Neutrino Oscillations Overview

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Tau 2010

Manchester, England

September 17, 2010

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OUTLINE

1. Neutrino Masses and Mixing
2. Leptogenesis: Matter-Antimatter Asymmetry
3. Leptonic CP Violation

   i) F.O.M. Insensitivity to θ_{13} & L (Osc. Length)

   ii) Requirements~300kton H_2O, 1-2MW protons,
   Neutrino Wide Band Beam (WBB) $E_{\nu} \approx 0.5$-5GeV
4. "New Physics" search via ν_{μ} & $\bar{\nu}_{\mu}$ disappearance
5. Outlook

1. Neutrino Masses and Mixing

- 1969-90s Ray Davis Measures Solar ν_e Flux at Homestake Deep Underground Mine ~1/3 Expected!
  Gallex, Sage, SuperK, SNO, Kamland (Reactor)
  Interpretation: solar $\nu_e \rightarrow 1/3\ \nu_e + 1/3 \nu_\mu + 1/3 \nu_\tau$ (roughly)

- 1980s IMB, Kamioka, measure atm. ν_μ flux, less than expected (Also observe supernova 1987a neutrinos!)
  SuperK; K2K, MINOS (Accelerators)
  Interpretation: atm. $\nu_\mu \rightarrow 1/2 \nu_\mu + 1/2 \nu_\tau$(near maximal!)

Neutrino Oscillations Established →Neutrino Masses & Mixing Measured (Great Progress!)

3 Generation Mixing Formalism & Status)

$$\begin{pmatrix} |\nu_e> \\ |\nu_\mu> \\ |\nu_\tau> \end{pmatrix} = U \begin{pmatrix} |\nu_1> \\ |\nu_2> \\ |\nu_3> \end{pmatrix} \qquad (1)$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij} \quad , \quad s_{ij} = \sin\theta_{ij}$$

$$J_{CP} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13} \sin\delta. \qquad (2)$$

Current Neutrino Mass & Mixing Parameters

- $\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm\, 2.4(1) \times 10^{-3}\ \mathrm{eV}^2$ (atmospheric)
- $\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.6(2) \times 10^{-5}\ \mathrm{eV}^2$ (solar)

(Very precise Minos & KamLAND Measurements)

$|\Delta m_{21}^2/\Delta m_{32}^2 \approx 1/30| \rightarrow$ CP Violation Exp Doable!

Hierarchy $m_3 > m_1 \& m_2$ (normal) or $m_3 < m_1 \& m_2$ (inverted)?

Large Mixing!

$\theta_{23} \sim 45°$ $\sin^2 2\theta_{23} = 1.0$ (θ_{23} or $90° - \theta_{23}$) (atm.)

$\theta_{12} \sim 34°$ $\sin^2 2\theta_{12} = 0.87(3)$ (solar)

$\theta_{13} \leq 11°$ $\sin^2 2\theta_{13} \leq 0.15$ (How Small?)

$0 \leq \delta \leq 360°$?

$J_{CP} \cong 0.11 \sin 2\theta_{13} \sin\delta$ (potentially large!)

What do we still need to learn?

- 1. **Value of θ_{13}?** (Reactors: $\sin^2 2\theta_{13} \rightarrow 0.01$)
  (Long Baseline $\nu_\mu \rightarrow \nu_e$ similar)

- 2. **Sgn Δm_{32}^2?** (Important for Neutrinoless $\beta\beta$ Decay)

- 3. **Value of** δ?, J_{CP}?, CP Violation? ***(Holy Grail)***

- 4. **Precision** Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12} (better than 1%!)

- 5. **"New Physics"** - Sterile ν, ***Very Weak*** Long Distance Physics (*The Dark World*)…

2. Leptogenesis: Matter-Antimatter Asymmetry

- **More baryons than antibaryons in our Universe**
- Leptogenesis Scenario:

1. Heavy Majorana Neutrinos Created and Decay

$N \rightarrow H^- e^+, H^0 \overline{\nu}$ (***L & CP VIOLATION***)

Leads to antilepton (excess)-lepton Asymmetry

2. Electroweak Phase Transition (250GeV) (Baryogenesis)

'‘t Hooft Mechanism B-L Conserved (B&L Violated)

antilepton excess $\rightarrow$ baryon (quark) excess by 1 in 10^9

Is L Violated in Nature? ***(Neutrinoless $\beta\beta$ Decay)***

Is there Leptonic CP Violation? ***(ν oscillations)***

Indirect evidence for Leptogenesis (Best we can do.)

