W. Marciano
3/7/03

Long Baseline Neutrino Oscillations

Matter Effects, $\theta_{23}, \theta_{12}, \theta_{13}, \delta, \Delta m^2_{32}, \Delta m^2_{21}$

(Precision Measurements in One Experiment!) ← Provacative

Study: $\nu_\mu \to \nu_\mu + \nu_\mu \to \nu_e$ (perhaps $\bar{\nu}_\mu \to \bar{\nu}_\mu + \bar{\nu}_\mu \to \bar{\nu}_e$)

Atm. Parameters: $\Delta m^2_{32} = \pm 2.5^{+1.5}_{-1.2} \times 10^{-3}\,eV^2$ → $\pm 1\%$ stat. sgn

$\sin^2 2\theta_{23} \simeq 0.85 - 1.0$ → $\pm 1\%$

Solar Parameters: $\Delta m^2_{21} = 7.3 \pm 2 \times 10^{-5}\,eV^2$
(Kamland) $\sin^2 2\theta_{12} = 0.86 \pm 0.14$ } → $\pm 5\text{-}10\%$ $\nu_\mu \to \nu_e$

θ_{13}, δ → $0.01 \le \sin^2 2\theta_{13} \le 0.20$ measurement

$0 \le \delta < 2\pi$ $\sin\delta + \cos\delta$ measurements $\pm 20°$

$J_{CP} = \sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\cos\theta_{12}\cos\theta_{23}\cos^2\theta_{13}\sin\delta$ (The Prize!)

$\simeq 0.23 \sin\theta_{13}\sin\delta$ (Potentially Large) → $\pm 25\%$

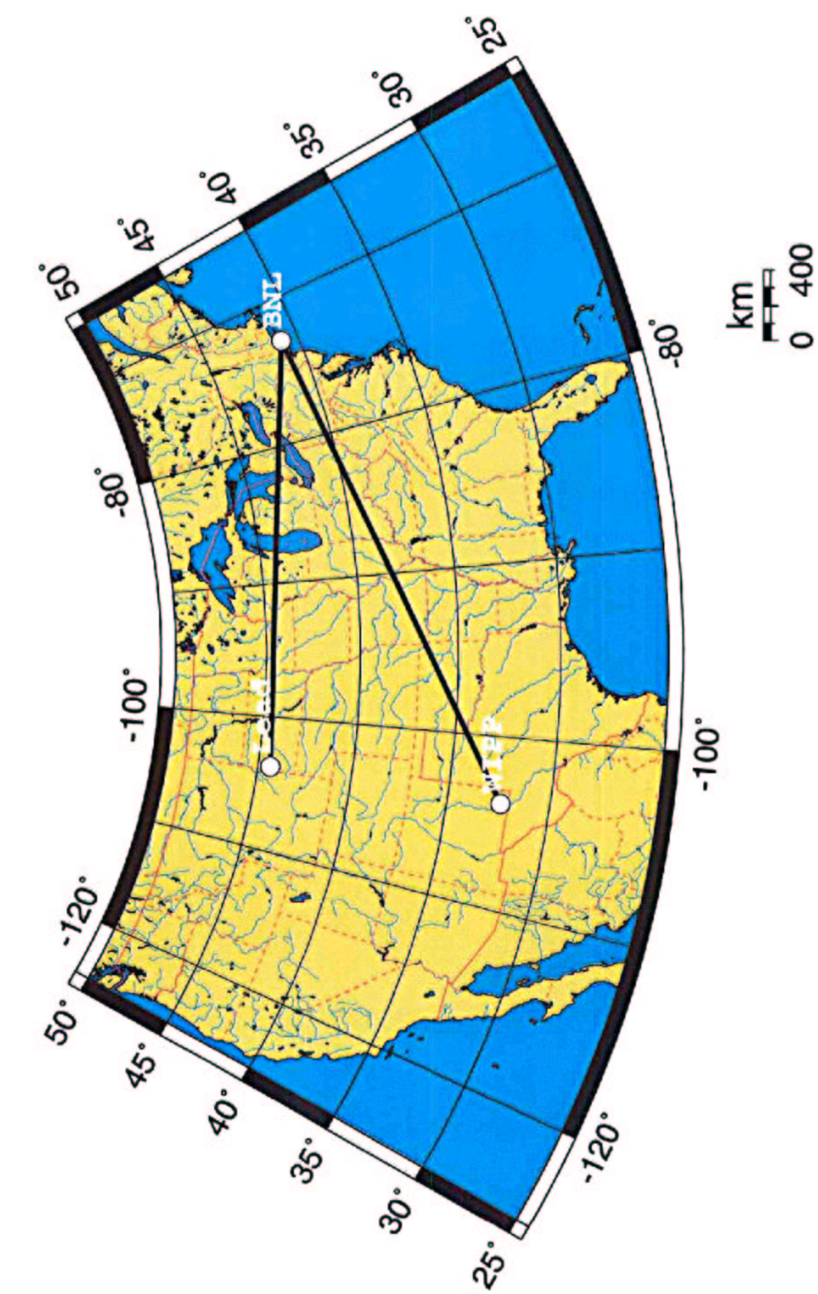
$J_{CP}^{Quarks} \simeq 3 \pm 1 \times 10^{-5}$ (Tiny) → (Future $\pm 7\%$?)

CP Violation in lepton sector - Potentially Large!

We could know lepton mixing as well as quark mixing!

From 1 Experiment!

(Also, search for "New Physics" - eg Sterile Neutrinos, Extra Dim.)



-2-

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

Start 2001-2002 $\underbrace{\left(\frac{5\times10^{-5}eV^2}{3\times10^{-3}eV^2}\right)^2}_{2.2\times10^{-4}} 0.8 \times 500$kton $\times$ 1MW $\times 5\times10^7$sec

Now 2003 $\underbrace{\left(\frac{7.3\times10^{-5}eV^2}{2.5\times10^{-3}eV^2}\right)^2 0.86}_{7.3\times10^{-4}}$

Factor 3.3 increase! → More Robust (Easier)

If $\Delta m^2_{21} \simeq 14\times10^{-5}eV^2$ (LMA II) → 4 times easier! (Hope) Descope?

Outline of Talk

1.) Neutrino Superbeams (BNL seminar 5/3/2000)
Intense Conventional Horn Beam $\pi^+ \to \mu^+ \nu_\mu$

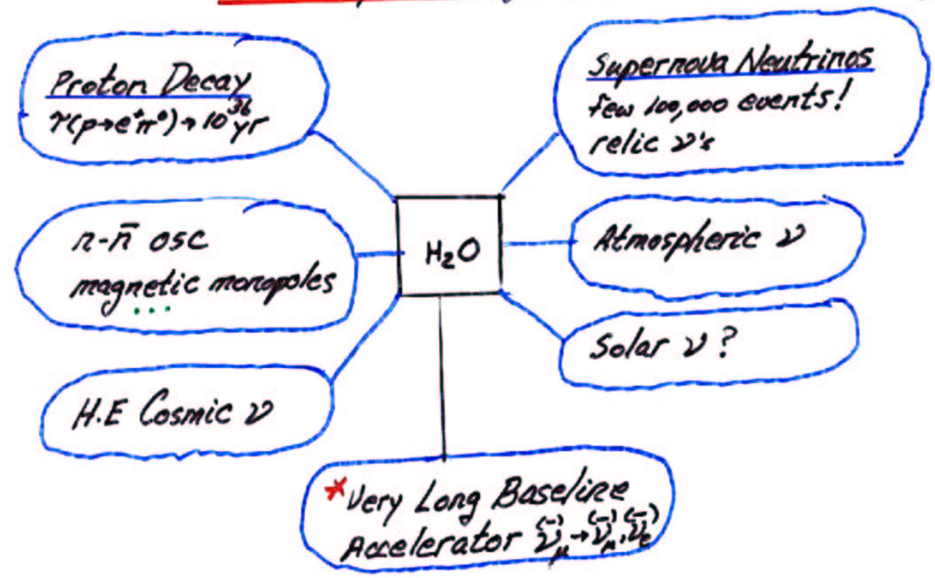
2.) CP Violation (BNL preprint 2001)
Measurement of $\sin\delta$: insensitive to θ_{13} value (Approx.)
for $0.01 \lesssim \sin^2 2\theta_{13} \lesssim 0.2$
insensitive to peak used
$\frac{\Delta m^2_{31} L}{4E_\nu} = (2n+1)\frac{\pi}{2}$, $n = 0,1,2..$

Extra Long Baselines eg BNL-Homestake 2540km
($L_{peak} \sim (2n+1)\cdot 500km \cdot E_\nu$(GeV)) BNL-WIPP 2900 km.

Next Generation Underground Water Cerenkov Detector(s)

20-40 × SuperK → 500-1000 kton!

Full Physics Program (Potential Revolutions)



Anchor project for National Underground Lab

500kton in USA 500kton in Japan

-3-

3.) BNL - Homestake Study hep-ex/0211001 White Paper...

Powerful Physics Case (All ν-mixing, Δm^2_{ij}...)

500kton Detector → Proton Decay (Explore $m_X \simeq 10^{16}$ GeV)

(Program) Supernova $p \to e^+\pi^0$

Atm. Neutrinos

⋮

* Long Baseline Osc

1.) Neutrino Superbeams - Intense Conventional Horn Beam

$p \to$ $\boxed{\text{target}}$ $\xrightarrow{\pi^+}$ $\pi \to \mu\nu_\mu$ ⟶ ν_μ beam

zoom

~0.15 ν_μ/proton! very efficient

vs Neutrino Factory $\pi^+ \to \mu^+\nu_\mu$ capture + cool low energy μ^+

accelerate $\mu^+ \to$ 20-50 GeV

μSR μ μ^+ $\nu_e, \bar{\nu}_\mu$ beam ~0.03 ν_e/proton

Advantages: Clean, High Energy, Small Opening Angle

(Is High Energy Useful?) $\cancel{CP}$?

