The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

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Summer School on Particle Physics

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Neutrino Physics - III

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Neutrino Physics
Past, "Present" and Future
"Puzzle Solving"
***News Flash** $0.03 \leq \sin^2 2\theta_{13} \leq 0.3$ by T2K*
Best Fit 0.11!

William J. Marciano

ICTP Lecture 4

Trieste, Italy

June, 2011

BROOKHAVEN
NATIONAL LABORATORY

<u>***OUTLINE***</u>

1.) ***Early History*** (1931- 1973) the first 42 years

2.) ***Weak Neutral Currents***: $SU(2)_L xU(1)_Y$ confirmation

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3.) ***Neutrino Oscillations***: Reactor, Solar, Atmospheric

*4.) ***Neutrino Masses, Mixing, & Matter***

"<u>New T2K Result</u>" $sin^2 2\theta_{13} \approx 0.11$ (best fit)!

5.) ***Leptogenesis***: Matter-Antimatter Asymmetry (Universe)

6.) ***Neutrinoless Double Beta Decay*** (Dirac vs Majorana)

7.) ***Leptonic CP Violation*** (neutrino vs antineutrino)

Requirements~300kton H_2O, 1-2MW protons,

8.) ***Future Neutrino Physics*** ➔ **Muon Collider**

9.) <u>***Outlook & Speculation***</u>

3.) ***Neutrino Oscillations*: Reactor, Solar, Atmospheric…**

- If states are nearly degenerate & mix, quantum oscillations are possible. Produce a state that is not a Hamiltonian eigenstate, but a linear combination of several. Each will evolve separately in time and overall oscillations will occur.

Examples: ***K^0-K^0bar, B^0-B^0bar etc max mixing 45^O***

$K^0(t=0)$ → K^0bar → K^0… (modulo decay)

Neutrinos similar but different (Fundamental point particles) not bound states

Non zero (but small) neutrino masses → oscillations

Or oscillations → neutrino masses & mixing

Blackboard Discussion of Neutrino Mass

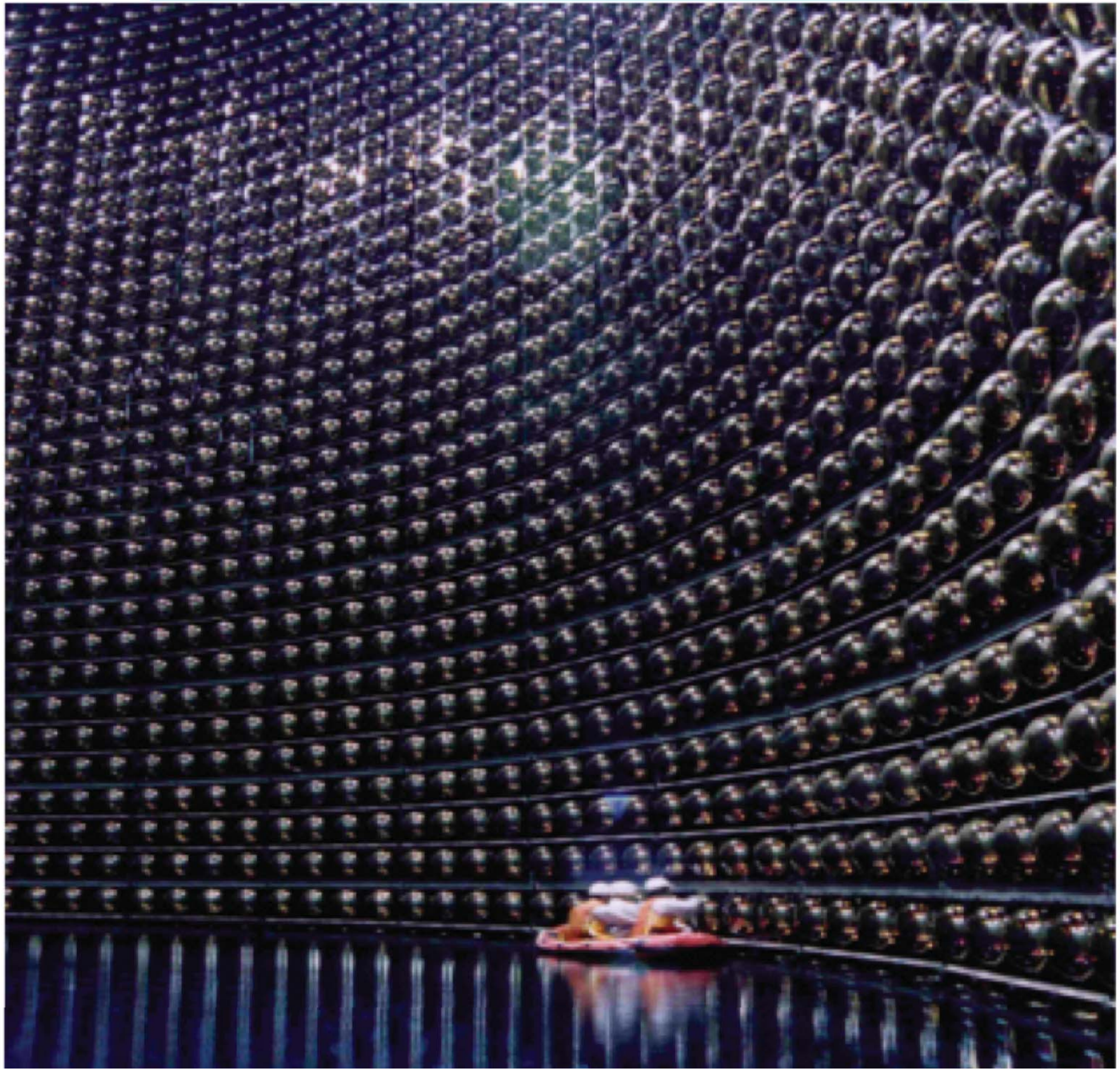
4. Neutrino Masses, Mixing and Matter

- 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!)

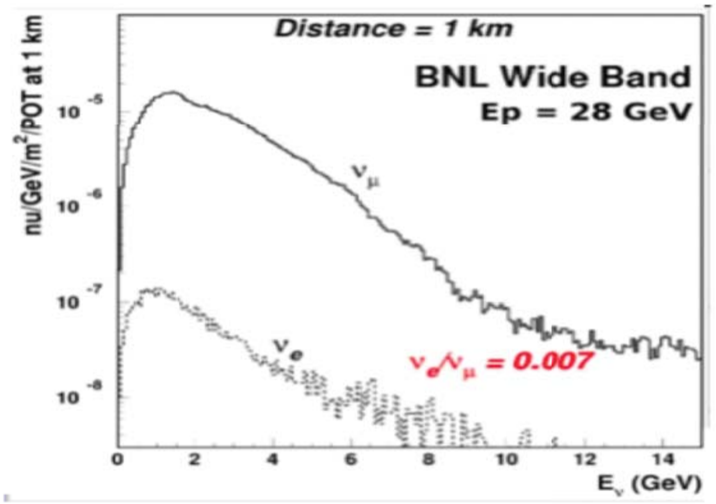
Neutrino Oscillations Established →Neutrino Masses & Mixing Measured (Great Progress!)

SUPER KAMIOKANDE

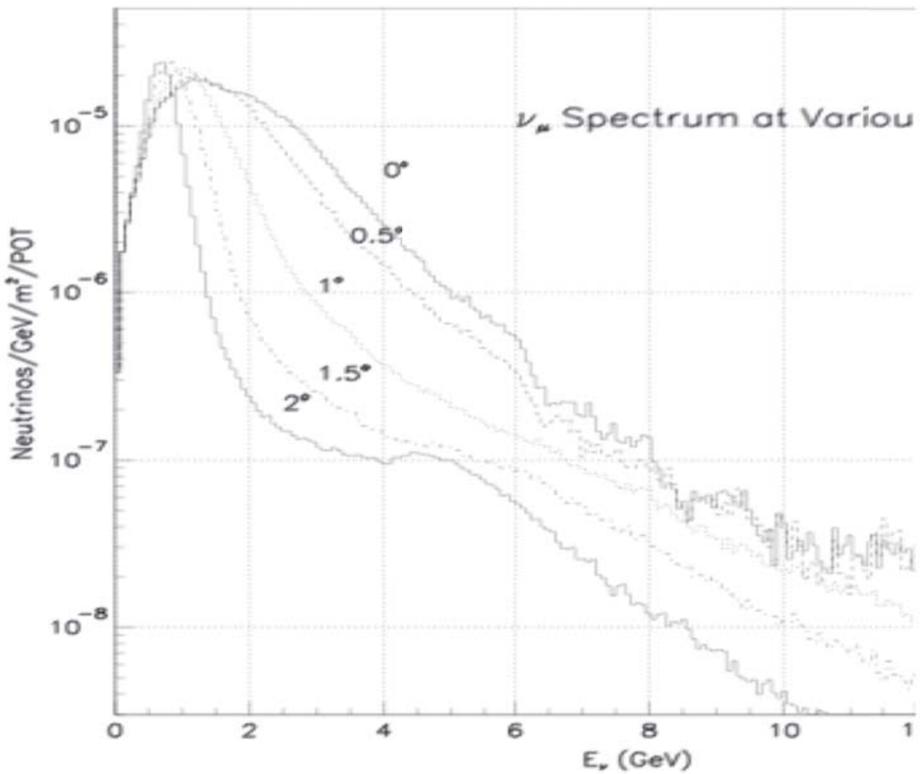


Wide Band Neutrino Beam

Horn Focused Neutrino Beam



Neutrino Beam For Off-Axis Detector



3 Generation Mixing Formalism & Status)

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

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

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

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

$\nu_\mu \rightarrow \nu_\mu$ *Disappearance*

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{13} \sin^2(\Delta m_{32}^2 L/4E_\nu) + \ldots \Delta m_{21}^2 \text{ terms}$$

