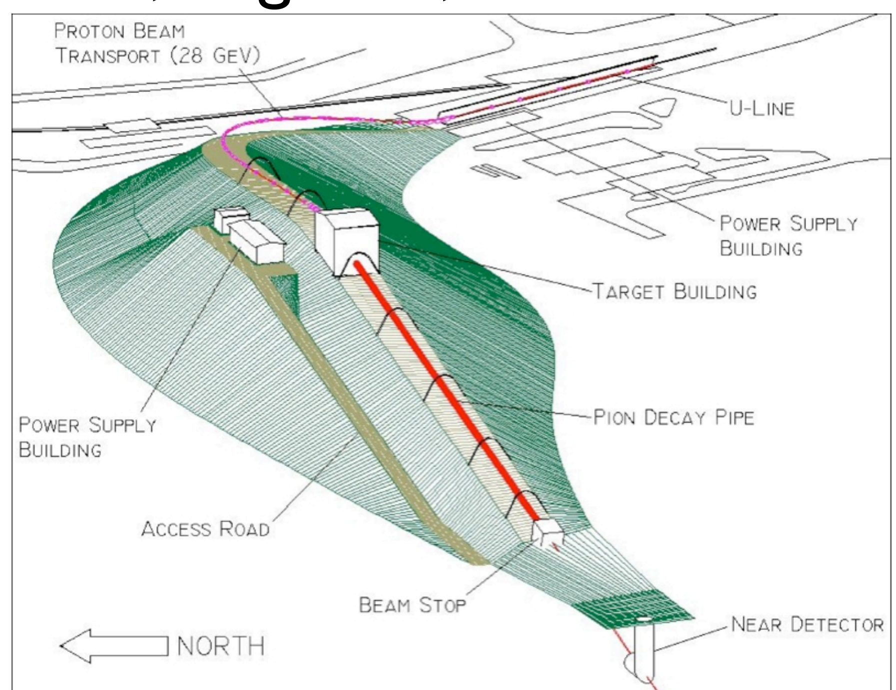
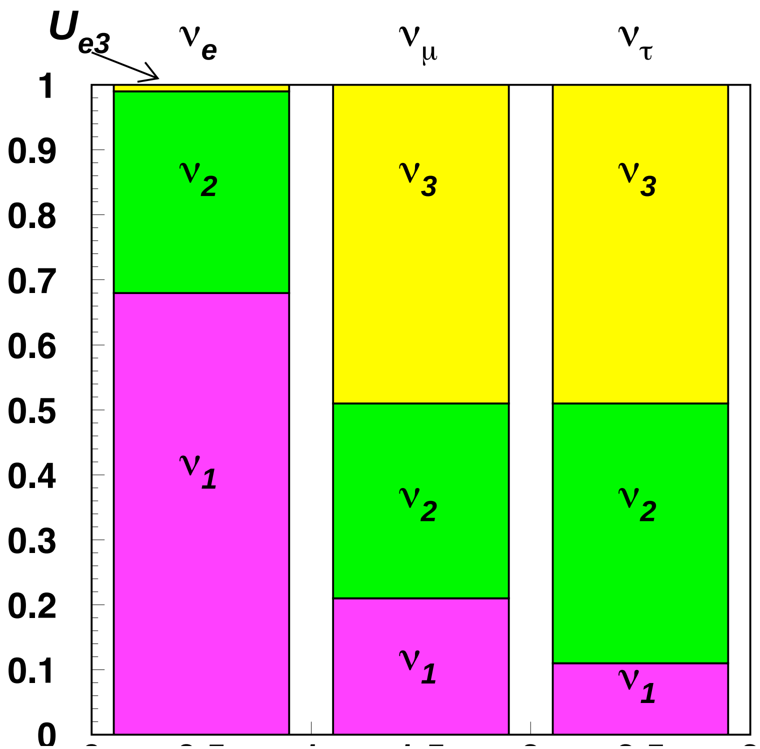
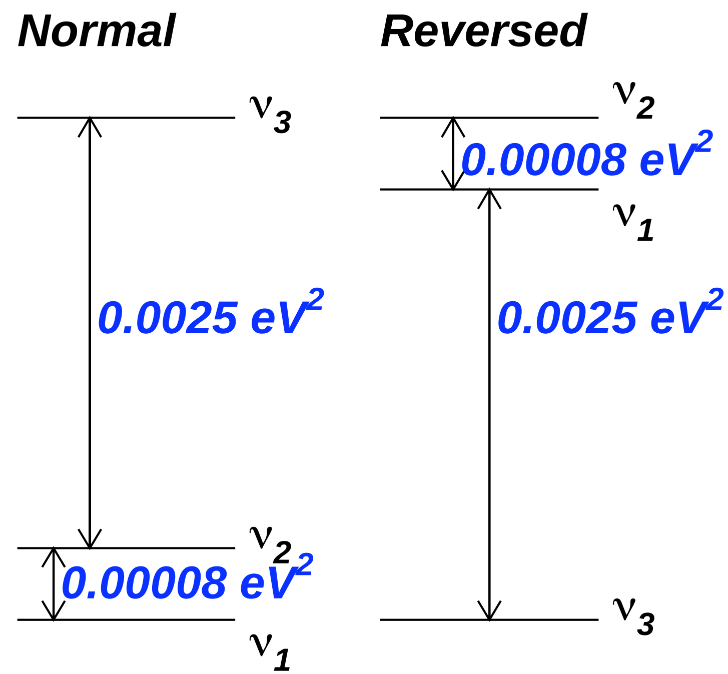
Very Long Baseline Neutrino Oscillations with a broadband beam

Milind Diwan
Brookhaven national Laboratory
INO workshop, Mumbai, August 2, 2005



3 Generation oscillations





Difference in mass squares: $(m_2^2 - m_1^2)$

2-nu: $$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

3-nu: CP phase

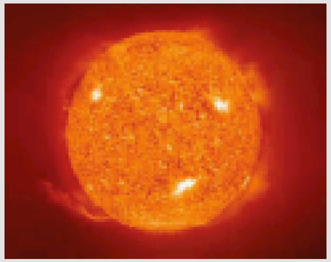
$$\begin{aligned} P(\nu_a \to \nu_b) \;\; = \;\; & \textstyle\sum_i |U_{ai}|^2 |U_{bi}|^2 \\ & +2Re(U_{a1}^* U_{b1} U_{a2} U_{b2}^* \times exp(-i\Delta m_{21}^2 L/2E) \\ & +2Re(U_{a1}^* U_{b1} U_{a3} U_{b3}^* \times exp(-i\Delta m_{31}^2 L/2E) \\ & +2Re(U_{a2}^* U_{b2} U_{a3} U_{b3}^* \times exp(-i\Delta m_{32}^2 L/2E) \end{aligned}$$

no matter effects

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1 GeV$, $L = 494 km$.

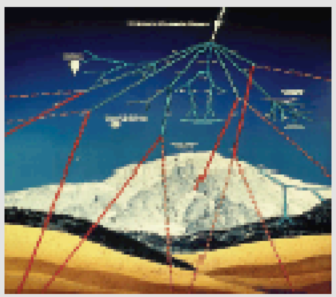
Solar : L~15000km

Neutrino Oscillations Results



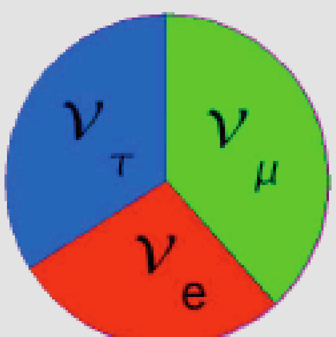
$$\Delta m^2_{21} = (8.0 \pm 0.3)\, 10^{-5}\, eV^2$$

$$\sin^2 2\theta_{12} = 0.86 \pm 0.04$$



$$|\Delta m^2_{32}| = (2.5 \pm 0.3)\, 10^{-3}\, eV^2$$ sign?

$$\sin^2 2\theta_{23} = 1.02 \pm 0.04$$ degeneracy?



$$\sin^2 2\theta_{13} < 0.12$$ (99% C.L.)

$$\delta_{CP} = ???$$

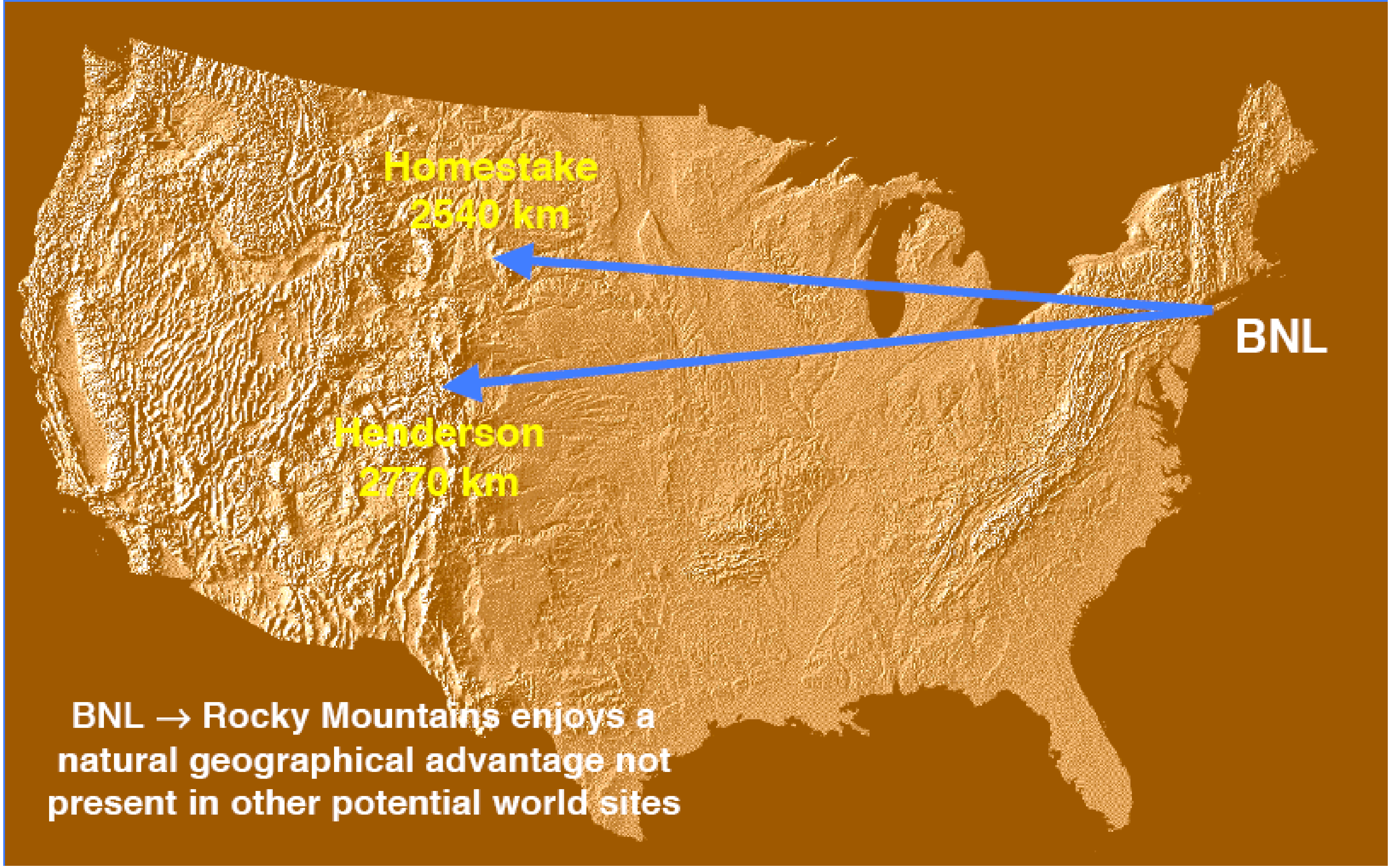
Values from: A. Strumia & F Vissani
hep-ph/0503246 - ifup-th/2005-06

