W. Marciano
4/22/04

Very Long Baseline Neutrino Oscillation Experiments

(eg. BNL - Homestake 2540 km)

Outline

1) The BNL Concept (Goal CP Violation + Much More)

   i) $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ & $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$

   ii) Very Large Detector (100-500 ktor)

   iii) Very Long Distance (1500-4000 km)

   iv) Conventional Horn Focused $\overset{(-)}{\nu}_\mu$ Superbeam (1-2MW AGS)

2) Neutrino Physics Capabilities

   δ, θ_{13}, θ_{12}, θ_{23}, Δm^2_{31}, sgn Δm^2_{31}, Δm^2_{21}, "New Physics"

   (No 8 Fold Ambiguity !)

3) Recent Developments

   i) Workshops: BNL-UCLA, APS Superbeams

   ii) National Underground Lab

4) Concluding Comments

1) The BNL Concept (Goal CP Violation + Much More)

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

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

$|\Delta m^2_{31}| = |m_3^2 - m_1^2| \simeq \underline{2.5 \times 10^{-3}\ eV^2}$ (Atmosphere)

$\Delta m^2_{21} = m_2^2 - m_1^2 \simeq \underline{7.3 \times 10^{-5}\ eV^2}$ (solar + Kamland)

$\underline{\sin^2 2\theta_{23} \simeq 1 \quad \theta_{23} \simeq 45^\circ}$

$\underline{\sin^2 2\theta_{12} \simeq 0.85 \quad \theta_{12} \simeq 36^\circ}$

$\underline{\sin^2 2\theta_{13} \lesssim 0.2}$, $\underline{\delta = ?}$, $\underline{\text{sgn}\ \Delta m^2_{31} = ?}$, $\underline{\text{New Physics?}}$

Measure All Parameters Precisely!

Next Generation Reactors: $P(\nu_e \to \nu_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)$
(very clean)

$0.01(?) \le \sin^2 2\theta_{13} \le 0.20$ (Must Do)

Our Original Goal: Measure δ in $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Oscillations

Requires: Intense proton source 1~4 MW
Large Detector 100-500 kton {proton decay class}
Water, LArgon...

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

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

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

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

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

$$\left\{ \sin\delta \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \cos\delta \sin \frac{\Delta m^2_{31} L}{4E_\nu} \cos \frac{\Delta m^2_{31} L}{4E_\nu} \right\}$$

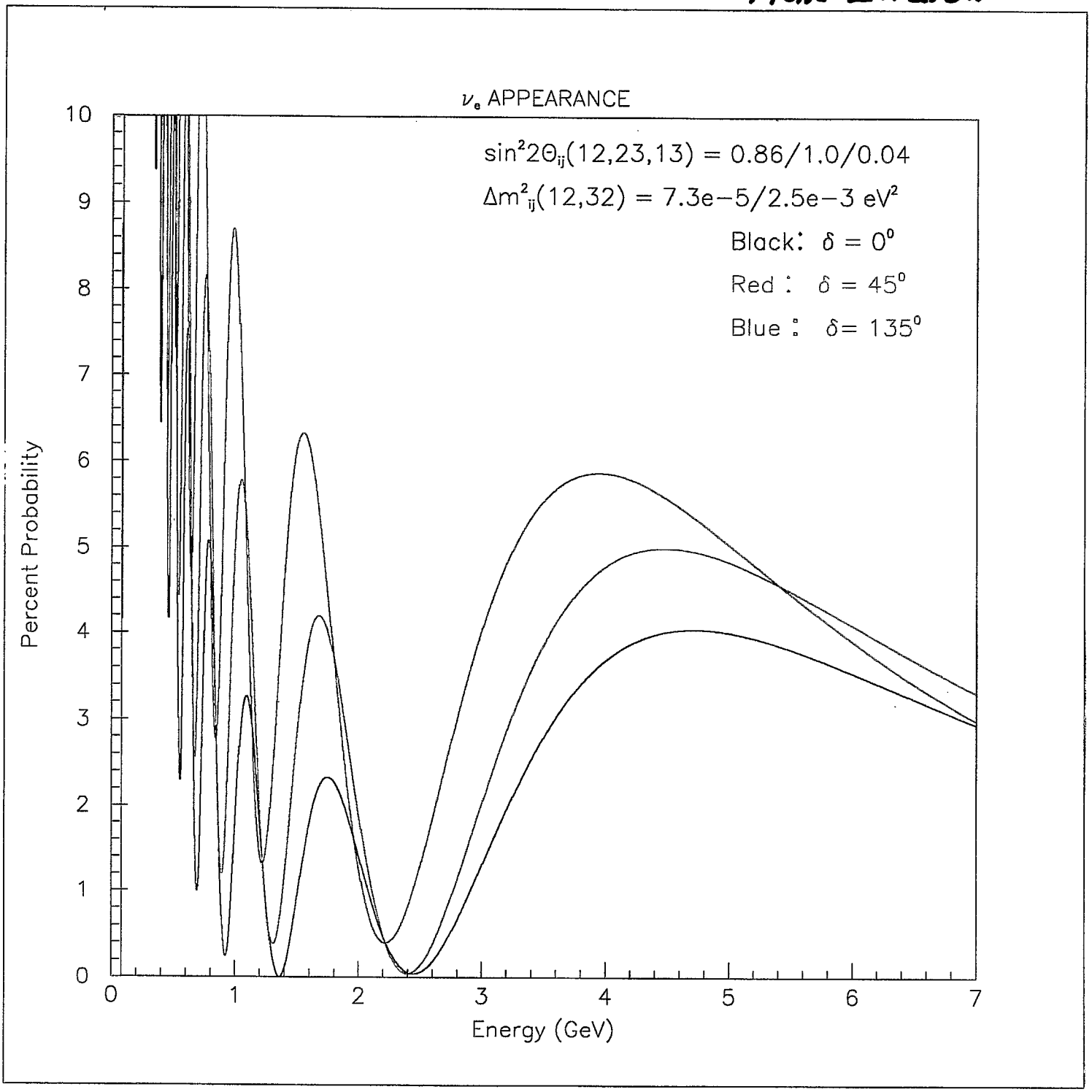
$$P_{III}(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12} \cos^2\theta_{23} \cos^2\theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

