

Mapping the Neutrino Mixing Matrix with Long Baseline Neutrino Experiments



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UBC

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The Building Blocks of Matter

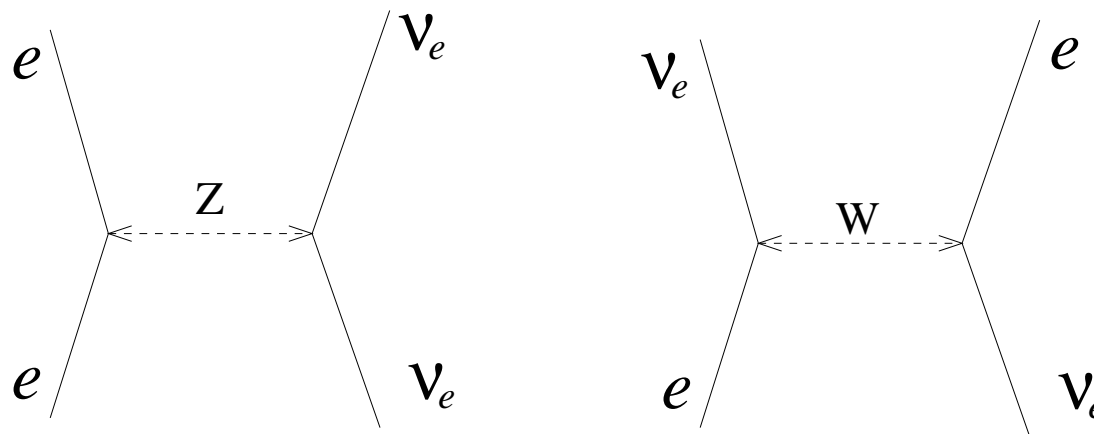
Leptons	Quarks	u up	c charm	t top		
		d down	s strange	b bottom		
		ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino		
	e electron	μ muon	τ tau			
	I			II		III
	The Generations of Matter					

A neutrino is a neutral cousin of the electron and the other charged leptons:

- Chargeless
- (Almost) Massless — $m < \text{few eV}$ (electron is 511 keV)
- Only weak interactions — go right through ordinary matter
- Come in 3 different “flavours”

Why do neutrinos interact so weakly?

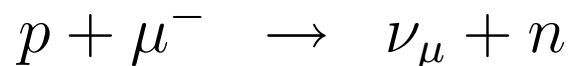
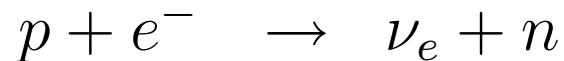
- No electric charge — no electromagnetic interactions
- No “colour” — no strong interactions
- Only weak interactions — carried by very heavy W, Z particles with short ranges



Neutrino interactions are very rare, hard to see!

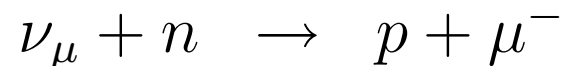
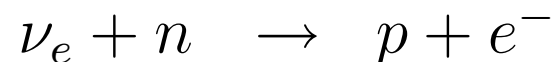
Different Kinds of Neutrinos: “Flavours”

Each charged lepton (e, μ, τ) has its own kind of neutrino. For example, in these reactions you get:



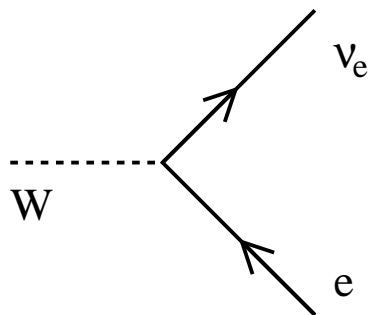
Note that the number of particles of each flavour type seems to be conserved in each reaction.

Flavour is also conserved in the other direction:



Neutrino Mixing

Weak interactions couple each charged lepton to its neutrino.



But what if the flavor eigenstates (ν_e, ν_μ, ν_τ) are not equal to the free particle (mass) eigenstates?

$$|\nu_e\rangle = \cos\theta |\nu_1\rangle + \sin\theta |\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta |\nu_1\rangle + \cos\theta |\nu_2\rangle$$

This is a rotation of the mass eigenstates relative to the flavor eigenstates.

Suppose we make a ν_e with momentum p . Each mass component propagates with a QM phase factor

$$\exp(i(px - Et)/\hbar) =$$

$$\exp(i(pct - \sqrt{p^2c^2 + m^2c^4}t)/\hbar)$$

A relative phase difference develops between the two components.

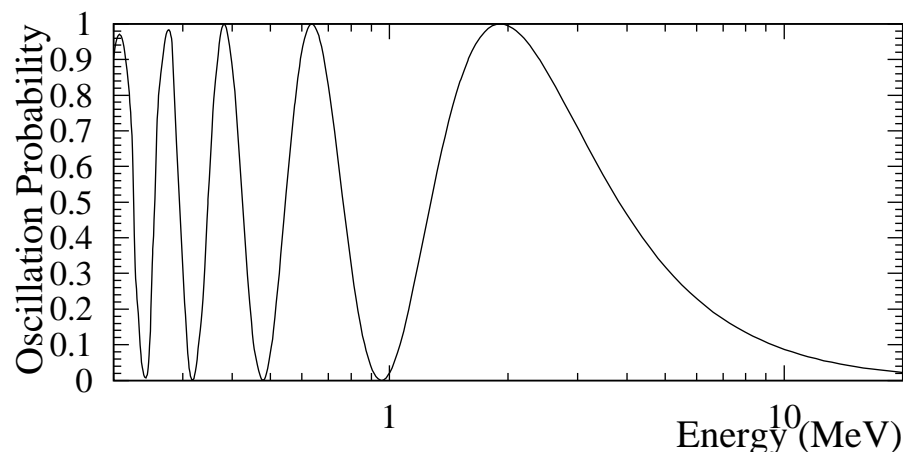
$$|\nu(t)\rangle \propto \cos\theta |\nu_1\rangle + e^{i\phi} \sin\theta |\nu_2\rangle$$

with

$$\phi = \left(\frac{m_1^2}{2p} - \frac{m_2^2}{2p} \right) \frac{c^3 t}{\hbar}$$

Neutrino Mixing

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



θ = neutrino mixing angle

Δm^2 = $m_1^2 - m_2^2$ (in eV^2)

L = distance ν has travelled (in km)

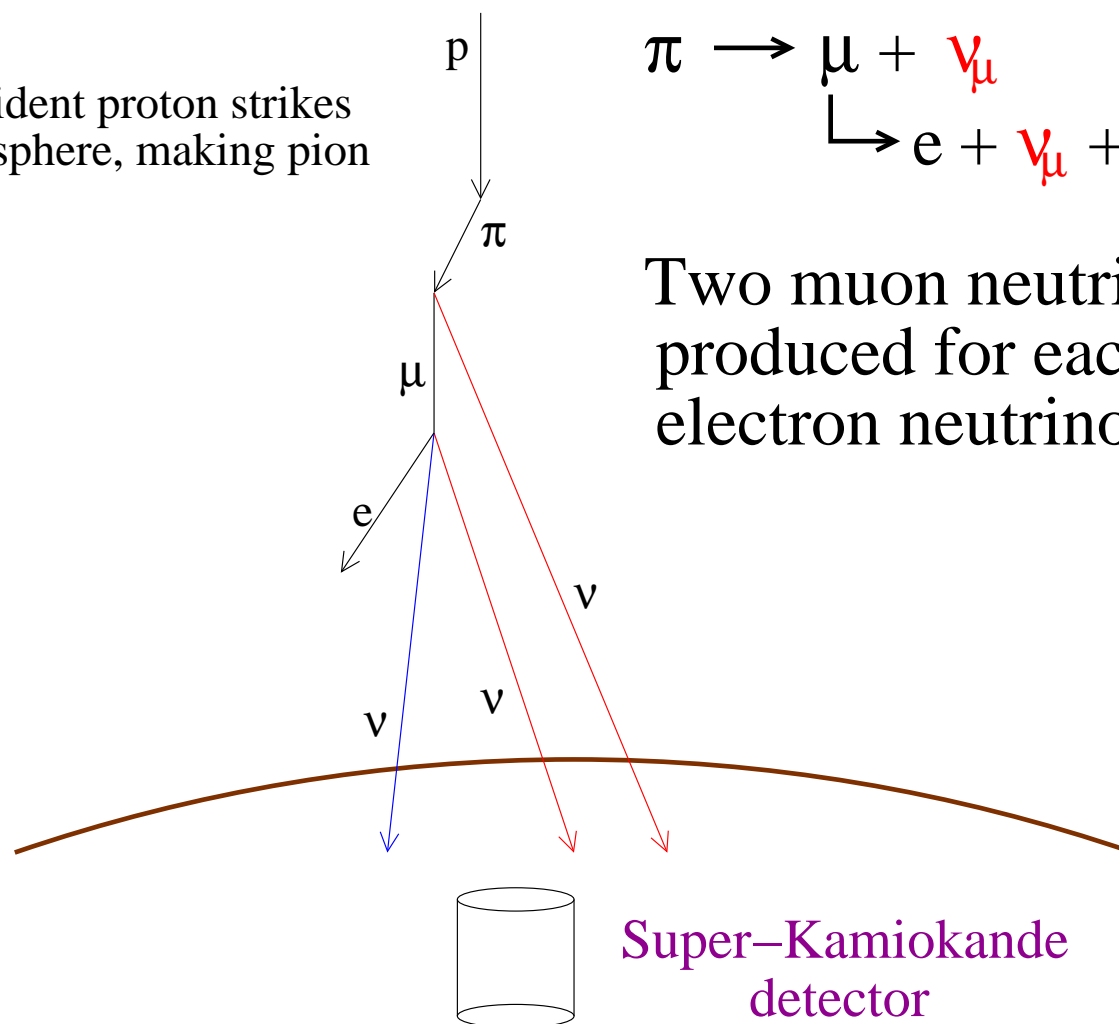
E = neutrino energy (in GeV)

Really we have a 3×3 mixing matrix. $\Delta m^2 = (m_i^2 - m_j^2)$ determines the frequency of oscillation. The value of L/E determines which Δm^2 we study.

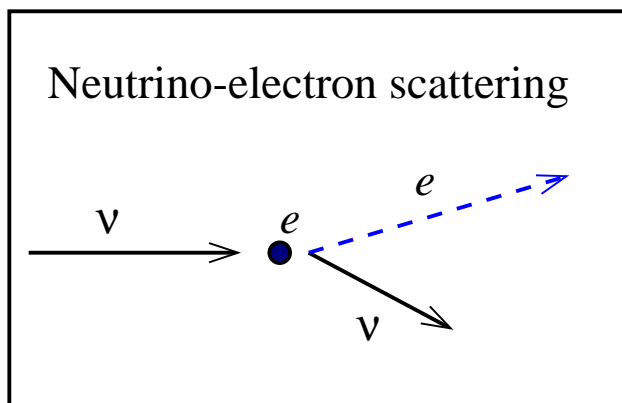
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric Neutrinos

Incident proton strikes atmosphere, making pion



Water Cherenkov Detectors



Elastic scattering of electrons by ν 's

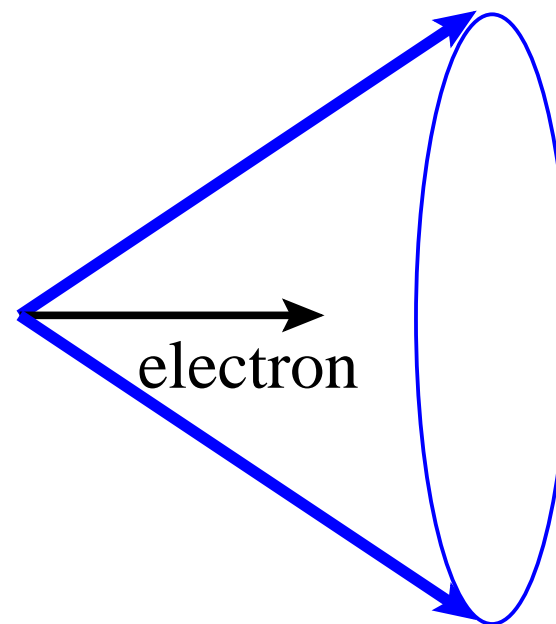
Scattered electron can move faster than light in water (since water has slowed down light).