Next Generation Experiments

- increase sensitivity $\sin^2 2\theta_{13}$ & δ_{CP} significantly
- precision measurements of Δm^2_{32} & $\sin^2 2\theta_{23}$
- resolve mass hierarchy (sign of Δm^2_{32})
- sensitive to new physics

The heart of the 3 generation picture needs an appearance experiment with L/E that includes effects from both mass differences. This implies baseline > 2000 km

This performs all remaining physics in one project

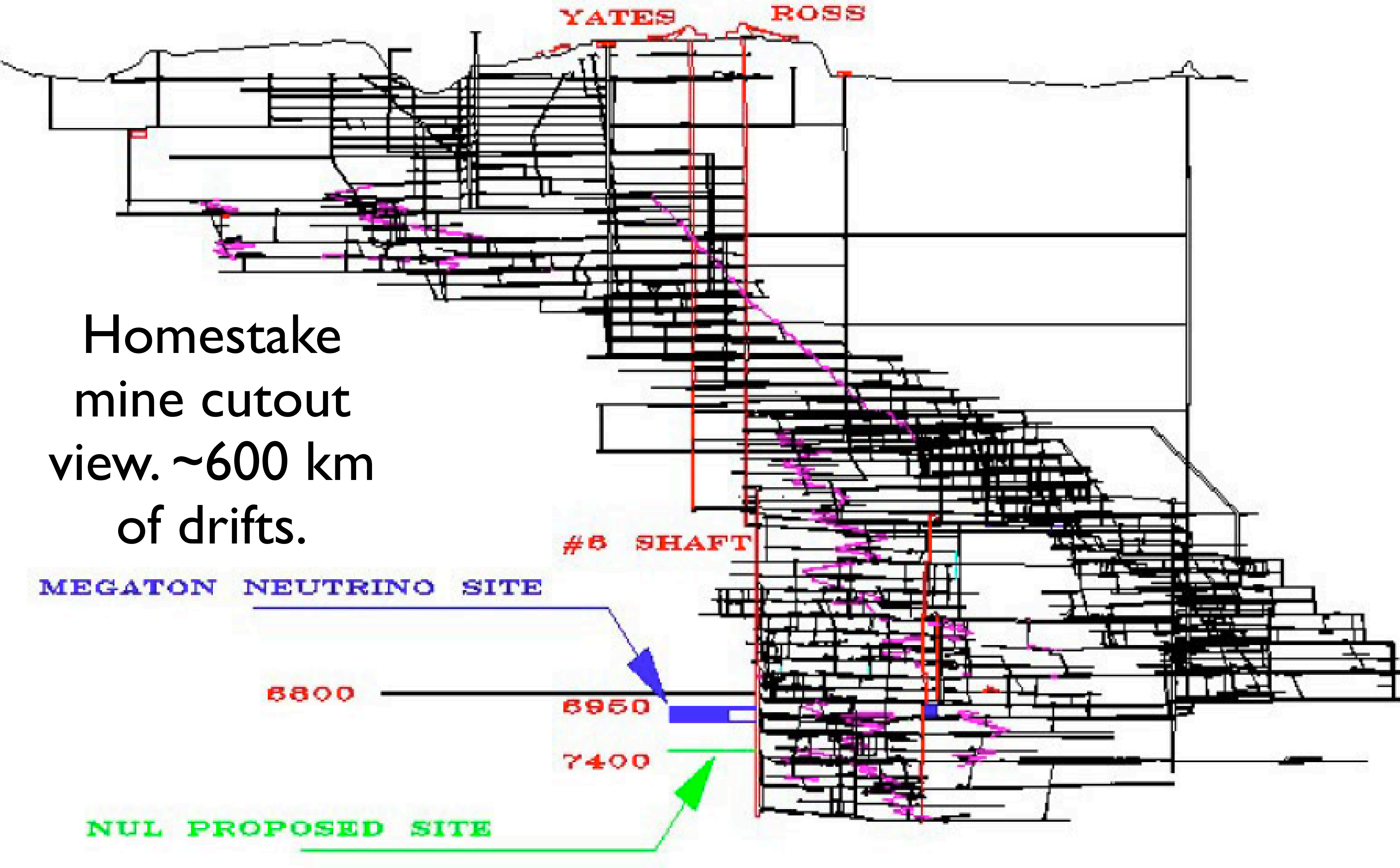


- 28 GeV protons. 1 MW beam power. Horn focussed
- 500 kT water Cherenkov detector stationed in a new DUSEL.
- baseline > 2500 km. WIPP, Henderson, Homestake
- We have proven by 3 years of work that this can be done.

Some development on US site for a deep underground science and engineering laboratory

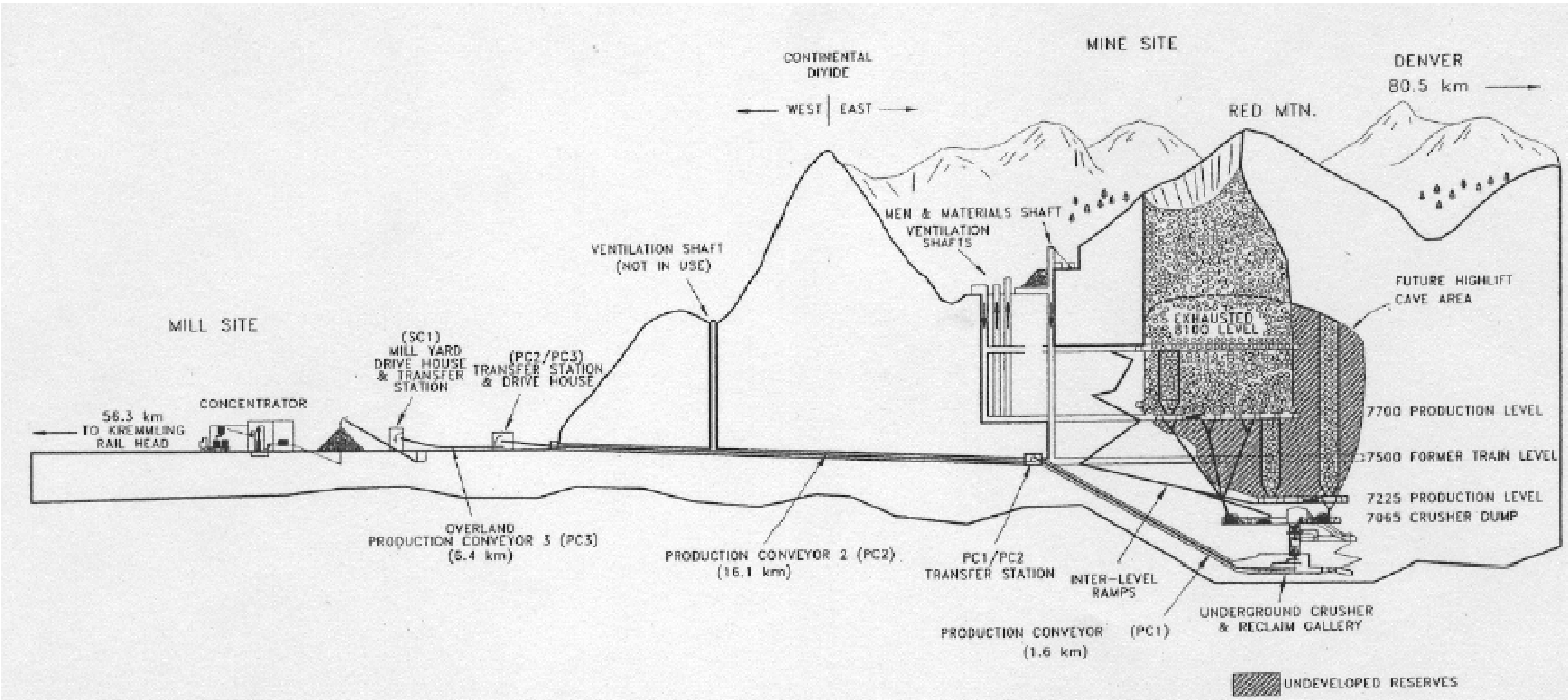
- In 2004, US National Science Foundation launched a process to create a deep underground science and engineering facility (DUSEL).
- The science case is being made in a single proposal by the entire US community including geo-scientists, geo-engineers, and biologists. Leader: Bernard Soudulet (Berkeley).
- Meanwhile, 8 sites were proposed by individual groups of scientists.
- 2 sites have been chosen (July, 2005) after a review by an NSF panel. The 2 sites are the Homestake gold mine in South Dakota and the Henderson mine in Colorado.

