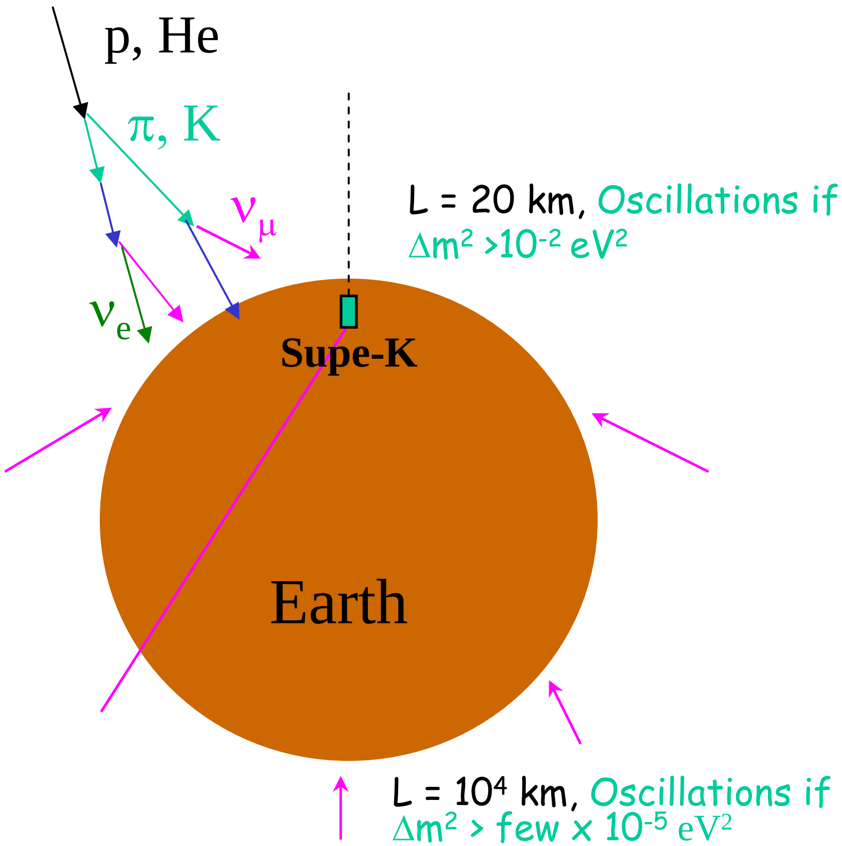
# Accelerator-based Long-Baseline Neutrino Oscillation Experiments

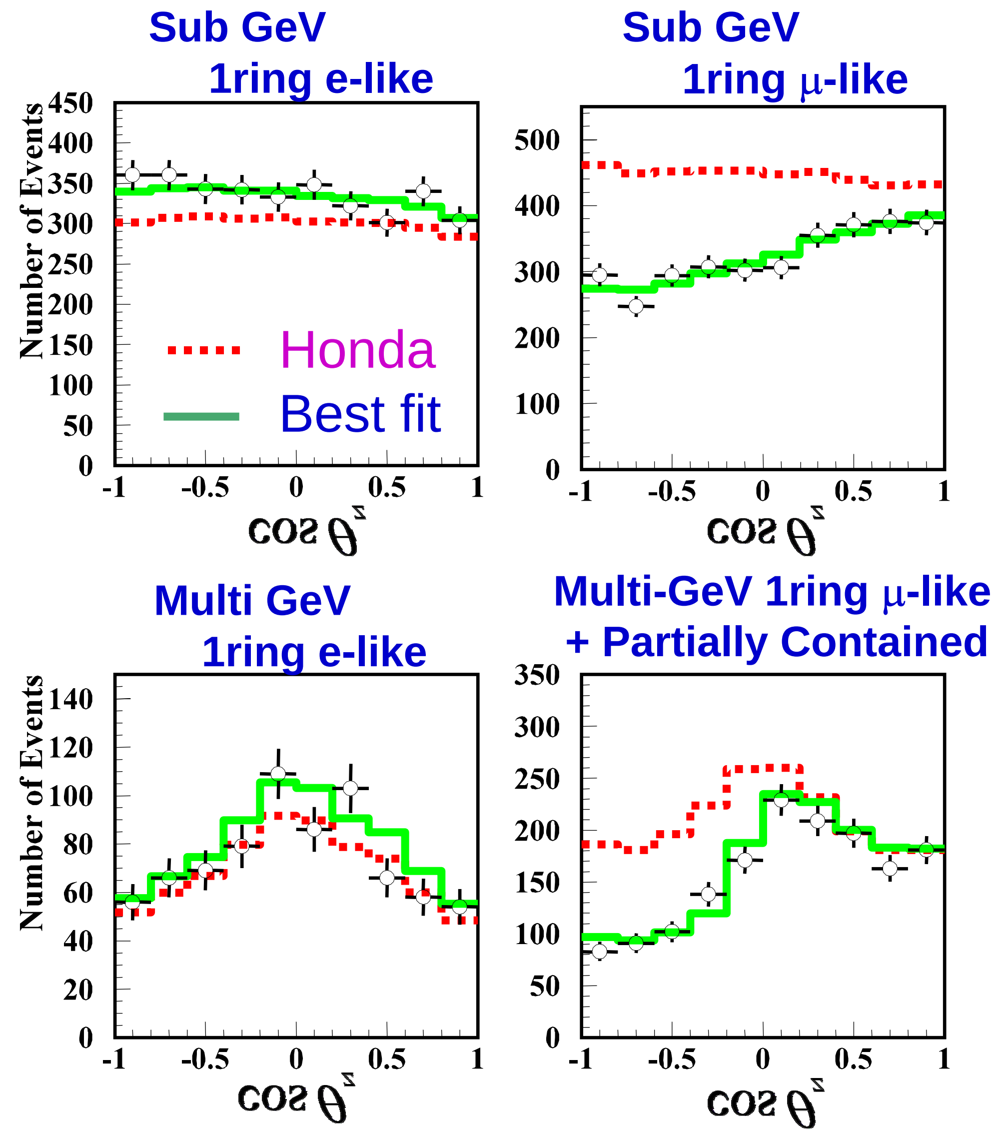
Kam-Biu Luk

University of California, Berkeley
and
Lawrence Berkeley National Laboratory

# Discovery of Atmospheric Neutrino Oscillation



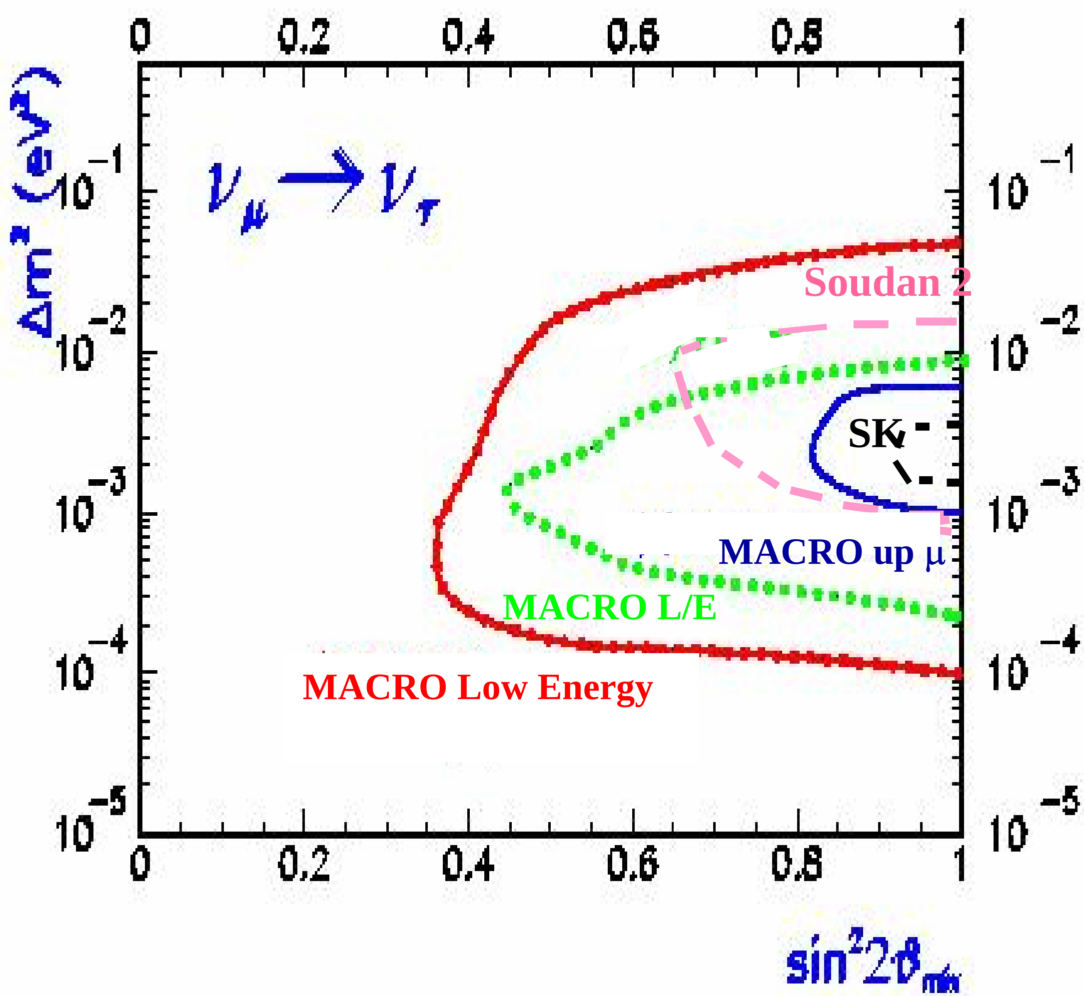

$E_\nu$ ~ 300 MeV - 2 GeV




Oscillation probability:

$$P(\nu_l \to \nu_l) \approx 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

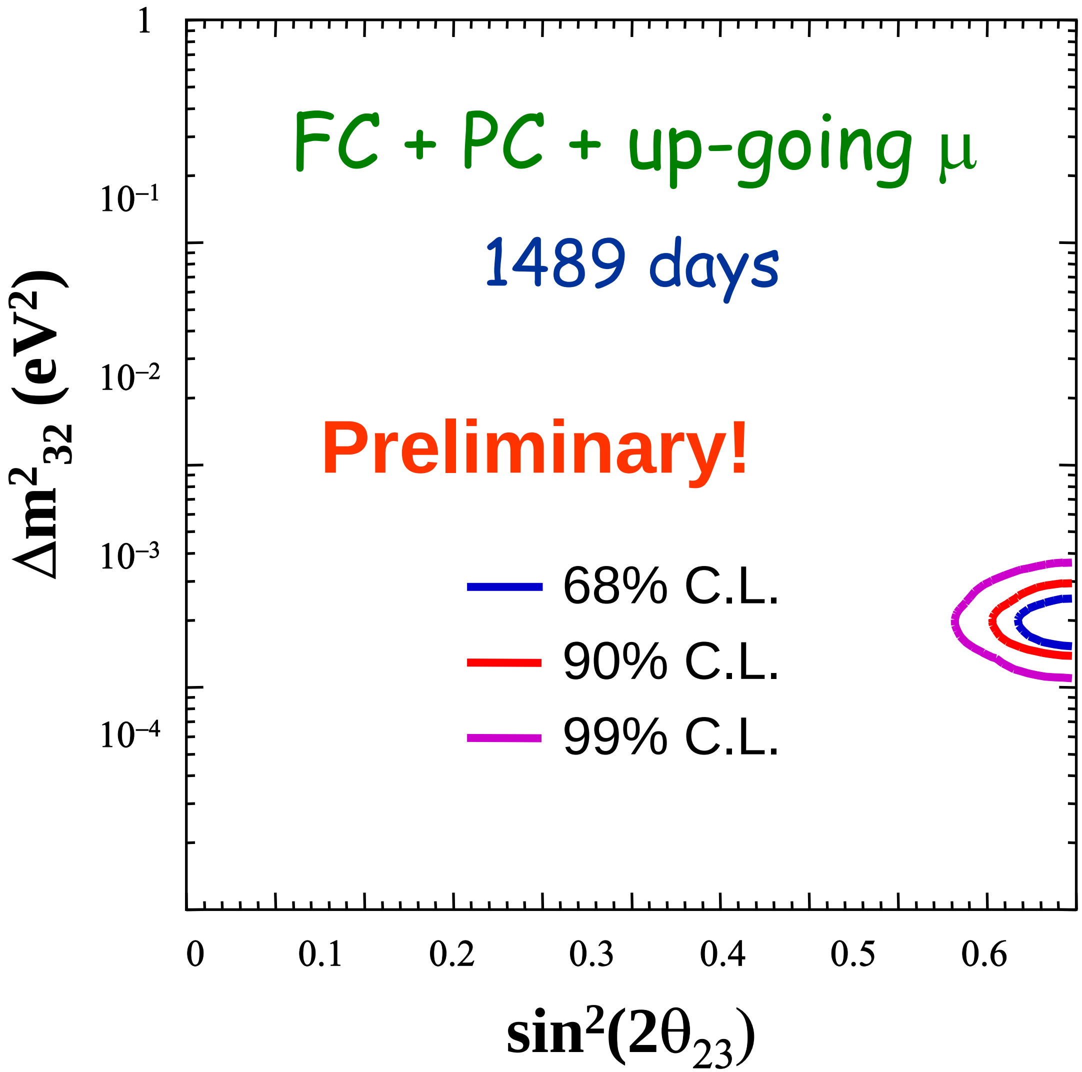
# What Have We Learned From Atmospheric ν?




