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10/4/04

Brookhaven Neutrino Studies: Goals + Plans

(Very Long Baseline ν-osc. eg BNL-Homestake 2540km)

Outline

1) Physics Goals: CP Violation + Much More!

* 2) AGS Upgrade: 0.14MW → 1MW → 2MW (?)
CDR0 (Under Study)

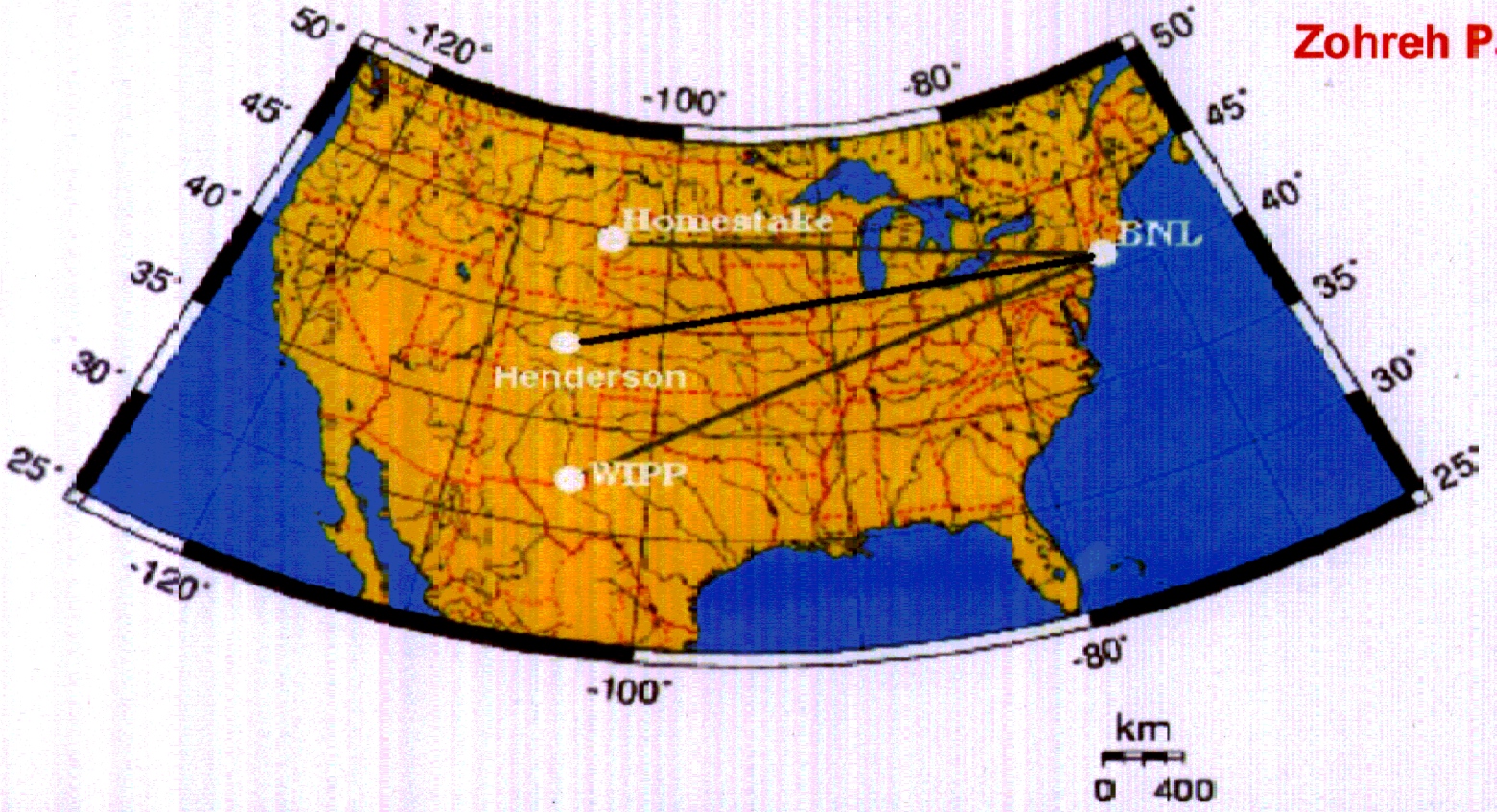
3) Detector: 500 kton H_2O or equivalent (eg LAr)
proton Decay ~150kton

4) Other Physics: proton decay, atm ν, supernova ν...

5) Outlook

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 →

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

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

$0 \leq \delta < 360°$ 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

± Hierarchy

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

2) Determine sgn Δm^2_{32} Mass Hierarchy

3) Precision θ_{23} (±1°), $90° - \theta_{23}$ ambiguity

4) Precision θ_{13} + θ_{12}

5) Precision Δm^2_{32} (±1%) Δm^2_{21} (±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 eg BNL - Homestake

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

Large Detector ~ 300 kton H_2O (Proton Decay)

To measure δ: (to ~ ±20°) 1MW Proton Driver → WBB (0.5-5GeV) On Axis
500kton H_2O
5×10^7 sec
$\nu_\mu \to \nu_e$ ($\nu_\mu \to \nu_\mu$ at same time)

In the same experiment determine $\text{sgn}\,\Delta m^2_{32}$
and measure all parameters precisely!

Search For New Physics

* Basic Starting Point: Statistical Ability to determine
δ insensitive to L & specific
value of $0.01 \leq \sin^2 2\theta_{13} \leq 0.2$!

So, send a ν beam anywhere in the USA where
a very large detector is located ~ 500kton H_2O

Phase I: 1MW $\nu_\mu \to \nu_\mu + \nu_\mu \to \nu_e$ for 5×10^7 sec
Phase II: 2MW $\bar{\nu}_\mu \to \bar{\nu}_\mu + \bar{\nu}_\mu \to \bar{\nu}_e$ for 5×10^7 sec
} example

or start with 2MW 3×10^7 sec ν_μ + 5×10^7 sec $\bar{\nu}_\mu$

Running Strategy - Discovery Dependent

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

θ_{23}, $\frac{\pi}{2} - \theta_{23}$ degeneracy (Is $\theta_{23} = 45°$?)

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 + ...

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

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

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

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

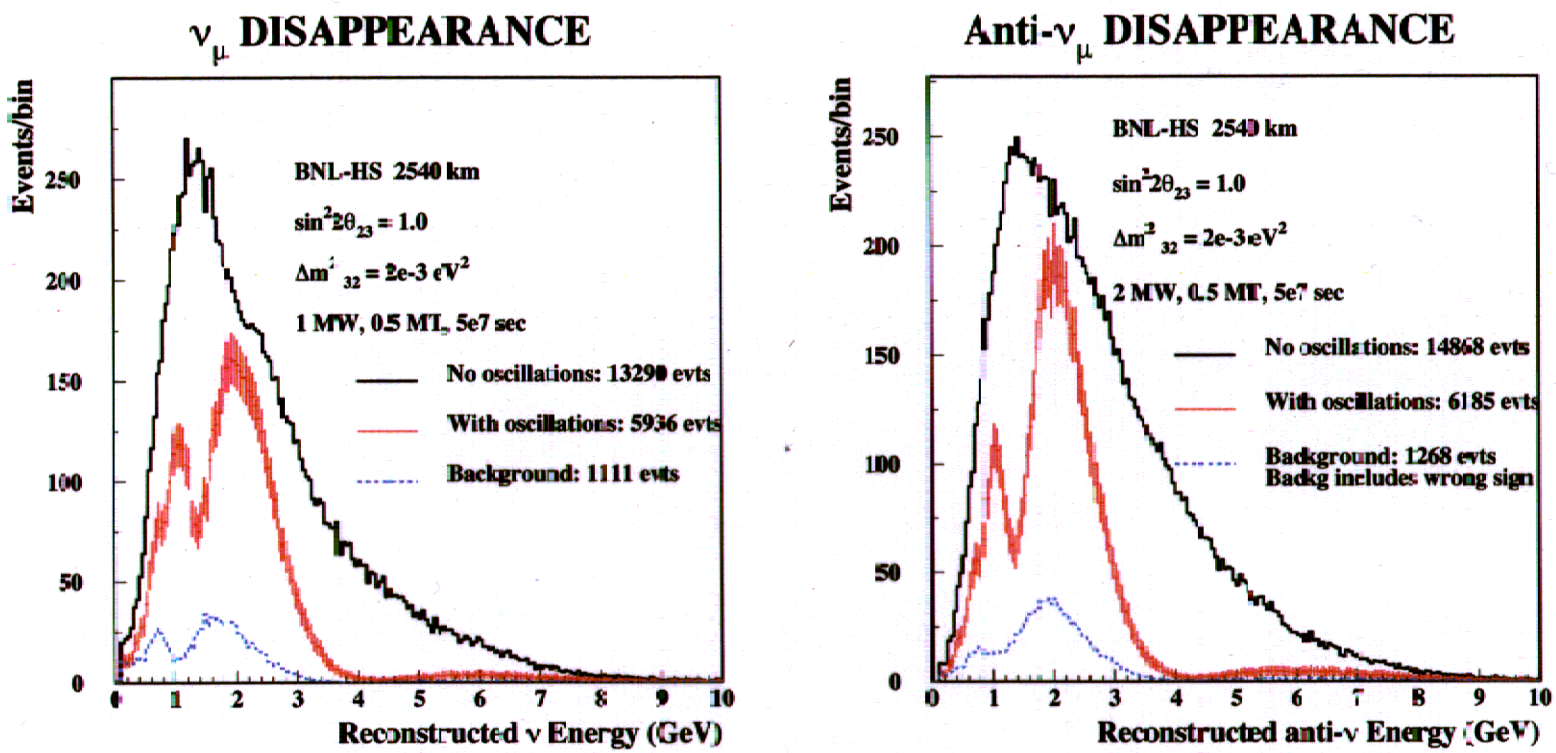
For P_I we want $L/E_\nu \simeq 500$ km/GeV
P_{III} we want $L/E \simeq 15{,}000$ km/GeV
} 1st Peaks

