
MINOS
20

Neutrino Oscillations and the MINOS experiment

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This Talk:

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

Recent History

6 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....!

6 Years on.......

Now (PDG2002+):

- ★ Standard Model : massive ν
- ★ Fundamental states : ν_1 , ν_2 , ν_3
- ★ $\Delta m^2_{12} \sim 7\times10^{-5}\ eV^2$, $\Delta m^2_{23} \sim 2\times10^{-3}\ eV^2$

Neutrino Oscillations – Convincing evidence

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

★ **Almost all ⓘ from neutrino oscillations**

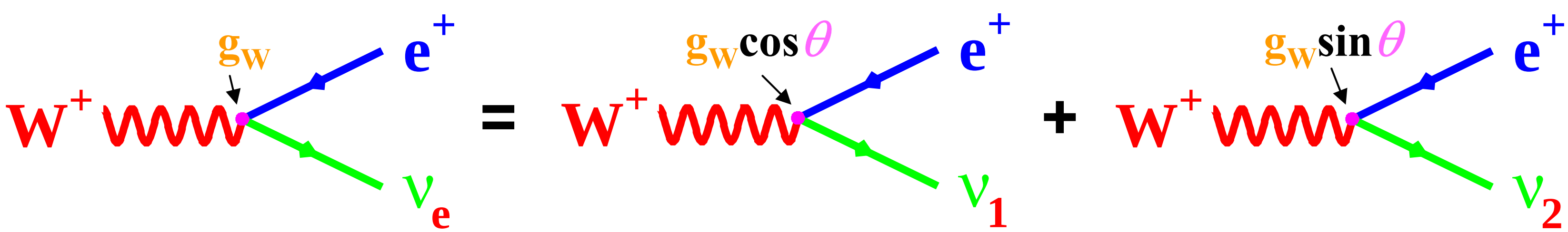
Neutrino Oscillations

- 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 <u>time evolution</u> 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 $E_1 \neq E_2$ ⟹ <u>Observable</u> phase difference

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

★ Then its just algebra......

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

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)

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

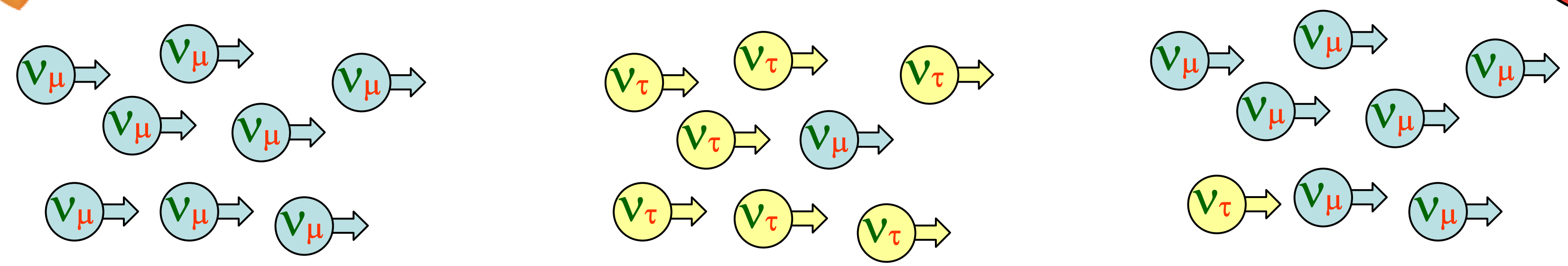
Atmospheric ν — **CP Phase** — **Solar ν**

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

Neutrino oscillations described by 6 new SM parameters

Aim to measure them all.....

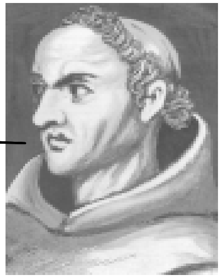
Golden ν Oscillation Signal



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 interact only weakly

  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, …..

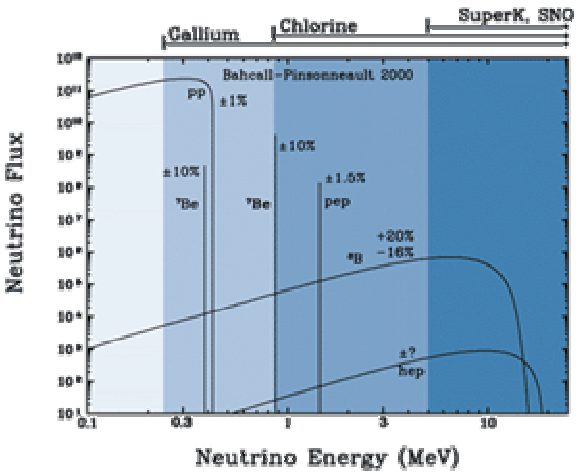
  Reactor Neutrinos (KamLAND)

  Neutrino beams (K2K)

- ★ For this talk – ignore LSND !

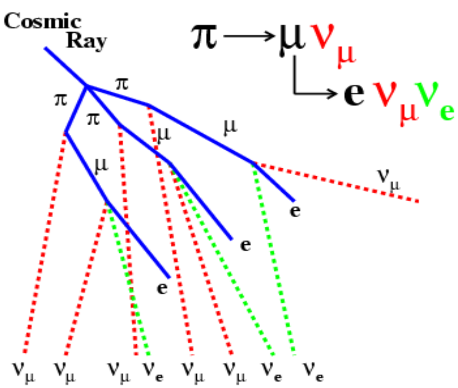
Wait for MiniBoone

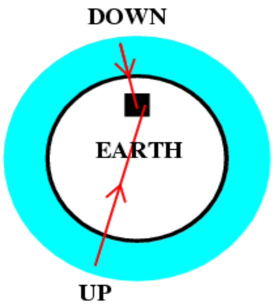
Solar Neutrinos



- ★ 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



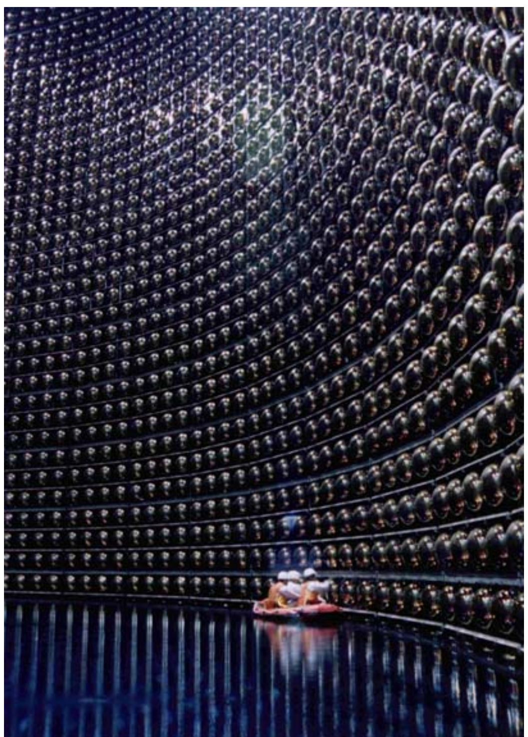


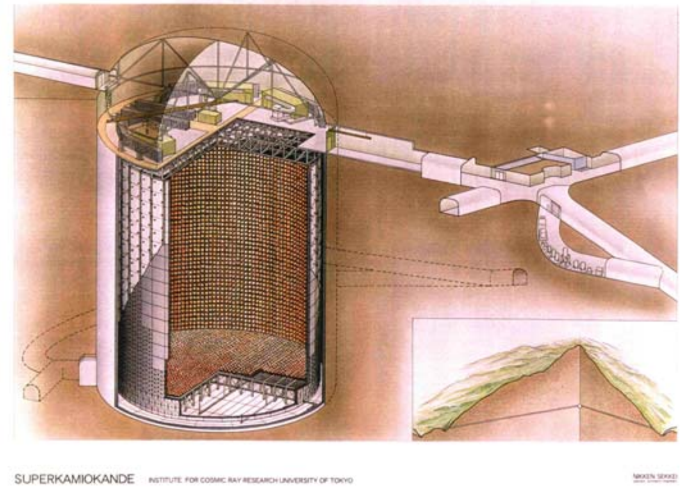
- ★ Cosmic Rays (mainly p,He) hitting upper atmosphere produce νs:
  $\pi \rightarrow \mu\nu_\mu$ and $\mu \rightarrow e\nu_e\nu_\mu$ decays
- ★ Flux ~ 1 cm^{-2} sr^{-1} s^{-1}
- ★ E_ν ~ 1 GeV
- ★ $N(\nu_\mu)/N(\nu_e)$ ~ 2

★ **Super-Kamiokande dominates atmospheric ν**

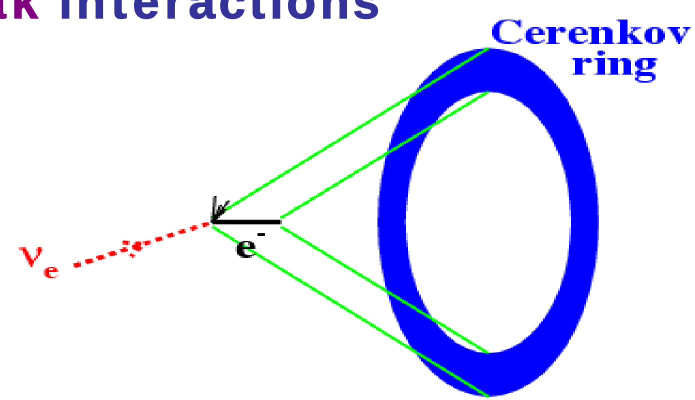
Super-Kamiokande

- ★ 50 ktons H_2O
- ★ 11246 PMTs
- ★ Accident in 11/2001
- ★ Operational again – reduced number of PMTs



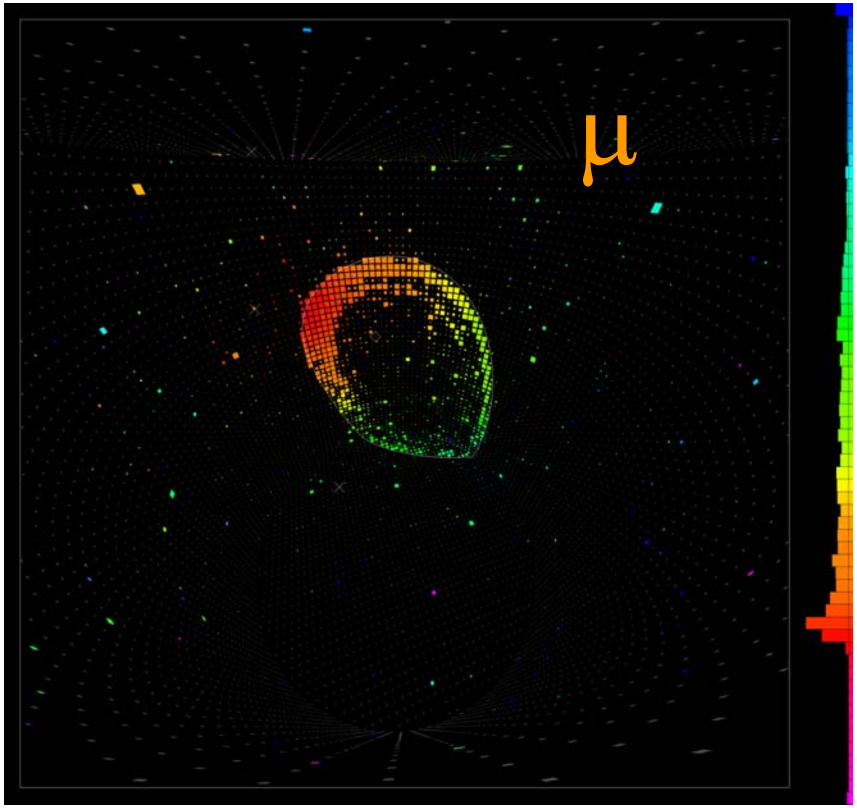


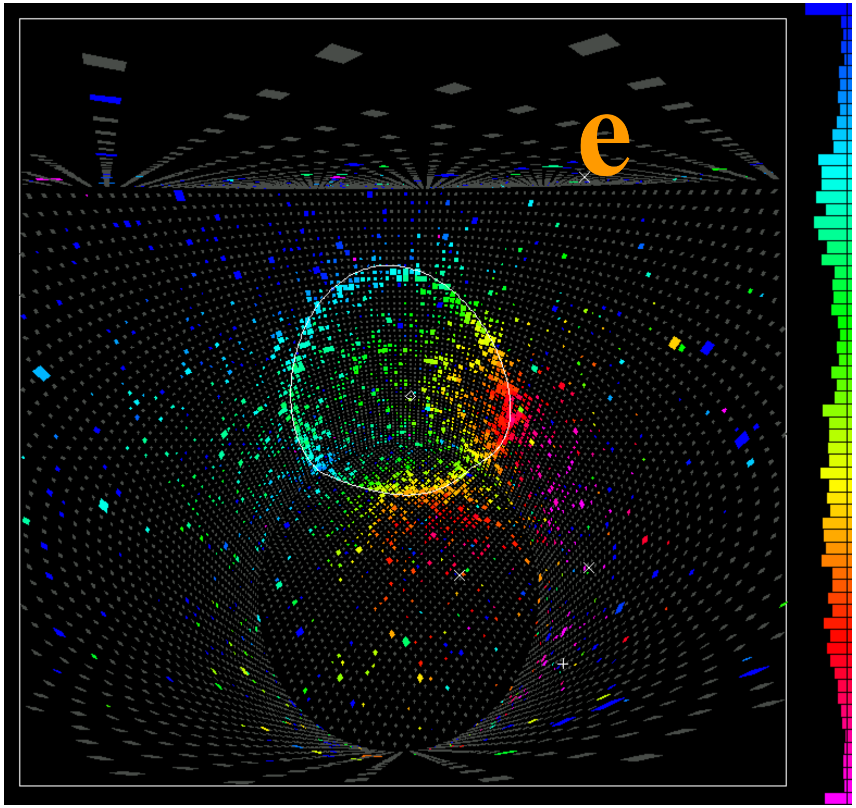
ν_e , ν_μ detected via Cerenkov radiation from lepton produced in CC weak interactions



SK particle ID

★ Electrons and muons cleanly identified ~ 99 % purity

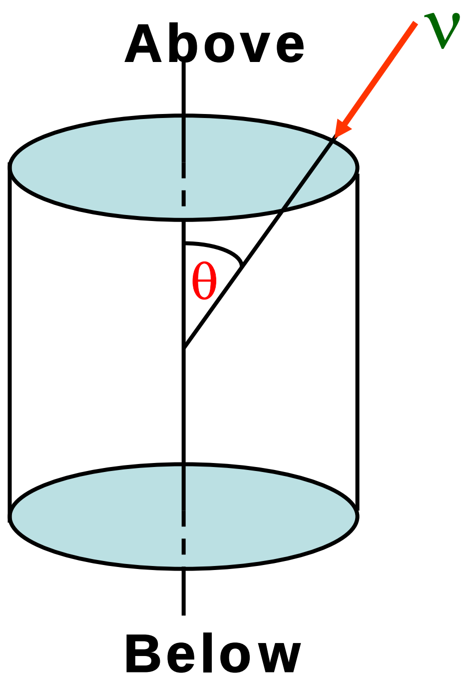


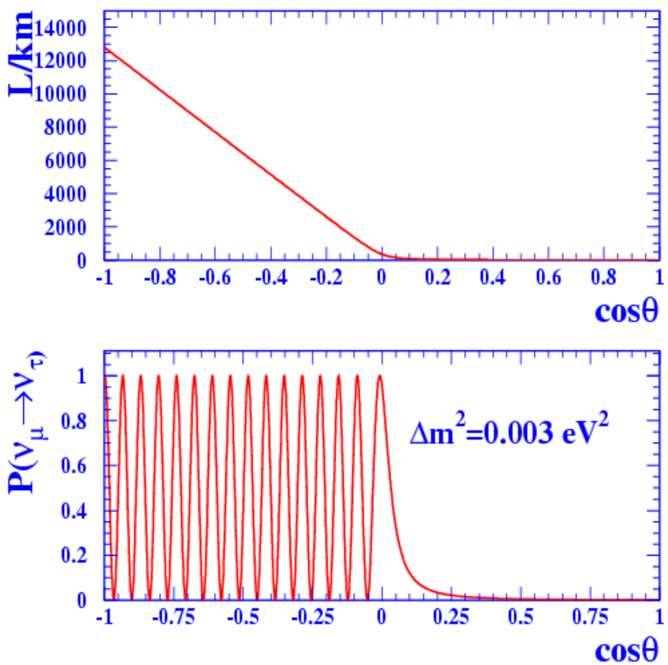


`Clean' ring

`Diffuse/fuzzy' ring due to scattering/showering

Measure ν_e/ν_μ fluxes vs zenith angle, θ





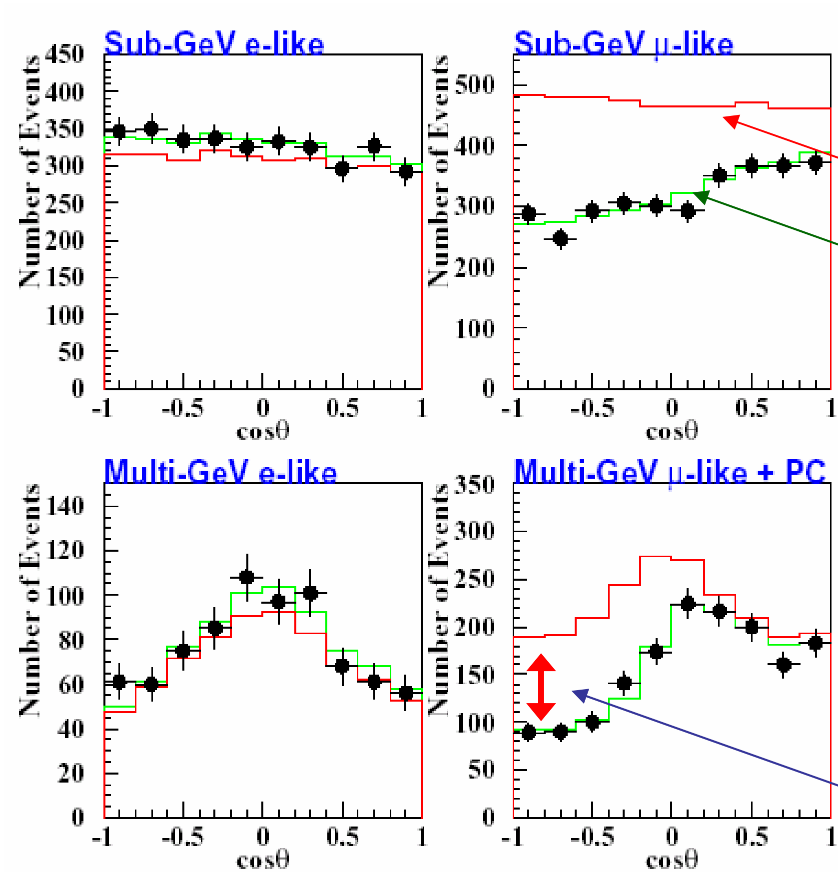
★ In doing so, scan over large range of L: **10km<L<12000km**

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

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

Super-Kamiokande Results

Observe clear disappearance signal



No oscillations fit:

