W. Marciano
10/30/05

Leptonic CP VIOLATION

The BNL Approach

What does it take to determine CP in neutrino osc.? Measure δ & J_{CP}

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

$$\simeq 0.23 \sin\theta_{13} \sin\delta$$ potentially enormous

$$J_{CP}^{CKM} \simeq 3\times10^{-5}$$

* **Requires**: i) 1MW Proton Beam → WBB $0.5\,GeV \lesssim E_\nu \lesssim 5\,GeV$ (traditional horn focused)

ii) 500 kton H_2O Detector (20% acceptance) $\nu_\mu \to \nu_e \to e^-$
or ~125 kton LArgon
or hybrid 250 kton H_2O + 62 kton LAr

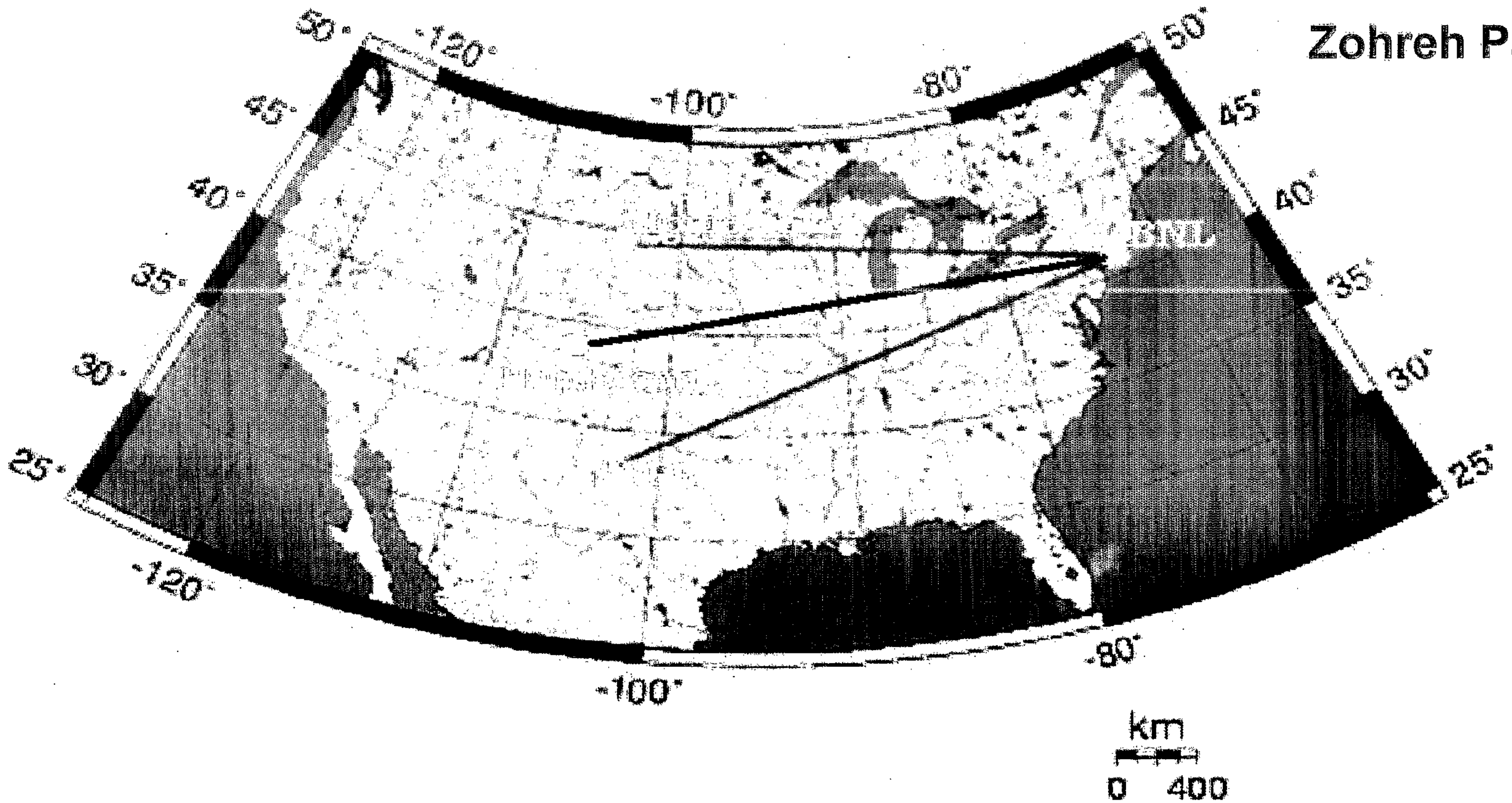
iii) $L \gtrsim 600\,km \times E_\nu/GeV$ (1300 ~ 4000 km)

iv) $T \simeq 5\times10^7$ sec.

Perhaps easier $\left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \simeq \frac{1}{25}$ not $\frac{1}{40}$

BNL Intense Neutrino Beam→ Homestake, WIPP, or Henderson

Zohreh Parsa



AGS 28 GeV protons, 1 MW beam (power achievable) + 500 kT Water Cerenkov detector, 5e7 sec of running, Conventional Horn based beam ➔

P889 Spectrum $E_p \simeq 28\,GeV$

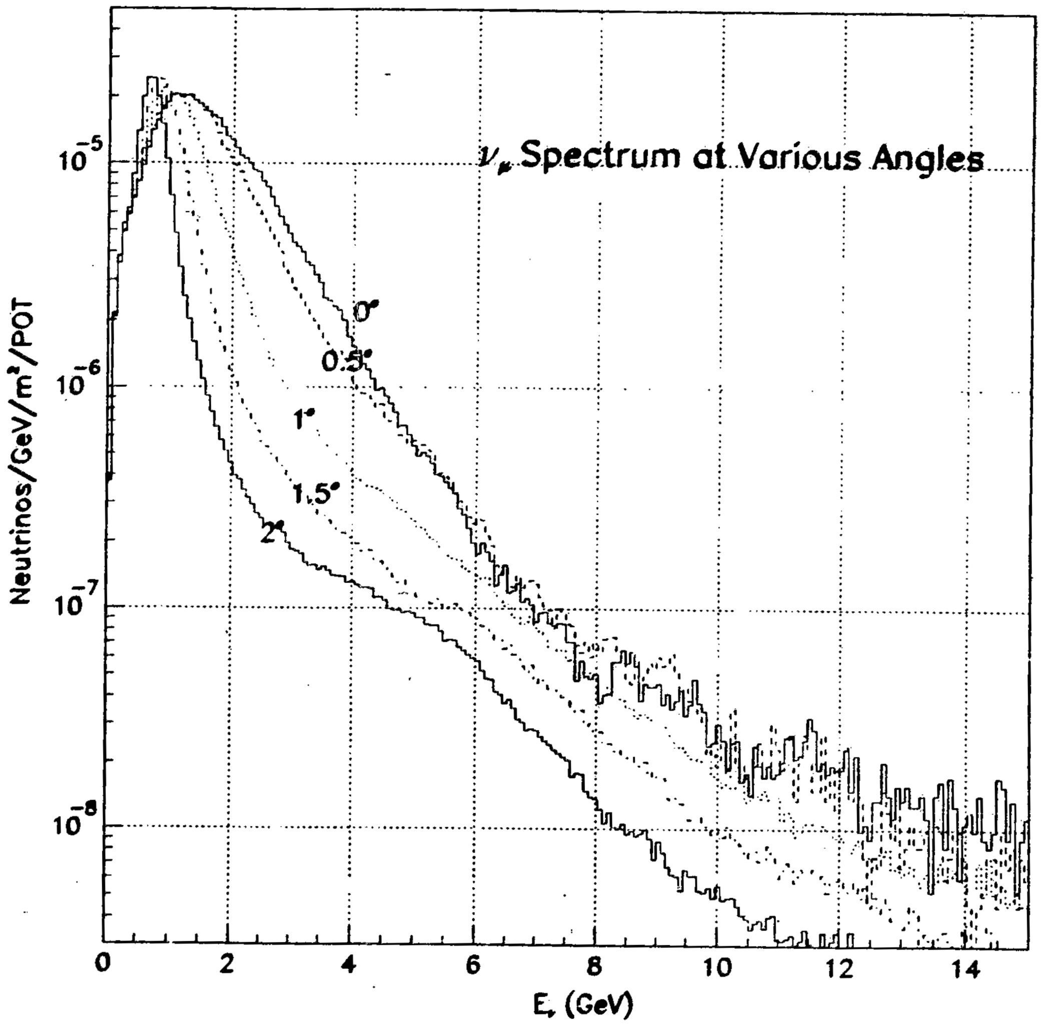


Figure 3: *Spectrum of neutrinos at 1 km at various angles with respect to the decay tunnel axis. The 1.5 degree spectrum was used for calculating the total event rates, however the event simulations in the detectors were performed using the full energy-angle correlation on an event by event basis.*

*Insensitive to value of $\sin^2 2\theta_{13}$ for $0.01 \lesssim \sin^2 2\theta_{13} < 0.2$ and L as long as $L \gtrsim 1000\,km$

eg <u>BNL → Homestake (2540 km)</u>
<u>FNAL → Homestake (1300 km)</u>
} Roughly Same Physics Potential

<u>Natural Marriage with Proton Decay Detector</u>

*<u>Doable At DUSEL</u>

<u>Major Facility</u>: $\tau(p \to e^+\pi^0) \simeq 10^{36}$ yr ! n-$\bar{n}$ osc. ...
Atm $\nu_\mu \to \nu_\mu$
Supernova ν (100,000 events), relic
⋮

$\nu_\mu \to \nu_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$
$\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$
} Acc. Studies

<u>Measure</u>: $|\Delta m^2_{32}|$ & $\sin^2 2\theta_{23}$ to ±1%!
(Everything)
Δm^2_{21}, $\sin 2\theta_{12}$, $\cos\theta_{23}$ to ± 5%, $\sin^2 2\theta_{13} \to 0.002$
<u>δ to ± 10-15°</u> (for $\sin^2 2\theta_{13} \gtrsim 0.01$) $\sin\delta$, $\cos\delta$
sgn Δm^2_{32} (for $\sin^2 2\theta_{13} \gtrsim 0.002$)

<u>Probe</u>: Sterile ν, Extra Dim, Dark Energy ?

