The (Low) Energy Frontier in Neutrino Physics

Kevin McFarland
University of Rochester
NUINT ’02
12 December, 2002

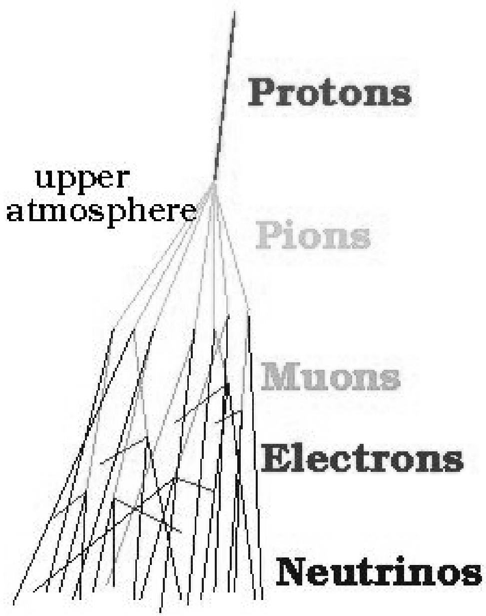
Low Energy Neutrino Physics

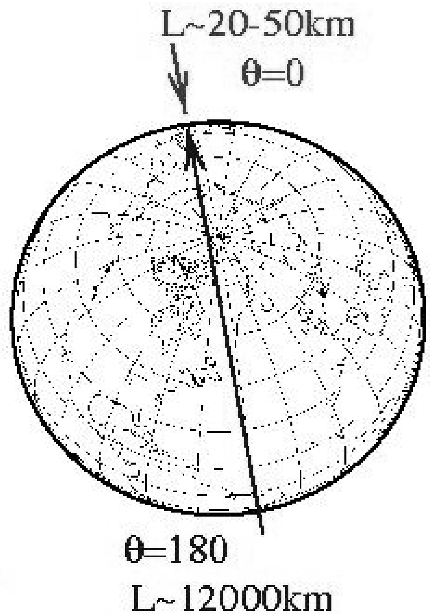
High Rate Neutrino Beams

- **Neutrino Oscillations** ★ ★ ★
- **Neutrinos as Probes of Hadron/Nuclear Structure, QCD** ★ ★
- **Non-Standard Neutrino Interactions** ★

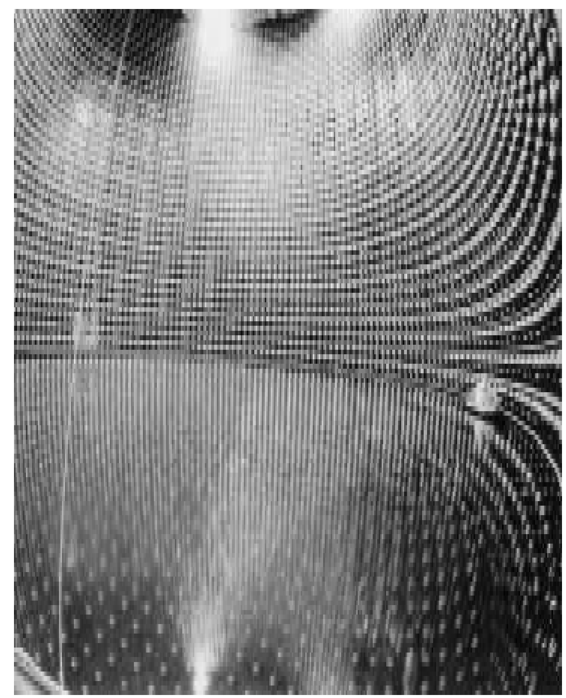
I have opted to view my job as setting the stage for discussions of details of the first, outlining in broad brush the rules of the second, and ignoring the third.

"Discovery of Oscillations": Atmospheric Neutrino Anomaly





- Neutrinos are produced in cosmic ray showers
  - Flight distance 20-10000 km

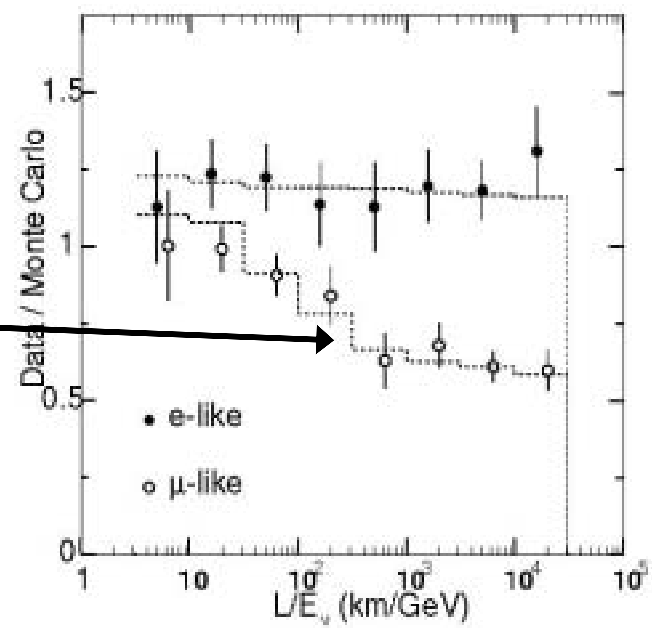


- Super-Kamiokande detector
  - 2^{nd} generation water-Cherenkov det.
    - ~11000 photomultiplier tubes
  - 50 kilotons, deep underground
  - ~100 events/kiloton-year

Atmospheric Neutrinos (cont'd)

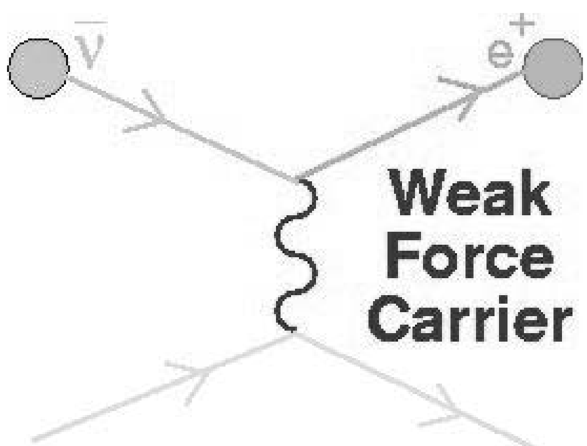
- Neutrinos from cosmic rays come in 2:1 μ to e flavor ratio
  - But this is NOT observed at detector!

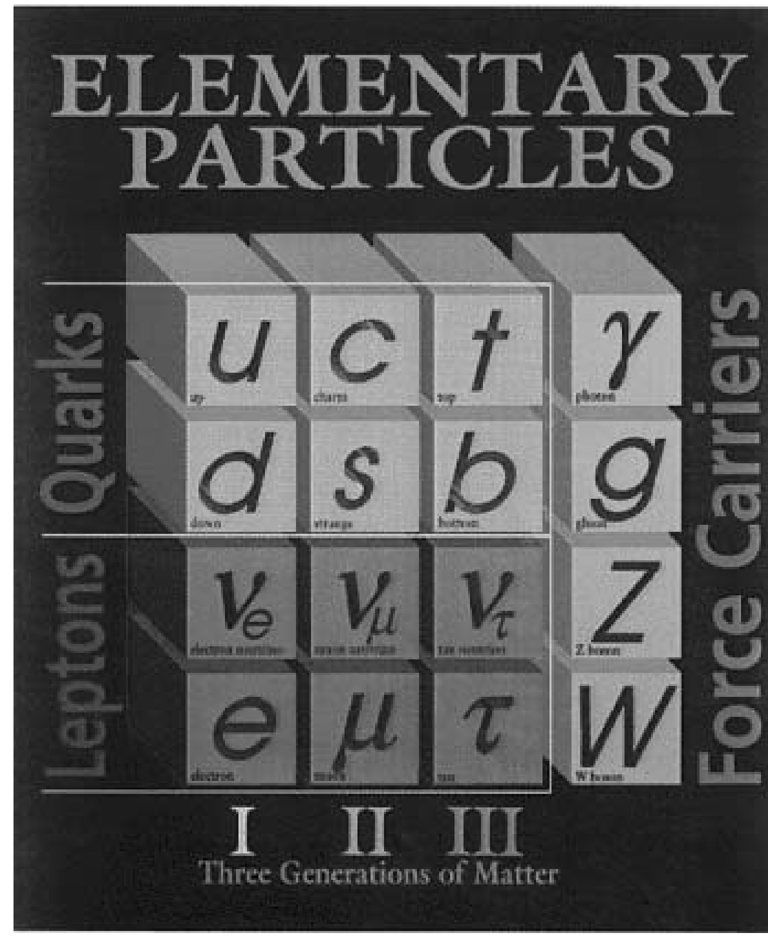
Muon deficit at large L/E



Quarks, Leptons and Weak Interactions

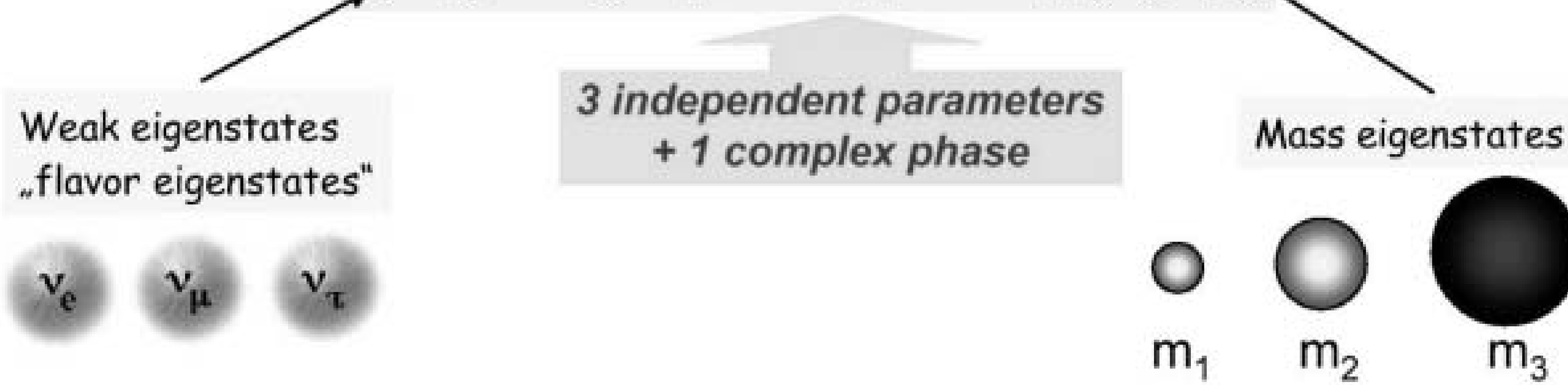
- Charged-current weak force (mediated by W boson)
  - Connects charged leptons to neutrinos
  - Conserves lepton "flavor", e.g., $W^+ \to \mu^+ \nu_\mu$