P_{II} interference → δ, $\not{CP}$

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

$$\times \cos\left(\frac{\Delta m^2_{31} L}{4E_\nu} - \delta\right) \qquad 0 \le \delta < 2\pi$$

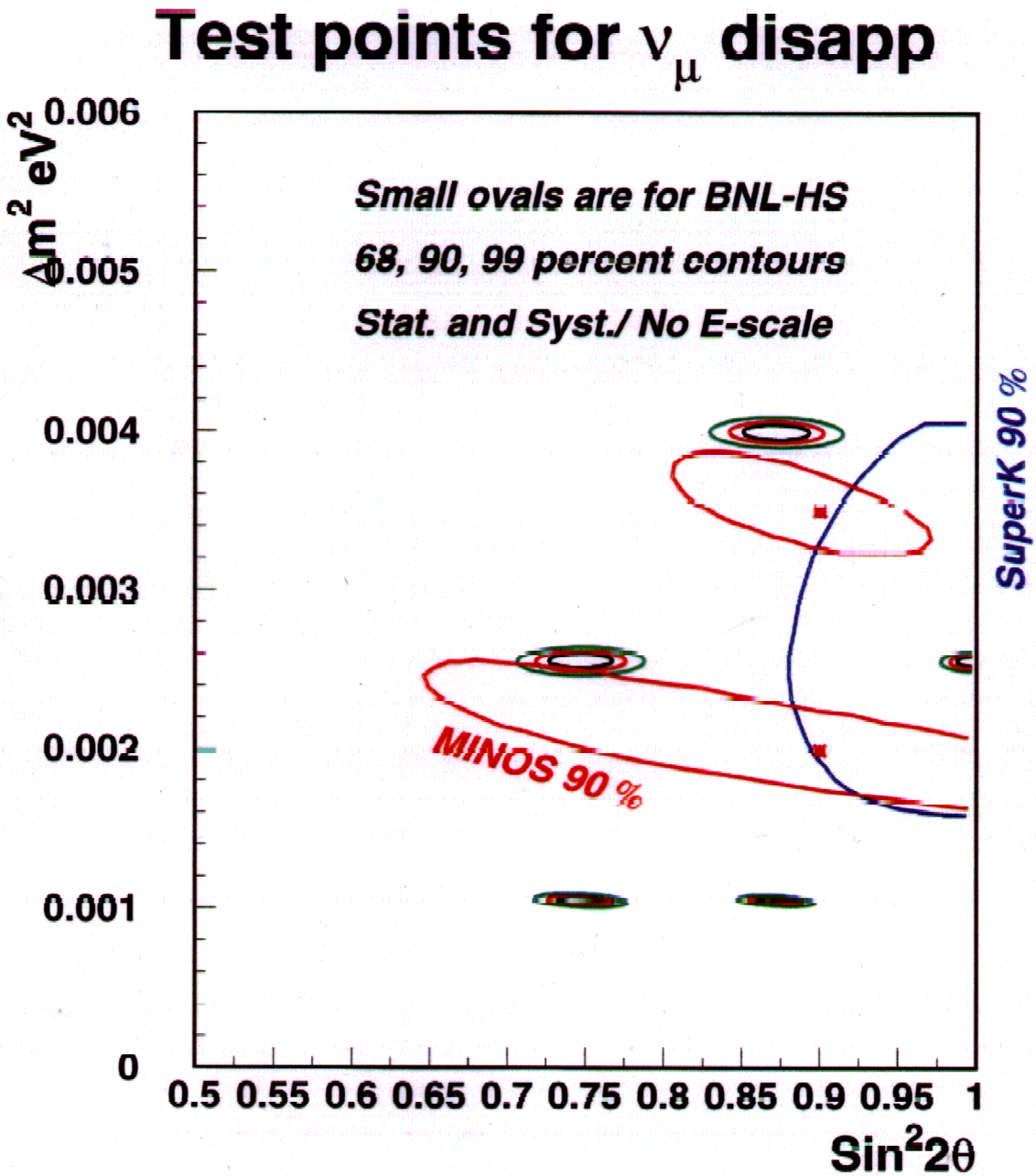
$\frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}$ peaks



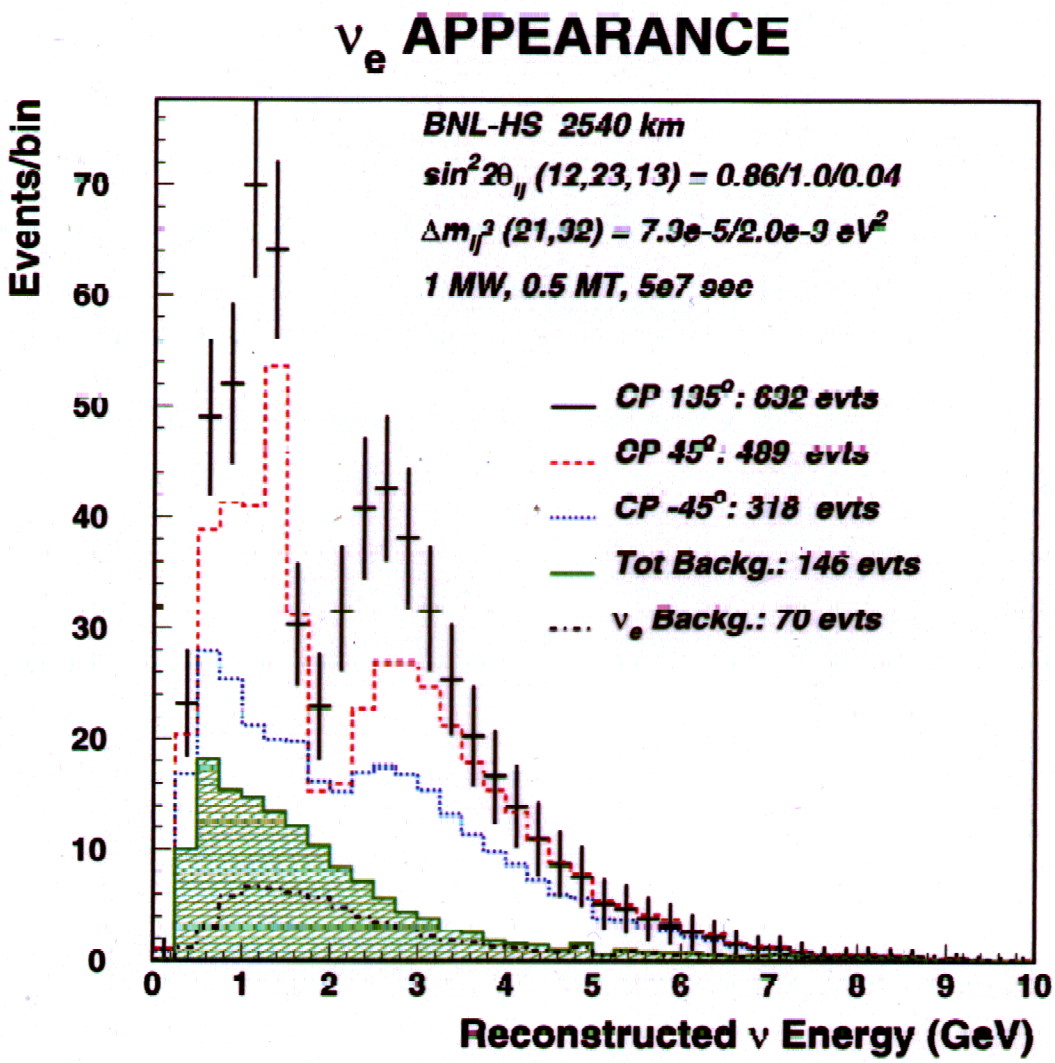
Node pattern provides high Δm^2_{32} resolution. Energy calibration is very important.

