PHYS 5326 – Lecture #12

Monday, Mar. 3, 2003
Dr. Jae Yu

1. Neutrino Oscillation Measurements
   1. Atmospheric neutrinos
   2. Accelerator Based Oscillation Experiments

•Next makeup class is Friday, Mar. 14, 1-2:30pm, rm 200.
•We will have an in-class, 2 hour, mid-term exam on that day.

Oscillation Probability

- Substituting the energies into the wave function:

$$\left|n_m(t)\right\rangle = \exp\left[-it\left(p + {m_1^2}\big/{2E_n}\right)\right]\left[-\sin q\left|n_1\right\rangle + \cos q\left|n_2\right\rangle \exp\left[{i\Delta m^2 t}\big/{2E_n}\right]\right]$$

where $\Delta m^2 \equiv m_1^2 - m_2^2$ and $E_n \cong p$.

- Since the ν's move at the speed of light, t=x/c, where x is the distance to the source of ν_μ.
- The probability for ν_μ with energy E_ν oscillates to ν_e at the distance *L* from the source becomes

$$\boxed{P\left(n_m \to n_e\right) = \sin^2 2q \sin^2\left(\frac{1.27\Delta m^2 L}{E_n}\right)}$$

Oscillation Detectors

- The most important factor is the energy of neutrinos and its products from interactions
- Good particle ID is crucial
- Detectors using natural sources
  - Deep under ground to minimize cosmic ray background
  - Use Cerenkov light from secondary interactions of neutrinos
    - $\nu_e + e \rightarrow e + X$: electron gives out Cerenkov light
    - ν_μ CC interactions, resulting in muons with Cerenkov light
- Detectors using accelerator made neutrinos
  - Look very much like normal neutrino detectors
    - Need to increase statistics

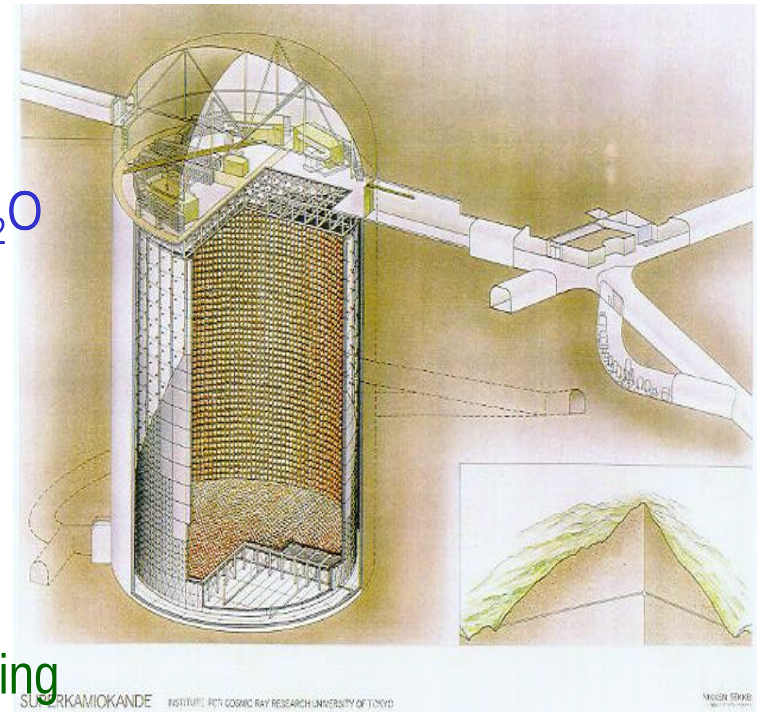
Atmospheric Neutrinos

- Neutrinos resulting from the atmospheric interactions of cosmic ray particles
  - ν_μ to ν_e is about 2 to 1
  - He, p, etc + N → π,K, etc
    - $\pi \rightarrow \mu+\nu_\mu$
    - $\mu \rightarrow e+\nu_e+\nu_\mu$
  - This reaction gives 2 ν_μ and 1 ν_e
- Expected flux ratio between ν_μ and ν_e is 2 to 1
- Form a double ratio for the measurement

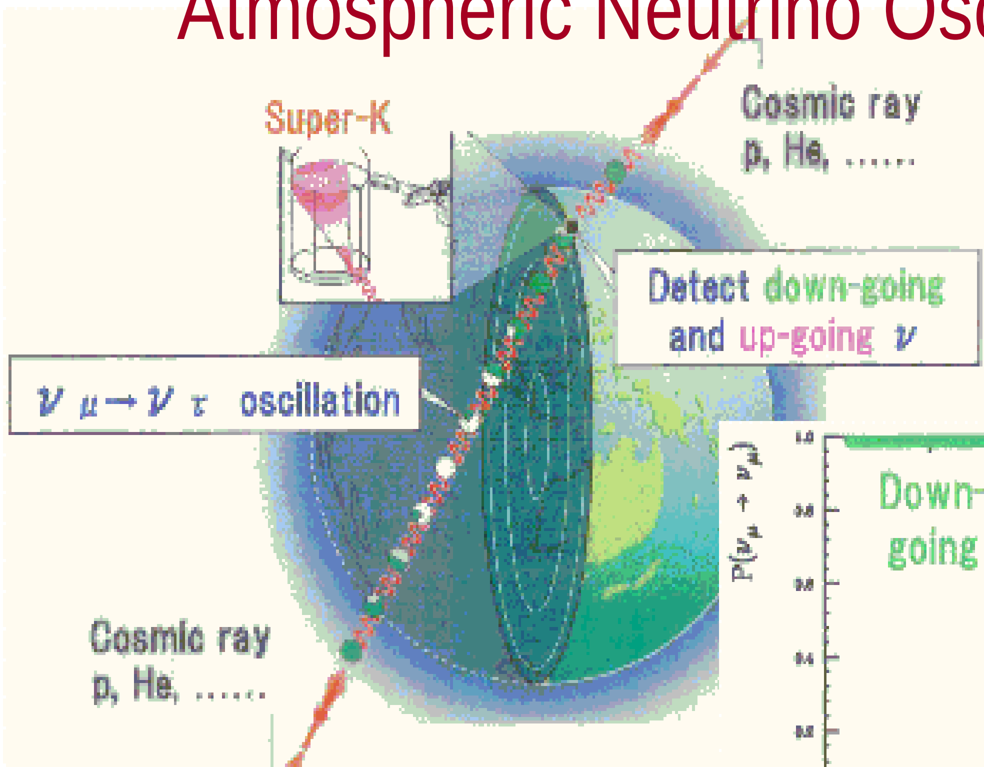
$$R \equiv \frac{\left(N_{\nu_e} / N_{\nu_\mu}\right)^{Exp}}{\left(N_{\nu_e} / N_{\nu_\mu}\right)^{The}}$$

