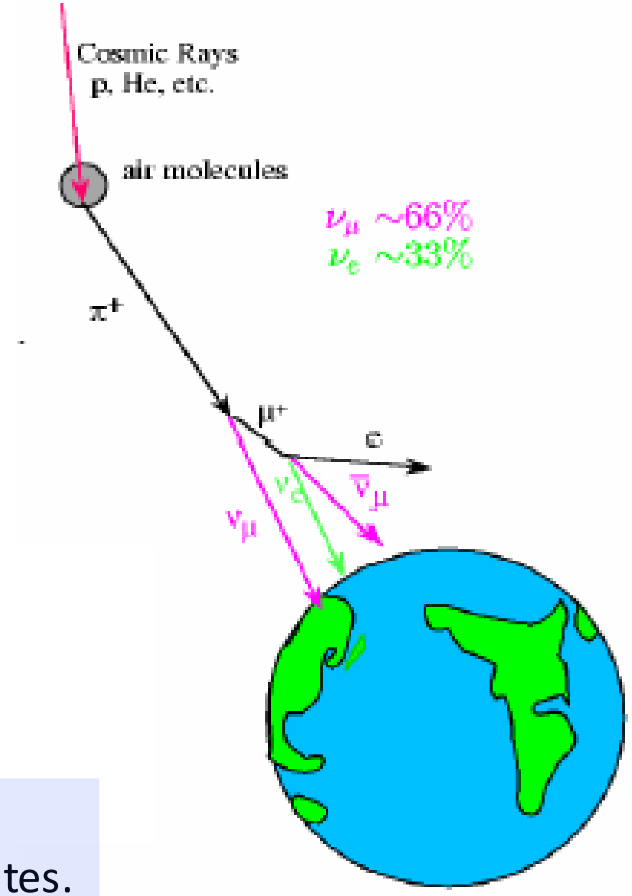
Atmospheric Neutrinos

- Another evidence for ν oscillations
- First atm. ν observations:
  - Kamiokande
  - Soudan
  - IMB

and then:

  - MACRO LNGS
  - SUPERKAMIOKANDE



Neutrinos have non-zero masses.
Mass eigenstates are distinct from weak interaction eigenstates.

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

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

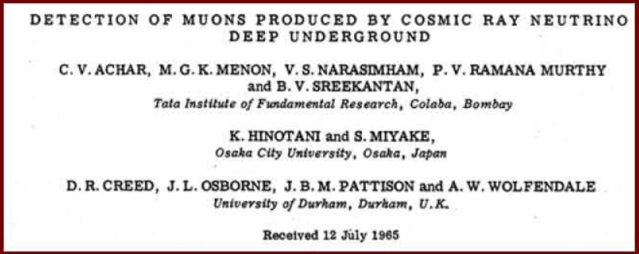
- The Indian team was led by

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

  F. Reines et al.

KGF – The 1st 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

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

Received 12 July 1965

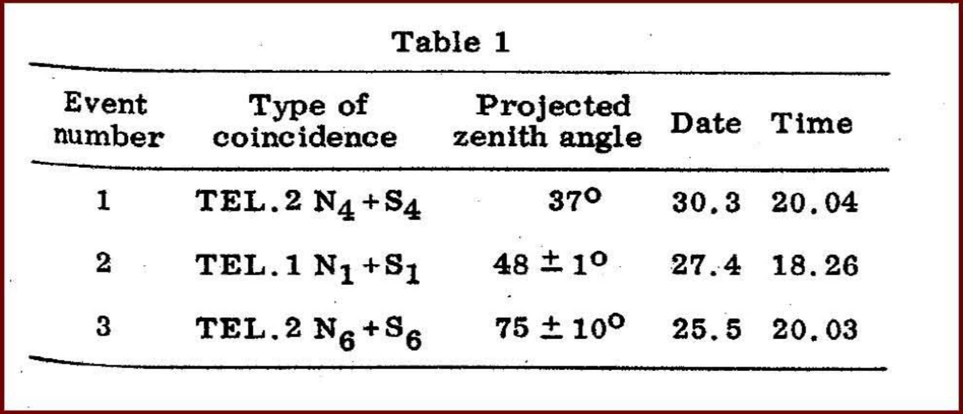
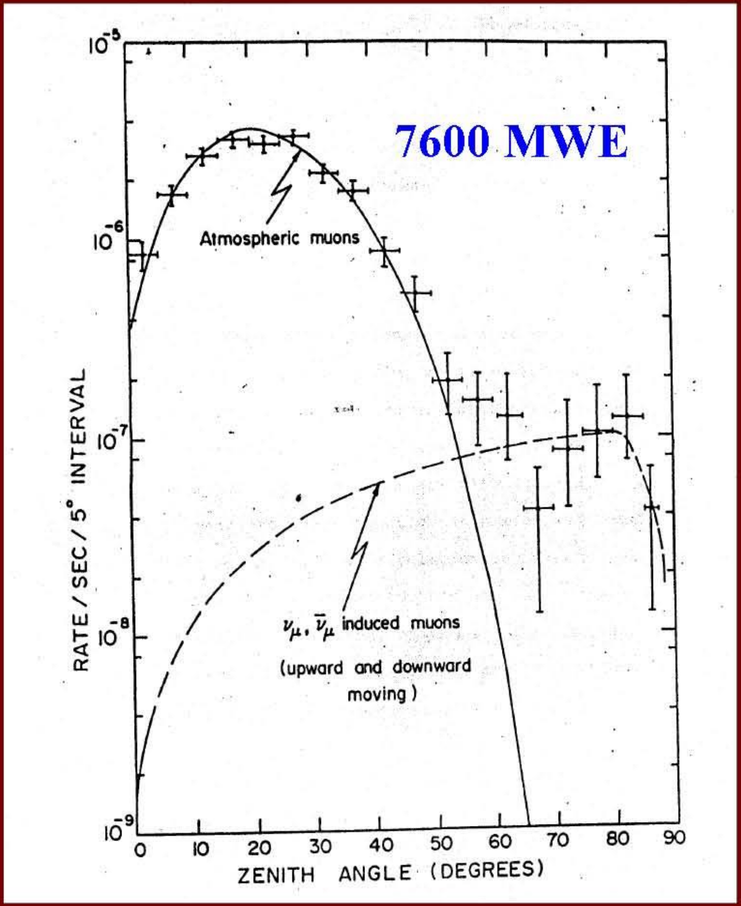


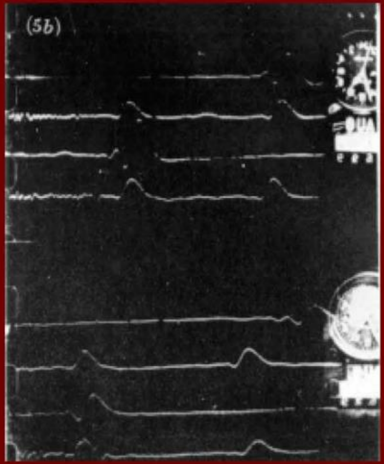
Table 1

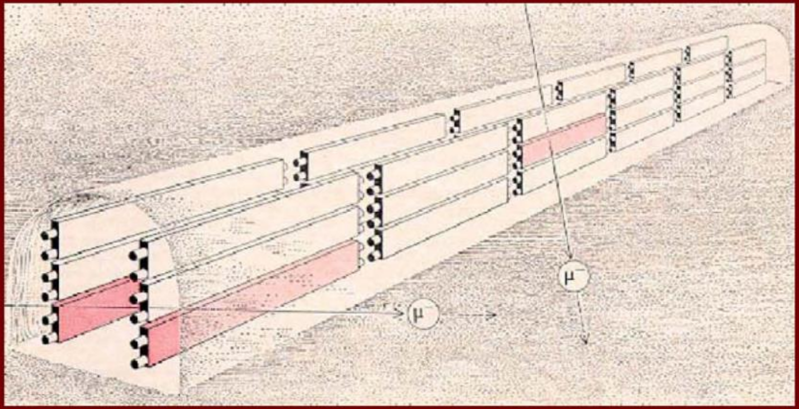
Event number	Type of coincidence	Projected zenith angle	Date	Time
1	TEL.2 $N_4 + S_4$	37°	30.3	20.04
2	TEL.1 $N_1 + S_1$	48 ± 1°	27.4	18.26
3	TEL.2 $N_6 + S_6$	75 ± 10°	25.5	20.03

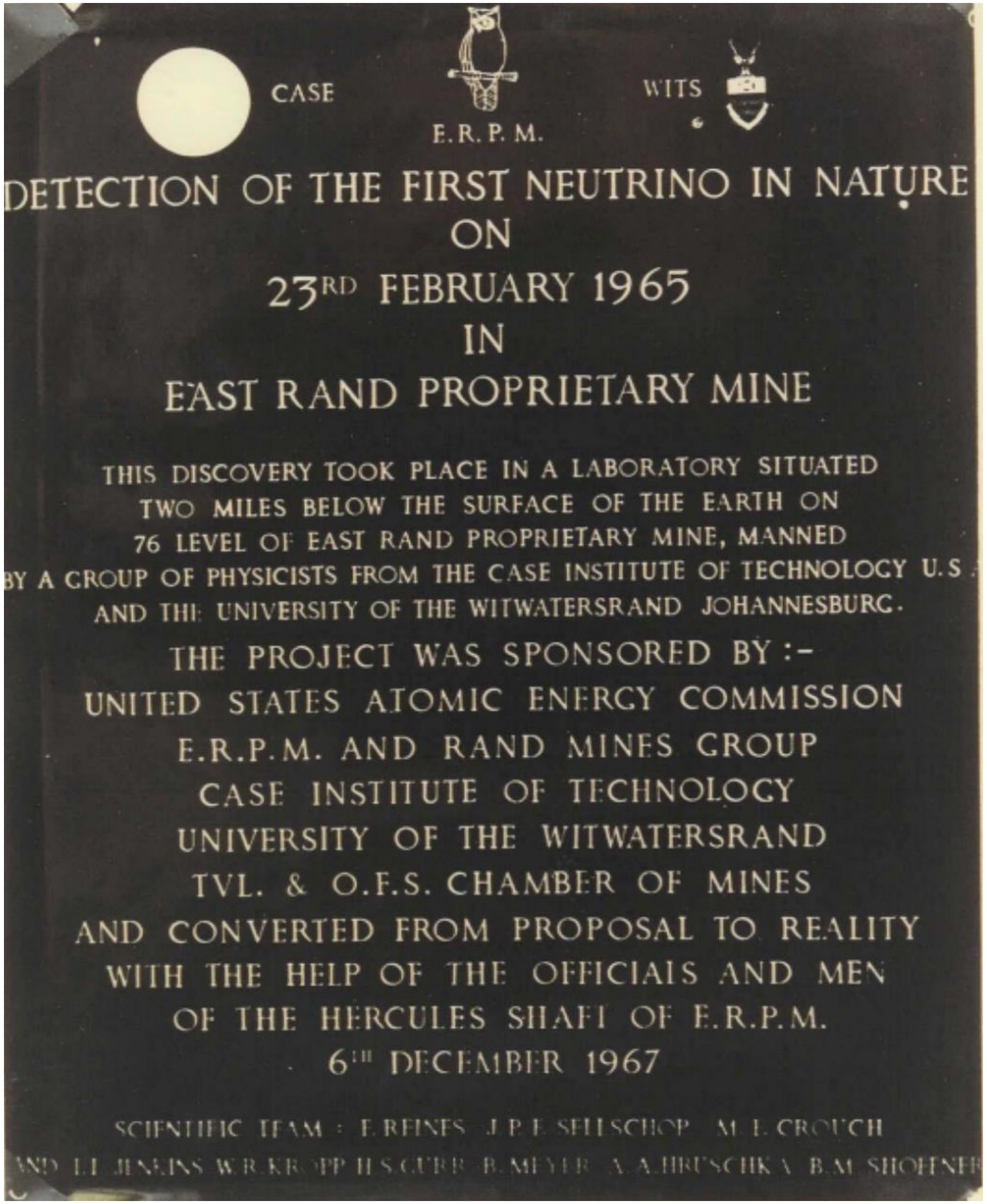


CWI – The 1st recorded Atmospheric ν

First ν
February 29, 1965
Recorded 100 (1/month)







CASE

E.R.P.M.

WITS

DETECTION OF THE FIRST NEUTRINO IN NATURE
ON
23RD 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.
6TH DECEMBER 1967

SCIENTIFIC TEAM : F. REINES J. P. F. SELLSCHOP M. F. CROUCH
AND T.L. JENKINS W.R. KROPP H.S. GURR B. MEYER A. A. HRUSCHKA B.M. SHOEFNER

“Atmospheric” neutrinos

Main sources of atmospheric neutrinos

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

$$\hookrightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

For energies $E < 2$ 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

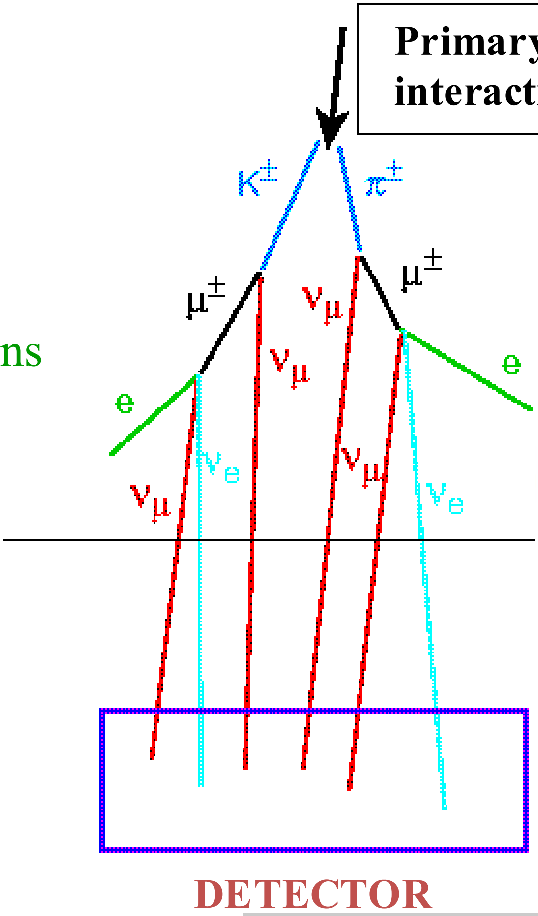
Very low event rates: ~100 /year for a 1000-ton detector

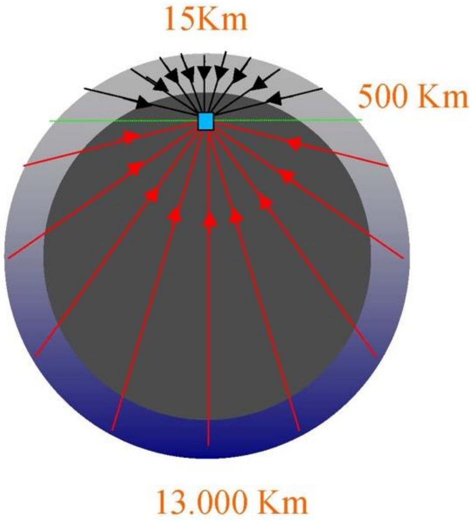
Typical uncertainty on the atmospheric neutrino fluxes: ± 30%

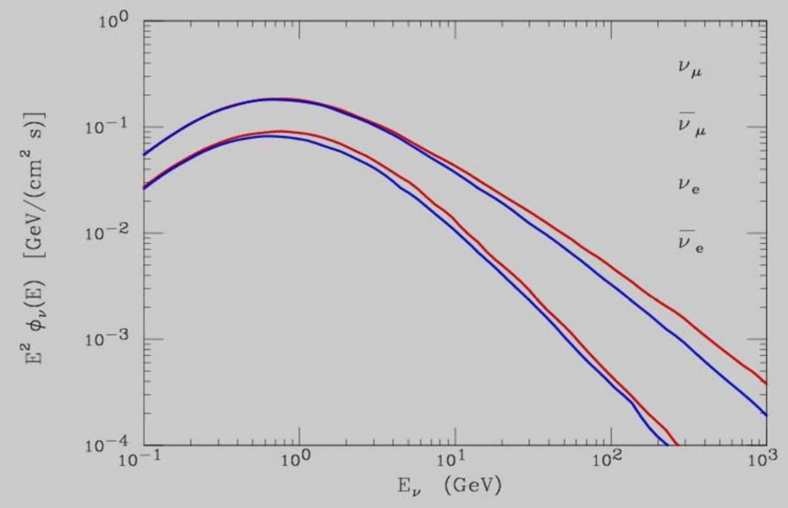
(from uncertainties on the primary cosmic ray spectrum, on hadron production, etc.)

