LBNE Neutrino Oscillations

CP Violation and so much more!

Precision, Matter Effects, "New Physics"…

Atm. Neutrinos, Supernova Neutrinos, Proton Decay…

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OUTLINE

1. Introductory Remarks *(Including proton decay)*
2. Neutrino Masses and Mixing
3. Leptogenesis: Matter-Antimatter Asymmetry
4. Leptonic CP Violation

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

   ii) Requirements ≥100kton H_2O (or 35kton LArgon),

   1-2MW protons

   Neutrino Wide Band Beam (WBB) $E_\nu \approx 0.5$-5GeV

   Long Distance (>1000km)

5. "New Physics" search via ν_μ Oscillations

   (Very Weakly Coupled Long/Short Distance Physics!)

6. Anticipate Surprises - Unexpected Discoveries!

1. Introduction

- What is LBNE?

  Long Baseline (1300km) Neutrino (Oscillation)

  Experiment: Fermilab – DUSEL

  Build a large neutrino detector in the Homestake Mine

  Deep (4850ft) Underground

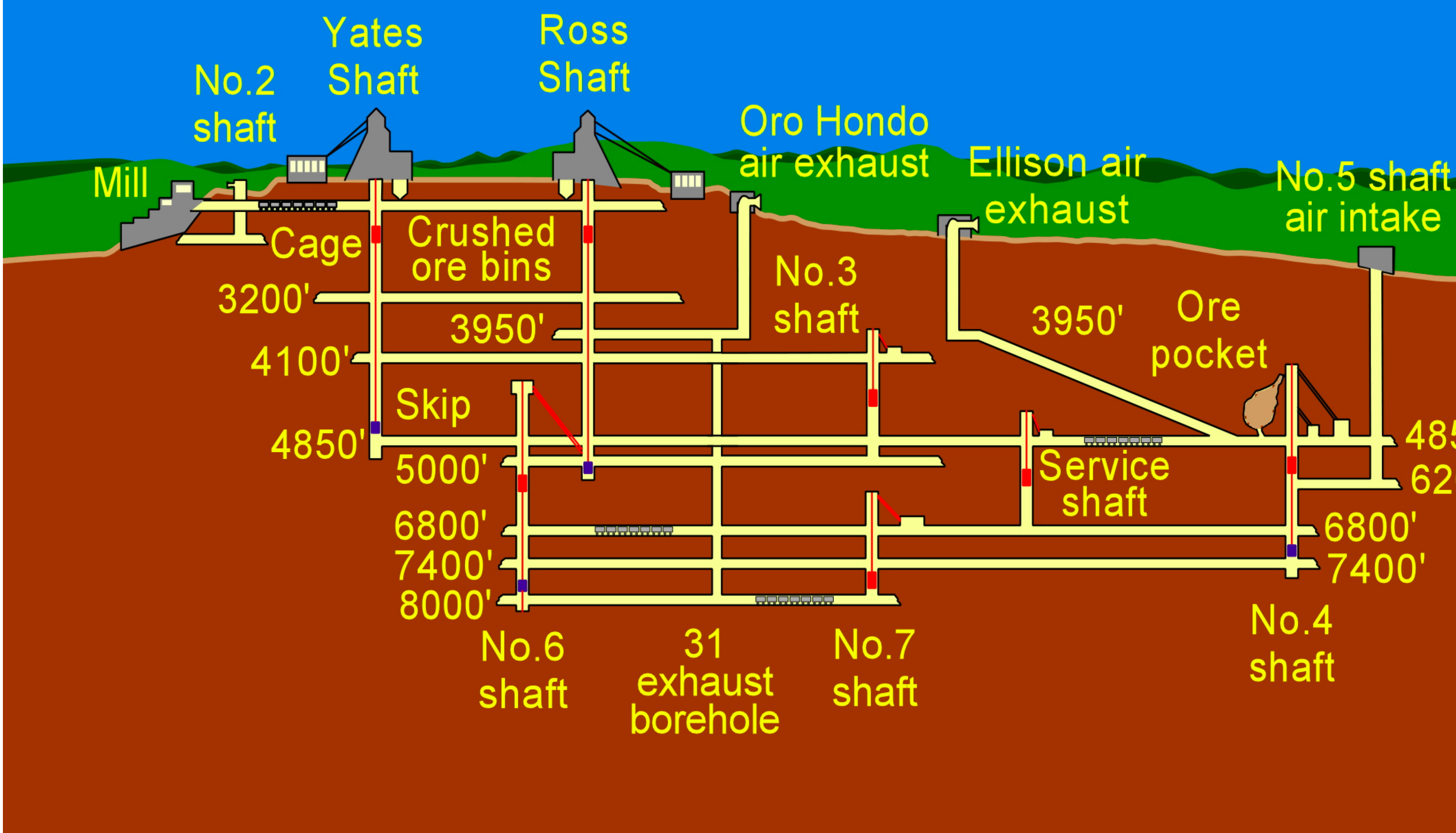
  (100kton water or 35kton LArgon (Approx 6x better/kton))

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

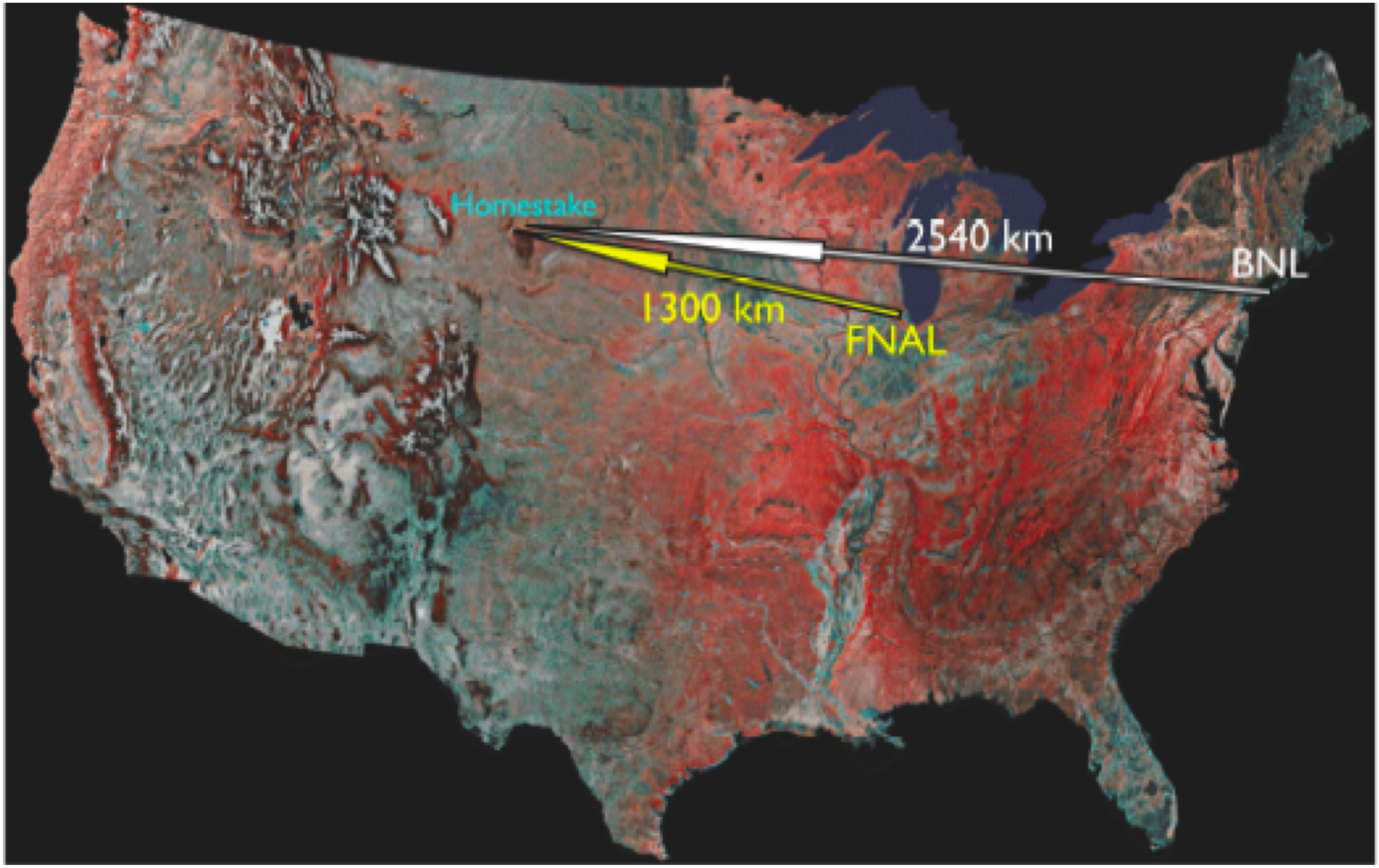
$P(\nu_\mu \rightarrow \nu_e)$ appearance

do Neutrinos and antiNeutrinos Difference? CP?

General Homestake Mine Development



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



Primary Physics Goals

- ***Measure Leptonic CP Violation***

  Our Origin (Leptogenesis Matter-antiMatter Asy.)

  Determine (Precisely) Neutrino Mixing Parameters

  Understand Pattern (Underlying Symmetry eg A4)

  Search for “New Physics” eg very weakly coupled long or short distance effects

  Search for Sterile Neutrinos (small mixing)

Other Physics

- ***Atm. Neutrino Oscillations,***
- ***Supernova Neutrinos (Relic & New),***
- ***Proton Decay…***
- ***Neutron-antiNeutron Osc.***

Broad Revolutionary Discovery Potential

Big Underground Detectors Originally Proposed for Proton Decay Searches Motivated by Grand Unification

1974: A Great Year For Unification

1974 Classics

- ***Pati & Salam:***

  Lepton Number as the Fourth Color

  3186 Citations

- ***Georgi & Glashow:***

  Unity of All Elementary Particle Forces

  3375 Citations

- ***Georgi, Quinn & Weinberg:***

  Hierarchy of Interactions in Unified Gauge Theories

  1520 Citations

Natural Consequence – Proton Decay!