χ^2_{min} = **469 / 170** d.o.f

no oscillations

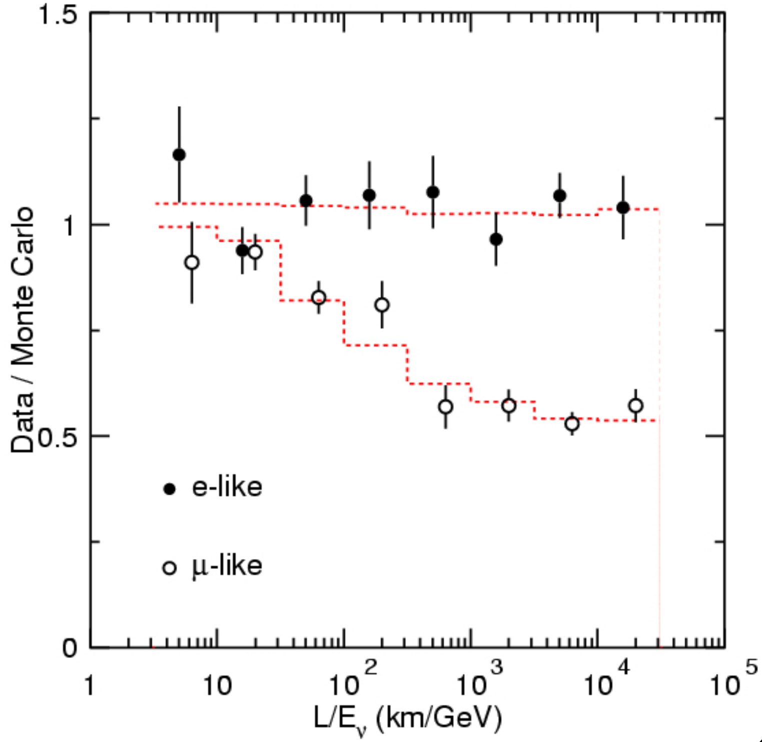
best fit : $\nu_\mu \rightarrow \nu_\tau$ oscillations

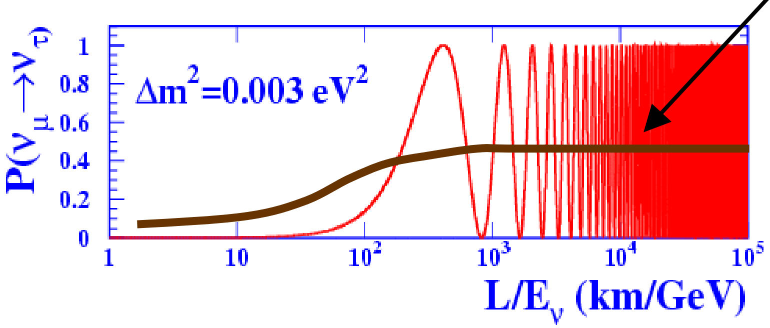
Electrons consistent with no oscillations

Muons dissappear at low $\cos\theta$
i.e. large L

determines $\sin 2\theta$

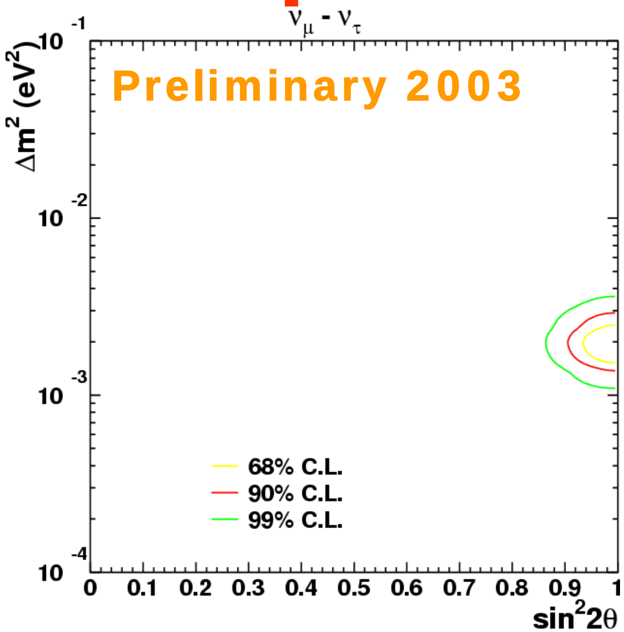
But don't see oscillation pattern





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

SuperKamiokande Result



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

90 % C.L.

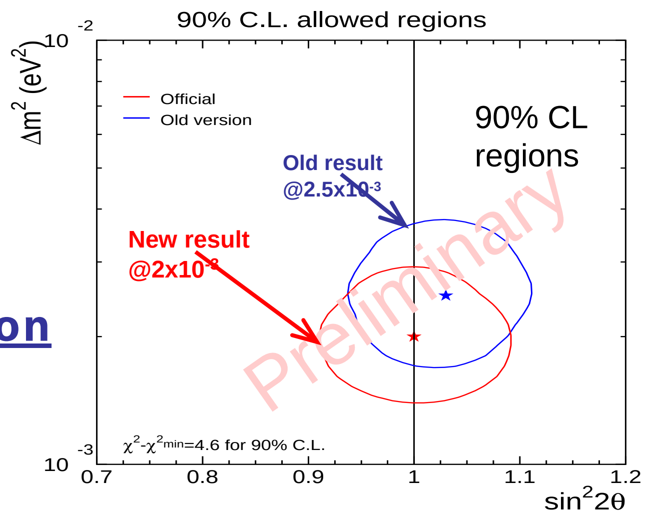
$1.6\times10^{-3} < \Delta m^2 < 3.0\times10^{-3}$ eV^2

$\sin^2 2\theta > 0.92$

BEST FIT:

$\Delta m^2 = 2.0\times10^{-3}$ eV^2

$\sin^2 2\theta = 1.0$



What's Changed :

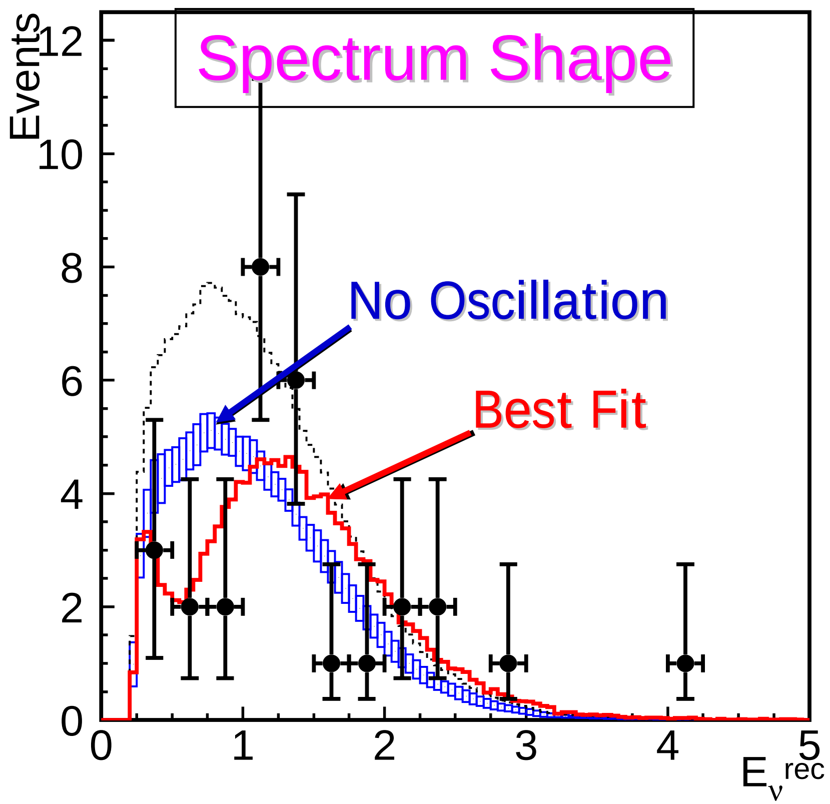
★ Neutrino Flux : 3D Calculation
★ ν interaction model tuned to K2K data
★ Improved detector simulation / reconstruction

Supported by K2K

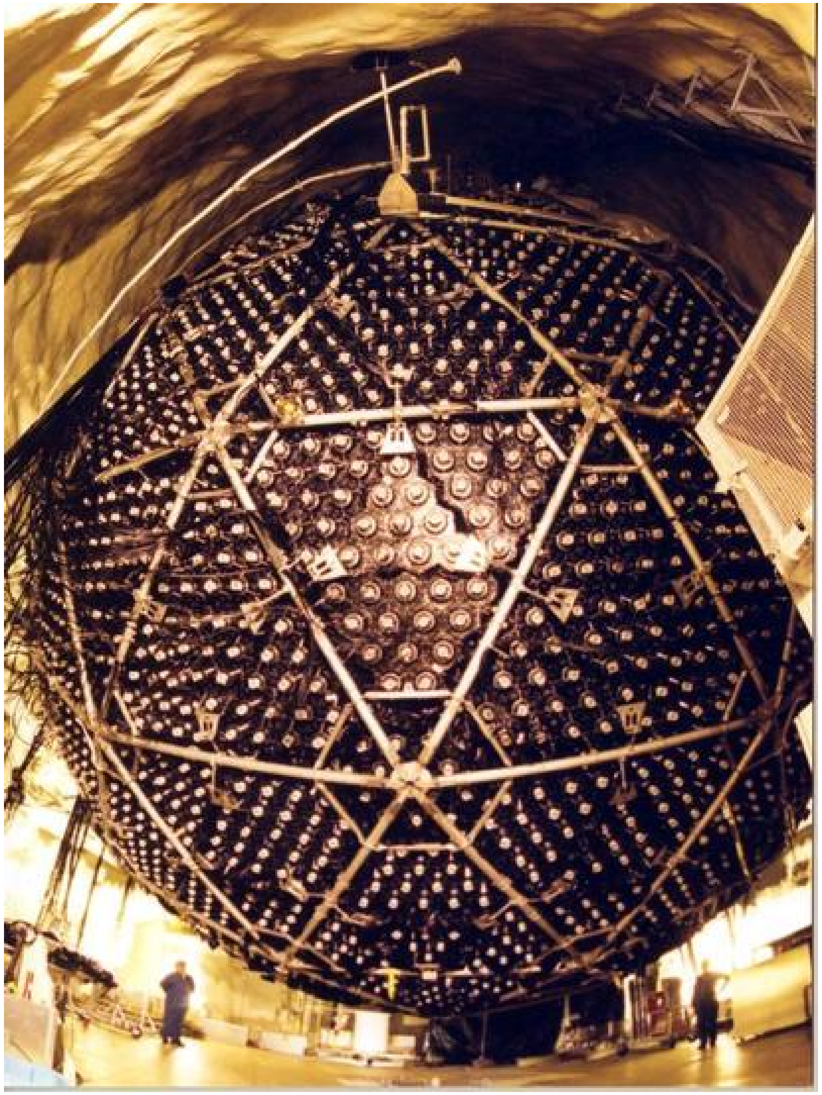
K2K Best fit point: $(\sin^2 2\theta, \Delta m^2) = (1.0, 2.8\times10^{-3} eV^2)$

c.f. SuperK: $(\sin^2 2\theta, \Delta m^2) = (1.0, 2.0\times10^{-3} eV^2)$

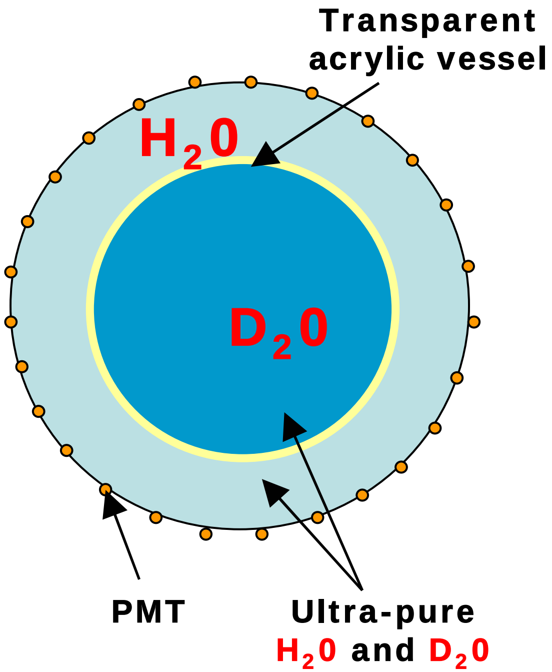
Number of events	
Observation:	56
Best Fit:	54.2
Null-oscillation	80.1



Solar Neutrinos (SNO)

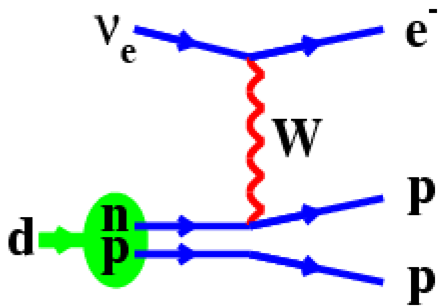


- ★ 1000 tonnes D_2O, inside a 12m diameter acrylic vessel.
- ★ ~9500 PMTs + concentrators.
- ★ 17m diameter PMT support.
- ★ 7000 tonnes H_2O.



ν Detection in SNO

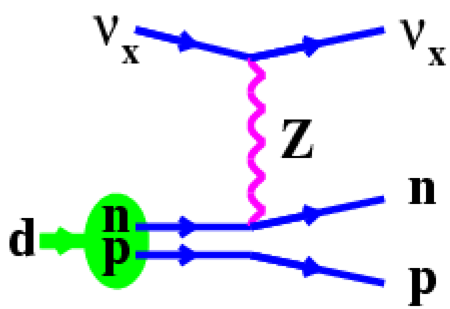
CC



Charged Current (CC)

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

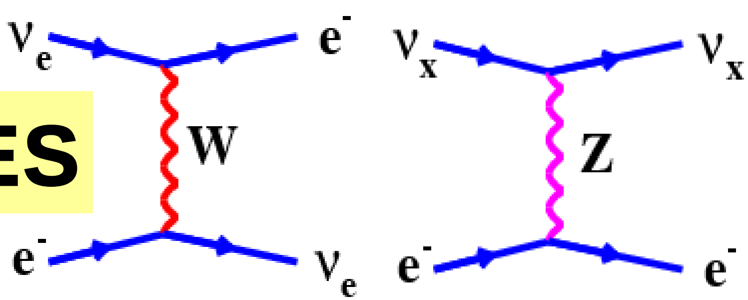
NC



Neutral Current (NC)

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

ES



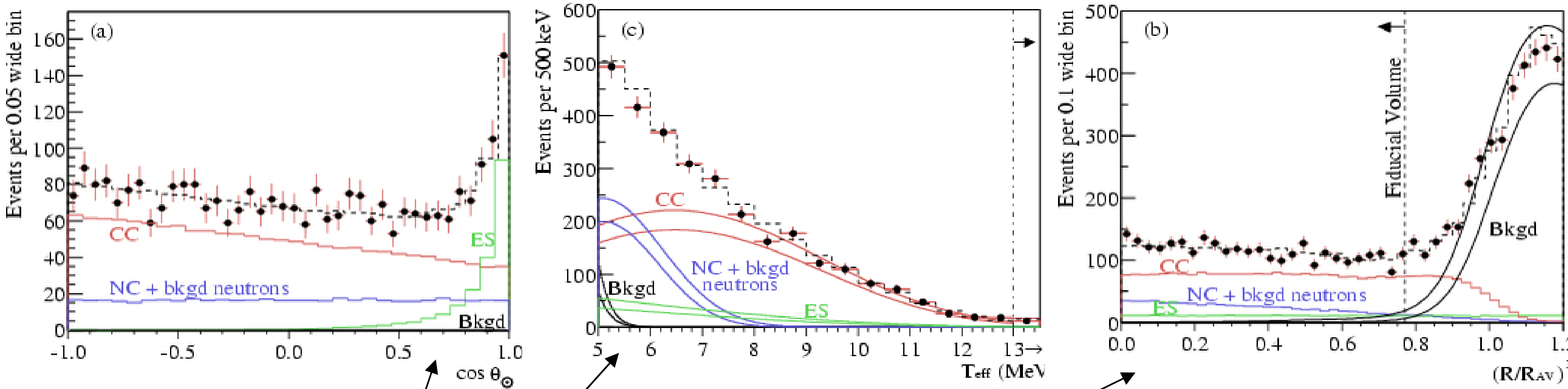
Elastic Scattering (ES)

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

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

SNO Results (pre NaCl)

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 $576.5^{+49.5}_{-48.9}$

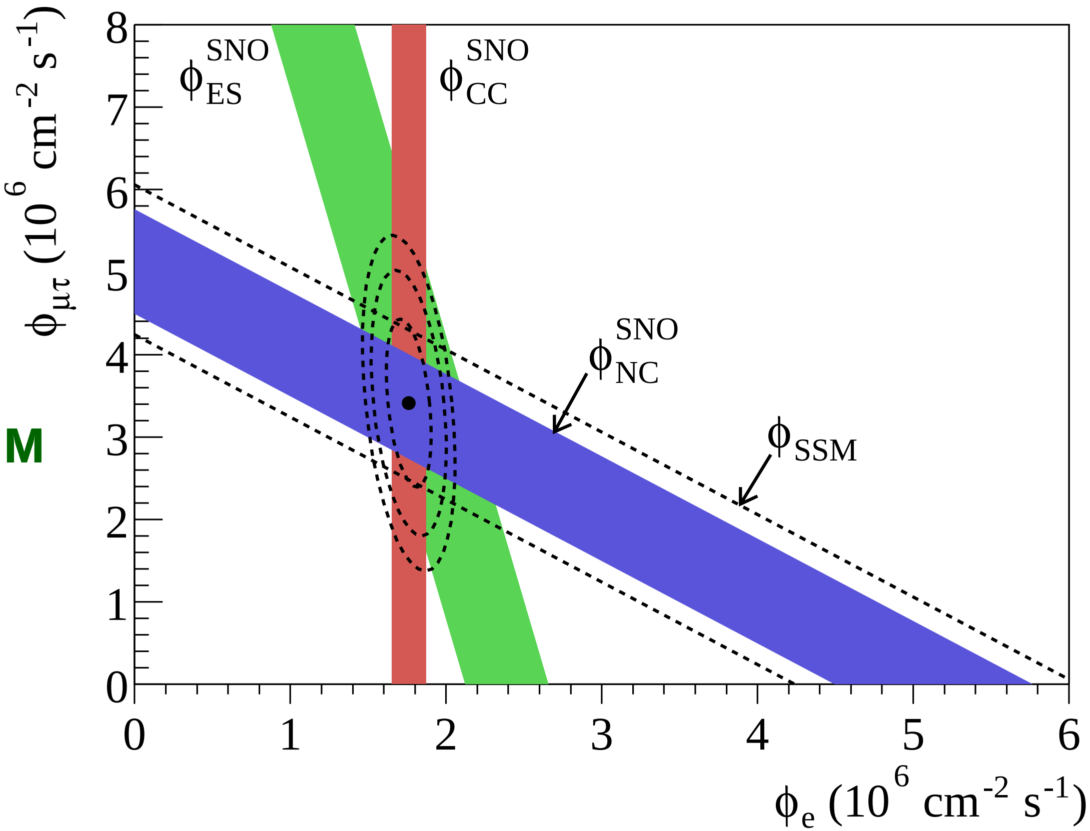
bkgd neutrons 78 ± 12

Results (pre-NaCl)

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 ~ $\Phi(\nu_e)$



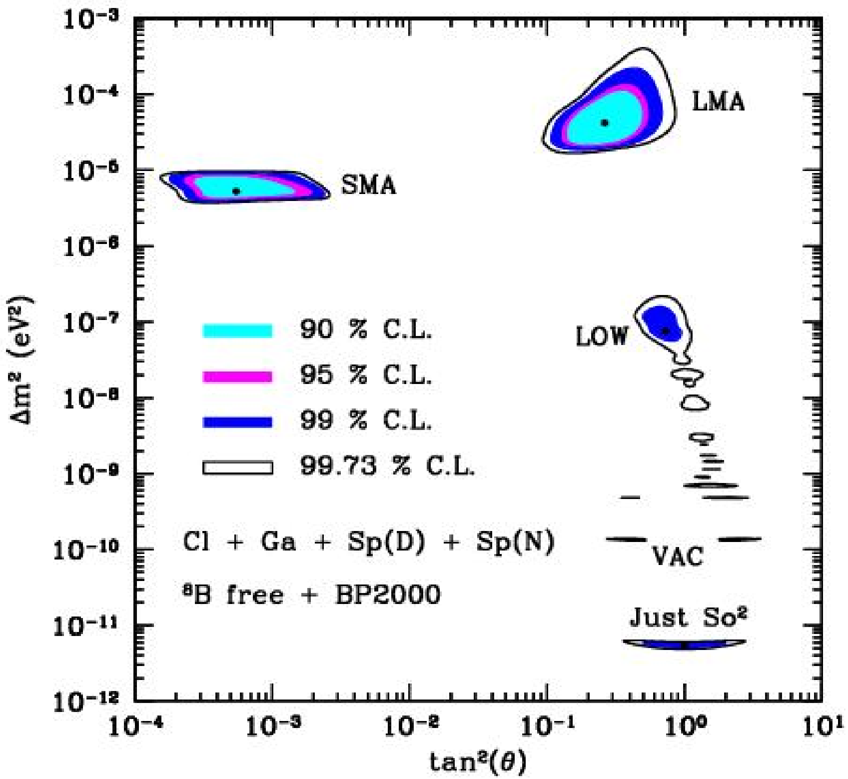
- **Clear evidence for a ν_μ/ν_τ flux from sun !**
- **+ Consistency with SSM**