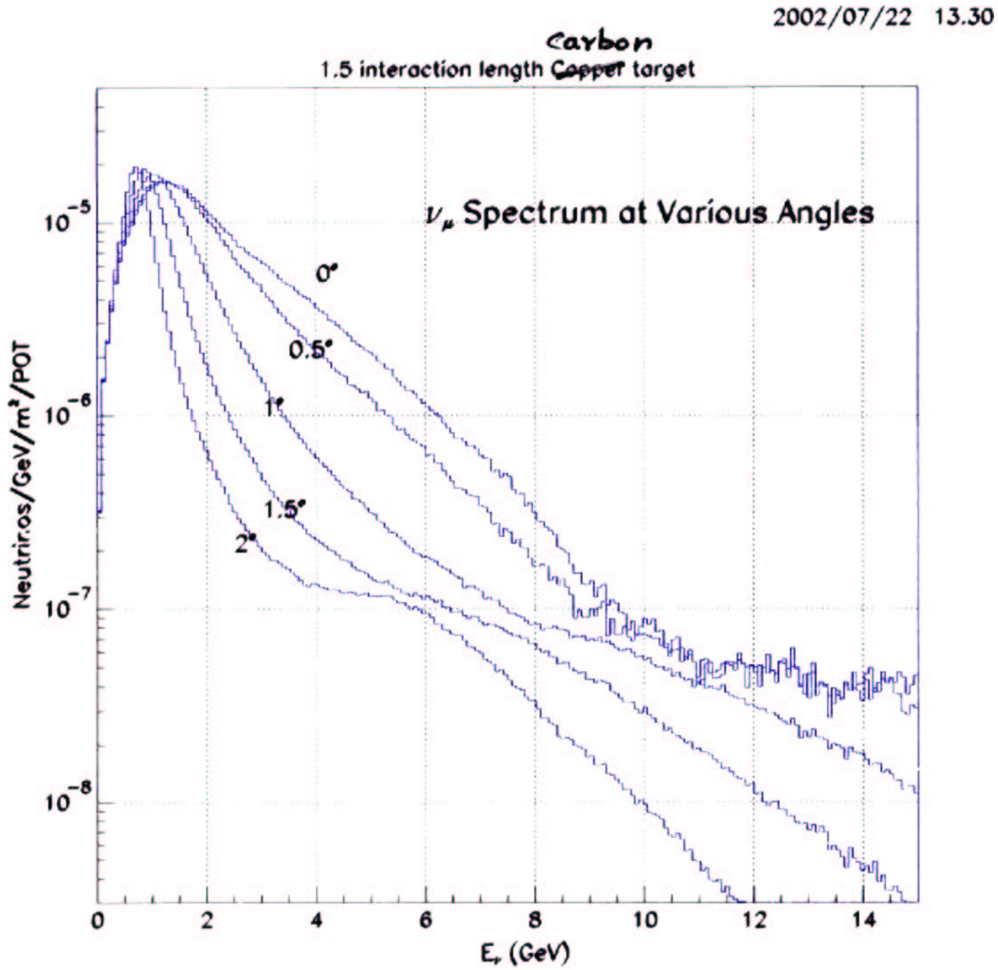
Yes, if $\sin^2 2\theta_{13}$ very small $\lesssim 0.005$

Superbeams (0.7% ν_e contamination)

* Very Good For $0.01 \lesssim \sin^2 2\theta_{13} \lesssim 0.2$

Neutrino Factory Becomes More Important if $\sin^2 2\theta_{13} \lesssim 0.005$

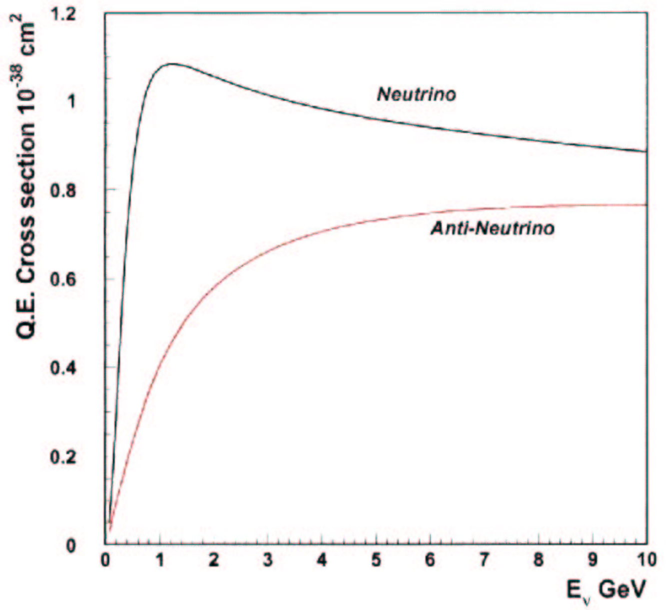
Strategy for $\cancel{CP}$: Relatively short distance, high energy



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.

-4-

Superbeam? eg BNL AGS 24GeV protons, ~4×10^{13} p/sec, 0.14MW
FNAL MI 120GeV protons, ~1.3×10^{13} p/sec, 0.25MW

Upgrades: BNL → 1-2 MW
FNAL → 2 MW } 7-10 times more neutrinos — Superbeams

Japan (JAERI) construction 50GeV protons → 0.7 MW $\xrightarrow{\text{upgrade}}$ 4MW!

JAERI - Super K (22kton) 295 km $\nu_\mu \to \nu_e$ search $\sin^2 2\theta_{13} \to 0.006$!

Stage II SK → Hyper K (1000kton), 4MW source
2×10^7 sec $\nu_\mu \to \nu_e$ 6×10^7 sec $\bar{\nu}_\mu \to \bar{\nu}_e$ } very ambitious!
CP Violation

Very Difficult Effort
1000 kton Construction ~5-10 yr excavation ~ $\$10^9$
4MW → liquid targets
$\bar{\nu}_\mu$ cross-section

Weakness: Distance too short, Off-Axis Beam (Reduced Flux), $E_\nu \simeq 0.6$GeV (lower cross-sect.)

Can One Do Better? → Longer Distance
Better for CP
Other Advantages:
On Axis Flux (x2)
Higher E_ν 0.5GeV - 5GeV
etc.

-5-

2. Physics of $\nu_\mu \to \nu_e$ Osc.

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

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

$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\sin^2 2\theta_{23}}_{\sim 1.0} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) + \dots$$

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

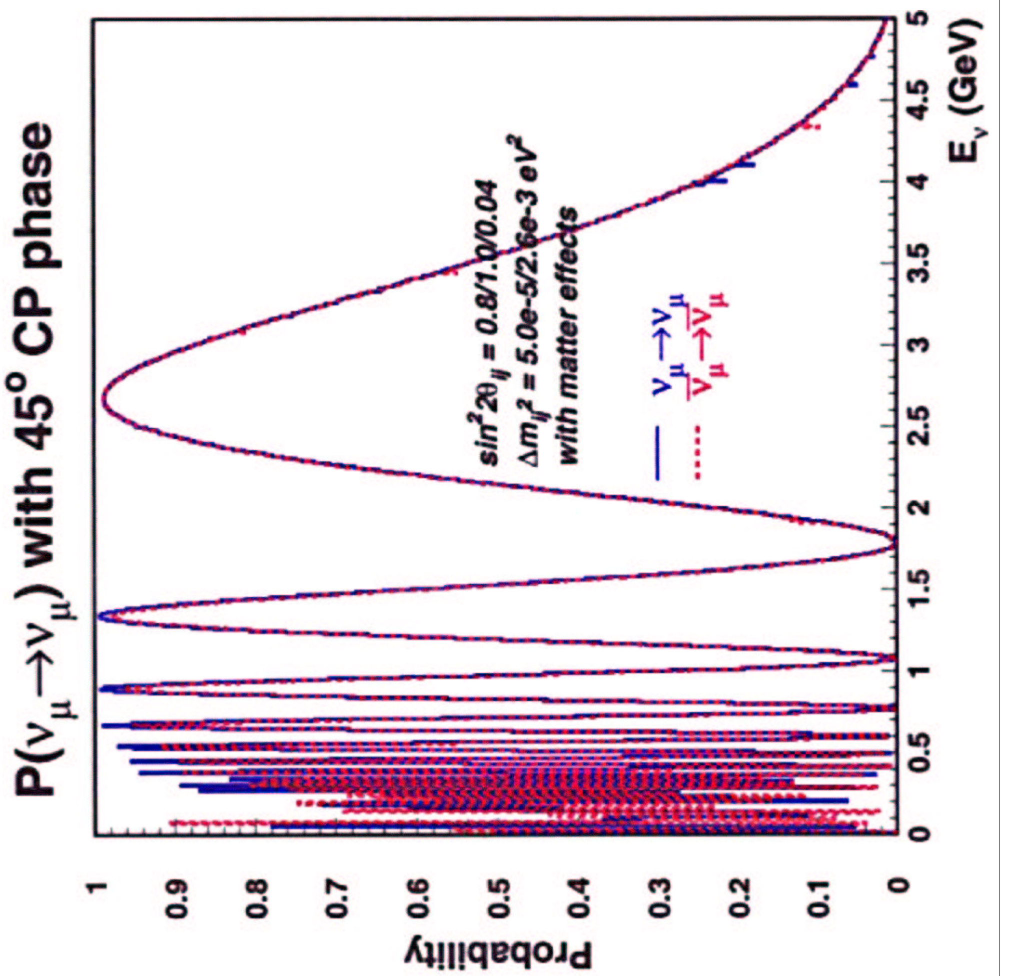
for $\Delta m_{31}^2 = m_3^2 - m_1^2 \simeq 2.5\times10^{-3}\,\text{eV}^2$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)$$
$$+ \frac{1}{2} \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) \sin\left(\frac{\Delta m_{21}^2 L}{2E_\nu}\right) \sin\delta$$
$$+ \frac{1}{2} \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \sin\frac{\Delta m_{31}^2 L}{4E_\nu} \cos\frac{\Delta m_{31}^2 L}{4E_\nu} \sin\frac{\Delta m_{21}^2 L}{2E_\nu} \cos\delta$$
$$+ \sin^2 2\theta_{12} \cos^2\theta_{23} \cos^2\theta_{13} \sin^2\frac{\Delta m_{21}^2 L}{4E_\nu}$$