Grand Unified Theories: SU(5), SO(10), E_6…

Explain: Electric Charge-Color Quantization

$g^0_3 = g^0_2 = g^0_1 = g^0_{GUT}$ For $SU(3)_c \times SU(2)_L \times U(1)_Y$

$\sin^2\theta^0_W = 3/8$ Natural Relations – RC Finite and Calculable

Quarks & Leptons: 3 Mixed Families

10 + 5* + 1 of SU(5), 16 of SO(10), 27 of E_6

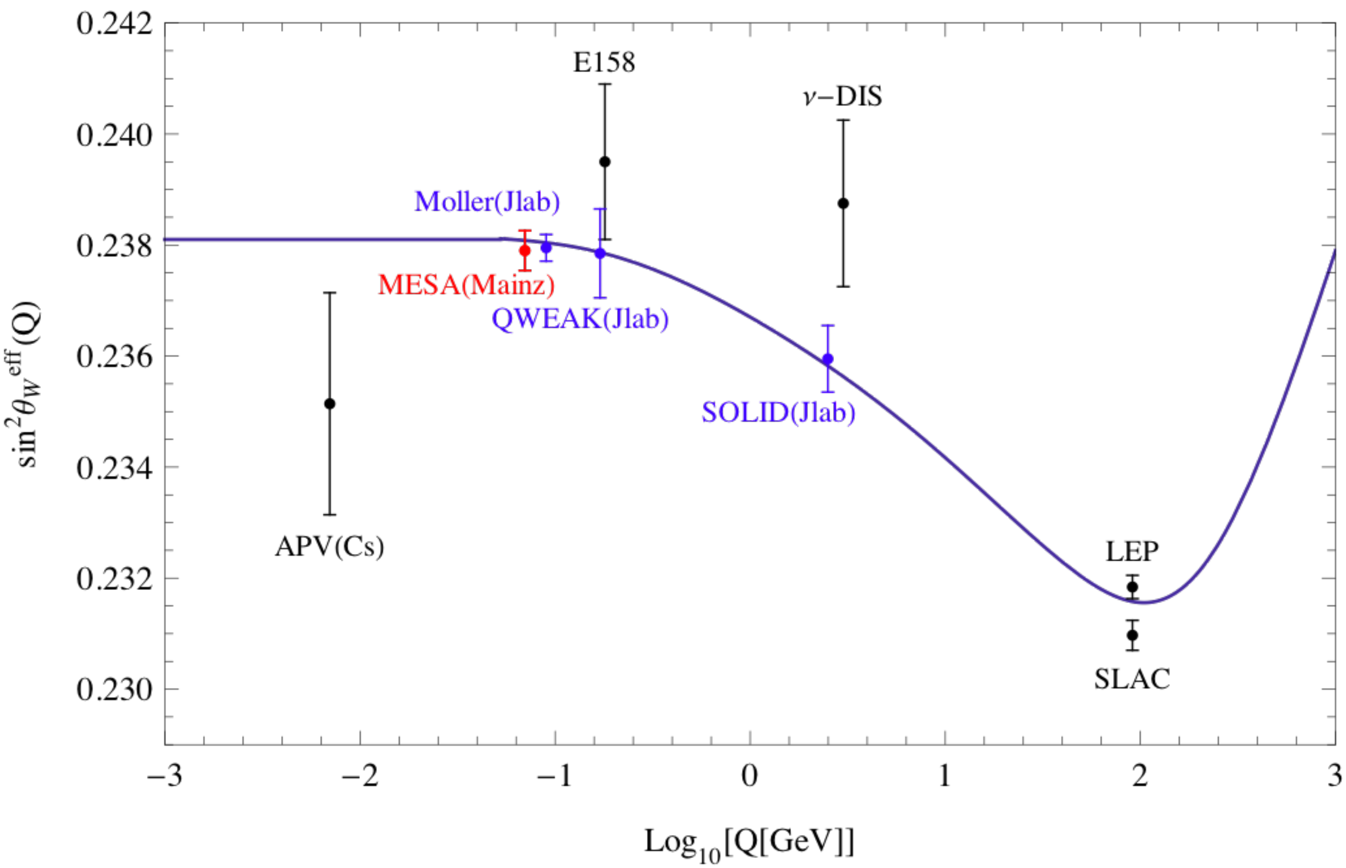
Provide a natural extension of the Standard Model

Easily include (suggest) supersymmetry

Superstring connection

Part of the Particle Physics Vernacular

APV Update & Possible A_{RL} Measurements



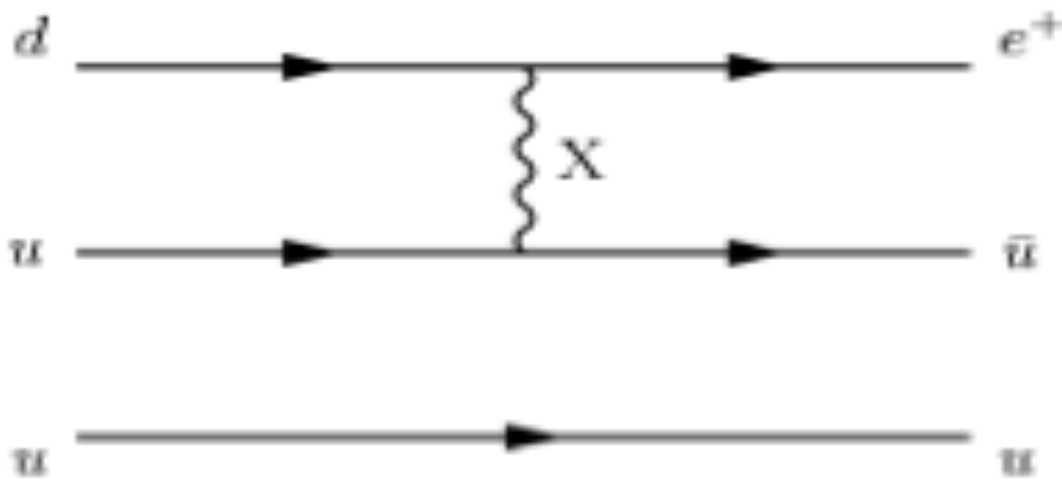
GUT Symmetry Breaking

<u>SU(5)</u>➔$SU(3)_c xSU(2)_L xU(1)_Y$ by 24 Higgs plet
12 of 24 gauge boson **$(X^{\pm 4/3}, Y^{\pm 1/3})_i$** color triplet get
very large masses **$M_X = M_Y = M_{GUT}$**, violate B & L
Mediate proton decay eg. **p➔$e^+\pi^0$, $e^+\rho^0$… n➔$e^+\pi^-$, $e^+\rho^-$…**

$SU(3)_c xSU(2)_L xU(1)_Y$ ➔$SU(3)_c xU(1)_{em}$ by 5 + 45 Higgs
Doublet components break EW symmetry
Color Triplets mediate proton decay: **p➔$K^+ v$, $K^0\mu^+$, $\mu^+\pi^0$…**
(Enhanced p➔$K^+ v$ from dim. 5 SUSY operators)

In **SO(10) & E_6**, a second **$(X'^{\pm 2/3}, Y'^{-/+1/3})_i$** color gauge triplet
can also mediate proton decay (increases **p➔$e^+\pi^0$**)
<u>All proton decay mediators must be very heavy ≥O(10^{16}GeV)</u>

($X^{\pm 4/3}$, $Y^{\pm 1/3}$) Mediated Proton Decay



$p \rightarrow e^+\pi^0$, $e^+\omega$ or ρ^0…$\pi^+\nu$..

Similarly, $n \rightarrow e^+\pi^-$ (via $Y^{\pm 1/3}$)

Isospin: $\Gamma(n \rightarrow e^+\pi^-) = 2\Gamma(p \rightarrow e^+\pi^0)$

$\Gamma(p \rightarrow \pi^+\nu) = 2\Gamma(n \rightarrow \pi^0\nu)$

SU(5) Expectations

proton lifetime ≈ bound neutron lifetime (±10-20%)

Br($p \rightarrow e^+\pi^0$) ≈ 0.35

Br($p \rightarrow e^+\omega$ or ρ^0) ≈ 0.35 (multi-pion final states)

Br($p \rightarrow \pi^+\nu$) ≈ 0.15

Br($p \rightarrow \rho^+\nu$, $e^+\eta$, μ^+K^0…) ≈ 0.15

Br($n \rightarrow e^+\pi^-$) ≈ 0.70

Br($n \rightarrow \pi^0\nu$) ≈ 0.07

Water Cherenkov ≈ 45% $p \rightarrow e^+\pi^0$ acceptance

≈ 19% $n \rightarrow e^+\pi^-$ acceptance

Similar Sensitivity

LArgon Efficiencies

LArgon≈ 45% $p \rightarrow e^+\pi^0$ acceptance

≈ 45% $n \rightarrow e^+\pi^-$ acceptance

Can you do better?

Neutrino Backgrounds?

Should be considered together: BR($Ar \rightarrow e^+\pi^0/\pi^- + N'$)

(Includes pion charge exchange in the nucleus)

Roughly 3-5xBR($p \rightarrow e^+\pi^0$) in LAr

Neutrino Background? Lar very clean!

