Long Baseline Oscillation Physics

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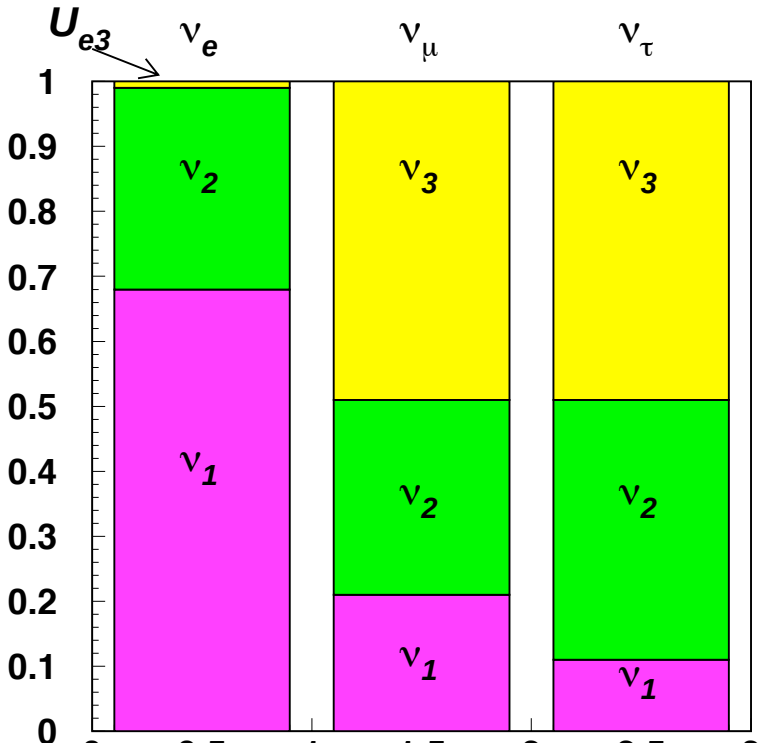
12/20/2005
Talk at Lawrence Berkeley Lab.

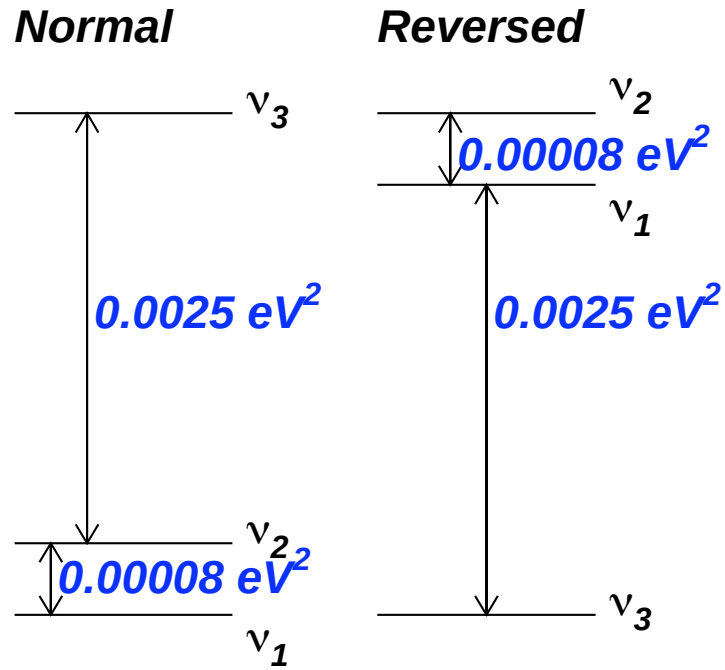
Outline of talk

- Concept of very long baseline with wide band beam.
- Event rates and sensitivity
  - The backgrounds issue
- Possibilities in USA
  - Unique situation with DUSEL
- Resources needed for study

Nucleon decay and neutrino oscillations

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:

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

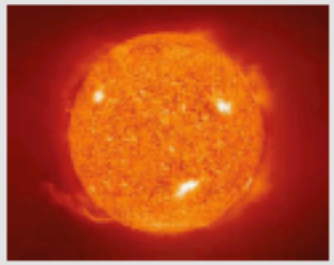
CP phase

no matter effects

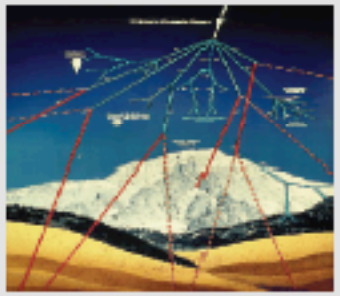
Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$.

Solar : L~15000km

Neutrino Oscillations Results



$$\Delta m^2_{21} = (8.0 \pm 0.3) 10^{-5}\, eV^2$$
$$\sin^2 2\theta_{12} = 0.86 \pm 0.04$$



$$|\Delta m^2_{32}| = (2.5 \pm 0.3) 10^{-3}\, eV^2 \quad \text{sign?}$$
$$\sin^2 2\theta_{23} = 1.02 \pm 0.04 \quad \text{degeneracy?}$$