K2K (250km) + Atmospheric disappearance
at SuperK detector $\nu_\mu \rightarrow \nu_\mu$ + (antineutrinos)
MINOS-Fermilab (730km) $\nu_\mu \rightarrow \nu_\mu$

$\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm\ 2.4(1) \times 10^{-3}\ eV^2$

$\sin^2 2\theta_{23} \approx 1.0$ **Maximal** $\theta_{23} \approx 45°$

In those experiments ($\nu_\mu \rightarrow \nu_e$) appearance not seen
Reactors anti-$\nu_e \rightarrow$ antiν_e not seen (short distance)

$\theta_{13} \leq 11°$ $\quad$ $\sin^2 2\theta_{13} \leq 0.15$

Before Today Neutrino Mass & Mixing Parameters

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

(Very precise Minos & KamLAND Measurements)

$|\Delta m_{21}^2/\Delta m_{32}^2 \approx 1/30|$ → 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 $\nu_\mu \rightarrow \nu_e$ 0.003)

- 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*)…

Leptogenesis: Matter-Antimatter Asymmetry

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

1. Heavy Majorana Neutrinos Created and Decay
   $N \rightarrow H^- e^+$, $H^0 \nu$bar (***L & CP VIOLATION***)
   Leads to antilepton (excess)-lepton Asymmetry

2. Electroweak Phase Transition (250GeV) (Baryogenesis)
   'tHooft Mechanism B-L Conserved (B&L Violated)
   antilepton excess→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.)

The Fundamental Importance of Neutrinos

Neutrino Physics May Be Responsible For Our Existence! (baryons & electrons)!

They help power the Sun (nuclear Reactions)

They Allow R Process in Supernova

(Supernova - Heavy Elements)

We are the remnants of Supernovae

7. 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

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

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

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

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

June 15, 2011 Neutrino History was made!

- P($\nu_\mu \rightarrow \nu_e$) = **$\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta m_{32}^2 L/4E_\nu)$ +…**
  matter effects + Δm_{21}^2 terms

ν_μ appearance observed by T2K Experiment

" Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam"

by T2K Collaboration $E_\nu \approx 0.6$GeV L=290km

6 ν_e events with 1.5(3) background observed

88 total neutrino events

Implications

- $\sin^2 2\theta_{13} \neq 0$ Major Result! (2.5sigma)
- $0.03(0.04) \leq \sin^2 2\theta_{13} \leq 0.28(0.34)$ Normal (Inverted)

Best Fit Value $\sin^2 2\theta_{13} = 0.11$ Large!

Reactors will go to ± 0.01

$J_{CP} \cong 0.11 \sin 2\theta_{13} \sin\delta \approx 0.04 \sin\delta$ (not small!)

Future Measurements (systematics) Much Easier!

Statistically, CP Violation still challenging

T2K Results as a function of δ

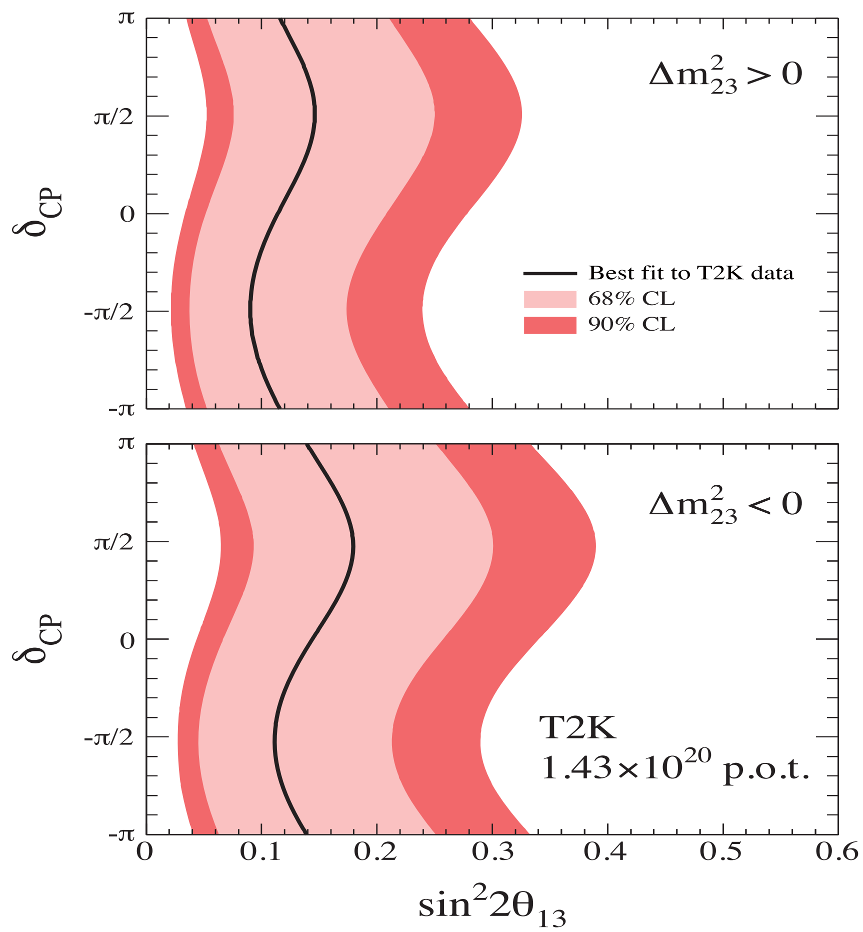
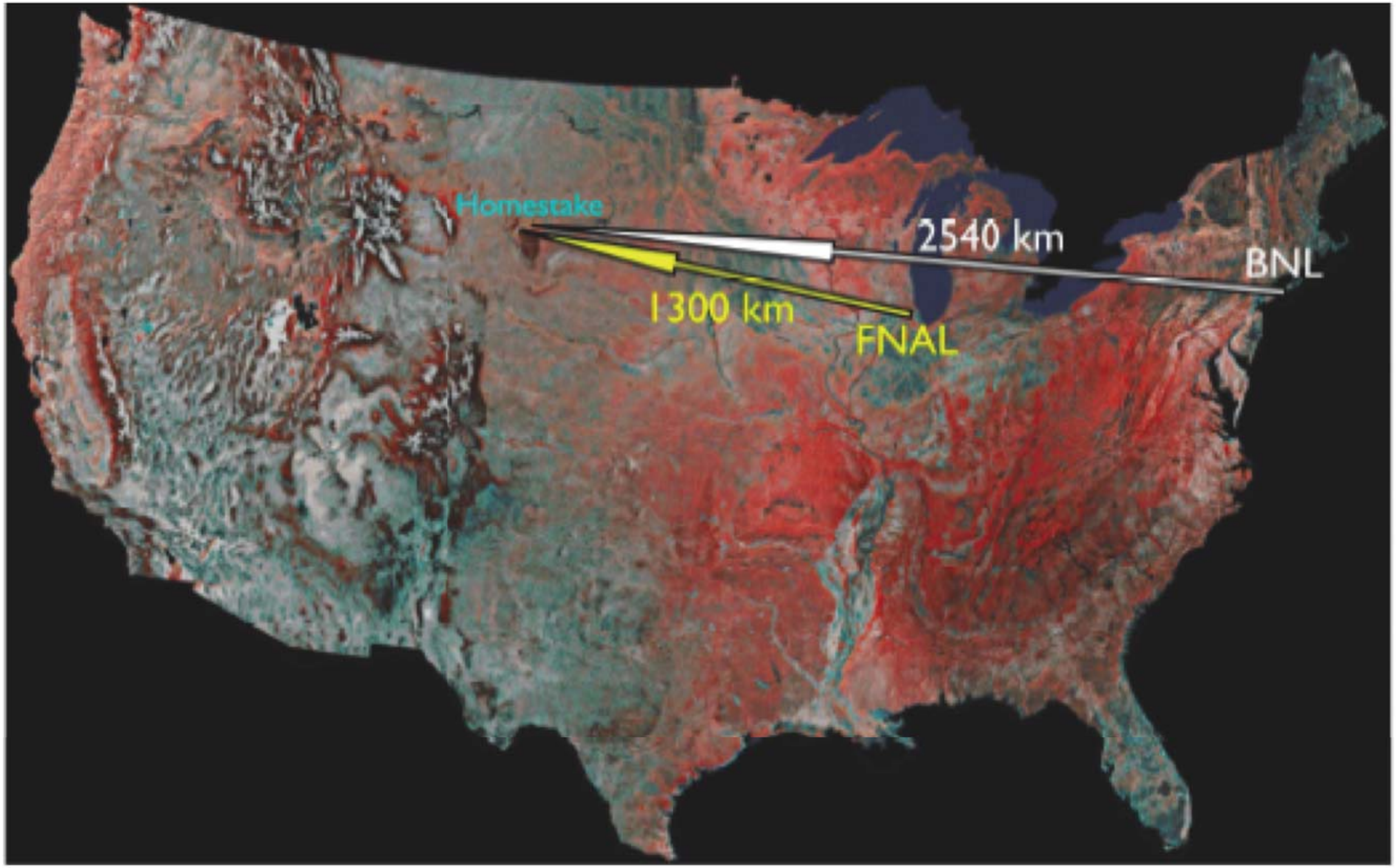