3. Leptonic CP Violation

$$P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e)$$

$+$ matter $+$ smaller terms

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

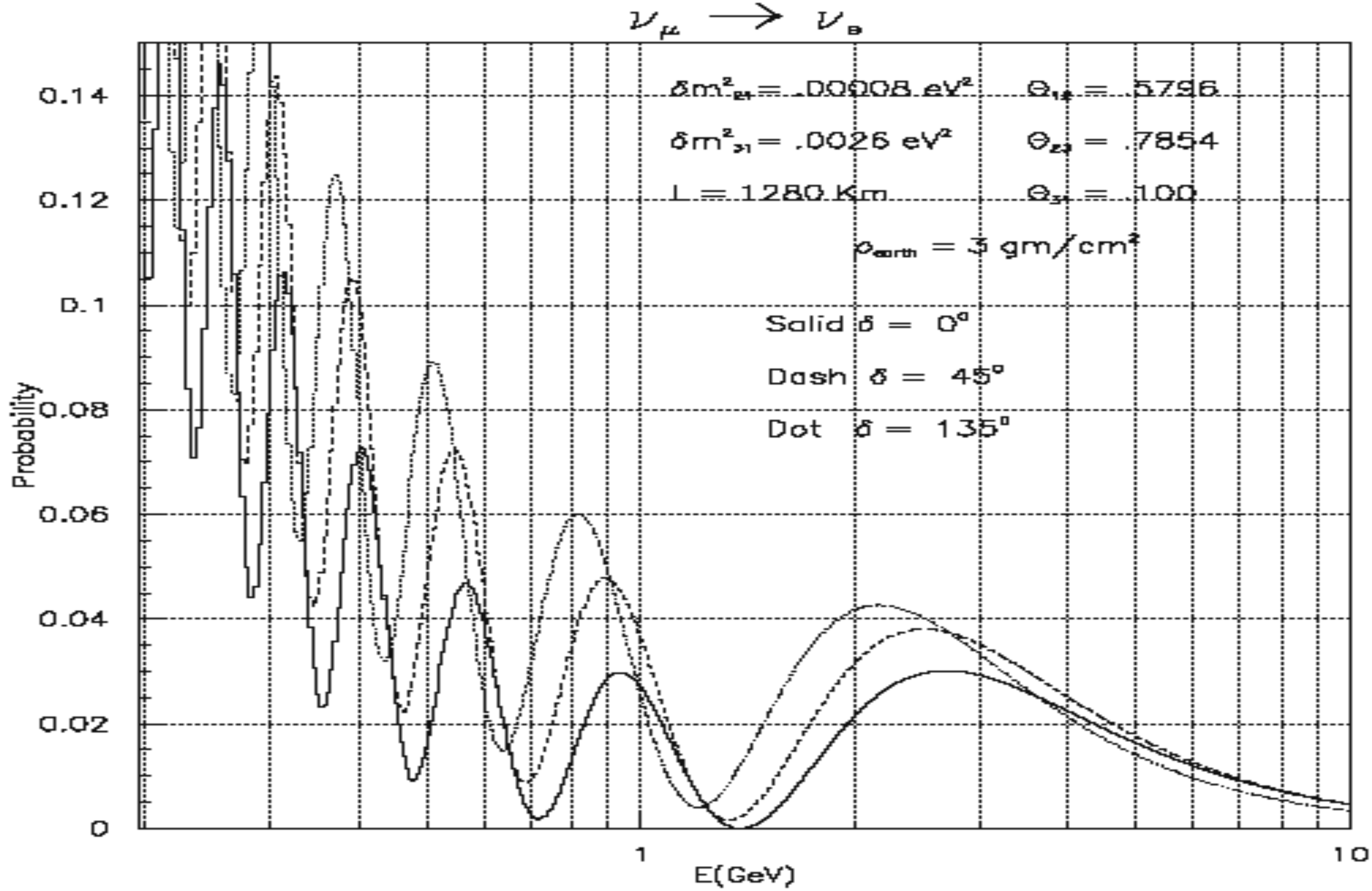
$$\mathbf{P}_{II}(\nu_\mu \to \nu_e) = \frac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$
$$\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right) \times \left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right.$$
$$\left. + \cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right]$$

$$\mathbf{P}_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12}\cos^2\theta_{13}\cos^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

For antineutrinos, $\delta \to -\delta$ and opposite matter effect.

Zohreh Parsa, BNL

FNAL



CP Violation Asymmetry

$$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \tag{3}$$

To leading order in Δm^2_{21} ($\sin^2 2\theta_{13}$ is not too small):

$$A_{CP} \simeq \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects} \tag{4}$$

$$F.O.M. = \left(\frac{\delta A_{CP}}{A_{CP}}\right)^{-2} = \frac{A^2_{CP} N}{1 - A^2_{CP}} \tag{5}$$

N is the total number of $\nu_\mu \to \nu_e + \bar{\nu}_\mu \to \bar{\nu}_e$ events.Since N falls (roughly) as $\sin^2\theta_{13}$ and $A^2_{CP} \sim 1/\sin^2\theta_{13}$, to a first approximation the F.O.M.is independent of $\sin\theta_{13}$. Similarly, given E_ν the neutrino flux and consequently N falls as $1/L^2$ but that is canceled by L^2 in A^2_{CP}.

