4/22/03
W. Marciano

Very Long Baseline Neutrino Oscillations
(CP Violation & Much More)

eg BNL - Homestake 2540km
or BNL - WIPP 2900km
BNL - Henderson, Colorado

BNL Study Commissoned by Tom Kirk → White Papers
Led by M. Diwan, W. Marciano & W. Weng +Many Participants

Outcome

Conventional Horn Focused ν_μ ($\bar{\nu}_\mu$) Beam (Wide Band)

+

AGS Upgrade 0.14MW → 1MW

+

500 kton Water Cerenkov Detector (2,000 ~ 3,000 km)

↓

Precision Measurements: $\sin^2 2\theta_{23}$, $\sin^2 2\theta_{12}$, Δm^2_{32}, Δm^2_{21}
(very powerful)
sign of $m_3^2 - m_2^2$ Hierarchy (Matter effect)

Measure: $\sin^2 2\theta_{13}$ or bound → 0.003!

Determine: CP Violating Phase δ

$J_{CP} = \sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\cos\theta_{12}\cos\theta_{23}\cos^2\theta_{13}\sin\delta$ to $\approx \pm 25\%$!

Also probe: Sterile Neutrino Mixing
Effects of Extra Dimensions
New Interactions with Matter
} Deviations From 3 Gen. Expectations

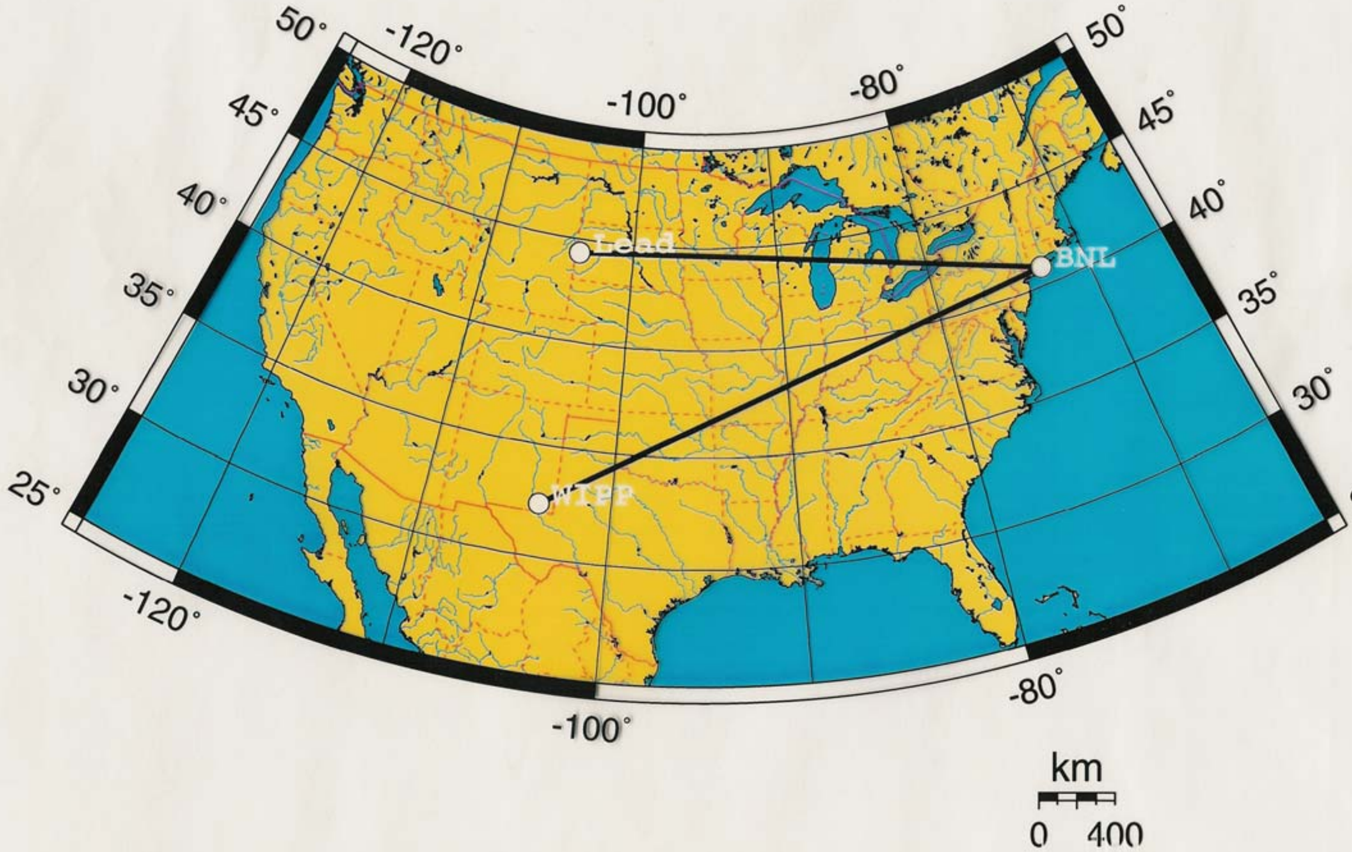
A Bold & Ambitious Neutrino Program for 21st Century
determines Lepton Mixing $\simeq$ Quark Mixing

Large Water Cerenkov Detector (500 kton)
$\sim$ 20 × Super K (eg UNO)

Proton Decay $\tau(p \to e^+\pi^0) \sim 10^{36}$ yr
Supernova Neutrino Studies (>100,000 events!)
Precision Atmospheric Neutrinos (multiple peaks)
Solar Neutrinos
n-$\bar{n}$ osc., magnetic monopoles ... Neutrino Sources etc.

A complete physics facility with potential for
Revolutionary Discoveries & Solid Measurements

Anchor for National Underground Lab!



50°
-120°
-100°
-80°
50°
45°
45°
40°
40°
35°
35°
30°
30°
25°
25°
-120°
-100°
-80°
Lead
BNL
WIPP
km
0 400

Current Status of Neutrino Mixing

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\quad 0 \le \delta < 2\pi$

Atmospheric $\nu_\mu \to \nu_\mu$ + K2K $\qquad \Delta m^2_{32} = m_3^2 - m_2^2 = \pm 2.5^{+1.5}_{-1.2} \times 10^{-3}\,\text{eV}^2$

(Rumored Lower Value!)

$\sin^2 2\theta_{23} \simeq 0.85 - 1.0$ (Maximal) $45°$

Solar $\nu_e \to \nu_e, \nu_x$ $\qquad \Delta m^2_{21} = m_2^2 - m_1^2 = 7.3 \pm 2 \times 10^{-5}\,\text{eV}^2$ LMA I

Kamland $\bar\nu_e \to \bar\nu_e$ $\qquad = 14 \pm 3 \times 10^{-5}\,\text{eV}^2$ LMA II

$\sin^2 2\theta_{12} \simeq 0.86 \pm 0.10 \qquad \theta_{12} \simeq 36°$

Left to determine θ_{13} + δ $\qquad \sin^2 2\theta_{13} \lesssim 0.2$ (Reactors)

$0 \le \delta < 2\pi$

$J_{CP}^{\text{Leptons}} \simeq 0.23 \sin\theta_{13} \sin\delta$ Potentially Enormous $\sim 10^{-2}$ Holy Grail

$J_{CP}^{\text{Quarks}} \simeq 3 \pm 1 \times 10^{-5}$ tiny

Potential Competition for CP Violation

JPARC (Phase II 2015+) → Hyper K (at 295 km)

4MW! 1000 kton (H_2O)!

