Future Opportunities in Long Baseline Oscillation Physics

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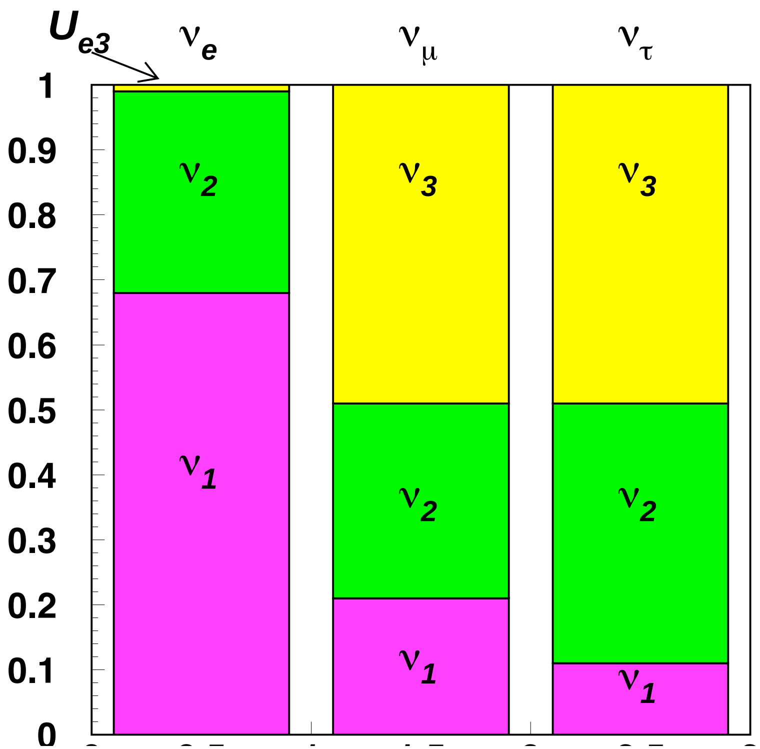
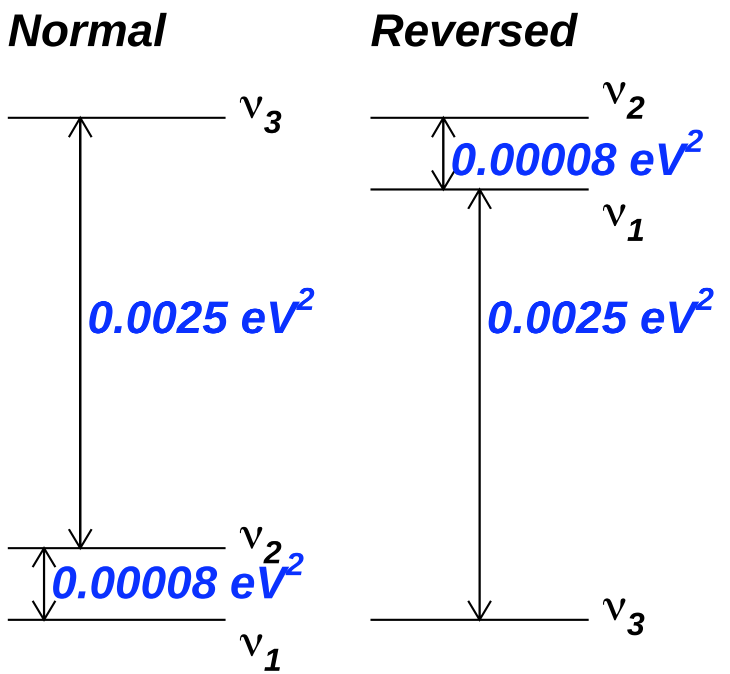
11/14/2005

Outline of talk

- Concept of very long baseline
- Possibilities in USA
  - Unique situation with DUSEL
- The backgrounds issue
- Resources needed for study

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

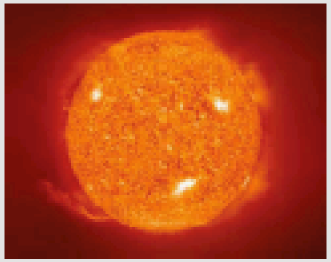
$$\begin{aligned} P(\nu_a \to \nu_b) &= \textstyle\sum_i |U_{ai}|^2 |U_{bi}|^2 \\ &+2Re(U_{a1}^* U_{b1} U_{a2} U_{b2}^* \times exp(-i\Delta m_{21}^2 L/2E) \\ &+2Re(U_{a1}^* U_{b1} U_{a3} U_{b3}^* \times exp(-i\Delta m_{31}^2 L/2E) \\ &+2Re(U_{a2}^* U_{b2} U_{a3} U_{b3}^* \times exp(-i\Delta m_{32}^2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

no matter effects

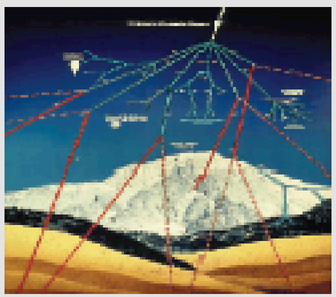
Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$.

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

Why Very Long Baseline?