i) CP Violation Insensitivities

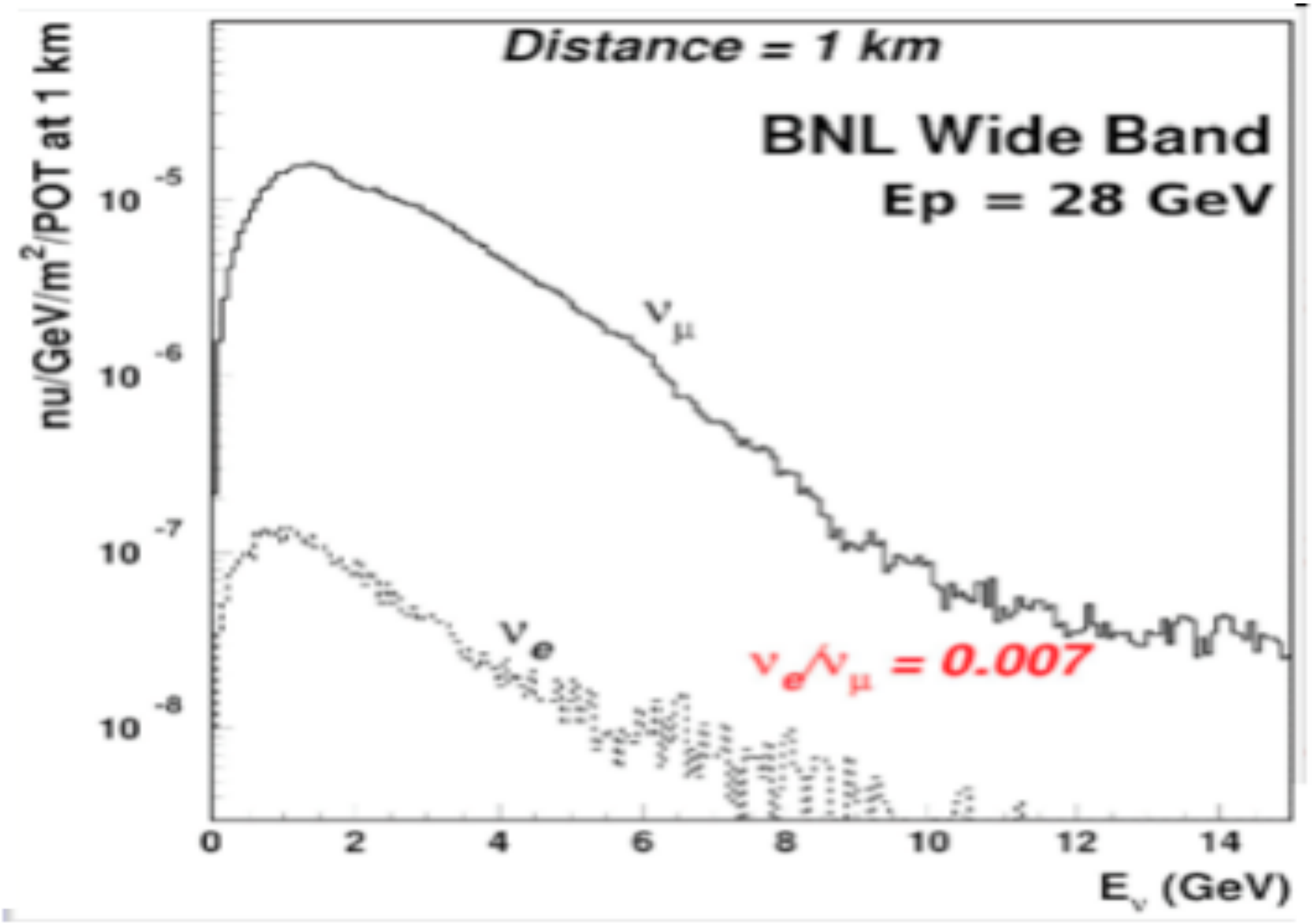
- To a very good approx., our statistical ability to determine δ or A_{cp} is **independent** of $\sin^2 2\theta_{13}$ (down to ~ 0.003) and the detector distance L (for long distance).

ii) CP Violation Requirements

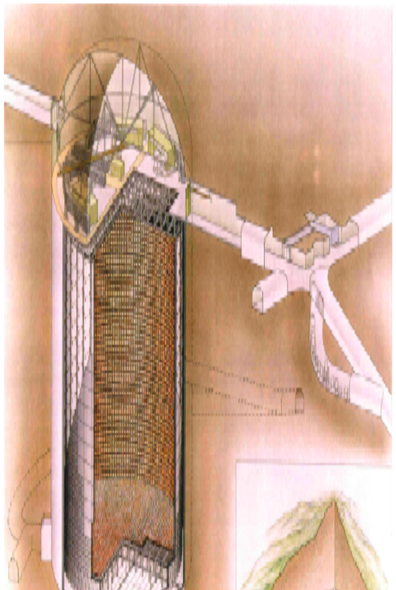
- Pick any reasonable θ_{13} (eg $\sin^2 2\theta_{13}$=0.04)
- What does it take to measure δ to ±15° in about $5x10^7$ sec?

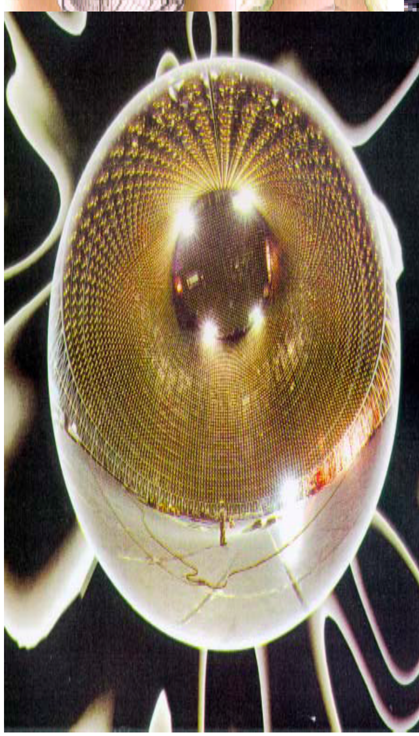
Answer (Approx.): 300kton Water Cerenkov Detector
Approx 20% Acceptance,
50 kton LArgon 90% Acceptance
or Hybrid combination
+ Traditional Horn Focused ν WBB powered by
1-2MW proton accelerator (egs. Project X at FNAL)