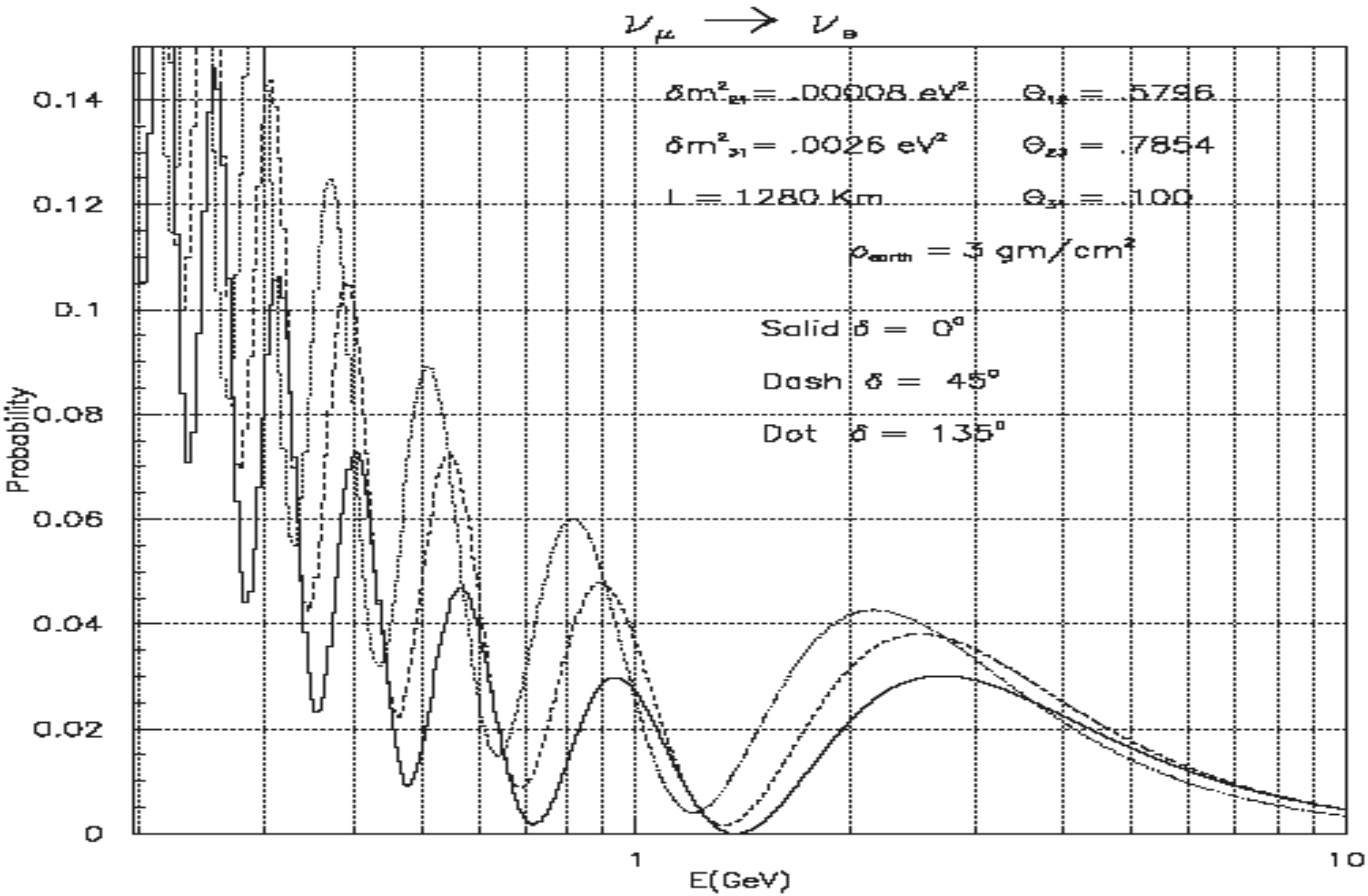
FIG. 6. The 68% and 90% C.L. regions for $\sin^2 2\theta_{13}$ for each value of δ_{CP}, consistent with the

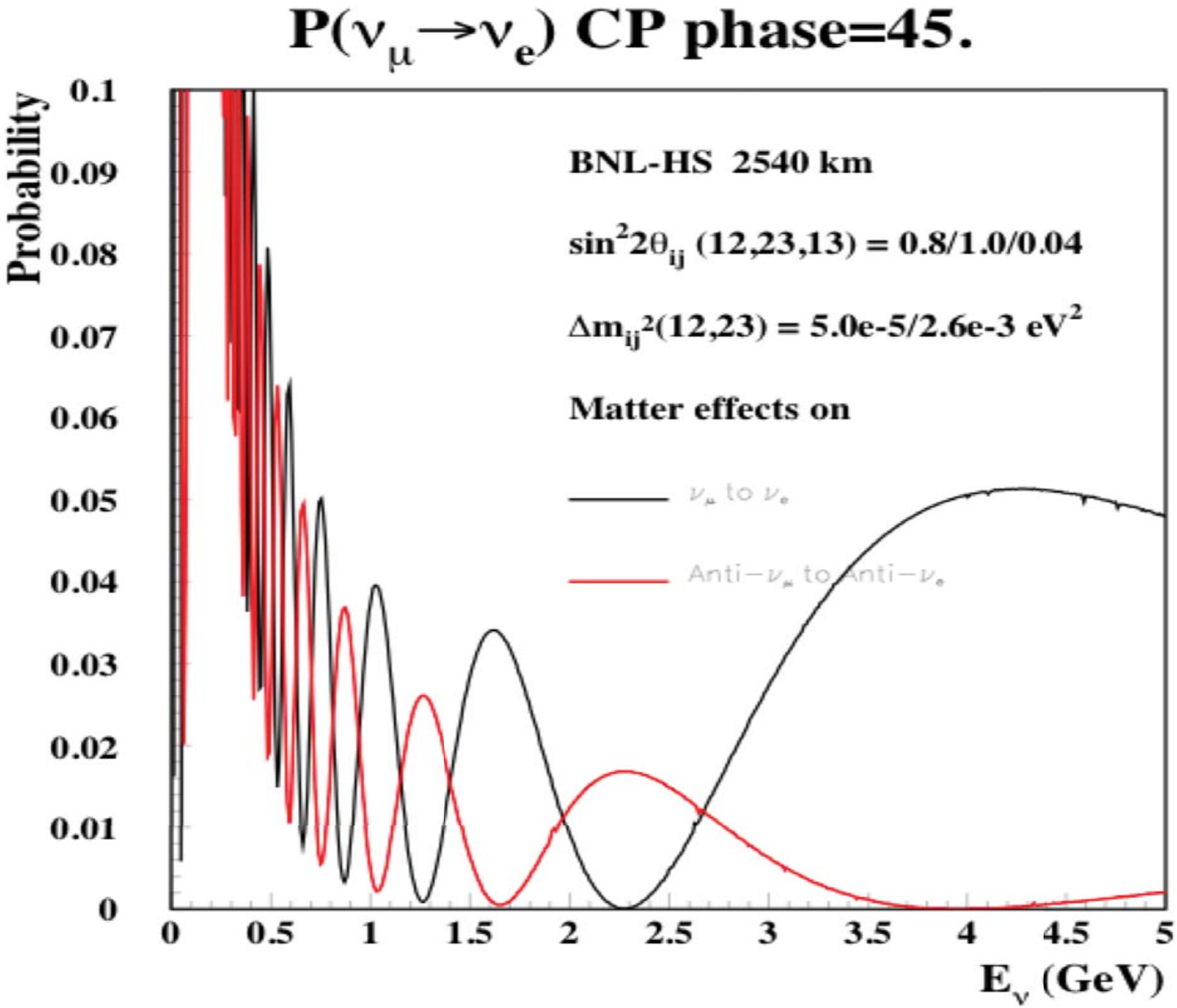
Very Long Baseline Neutrino Oscillations
(Fermilab or BNL- Homestake)