Uncertainty on the ν_{μ} / ν_{e} ratio : ± 5%

Primary cosmic ray interacting in the atmosphere

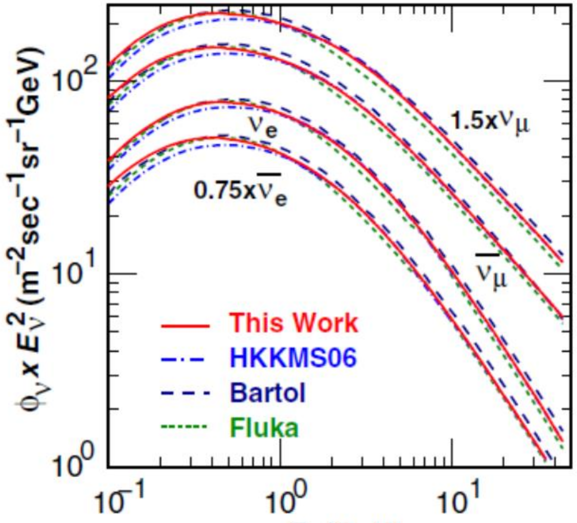


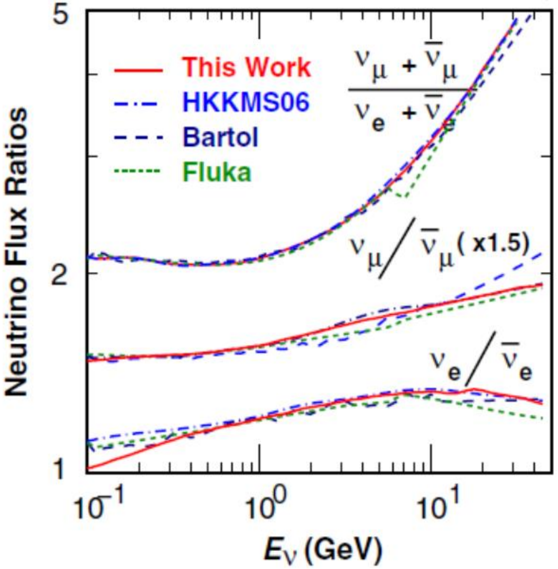


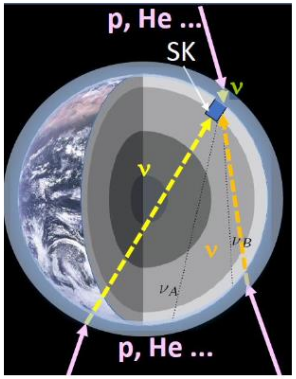


Atmospheric neutrinos

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







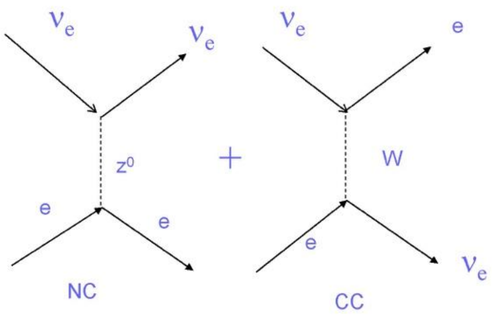
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$; $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$.

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

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

Neutrinos travel 10~12000 km

Neutrino scattering on electrons



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

Remember for ν_μ and ν_τ only NC

OSSERVAZIONI

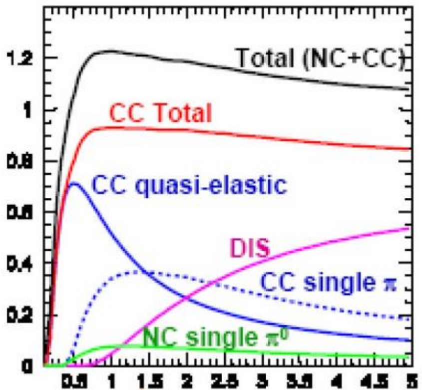
1) Le sezioni d'urto dei neutrini (interazioni deboli) sono molto piccole a 1 GeV:
   $\sigma(\nu\ p)/\sigma(p\ p) = 10^{-38}/10^{-26}$
   Questo richiede rivelatori massivi

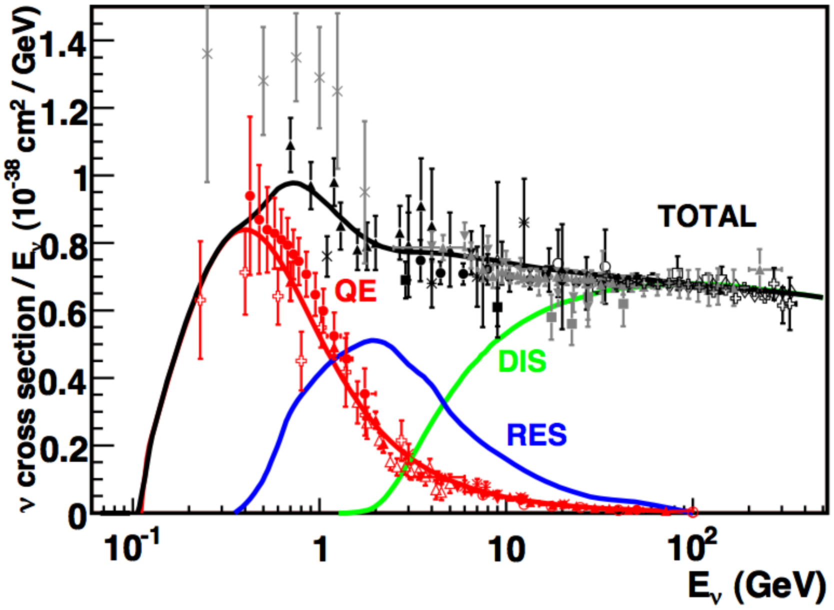
2) Il tipo di un neutrino che abbia interagito viene rivelato se esso abbia subito una interazione di corrente carica

3) Le sezioni d'urto su elettrone sono un fattore m_e/m_p più piccole

Neutrino cross section at low energy

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





Ad alte energie E > 10GeV

Deep inelastic scattering :scattering su quark

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

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

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

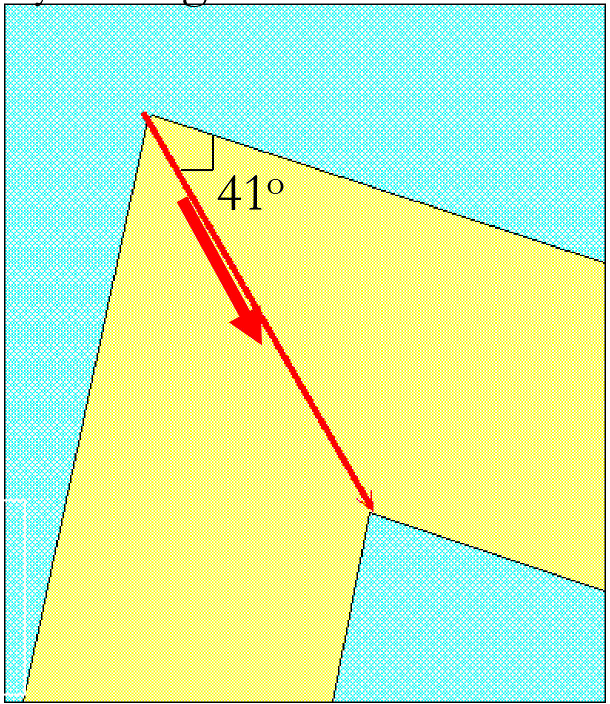
$\sigma(CC)/E = 0.34 \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}$ [antineutrini]

Atmospheric neutrino detection

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

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

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



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)

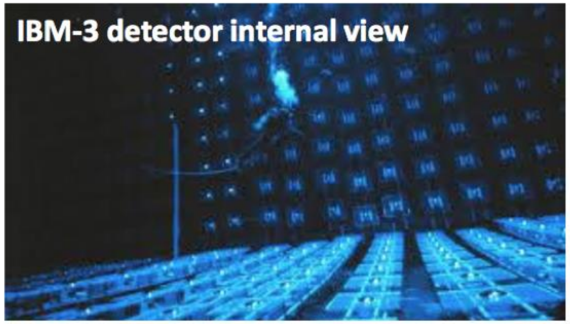
Direct measurement by exposing a 1000-ton water Čerenkov detector to electron and muon beams from a proton accelerator. Measured probability of wrong identification ~2%

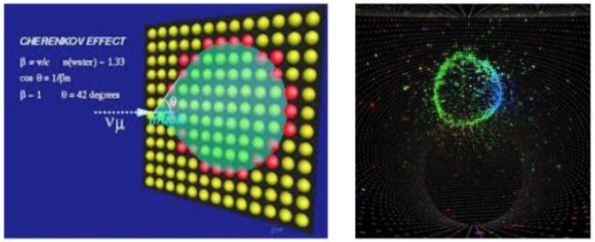
Measurement of the ν_μ/ν_e ratio: first hints for a new phenomenon in water Čerenkov detectors: Kamiokande (1988), IMB (1991), Super-K (1998) Conventional calorimeters (iron plates + proportional tubes): Soudan2 (1997)

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

Atmospheric neutrino

IMB detector: indication of muon neutrino oscillations





Reconstruction of muon trajectory and energy

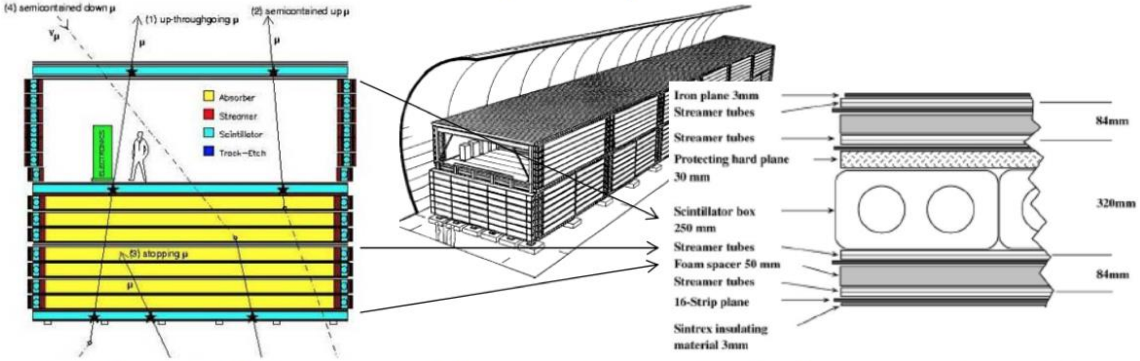
First hints of atmospheric ν oscillations

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 ν_e and ν_μ, the neutrino flavor content at the detector was be compared to calculated production rates in the atmosphere.

Nonshowering events comprise [41 ± 3(stat) ± 2(syst)]%.
While the expected fraction is [51 ± 5(syst)]%.