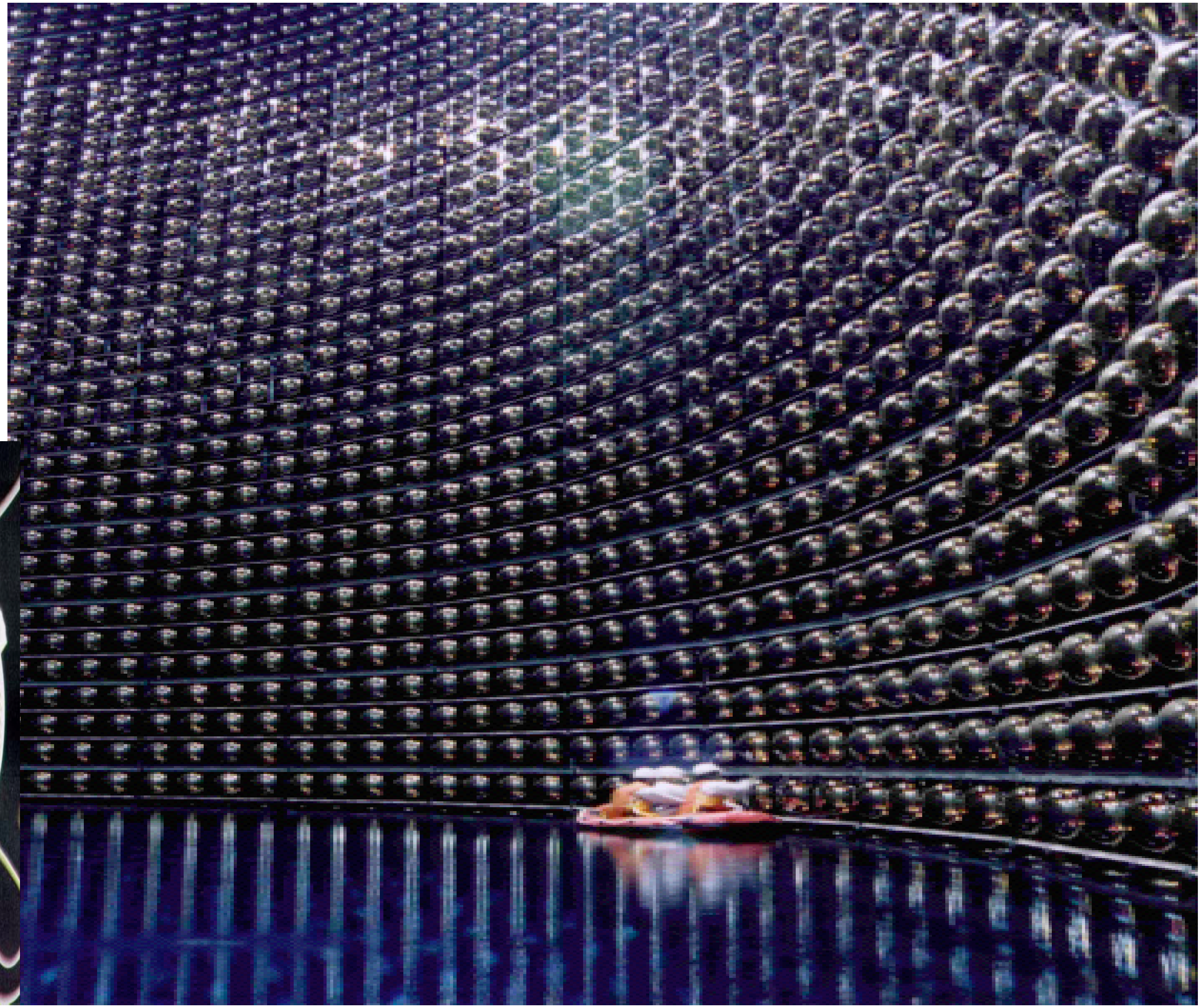
Horn Focused Neutrino Beam



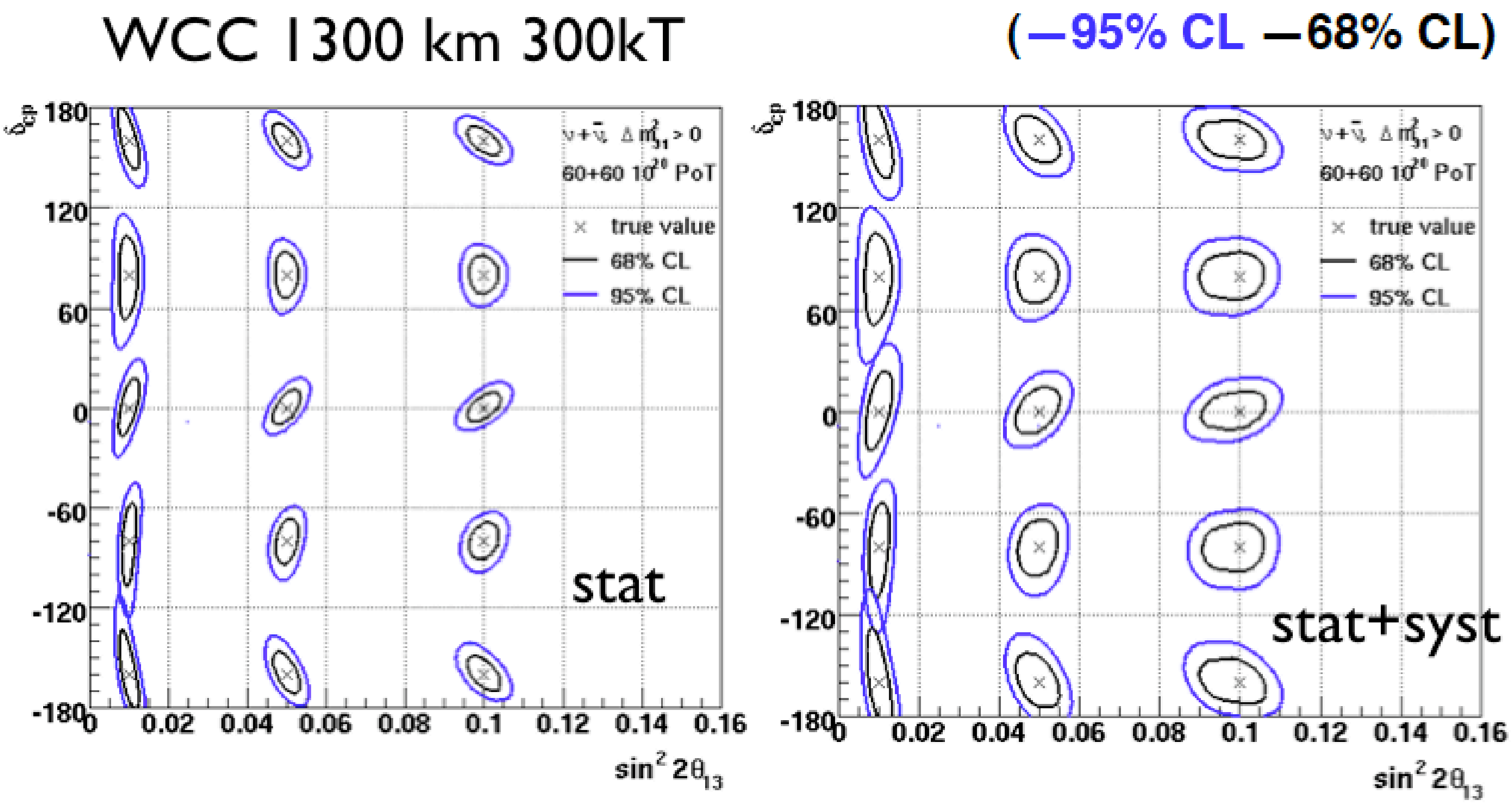
SUPER KAMIOKANDE







CP Phase Insensitivity to θ_{13} Value



4. "New Physics" search via ν_μ & $\bar{\nu}_\mu$ disappearance

Disappearance at MINOS $\nu_\mu \rightarrow \nu_\mu$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ show differences?

$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2(\Delta m^2_{32} L/4E_\nu)$

$\nu_\mu \rightarrow \nu_\mu$: $\Delta m^2_{32} = 2.35(11) \times 10^{-3} eV^2$ $\sin^2 2\theta_{32} \sim 1$ (>0.91)