$$\sin^2 2\theta_{13} < 0.12 \quad \text{(99\% C.L.)}$$
$$\delta_{CP} = ???$$

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

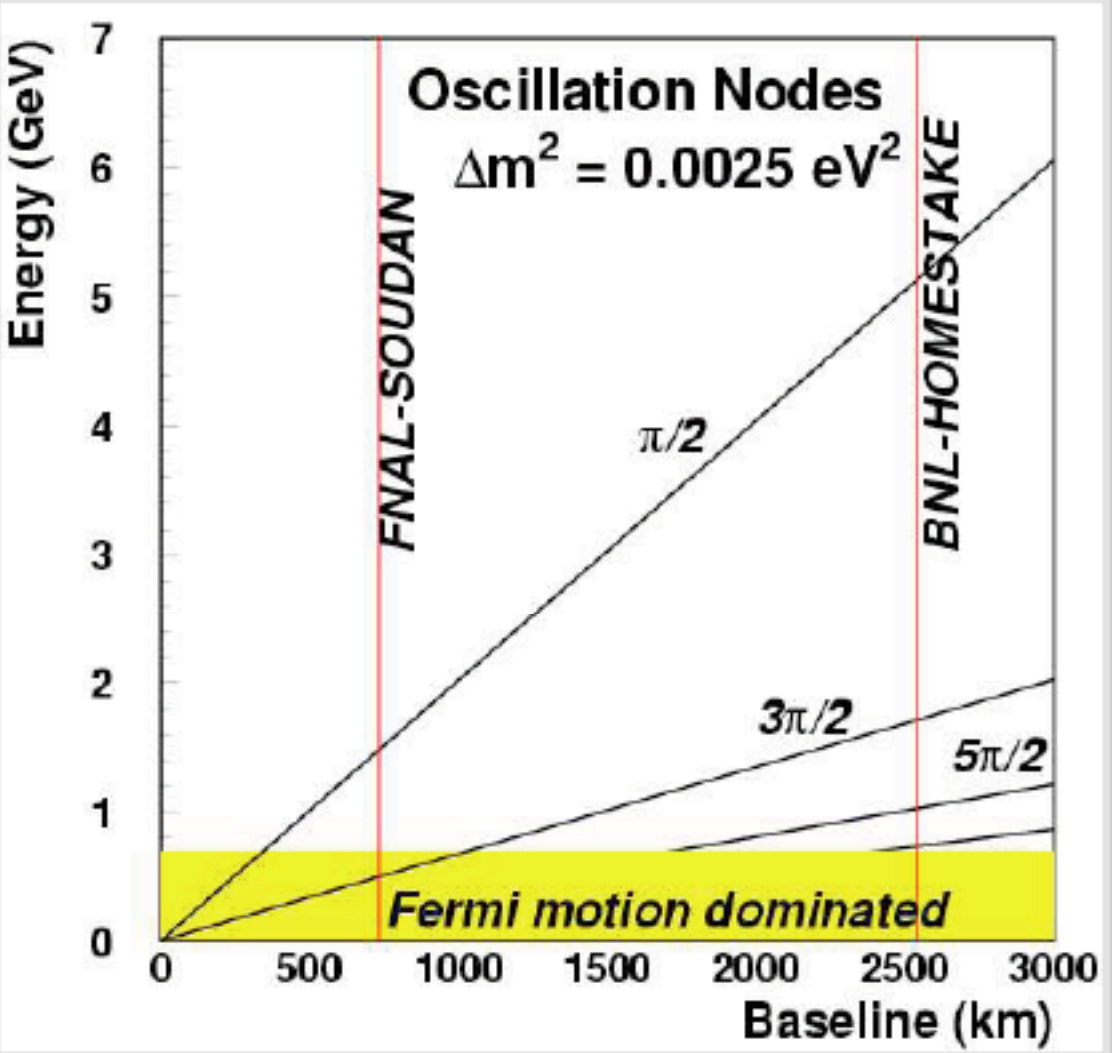
Why Very Long Baseline?

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)

$\nu_\mu \to \nu_e$ with matter effect

Approximate formula (M. Freund)

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \approx\ & \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta) \\
& +\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
& +\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta) \\
& +\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)
\end{aligned}
$$

$J_{CP} = 1/8 \sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$

$I_{CP} = 1/8 \cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$

$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta = \Delta m^2_{31} L/4E$

$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11$ For Earth's crust.

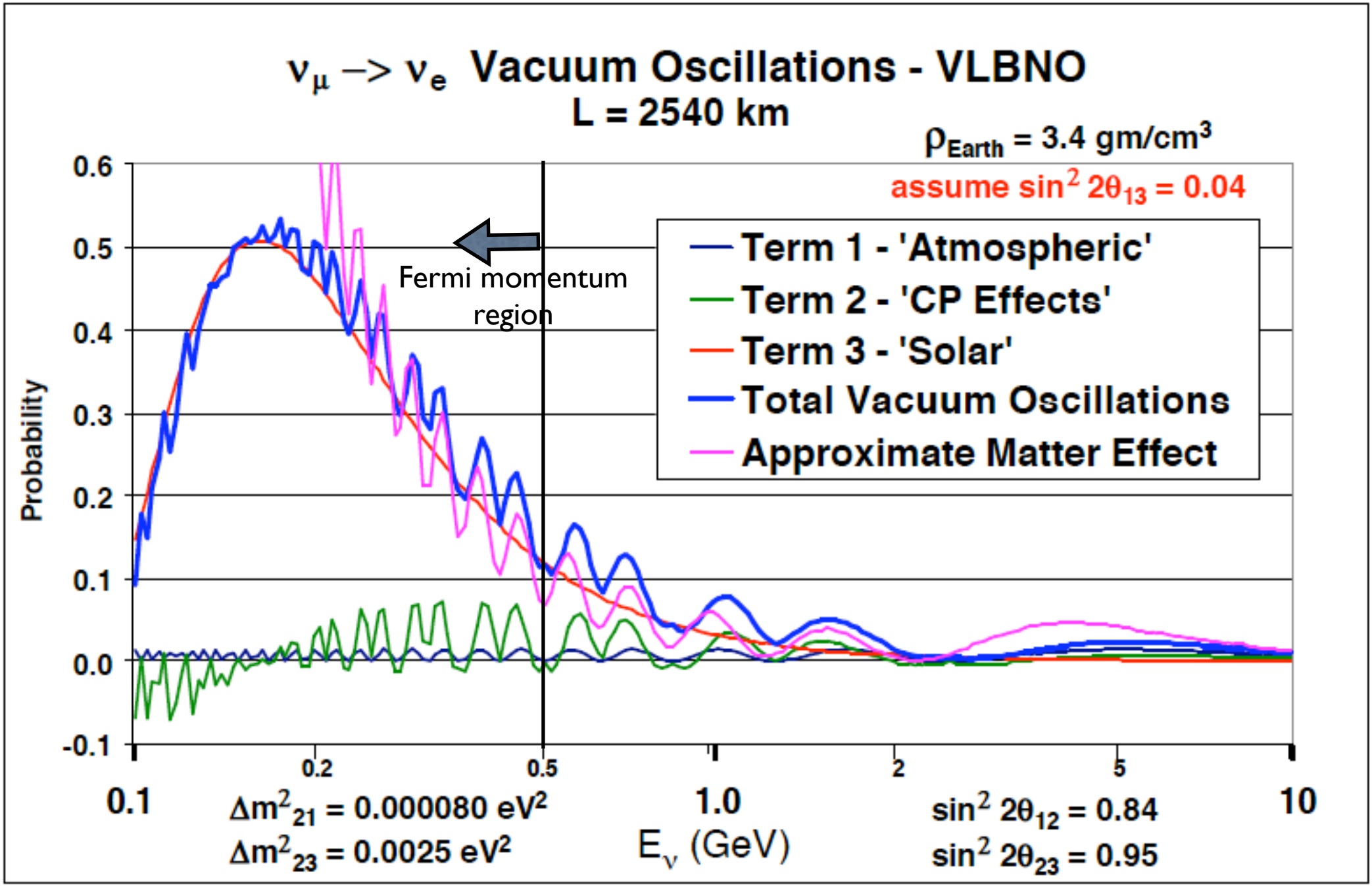
Comments about matter effect

$V = \sqrt{2} G_F n_e$. n_e is the density of electrons in the Earth.