SNO - interpretation

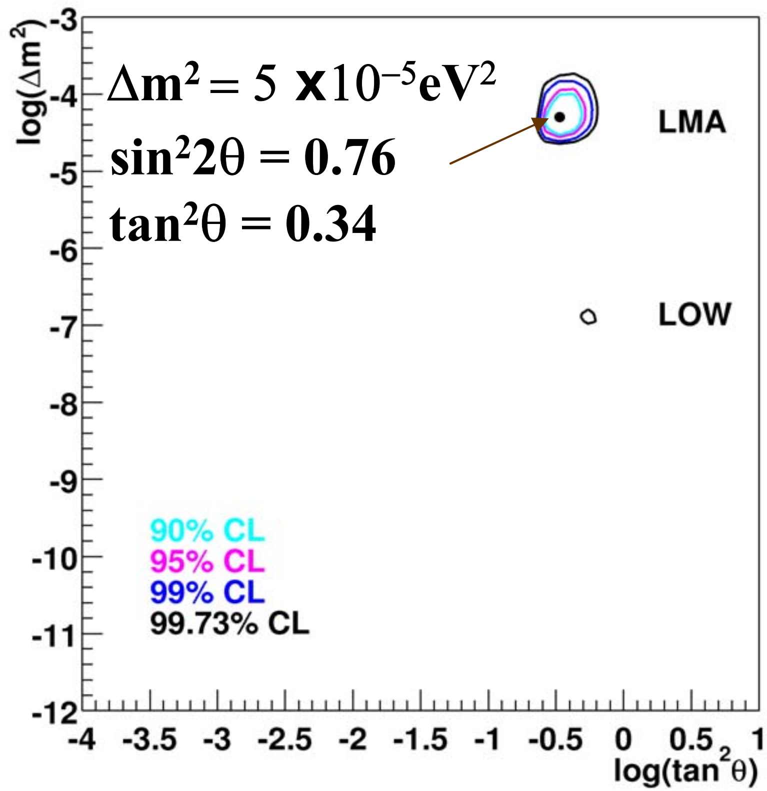
★ Interpretation of solar neutrino data complicated due to matter effects (**MSW**)

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

Before SNO

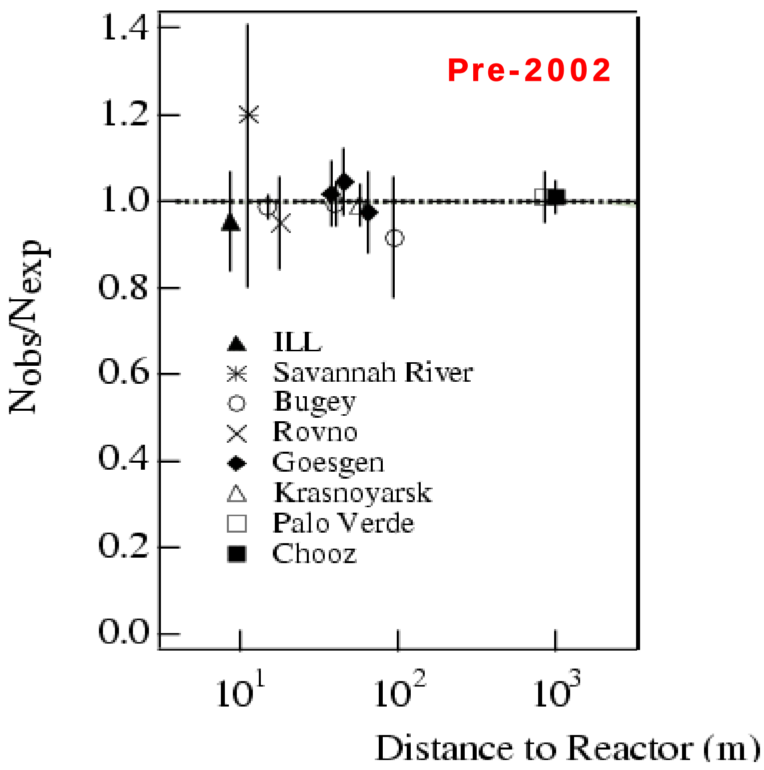


After SNO



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

Suggests that for

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

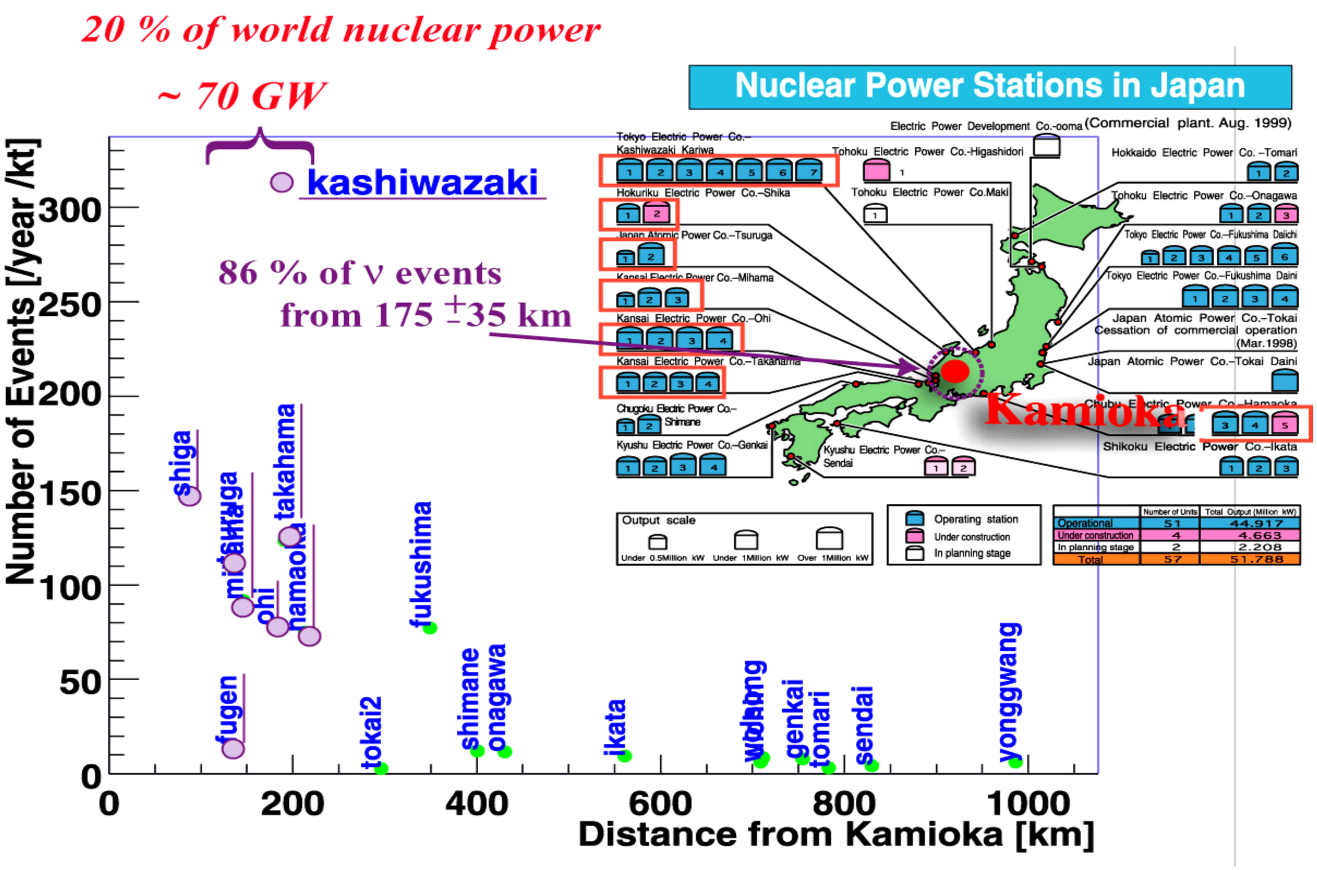
require L ~ 110 km

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

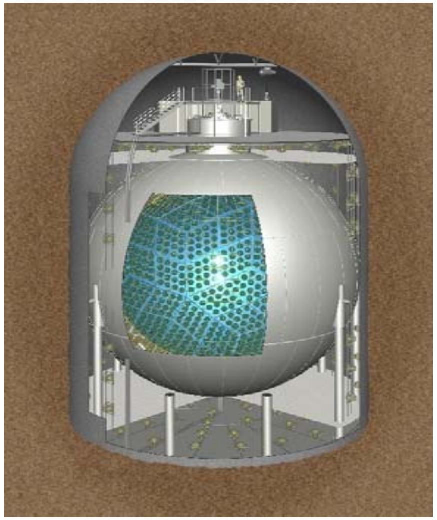
Serendipity

The ideal site exists – Kamioka !

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



KamLAND

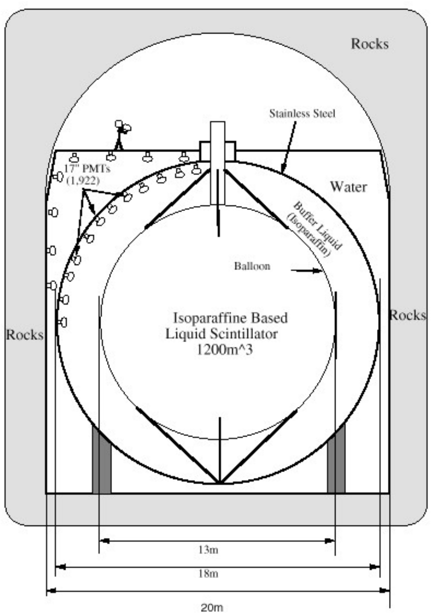


- ★ $\bar{\nu}_e$ detected via inverse β-decay

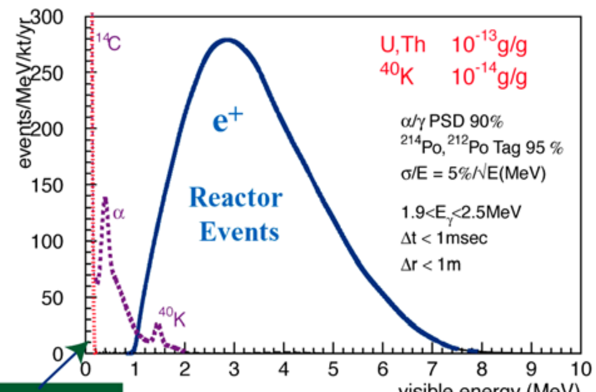
  $\bar{\nu}_e + p \longrightarrow e^+ + n$

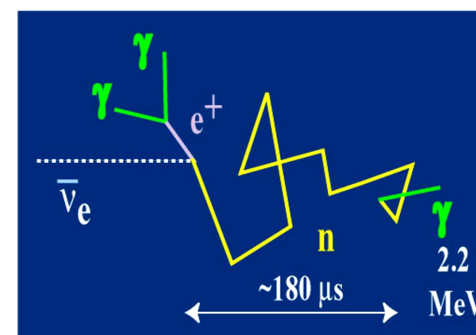
  $n + p \longrightarrow d + \gamma$ (2.2MeV)

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



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

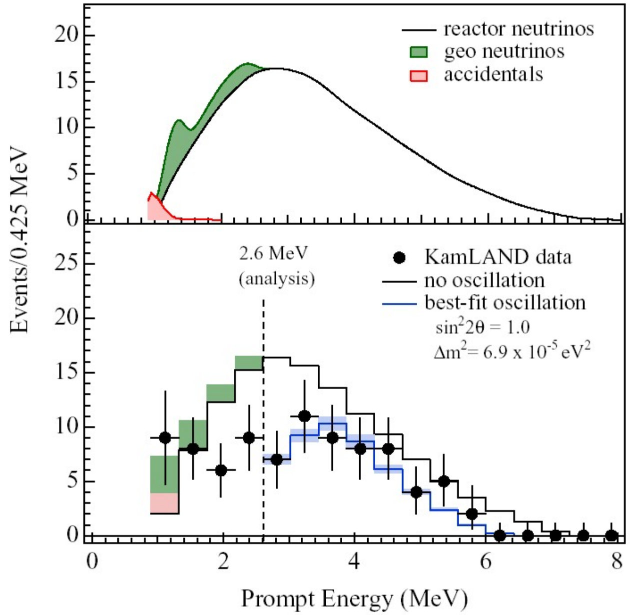




U, Th : 10^{-14} g/g
^{40}K : 10^{-15} g/g

Require ultra-pure Liquid Scintillator

KamLAND Results

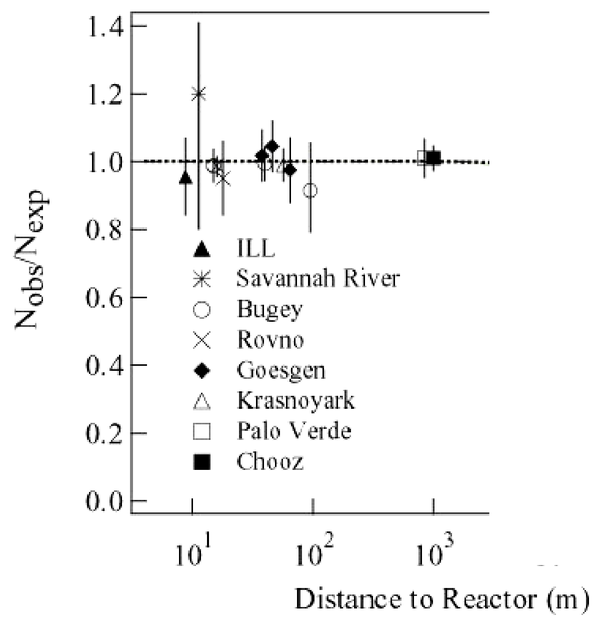


★ E_ν > 2.6 MeV

Observed	54
Expected	86+5.6
Background	0.96+0.99

★ Almost all ⓘ from rate

★ Confirmation of solar ν deficit (~3σ)

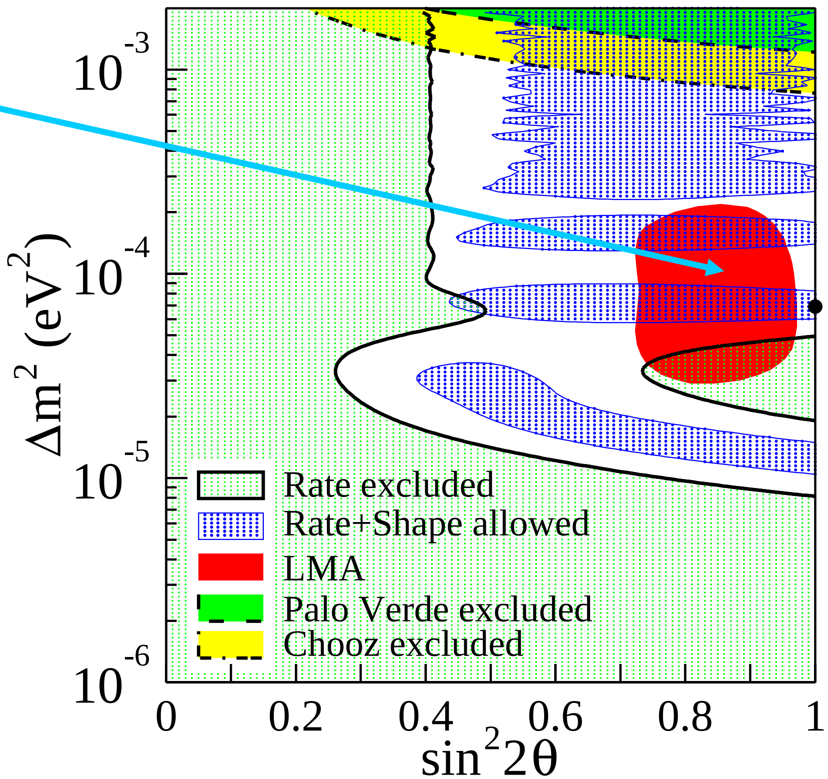


KamLAND vs SNO

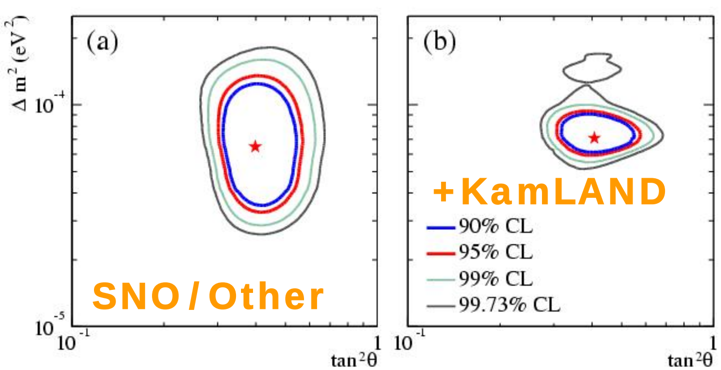
★ **Consistent results**

- **SNO/Other Solar n Expts.**
- **KamLAND**

★ **LMA confirmed**



★ **Current Limits:**



$\Delta m^2 \sim 7.1\times10^{-5}$ eV^2

Experimental Status : Summary

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

- ★ $\Delta m^2_{12} \sim 7\times10^{-5}\ \mathrm{eV}^2$
- ★ $\Delta m^2_{23} \sim 2\times10^{-3}\ \mathrm{eV}^2$
- ★ $\sin^2 2\theta_{23} \sim 1.00$
- ★ $\sin^2 2\theta_{12} \sim 0.75$
- ★ $\theta_{13} < 13^{\circ}$ (Chooz)

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

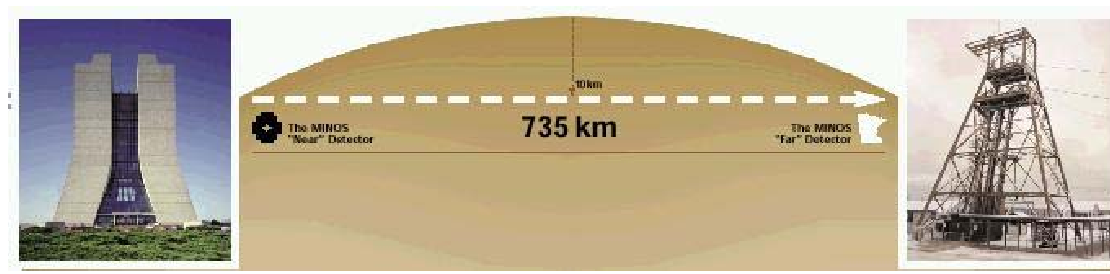
★ **But still haven't seen the oscillatory pattern !**