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \sim \frac{\sin\delta}{\sin\theta_{13}} \frac{\Delta m_{21}^2 L}{E_\nu}$$

Potentially Large

Proposal: Off-Axis ν_μ + $\bar{\nu}_\mu$ beams $E_\nu \simeq 0.6$ GeV

8yr { 2×10^7 sec: $\nu_\mu \to \nu_e n \to e^- p$; 6×10^7 sec: $\bar{\nu}_\mu \to \bar{\nu}_e p \to e^+ n$ } Quasi-Elastic

Very Challenging

Detector: Cost ~ 10^9, Excavation ~ 10 yr!

Machine: 4MW upgrade very expensive + difficult

Target-Horn: Liquid Target, Heating, Robotics ...

Physics - Not Robust (What if $\Delta m_{32}^2 < 2\times10^{-3}\,\mathrm{eV}^2$)

Untangle $\not{CP}$, θ_{13}, matter effects?

Weakness: 295 km Too Short!

BNL - Homestake 2540 km (1 MW, 500 kton) much more modest

On-Axis (0°) Wide Band Beam $0.5\,GeV \le E_\nu < 5\,GeV$

2-2.5 × More Flux

Quasi-Elastic $\nu n \to \ell p$ 2 × cross-section $E_\nu \gtrsim 1\,GeV$

3 × for $\bar{\nu} p \to \bar{\ell} n$

Run ν_μ alone for 5×10^7 sec (or 2yr ν_μ + 3yr $\bar{\nu}_\mu$)

Measure $\sin\delta$ + $\cos\delta$ (+ all other parameters)

More Robust - Gets better if Δm^2_{32} smaller!

Easier, Much Cheaper, Faster, Better!

Figure of Merit $\sim \left(\frac{\Delta m^2_{21}}{\Delta m^2_{32}}\right)^2 \sin^2 2\theta_{12}$ × Detector Size × Power × Time

Has been increasing! / Becoming Easier! } Factor of 3 since study start!

Basic Features: 1) Measure $\nu_\mu \to \nu_\mu$ disappearance

3 peaks

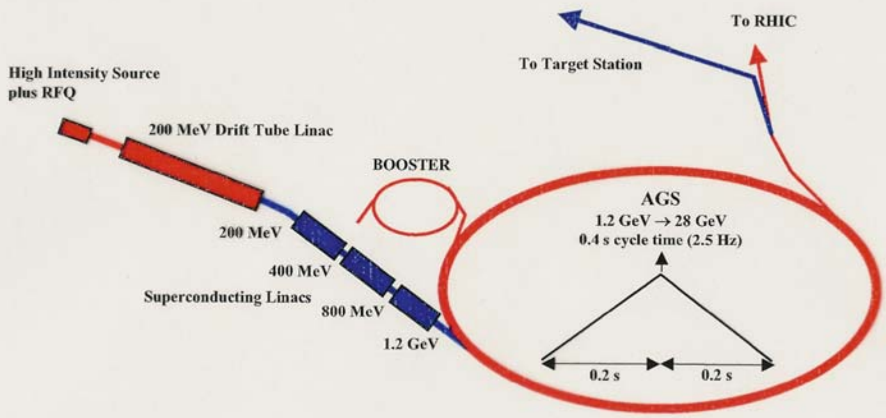
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) + \ldots$$

Min. * $L_{osc} \simeq (2n+1) \times 500\,km \times E_\nu(GeV)$ $n = 0, 1, 2$

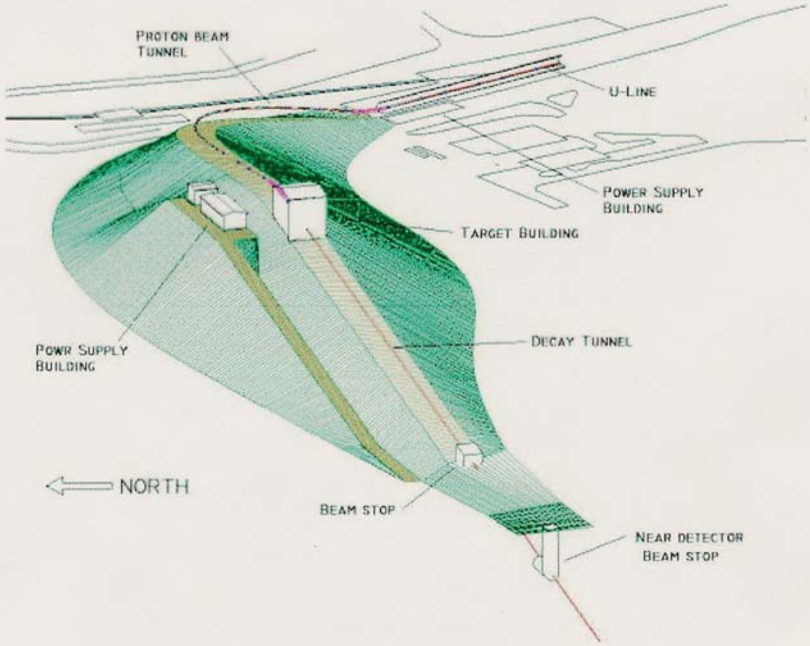
at 2500 km → peaks at ~ 2.5, 1.25, 0.83 GeV ...

The Accelerator

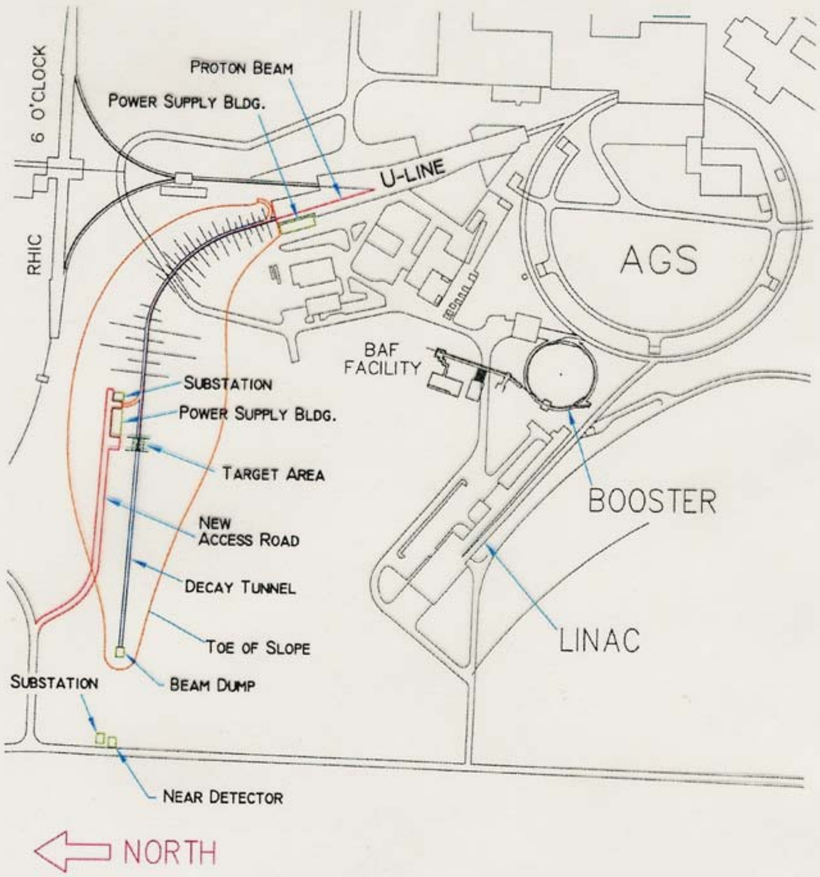
- Conceptually simple upgrade. No magic. Cost $\sim \$100M$.
- Run 28 GeV AGS at 2.5 Hz to get 1 MW.
- Need faster proton source: Super Conducting LINAC at 1.2 GeV
- Current: $7 \times 10^{13} ppp$ at 0.5 Hz => <u>LINAC: $10^{14} ppp$ at 2.5 Hz.</u>