Zohreh Parsa, BNL

FNAL





P(ν_μ→ν_e) CP phase=45.
Probability
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
BNL-HS 2540 km
sin²2θ_ij (12,23,13) = 0.8/1.0/0.04
Δm_ij²(12,23) = 5.0e-5/2.6e-3 eV²
Matter effects on
ν_μ to ν_e
Anti−ν_μ to Anti−ν_e
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_ν (GeV)

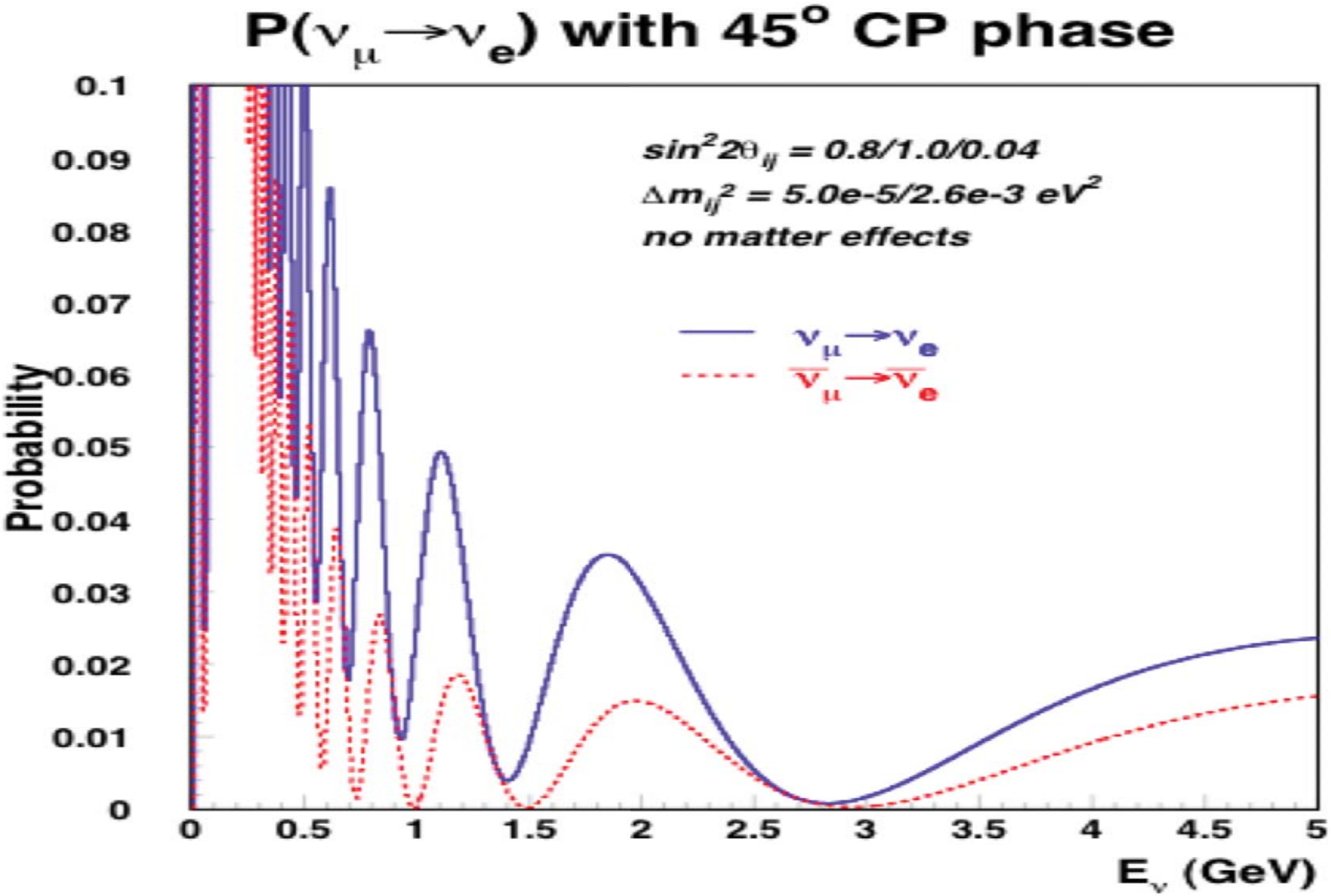
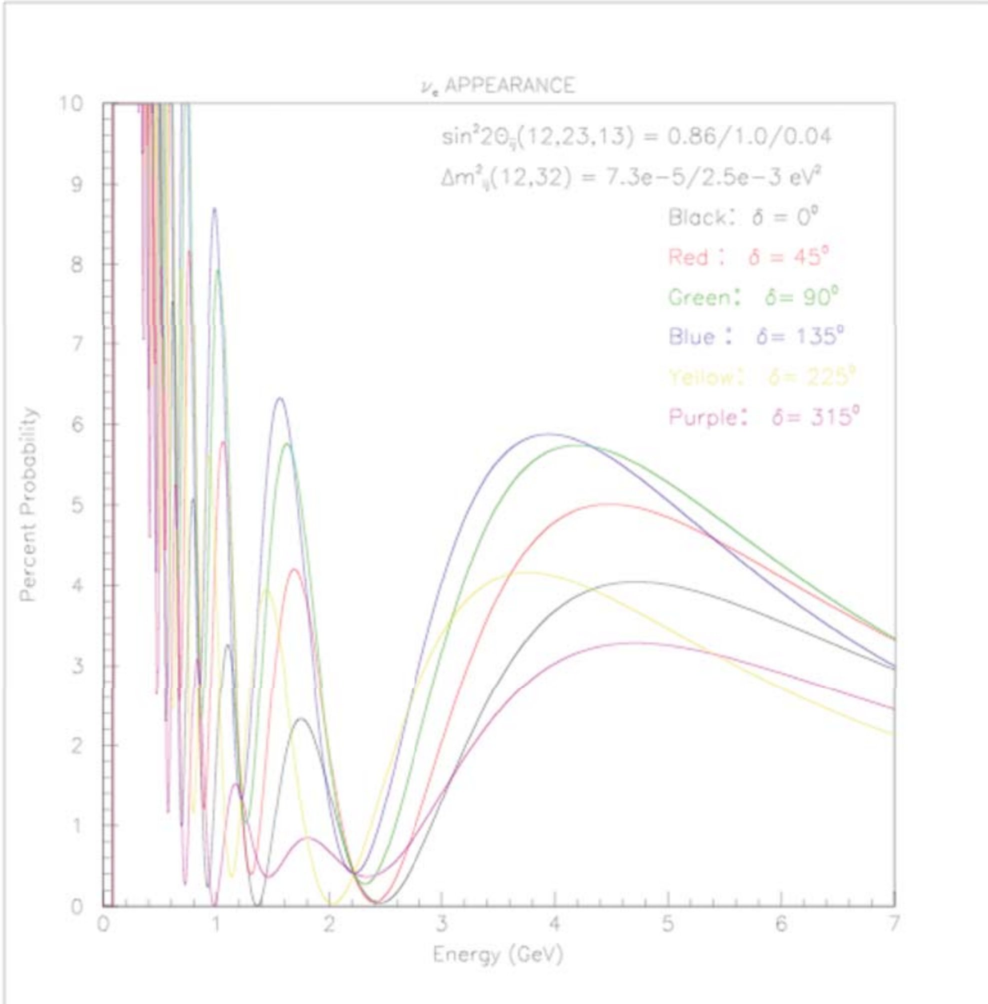


Figure 23: Probability of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations at 2540 km in vacuum. assuming a $\delta_{CP} = 45^\circ$ CP violation phase. It can be seen that the CP asymmetry between ν_μ and



ν_e APPEARANCE
sin²2Θ_ij(12,23,13) = 0.86/1.0/0.04
Δm²_ij(12,32) = 7.3e−5/2.5e−3 eV²
Black: δ = 0°
Red : δ = 45°
Green: δ= 90°
Blue : δ= 135°
Yellow: δ= 225°
Purple: δ= 315°
Percent Probability
Energy (GeV)
0
1
2
3
4
5
6
7
8
9
10

CP Violation Asymmetry

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

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

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

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

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 (0.11))
- What does it take to measure δ to ±15° in about 5×10^7 sec?