$\hat{A} = \approx 7.6 \times 10^{-5} \times (D/gm/cm^3) \times (E_\nu/GeV)/(\Delta m^2_{31}/eV^2)$,

Also recall $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$.

- This is a very approximate equation, not applicable below the first maximum.
- First term has the effect of $\sin^2 2\theta_{13}$ and matter.
- Second and third terms have effects of CP.
- Term with J_{CP} changes sign for $(Anti - \nu_\mu) \rightarrow (Anti - \nu_e)$
- Last term is almost independent of Δm^2_{31} and is purely dominated by the solar Δm^2_{21}


$\nu_\mu \rightarrow \nu_e$ Vacuum Oscillations - VLBNO
L = 2540 km
ρ_{Earth} = 3.4 gm/cm^3
assume $\sin^2 2\theta_{13} = 0.04$
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
E_ν (GeV)
$\Delta m^2_{21} = 0.000080$ eV^2
$\Delta m^2_{23} = 0.0025$ eV^2
$\sin^2 2\theta_{12} = 0.84$
$\sin^2 2\theta_{23} = 0.95$

Scaling Laws for CP Measurement

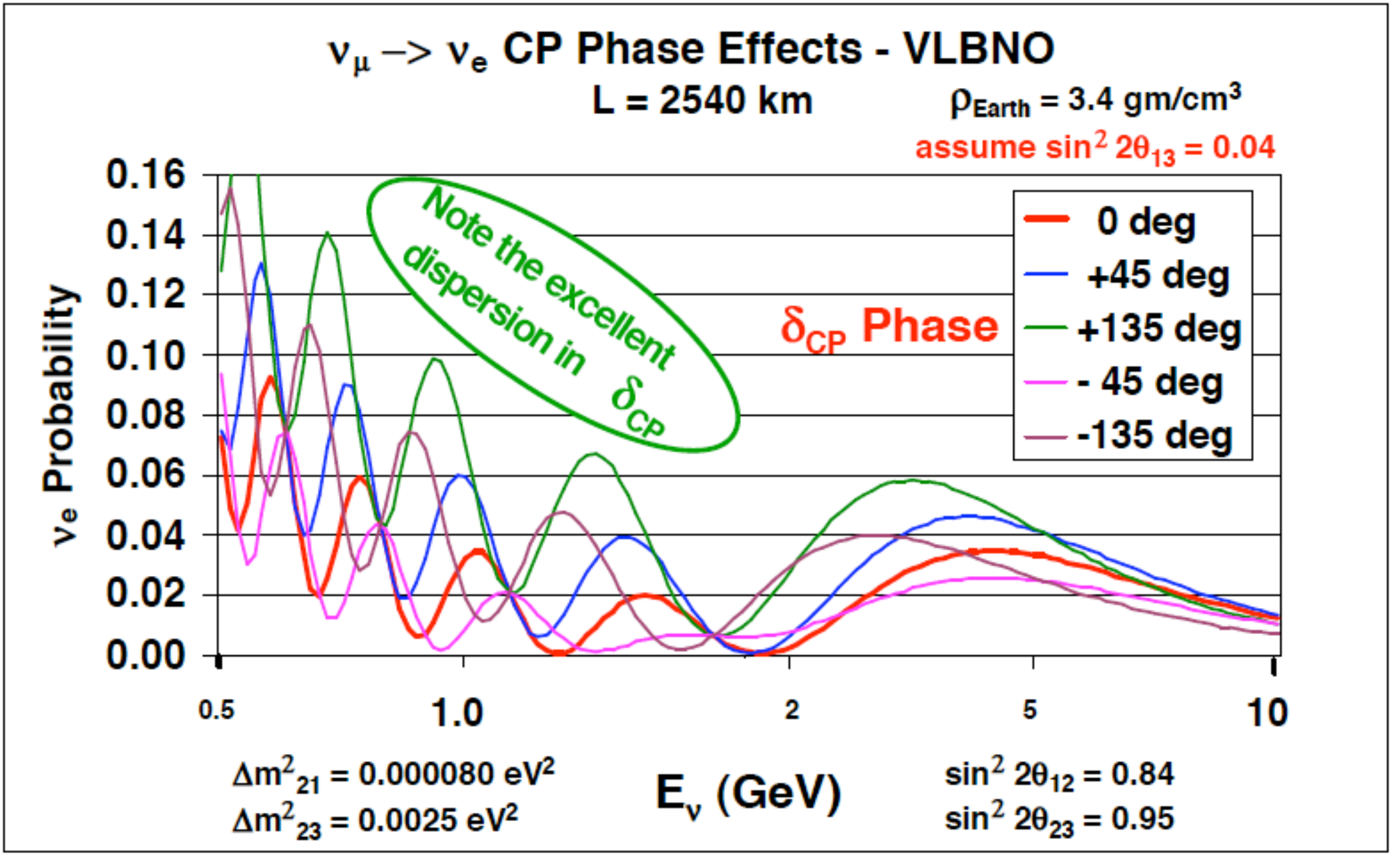
Effect of δ_{CP} compared to first term in appearance.