For P_I we want $L/E_\nu \simeq 500$ km/GeV

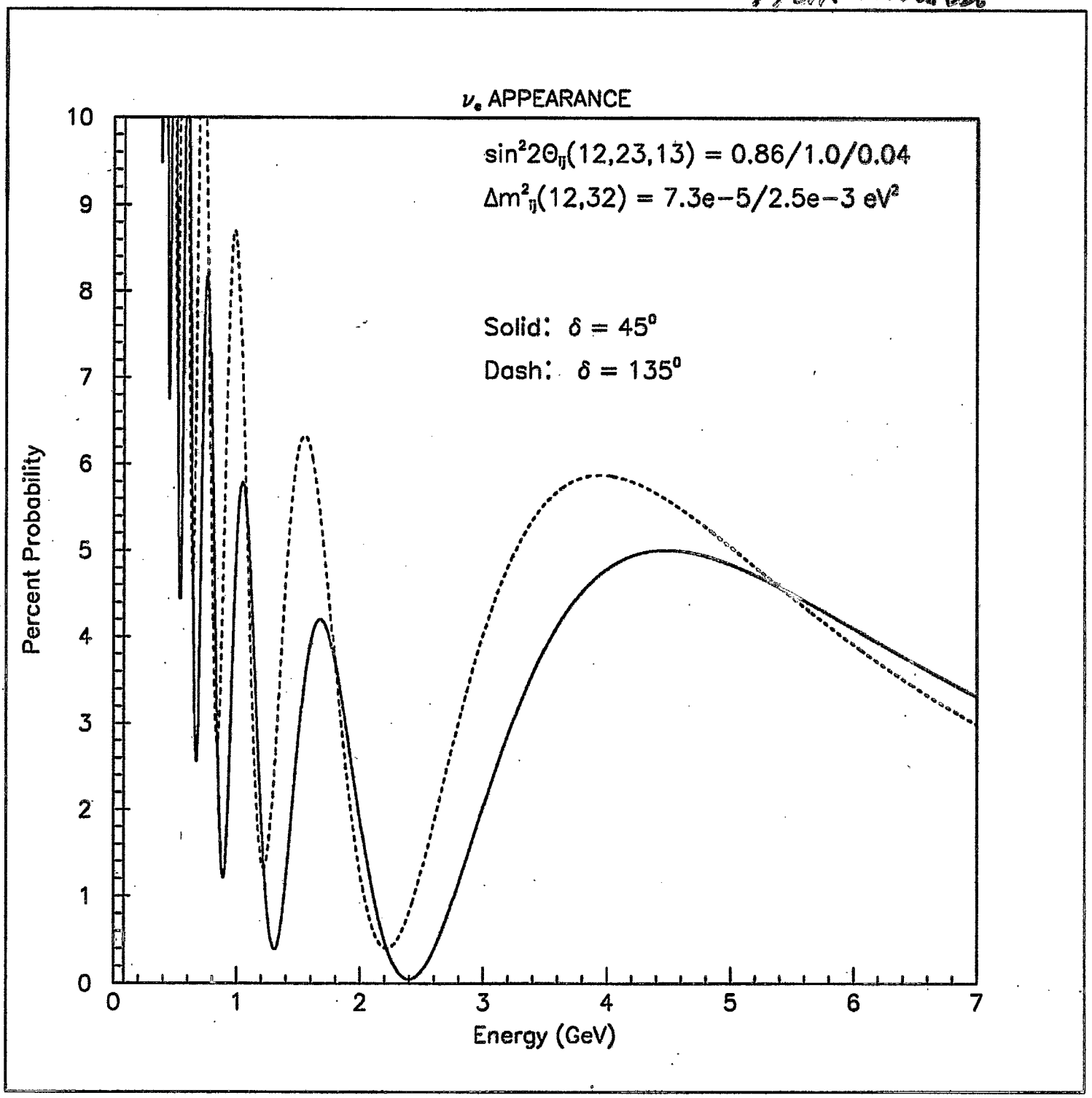
P_{III} we want $L/E \simeq 15{,}000$ km/GeV

P_{II} interference $\to \delta$, CP

From Z. Parsa


ν_e APPEARANCE
$\sin^2 2\Theta_{ij}(12,23,13) = 0.86/1.0/0.04$
$\Delta m^2_{ij}(12,32) = 7.3e{-}5/2.5e{-}3\ eV^2$
Black: $\delta = 0^0$
Red : $\delta = 45^0$
Blue : $\delta = 135^0$
Percent Probability
Energy (GeV)
0
1
2
3
4
5
6
7
8
9
10

From Z. Parsa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Percent Probability
Energy (GeV)
0
1
2
3
4
5
6
7
8
9
10

Statistical ability to measure δ is (roughly) independent of θ_{13} value ($\sin^2 2\theta_{13} \gtrsim 0.01$) and L/E ($\gtrsim 500$ km/GeV)

Minimal Requirements $\simeq$ 100~500 Kton Detector (Acceptance?)
1~2 MW proton source

ii) Detector — 500 Kton H_2O + very good π^0 rejection

$\nu_e n \to e^- p$ quasi-elastic $\to E_\nu$

$\nu_e n \to e^- p \pi$? ($\simeq 3\times$ rate of quasi el.)