1.) Physics Goals: CP Violation + Much More!

Currently: $\theta_{23} \sim 45^\circ$, $\theta_{12} \sim 32^\circ$, $\theta_{13} \lesssim 13^\circ$ $\quad \sin^2 2\theta_{13} \lesssim 0.2$

$0 \leq \delta < 360^\circ$ No Constraint

$|\Delta m^2_{32}| \sim 2.6 \times 10^{-3}\, eV^2$, $\Delta m^2_{21} \sim 8.2 \times 10^{-5}\, eV^2$ larger

$\pm$ Hierarchy $\qquad$ CP Violation Observable!

Next 5 yrs? $0.01 \lesssim \sin^2 2\theta_{13} \lesssim 0.2$ Explored at Reactors (expect determination)

Longer Term: (> 2012)

*1) Measure δ + $J_{CP} \equiv \frac{1}{8} \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} S_\delta$

2) Determine $\mathrm{sgn}\, \Delta m^2_{32}$ Mass Hierarchy

3) Precision θ_{23} ($\pm 1^\circ$), $90^\circ - \theta_{23}$ ambiguity

4) Precision θ_{13} + θ_{12}

5) Precision Δm^2_{32} ($\pm 1\%$), Δm^2_{21} ($\pm 5\%$)

6) New Physics: Sterile Neutrinos
Extra Dimensions
Dark Energy?

Major Advances Require A Major Program:

BNL Very Long Baseline Program

$L \simeq 2000 - 3000$ km $\quad$ eg BNL-Homestake

$E \simeq 0.5 \sim 5$ GeV Wide Band Beam On-Axis

Large Detector ~ 500 kton H_2O (Proton Decay)

ν_μ disappearance: $P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$

measure (~3 Peaks) $0.5\,\text{GeV} \leq E_\nu < 5\,\text{GeV}$: $\sin^2 2\theta_{23}$ to $\pm 1\%$, Δm^2_{32} to $\pm 1\%$

θ_{23}, $\frac{\pi}{2} - \theta_{23}$ degeneracy

Peaks $L = 620 \times (2n+1) \times E_\nu / \text{GeV km}$ ~ 7000 μ events

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

$$P_I(\nu_\mu \to \nu_e) = \underline{\sin^2\theta_{23} \sin^2 2\theta_{13}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) + \text{Matter}$$

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

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

Flux Falls As $1/L^2$

N_I + Backgrounds ~ $1/L^2$ (x Matter Enhancement)!

N_{II} ~ $1/L$ $\frac{N_{II}}{\sqrt{N_I + Bk}}$ indep of L

N_{III} ~ 1 (Indep. of L)   Relatively more important at large distance

$\frac{N_{III}}{\sqrt{N_I + Bk}}$ grows with L

3.) Very Long Baseline Neutrino Osc

ν_μ or $\bar{\nu}_\mu$ beam   AGS → Homestake 2540 km

i) ν_μ disappearance: $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)$

$0.5\,GeV \lesssim E_{\nu_\mu} \lesssim 5\,GeV$ → 3 osc peaks

~ 7000 μ events

Determine $\sin^2 2\theta_{23}$ + Δm_{31}^2 to ±1%

search for exotica

ii) $\nu_\mu \to \nu_e$ appearance: $P(\nu_\mu \to \nu_e) = P_I(\nu_\mu \to \nu_e) + P_{II}(\nu_\mu \to \nu_e) + P_{III}(\nu_\mu \to \nu_e)$ + matter effects

$P_I(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)$ + matter effects

dominates $E_\nu > 3\,GeV$

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

important for $E_\nu \simeq 1$-$3\,GeV$

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

(solar par.)   small

dominates $E_\nu < 1\,GeV$

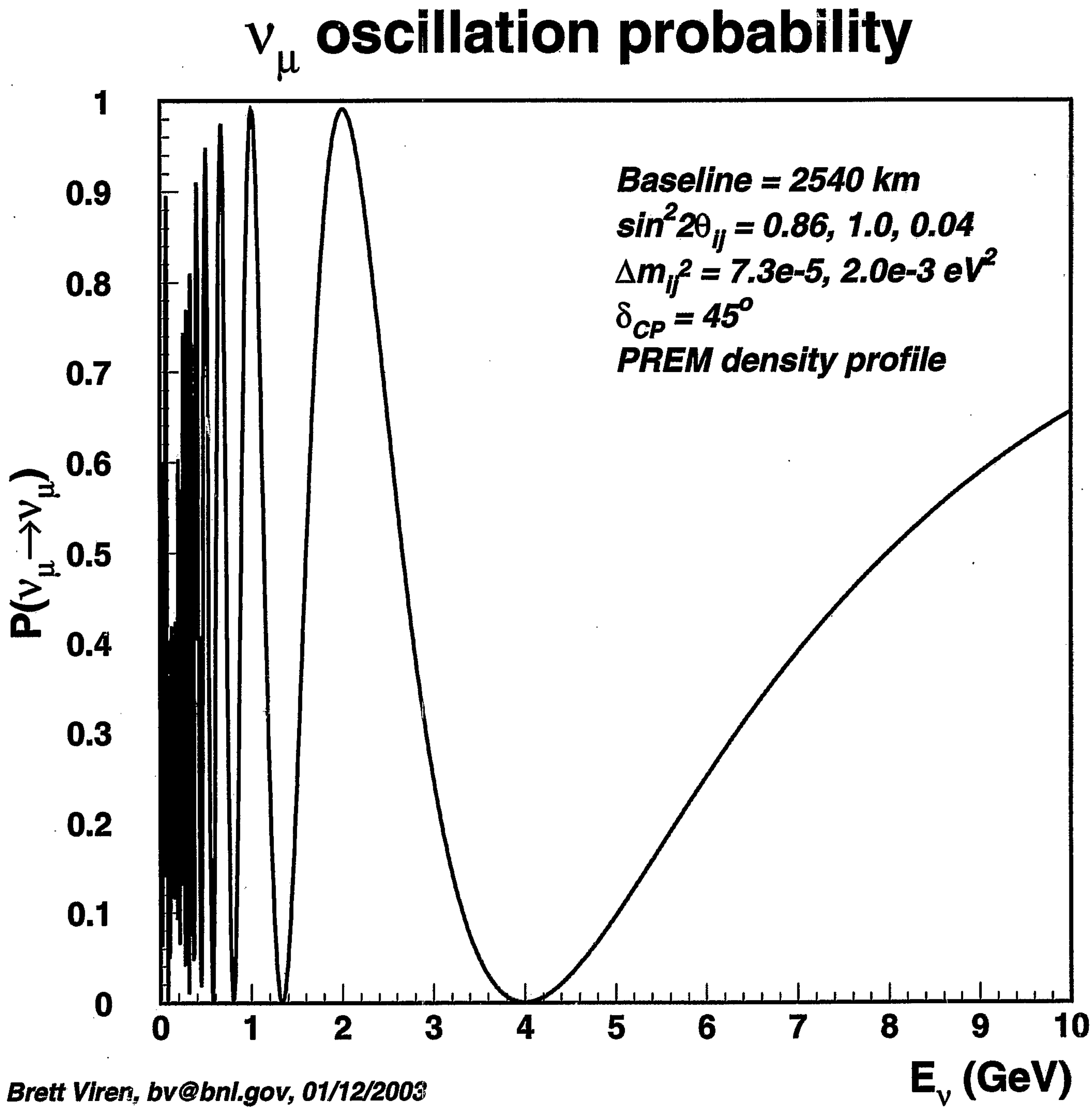
*Study precisely all 3gen. parameters in 1 exp.!

	99% CL		
$\sin^2 2\theta_{13}$	0.20 – 0.01 (95%)	0.01 – 0.002	< 0.002 (1%
Δm^2_{31}	±1% + sign	±1% + sign	±1%
$\sin^2 2\theta_{23}$	±1%	±1%	±1%
$\Delta m^2_{21} \sin 2\theta_{12} \cos\theta_{23}$	±5-7%	±4-6%	±3-5%
δ	±10°-15°	~±20-50°	?
$\sin^2 2\theta_{13}$	±10%-20%	Bound → 0.002 -0.004	?