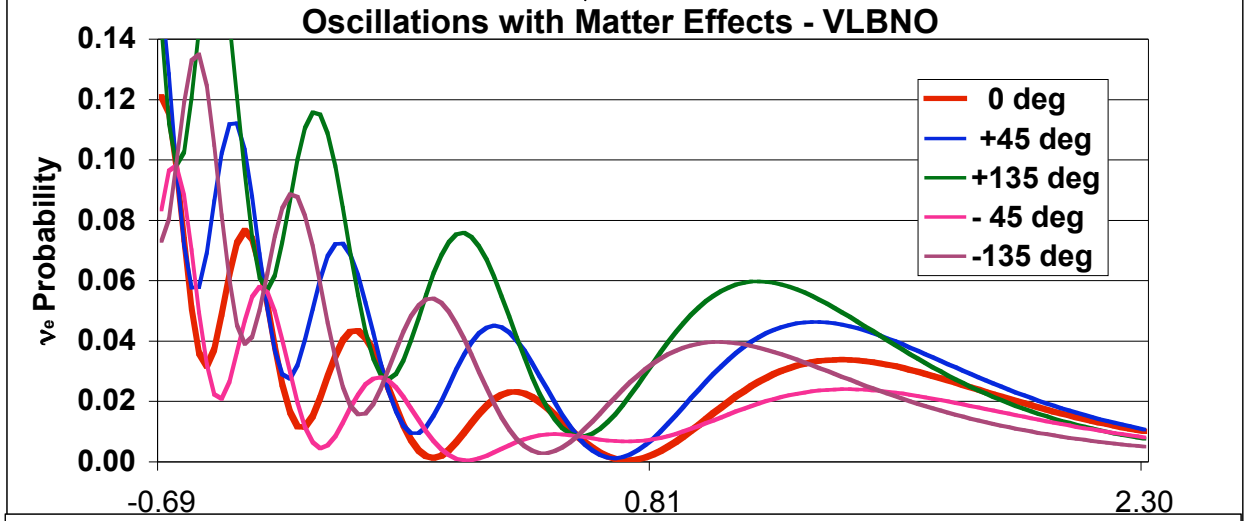
$R_{CP} \equiv$ Second term divided by First Term.

$$R_{CP} \propto \sin\delta_{CP} \frac{\Delta m^2_{21} L}{4E} \frac{1}{\sin 2\theta_{13}}$$

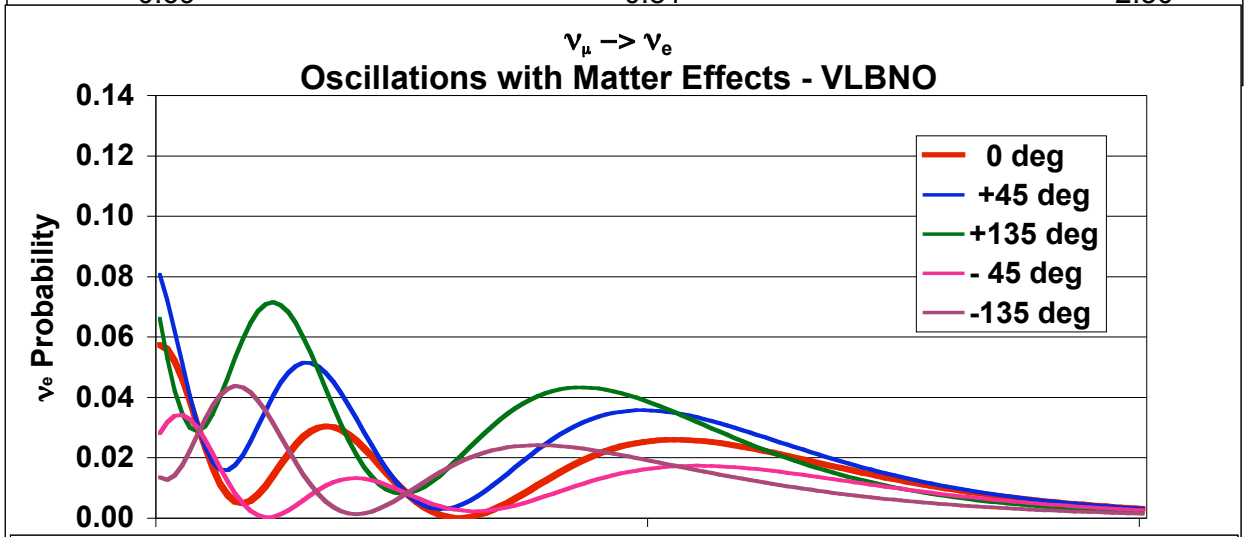
- $R_{CP} \propto 1/E$. Matter effect only at high E.
  Allows separation of matter effect and CP effect.
- $R_{CP} \propto L$. Event rate $\propto 1/L^2$.
  Statistical merit indep. of L for same sized detector.
- $R_{CP} \propto 1/\sin 2\theta_{13}$. Electron event rate $\propto \sin^2 2\theta_{13}$.
  Statistical merit indep. of θ_{13}.

  S. Parke: O.K. down to 0.002
- $R_{CP} \propto \Delta m^2_{21}$. Better CP resolution for higher Δm^2_{21}.
- For given resolution on δ_{CP} detector size is independent of L.

