Neutrino Oscillations and the MINOS experiment

Mark Thomson
University of Cambridge

This Talk:

- **Introduction to ν oscillations**
- **Experimental status of ν osc.**
- **MINOS Physics and Status**

Recent History

5 years ago (PDG1998):

- ★ Standard Model : <u>assumed</u> massless ν
- ★ Fundamental states : ν_e , ν_μ , ν_τ
- ★ $m\nu_e$ < 3 eV, ...

Neutrino Oscillations - hints

- ★ Atmospheric neutrino oscillations
  - Statistically marginal / positive & negative results
- ★ Solar neutrino oscillations
  - Required faith in Astrophysics/Astrophysicists....!

5 Years on.......

Now (PDG2002+):

- ★ Standard Model : massive ν
- ★ Fundamental states : ν_1 , ν_2 , ν_3
- ★ $\Delta m^2_{12} \sim 5\times10^{-5}\ eV^2$, $\Delta m^2_{23} \sim 2\times10^{-3}\ eV^2$

Neutrino Oscillations – Compelling evidence

- ★ Atmospheric neutrino oscillations
  - Compelling evidence : Super-Kamiokande (+K2K)
- ★ Solar neutrino oscillations
  - Compelling evidence : SNO (+KamLand)

★ Almost all ⓘ from neutrino oscillations

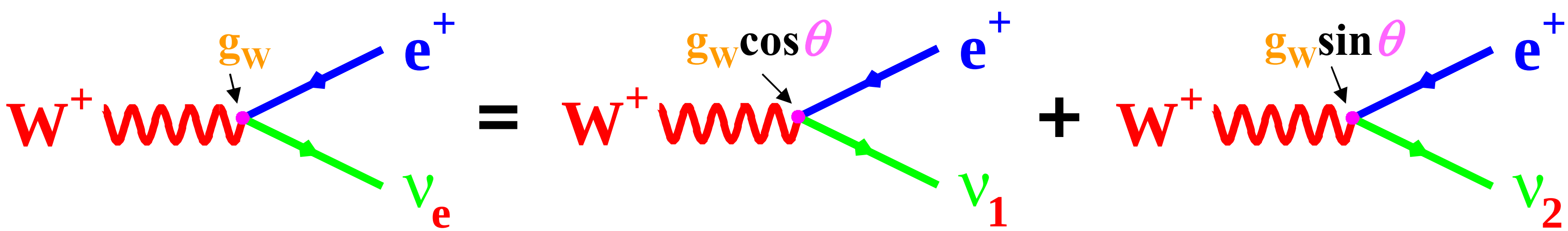
Neutrino Oscillations

- Pure Quantum Mechanical effect
- $\left| \text{Weak Eigenstates} \right\rangle \neq \left| \text{Mass Eigenstates} \right\rangle$

  ν_e, ν_μ, ν_τ ν_1, ν_2, ν_3

- ν produced/detected as WEAK eigenstates
- Weak states – mixture of mass states, e.g.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



- Time evolution of wave-function - mass eigenstates

Neutrino Oscillations

★ At t=0 produce a ν_e (momentum p)

$$|\nu(0)\rangle = |\nu_e\rangle$$
$$= \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

★ Time development of wave-function determined by time evolution of eigenstates of Hamiltonian

$$|\nu(t)\rangle = \cos\theta\,|\nu_1\rangle\, e^{-i\frac{E_1 t}{\hbar}} + \sin\theta\,|\nu_2\rangle\, e^{-i\frac{E_2 t}{\hbar}}$$
$$|\nu(t)\rangle = e^{-i\frac{E_1 t}{\hbar}}\left\{\cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle\, e^{-i\frac{(E_2-E_1)t}{\hbar}}\right\}$$

★ IF $E_1 \neq E_2$ ➡ Observable phase difference

★ In limit that $E \gg m_\nu$ then $(E_2 - E_1) \propto (m_2^2 - m_1^2)/2E$

★ Then its just algebra……

$$P(\nu_e \rightarrow \nu_\mu) \approx \sin^2 2\theta_{12}\, \sin^2\left(\frac{1.27 L\, \Delta m_{12}^2}{E}\right)$$

Simplest case

- Consider two generation maximal mixing

$$|\nu_e\rangle = \frac{1}{\sqrt{2}}(\nu_1 + \nu_2)$$

$$|\nu_\mu\rangle = \frac{1}{\sqrt{2}}(\nu_1 - \nu_2)$$

i.e. $\cos\theta = \sin\theta = \frac{1}{\sqrt{2}}$

- At t=0 produce a ν_e

$$|\nu(t)\rangle = \frac{1}{\sqrt{2}} e^{-i\frac{E_1 t}{\hbar}} \left\{ |\nu_1\rangle + |\nu_2\rangle\, e^{-i\frac{(E_2-E_1)t}{\hbar}} \right\}$$

- When $\frac{(E_2 - E_1)t}{\hbar} = \pi$ then

$$|\nu(t)\rangle \rightarrow \frac{1}{\sqrt{2}} e^{-i\frac{E_1}{\hbar}t} \{ |\nu_1\rangle - |\nu_2\rangle \}$$

$$= \frac{1}{\sqrt{2}} e^{-i\frac{E_1}{\hbar}t} |\nu_\mu\rangle$$

- IF the neutrino (originally ν_e) now interacts (via WEAK interaction) it will produce a μ

OSCILLATIONS

3 Generation ν oscillations

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

U: **Maki-Nakagawa-Sakata Matrix (MNS)**

the CKM matrix of the lepton sector

3 Mixing Angles

1 CP Phase

(+2 additional CP phases for Majorana ν)

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}_{\text{Atmospheric } \nu}\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar } \nu}$$

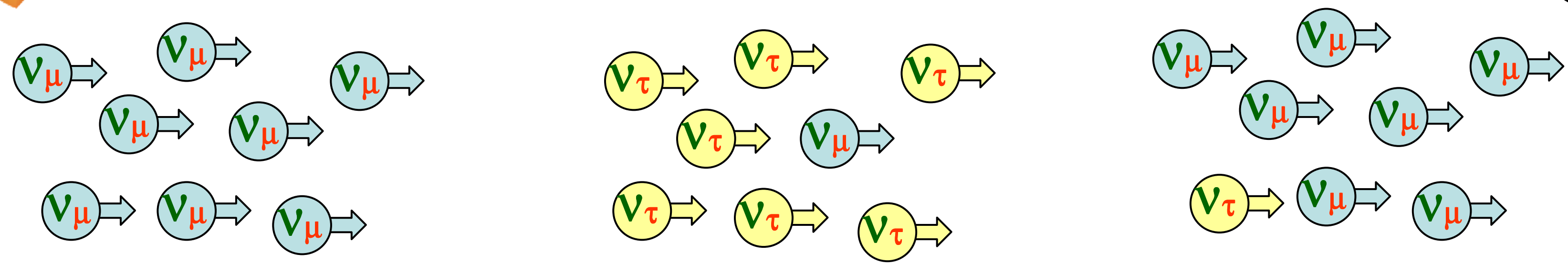
Atmospheric ν — **CP Phase** — **Solar ν**

$$\theta_{12}, \theta_{13}, \theta_{23}, \delta$$
$$\Delta m^2_{12}, \Delta m^2_{23}$$

Neutrino oscillations described by 6 new SM parameters

Aim to measure them all.....

Golden ν Oscillation Signal



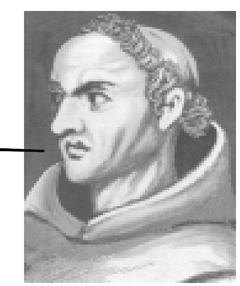
Pure ν_μ beam

ν_μ disappearance + ν_τ appearance

+observe oscillations e.g $\nu_\mu \rightarrow \nu_\tau \rightarrow \nu_\mu$

- **Currently most observations pure disappearance**
- **Only SNO observe appearance (indirectly)**
- **Oscillatory structure not yet seen !**

Most likely explanation of data is quantum mechanical neutrino oscillations

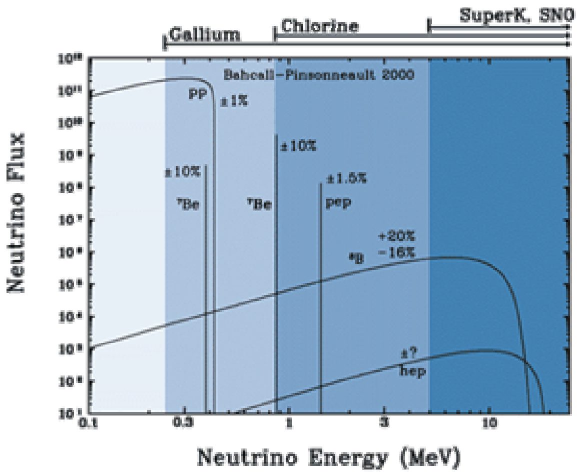


The trouble with neutrinos

- ★ **neutrinos are only weakly interacting**
  to stop/detect 1 ν need ~ 10 light-years of Pb
- ★ **need intense sources and large detectors**
- ★ **neutrino oscillations now seen from:**
  - **Atmospheric Neutrinos (SuperK, ...**
  - **Solar Neutrinos (SNO, SuperK, ...**
  - **Reactor Neutrinos (KamLAND)**
  - **Neutrino beams (K2K)**
- ★ **For this talk – ignore LSND !**

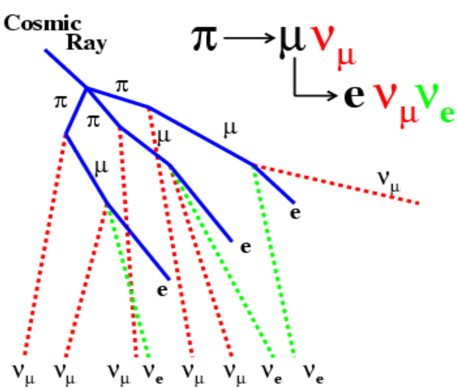
Wait for MiniBoone

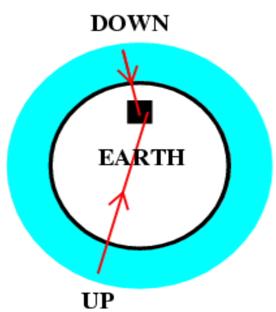
Solar Neutrinos



- ★ Fusion in sun is source of ν_e
- ★ Flux ~ 6×10^{10} cm^{-2} s^{-1}
- ★ E_ν ~ 1 MeV
- ★ Mainly concerned with ^{8}B ν_e

Atmospheric Neutrinos



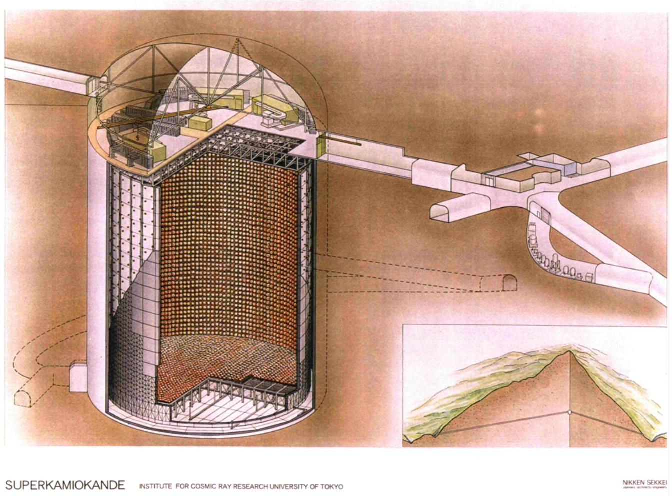


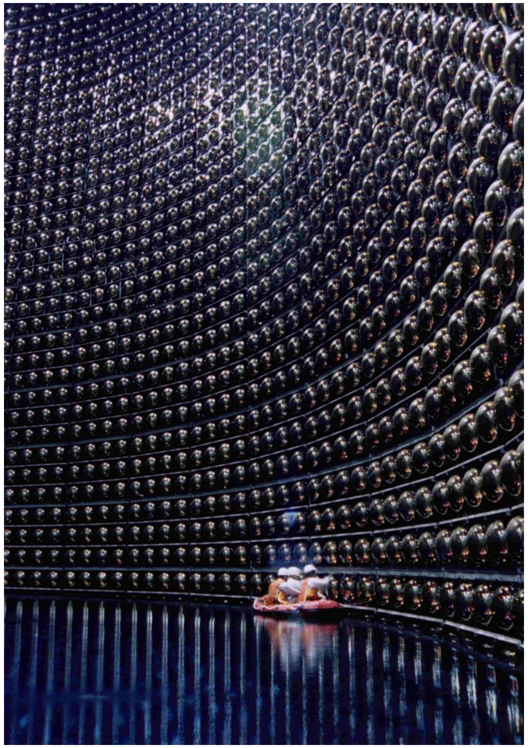
- ★ Cosmic Rays (mainly p,He) hitting upper atmosphere produce νs:
  $\pi \rightarrow \mu\nu_\mu$ and $\mu \rightarrow e\nu_e\nu_\mu$ decays
- ★ Flux ~ 1 cm^{-2} sr^{-1} s^{-1}
- ★ E_ν ~ 1 GeV
- ★ $N(\nu_\mu)/N(\nu_e)$ ~ 2

Super-Kamiokande dominates atmospheric ν

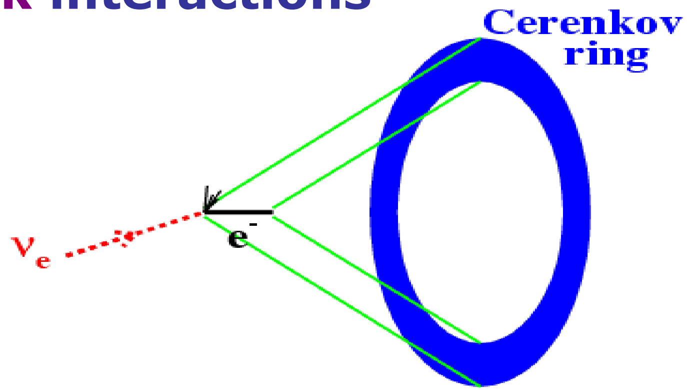
Super-Kamiokande

- ★ 50 ktons H_20
- ★ 11246 PMTs
- ★ Accident in 11/2001
- ★ Operational again – reduced number of PMTs



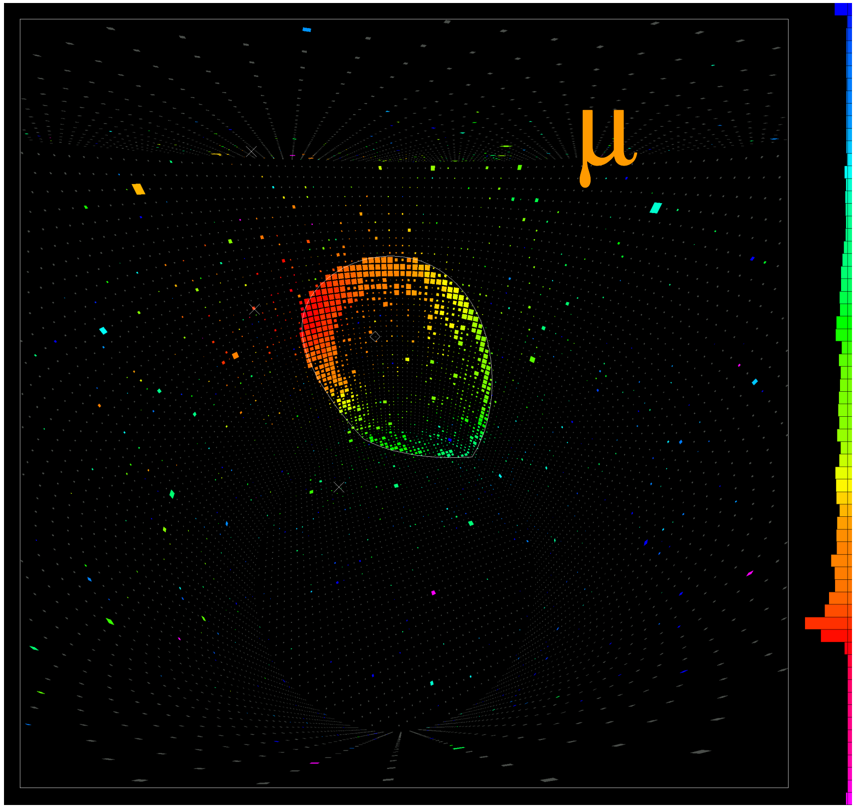


ν_e , ν_μ detected via Cerenkov radiation from lepton produced in CC weak interactions