100 Kton LArgon Better Acceptance

or Hybrid 250 Kton H_2O + 50 Kton LAr {My Favorite}

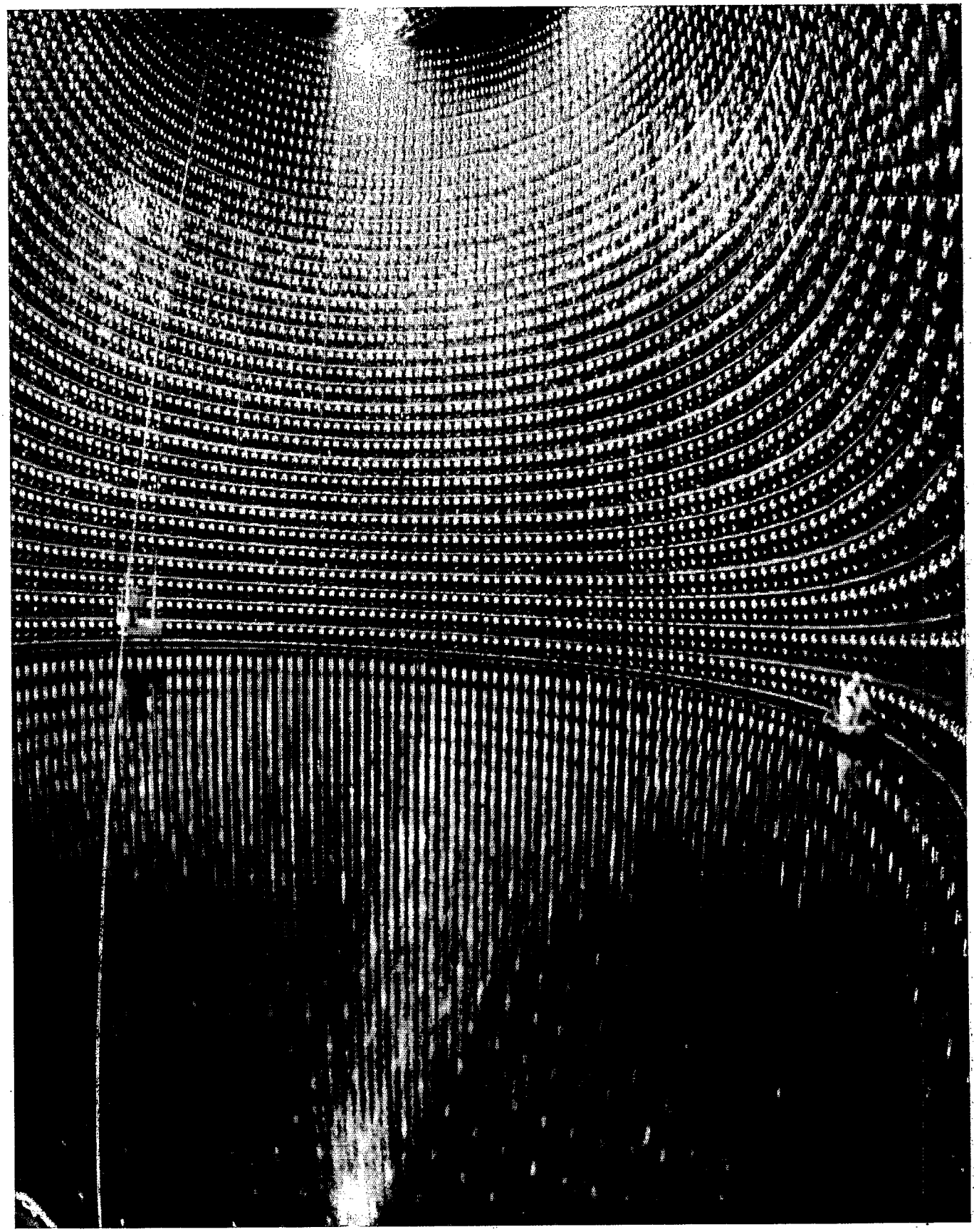
iii) Very Long Distance WBB $0.5\,\text{GeV} \lesssim E_\nu \lesssim 5\,\text{GeV}$

Maximize ν_μ flux → WBB, use it all!

$L/E_\nu \gtrsim 500$ km/GeV → $L \simeq 2500$ km

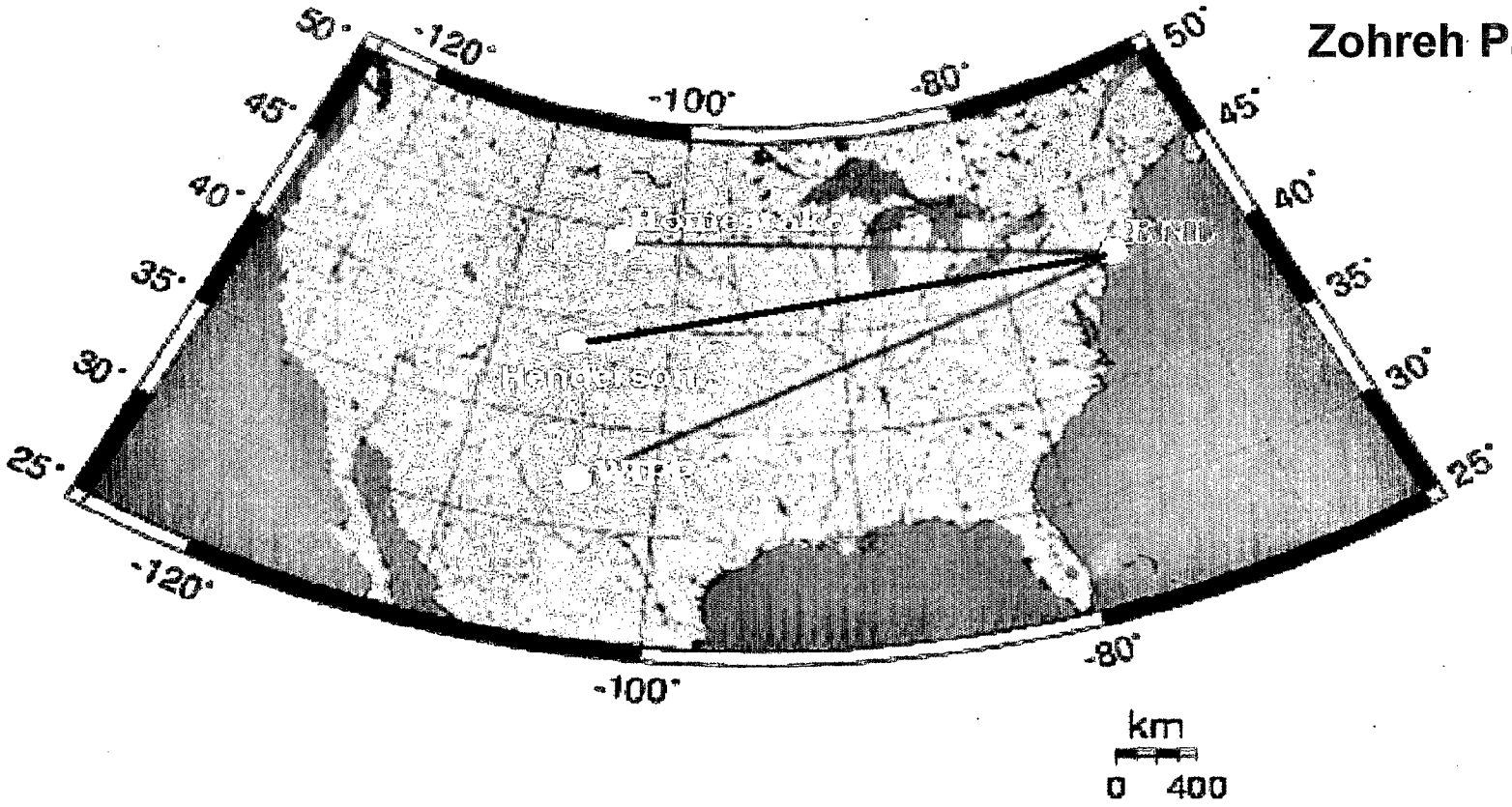
BNL - Homestake 2540 km (1500 - 4000 km okay)

iv) Superbeam — 1-2 MW Proton Source
Horn Focused (Conventional)
On Axis (0°) → WBB
Later Perhaps → 1° Off-Axis ?