Best Fit:

- Super-K:
  $\Delta m^2_{32}$ = 0.0025 eV$^2$
  $\sin^2(2\theta_{23})$ = 1.0
- MACRO:
  $\Delta m^2_{32}$ = 0.0025 eV$^2$
  $\sin^2(2\theta_{23})$ = 1.0
- Soudan 2:
  $\Delta m^2_{32}$ = 0.01 eV$^2$
  $\sin^2(2\theta_{23})$ = 1.0

# Recent Results FromSuper-K



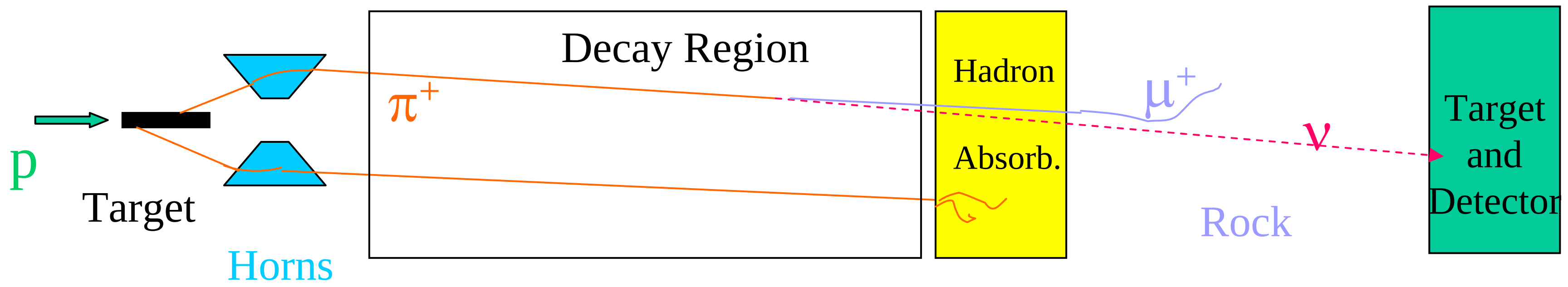

Best fit yielded

$\sin^2(2\theta_{23}) = 1.0$
$\Delta m^2_{32} = 2 \times 10^{-3}\ eV^2$

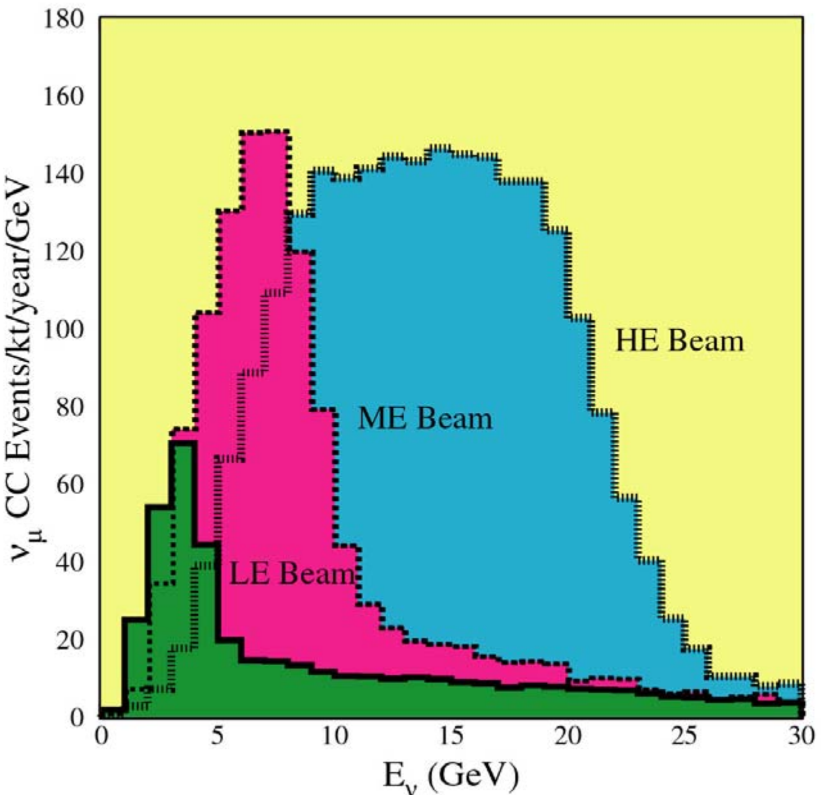
At 90% c.l.

$\sin^2(2\theta_{23}) > 0.9$
$\Delta m^2 < 3 \times 10^{-3}\ eV^2$
$> 1.3 \times 10^{-3}\ eV^2$

# Accelerator-based Neutrino Experiments




- High-purity $\nu_\mu$ beam, with a small amount of $\nu_e$
- Can control the energy of of the $\nu_\mu$ beam by changing the positions of the target and the horns



# Goals of Accelerator-based Long-baseline Neutrino Experiments

- Confirmation of $\nu_\mu$ oscillation and establish the oscillation pattern

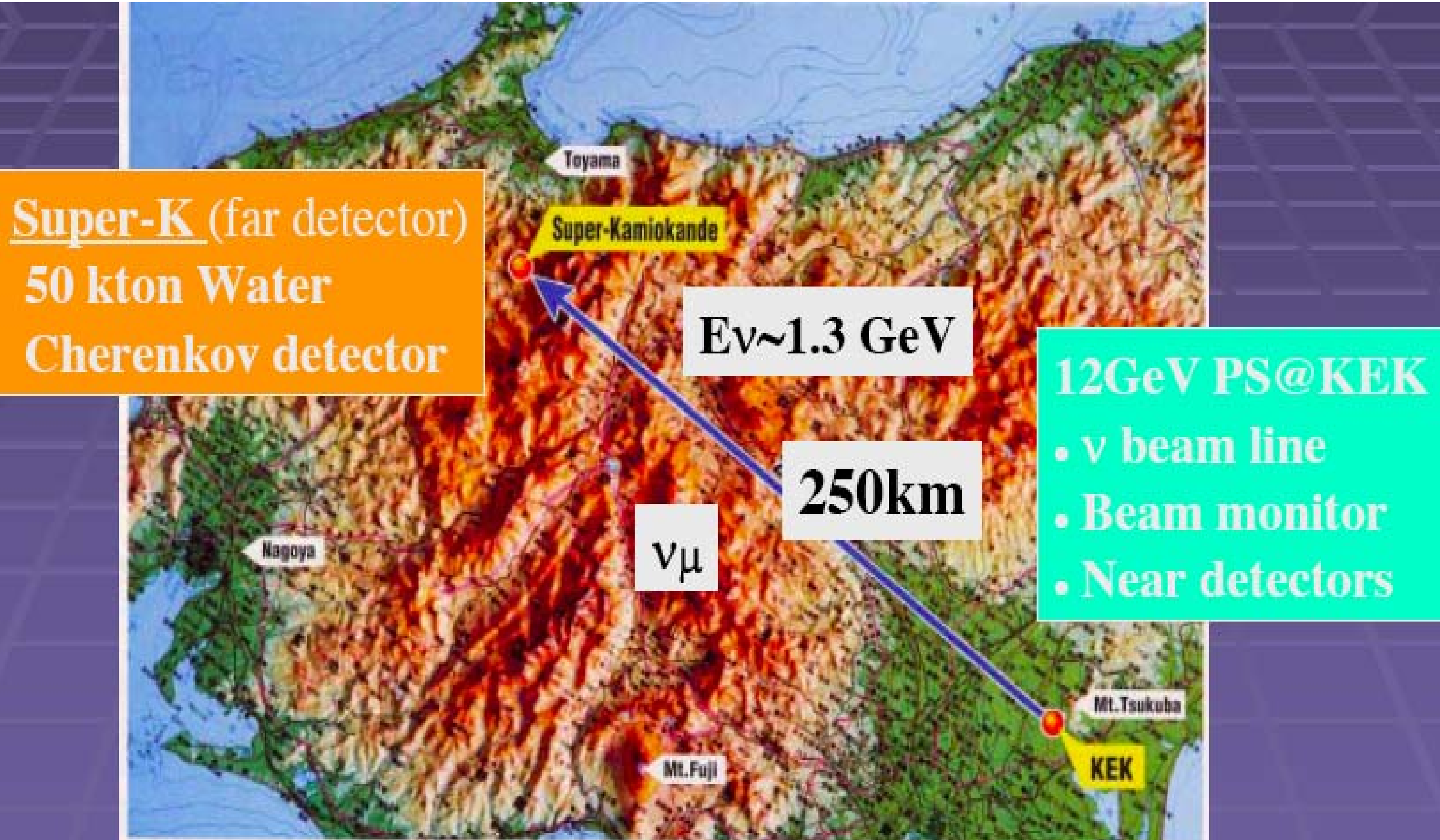
- Precise measurement of $\Delta m^2_{32}$ and $\sin^2(2\theta_{23})$
- Determination of participating neutrino types
  e.g. Positively identify $\nu_\tau$
- Look for $\nu_e$ appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{23})\sin^2(2\theta_{13})\sin\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

- Compare $\nu$ oscillation with $\bar{\nu}$ oscillation

# First Generation of Long-Baseline Experiment

K2K: reproducing atmospheric neutrino oscillation



# Near Detector of K2K

(6 ton)