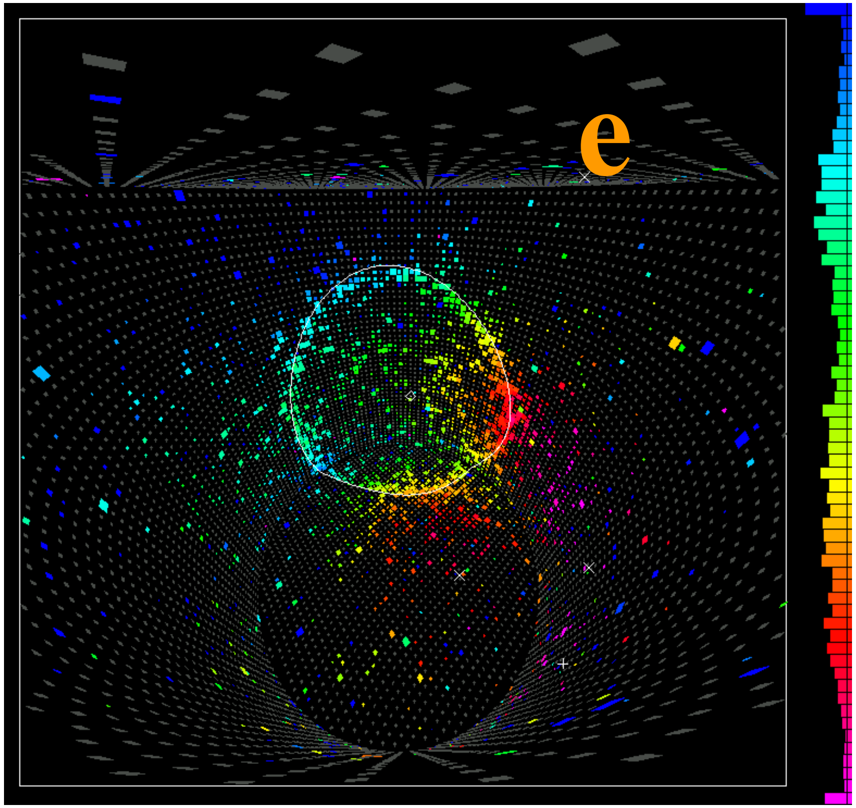


SK particle ID

★ Electrons and muons cleanly identified ~ 99 % purity

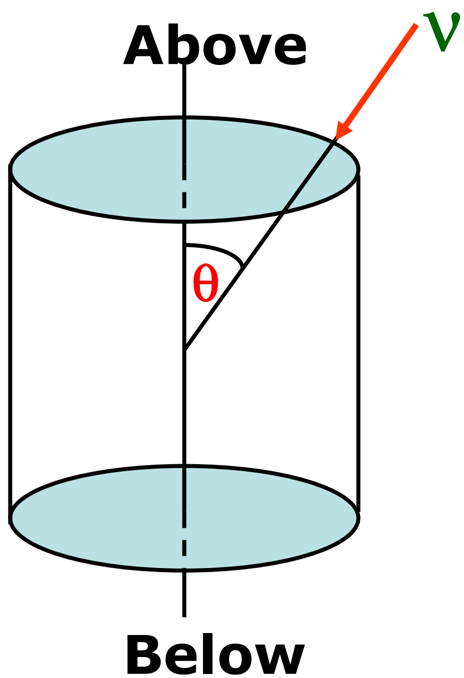


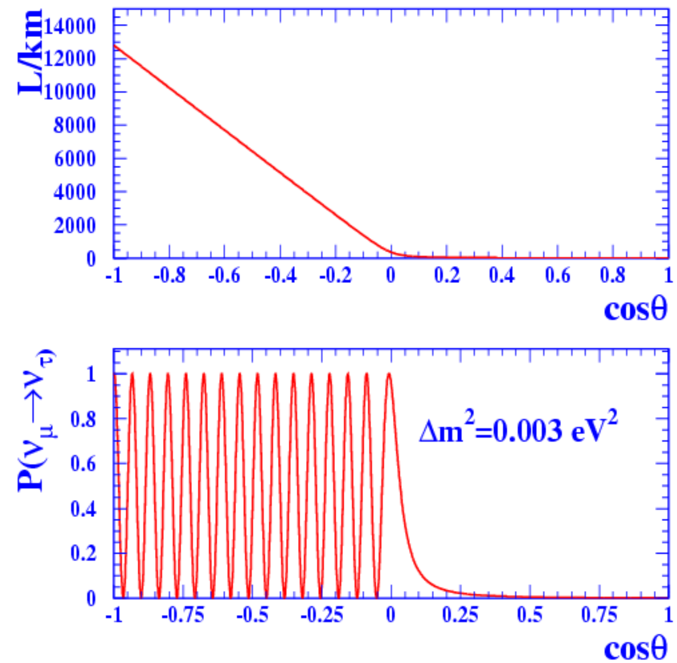
`Clean' ring



`Diffuse/fuzzy' ring
due to scattering/showering

Measure ν_e/ν_μ fluxes vs zenith angle, θ





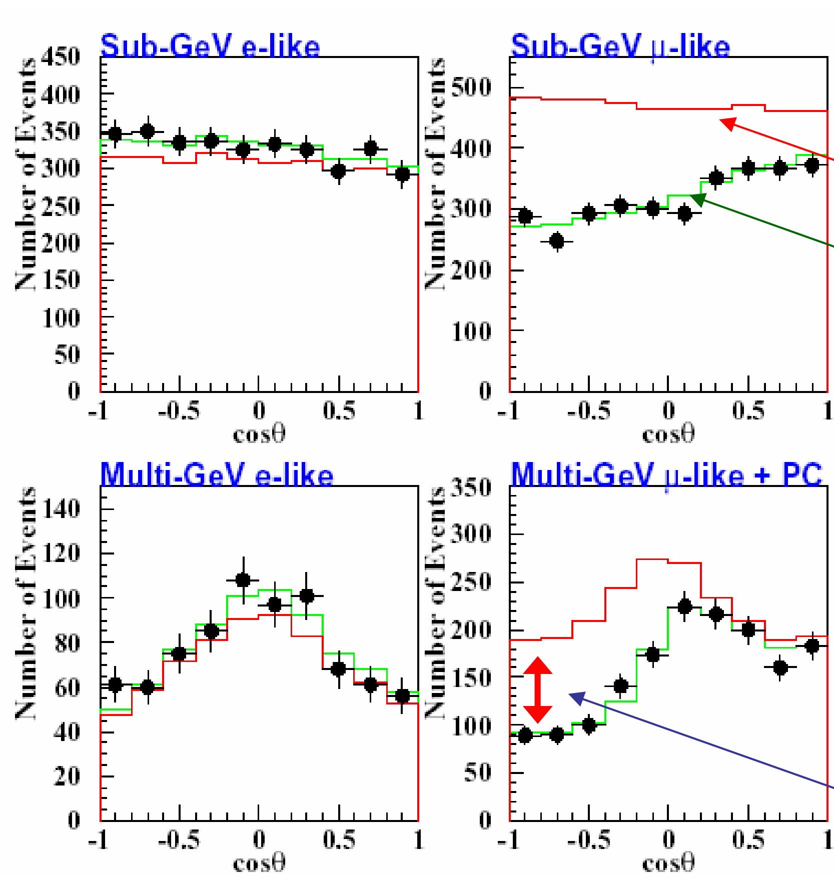
★ **In doing so, scan over large range of L: 10km<L<12000km**

$$P(\overline{\nu}_\mu \rightarrow \overline{\nu}_\tau) \approx \sin^2 2\theta_{23} \sin^2\left(\frac{1.27 L \Delta m^2_{23}}{E}\right)$$

NOTE: (L/km) , E(GeV) , $\Delta m^2(eV^2)$

SuperKamiokande Results

Observe clear disappearance signal



No oscillations fit:

χ^2_{min} = **465.5/170 d.o.f**

no oscillations

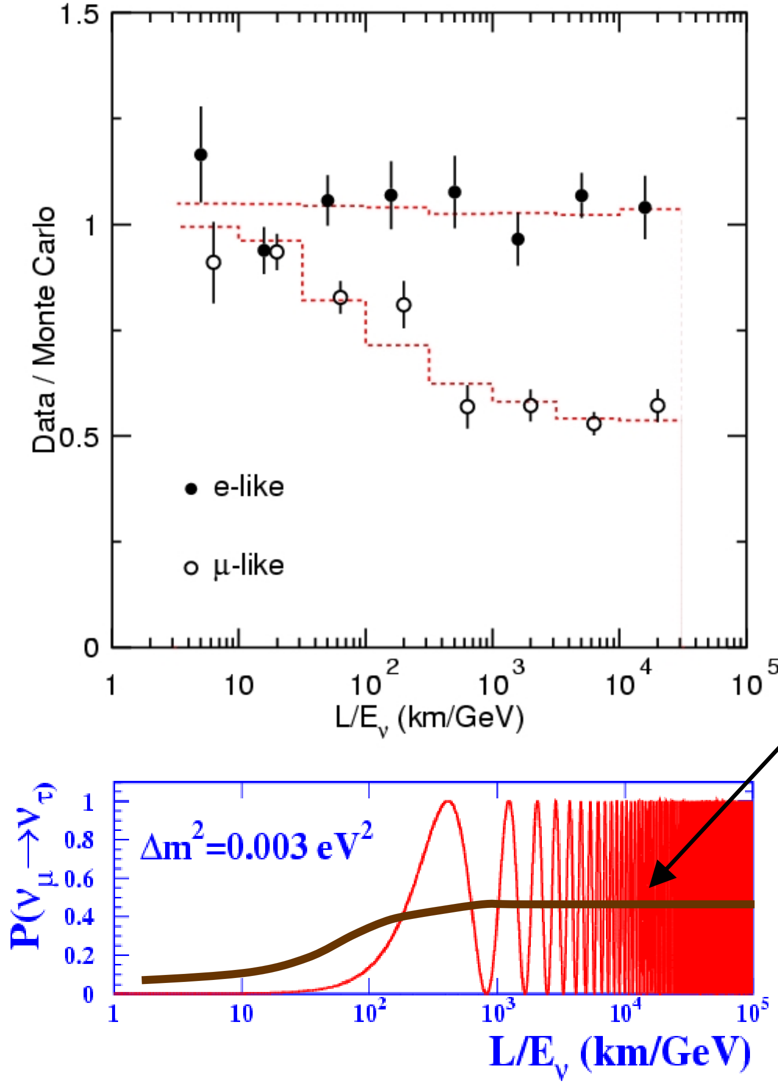
best fit : $\nu_\mu \rightarrow \nu_\tau$ oscillations

Electrons consistent with no oscillations

Muons dissappear at low cosθ i.e. large L

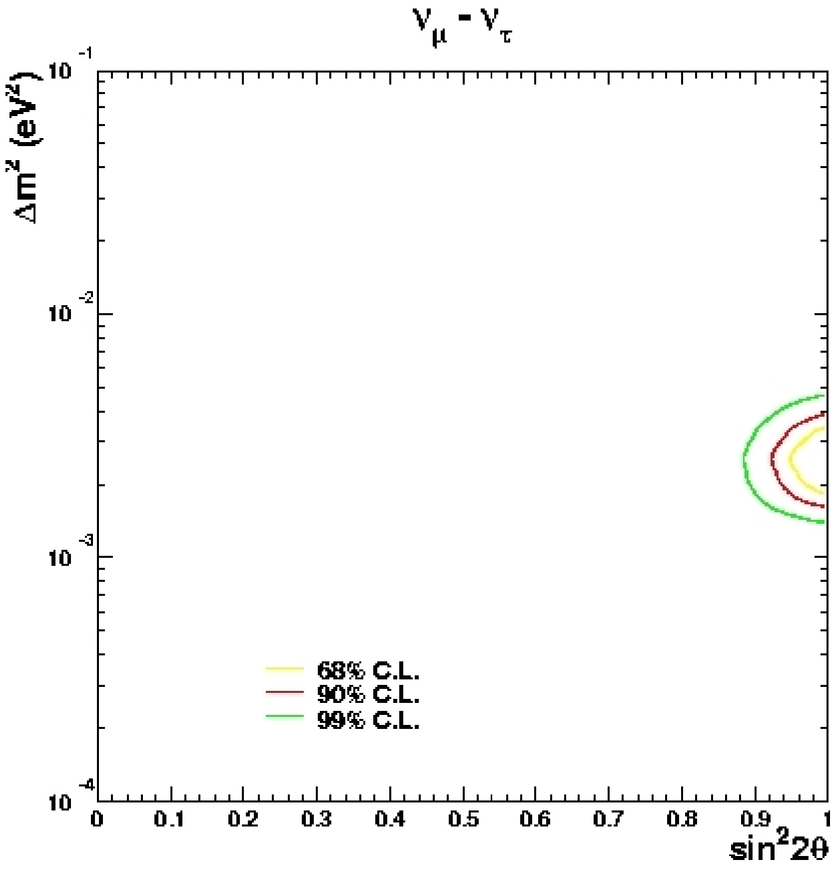
determines sin2θ

But don't see oscillation pattern



Smeared out due to finite resolution in:
E and L (i.e. cosθ)

SuperKamiokande Result



$\nu_\mu - \nu_\tau$ oscillation fit

90 % C.L.

$1.6\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ eV^2

$\sin^2 2\theta > 0.92$

BEST FIT:

$\Delta m^2 = 2.5\times10^{-3}$ eV^2

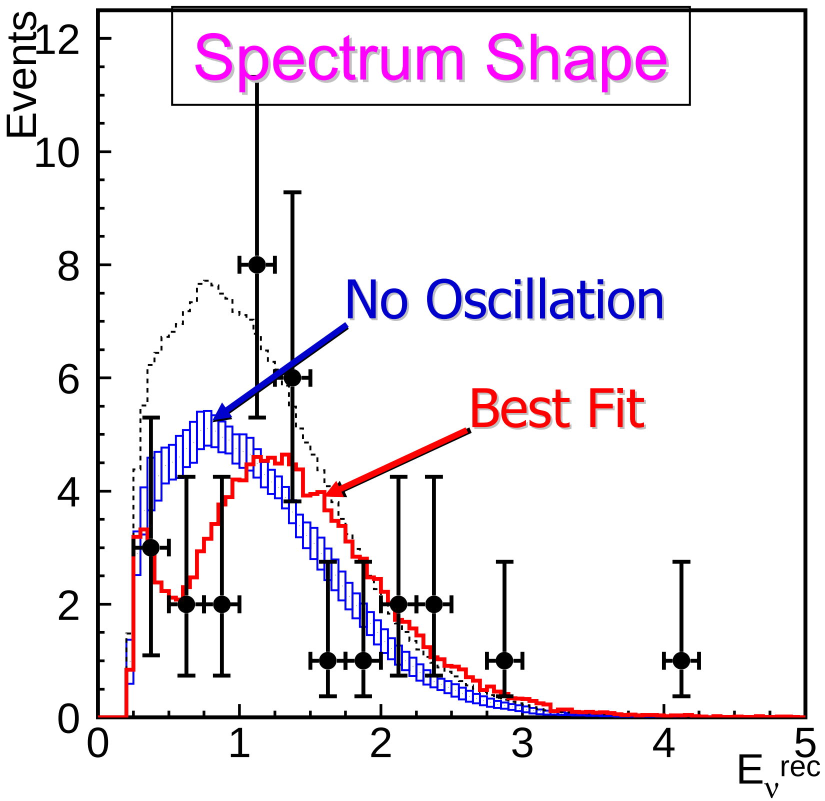
$\sin^2 2\theta = 1.0$

Supported by K2K

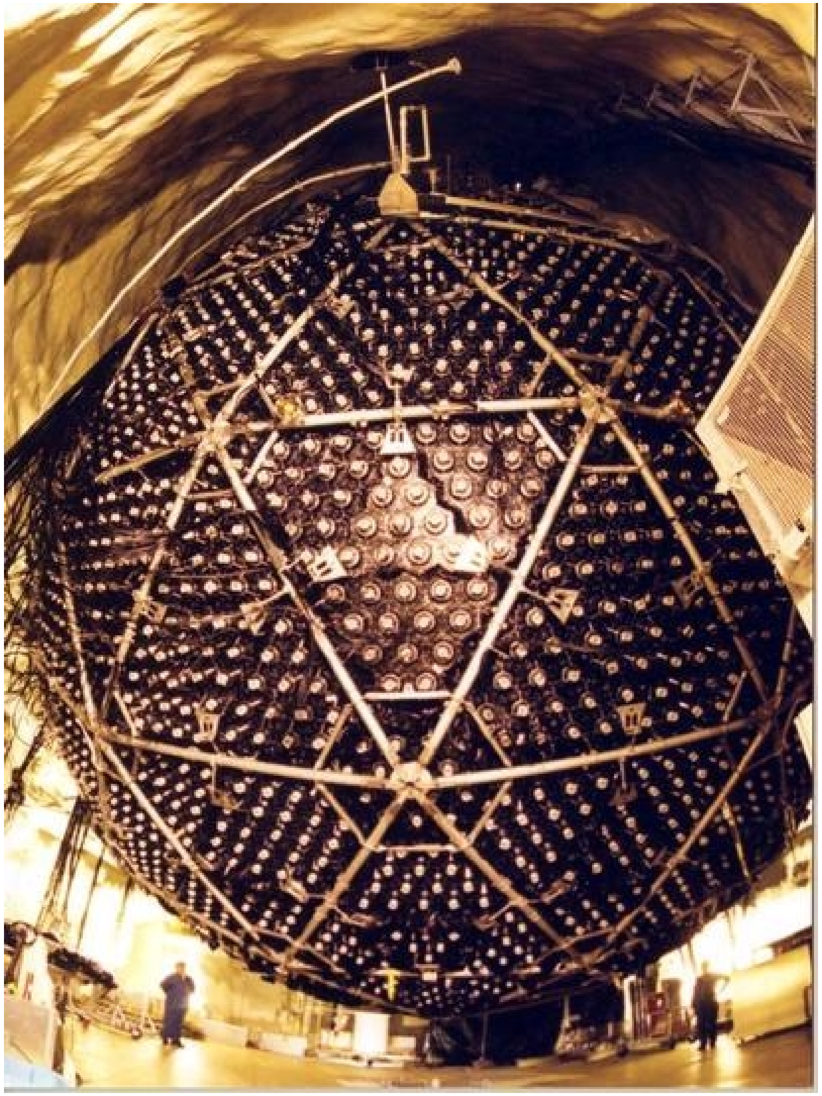
K2K Best fit point: $(\sin^2 2\theta, \Delta m^2) = (1.0, 2.8\times10^{-3}\,\mathrm{eV}^2)$

c.f. SuperK: $(\sin^2 2\theta, \Delta m^2) = (1.0, 2.5\times10^{-3}\,\mathrm{eV}^2)$