observe multiple nodes in oscillation pattern

☞ less dependent on flux normalization

neutrino travels larger distance through earth

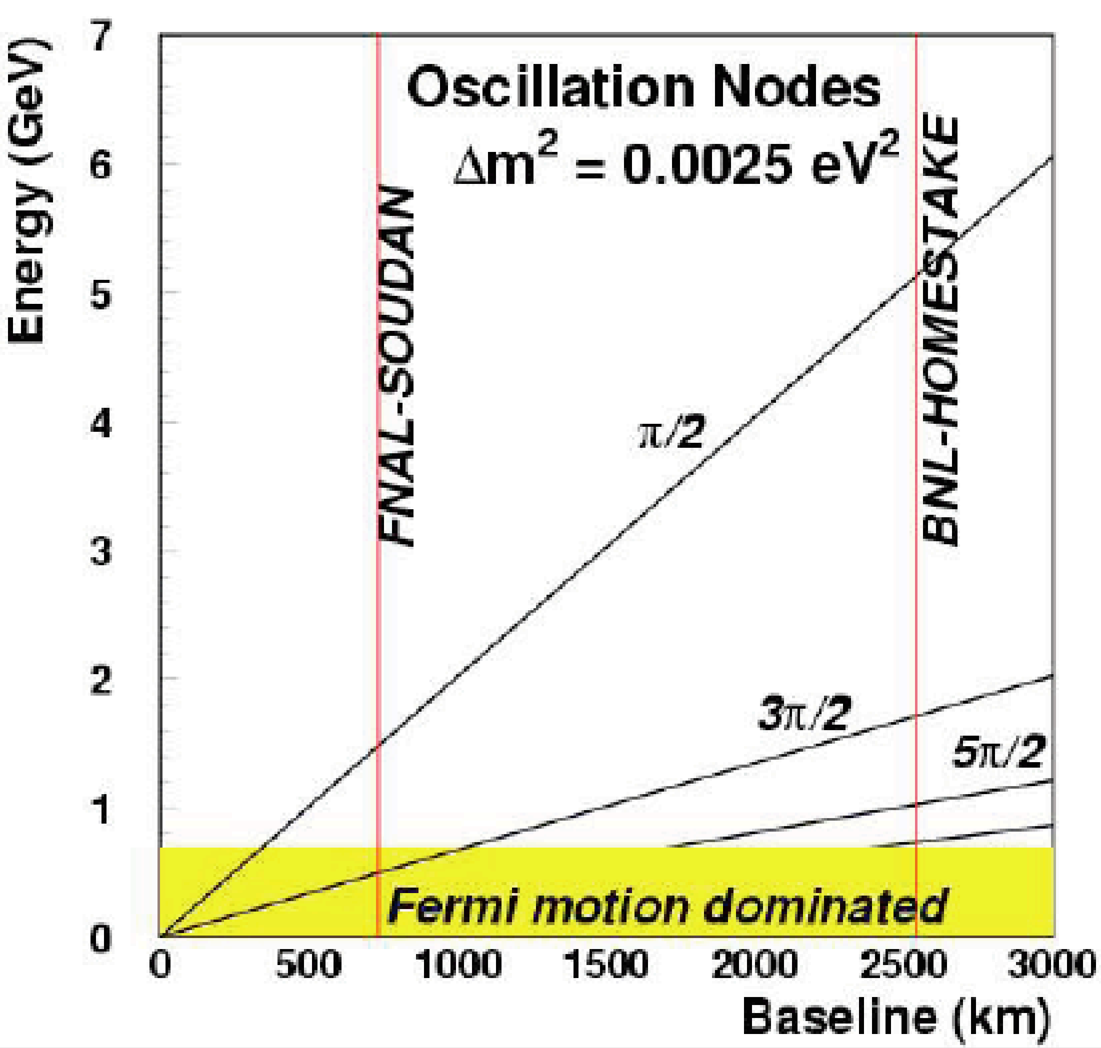
larger matter effects

flux ~ L^{-2}: lower statistics

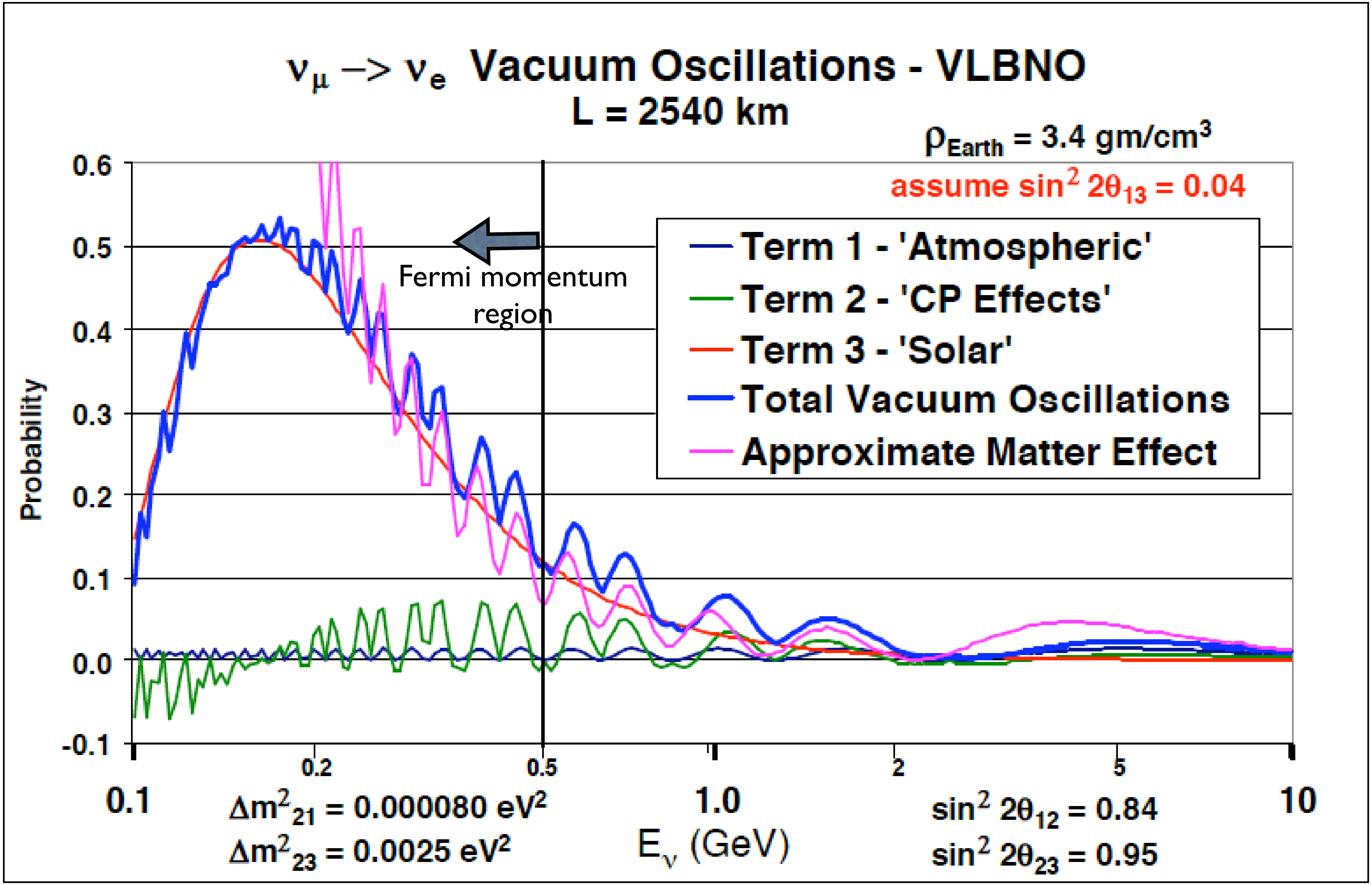
but: CP asymmetry ~ L

sensitivity to δ_{CP} independent of distance!