Answer (Approx.): 300kton Water Cerenkov Detector

Approx 20% Acceptance,

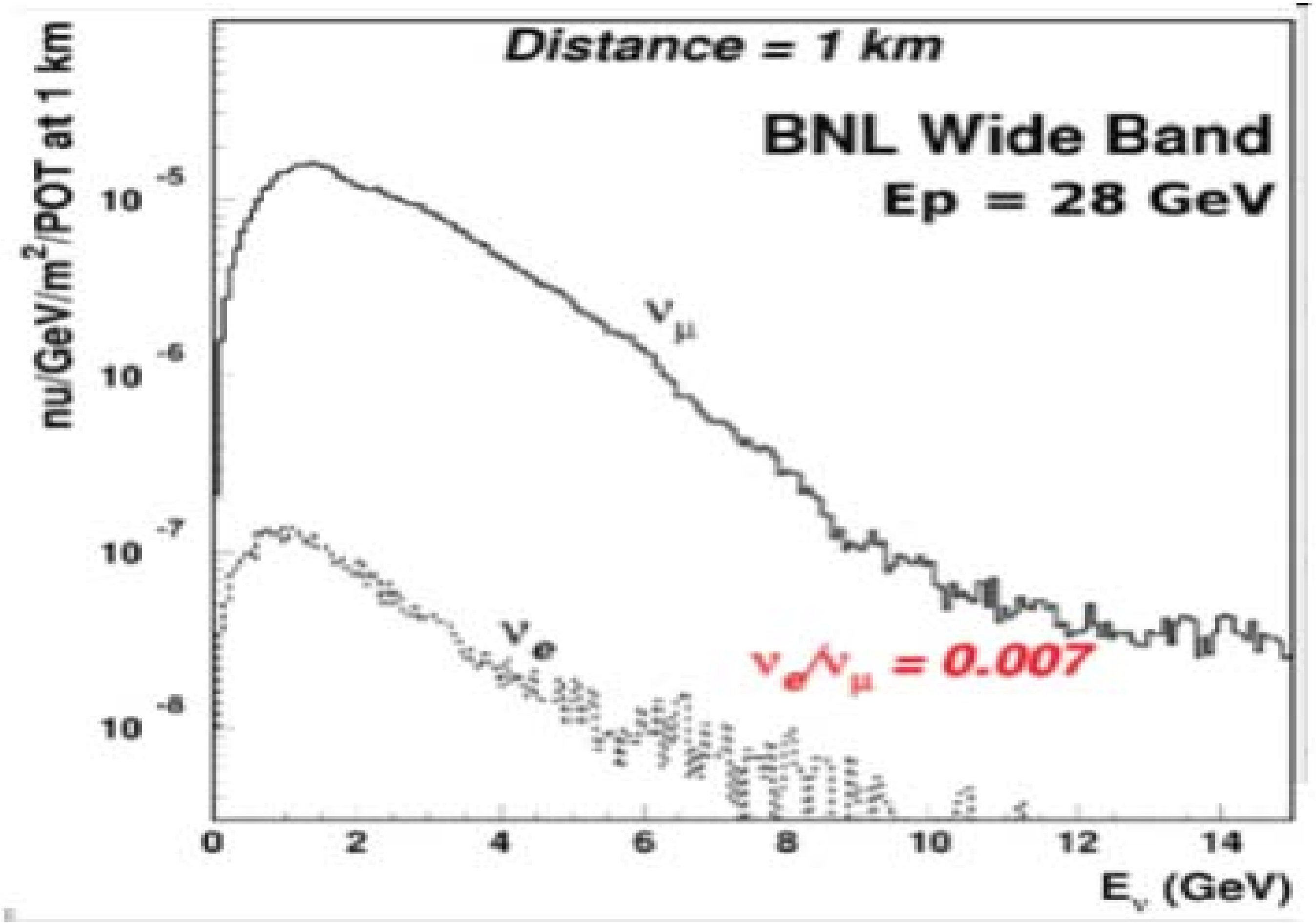
50 kton LArgon 90% Acceptance

or Hybrid combination

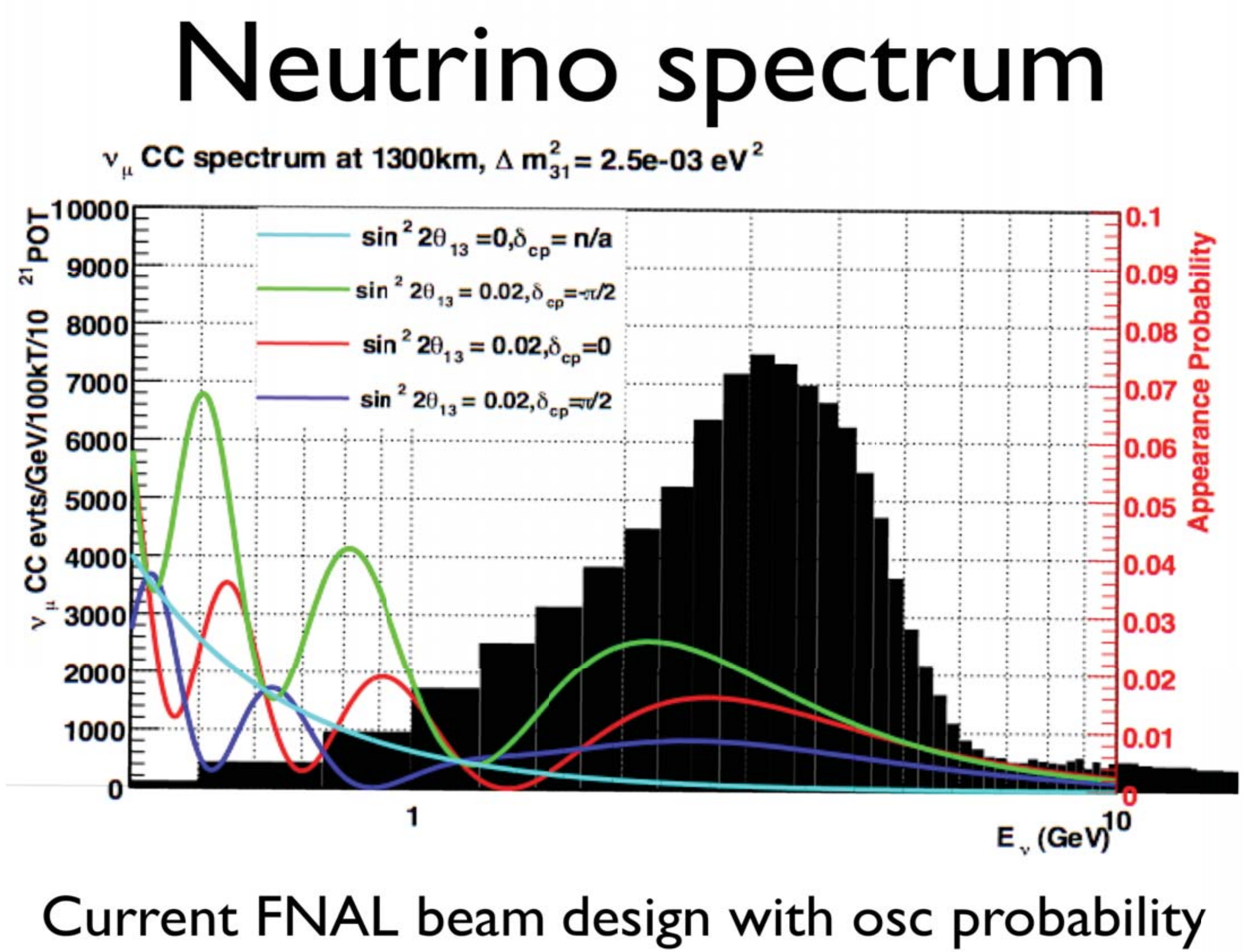
+ Traditional Horn Focused ν WBB powered by

1-2MW proton accelerator (egs. Project X at FNAL)