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

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


Test points for ν_μ disapp
Δm^2 eV^2
0.006
0.005
0.004
0.003
0.002
0.001
0
Small ovals are for BNL-HS
68, 90, 99 percent contours
Stat. and Syst./ No E-scale
SuperK 90 %
MINOS 90 %
0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1
Sin^{2}2θ

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

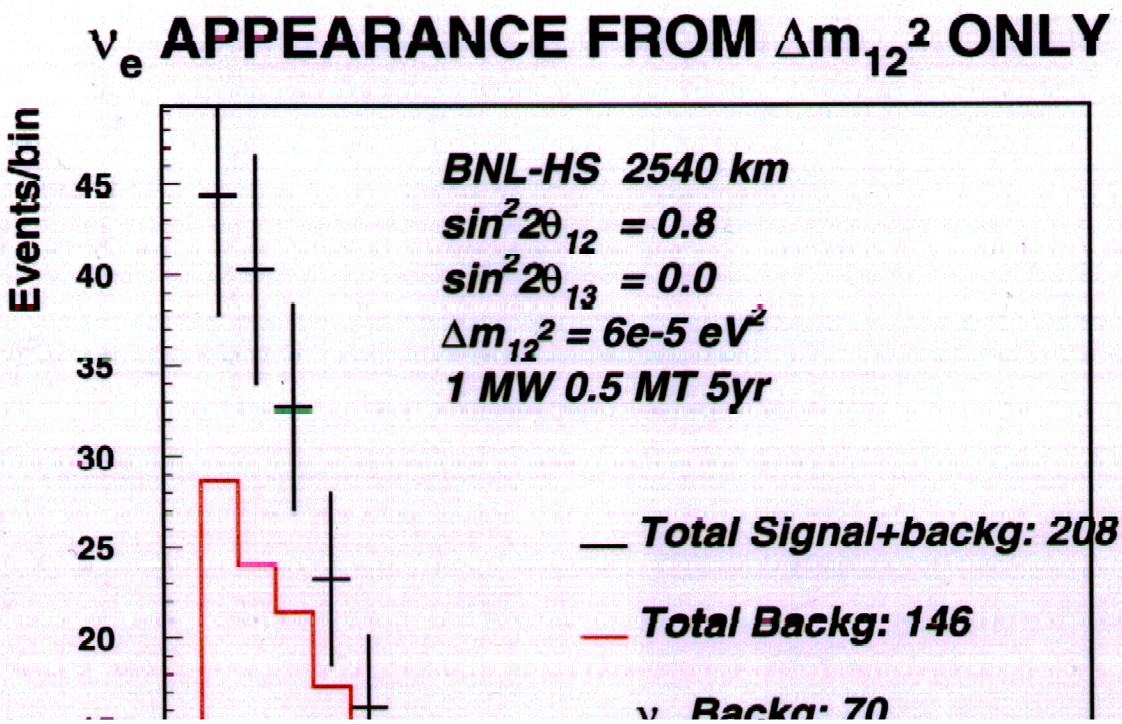


$\Delta m^2_{32} = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

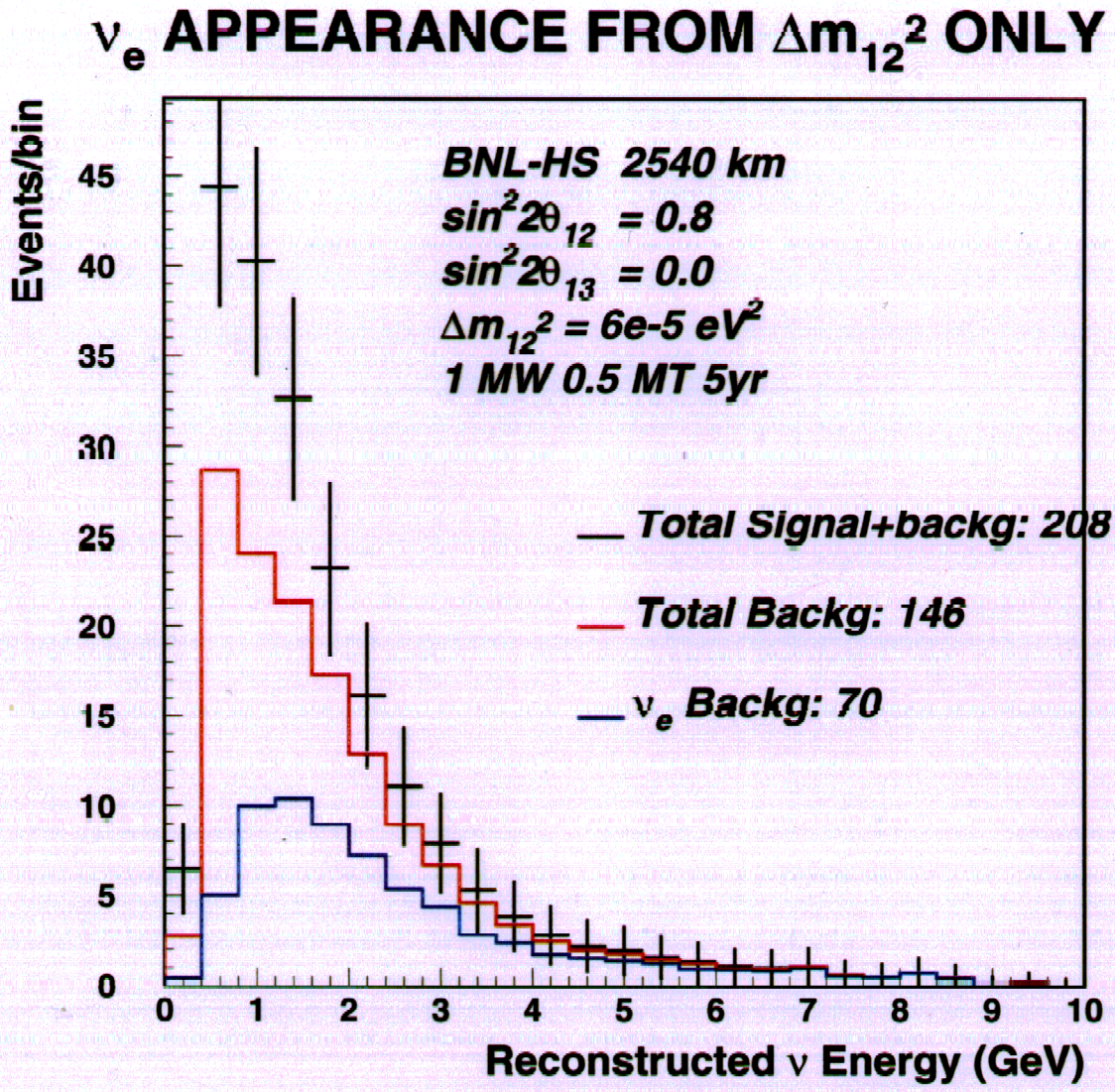
Assume normal mass hierarchy. $m_3 > m_2 > m_1$

Matter effects included.

Measurement of Δm^2_{12}



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

Phase I Physics Goals (5×10^7 sec @ 1MW)

1) $|\Delta m^2_{32}|$ to ±1% , θ_{23} to ±1° (=45°?)