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$: $\Delta m^2_{32} = 3.36(45) \times 10^{-3} eV^2$, $\sin^2 2\theta_{32} = 0.86(11)$

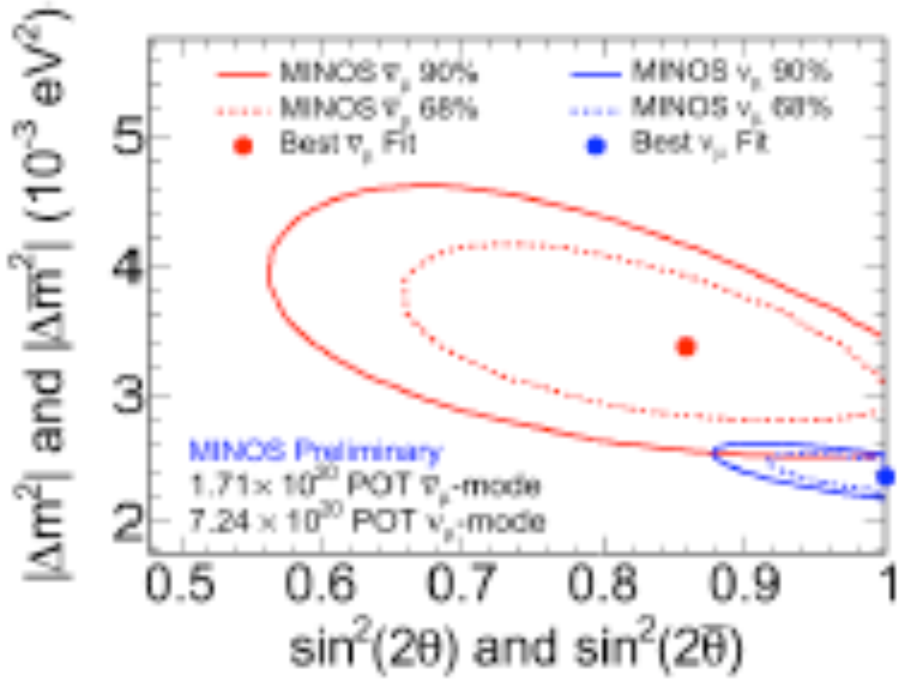
2σ difference? 30%?

(Collaboration does not claim discrepancy!)

But good motivation to examine "New Physics" effects in neutrino oscillation experiments, since in the future one might expect better than 1% measurements!

Anticipate Surprises!

$\overline{\nu}_\mu$ oscillation parameters



- Contours include the effects of systematic uncertainties

ν_μ Disappearance

Very easy to get this effect
Does not need extensive pattern recognition. Can enhance the seco minimum by background subtracti