Other exotic scalar multiplets: 10 + 15 + 50* of SU(5) (contained in 126 of SO(10))*

Can give rise to: ΔL=2 & ΔB=2 Interactions at much lower scales

Majorana neutrino masses ΔL=2

Neutrinoless double beta decay **nn➔ppe$^+$e$^+$** ΔL=2

Neutron-antineutron oscillations (Are neutrons majorana?) ΔB=2

Double proton decay **pp➔e$^+$e$^+$ or μ$^+$μ$^+$** (ΔB=ΔL=2)

ΔB=2 effects probed by proton decay exps.

Interesting but wide range of predictions

Coupling Unification

Current Values: $\alpha_3(m_Z)=0.117(1)$

$\alpha_2(m_Z)=0.0338(1)$

$\alpha_1(m_Z)=0.0170(1)$

Come together but do *not* quite unify without an intermediate mass scale: m_{susy}, m_R SO(10), m_{scalar}…

Generic SUSY GUT ➔ $m_X \approx (1\text{TeV}/m_{susy})^{2/15} \times \underline{10^{16}\text{GeV}}$

(G. Sejanovic & WJM)

Also depends on other mass splittings (eg. Scalars)

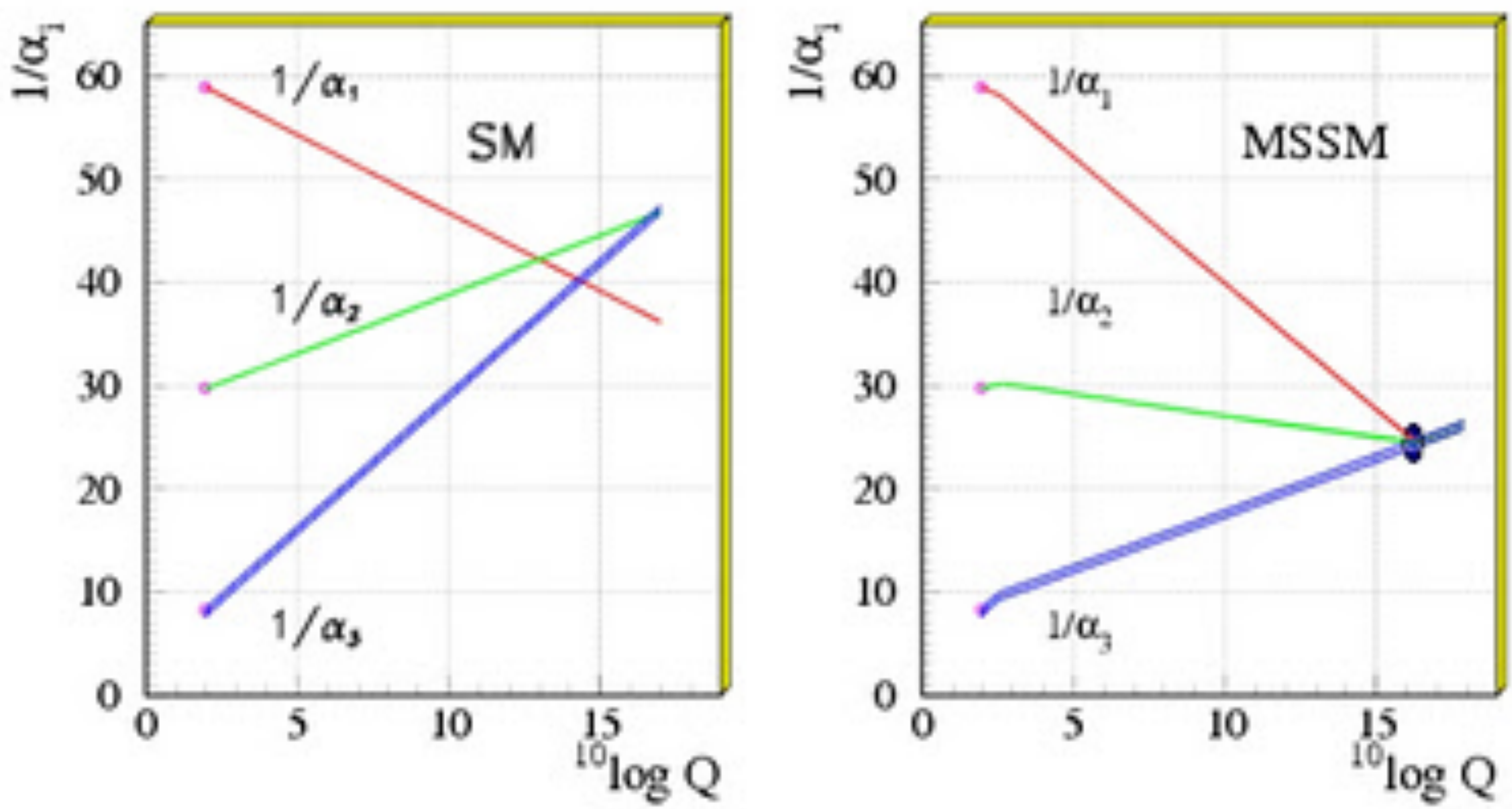
Proton Partial Lifetime:

$\boldsymbol{\tau(p \rightarrow e^+\pi^0)} \approx (1\text{TeV}/m_{susy})^{8/15} \times 10^{35\pm1}\text{yr}$

Uncertainties: Matrix Elements (Lattice), $\alpha_3(m_Z)$, mass splittings, particle content…

SUSY GUT Unification

S. Raby PDG (2010)



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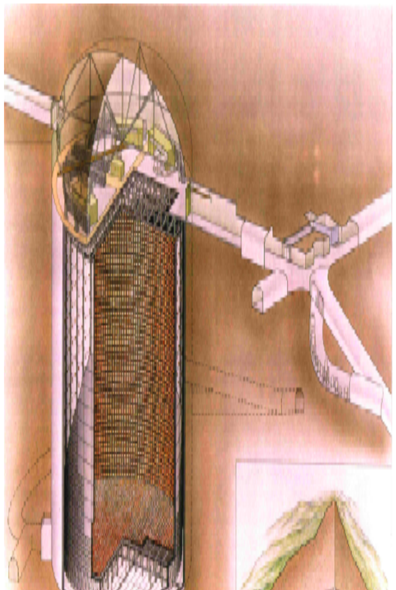
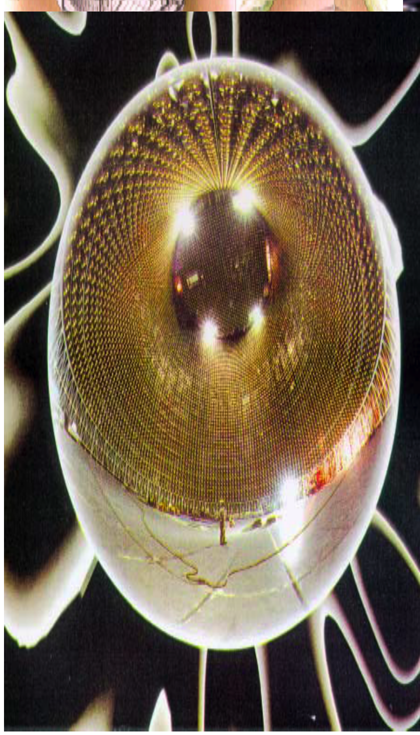
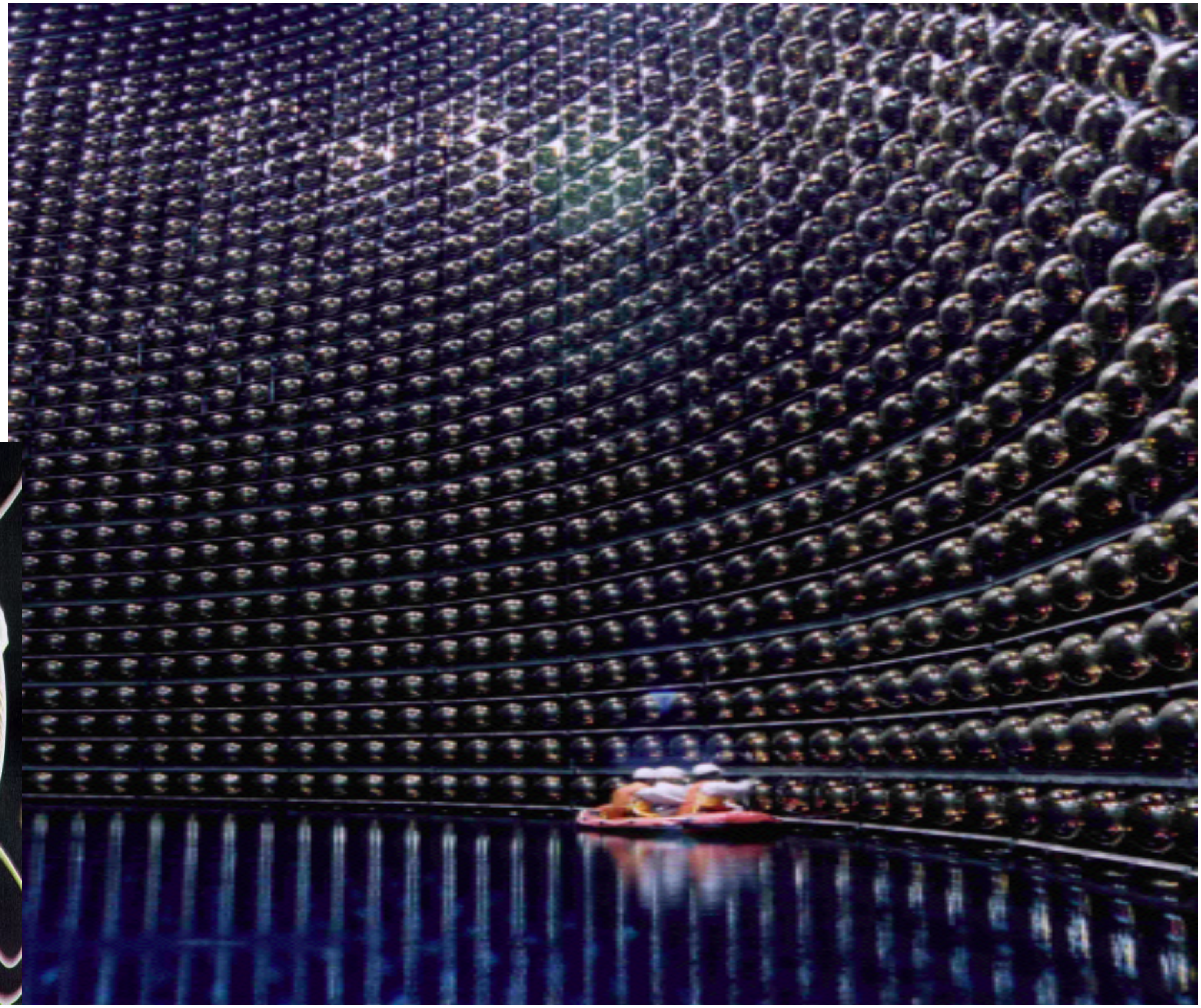