Beam 3d


PROTON BEAM
TUNNEL
U-LINE
POWER SUPPLY
BUILDING
TARGET BUILDING
POWR SUPPLY
BUILDING
DECAY TUNNEL
NORTH
BEAM STOP
NEAR DETECTOR
BEAM STOP

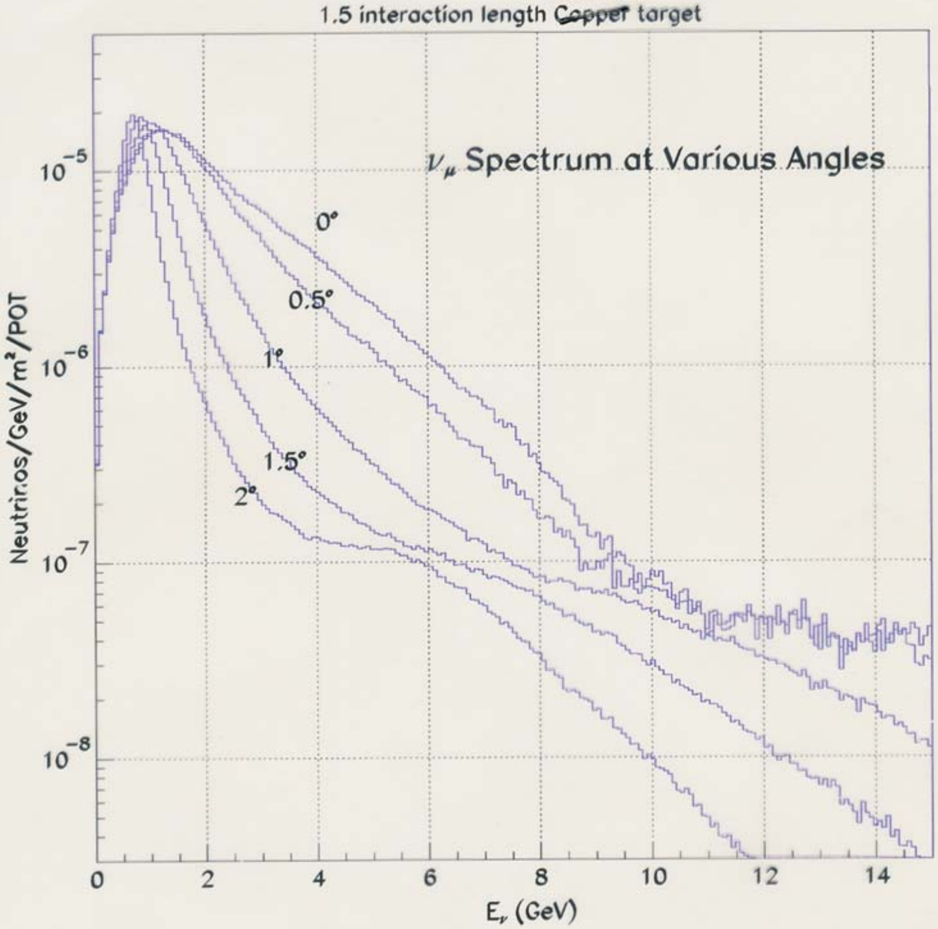
Beam Layout


6 O'CLOCK
RHIC
PROTON BEAM
POWER SUPPLY BLDG.
U-LINE
AGS
BAF
FACILITY
SUBSTATION
POWER SUPPLY BLDG.
TARGET AREA
NEW
ACCESS ROAD
DECAY TUNNEL
TOE OF SLOPE
BEAM DUMP
SUBSTATION
NEAR DETECTOR
BOOSTER
LINAC
NORTH

2002/07/22 13.30

Carbon

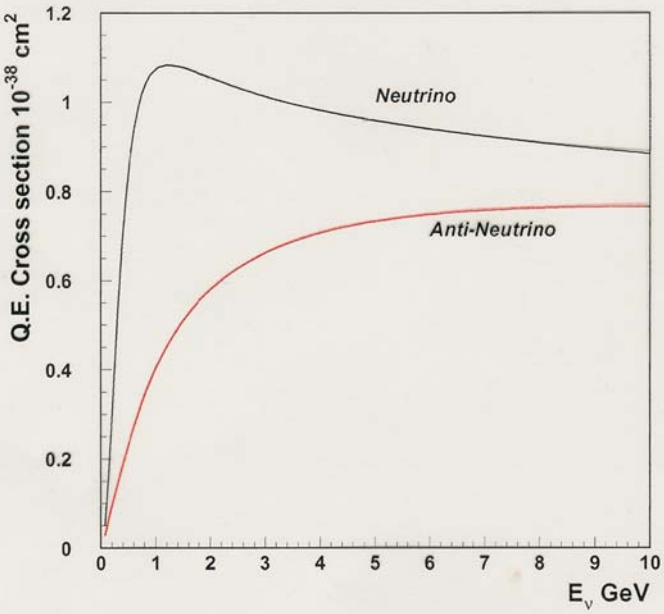
1.5 interaction length ~~Copper~~ target