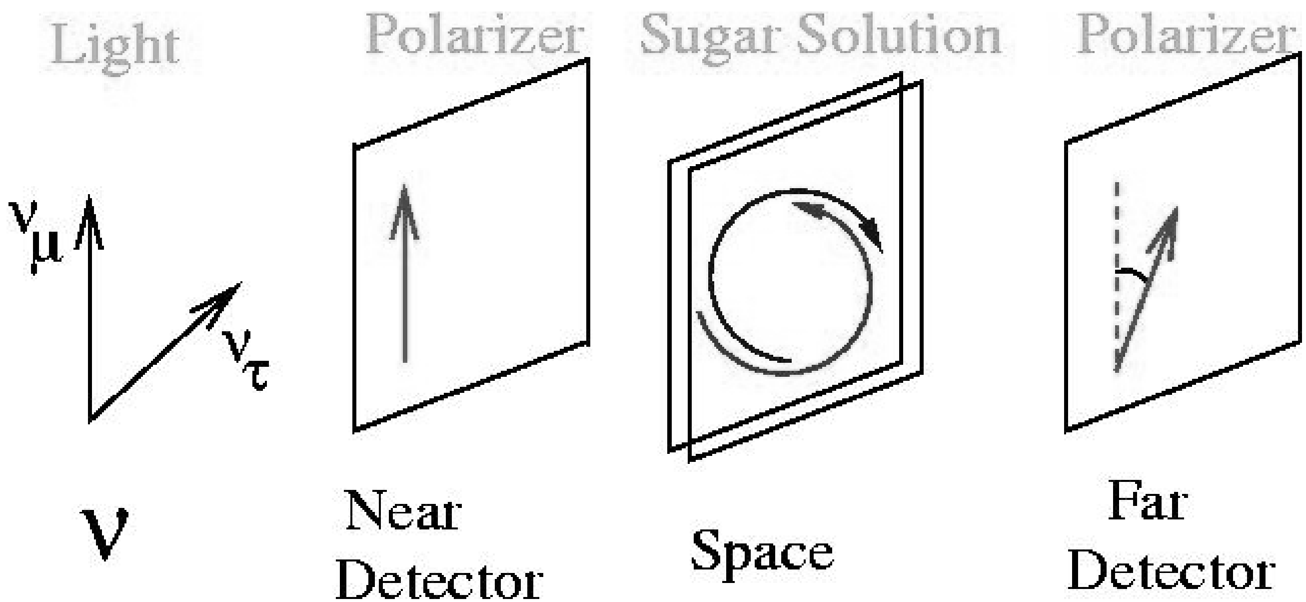
Neutrino Mass and Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Flavor eigenstates not equivalent to mass eigenstates
  - Mixing between two contained in MNS matrix
  - Complex phase in 3-generation matrix can lead to CP violation

Neutrino Oscillation: an analogy



- Consider light, polarized in "μ" direction.
- Chiral medium: different speed for LH and RH polarizations

- Propagation through solution rotates polarization vector
  - Result is a mixture of μ and τ states
- What about space is analogous to a sugar solution?
  - "μ" and "τ" composed of different states ("vacuum oscillation")
  - "μ" and "τ" *(well, "e", actually)* may interact differently in matter ("MSW effect")

Neutrino Oscillation

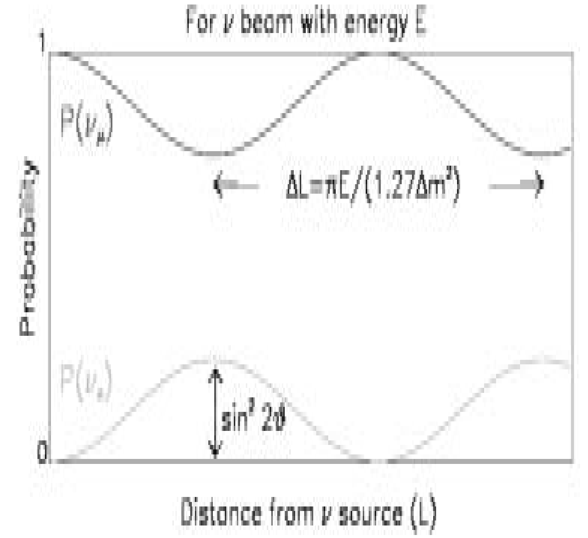
- In vacuum, different time evolution of different mass eignestates…
  - (richer phenomenology from ν potential in matter)
- …result in the oscillation from one flavor eigenstate to another in vacuum or matter

$$P_{oscillation} = \sin^2 2\theta \times \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

- Flavor oscillation probability (two flavor case) depends on
  - Δm^2, difference in masses squared
  - L, flight length from creation to detection (time to evolve)
  - E, energy of neutrino

Neutrino Oscillations (cont'd)

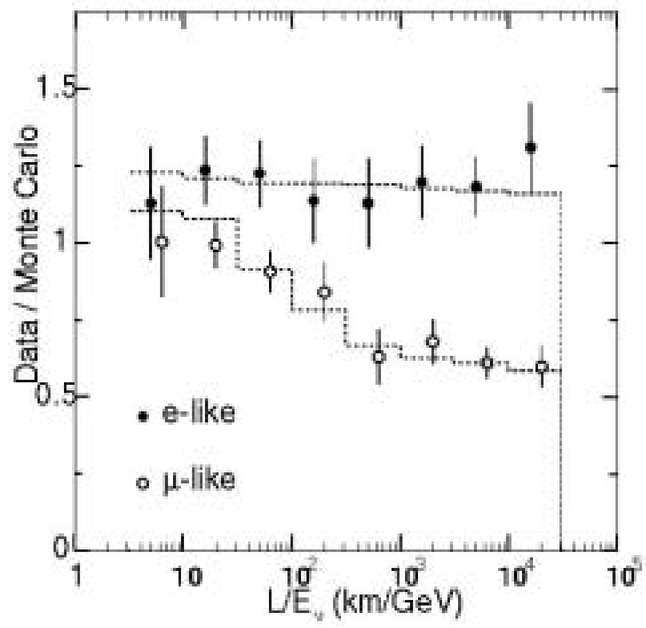
$$P_{oscillation} = \sin^2 2\theta \times \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

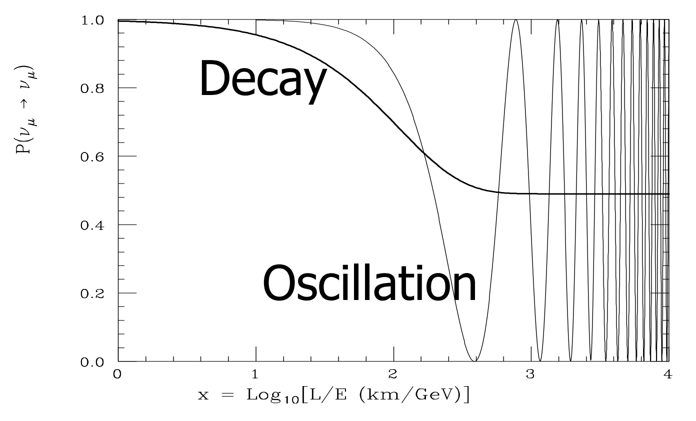


- Flavor evolution with time
  - Oscillation L/E ~ 2.5/Δm^2
  - For disappearance of atmospheric neutrinos, first oscillation maximum is at ~400 km/GeV
- Two types of observations are possible
  - Disappearance: fail to see neutrinos at distance L
  - Appearance: observe a flavor not in the original beam

Interpretation of Atmospheric Neutrino Anomaly

- μ but not e neutrinos oscillate
  - "Disappearance" means $\nu_\mu \to \nu_\tau$
  - ν_τ charged-current interactions not observed because m_τ (1.7 GeV) too large to produce τ
- Interestingly, decay *could* also explain *this* data
  - But decay doesn't fit all data
- 50% ν_μ survival
  - maximum flavor mixing!

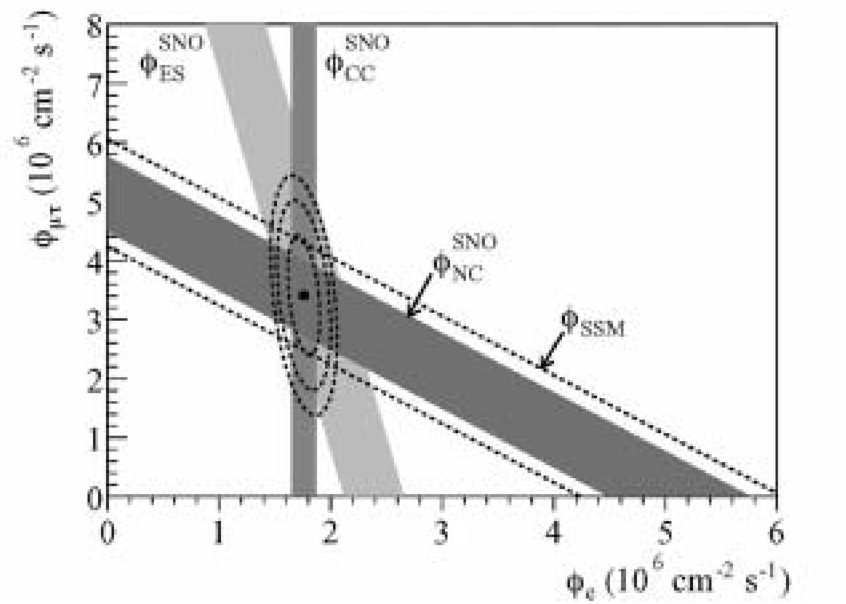


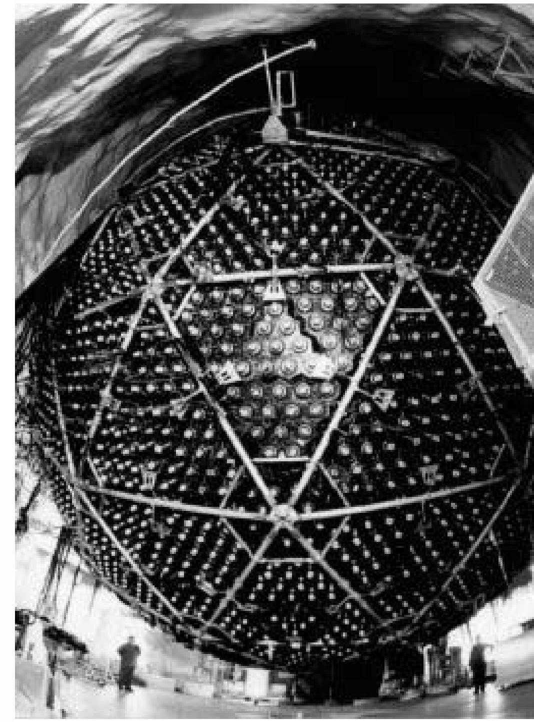


Solar Neutrino Oscillations

- Deficit of electron neutrinos from sun observed in many experiments
- SNO has recently shown these appear as other flavors

Fluxes	$(10^6\ cm^{-2}\ s^{-1})$
ν_e	1.76(11)
$\nu_{\mu\tau}$	3.41(66)
ν_{total}	5.09(64)
ν_{SSM}	5.05