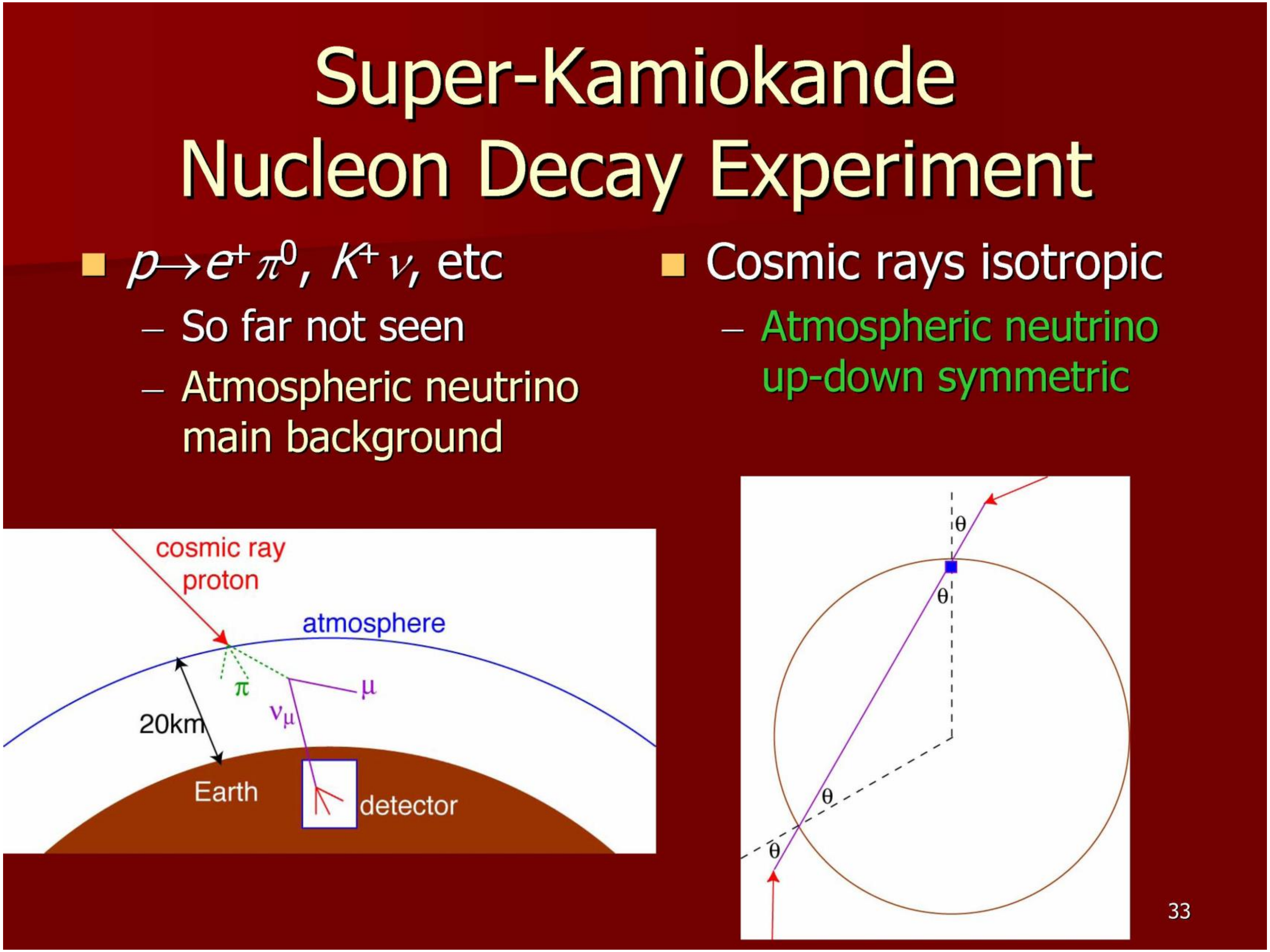
Atmospheric neutrino

MACRO detector, atmospheric ν deficit



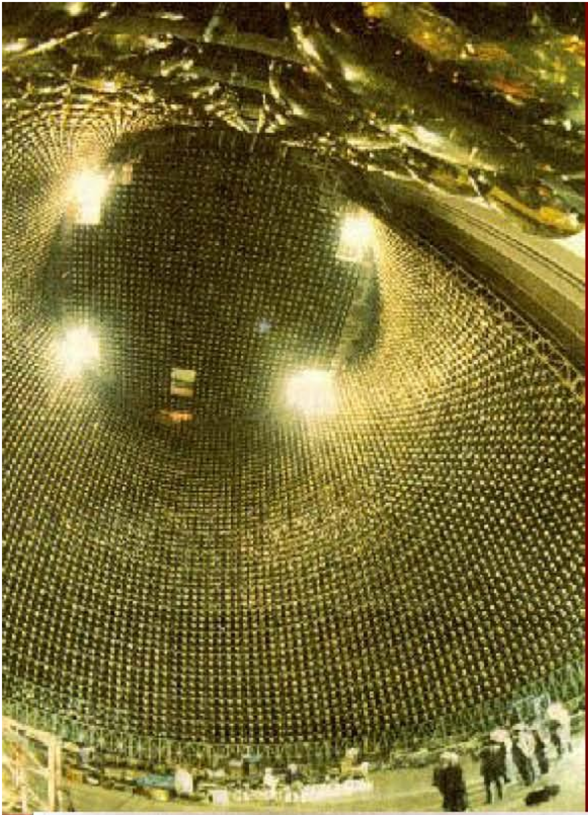
The principal goal of MACRO was to search for magnetic monopoles. The detector was also searching for WIMP annihilations in the Earth and the Sun, neutrino bursts from stellar collapses, and measurements of the flux of up-going muons showing evidence for neutrino oscillations. The apparatus consisted 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



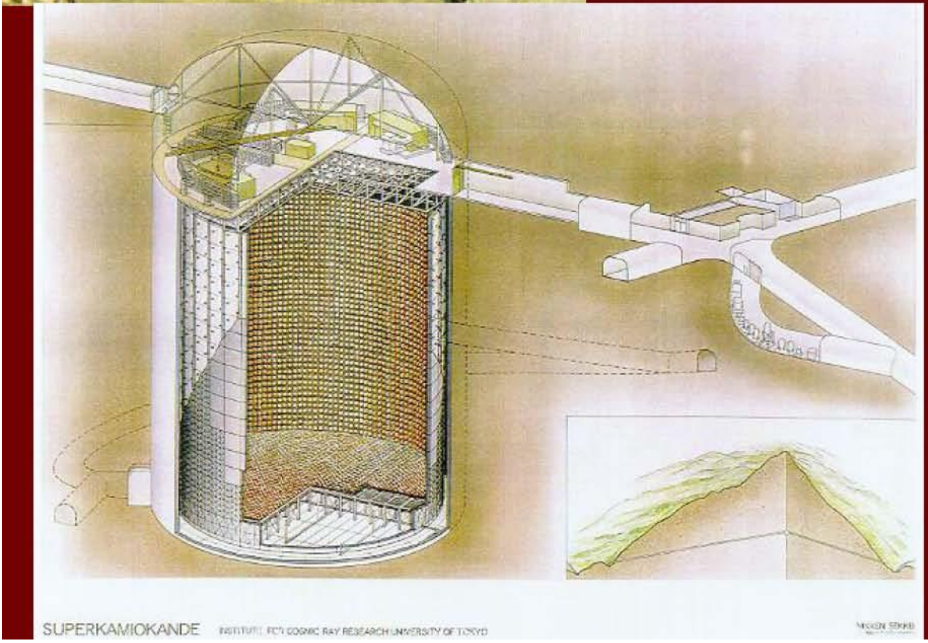
Super-Kamiokande Nucleon Decay Experiment

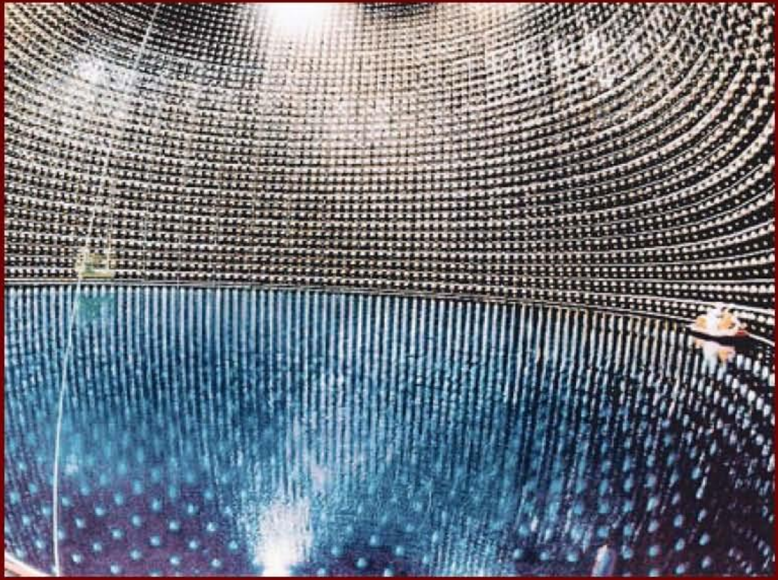
- $p \rightarrow e^{+} \pi^{0}$, $K^{+} \nu$, etc
  - So far not seen
  - Atmospheric neutrino main background
- Cosmic rays isotropic
  - Atmospheric neutrino up-down symmetric



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)

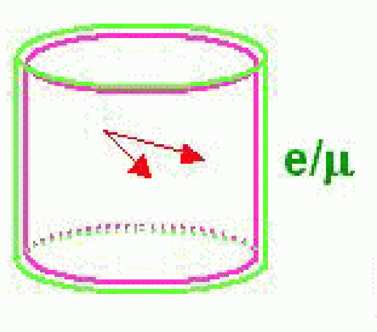




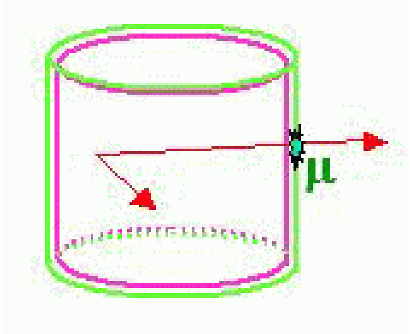
Different typologies of events in SK

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

Fully contained (FC)



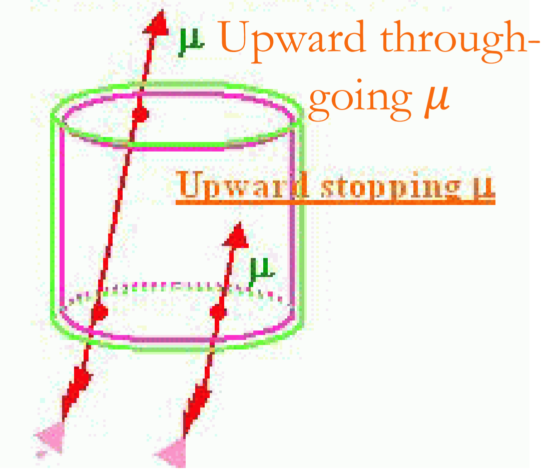
Partially contained (PC)



H_2O radiation length ≈ 36 cm

→ energetic electrons are totally absorbed in ~8 m of water

Up-going muons from ν_μ interactions in the rock



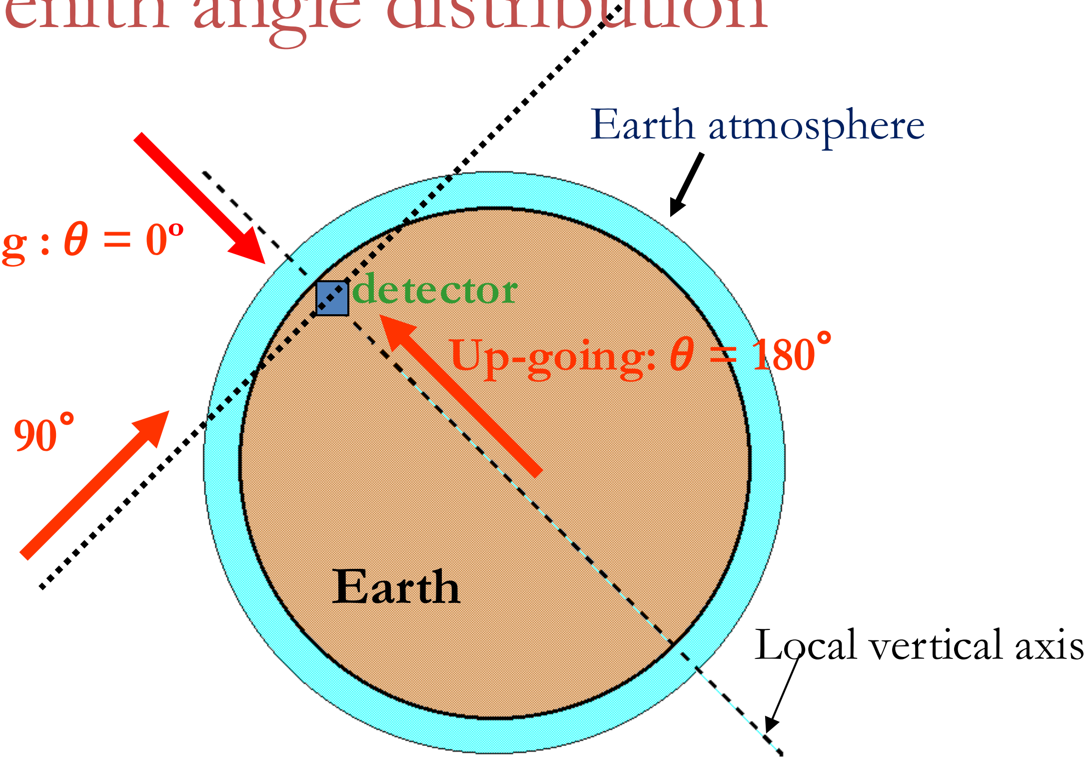
Note: down–going muons are mainly due to $\pi \rightarrow \mu$ decays in the atmosphere

Measurement of the zenith angle distribution

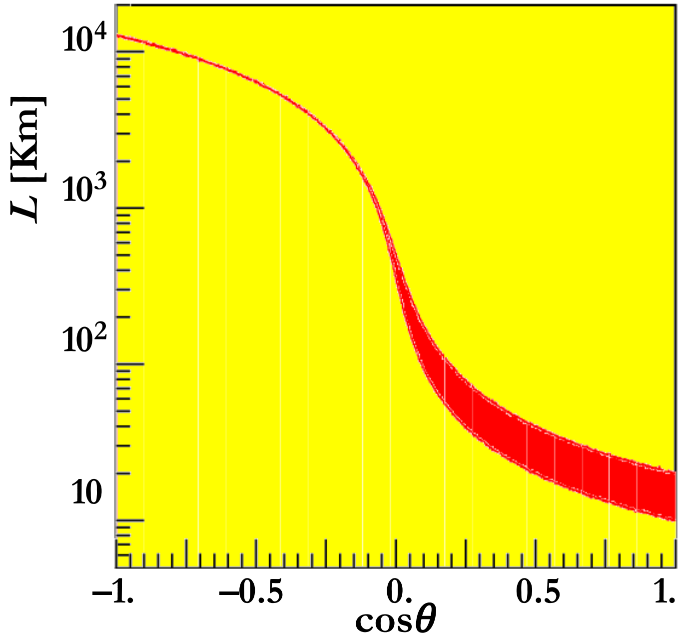
Definition of the zenith angle θ:
Polar axis along the local vertical axis,
pointing downwards

Down-going : $\theta = 0^{o}$

Horizontal : $\theta = 90^{\circ}$

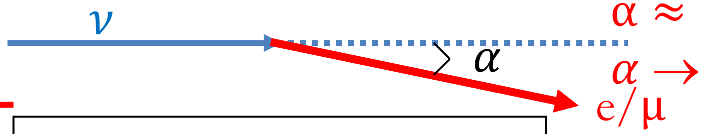


L (distance between neutrino production point and detector) depends on zenith angle