Neutrino Running

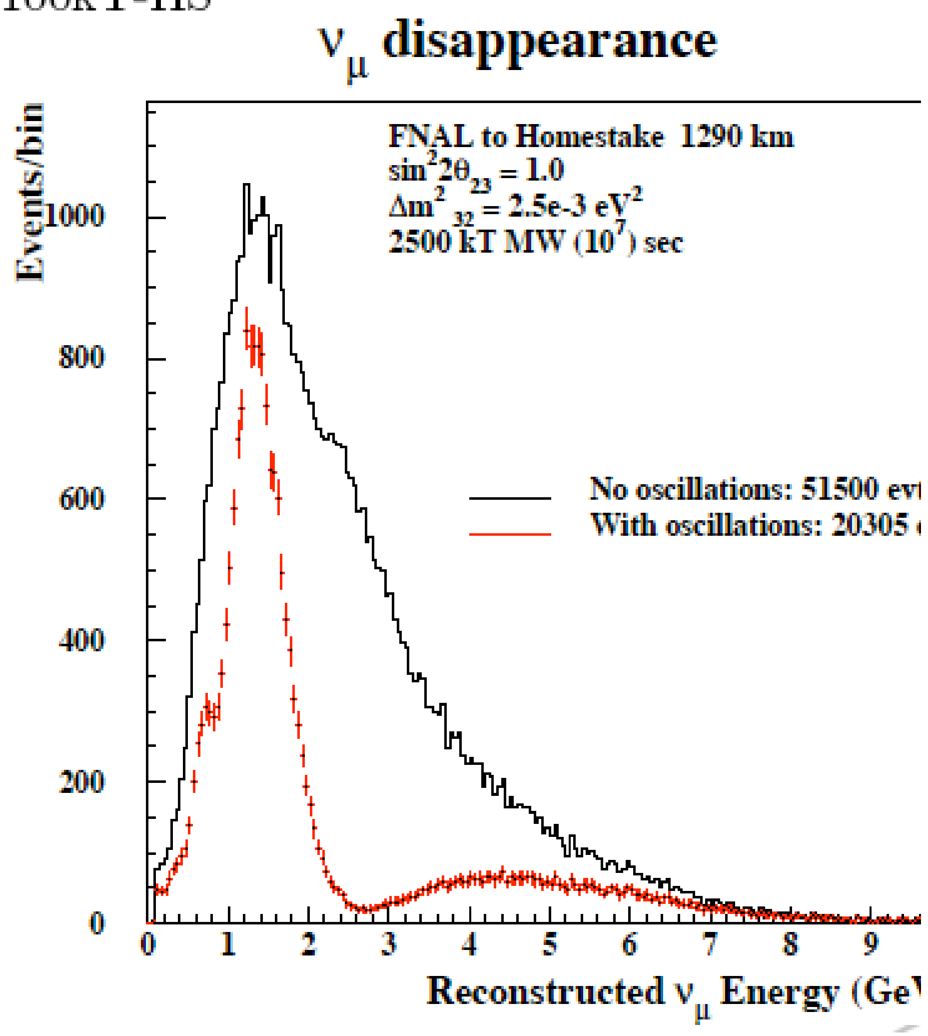
- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

Measurements

- 1% determination of Δm^2_{32}
- 1% determination of $\sin^2 2\theta_{23}$
- Most likely systematics limited.

$\bar{\nu}$ running

- Need twice the exposure for similar size data set.
- very precise CPT test possible.



Δm^2_{32} and $\sin^2 2\theta_{32}$ can be measured in long baselines as functions of E_ν (also obtained from atmospheric ν).

$\nu_\mu \to \nu_\mu$ & $\bar{\nu}_\mu \to \bar{\nu}_\mu$ *Comparison*

Usually phrased as a test of CPT (true in vacuum)

Apparent CPT violation → "New Physics" in ν interactions

(in matter) $\varepsilon\sqrt{2}G_F\bar{\nu}\gamma_\mu\nu'\bar{f}\gamma^\mu f$, $f=e, u, d$

Potential changes sign $\nu_\mu \to \bar{\nu}_\mu$

Sterile Neutrinos? etc

"General bounds on non-standard neutrino interactions" by Biggio, Blennow and Fernandez-Martinez (2009)

Using solar and atmosheric oscillation data in $\nu_e\, \nu_\mu\, \nu_\tau$ space

From Solar and Atmospheric.

$$|\varepsilon| < \begin{array}{cccc} \nu_e & \nu_\mu & \nu_\tau & \\ 2.5 & 0.21 & 1.7 & \nu_e \\ 0.21 & 0.046 & 0.21 & \nu_\mu \\ 1.7 & 0.21 & 9.0 & \nu_\tau \end{array}$$

(Bounds being updated-Take with a grain of salt)

ε represents the size of the "New Physics" potential relative to MSW potential (Weak Strength $\sqrt{2}G_F\bar{\nu}_e\gamma_\mu\nu_e\bar{e}\gamma^\mu e$)

Some Interesting Recent $\varepsilon \neq 0$ Examples

Engelhardt, Nelson and Walsh: sterile neutrinos & gauge B-L
new long distance physics
weakly coupled

Heeck and Rodejohann: gauge L_μ-L_τ (violate e-μ-τ universality)
very long range interaction, $m_V<10^{-18}$eV!

Earlier: *Joshipura &Mohanty* Gauged L_e-L_μ, L_e-L_τ, L_μ-L_τ
Fifth Force: $\alpha' \approx 10^{-52}$!

Mann et al.: New $\nu_\mu \rightarrow \nu_\tau$ Interaction $\varepsilon_{\mu\tau}$~-0.1 (see figure, some generic features)

