Neutrino Physics

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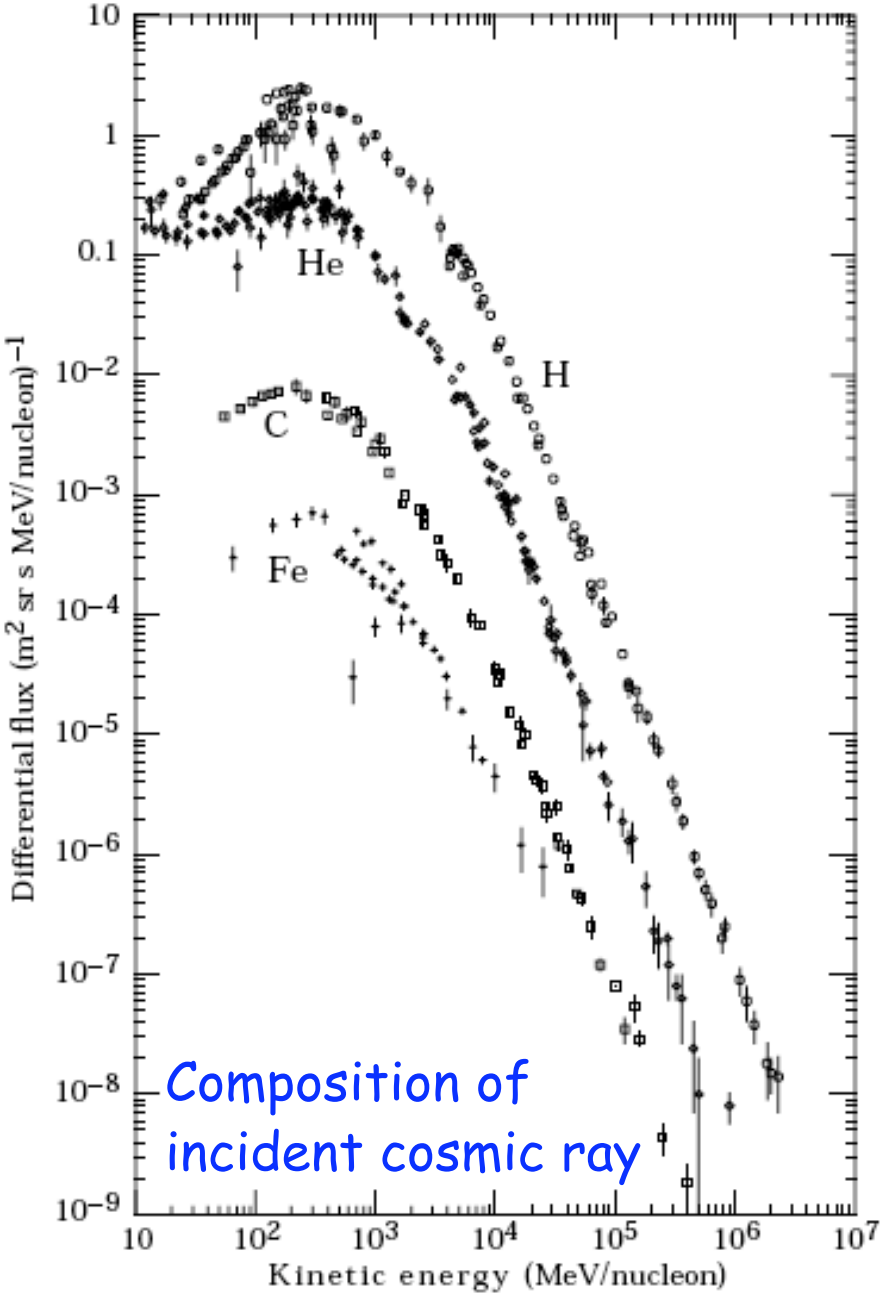
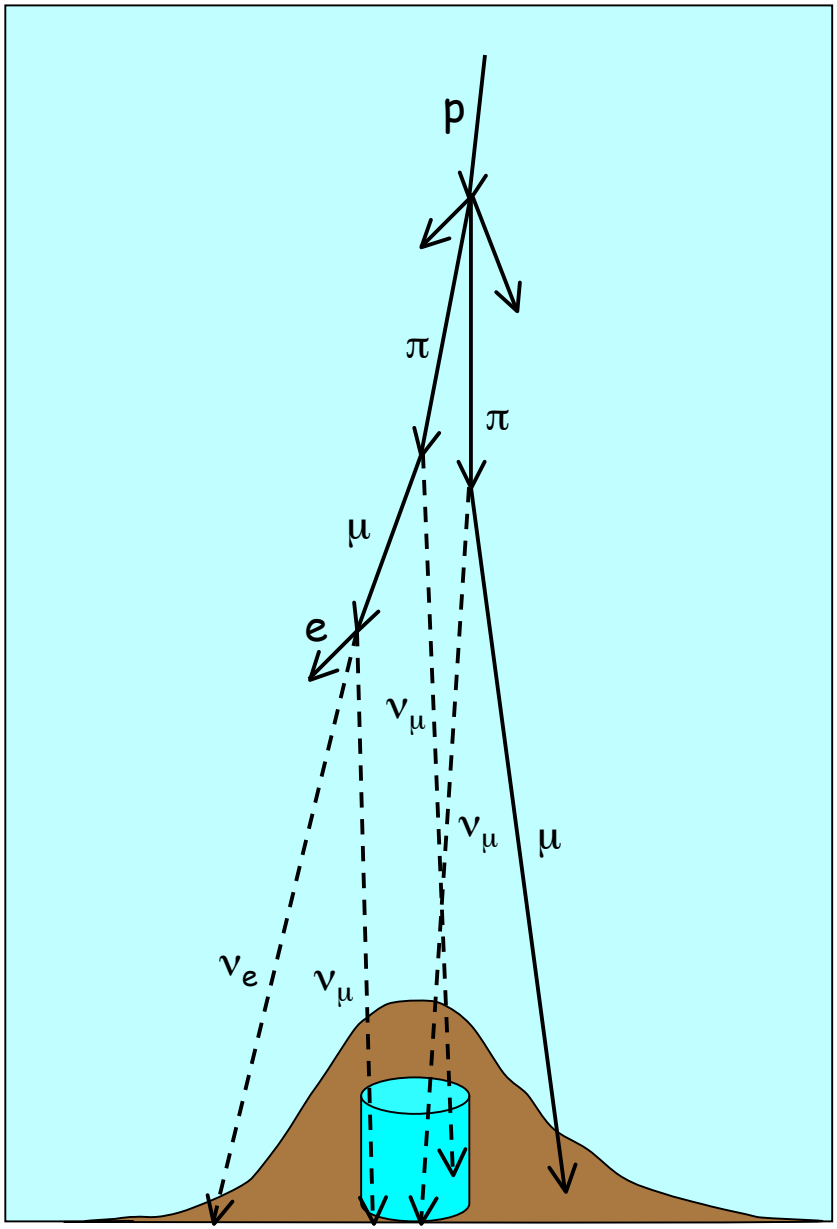
Outline

- Study of atmospheric neutrino
  - Super-K
  - Soudan 2
- Confirming atmospheric neutrino oscillation
  - K2K
  - MINOS

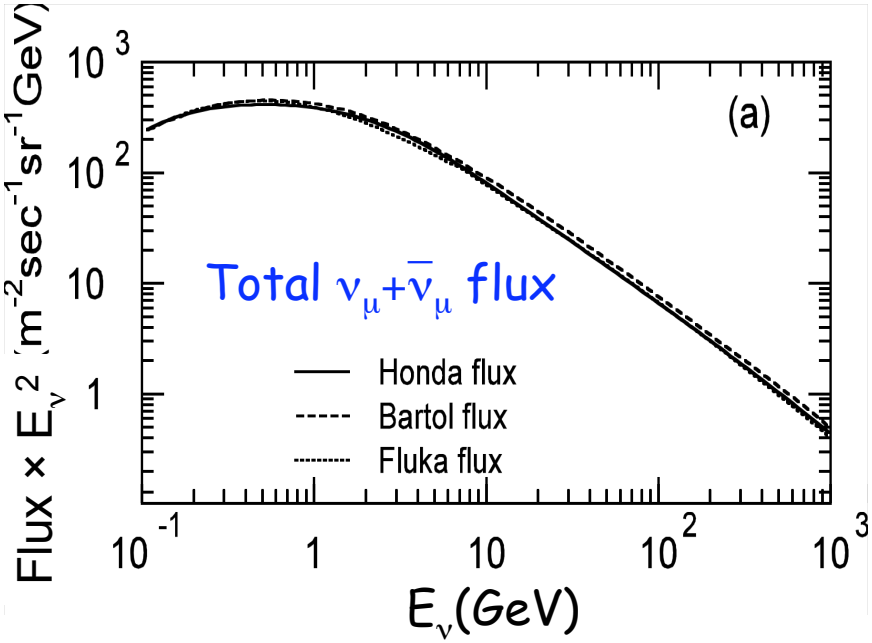
Production Of Cosmic-ray Neutrinos

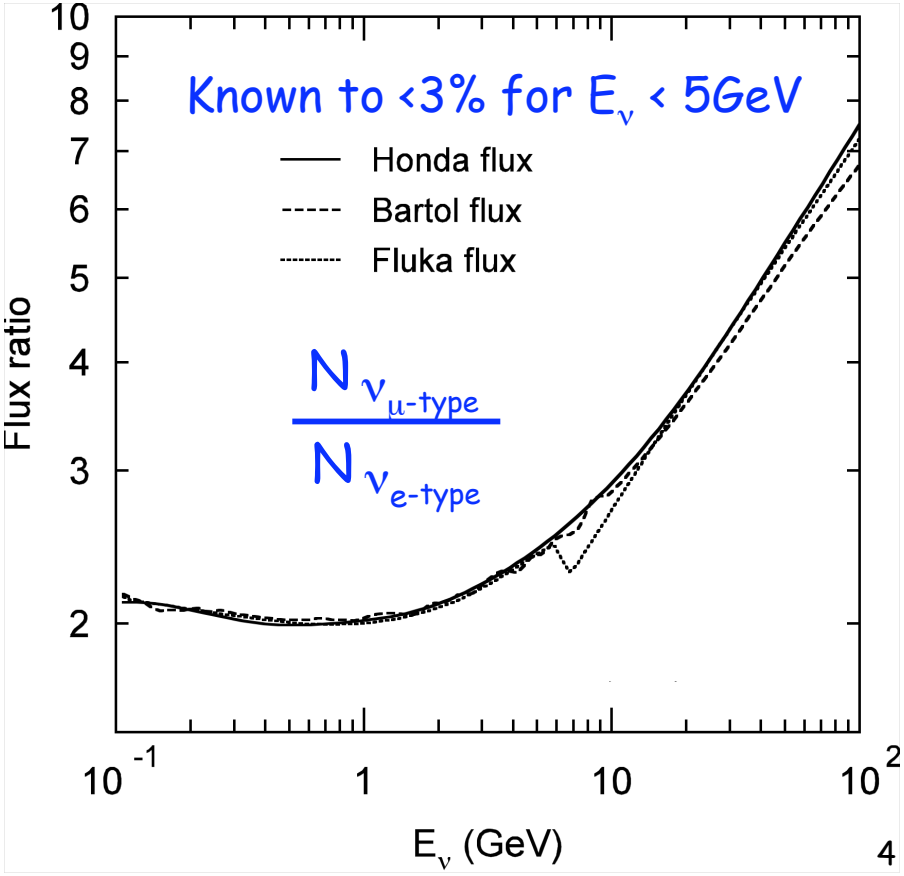




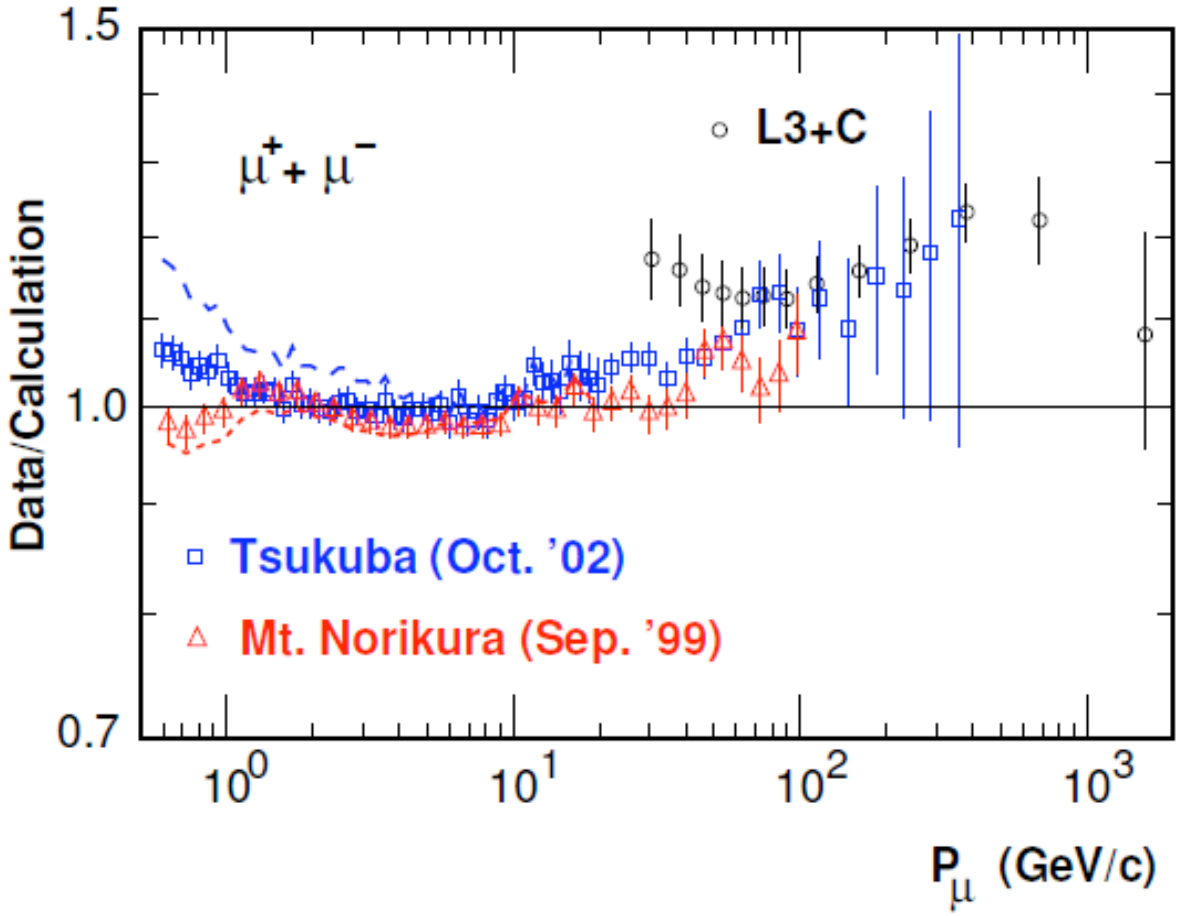
Estimating Atmospheric Neutrino Flux

- Use measured cosmic-ray intensity at upper atmosphere and cross section of p-nucleon interaction to calculate the numbers of π and K produced.
- Transport the mesons through the atmosphere, taking the effect of the geomagnetic field into account and allow them to decay.