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

Long Baseline Experiments

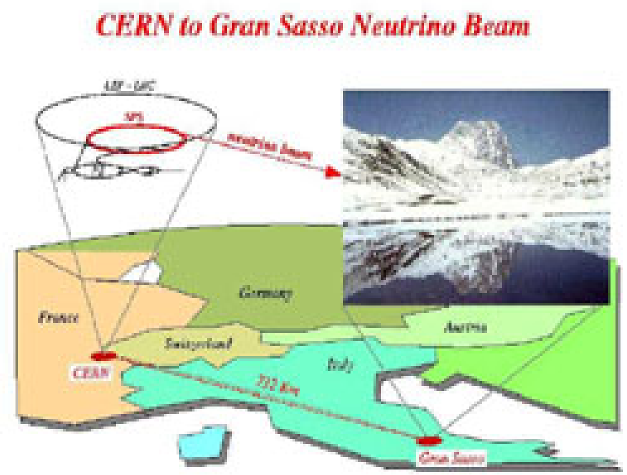
K2K

MINOS



CNGS

(CERN Neutrinos to Gran Sasso)

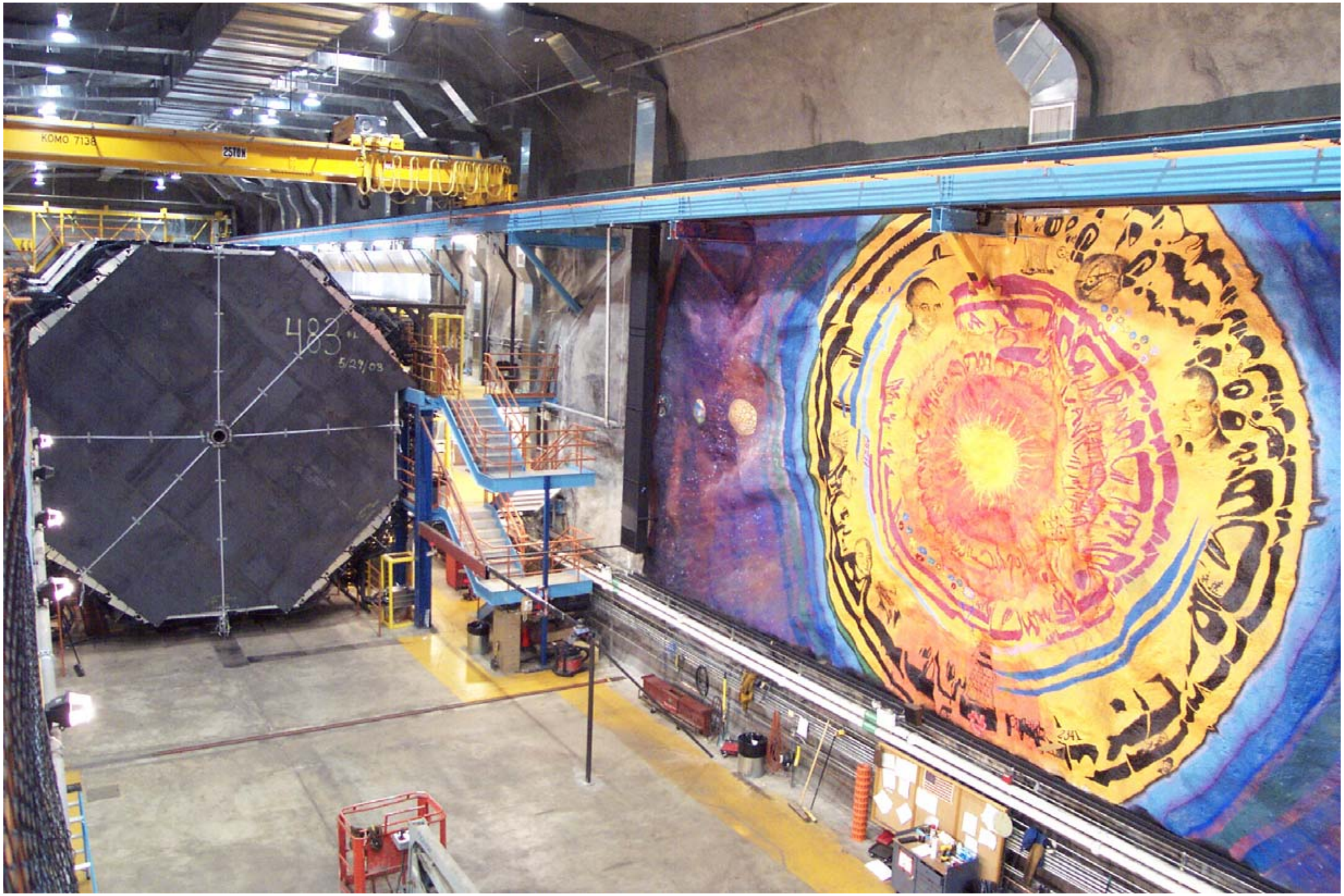


Comparison

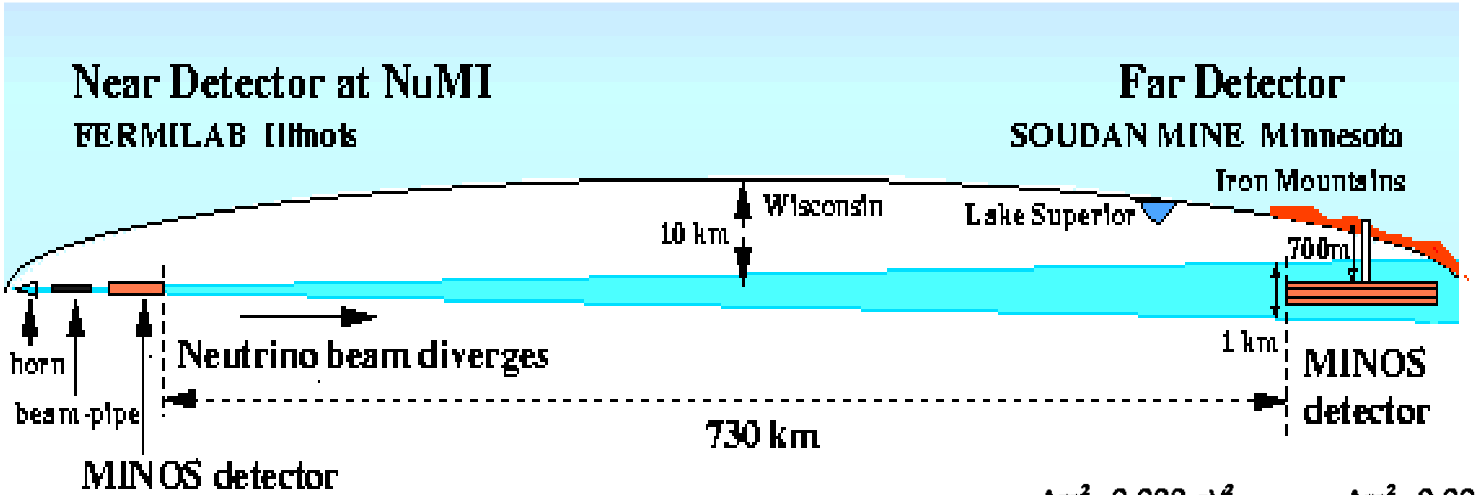
	K2K	MINOS	CGNS
Run	1999-	2005-	2006-
Fid. Volume	22 kton	5 kton	2 kton +
$<E_\nu>$	1.3 GeV	3 GeV	17 GeV
L	250 km	735 km	732 km
POT / year	$5x10^{19}$	$2.5x10^{20}$	$7.6x10^{19}$
$\delta(\Delta m^2)$	~ 50 %	~ 10 %	~ 15 %
τ appearance	No	No	Yes
Oscillation Dip ?	No (?)	Yes	?

MINOS

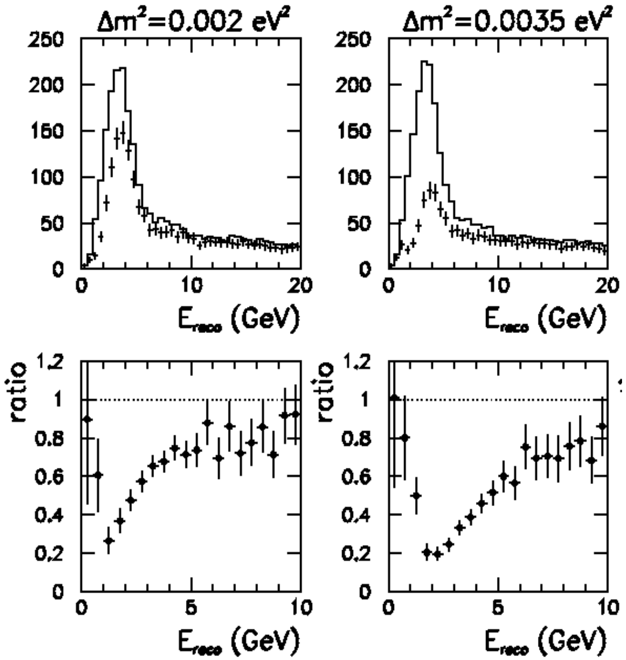
where science and art meet



Basic Idea

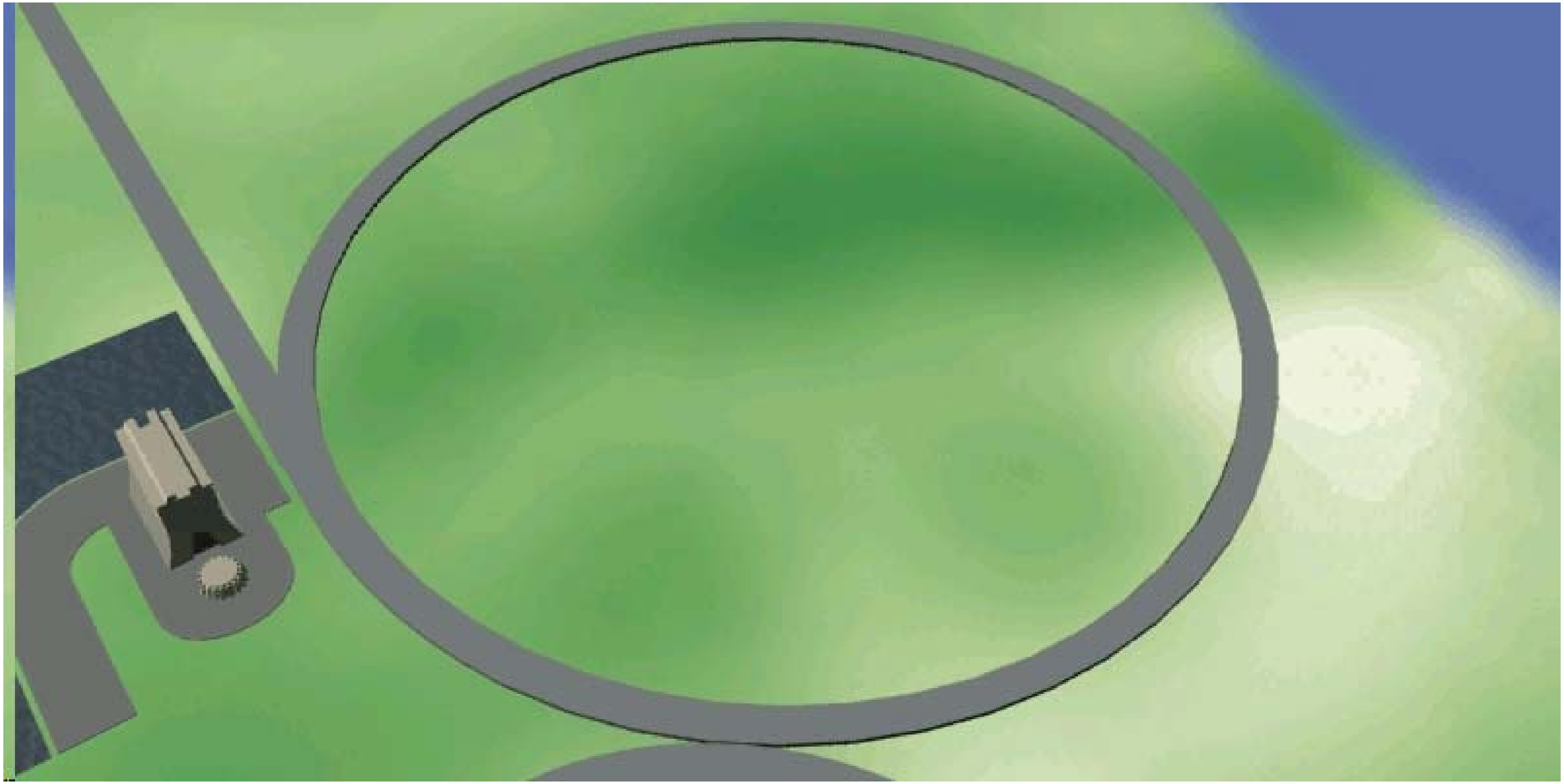


- Measure ratio of neutrino energy spectra in far detector **(oscillated)** to that observed in the near detector **(unoscillated)**



- **Partial cancellation of systematics**

Basic Idea



MINOS Physics Goals

★ **Demonstrate oscillation behaviour**

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

★ **Precise Measurement of Δm^2_{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**

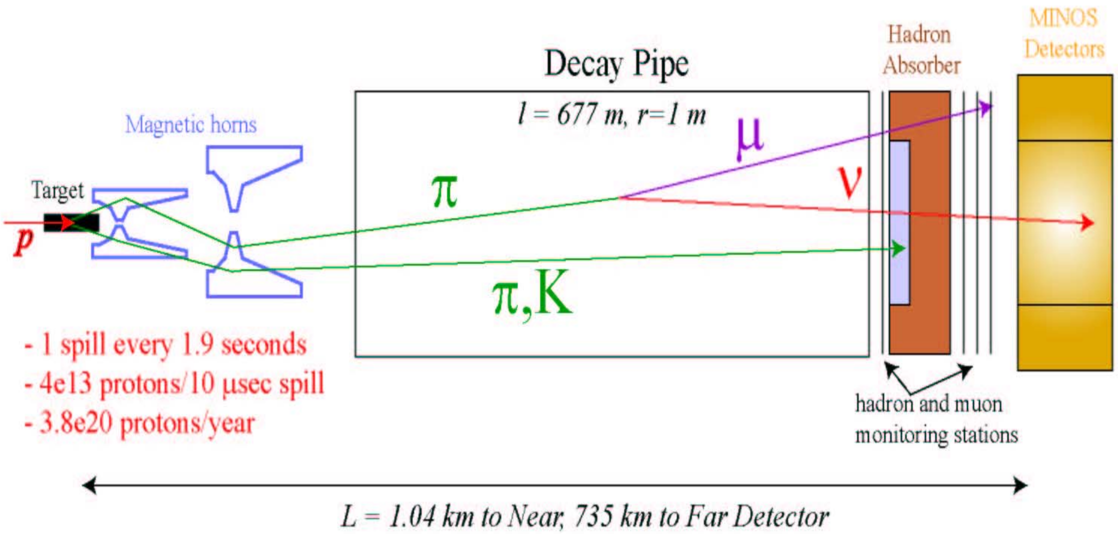
- first direct measurements of ν vs $\bar{\nu}$ oscillations from atmospheric neutrino events

How to make a ν beam

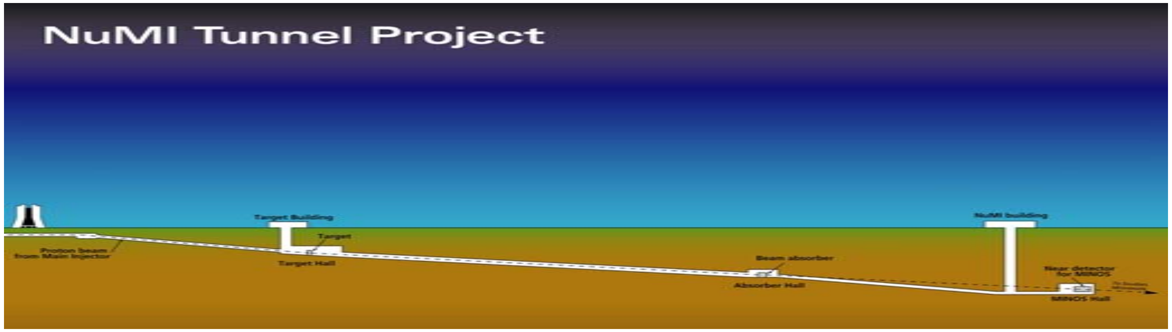
120 GeV/c protons strike graphite target

Magnetic horns focus charged mesons (pions and kaons)

Pions and kaons decay giving neutrinos



To scale……



677 m decay pipe

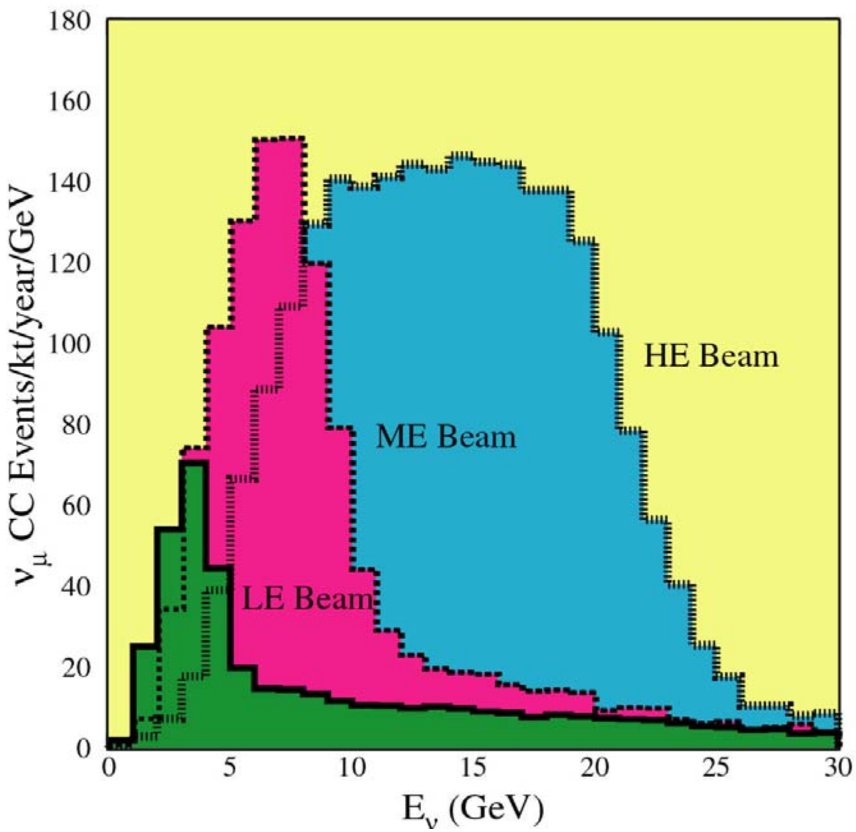
Target

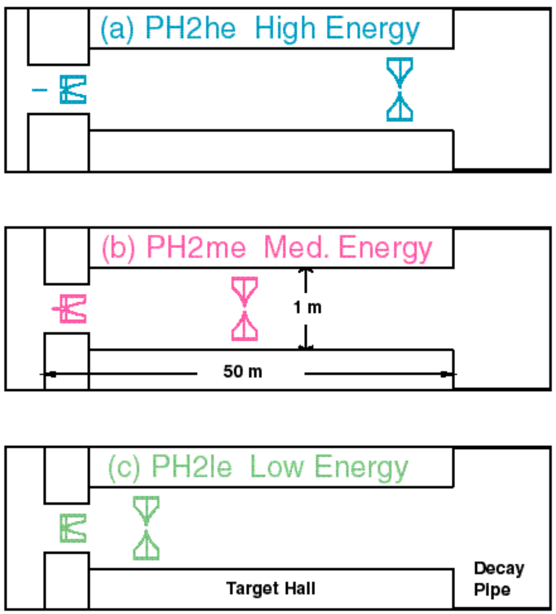
Near Detector

Tunable beam

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

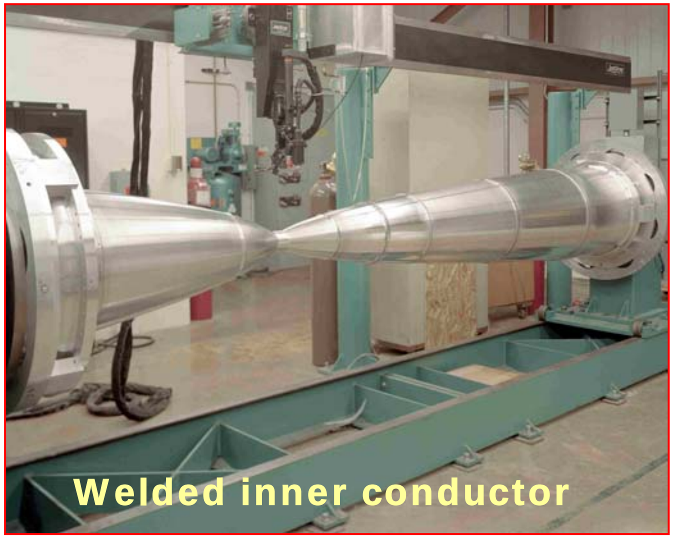
★ Start with LE – but maintain flexibility