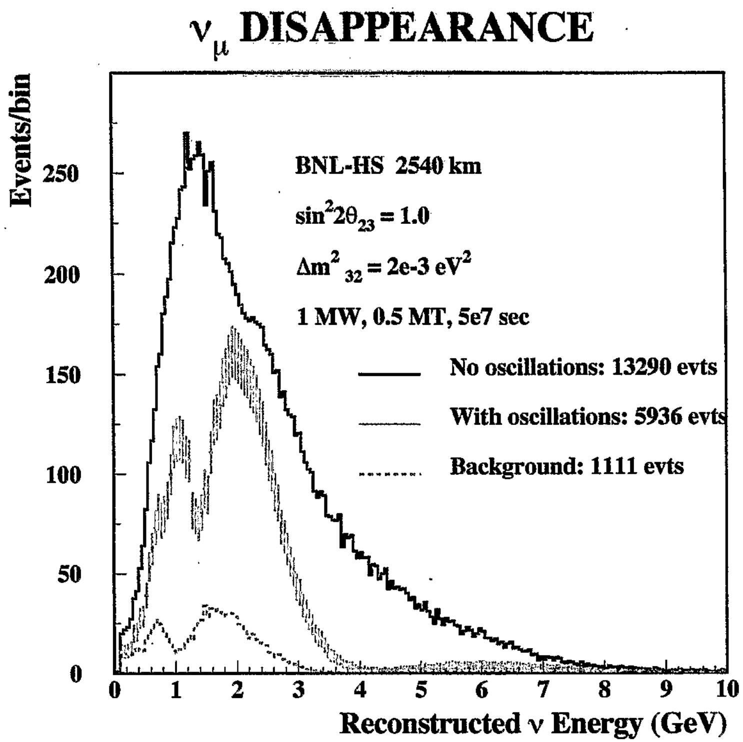
Whatever we learn about $\sin^2 2\theta_{13}$ during the next 5-10 yrs (reactors, acc.), we will have to build ~ 500kton H_2O + 1MW p source + $L \gtrsim 1300$km

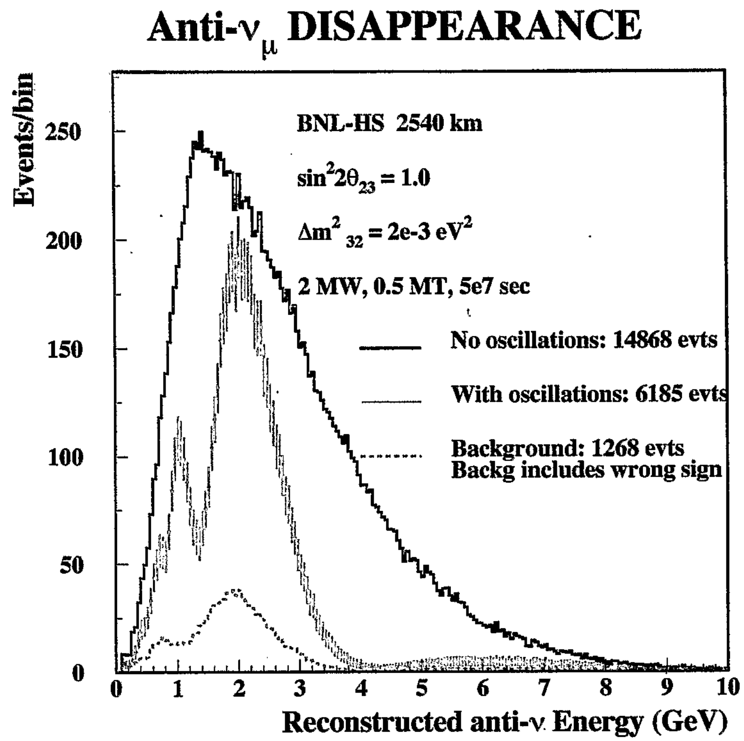
So Why Not Start Now?

Either AGS or Main Inj → 1MW
500kton H_2O or 125 kton LAr in Homestake or Henderson
DUSEL



νμ oscillation probability
Baseline = 2540 km
sin²2θij = 0.86, 1.0, 0.04
Δmij² = 7.3e-5, 2.0e-3 eV²
δCP = 45°
PREM density profile
P(νμ→νμ)
Eν (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7
8
9
10
Brett Viren, bv@bnl.gov, 01/12/2003





Node pattern provides high Δm^2_{32} resolution. Energy calibration is very important.

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

Minimum systematics in ν_μ and $\bar{\nu}_\mu$ comparison

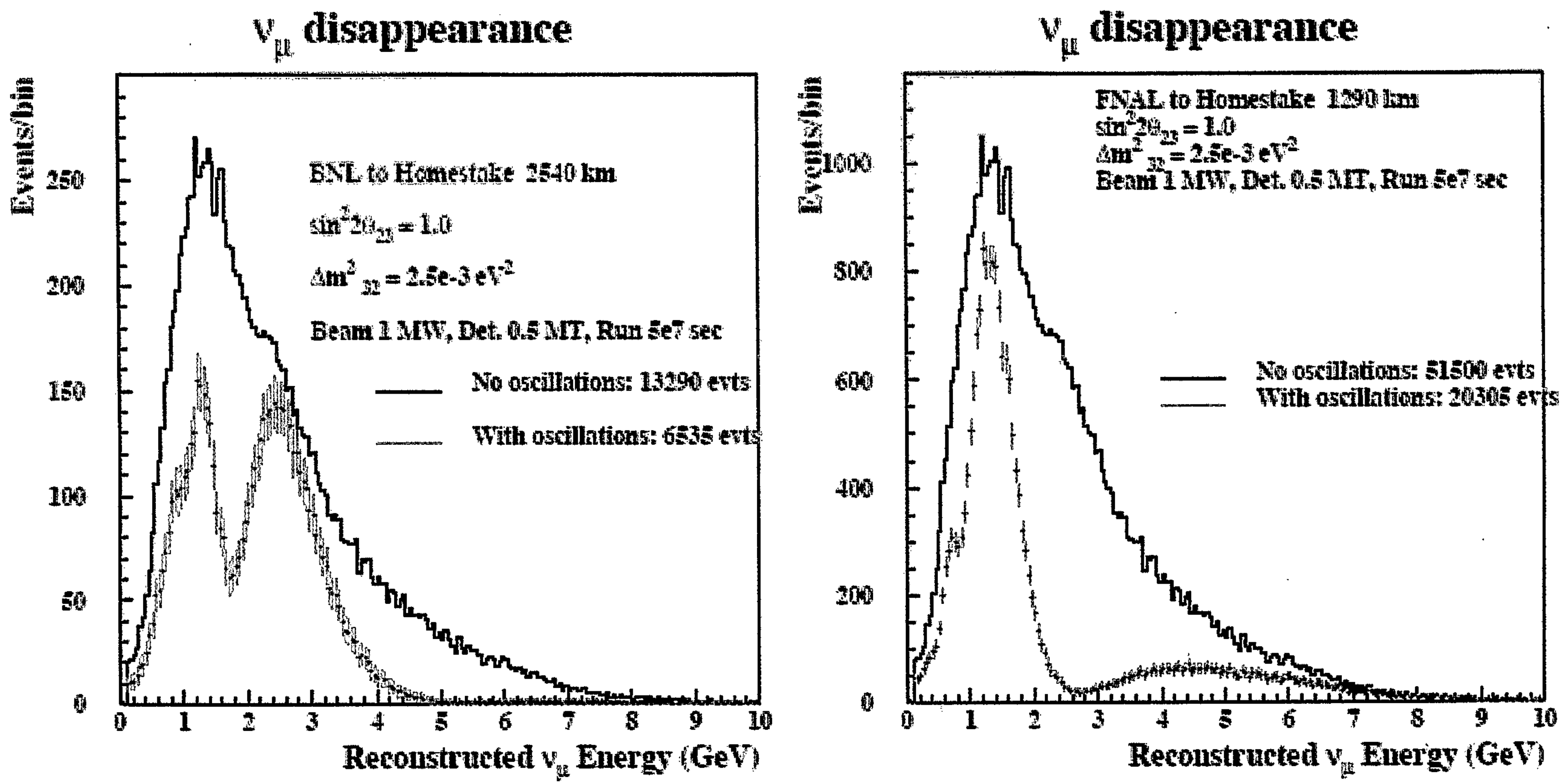
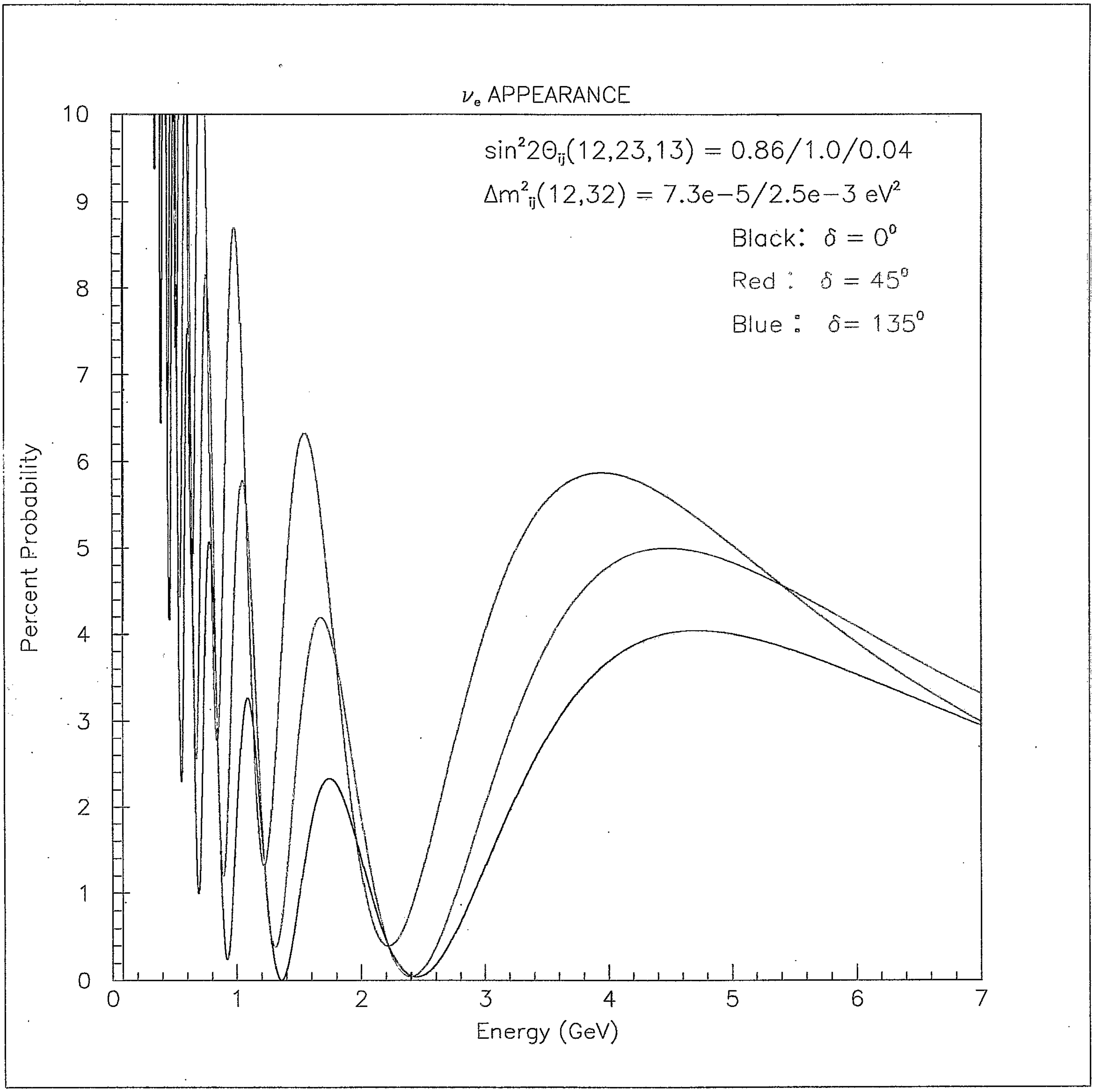