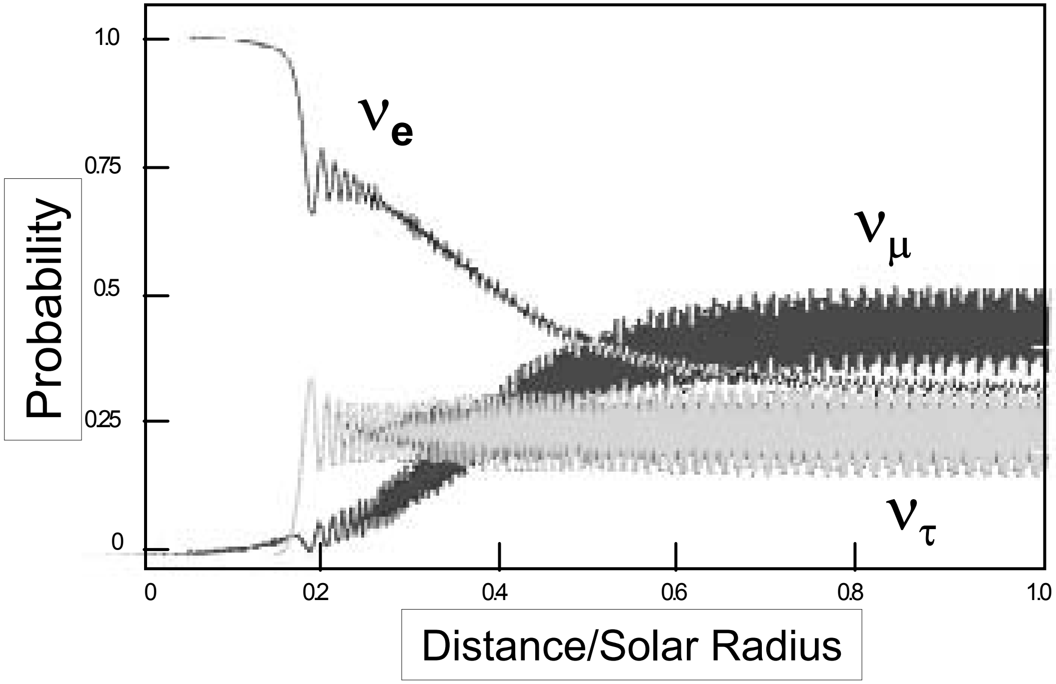


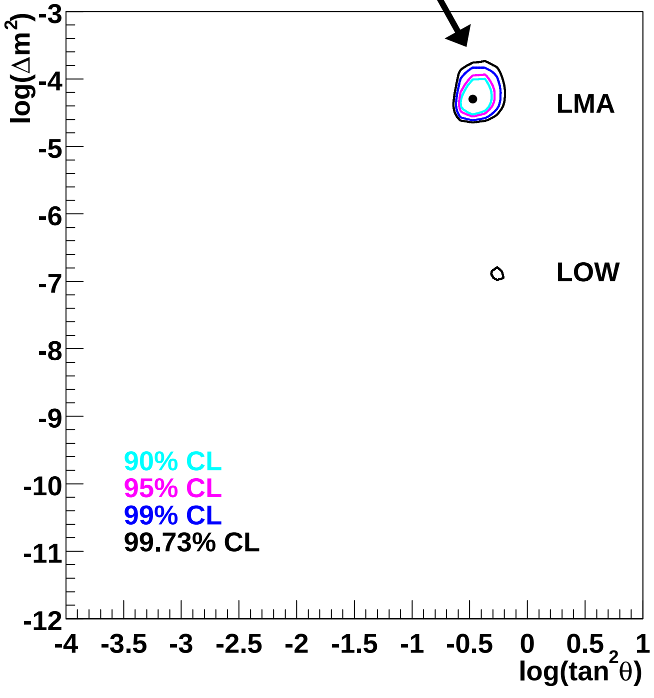


Interpretation of Solar ν

- Matter-enhanced oscillations
  - Resonant transition inside sun

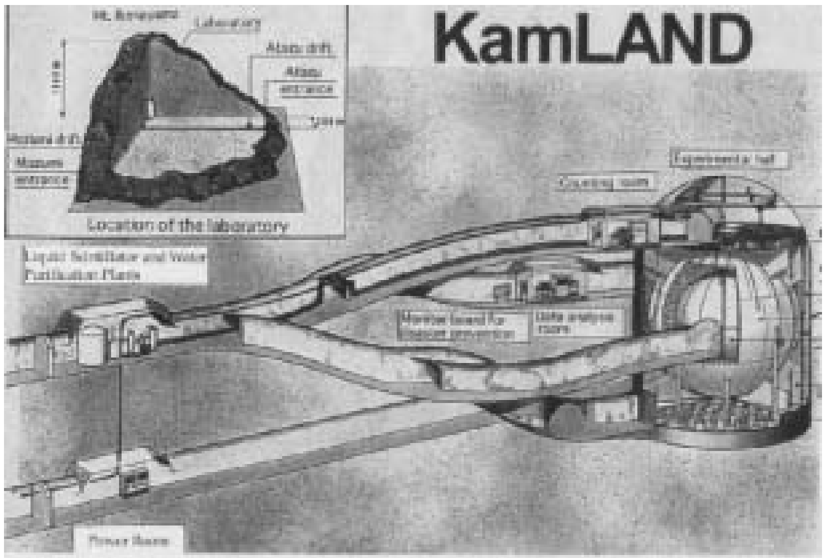
Large mixing
$\Delta m^2 \sim 10^{-4} eV^2$

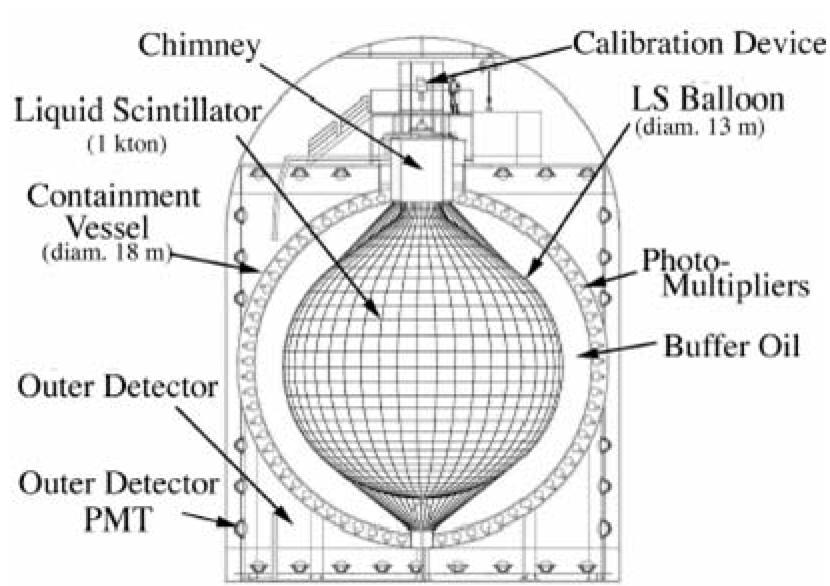




News from KAMLAND

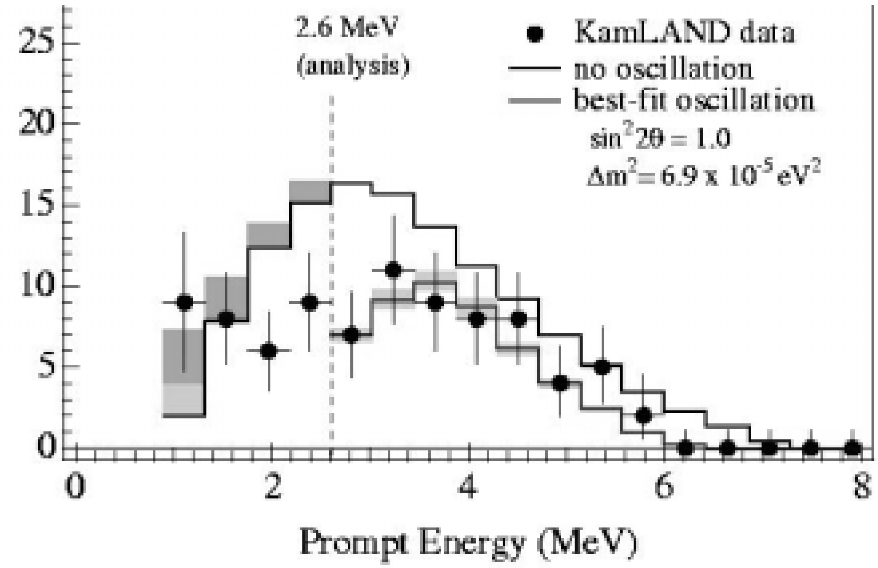
- $\overline{\nu}_e$ from nuclear reactors located 140-210 km from detector (1kTon scintillator)
- $L/E \sim 10^5$ km/GeV
- Solar MSW solution would predict disappearance

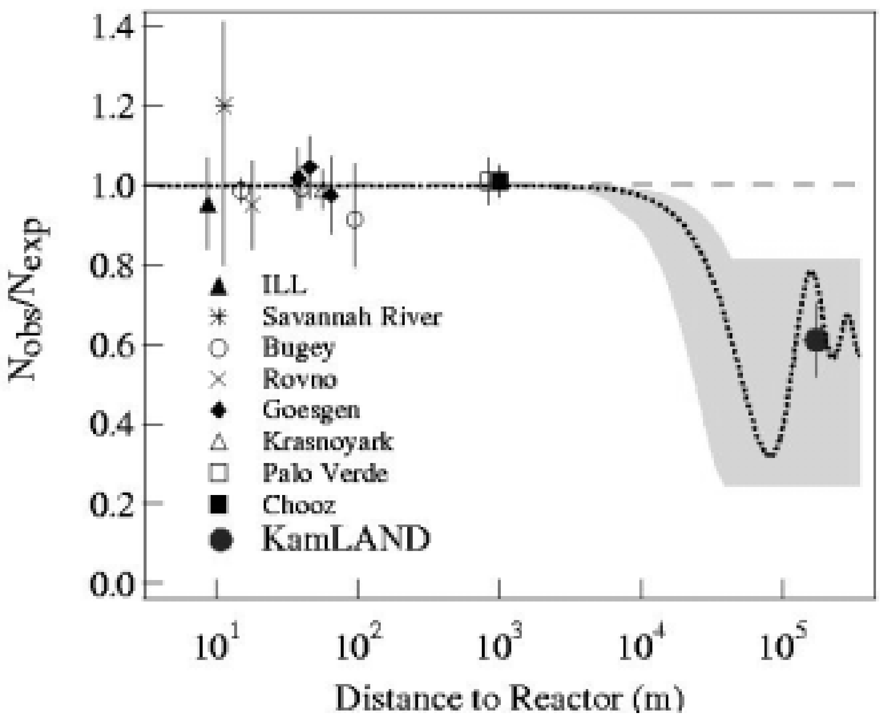




KAMLAND

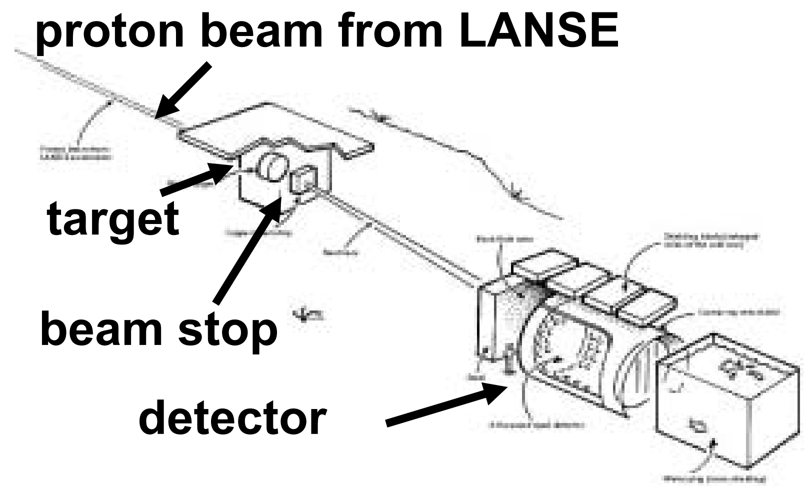
- $\overline{\nu}_e$ disappear!
- First observation with reactor source