θ = 0° — 180°
L = ~10 — ~12800 km

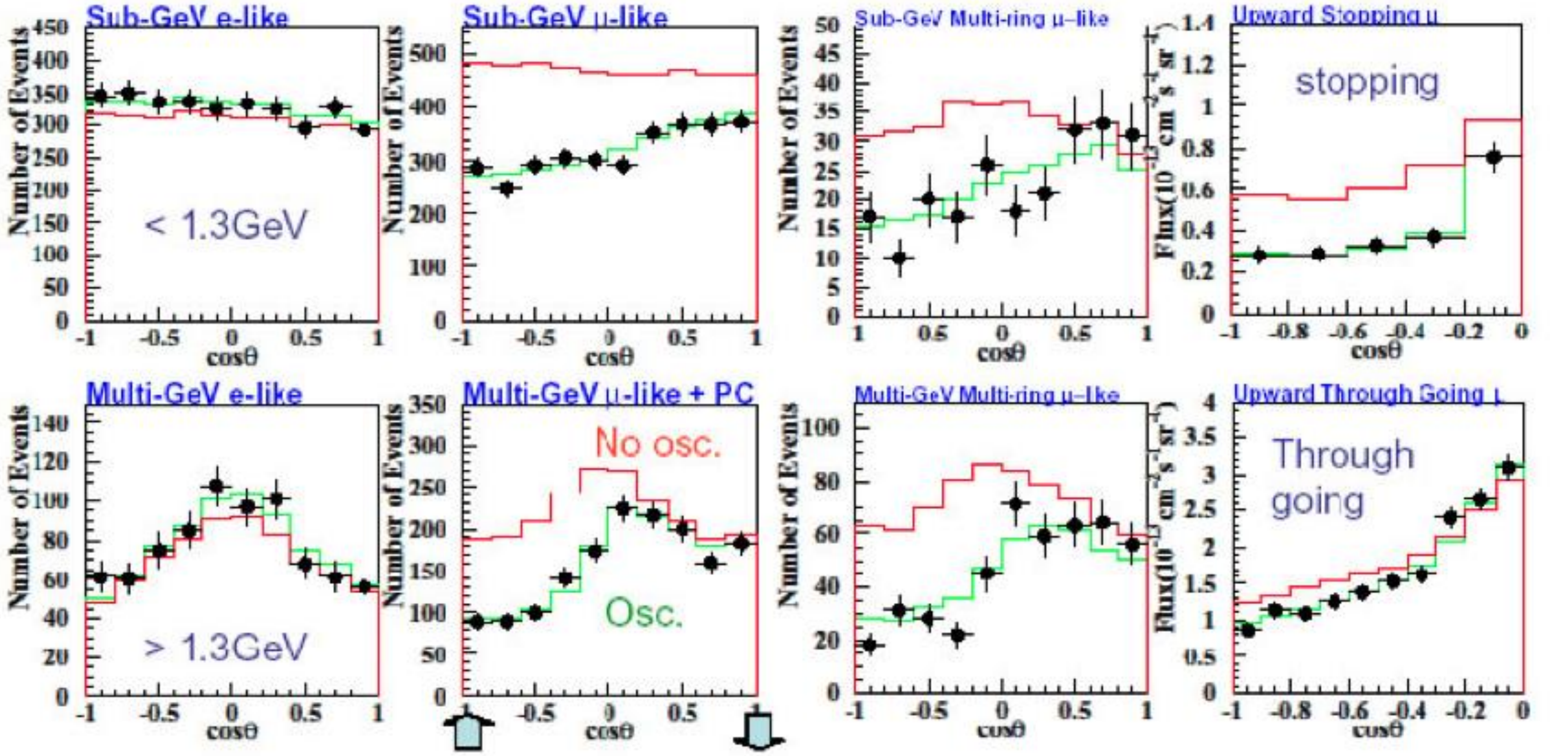
- Search for oscillations with variable distance L
- Strong angular correlation between incident neutrino and produced electron/muon for $E > 1$ GeV:



$\alpha \approx 25°$ at $E = 1$ GeV;
$\alpha \to 0$ for increasing E

Uncertainty on neutrino production point ±5 km

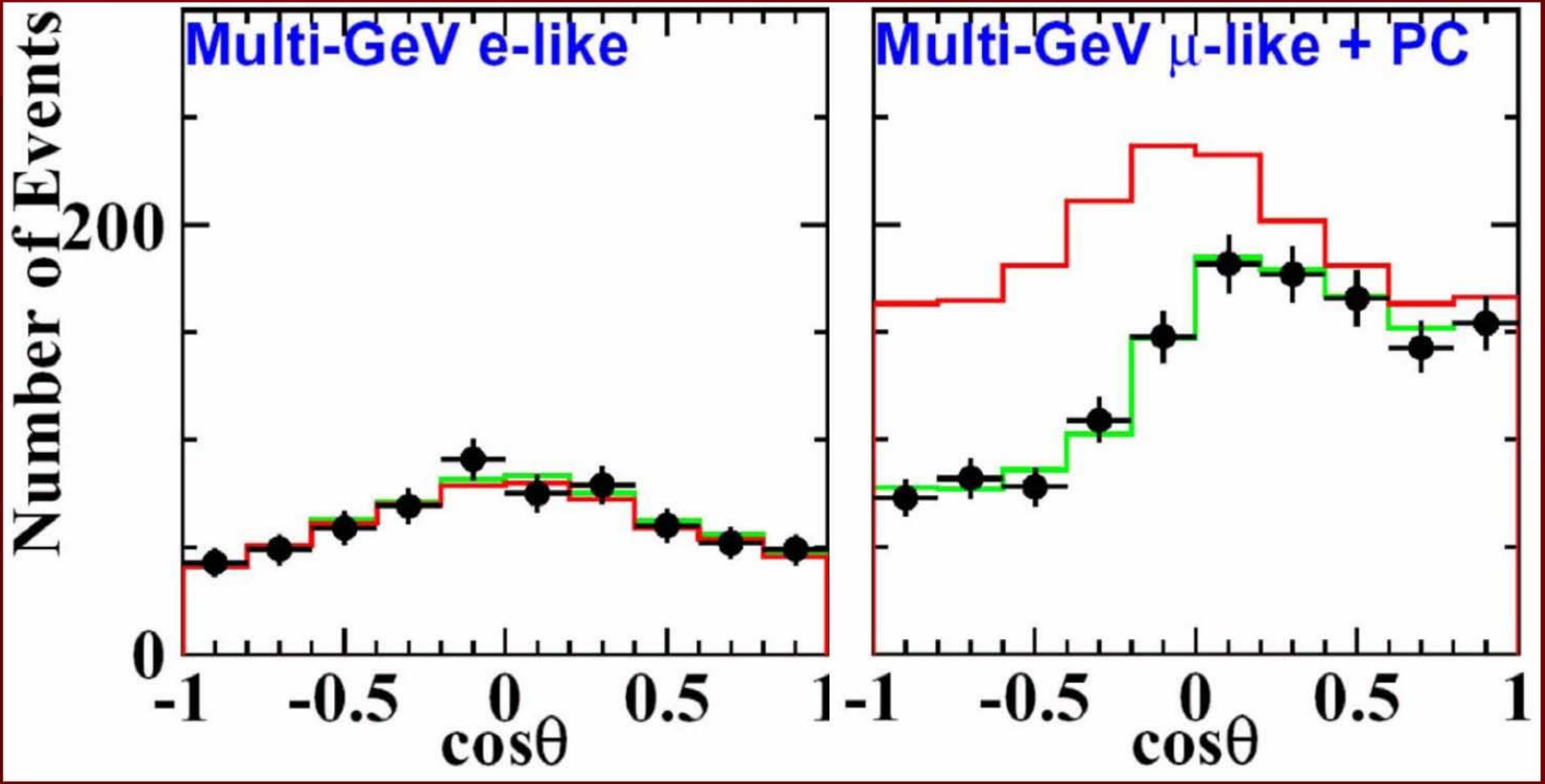
The up-ward going ν_μ flux is depleted in SK



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

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

Half of ν_μ lost!



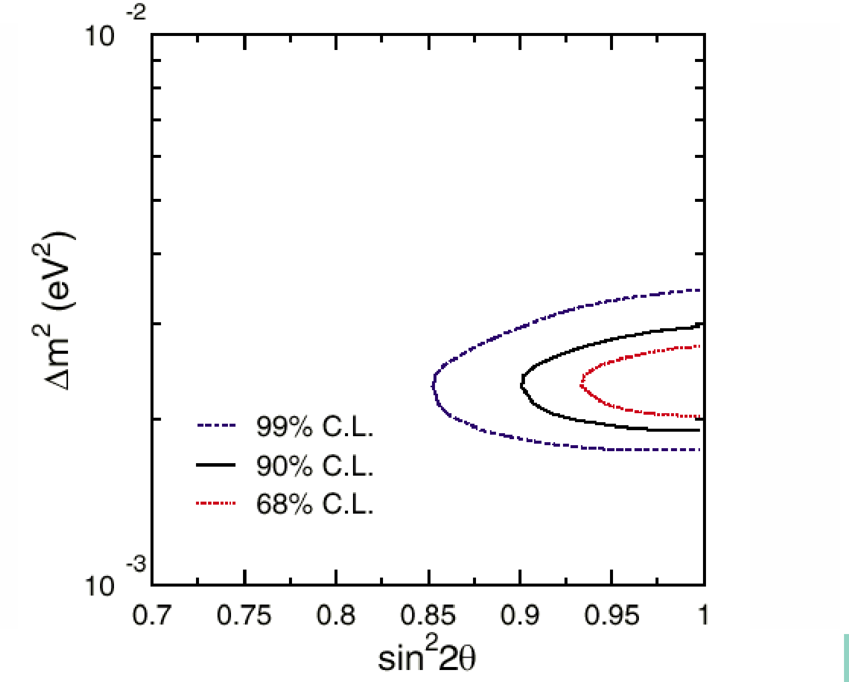
SUPERKAMIOKANDE

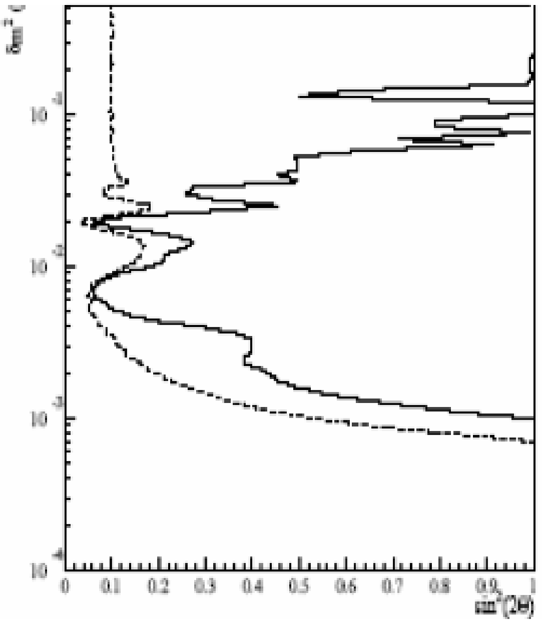
SK showed that at L/E of atmospheric neutrinos

1) ν_μ DO oscillate
2) ν_e DO NOT oscillate

This is confirmed by CHOOZ

Region of oscillation parameters (confidence level 90%):
$1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2
$\sin^2 2\theta > 0.90$



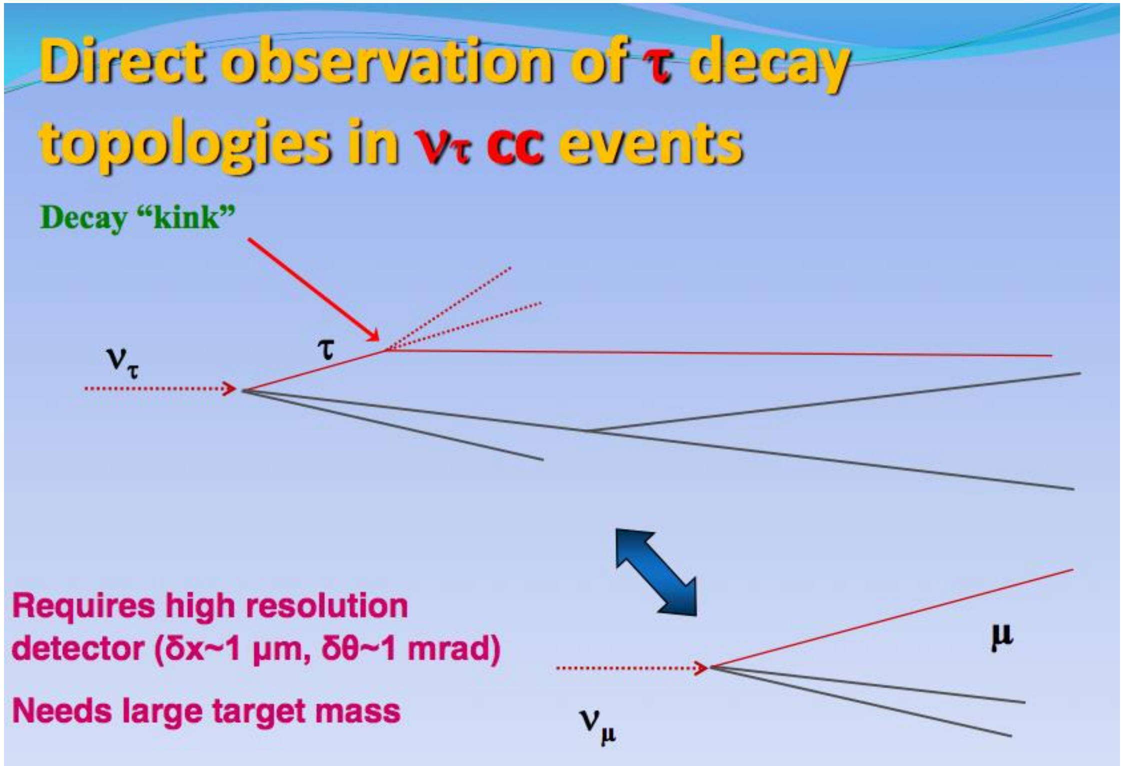


$\nu_\tau + N \rightarrow \tau + X$ requires $E(\nu_\tau) > 3.5$ GeV;
fraction of $\tau \rightarrow \mu$ decays $\approx 18\%$

- Atmospheric ν_μ do oscillate, but not to ν_e
- In a scenario with three neutrinos, ν_μ do oscillate to ν_τ
- Sterile neutrinos?
- Direct evidence of oscillation to ν_τ is from OPERA at LNGS (5 ν_τ observed)

OPERA: Oscillation Project with Emulsion tRacking Apparatus

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



Direct observation of τ decay topologies in ν_τ CC events

Requires high resolution detector (δx~1 μm, δθ~1 mrad)