Some Current SuperK Bounds

SuperK 22.5Kton Fiducial Vol. H_2O Cerenkov

Bounds on ***many*** p & n decay modes

$\tau(p \rightarrow e^+\pi^0) > 1x10^{34}yr$ ($m_X > 5x10^{15}GeV$)

$\tau(n \rightarrow e^+\pi^-) > 2x10^{33}yr$

$\tau(p \rightarrow K^+v) > 3x10^{33}yr$

Reaching asymptotic capabilities

Sensitivity goals for future detectors: ≥10xSuperK

$\tau(p \rightarrow e^+\pi^0) > 10^{35}yr$ ($m_X \geq 10^{16}GeV$)

$\tau(p \rightarrow K^+v) > 2x10^{34}yr$

Also probe neutron-antineutron osc. ($\tau_{nnbar} > 10^9sec$)

Double proton decay $pp \rightarrow e^+e^+$

GUT Magnetic Monopole Catalysis of proton decay

Quantum Virtual Black Hole Effects

- Publication in preparation

	SK-I+II			
	eff. (%)	BG (/141)	N_c	τ
$p \to e^+\pi^0$	44.6	0.31	0	8.2
$p \to \mu^+\pi^0$	35.5	0.34	0	6.6
$p \to e^+\eta$	26.9	0.44	0	4.2
$p \to \mu^+\eta$	18.5	0.49	2	1.3
$p \to e^+\rho^0$	4.9	0.35	0	0.71
$p \to \mu^+\rho^0$	1.8	0.42	1	0.16
$p \to e^+\omega$	4.9	0.53	1	0.32
$p \to \mu^+\omega$	5.5	0.48	0	0.78
$n \to e^+\pi^-$	19.4	0.27	0	2.0
$n \to \mu^+\pi^-$	16.7	0.43	1	1.0
$n \to e^+\rho^-$	1.8	0.38	1	0.07
$n \to e^+\rho^-$	1.1	0.29	0	0.04
Total		4.7	6	

H. Nishino Ph.D. thesis, U. Tokyo (2009)

Future proton decay detectors

Given the SuperK bounds, the next generation water cerenkov detector should be at least 10x larger, i.e. ≥200Kton

A future LArgon detector should have **$\tau(p \rightarrow K^+ \nu) > 2 \times 10^{34}$yr** sensitivity, i.e. fiducial mass ≥35Kton

Those requirements are well matched to future neutrino Oscillation experiments designed to measure CP violation (differences between neutrinos and antineutrinos)

Japan HyperK: 20xSK H_2O, > Megawatt p, (off axis ν's), 5yrs

USA LBNE: 35 Kton LAr, 1-2 Megawatt p, (WBB ν's), 5yrs

LHC/ Proton Decay Complementarity

Current best experimental "hint" of SUSY

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(63)(49) \times 10^{-11}$ (*3.6σ*)

suggests ***$m_{susy} \approx$ 100-500GeV***

some tension with LHC $m_{susy} \geq$ 1 TeV (squarks & gluinos)

SUSY GUTS also prefer heavier $m_{susy} \approx$ 10TeV

Heavier m_{susy} → shorter $\tau(p \to e^+\pi^0) \approx (1\text{TeV}/m_{susy})^{8/15} \times 10^{35\pm1}$yr

Heavier m_{susy} makes $p \to e^+\pi^0$ easier to observe!

but it makes direct SUSY at the LHC less likely

Together They Squeeze SUSY

2. 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)

  $\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.6(2) \times 10^{-5}\ eV^2$ (solar)

- 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!)

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

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

3 Generation Mixing Formalism & Status)

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

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

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

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

Current 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)

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

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

Large Mixing!

$\theta_{23}\sim$ 40-45° $\sin^2 2\theta_{23} \approx 1.0$ (θ_{23} or 90°- θ_{23}) (atm.)

$\theta_{12}\sim$ 34±1° $\sin^2 2\theta_{12} = 0.85(3)$ (solar)

$\theta_{13} \leq$ 8.7±0.5° $\sin^2 2\theta_{13}$ = 0.09±0.01

$0 \leq \delta \leq 360°$?

$J_{CP}\sim 0.03\sin\delta$ (potentially large!) CKM~2×10^{-5}

What do we still need to learn?

1. **Sgn Δm_{32}^2?** Earth Matter Effect
   (Important for Neutrinoless $\beta\beta$ Decay)

- 2. **Value of** δ?, J_{CP}?, CP Violation? ***(Holy Grail)***
- 3. **Precision** Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12}, $\boldsymbol{\theta_{13}}$ (better than 1%!) Redundancy neutrinos vs antineutrinos
  Unitarity Violation? – Sterile neutrino Mixing
- 4. **"New Physics"** - Sterile ν, ***Very Weak*** Long/Short 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

   $N_R \rightarrow H^- e^+, H^0 \nu$ (***ΔL=2 & 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 ββ 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

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

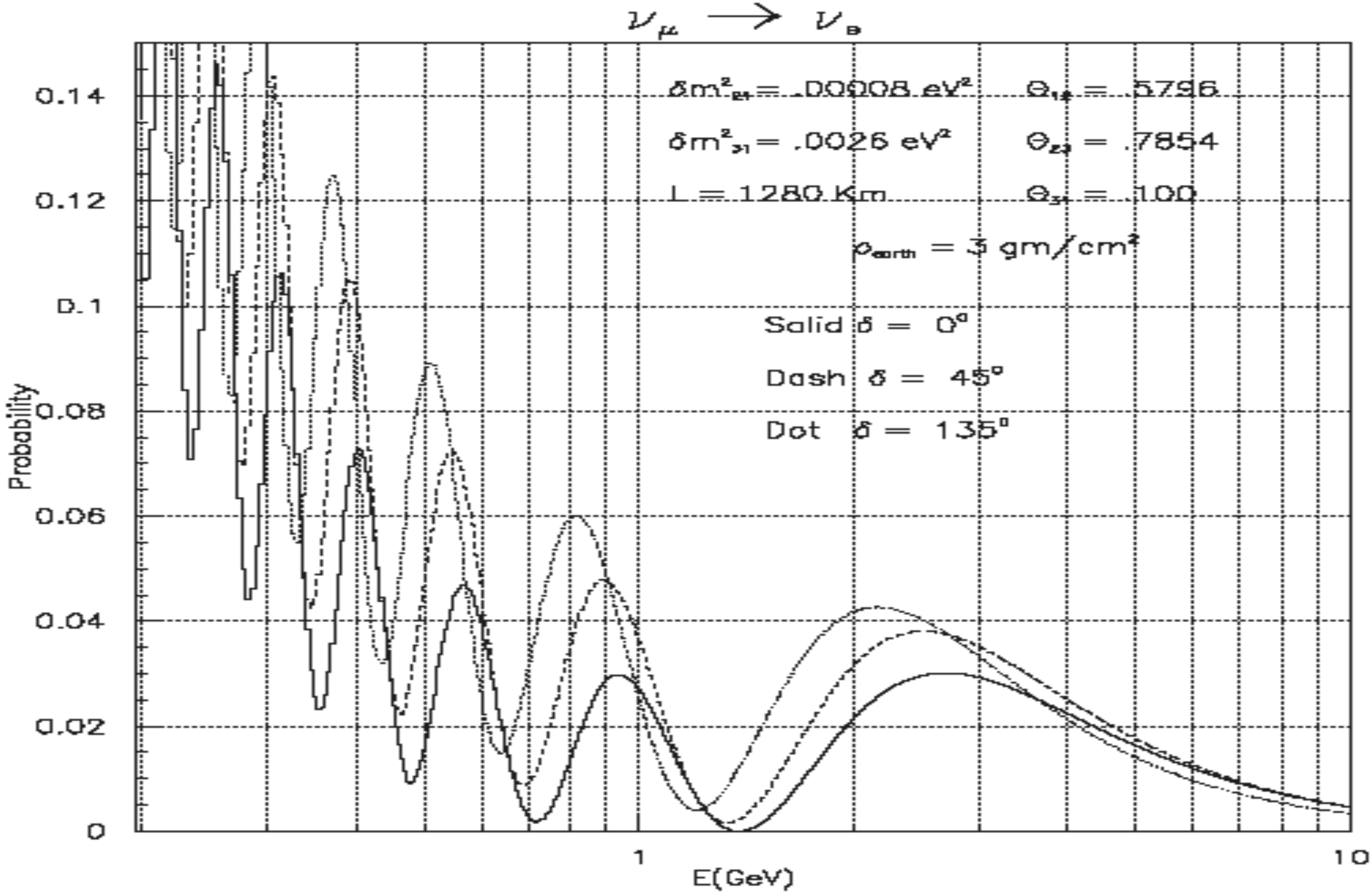
$$\mathbf{P}_{II}(\nu_\mu \to \nu_e) = \tfrac{1}{2}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$
$$\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right) \times \left[\sin\delta\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\right.$$
$$\left. + \cos\delta\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\cos\left(\frac{\Delta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