From $\nu_\mu \to \nu_\mu$ 3peaks

2) $\sin^2 2\theta_{13} \to$ 0.003-0.005 sensitivity

if $0.01 \leq \sin^2 2\theta_{13} < 0.2$

measure $\sin\delta$ + $\cos\delta$ no $180°-\delta$ ambiguity

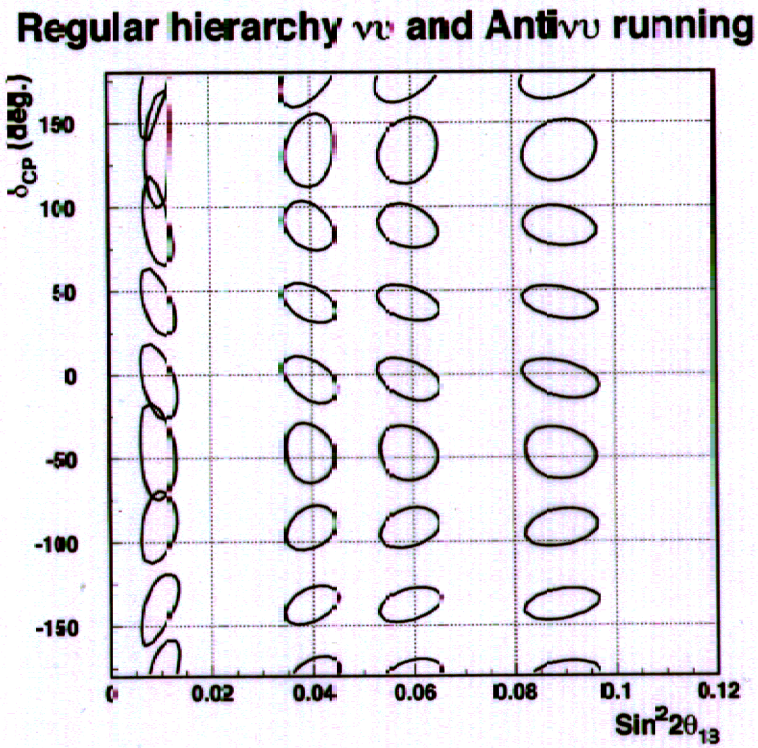
δ to ±15-20°

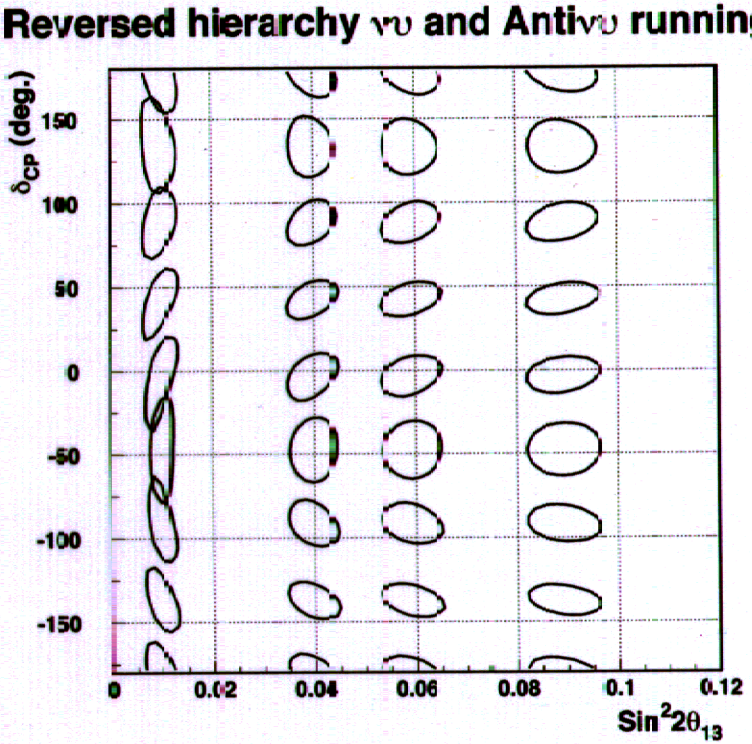
Determine sgn Δm^2_{32} easy

Measure $\underbrace{\Delta m^2_{21}, \sin 2\theta_{12}}_{\text{Kamland}}$ $\underbrace{\cos\theta_{23}}_{\theta_{23},\ 90°-\theta_{23}\ \text{ambiguity}}$ to ±5%

3) Search for New Physics Anomalies $0.5\,\text{GeV} < E_\nu < 5\,\text{GeV}$

CP measurement after nu and anti-nu



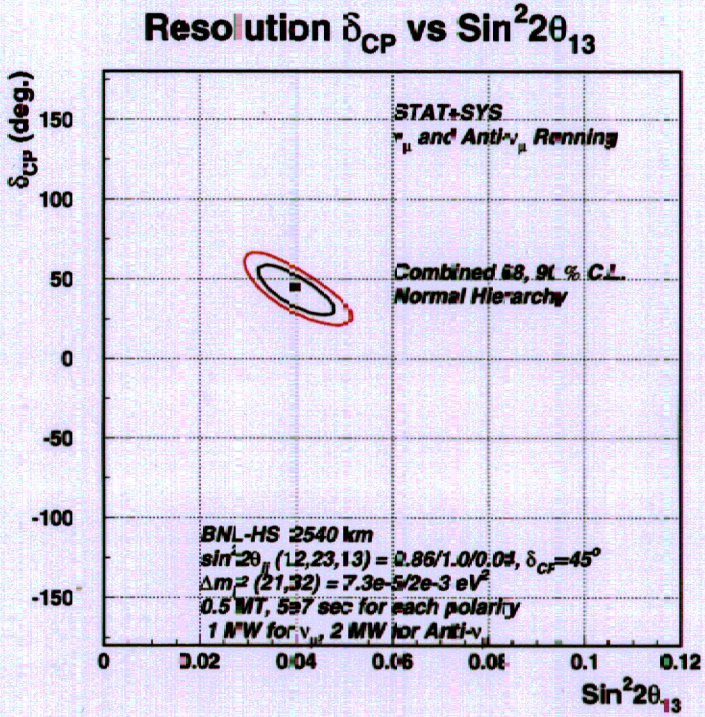


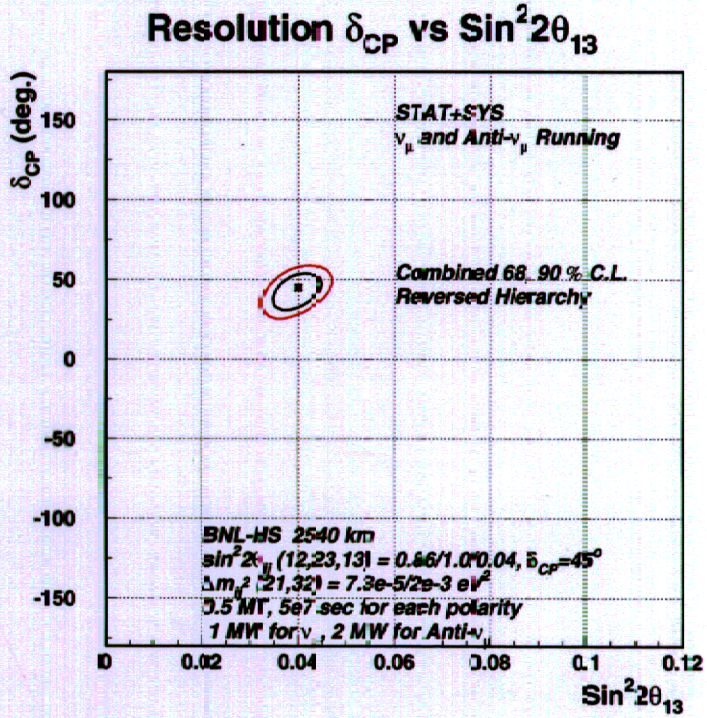
Left: Regular mass hierarchy Right: reversed mass hierarchy.

Only the θ_{23} ambiguity is left.

more about this later...