Needs large target mass

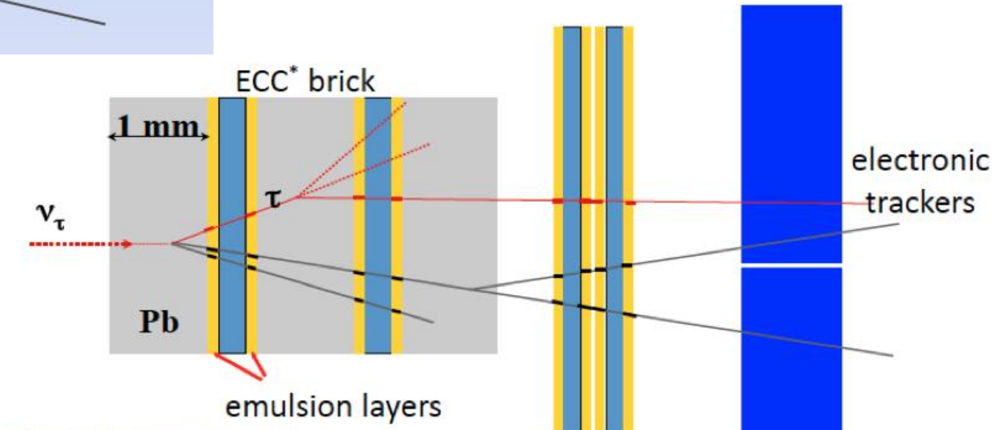
OPERA @ LNGS

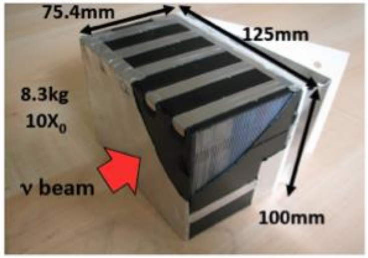
Tau lifetime = 0.29 ps (≈100 μm)

Tau decays:

- 64.79% hadronically
- 17.82% into a ν_τ, e and ν_e
- 17.39% into a ν_τ, μ and ν_μ

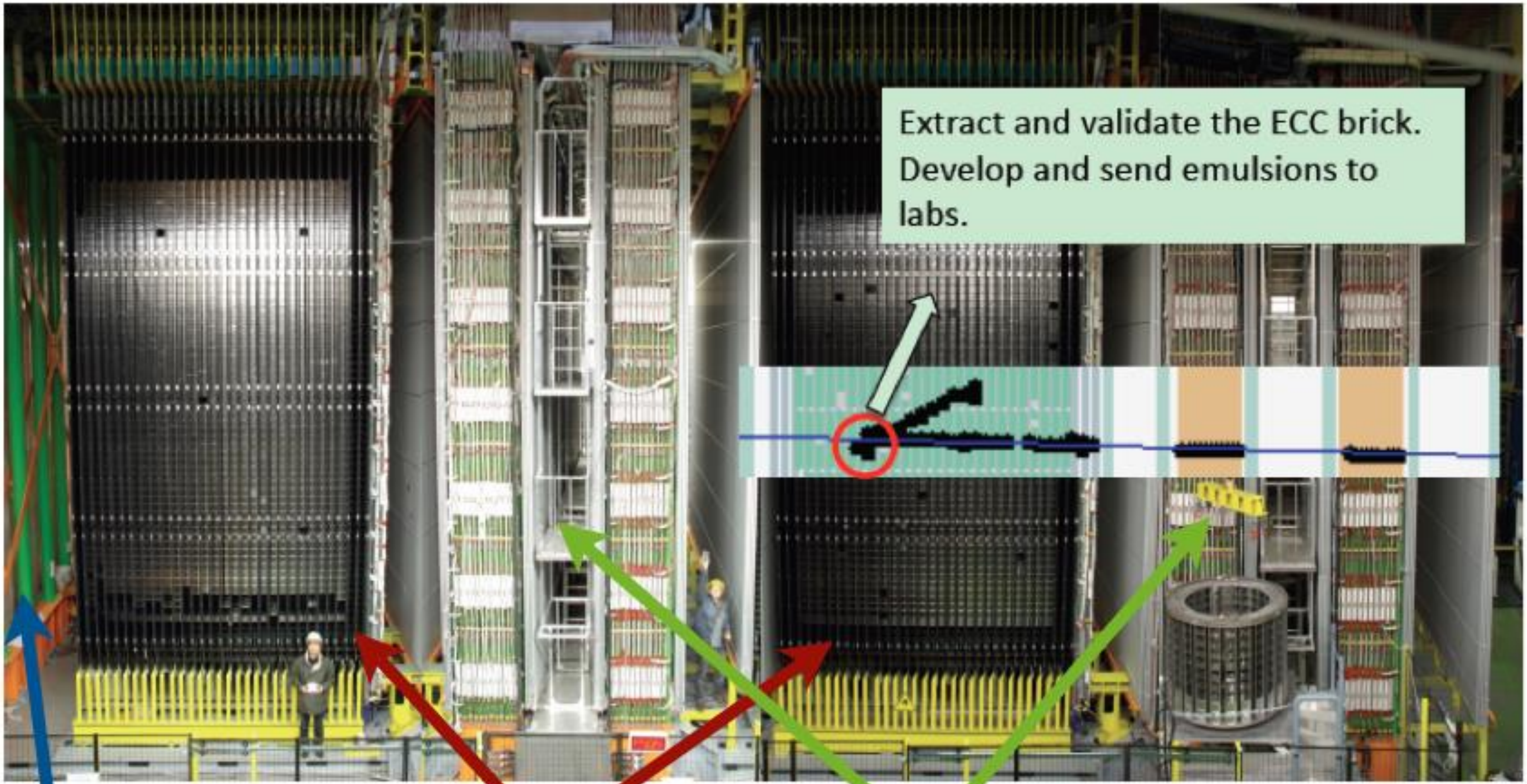
How to detect tau vertex





ECC: Emulsion Cloud Chamber

OPERA How to detect tau vertex



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

Target:
- Trackers (scintillators)
- Lead/Emulsion bricks

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

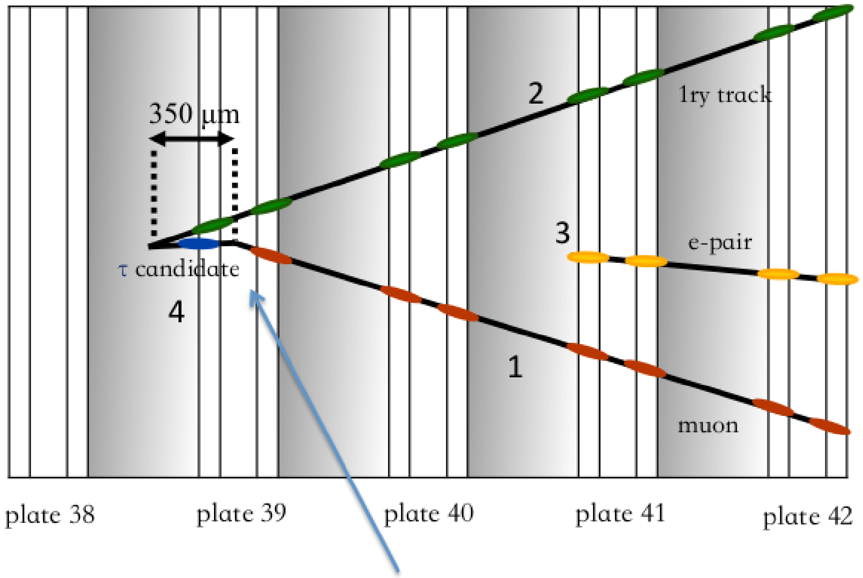
Veto

Five ν_τ candidates observed until 2015

Examples:

PRL 115 (2015) 121802.

Third candidate (muon decay)

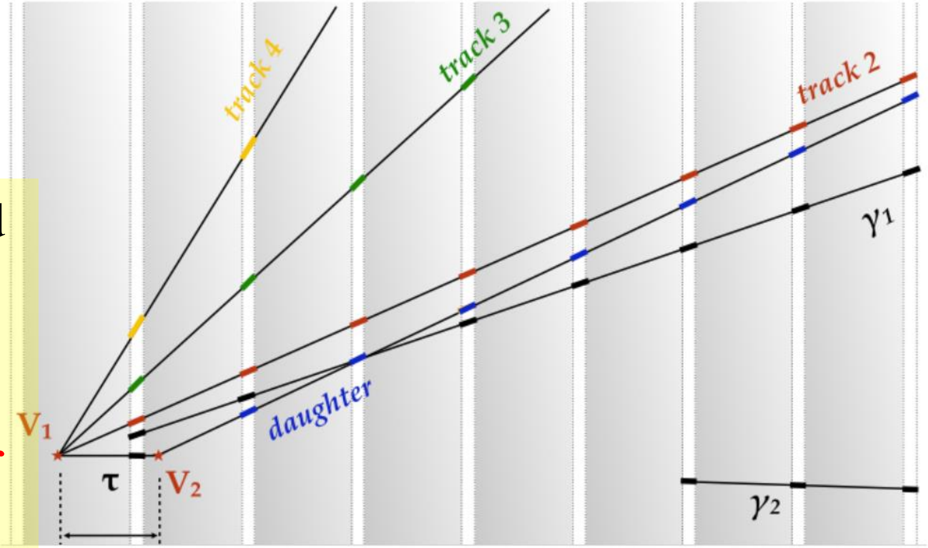


Decay in the plastic base

- OPERA was designed to search for ν_μ□ν_τ oscillations in **appearance** mode, i.e. by detecting the τ leptons produced in charged current ν_τ interactions.

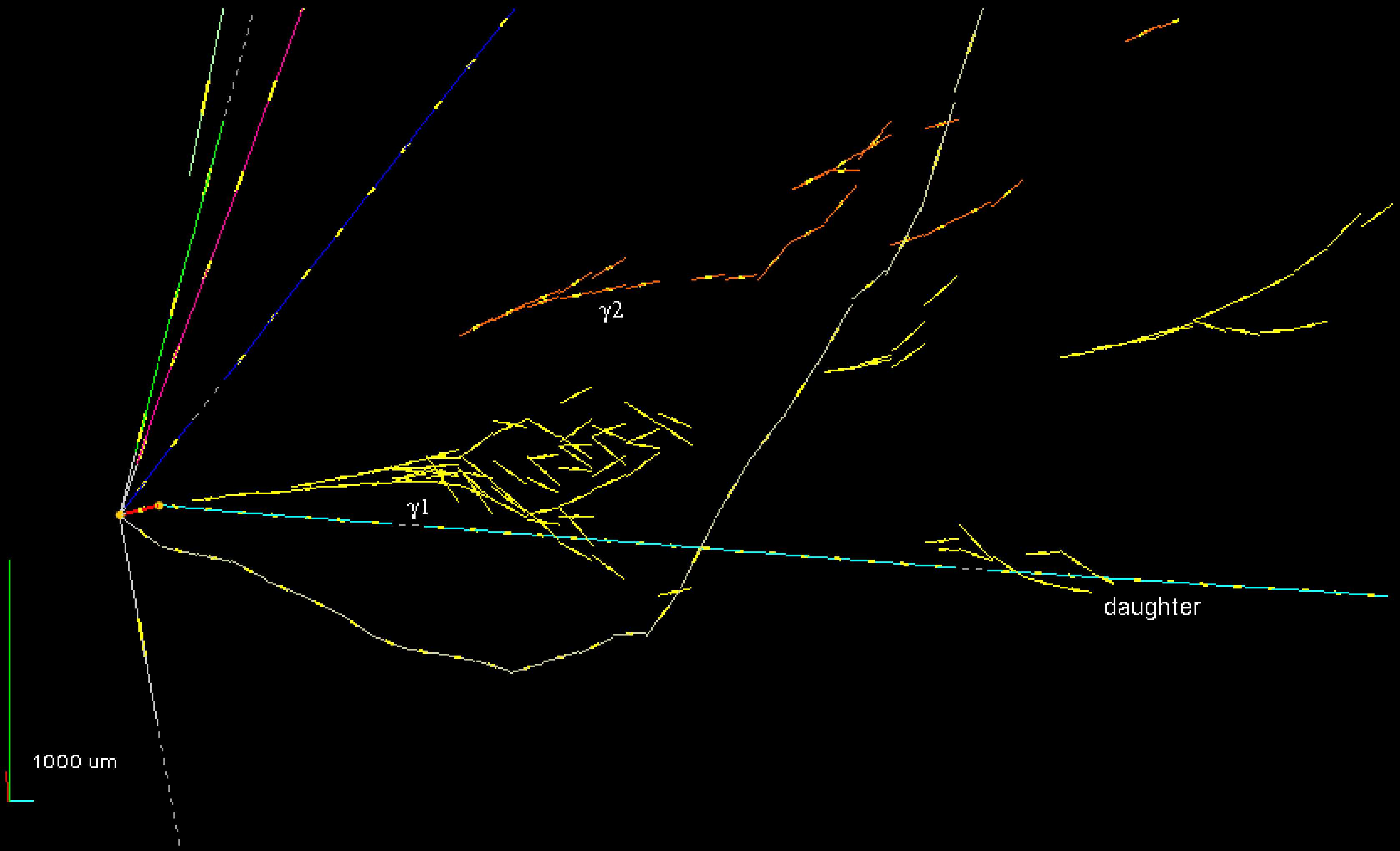
Final result (2018) 10 ν_τ candidates observed, with less stringent selection of events

Fourth candidate (hadronic decay, single prong)



- Observation of the ν_μ□ν_τ 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 ν_μ□ν_τ oscillations** in appearance mode with a significance larger than **5 σ**

Event reconstruction (1)

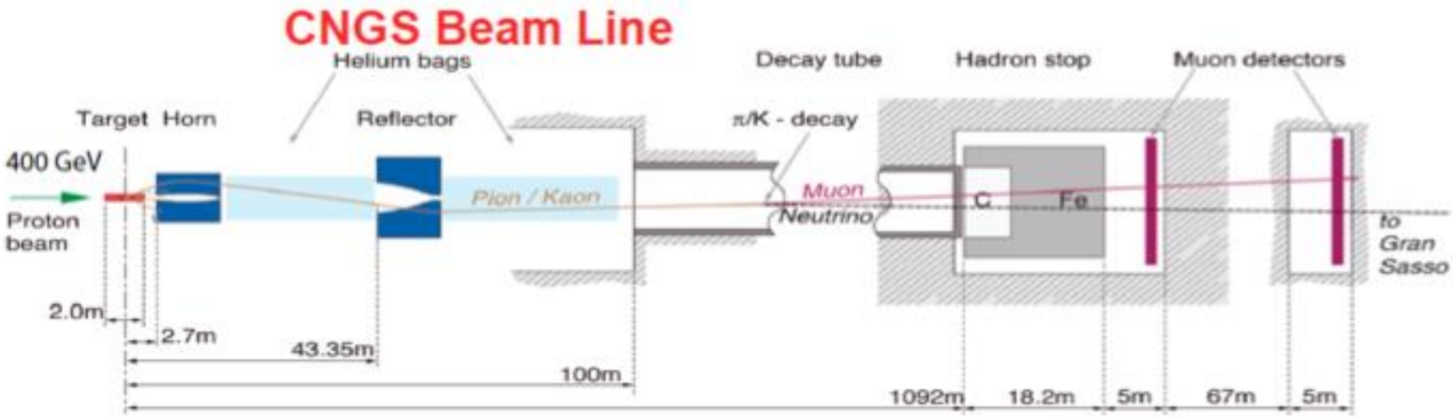


SK results for atmospheric neutrinos have been confirmed by “Long Baseline” expts