Figure 2: *Simulated spectrum of detected muon neutrinos for 1 MW beam and 500 kT detector exposed for* 5×10^7 *sec. Left side is for baseline of 2540 km, right side for baseline of 1290 km. The oscillation parameters assumed are shown in the figure. Only clean single muon events are assumed to be used for this measurement (see text).*

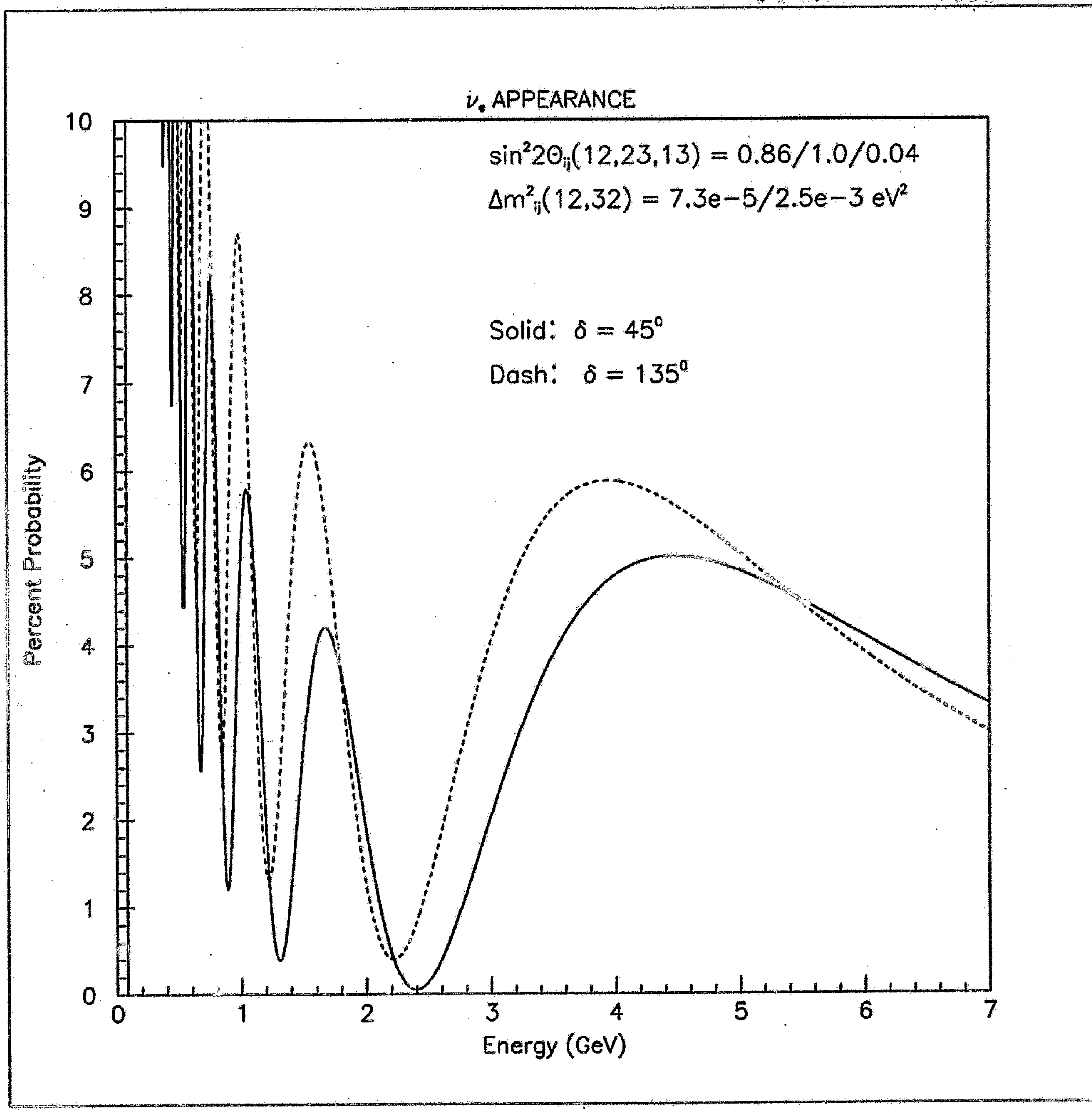
L=2540km

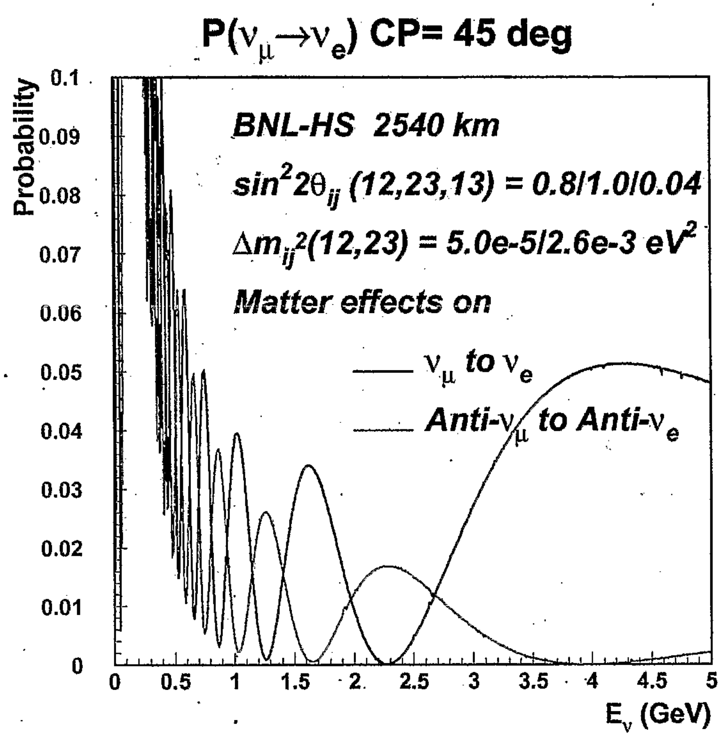
From Z. Parsa



L=2540km

From Z. Parsa

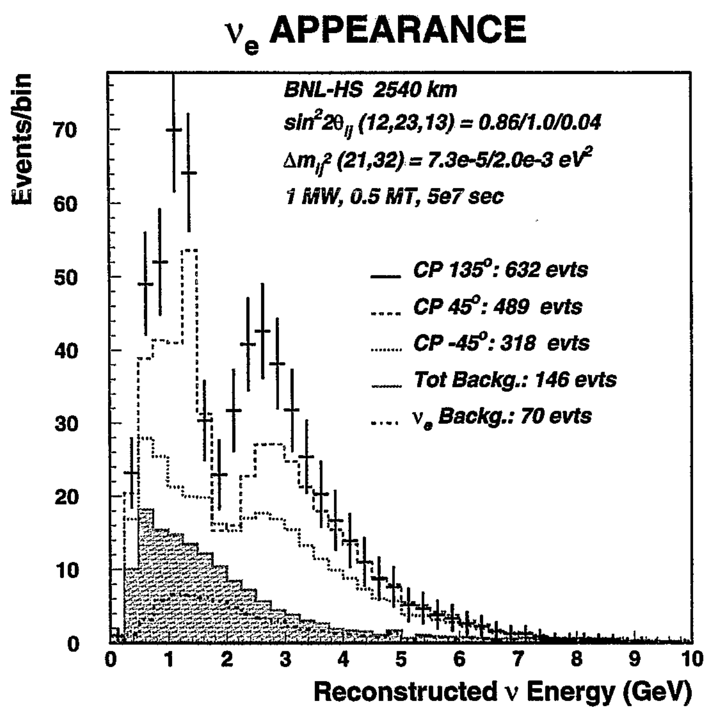


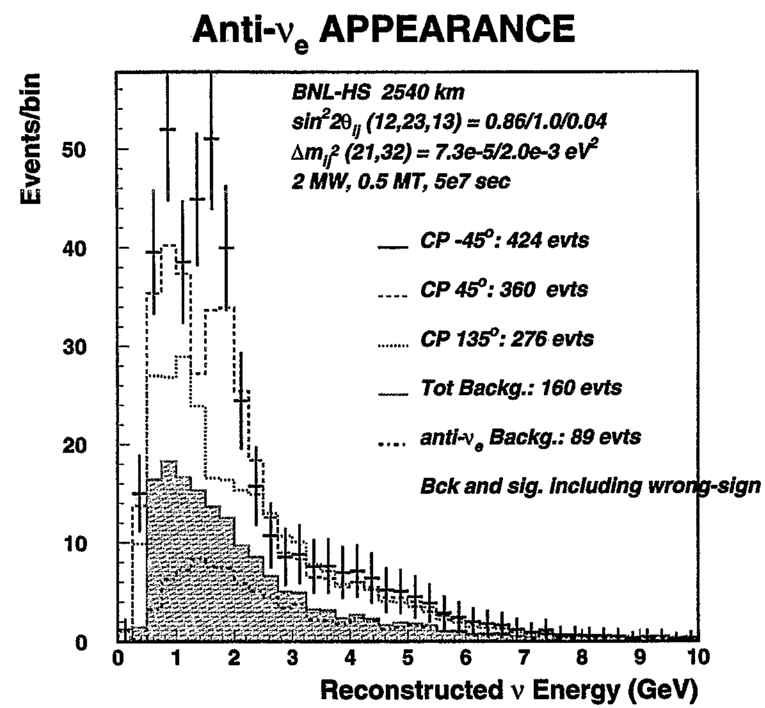


Compare Neutrino to Antineu.