CP with Neutrino and Antineutrino

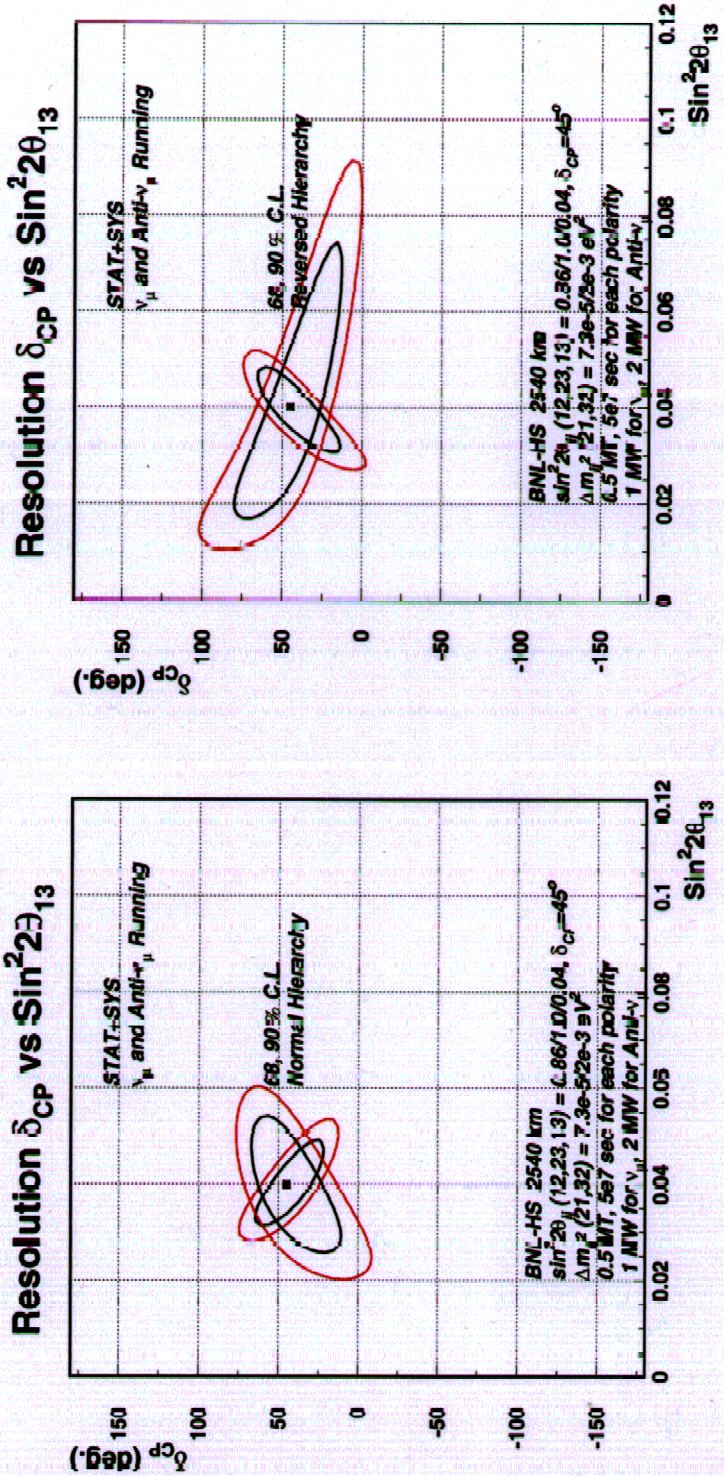




Milind Diwan

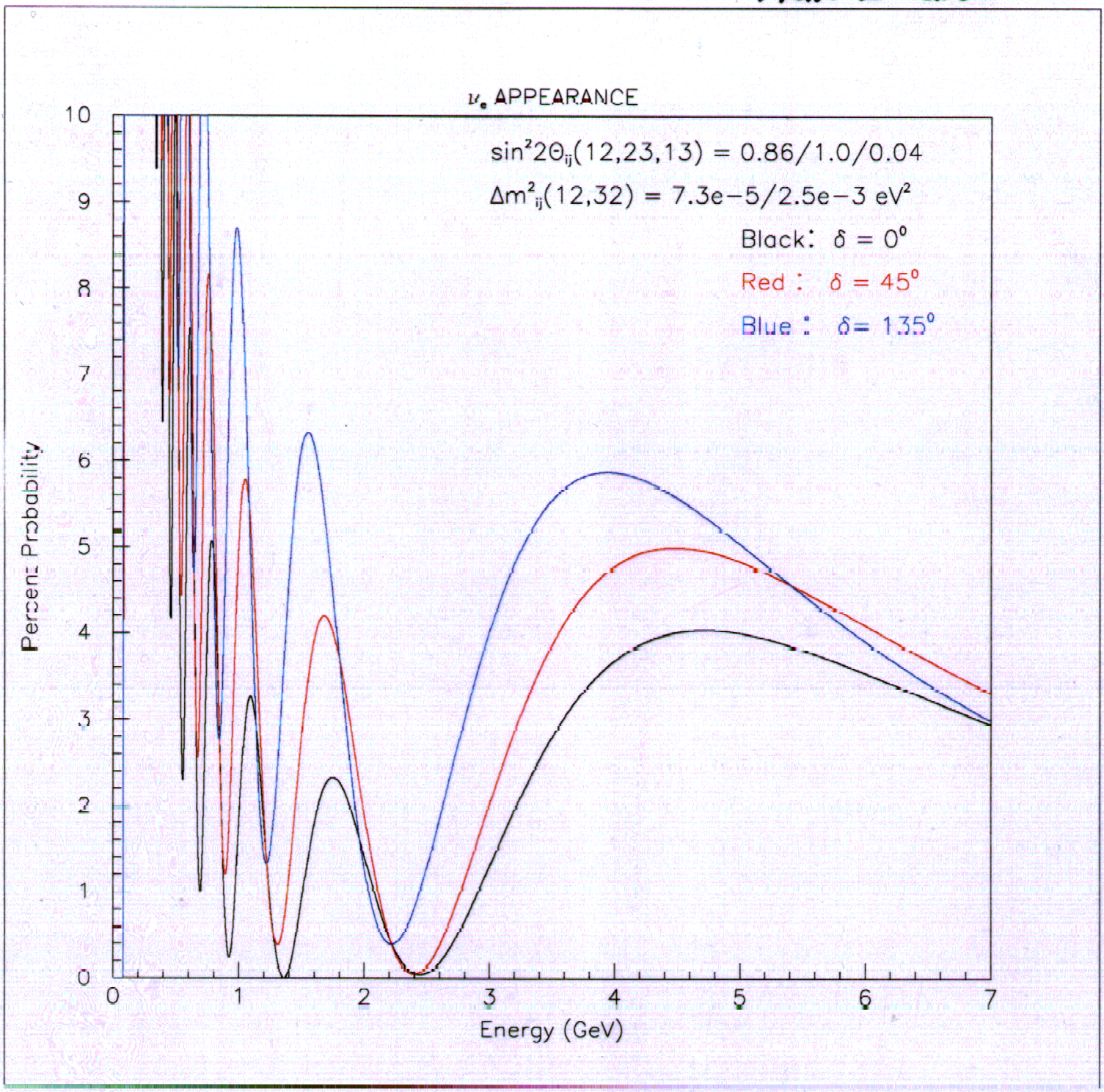
Very long baselines with a superbeam

CP with Neutrino and Antineutrino



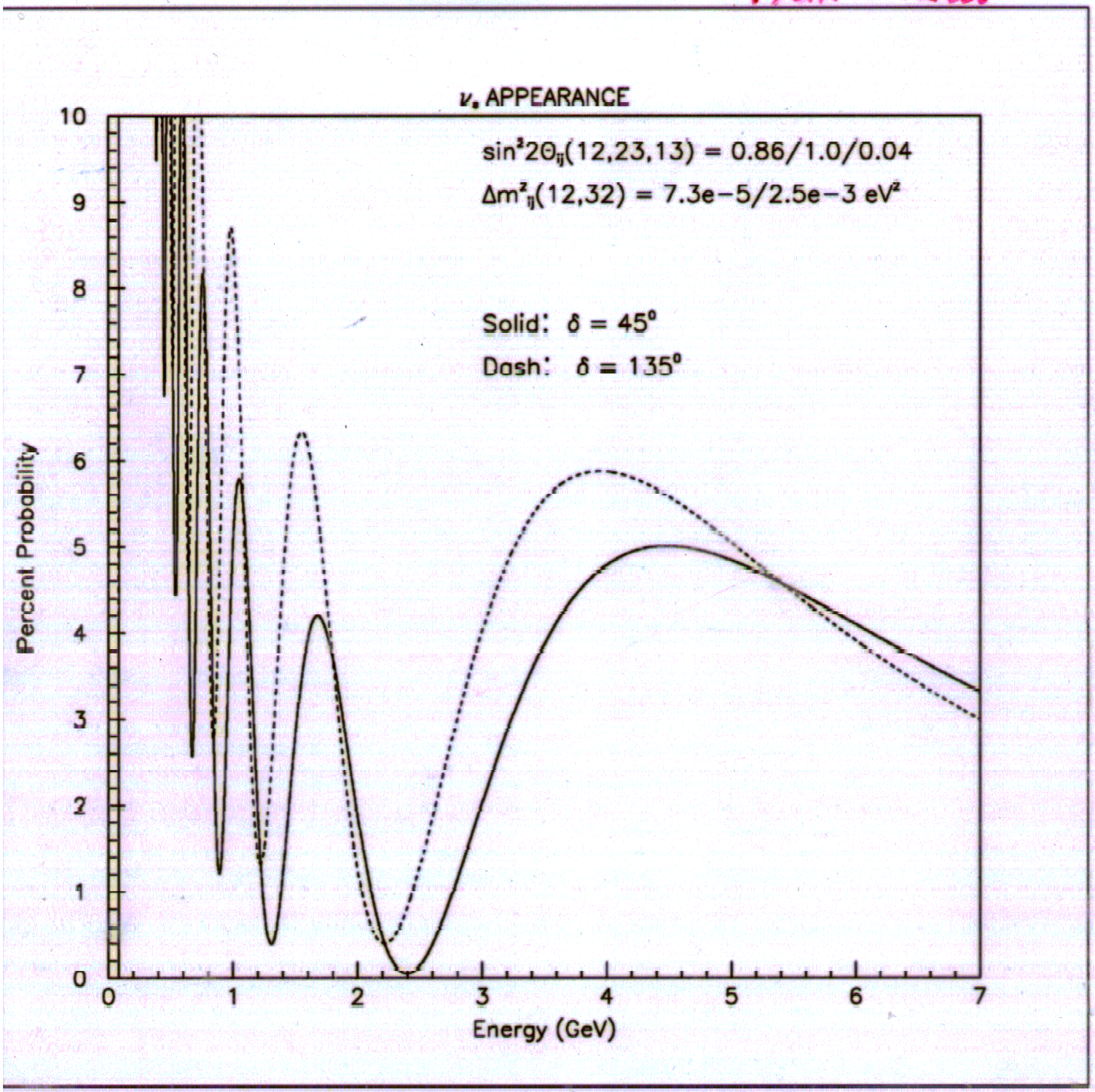
L = 2540km

From Z. Parsa



L=2540km

From Z. Parsa



2.) AGS Upgrade : 0.14 MW → 1MW (CDR) → 2MW (In Study Progress)

E_p = 24 GeV → 28 GeV

7×10^{13} ppp at 0.5 Hz → 10^{14} ppp at 2.5 Hz

} ~1MW goal 2012?

Estimated Cost:

1.2 GeV Linac	147.3 M
AGS Upgrade (1MW)	40.7 M
Neutrino Target + Horn	5.3 M
Facilities	68.8 M
ES+S	0.8 M
Project Support	5.6 M
	268.5 M

Total Direct Cost = $268.5 M

+ Contingency + Overhead → $400 M

2MW Concept: 1.2 GeV Linac → 1.5 GeV Linac

1MW → 1.5-2.0 MW

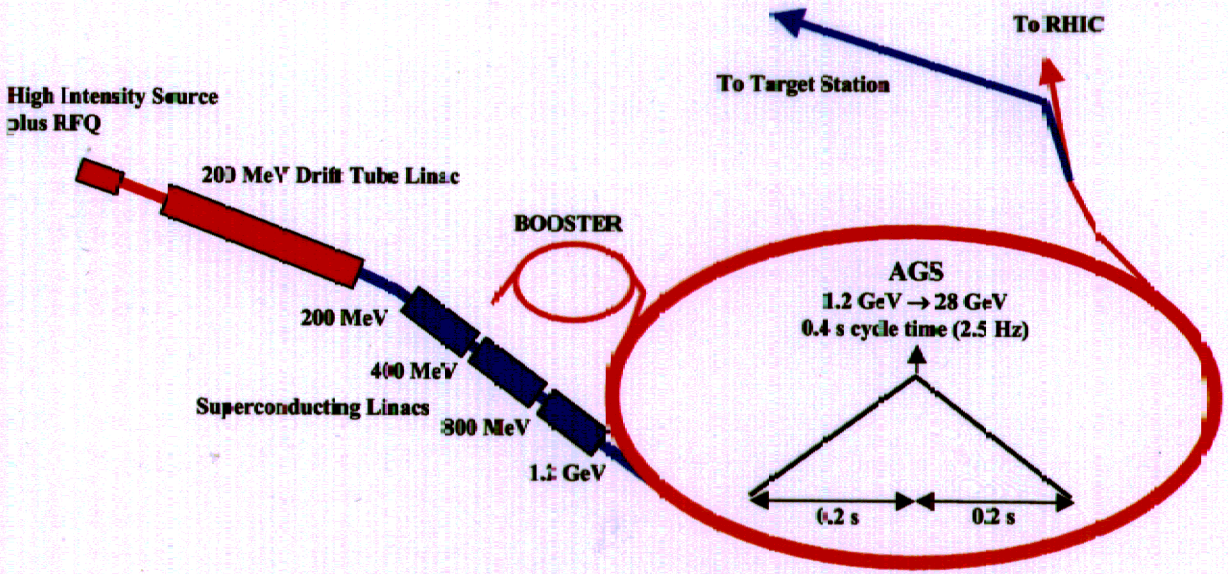
2MW Better Matched To Physics, Time, Detector