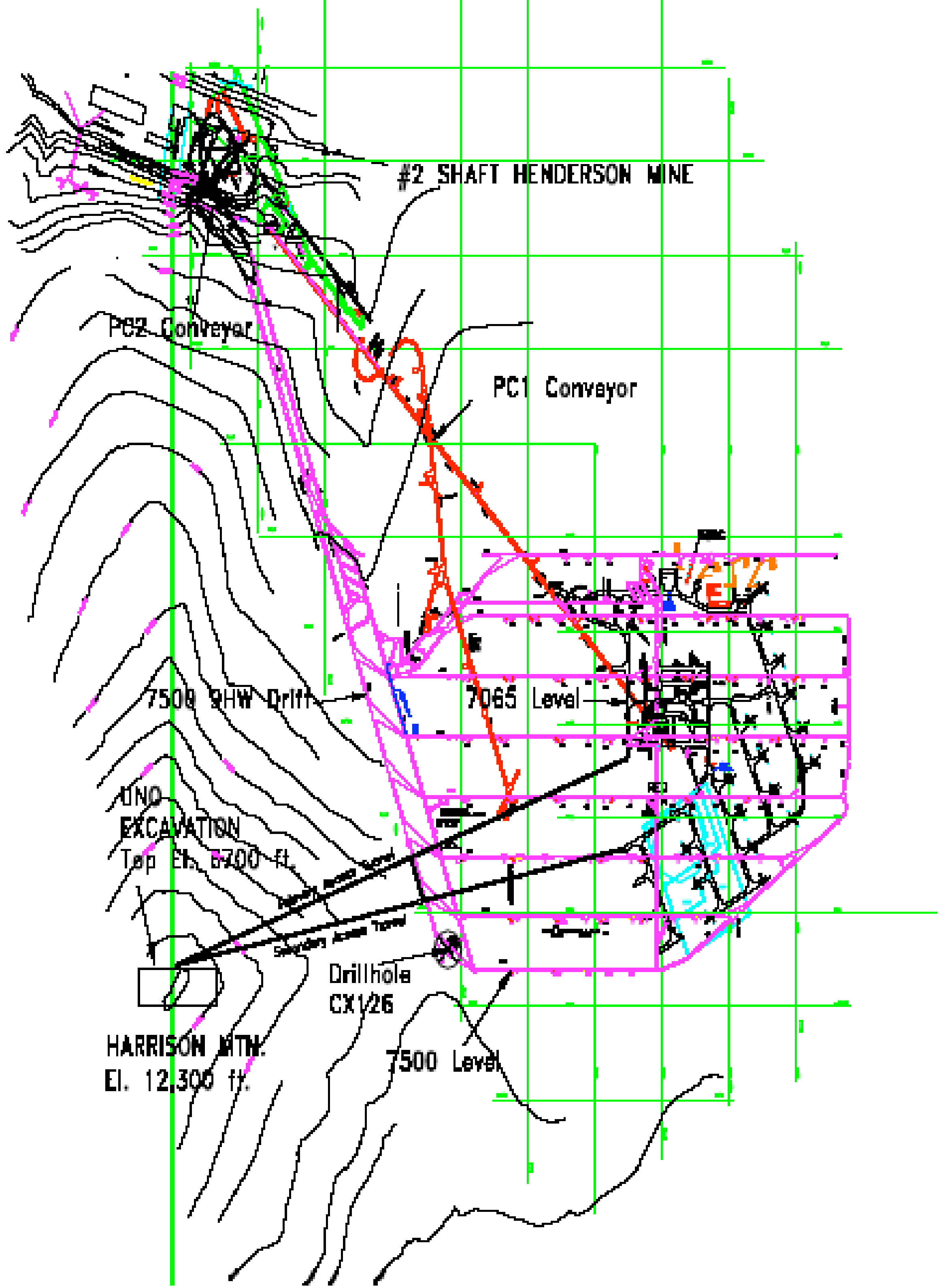
Homestake mine cutout view. ~600 km of drifts.




north
Yates
Ross

Henderson mine





#2 SHAFT HENDERSON MINE
PC2 Conveyor
PC1 Conveyor
7500 9HW Drift
7065 Level
UNO
EXCAVATION
Top El. 8700 ft.
Drillhole
CX1/26
HARRISON MTN.
El. 12,300 ft.
7500 Level

Some working group written material

back to discussion of long baseline.

W. J. Marciano, "Long baseline neutrino oscillations and leptonic CP violation," Nucl. Phys. Proc. Suppl. **138**, 370 (2005).

M. V. Diwan, "The case for a super neutrino beam," Heavy Quarks and Leptons Workshop 2004, San Juan, Puerto Rico, 1-5 Jun 2004. arXiv:hep-ex/0407047.

J. Alessi, et al., "The AGS-based Super Neutrino Beam Facility, Conceptual Design Report," BNL-73210-2004-IR, 1 Oct. 2004.

W. T. Weng *et al.*, J. Phys. G **29**, 1735 (2003).

W. J. Marciano, "Extra long baseline neutrino oscillations and CP violation," BNL-HET-01-31, Aug 2001. 11pp. arXiv:hep-ph/0108181.

M. V. Diwan *et al.*, "Very long baseline neutrino oscillation experiments for precise measurements of mixing parameters and CP violating effects," Phys. Rev. D **68**, 012002 (2003) [arXiv:hep-ph/0303081].

Why Very Long Baseline?

observe multiple nodes in oscillation pattern

☞ less dependent on flux normalization

neutrino travels larger distance through earth

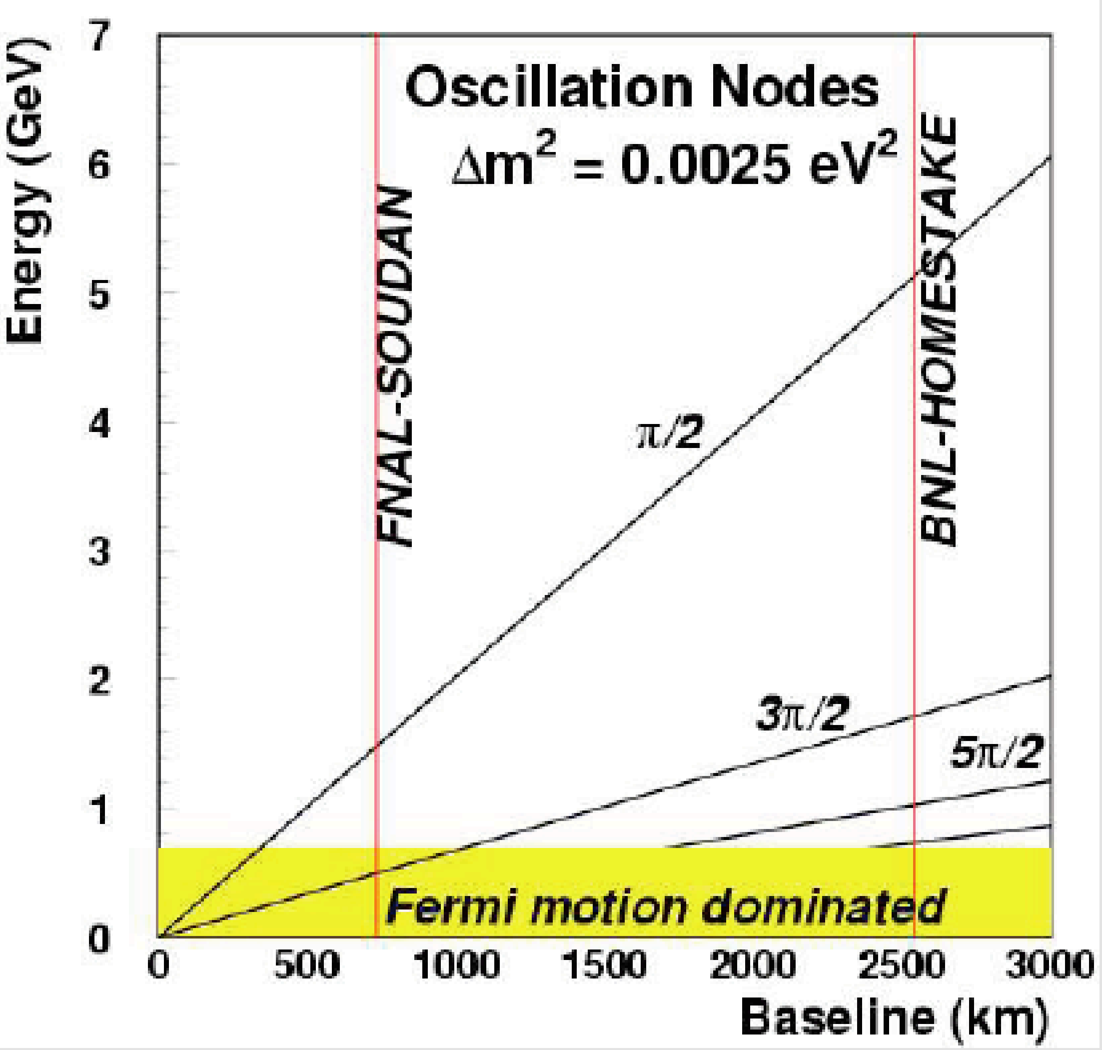
larger matter effects

flux ~ L^{-2}: lower statistics

but: CP asymmetry ~ L

sensitivity to δ_{CP} independent of distance!

better S:B



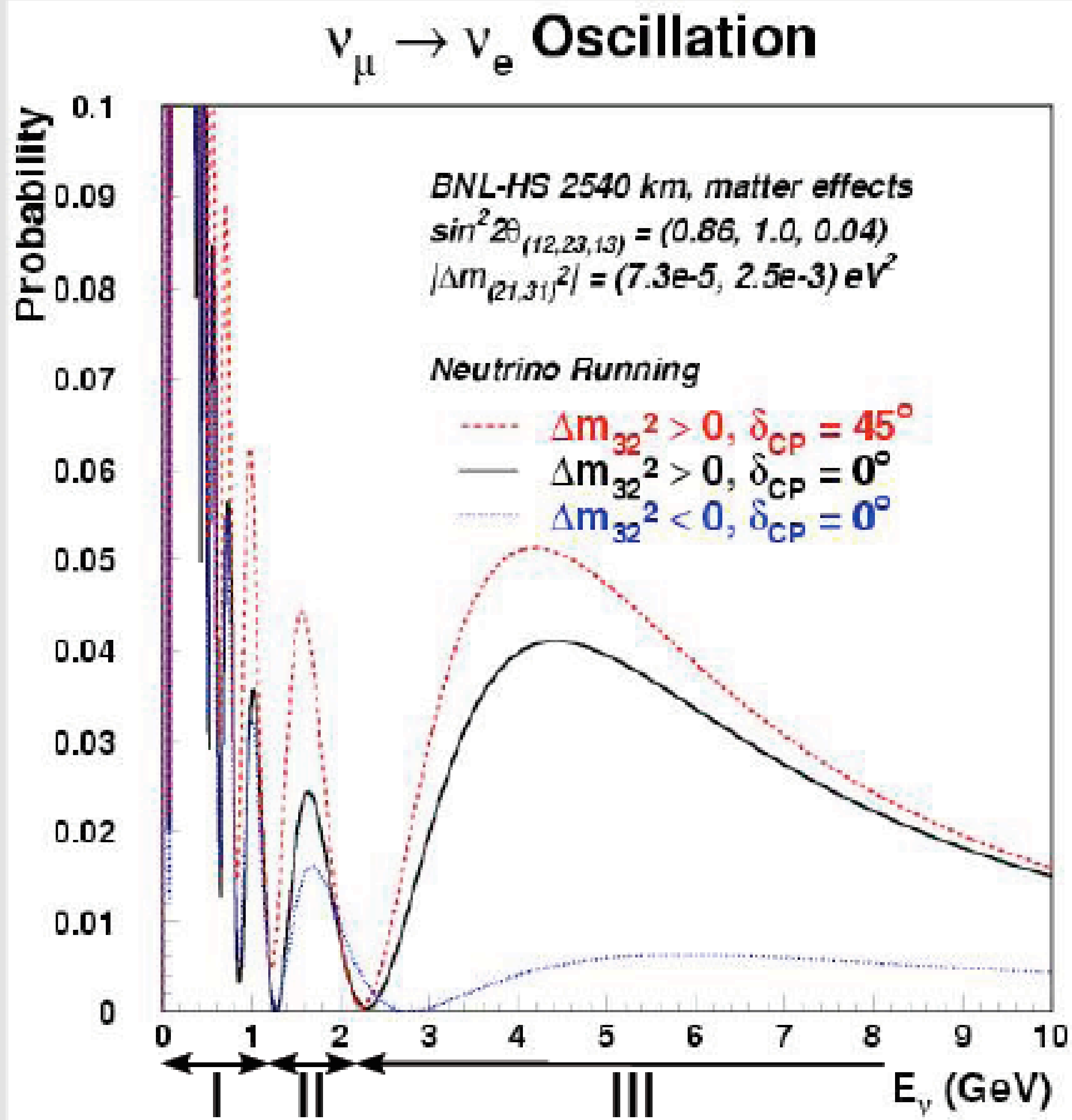
(Marciano hep-ph/0108181)