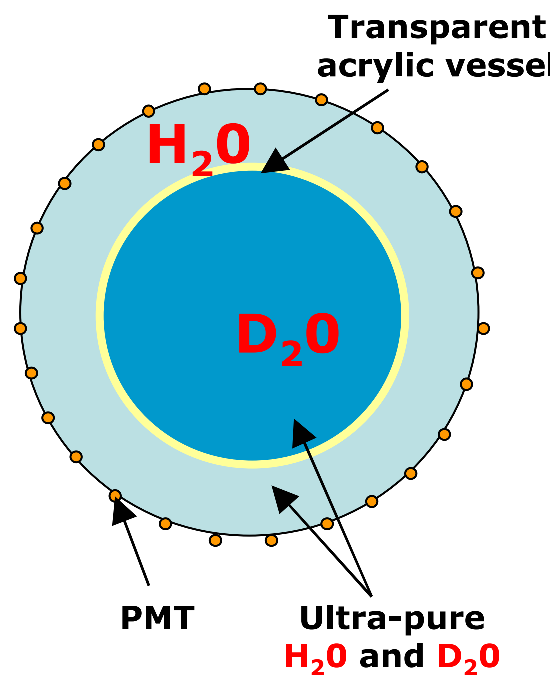
Number of events	
Observation:	56
Best Fit:	54.2
Null-oscillation	80.1



Solar Neutrinos (SNO)

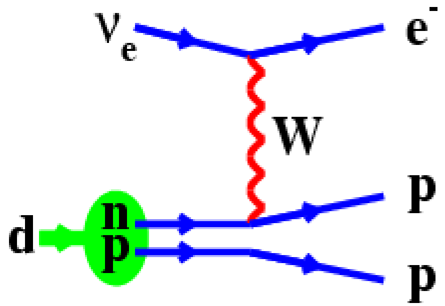


- 1000 tonnes D_2O, inside a
- 12m diameter acrylic vessel.
- ~9500 PMTs + concentrators.
- 17m diameter PMT support.
- 7000 tonnes H_2O.



ν Detection in SNO

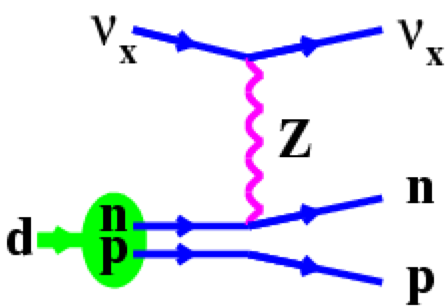
CC



Charged Current (CC)

- ★ Detect electron
- ★ Sensitive to ν_e only
- ★ Rate α $\Phi(\nu_e)$

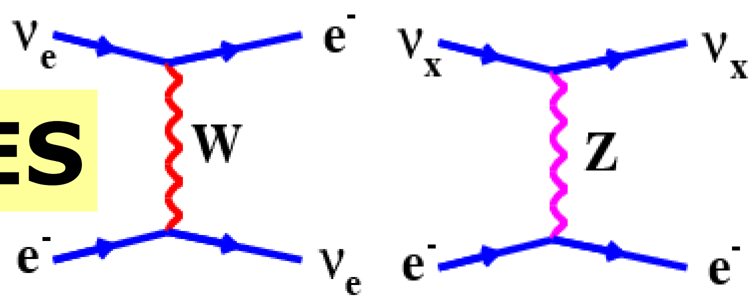
NC



Neutral Current (NC)

- ★ Detect γ from **n** capture on **d**
- ★ Equally Sensitive to ν_e, ν_μ, ν_τ
- ★ Rate α $\Phi(\nu_e) + \Phi(\nu_\mu) + \Phi(\nu_\tau)$

ES



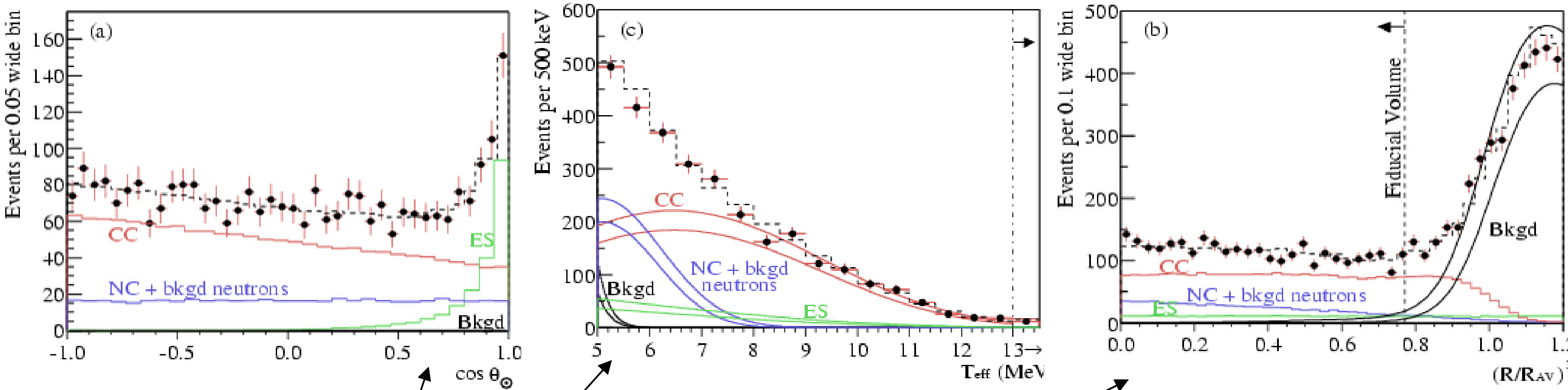
Elastic Scattering (ES)

- ★ Detect scattered e^-
- ★ Sensitive to ν_e, ν_μ, ν_τ
- ★ Rate α $\Phi(\nu_e) + 0.154[\Phi(\nu_\mu) + \Phi(\nu_\tau)]$

★ Processes have different sesitivities. By measuring all rates can determine: $\Phi(\nu_e)$ **AND** $\Phi(\nu_\mu) + \Phi(\nu_\tau)$

SNO Results

Extract number of CC + NC + ES + Background event from maximum likelihood fit to:



- ★ cosθ wrt sun
- ★ Kinetic energy
- ★ Radius from centre of SNO

CC	$1967.7^{+61.9}_{-60.9}$
ES	$263.6^{+26.4}_{-25.6}$
NC	$576.5^{+49.5}_{-48.9}$

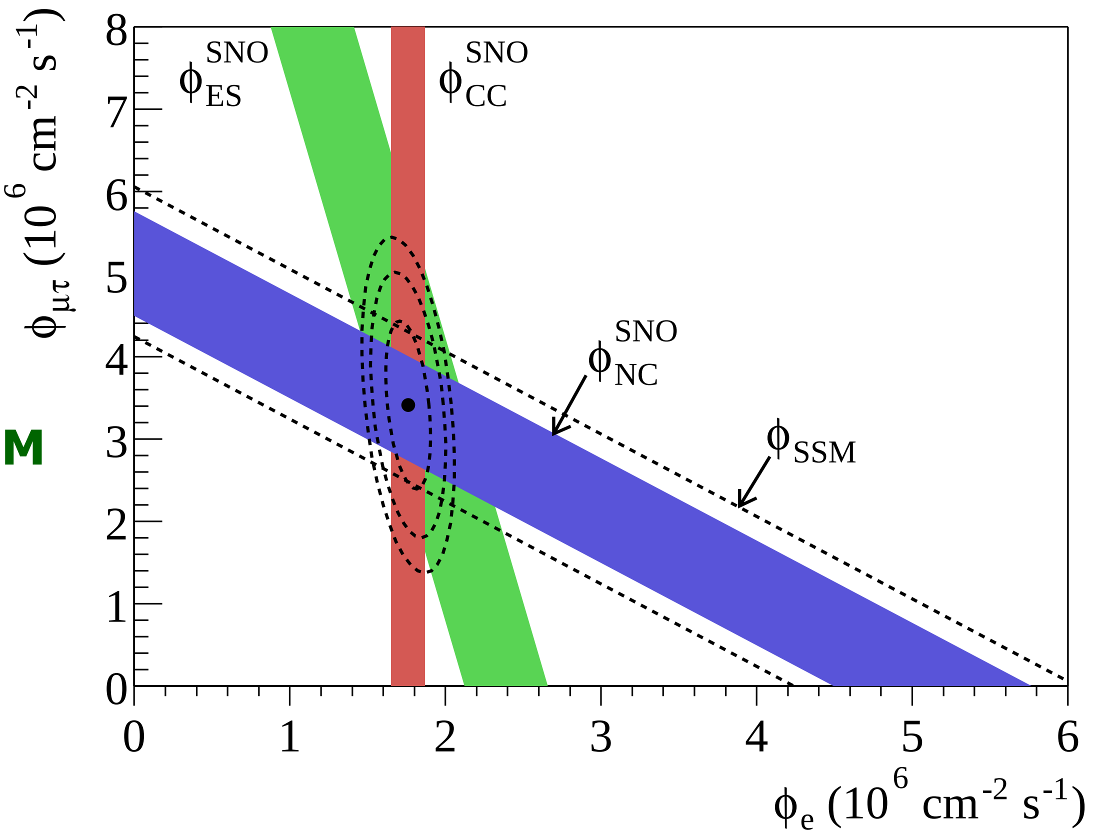
bkgd neutrons 78 ± 12

ES Events ~ $\Phi(\nu_e) + 0.154[\Phi(\nu_\mu) + \Phi(\nu_\tau)]$

NC Events ~ $\Phi(\nu_e) + \Phi(\nu_\mu) + \Phi(\nu_\tau)$

CC Events ~ $\Phi(\nu_e)$

- **Clear evidence for a ν_μ/ν_τ flux from sun !**
- **+ Consistency with SSM**

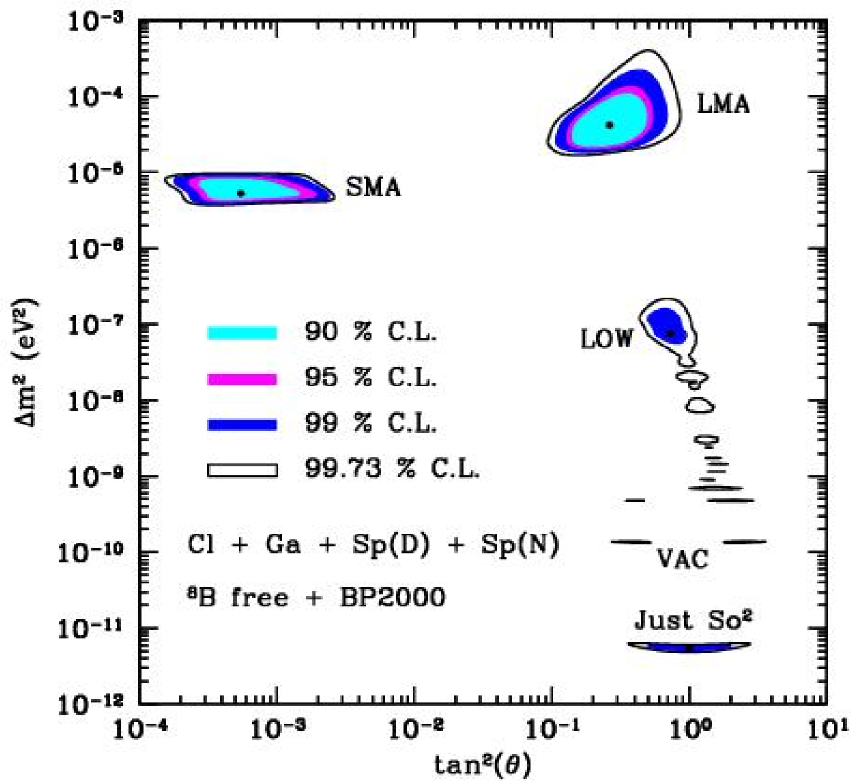


SNO - interpretation

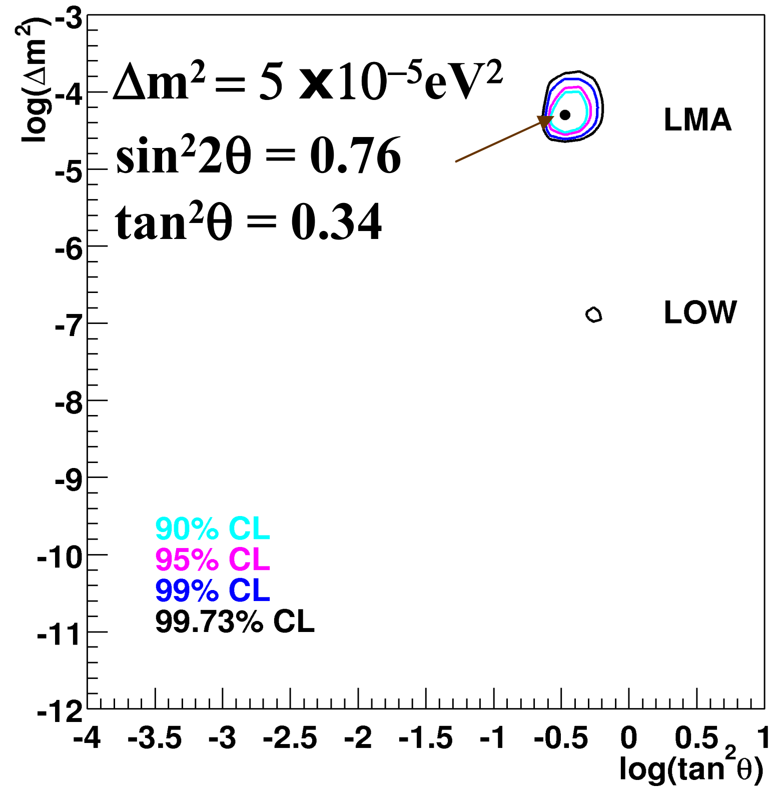
★ Interpretation of solar neutrino data more complicated due to matter effects (**MSW**)

★ But SNO data strongly favour **LMA** solution

Before SNO

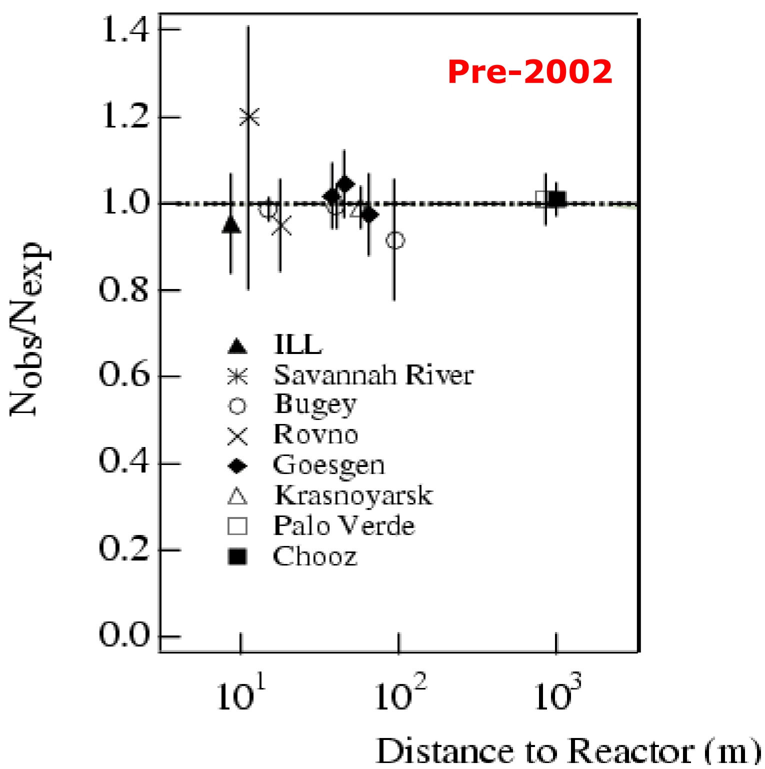


After SNO



Reactor Experiments

- Nuclear reactors produce a large flux of $\bar{\nu}_e$ ($E_\nu \sim 5$ MeV)
- Experiments search for $\bar{\nu}_e$ disappearance