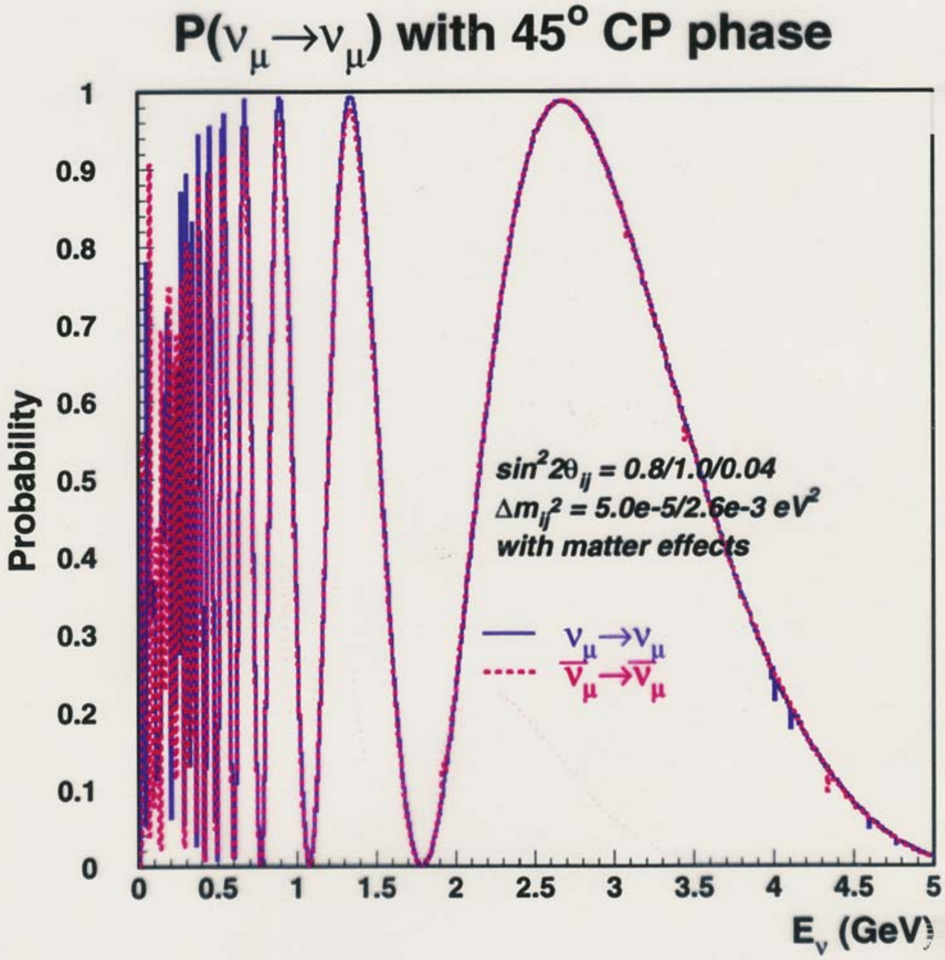
L = 1 km   T = 200 m

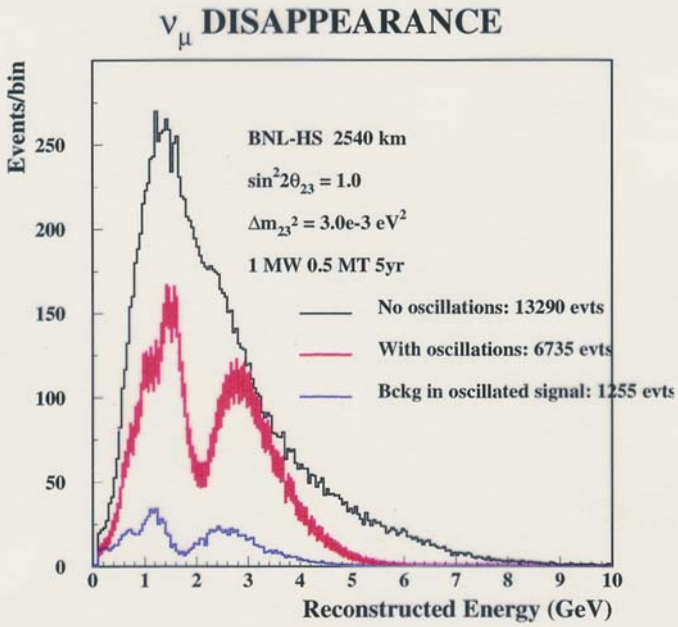
Quasielastic cross section

$\nu_\mu n \to \mu^- p$, $\bar{\nu}_\mu p \to \mu^+ n$ $\to E_\nu$



An experiment searching for signal at high energies may not need much more anti-neutrino running than neutrino running.


P(ν_μ→ν_μ) with 45° CP phase
Probability
E_ν (GeV)
sin²2θ_ij = 0.8/1.0/0.04
Δm_ij² = 5.0e-5/2.6e-3 eV²
with matter effects
ν_μ→ν_μ
ν̄_μ→ν̄_μ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

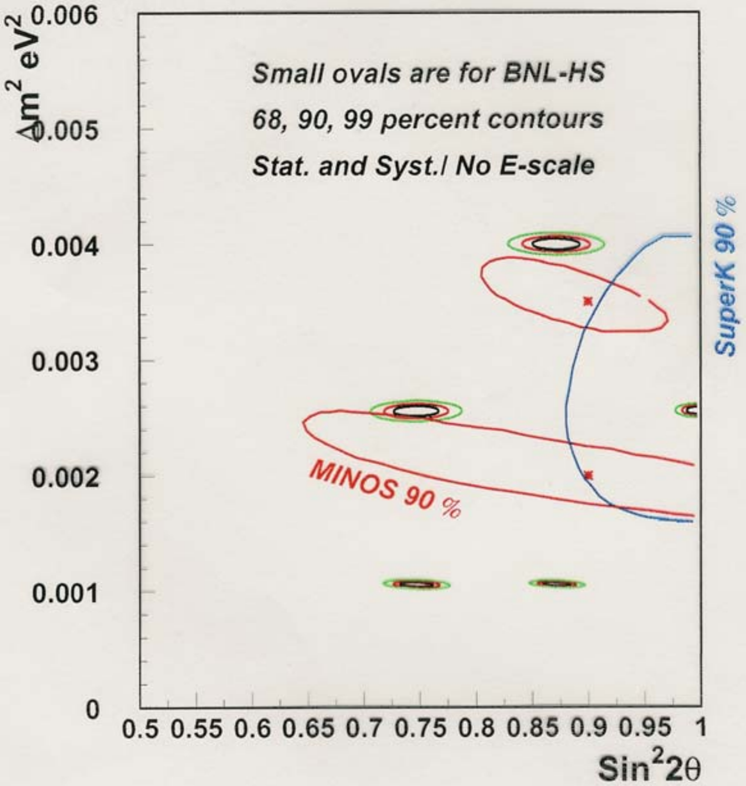


Node pattern provides high Δm^2_{23} resolution.
Energy calibration is very important.

Flux normalization not important for
measurement of $\sin^2 2\theta_{23}$

Background shape can be measured independently
Minimum systematics in ν_μ and $\bar{\nu}_\mu$ comparison

Test points for ν_μ disapp



Measure Δm^2_{32} + $\sin^2 2\theta_{23}$ to $\pm 1\%$ (or better)!

No. Osc. $\nu_\mu n \to \mu^- p$ 15,000 events

$\sin^2 2\theta_{23} \simeq 1$ Osc. $\longrightarrow$ 7,500 events

} 1 event/hr — $4\times$ $\nu_\mu N \to \mu^- X$

(Sterile ν mixing, Extra Dim, Exotic Int...)

2) $\nu_\mu \to \nu_e$ Appearance (Rich Structure) (3-4 peaks)

$$P(\nu_\mu \to \nu_e) = 0.5 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$$

$$+ 0.93 \sin\theta_{13} \sin\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)\left\{\sin\frac{\Delta m^2_{31} L}{4E_\nu} \sin\delta + \cos\frac{\Delta m^2_{31} L}{4E_\nu} \cos\delta\right\} \frac{\Delta m^2_{21} L}{2E_\nu}$$

$$+ 0.36 \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 + \text{matter effects} + \text{small terms}$$

Term 2 : $\cos\left(\frac{\Delta m^2_{31} L}{4E_\nu} - \delta\right)$

To explore $0 \leq \delta < 2\pi \rightarrow \frac{\Delta m^2_{31} L}{4E_\nu} \simeq \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}$

($L = 2540$ km)

3 peaks

$E_\nu \simeq 5, 5/3, 1$ GeV

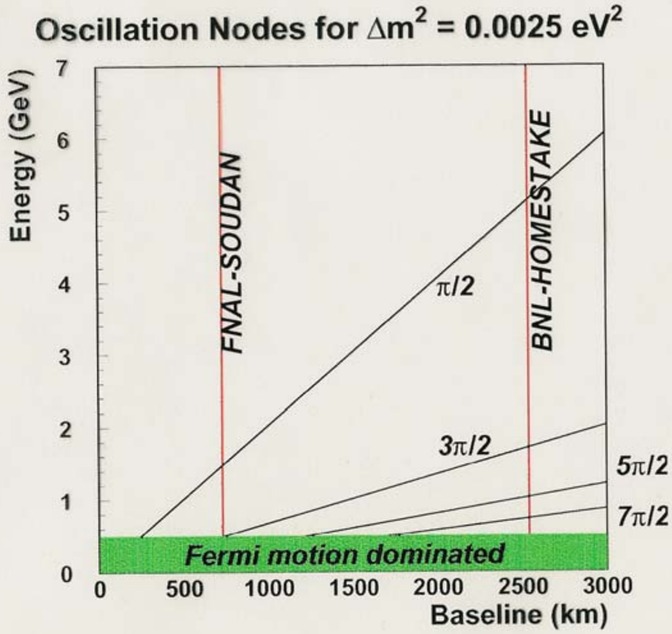
Broad Band (On-Axis) Beam $0.5\text{ GeV} < E_\nu < 5\text{ GeV}$

i) $3\text{ GeV} < E_\nu < 5\text{ GeV}$ (very sensitive to matter)