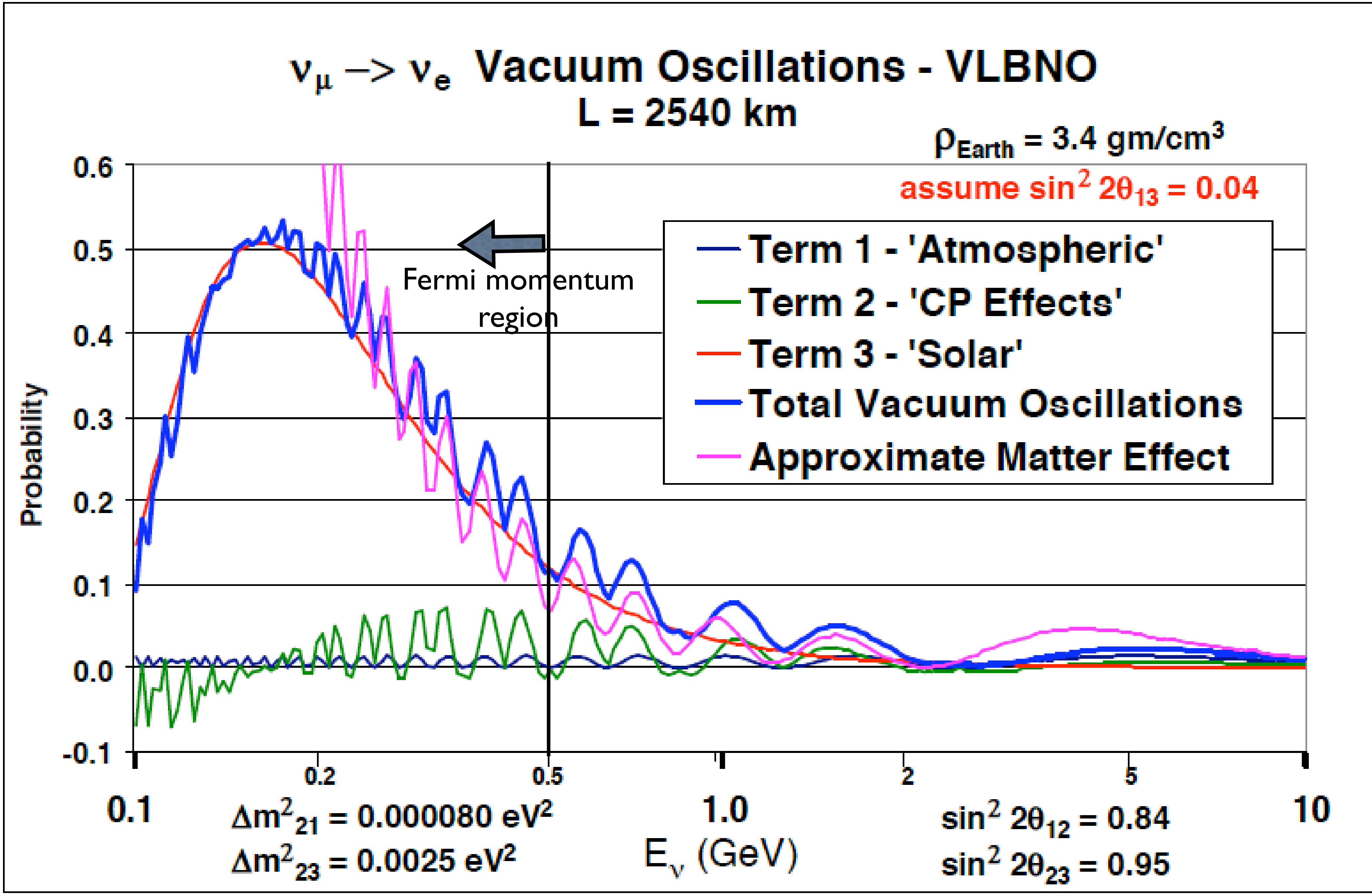
Why Broadband Beam?

observe multiple nodes extraction of oscillating signal from background.

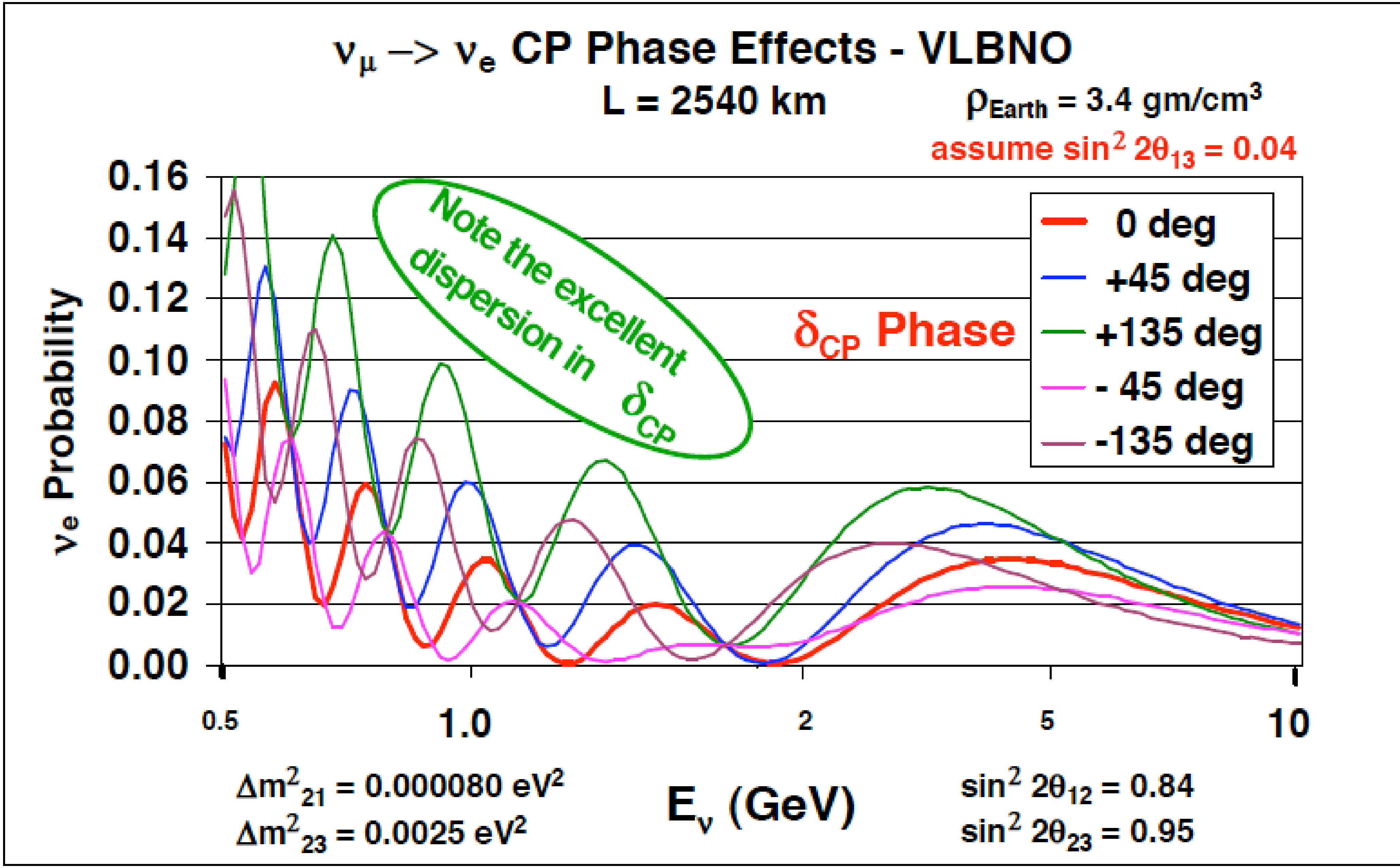
- larger energies
  - larger cross sections
  - less running time for anti-neutrinos
- Sensitive to different parameters in different energy regions:

	I	II	III
$\sin^2 2\theta_{13}$	+	+	+
$\text{sign}(\Delta m^2_{32})$	0	0	++
δ_{CP}	+	++	+
solar	++	+	+