SNO Result : $\Delta m^2 \sim 5\times10^{-5}$ eV^2

Suggests that for

$\sin^2(1.27\Delta m^2 L/E) \sim 1$

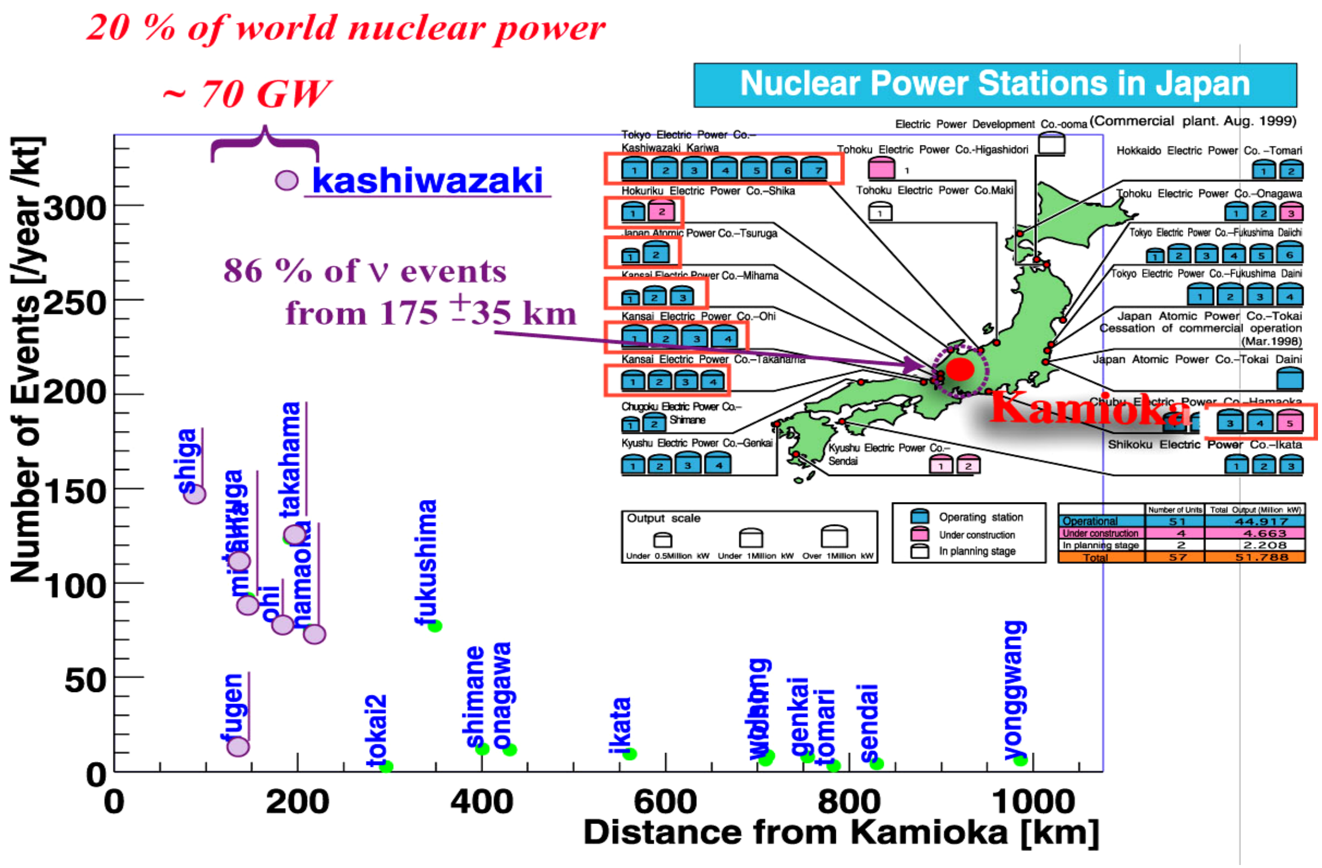
require L ~ 110 km

★ Significantly larger distance, therefore, require very large flux i.e. more than 1 reactor at the right distance

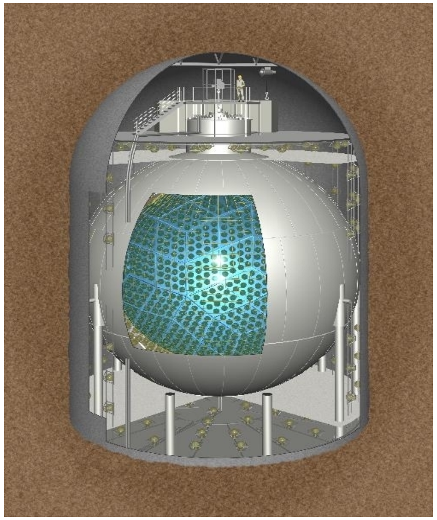
Serendipity

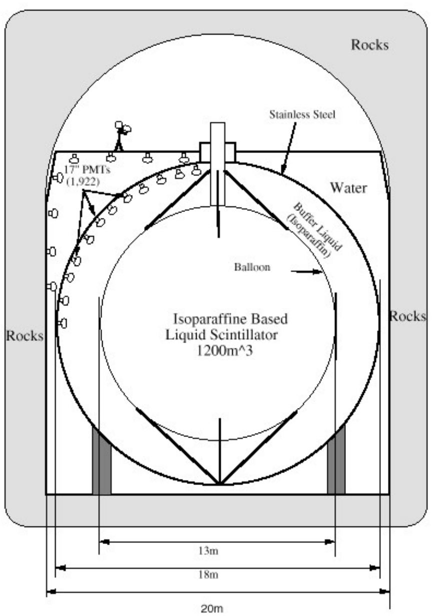
The ideal site exists – Kamioka !

many reactors at ~ 150 km (including most powerful power station in the world ~25GW)



KamLAND





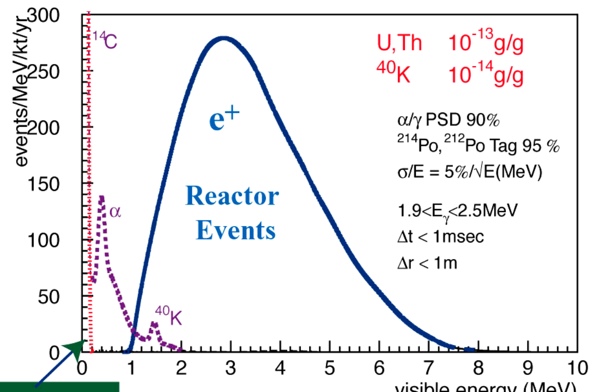
- ★ $\bar{\nu}_e$ detected via inverse β-decay

$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

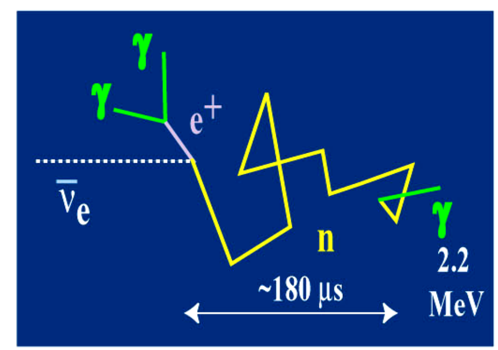
$$n + p \longrightarrow d + \gamma\,(2.2\,\text{MeV})$$

- ★ Two step process:
  - Prompt e^+ gives measurement of ν_e energy
  - Delayed γ

- ★ Event tagging:
  energy + correlation in space/time

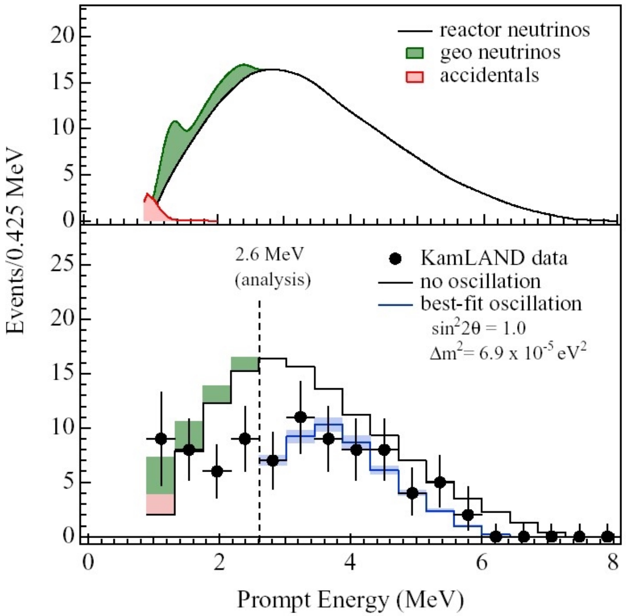


U, Th : 10^{-14} g/g
^{40}K : 10^{-15} g/g



Require ultra-pure Liquid Scintillator

KamLAND Results

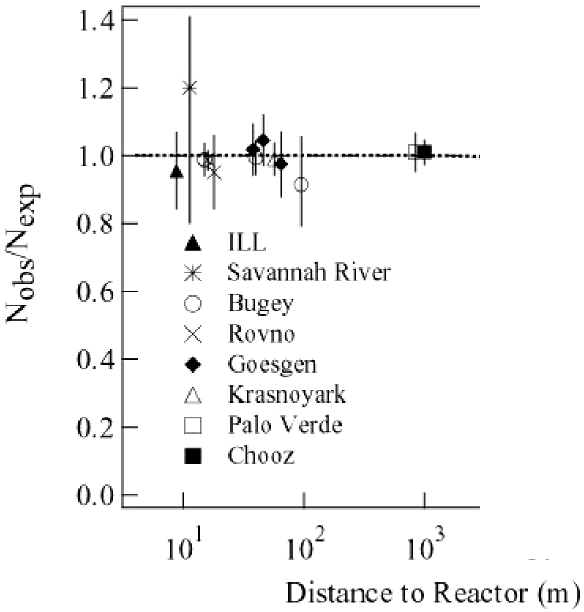


★ E_ν > 2.6 MeV

Observed	54
Expected	86+5.6
Background	0.96+0.99

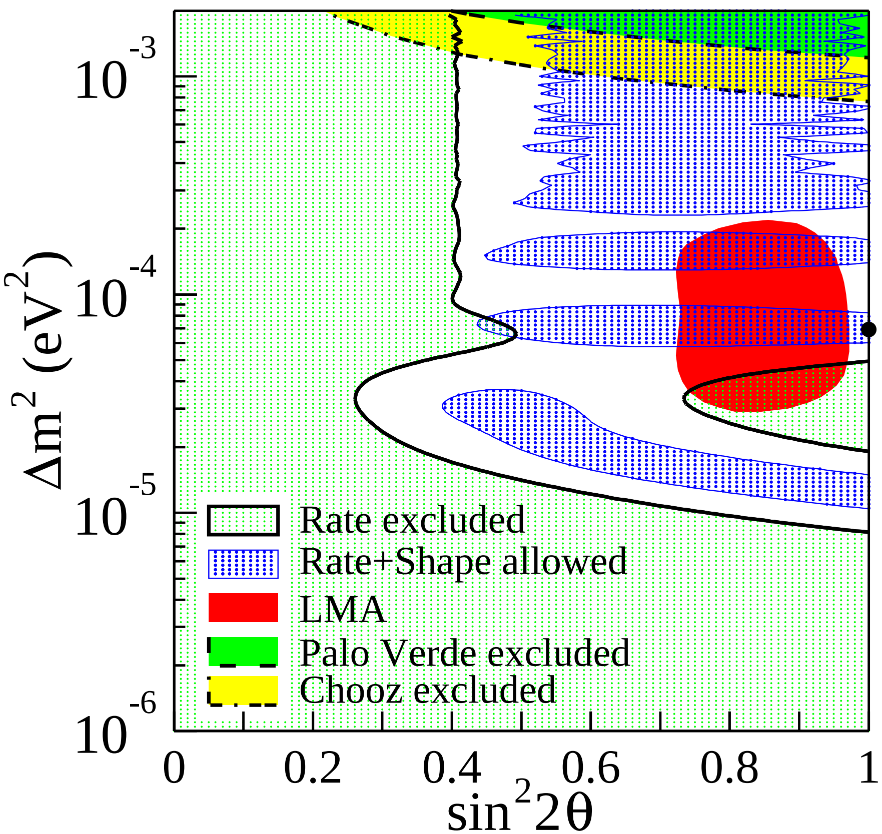
★ Almost all ⓘ from rate

★ Confirmation of solar ν deficit (~3σ)



KamLAND vs SNO

- ★ **Consistent results**
- ★ **LMA confirmed**



Experimental Status : Summary

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- ★ $\Delta m^2_{12} \sim 5\times10^{-5}\ \mathrm{eV}^2$
- ★ $\Delta m^2_{23} \sim 2\times10^{-3}\ \mathrm{eV}^2$
- ★ $\sin^2 2\theta_{23} \sim 1.00$
- ★ $\sin^2 2\theta_{12} \sim 0.75$
- ★ $\theta_{13} < 13^\circ$ (Chooz)

We know a lot more than we did 5 years ago !

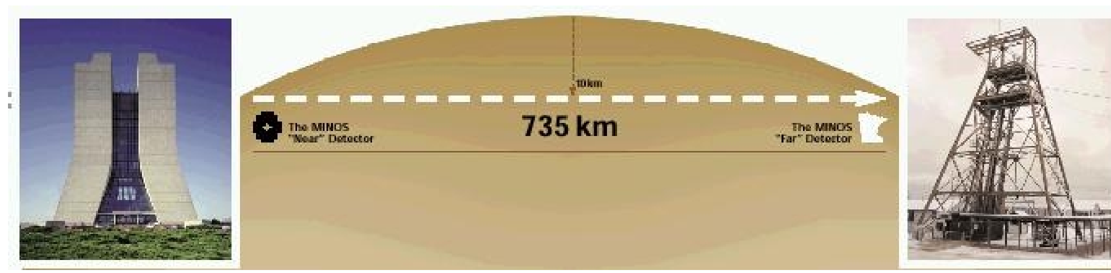
But still haven't seen the oscillatory pattern !

Bring on the next generation…….. MINOS (and others)

Long Baseline Experiments

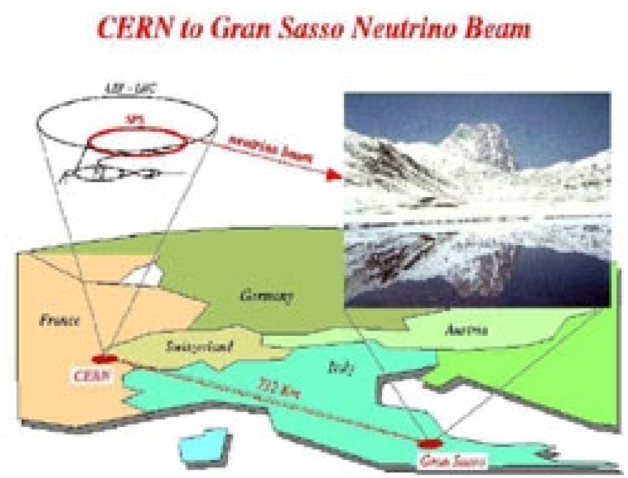
K2K

MINOS



CNGS

(**C**ERN **N**eutrinos to **G**ran **S**asso)



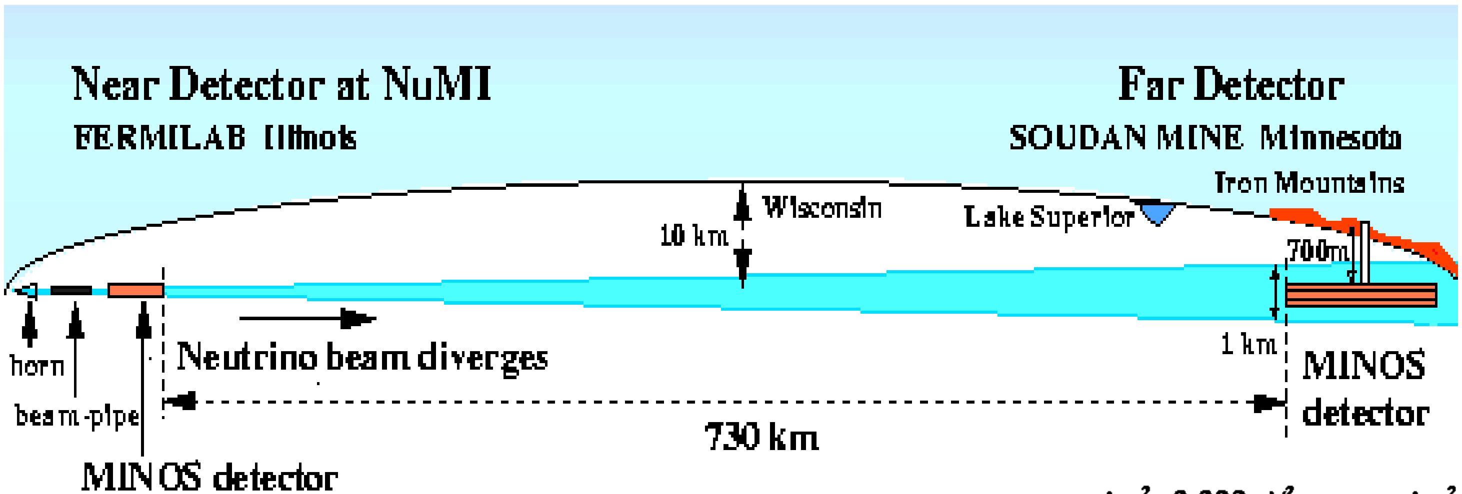
Comparison

	K2K	MINOS	CGNS
Run	1999-	2005-	2006-
Fid. Volume	22 kton	5 kton	2 kton +
$<E_\nu>$	1.3 GeV	3 GeV	17 GeV
L	250 km	735 km	732 km
POT/year	$5x10^{19}$	$4x10^{20}$ (?)	$7.6x10^{19}$
$\delta(\Delta m^2)$	~ 50 %	~ 10 %	~ 15 %
τ appearance	No	No	Yes
Oscillation Dip ?	No (?)	Yes	?