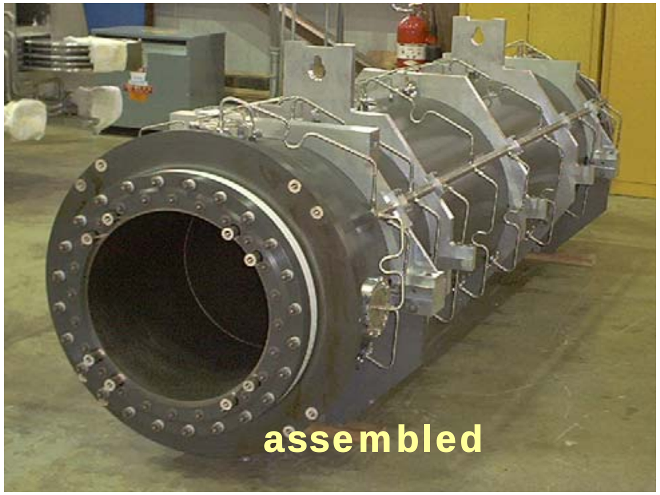


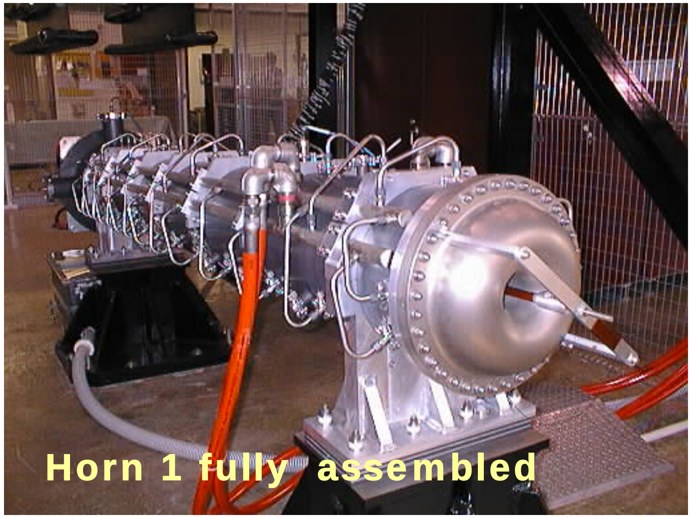
Horn 2


Inner conductors


Welded inner conductor


Insertion into
outer conductor


assembled


Horn 1 fully assembled

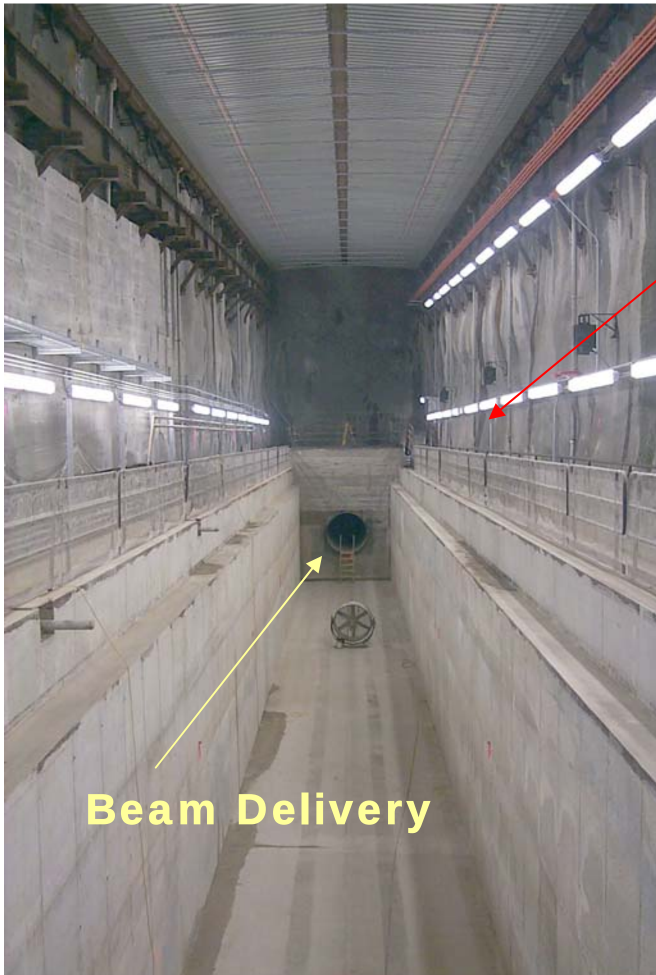
Decay tunnel

Tunnelling complete

Beam due to turn on Dec 2004

Pipe is embedded in concrete to protect groundwater.

Recent Status



Target Hall

Beam Delivery

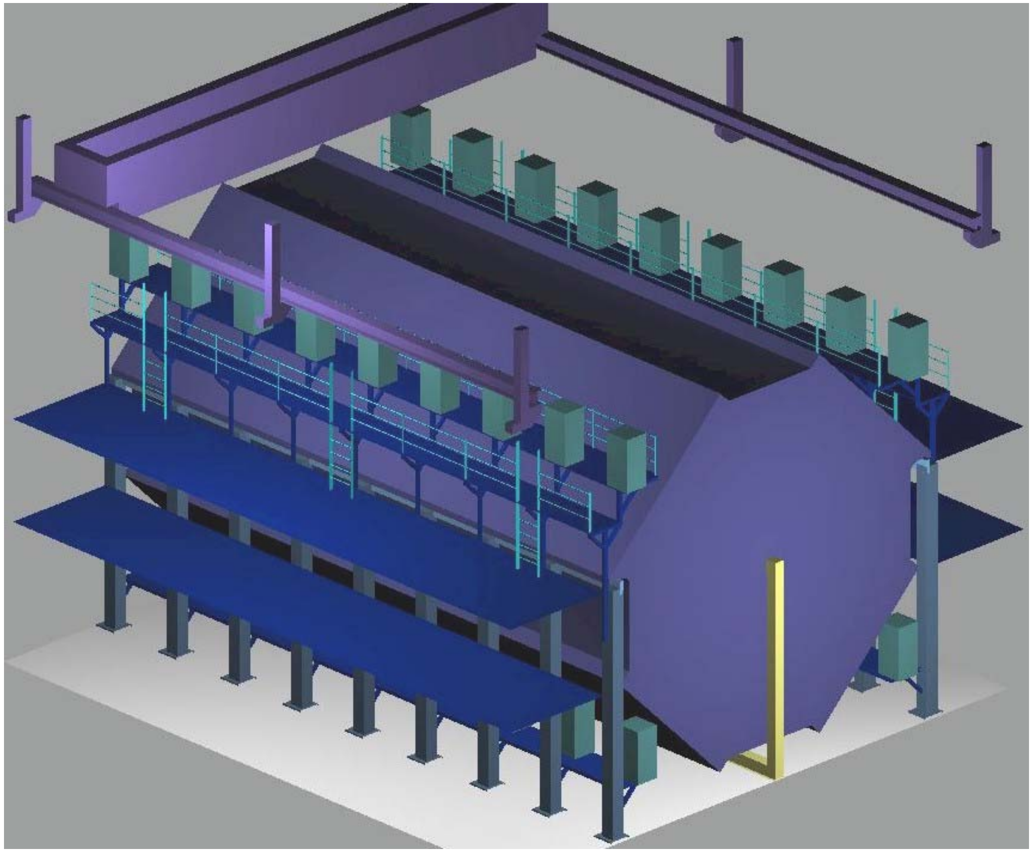
MINOS Far Detector

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)

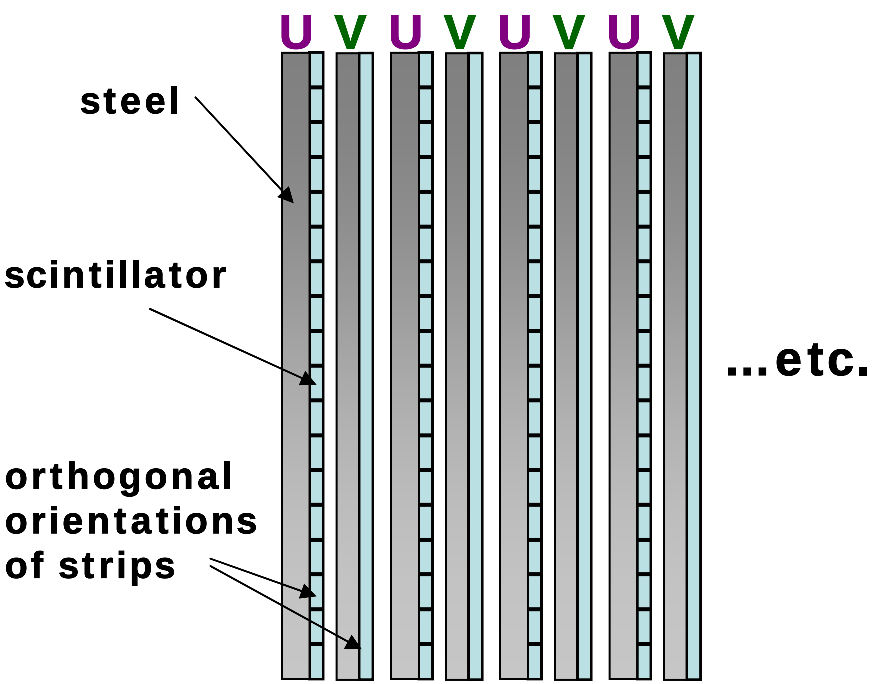
484 planes of scintillator

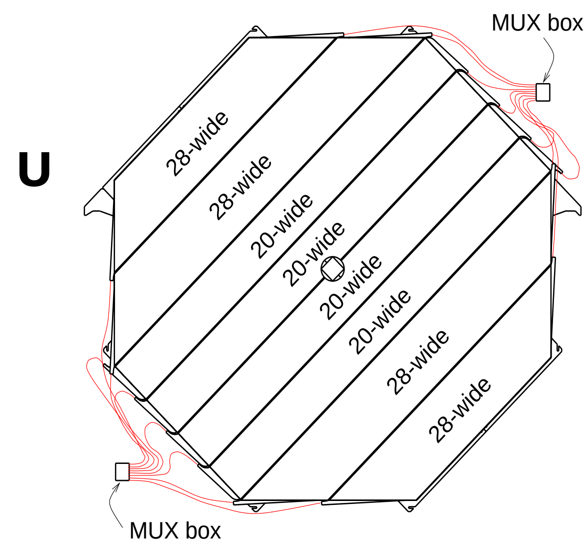


One Supermodule of the Far Detector… Two Supermodules total.