Perhaps 2 Neutrino Beams (Same Tunnel)

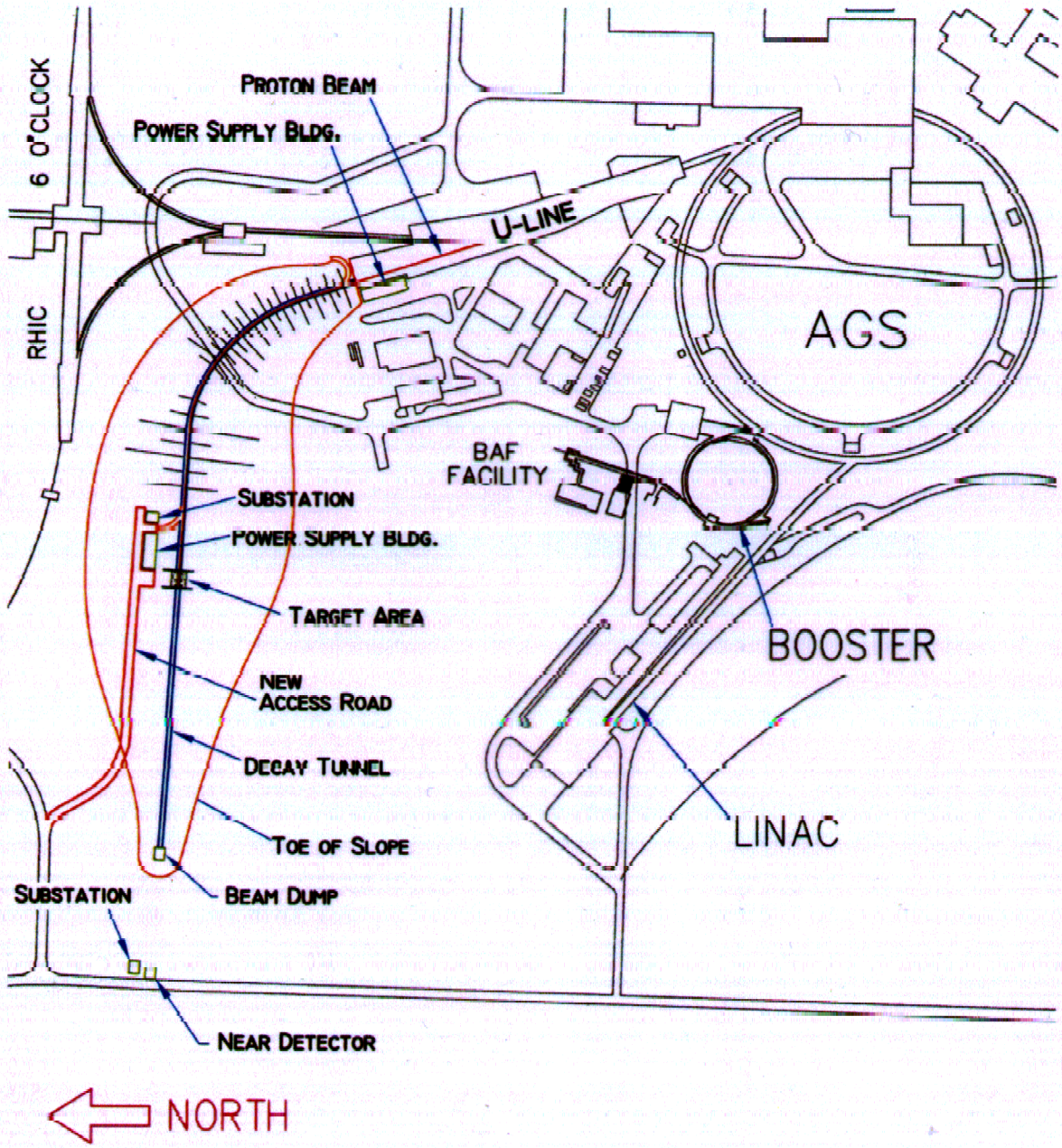
(Cost Estimate in Progress)

The Accelerator

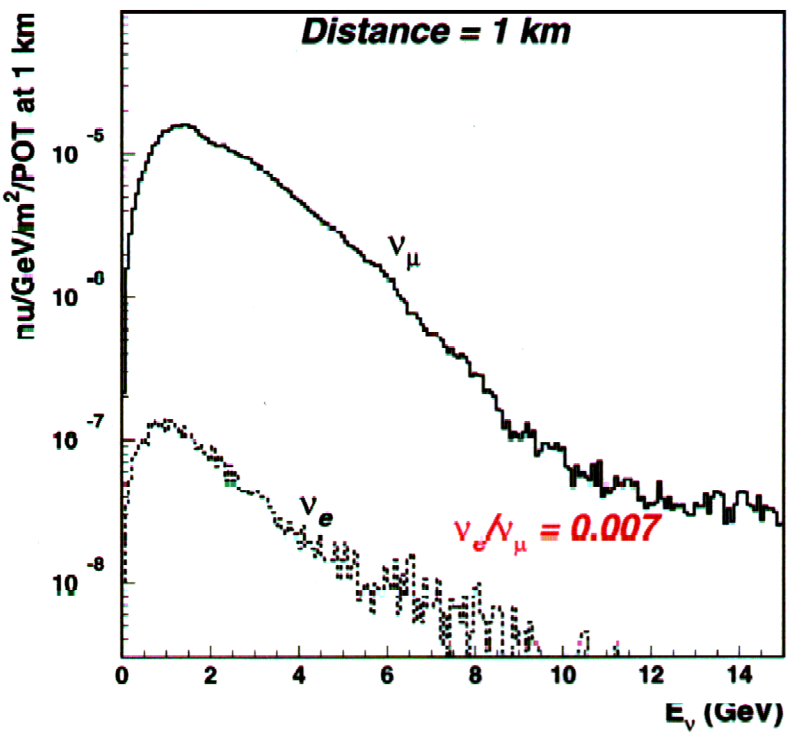
- Conceptually simple upgrade. No magic.
- Run 28 GeV AGS at 2.5 Hz to get 1 MW.
- Need faster proton source: Super Conducting LINAC at 1.2 GeV
- Current: $7 \times 10^{13} ppp$ at 0.5 Hz => LINAC: $10^{14} ppp$ at 2.5 Hz.