+ smaller terms + matter effects

Note θ_{13} + $\frac{\Delta m_{21}^2 L}{2E_\nu}$ dependence

$$\sin^2\theta_{13} : \sin\theta_{13}\sin\delta : \sin\theta_{13}\cos\delta : 1$$
$$1 : \frac{\Delta m_{21}^2 L}{4E_\nu} : \frac{\Delta m_{21}^2 L}{4E_\nu} : \left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)^2$$



-6-

If primary $\nu_\mu \to \nu_e$ from $\frac{1}{2}\sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$

then, relative $\sin\delta$ effect at distance L

Flux falloff $1/L^2$

$$\frac{\delta \text{ Signal}}{\sqrt{N_{13}}} \sim \frac{0.45 \sin 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \frac{\Delta m^2_{21} L}{2E_\nu} \sin\delta \frac{1}{L^2}}{0.7 \sin 2\theta_{13} \sin\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \frac{1}{L} + \cdots}$$

Significance $\sim 0.33 \left|\sin \frac{\Delta m^2_{31} L}{4E_\nu}\right| \sin\delta \frac{\Delta m^2_{21}}{E_\nu}$ independent of θ_{13} & L (at peaks) $\frac{\Delta m^2_{31} L}{4E_\nu} \simeq (2n+1)\frac{\pi}{2}$

Same ~ arguement for $\cos\delta$ (except peaks)

So, to first approx. our ability to measure $\sin\delta$ is insensitive to θ_{13} (until $\sin^2 2\theta_{13} \lesssim 0.01$) and what peak we sit at!

Ability to measure $\Delta m^2_{21} \sin 2\theta_{12}$ improves as L increases & θ_{13} decreases!

What about: $A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar\nu_\mu \to \bar\nu_e)}{P(\nu_\mu \to \nu_e) + P(\bar\nu_\mu \to \bar\nu_e)}$ CP Asymmetry

-7-

$$A_{CP} \simeq \frac{1.9 \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) \sin\delta}{\sin 2\theta_{13} + \cdots}$$ grows with L/E, grows as $1/\sin 2\theta_{13}$

Statistics $N_{\nu_e} + N_{\bar\nu_e} \simeq \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \underbrace{\frac{1}{L^2}}_{\text{Flux}}$

Figure of Merit $\equiv \left(\frac{A_{CP}}{\delta A_{CP}}\right)^2 = \frac{A^2_{CP}(N_{\nu_e} + N_{\bar\nu_e})}{1 - A^2_{CP}}$

L. Wolfenstein Thesis

Note, F.O.M. insensitive to θ_{13} & L (sit at peak)

Very large asymmetries at 2nd & 3rd peaks (Smaller Systematic Unc.)

Work at 2nd or 3rd Peak

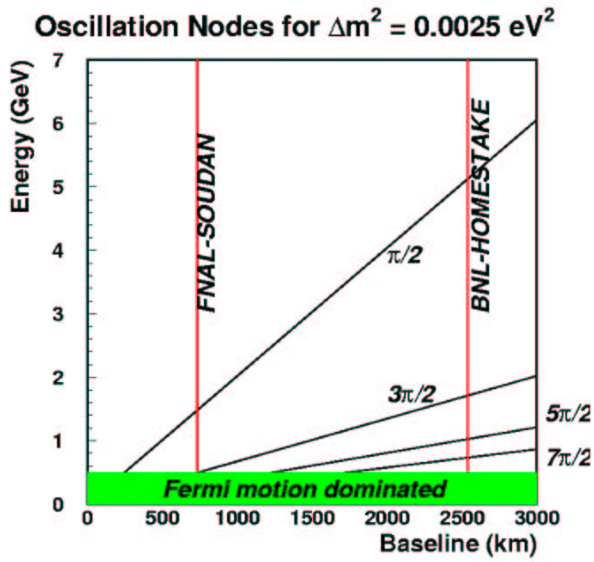
$L_{peak} = (2n+1) \times 500\,\text{km} \times E(\text{GeV})$ Large Matter Effects

For $E_\nu \simeq 1\,\text{GeV} \to L_{peak} \simeq 500\,\text{km}, 1500\,\text{km}, 2500\,\text{km} \cdots$

Work at peak where $A_{CP} \simeq 1$!

3.) BNL - Homestake Study (White Paper)

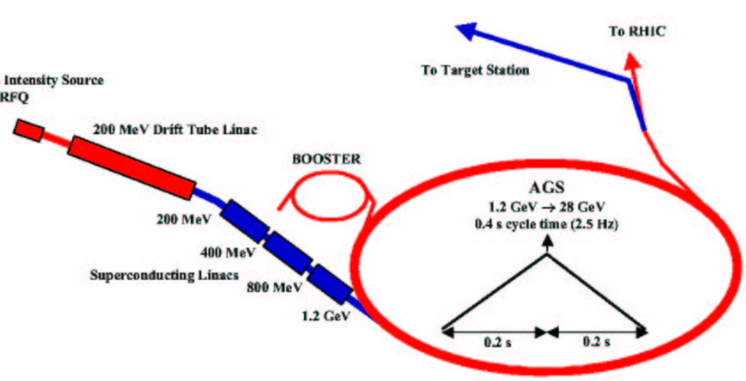
Try to optimize, minimize cost, size, time
Combine with proton decay detector



- 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.

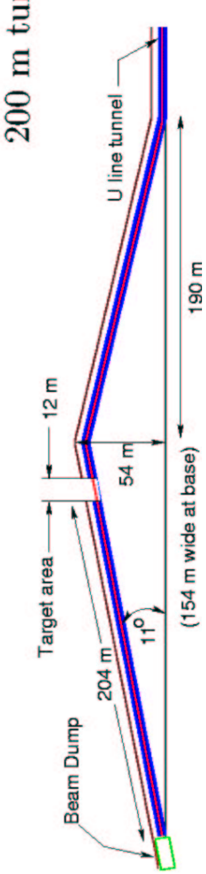
The Accelerator

- 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 => LINAC: $10^{14} ppp$ at 2.5 Hz.



Beam on the Hill

- BNL-Lead 2540km
  BNL-Wipp: 2880km
- Avoids water table.
- Hills are inexpensive: highway ramps.
- Total cost $35 M for 200 m tunnel.



Event Rates with Neutrinos

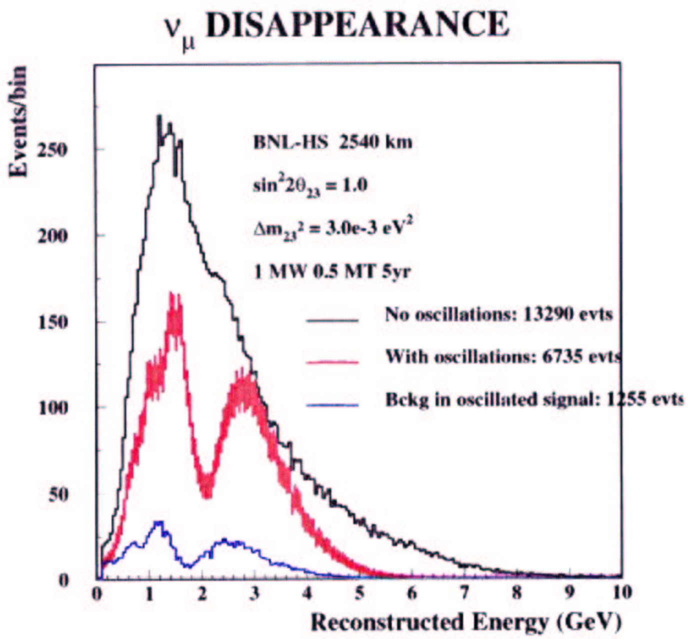
Assume 1 MW, 500 kT Fiducial, 5×10^7 sec running. (1.22×10^{22} Protons at 28 GeV.)

Assume Water Cerenkov detector (with ~10% PMT coverage)

CC $\nu_\mu + N \to \mu^- + X$	51800
NC $\nu_\mu + N \to \nu_\mu + X$	16908
CC $\nu_e + N \to e^- + X$	380
QE $\nu_\mu + n \to \mu^- + p$	11767
QE $\nu_e + n \to e^- + p$	84
CC $\nu_\mu + N \to \mu^- + \pi^+ + N$	14574
NC $\nu_\mu + N \to \nu_\mu + N + \pi^0$	3178
NC $\nu_\mu + O^{16} \to \nu_\mu + O^{16} + \pi^0$	574
CC $\nu_\tau + N \to \tau^- + X$ (if all $\nu_\mu \to \nu_\tau$)	319

Backgrounds to clean (QE) events SMALL
NC dominated by elastic and single π.
Low τ production.