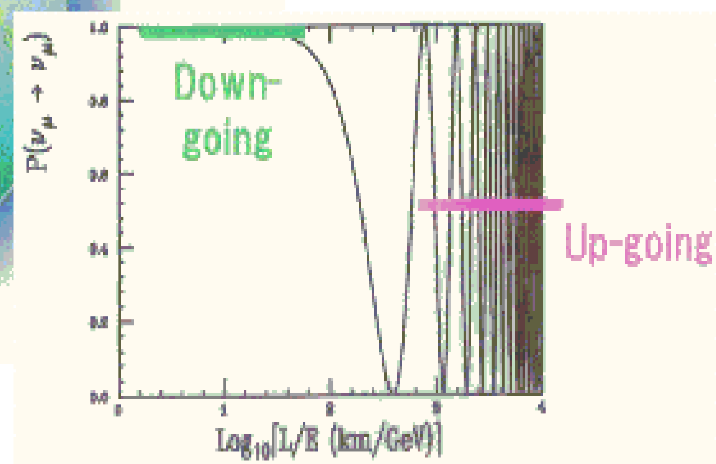
Super Kamiokande

•Kamioka zinc mine, Japan
• 1000m underground
•40 m (d) x 40m(h) SS
•50,000 tons of ultra pure H_2O
•11200(inner)+1800(outer) 50cm PMT's
•Originally for proton decay experiment
•Accident in Nov. 2001, destroyed 7000 PMT's
•Dec. 2002 resume data taking