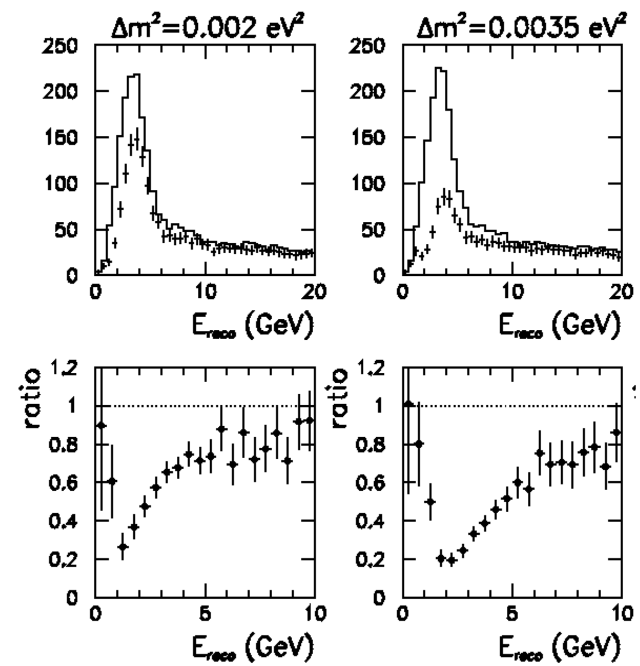
MINOS

where science and art meet

Basic Idea



- **Measure ratio of neutrino energy spectra in far detector (oscillated) to that observed in the near detector (unoscillated)**
- **Partial cancellation of systematics**



MINOS Physics Goals

★ **Demonstrate oscillation behaviour**

- observe oscillatory dip/rise
- confirm flavour oscillations describe data
- discriminate against alternative scenarios

★ **Precise Measurements of Δm^2_{23} & θ_{23}**

- ~10% measurement of Δm^2_{23}

★ **Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations**

- first measurements of θ_{13} ?

+ **MINOS is the 1st large deep underground detector with a B-field**

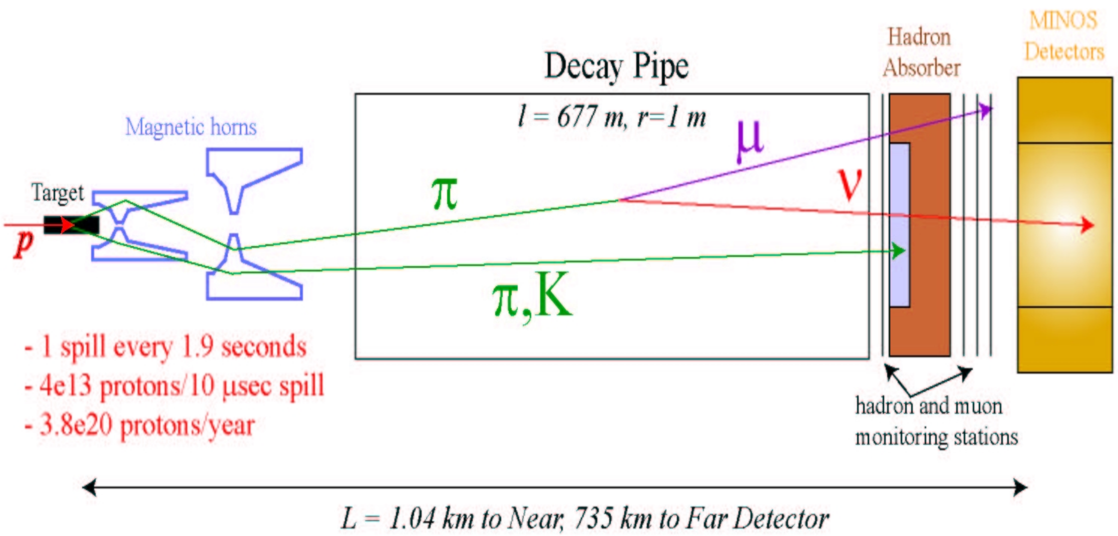
- first direct measurements of ν vs $\bar{\nu}$ oscillations from atmospheric neutrino events

How to make a ν beam

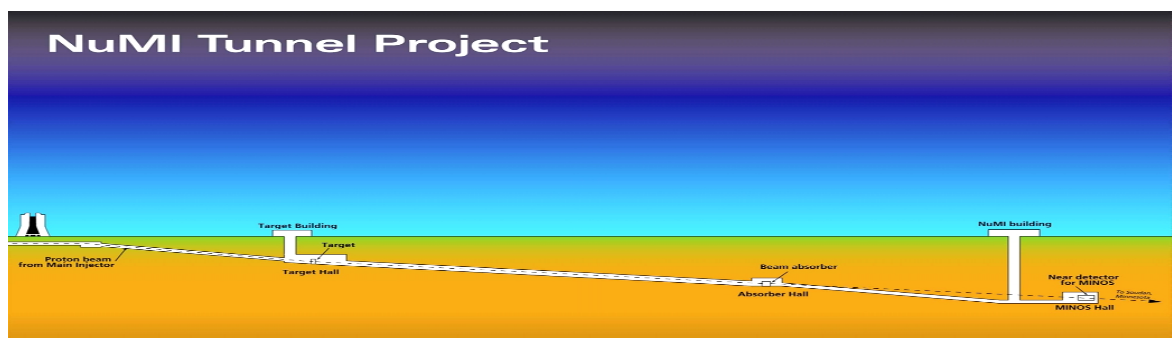
120 GeV/c protons strike graphite target

Magnetic horns focus charged mesons (pions and kaons)

Pions and kaons decay giving neutrinos



To scale……



677 m decay pipe

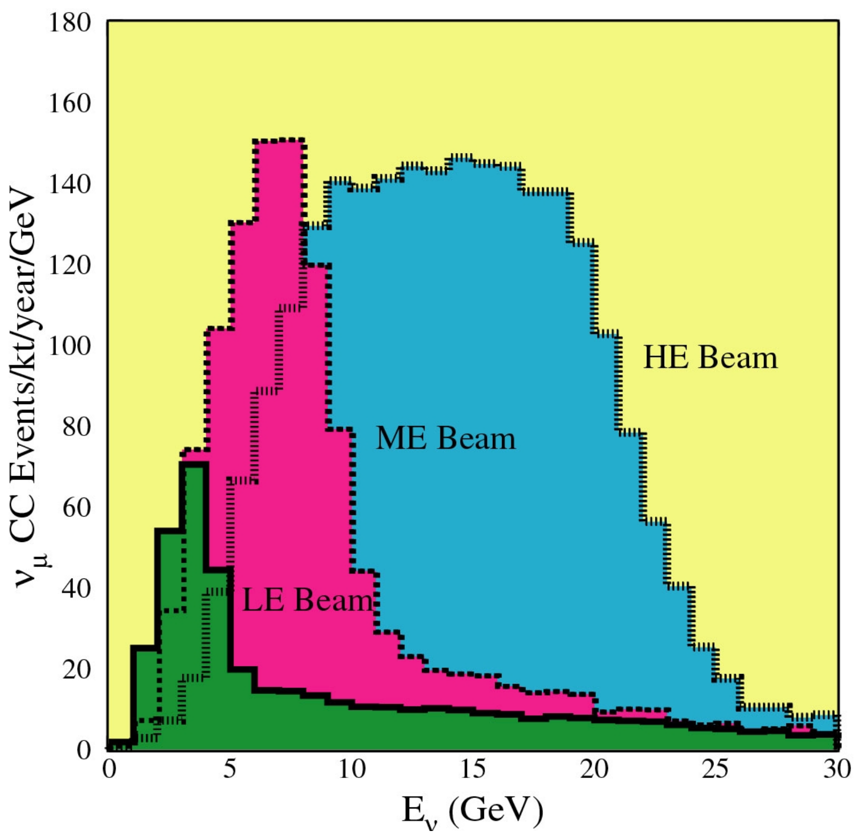
Target

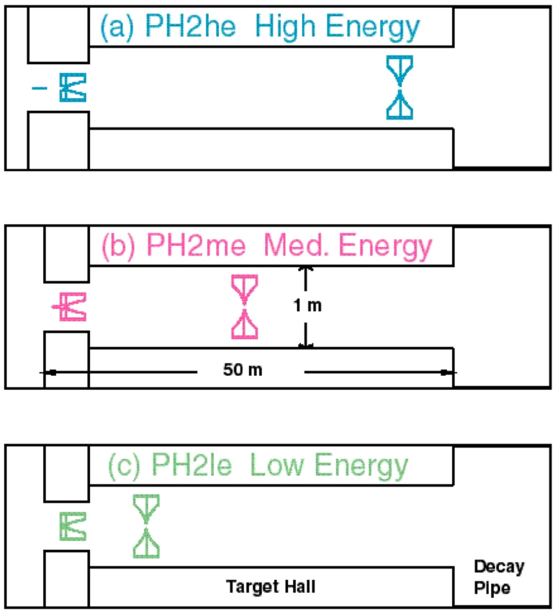
Near Detector

Tunable beam

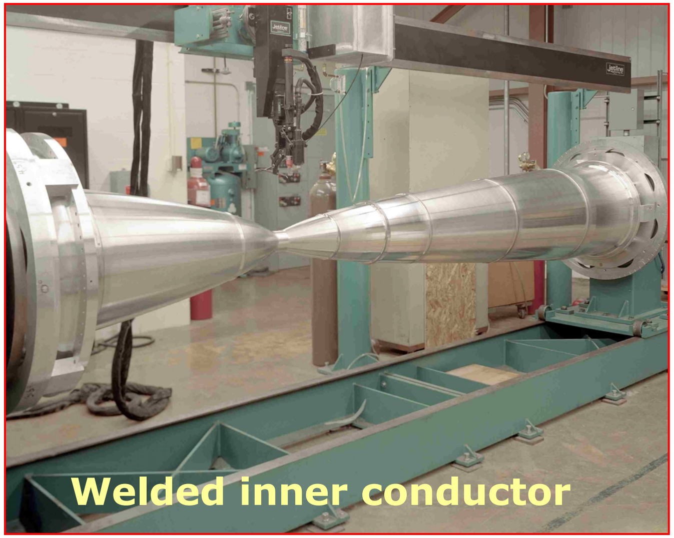
★ Relative positions of the neutrino horns allow beam energy to be tuned.

★ Start with **LE** – but maintain flexibility

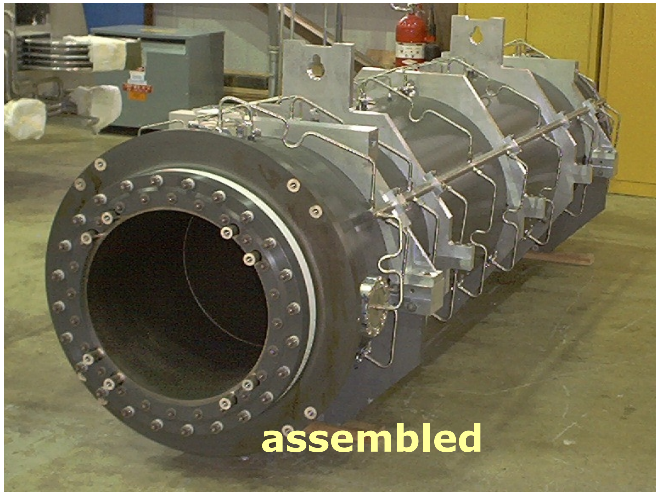


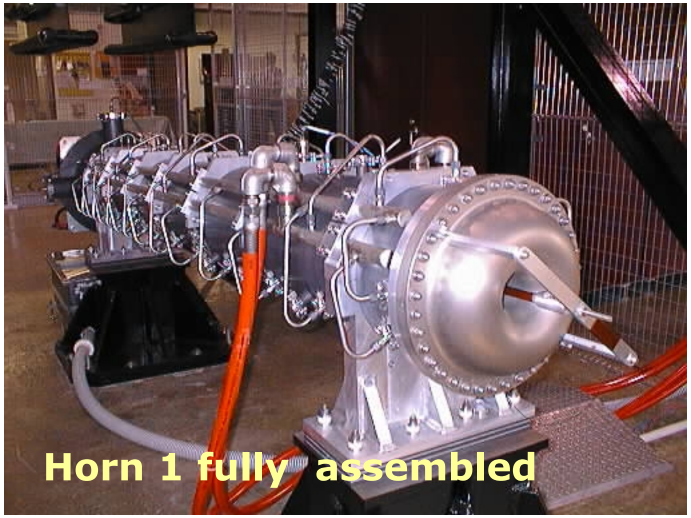


Horn 2



Insertion into outer conductor





Decay tunnel

Tunnelling complete

Beam due to turn on Dec 2004

Pipe is embedded in concrete to protect groundwater.

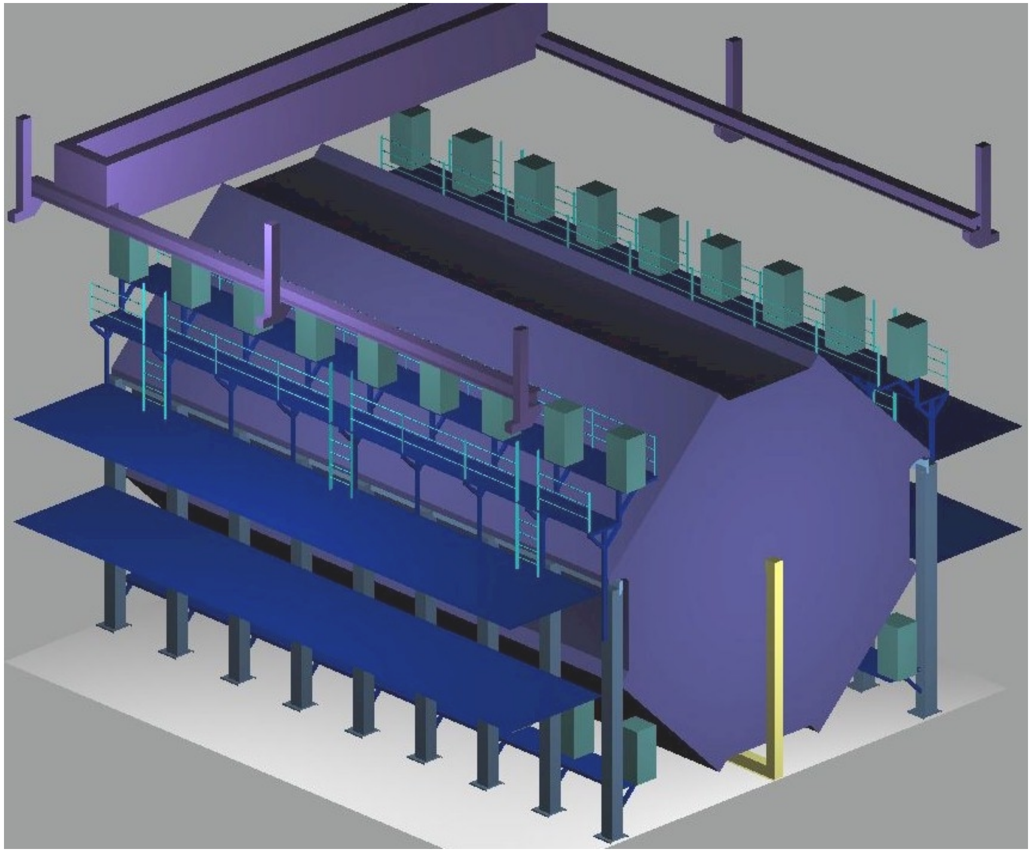
MINOS Far Detector

8m octagonal steel & scintillator tracking calorimeter

- **2 sections, 15m each**
- **5.4 kton total mass**
- **55%/√E for hadrons**
- **23%/√E for electrons**

Magnetized Iron (B~1.5T)

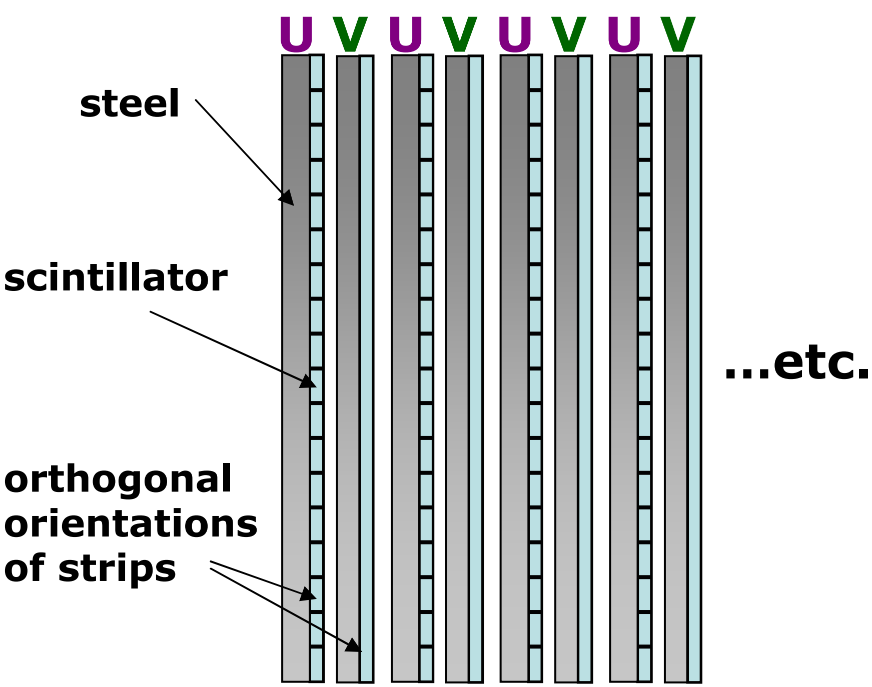
484 planes of scintillator

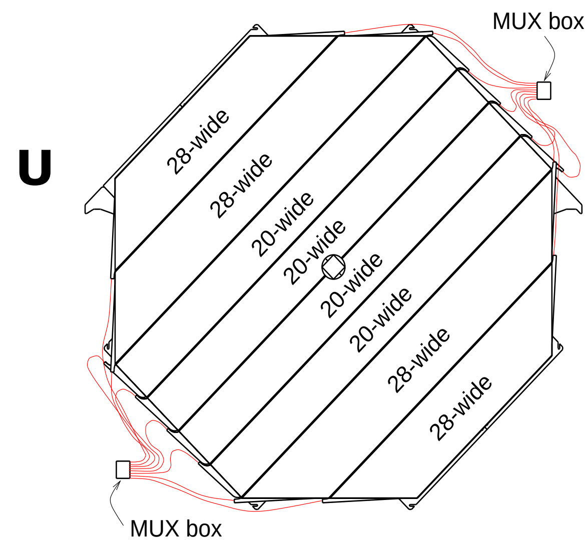


One Supermodule of the Far Detector… Two Supermodules total.