BNL Intense Neutrino Beam→ Homestake, WIPP, or Henderson

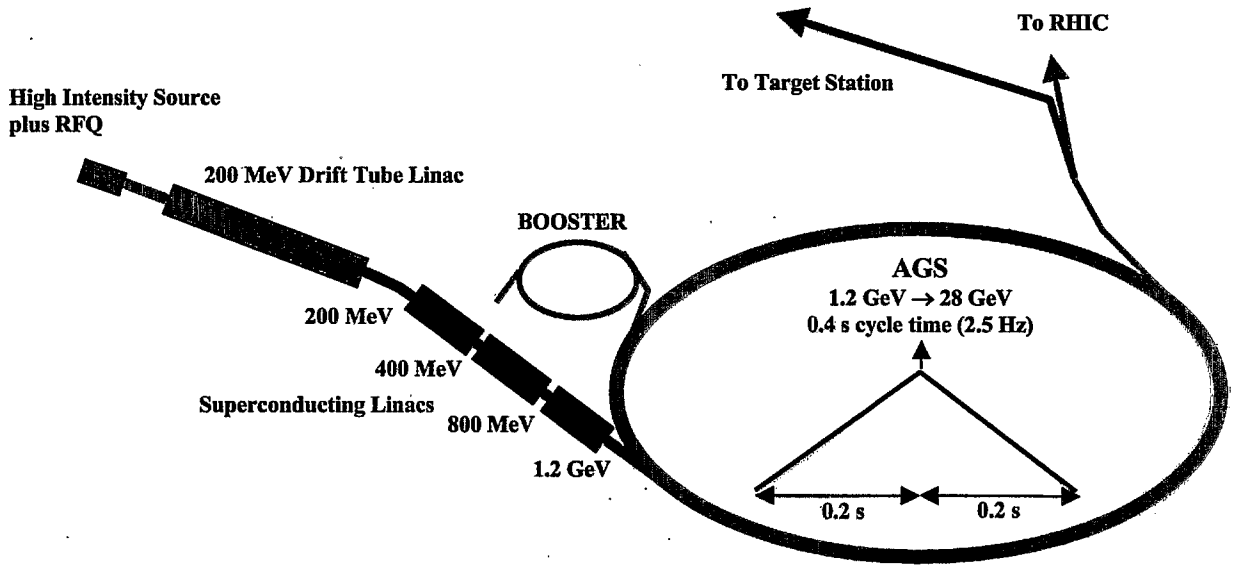
Zohreh Parsa



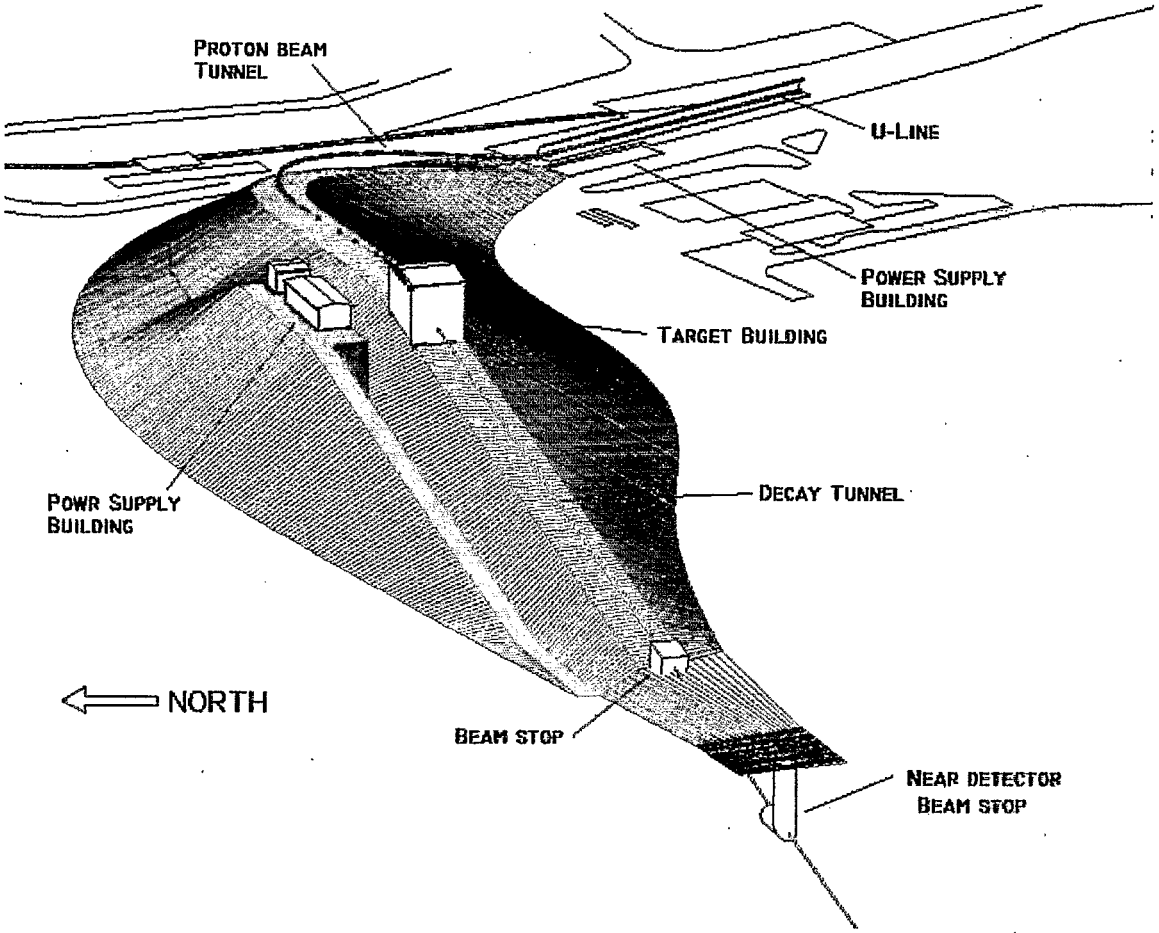
AGS 28 GeV protons, 1 MW beam (power achievable) + 500 kT Water Cerenkov detector, 5e7 sec of running, Conventional Horn based beam →

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.