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

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

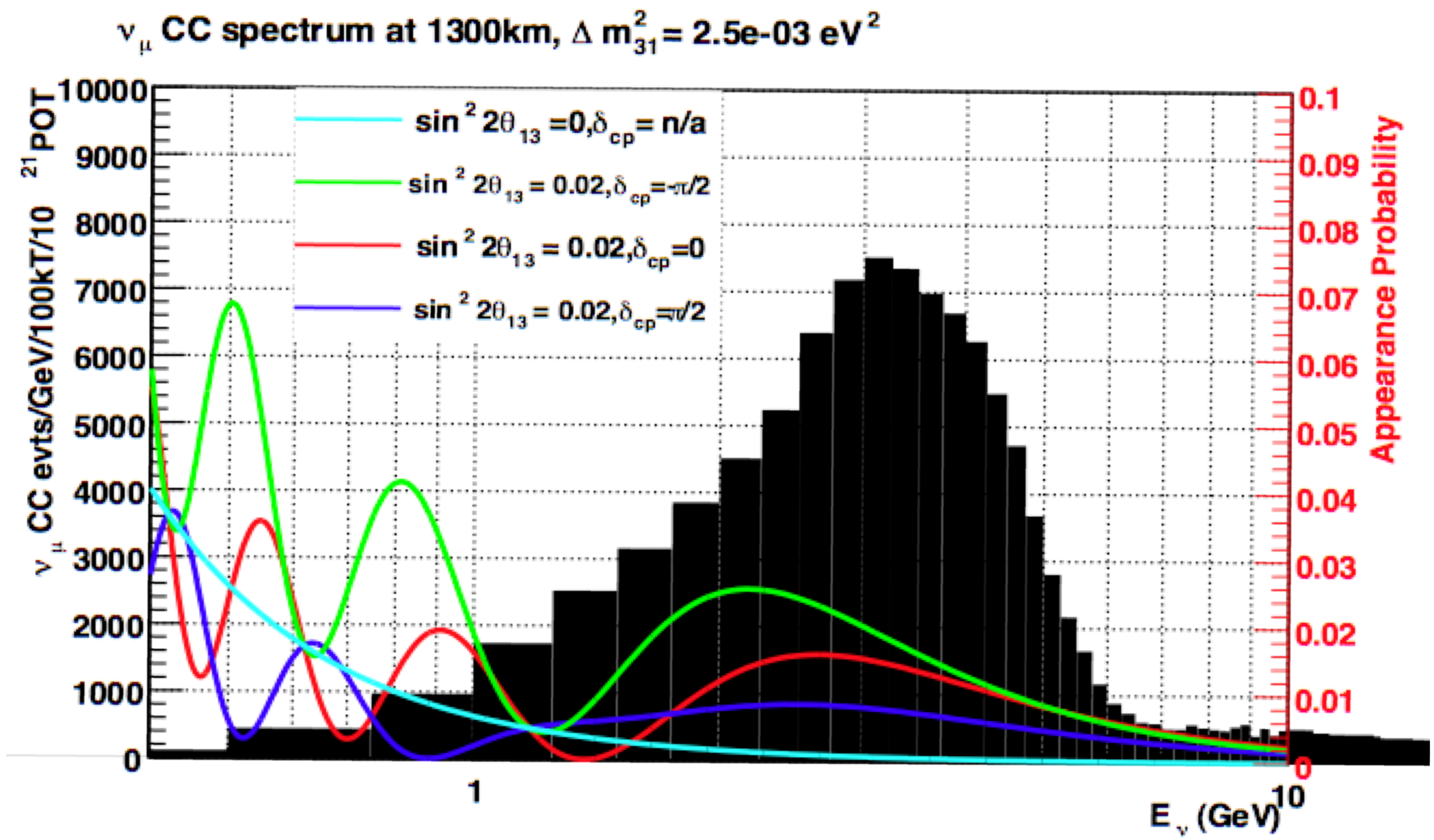
Zohreh Parsa, BNL

FNAL

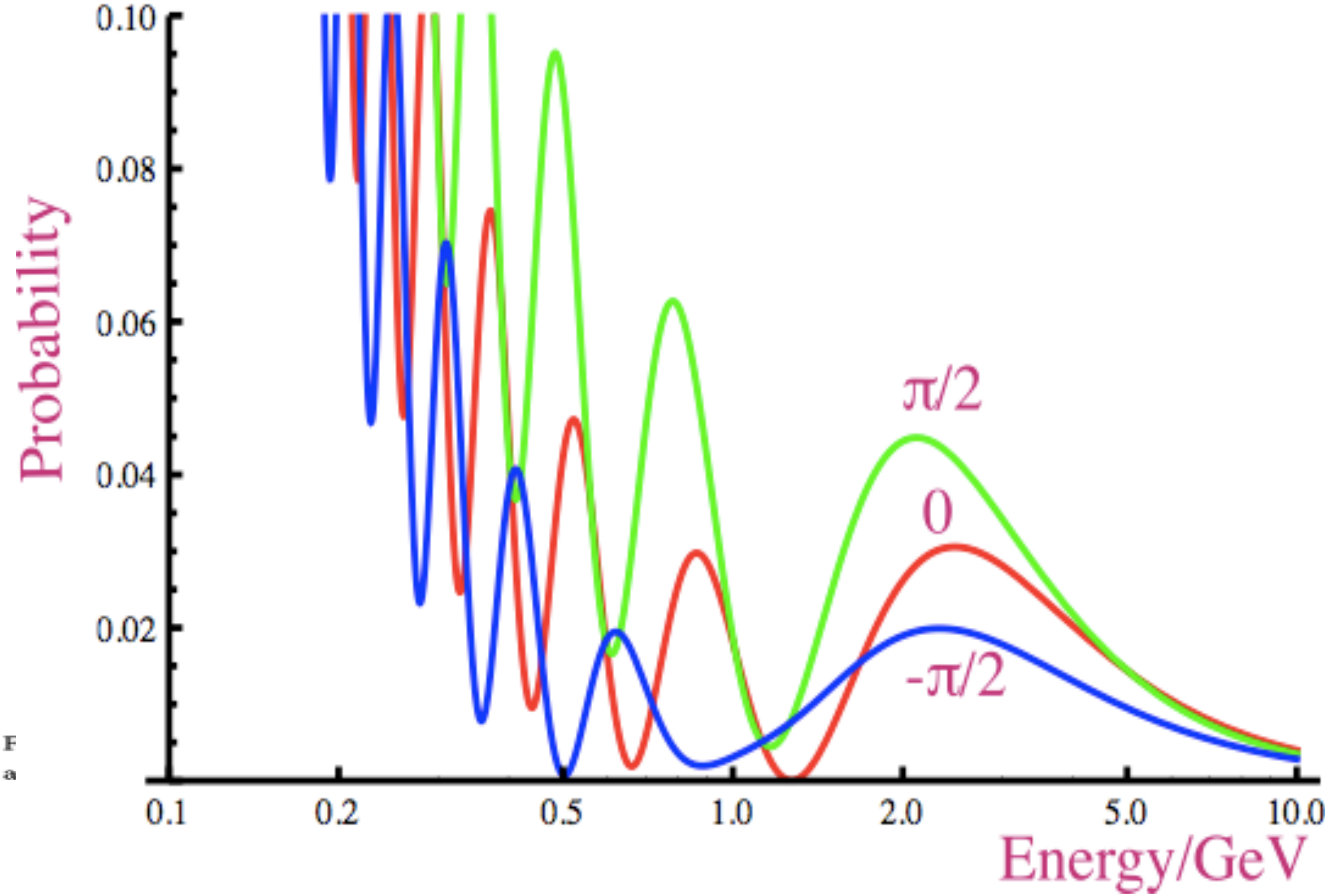


Fermilab Neutrino Spectrum

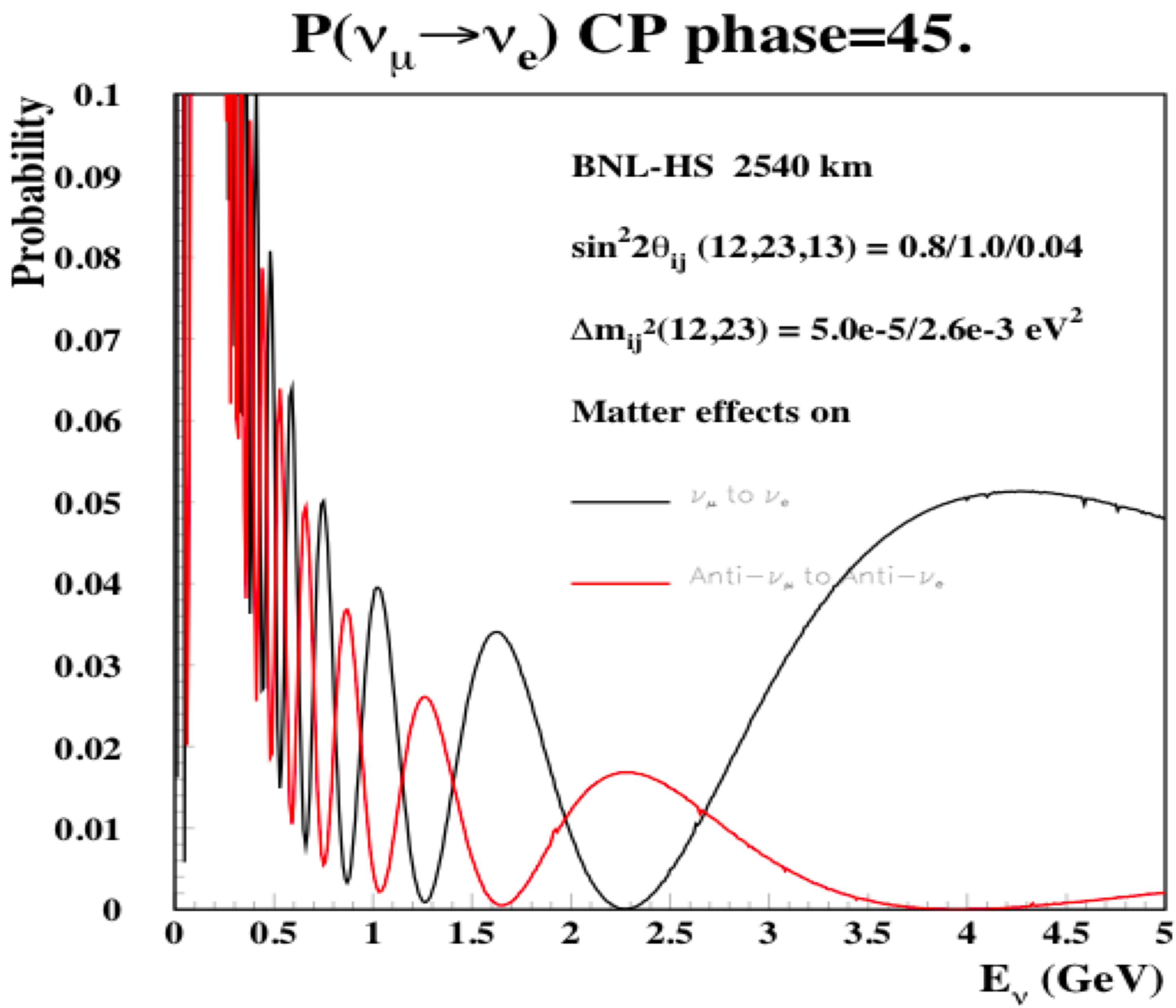
Neutrino spectrum



Current FNAL beam design with osc probability



Probability
0.10
0.08
0.06
0.04
0.02
0.1
0.2
0.5
1.0
2.0
5.0
10.0
Energy/GeV
π/2
0
-π/2



P(νμ→νe) CP phase=45.
Probability
BNL-HS 2540 km
sin²2θij (12,23,13) = 0.8/1.0/0.04
Δmij²(12,23) = 5.0e-5/2.6e-3 eV²
Matter effects on
νμ to νe
Anti−νμ to Anti−νe
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Eν (GeV)

CP Violation Asymmetry

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