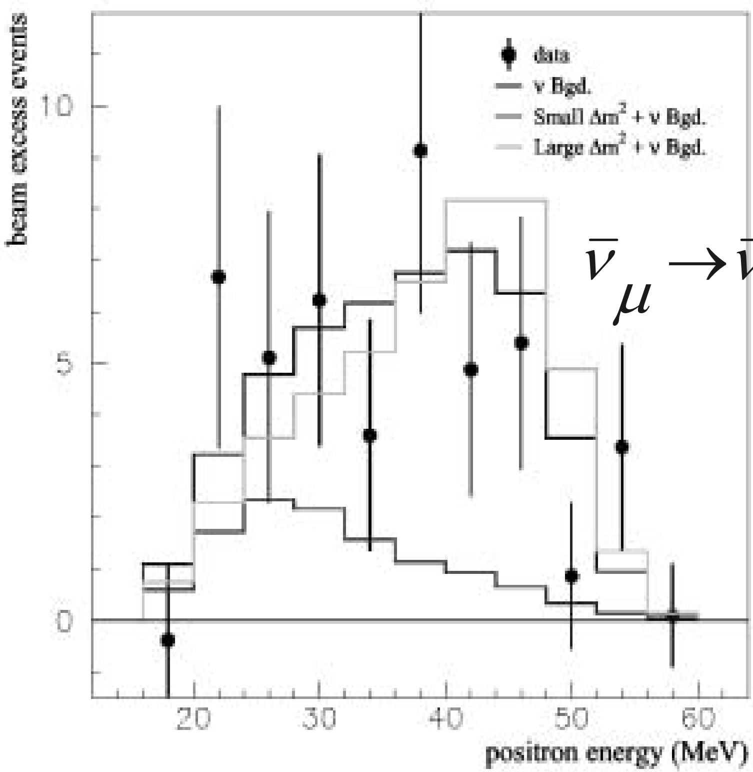




- Consistent with solar neutrino MSW explanation
- Not (yet) enough precision to measure δm^2

LSND Neutrinos



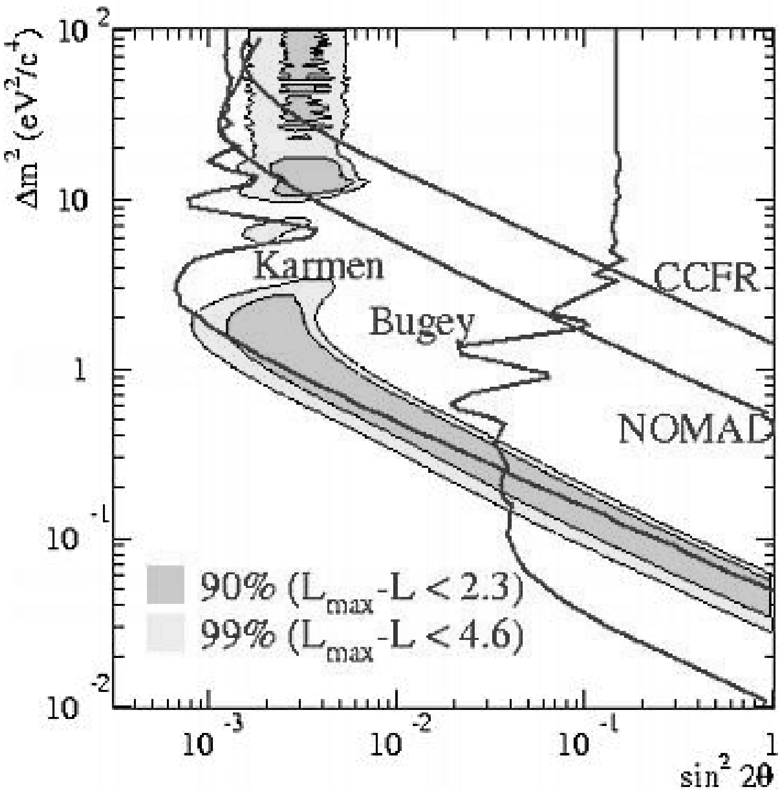


$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

π^+, μ^+ decay at rest

- Signal: 88 ± 22 ±6 events
- Similar experiment with larger flux, slightly smaller L/E (KARMEN) sees no effect

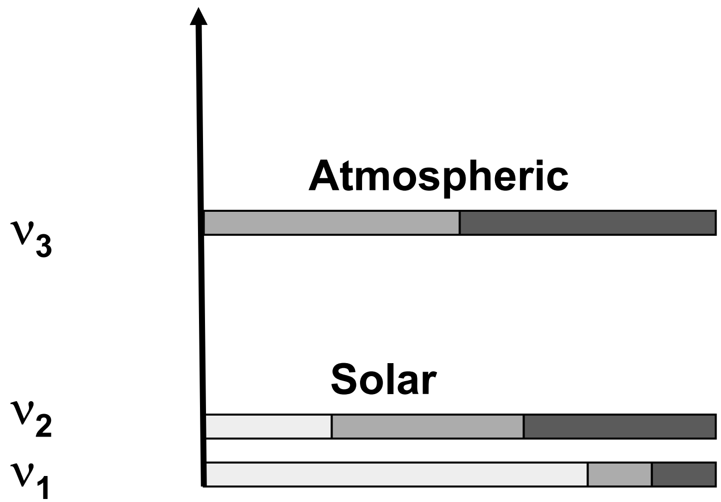
LSND Neutrinos



If neutrino oscillations, corresponds to oscillation probability (large δm^2)
$P \approx 0.25\%$

- Atmospheric, solar and LSND δm^2 cannot all be accommodated with three neutrinos
- Exotic scenarios? CPT violation?

Neutrino Mixings and Spectrum



Mass (eV)	Percentages: e	mu	tau
0.05	small	50	50
0.007	28	36	36
≡0	72	13	13

- A viable model:
  - Atmospheric splitting is largest
  - Data consistent with maximal $\mu-\tau$ mixing
  - Large e mixing, *except in ν_3 eigenstate*
    - CHOOZ/Palo Verde (reactor) sees no ν_e disappearance

Long Baselines, Low Energies

- Recall a rather sobering fact we introduced a few slides back…
  - For disappearance of atmospheric neutrinos, first oscillation maximum is at ~400 km/GeV

two neutrino oscillation probability

$$P_{oscillation} = \sin^2 2\theta \times \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

- If L is small, $P_{\mathrm{oscillation}}$ goes as L^2/E^2
  - which cancels the $1/R^2$ effect of beam divergence over long distances
  - *lower energy is the way to the oscillation maximum*

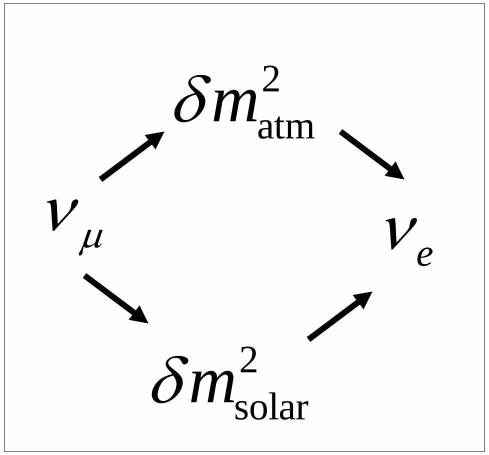
Back to the mixing matrix…

- Lepton Mixing Matrix (MNS) has different structure than quark (CKM) matrix
- Big elements (B) are numerically 0.2-0.7
- “?” Element, U_{e3}, is less than 0.15
  - CHOOZ/Palo Verde reactor bounds
  - Theory “bet” is that U_{e3} is near bound
- U_{e3} carries a phase that leads to CPV

CP Violation

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

- In general, *CP violation in mixing* can occur if
  - There are two amplitudes with different mixings contributing to a process
  - There is a relative phase between the two
- CPV in $\nu_\mu \to \nu_e$ may be large at $\delta m^2_{\mathrm{atmospheric}} L/E \sim 1$
  - One amplitude suppressed by $|U_{e3}|$
  - The other suppressed by small $\delta m^2_{\mathrm{solar}} L/E$
  - If comparable, CPV can be large



Matter Effects

$$\frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \neq 0$$

may arise from interactions in terrestrial matter

- Just as in MSW effect in solar neutrinos, matter modifies potential of ν_e
  - Different modification of transition rates for neutrinos and anti-neutrinos
  - Effect depends on sign of δm^2
    - This is often characterized as an "opportunity" to measure the hierarchy of neutrino masses

Transition Probabilities to Parameters

- Transition depends on magnitude and phase of U_{e3}
  - also "hierarchy" of neutrino mass eigenstates
  - degeneracy in parameters for given P

$$P(\overset{(-)}{\nu}_{\mu} \to \overset{(-)}{\nu}_{e}) \approx 4 s_{23}^2 s_{13}^2 c_{13}^2 \frac{\sin^2\left[\left(1 \mp \hat{A}\right)\Delta\right]}{\left(1 \mp \hat{A}\right)^2} + 4\left(\frac{\left|\delta m^2{}_{sol}\right|}{\left|\delta m^2{}_{atm}\right|}\right)^2 c_{23}^2 s_{12}^2 c_{12}^2 \frac{\sin^2\left[\hat{A}\Delta\right]}{\hat{A}^2}$$