- $0.5-1$ 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.

Running for $\sin^2 2\theta_{13}$





$\Delta m_{32}^2 = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$. Assume normal mass hierarchy. $m_3 > m_2 > m_1$ Matter effects included.

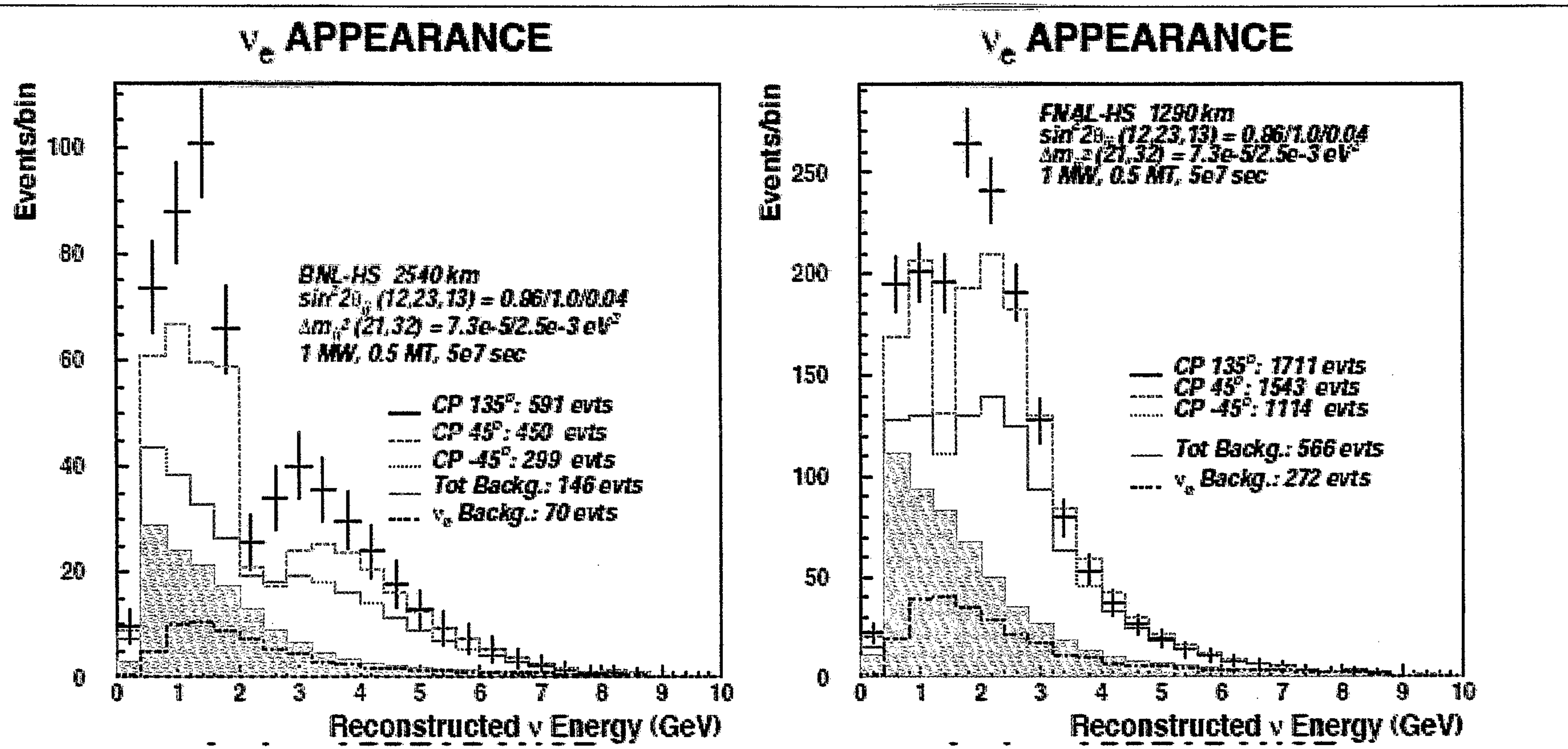
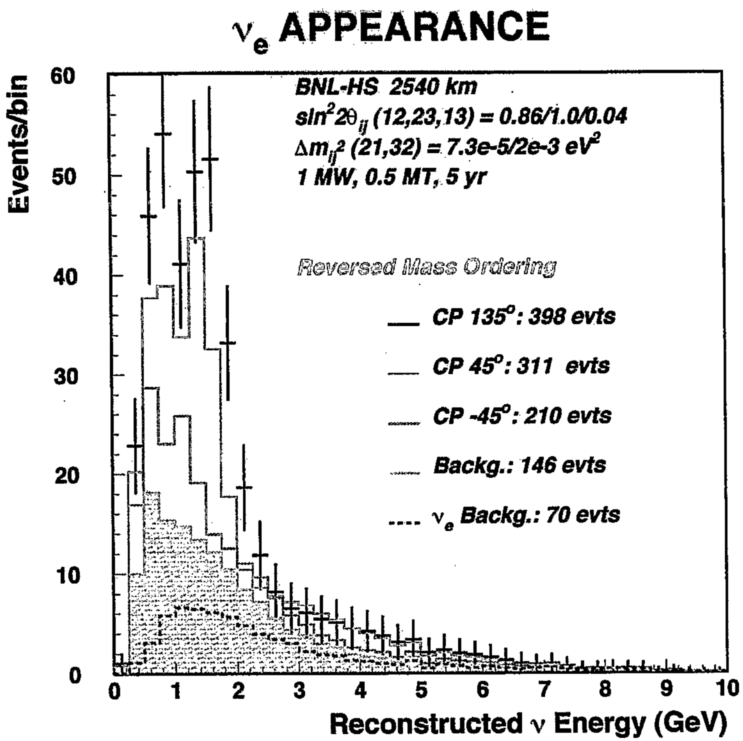
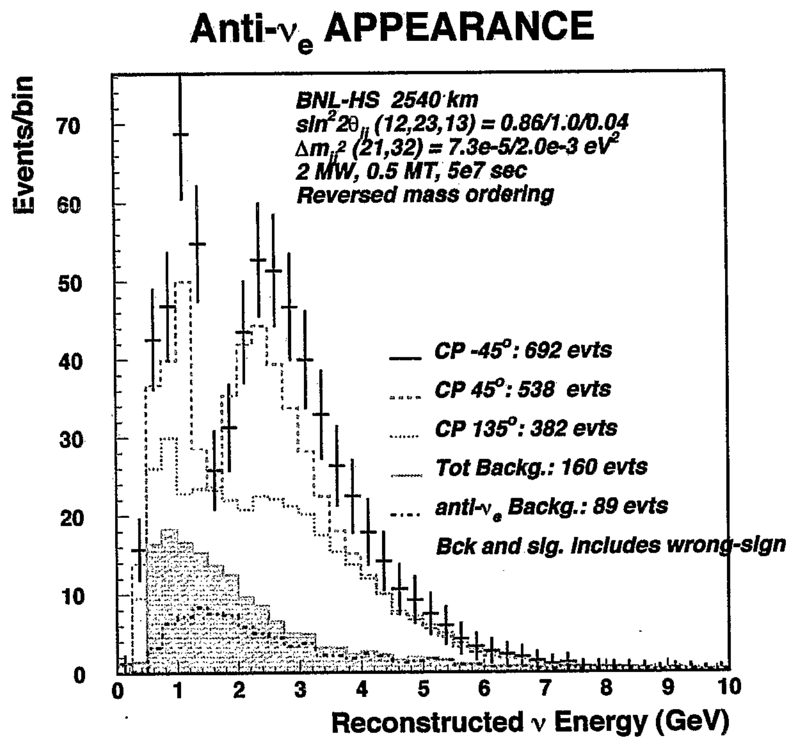


Figure 4: *Simulation of detected electron neutrino (top plots)* ~~*and anti neutrino (bottom plots)*~~ *spectrum (left for BNL-HS 2540km, right for FNAL-HS 1290 km) for 3 values of the CP parameter* δ_{CP}, 135°, 45°, *and* −45°, *including background contamination. Obviously, the dependence of event rate on the CP phase has the opposite order for neutrinos and anti-neutrinos. The hatched histogram shows the total background. The* ν_e *beam background is also shown. The other assumed mixing parameters and running conditions are shown in the figure. These spectra are for the regular mass hierarchy (RO).*