Very long baselines with a superbeam

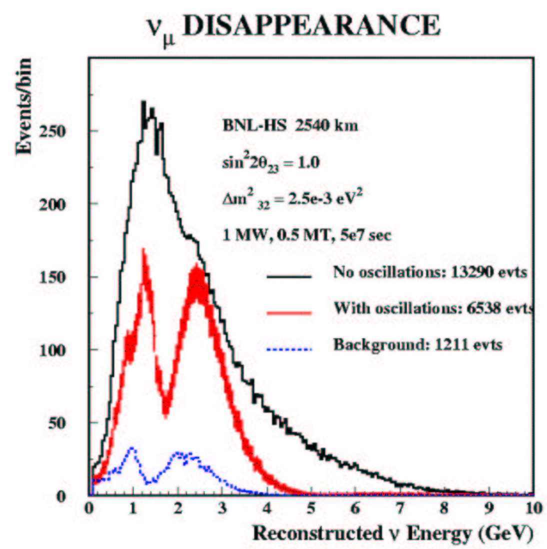


Node pattern provides high Δm^2_{23} resolution.
Energy calibration is very important.

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

Very long baselines with a superbeam



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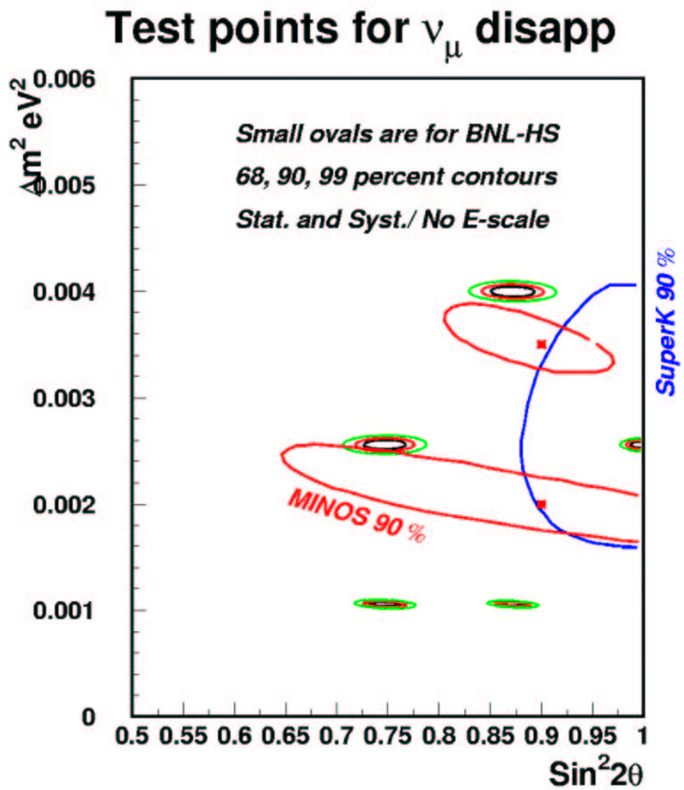
Very long baselines with a superbeam



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- 8 -

Evolution of Study

Proton decay $p \to e^+\pi^0$ SK (22kton) $\xrightarrow[20\times]{}$ 500kton (water cerenkov)

1000 kton too large (costly)

Superbeam 1MW Reasonable (4MW too hard)

On-Axis (0°) More Flux (2x Off-Axis)
Wide Band $0.5\,\text{GeV} \le E_\nu \le 5\,\text{GeV}$

Use $E_\nu \simeq 3\text{-}5\,\text{GeV}$ → Matter Effect sgn Δm^2_{31}
Measure $\sin^2 2\theta_{13}$

$E_\nu \simeq 1\text{-}3\,\text{GeV}$ → $\sin\delta$, $\cos\delta$ → J_{CP}

$E_\nu \simeq 0.5\text{-}1\,\text{GeV}$ → $\Delta m^2_{21} \sin 2\theta_{12}$

} $\nu_\mu \to \nu_e$

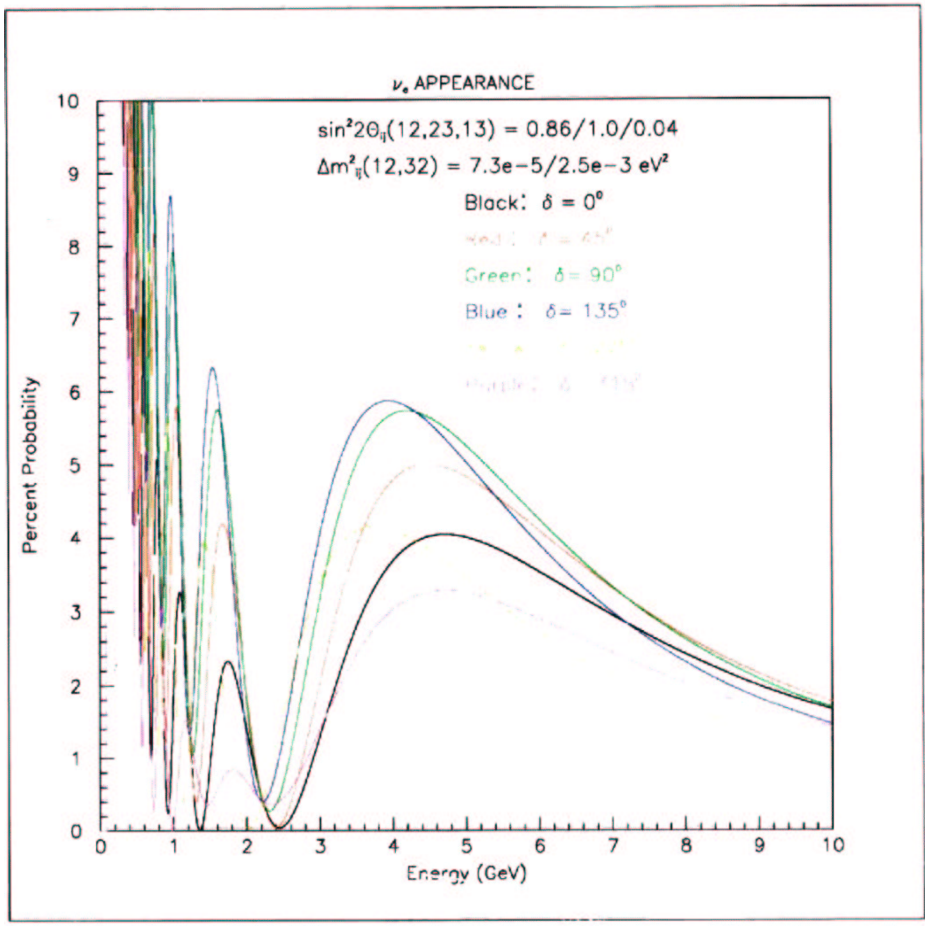
Use $\nu_\mu \to \nu_\mu$ disappearance → Δm^2_{31}, $\sin^2 2\theta_{23}$ Precision
Multiple Peaks

Any unusual structure → Sterile ν, Extra Dim.

In 5×10^7 sec (ν_μ only) pretty good statistics

later run $\bar{\nu}_\mu$ (2MW source) Inverted Hierarchy ...

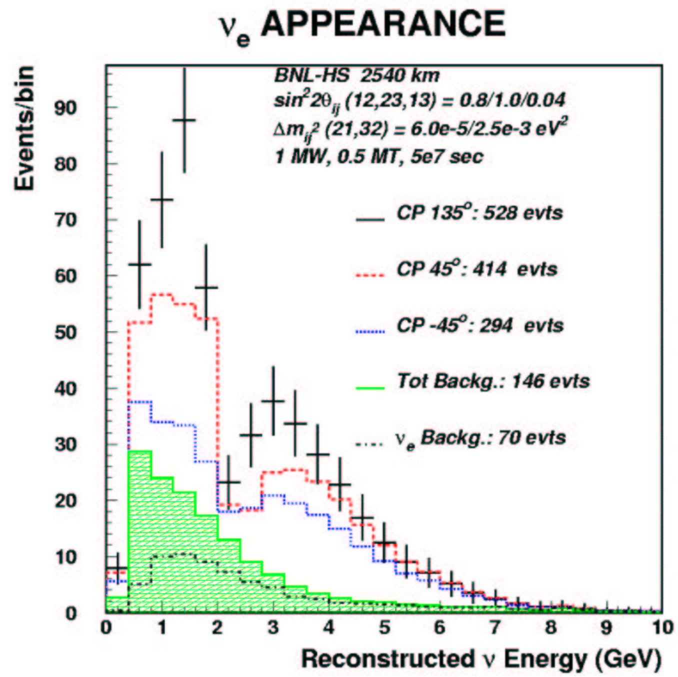
Zohreh Parsa
BNL – Feb 03



[E 0 to 10 GeV]

Very long baselines with a superbeam

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.

