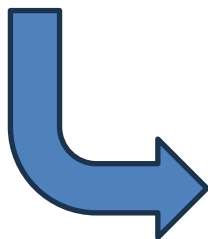
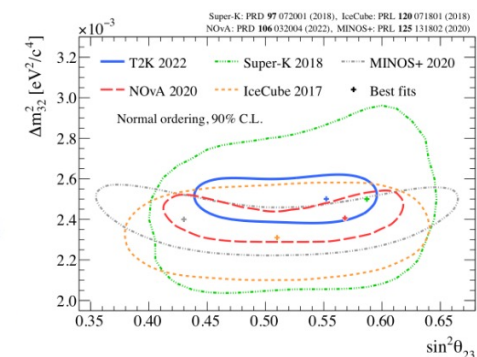
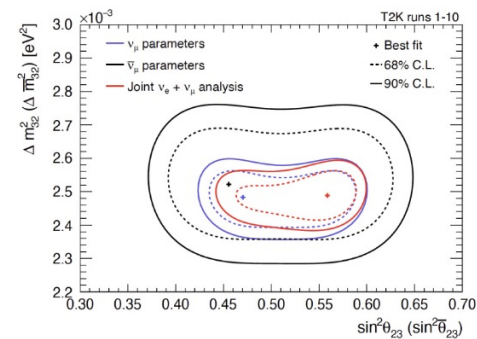
The NOvA experiment place a second off-axis detector, with a shorter baseline, such that, by exploiting matter effects, the **type of neutrino mass hierarchy could be determined** with only the neutrino run. The determination of this parameter is free of degeneracies, provided the ratio  $L/E$ , where  $L$  is the baseline and  $E$  is the neutrino energy, is the same for both detectors [1].



[1] O.M. Requejo et al., Super-NOA: A long-baseline neutrino experiment with two off-axis detectors, Phys. Rev. D 72 (2005) 053002

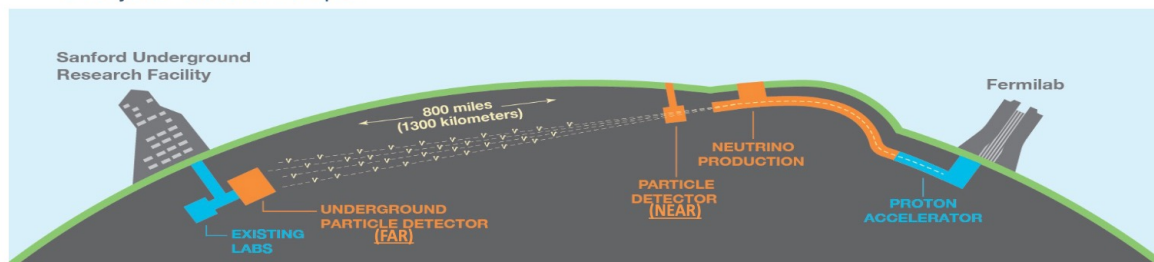


	T2K	NOvA
<b>Proton energy &amp; power</b>	30 GeV / -500 kW	120 GeV / -700 kW
<b>Peak neutrino energy</b>	0.6 GeV	1.8 GeV
<b>Baseline</b>	295 km	810 km
<b>Far detector mass</b>	50 kton	14 kton
<b>Detector technique</b>	Water Cherenkov	Segmented liquid scintillator bar
<b>Run period</b>	2010 – (~2027)	2014 – (~2026)



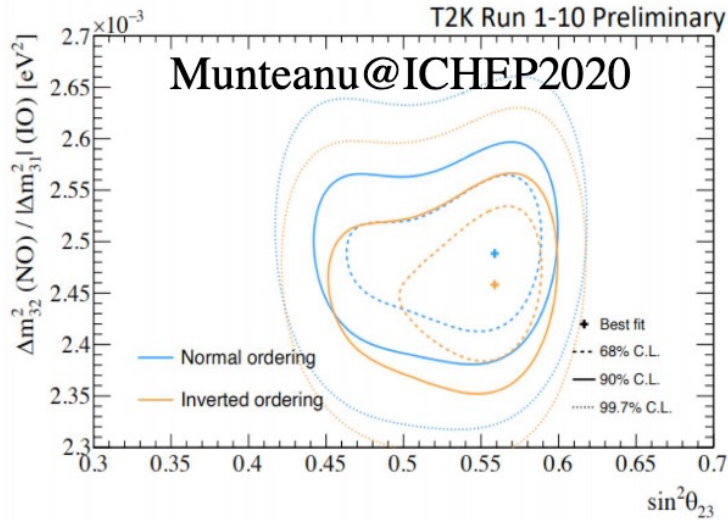
## Deep Underground Neutrino Experiment

- Long-baseline (LB - 1300 km) experiment:
  - Neutrino and antineutrino beams
- ~ 70 kton volume far detector, 1.5 km underground, divided in 4 modules
- Multi-technology Near Detector, focused on beam characterization and physics
- > 20 years foreseen life span
- **Primary physics goals:**
  - 3-neutrino oscillations parameters:  $\nu_\mu/\bar{\nu}_\mu$  disappearance,  $\nu_e/\bar{\nu}_e$  appearance
  - $\delta_{CP}$ ; mass hierarchy
- **SuperNova** burst neutrinos
- **Beyond-Standard-Model physics:** baryon number violation, sterile neutrinos, non-standard interactions, etc.