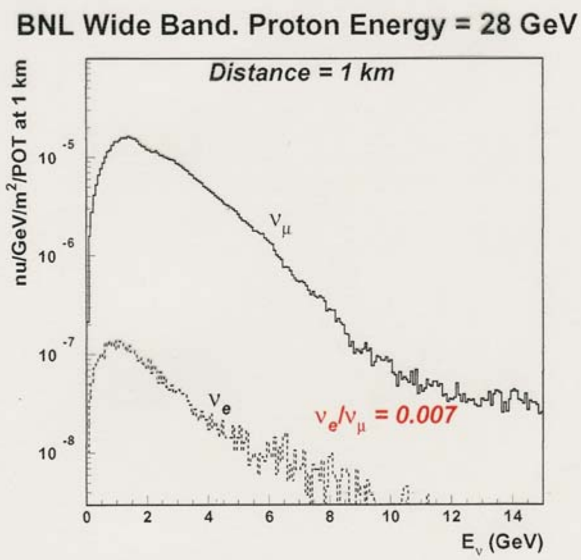
sgn Δm^2_{32} easy

measure θ_{13} $0.01 \leq \sin^2 2\theta_{13} \leq 0.2$ Factor 20!

Bound $\rightarrow 0.003$

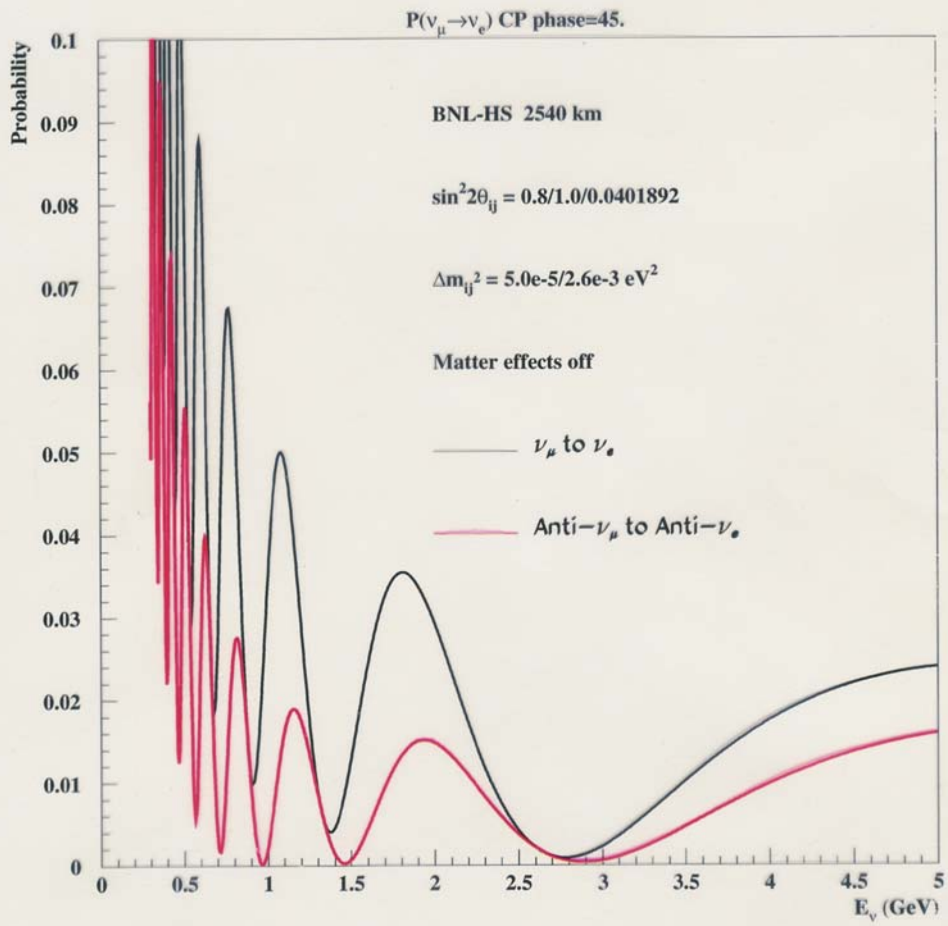


- Large effects: Multiple oscillation nodes.
- Low cross section at low energies
- Fermi motion limits resolution at low energies: wide band beam $(0.5 \rightarrow 8$ GeV$)$.
- $\Delta m^2 \approx 0.0025 eV^2$: Baseline > 2000 km.

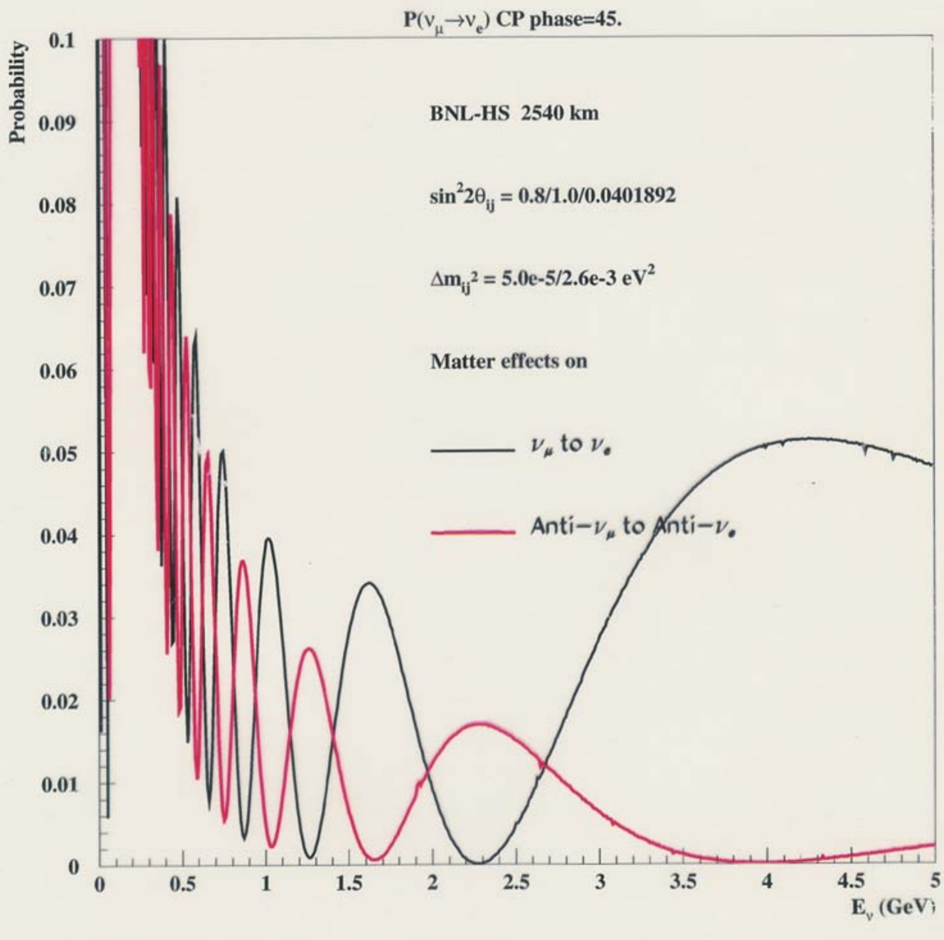


- New design spans 0.5-6 GeV
- Low ν_e background 0.7%
  0.0073 ± 0.0014 (E734 1986).
- Low background from high energies (NC and ν_τ for ν_e)
- 200 m decay tunnel
- Graphite target embedded in horn
- Target cooling achievable for 1 MW