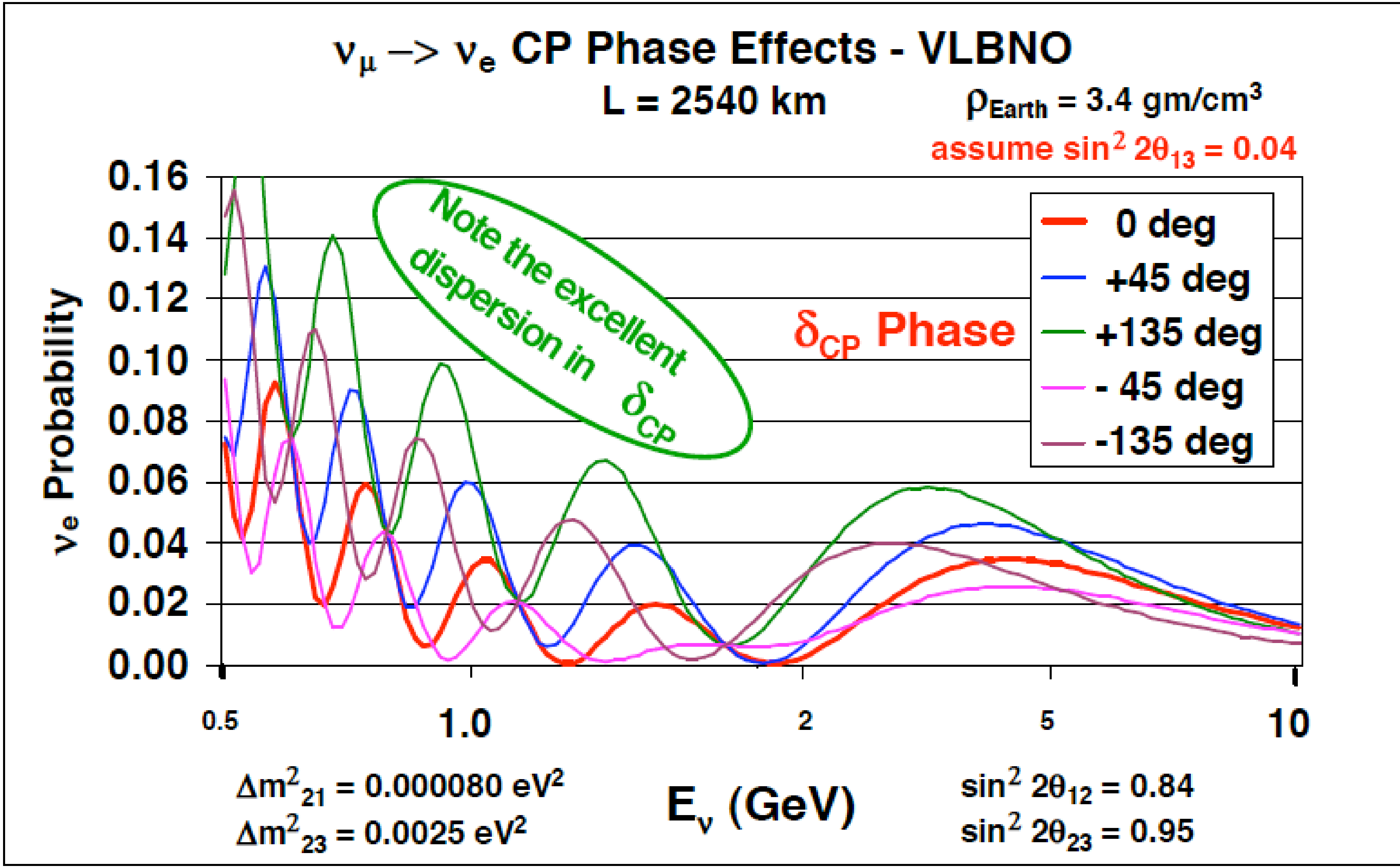
better S:B



(Marciano hep-ph/0108181)



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



νμ -> νe CP Phase Effects - VLBNO
L = 2540 km
ρEarth = 3.4 gm/cm3
assume sin2 2θ13 = 0.04
Note the excellent dispersion in δCP
δCP Phase
0 deg
+45 deg
+135 deg
- 45 deg
-135 deg
νe 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
Δm221 = 0.000080 eV2
Δm223 = 0.0025 eV2
Eν (GeV)
sin2 2θ12 = 0.84
sin2 2θ23 = 0.95

US possibilities for beam

Source	Proton beam energy	Proton beam power
FNAL MI (McGinnis upgrade)	Ep=8-120GeV	1-2 MW X (Ep/120GeV)
FNAL MI (with 8GeV LINAC)	Ep=8-120 GeV	2 MW @ any Ep
BNL-AGS (upgrade 2.5- 5 Hz)	Ep=28 GeV	1-2 MW

US possible baselines

Source	Detector	Distance	Depth	Comment
FNAL	Soudan	735 km	2300ft	High E beam exists, not DUSEL site
FNAL	Homestake	1290 km	7700ft	no beam, DUSEL site, capable of large exca.
FNAL	Henderson	1500km	5000 ft	no beam, DUSEL site, capable of large exca.
BNL	Soudan	1711 km	2300 ft	--
BNL	Homestake	2540km	7700 ft	study of beam and physics exists and documented
BNL	Hendersn	2767km	5000 ft	--

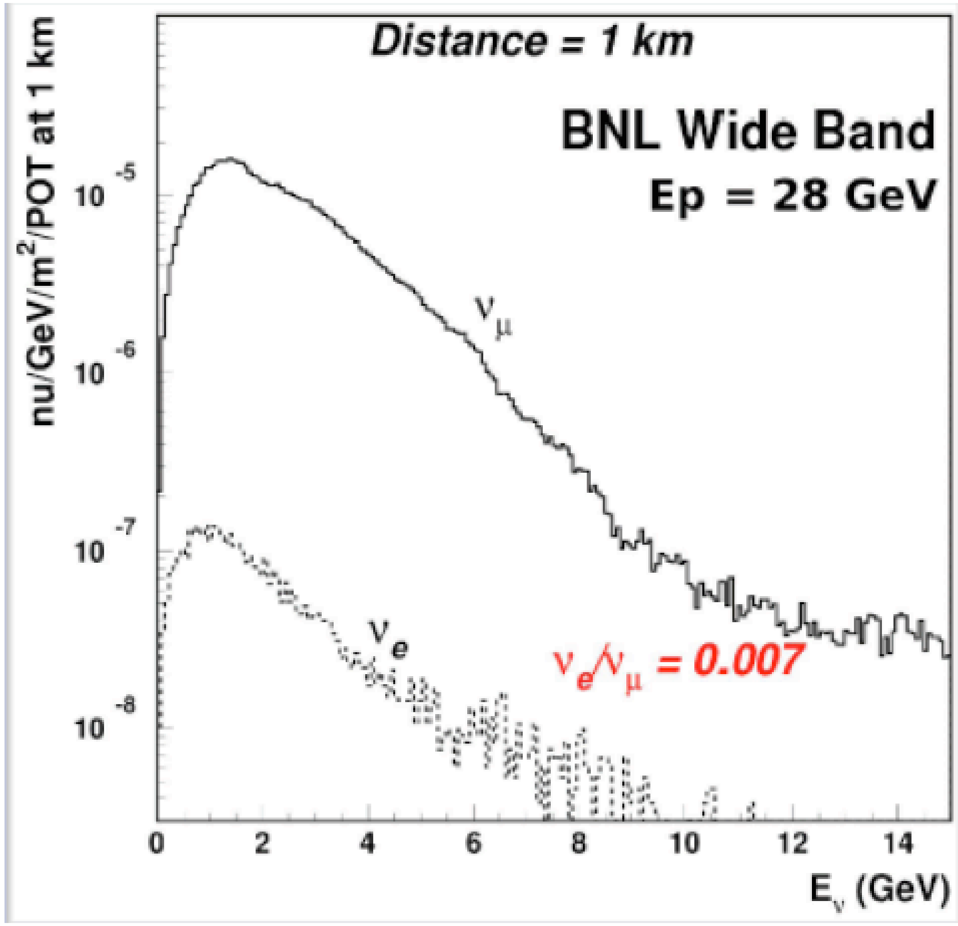
Possibilities for study

Source-det	Detector size	beam E and power	Event rate for neutrino running
BNL-HS (2540)	500 kT	1 MW@28 GeV	50000 CC 17000 NC
FNAL-HS(1290)	500kT	1 MW@28 GeV	194000CC 66000NC
FNAL-HS(1290)	200kT	0.5MW@60GeV	~60000 ~20000
FNAL-Hend(1500)	200kT	0.5MW@60GeV	~44000 ~15000
FNAL-HS(1290)	200kT	2MW@8GeV	2188 CC 850 NC