Detector Elements

- ★ MINOS detector : **SAMPLING CALORIMETER**
- ★ Steel-Scintillator sandwich
- ★ Each plane consists of a **2.54 cm** steel +**1 cm** scintillator
- ★ Each scintillator plane divided into **192 x 4cm** wide strips
- ★ Alternate planes have orthogonal strip orientations U and V
- ★ Octagonal Geometry

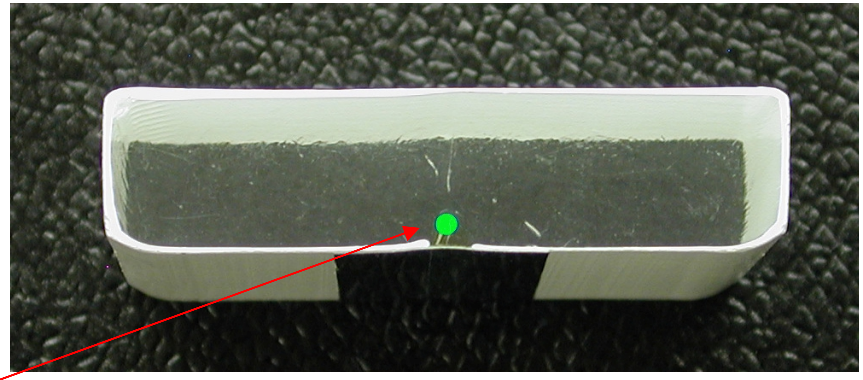




Basic Technology

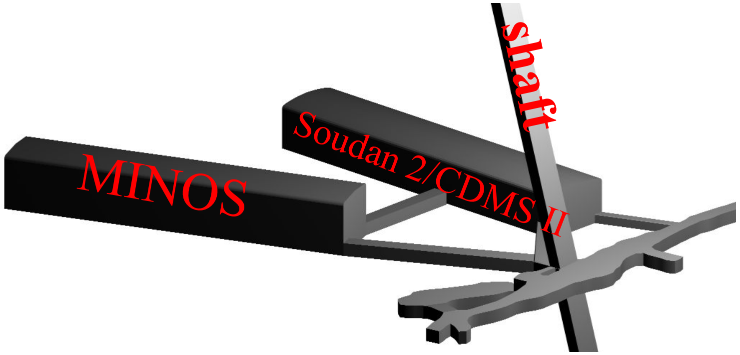
★ **MAIN FEATURES:**

★ **Extruded scintillator strips**
★ **Wavelength-shifting fibres**
+ clear fibre optical readout
★ **Multi-anode PMT readout**
M16 in Far
M64 in Near
★ **8-fold optical multiplexing in Far Detector**



WLS fibre glued into groove

Going underground



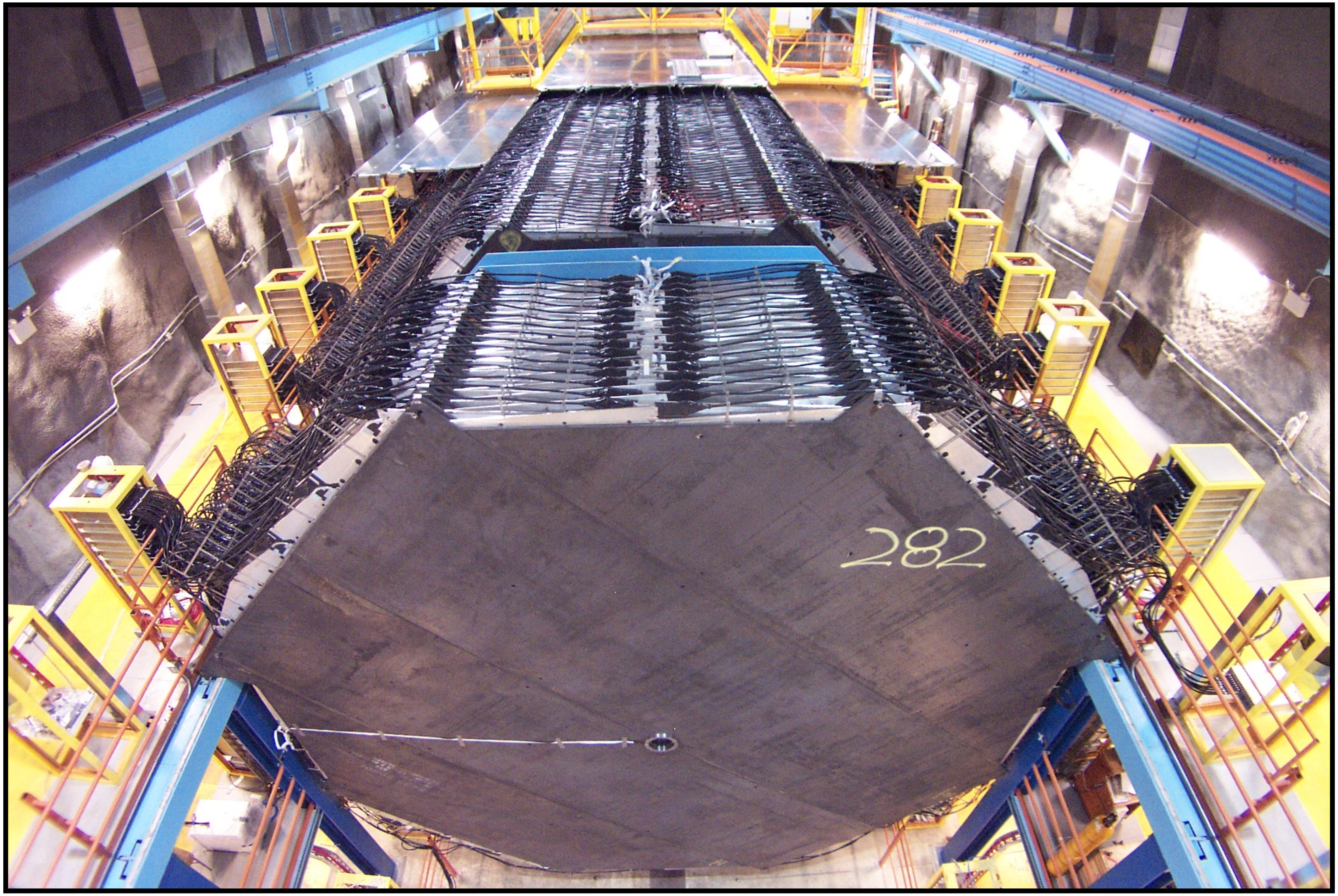
Components taken undergrounds…

Plane Assembly

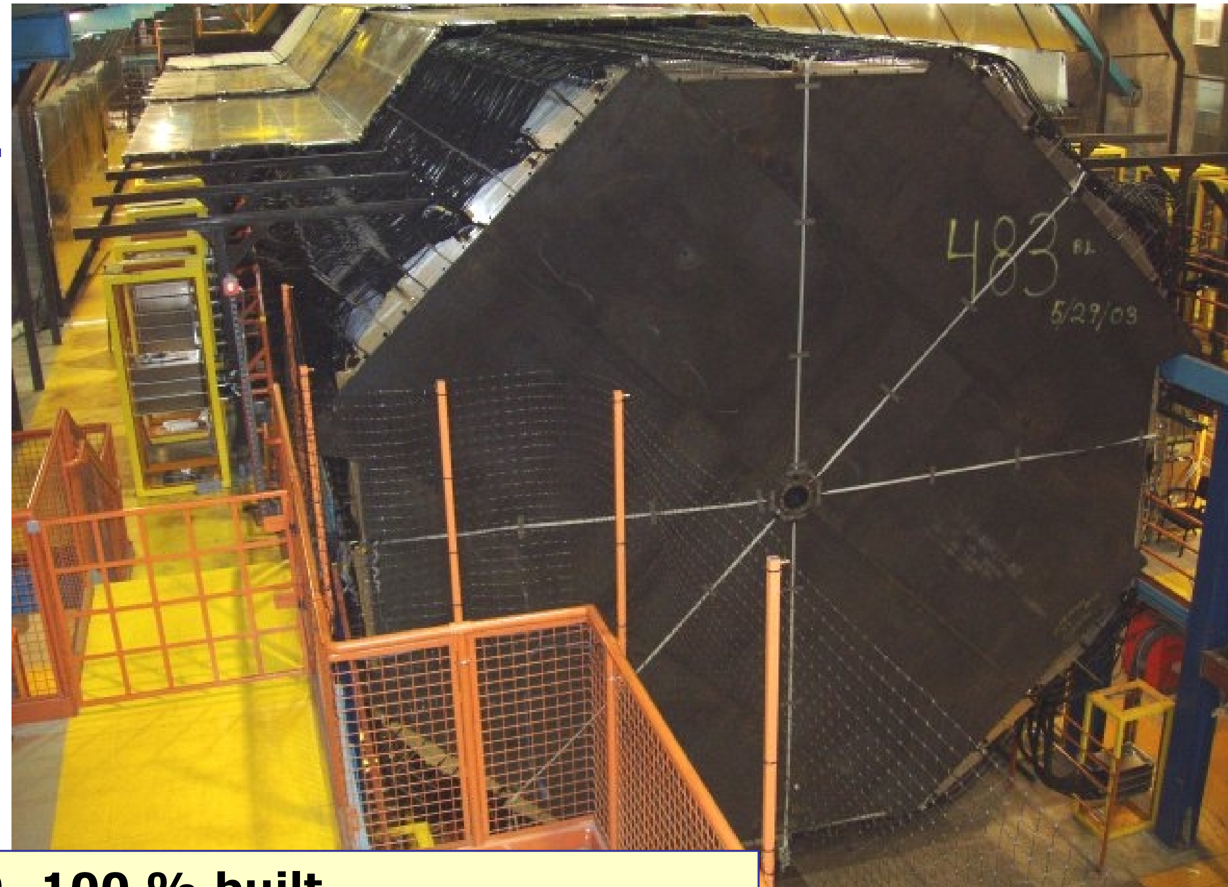
Crane carries plane down the hall for installation

6-8 Planes per week

Some detector pictures



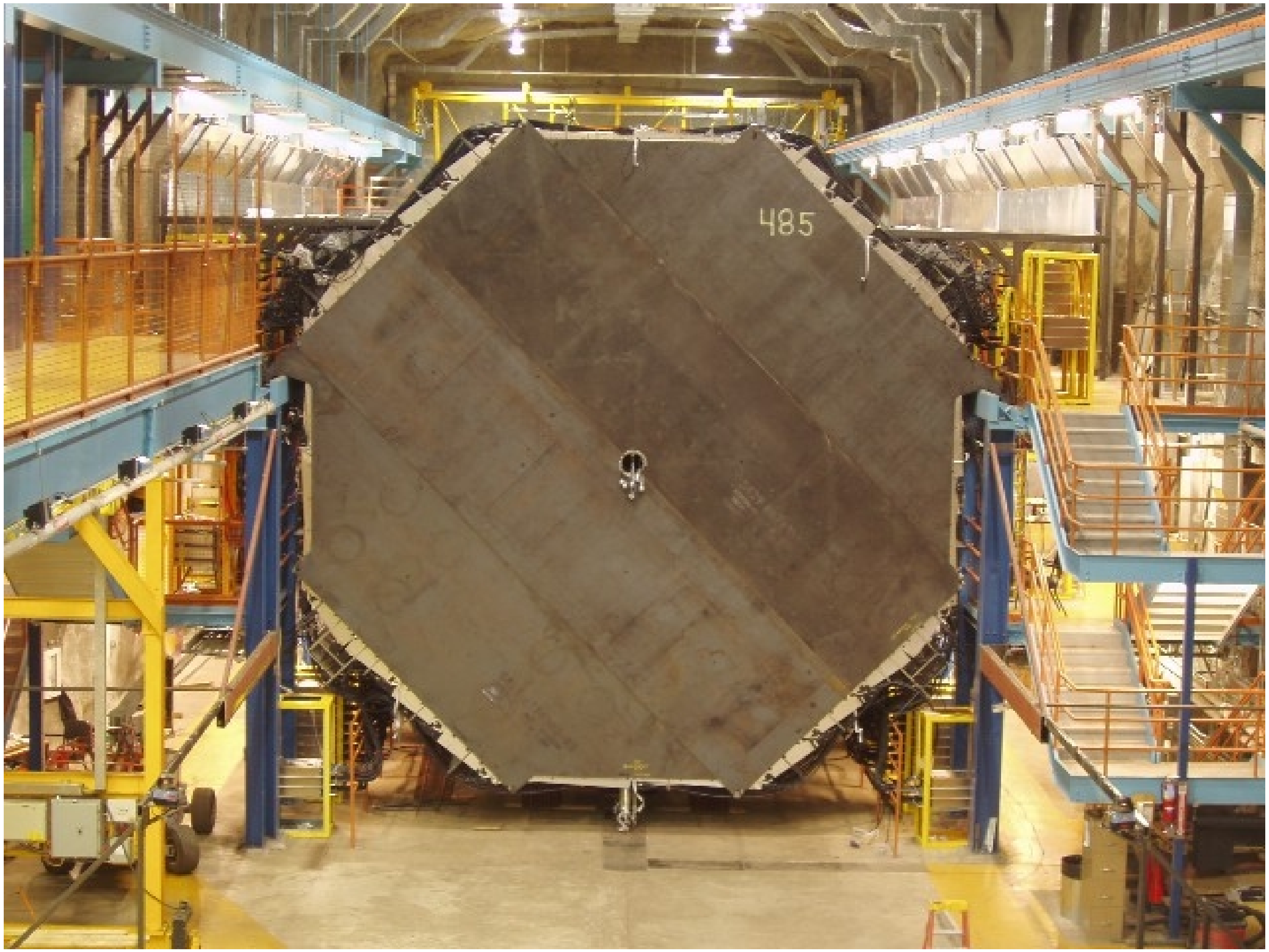
Current Status



Detector on June 2:
483/484 planes installed.
all planes being readout

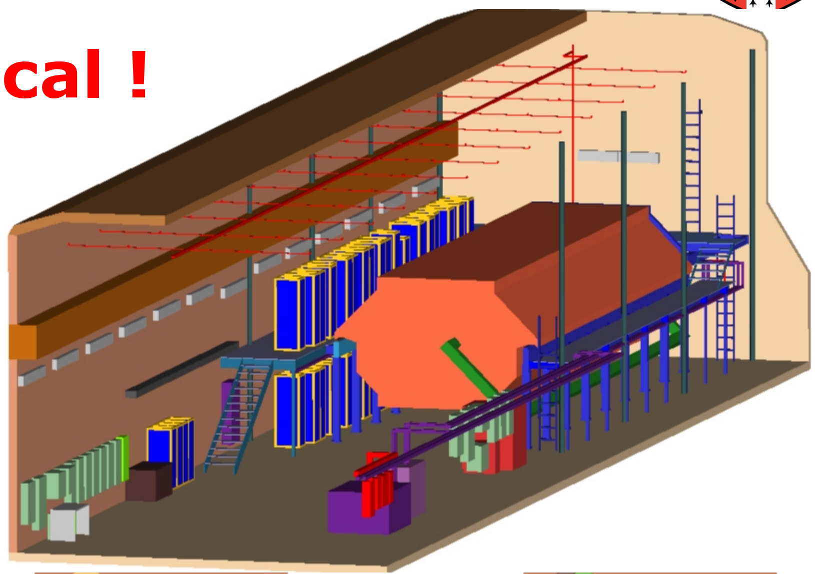
- **The far detector is 99 -100 % built**
- **The magnetic field is on for Super-Module 1**
- **Complete far detector later this month (June 2003).**
- **Atmospheric Neutrino data are being collected**

Last Plane Hung Yesterday !