2002/07/19 18.08



2002/07/22 11.00



1GeV < E_ν < 3GeV Measure δ ($\sin\delta$, $\cos\delta$)

If inverted hierarchy 2yr ν_μ + 3yr $\bar{\nu}_\mu$

0.5GeV < E_ν < 1GeV Measure $\Delta m^2_{21} \sin 2\theta_{12}$ to ±5% !

special feature of long dist (unique)

Statistical Figure of Merit (for CP, δ)

Insensitive to L & $\sin^2 2\theta_{13}$

Asym. grows ~ L $N_\nu \sim 1/L^2$

F.O.M. ~ $A^2_{CP} N_\nu$

with about 300 - 400 $\nu_e n \to e^- p$ quasi-elastic events

measure

sgn Δm^2_{32}

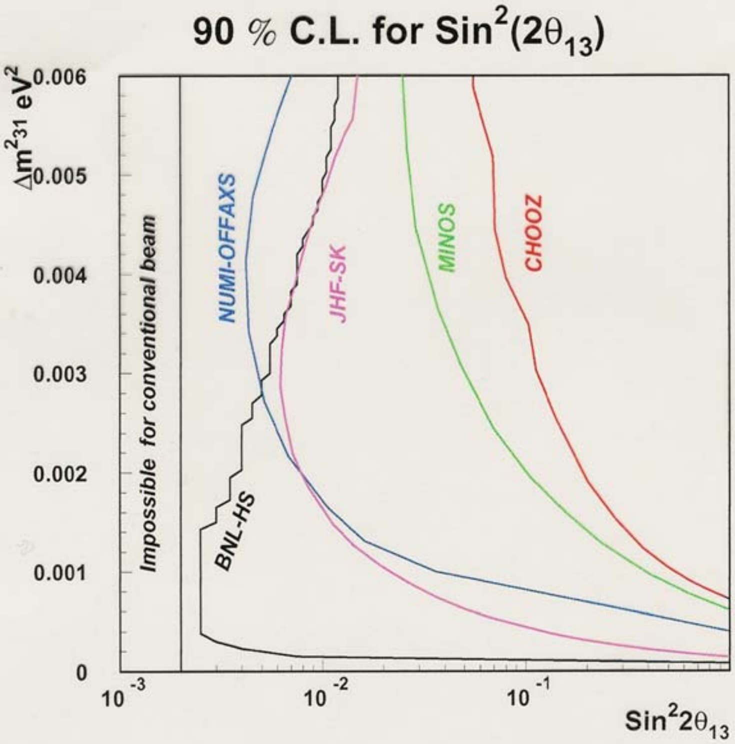
$\Delta m^2_{21} \sin 2\theta_{12}$ to ± 5%

$0.01 < \sin^2 2\theta_{13} < 0.2 \to$ $\sin^2 2\theta_{13}$ to ± 10%

δ to ± 15-20°

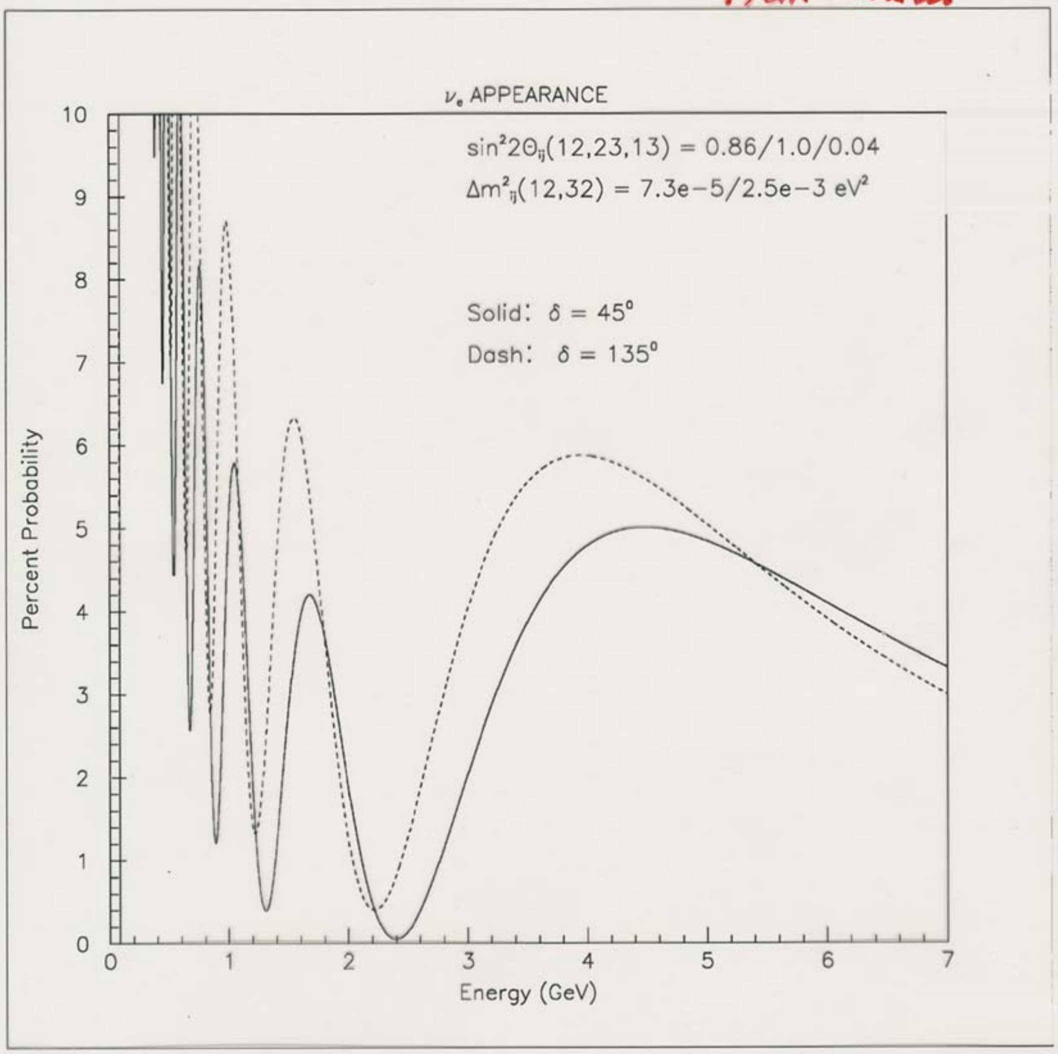
} Very Powerful (Robust)

Measurement of $\sin^2 2\theta_{13}$ 90% C.L.