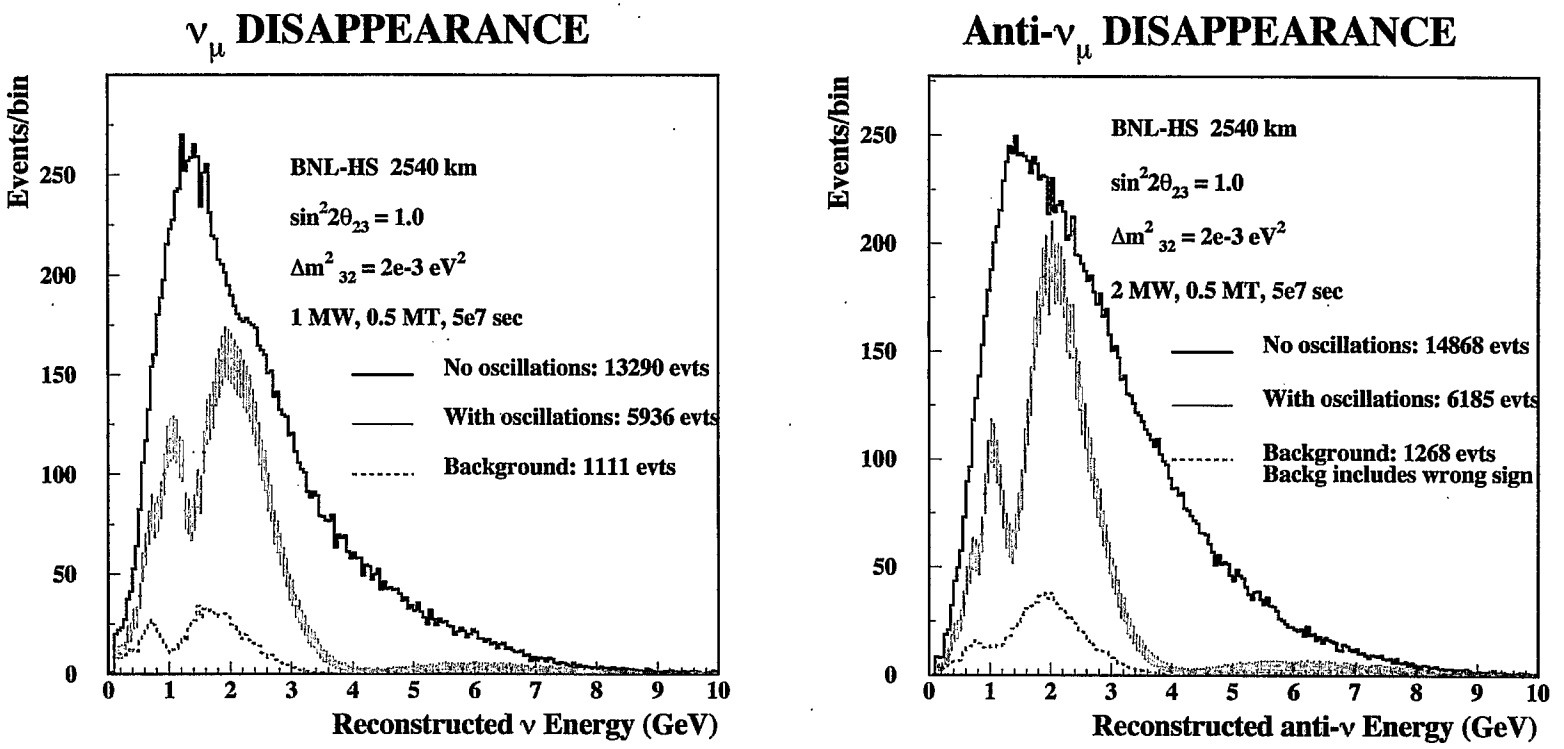


Beam 3d


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

Some comments on detector

- Need much more manpower for detector studies.
- Water Cherenkov
  - 50 kT SuperK is existence proof.
  - Background rejection ? (Yanagisawa)
    need another $\times 3 \rightarrow 5$
  - Additional imaging capability (Viren)
- Liquid Argon TPC
  - scale up to 100 kT module ?
  - Current size 300Ton.
  - Needs detailed simulations.
- Any other technology ?



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

Scenario No. 1 Wide band (No Oscillations $\nu_\mu \to \nu_e$)