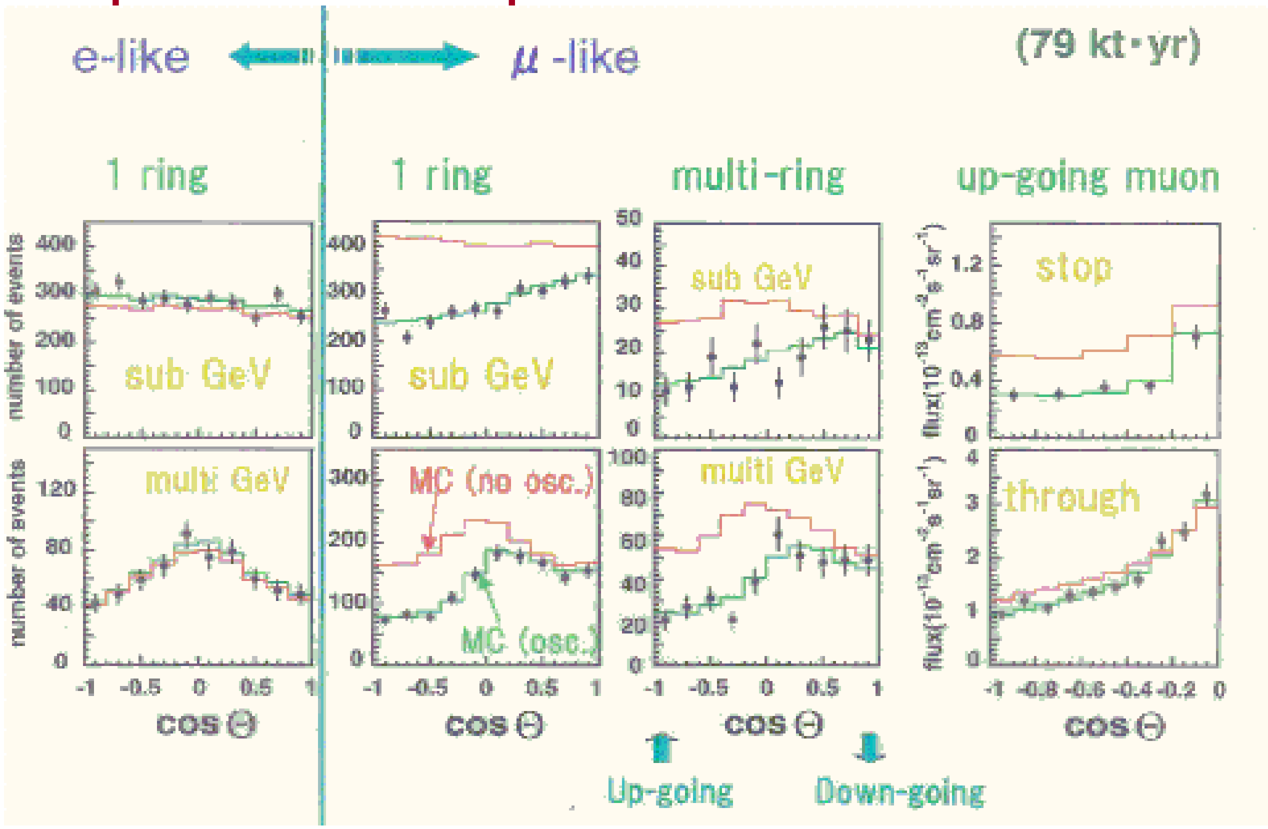


Atmospheric Neutrino Oscillations

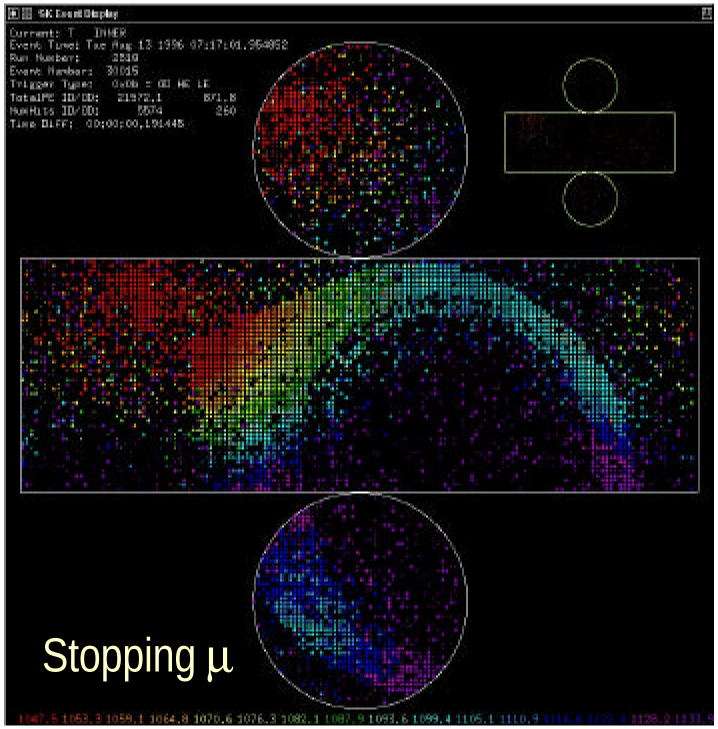


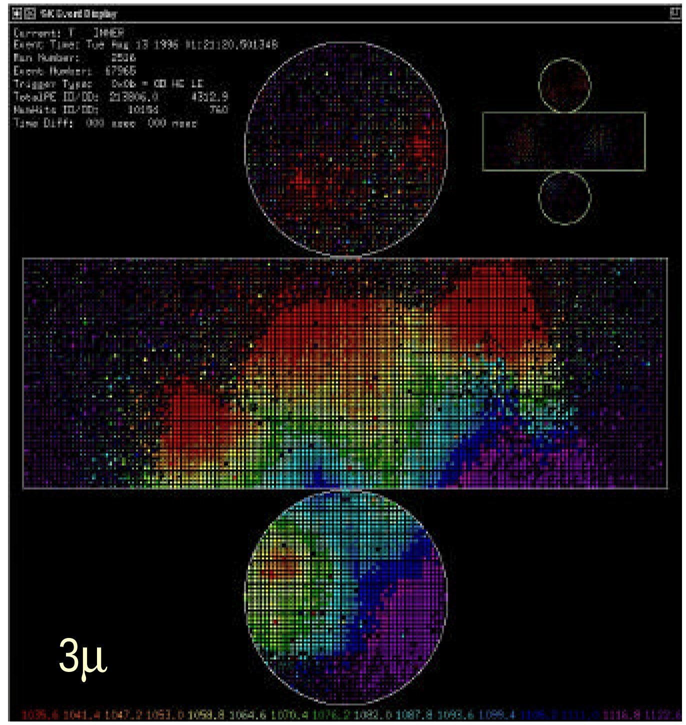


Super-K Atmospheric Neutrino Results

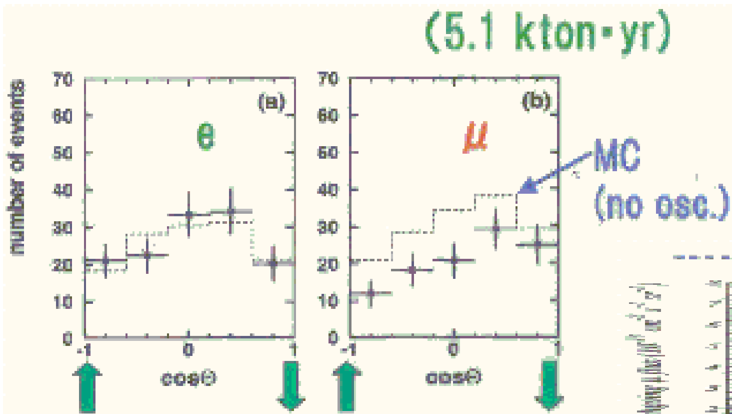


Super-K Event Displays



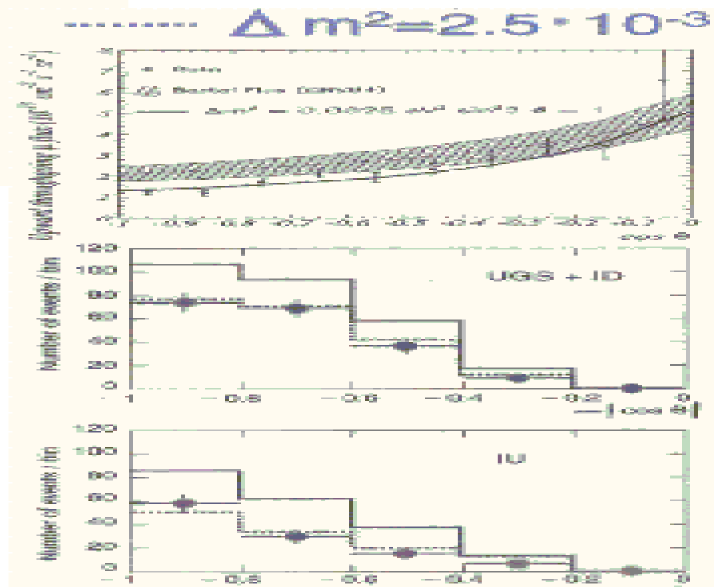


Other Experimental Results



Soudan 2 experiment

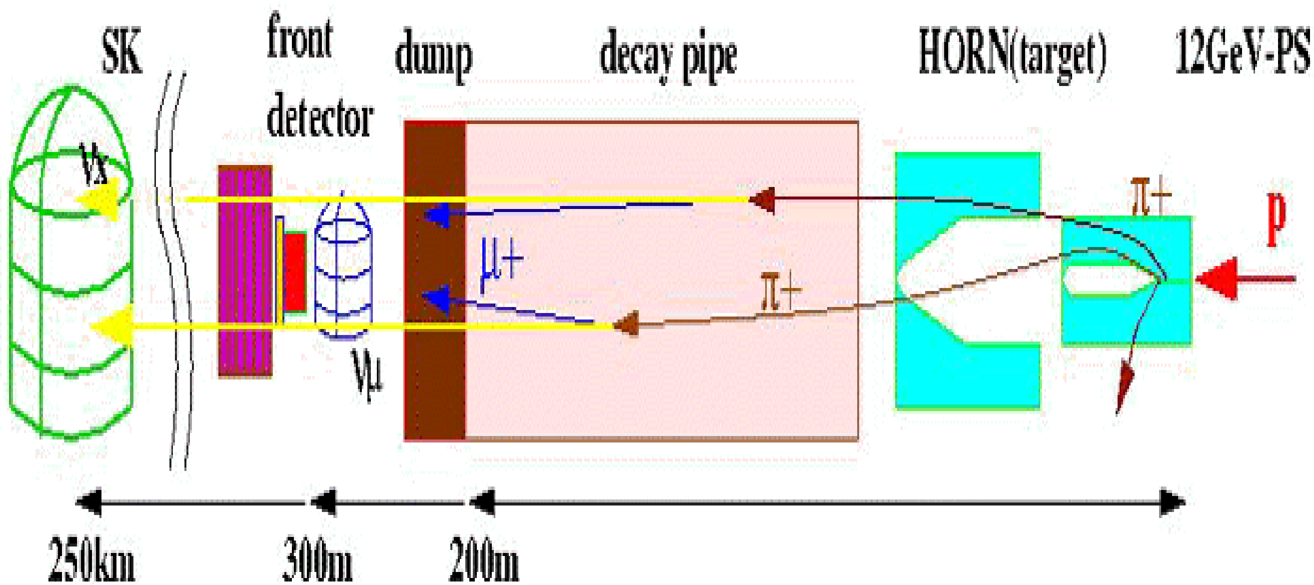
Macro experiment