- neutrino beams in the world (at the end of their projects)

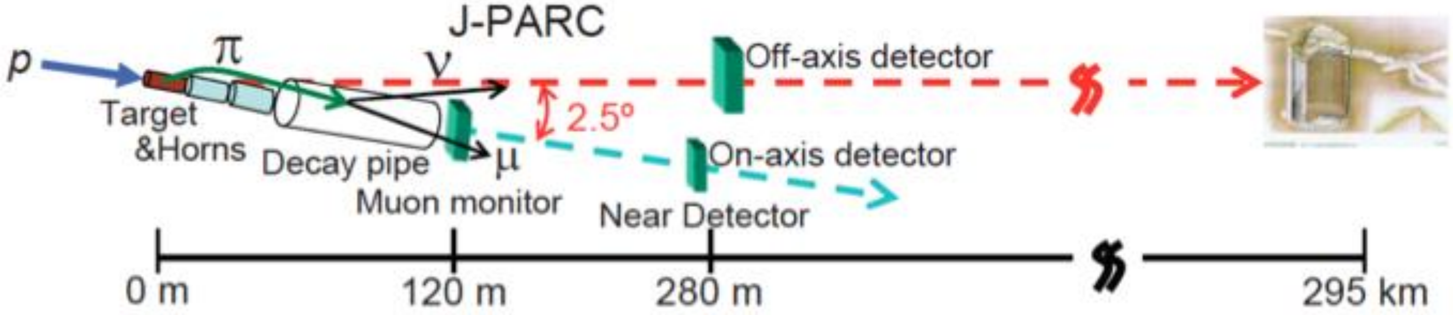
CERN-
Gran Sasso
~730 km
ν_τ appearance

2008 – 2012



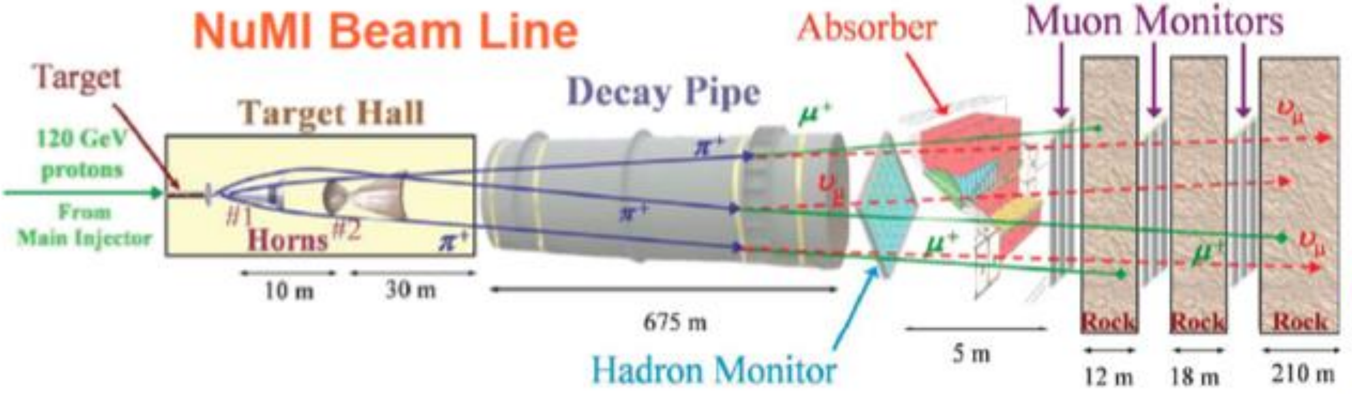
KEK-
SuperK
~295 km
θ_{13}

1999 – 2004



Fermilab-
Minnesota
~730 km
ν_μ disappearance

2005 – 2016

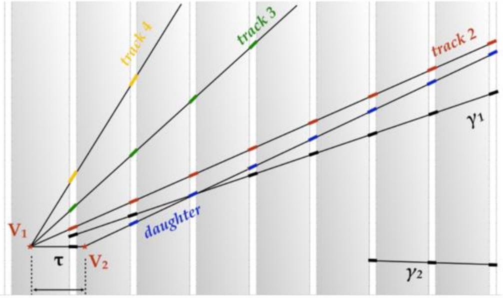


SK results for atmospheric neutrinos have been confirmed by "Long Baseline" expts

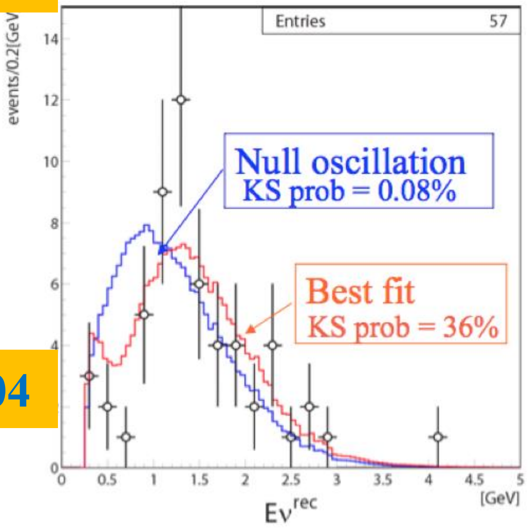
- neutrino beams in the world (at the end of their projects)

CERN-
Gran Sasso
~730 km
ν_τ appearance
2008 – 2012

- Five ν_τ candidates observed
- Discovery of ν_τ appearence



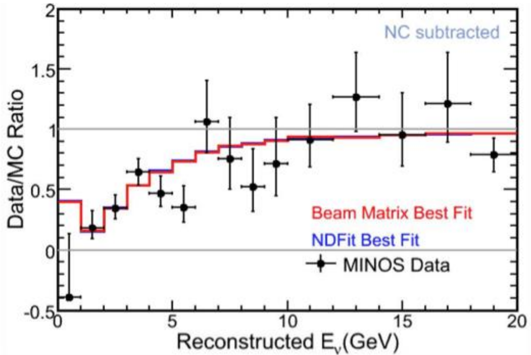
KEK-
SuperK
~295 km
θ_{13}
1999 – 2004

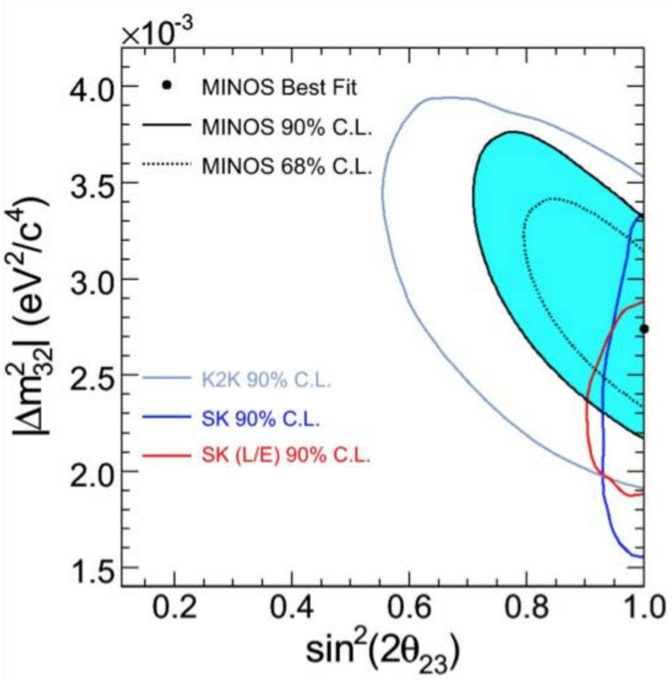


- Expected ν interactions with osc. is 104 (107 observed), 151 w/out.

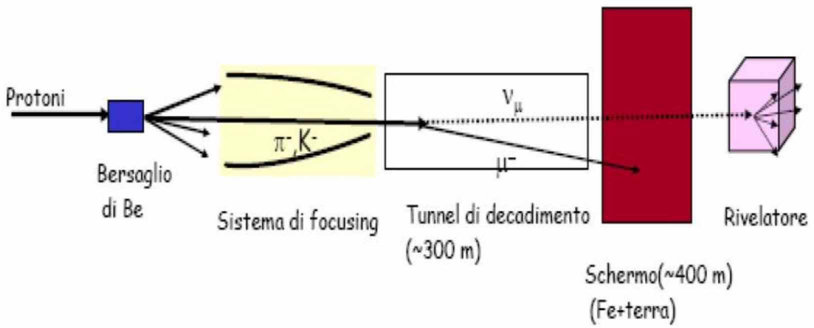
Fermilab-
Minnesota
~730 km
ν_μ disappearance
2005 – 2016

- MINOS





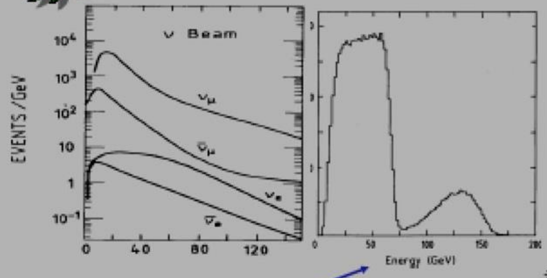
Fasci di neutrini:schema generale



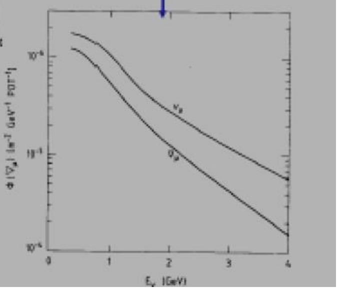
WBB (Wide Band Beam) : π^-,K- focalizzati → fascio intenso di ν_μ

NBB (Narrow Band Beam): π^-,K- focalizzati e selezionati in momento → fascio meno intenso di ν_μ ma con energia maggiormente definita

Fasci di neutrini:esempi



Fascio a bassa energia da protoni di 19 GeV del ProtoSincrotrone

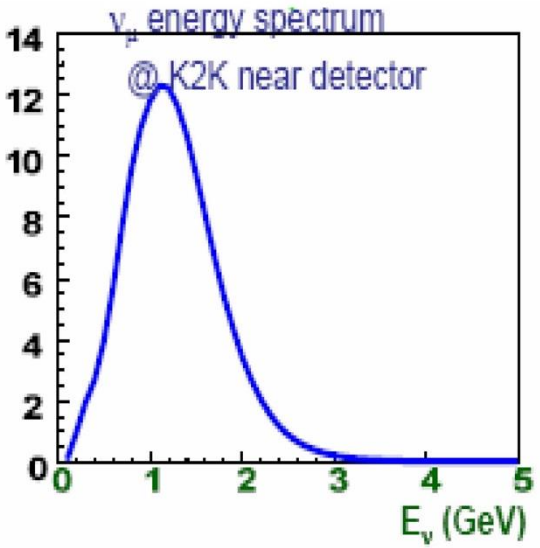


WBB e NBB ottenuti con i protoni di 400 GeV del SuperProtoSincrotrone

Note sui fasci di neutrini

- I fasci di neutrini da acceleratori sono fasci di ν_μ con piccola contaminazione ν_e e ν_τ
- Per questo motivo solo recentemente le interazioni dei ν_τ sono state osservate: esperimento Donuts a Fermilab

Low energy beam



Off-Axis Neutrino Beams

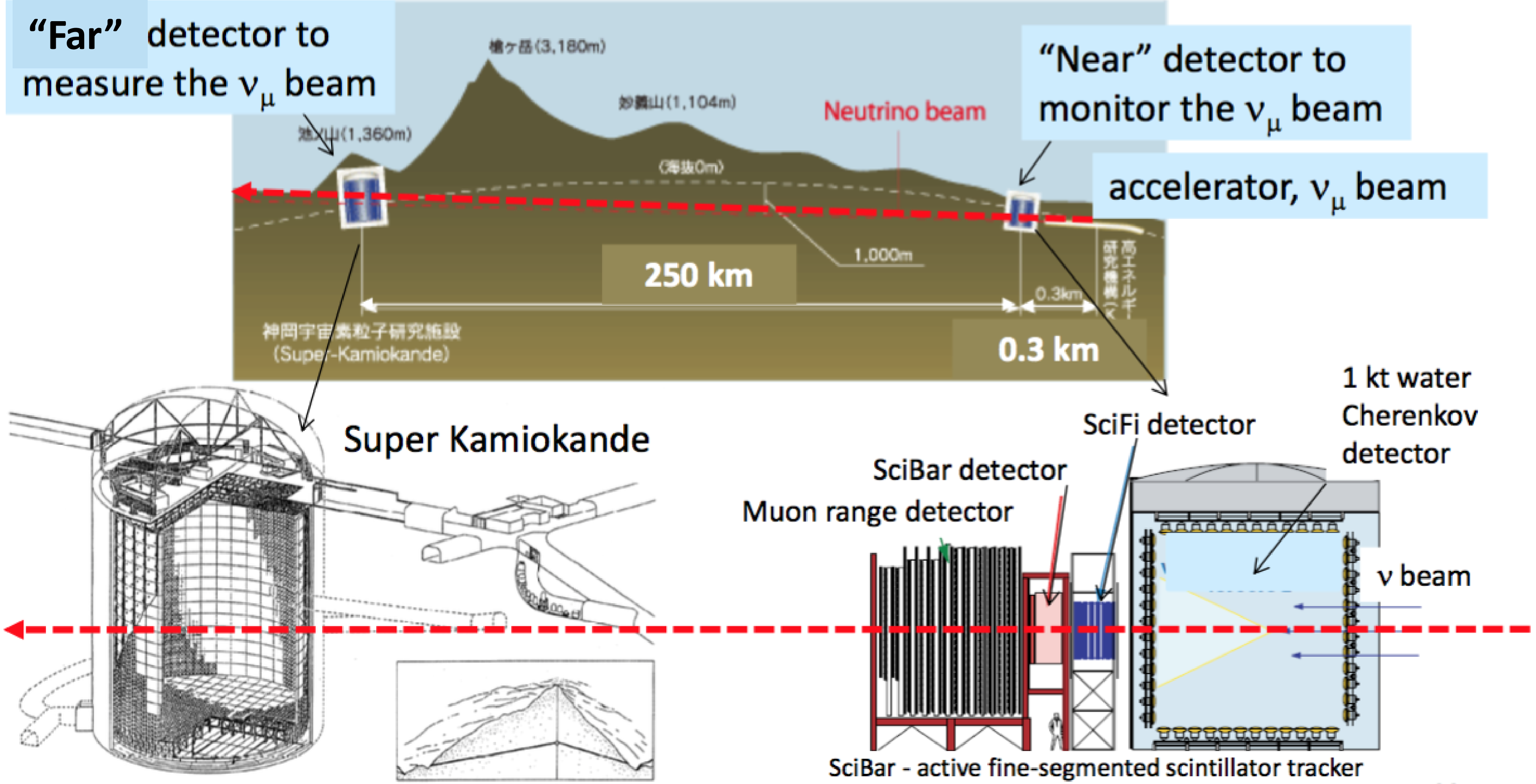
$$F = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