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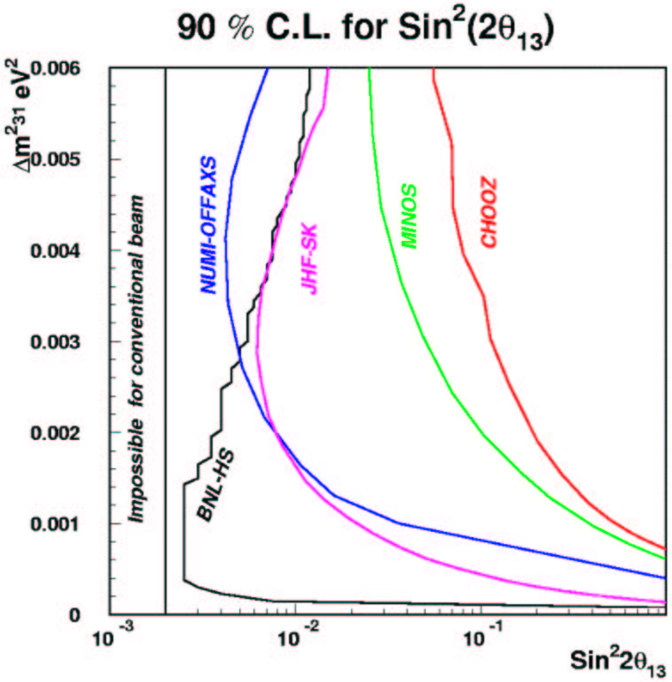
Very long baselines with a superbeam

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



Distinctive signature with multiple oscillations above 0.001 eV^2

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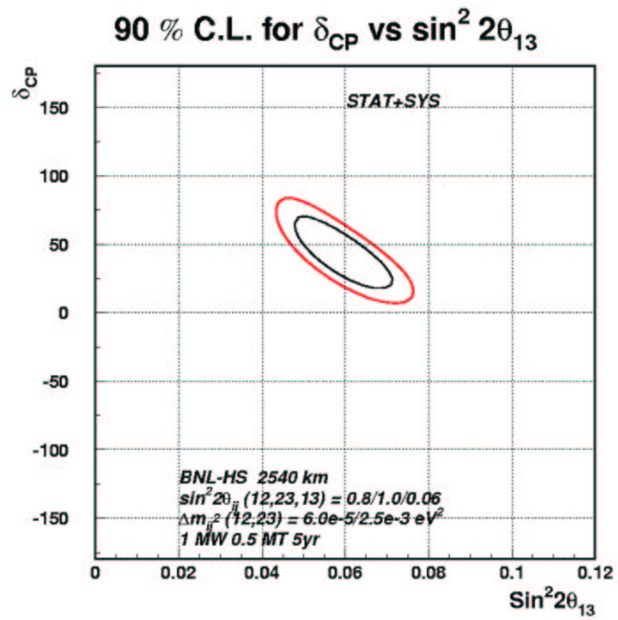
Very long baselines with a superbeam

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.

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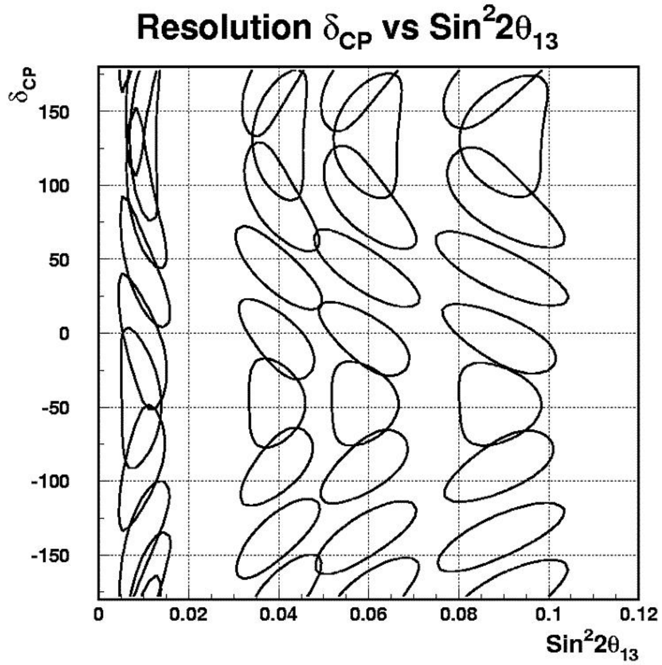
Very long baselines with a superbeam

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



Assume all other parameters are well-known.

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

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

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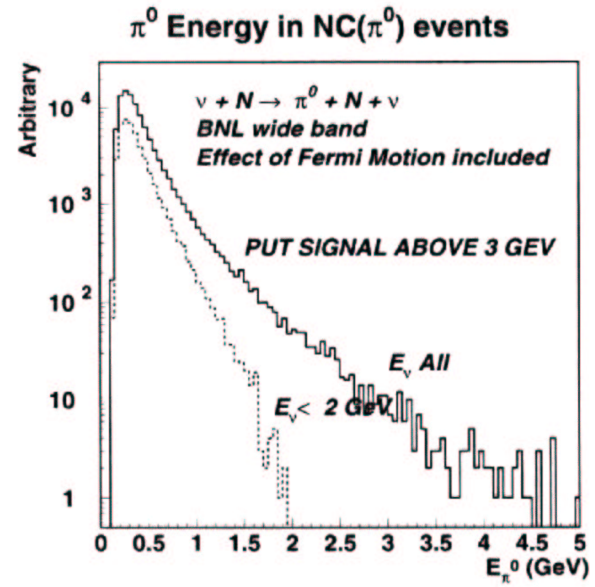
NC π^0 background for $\nu_\mu \rightarrow \nu_e$



- The NC energy distribution is independent of ν-energy except the kinematic limit.
- In $\nu_\mu N \rightarrow \nu_\mu N \pi^0$ events all energy ν produce peak at the same energy except the tail.
- For a very long baselines and wide band beam ν_e signal will be above 3 GeV with little π^0 background.

-9-

Use Quasi-Elastic $\nu_\mu n \to \mu^- p$ Reconstruct E_ν
$\nu_e n \to e^- p$ Better than ±10% Resol

$\nu_\mu \to \nu_\mu$ ~6000 events → several peaks (structure)

$\nu_\mu \to \nu_e$ ~ 300-400 events (LMA I)