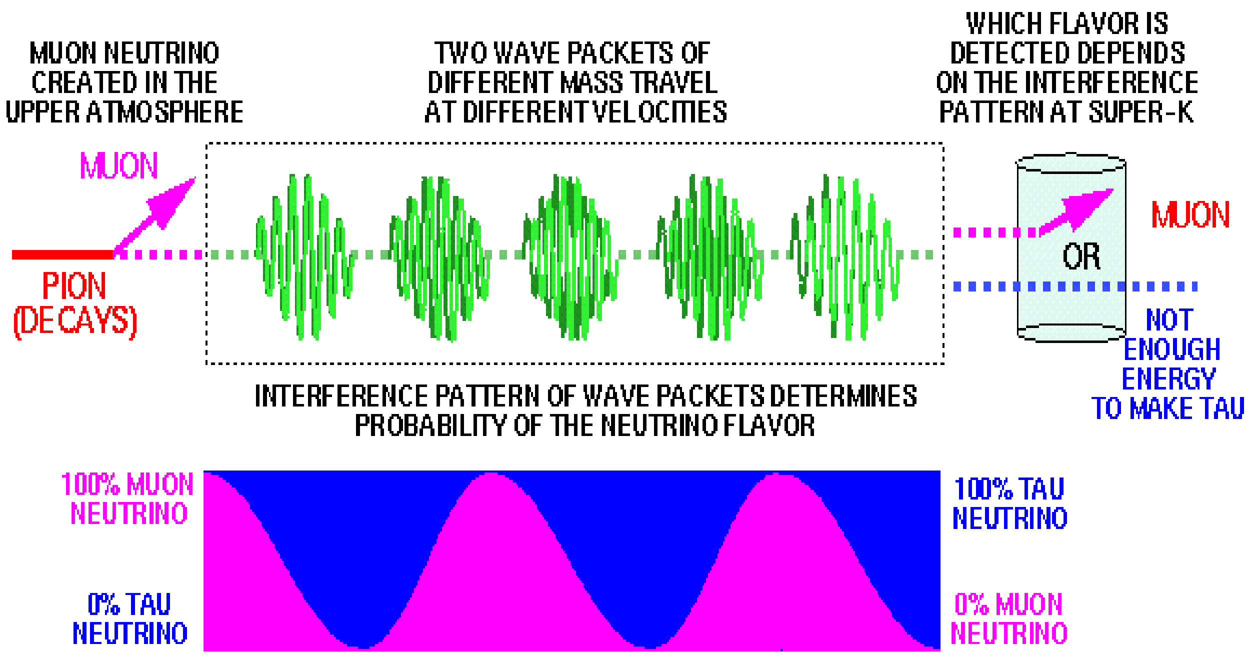
Accelerator Based Experiments

- Mostly ν_μ from accelerators
- Long and Short baseline experiments
  - Long baseline: Detectors located far away from the source, assisted by a similar detector at a very short distance (eg. MINOS: 370km, K2K: 250km, etc)
    - Compare kinematic quantities measured at the near detector with the far detector, taking into account angular dispersion