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**

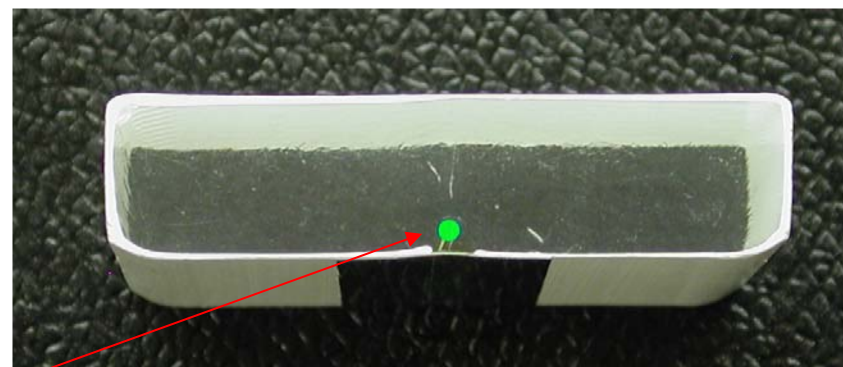




Basic Technology

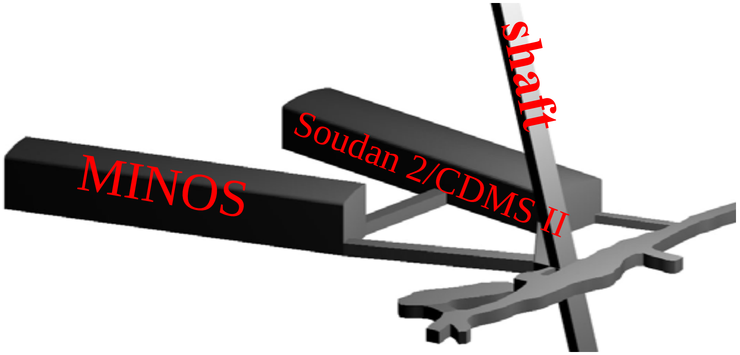
★ **MAIN FEATURES:**

★ 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



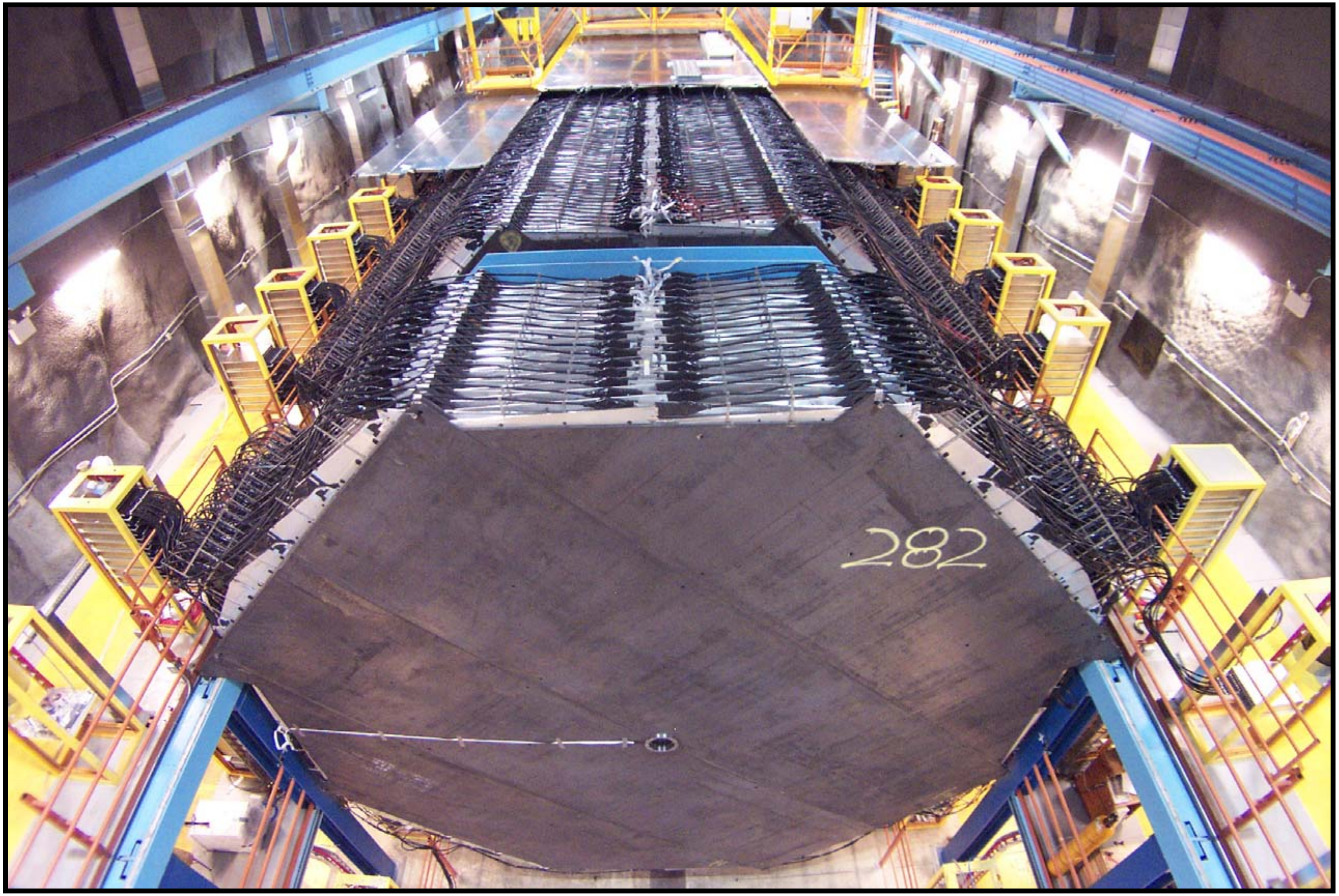
WLS fibre glued into groove

Going underground

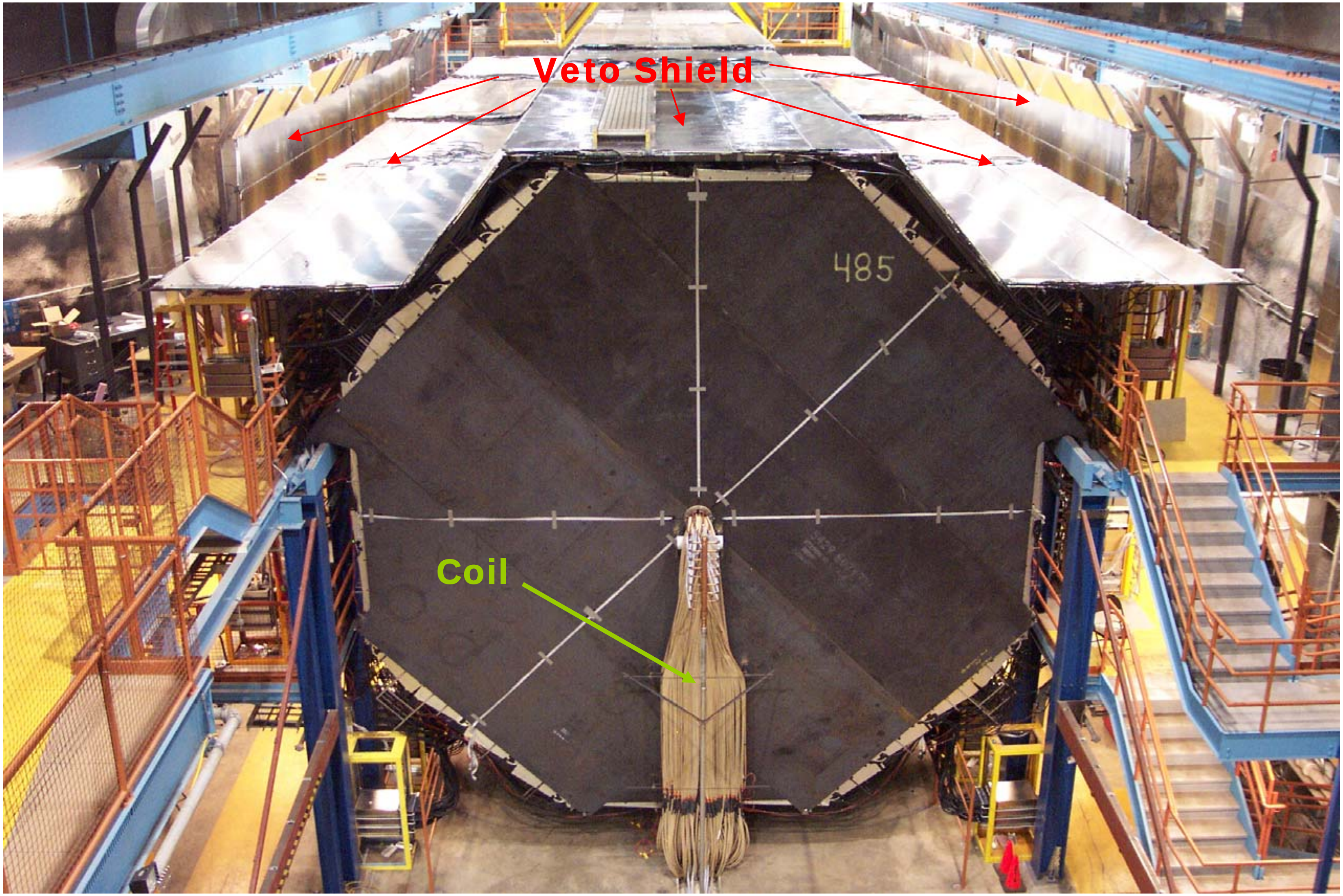


Components taken undergrounds…

Some detector pictures

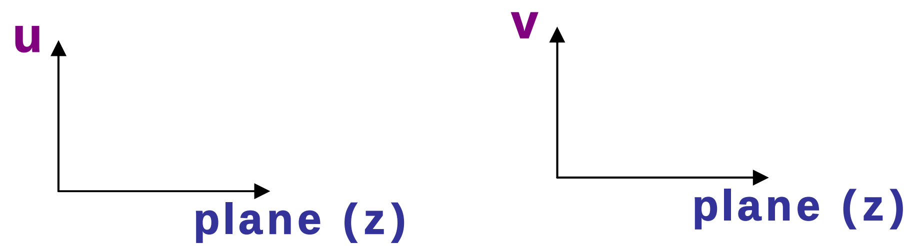


Far Detector fully operational since July 2003

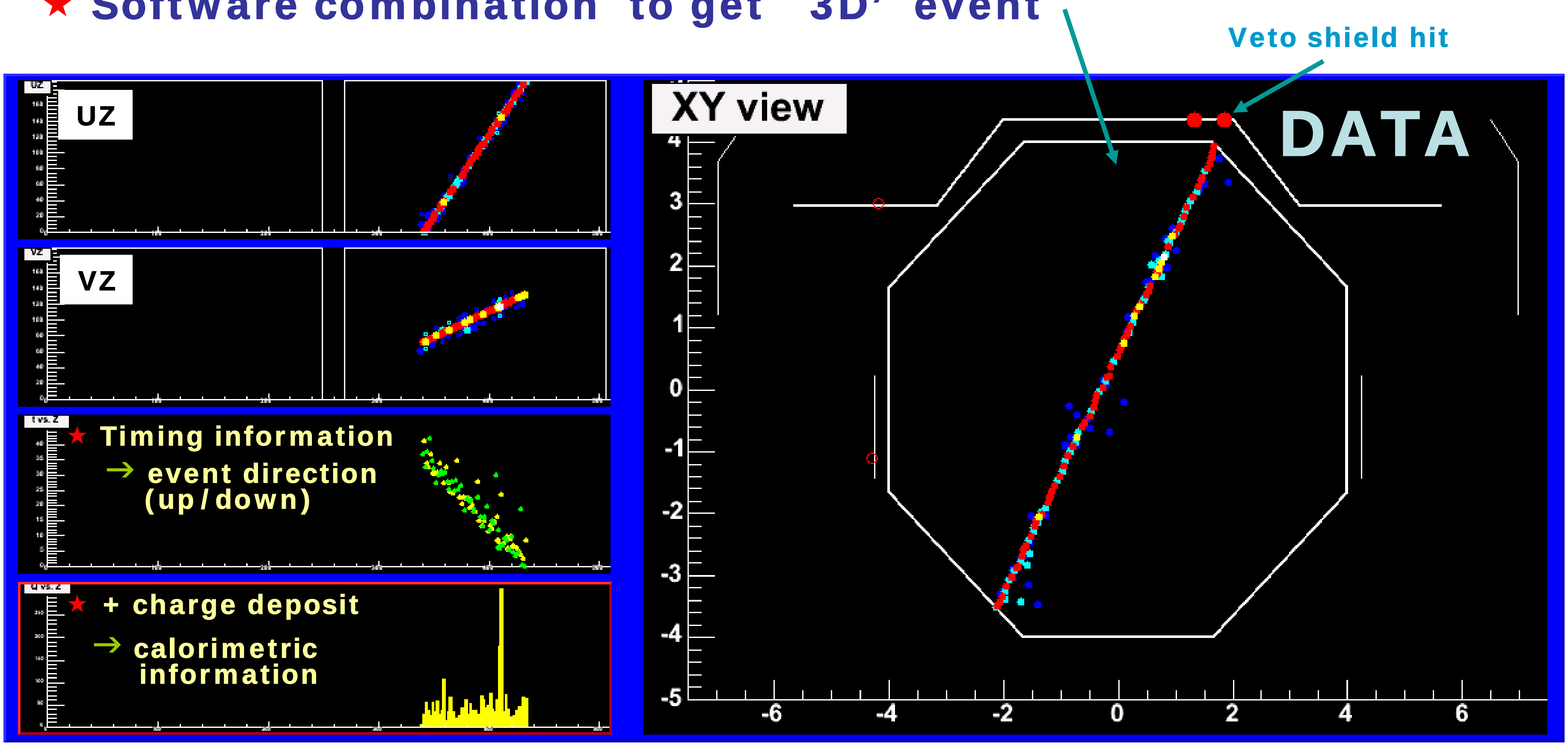


Event Information

★ Two 2D views of event



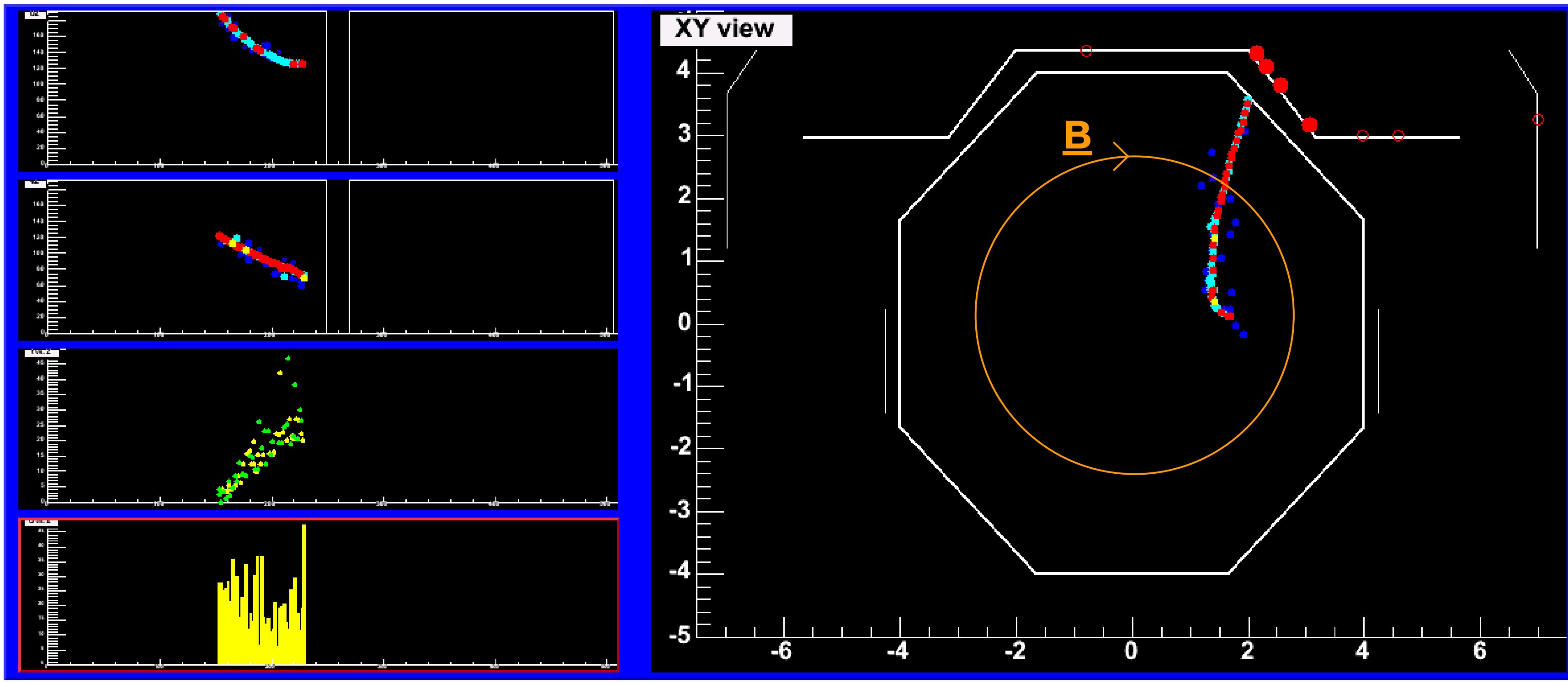
★ Software combination to get `3D' event



B-Field

~ 1.5 T Magnetic Field

- ★ Charge separation
- ★ Momentum measurement



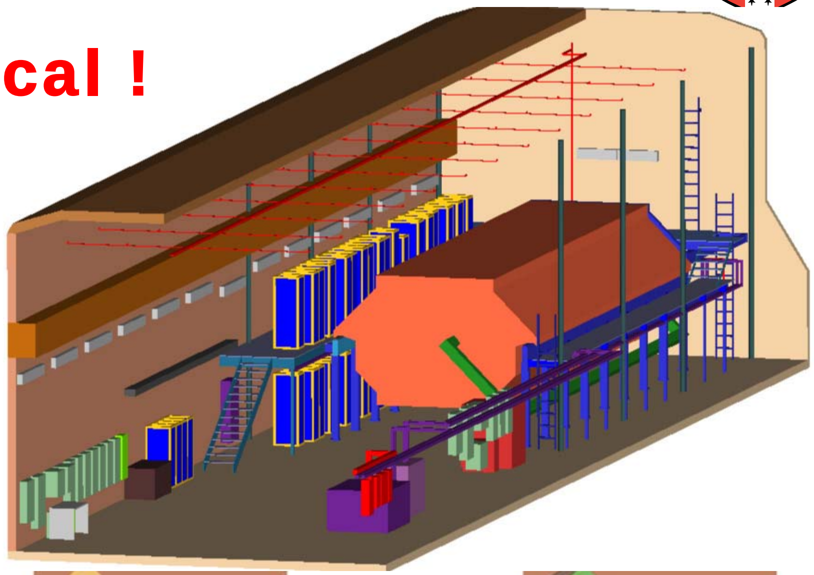
Stopping muon

P_{range} = 3.86 GeV/c

$P_{curvature}$ = 4.03 GeV/c

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.

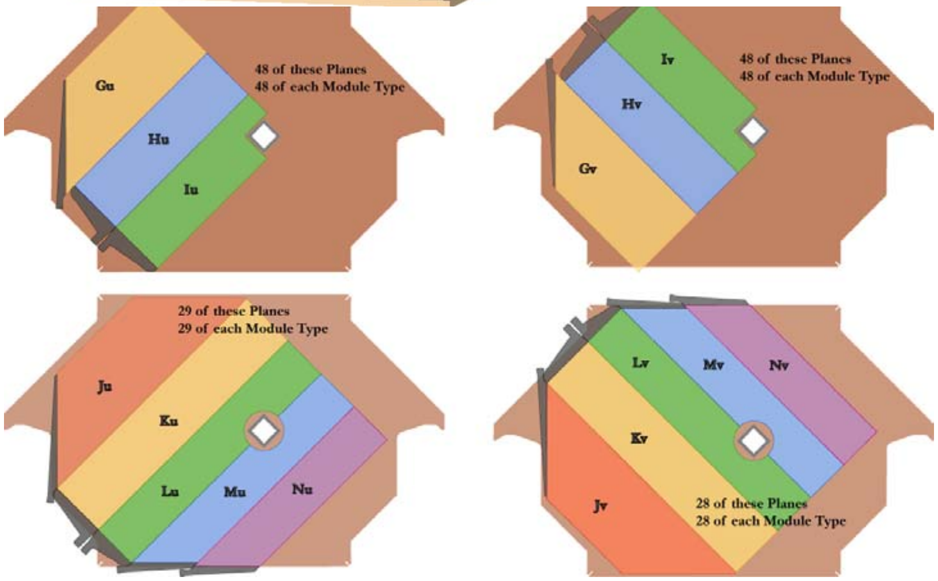
No multiplexing in the main part of the detector due to small size and high rates.

Hamamatsu M64 PMT

Faster Electronics (QIE)

282 planes of steel

153 planes of scintillator

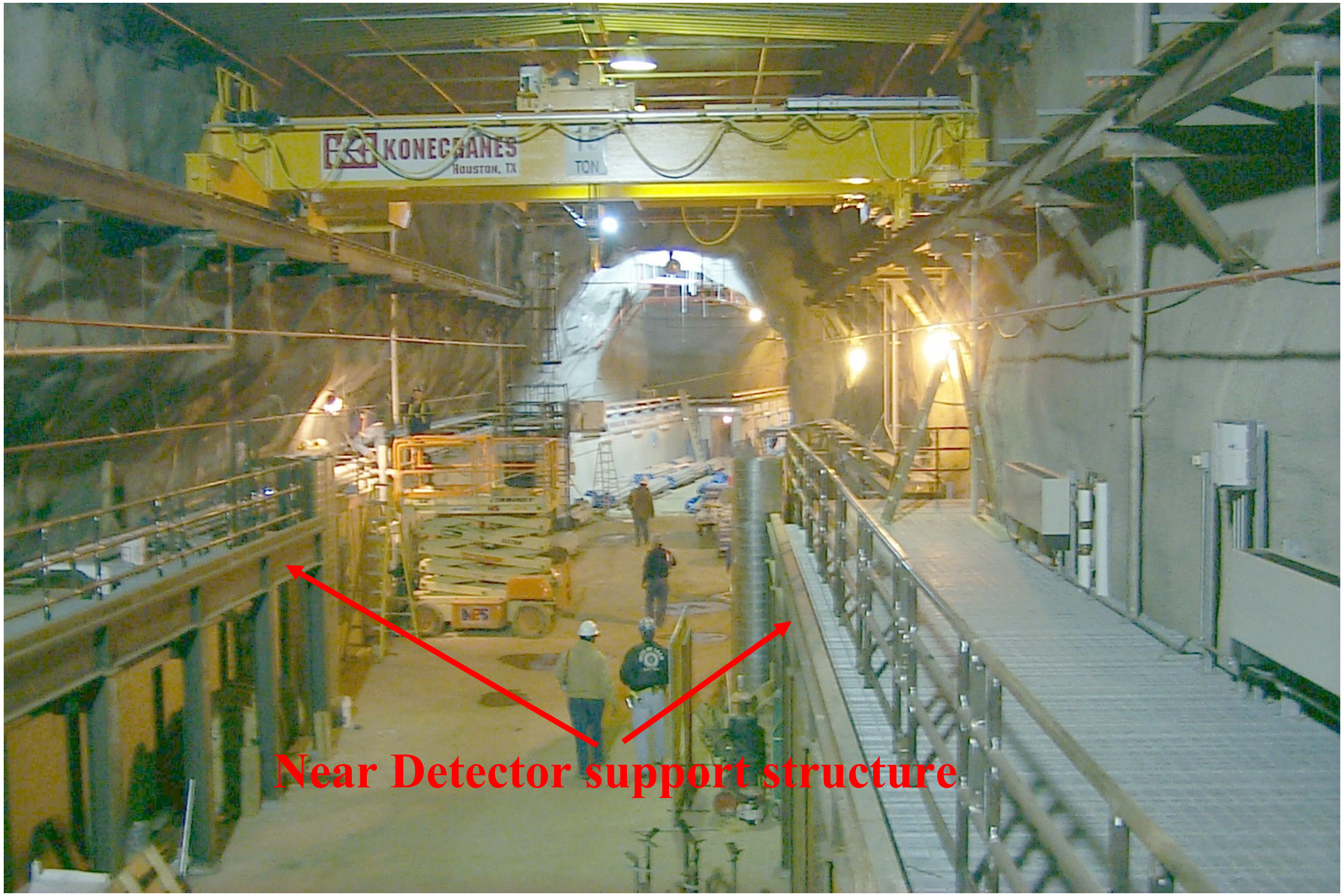


Near Detector Status

Not quite so far advanced as Far Detector

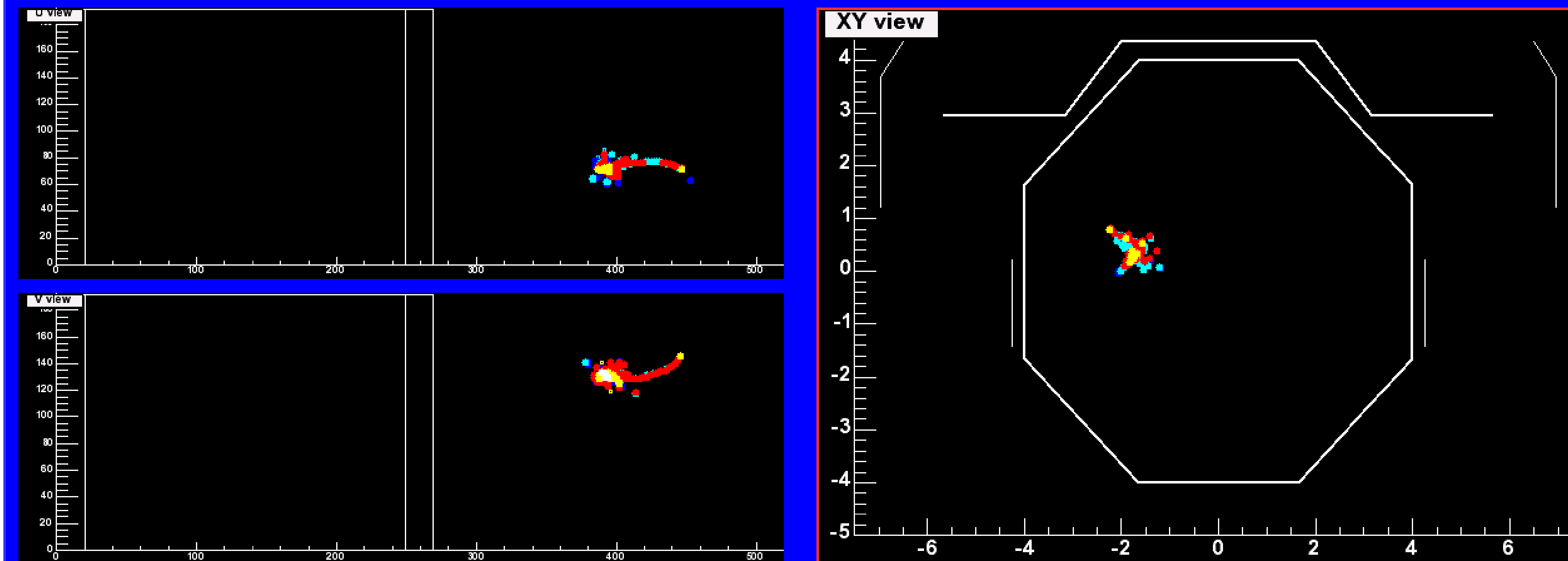
Detector components ready – waiting to be installed in experimental hall

Near Detector Hall



Near Detector Installation commences in February

Beam Neutrinos (Simulation)