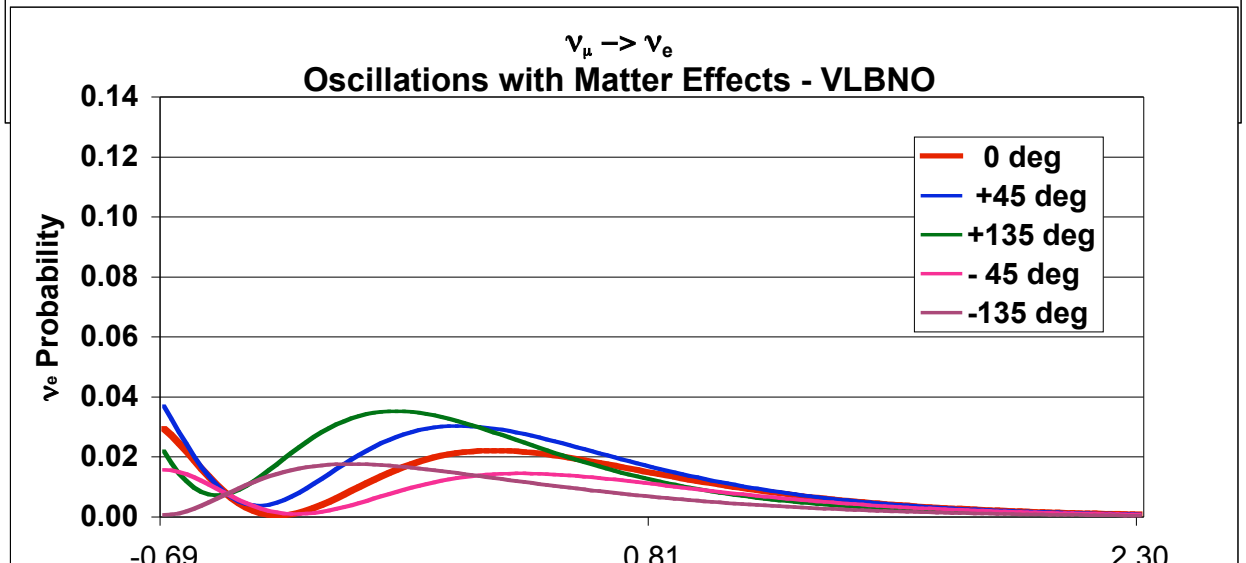

$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - VLBNO
L = 2540 km
ρ_{Earth} = 3.4 gm/cm^3
assume $\sin^2 2\theta_{13} = 0.04$
Note the excellent dispersion in δ_{CP}
δ_{CP} Phase
0 deg
+45 deg
+135 deg
- 45 deg
-135 deg
ν_e Probability
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.5
1.0
2
5
10
$\Delta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