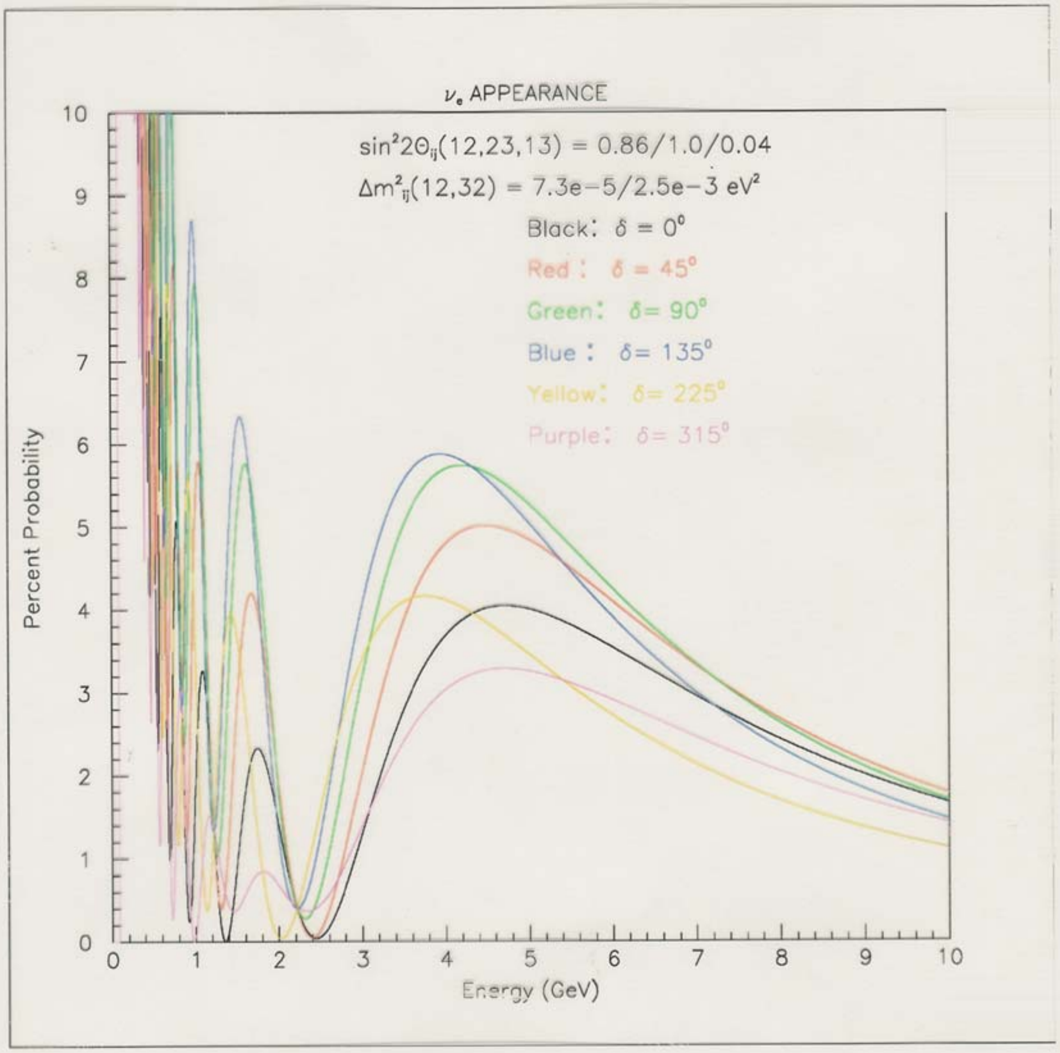
Distinctive signature with multiple oscillations above $0.001\ eV^2$

From Z. Parsa



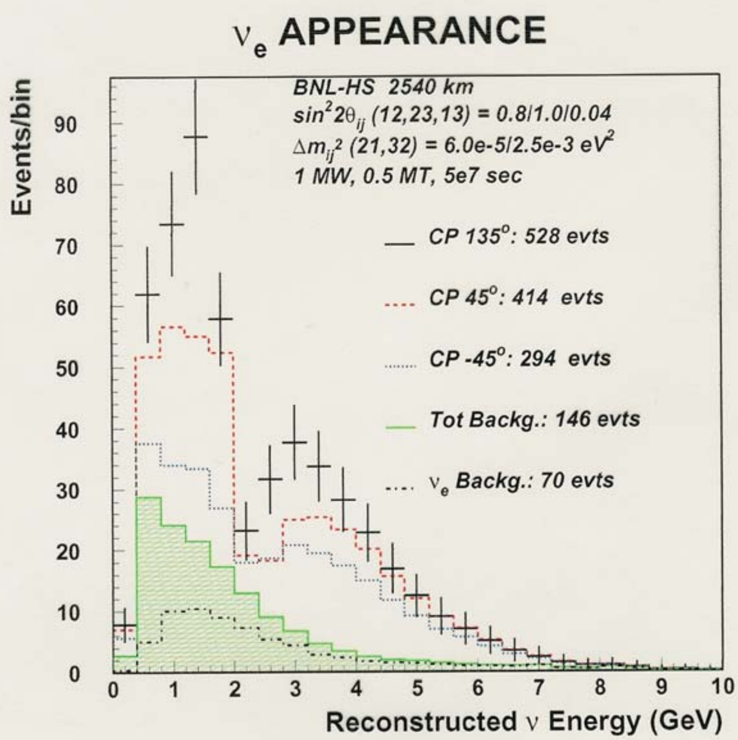
ν_e APPEARANCE
sin²2Θ_ij(12,23,13) = 0.86/1.0/0.04
Δm²_ij(12,32) = 7.3e−5/2.5e−3 eV²
Solid: δ = 45°
Dash: δ = 135°
Percent Probability
Energy (GeV)
0
1
2
3
4
5
6
7
8
9
10

Zohreh Parsa
BNL – Feb 03



[E 0 to 10 GeV]

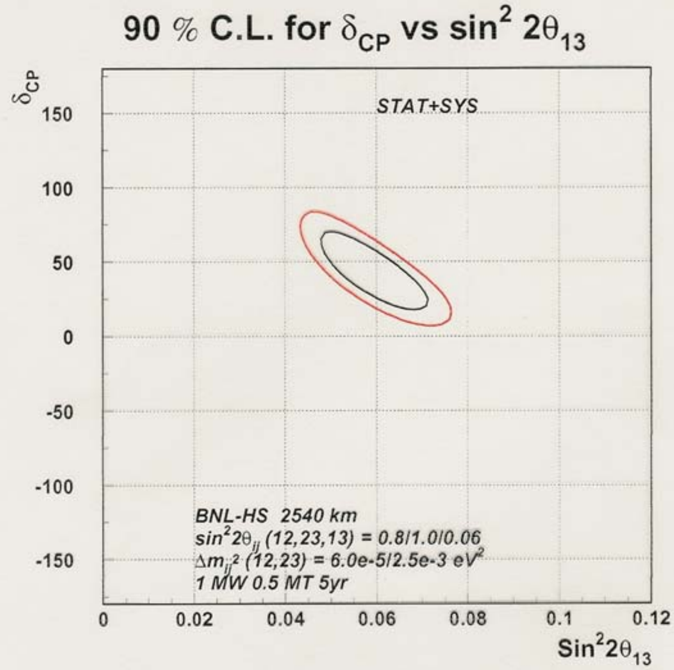
δ_{CP} Measurement. BNL-to-HS, 2540 km, 1 MW, 500kT, 5×10^7 sec



CP parameter can be determined from only neutrino data.

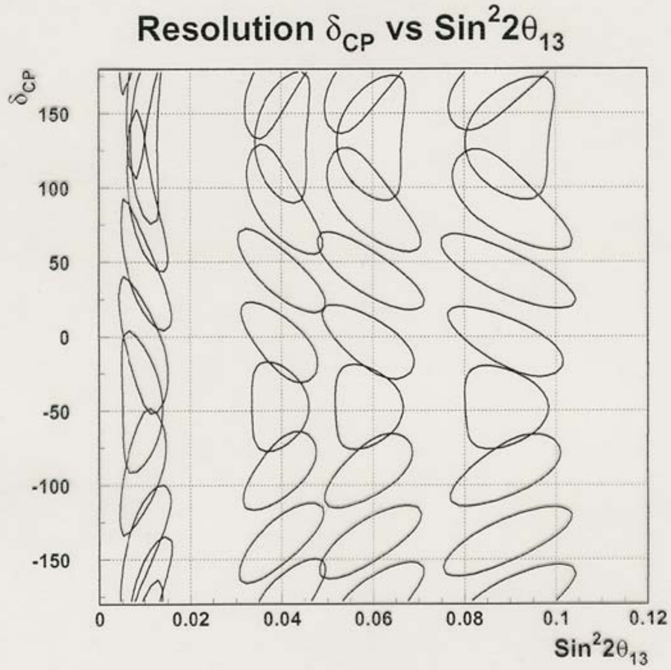
Good background subtraction can help.