Running for $\sin^2 2\theta_{13}$



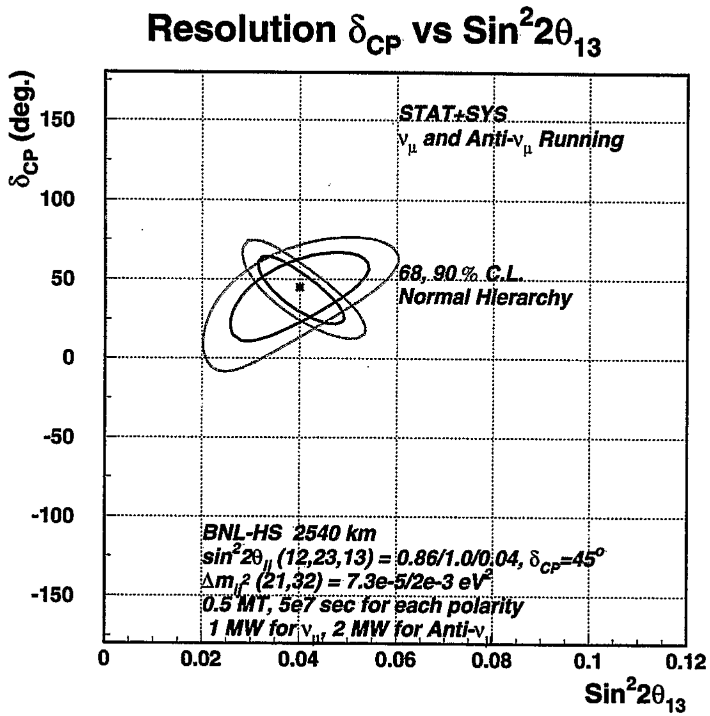


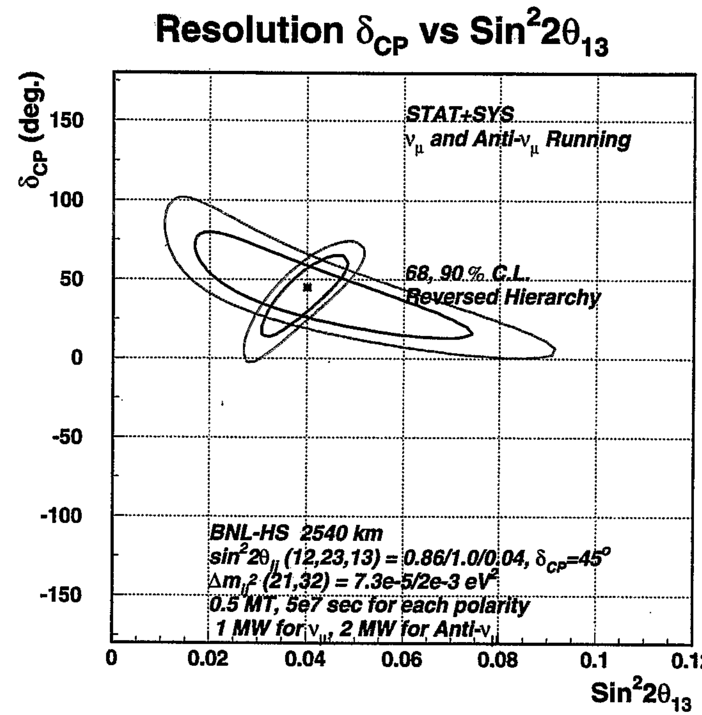
$\Delta m^2_{32} = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

Reversed Mass Hierarchy

Matter effects included.