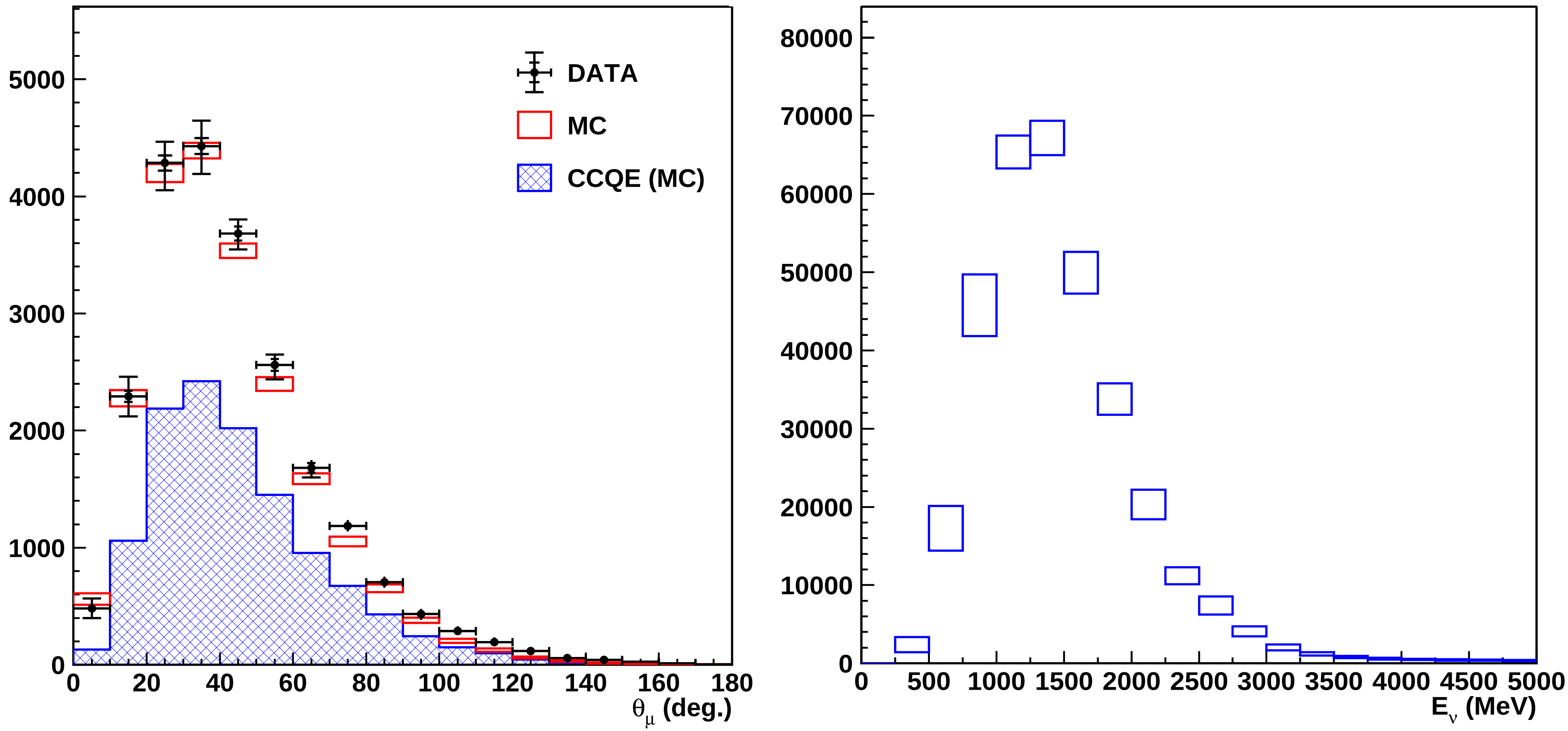
~700 ton

Fid. mass = 25 ton

QuickTime?and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

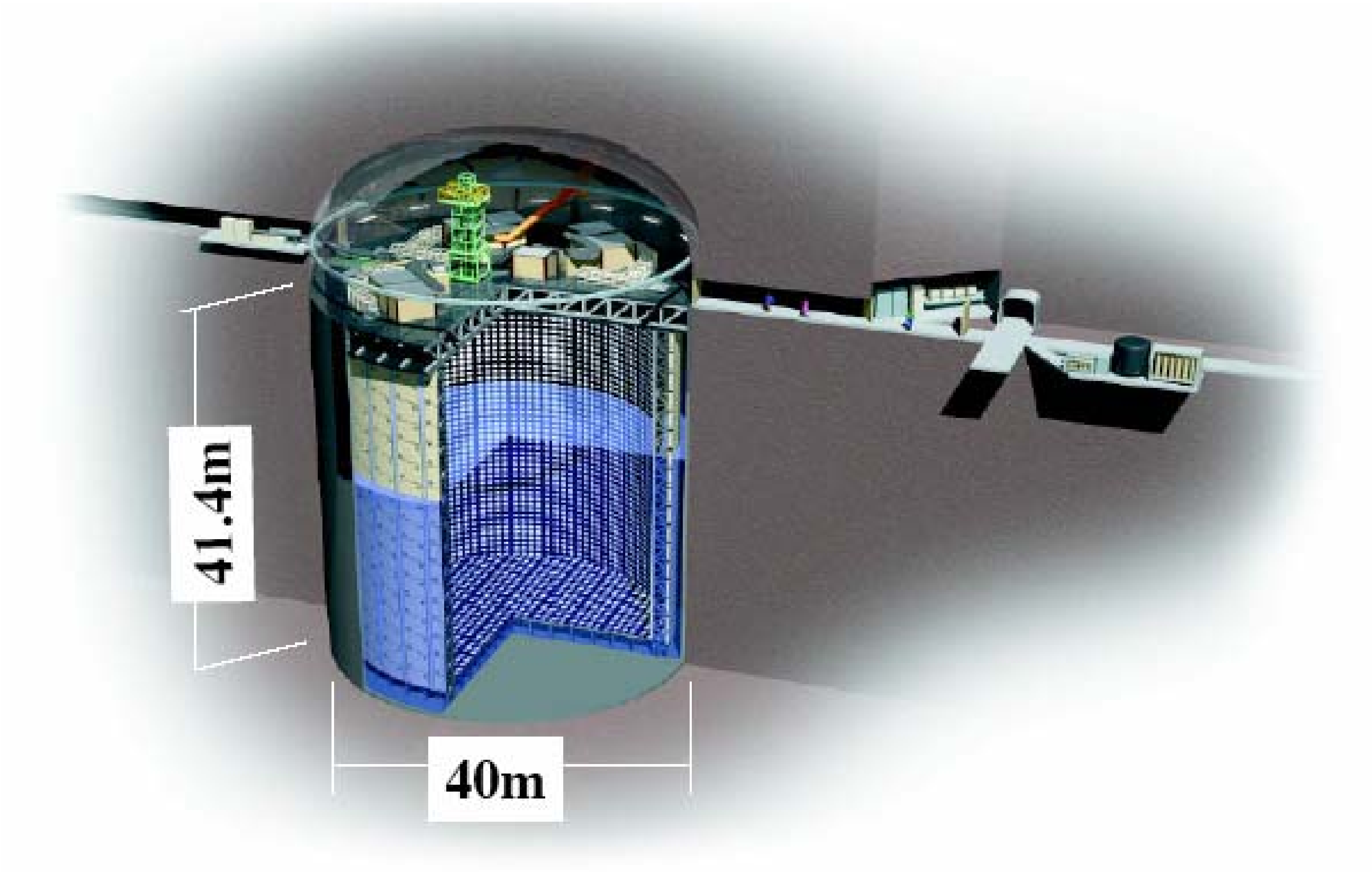
# Usage of the Near Detector

- Determine direction and divergence of $\nu_\mu$ beam through muons
- Study low-energy $\nu_\mu$ interaction
- Measure $\nu_\mu$ spectrum

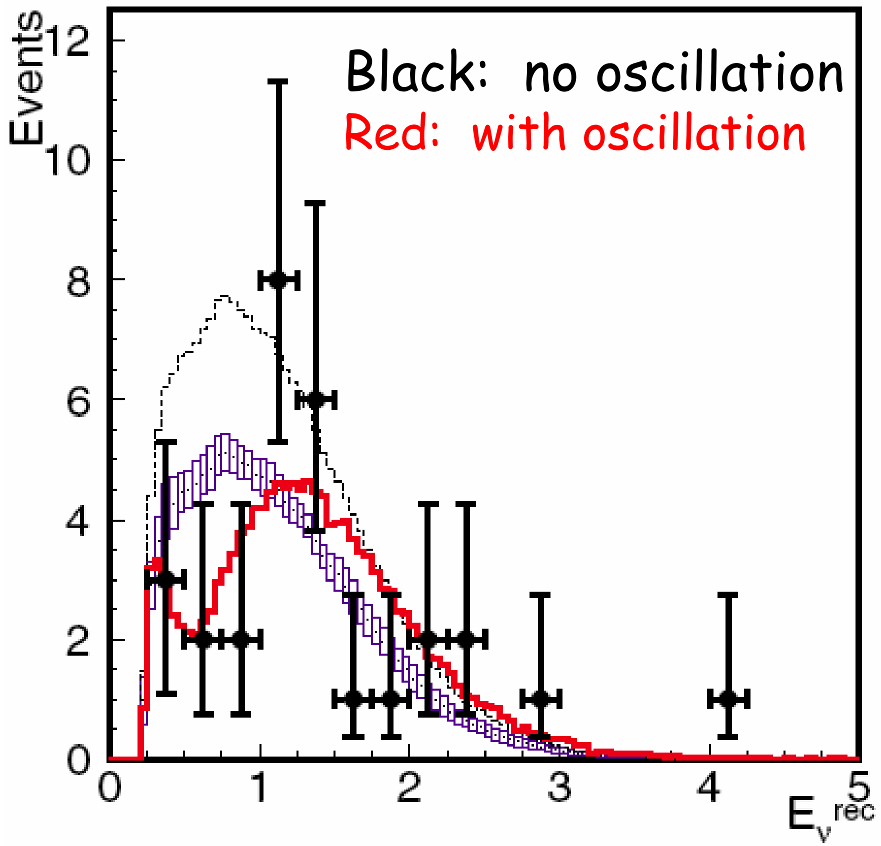


# Far Detetor of K2K: Super-Kamiokande

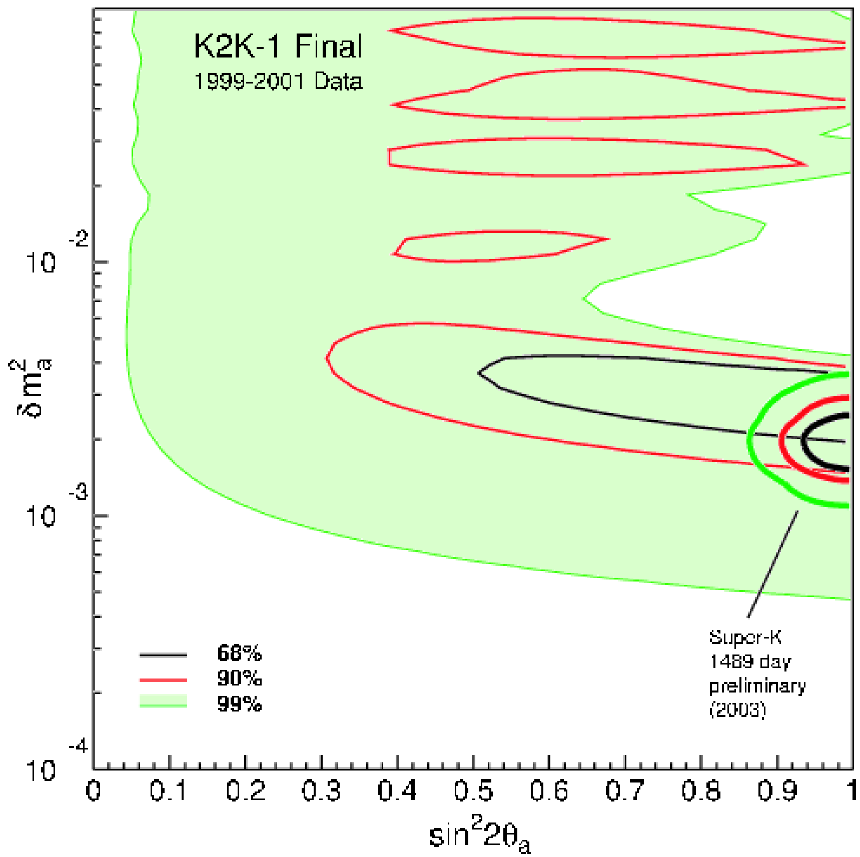
- 50 kton water Cherenkov counter with a fiducial mass of 22.5 kton
- Inner and outer regions are optically separated



# Results of K2K-I




Observed 56 events in 2 years, expect $80^{+7.3}_{-8.0}$

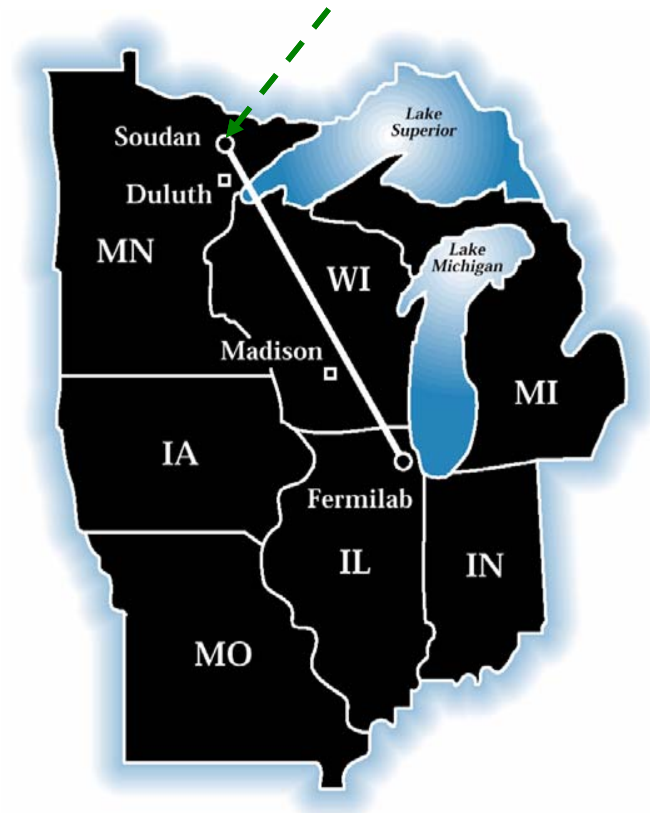



- K2K result is consistent with SK.
- More data are being taken.

# Second Generation of Long-Baseline Experiments

- MINOS

Soudan Mine
730 km away

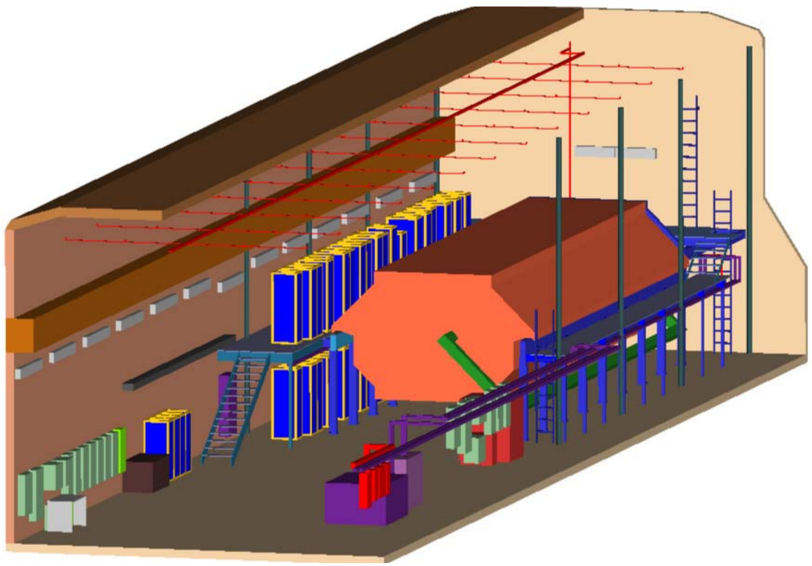


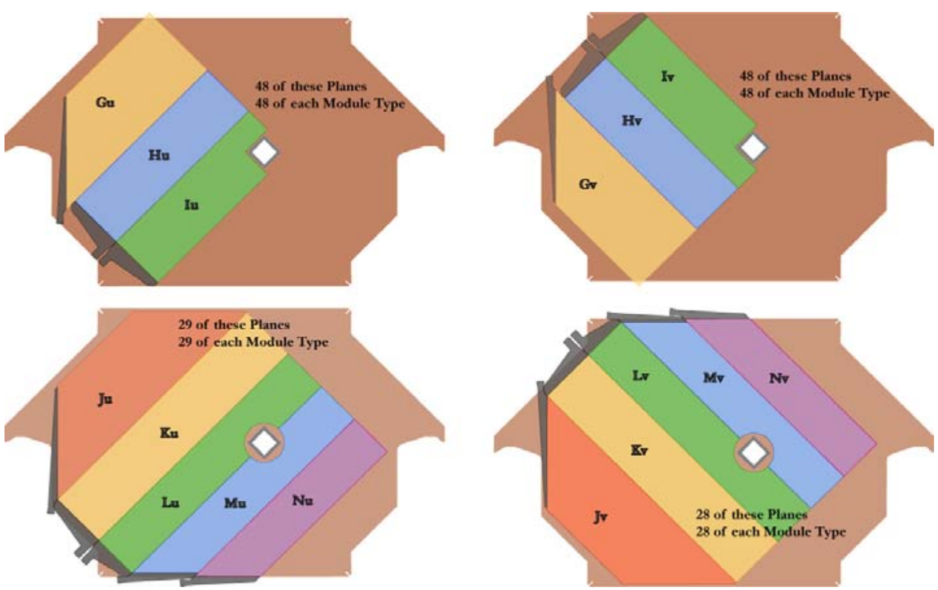

- Determine energy distribution of oscillations
- Precised measurement of oscillation parameters
- Determine neutrino flavors involved
- Direct measurement of $\nu$ vs $\nu$ oscillation using a magnetized far detector:
  - using atmospheric $\nu$'s.
  - eventually with beam