  - Short baseline: Detectors located at a close distance to the source
    - Need to know flux well

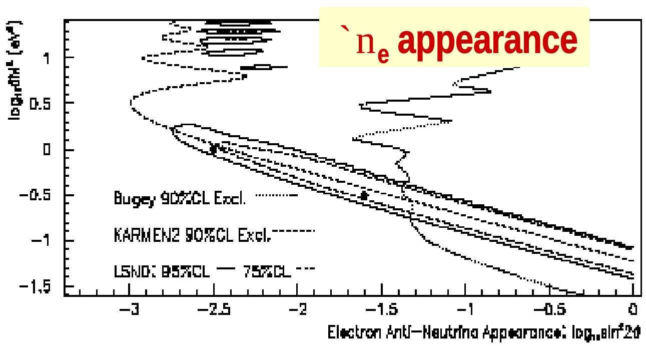
Long Baseline Experiment Concept (K2K)

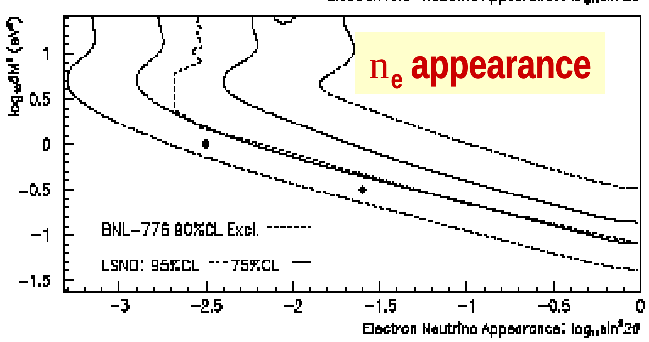


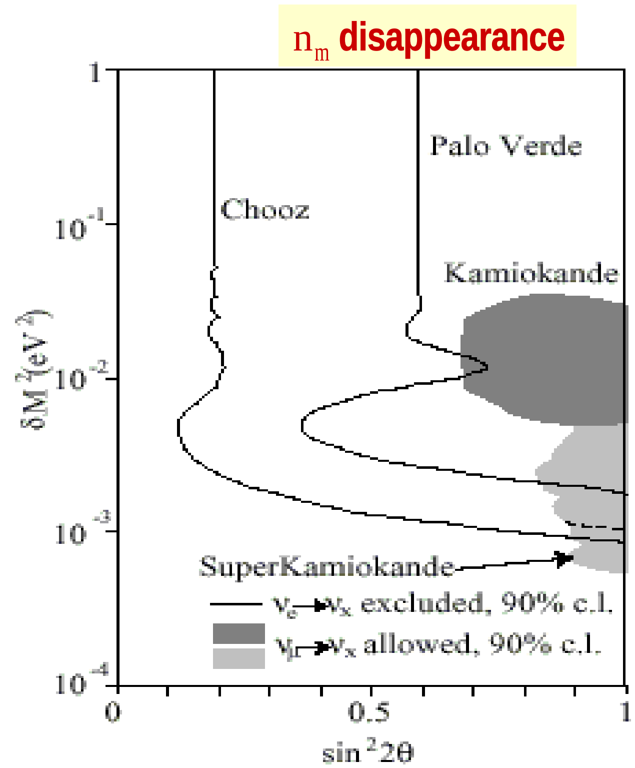
Different Neutrino Oscillation Strategies



Exclusion Plots

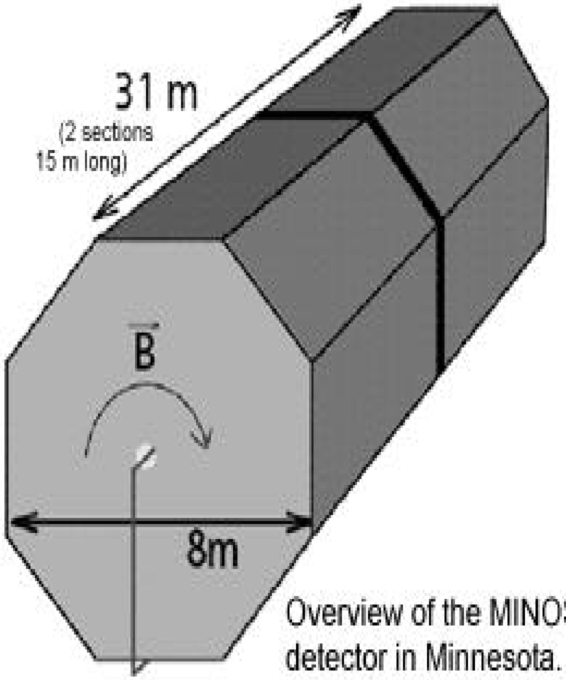






MINOS (Main Injector Neutrino Oscillation Search)