Cross Check Calculation With Cosmic-ray Muons

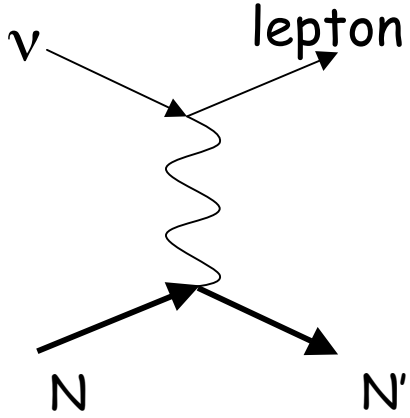


Calculation is good to better than 10% for momentum less than ~100 GeV

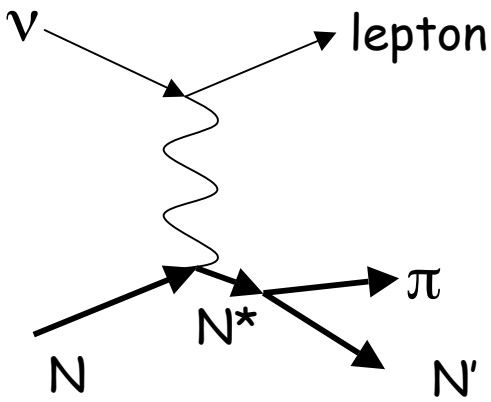
Neutrino Interactions

More on the charge-current processes:

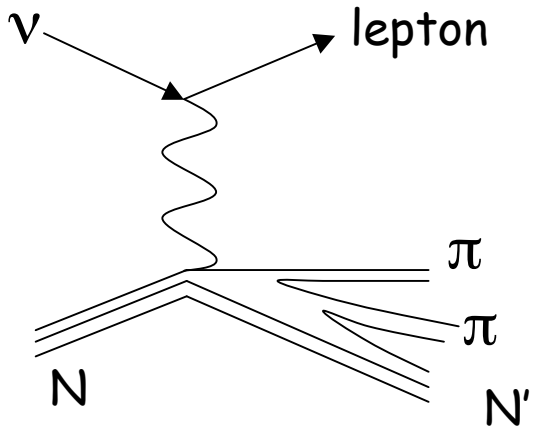
Quasi-elastic



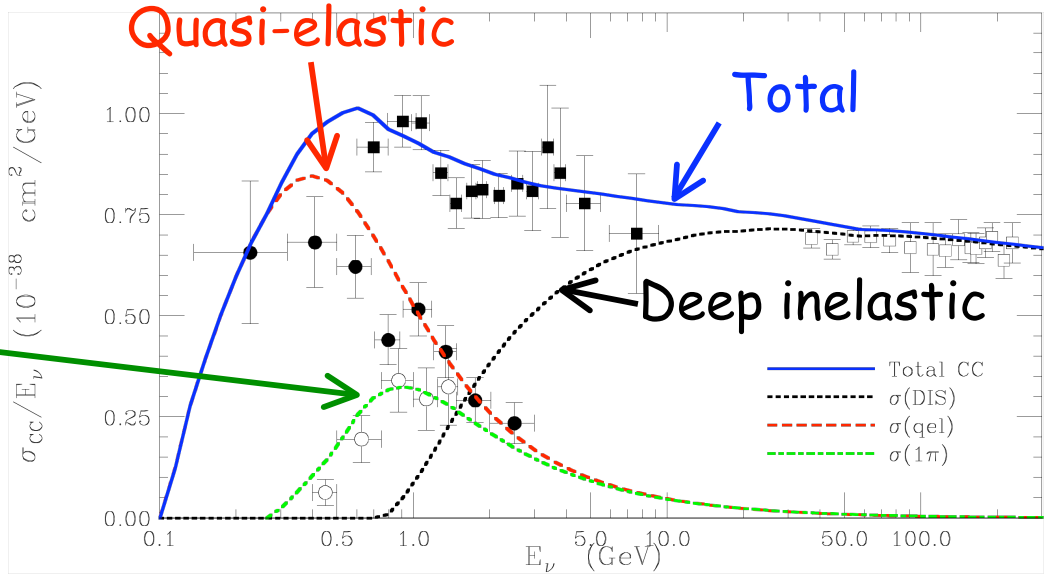
1π production



Deep inelastic

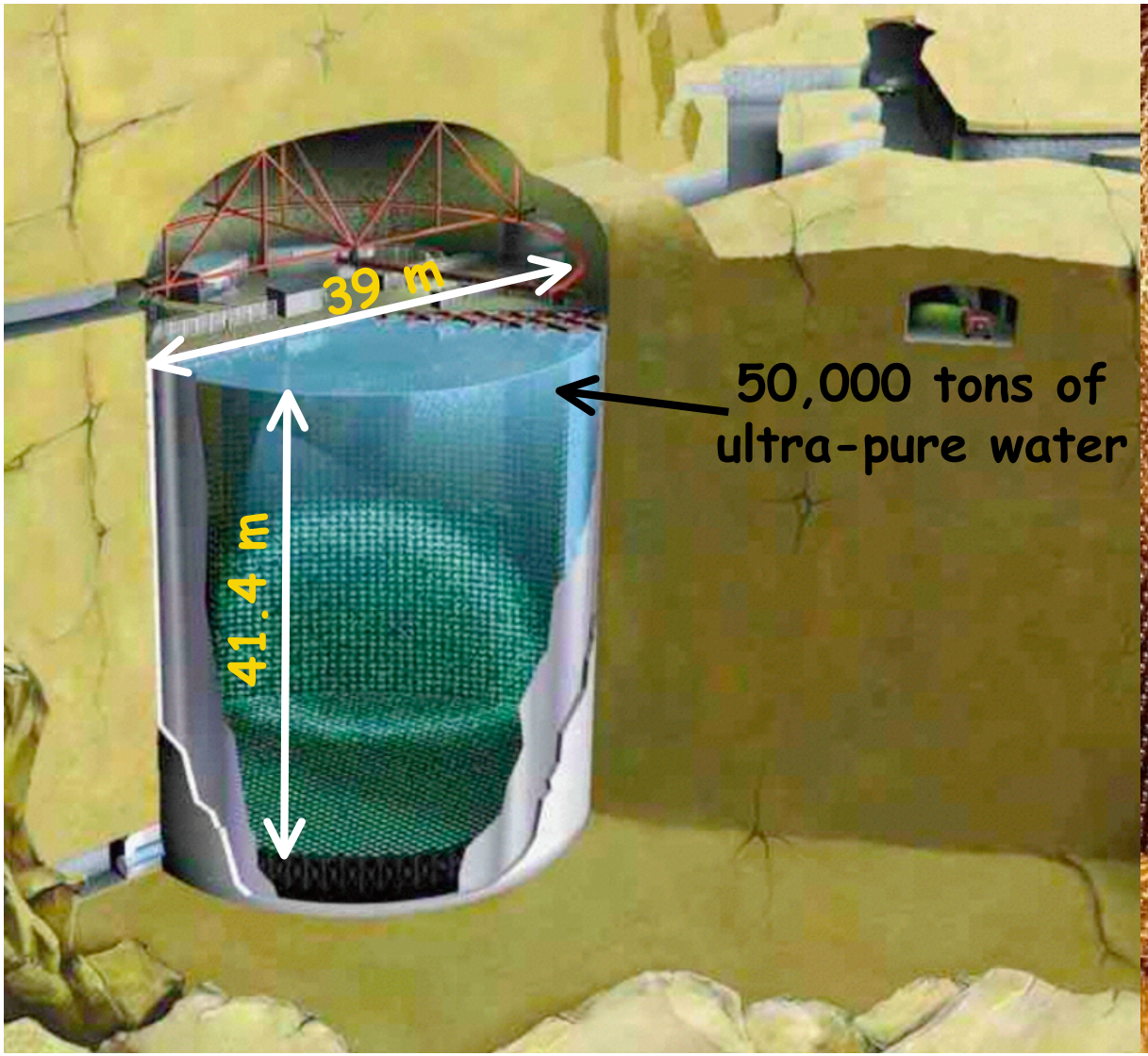


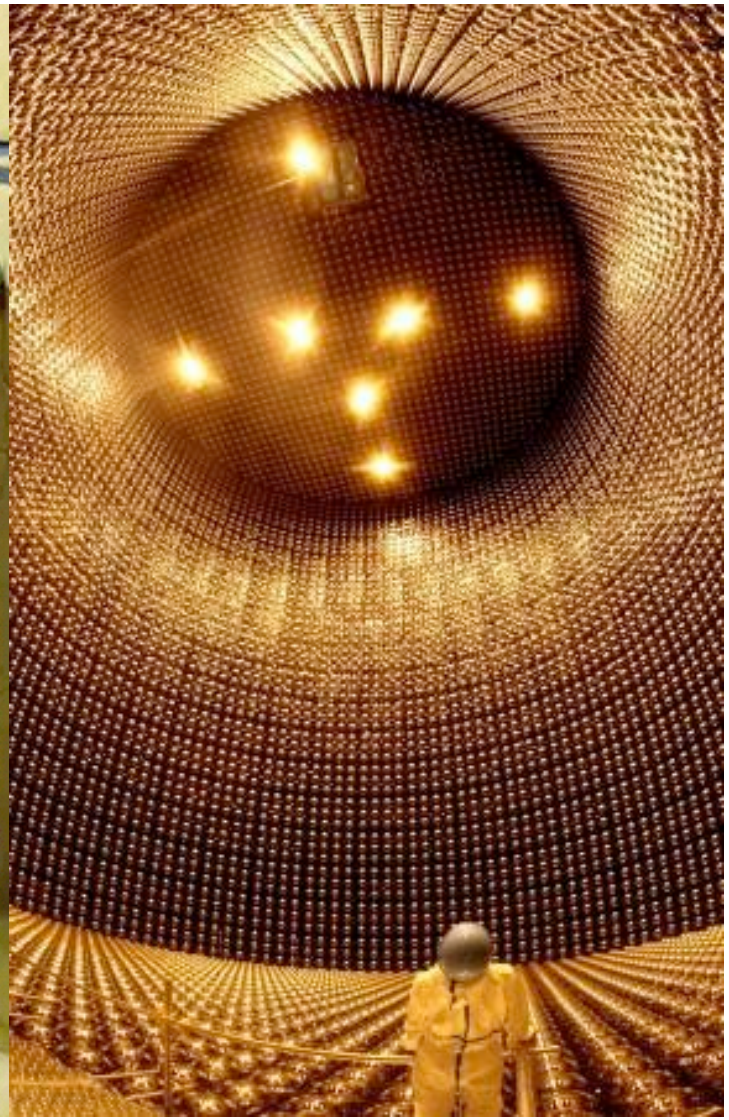
1π production



Study Atmospheric Neutrino With Water Cherenkov

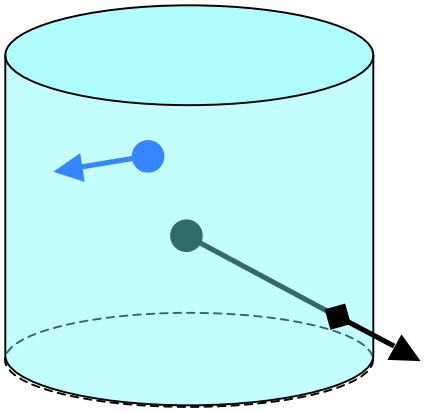
- Kamiokande, and Super-Kamiokande in Japan