# Far Detector of MINOS


- 8m octagonal steel & scintillator tracking calorimeter
  - Sampling every 2.54 cm
  - 4cm-wide strips of scintillator
  - 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
  - 26,000 $m^2$

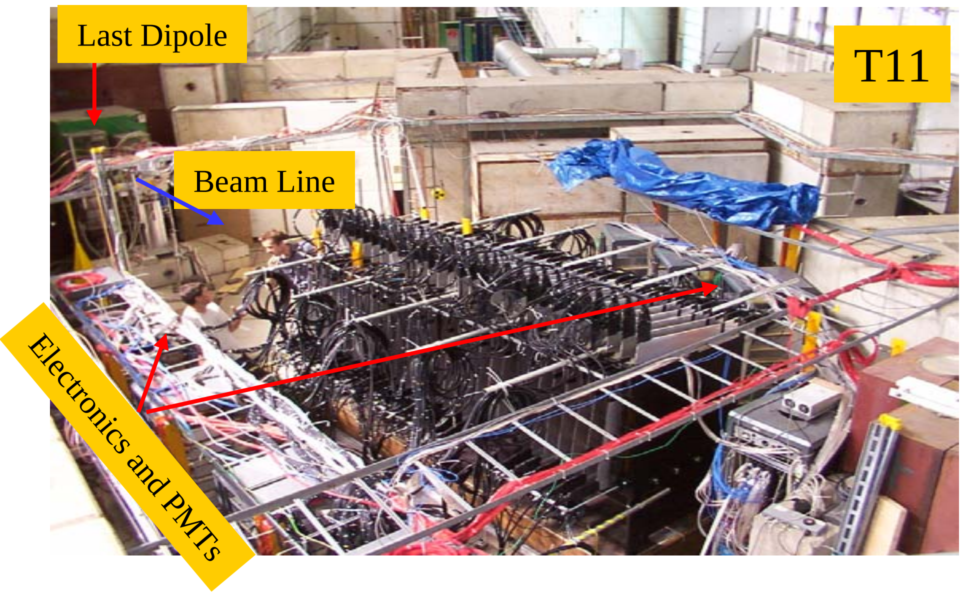
# MINOS Near Detector

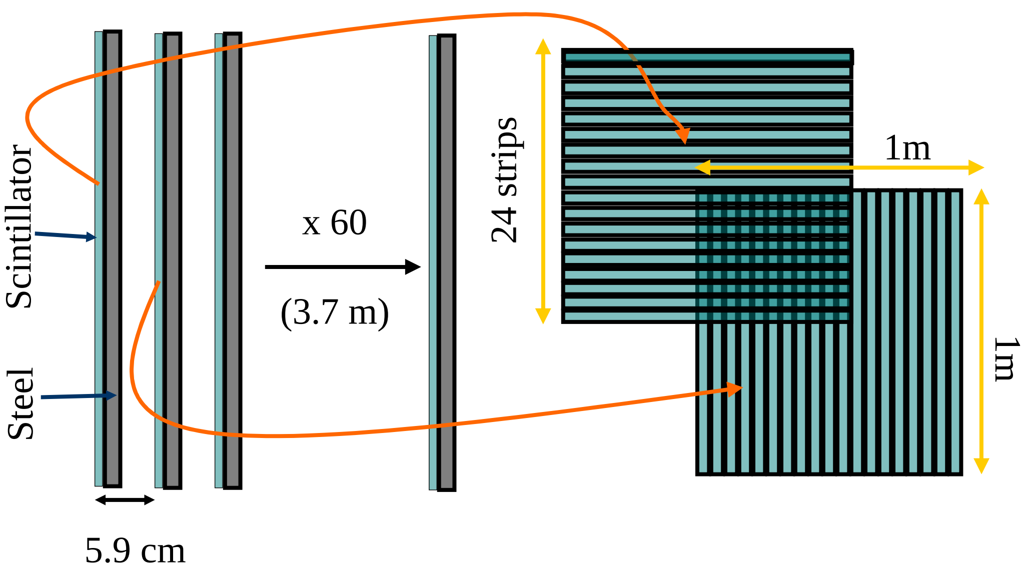





- **3.8 x 4.8m** "octagonal" steel & scintillator tracking calorimeter
- Same basic construction, sampling and response as the far detector.
- No multiplexing in the main part of the detector due to small size and high rates.
  - Hamamatsu M64 PMT
  - Faster Electronics (QIE)
- **282 planes of steel**
- **153 planes of scintillator**

# MINOS Calibration Detector




- Mini-version of the MINOS near and far detectors
  - 1m x 1m x 3.7 m
  - 60 planes x 24 strips/plane
  - Readout technologies of both the near and far detectors
- Exposed to $e^-$, $\pi$, p and $\mu$ beams from 0.5-10 GeV/c at CERN PS
  - First data in 2001 up to 3.5 GeV using far detector readout.
  - Data in 2002 up to 10 GeV and to compare near and far electronics.
  - Additional running in 2003 with full near readout system.

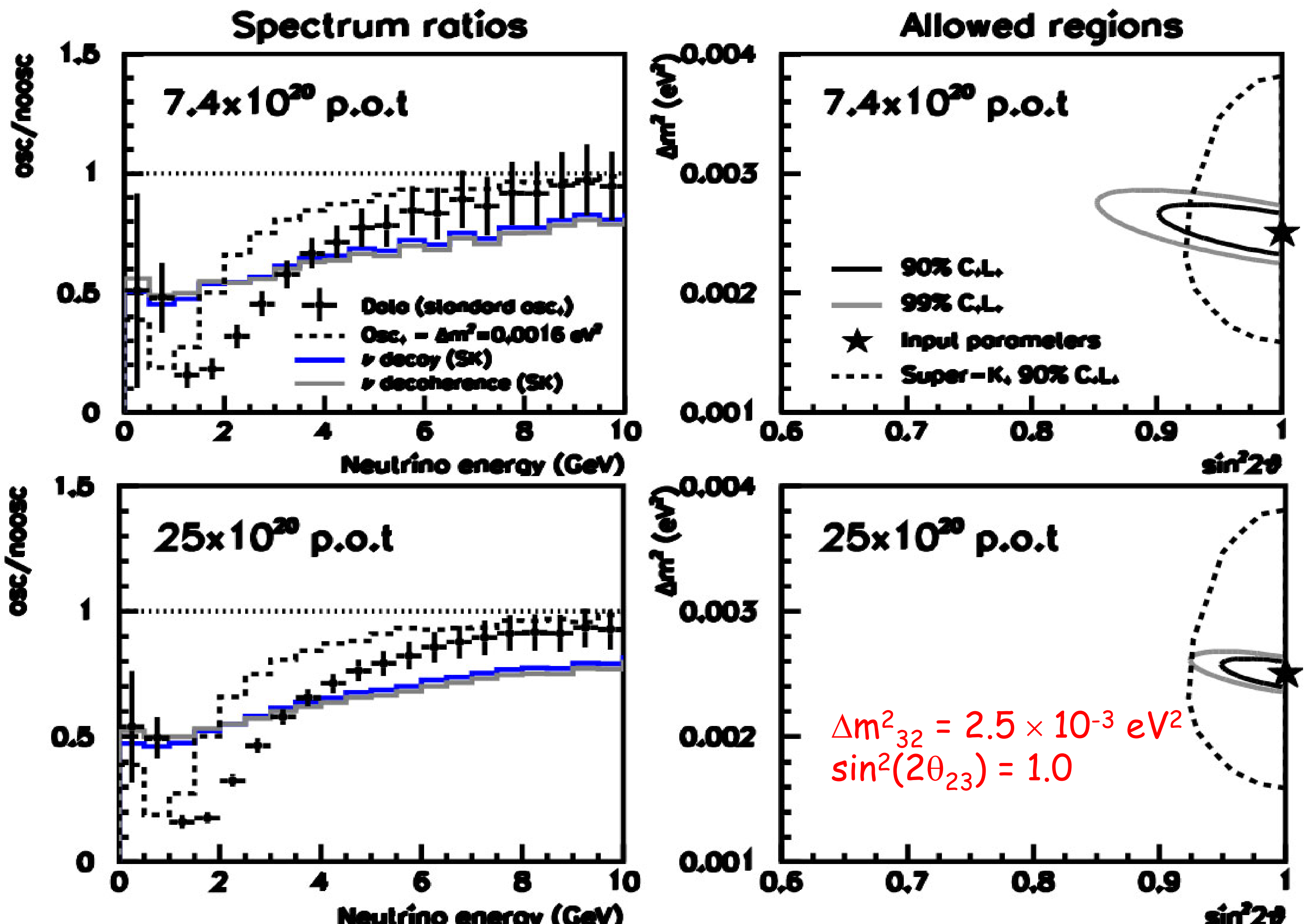
**Physics Goals:**

- EM and Hadron energy response
- EM and Hadron event topology
- Near/Far readout comparison

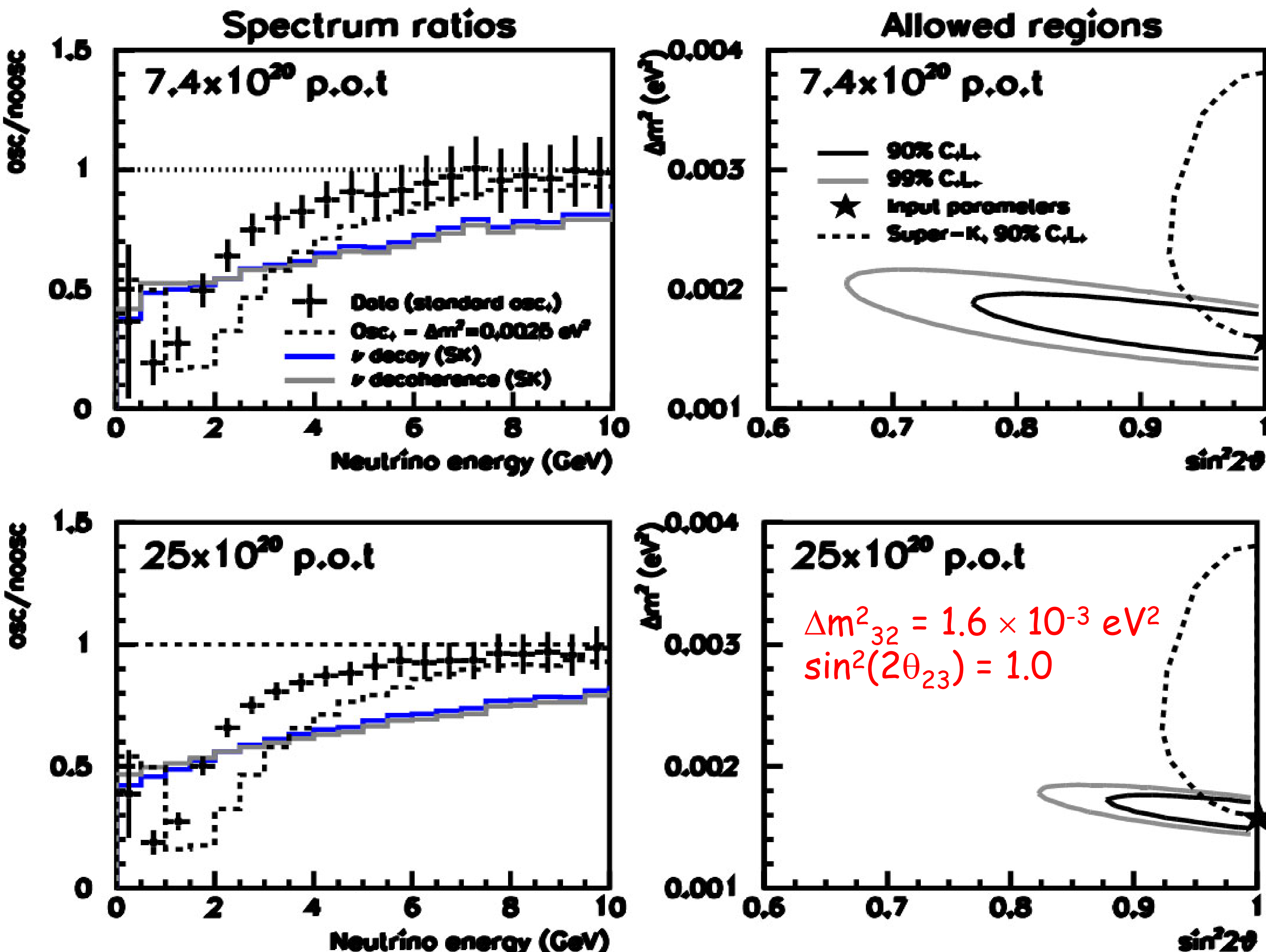
# Run Plan of NuMI/MINOS

- Commissioning of NuMI beam in Dec. 2004
- Physics running for MINOS starting in April 2005
- Goal for protons on target in first year = $2.5 \times 10^{20}$
- Plans are being developed for increased proton intensity
- Request to Fermilab for 5 years of running with a total of $25 \times 10^{20}$ protons on target in that time. (Original MINOS physics sensitivity was based on $7.4 \times 10^{20}$ pot.)