$E_\nu \simeq 0.5$-1GeV ~100 events

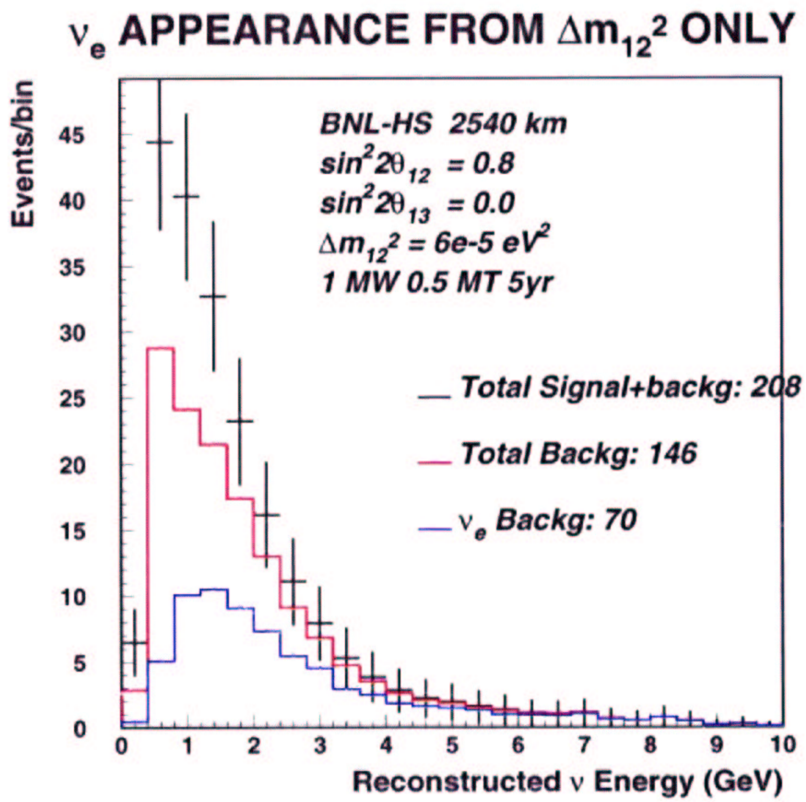
$E_\nu \simeq 1$-3GeV ~150 events

$E_\nu \simeq 3$-7 GeV ~150 events

Ongoing study of non-quasielastic $\nu_e N \to e^- X$
3-4 x statistics

Very long baselines with a superbeam

Measurement of Δm^2_{12}



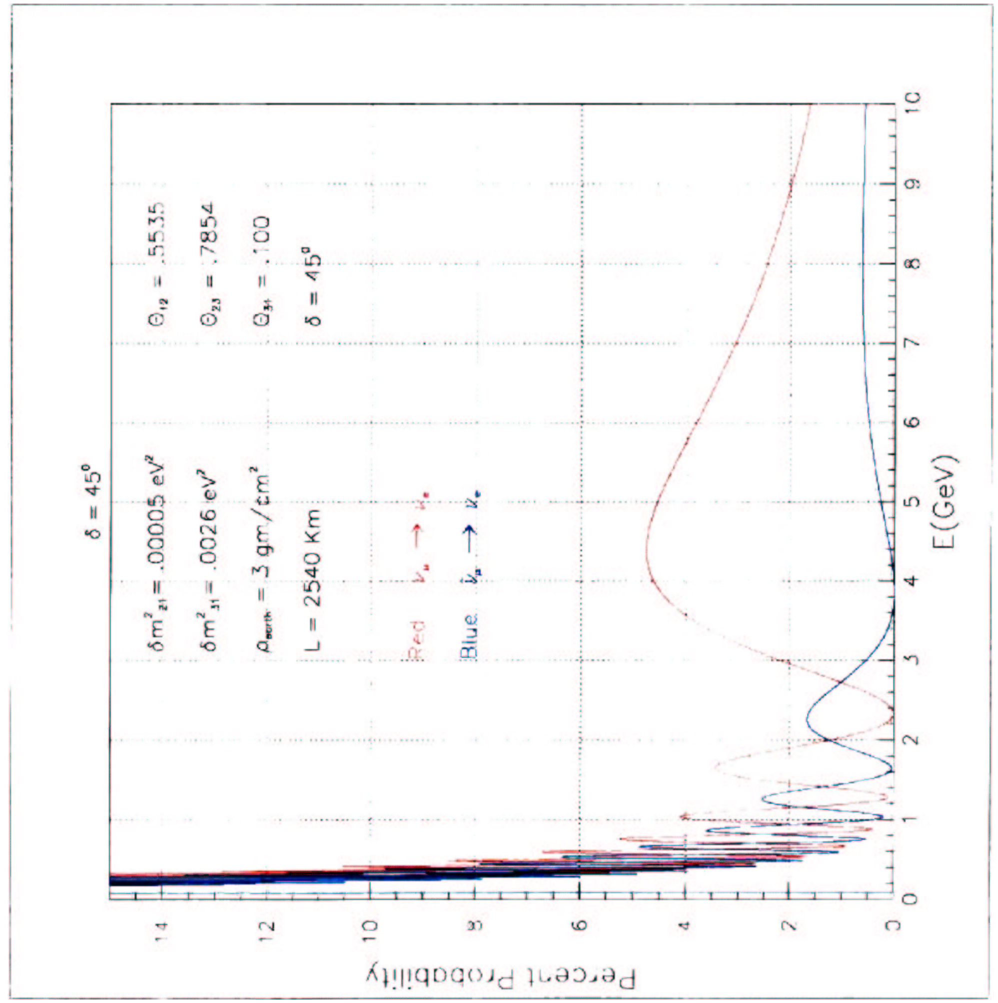
$\theta_{13} = 0,\ \Delta m^2_{12} = 6 \times 10^{-5} eV^2$

Excess of ~ 50 events. Must know background

Recall $\sin^2(1.27\Delta m^2_{12} 2540\ km/1\ GeV) = 0.037$

Summary of our study

- Baseline of > 2000 km with wide band conventional beams are the next step in accelerator neutrino physics.
- Extraordinary, large physical effects will be seen in such an experiment.
- Very good sensitivity to neutrino properties.
  - $< 1\%$ resolution on Δm^2_{32}
  - $< 1\%$ resolution on $\sin^2 2\theta_{23}$
  - Sensitivity to $\sin^2 2\theta_{13} \sim 0.005$ over a wide range of Δm^2_{32}
  - Sensitivity to CP violation $\pm 25^o$ with neutrinos alone.
  - Sign of Δm^2_{32} over a wide range.
  - Measurement of Δm^2_{12} at $\pm 15\%$
- The electron spectrum has a lot of physics. It can be extracted using some outside information on parameter.



-10-

My Opinion: The World needs ~1000 kton water cerenkov det.
$\tau(p \to e^+ \pi^0) \to 10^{35} - 10^{36}$ yr

500 kton in USA 500 kton in Japan
International Collaboration

Also do Supernova - Matter Effects 200,000 events!
Relic Supernova
Atmospheric $\nu_\mu \to \nu_\mu$ Multi-Peak, θ_{13}, matter
Solar ν
H.E. ν
n-$\bar{n}$ Osc, Mag. Monopole

(50-100 yr lifetime - Anchor of National Underground Lab)

Long Baseline Osc. Japan 295 km

USA BNL - Homestake (2540 km) Wipp (2900 km)
FNAL - Homestake (1250 km)

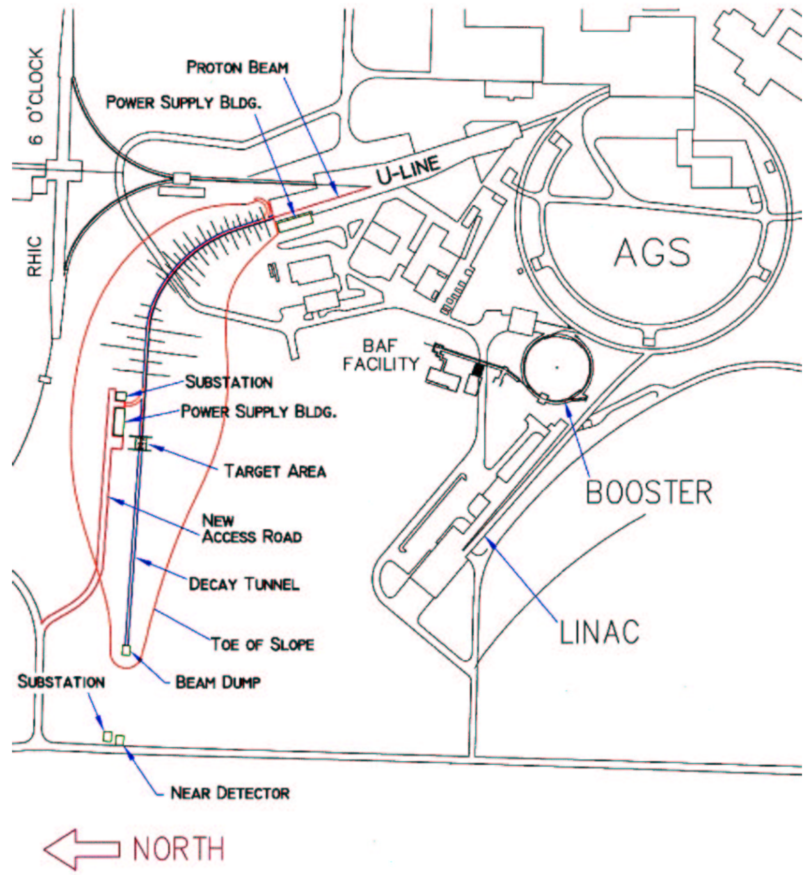
Cost Detector $500M (Less?)
Superbeam (Source + Beam) ~ $345 M

A Facility For Physics & The Public

Will it catch on?
Stay Tuned

Very long baselines with a superbeam

Beam Layout



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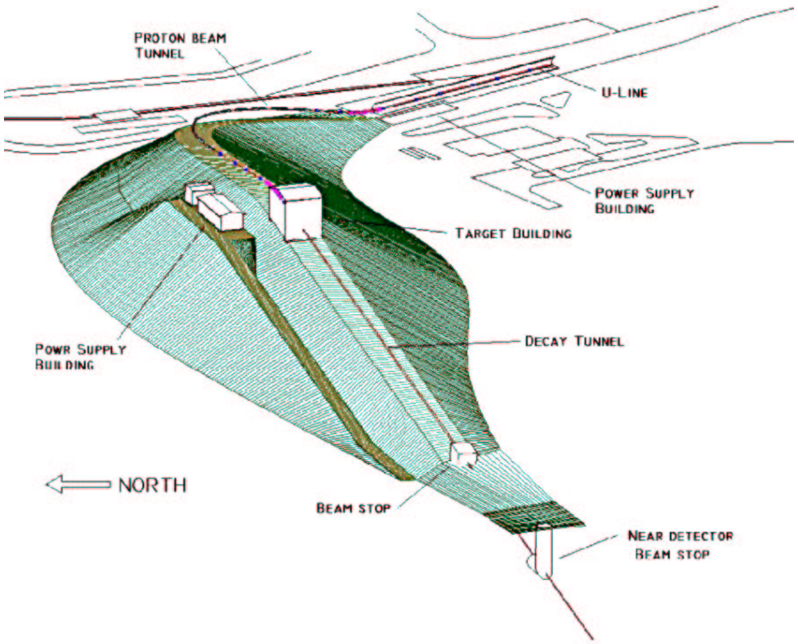
Very long baselines with a superbeam

Beam 3d



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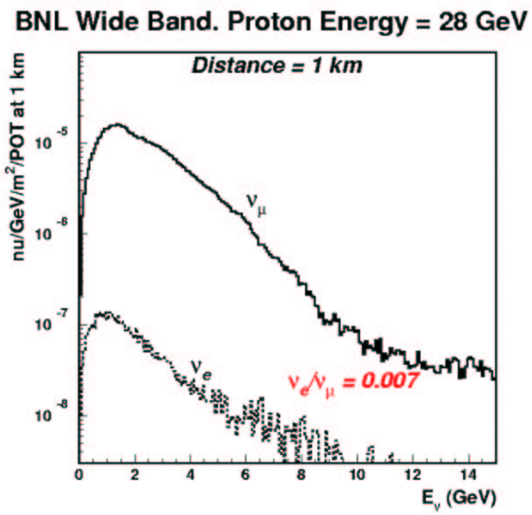
Very long baselines with a superbeam



- 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

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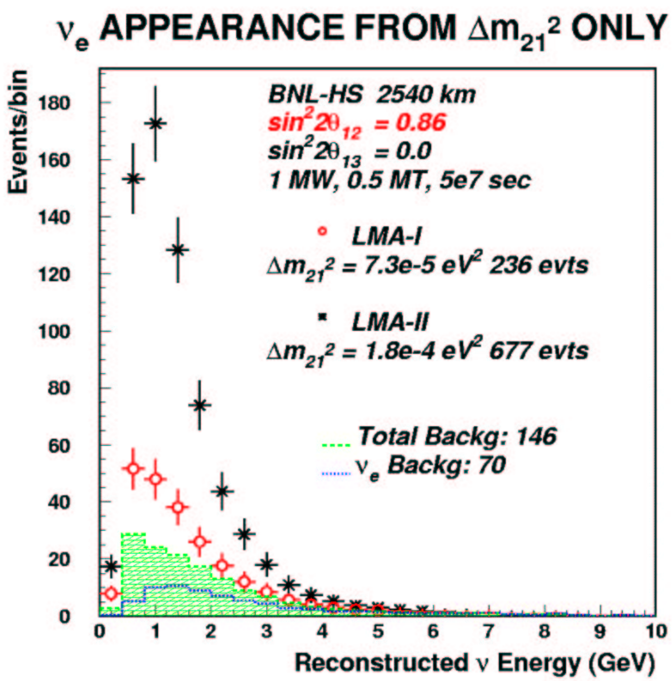
Very long baselines with a superbeam