Get *Cherenkov light*—an electromagnetic sonic boom!

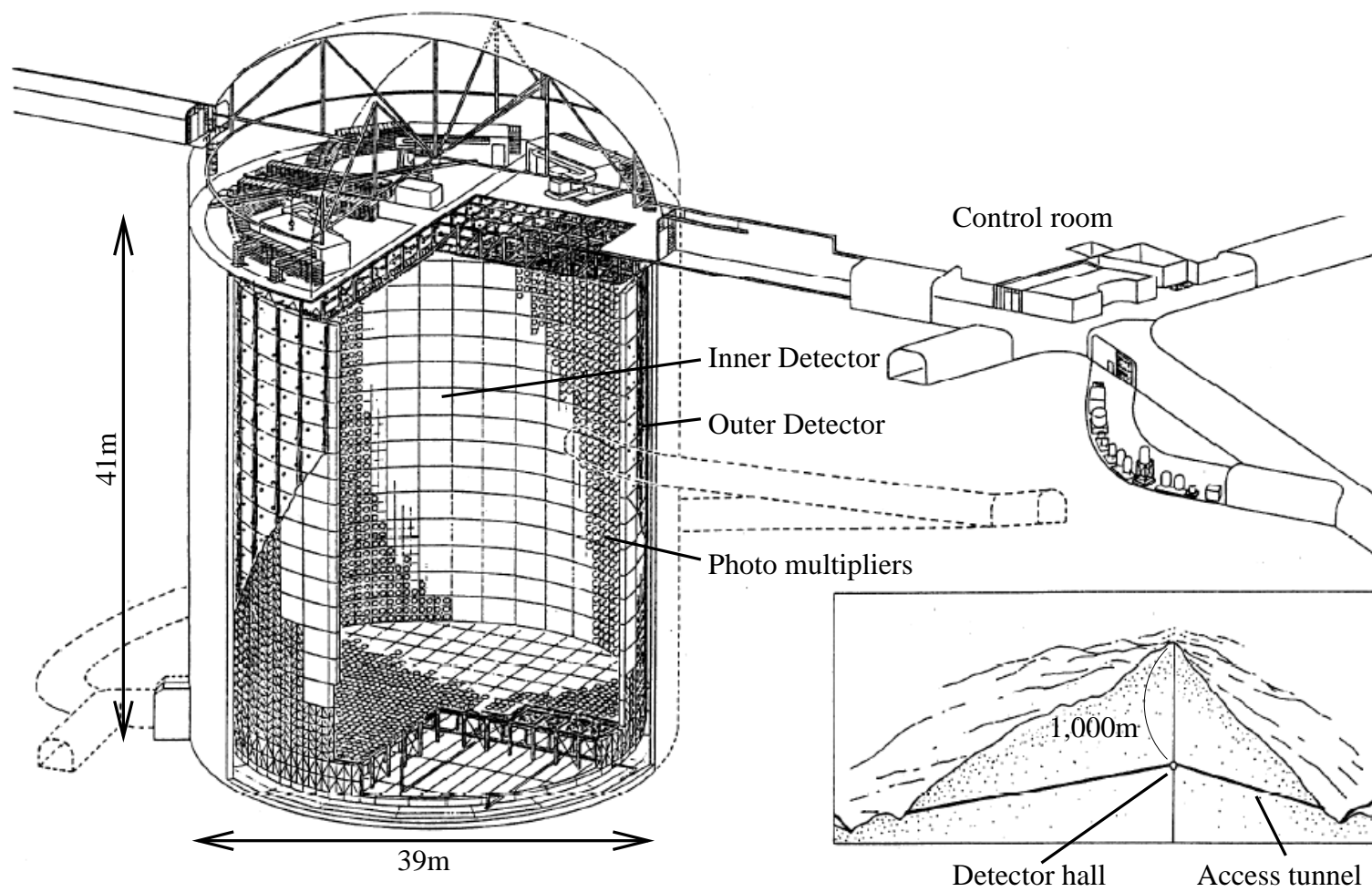
- Light is blue
- Comes out in cone
- More energy \rightarrow more light!



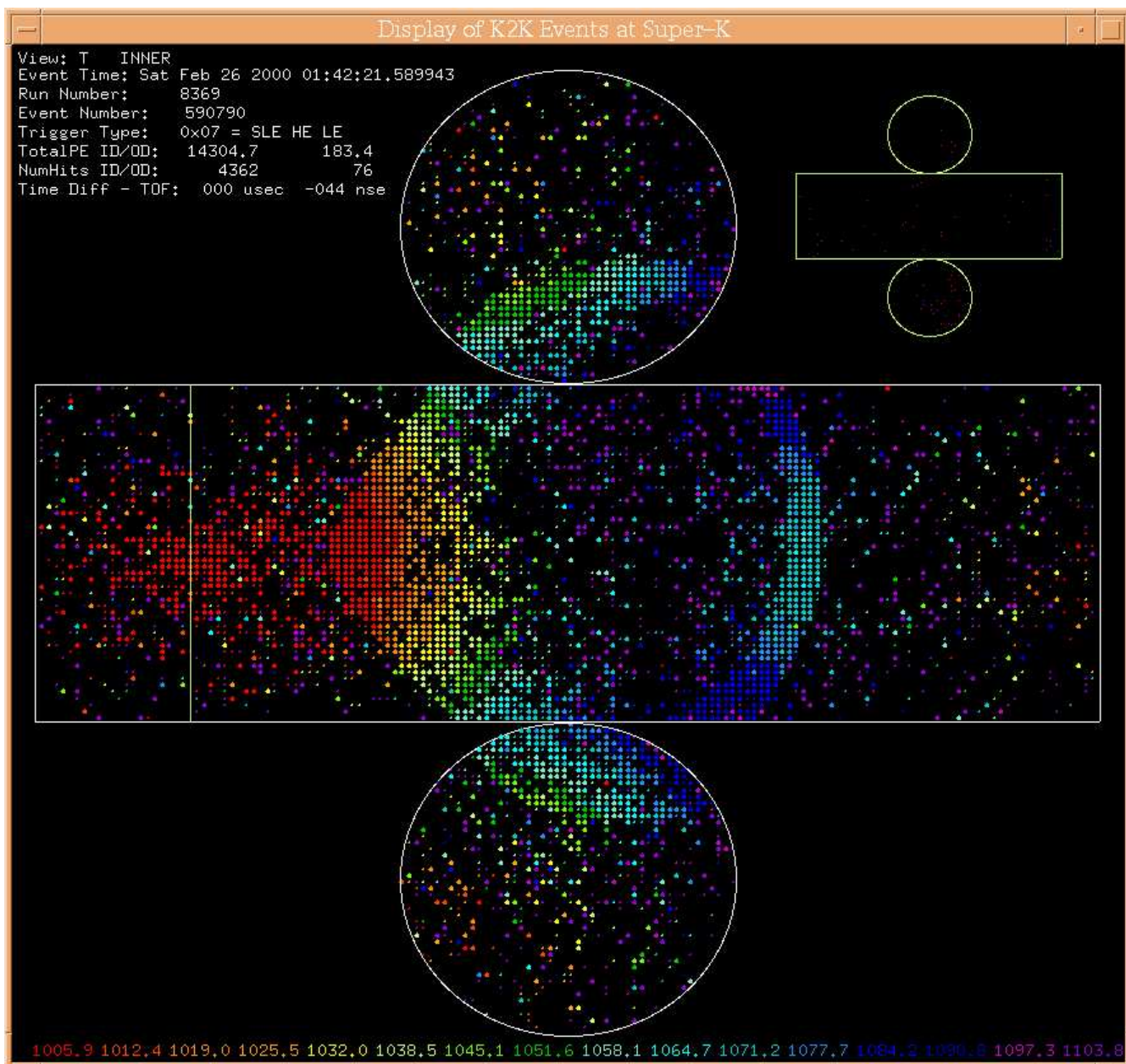
Cherenkov cone



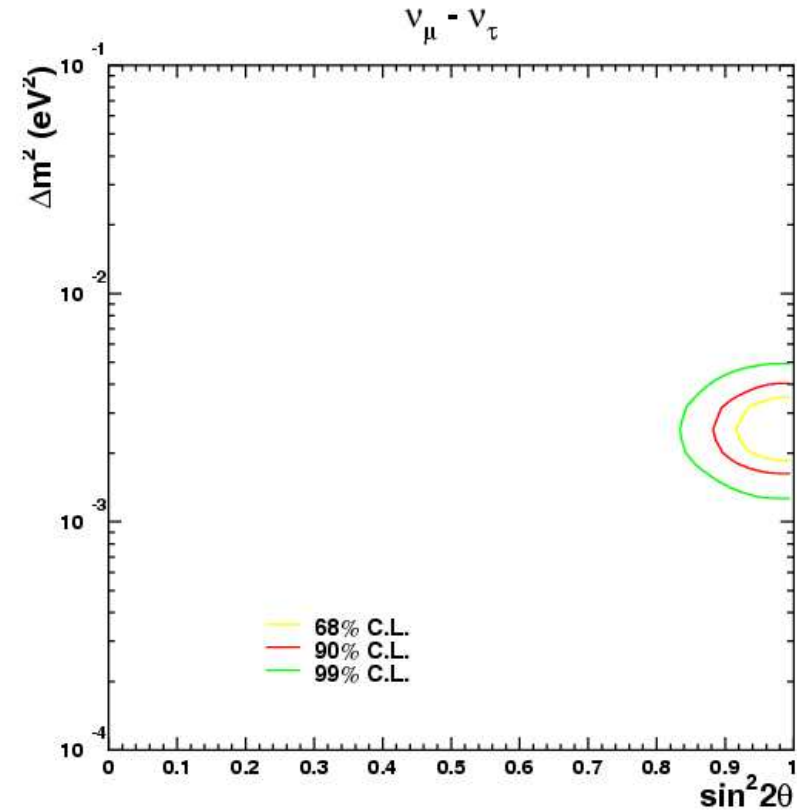
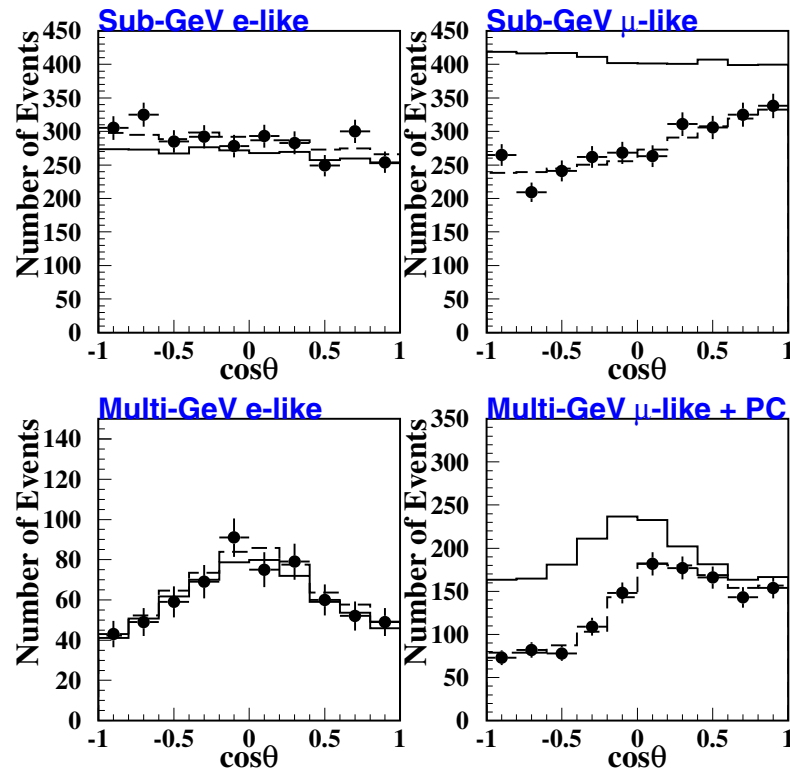
Super-Kamiokande