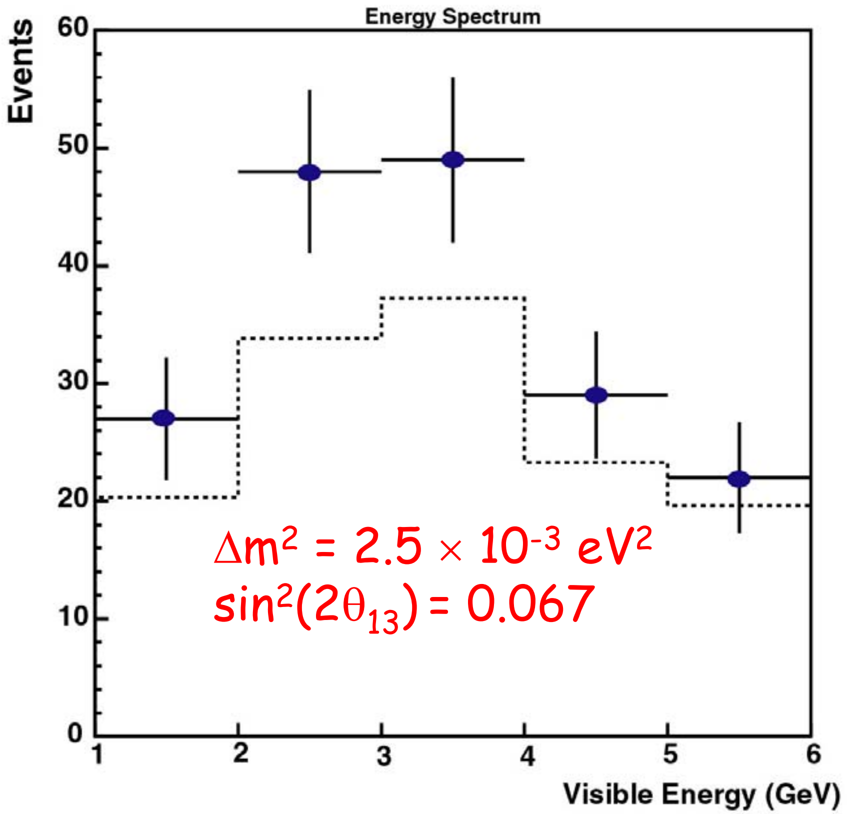
# Expectations of MINOS in $\nu_\mu$ Disappearance



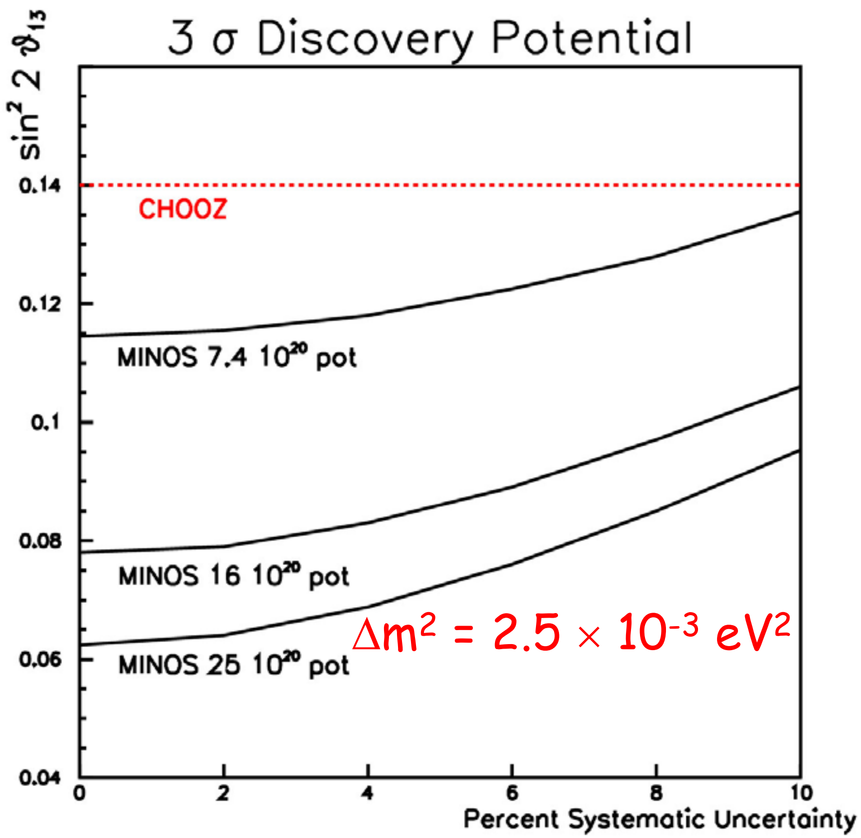
# Expectations of MINOS in $\nu_\mu$ Disappearance



# Sensitivity of MINOS in $\nu_e$ Appearance

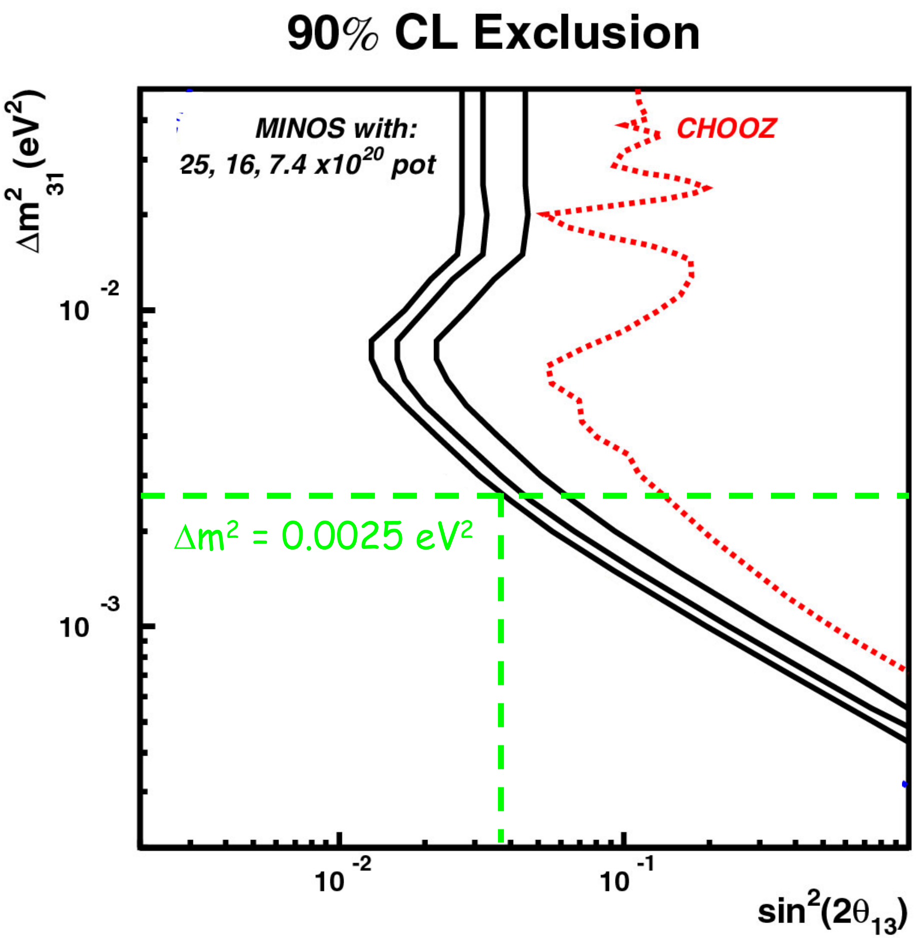


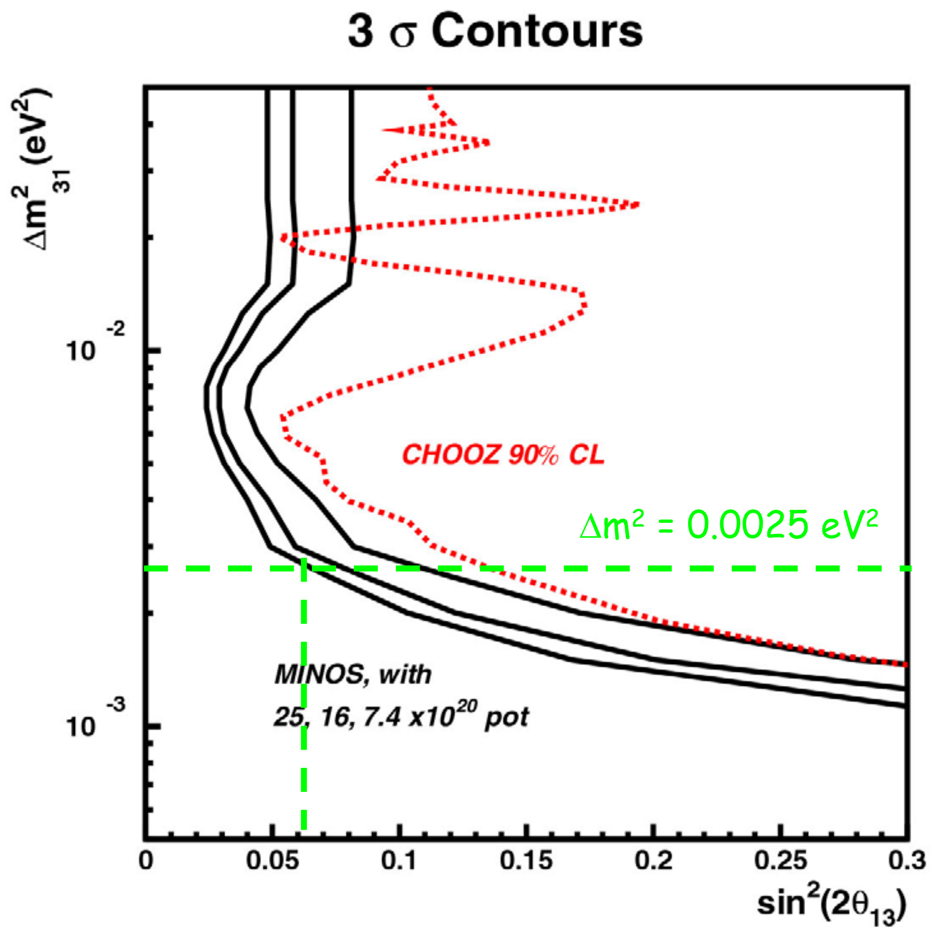

Observed number of events identified $\nu_e$ CC interactions with and without oscillations for 25 x $10^{20}$ protons on target.




$3\sigma$ discovery potential versus systematic uncertainty on the background.