Horn Focused Neutrino Beam



Fermilab Neutrino Spectrum



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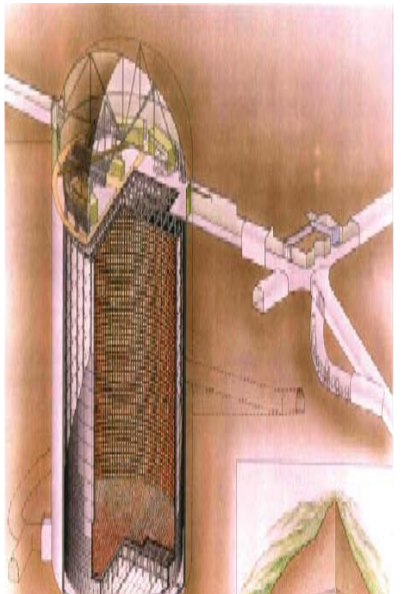
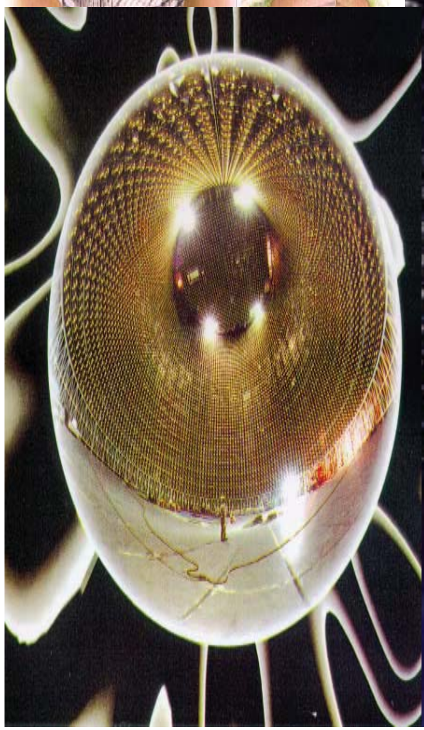
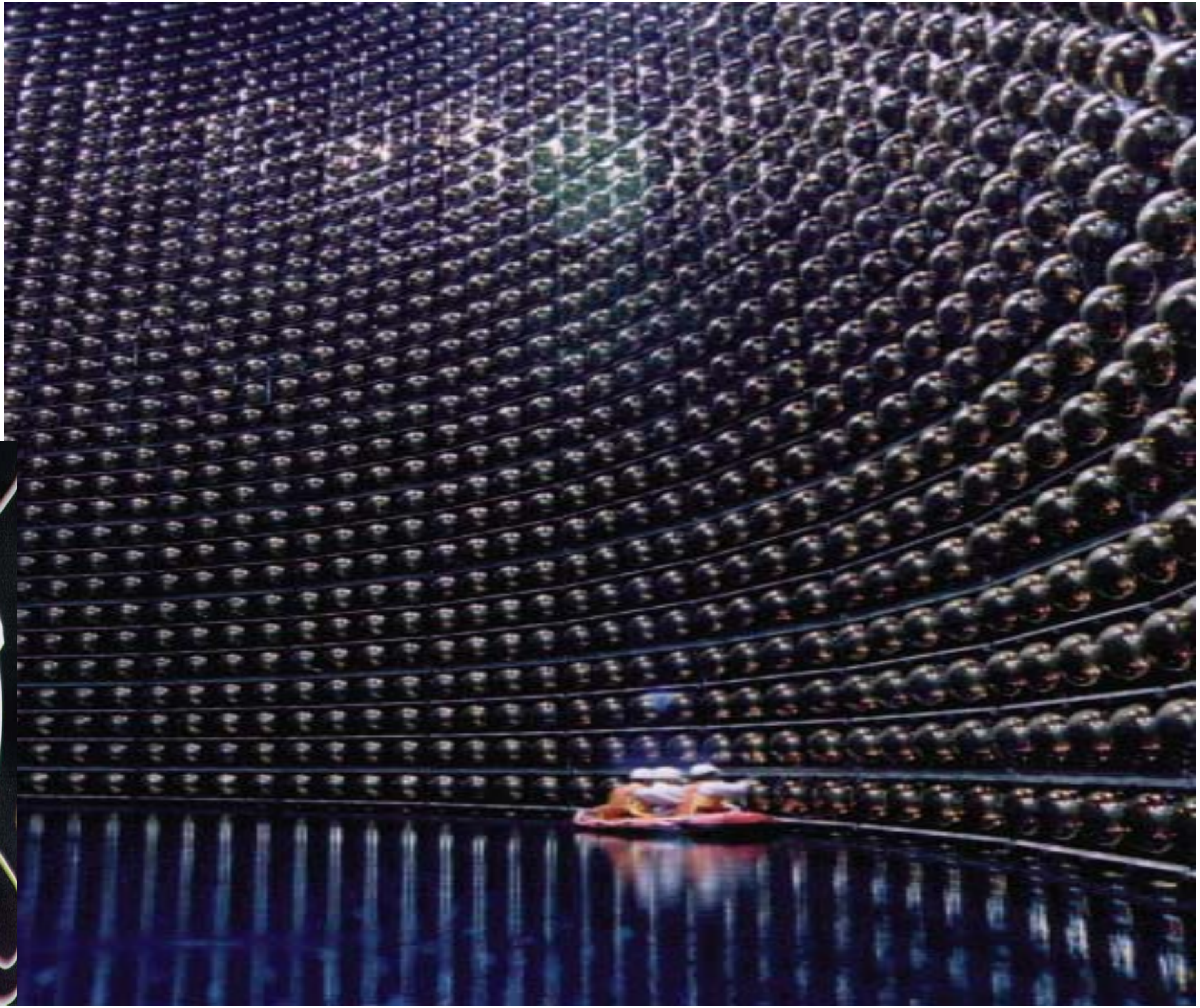