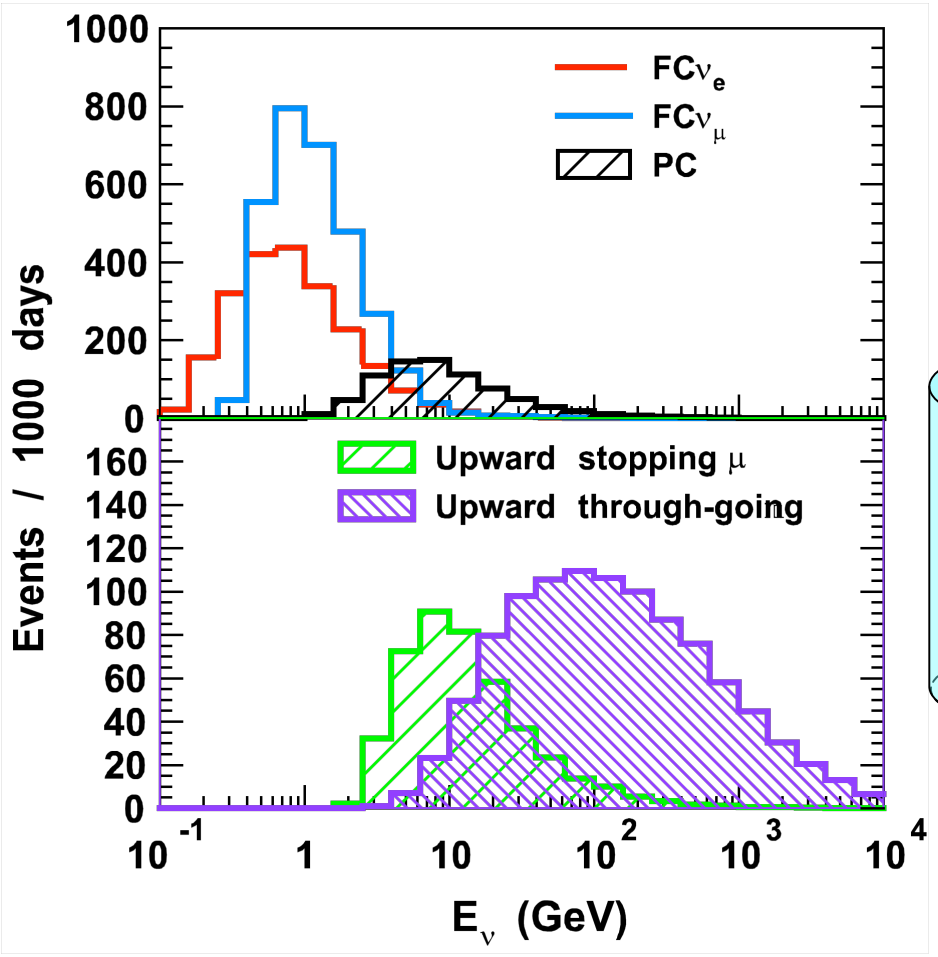


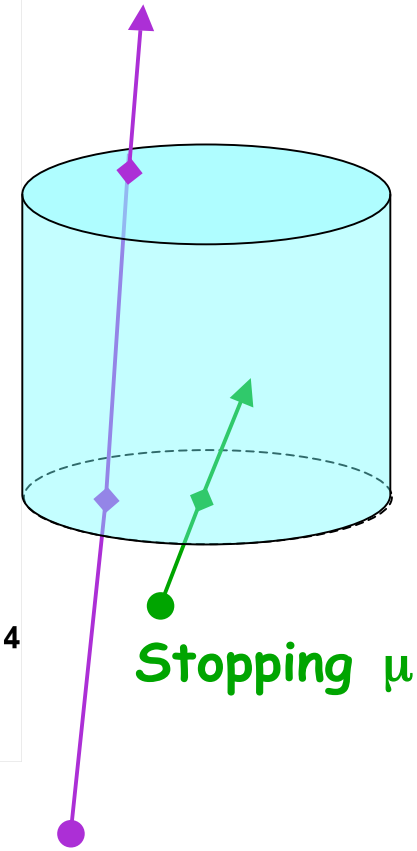
Classification Of Detected Neutrino Events

Fully Contained (FC)



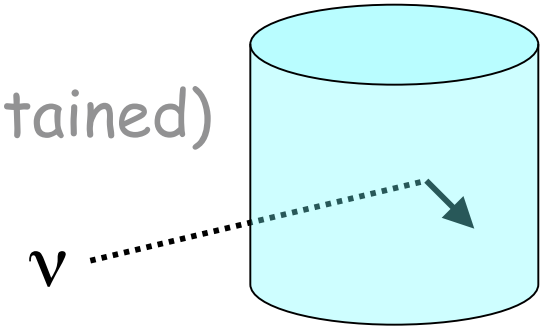
Partially Contained (PC)





Examples Of Charged-current Events

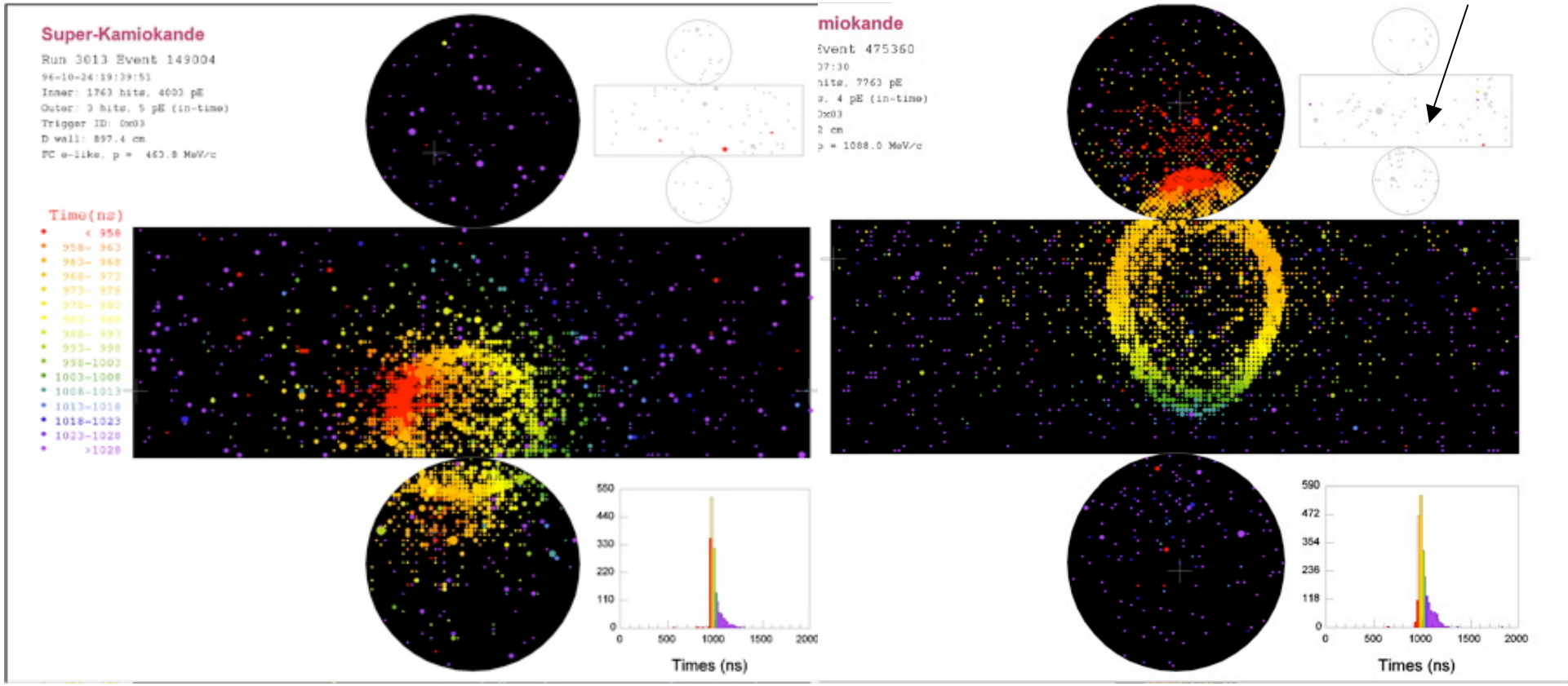
FC
(fully contained)



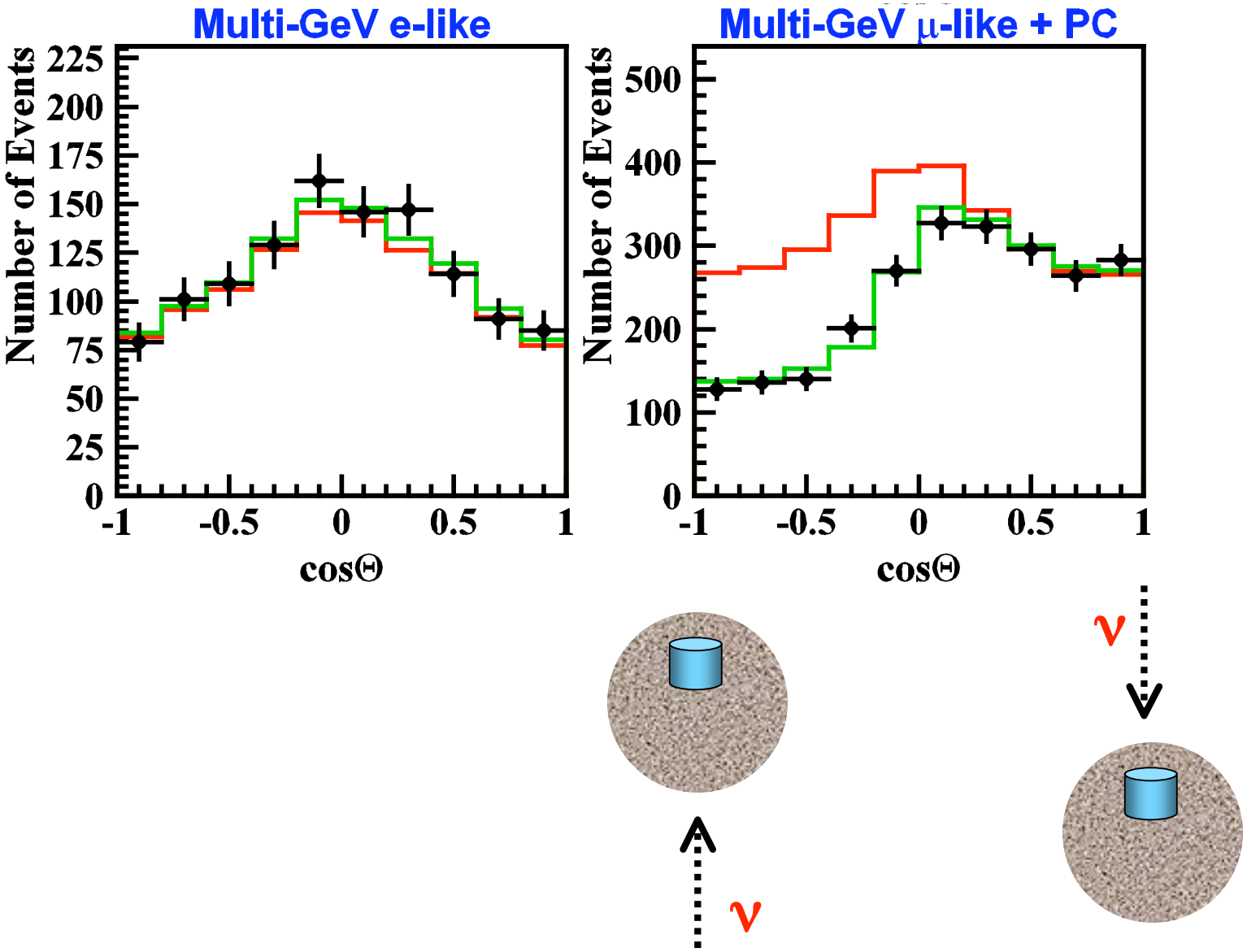
electron-like Cherenkov ring

muon-like Cherenkov ring

Outer detector
(no signal)



Surprising Behavior Of ν_μ

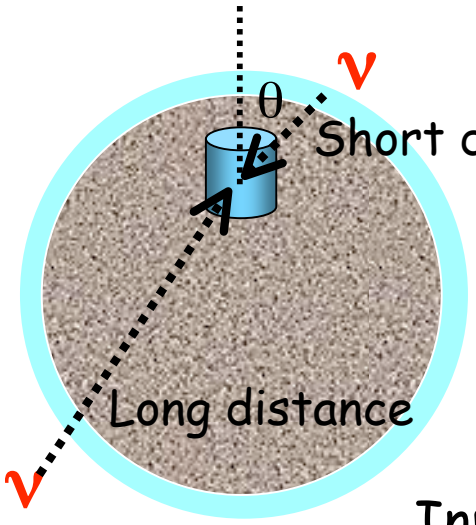


Interpretation Of Atmospheric ν Results

- The unexpected results are evidence of neutrino oscillation.
- There is no compelling evidence of $\nu_\mu \rightarrow \nu_e$ oscillation.
- The disappearance of ν_μ is due to $\nu_\mu \rightarrow \nu_\tau$ oscillation.
- Adopt 2-flavour model to analyze the data:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