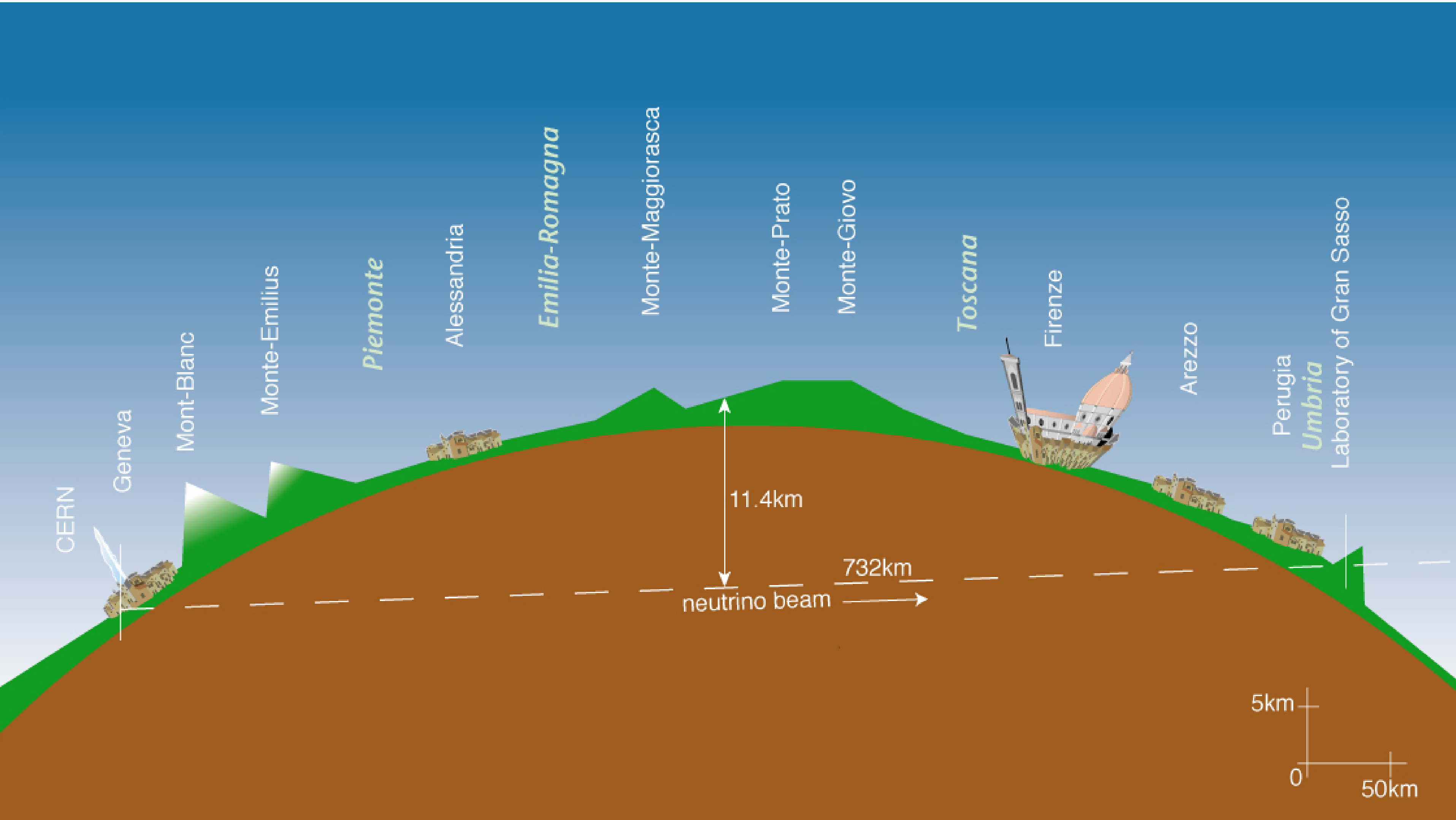
# Sensitivity of MINOS in $\nu_e$ Appearance



# Long-Baseline Neutrino-Oscillation Experiments in Europe

## CNGS-ICARUS-OPERA



# Go After $\nu_\mu \to \nu_\tau$ Oscillation

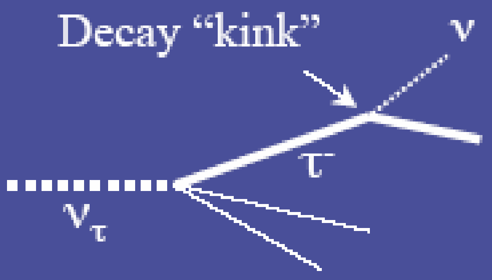
$\nu_\mu$ ..... $\nu_\tau \rightarrow \tau^- + X$

oscillation — CC interaction

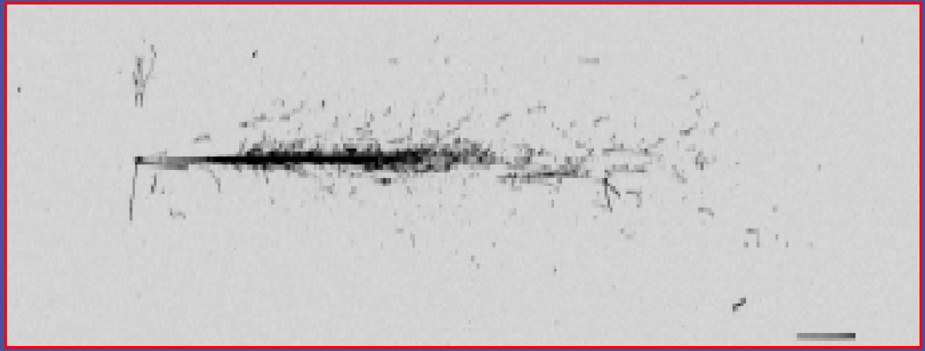
| | |
|---|---|
| $\mu^- \ \nu_\tau \ \nu_\mu$ | BR 18 % |
| $h^- \ \nu_\tau \ n\pi^o$ | 50 % |
| $e^- \ \nu_\tau \ \nu_e$ | 18 % |
| $\pi^+ \pi^- \pi^- \ \nu_\tau \ n\pi^o$ | 14% |

OPERA: Observation of the decay topology of $\tau$ in photographic emulsion

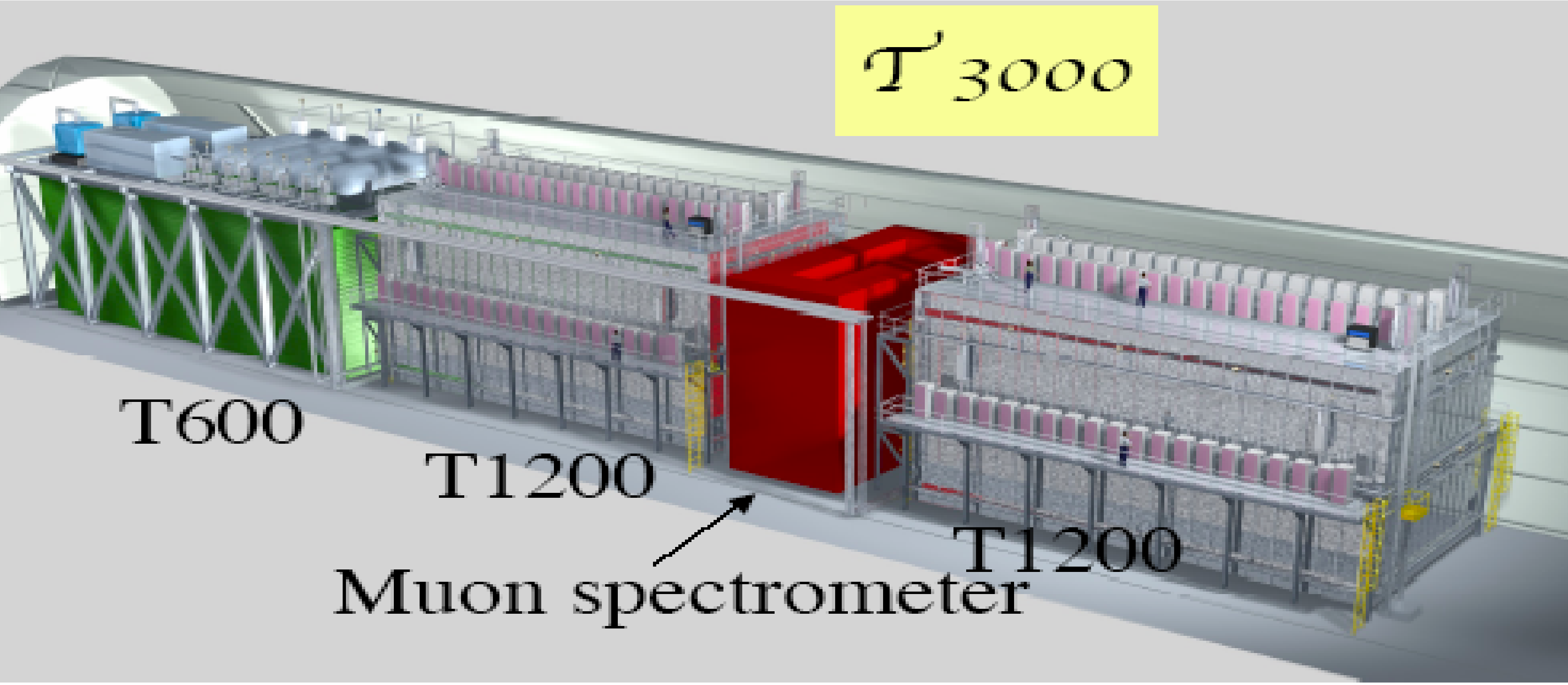
(~ μm granularity)




ICARUS: detailed TPC image in liquid argon and kinematic criteria (~ mm granularity)

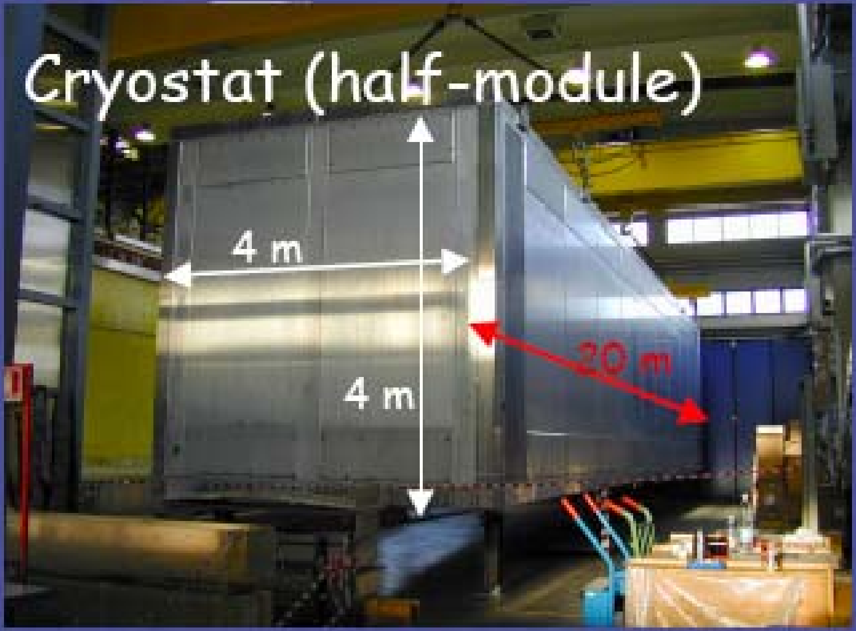


# ICARUS

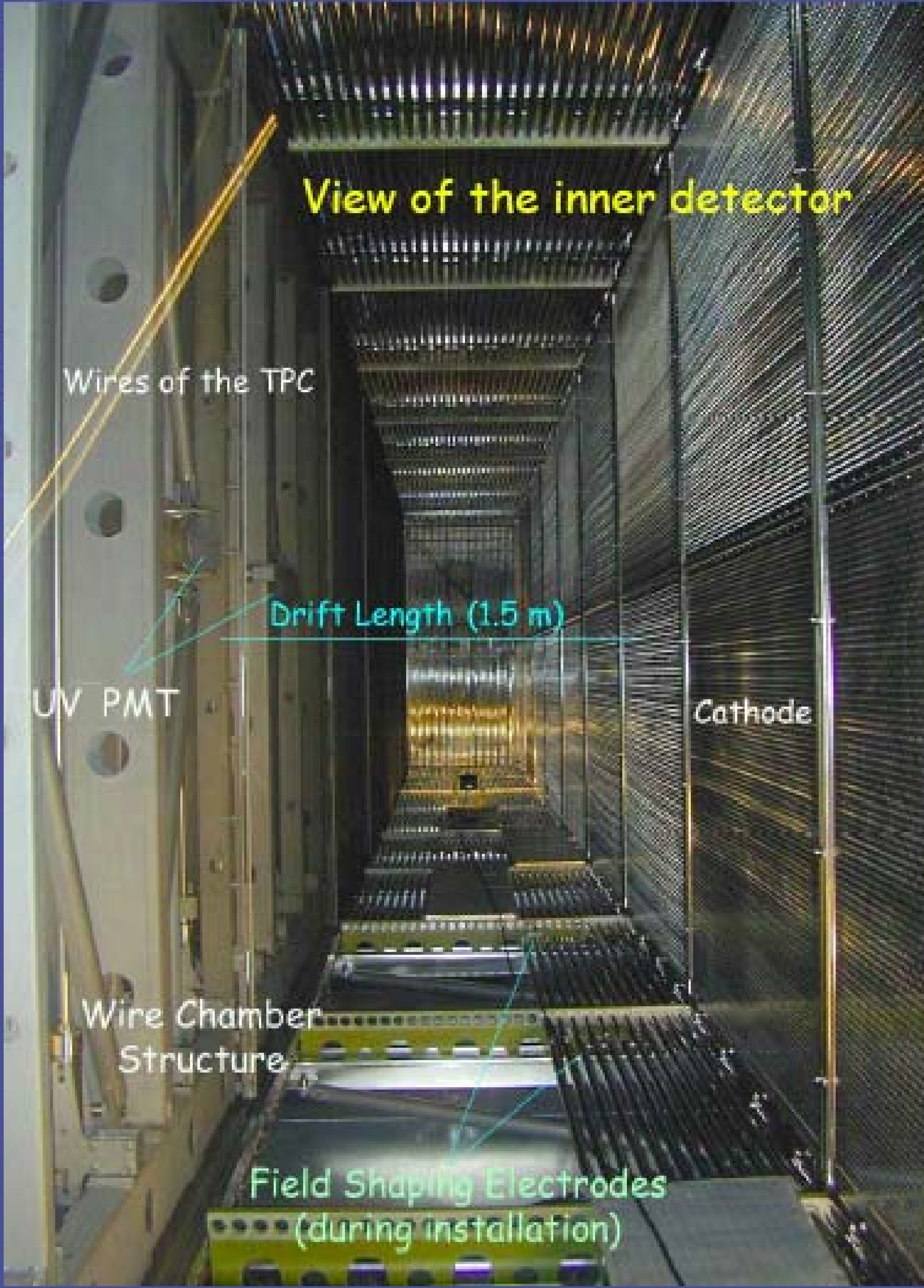



- Liquid argon TPC, acting as an electronic bubble chamber
- Continuous operation