MINOS Near Detector

★ **Similar – but not identical !**



3.8 x 4.8m "octagonal" steel & scintillator tracking calorimeter

Same basic construction, sampling and response as the far detector.

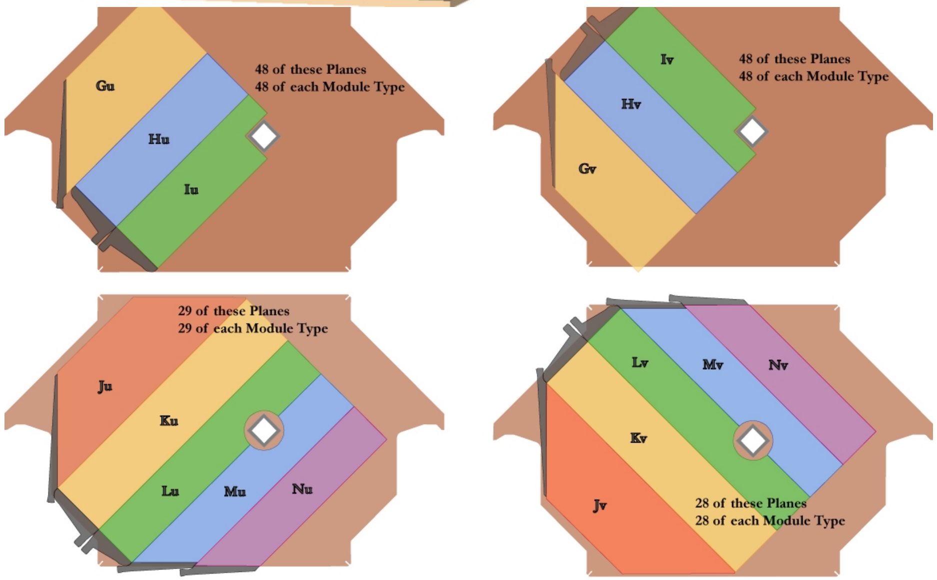
No multiplexing in the main part of the detector due to small size and high rates.

Hamamatsu M64 PMT

Faster Electronics (QIE)

282 planes of steel

153 planes of scintillator

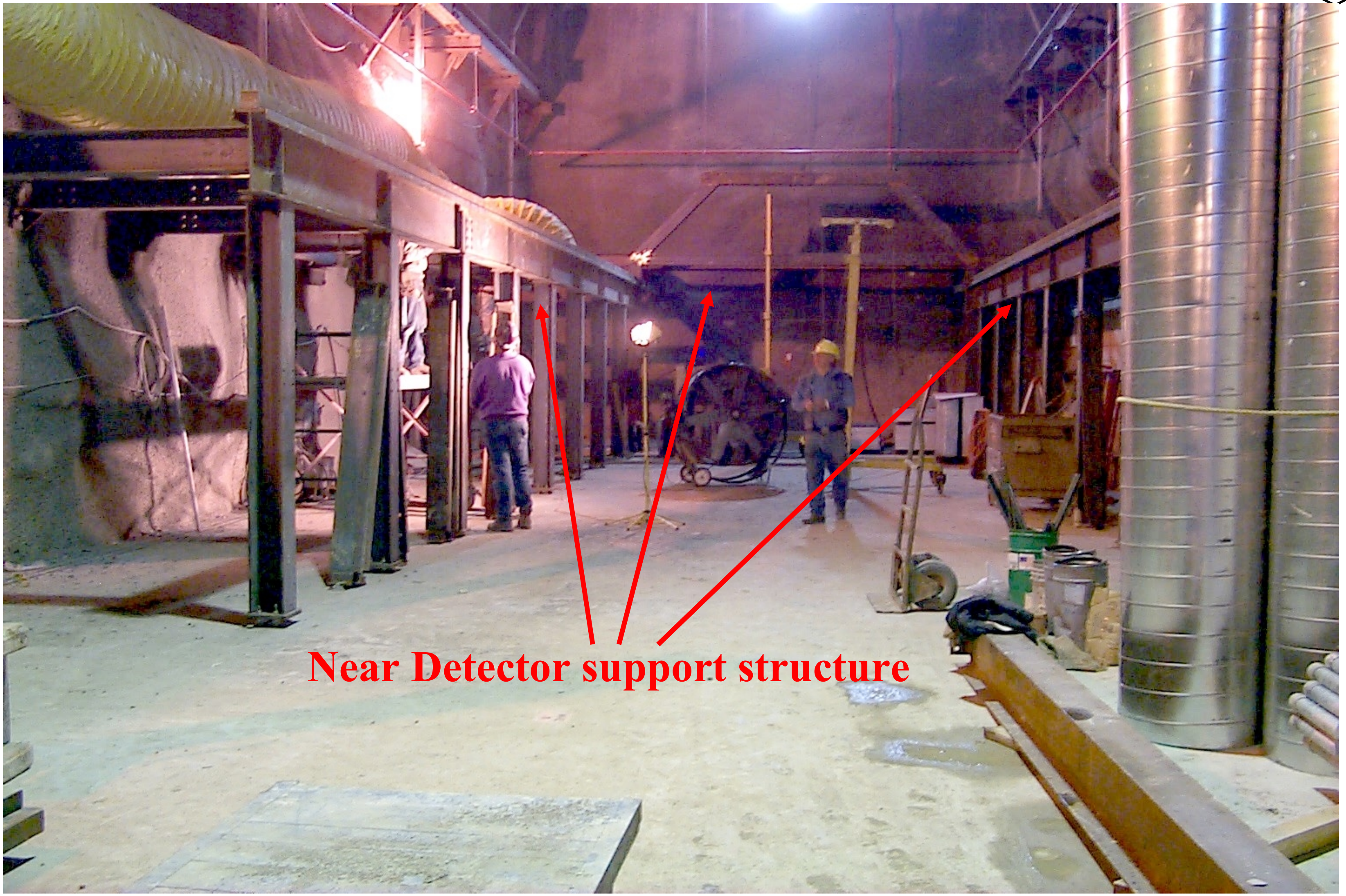


Near Detector Status

Not quite so far advanced as Far Detector

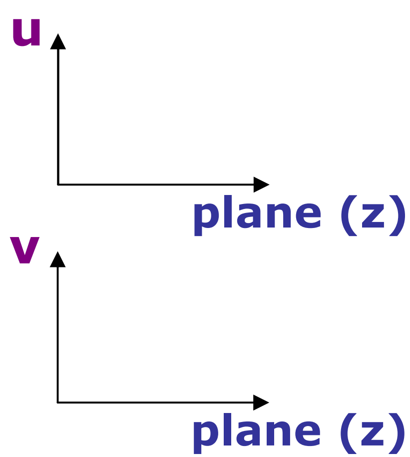
Detector components ready – waiting to be intalled in experimental hall

Near Detector Status



Event Information

★ **Two 2D views of event**

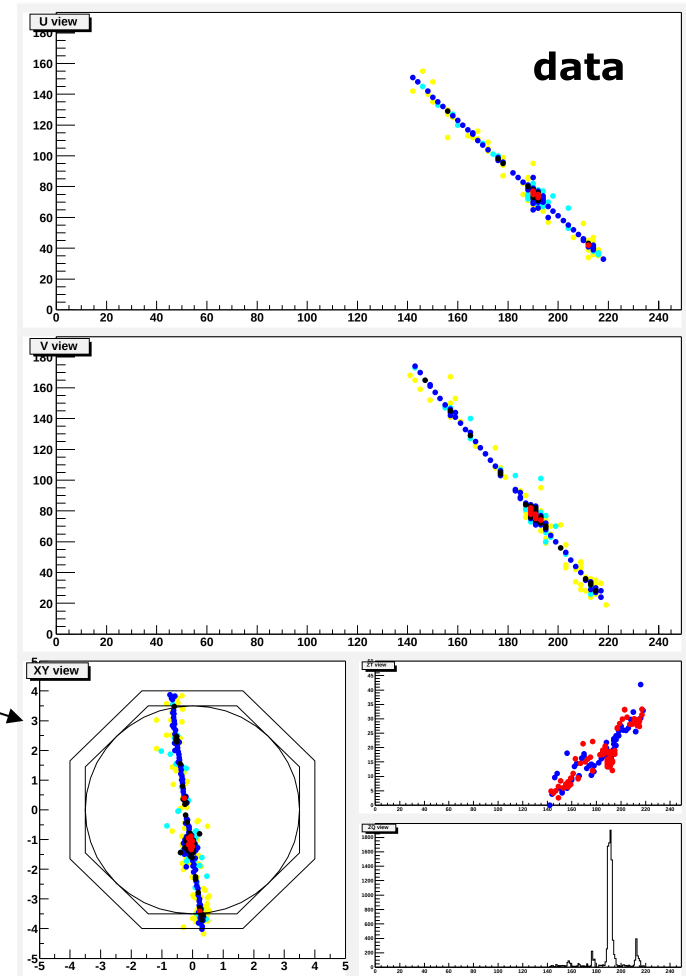


★ **Software combination → `3D'**

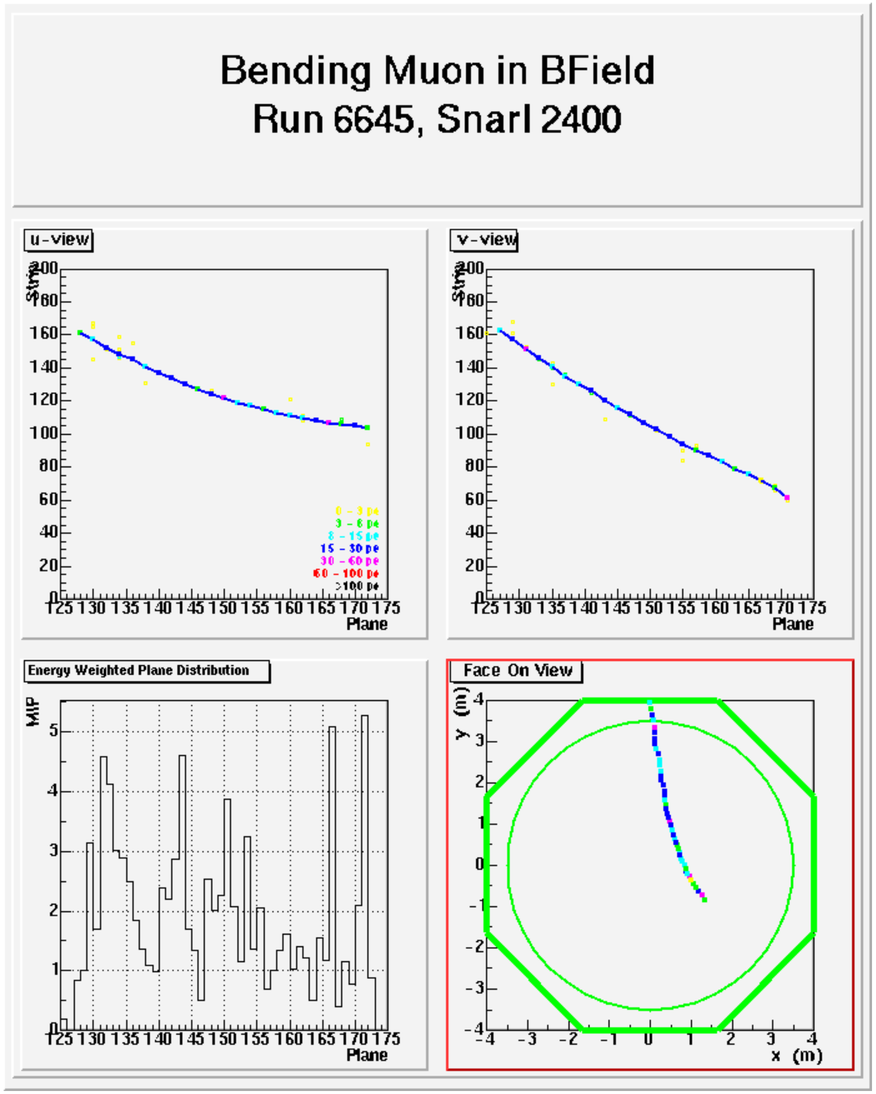
★ **Timing information (~2.5 ns)**
gives event direction (up/down)