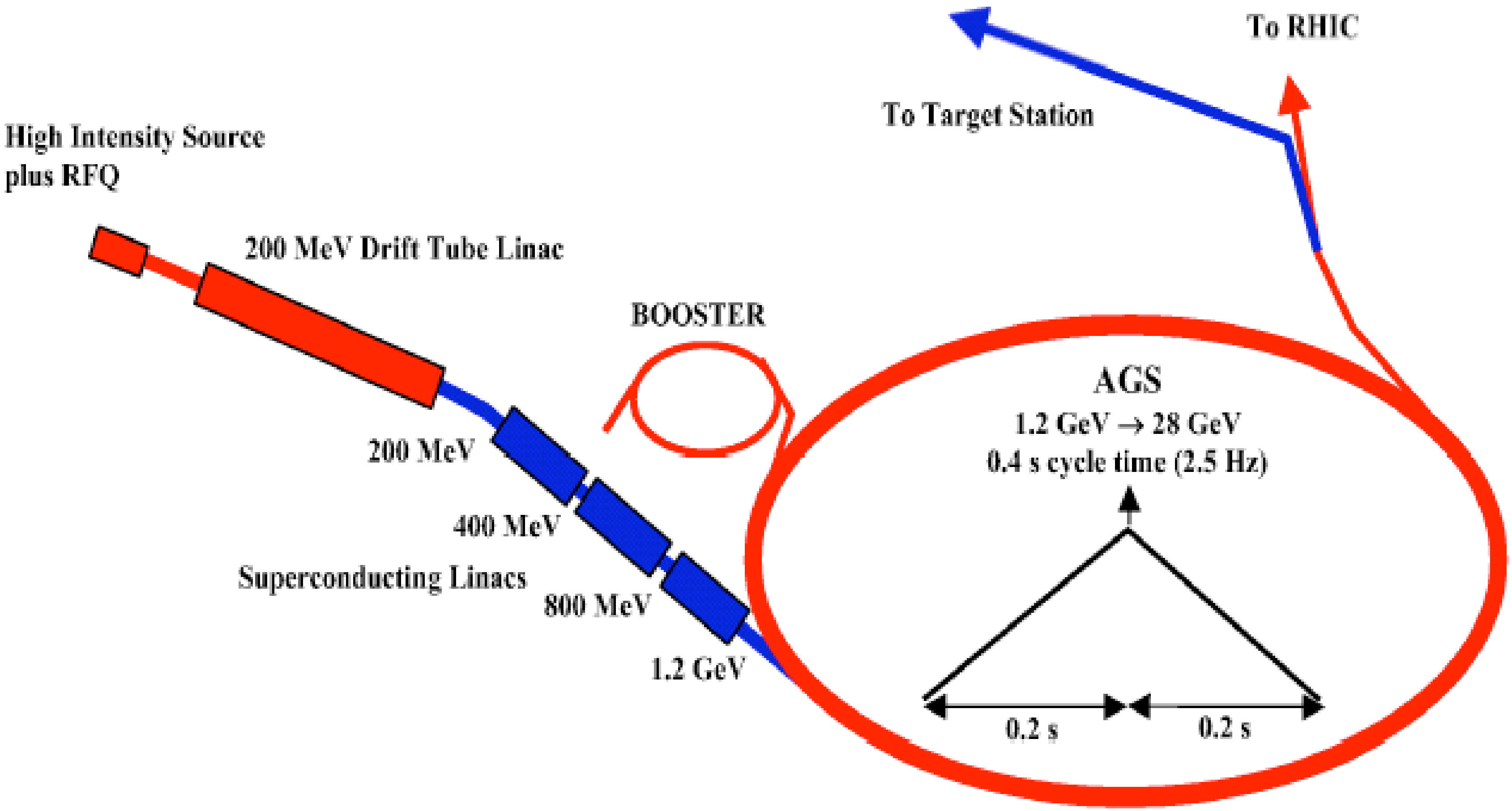


νμ -> νe Vacuum Oscillations - VLBNO
L = 2540 km
ρEarth = 3.4 gm/cm3
assume sin2 2θ13 = 0.04
Fermi momentum region
Term 1 - 'Atmospheric'
Term 2 - 'CP Effects'
Term 3 - 'Solar'
Total Vacuum Oscillations
Approximate Matter Effect
Probability
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0.1
0.2
0.5
1.0
2
5
10
Δm2 21 = 0.000080 eV2
Δm2 23 = 0.0025 eV2
Eν (GeV)
sin2 2θ12 = 0.84
sin2 2θ23 = 0.95



$\nu_\mu \to \nu_e$ CP Phase Effects - VLBNO
L = 2540 km
ρ_{Earth} = 3.4 gm/cm^3
assume $\sin^2 2\theta_{13} = 0.04$
Note the excellent dispersion in δ_{CP}
δ_{CP} Phase
0 deg
+45 deg
+135 deg
- 45 deg
-135 deg
ν_e Probability
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.5
1.0
2
5
10
E_ν (GeV)
Δm^2_{21} = 0.000080 eV^2
Δm^2_{23} = 0.0025 eV^2
$\sin^2 2\theta_{12}$ = 0.84
$\sin^2 2\theta_{23}$ = 0.95

1-2 MW *Super Neutrino Beam* at AGS



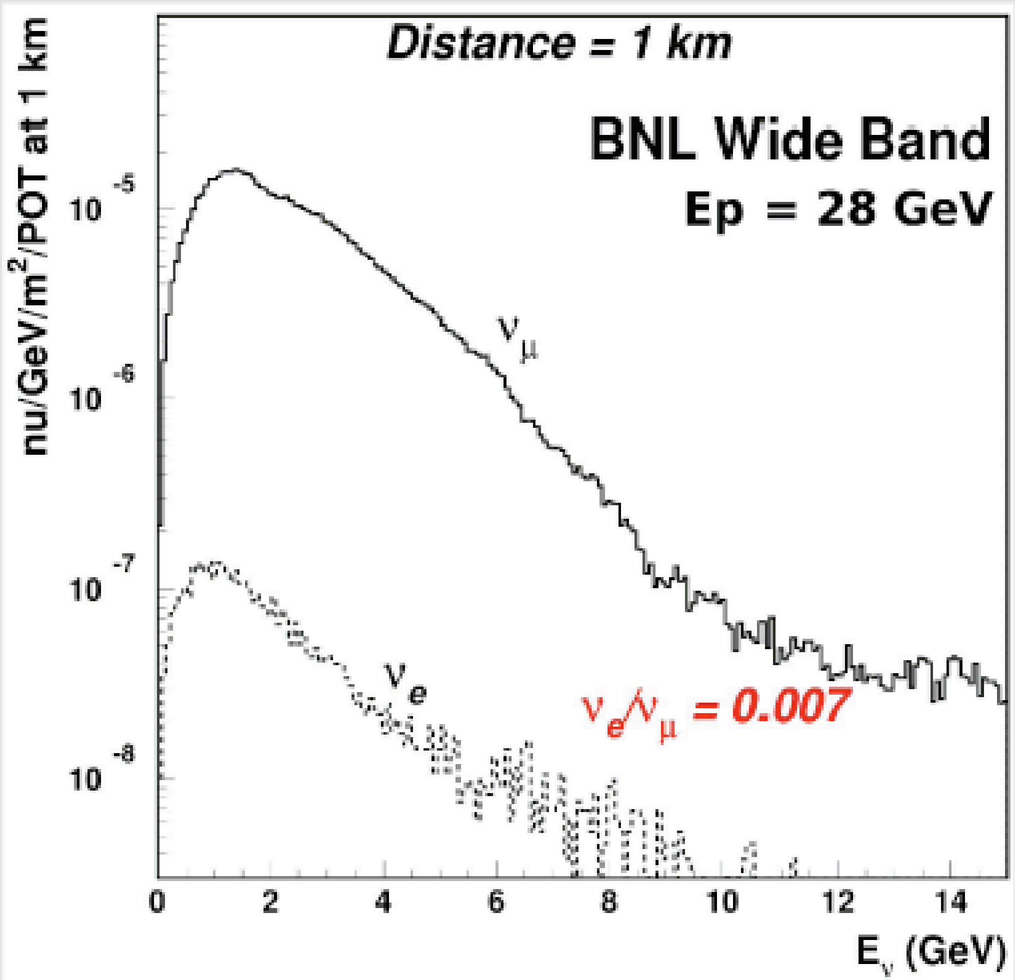
- BNL completed October 8, 2004, a Conceptual Design to support a new proposal to DOE to upgrade the AGS to 1-2 MW target power and construct the wide-band ***Super Neutrino Beam*** as listed in the DOE's "Facilities for the Future of Science" plan of November 2003

AGS 1MW proton beam

Upgrade AGS (28 GeV protons)

intensity: $7.10^{13} \rightarrow 9.10^{13}$ ppp

rep. rate: ~0.3Hz → 2.5Hz



1) ramp time: ~1.2s → 0.2s
   repl. power supply, rf, ...

2) filling time: 0.6s → 1ms
   replace booster:
   extend warm linac 200 MeV
   new SC linac 1 GeV

3) Work continues to goto 1.5 or 2 MW.

4) Experimental work on 1 MW carbon-carbon target.

Detector

- 500 kT fiducial mass for both proton decay and neutrino astro-physics and neutrino beam physics.
- ~10% energy resolution on quasielastic events.
- muon/electron separation at <1%
  - 1,2,3 track event separation.
  - Showering NC event rejection at factor of ~20.
- Low threshold (~5 MeV) for solar and supernova physics.
- Time resolution ~few ns for pattern recognition and background rejection.

Previous issues being solved

Water Cherenkov can satisfy these requirements

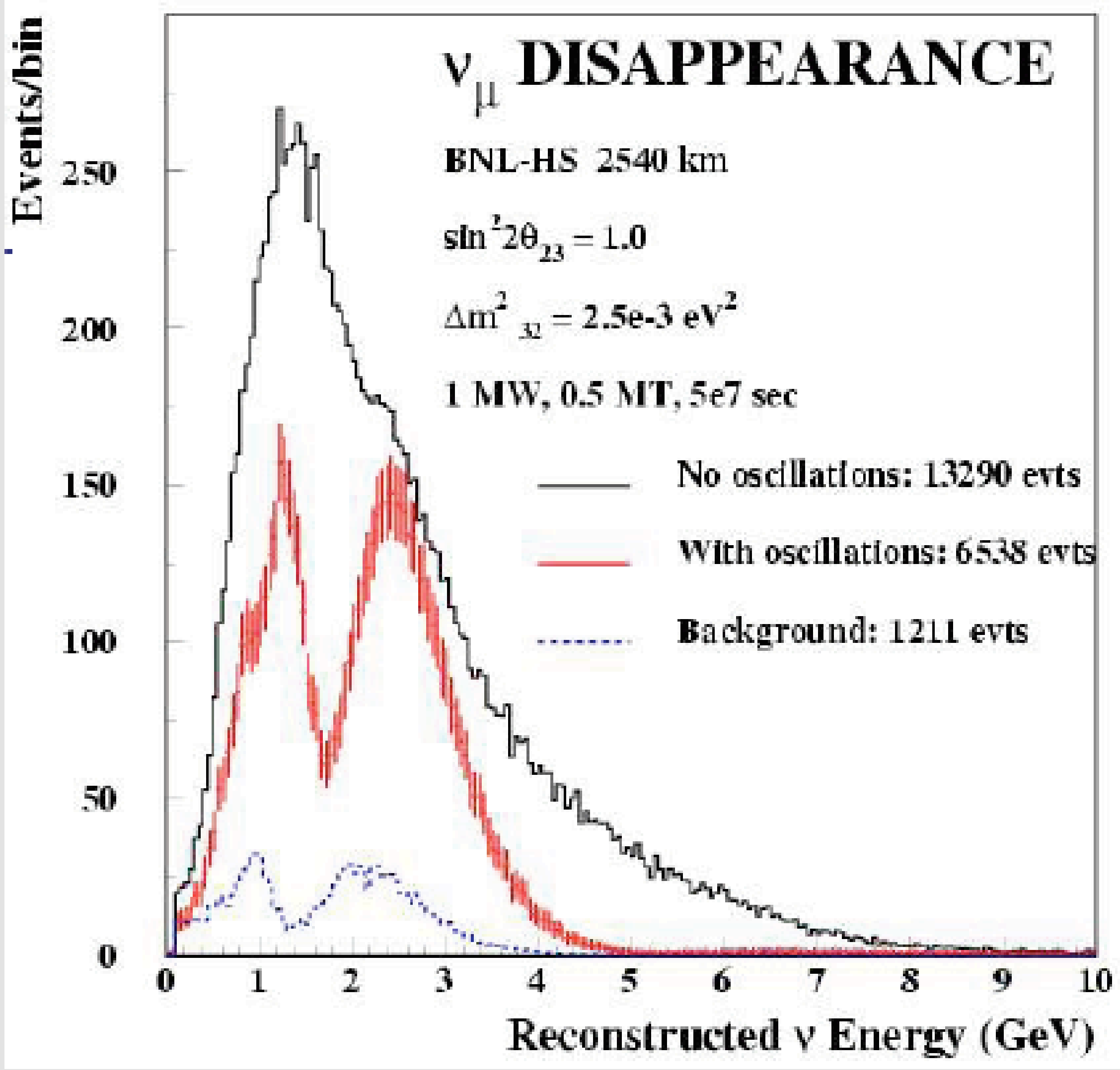
Not magic. Performance is obtained by giving up large fraction of potential signal CC events; and using the kinematics of NC events.