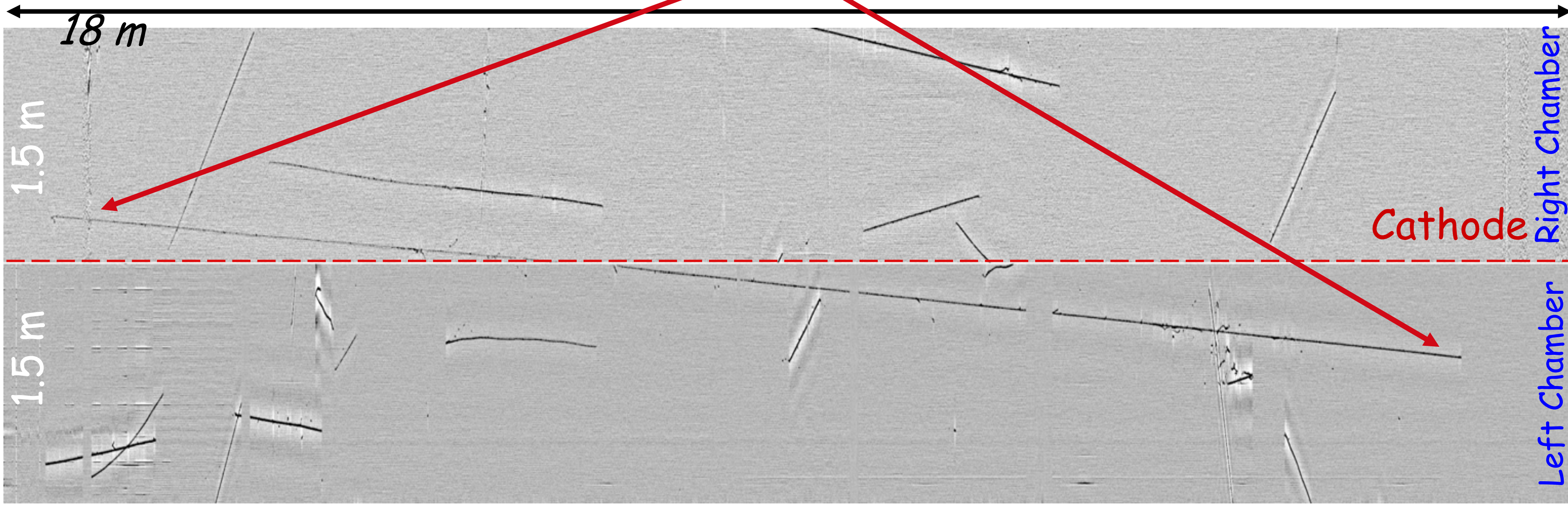

T300 ≈300'000 kg LAr

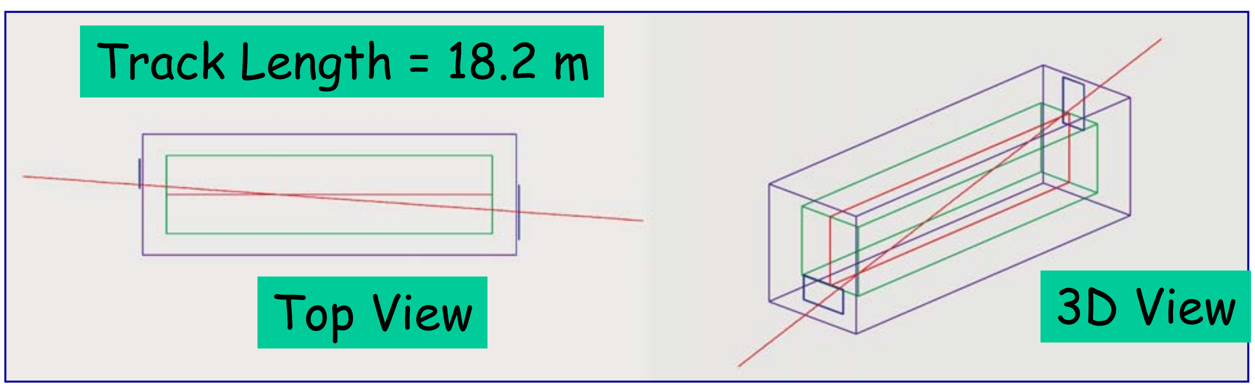

Cryostat (half-module)
4 m
4 m
20 m


Readout electronics

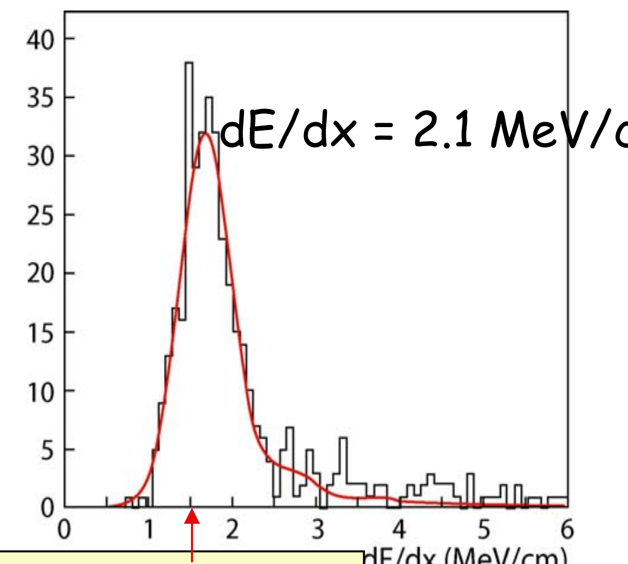

View of the inner detector
Wires of the TPC
Drift Length (1.5 m)
UV PMT
Cathode
Wire Chamber
Structure
Field Shaping Electrodes
(during installation)

Long longitudinal muon track crossing the cathode plane




3-D reconstruction of the long track



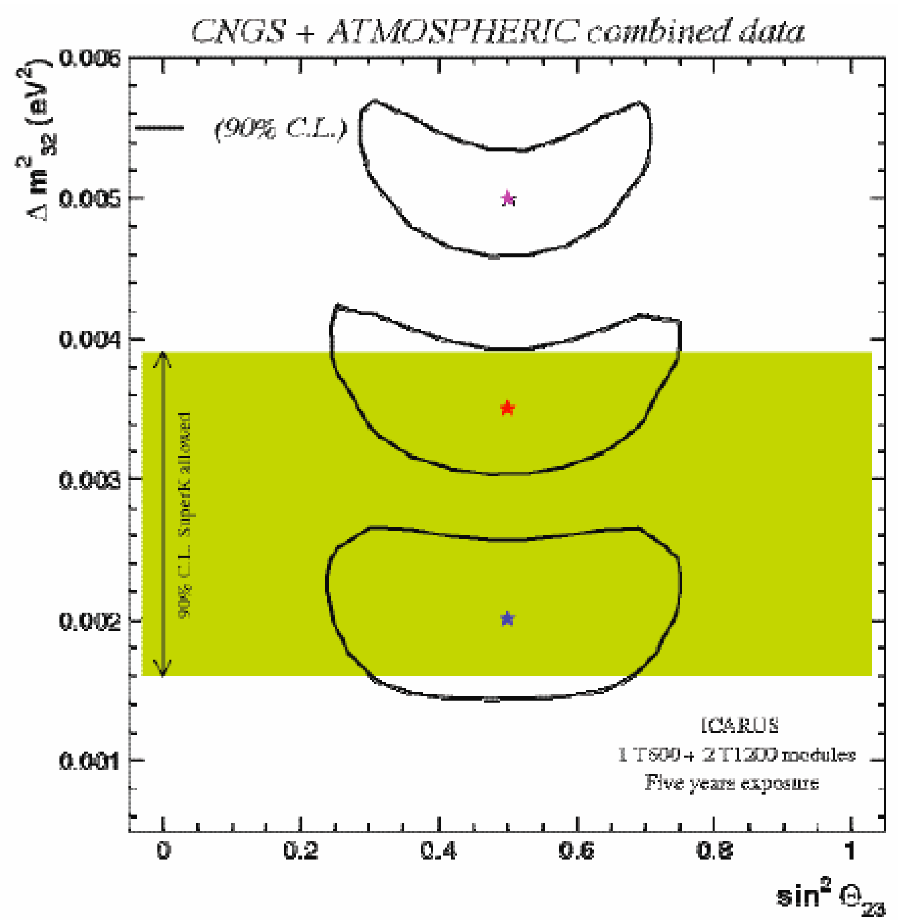

dE/dx distribution along the track

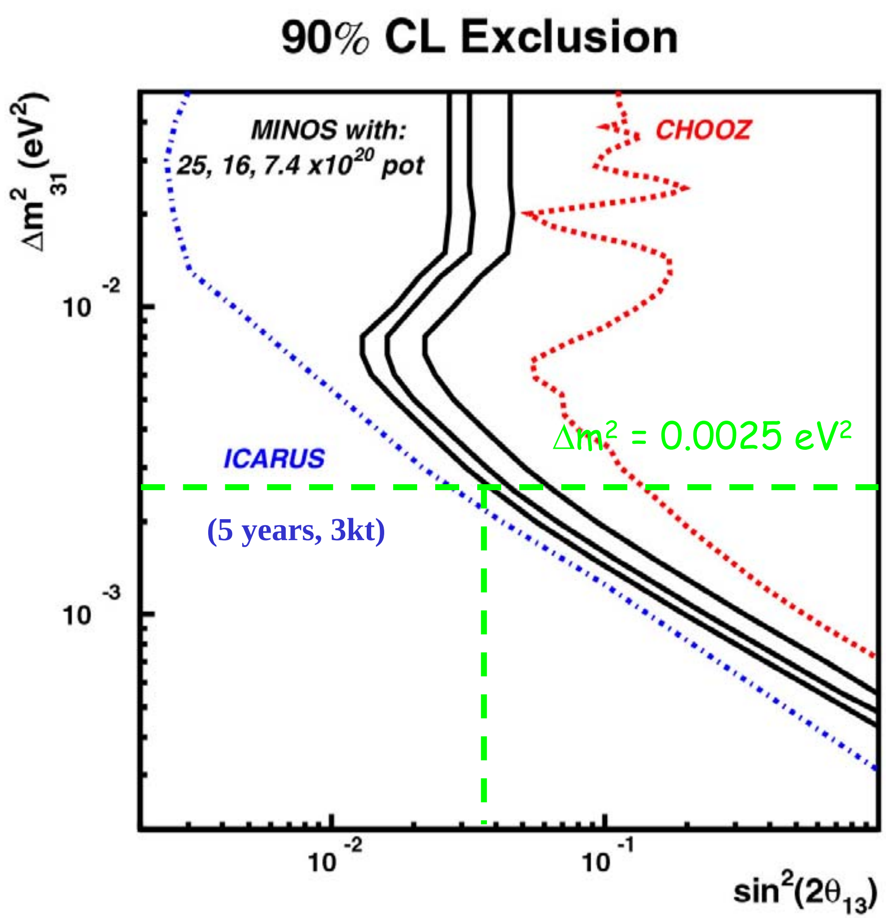
# Status and Plan of CNGS-ICARUS

- ICARUS was approved in 1997 by INFN; currently funded as part of the LNGS program.
- In summer 2001, successful operation of the T300 half-module.
- Second T300 half-module has been completed with industry.
- In 2003, installation of T600 recommended by Gran Sasso Scientific Committee, placed in Hall B of LNGS and commissioned for physics right after.
- LNGSSC and CERN-SPSC recommended to duplicate T600 to reach the design mass.
- INFN approved the T3000 scientific program. The first T1200 module is funded and its design ongoing.
- Complete the T1200 modules by early 2006 in time for CNGS start up.