- Located in the Soudan mine in Minnesota, 800m underground
- Detector consists of iron and scintillation counters, weighing a total of 5400 tons
- 9000 neutrino events/year expected

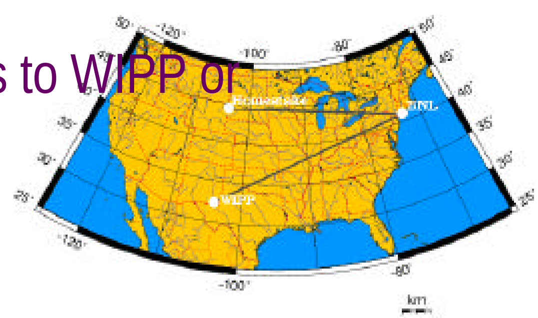


Overview of the MINOS detector in Minnesota.

Long Baseline Experiments

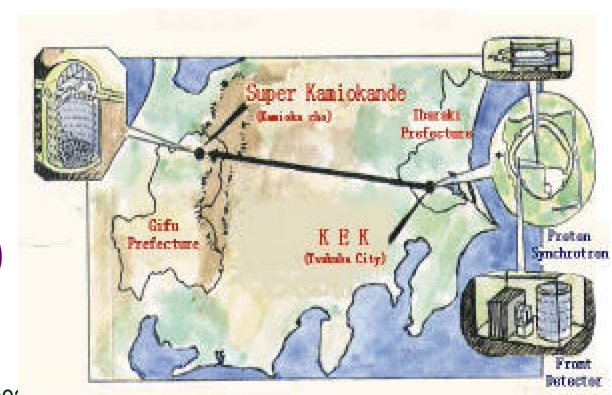
- Baseline length over a few hundred km
- Neutrino energies can be high
- Experiments and Facilities
  - Fermilab (to Soudan Underground Facility):
    - MINOS: Main Injector Neutrino Oscillation Search (L=730km)
    - Off Axis Neutrino Appearance Experiment (Near Soudan mine)
    - New Neutrino Oscillation Experiment at Soudan (Emulsion+iron) ➔ Tau appearance
  - BNL: A proposal to shoot neutrinos to WIPP or Homestake

$$\boxed{P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)}$$



Long Baseline Experiment Cont'd

- CERN (CNGS, CERN Neutrinos to Grand Sasso):
  - Baseline length, L=730km
  - ICANOE (Ring Imaging Cerenkov Detector)
  - ICARUS (LAr Cerenkov detector)
  - OPERA ($\nu_\mu \rightarrow \nu_\tau$): Lead+Emulsion
  - NOE (Neutrino Oscillation Experiment)
- KEK, Japan:
  - K2K: KEK to Kamioka Mine (L=250km)



Short Baseline Experiments

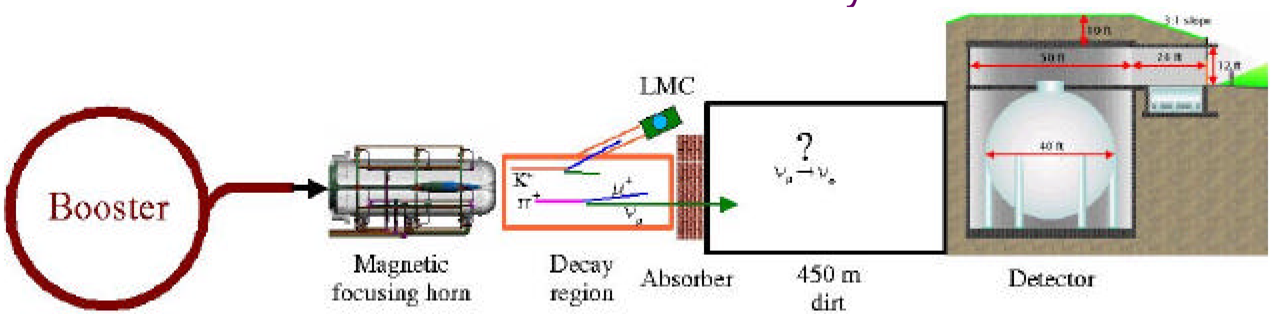
- Baseline less than a few km
- Neutrino energies need to be low