ν_μ disappearance

<u>neutrino running:</u>

1MW beam
0.5Mt water Cerenkov det.
2540km distance
5e7s running time
~50000 tot CC events

determine Δm^2_{32}
& $\sin^2 2\theta_{23}$ to 1%
systematics dominated



<u>anti-neutrino running:</u>

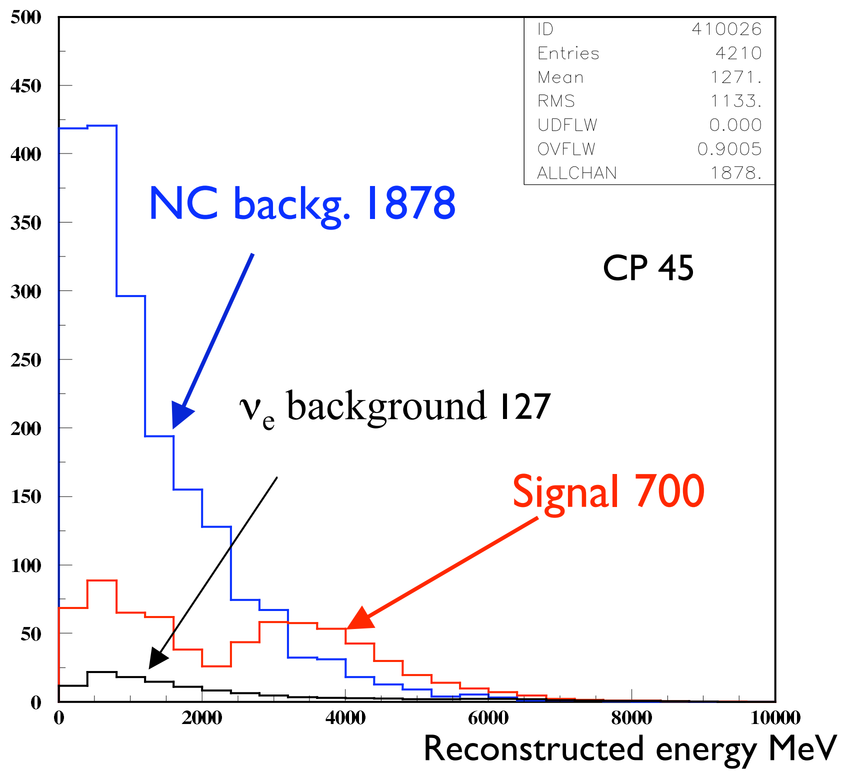
same as ν but with
2MW beam

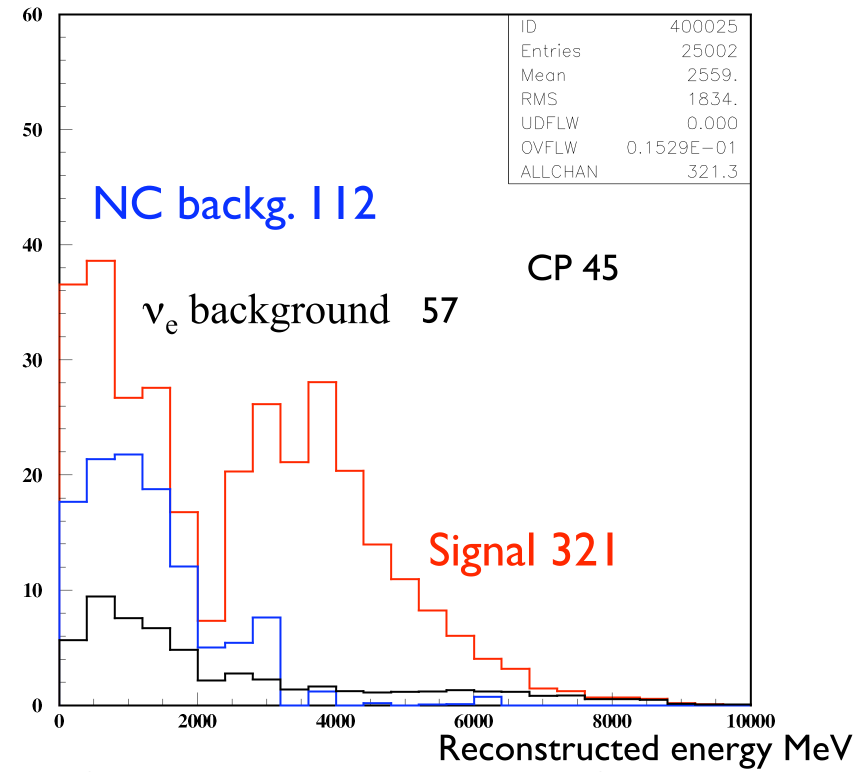
including anti-ν running:
- CPT test possible
- errors below 1% achievable

Complete water Cherenkov detector simulations progress

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

- **Δm^2_{21} =7.3 x 10^{-5} eV^2, Δm^2_{31}=2.5 x 10^{-3}eV^2**
- **$\sin^2 2\theta_{ii}$(12,23,13)=0.86/1.0/0.04, δ_{CP}=+45,+135,-45,-135^o**





Select single ring events and select electrons

Signal/backg = 700/2005

Perform analysis of single electron pattern, likelihood cut retaining ~50% of signal.

Signal/back = 321/169

C. Yanagisawa (Stony Brook), 3rd BNL/UCLA workshop
http://www.physics.ucla.edu/hep/proton/proton2005.htm

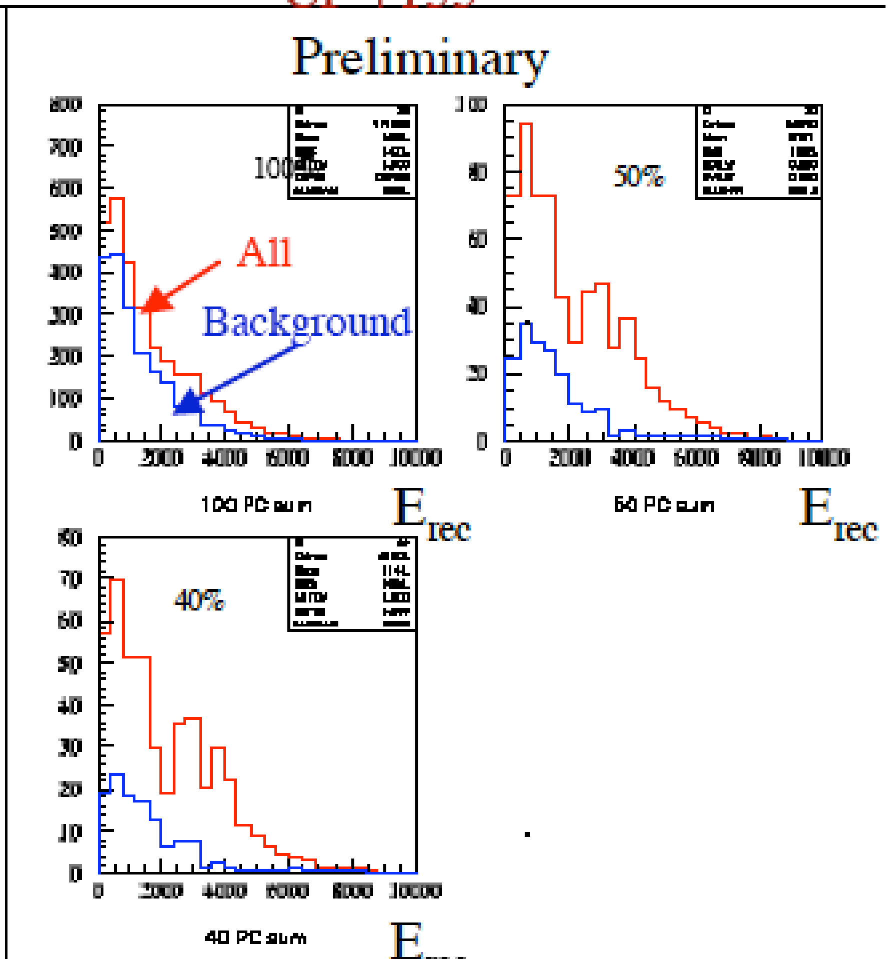
Maximum Likelihood Method

S/B

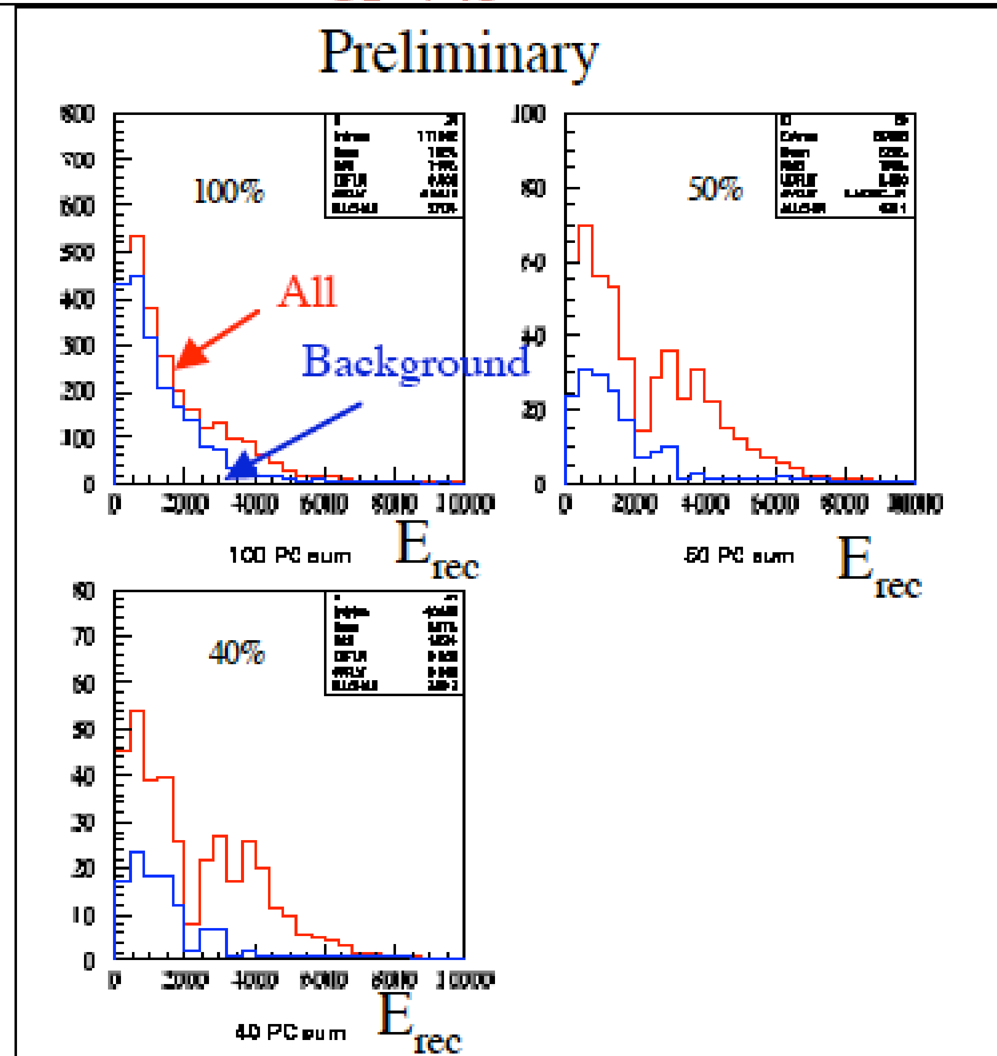
- Effect of cut on likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