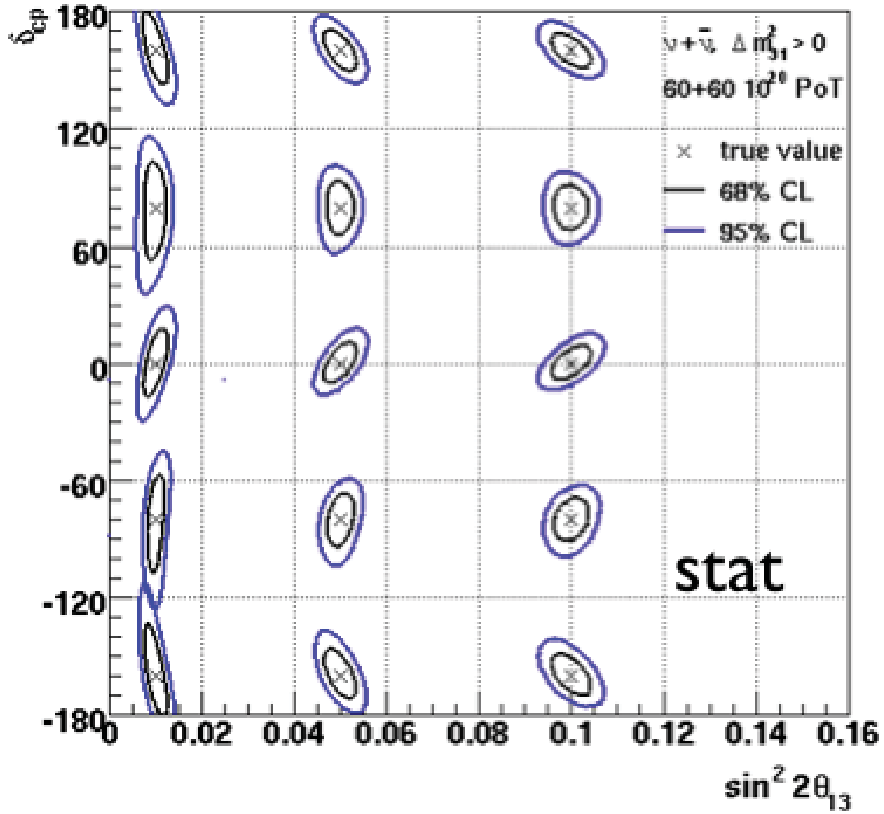


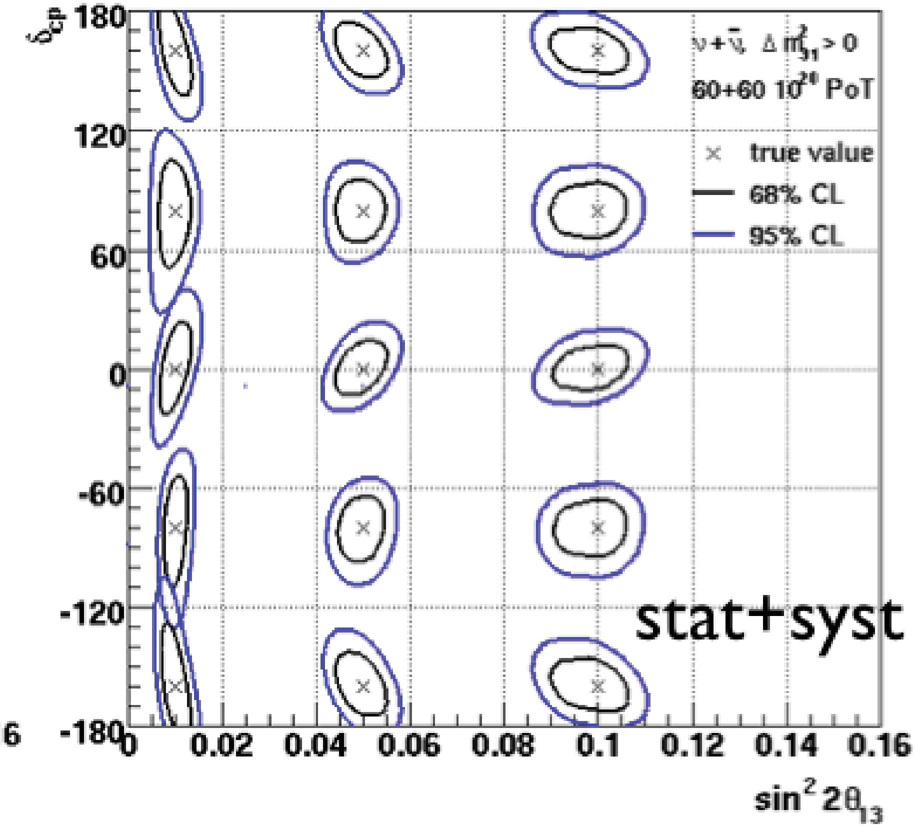


CP Phase Insensitivity to θ_{13} Value

WCC 1300 km 300kT

(—95% CL —68% CL)





4. "New Physics" search via ν_μ & ν_μ disappearance

Disappearance at MINOS $\nu_\mu \rightarrow \nu_\mu$ & anti-$\nu_\mu \rightarrow$anti-ν_μ 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)

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

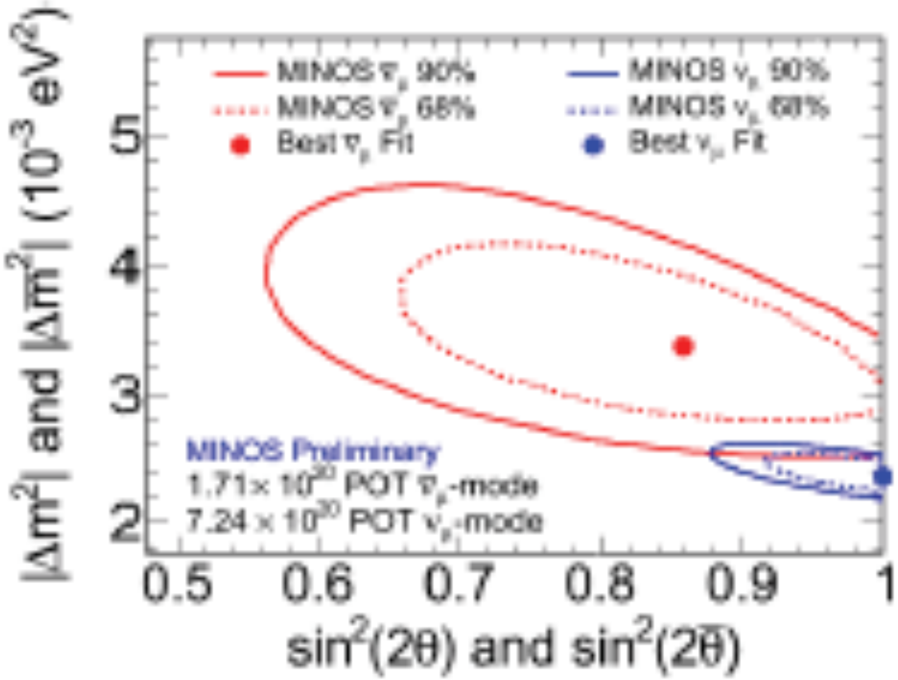
<u>2σ difference? 30%?</u>

(Collaboration does not claim discrepancy!)

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

<u>Anticipate Surprises!</u>

$\overline{\nu}_\mu$ 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

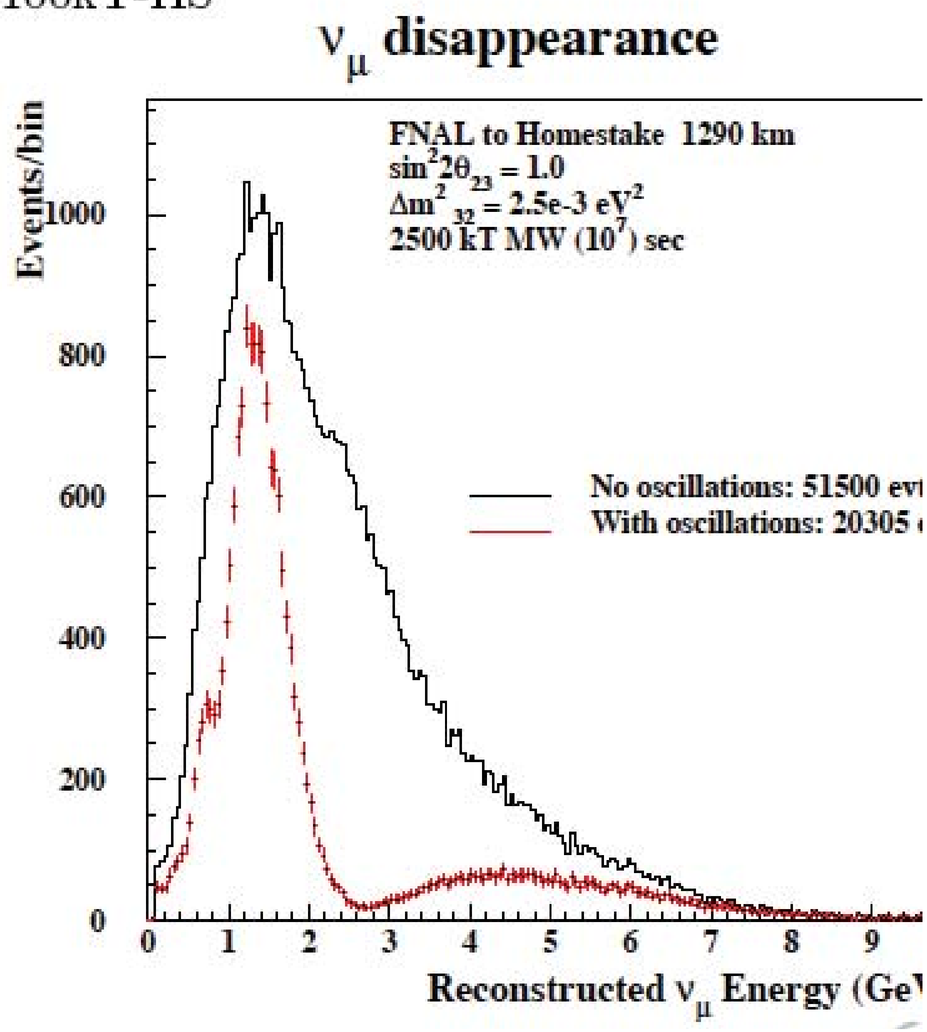
- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

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).

$\nu_\mu \rightarrow \nu_\mu$ & anti-$\nu_\mu \rightarrow$anti-ν_μ Comparison

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

Apparent CPT violation → "New Physics" in ν interactions

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

long range interactions Potential changes sign $\nu_\mu \rightarrow$ anti-ν_μ

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.

$|\varepsilon| <$

	ν_e	ν_μ	ν_τ	
	2.5	0.21	1.7	ν_e
	0.21	0.046	0.21	ν_μ
	1.7	0.21	9.0	ν_τ

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

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

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 $\varepsilon_{\mu\tau} \sim -0.1$ (see figure, some generic features)