Measurement of Δm^2_{12}



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

Excess of $\sim$ 90 events. Must know background

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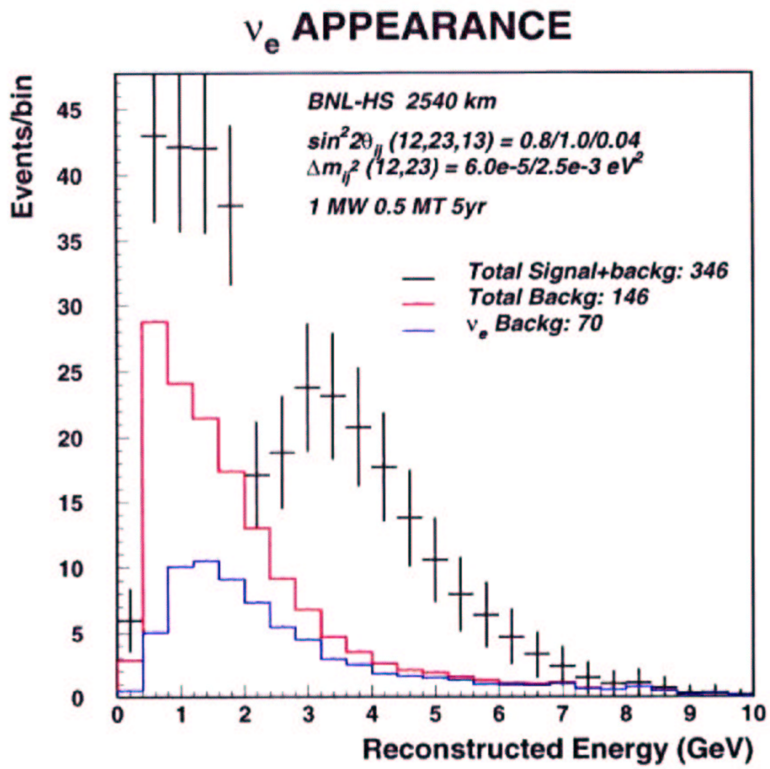
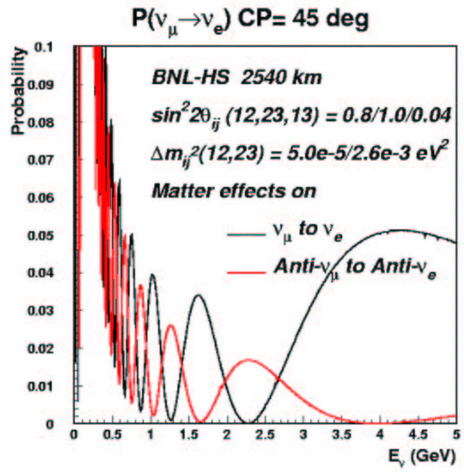
Measurement of $\sin^2 2\theta_{13}$



$\Delta m^2_{23} = 0.0025 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

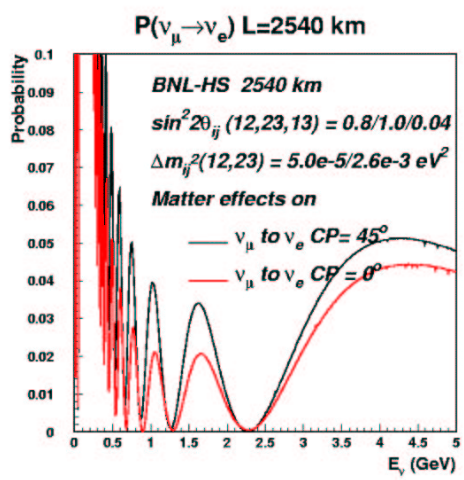
Assume normal mass hierarchy. $m_3 > m_2 > m_1$

Matter effects included.



Compare Neutrino to Antineu.

- $0.5 - 1$ GeV: Δm^2_{12} (LMA) region.
- $1 - 3$ GeV: CP region
- $>$ 3 GeV: Matter enhanced (ν_μ), suppressed ($\bar{\nu}_\mu$). ($\Delta m^2_{32} > 0$) Region.



General Features

- $0.5 - 1$ GeV: Δm^2_{12} (LMA) region.
- $1 - 3$ GeV: CP large effects region
- $>$ 3 GeV: Matter enhanced (ν_μ), suppressed ($\bar{\nu}_\mu$). ($\Delta m^2_{32} > 0$) Region.

I. Mocioiu and R. Shrock, Phys. Rev. D62, 053017 (2000), JHEP 0111, 050 (2001)

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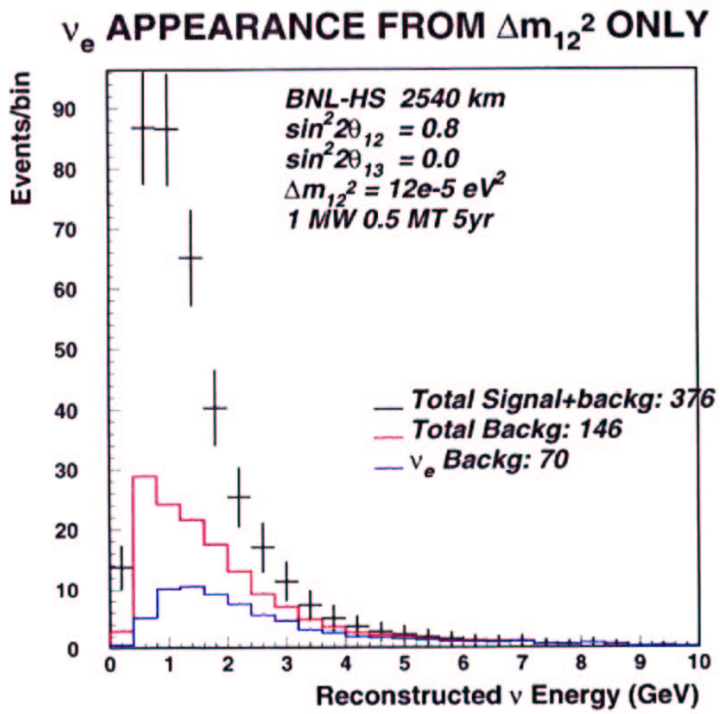
Measurement of Δm^2_{12}