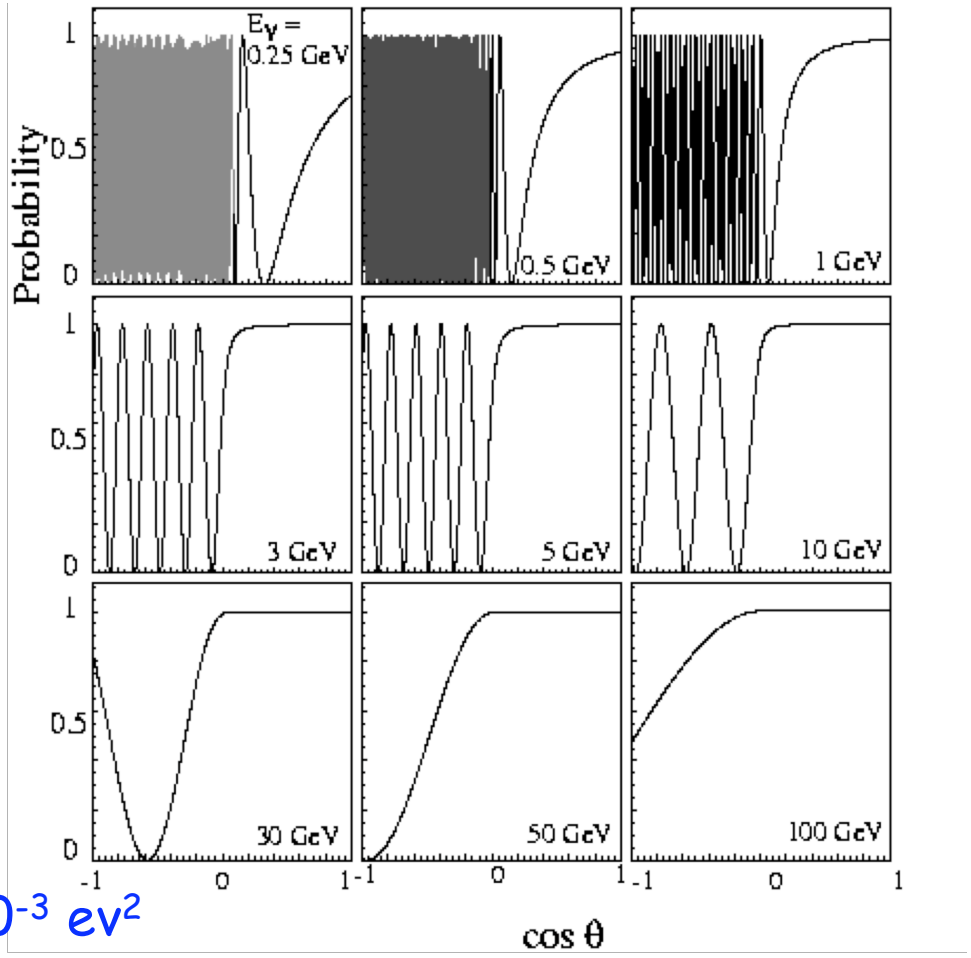
L changes with zenith angle



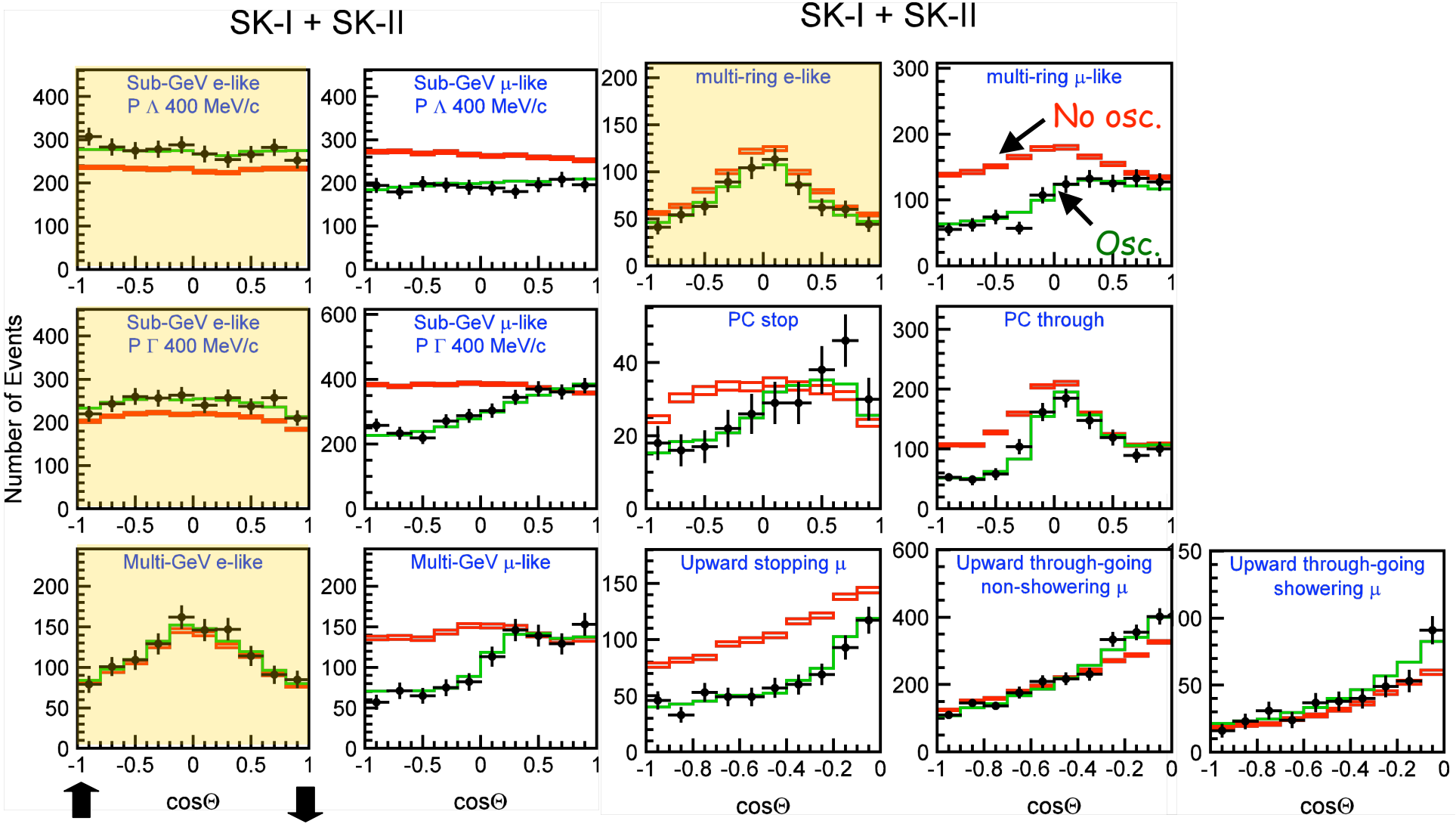
Inputs:

$\sin^2 2\theta = 1.0$,

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

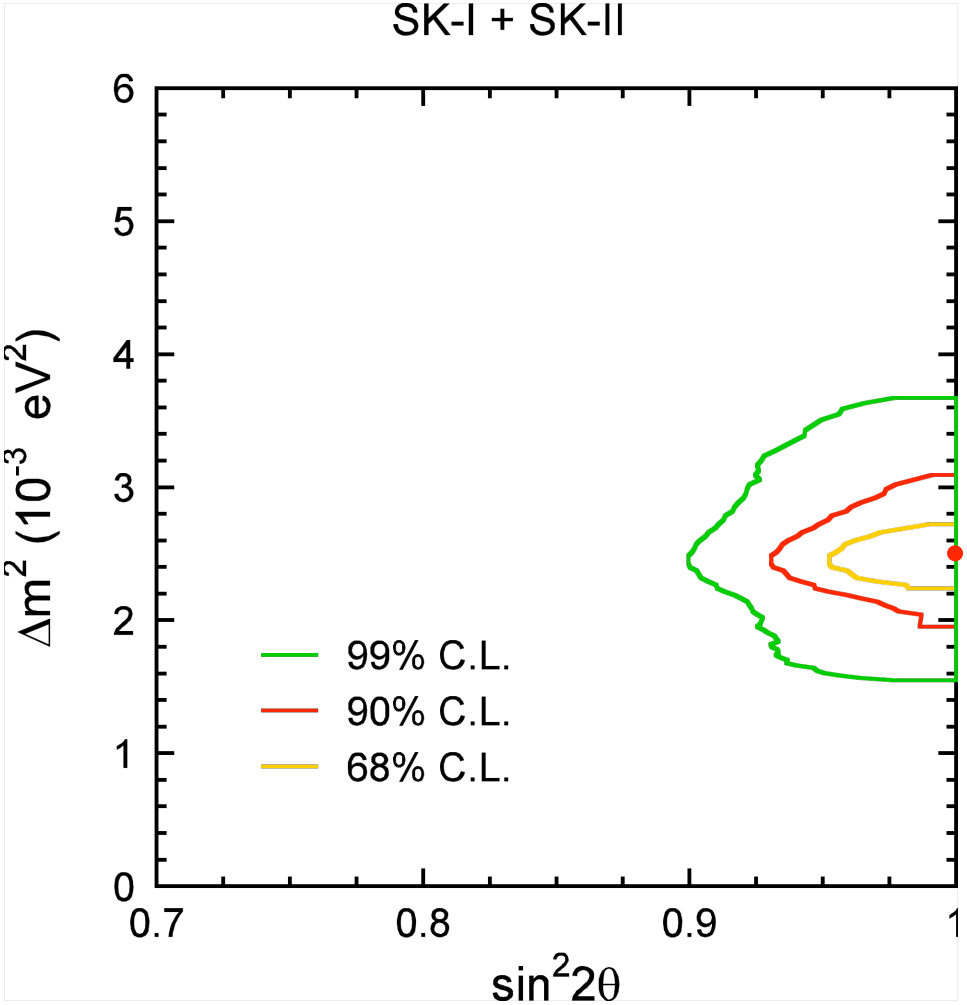


More Results From Super-K



Results On Oscillation Parameters

Using number of events only:



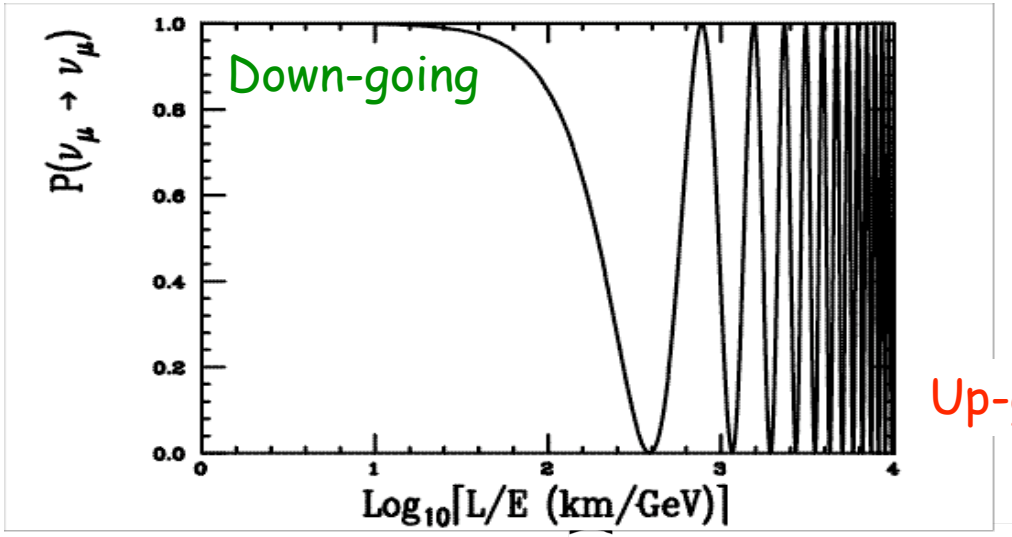
← Best Fit:

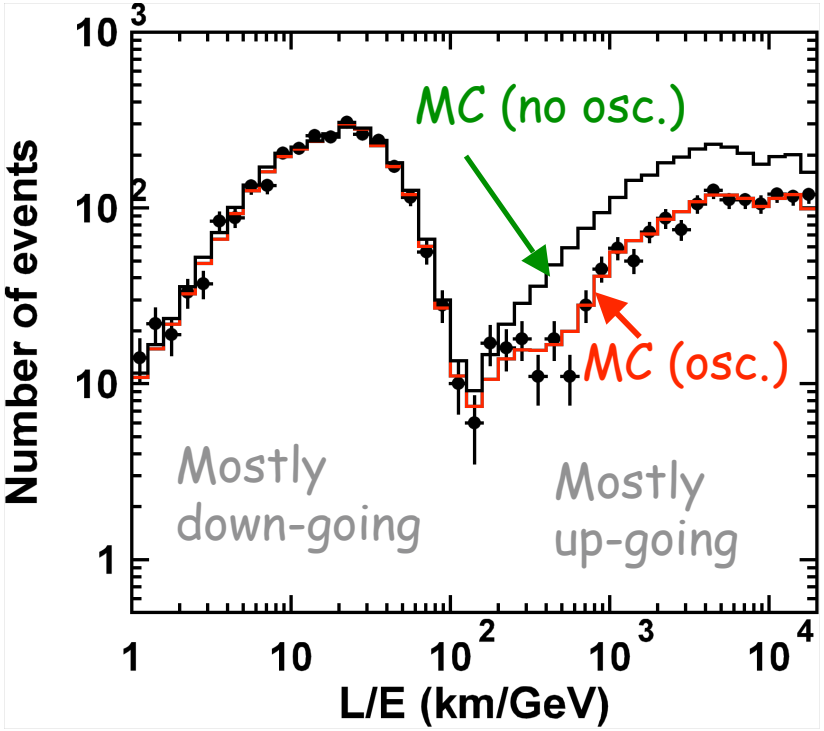
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