CP +135°



CP +45°



ν_e Appearance

backgrounds:

- beam ν_e
- NC ν_μ

neutrino running:

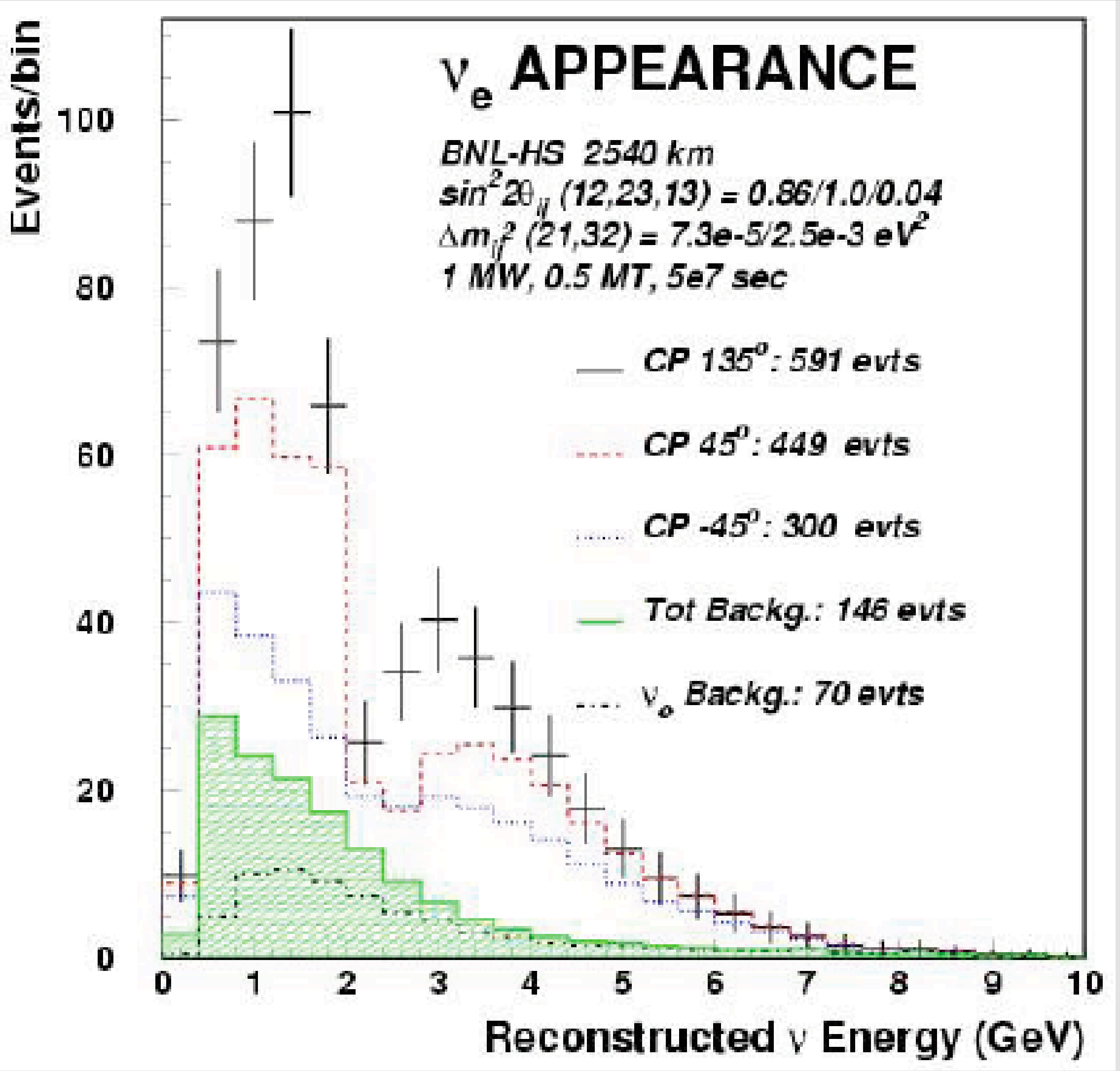
measure $\sin^2 2\theta_{13}$ and δ_{CP}

for $\sin^2 2\theta_{13} > 0.01$

resolve mass hierarchy

include anti-neutrino run:

exclude $\sin^2 2\theta_{13} > 0.003$

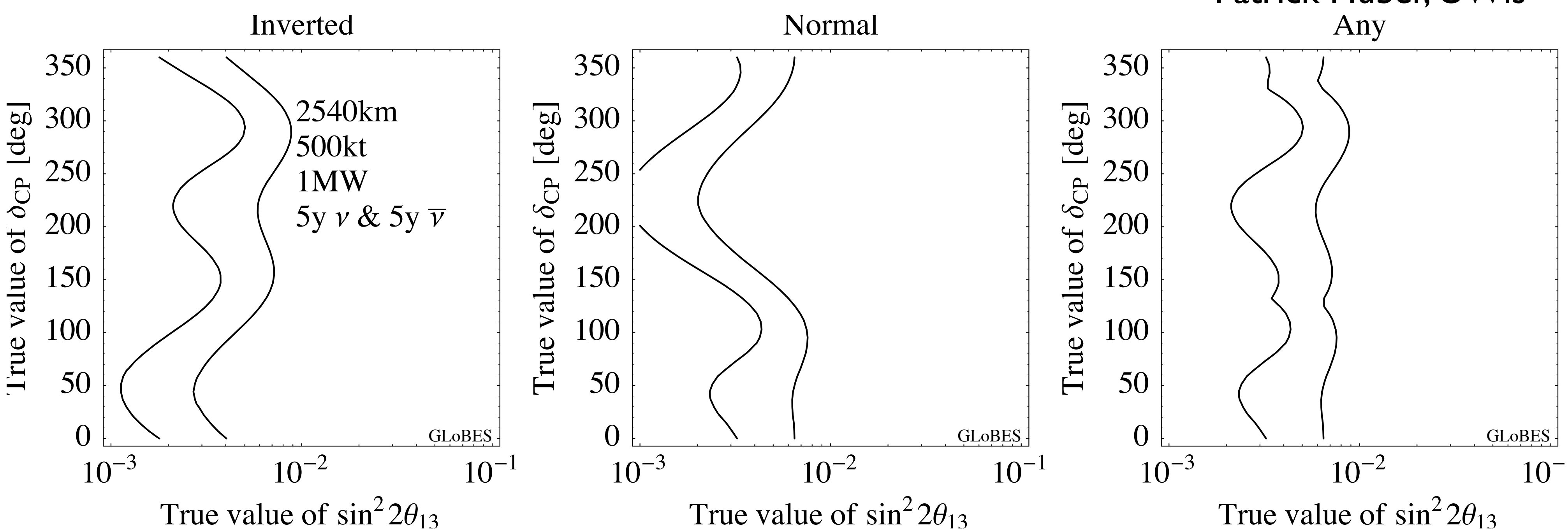


if $\sin^2 2\theta_{13}$ too small → δ_{CP} measurement not possible

observation ν_e appearance possible through solar term

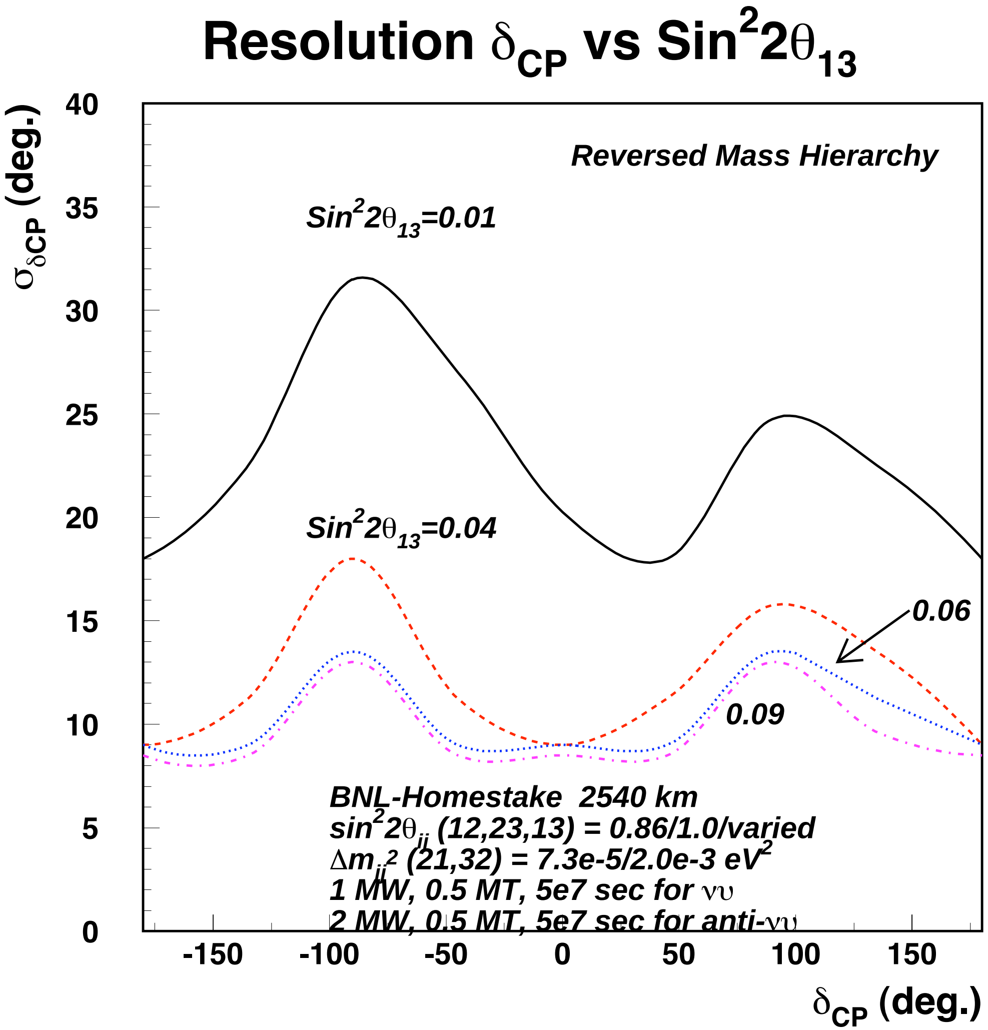
Resolution of mass hierarchy (preliminary work) at 1 and 2 sigma.