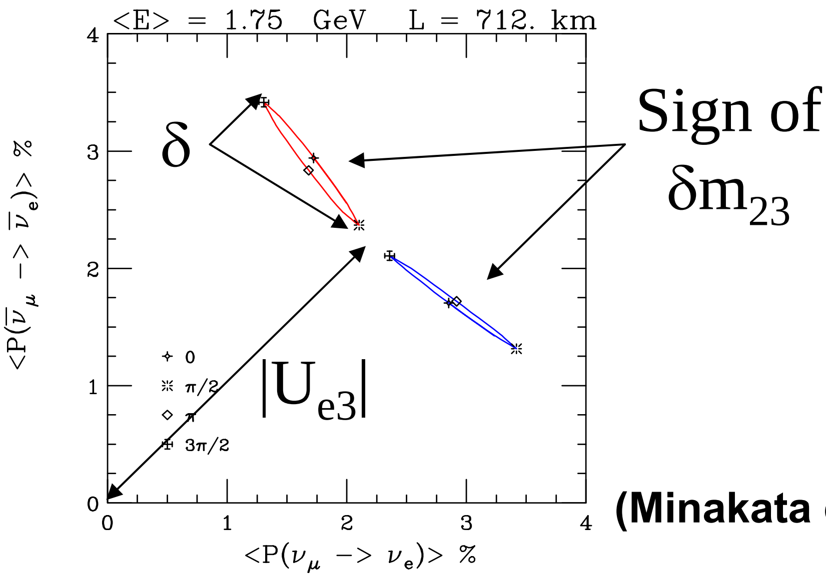
$$+4J \frac{\left|\delta m^2{}_{sol}\right|}{\left|\delta m^2{}_{atm}\right|} \frac{\sin\left[\left(1 \mp \hat{A}\right)\Delta\right] \sin\left[\hat{A}\Delta\right]}{\left(1 \mp \hat{A}\right)\hat{A}} \left(\cos\delta \cos\Delta \mp \sin\delta \sin\Delta\right)$$

$\hat{A}$ parameterizes matter effect

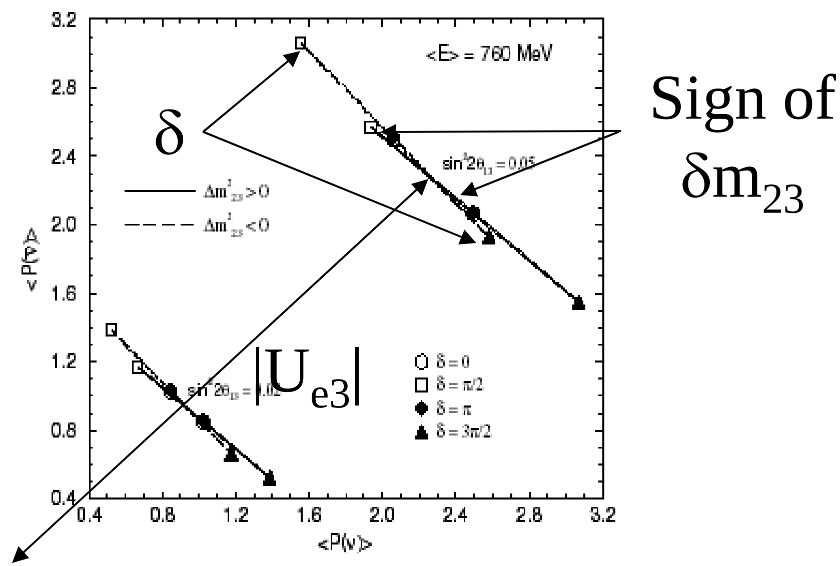
$$\Delta \equiv \left|\delta m^2_{\text{atm}}\right| L / 4E$$

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

- Comparison of two *precise* measurements of $\nu_\mu \rightarrow \nu_e$ can untangle magnitude and phase of U_{e3} and mass hierarchy
  - ν and anti-ν measurements
  - or two ν measurements at different *E* or *L/E*
  - This is not easy
    - low statistics and incoherent systematic uncertainties



(Minakata et al.)



What Do We Learn from ν Oscillation Parameters?

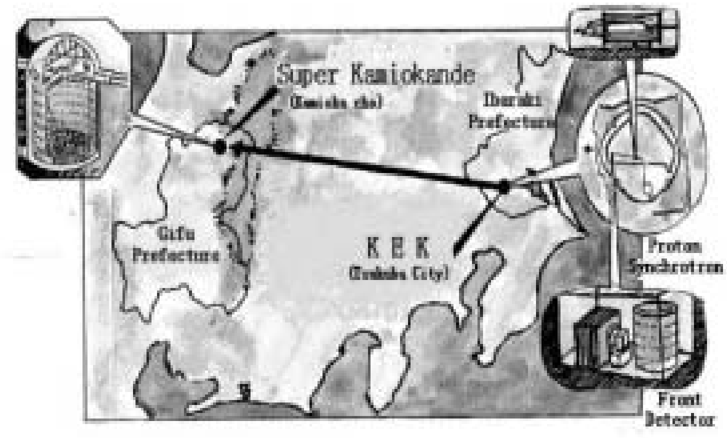
- δm^2 measurements constrain models of ν mass generation
  - In a practical sense, at accelerators, δm^2 dominates observable phenomena, since L/E is usually very narrow
- GUT models of mixing matrix
  - Magnitude of U_{e3} element
  - Is $\mu-\tau$ mixing maximal?

What Do We Learn from ν Oscillation Parameters?

- CP Violation is the ★★★ destination
  - Connection between quarks and leptons?
  - CP Violation in leptons can lead to baryogenesis (but not through phase of U_{e3}!)
- Observable CP Violation requires
  - Non-zero U_{e3}
  - Solar δm^2 and mixing sufficiently large

    (SNO allowed region for MSW oscillations is good enough)

Current Experiments

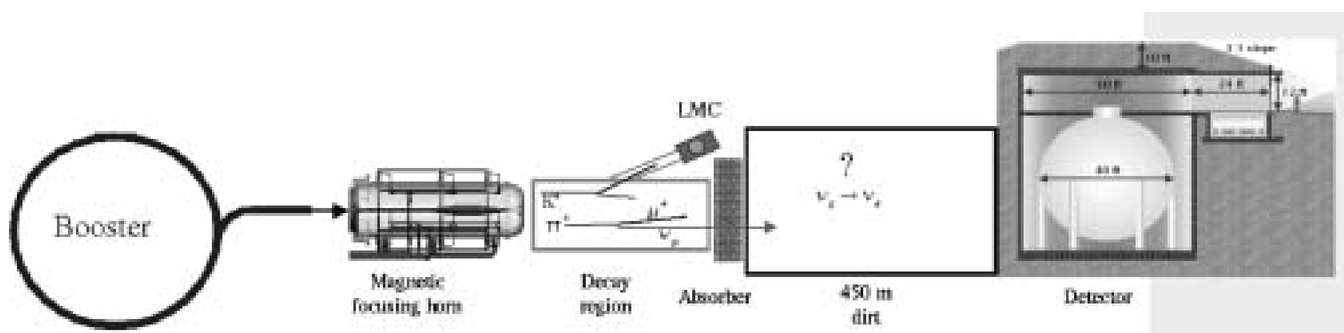


K2K

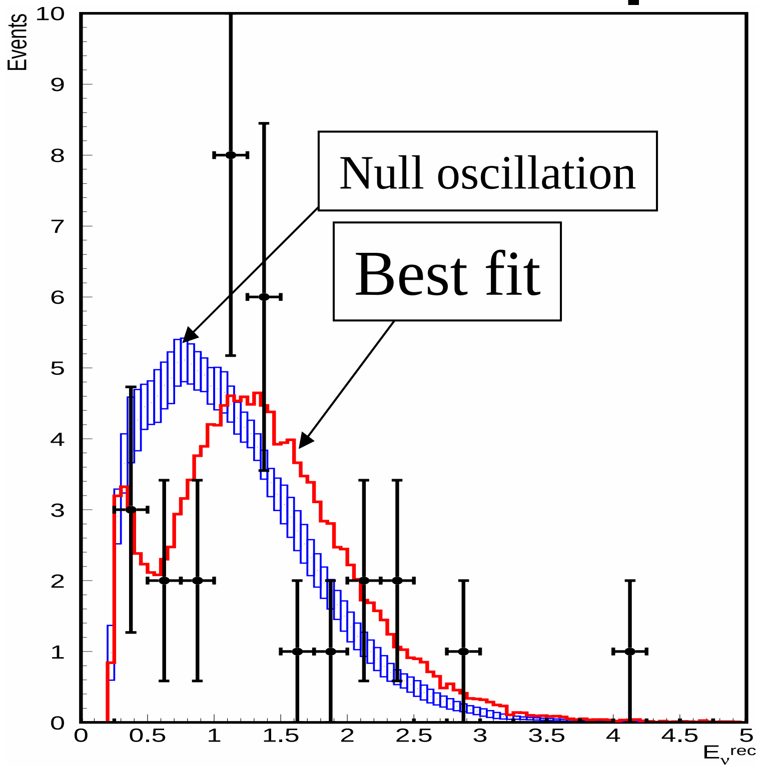
Designed to study atmospheric mass splitting $\Delta m^2 > 2 \times 10^{-3} eV^2$

BooNE

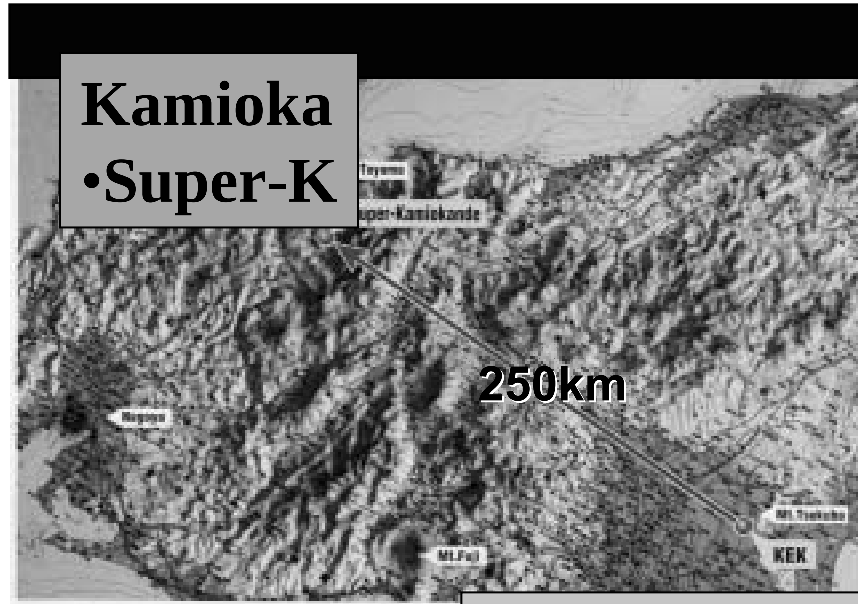
Rufute or confirm LSND as oscillations

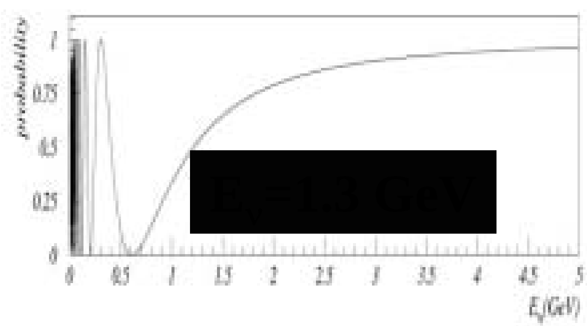


Current Experiments (cont'd)