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

1999 – 2004



"Far" detector to measure the ν_μ beam

"Near" detector to monitor the ν_μ beam

accelerator, ν_μ beam

Super Kamiokande

SciFi detector

SciBar detector

Muon range detector

1 kt water Cherenkov detector

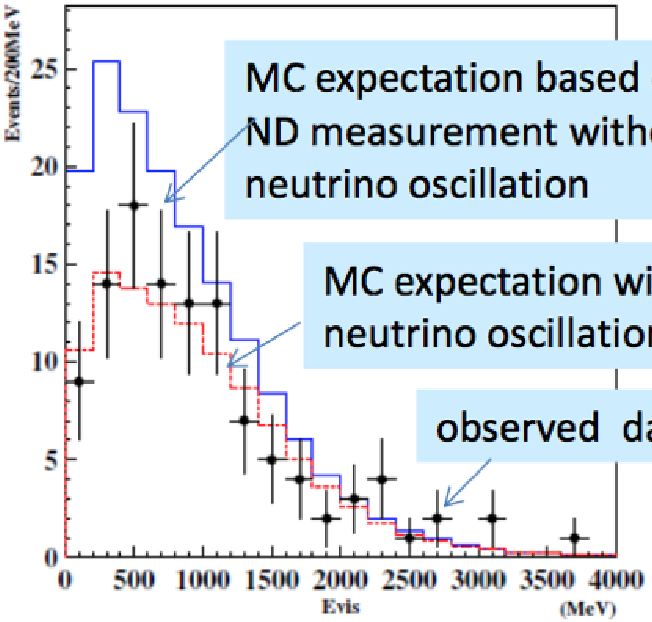
ν beam

SciBar - active fine-segmented scintillator tracker

SciFi - scintillating-fiber/water-target tracker

Long-baseline oscillation experiments

K2K results



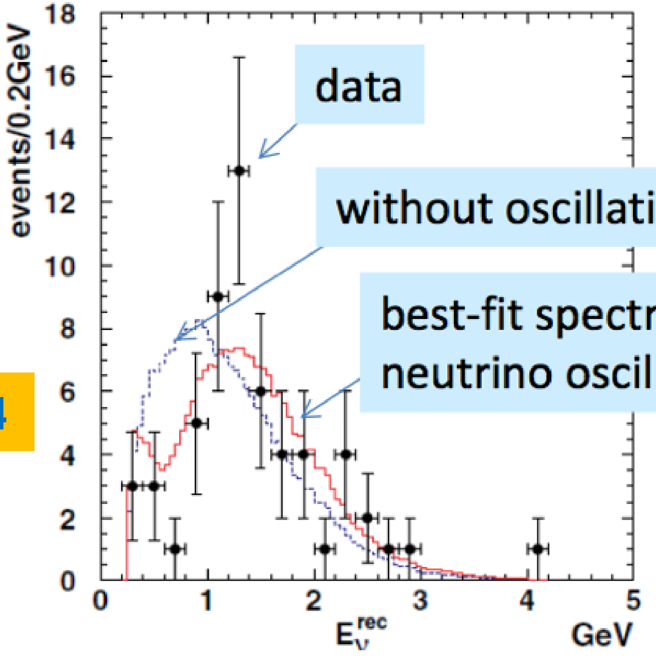
MC expectation based on the ND measurement without neutrino oscillation

MC expectation with neutrino oscillation

observed data

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 $\Delta m^2 = 2.8\times10^{-3}$ eV$_2$

1999 – 2004



data

without oscillation

best-fit spectrum wit
neutrino oscillation

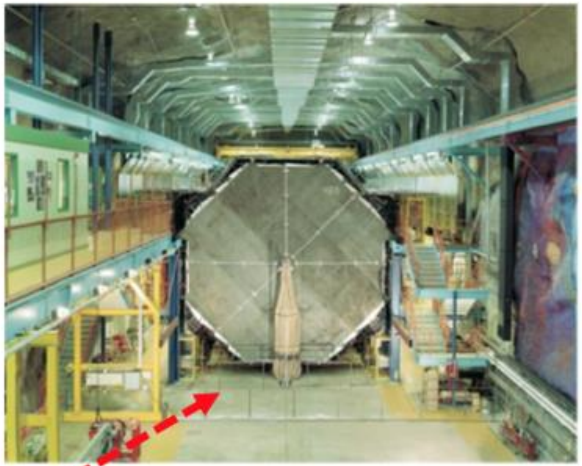
Energy distribution for the 58 one-ring μ-like events

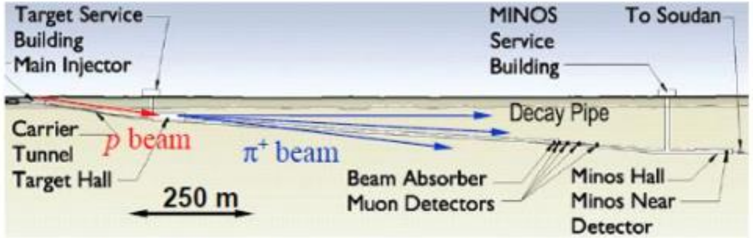
This experiment was completed in Nov. 2004. As a result, 112 neutrino events are observed in Super-Kamiokande, while the expected number of events without oscillations is 158. The probability to observe the deficit without neutrino oscillations is estimated to be 0.0015% and this deficit confirms the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





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

735 km

2005 – 2016

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

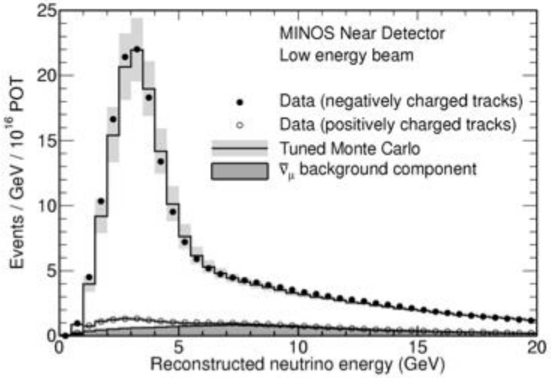
D.G. Michael et al., The magnetized steel and scintillator calorimeters of the MINOS experiment, Nucl. Instr. Meth. A 596 (2008) 190

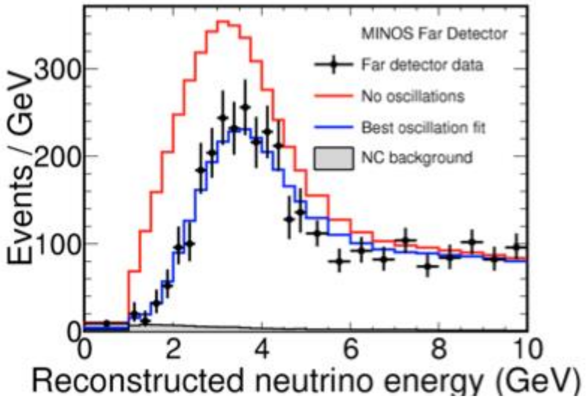
Minos: ν_μ disappearance

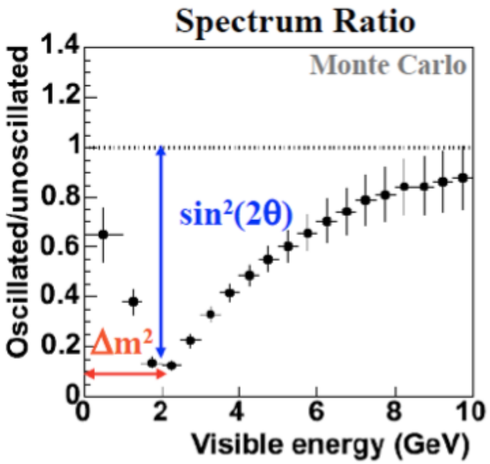
- By counting CC events at the far detector, the residual ν_μ flux is obtained, and the survival probability is measured:

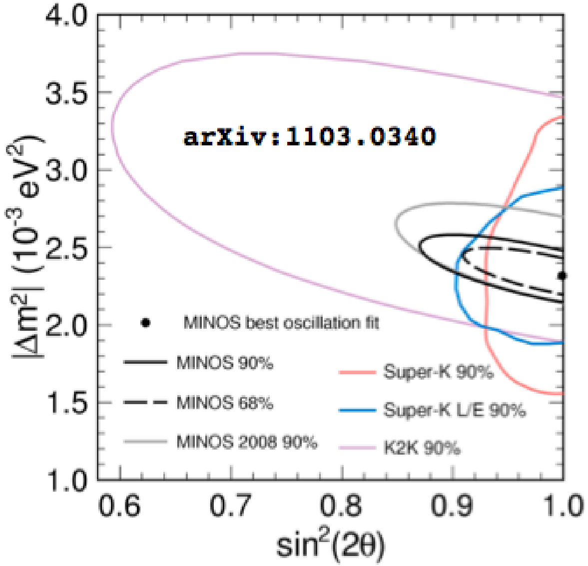
2005 – 2016

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







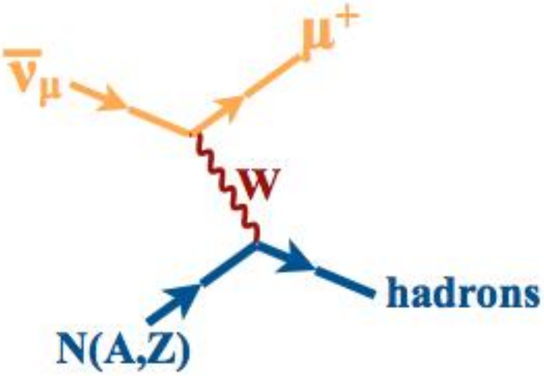


MINOS vs atmospheric neutrinos

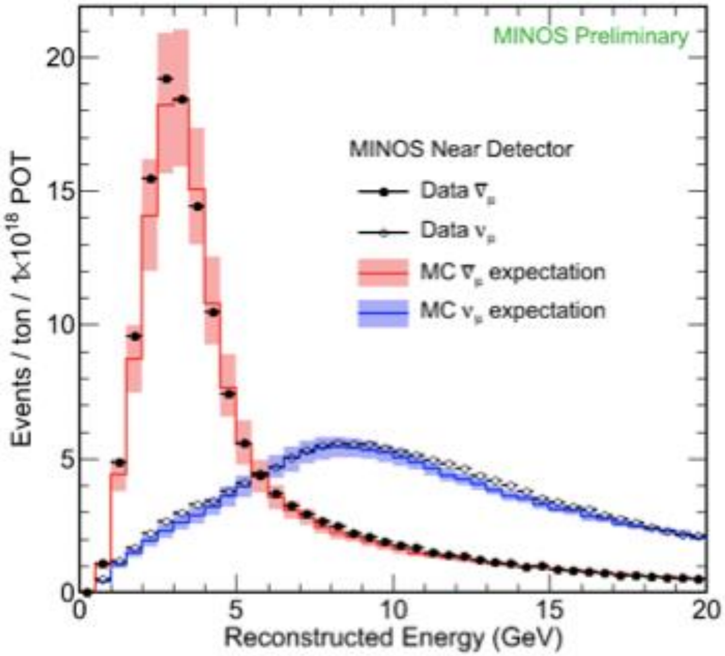
$$|\Delta m^2| = 2.32^{+0.12}_{-0.08}\ 10^{-3} eV^2$$

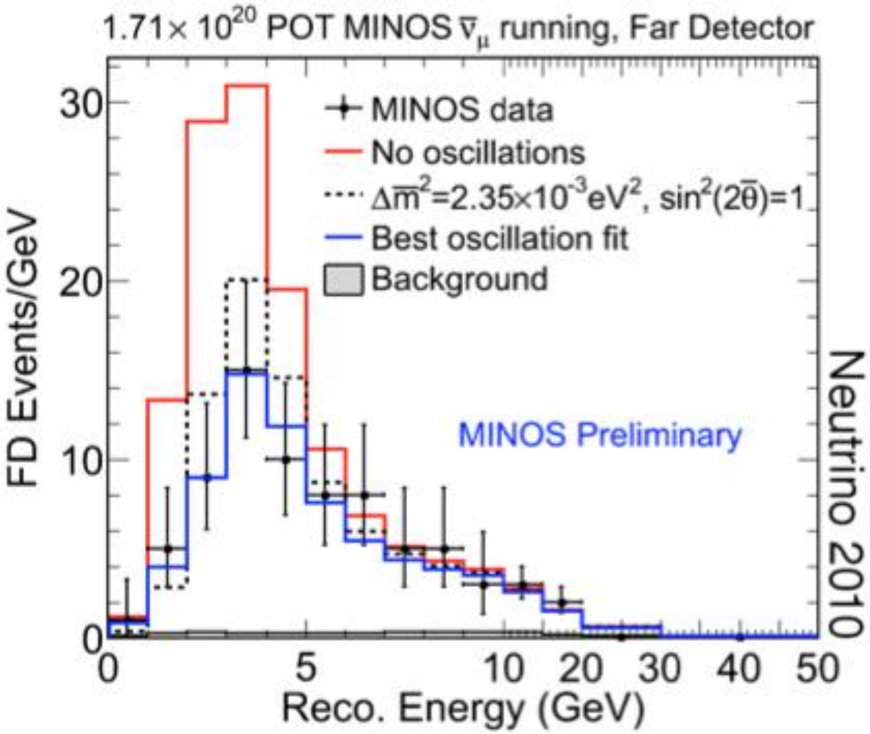
$$sin^2(2\theta_{23}) > 0.90 \qquad 90\%\ \text{c.l.}$$