Super-Kamiokande Event Display



Super-Kamiokande Atmospheric ν Results



Super-K sees suppression of ν_μ flux at large zenith angles (distances).

ν_e flux is unaffected.

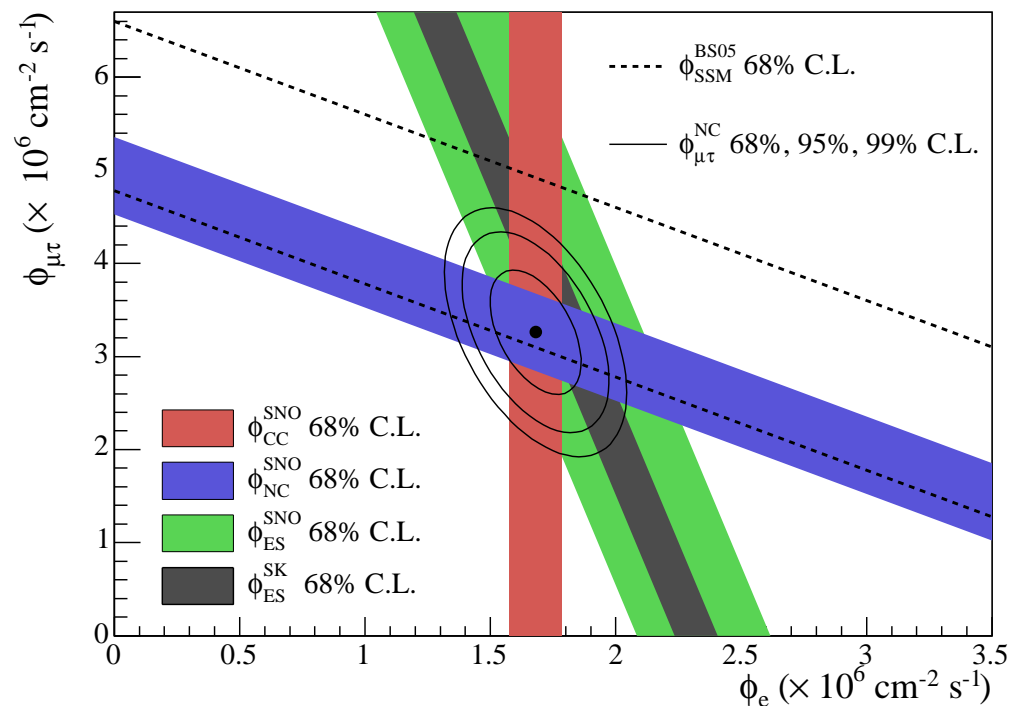
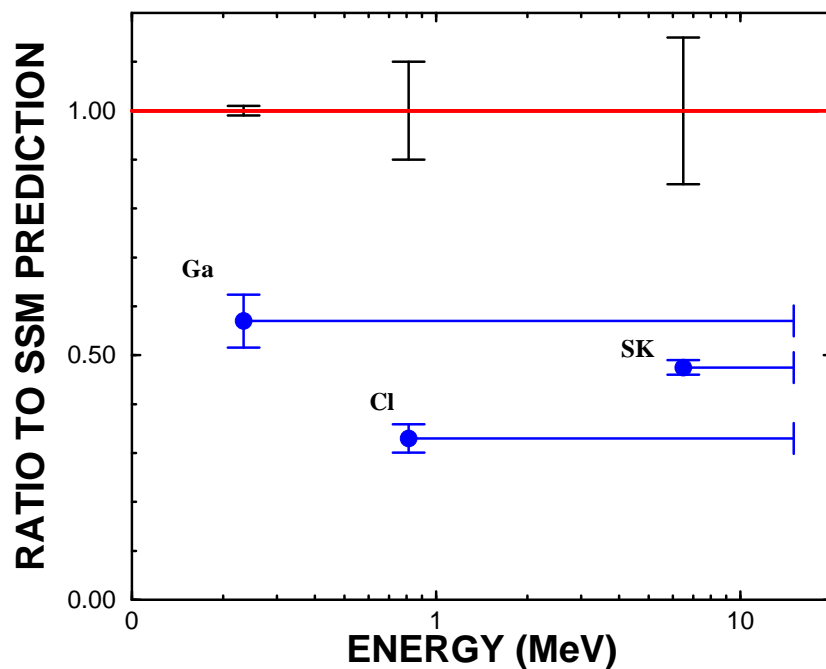
Looks to be $\nu_\mu \rightarrow \nu_\tau$ oscillations

Evidence for Solar Neutrino Oscillation

The Sun makes ν_e 's in the process

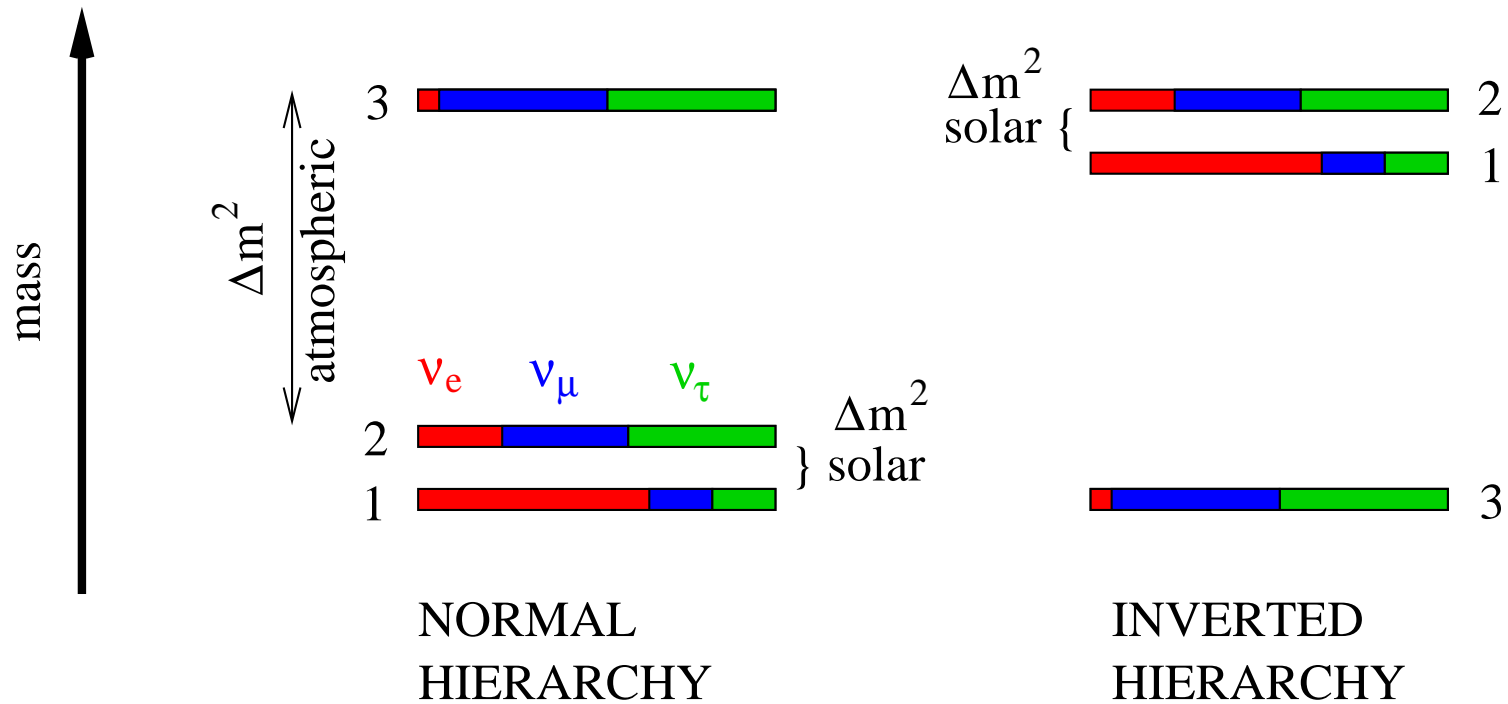


But all experiments see a rate deficit compared to solar model predictions ...



By measuring both ν_e flux and total ν flux, SNO produced direct evidence that solar neutrinos also change flavour.

Neutrino Mass Hierarchy



$$\Delta m^2_{\text{atm}} \approx 3 \times 10^{-3} \text{ eV}^2$$

$$\Delta m^2_{\text{sol}} \approx 8 \times 10^{-5} \text{ eV}^2$$

Neutrino Mixing Matrix

Adjust L/E to view oscillations at different Δm^2 's

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric } \nu\text{'s:}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Short baseline reactor } \nu\text{'s:}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar } \nu\text{'s:}}$$

$\theta_{23} \approx \pi/4$
 Maximal mixing! (?)

$\theta_{13} < \pi/20$
 Small, quark-like mixing

$\theta_{12} \approx \pi/6$
 Large, non-maximal mixing

Compare to identical parameterization of CKM matrix ...

$$\theta_{23} \approx \pi/76$$

$$\theta_{13} \approx \pi/870$$

$$\theta_{12} \approx \pi/14$$

Physics of Long Baseline ν Experiments



Basic idea: shoot a man-made neutrino beam through the Earth, and study neutrino oscillations in controlled way

K2K: KEK to Kamioka

T2K: J-PARC to Kamioka

($\times 50$ stats.)