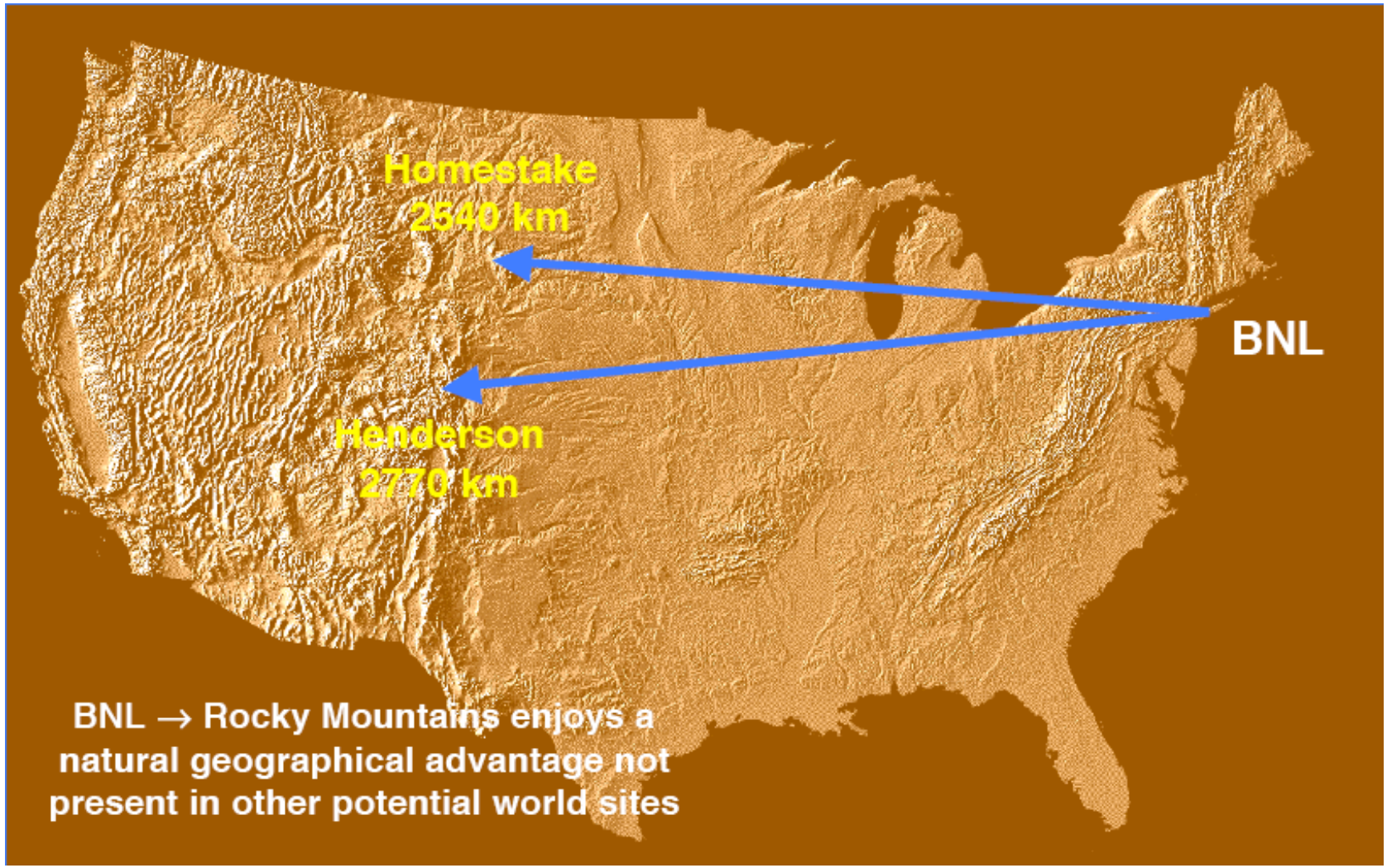
2767 km



1500 km

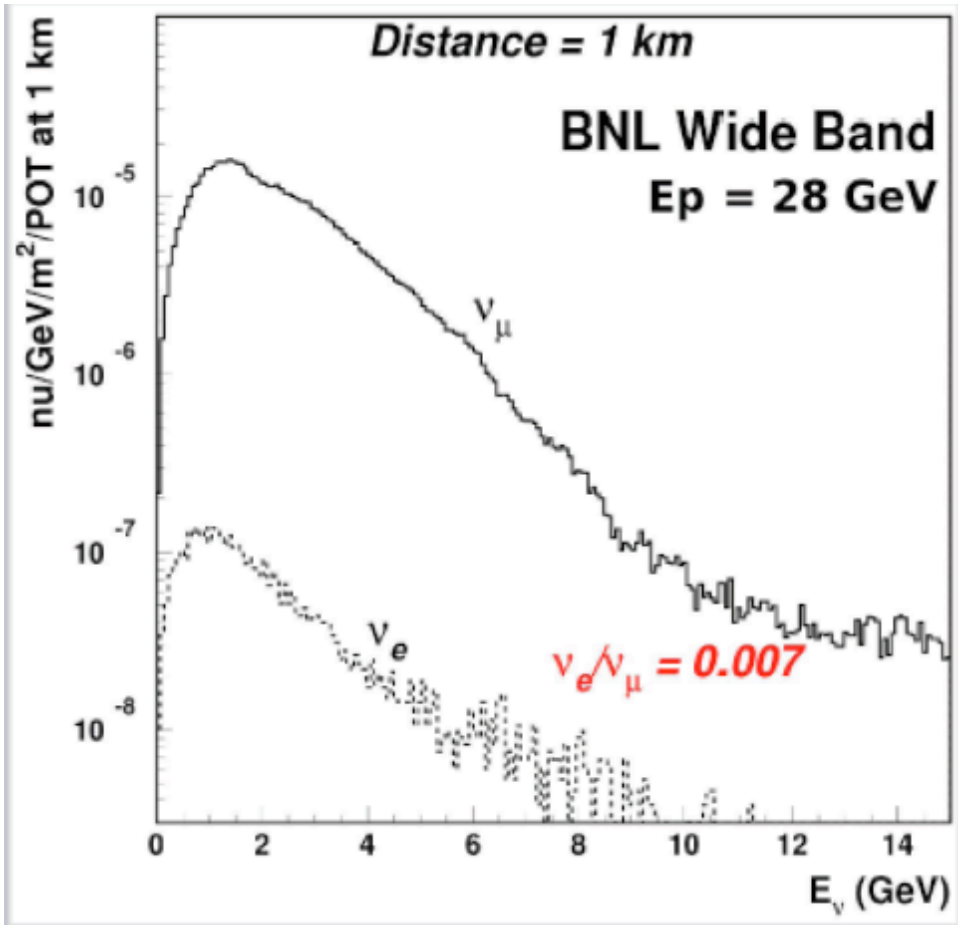


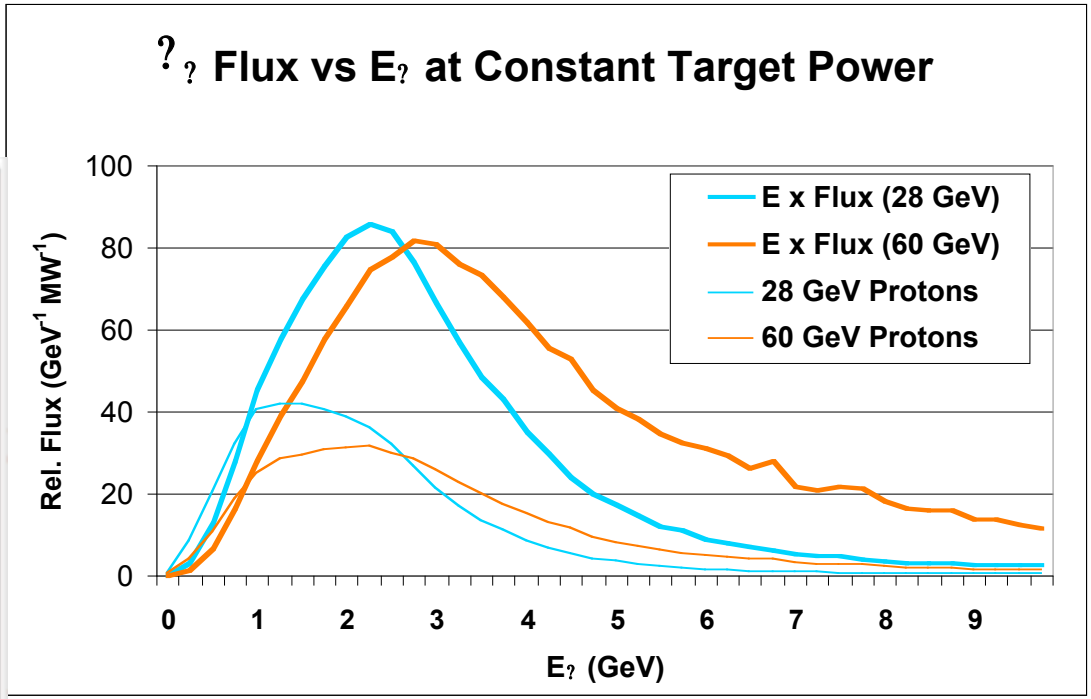
810 km

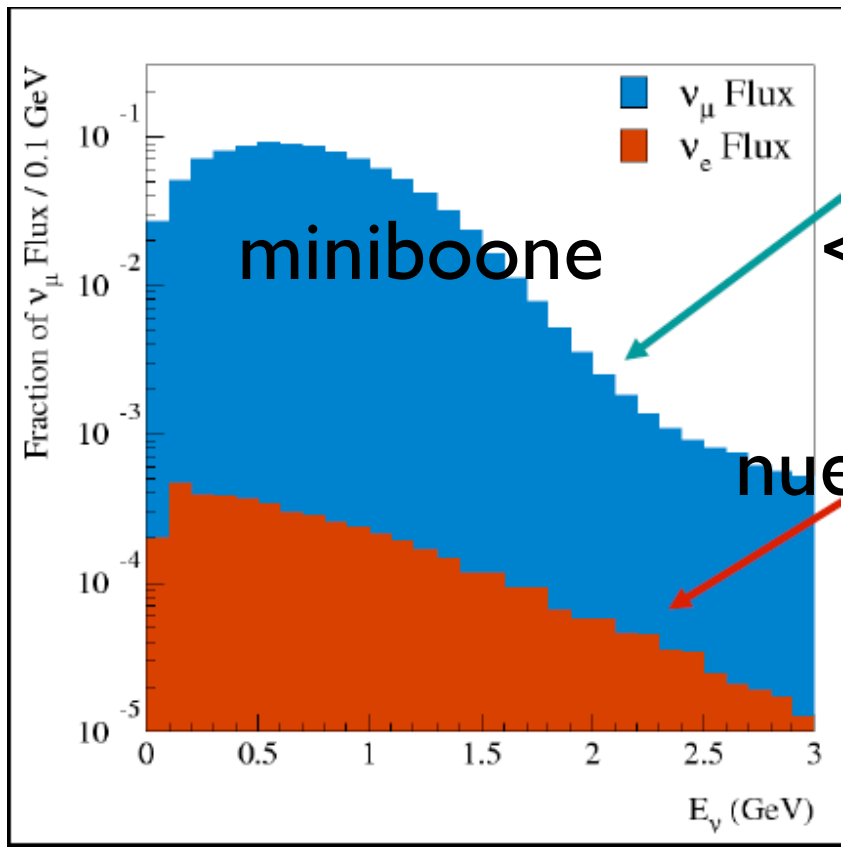


- 28 GeV protons. 1 MW beam power. Horn focussed
- 500 kT water Cherenkov detector stationed in a new DUSEL.
- baseline > 2500 km. WIPP, Henderson, Homestake
- We have proven by 3 years of work that this can be done. But much remains, especially on the detector design.