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

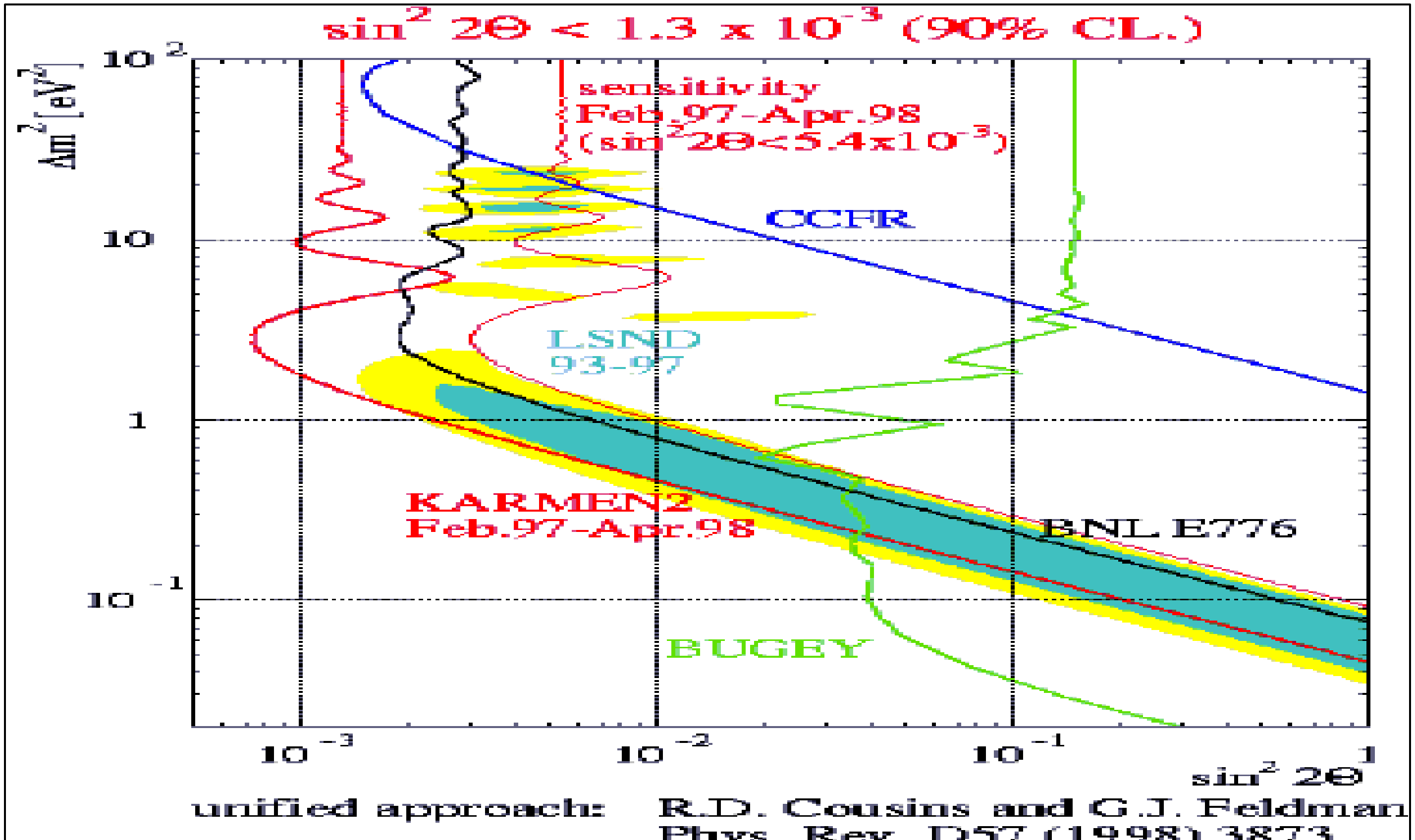
- Experiments and laboratories
  - CERN, Geneva: NOMAD, CHORUS,
  - Fermilab: BooNE, COSMOS (rejected)
  - Los Alamos: LSND (Completed)
  - Rutherford, UK: KARMEN
  - Oak Ridge: ORLanD (Using spallation neutrino source)

MiniBooNE (**Boo**ster **N**eutrino **E**xperiment)

- Goal: To investigate the signal from LSND on $\bar{\nu}_\mu \rightarrow \nu_e$ oscillation at $\Delta m^2 \sim 1 eV^2$
  - A bit contradictory to Super-K results
  - Measure oscillation properties
- Uses 8GeV protons from Fermilab's Booster on a target embedded in a Horn magnet
- Use Cerenkov light in a liquid scintillator detector
  - 40ft sphere with 800 tons of mineral oil and 1520 PMT's
  - Observe 1 neutrino event/20 sec $\rightarrow$ 1M/year

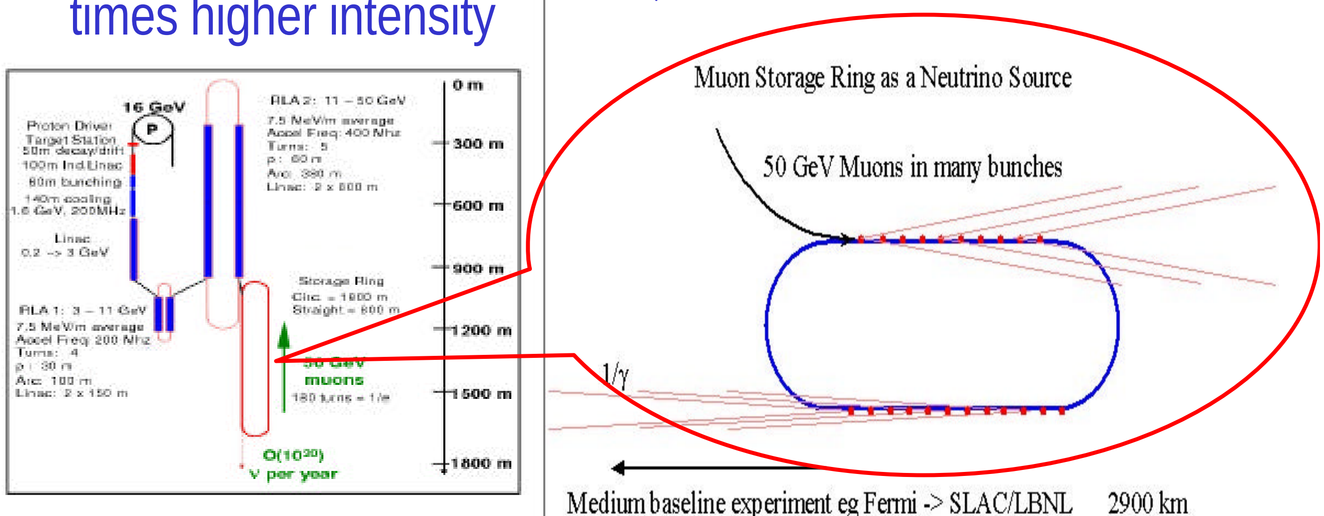


KARMEN Results



Future: Neutrino Factory

- Spin-off of a muon collider research
  - One a hot, summer day at BNL, the idea of neutrino storage ring popped up
- Future facility using muon storage ring, providing well understood neutrino beam (ν_μ and ν_e) at about 10^6 times higher intensity