Far detector: Super-K

Measure	Determine
$P(\nu_\mu \rightarrow \nu_\mu)$	$\Delta m_{23}^2, \theta_{23}$
$P(\nu_\mu \rightarrow \nu_e)$	θ_{13}
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$	CPT
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$	$\delta_{CP}, \text{sign}(\Delta m_{23}^2)$

K2K: KEK to Kamiokande



250 km baseline, wide-band beam

Beam	
ν_μ	98.2%
ν_e	1.3%
$\bar{\nu}_\mu$	0.5%

K2K-I: March 1999 - July 2001

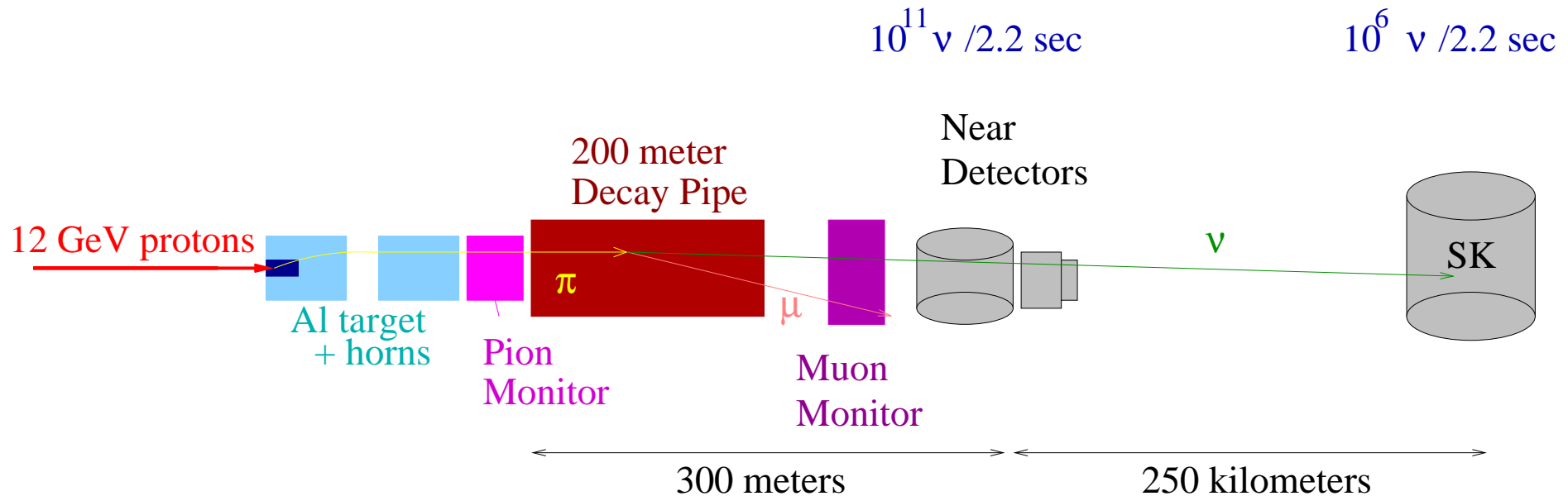
Super-K accident, reconstruction

K2K-II: December 2002 - November 2004

The first long baseline ν experiment

Goal: measure ν_μ disappearance at atmospheric Δm^2

Anatomy of a Long Baseline Experiment



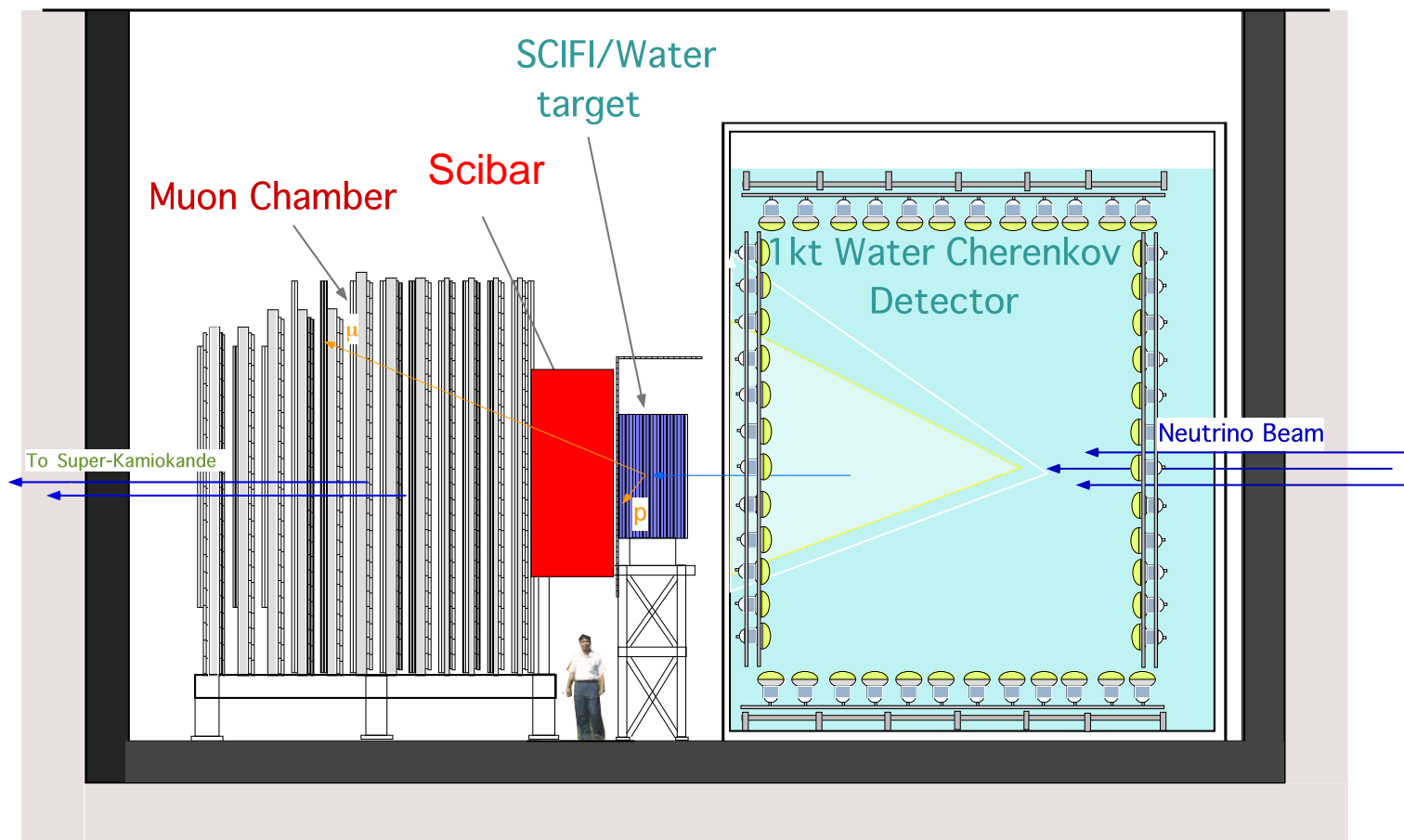
Target: 3cm dia \times 66cm long Al cylinder

Horns: toroidal B fields, pulsed at 250 kA

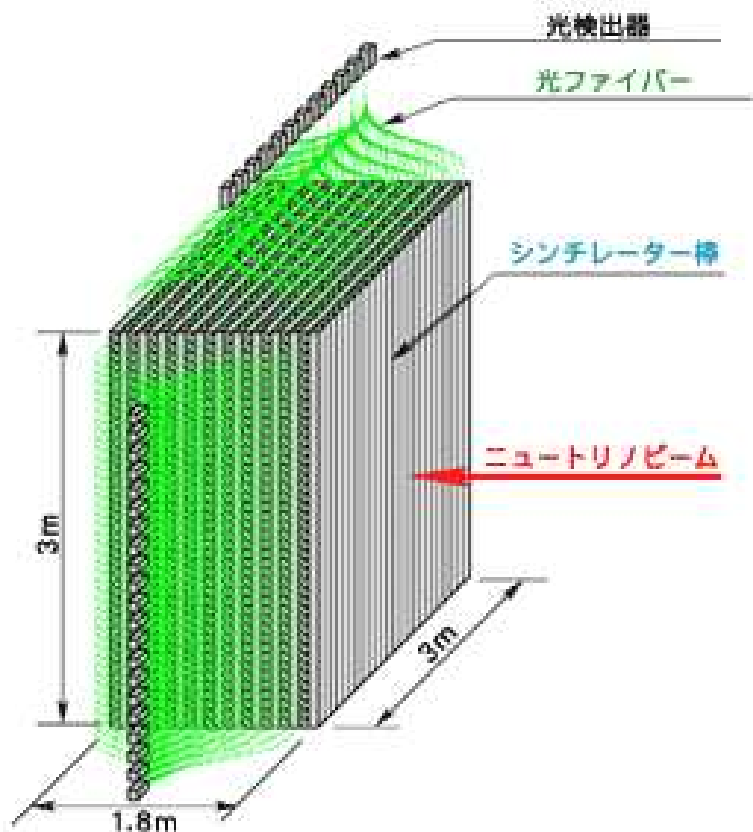
Pion monitor: gas Cherenkov detector

Muon monitor: segmented ionization chamber + array of silicon pad detectors

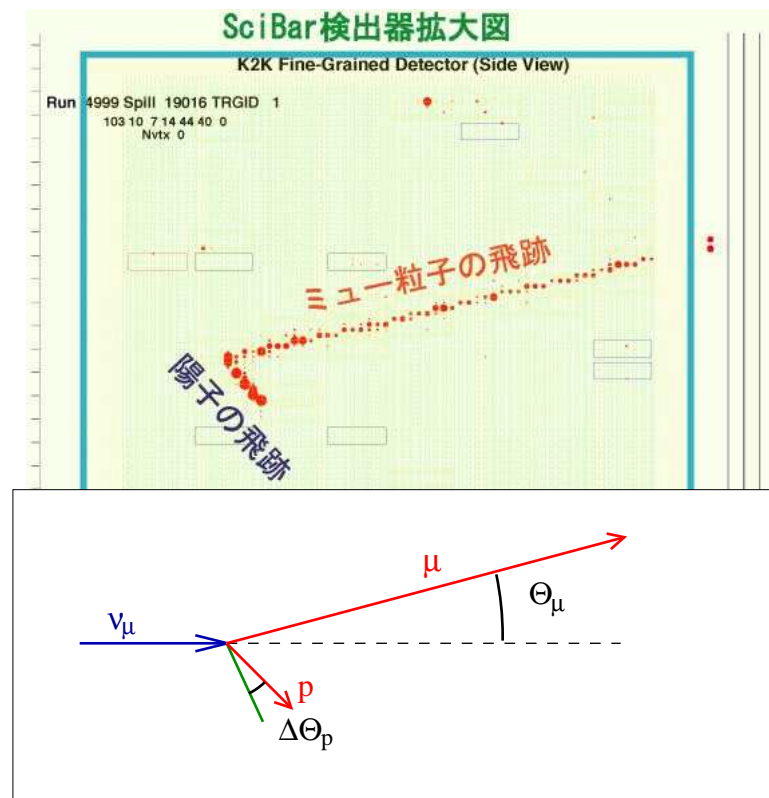
K2K Near Detectors



Scibar Detector



14848 extruded scintillator strips
 Read out by 1.5mm diameter WLS fibres
 with multi-anode PMTs



Compare measured proton recoil
 direction to quasielastic prediction to
 identify or reject CCQE events
 $(\nu_{\mu} + n \rightarrow \mu + p)$.