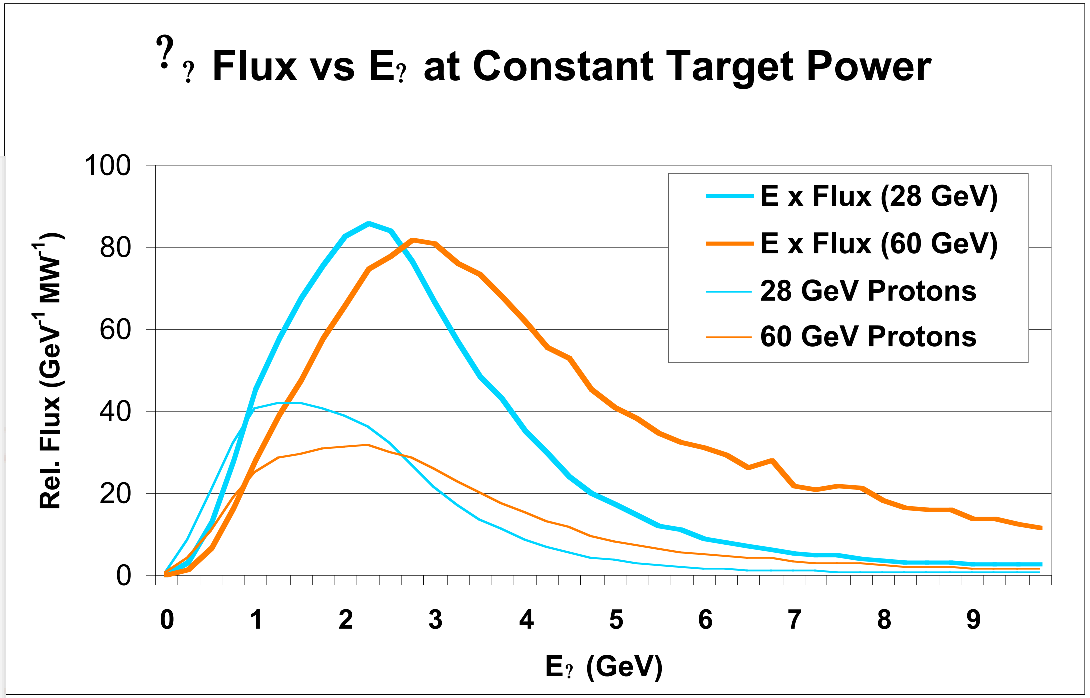
using Miniboone data

5 X 10^7 sec of running assumed

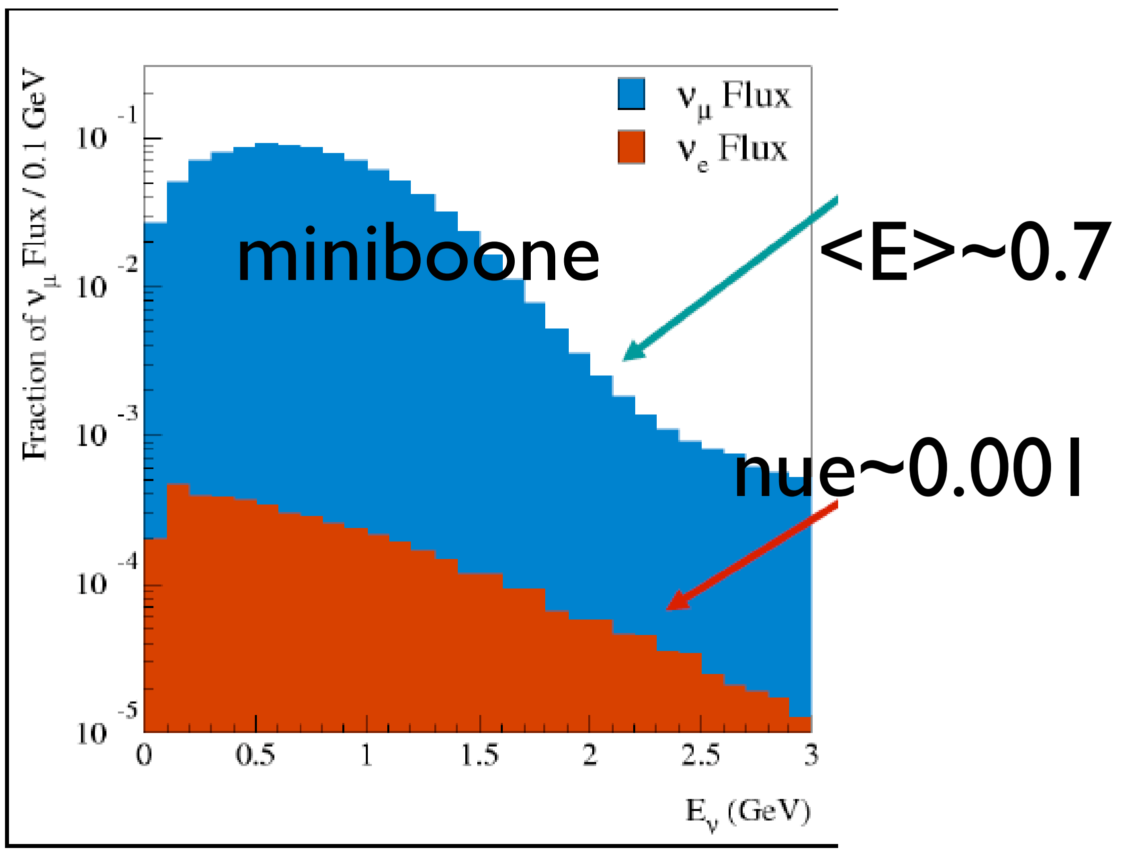
Flux shapes



Distance = 1 km
BNL Wide Band
Ep = 28 GeV
nu/GeV/m^2/POT at 1 km
ν_μ
ν_e
ν_e/ν_μ = 0.007
E_ν (GeV)



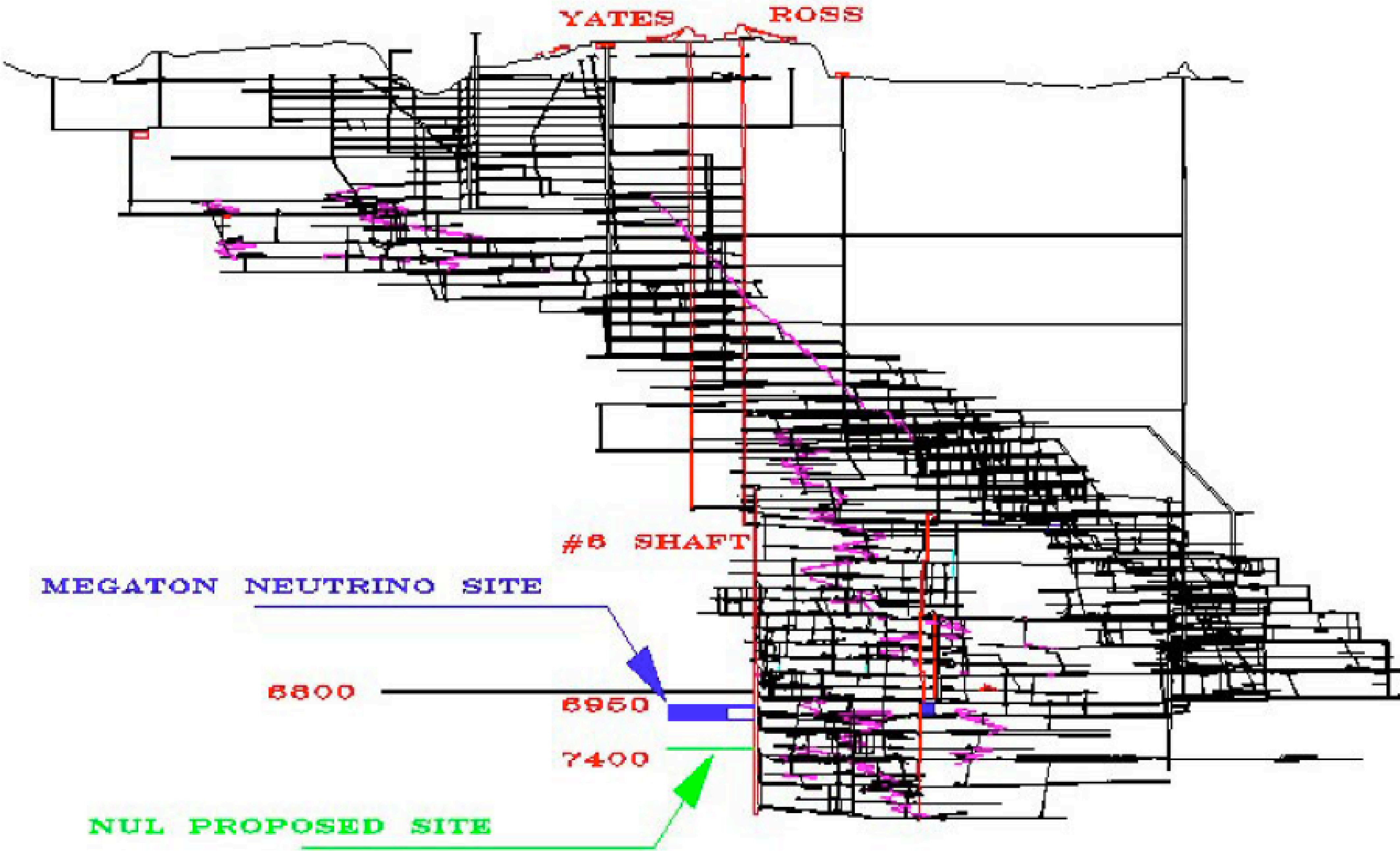
? ? Flux vs E? at Constant Target Power
E x Flux (28 GeV)
E x Flux (60 GeV)
28 GeV Protons
60 GeV Protons
Rel. Flux (GeV^{-1} MW^{-1})
E? (GeV)