1 MW, Neutrinos, 500 kT, L=2540km, $5 \times 10^7 sec$

2 MW, Anti-Neutrinos, 500 kT, L=2540km, $5 \times 10^7 sec$

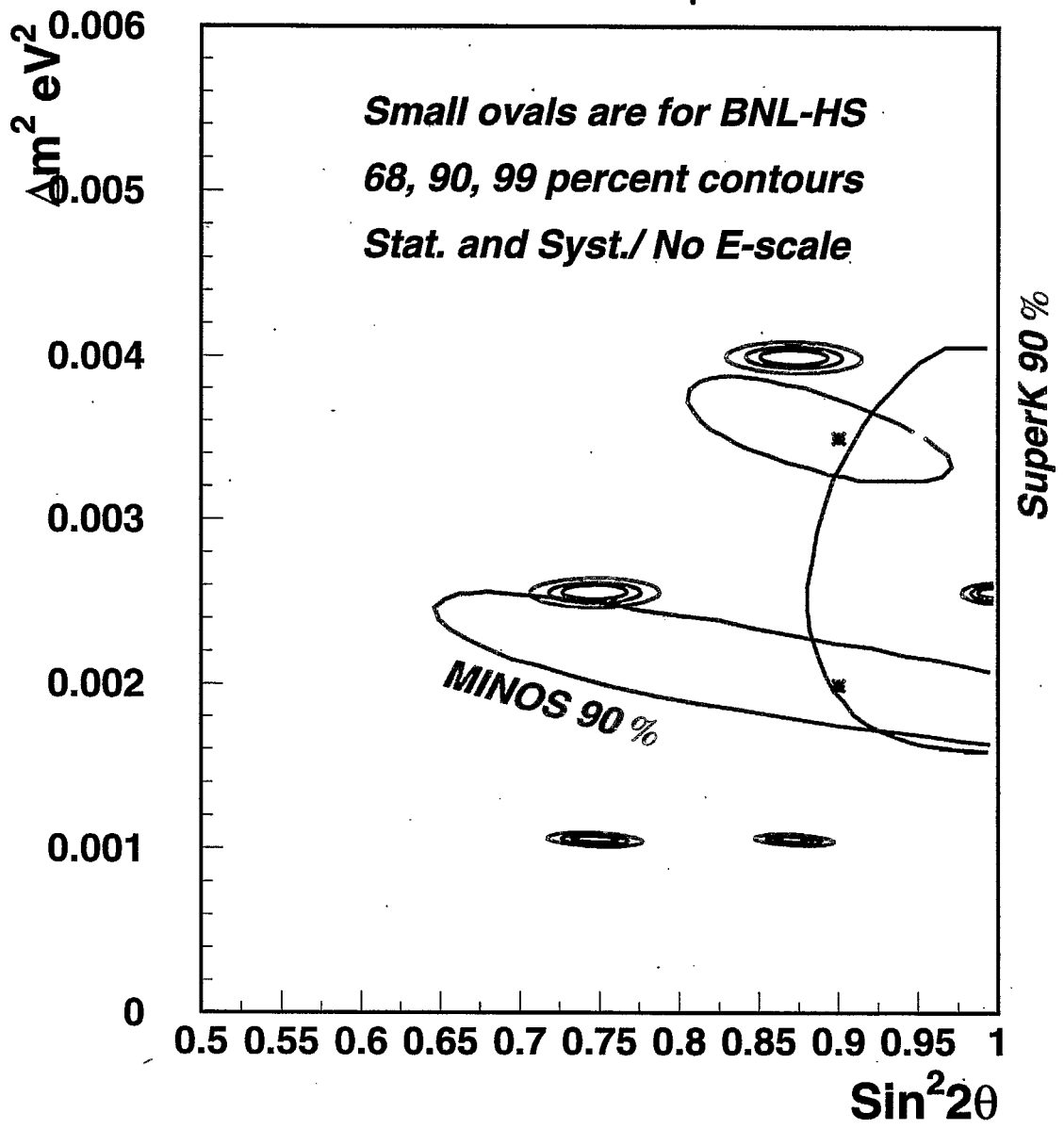
Strong Background Rejection.

CC $\nu_\mu N \to \mu^- X$	51800 (30050)	NC $\nu_\mu N \to \nu_\mu X$	18323 (11540)
CC $\nu_e N \to e^- X$	380 (106)		
QE $\nu_\mu n \to \mu^- p$	11767 (11868)	NC elastic	4575 (3882)
QE $\nu_e n \to e^- p$	84 (80)		
CC Single π	22053 (11872)	NC Single π	7741 (5074)
CC Two π	10143 (3336)	NC Two π	3557 (1630)
CC $> 2\ \pi$	4882 (500)	NC $> 2\ \pi$	1729 (560)
CC $\nu_\tau N \to \tau^- X$	~ 110 (40)	(depends on Δm^2)	

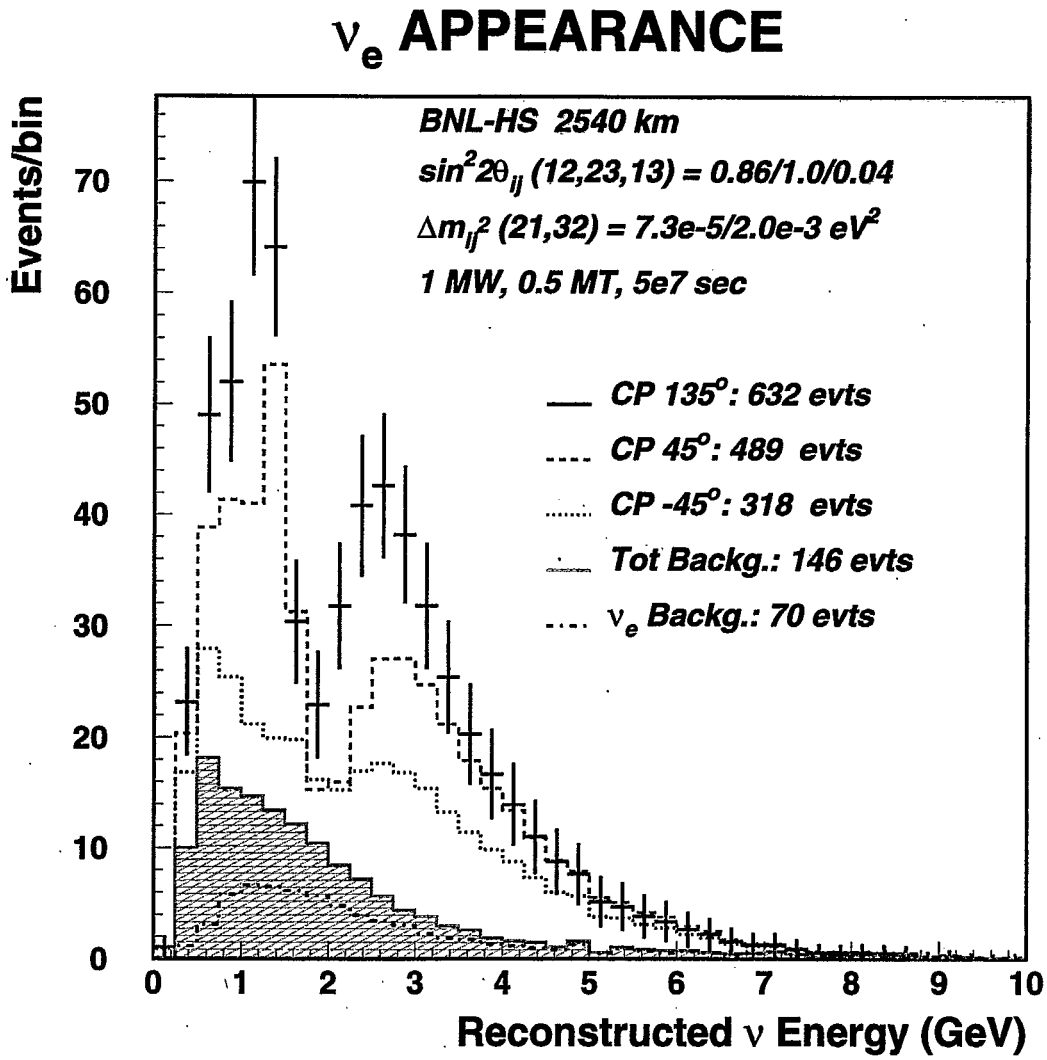
Anti-neutrino rate (brackets) for 2 MW.

(Add Nu cont. to antinu rate: 7696 CC and 2600 NC.)