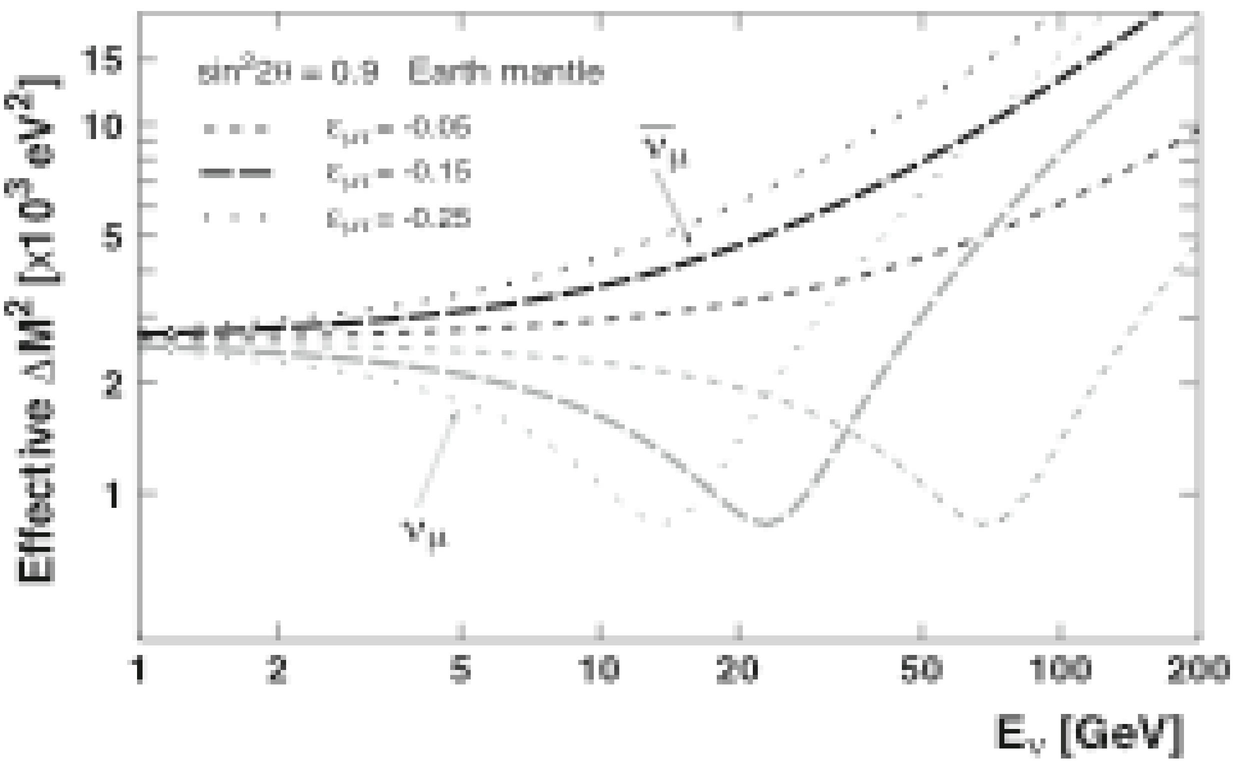
Either $O(\alpha/\Lambda^2)$ Λ large or $O(\alpha'/m^2)$ *α' and m small* (long distance)

Effective potential changes sign for $\nu_\mu \rightarrow \bar{\nu}_\mu$

All lead to different ν_μ and $\bar{\nu}_\mu$ oscillations (in matter)

E_ν Dependence of Oscillation Parameters

From Mann, Cherdack, Musial and Kafka (Example)



$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ disappearance

- $$i\,d/dt \begin{vmatrix} \nu_\mu(t) \\ \nu_\tau(t) \end{vmatrix} = \begin{vmatrix} \Delta m^2_{32} s^2/2p_\nu & \Delta m^2_{32} sc/2p_\nu \\ \Delta m^2_{32} sc/2p_\nu & \Delta m^2_{32} c^2/2p_\nu - p_\nu(n_{\nu\tau}-n_{\nu\mu}) \end{vmatrix} \begin{vmatrix} \nu_\mu(t) \\ \nu_\tau(t) \end{vmatrix}$$

  $s=\sin\theta_V$ $c=\cos\theta_V$

  Could also be off diagonal matter effects, eg Mann et al

  $L_\nu=2(2p_\nu/\Delta m^2_{32})\sim 1000(E_\nu/1\text{GeV})\text{km}$

  $L_0=2\pi/p_\nu(n_{\nu\tau}-n_{\nu\mu})\sim 5000/\varepsilon\,\text{km}$ Refraction index length

  $y=L_\nu/L_0\sim E_\nu\varepsilon/5\text{GeV}$ (Big Effects For $y\sim O(1)$)

  $P(\nu_\mu\to\nu_\mu)=1-\sin^2 2\theta_m \sin^2(\pi x/L_m)$ disappearance

  (Suggests studies at high energies & long distances)

  $E_\nu > 5\text{GeV}/\varepsilon$ Atmospheric & Very Long Baseline

$\sin^2 2\theta_m = \sin^2 2\theta_V / (1 \pm 2y\cos 2\theta_V + y^2)$ **$y = L_v / L_0 \sim E_\nu \varepsilon / 5\text{GeV}$**

$L_m = L_v / (1 \pm 2y\cos 2\theta_V + y^2)^{1/2}$ for 3 gm/cm^3

$\Delta m^2_{32}(\text{matter}) = \Delta m^2_{32}(1 \pm 2y\cos 2\theta_V + y^2)^{1/2}$

for $y \gg 1$ oscillations highly suppressed $L_m \sim L_0$

for $y \ll 1$ matter effects very small

Resonance $y = \cos 2\theta_V \rightarrow \theta_m = 45°$, minimum $\Delta m^2_{32}(\text{matter}) = \Delta m^2_{32} \sin 2\theta_V$

<u>No resonance for maximal vacuum mixing $\theta_V = 45°$ (our world)</u>

No Δm^2_{32} difference in $\boldsymbol{\nu_\mu}$ **vs** $\boldsymbol{\bar{\nu}_\mu}$ for $\theta_V = 45°$ (but depends on E_ν)

<u>Note high E_ν more sensitive to matter!</u>

Anticipate possible differences in ν_μ and $\bar{\nu}_\mu$ effective energy dependent mixing angles and Δm^2_{32} in matter

Future experiments will measure those parameters with very high precision! Atmospheric as well as Long Baseline ν_μ and $\bar{\nu}_\mu$ disappearance will be very powerful probes of non standard (long and short distance) neutrino interactions!