ν_μ Flux
ν_e Flux
miniboone
<E>~0.7
nue~0.001
Fraction of ν_μ Flux / 0.1 GeV
E_ν (GeV)

Unique situation in US

- Baselines of 1000 - 2000 km are easy.
- At least two sites with depths of ~5000mwe (needed for low deadtime in these large detectors, big issue for HyperK)
- DUSEL process already in the works.
- In particular, Homestake is ready !
- DUSEL community is very interested in this meeting. Some consider this meeting make or break for DUSEL.



Mine has been transferred to State Oct. 05
South Dakota is prepared to spend $45M in initial funding to get lab started. Call for LOI's issued.

http://neutrino.lbl.gov/Homestake/LOI

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.

Background issues

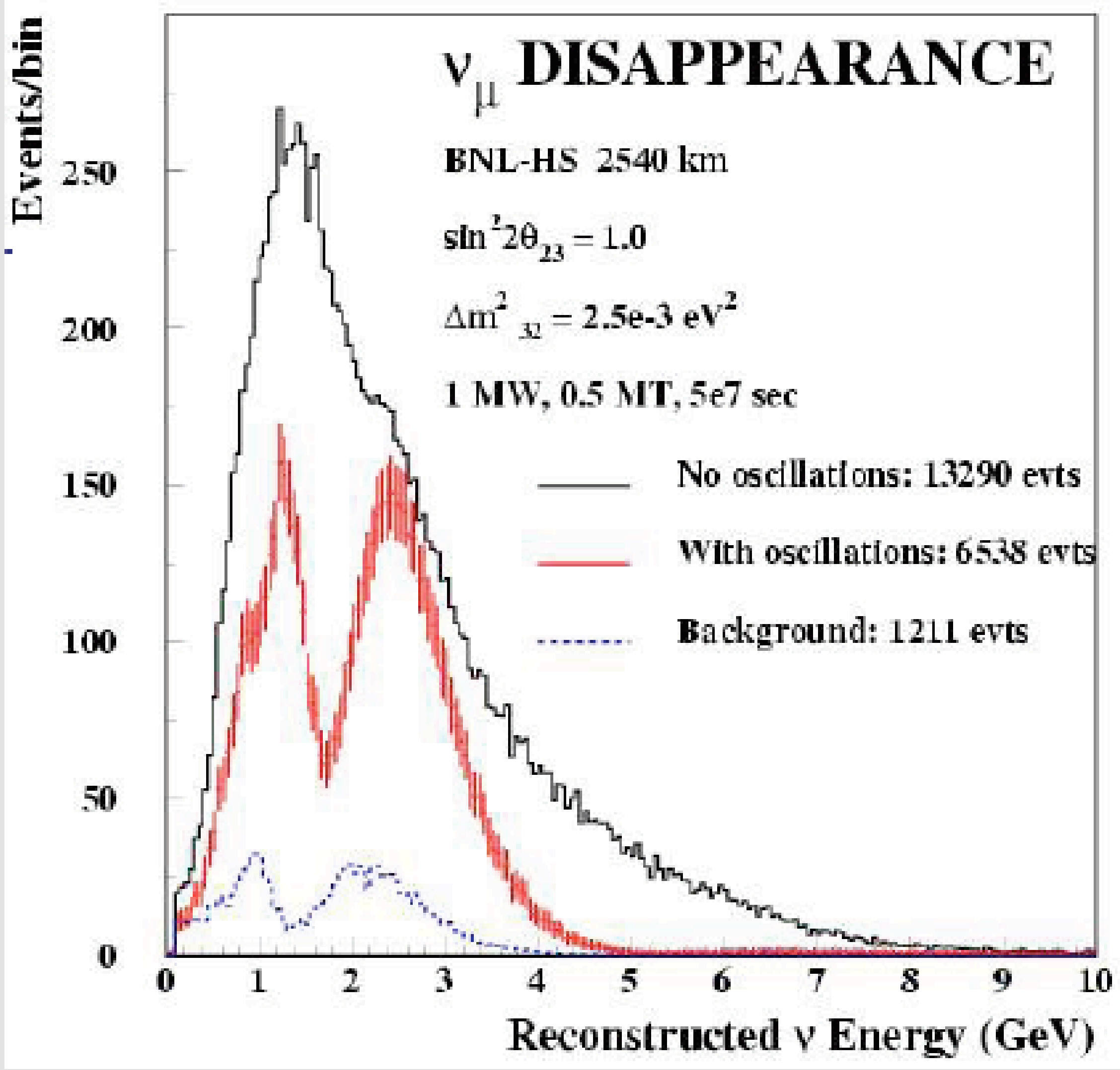
- NC kinematics favors a falling spectrum. Background is pushed to low energies.
- Currently we are assuming that we use only the cleanest events. eff. < 20 %. Large fraction of CC events could be used if detector can be finer grained.
- No hardware enhancements assumed for water Cherenkov detector so far.