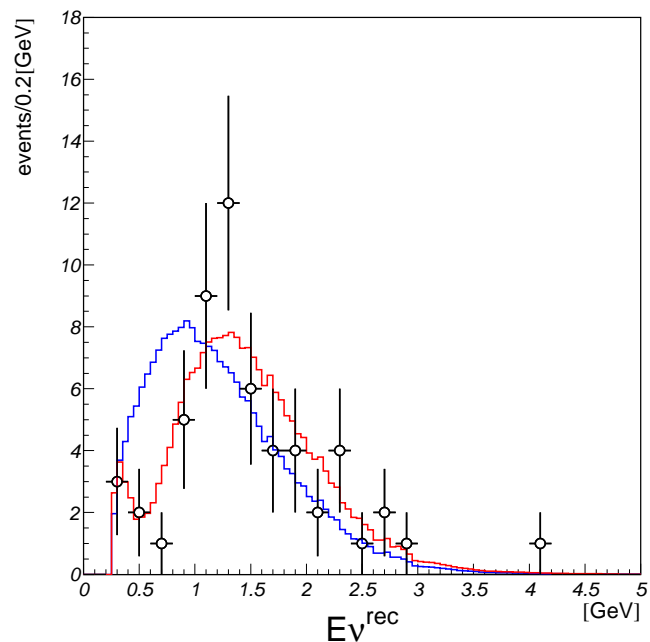
K2K Oscillation Results

Using all fully contained events at SK:

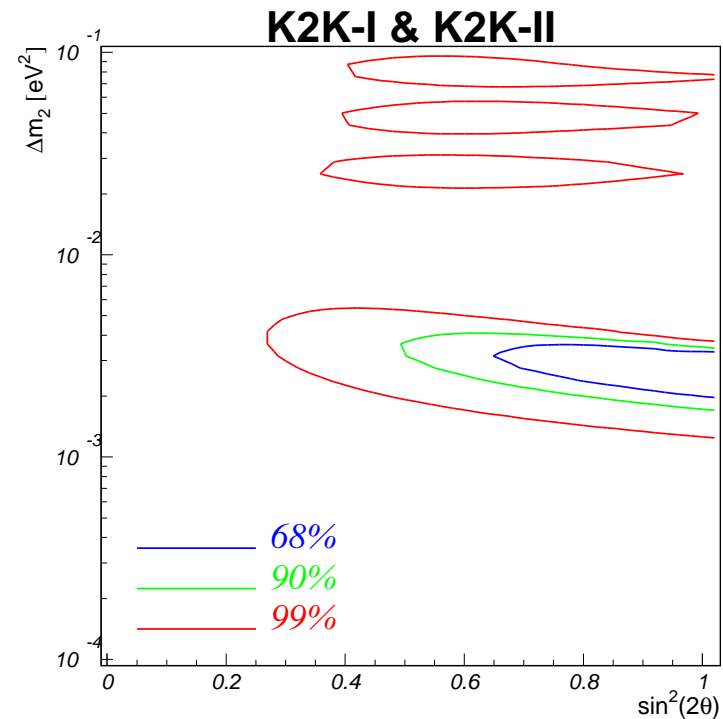
Expected $150.9^{+11.6}_{-10.0}$

Observed 108 events

Reconstructed energy spectrum from
1-ring μ events



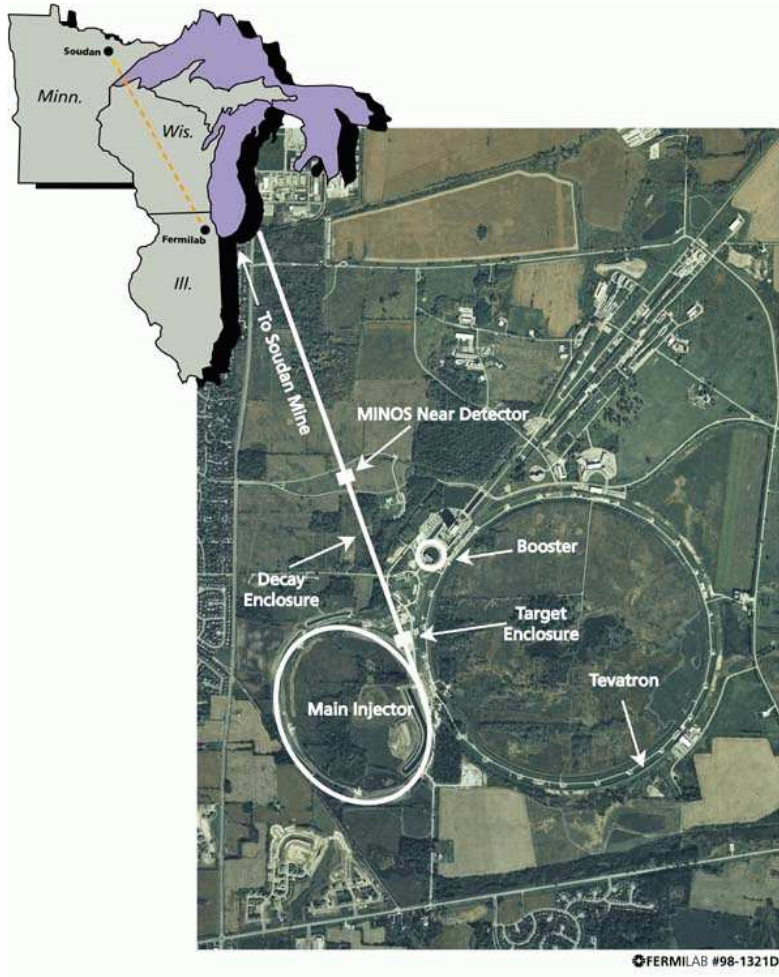
Indications of spectral distortion in
0.5-0.75 GeV region



Consistency with null oscillation
hypothesis:

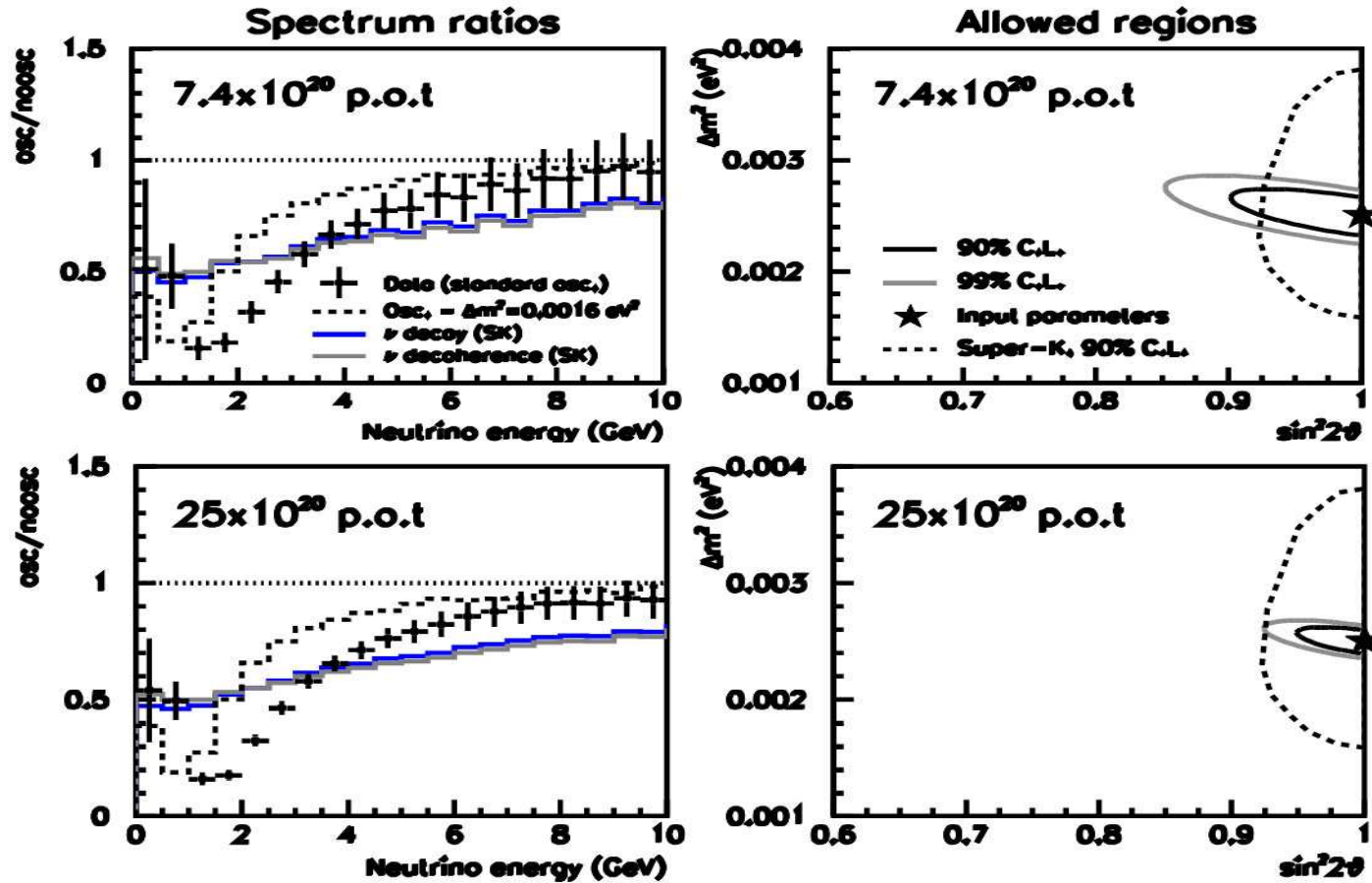
Using normalization only	0.26%
Using spectrum only	0.74%
Using spectrum and normalization	0.005%

The MINOS Experiment



A beam from Fermilab's Main Injector to the Soudan mine located 720 km away

Expected MINOS Sensitivity



Goals of MINOS;

- precise measurement of Δm^2
- test alternatives of oscillation model (eg. neutrino decay)