★ **+ charge deposit (ADC counts)**

FarDet Cosmic Ray Muon



B-Field



~ 1.5 T Magnetic Field

- ★ Charge separation
- ★ Momentum measurement

Stopping muon

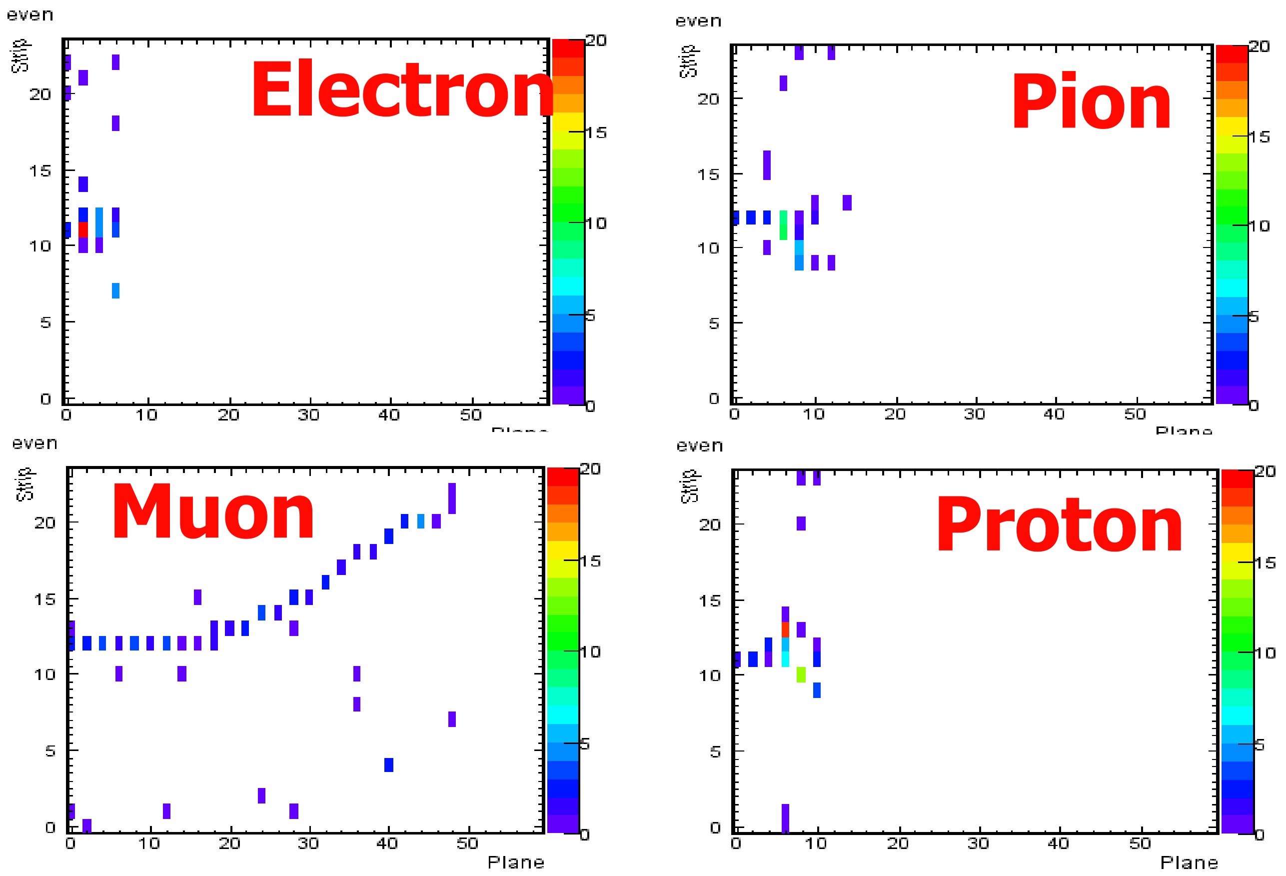
P_{range} = 3.86 GeV/c

$P_{curvature}$ = 4.03 GeV/c

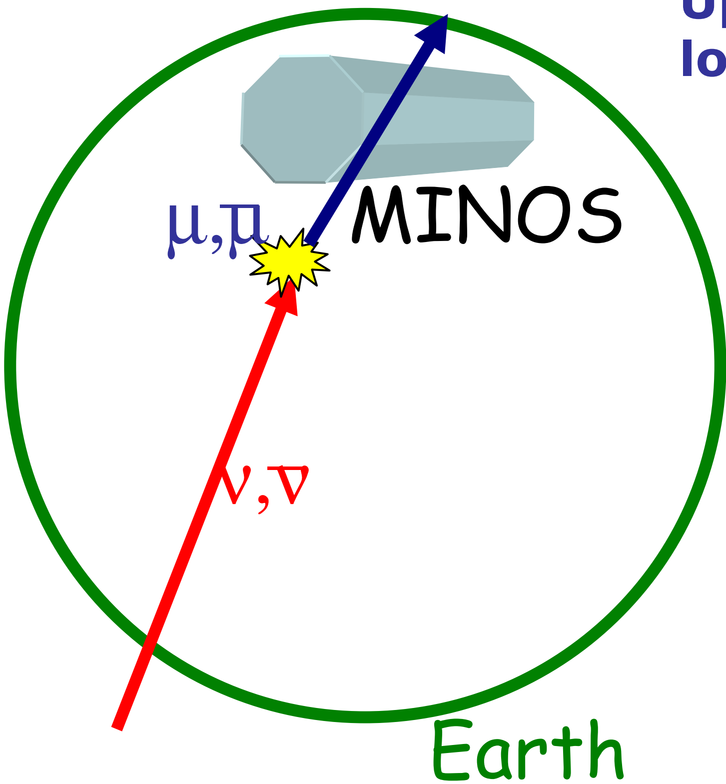
Test Beam

Response/Calibration being measured in CERN test beam using a MINI-MOS

e.g. response to 2 Gev particles



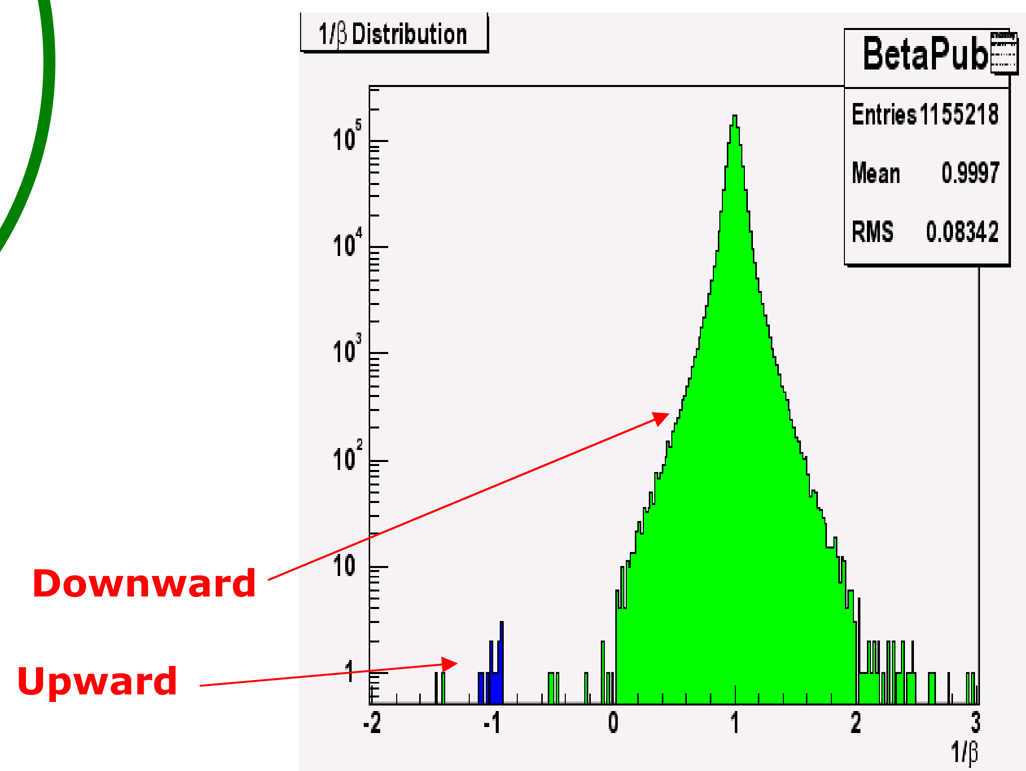
First `results'



Upward going muons produced by local neutrino interactions in rock

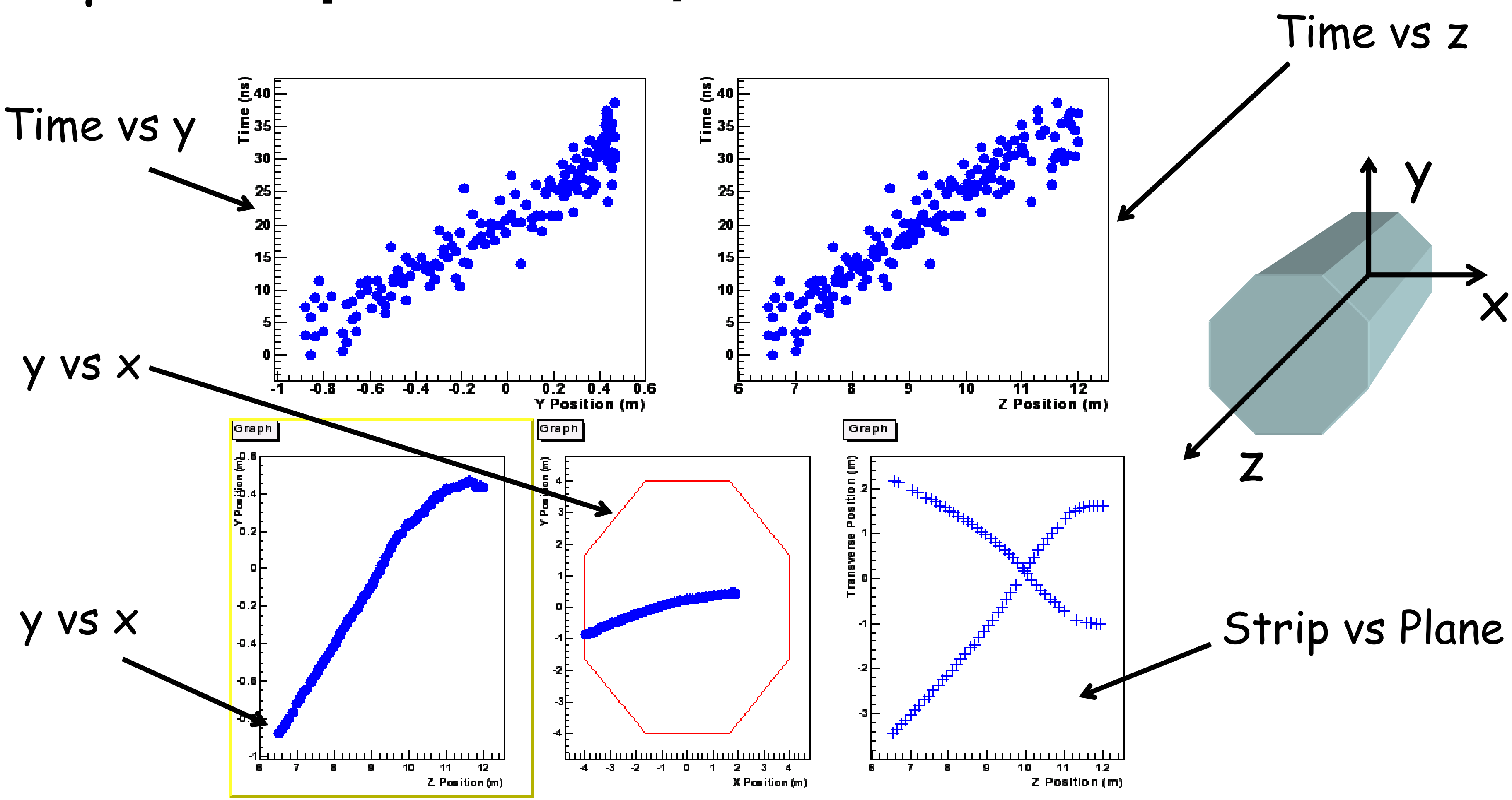
Determine velocity from timing

β = v/c (β=-1 upward)



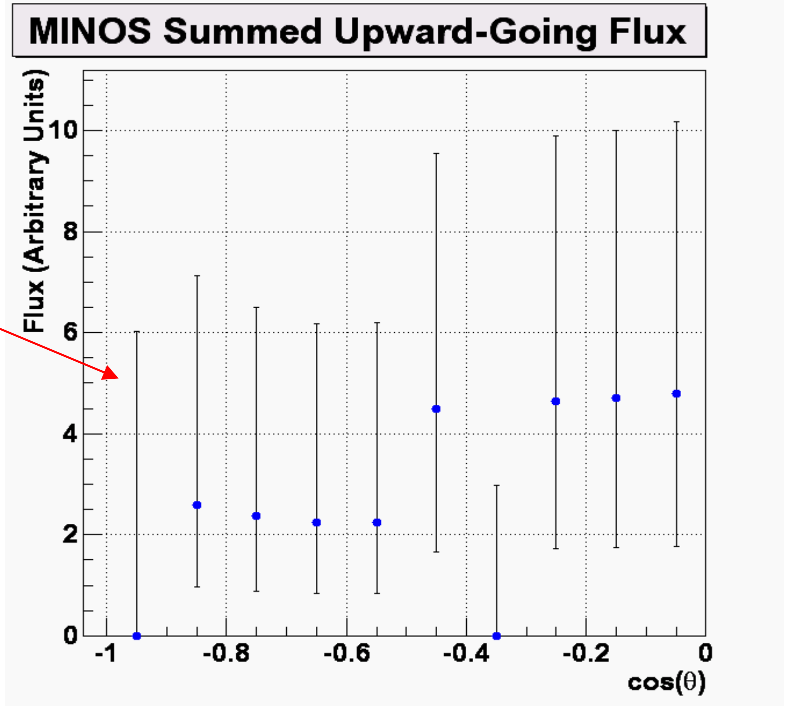
Example Candidate Event

μ^+ with p = 5.4 GeV/c



12 Candidate Events consistent with MC expectation

and a token data `physics' plot



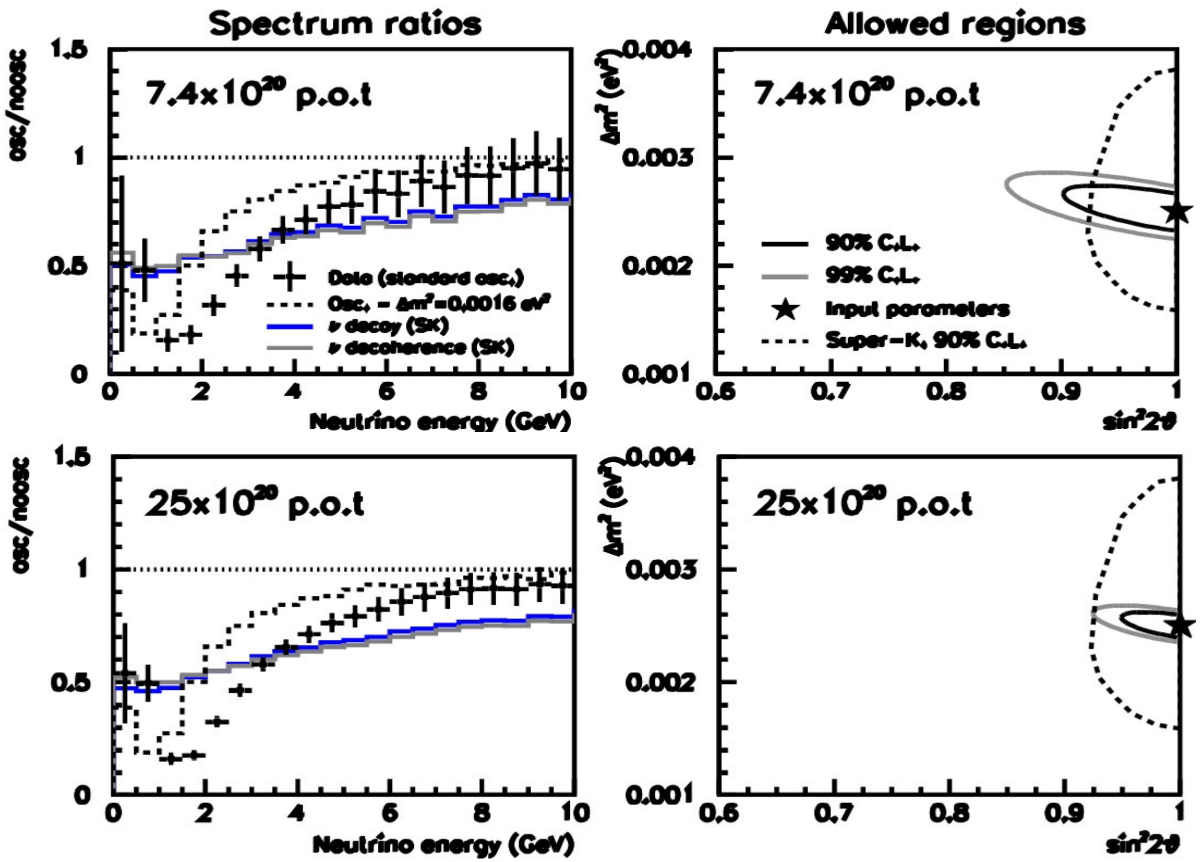
- Data analysis underway !
- Hope to have preliminary results on atmospheric neutrinos for Summer 2004

- And finally what I'd like to be presenting here in a few years time……

cos(zenith)

MINOS Sensitivity

★ **Measurement of Δm^2 and $\sin^2 2\theta$**



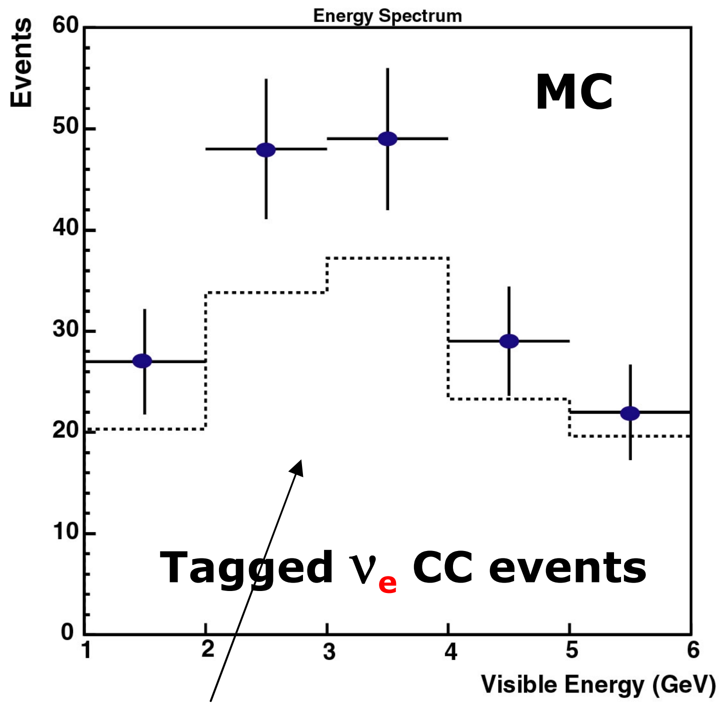
For Dm² = 0.0025 eV², sin² 2q = 1.0

Factor 10 improvement in precision !

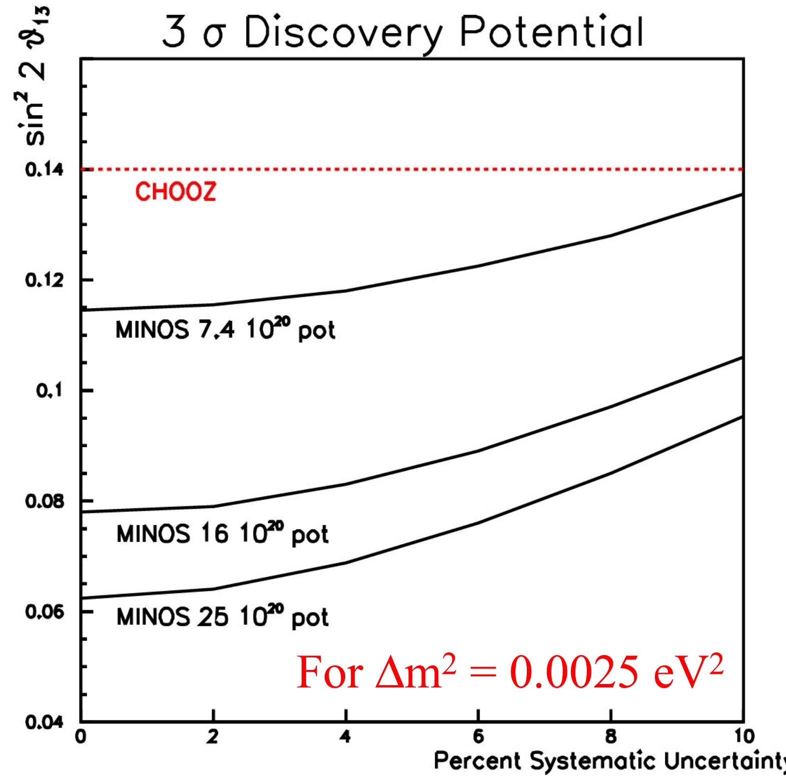
Final sensitivity depends on <u>protons</u> delivered to MINOS

ν_e Appearance

For $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta_{13} = 0.067$



Assumes 25x10^{20} protons on target.



- **3 σ discovery potential** may significantly eat into current allowed region – exact reach depends on protons
- <u>MINOS has a reasonable chance of making the first measurement of θ_{13}</u>

Conclusions

- Over the last **5 years** our knowledge of the neutrino sector has increased hugely !
- Over **next 5** years a number of new experiments + `precise' measurements
- May shed light on fundamental questions, e.g. flavour symmetry - why near maximal mixing matrix (in contrast to CKM) ? ......
- MINOS is a major part of this experimental effort
- Construction is going well – already taking high quality data with the MINOS Far Detector
- Eagerly awaiting first beam, due **December 2004** – and who knows, maybe some suprises !

The word is getting around.....