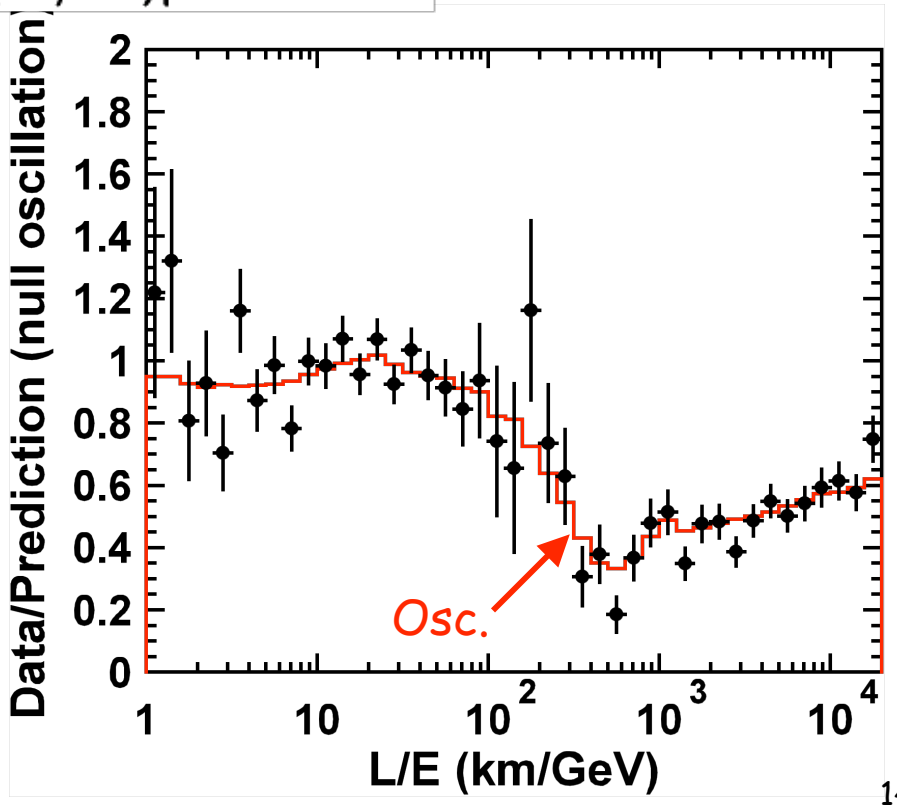
$\sin^2 2\theta = 1.00$

$\chi^2 = 839.7 / 755$ dof

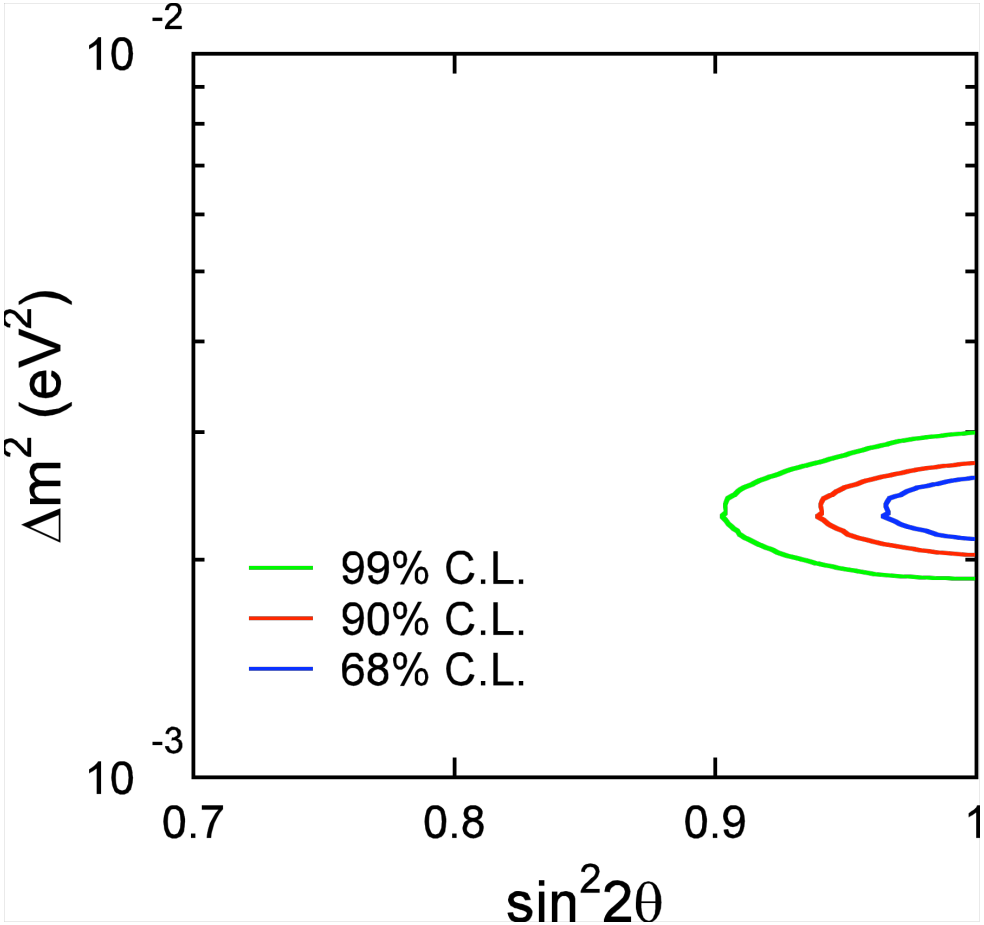
How About The Oscillation Pattern?







Results of Atmospheric Neutrino Oscillation

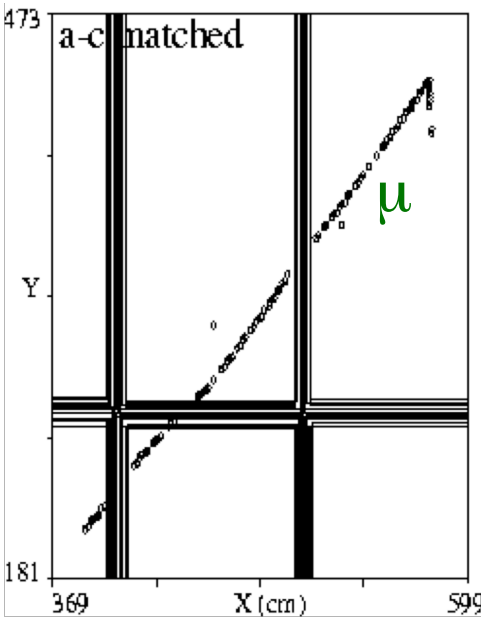


At 90% CL:

$2.0 \times 10^{-3}\ eV^2 < \Delta m^2 < 2.8 \times 10^{-3}\ eV^2$

$\sin^2 2\theta > 0.93$

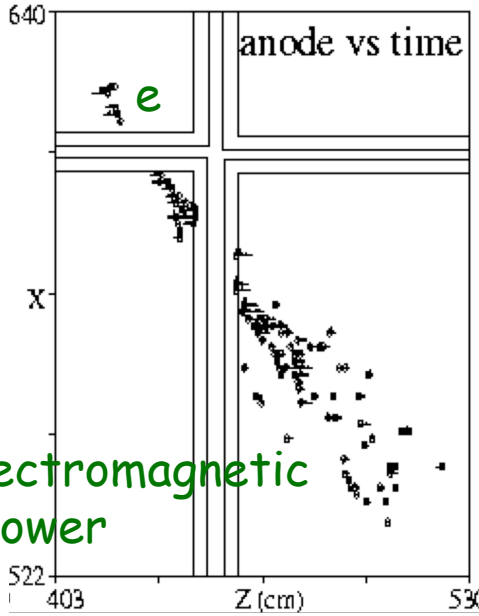
Soudan 2 In U.S.A.



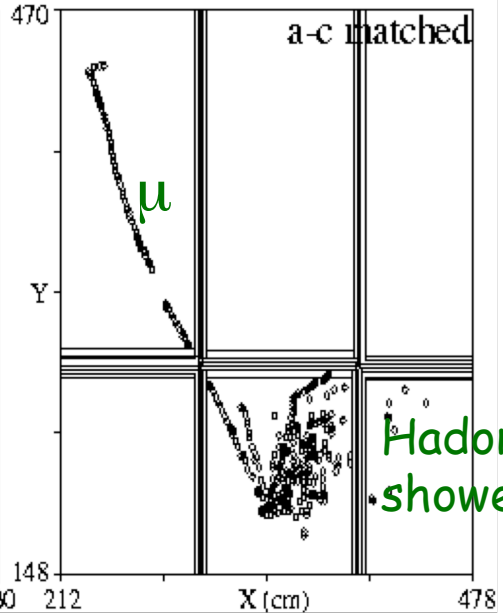
ν_μ CC

Quasi-elastic

ν_e CC



electromagnetic shower



Hadonic shower

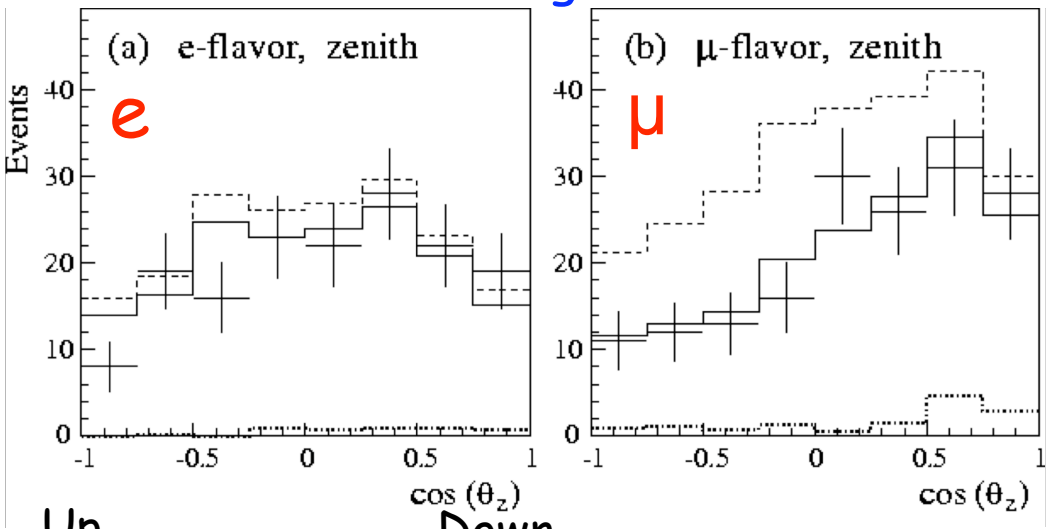
ν_μ CC

Deep inelastic

Confirmation From Soudan 2

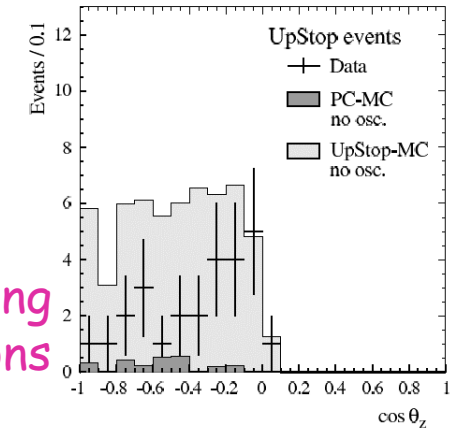
- 5.9 kton-yr exposure
- Studied partially-contained and upward stopping muon events.
- Measured L/E with the high resolution sample