From ν_e appearance to θ_{13}

Super-K, K2K oscillations seem to be of type $\nu_\mu \rightarrow \nu_\tau$

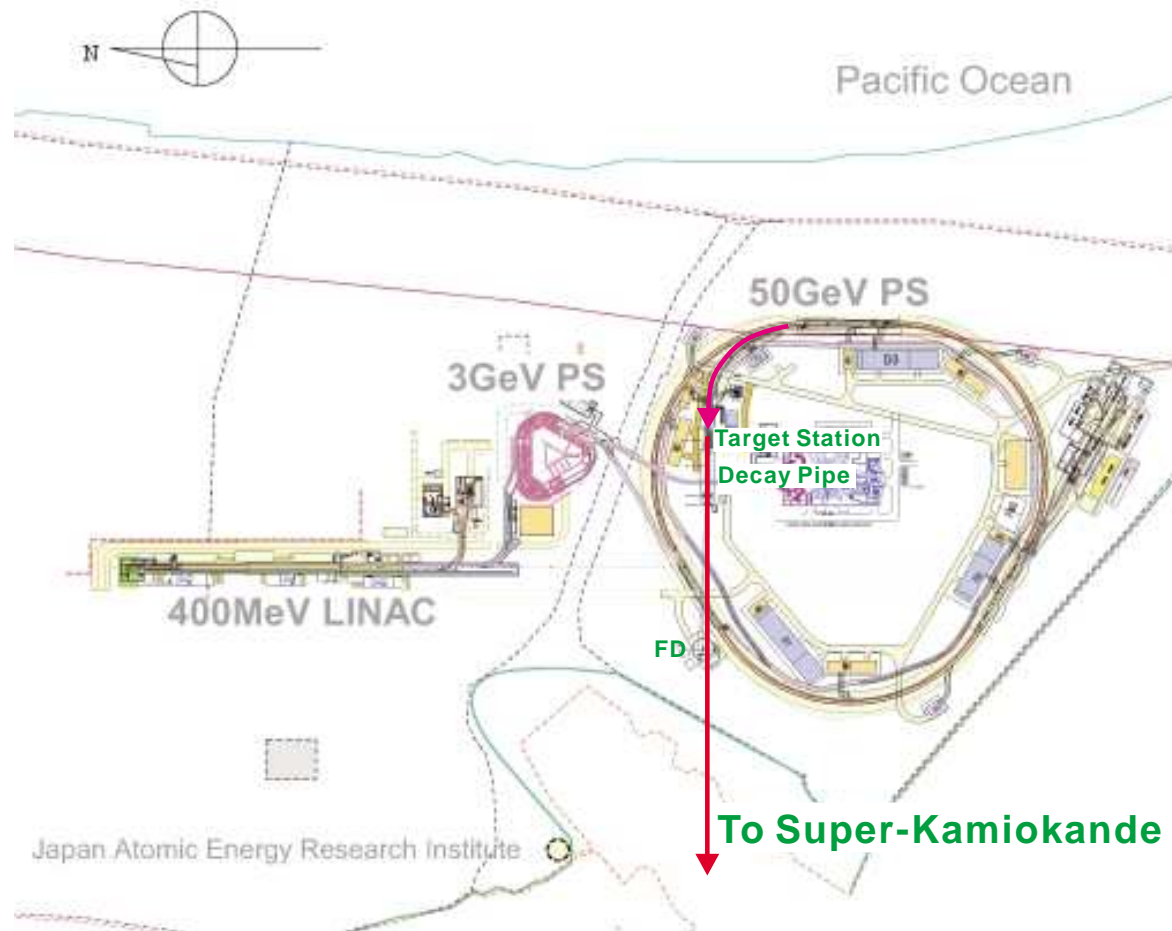
But some ν_μ should oscillate to ν_e . At Δm_{atmos}^2 :

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \\ \approx \frac{1}{2} \sin^2 2\theta_{13}$$

Current best limit is $\sin^2 2\theta_{13} < 0.1$, from reactor searches for $\bar{\nu}_e$ disappearance searches.

Measure $P(\nu_\mu \rightarrow \nu_e)$ to determine θ_{13} !

The T2K Experiment



Megawatt-scale neutrino beam from Tokai to Kamioka
(beam in 2009)

NOW FUNDED!

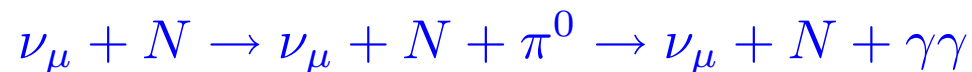
Experimental Challenges of ν_e Appearance

It sounds easy ... shoot a beam of ν_μ 's, look for ν_e 's.

But there are complications:

- The beam contains a small contamination of ν_e
- There are insidious backgrounds

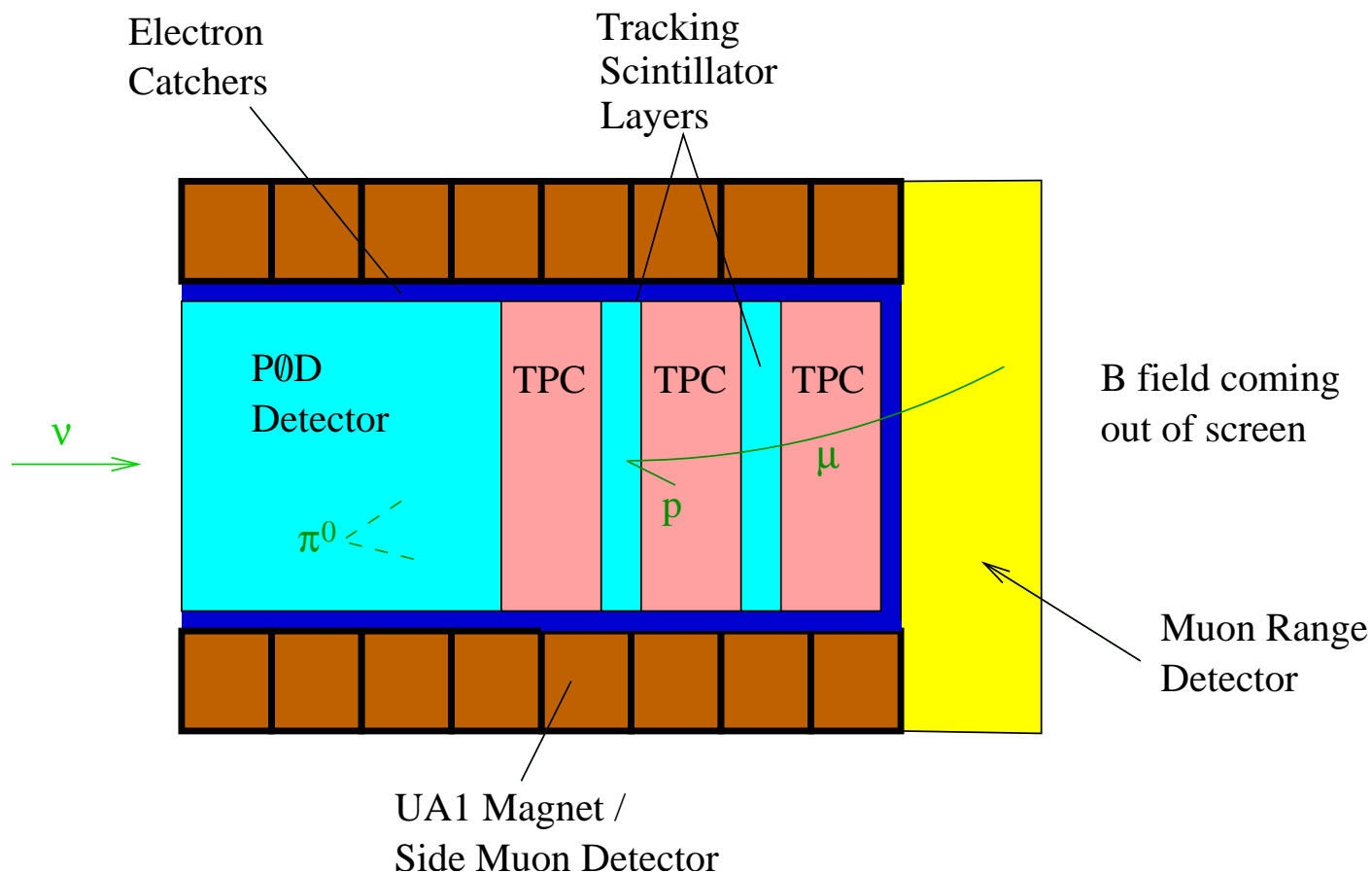
The real headache: neutral current π^0 's



If your detector misses one of the γ 's from the π^0 decay, the lone remaining γ (after Compton scattering) is easily mistaken for an electron!

We need a very capable near detector to measure the rates of such backgrounds.

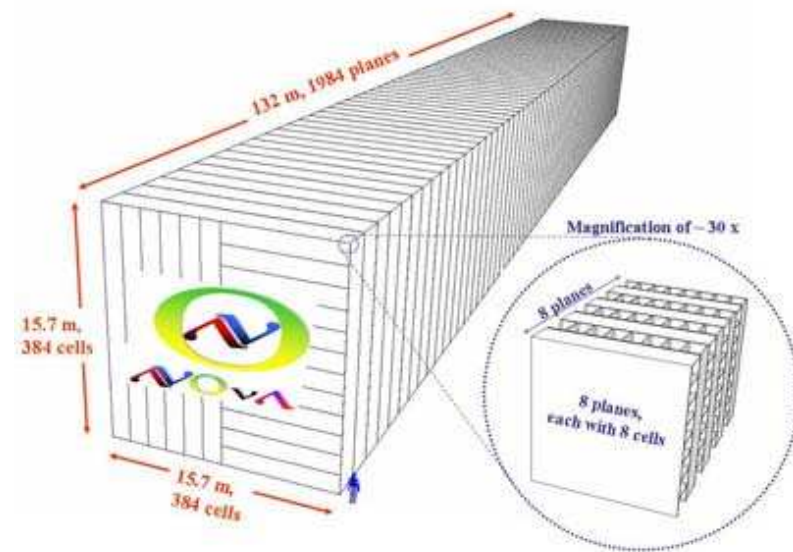
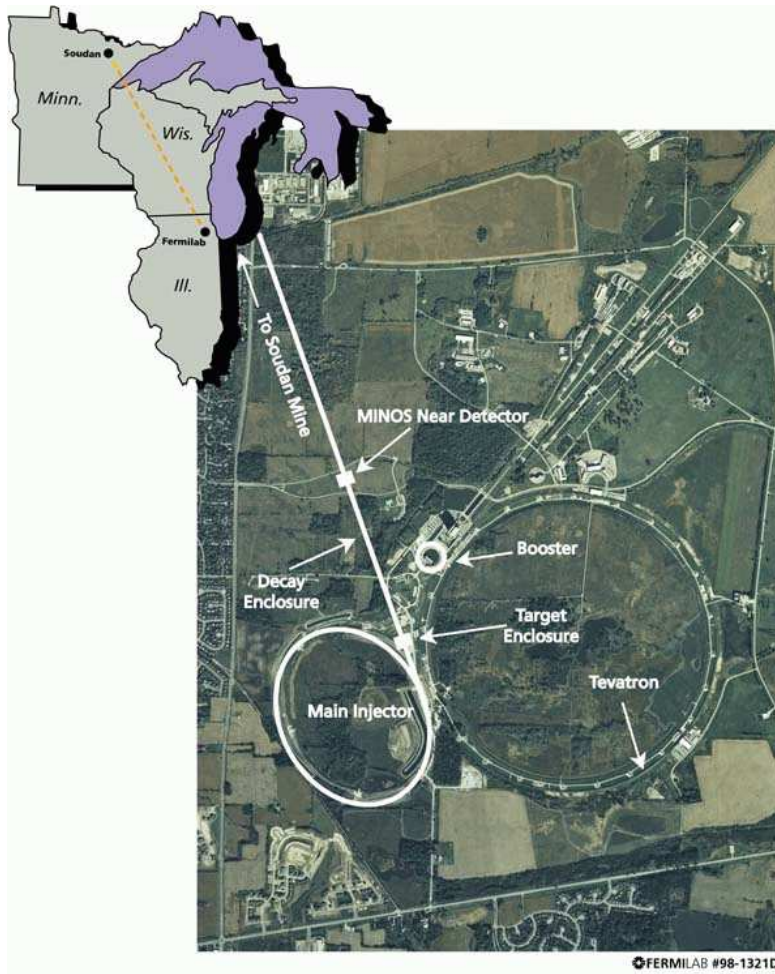
A Possible Near Detector Concept



- P0D detector optimized to convert π^0 's - segmented scintillator layers
- Downstream scintillator layers optimized for CC interactions
- B field, gas TPCs with GEM readout for momentum measurement
- Magnet instrumented as side muon detector