# Physics Goals of CNGS-ICARUS

- Study $\nu_\mu$ CC, similar to the goals of MINOS.
- Search for $\nu_\mu \rightarrow \nu_e$ oscillation by observing $\nu_e$ CC
- Search for $\nu_\mu \rightarrow \nu_\tau$ oscillation by observing $\nu_\tau$ CC
- Search for $\nu_\mu \rightarrow \nu_s$ oscillations or exotics by studying NC events



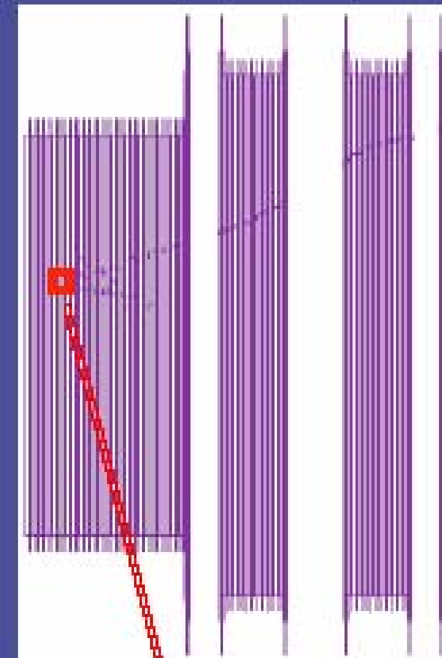



QuickTime?and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

ν interaction

Spectrometer (drift tubes-RPCs)

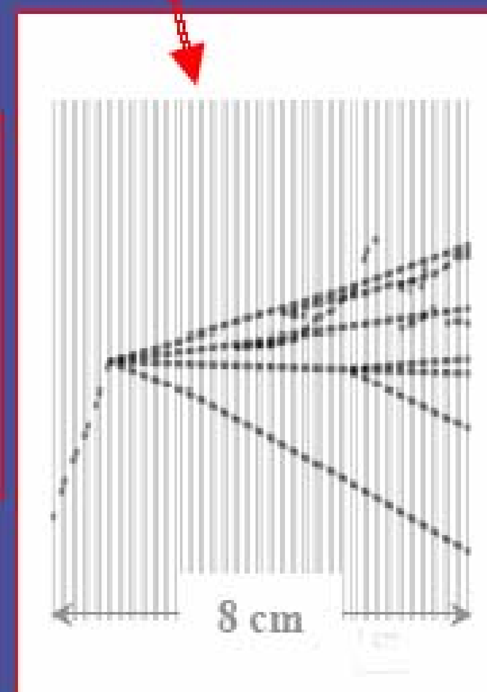
Emulsions+lead + target tracker (scintillator strips)



Electronic detector

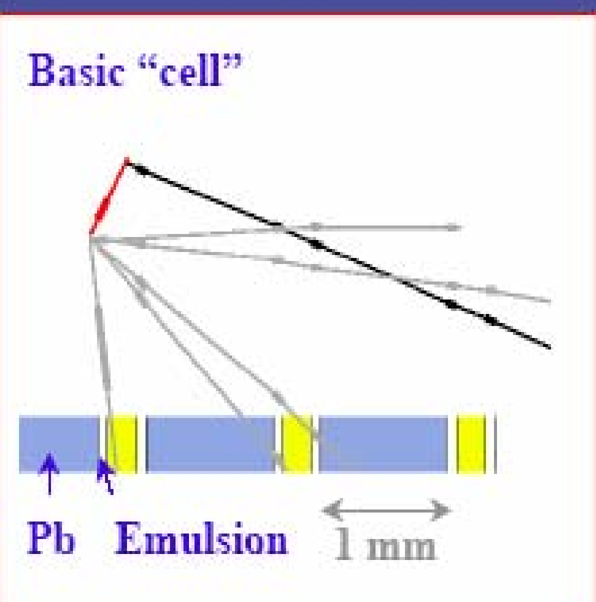
→ finds the brick of ν interaction

→ μ ID, charge and p




Emulsion analysis:

- ✓Vertex
- ✓Decay kink
- ✓e/gamma ID
- ✓Multiple scattering, kinematics



# Status and Plan of OPERA

- Production of detector subsystems has started
- Works in Gran Sasso Halls B and C are on-going
- In September 2003, started to install SM1 magnet and RPC
- August 2004, will install SM1 target
- July 2005, will stack bricks
- May 2006, will begin commissioning

# Physics Reach of OPERA

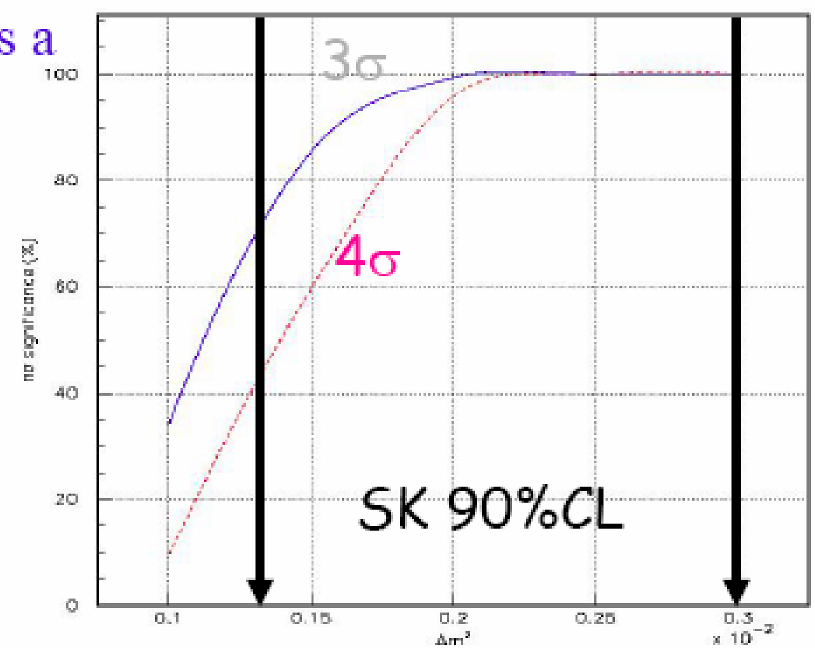
$\nu_\mu \rightarrow \nu_\tau$ search

full mixing, 5 years run @ $6.76 \times 10^{19}$ pot / year

| channel | Signal ($\Delta m^2$ ($eV^2$)) | | | ε.BR | Background |
|---|---|---|---|---|---|
| | $1.3\ 10^{-3}$ | $2.0\ 10^{-3}$ | $3.0\ 10^{-3}$ | | |
| e | 1.8 | 4.1 | 9.2 | 3.4% | 0.31 |
| μ | 1.4 | 3.4 | 7.6 | 2.8% | 0.33 |
| h | 1.5 | 3.5 | 7.8 | 2.9% | 0.42 |
| total | 4.7 | 11.0 | 24.6 | 9.1% | 1.06 |

5 YEARS

Nσ significance probability as a function of $\Delta m^2$



# $\nu_\mu \rightarrow \nu_e$ search:

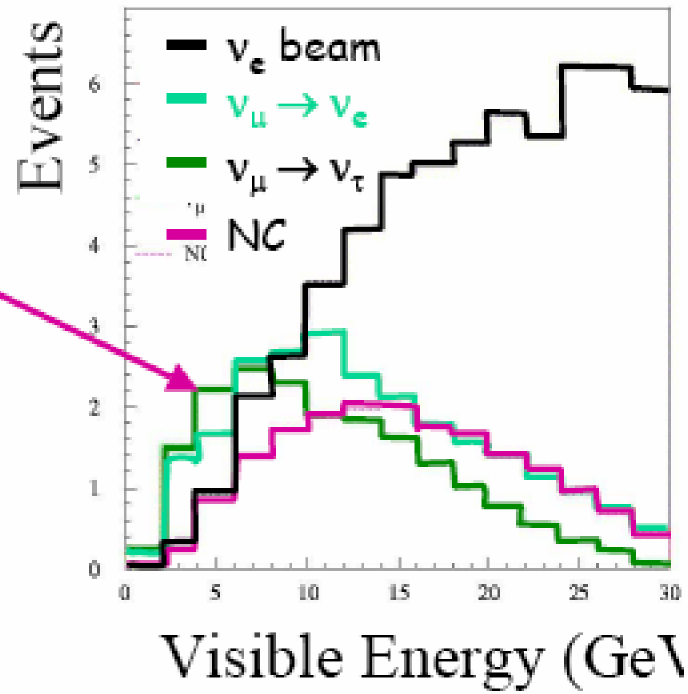
Assuming $\Delta m_{12}^2 << \Delta m_{23}^2 = \Delta m_{13}^2 = \Delta m^2$, in the 3 flavour $\nu$ oscillation framework

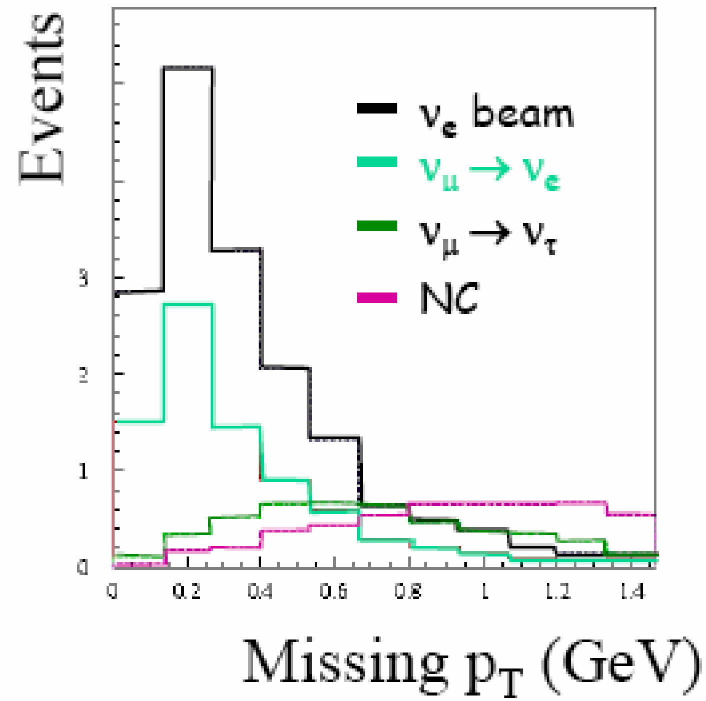
$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2(1.27\, \Delta m^2\, L/E)$

$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\, \Delta m^2\, L/E)$ ← subleading transition

- look for an excess of $\nu_e$ CC events
- take into account electron event from $\nu_\mu \rightarrow \nu_\tau$, $\tau \rightarrow e \nu_\tau \nu_e$

Both oscillations distort $E_{vis}$ at low energy




Fit oscillation components simultaneously → $\sin^2 2\theta_{13}$

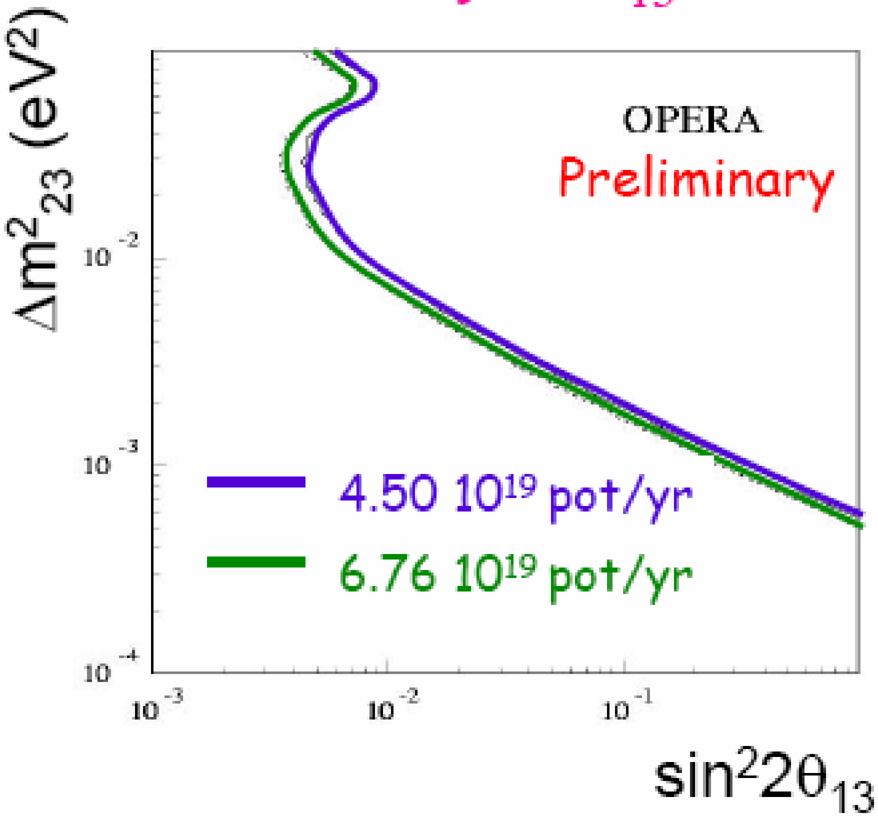
use $E_{vis}$, $P_T^{miss}$, $E_{el}$

## $\nu_\mu \rightarrow \nu_e$ expected signal and background 5 years: $2.25 \times 10^{20}$ pot

| $\theta_{13}$ (deg) | $\sin^2 2\theta_{13}$ | Signal $\nu_\mu \rightarrow \nu_e$ | $\nu_\mu \rightarrow \nu_\tau$ , $\tau \rightarrow e\nu_\tau\nu_e$ | $\nu_\mu$ CC | $\nu_\mu$ NC | $\nu_e$ CC |
|---|---|---|---|---|---|---|
| 9 | 0.095 | 9.3 | 4.5 | 1.0 | 5.2 | 18 |
| 7 | 0.058 | 5.8 | 4.6 | 1.0 | 5.2 | 18 |
| 5 | 0.030 | 3.0 | 4.6 | 1.0 | 5.2 | 18 |

syst. on the $\nu_e$ contamination up to 10%

## OPERA sensitivity to $\theta_{13}$




Limits at 90% CL for $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$ full mixing

| | $\sin^2 2\theta_{13}$ | $\theta_{13}$ |
|---|---|---|
| **CHOOZ** | **< 0.14** | **$11^0$** |
| **OPERA** | **< 0.06** | **$7.1^0$** |

# Conclusions

- In the next two years, the best knowledge on $\Delta m^2_{32}$ will still come from Super-Kamiokande and K2K, and may be MINOS as well.

- By the end of this decade, MINOS, ICARUS, and OPERA could either observe oscillation, or improve the limit in $\sin^2(2\theta_{13})$ to ~0.04 at 90% c.l.

This report is based on materials extracted from the web sites of Super-K, K2K, MINOS, ICARUS, OPERA, and talks of Nishikawa, Itow, Michael, Arneodo, and Duchesneau.