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

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

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

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).

It turns out $\sin^2 2\theta_{13} \approx 0.1$! Helps systematics 2½ times larger than assumed in studies

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 $\pm 15°$ in about 6×10^7 sec?

Answer (Approx.): 100kton Water Cerenkov Detector

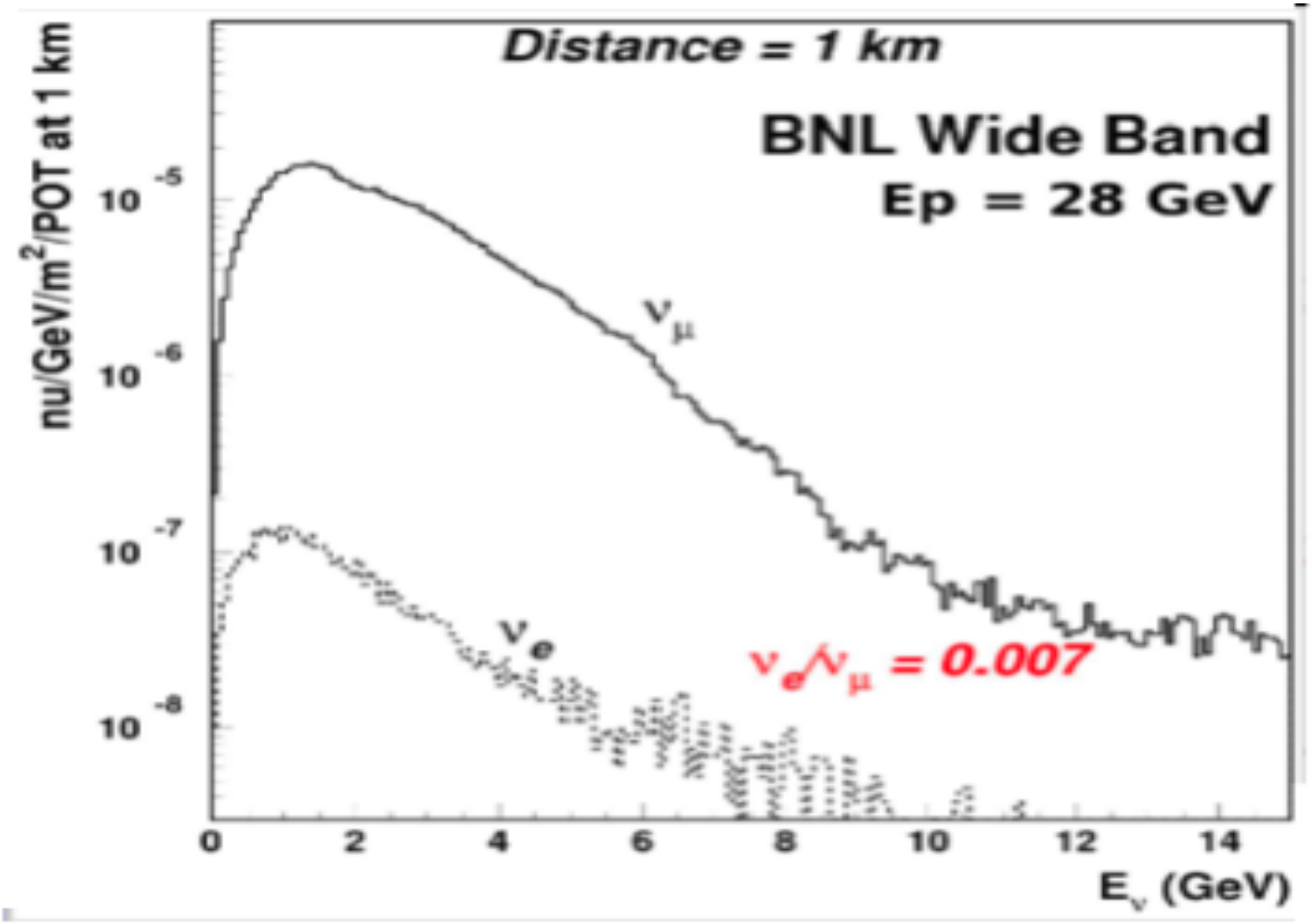
Approx 20% Acceptance qr

35 kton LArgon 90% Acceptance

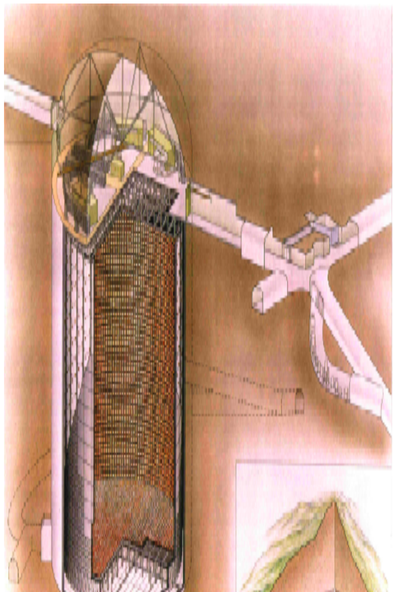
or Hybrid combination

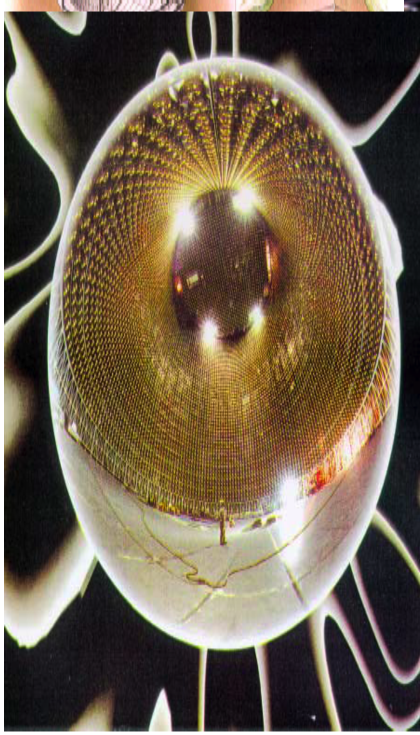
+ Traditional Horn Focused ν WBB powered by 1-2MW proton accelerator (egs. Project X at FNAL)