The NO ν A Proposal

NuMI Off-Axis ν_e Appearance Experiment



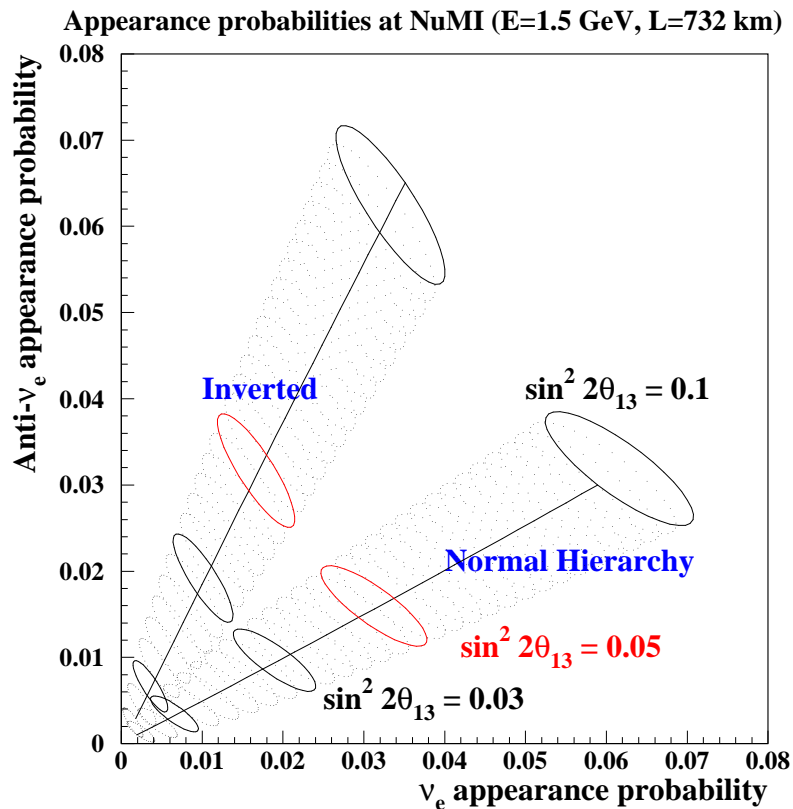
A 30 kton active scintillator detector with fine segmentation to see ν_e appearance.

Similar concept to T2K, but with longer baseline, higher beam energy, and different far detector design.

Currently in proposal stage: \$165M

Idea: build a new detector viewing the NuMI beam used by MINOS, optimized for observing $\nu_\mu \rightarrow \nu_e$

From ν_e Appearance to CP Violation



CP requires

$$P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

For ν_e appearance at Δm_{atmos}^2 :

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

$$\approx \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta_{CP}$$

Measurements with ν 's and $\bar{\nu}$'s over different baselines can fix mass hierarchy and see ν CP violation ... but only with very high statistics and if $\theta_{13} \neq 0$!

Mixing Mysteries!

1. Why are lepton mixings large compared to quark sector?
2. How close is θ_{23} to maximal?
3. How small is θ_{13} ? Why $\theta_{13} \ll \theta_{12}, \theta_{23}$?
4. What is the neutrino mass hierarchy?
5. Do neutrinos violate CP?
6. Does CP violation in neutrinos have anything to do with the matter-antimatter asymmetry in our universe (leptogenesis)?

Must measure θ_{13} , hierarchy, and ultimately CP!!!

Conclusions

- Neutrino physics making extremely rapid progress
- Evidence for oscillations now seen with both atmospheric and solar neutrinos
- Long baseline neutrino experiments allow one to explore the entire neutrino mixing matrix in a controlled way.
- K2K seems indications of oscillations with terrestrial beam. MINOS will attempt to confirm and improve on this.
- Next generation experiments (T2K, No ν A) will target unknown mixing parameters: θ_{13} , δ_{CP}

Backup slides follow

KamLAND concept



Probe solar neutrino mixings
with reactor experiment

Identify $\bar{\nu}_e$'s by coincidence
signal:

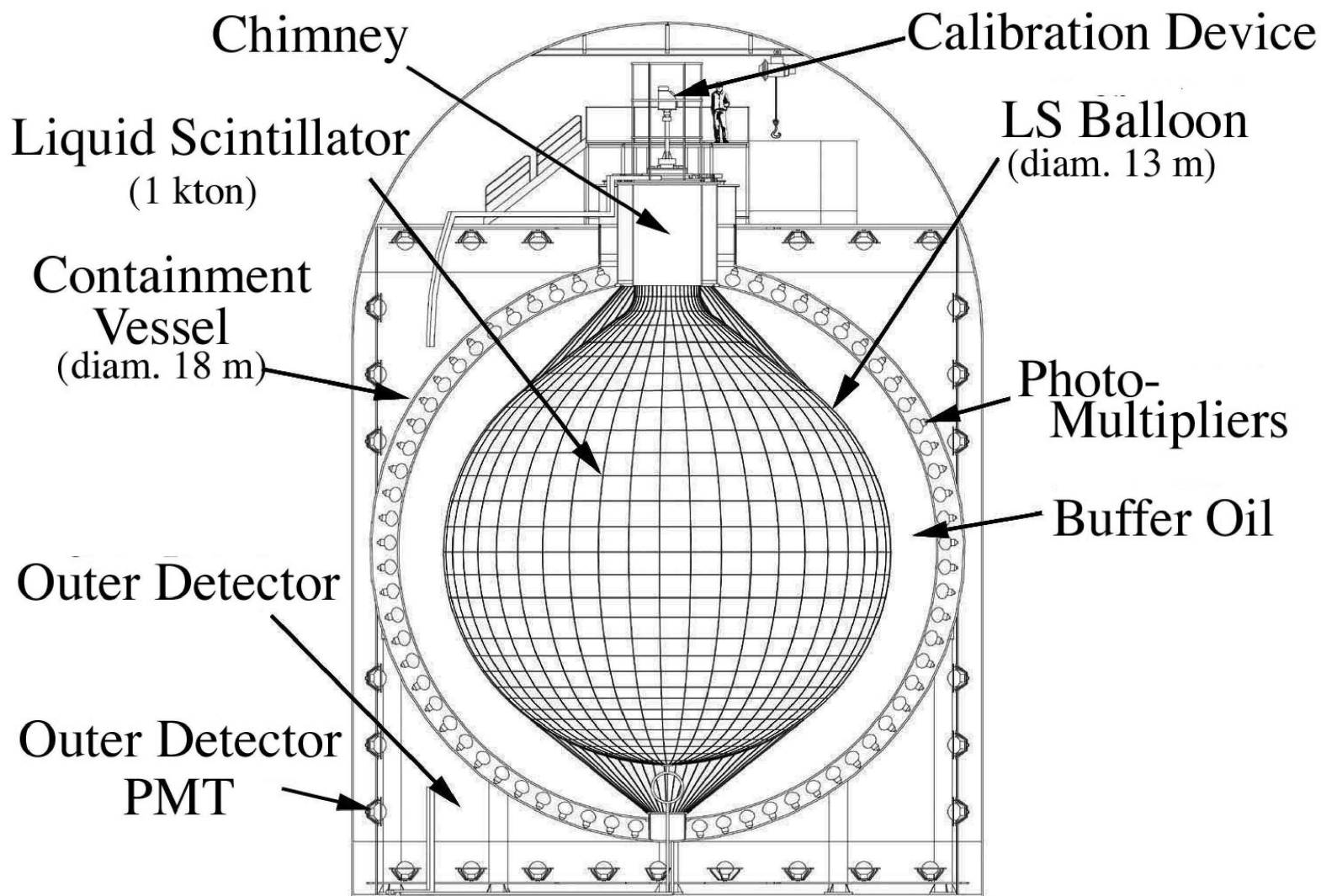


For solar ν parameters, see
vacuum oscillations,
disappearance of $\bar{\nu}_e$'s

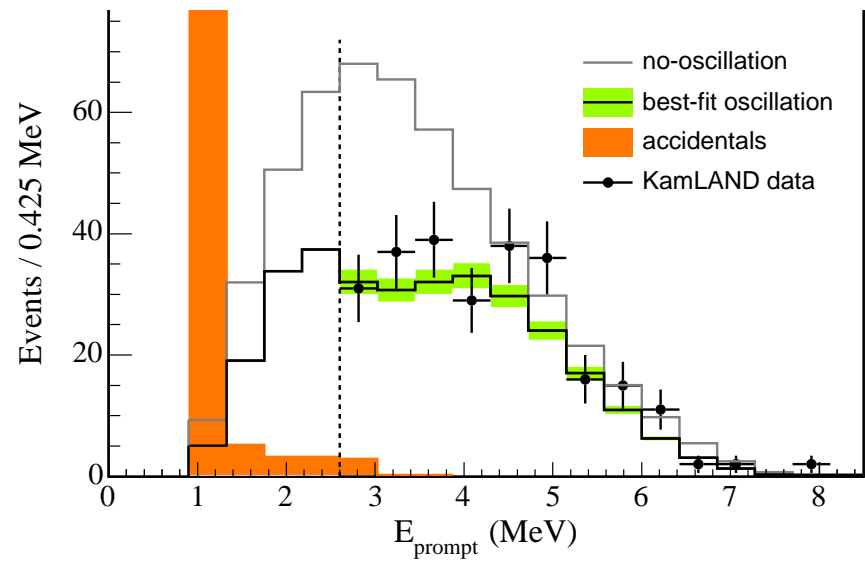
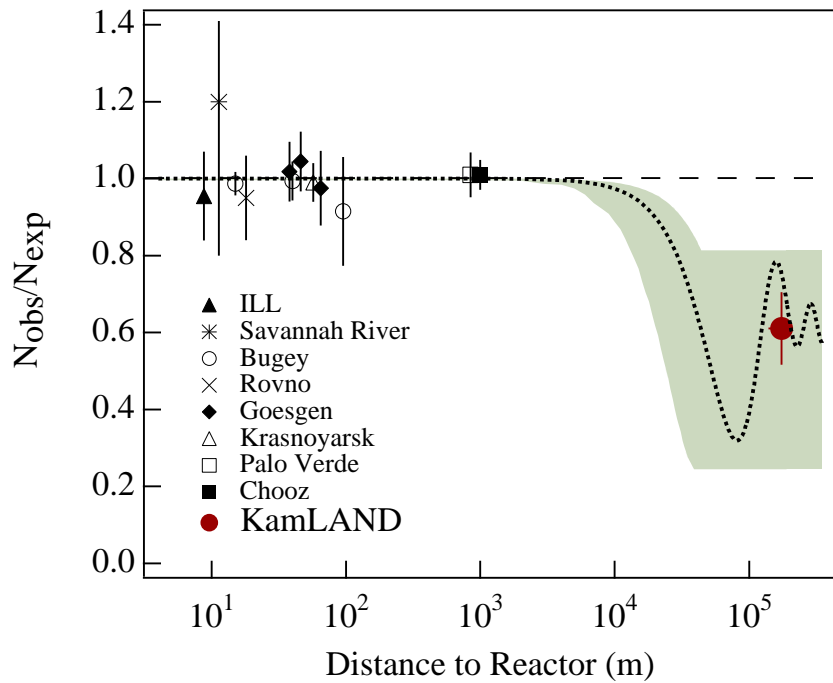
See $\bar{\nu}_e$'s from multiple
reactors, at average distance
of $L \approx 180$ km