Measurement of $\delta_{CP} = 45^o$
No anti-neutrino running.



Systematic error of 10% on backg.
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$
$\sin^2 2\theta_{12} = 0.8$, $\sin^2 2\theta_{23} = 1.0$
$\delta_{CP} = 45^o$, $\sin^2 2\theta_{13} = 0.06$
68%, and 90% C.L.

Error on δ_{CP} vs $\sin^2 2\theta_{13}$

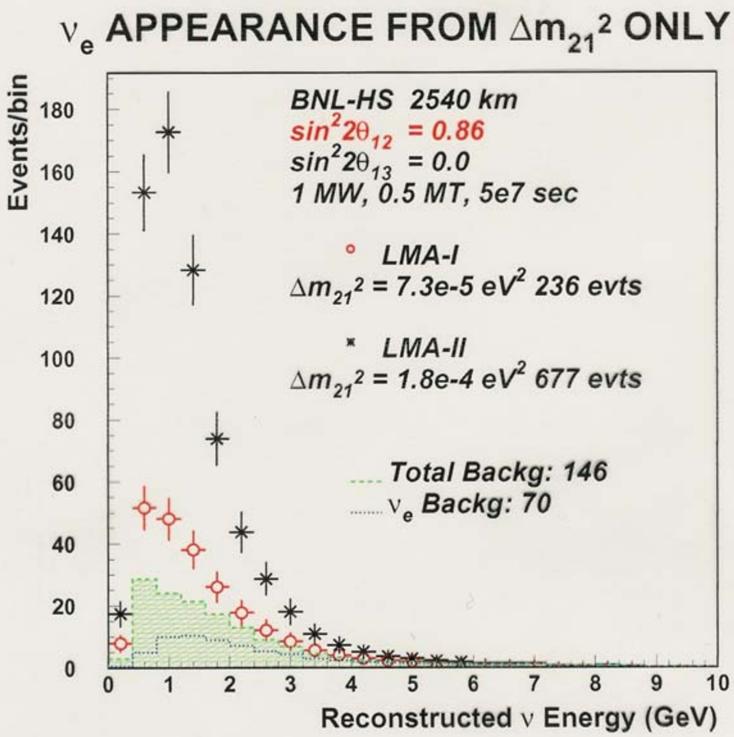


Assume all other parameters are well-known.

$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

$\sin^2 2\theta_{12} = 0.8$, $\sin^2 2\theta_{23} = 1.0$

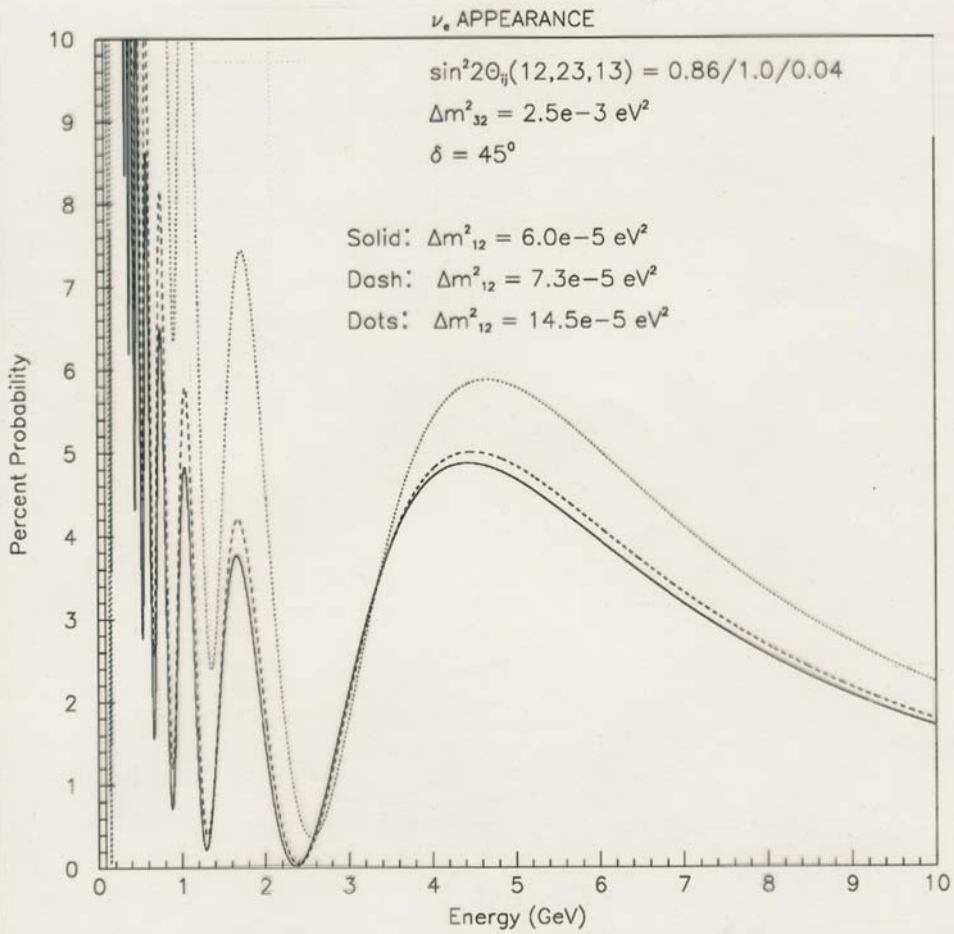
Measurement of Δm^2_{12}



$\theta_{13} = 0,\ \Delta m^2_{12} = 7.3 \times 10^{-5} eV^2$

Excess of ~ 90 events. Must know background

Zohreh Parsa
Feb 28, 2003



Outlook

We have shown: 1MW AGS + 500 kton H_2O Detector

$L \simeq$ 2000-3000 km

(Homestake, WIPP, Henderson)

$\nu_\mu \to \nu_\mu, \nu_e \to$ Measure: $\Delta m^2_{ij}, \theta_{ij}, \delta \ldots$ (May do $\bar{\nu}_\mu$ as well)

Detector (Work with UNO Collaboration + Others)
Cost \$300-500 Million
R+D to Reduce
Note: 50yr Physics Facility ($\tau_p, \nu \ldots$)
Could Start Soon!

AGS Upgrade (see study) Straightforward 0.14MW→1MW
1MW→2MW

Neutrino Beam Hill better than Hole (Cheaper, Cleaner)

Study Continues (Backgrounds etc.)

Best Idea for ν Future (No real competition)
An Idea Whose Time Has Come (Straightforward)

Should be supported + pursued!

Accelerator Based Experiments in the USA

FNAL
- CDF & DØ
- MiniBOONE
- MINOS
- BTeV
- CKM
- Off-Axis ν

(BTeV, CKM, Off-Axis ν: Future 2008 →)

SLAC
- Ba Bar
- Pol. e^-e^-
- Pol. eD
- Super b?

CESR
- CLEO-C

BNL-AGS
- $g_\mu - 2$
- $K^+ \to \pi^+ \nu \bar{\nu}$
- MECO ($\mu^- N \to e^- N$)
- KOPIO ($K_L \to \pi^0 \nu \bar{\nu}$)
- VLB ν osc.
- EDM

(MECO, KOPIO, VLB ν osc., EDM: Future 2008 →)

Future BNL Program is an Essential Component!