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



- Very similar analysis with respect to νμ but reversed horn current to select π- instead of π+
- Background:
  - Neutral current at low energy
  - Wrong muon sign in CC events

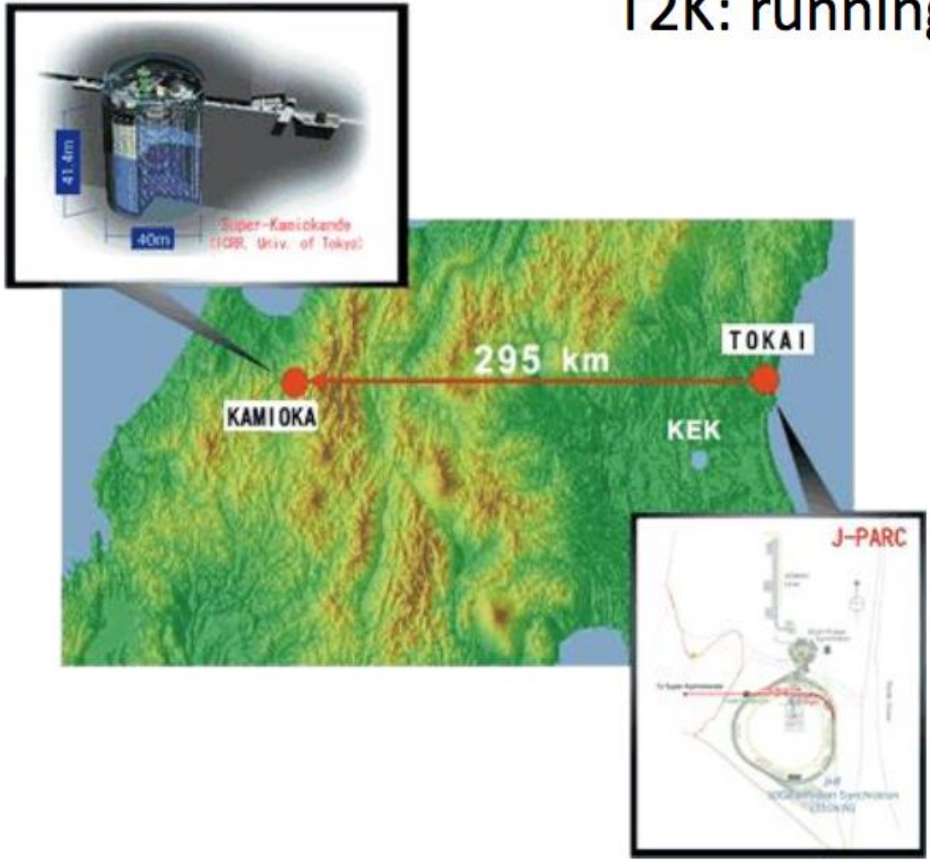




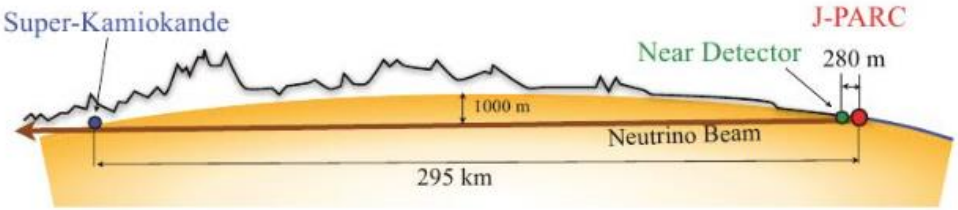
Long-baseline oscillation experiments

T2K: running experiment

2010 –



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.



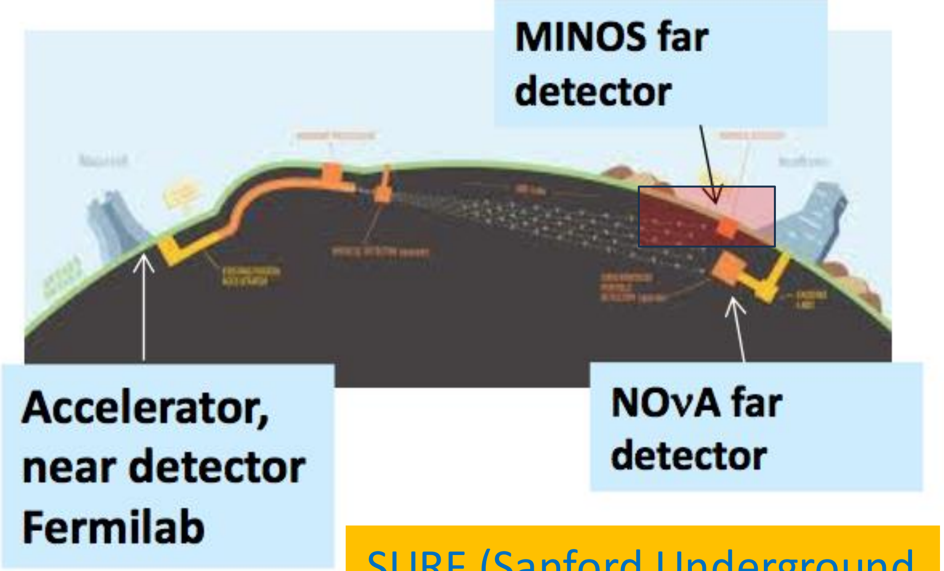
K.Abe et al.,The T2K experiment, Nucl. Instr. Meth. A 659 (2011) 106

Long-baseline oscillation experiments

NOνA

2014 –

The NOνA 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].



MINOS far detector

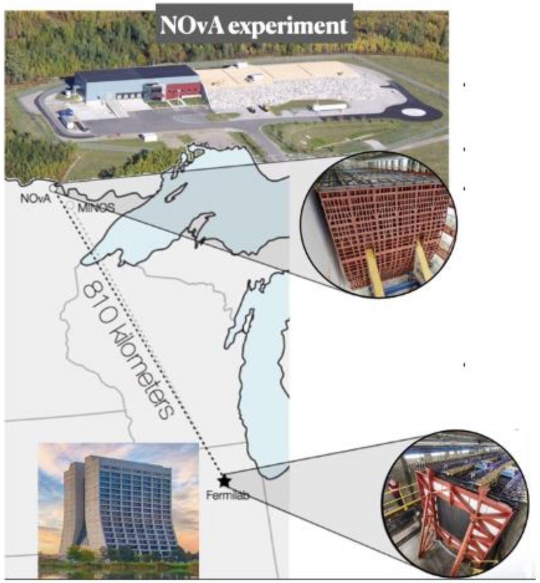
Accelerator, near detector Fermilab

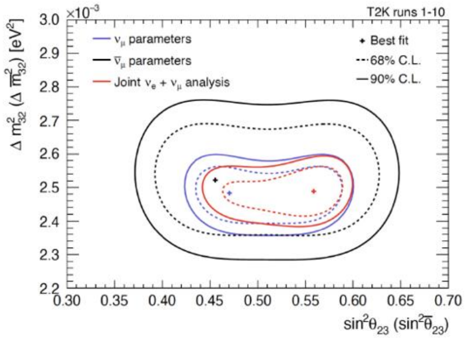
NOνA far detector

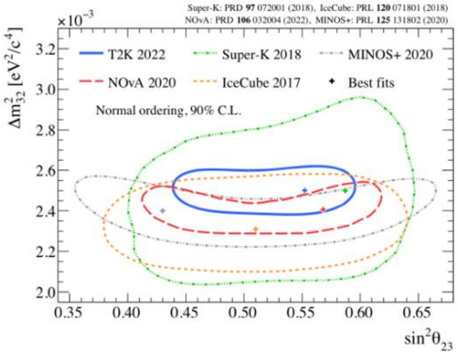
SURF (Sanford Underground Research Facility)

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



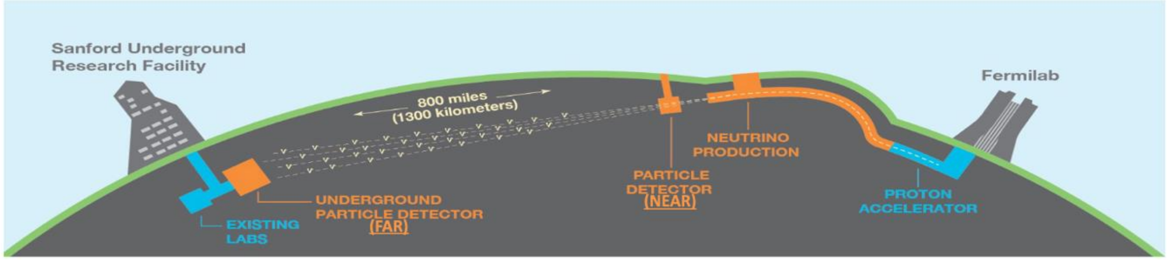




Deep Underground Neutrino Experiment

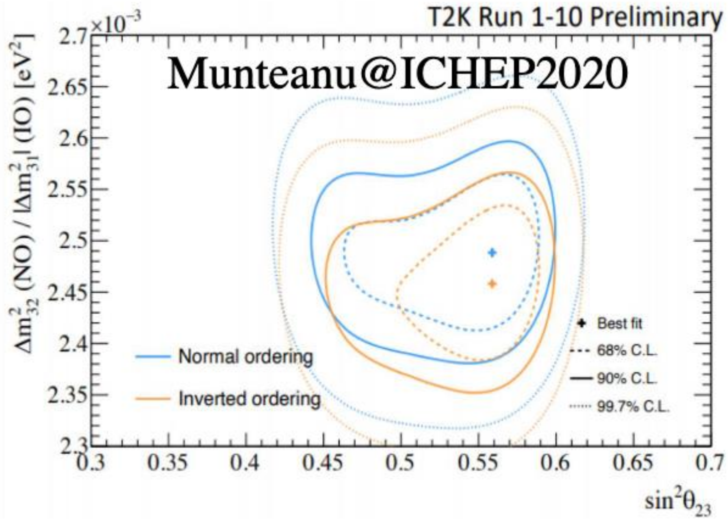
- Long-baseline (LB - 1300 km) experiment:
  - Neutrino and antineutrino beams
- ~ 70 kton volume far detector, 1.5 km underground, divided in 4 modules
- Multi-technology Near Detector, focused on beam characterization and physics
- > 20 years foreseen life span

- **Primary physics goals**:
  - 3-neutrino oscillations parameters: $\nu_\mu/\overline{\nu_\mu}$ disappearance, $\nu_e/\overline{\nu_e}$ appearance
  - δ_{CP} ; mass hierarchy
- **SuperNova** burst neutrinos
- **Beyond-Standard-Model physics**: baryon number violation, sterile neutrinos, non-standard interactions, etc.



Accelerator neutrino results

T2K

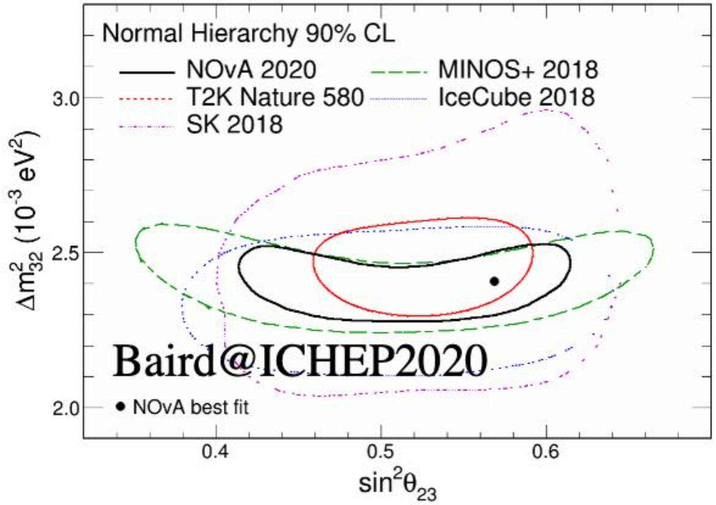


Munteanu@ICHEP2020

NOvA

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

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

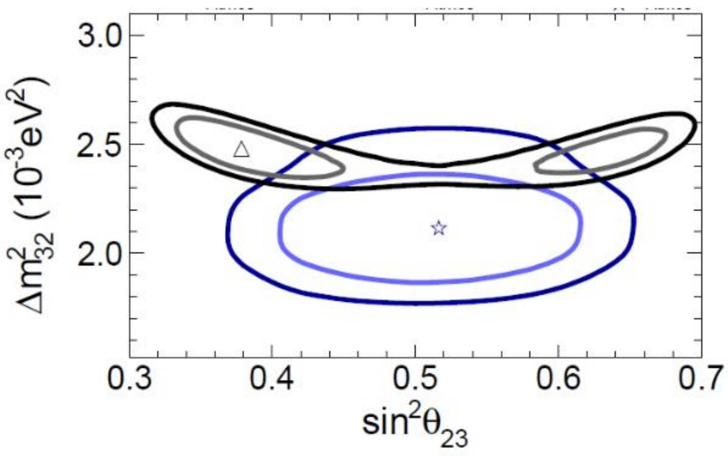


Baird@ICHEP2020

Minos/Minos+

Beam Best Fit
Normal Hierarchy
$\Delta m^2_{32} = 2.48 \times 10^{-3}$ 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 θ 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}U and ^{232}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 NOνA 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

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

	$L(m)$	$E\ (MeV)$	$\Delta m^2\ (eV^2)$	$1.27\frac{\Delta m^2}{eV^2}\frac{L}{km}\frac{GeV}{E}$	
Sol	10^{10}	1	10^{-10}	1.27	Vacuum osc
	10^{10}	1	7.5×10^{-5}	10^{6}	MSW
React LBL	180×10^{3}	1 – 10	7.5×10^{-5}	1.7 – 17	KamLand
Atm	$10^{4} – 10^{7}$	$10^{2} – 10^{5}$	3.5×10^{-3}	$5\times10^{-4} – 5\times10^{2}$	
Acc LBL	$10^{5} – 10^{6}$	$10^{3} – 10^{4}$	3.5×10^{-3}	$5\times10^{-2} – 5$	
React SBL	$10^{2} – 10^{3}$	1 – 10	3.5×10^{-3}	$5\times10^{-2} – 5$	Hints for L>1 km
Acc SBL	10^{2}	$10^{3} – 10^{4}$	1	0.13 – 0.013	Sterile ν?
React ν Acc LBL	10^{3} $10^{5} – 10^{6}$	1 – 10 $10^{3} – 10^{4}$	3.5×10^{-3}	Far from sol ν solution	Theta13

Δm^2_{21}

Δm^2_{32}

$\Delta m^2_{31} \approx \Delta m^2_{32}$