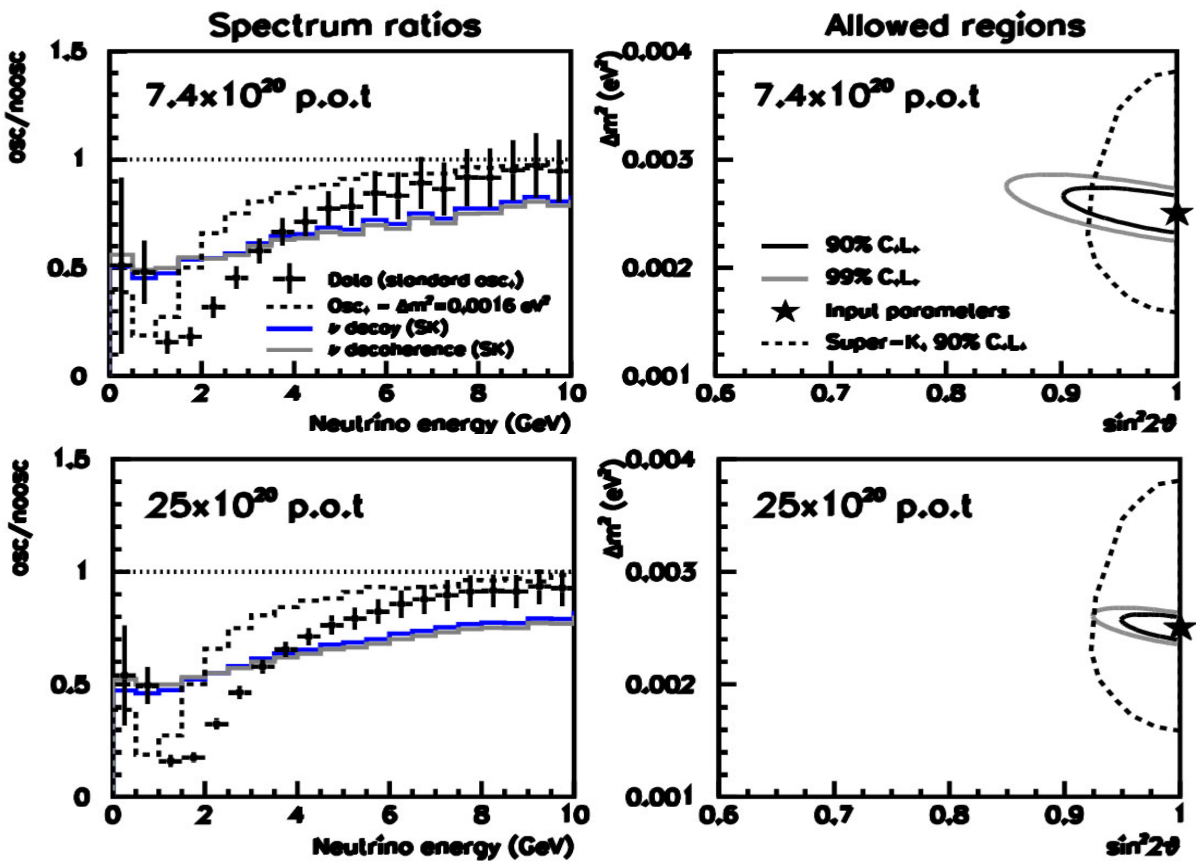


★ **Energy resolution all important**

- ♦ μ **momentum from range** ($\sigma_p / p \sim 5\%$) **or curvature** ($\sigma_p / p \sim 10\%$)
- ♦ **hadronic energy from pulse height** ($\sigma_E / E \sim 55\% / E^{1/2}$)
- ♦ $E_\nu = p_\mu + E_{had}$

MINOS Sensitivity

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

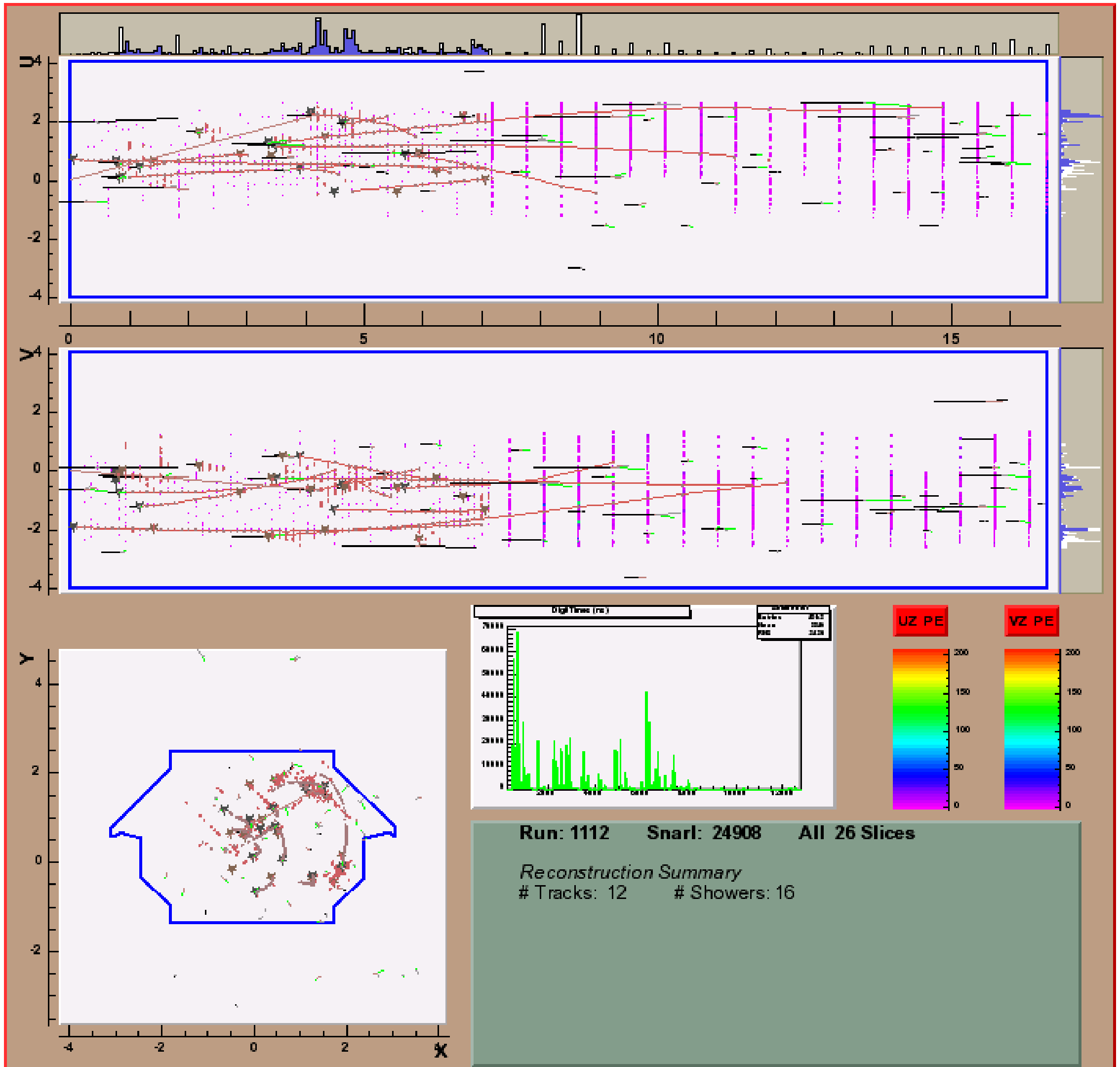


For $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta = 1.0$

Factor 10 improvement in precision !

Final sensitivity depends on protons delivered to MINOS

Near Detector Events

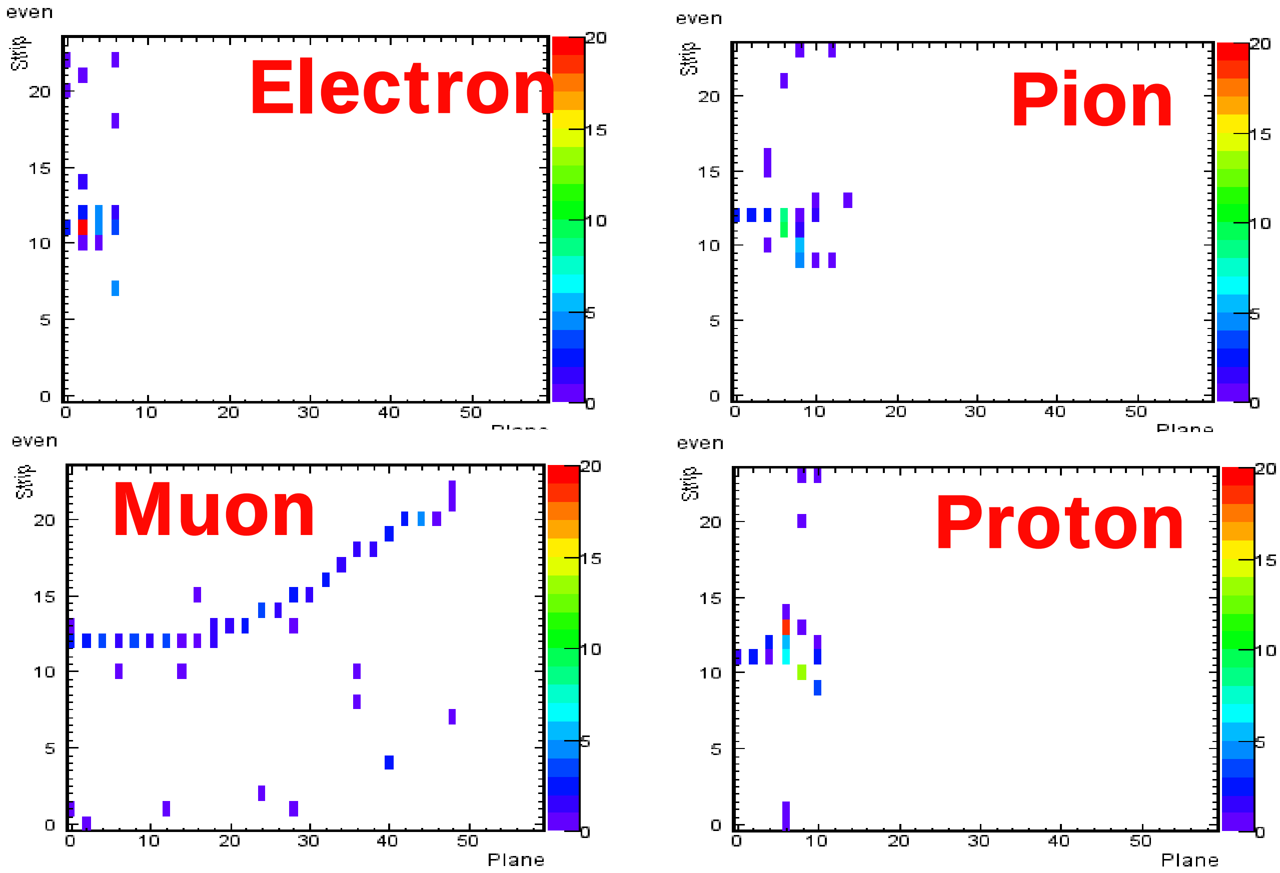


- ★ **Multiple ν interactions per spill ! (~10)**
- ★ **Separate in time**
  - **still tricky**
- ★ **Need to understand ND/FD differences !**
  - **e.g. relative calibration**
- ★ **Also need absolute calibration !**

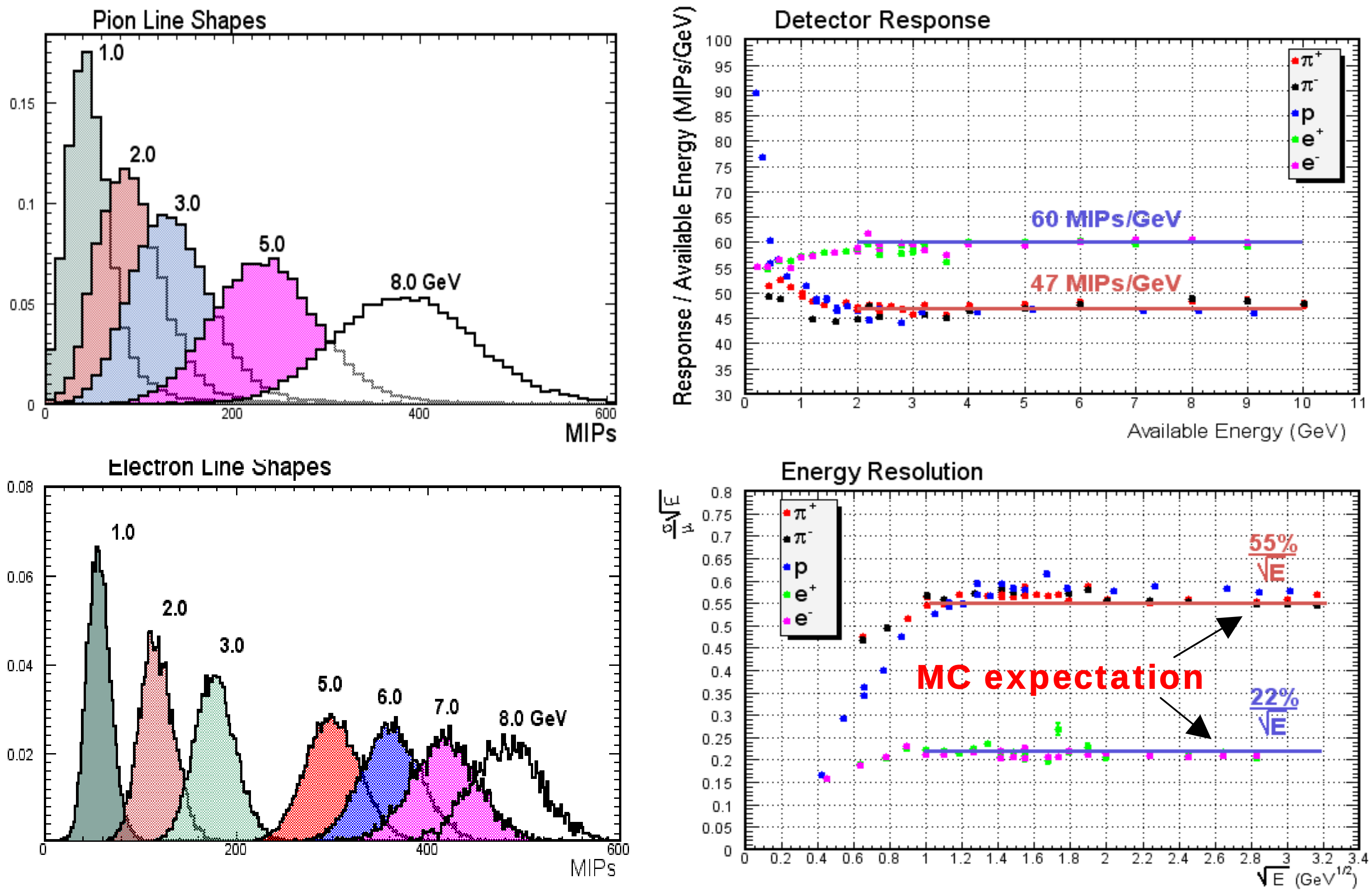
Test Beam

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

e.g. response to 2 GeV particles



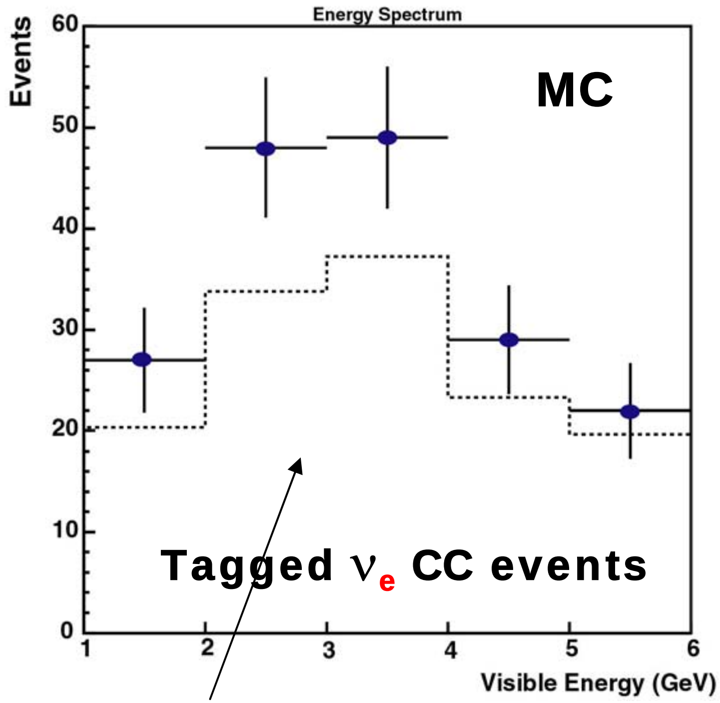
Preliminary test beam results



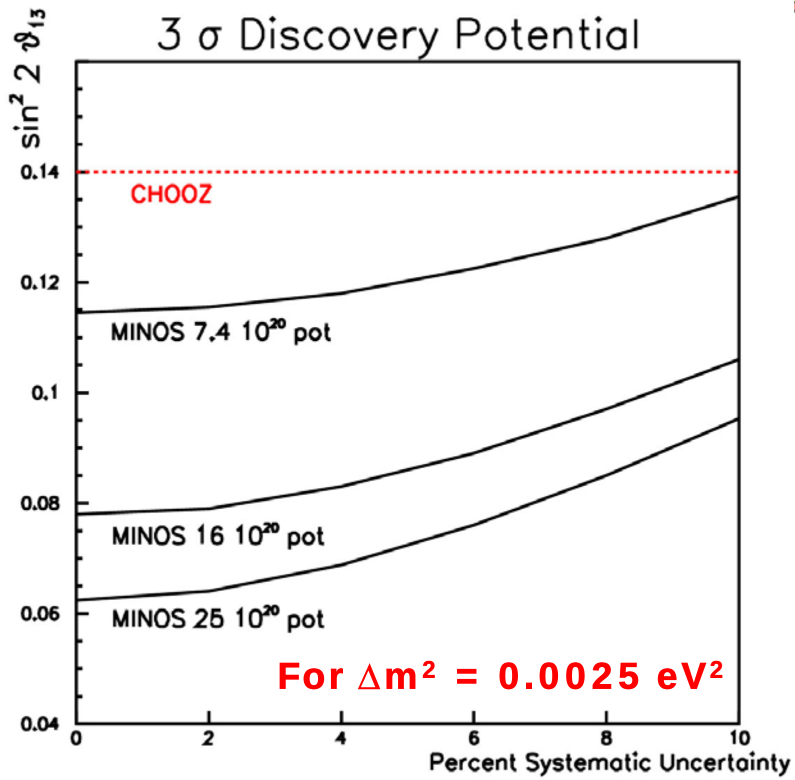
- Provides Calibration / Monte Carlo validation

ν_e Appearance

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



Assumes 25x10^{20} protons on target.