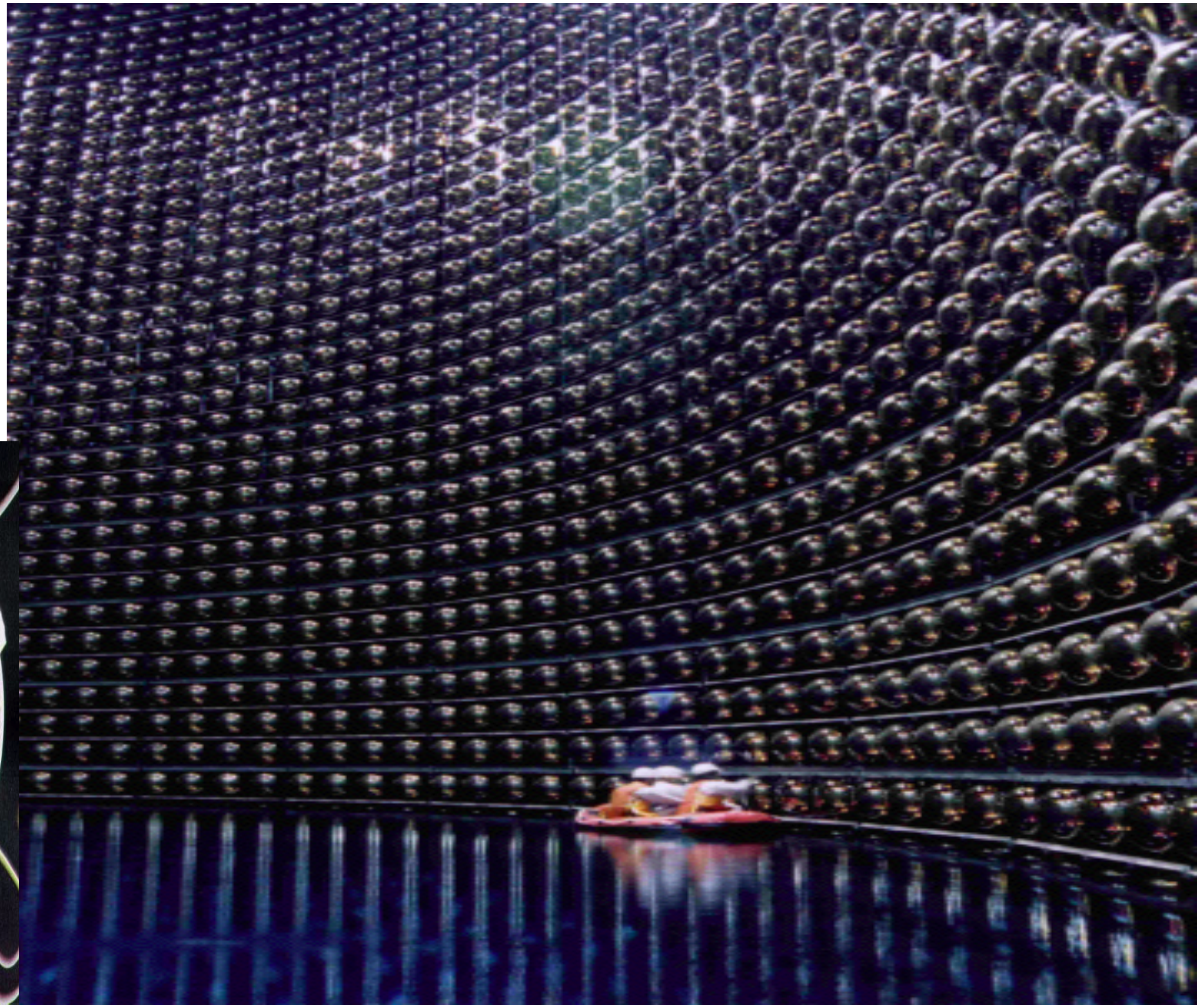
Horn Focused Neutrino Beam



SUPER KAMIOKANDE



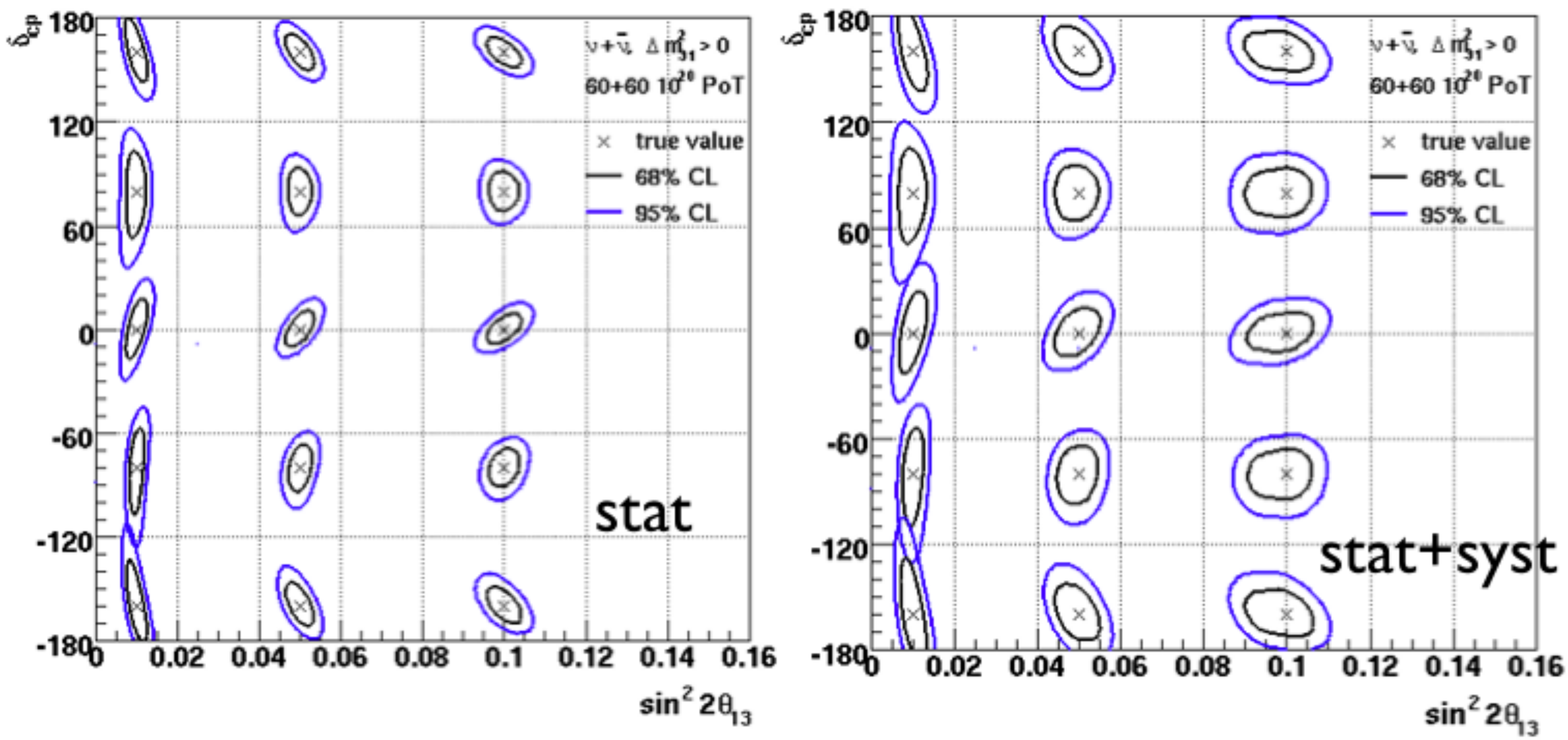




CP Phase Insensitivity to θ_{13} Value

WCC 1300 km 300kT

(—95% CL —68% CL)



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

Disappearance at MINOS $\nu_\mu \to \nu_\mu$ & anti$\nu_\mu \to$antiν_μ for a while Showed differences! CPT Violation? (last resort!)

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

$\nu_\mu \to \nu_\mu$: $\Delta m^2_{32}=2.35(11)\times10^{-3}eV^2$ $\sin^2 2\theta_{32}\sim1$ (>0.91)

anti$\nu_\mu \to$antiν_μ: $\Delta m^2_{32}=3.36(45)\times10^{-3}eV^2$, $\sin^2 2\theta_{32}=0.86(11)$

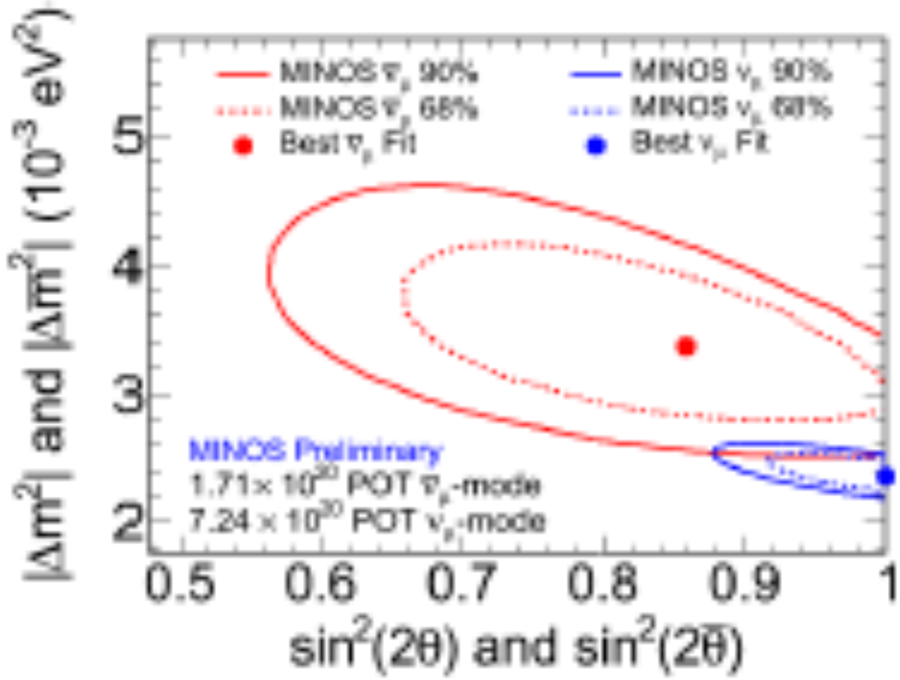
2σ difference? 30%?

(Collaboration never claimed discrepancy!)