First ν_μ disappearance





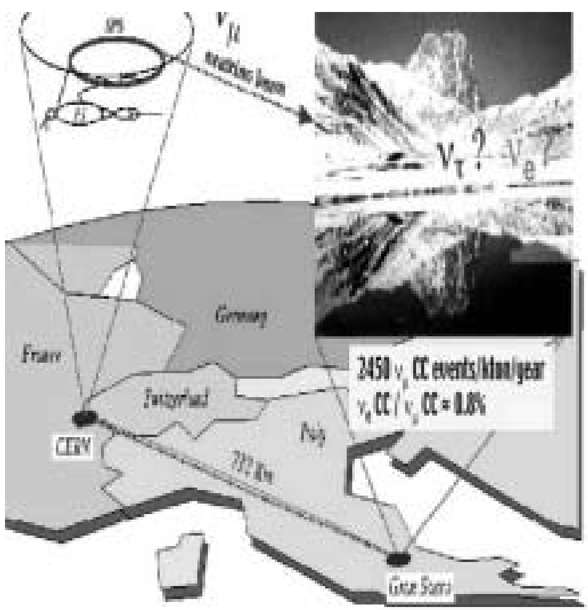
KEK

- **ν beam line**
- **Beam monitor**
- **Near detectors**

Future Experiments

JHF

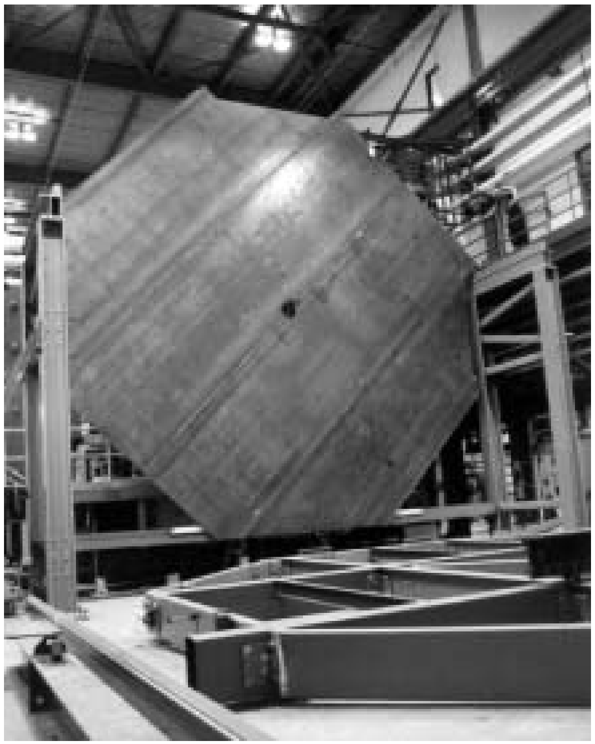
NUMI/MINOS

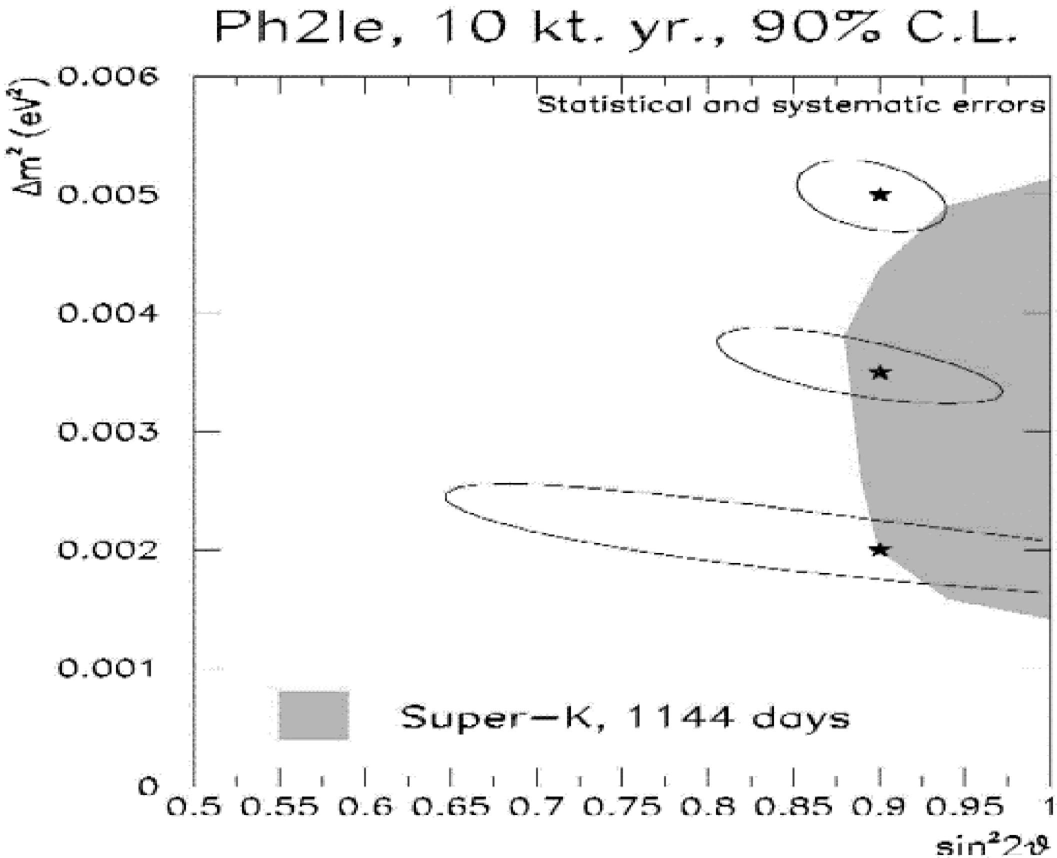


CERN → GS

All designed to study atmospheric mass splitting $\Delta m^2 > 2 \times 10^{-3} eV^2$

Future Experiments (cont'd)

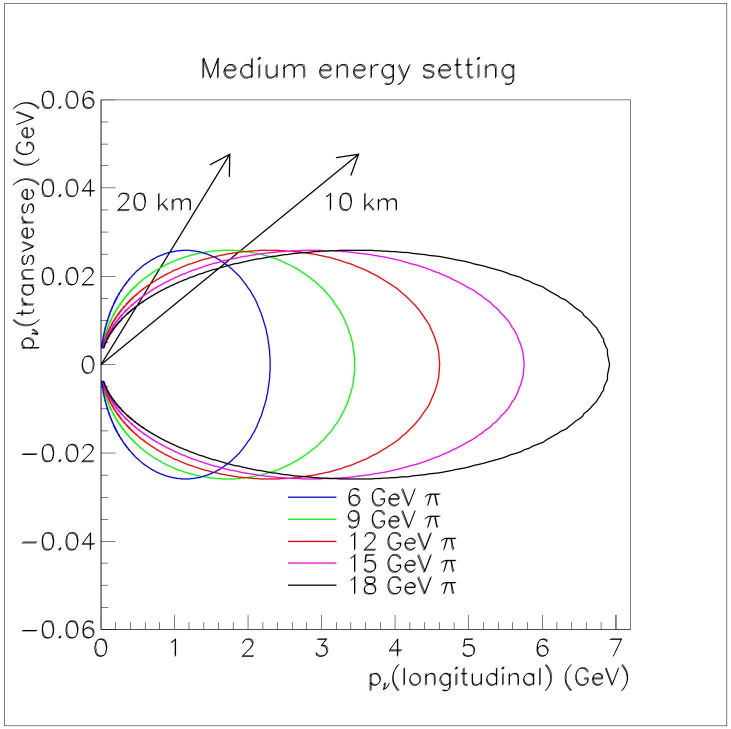




Precision ν_μ disappearance

Difficulties of the Next Step

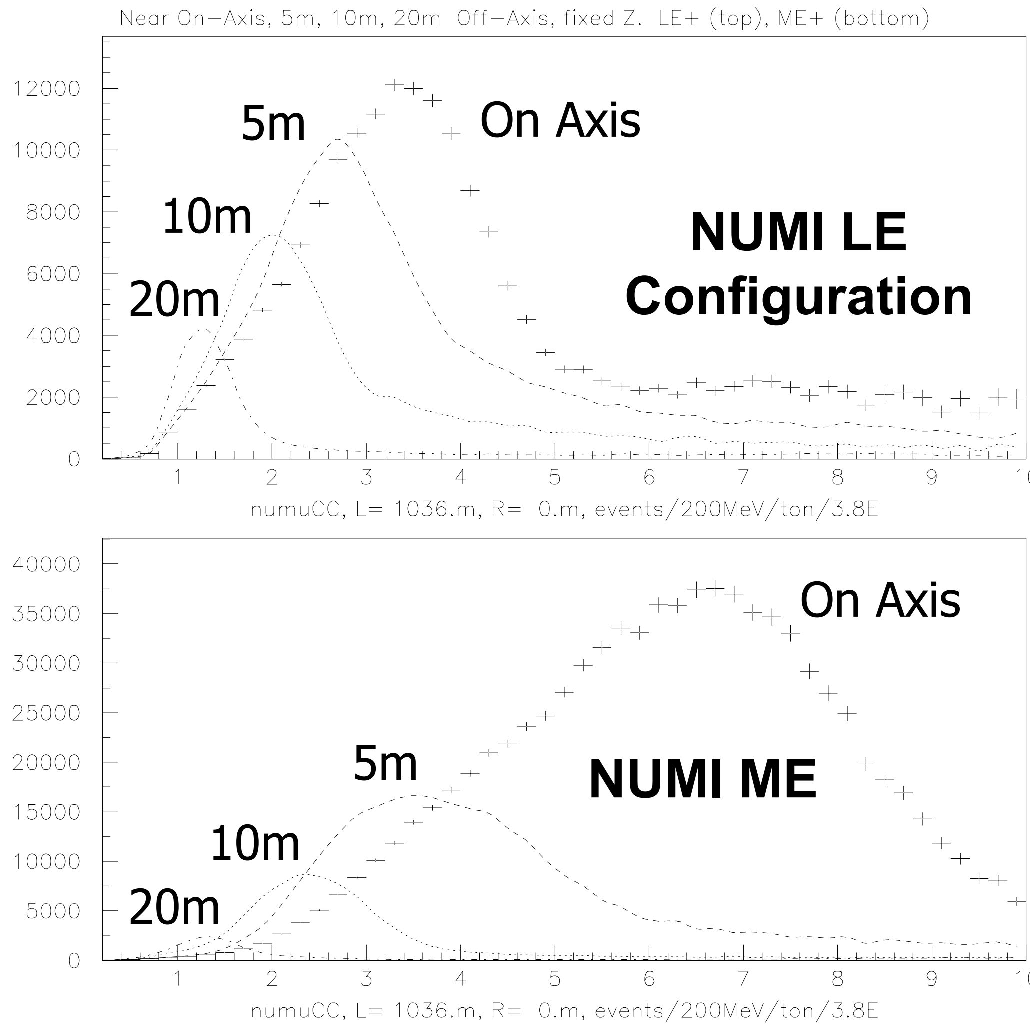
- ν_e appearance signal difficult to extract
  - beam backgrounds (ν_e from μ, K decay)
  - high energy “feed-down” (neutral currents)
- Off-axis beam technique makes it possible
  - Monochromatic beam at oscillation maximum
  - Less feed-down
  - Fewer electron neutrinos in beam