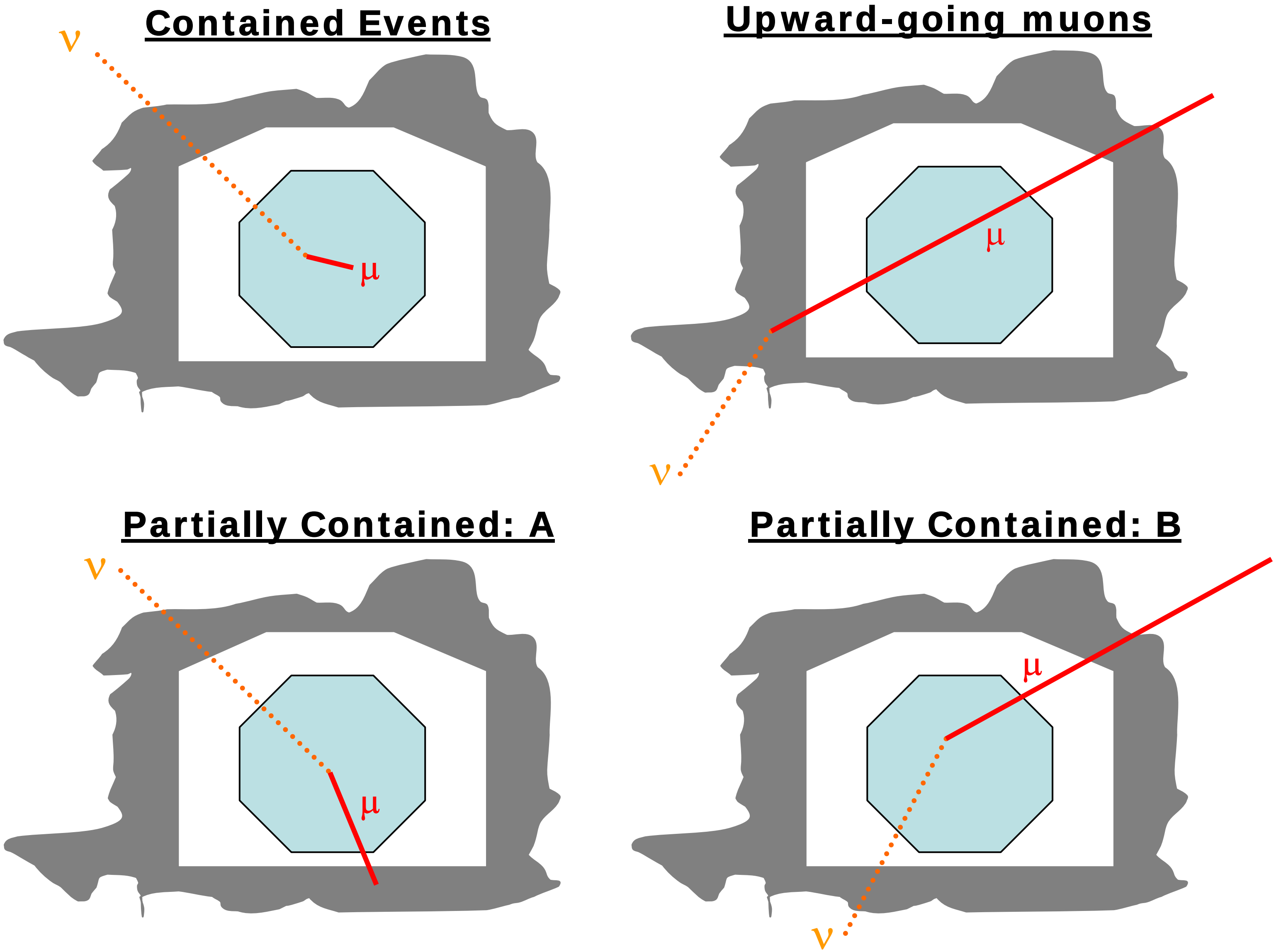


- **3 σ discovery potential** may significantly eat into current allowed region – exact reach depends on protons
- MINOS has a reasonable chance of making the first measurement of θ_{13}

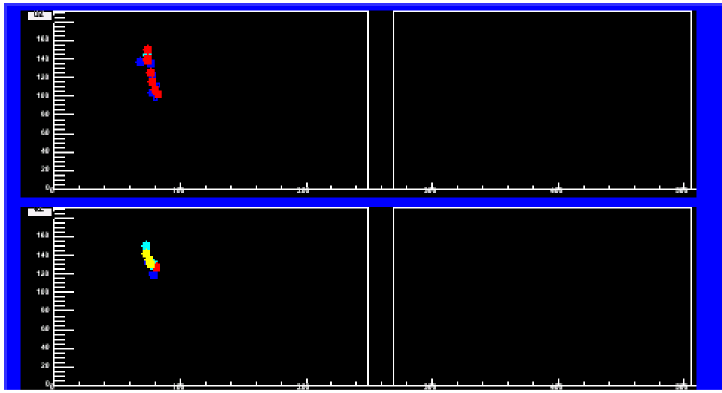
First beam in December 2004

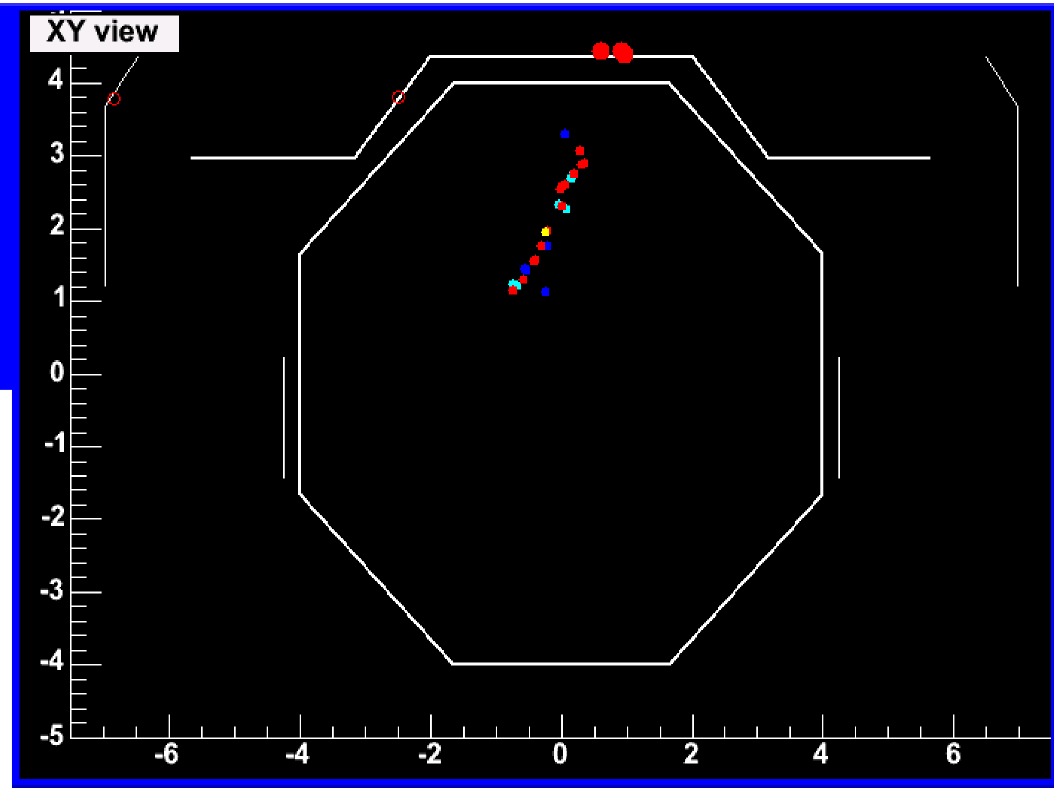
BUT Already Have Neutrino Data....

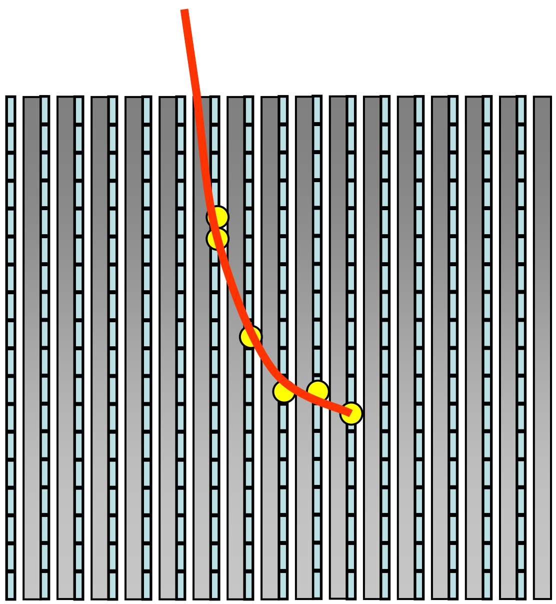
Atmospheric Neutrinos



Hermeticity





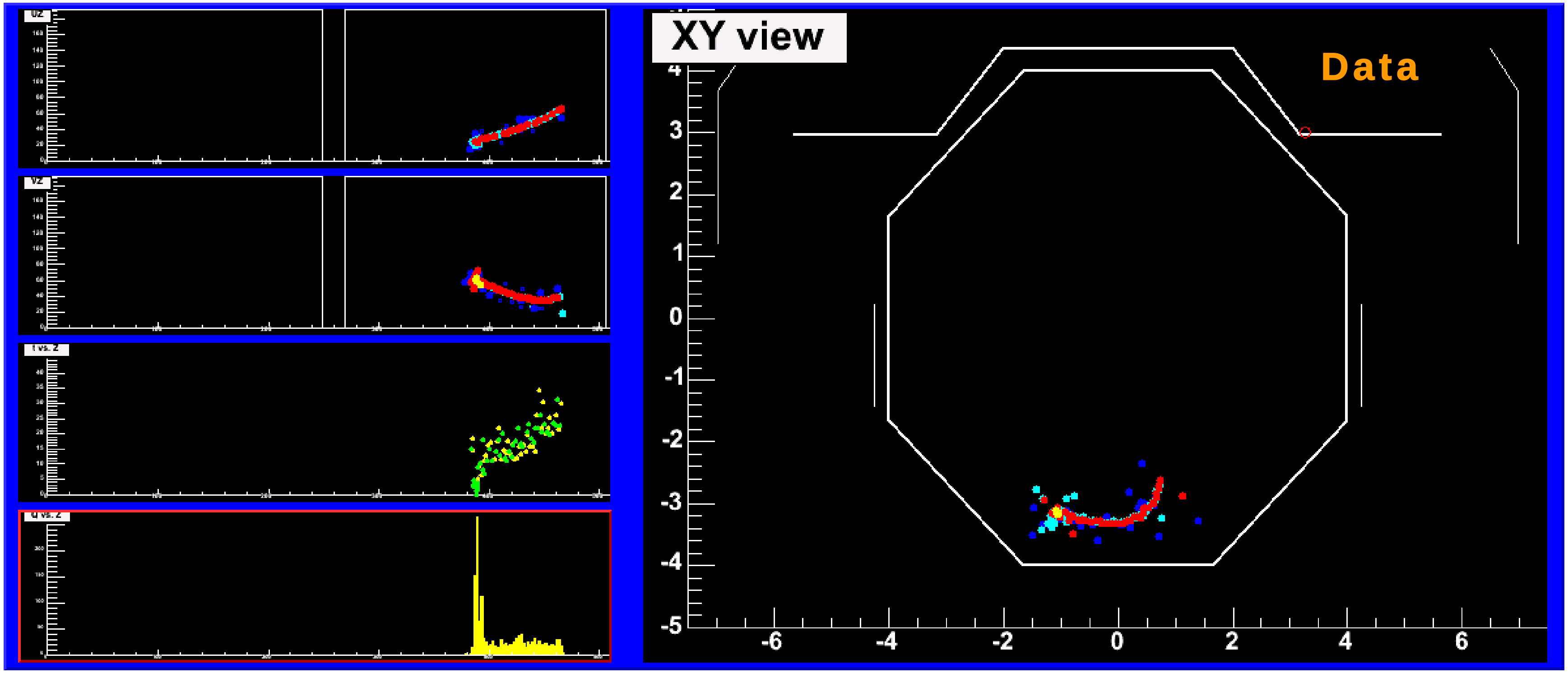


For Atmospheric Neutrinos:

- large background from cosmics
- reduced using ‘veto shield’

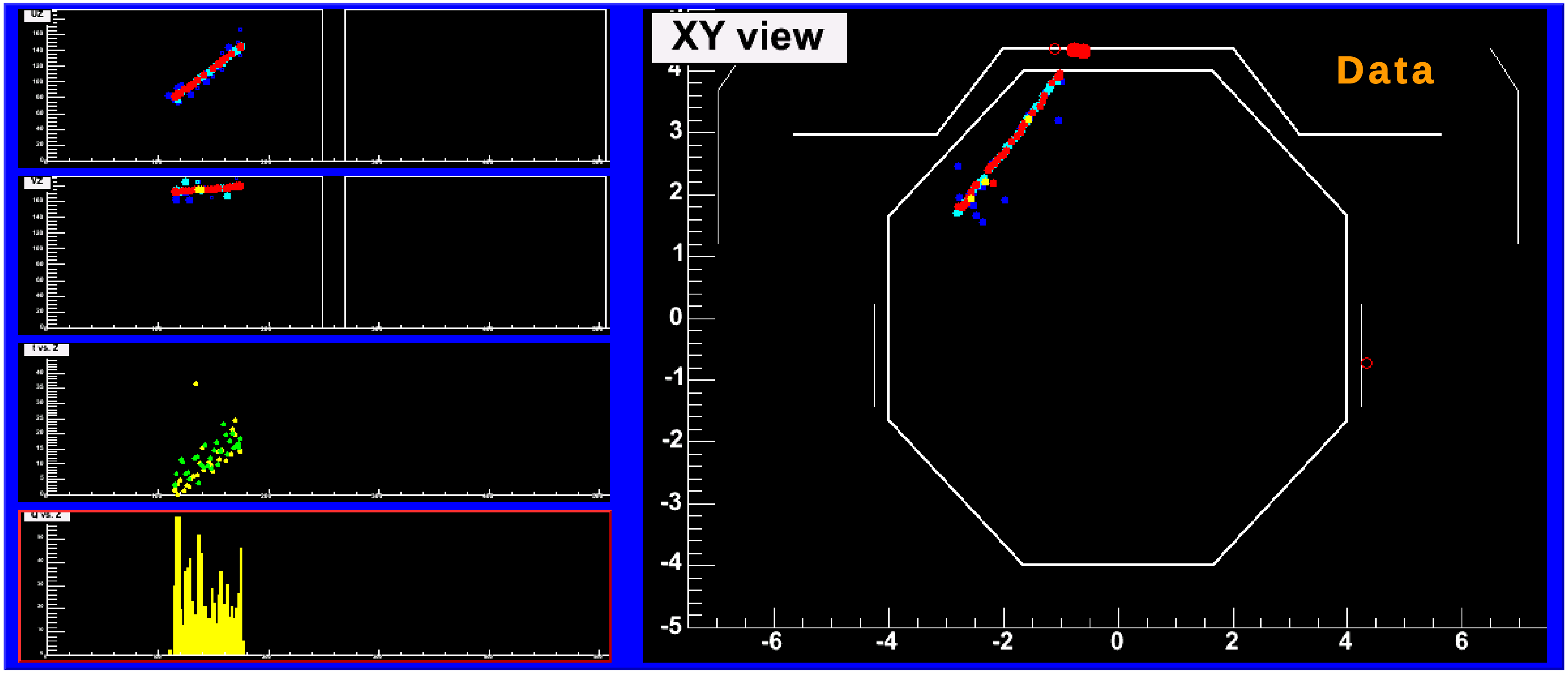
Contained Events

- Signal / Noise (cosmics) = 1 / 100,000
- Require rejection factor of ~ 1:10,000,000 !
- Veto Shield helps : efficiency ~ 98 %
- Very sensitive to reconstruction errors
- Have achieved: Efficiency ~ 75 % with 98 % purity

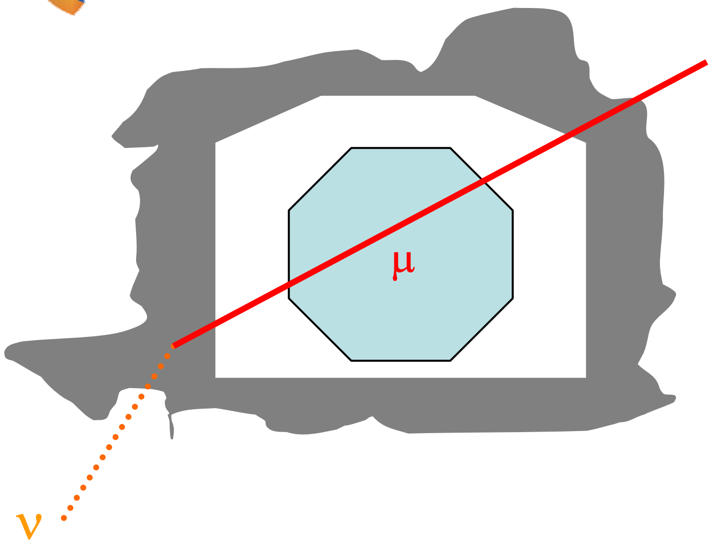


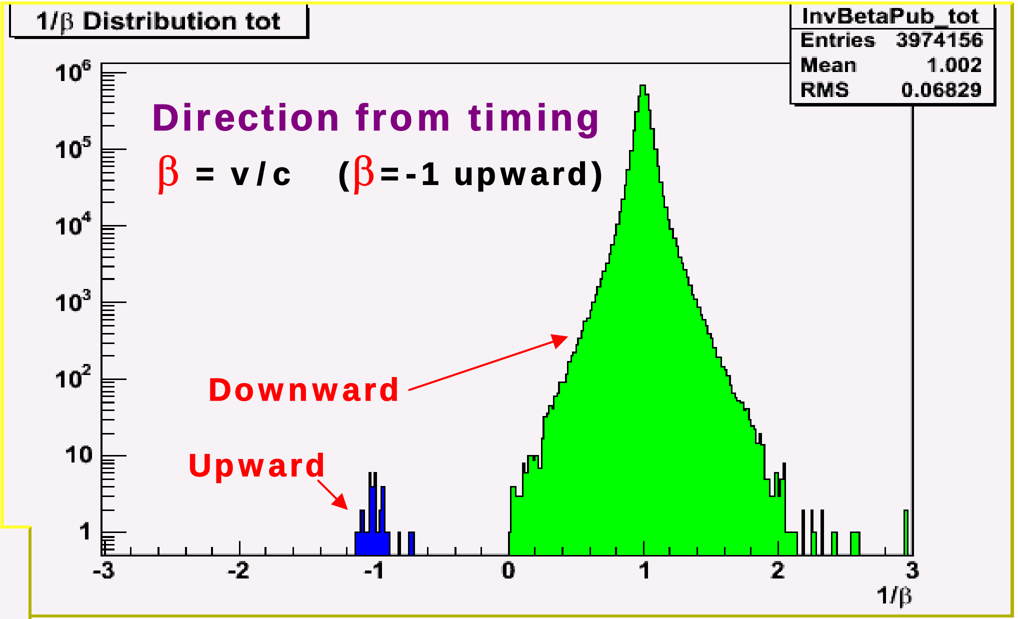
Partially Contained Events

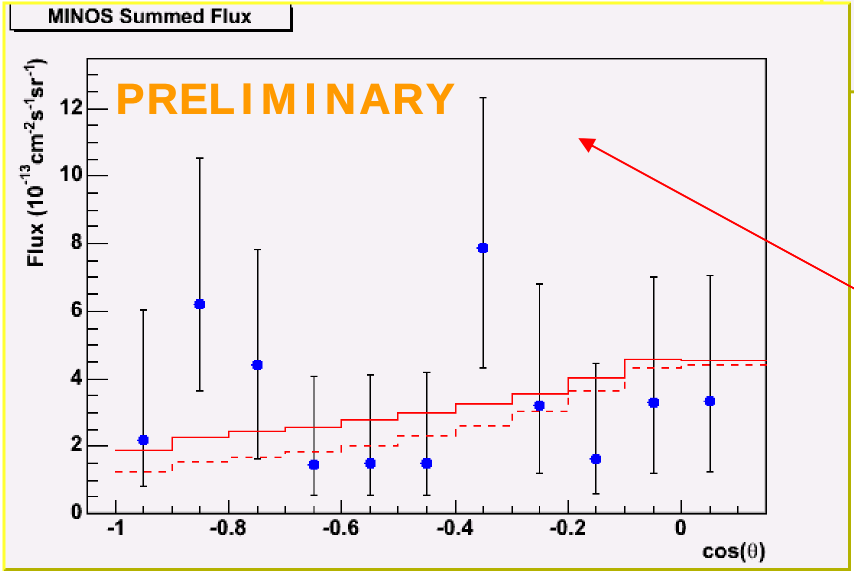
For upward going PC events rely on timing :



Upward-going muons







37 Candidate Events consistent with MC expectation

and a token data `physics' plot

★ **Data analysis underway !**

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
- First results on atmospheric neutrinos this Summer
- Eagerly awaiting first beam, due **December 2004** – and who knows, maybe some suprises !

The word is getting around.....