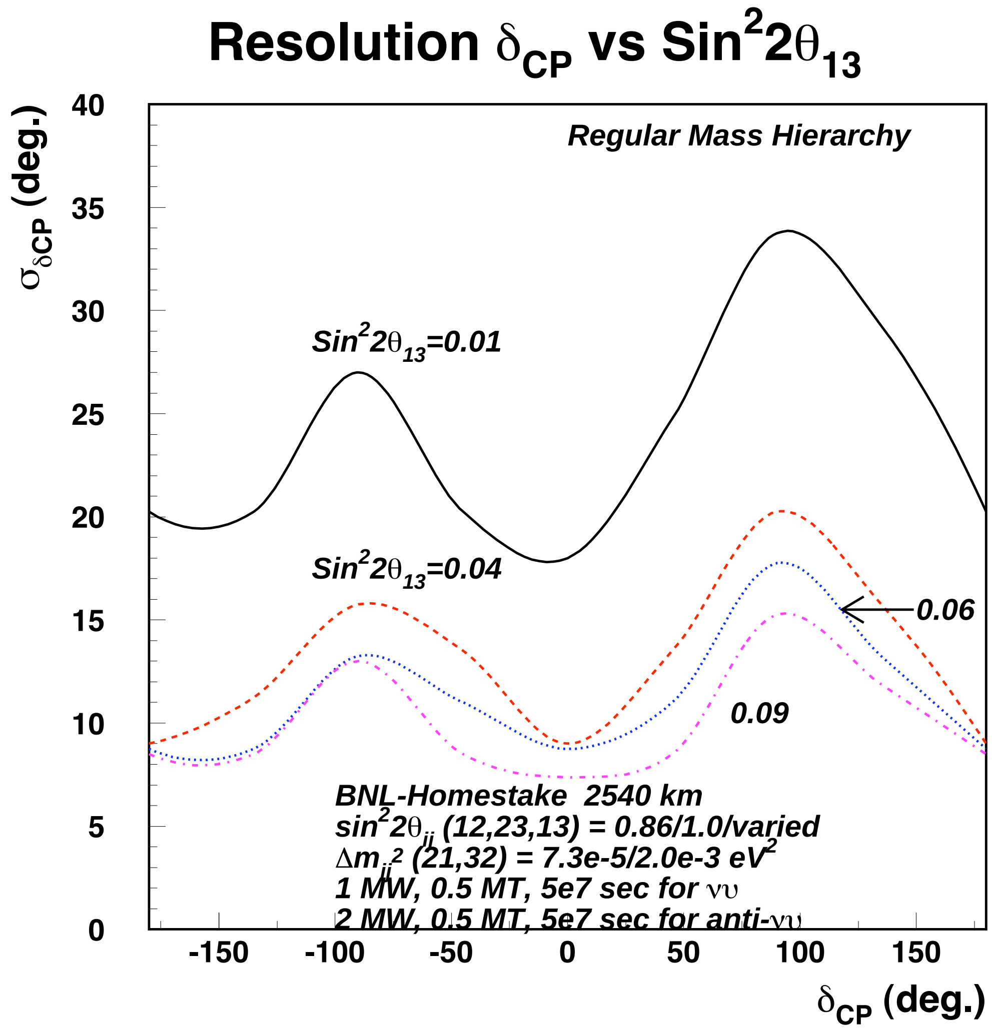
Patrick Huber, UWis



- Includes correlations and errors on all parameters including earth's density. 10% bckg uncertainty.
- As parameters improve this plot gets better.
- Entire range of delta is covered.

CP resolution





Complete resolution of mass hierarchy after anti-neutrino running and excellent resolution on delta-CP.

What if Theta13 is 0 ? Will still see appearance !

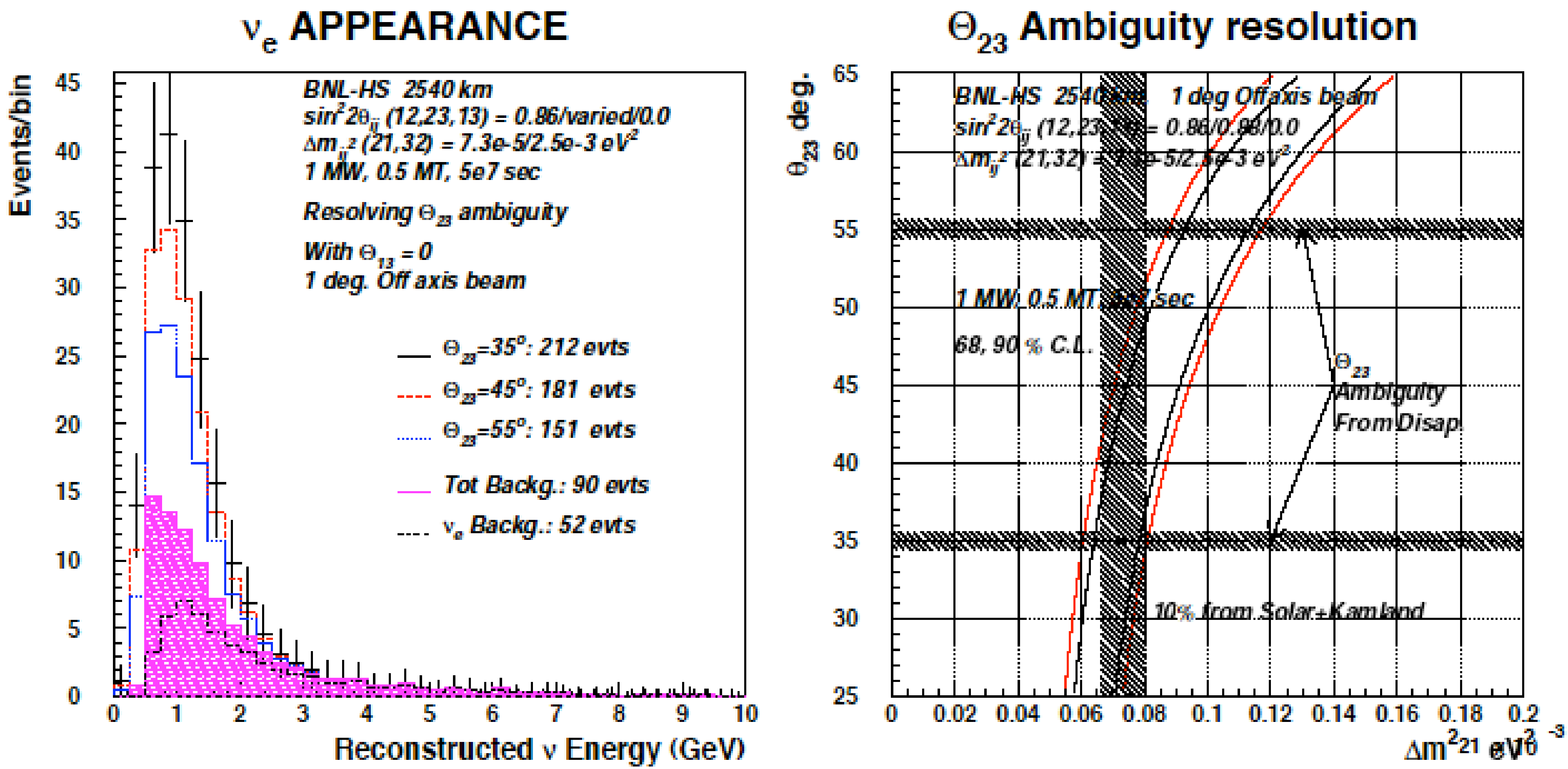


Figure 8: *Expected spectrum of electron neutrinos (left) for $\theta_{13} = 0$ and other assumed parameters indicated in the figure. The right hand side shows the resolution of the $\theta_{23} \to \pi/2 - \theta_{23}$ ambiguity using the measurement of $\sin^2 2\theta_{23}$ from disappearance and assuming a 10% measurement of Δm^2_{21} from KAMLAND. The area between the curves is allowed by the appearance spectrum (left) for $\theta_{23} = 35^o$.*

Scientific Reach of Future Neutrino Oscillations Exps.

Parameter	T2K	T2H	Reactor	Nova	Nova2	VLBNO.
Δm_{32}^2	± 4 %	± 4 %	-	± 2 %	± 2 %	± 1 %
$\sin^2(2\theta_{23})$	±1.5 %	± 0.4 %	-	± 0.4 %	± 0.2 %	± 0.5 %
$\sin^2(2\theta_{13})$ [a]	>0.02	>0.01	>0.01	>0.01	>0.01	>0.01
$\Delta m_{21}^2 \sin(2\theta_{12})$ [b]	-	-	-	-	-	12 %
sign of (Δm_{32}^2) [c]	-	-	-	possible	yes	yes
measure δ_{CP} [d]	-	~20°	-	-	~20°	±13°
N-decay gain	x1	x20	-	-	-	x8
Detector (Ktons)	50	1000	20t	30	30+50	400
Beam Power (MW)	0.74	4.0	14000	0.4	2.0	1.5
Baseline (km)	295 [e]	295 [e]	1	810 [e]	810 [e]	>2500
Detector Cost ($M)	exists	~1000	20	165	+200	400
Beam Cost ($M)	exists	500	exists	50	1000	400
Ops. Cost ($M/10 yrs)	500	700	50	500	600	150/500 [f]

Both results needed to resolve ambiguities!

[a] detection of $\nu_\mu \rightarrow \nu_e$, upper limit on or determination of $\sin^2(2\theta_{13})$

[b] detection of $\nu_\mu \rightarrow \nu_e$ appearance, even if $\sin^2(2\theta_{13}) = 0$; determine θ_{23} angle ambiguity

[c] detection of the matter enhancement effect over the entire δ_{CP} angle range

[d] measure the CP-violation phase δ_{CP} in the lepton sector; Nova2 depends on T2K2

[e] beam is 'off-axis' from 0-degree target direction; [f] with/without RHIC operations

Best Bets

Office of Science
U.S. DEPARTMENT OF ENERGY

T. Kirk/M. Diwan

BROOKHAVEN NATIONAL LABORATORY

Comments on Neutrino Oscillations Experiments

- *All* parameters of neutrino oscillation can be measured in _one_ experiment
  - a Very Long Baseline Neutrino Oscillation (VLBNO) at >2000 km
  - the cost of VLBNO is comparable to (or less than) competing proposals
  - the mass of the VLBNO target enables a powerful *Nucleon Decay* search
- Use of a *broadband neutrino beam* at *very long distances* is the key
  - Oscillatory signal very important for extracting signal from background and measuring parameter without systematics.
- Focus on CP because **The CP-violation parameter is the most difficult parameter to determine**
  - matter effects interact with CP-violation effects
  - the CP-violation phase δ_{CP} has distinct effects over the full 360° range
- Off-axis beam method requires multiple distances and detectors to get same science.
  - each step in offaxis will require of order 10 Snomass years of running
- All measured oscillation parameters will be limited to ~1% precision by systematic errors except $\sin^2(2\theta_{23})$

Conclusions

- Powerful method for neutrino oscillations and CP violation study.
- We have made great progress on many technical issues.
- Important work performed on detector background issue.
- Lowest risk most cost effective option for a long baseline second generation experiment.
- GUARANTEED TO SEE CONVERSION OF MUON TO ELECTRON TYPE NEUTRINOS