KamLAND detector



(hep-ex/0212021)



Energy-dependence suppression
seen

PRL 90 (2003) 021802; hep-ex/0406035, submitted to PRL

KamLAND Disappearance Signal

Mass Hierarchy from Matter Effects

Matter effects modify oscillation probability. At first oscillation max:

$$P_{matter}(\nu_{\mu} \rightarrow \nu_e) \approx \left(1 + 2\frac{E}{E_R}\right) P_{vac}(\nu_{\mu} \rightarrow \nu_e)$$

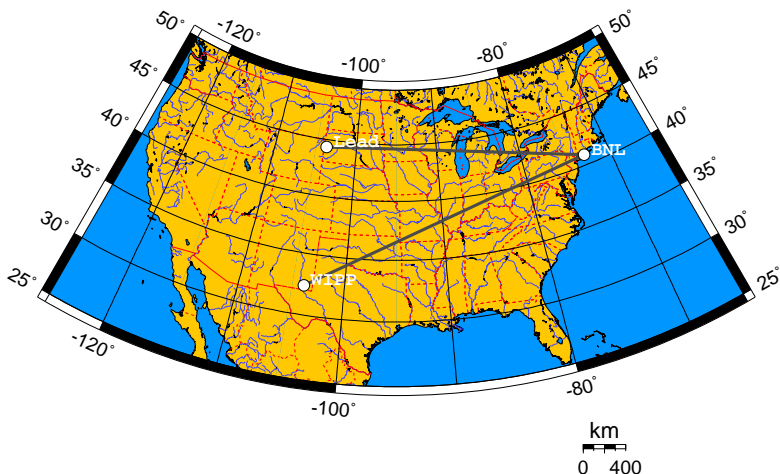
$$E_R = \frac{\Delta m_{32}^2}{2\sqrt{2}G_F N_e} \approx 13 \text{ GeV} \left(\frac{\Delta m_{32}^2}{3 \times 10^{-3} \text{ eV}^2} \right)$$

Sign of matter effect depends on mass hierarchy!

Matter effects increase with L , E .

Matter effects for ν , $\bar{\nu}$ have opposite sign—potential 'fake' A_{CP}

BNL → Homestake



1 MW wide band on-axis beam from AGS

Mton-scale detector at Homestake/WIPP

$L = 2540$ km!

Views multiple oscillation nodes
simultaneously

Near detector location problematic

Advantages:

- Truly complementary to T2K or NuMI
- Long baseline maximizes matter and CP effects—can be huge!
- With wide band beam, see modulation of oscillation by CP and matter effects even with a single-sign beam

Disadvantages:

- Requires enormous detector, new beam right from start—big initial cost
- Statistics just adequate with ν 's, scanty with $\bar{\nu}$'s
- More plausible as followup expt.

Leptogenesis

Sakharov conditions for baryogenesis:

- baryon number violations
- C and CP violation
- deviation from thermal equilibrium

Standard leptogenesis (Fukugita & Yanagida, Phys. Lett B 174, 45 (1986)):

- Heavy Majorana neutrinos (needed for see-saw)
- CP-violating decay modes
- Both Dirac CP phase (MNS matrix) and Majorana CP phases contribute

Asymmetry in lepton number turned into asymmetry in baryon number

Many variations:

- Leptogenesis with Dirac neutrinos (Murayama & Pierce, hep-ph/0206177)
- 155 papers on XXX!
- Relation between CP violation in oscillation experiments and CP violation in leptogenesis very model-dependent!

Difficult to connect experimental results with leptogenesis ...

but observation of large δ_{CP} would provide “circumstantial” evidence

Connections to GUTs

$$m_\nu \ll m_\ell, m_q$$

Seesaw mechanism \rightarrow naturally small m_ν

$$m_\nu \propto \frac{m_D^2}{M_R}$$

For $m_D \sim 200$ GeV & $m_\nu \sim 0.01 - 0.1$ eV:

$$M_R \sim 10^{15} \text{ GeV} \sim \text{GUT scale!}$$

Natural to cast as GUT (SO(10), SUSY GUT, etc.)

Interesting challenges:

- Put CKM, neutrino mixing matrices in common family structure
- Explain observed symmetries of mixing matrix

Event Classes Used in Near Detector Fits

Kiloton:

- Fully contained single-ring μ like events

Scibar:

- Single track events
- 2 track Quasi-Elastic ($\Delta\Theta_p \leq 25^\circ$)
- 2 track non-QE ($\Delta\theta_p > 25^\circ$) where one track is a muon

SciFi:

- Single track events
- 2 track Quasi-Elastic ($\Delta\theta_p \leq 25^\circ$)
- 2 track non-QE ($\Delta\theta_p > 30^\circ$) where one track is a muon

Low q^2 Anomaly

K2K observes a deficit of forward-going μ relative to MC in all near detectors

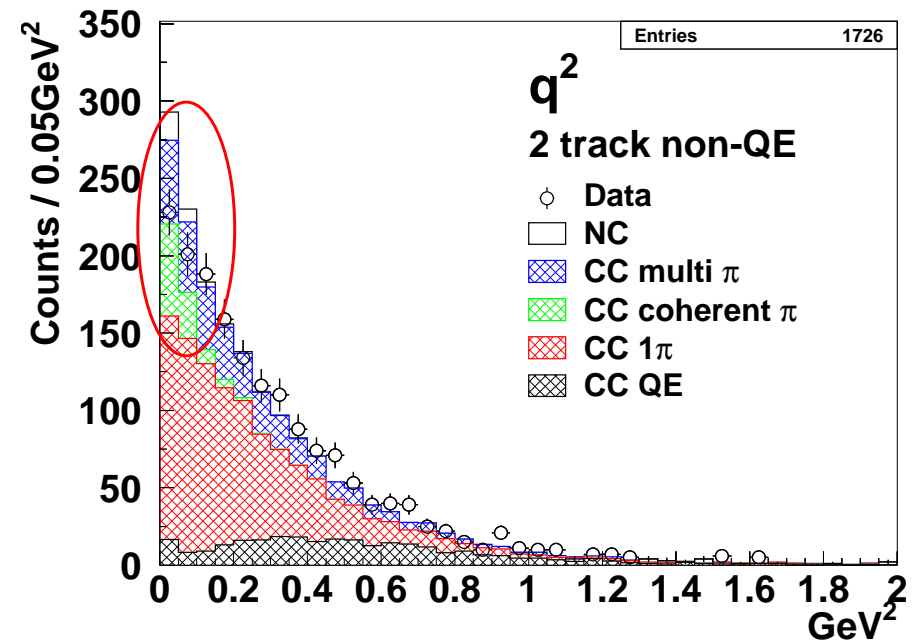
- Seen in non-QE events

Two possible explanations:

- Suppression of CC- 1π at $q^2 < 0.1 \text{ GeV}^2$
- Absence of CC coherent π production

Significant nuclear effects (poorly understood).

Scibar data



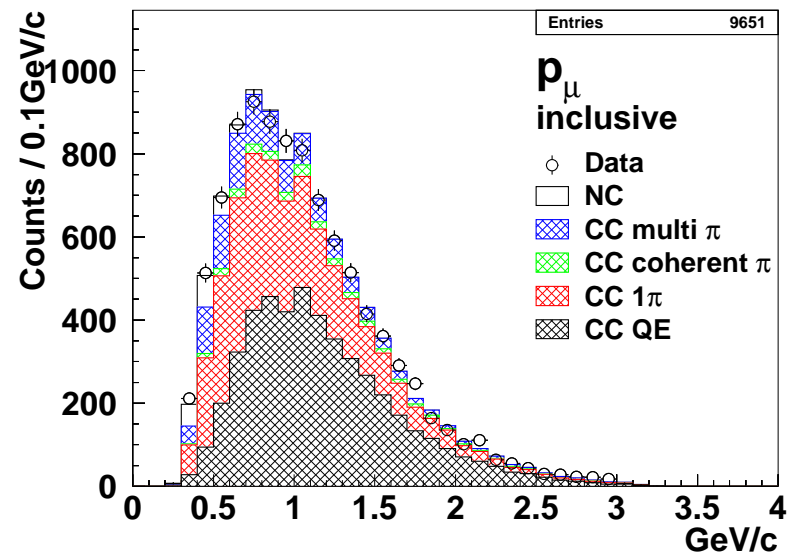
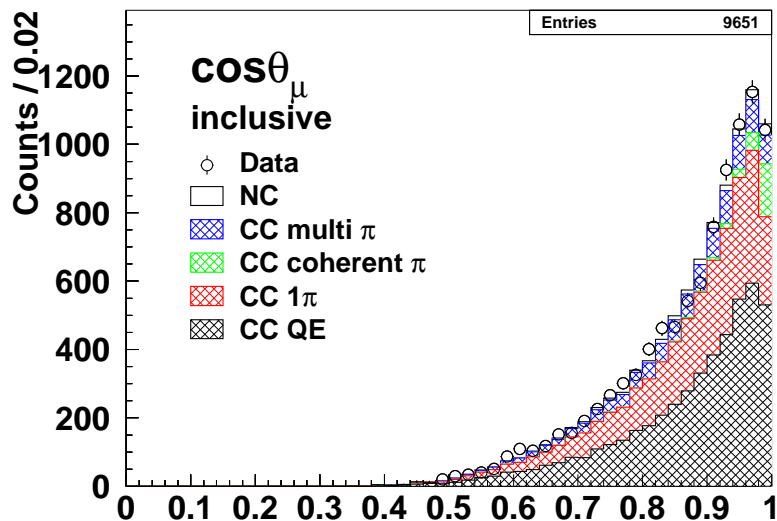
The data cannot distinguish between possible explanations.

Phenomenological suppression of CC- 1π is applied.

Oscillation analysis is insensitive to how q^2 deficit is modelled.

Results with phenomenological q^2 suppression

Scibar data distributions compared to MC with low q^2 suppression



Method	nQE/QE ratio (Data/MC)
Cut low q^2 region from fits	0.95
CC1 π suppression below 0.1 GeV ²	1.02
Eliminate coherent π^0 production	1.06
Used in oscillation analysis	1.02 ± 0.1

Likelihood analysis for oscillation

Observables at Super-K

- Total number of events
- Reconstruction energy spectrum of FC single-ring μ -like events

Use maximum likelihood fit, including term for systematic uncertainty parameters $\vec{\beta}$

$$\mathcal{L}(\Delta m^2, \sin^2 2\theta, \vec{\beta}) = \mathcal{L}_{norm}(\Delta m^2, \sin^2 2\theta, \vec{\beta}) \cdot \mathcal{L}_{shape}(\Delta m^2, \sin^2 2\theta, \vec{\beta}) \cdot \mathcal{L}_{sys}(\vec{\beta})$$

Systematic uncertainty parameters ($\vec{\beta}$): neutrino spectrum measured by near detectors, nQE/QE ratio, far/near ratio from beam MC, SK reconstruction efficiency, SK absolute energy scale, overall rate normalization.

K2K-SK event totals

—Preliminary—

	DATA	MC
FC 22.5 kt	107	150.9
1 ring	67	94.2
1 ring μ -like	57	85.5
1 ring e -like	10	8.7
multi-ring	40	56.7