Zenith angle



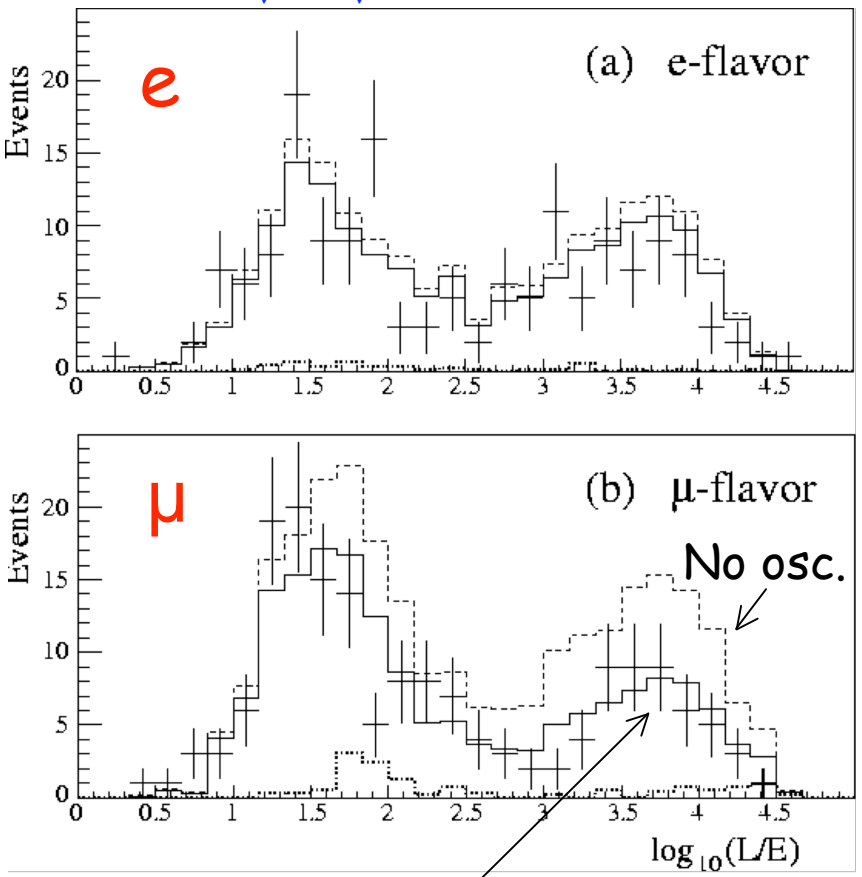
Up-going

Down-going



Upward stopping muons

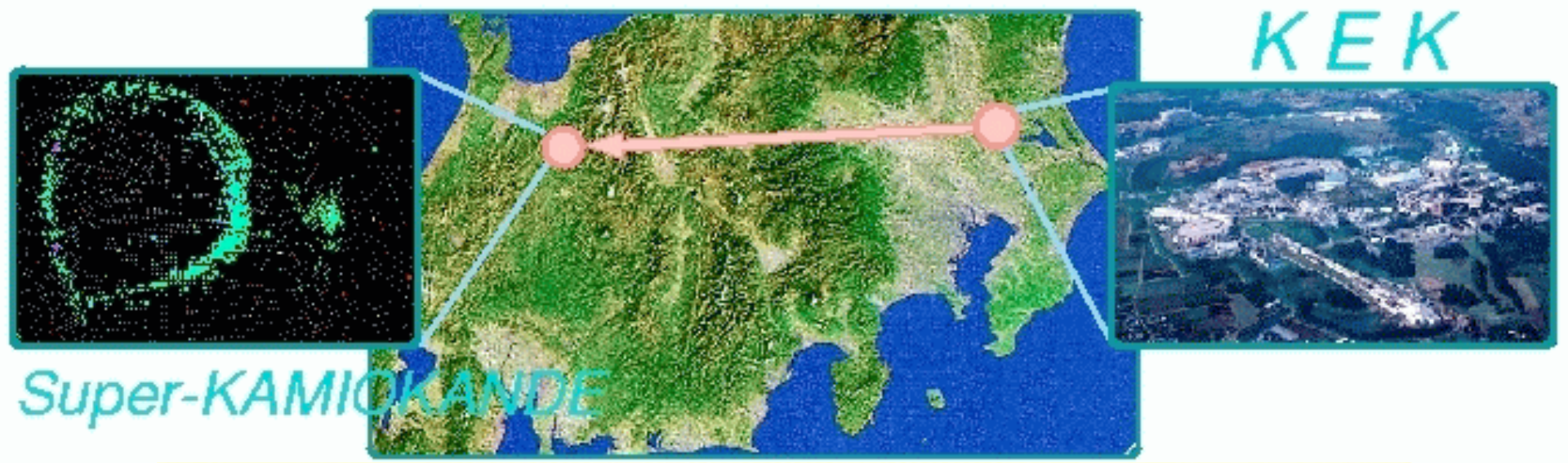
L_ν / E_ν distribution

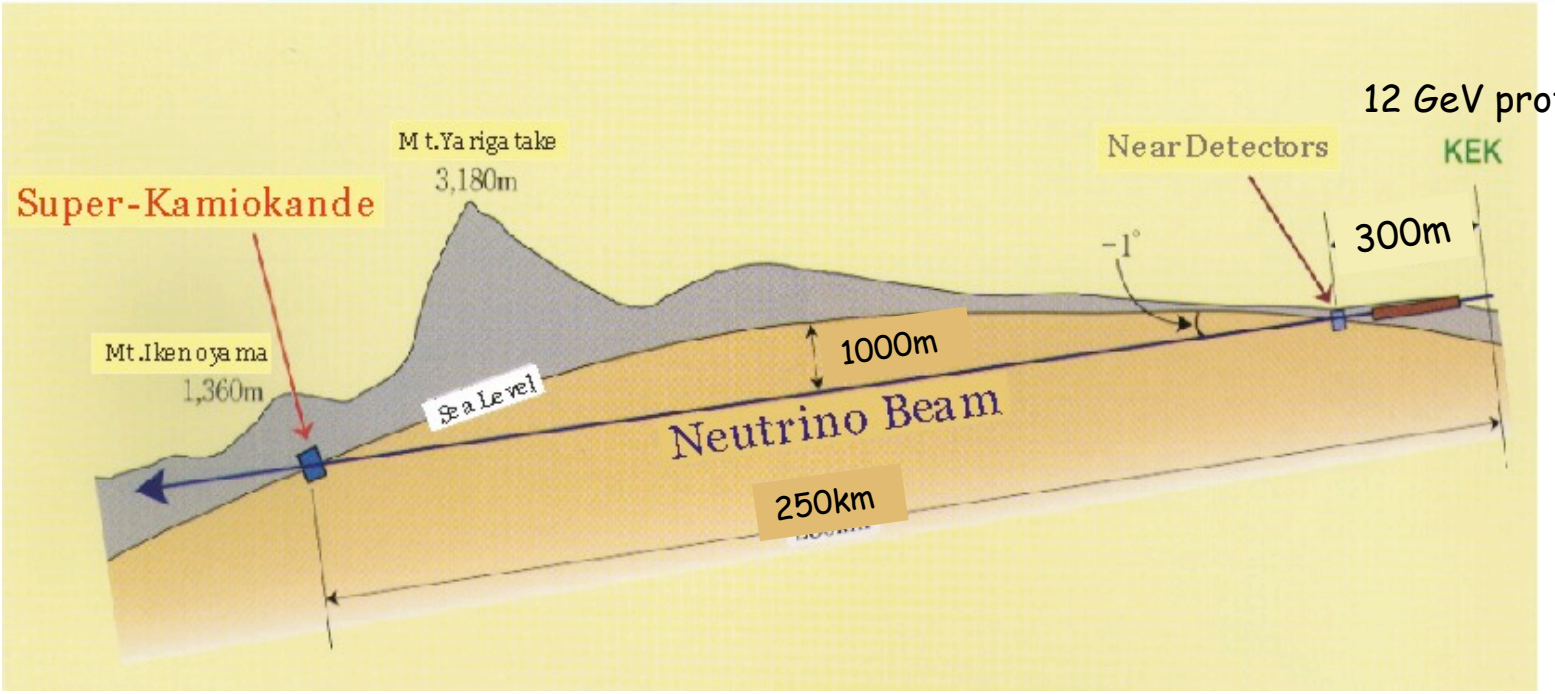


$\nu_\mu \rightarrow \nu_\tau$ osc.

Verifying The Atmospheric Neutrino Results With Artificial Muon-neutrino Beams

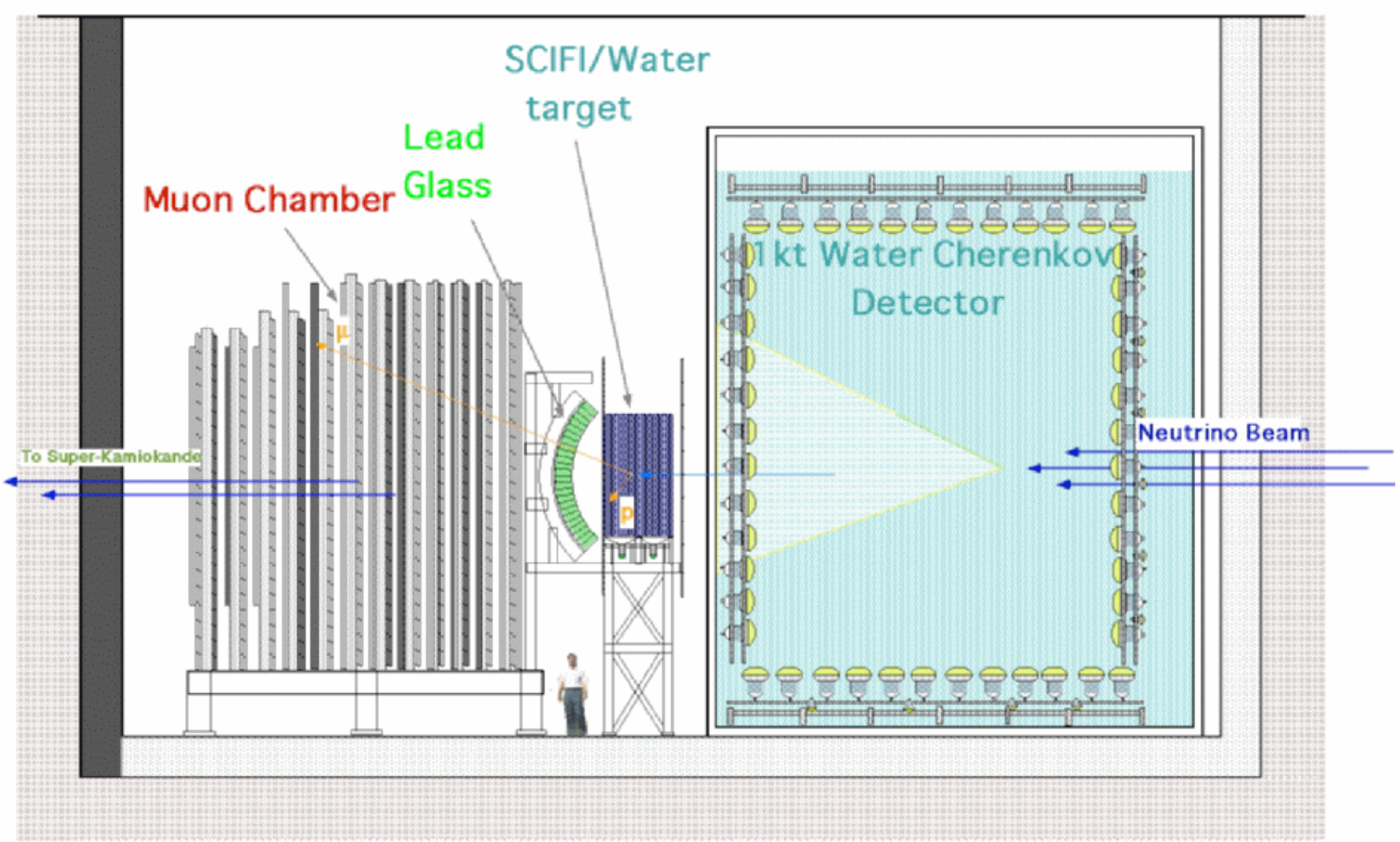
K2K: Long-baseline Neutrino Oscillation Experiment





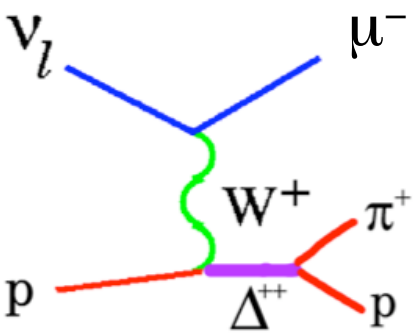
Near Detector of K2K

- To determine the neutrino flux and its energy distribution
- Study low-energy charged-current neutrino reactions

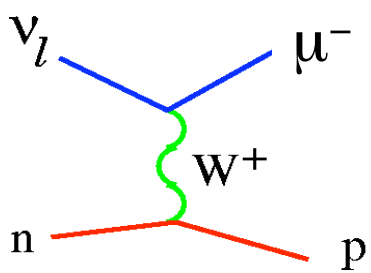


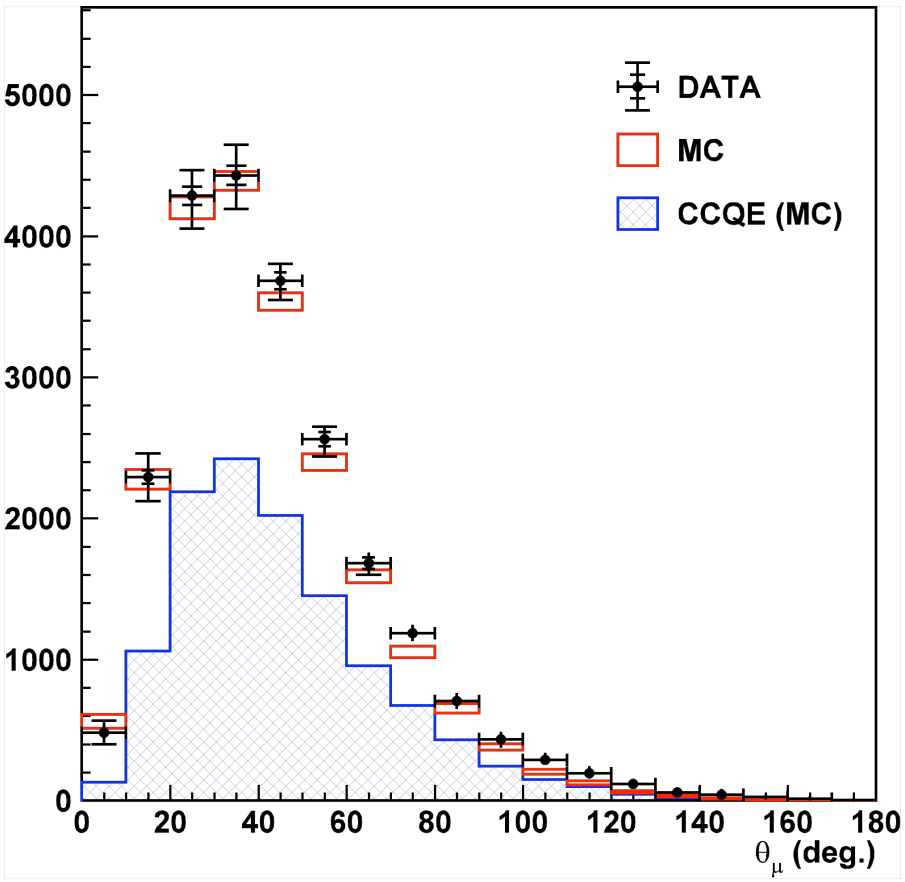
Study Charged-current With Near Detector