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>

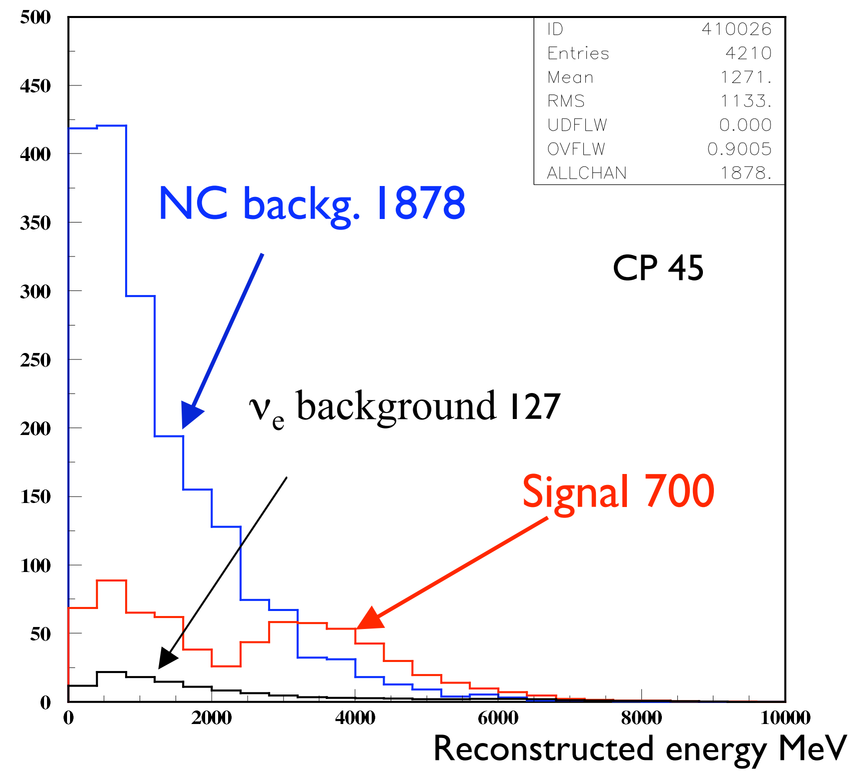
same as ν but with
2MW beam

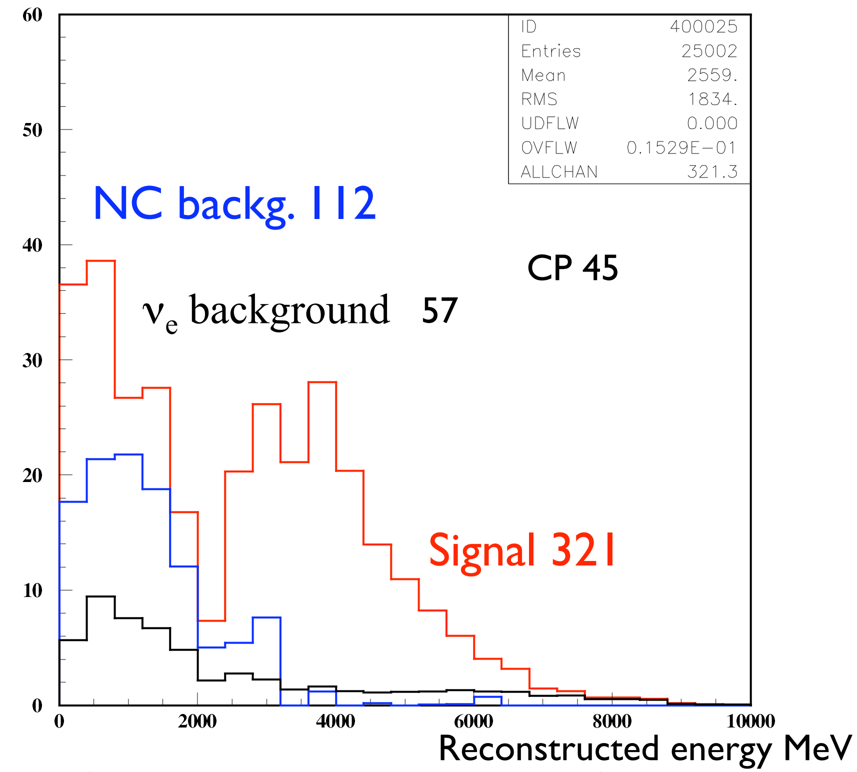
including anti-ν running:
- CPT test possible
- errors below 1% achievable

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
- $\sin^2 2\theta_{ij}$(12,23,13)=0.86/1.0/0.04, δ_{CP}=+45,+135,-45,-135°





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

ν_e Appearance

backgrounds:

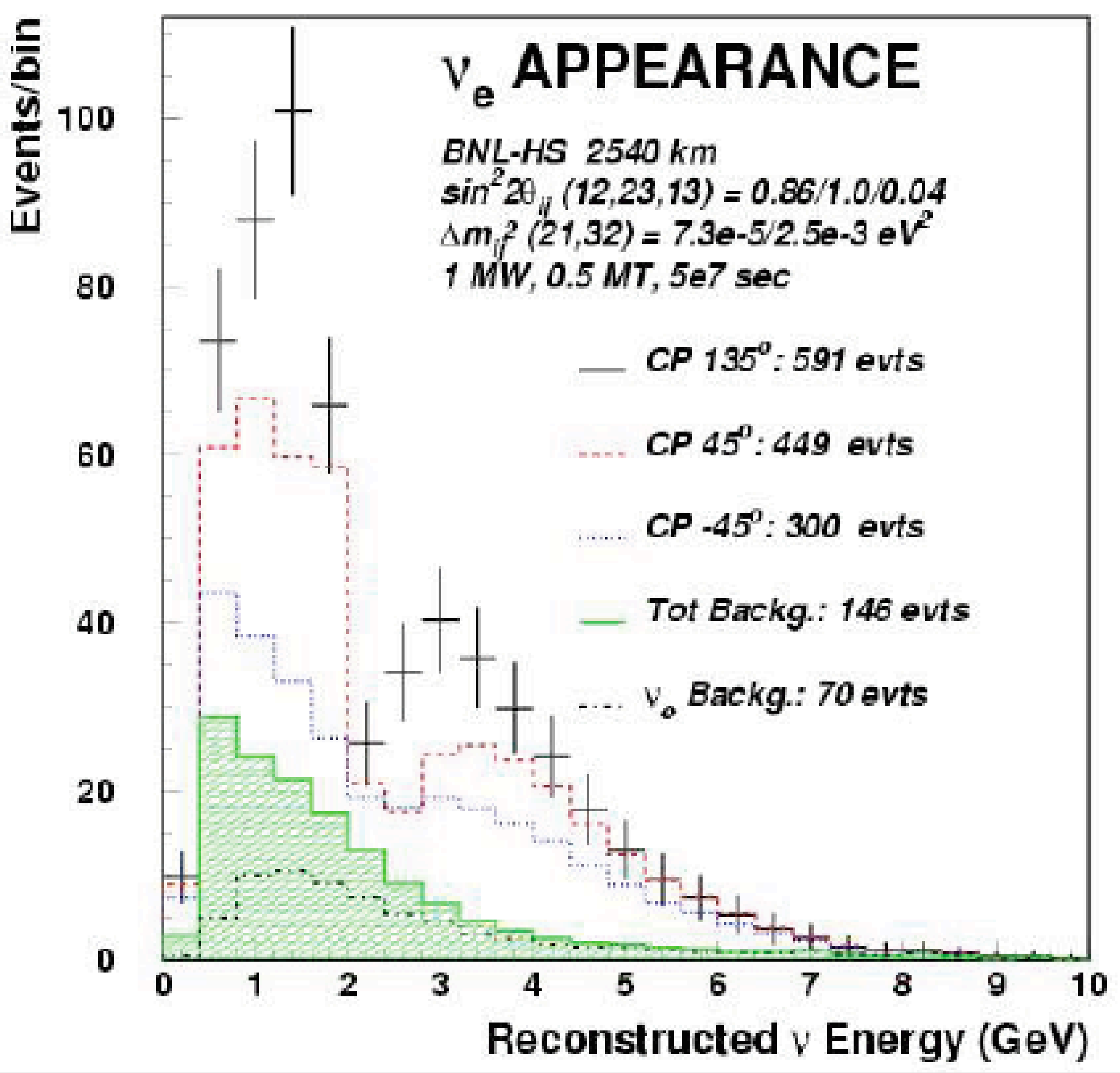
- beam ν_e
- NC ν_μ

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

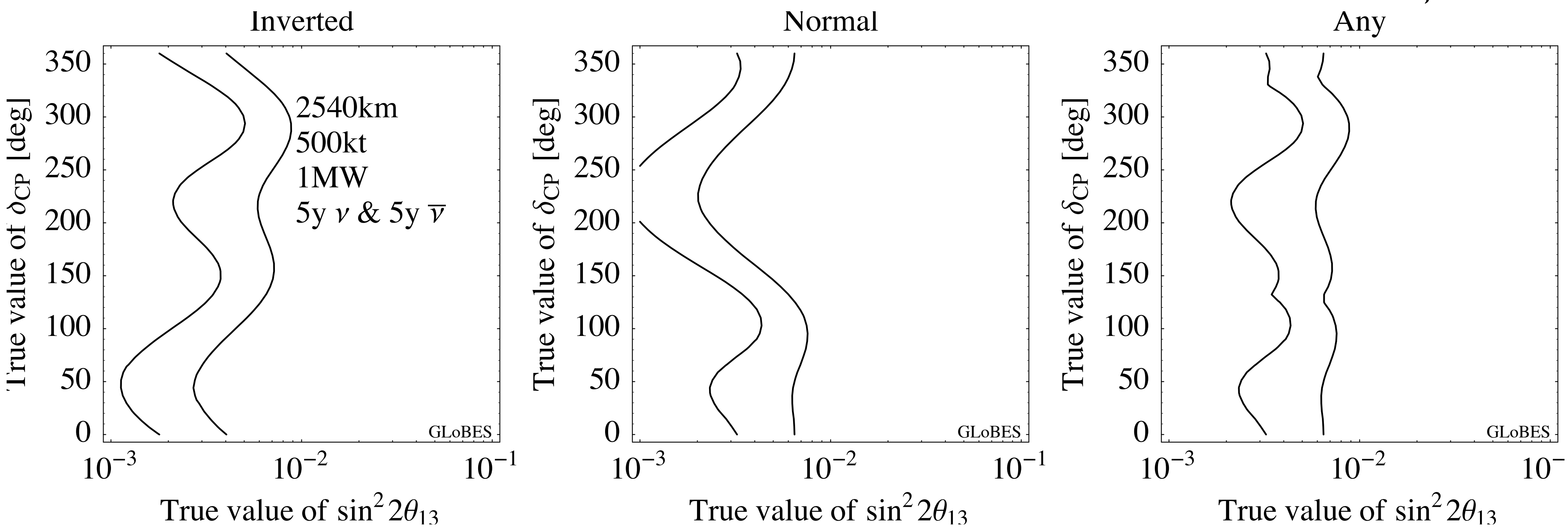


if $\sin^2 2\theta_{13}$ too small → δ_{CP} measurement not possible

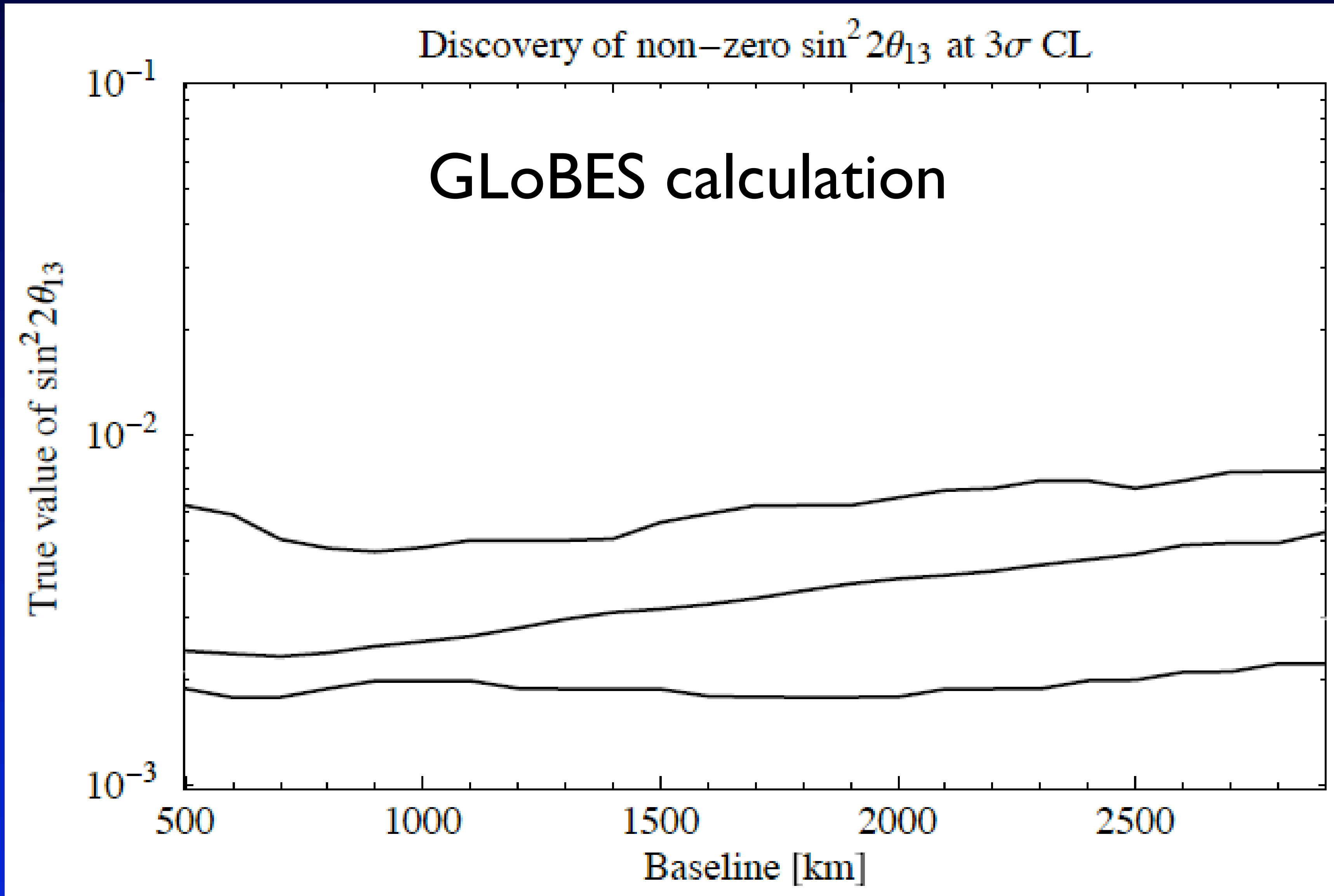
observation ν_e appearance possible through solar term