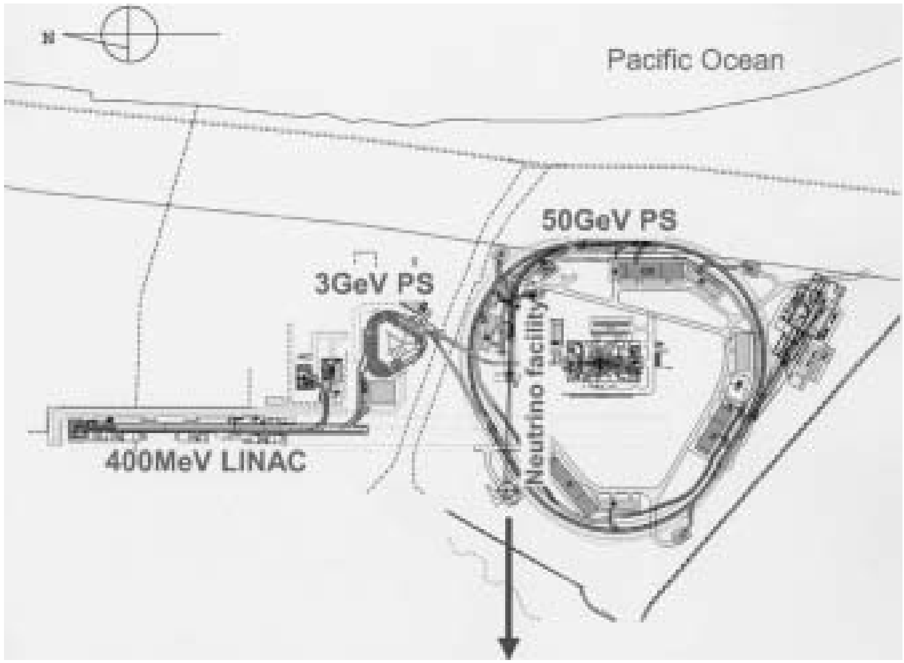
Off-Axis Beams

- Illustration at NUMI near detector site
  - Peak energy lower
  - Width decreases
  - High energy tail suppressed
  - Rate significantly decreased, but still impressive for ν!
- Works *better* at far detector

NUMI Near On and Off-Axis Beams (beam sim. courtesy M. Messier)



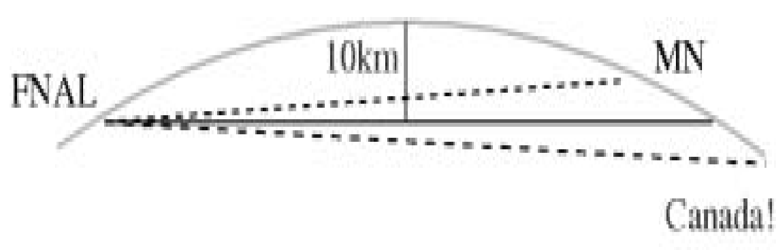
JHF Neutrino



- JAERI 50 GeV PS
  - 0.77MW initially
    - 4MW upgrade planned
  - Extraction point for ν beam is being built
    - Off-axis beam to Super-K detector, Seoul
  - At Super-K, *L/E*~295km/0.7GeV

NUMI Off-Axis

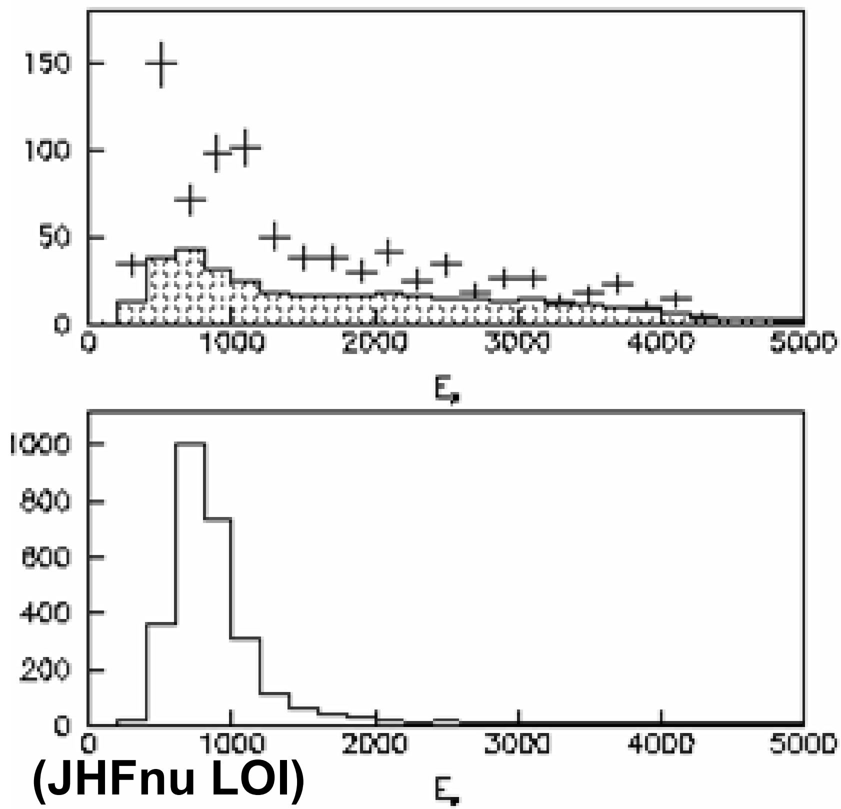
- NUMI (on-axis) experiment for ν_μ disappearance will commence 2005
  - 0.25-0.4 MW proton power
  - Run 10 km off axis at L/E~700km/2GeV? Other?
    - LOI submitted to PAC



Where do Cross-Sections matter?

- $\nu_\mu \rightarrow \nu_\mu$, δm^2_{23}, θ_{23}
  - Signal is suppression in 600-800 MeV bin (peak of beam)
- Dominated by non-QE background
  - 20% uncertainty in non-QE is comparable to statistical error
- Non-QE background feeds down from $E_\nu > E_{peak}$
- Quantitatively different for MINOS, NUMI-OA

JHF->SK, 0.8MW-yr, 1ring FC μ-like



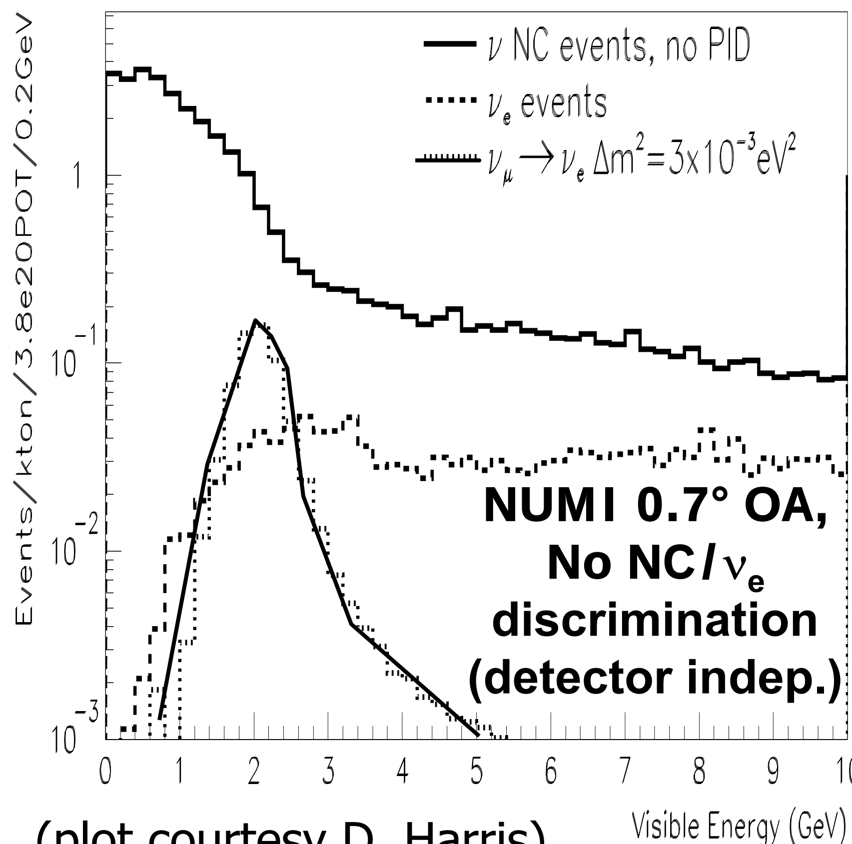
(JHFnu LOI)

Reconstructed Eν (MeV)

Where do Cross-Sections matter?

- $\nu_\mu \rightarrow \nu_e$, θ_{13}
  - Shown at right is most optimistic θ_{13}; we may instead be fighting against background
- NC π^0 and beam ν_e background both in play
  - NC π^0 cross-section poorly known
  - We can model $\sigma^{CC}(\nu_e)/\sigma^{CC}(\nu_\mu)$. Is it right?
- Precision measurement is the endgame

$\sin^2 2\theta_{\mu e}=0.05$
$(\sin^2 2\theta_{\mu e} \equiv 0.5\sin^2 2\theta_{13})$

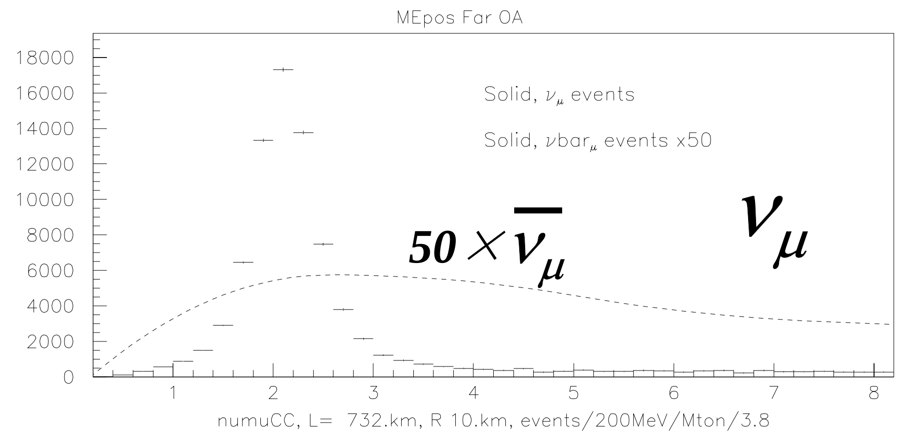


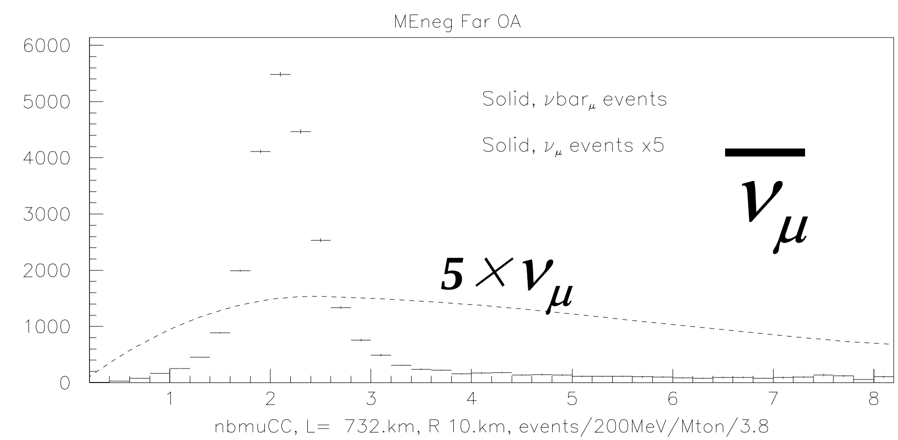
(plot courtesy D. Harris)

Where do Cross-Sections matter?