Test points for ν_μ disapp



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

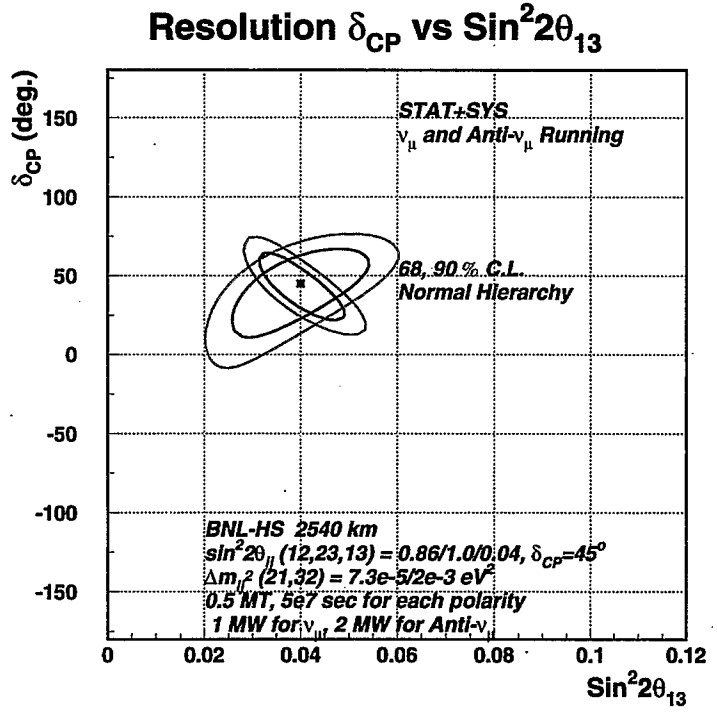


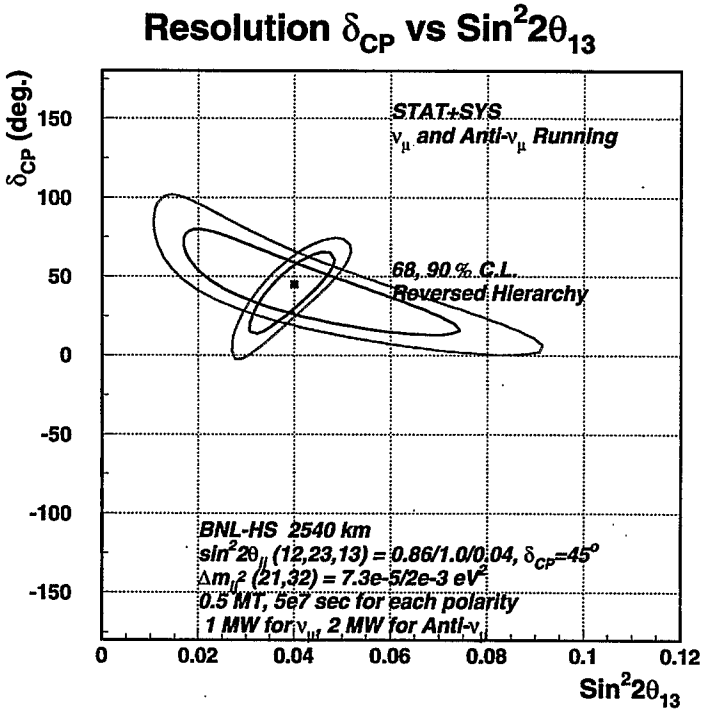
$\Delta m^2_{32} = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

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

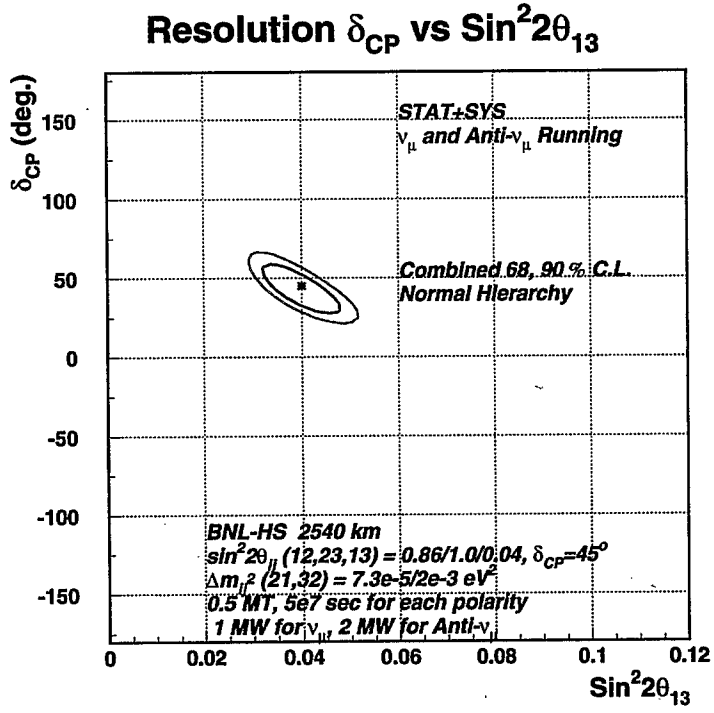
Matter effects included.