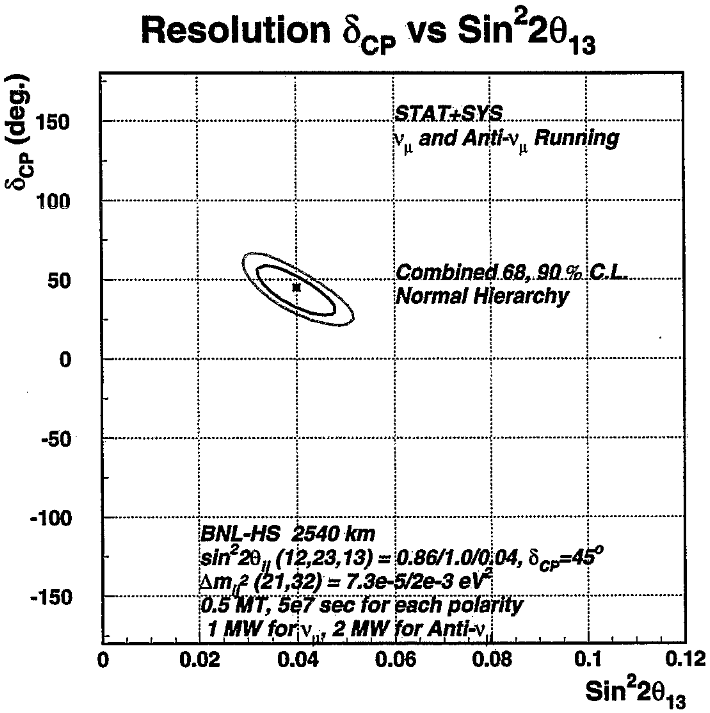
CP with Neutrino and Antineutrino

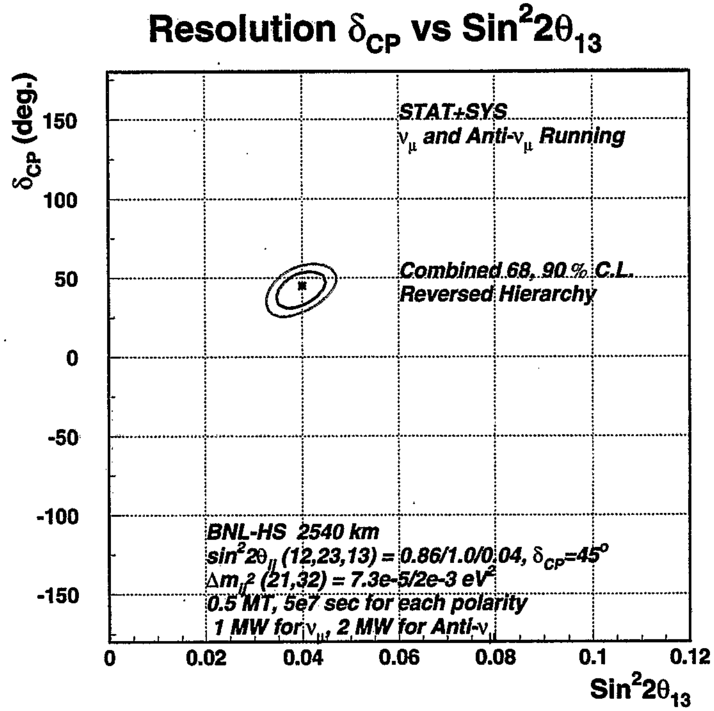




Milind Diwan

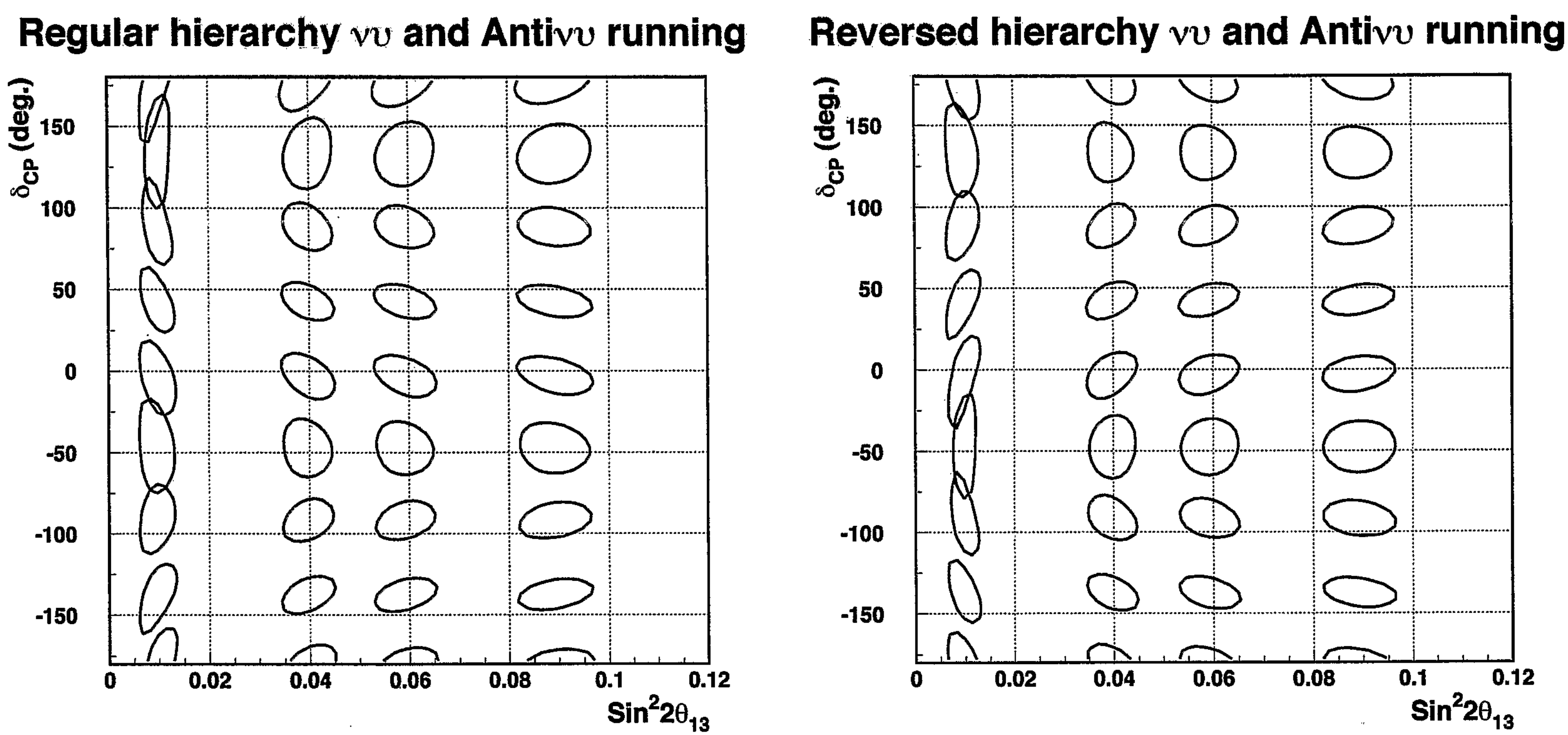
CP with Neutrino and Antineutrino





Milind Diwan

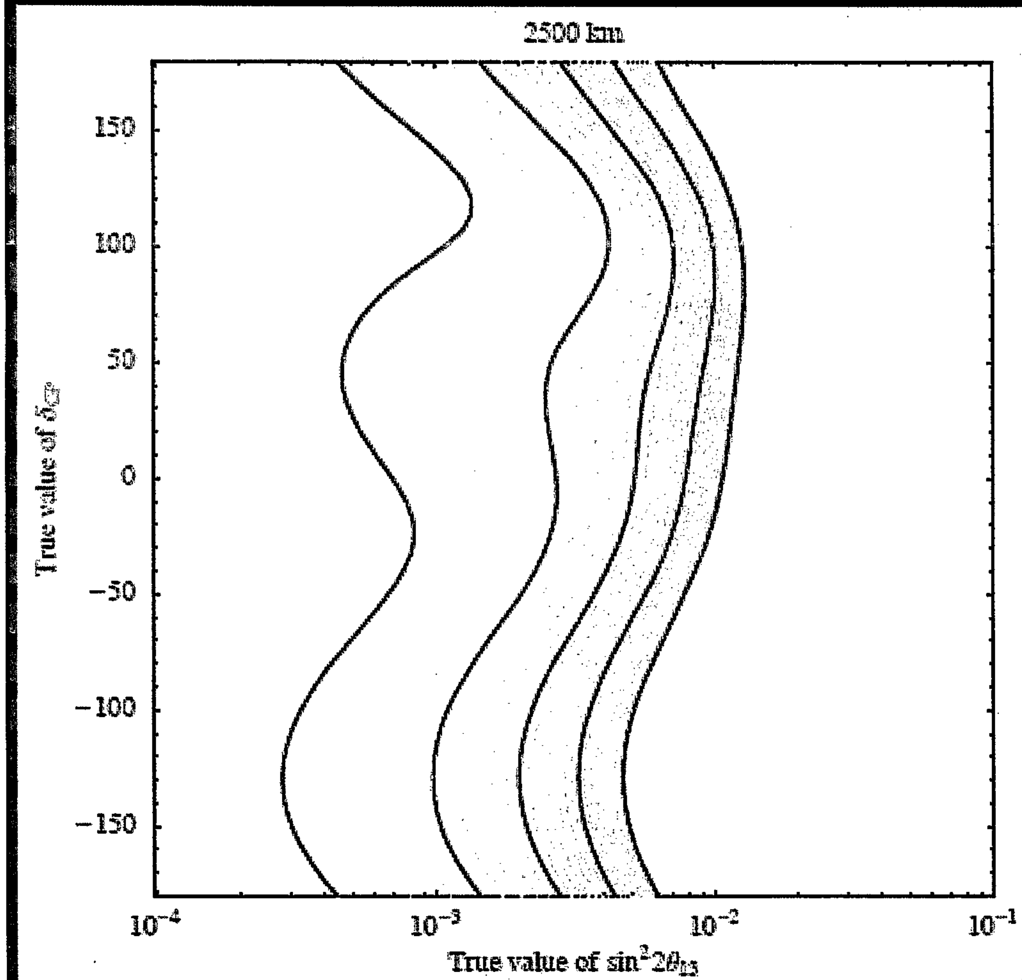
CP measurement after nu and anti-nu



Left: Regular mass hierarchy Right: reversed mass hierarchy.

Only the θ_{23} ambiguity is left.
more about this later...

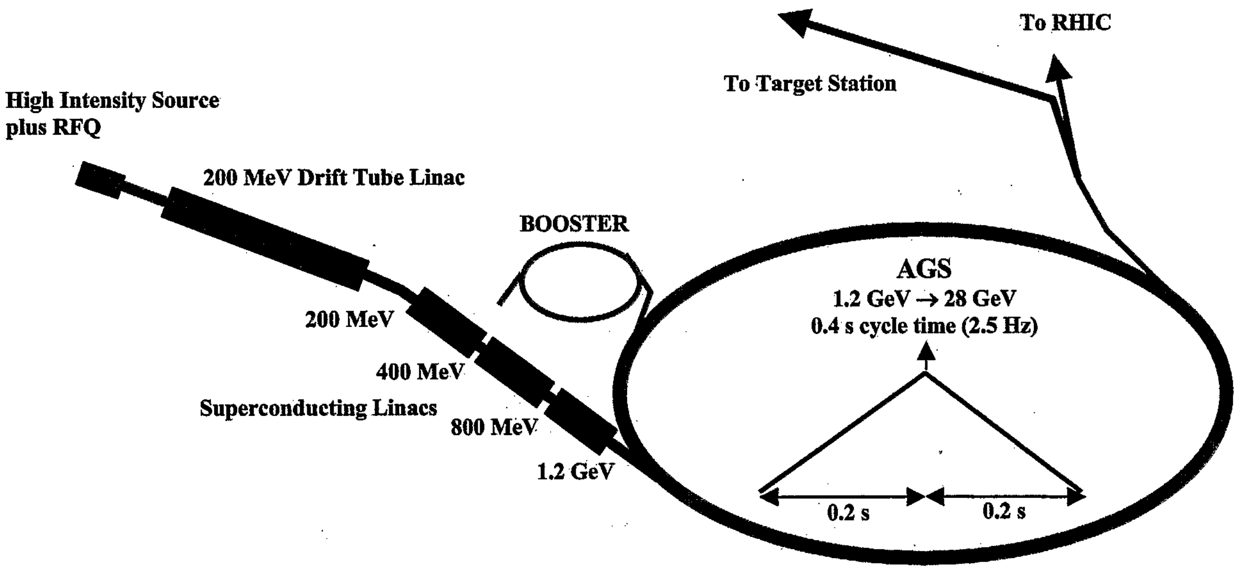
Discovery of θ_{13}



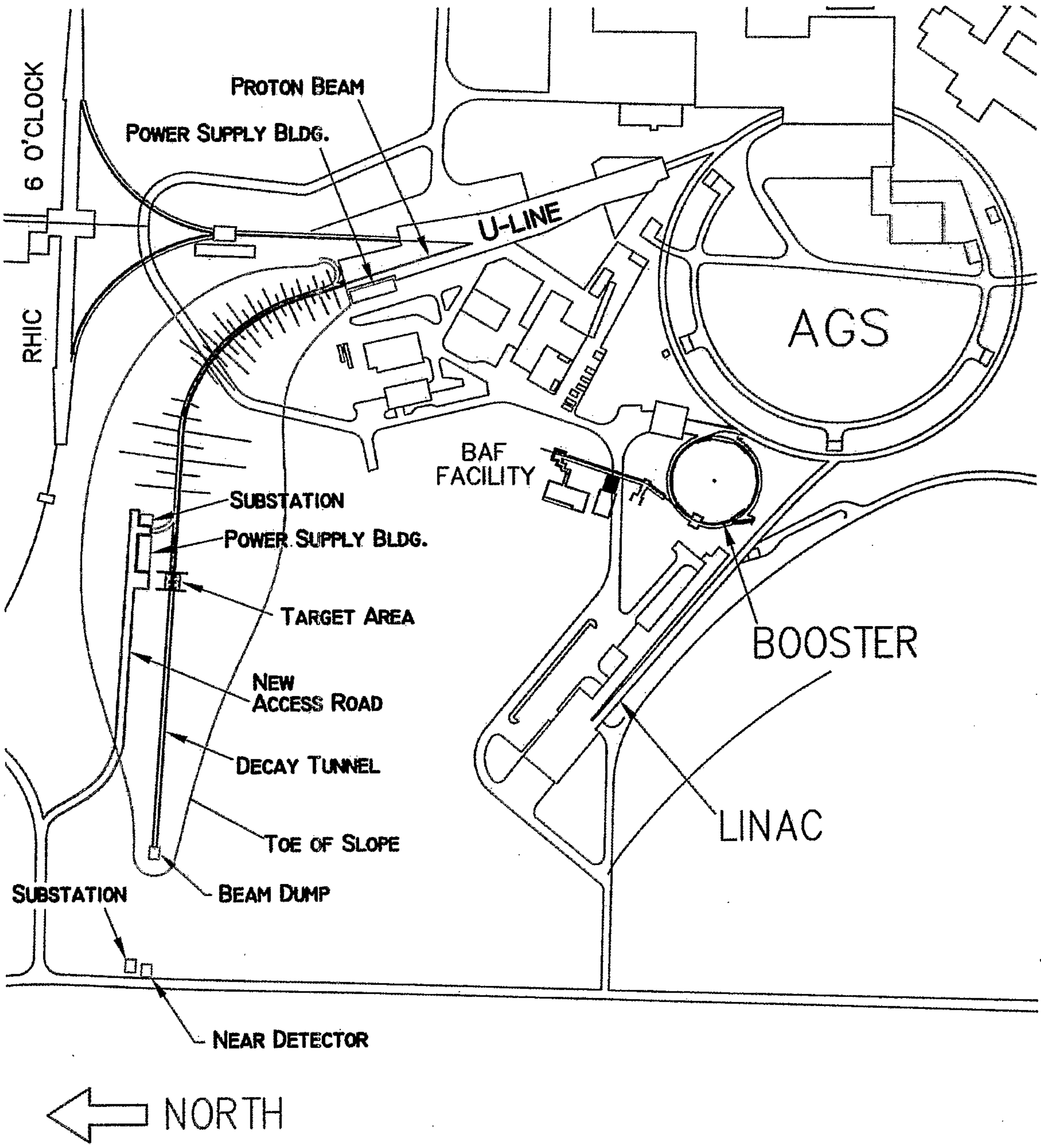
- simulate data for δ and $\theta_{13} \neq 0$
- try to fit them with $\theta_{13} = 0$
- repeat the fit for the wrong hierarchy
- take the smallest χ^2