***Note,** $\nu_\mu \rightarrow \nu_\tau$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ appearance potentially very interesting*

***Moral**: Neutrino ν_μ and $\bar{\nu}_\mu$ Osc in Matter provides a potentially powerful probe of (weakly coupled) light and heavy "New Physics". Particularly light $\varepsilon \sim \alpha'/G_F m^2$*

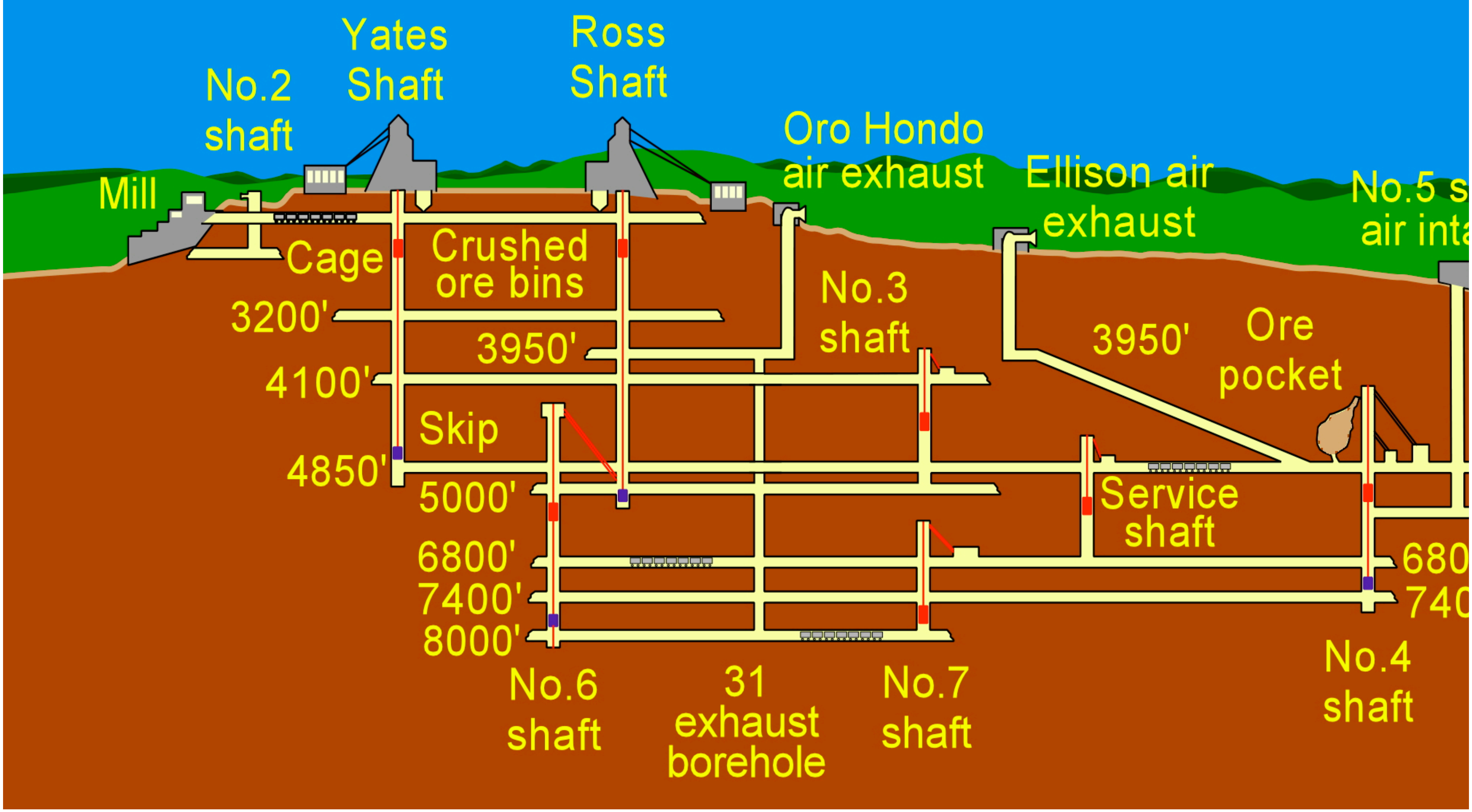
(Does not depend sensitively on $\sin^2 2\theta_{13}$ value!)

5. Outlook

- Neutrino exps will advance: θ_{13} Mass Hierarchy, ν CP Violation
  … via LBNE Requires Big Detector: 300kton H_2O or equivalent
  2MW Accelerator wide band neutrino beam
- ***Also***
- Atmospheric & Solar ν
- 100,000 supernova ν events (if in our galaxy)!
- Observe relic supernova ν (universe history)!
- ***"New Physics"***: sterile ν, extra dim. dark energy…
- Proton decay, n-$\bar{n}$ osc.,…magnetic monopoles

The potential for major discoveries & surprises is great!

General Homestake Mine Development



Fermilab Activities

- What does Fermilab do after the LHC starts?
- (Great Hope - ILC e^+e^- Collider ($\mu^+\mu^-$ Collider?))

In the meantime? New Working Group Report

Project X Option- 2MW 8GeV proton linac (ILC R&D)

8GeV fixed target program (eg. $\mu N \rightarrow eN$…)

+ Main Injector 30-120GeV (also at 2MW)

2MW at 50GeV provides nice neutrino beam for FNAL-Homestake (Cost ?) Total Project ≈$1-2 Billion

Doable! Must Do!

(START AS SOON AS POSSIBLE!)