Summary of ν_τ Appearance Experiments

Neutrino oscillation data page - Microsoft Internet Explorer provided by America Online - [Working Offline]

File Edit View Favorites Tools Help

Address D:\UTA\Classes\5326-spring03\Lectures\Wee of Mar. 3\Neutrino oscillation data page.htm Go Links

Experiment	Location	Source	Baseline	Observation	Status	Years
E531	Fermilab	accelerator	949 m	no osc	finished	86
CHORUS	Cern	SPS	820 m	no osc	scanning and analyzing data	1994-1997-
Nomad	Cern	SPS	820 m	no osc	analyzing data	1995-1998
OPERA	Gran Sasso	Cern	740 km		proposed	2005-
TOSCA	Cern	SPS			rejected	-

Internet

Summary of ν_e Appearance Experiments

Neutrino oscillation data page - Microsoft Internet Explorer provided by America Online - [Working Offline]

File Edit View Favorites Tools Help

Address D:\UTA\Classes\5326-spring03\Lectures\Wee of Mar. 3\Neutrino oscillation data page.htm Go Links

Experiment	Location	Source	Baseline	Observation	Status	Years
BEBC	Cern	SPS		no osc	finished	– 1986?
CCFR	Fermilab	Tevatron	0.9 km to 1.4 km	no osc	taking data (?)	1990? –
E776	BNL	AGS	1 km	no osc	finished	85–86
LSND	Los Alamos	LAMPF proton beam	30 m	excess of $\bar{\nu}_e$: 40 ± 9 ν_e: 18 ± 7	completed	1994–1998
Karmen	Rutherford	ISIS proton beam	18 m	no osc	taking data	1994–2001
Nomad	Cern	SPS	820 m	no osc	analyzing data	1995–1998
K2K	Kamioka	KEK beam	250 km		taking data	1999–
Minos	Soudan mine, MS	Main Injector at Fermilab	730 km		under construction	2004-
miniBooNE	Fermilab	Fermilab Booster	0.5 km/ 1 km		Taking Data	2003-
NOE	Gran Sasso	Cern	732 km		merged to Icanoe	
Icanoe	Gran Sasso	Cern	732 km		proposed	about 2005
Cosmos	Fermilab	Main Injector	1 km		rejected	

ν_e Disappearance Experiments

Experiment	Location	Baseline	Observation	Status	Years
Gösgen	Switzerland	37.9 m, 45.9 m, 64.7 m	no osc	finished	81-85
Bugey	France	15 m, 40 m, 95 m	no osc	finished	1981-1994
Krasnoyarsk	Russia	57 m, 57.6 m, 231.4 m	no osc		19??
Chooz	Ardennes, France	1 km	O/E=0.98 ± 0.4 ± 0.4	analyzing data	1997-1998
Palo Verde	Arizona, U.S.A.	750 m	O/E= 1.04 ± 0.03 ± 0.08	taking data	1998-2000 (July)
KamLAND	Japan	100 km		Taking Data	2001-
San Onofre	U.S.A.	about km		rejected	

What do we know now?

- We clearly know neutrinos oscillate ➔ Neutrinos have masses
- It seems that there are three allowed regions of parameters ($\sin^2 2\theta$ and Δm^2) that the current data seem to point
  - LSND ~1eV^2; Super-K ~ 10^{-3} eV^2, Solar (LMA) ~ 10^{-5} eV^2
  - There are at least three flavors participating in oscillation
  - $\mathrm{Sin}^2 2\theta_{23} \sim 1$ at 90% confidence level
  - $|\Delta m_{32}^2| \sim 2\mathrm{x}10^{-3}$ eV^2
    $\Delta m_{21}^2 \sim$ 2x10-3 eV2 (If LMA confirmed)
  - $\mathrm{Sin}^2 2\theta_{12} \sim 0.87$ at 90% confidence level (if LMA confirmed)
  - $\mathrm{Sin}^2 2\theta_{13} < O(0.1)$

What do we not know?

- Does 3-flavor mixing provide right framework?
  - For CP–violating oscillation, additional neutrino flavors, neutrino decay, etc?
- How many flavors of neutrinos do we have?
- Is $\sin^2 2\theta_{13}$ 0 or small?
- What is the sign of Δm_{32}?
  - What are the configuration of neutrino masses?
  - What are the actual masses of neutrinos mass eigenstates?
- What are the matter effects?
- Is $\sin^2 2\theta_{23} = 1$?
- While there are a lot of questions and measurements need to be performed, neutrino oscillation provides an exciting new area in HEP.

Useful Links for Neutrinos Oscillations

- http://www.hep.anl.gov/ndk/hypertext/nuindustry.html
- http://www.ps.uci.edu/~superk/oscillation.html
- http://wwwlapp.in2p3.fr/neutrinos/ankes.html