# Accelerator neutrino results

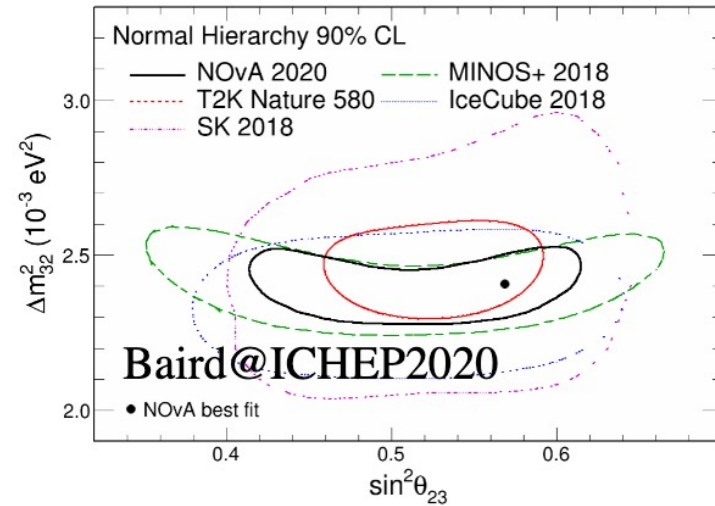
**T2K**



**NOvA**

$$\Delta m_{32}^2 = (2.41 \pm 0.07) \times 10^{-3} \text{ eV}^2$$

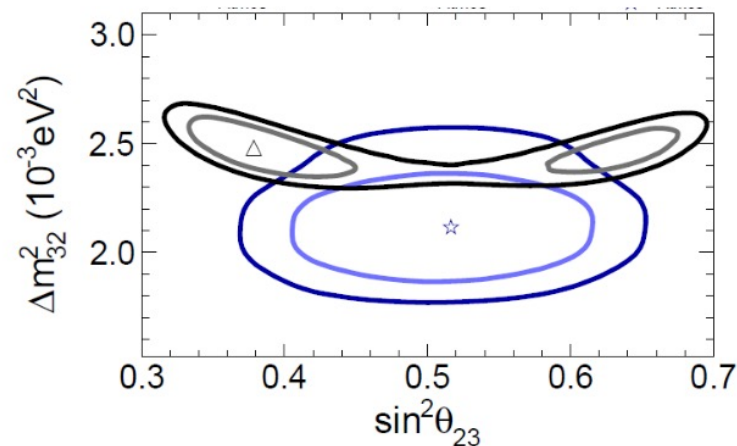
$$\sin^2(\theta_{23}) = 0.57^{+0.04}_{-0.03} \quad (49^\circ)$$



**Minos/Minos+**

Beam Best Fit  
Normal Hierarchy  
 $\Delta m_{32}^2 = 2.48 \times 10^{-3} \text{ eV}^2$   
 $\sin^2 \theta_{23} = 0.38$

arXiv:2006.15208v2 (2020)



# What we learnt from Atmospheric Neutrino vs Long-baseline expts

$$\nu_{\mu} = (\nu_2 + \nu_3) / \sqrt{2}$$

$$\nu_{\tau} = (\nu_2 - \nu_3) / \sqrt{2}$$

This corresponds to a mixing angle  $\theta$  of 45 deg (maximal mixing).

We also learnt that the squared mass difference is

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

# Conclusions

- Antineutrino from radioactive decays of  $^{238}\text{U}$  and  $^{232}\text{Th}$  chains in Earth were detected by KamLAND and Borexino detectors (see later)
- Investigations of atmospheric neutrinos confirmed oscillations of muon neutrino
- MINOS, K2K, and Super-K experiments have all independently observed muon neutrino disappearance over long baselines
- T2K and NOvA measured with high accuracy the oscillation parameters (+matter effects)
- OPERA confirmed for the first-time appearance of tau neutrino from muon neutrinos
- Results of the experiments strongly rely on simulation of effect and background, calibration of the detectors
- Precise measurements of all the neutrino mixing parameters are requested to extent the Standard Model

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta) \sin^2\left(1.27 \frac{\Delta m^2 L}{E}\right)$$

	$L(m)$	$E (MeV)$	$\Delta m^2 (eV^2)$	$1.27 \frac{\Delta m^2 L}{eV^2 km} \frac{GeV}{E}$	
Sol	$10^{10}$	1	$10^{-10}$	1.27	Vacuum osc
	$10^{10}$	1	$7.5 \times 10^{-5}$	$10^6$	MSW
React LBL	$180 \times 10^3$	1 – 10	$7.5 \times 10^{-5}$	1.7 – 17	KamLand
Atm	$10^4 - 10^7$	$10^2 - 10^5$	$3.5 \times 10^{-3}$	$5 \times 10^{-4} - 5 \times 10^2$	
Acc LBL	$10^5 - 10^6$	$10^3 - 10^4$	$3.5 \times 10^{-3}$	$5 \times 10^{-2} - 5$	
React SBL	$10^2 - 10^3$	1 – 10	$3.5 \times 10^{-3}$	$5 \times 10^{-2} - 5$	Hints for $L > 1$ km
Acc SBL	$10^2$	$10^3 - 10^4$	1	0.13 – 0.013	Sterile $\nu$ ?
React $\nu$	$10^3$	1 – 10	$3.5 \times 10^{-3}$	Far from sol $\nu$ solution	Theta13
Acc LBL	$10^5 - 10^6$	$10^3 - 10^4$			$\Delta m_{31}^2 \approx \Delta m_{32}^2$

}  $\Delta m_{21}^2$   
 }  $\Delta m_{32}^2$