Beam Layout

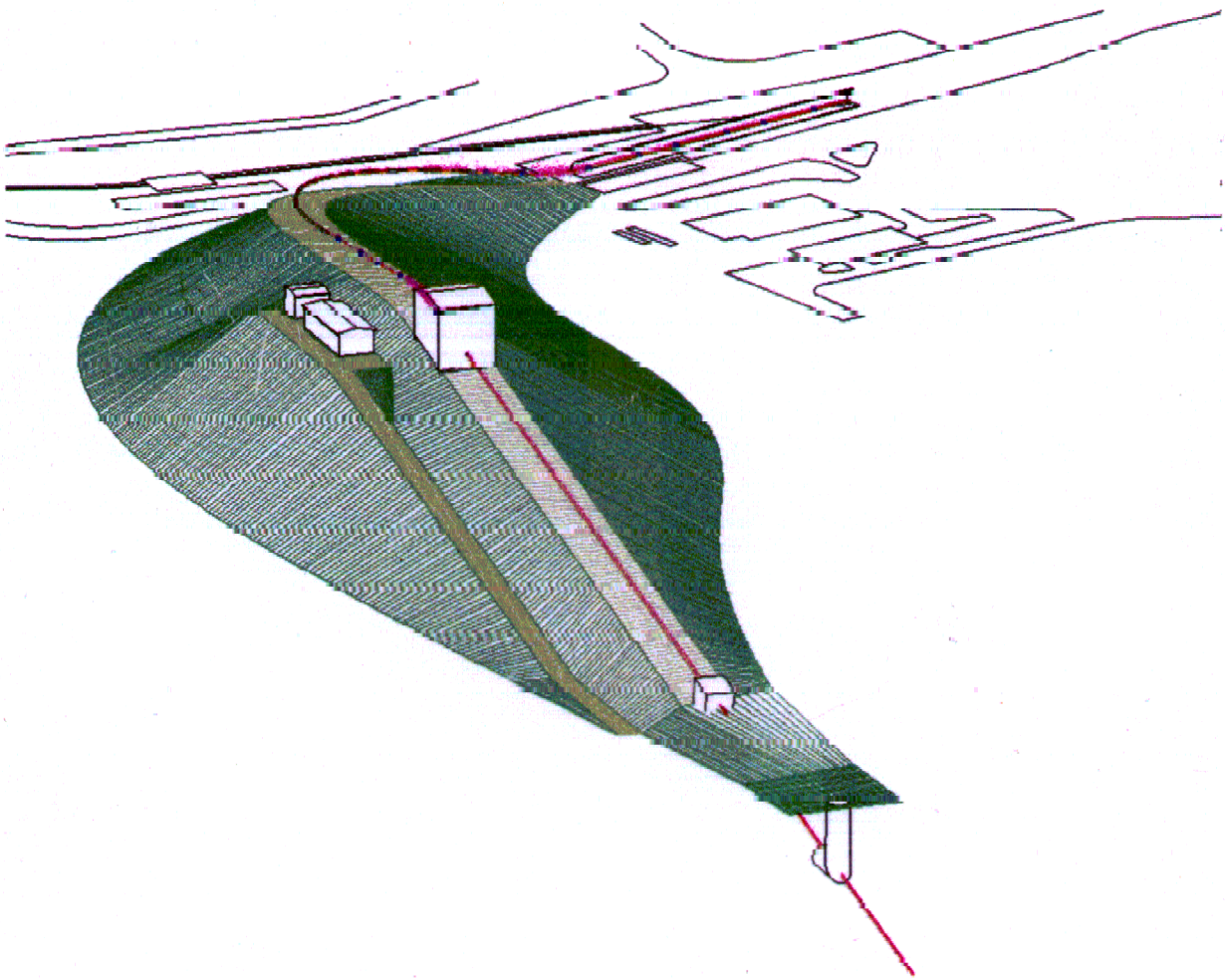

6 O'CLOCK
RHIC
PROTON BEAM
POWER SUPPLY BLDG.
U-LINE
AGS
BAF
FACILITY
SUBSTATION
POWER SUPPLY BLDG.
TARGET AREA
NEW
ACCESS ROAD
DECAY TUNNEL
TOE OF SLOPE
BEAM DUMP
SUBSTATION
NEAR DETECTOR
BOOSTER
LINAC
NORTH

BNL Wide Band. Proton Energy = 28 GeV

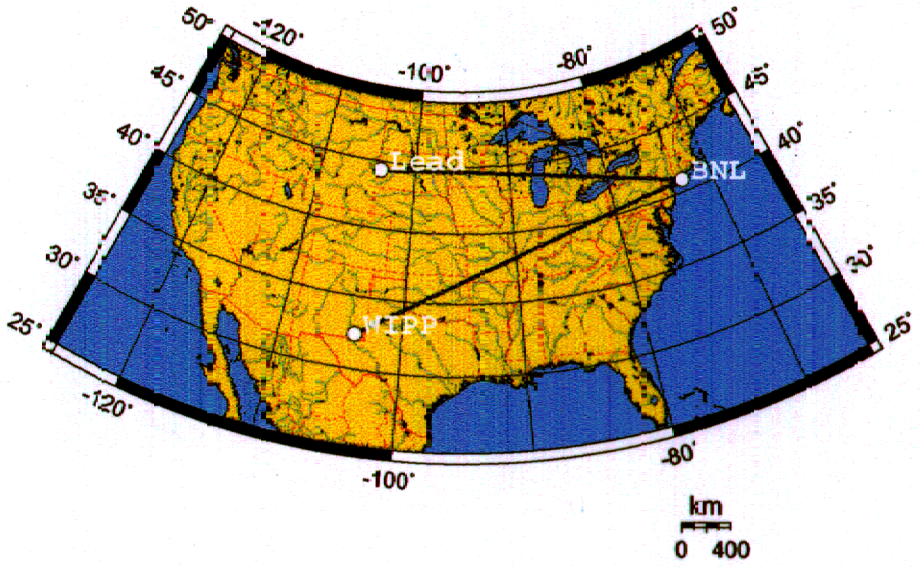


- New design spans 0.5-6 GeV
- Low ν_e background 0.7%
  0.0073 ± 0.0014 (E734 1986).
- Low background from high energies (NC and ν_τ for ν_e)
- 200 m decay tunnel
- Graphite target embedded in horn
- Target cooling achievable for 1 MW

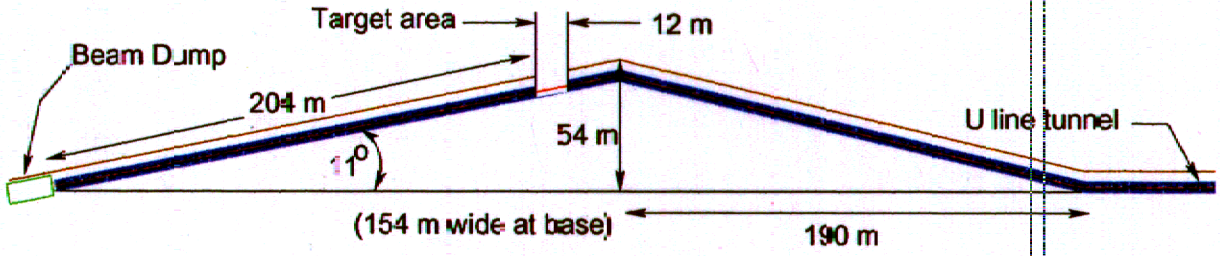
Beam 3d



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.



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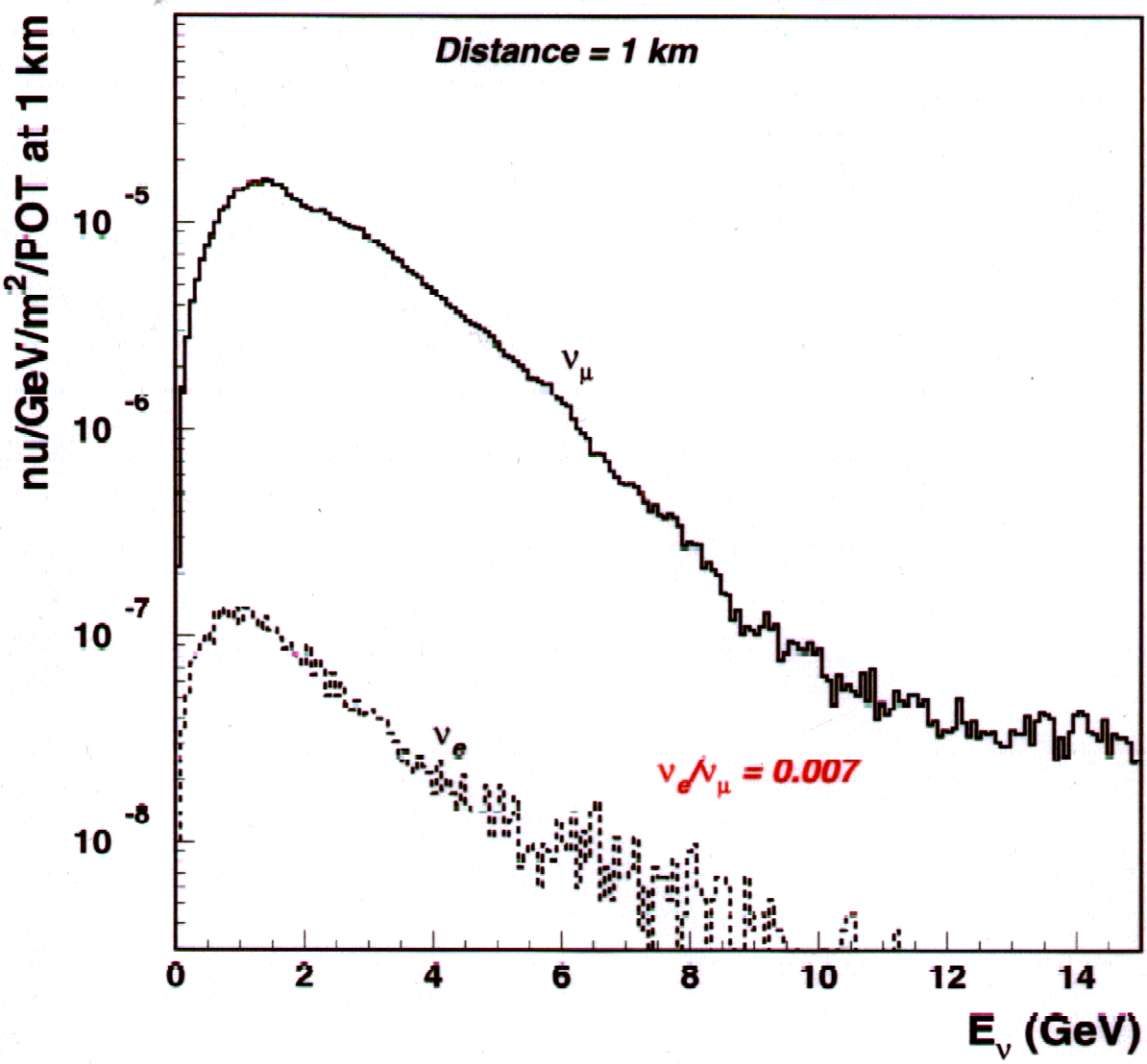
Very long baselines with a superbeam

BNL Wide Band. Proton Energy = 28 GeV



1. Proton Decay (Rich History)

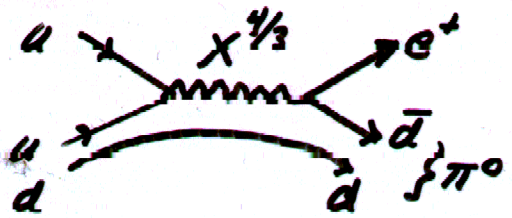
IMB, Kamiokande, Super K ... Next Generation

Supernova 1987a
Solar ν osc. ν_e-ν_e
atm. ν osc $\nu_\mu \to \nu_\tau$
} Great Discoveries

>20yrs Ago IMB $\tau(p \to e^+\pi^0) > 9\times10^{32}$ yr Min SU(5) Ruled Out!
SK $\tau(p \to K^+\bar{\nu}) > 5\times10^{32}$ yr Min SUSY SU(5) Ruled Out?