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

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

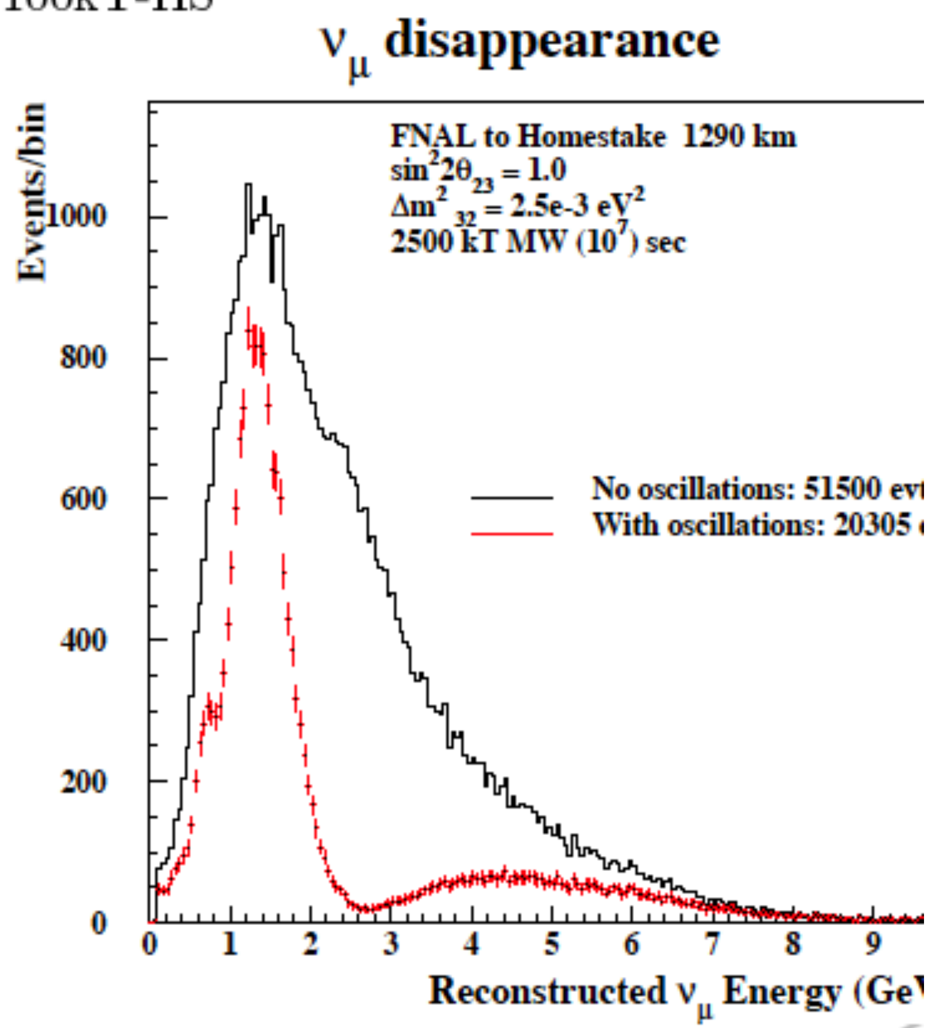
- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

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).

$\nu_\mu \rightarrow \nu_\mu$ & anti$\nu_\mu \rightarrow$antiν_μ Comparison

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

Apparent CPT violation → "New Physics" in ν interactions

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

Potential changes sign $\nu_\mu \rightarrow \nu_\mu$

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.

	ν_e	ν_μ	ν_τ	
	2.5	0.21	1.7	ν_e
$\vert\varepsilon\vert <$	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 $\varepsilon_{\mu\tau}$~-0.1 (see figure, some generic features)

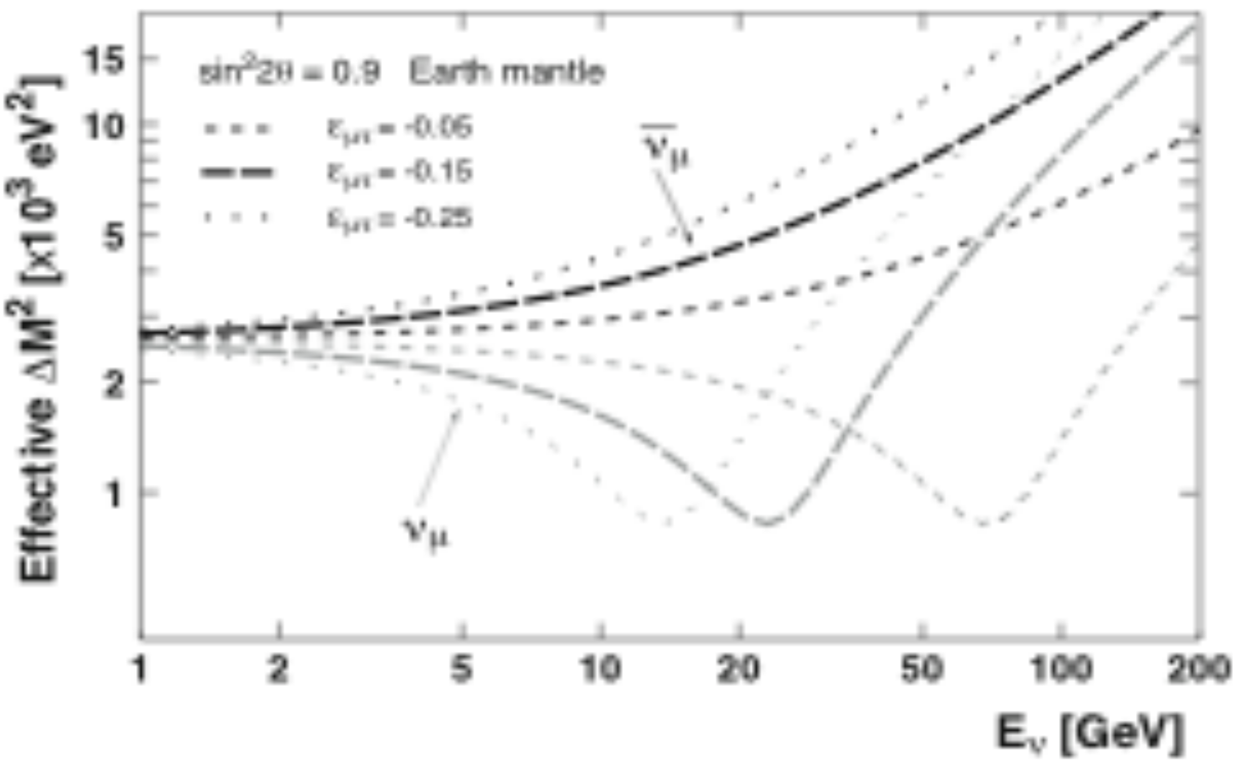
Either $O(\alpha/\Lambda^2)$ Λ large or $O(\alpha'/m^2)$ *α' and m small* (long distance)

Effective potential changes sign for $\nu_\mu \rightarrow$ antiν_μ

All lead to different ν_μ and antiν_μ oscillations (in matter)

E_ν Dependence of Oscillation Parameters

From Mann, Cherdack, Musial and Kafka (Example)



$\nu_\mu \to \nu_\mu$ and anti$\nu_\mu \to$ antiν_μ disappearance

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

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

  <u>Could also be off diagonal matter effects, eg Mann et al</u>

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

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

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

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

  <u>(Suggests studies at high energies & long distances)</u>

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

  Ice Cube Detector (Upgrade)

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

$L_m = L_v/(1 \pm 2y\cos 2\theta_V + y^2)^{1/2}$ 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 $y >> 1$ oscillations highly suppressed $L_m \sim L_0$

for $y << 1$ 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 $\theta_V = 45°$</u>

No Δm^2_{32} difference in **ν_μ vs antiν_μ** for (but depends on E_ν)

Recent Deviation from $\theta_V = 45°$ currently observed

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

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

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

Moral: ***Neutrino ν_μ and antiν_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!)

LBNE Neutrino Oscillations

(Currently ~500 neutrino papers/yr!)

Many Many Topics!

Neutrinos are very interesting!

Complements LHC Activity

Lepton Mixing Model Building

Lepton mixing angles suggest discrete symmetry,

Mass Matrix Textures A4, Δ(27)…

See-Saw Mechanism looks correct

Neutrinoless Double Beta Decay ΔL=2 (Mass Hierarchy)

Measurement of (relatively large) θ_{13} ruled out many models

Determination of δ will significantly constrain models

Pieces of the puzzle ➔ Big Picture

LEPTOGENESIS

You can't discover if you don't explore!

5. Outlook

- Neutrino exps will advance: θ_{13} Mass Hierarchy, ν CP Violation … via LBNE Requires Big Detector: >100kton H_2O or 35kton LAr
  2MW Accelerator wide band neutrino beam, Long Distance
- ***Also***
- Atmospheric & Solar ν Complementary
- 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!

<u>Fermilab Activities</u>

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

  <u>Higgs Factory</u>

In the meantime? <u>Pursue Neutrino Physics</u>

<u>Project X Option</u>- 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

<u>Doable!</u> <u>Must Do!</u>

(START AS SOON AS POSSIBLE!)

Current LBNE Funding

- LBNE Approved by DOE for ~ $800M
- Enough for 10kton Lar above ground!
- Or 5kton LAr Underground (too small)

No proton decay, no supernova, no projectX

Too little, too late

Collaboration looking for foreign participation

India, Italy, Japan… Discussions

Expect to proceed with 35kton LAr underground

To make revolutionary physics discoveries

we must do such experiments

The Results Last Forever

Goals

Primary: CP violation in neutrino oscillations

LBNE: 1300km, WBB, 1-2MW, 34kton LAr, 10yrs

Proton Decay has Similar Detector Requirements (Fortuitous)

Also: Atm & supernova ν, neutron-antineutron osc.,…

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

Precision Δm_{32}^2, Δm_{21}^2, θ_{23}, θ_{12}, θ_{13} (goal? ±few%!)

"New Physics" - Sterile ν, ***Very Weak*** New Interactions…

Neutrino-antineutrino differences?

Anticipate (Hope For) Surprises