- $\nu_\mu \rightarrow \nu_e$ vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, δ
  - Cross-sections very different in two modes
  - "Wrong sign" background only relevant in anti-neutrino
    - Crucial systematic in comparing neutrino to anti-neutrino
- Need $\sigma^{CC}(\bar{\nu})/\sigma^{CC}(\nu)$ in sub- to few-GeV region

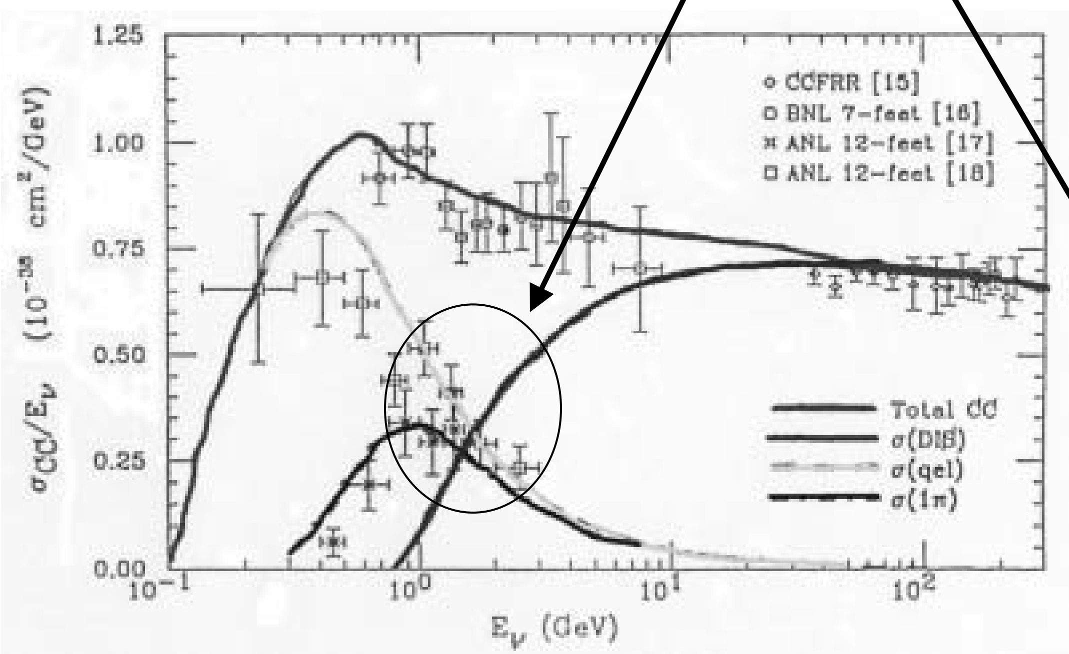
NUMI 0.7° OA, 3.8E20 POT

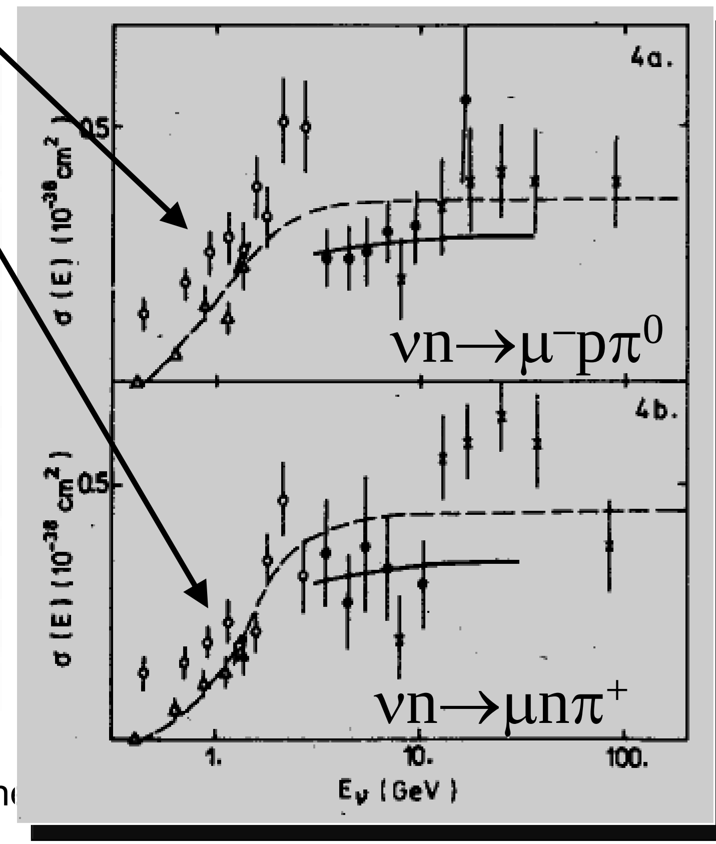




Status of Cross-Sections

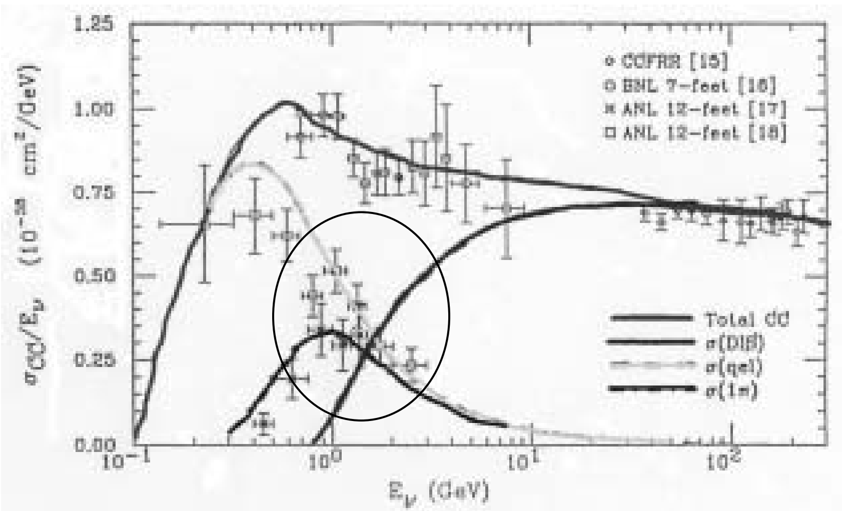
- Not well-known at 1-few GeV
  - Knowledge of exclusive final states particularly poor
  - Understanding of backgrounds requires *differential* cross-sections for these processes!
  - A dependence?





Cross-Section Modeling

Neutrino interactions

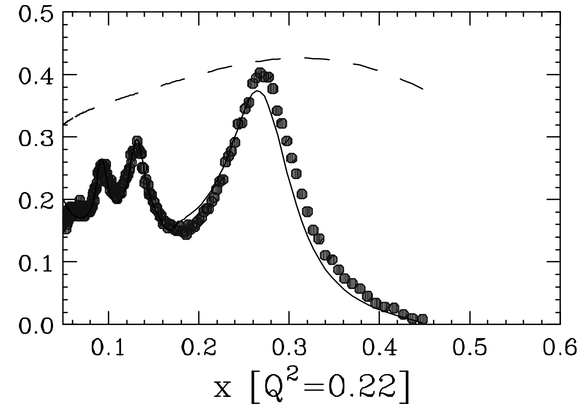


- Quasi-Elastic / Elastic
  $\nu_\mu n \rightarrow \mu^- p$ (x =1, W=M_p)
- Resonance
  $\nu_\mu p \rightarrow \mu^- \pi p$ (low Q^2, W)
- Deep Inelastic
  $\nu_\mu N \rightarrow \mu^- X$ (high Q^2, W)

- Plausible models exist to describe some aspects of data in each region
  - Transitions between regions?
  - A dependence, final-state interactions, etc.

Theoretical Framework

- Tools available:
  - Good descriptions of QE, DIS regions
  - Precise low Q^2 charged lepton data (JLab, SLAC)
  - Precise high Q^2 DIS data
- Quark-Hadron Duality?
  - “When you get near a resonance, it sucks you in.”
  - Bodek and Yang have shown some promising initial steps in tests with electron data

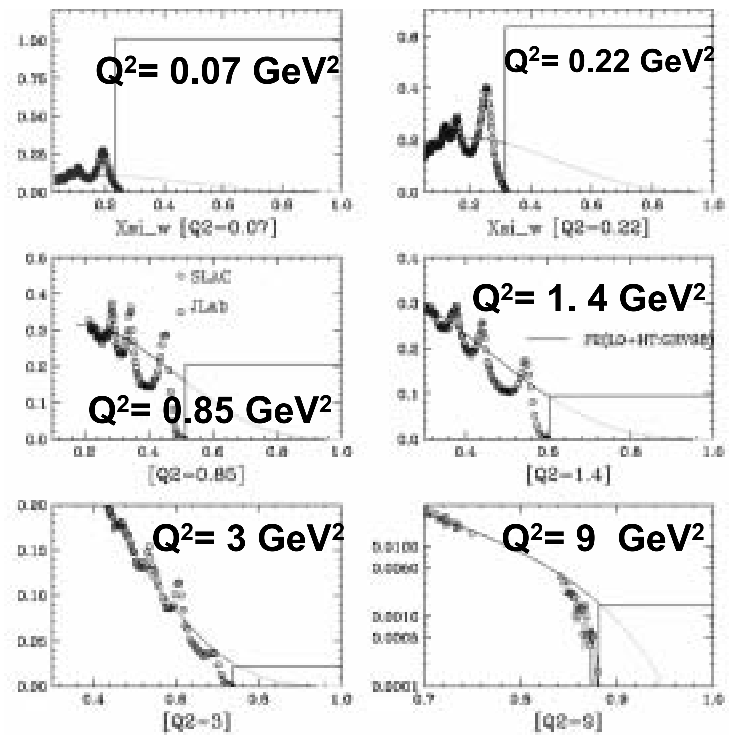


at x = 1

(quasi)elastic

F2 integral=0.43

SLAC data at Q^2=0.22



Conclusions

- There are excellent motivations for studying low energy neutrino cross-sections
  - The next steps in neutrino oscillation and mixing studies rely on this
  - Inherent interest in reactions themselves
- NUMI and JHF will provide idea laboratories for these studies