Super K (25 kton H_2O) $\tau(p \to e^+\pi^0) < 1.4\times10^{34}$ yr (~10 yr)

Generic SUSY SU(5) Expectations



$p \to e^+\pi^0, e^+\rho^0, \pi^+\bar{\nu}, \mu^+K^0, K^+\bar{\nu}$..
0.4, 0.3, 0.16, 0.03, 0.03..

$$\tau(p \to e^+\pi^0) \simeq (0.5\text{-}1)\times10^{35}\text{ yr} \times \left(\frac{m_X}{10^{16}\text{GeV}}\right)^4$$

$$m_X = \frac{1}{2} m_Z \exp\left[\frac{\pi}{2}\left(\frac{\sin^2\theta_W(m_Z)}{\alpha(m_Z)} - \frac{1}{\alpha_{QCD}(m_Z)}\right)\right] \simeq 10^{16}\text{GeV}$$

~another $2^{\pm4}$ unc. SUSY+Higgs Masses

$$\tau(p \to e^+\pi^0) \simeq 10^{34}\text{ yr} - 2\times10^{36}\text{ yr}$$

Will SK Get Lucky?

Need 500-1000 kton H_2O + 5yr Running! (Background?)

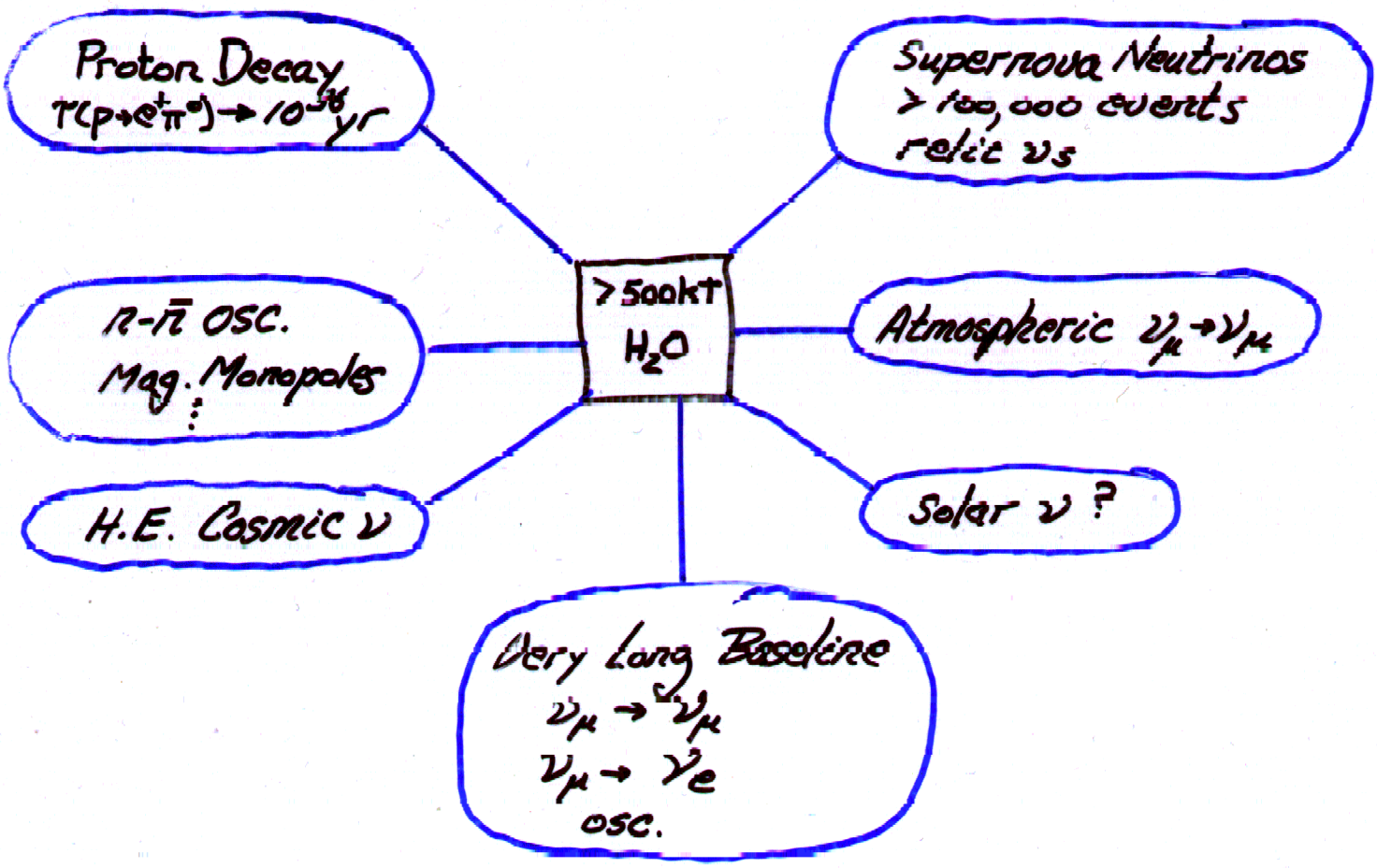
Study of $\not{CP}$ in ν osc. also requires $\gtrsim$ 500 kton H_2O

At What Distance?

$\nu_\mu \to \nu_e$ peak @ $L \simeq 620\,km \times E_\nu/GeV$

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

Next Generation Water Cerenkov Detector Program



Potential Revolutionary Discoveries!

50-100 yr Program!

Very Compelling!

Take $L \simeq$ ~~1600~~ 2000 - 4000 km eg BNL - Homestake 2540 km

$0.5\,GeV \leq E_\nu \leq 5\,GeV$

1) $E_\nu \simeq 3-5\,GeV$ P_I + Large Matter Effect

measures $\sin^2\theta_{23}\sin^2 2\theta_{13}$ vs Reactor $\rightarrow \sin^2\theta_{23}$

$\operatorname{sgn}\Delta m^2_{31}$ easy

2) $E_\nu \simeq 1-3\,GeV$ $P_{II} \rightarrow \sin\delta + \cos\delta$!

3) $E_\nu \lesssim 1\,GeV$ $P_{III} \rightarrow \cos^2\theta_{23}\underbrace{\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)}_{\text{Kamland}} \rightarrow \cos\theta_{23}\underbrace{\sin 2\theta_{12}\Delta m^2_{21}}_{\text{kamland}}$

1+3 $\rightarrow$ θ_{23}, $\frac{\pi}{2}-\theta_{23}$ Ambiguity (vs Reactors) Resolved

2 $\rightarrow$ $\sin\delta$, $\cos\delta$ δ + $\delta-\pi$ resolved $\pm 15°$

1 $\rightarrow$ Matter $\rightarrow$ Hierarchy Resolved

No Degeneracies !

1 Experiment $\xrightarrow[+\text{Kamland}]{}$ All Parameters { later $\bar\nu_\mu \rightarrow \bar\nu_\mu$, $\bar\nu_\mu \rightarrow \bar\nu_e$ "New Physics"?

Compelling On Its Own

but

Also Proton Decay (10^{34} yr), Supernova ν, Atm ν ...

50+ years of physics !

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 *Better Acceptance ~ 3Times!*
  - scale up to 100 kT module ?
  - Current size 300Ton.
  - Needs detailed simulations.
- Any other technology ?

5) Outlook

Next Generation ν-ose program requires superbeam (1-4MW)
+ very large detector ~500 kton H_2O

Next Generation proton decay, atm ν, supernova } National/ Underground Lab
requires very large detector ~500 kton H_2O }

Marriage Seems Obvious - Physics Compelling

Easiest path to a superbeam (& cheapest) ~ $400M
AGS upgrade → 1-2 MW

Very long baseline ~2000+ km } lots of physics } All Parameters
+ WBB $\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$ }

Backgrounds under study $\nu_\mu N \to \nu_\mu N \pi^0$

Additional Signal $\nu_\mu \to \nu_e n \to p e^-$ + pion under study
3x statistics!

Must do physics for 21st Century ν-osc program