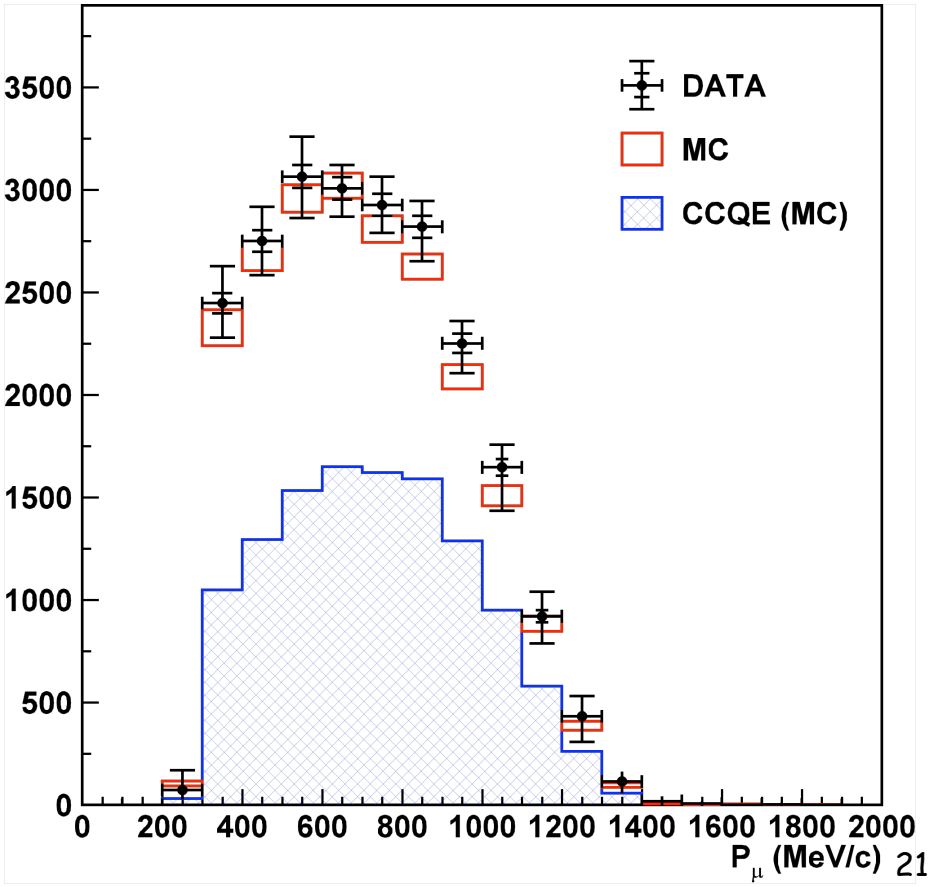
non-QE



QE

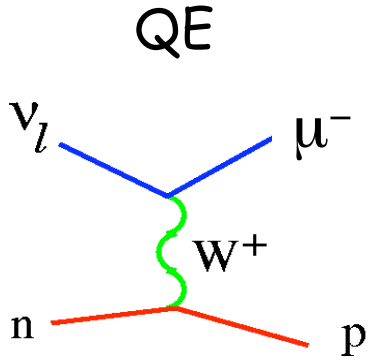






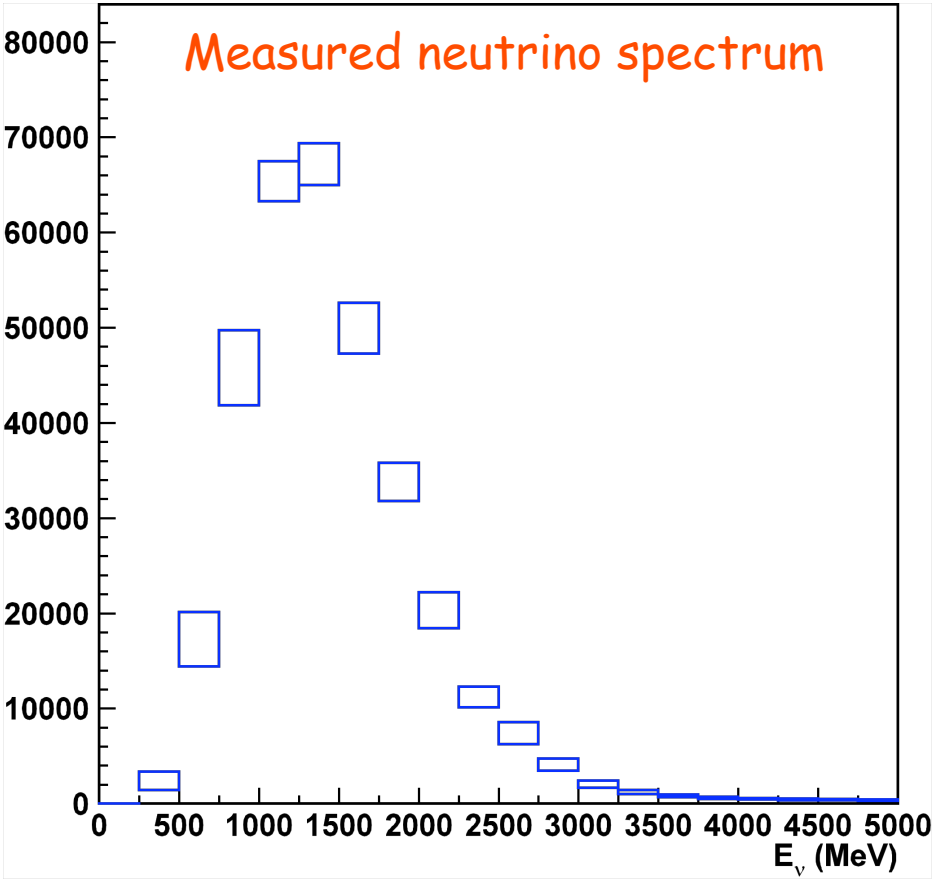
Determining The Neutrino Spectrum

The energy of ν_μ is related to the muon momentum in quasi-eleastic scattering:

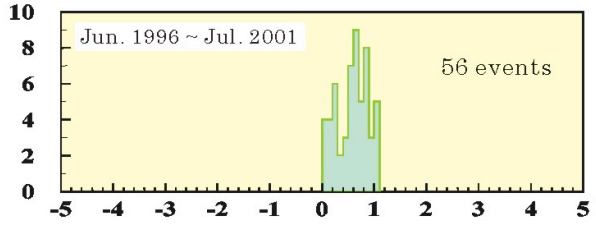


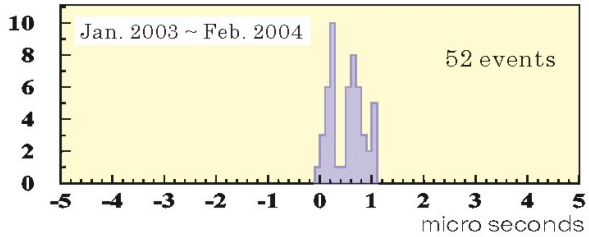
From kinematics:

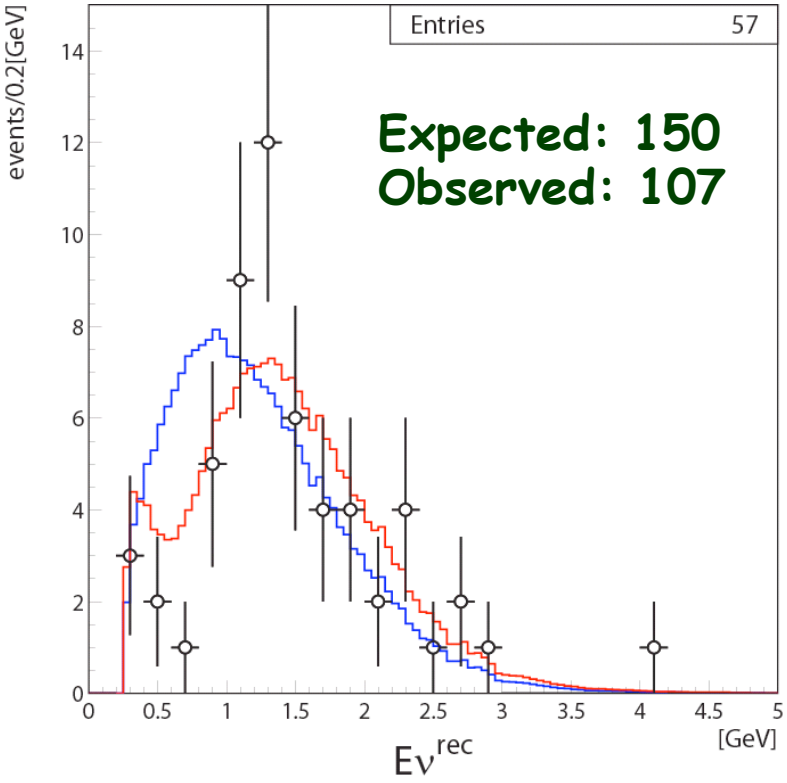
$$E_\nu = \frac{m_N E_\mu - \frac{1}{2} m_\mu^2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

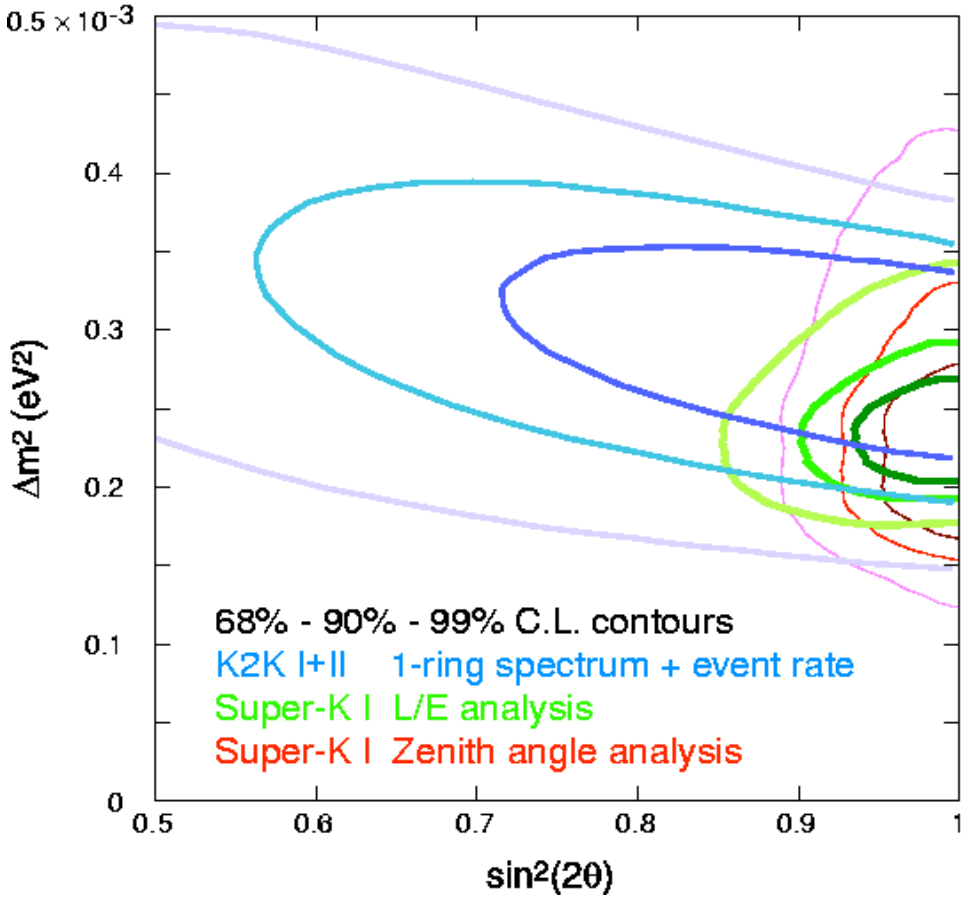


Indeed ν_μ Oscillates !!