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

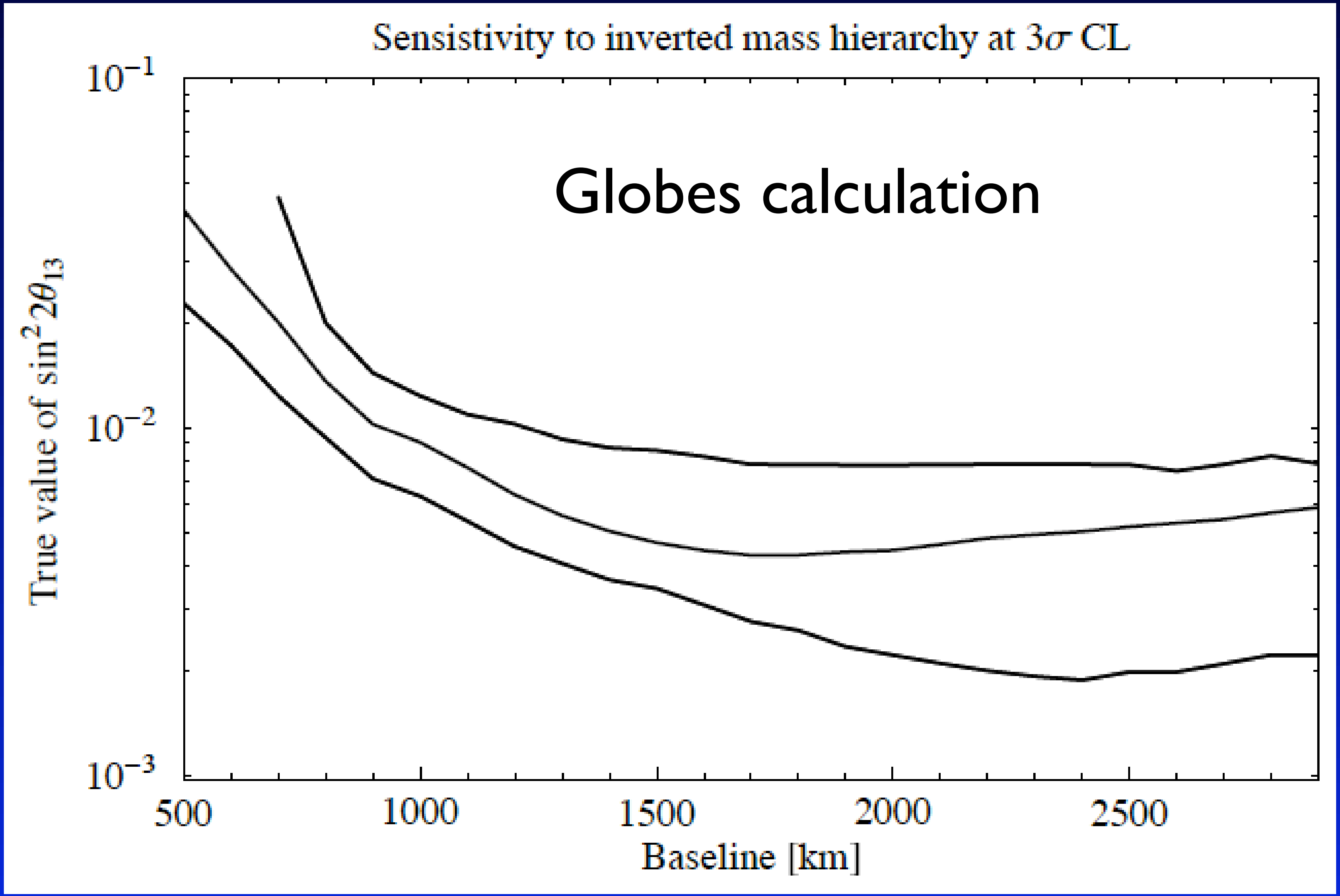
Patrick Huber, UWis



- 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.



- weak baseline dependence



- long baselines are clearly favored

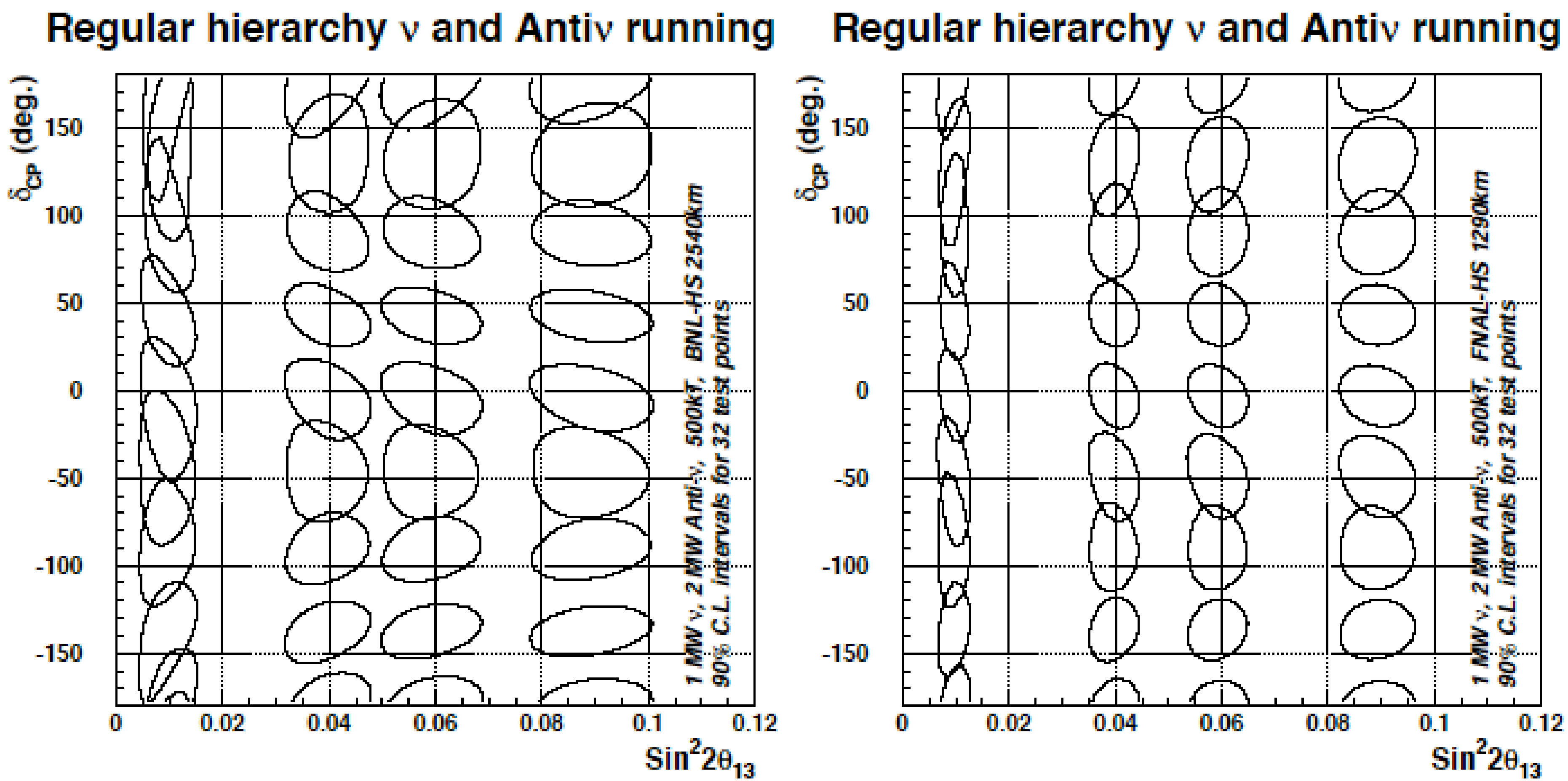


Figure 7: *90% confidence level error contours in* $\sin^2 2\theta_{13}$ *versus* δ_{CP} *for statistical and systematic errors for 32 test points. This simulation is for combining both neutrino and anti-neutrino data. Left is for BNL-HS and right is for FNAL-HS. We assume 10% systematic errors for this plot.*

What needs to be examined in detail

- Detector simulations: Spectrum versus background. 2 people
- Cost of excavation at DUSEL (preliminary numbers ~$20M/100 kT.) 2 people
- Cost of ~100 kT water Cherenkov detector. (well known cost dominated by PMTs) 2 people
- Beam optimization: FNAL spectrum versus power level tradeoffs. 1-2 people
- Cost of new beam to DUSEL. 1 person

Summary

- 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. Nucleon Decay, Solar and atmospheric neutrinos, supernova are all extras.
- If sufficiently long L/E, then you will see electron appearance through the solar term. This is essential physics.
- Need ~8 people for complete study from FNAL to DUSEL.