The Accelerator

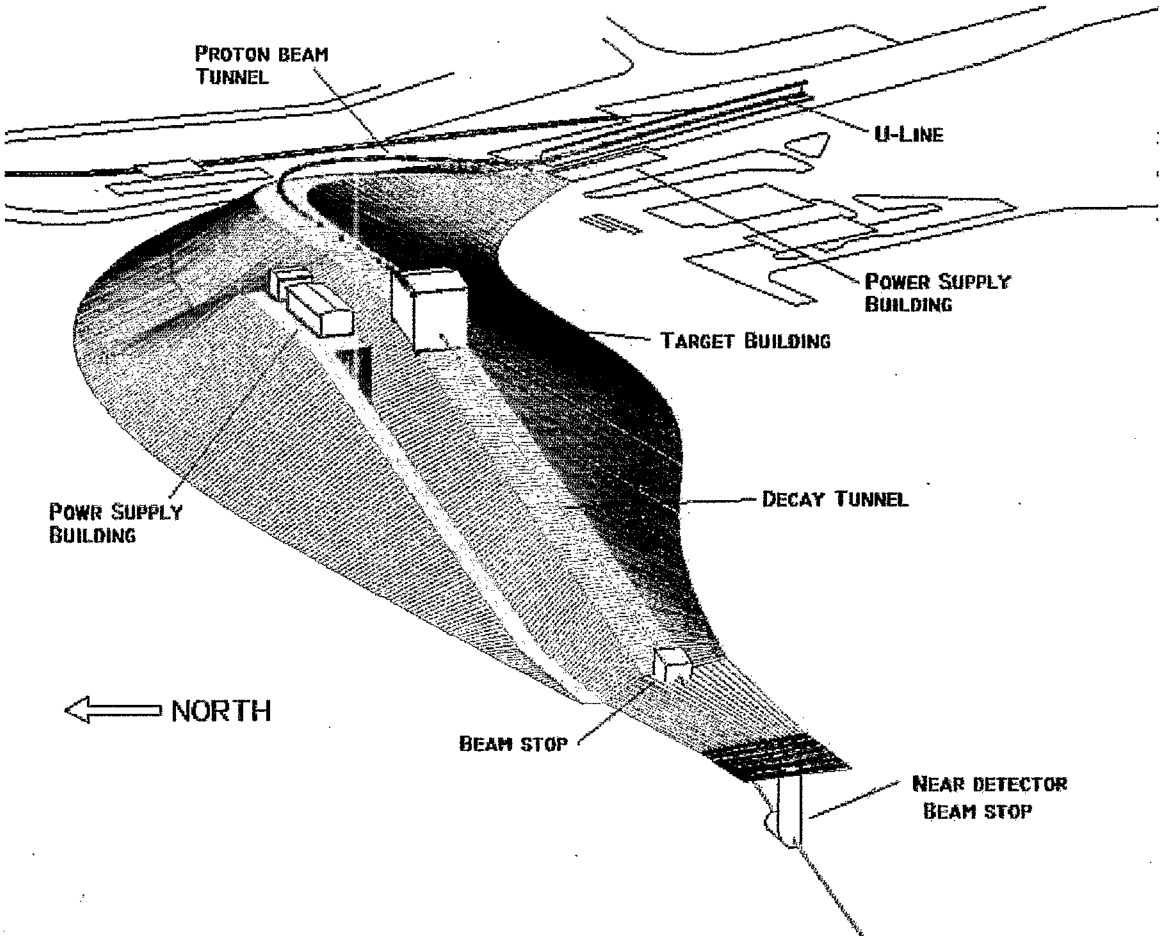
- Conceptually simple upgrade. No magic.
- Run 28 GeV AGS at 2.5 Hz to get 1 MW.
- Need faster proton source: Super Conducting LINAC at 1.2 GeV
- Current: $7 \times 10^{13} ppp$ at 0.5 Hz => LINAC: $10^{14} ppp$ at 2.5 Hz.



Beam 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

Beam 3d


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

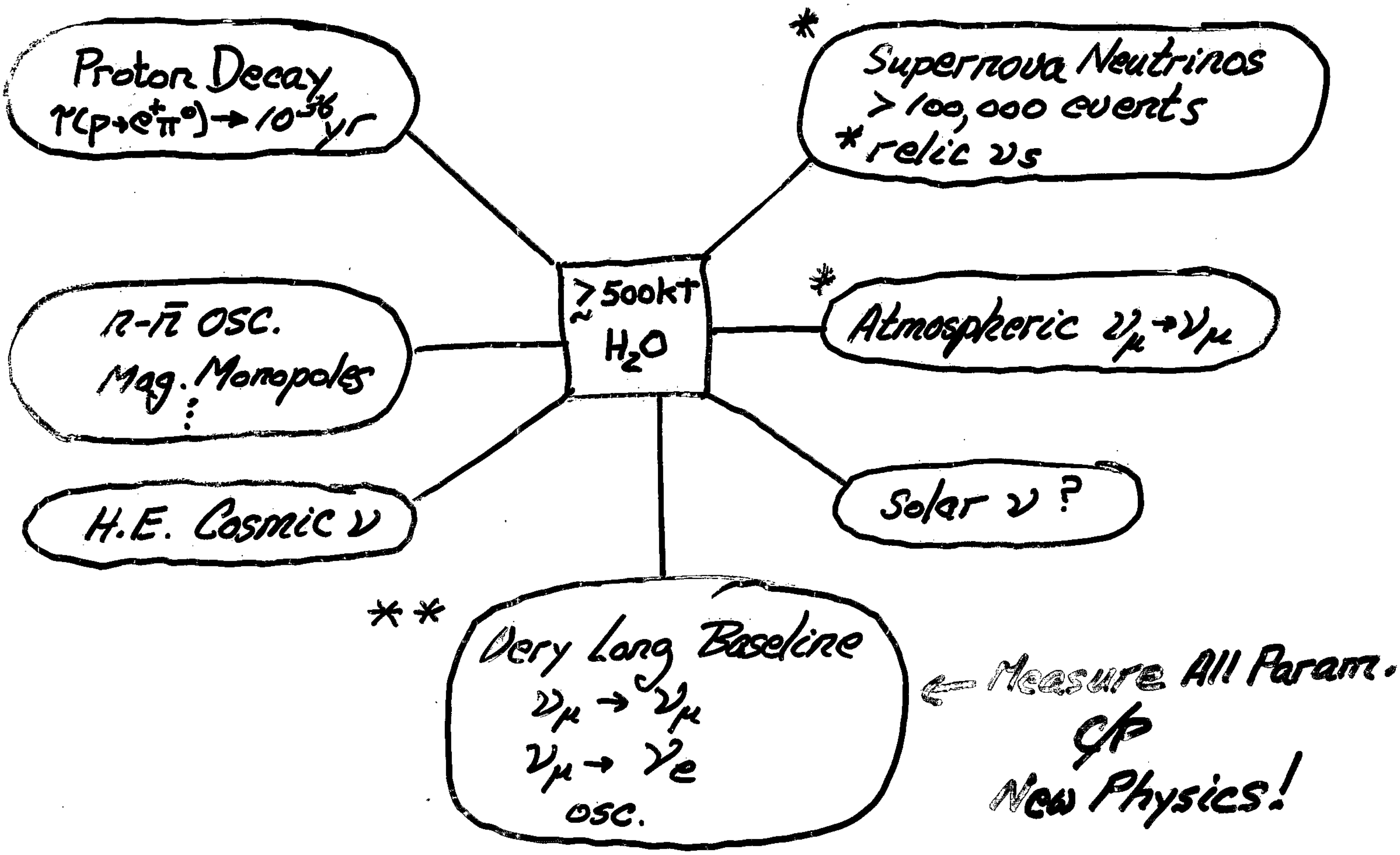
Study of CP in ν osc. also requires $\gtrsim$ 500 kton H_2O

At What Distance?

$\nu_\mu \to \nu_e$ peak $L \simeq 620\,km \times E_\nu/GeV$ $(\Delta m^2_{32} \simeq 2.2\times10^{-3}\,eV^2)$

eg Japan JPARC - SuperK $L = 295\,km$ (short)
$E_\nu \simeq 0.5\,GeV$

Next Generation Water Cerenkov Detector Program (Hybrid?)



Potential Revolutionary Discoveries!

50-100 yr Program!

Very Compelling! Must Do!

4.) Concluding Comments

BNL Initiative - Bold, Doable 50yrs of Physics!
(Great Investment)

Determine 3gen. osc. parameters precisely!
Find Leptonic CP Violation!
Search for New Physics - Sterile ν, Extra Dim.
Dark Energy...

+

Proton Decay $\tau(p \to e^+\pi^0) \to 10^{36}$ yr!
Supernova ν' (Relic + Recent) } outstanding
Atm. ν Precision
Surprises eg Magnetic Monopole

Detector + AGS Upgrade $\lesssim \$1 \times 10^9$ (doable)

USA is large (unique?)
* Needs stimulating + challenging scientific projects

Must Do