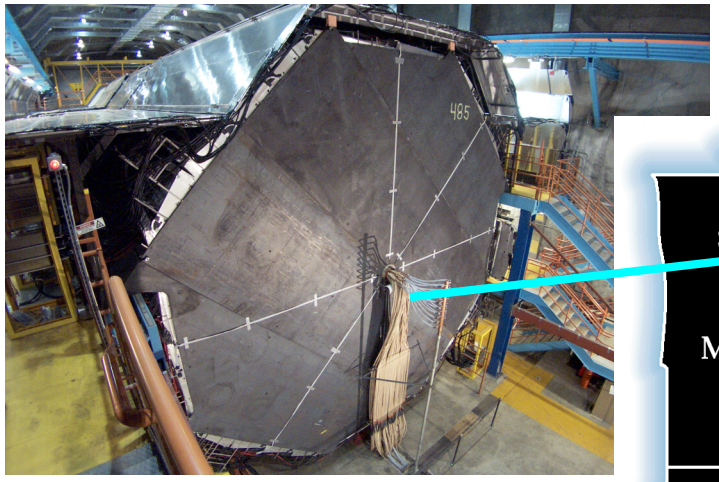


Best fit result:

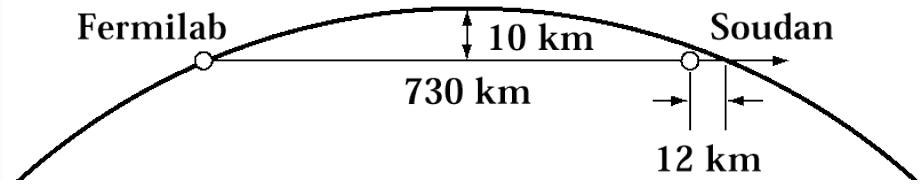
$\Delta m^2 = 2.8 \times 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.0$

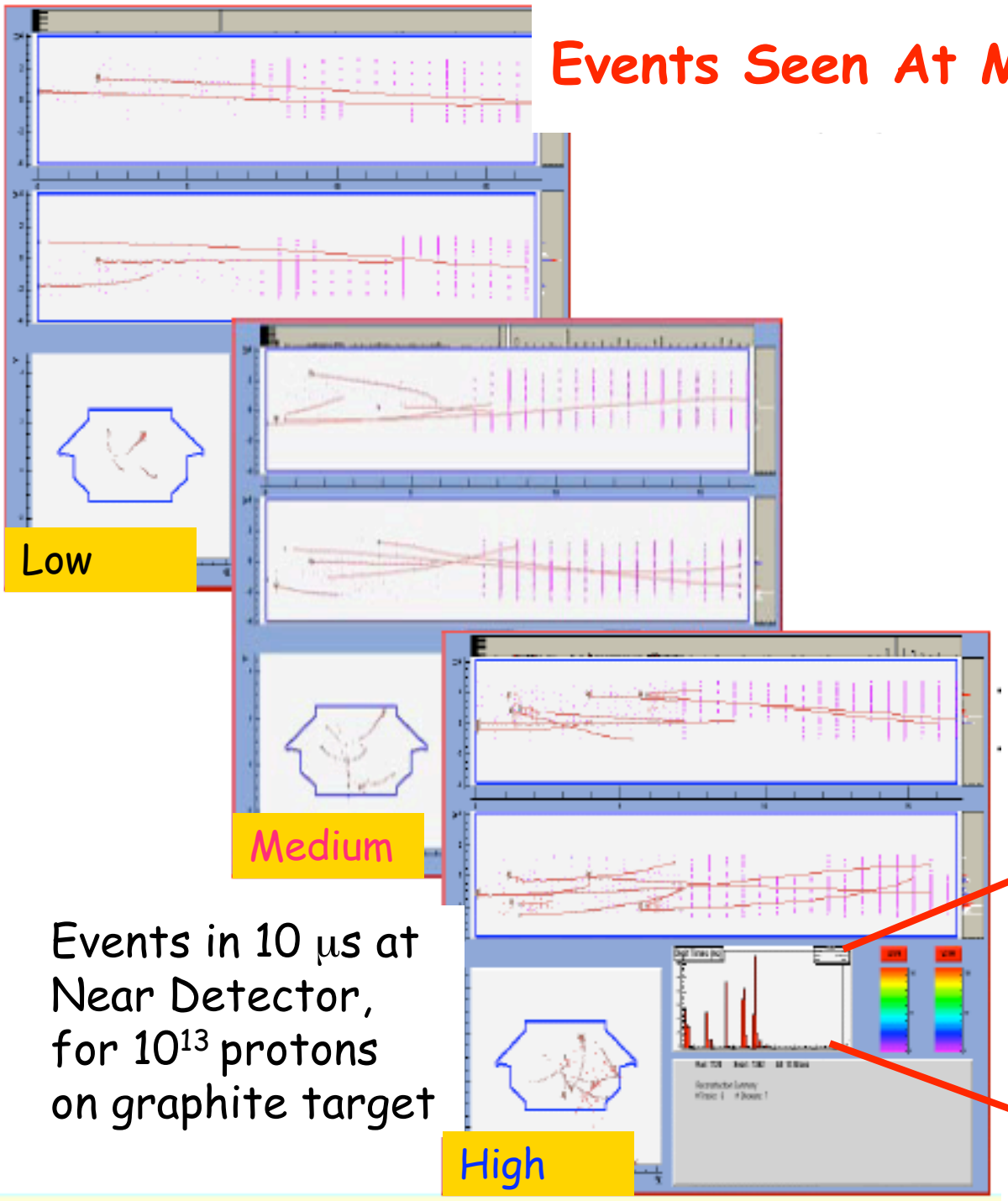
MINOS

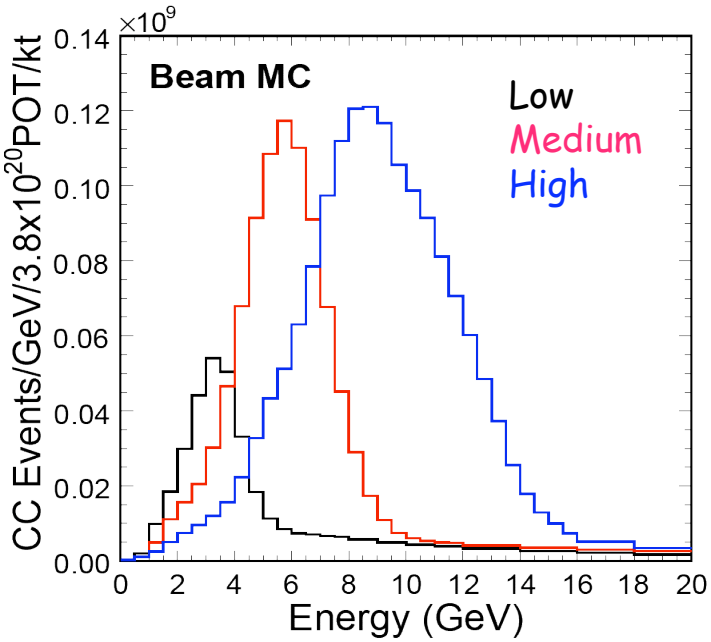


5.4 kt magnetized iron-scintillator used as a tracker and calorimeter

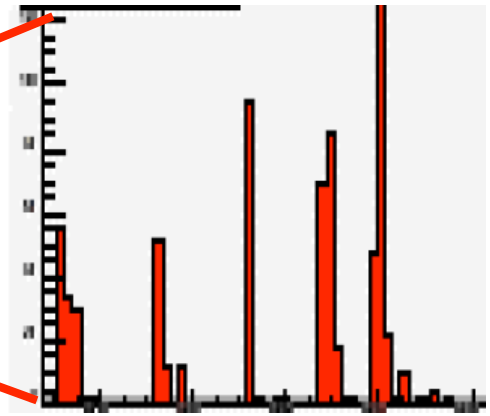


Events Seen At MINOS Near Detector



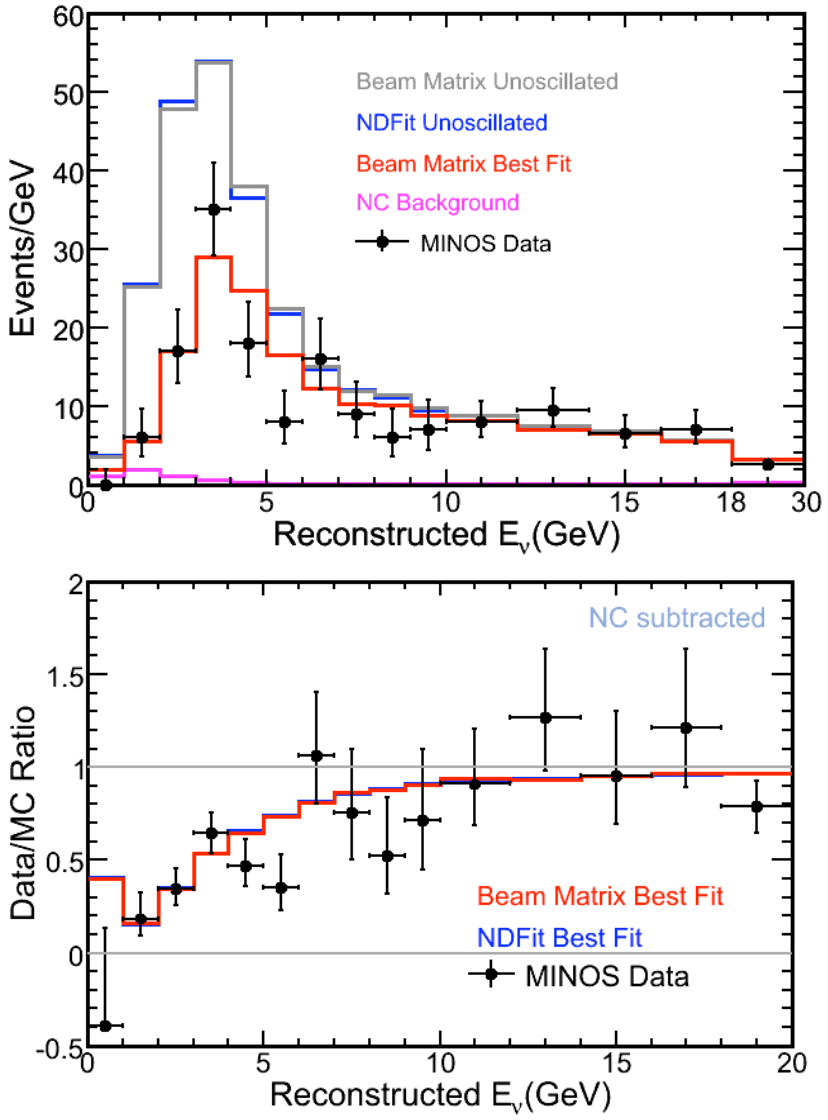


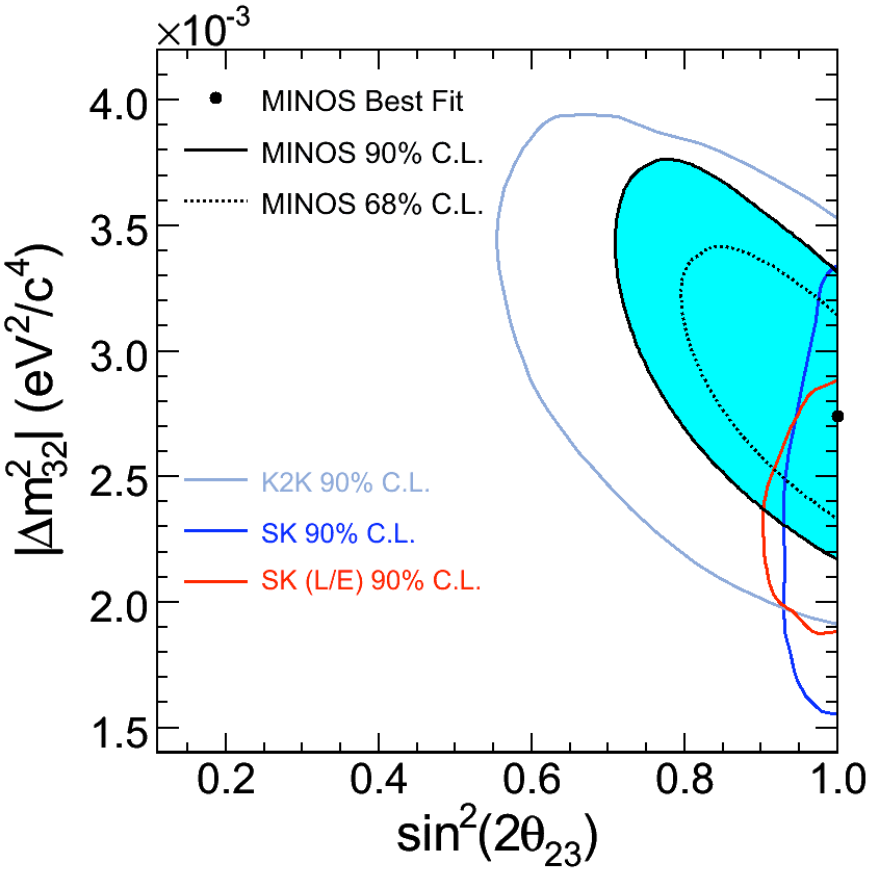
Signal Time (nsec)



Events in 10 μs at Near Detector, for 10^{13} protons on graphite target

First Disappearance Result From MINOS





$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26}\ (\text{stat}+\text{syst})\times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}\ (\text{stat}+\text{syst})$$

Summary

- Study of atmospheric neutrinos led to the discovery of significant disappearance of ν_μ but not ν_e, providing strong evidence for another type of neutrino oscillation.

- This observation has been confirmed by other underground, and accelerator-based experiments.

- Again, the new set of mixing parameters θ and Δm^2 using the 2-flavour formalism is measured.