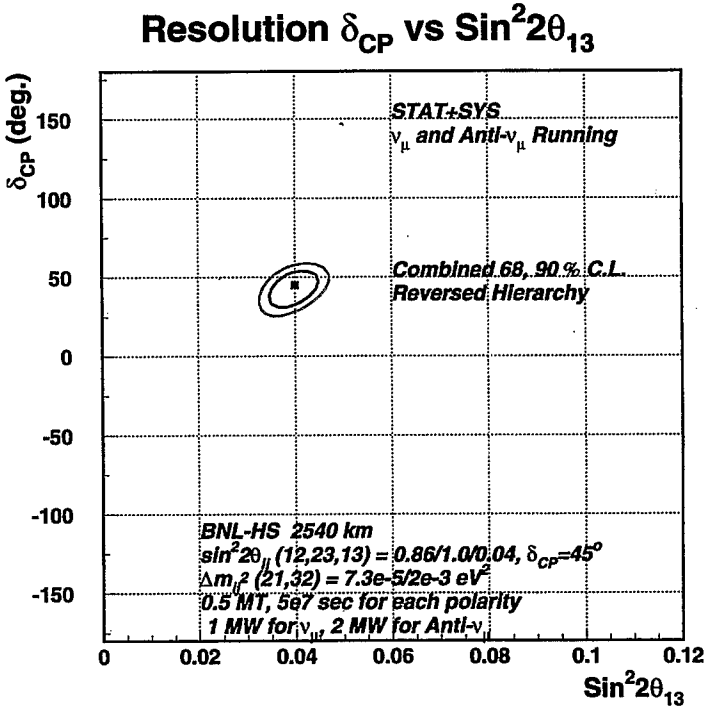
CP with Neutrino and Antineutrino



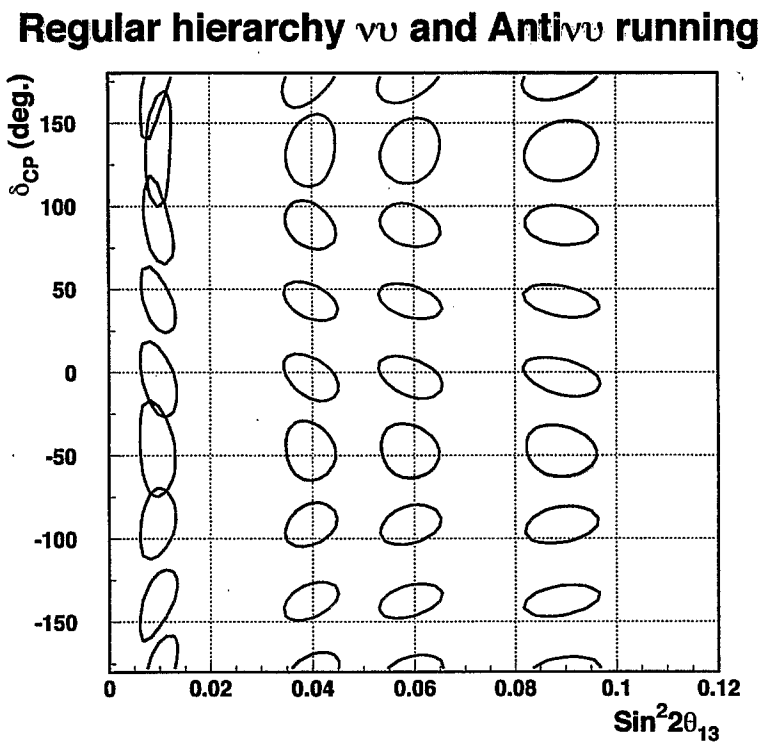


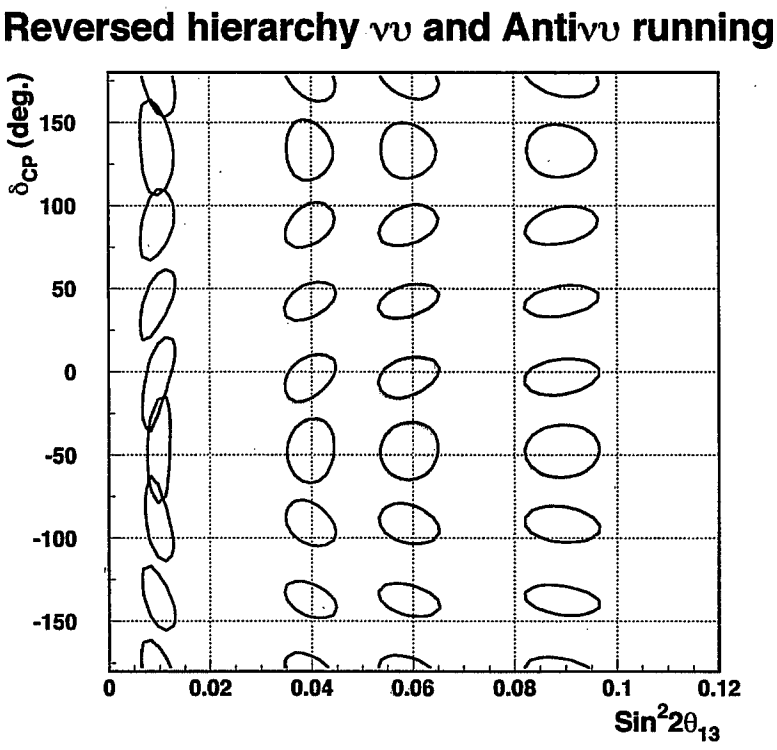
CP with Neutrino and Antineutrino





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...

2) Neutrino Physics Capabilities

(Possible) Phase I: 1MW AGS → WBB ν_μ only
$T = 5\times10^7$ sec
500 kton H_2O
Use only quasi-elastic $\nu_\ell n \to \ell^- p$

$\nu_\mu \to \nu_\mu$ → 3peaks → $\sin^2 2\theta_{23}$, $|\Delta m^2_{31}|$ } to ± 1%!

$\nu_\mu \to \nu_e$ → P_I + matter P_{II} P_{III}

5-3 GeV 3-1GeV 1-0.5GeV

5-3GeV → Matter Effect → sgn Δm^2_{31} (easy)
$\sin^2\theta_{23}\sin^2 2\theta_{13} \lesssim 0.0025$

3-1 GeV → $\sin\delta + \cos\delta$ $\Delta\delta \simeq \pm 20°$

1-0.5GeV → $\cos^2\theta_{23}$ $\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21} L}{4E_\nu}$

$\theta_{23}, \frac{\pi}{2}-\theta_{23}$? KAMLAND

* BNL + Reactors → All θ_{ij}, δ, Δm^2_{ij} Precisely Determined
No Degeneracy!

Anomalies → "New Physics"
Sterile ν, Extra Dim., Dark Energy ? ...

Phase II AGS → 2MW Run $\bar{\nu}_\mu$ for 5×10^7 sec

3) Recent Developments

i) Workshops:

BNL-UCLA 12/03 D. Cline & N. Samios
Proton Decay & Neutrino Osc
Gov. of S.D. Homestake Commitment
LArgon looks impressive

APS Superbeam Working Group
W. Marciano & D. Michael
FNAL Meeting Jan 2004
π^0 rejection in H_2O questions raised
Dark Energy Sensitivity? (Theory?)

BNL-UCLA & APS Joint Meeting
at Brookhaven 3/04
* π^0 rejection in H_2O looks much better
LArgon continues to be impressive

August 2004 APS Report
Dec. 2004 BNL-UCLA Meeting at UCLA

ii) National Underground Lab

NSF Call for proposals
We will propose: Neutrino Osc & Proton Decay Detector
$L \simeq 1500 \sim 4000$ km Site Independent
BNL - Homestake or Henderson Site Specific

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

} outstandin

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

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

Must Do