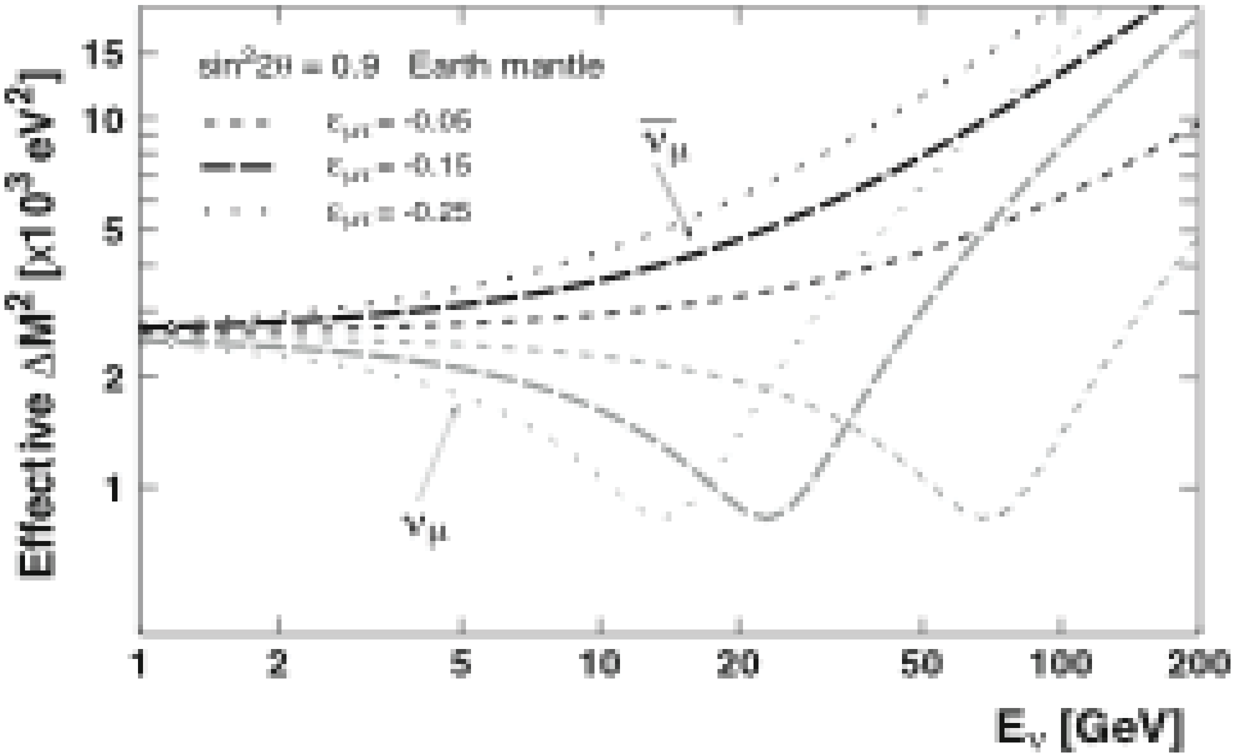
Either $O(\alpha/\Lambda^2)$ Λ large or $O(\alpha'/m^2)$ *α' and m small* (long distance)

Effective potential changes sign for $\nu_\mu \rightarrow$ anti-ν_μ

All lead to different ν_μ and anti-ν_μ oscillations (in matter)

E_ν Dependence of Oscillation Parameters

From Mann, Cherdack, Musial and Kafka (Example)



$\nu_\mu \rightarrow \nu_\mu$ and anti-$\nu_\mu \rightarrow$ anti-ν_μ disappearance

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

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

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

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

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

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

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

  (Suggests studies at high energies & long distances)

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

  Best Bet – Deep Core in Ice Cube E≈ 20GeV

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

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

$\Delta m^2_{32} \sin 2\theta_V$

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

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

Note high E_ν more sensitive to matter!

Anticipate possible differences in ν_μ and □ν_μ 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 □ν_μ disappearance will be very powerful probes of non standard (long and short distance) neutrino interactions!

***Note,** $\nu_\mu \rightarrow \nu_\tau$ and anti-$\nu_\mu \rightarrow$anti-ν_τ appearance potentially very interesting*

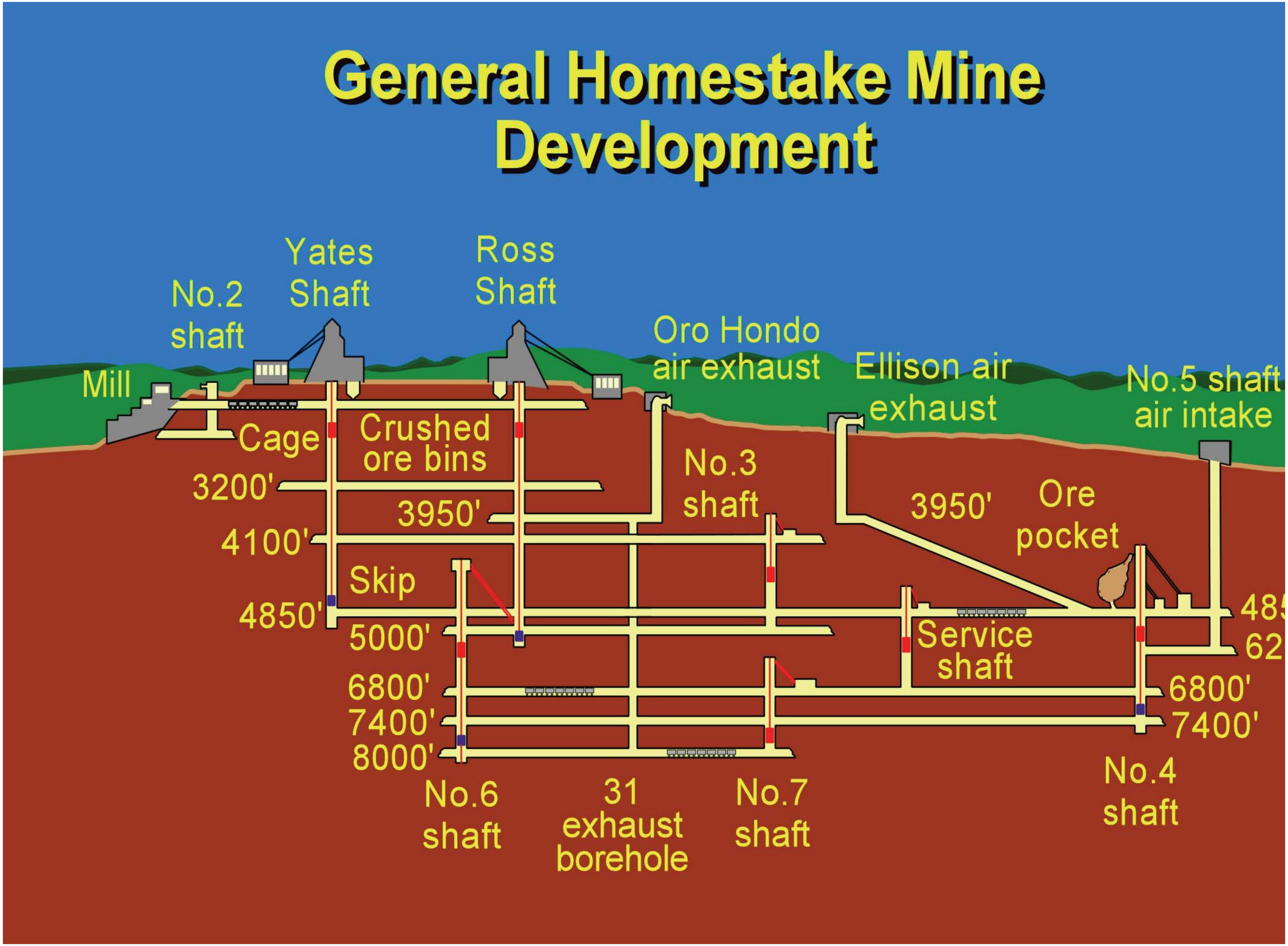
***Moral:** Neutrino ν_μ and anti-ν_μ Osc in Matter provides a potentially powerful probe of (weakly coupled) light and heavy "New Physics". Particularly light $\varepsilon \sim \alpha'/G_F m^2$*

(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-anti-n osc.,…magnetic monopoles

The potential for major discoveries & surprises is great!


General Homestake Mine Development
No.2 shaft
Yates Shaft
Ross Shaft
Mill
Oro Hondo air exhaust
Ellison air exhaust
No.5 shaft air intake
Cage
Crushed ore bins
3200'
3950'
4100'
No.3 shaft
3950'
Ore pocket
Skip
4850'
5000'
Service shaft
6800'
7400'
8000'
6800'
7400'
No.6 shaft
31 exhaust borehole
No.7 shaft
No.4 shaft

Supernova Neutrinos

- SN 1987A: 19 events observed by Kamiokande & IMB
  anti-$\nu_e p \rightarrow e^+ n$ Great Discovery - Confirmed SN Models
  A SN in our galaxy (every ~ 40yr) at typical10kpc would
  lead to about 100,000 anti-$\nu_e p \rightarrow e^+ n$ events/300kton H_2O
  Also, $\nu e \rightarrow \nu e$, ($\nu = \nu_e, \nu_\mu, \nu_\tau$,+antineutrinos) ~ 1000events
  We would like to see $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K$ (initial burst)
  ~250 events/kton LArgon
  Neutrino Spectrum → SN Dynamics & Oscillations
  Extremely Rich Discovery Possible
  We must have as many detectors as possible online
  Relic SN Neutrinos (10-40MeV) S/B/yr ~10/10

Fermilab Activities

- What does Fermilab do after the LHC starts?
- (Great Hope - ILC e^+e^- Collider (μ+μ- 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!)