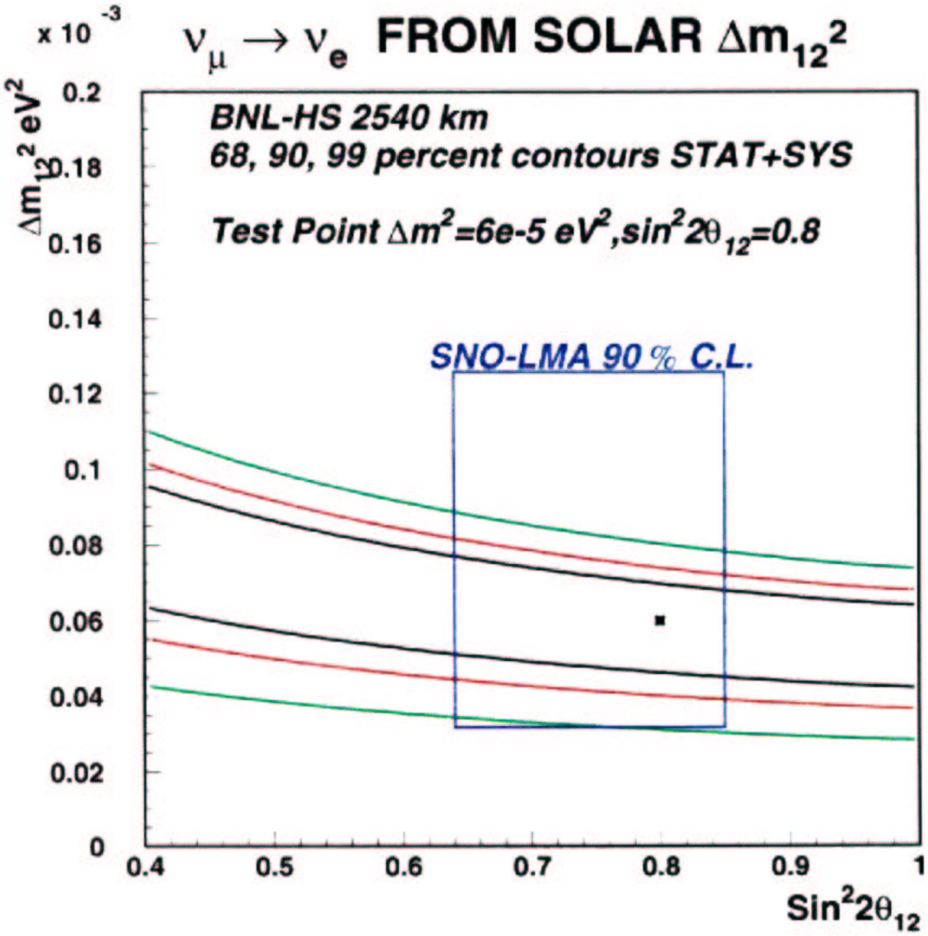


$\theta_{13} = 0$

$\Delta m^2_{12} = 12 \times 10^{-5} ev^2$

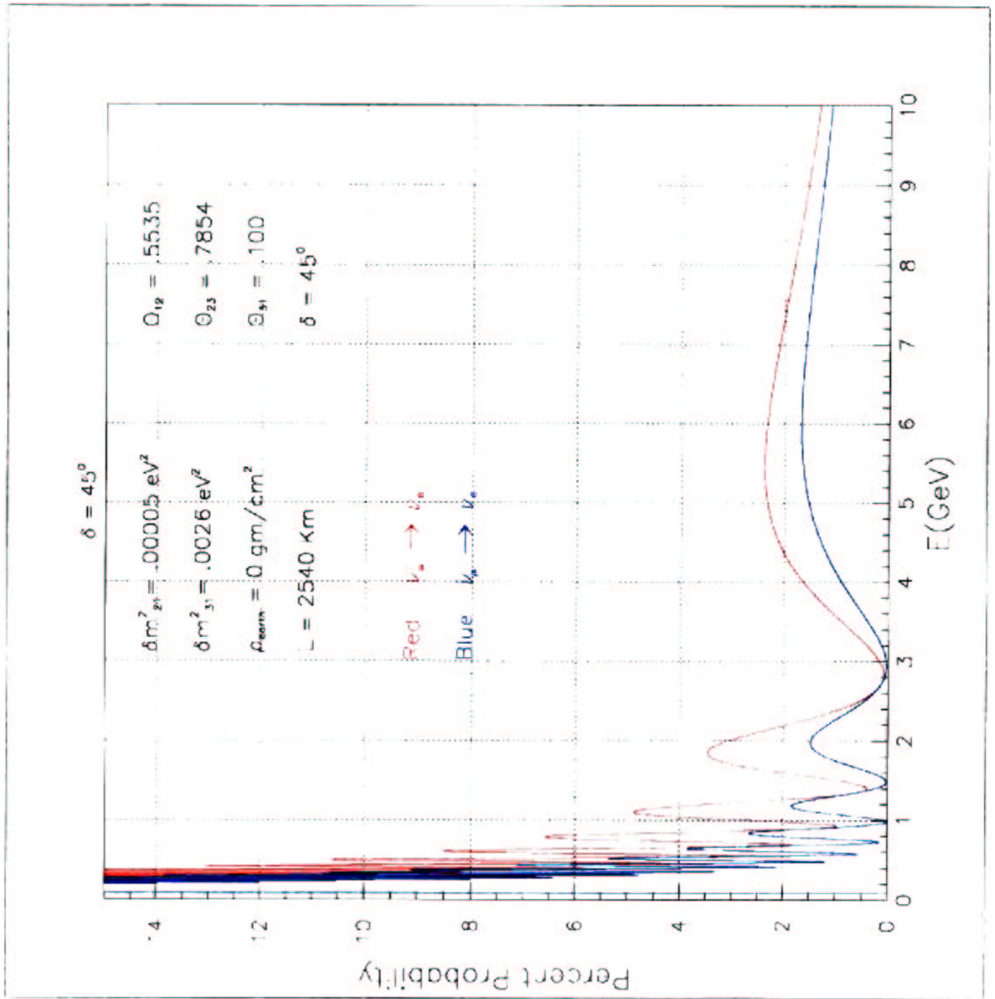
Excess of ~ 230 events. Unmistakable.

Measurement of Δm^2_{12}

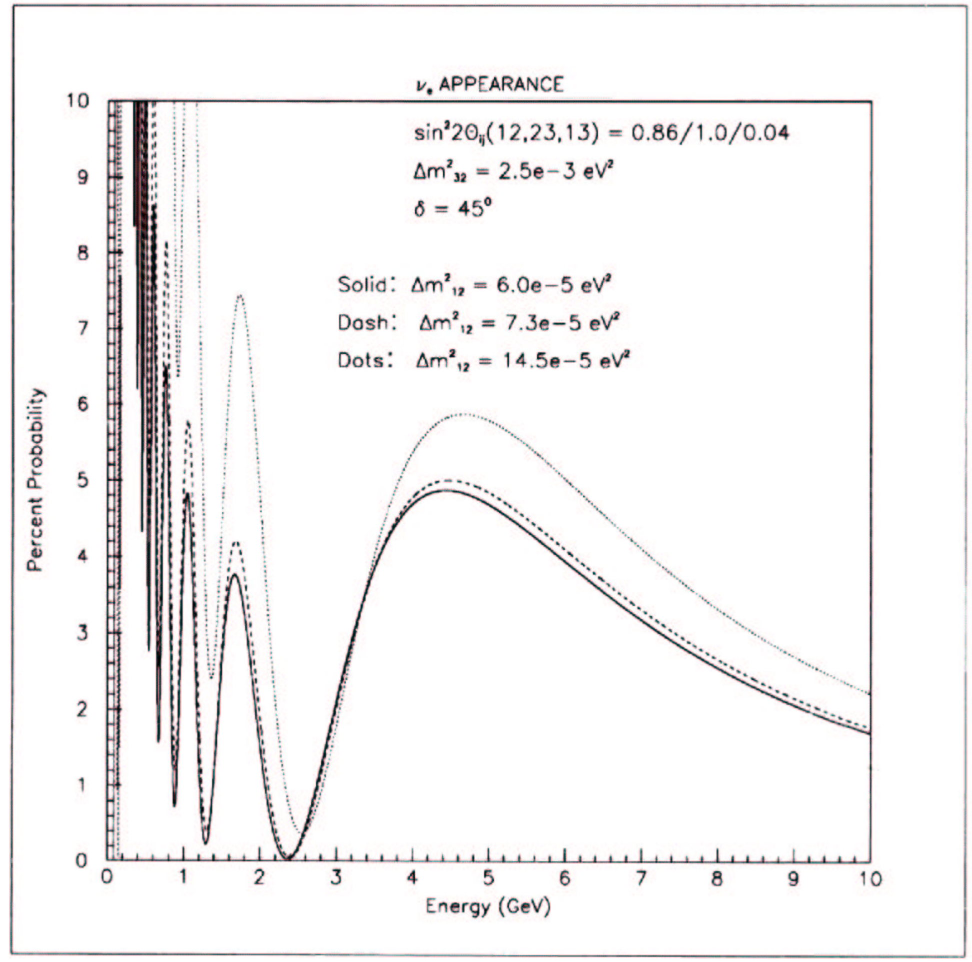


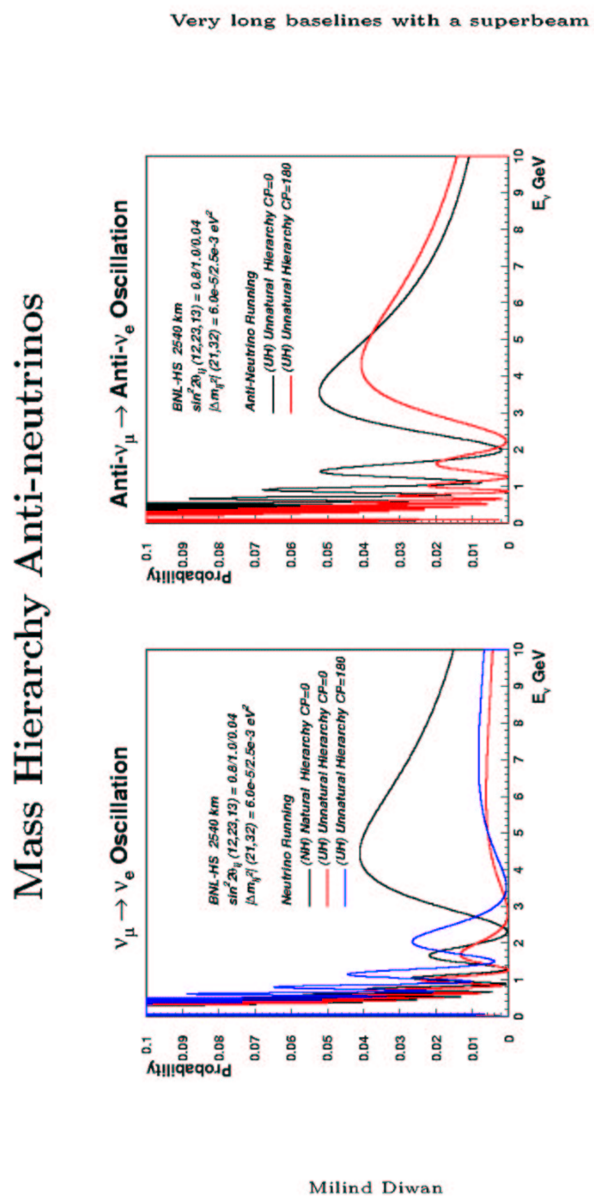
Independent $\sim 15\%$ measurement of Δm^2_{12}

Needs $\sim 10\%$ error on backg. => near detector.



Zohreh Parsa
Feb 28, 2003





Very long baselines with a superbeam
Mass Hierarchy Anti-neutrinos
ν_μ → ν_e Oscillation
BNL-HS 2540 km
sin²2θ_ij (12,23,13) = 0.8/1.0/0.04
|Δm_ij²| (21,32) = 6.0e-5/2.5e-3 eV²
Neutrino Running
(NH) Natural Hierarchy CP=0
(UH) Unnatural Hierarchy CP=0
(UH) Unnatural Hierarchy CP=180
Anti-ν_μ → Anti-ν_e Oscillation
BNL-HS 2540 km
sin²2θ_ij (12,23,13) = 0.8/1.0/0.04
|Δm_ij²| (21,32) = 6.0e-5/2.5e-3 eV²
Anti-Neutrino Running
(UH) Unnatural Hierarchy CP=0
(UH) Unnatural Hierarchy CP=180
Probability
E_ν GeV
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