Flux shapes







miniboone

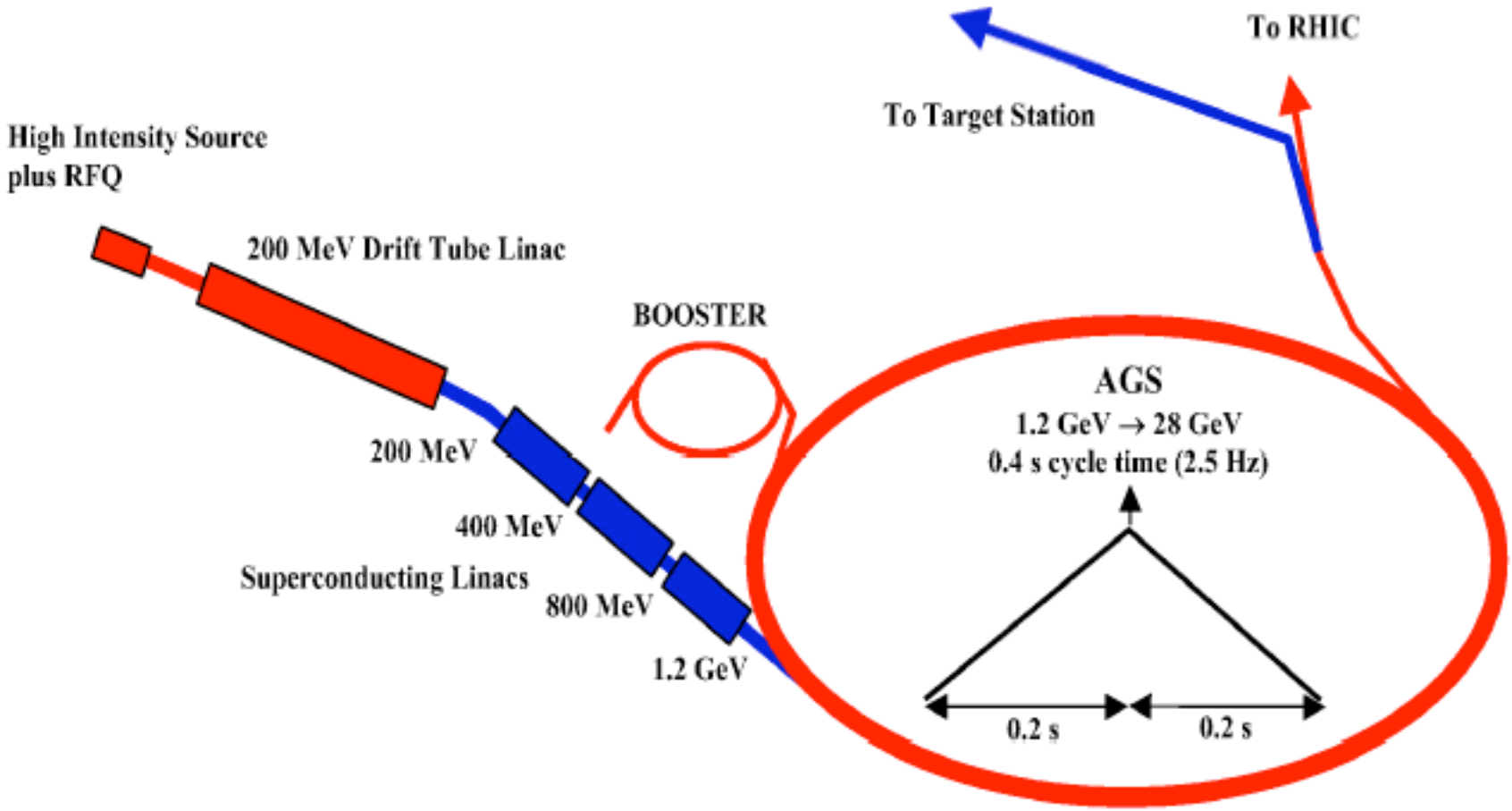
<E>~0.7

nue~0.001

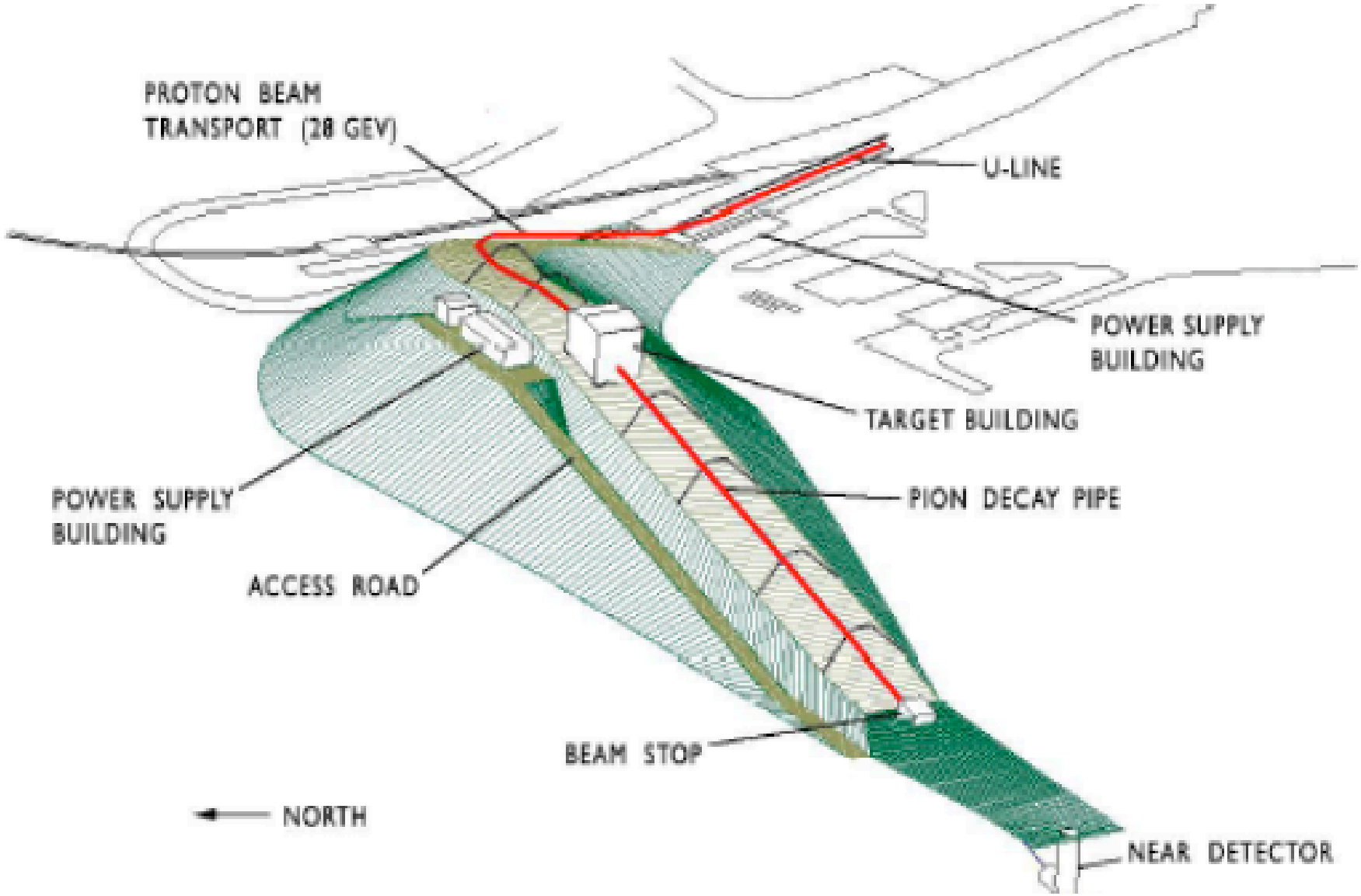
US possibilities for beam

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

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

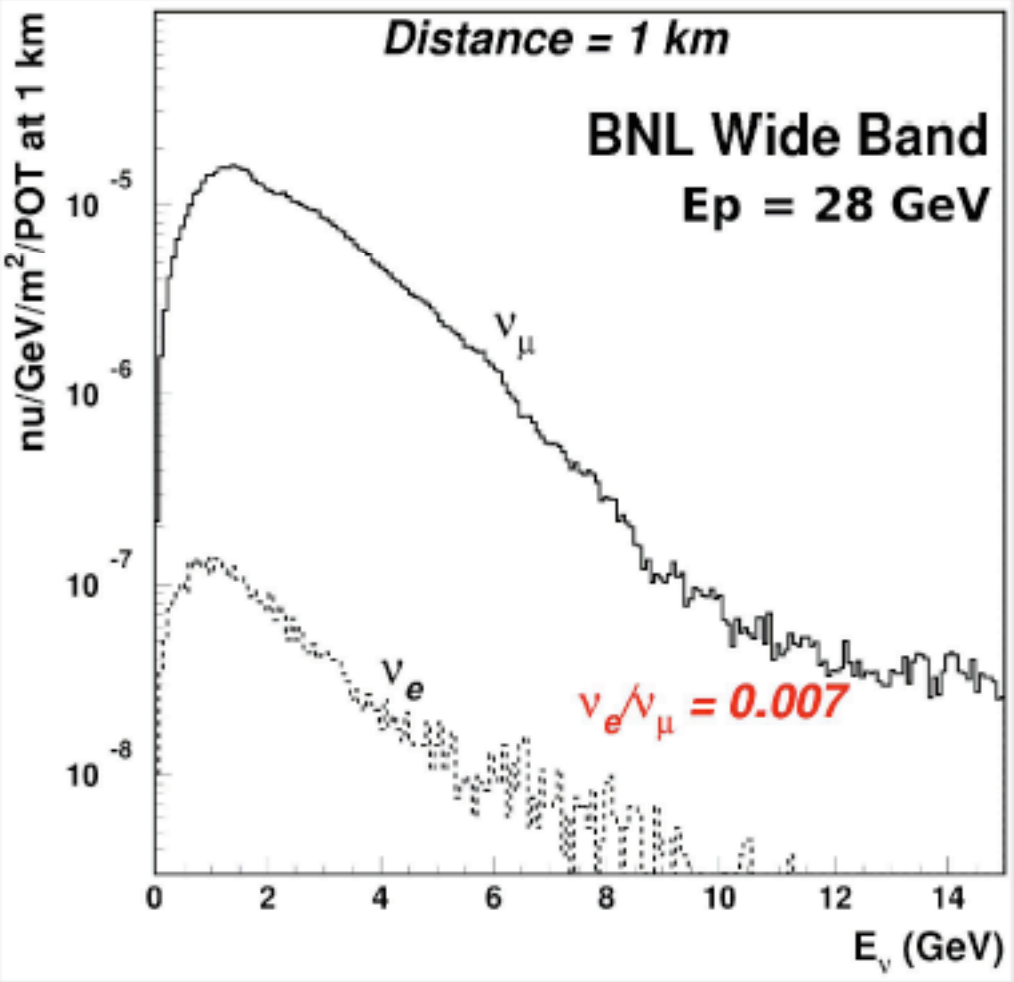

PROTON BEAM
TRANSPORT (28 GEV)
U-LINE
POWER SUPPLY
BUILDING
TARGET BUILDING
POWER SUPPLY
BUILDING
PION DECAY PIPE
ACCESS ROAD
BEAM STOP
NORTH
NEAR DETECTOR

AGS 1MW proton beam

Upgrade AGS (28 GeV protons)

intensity: 7.10^{13} → 9.10^{13} ppp

rep. rate: ~0.3Hz → 2.5Hz



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

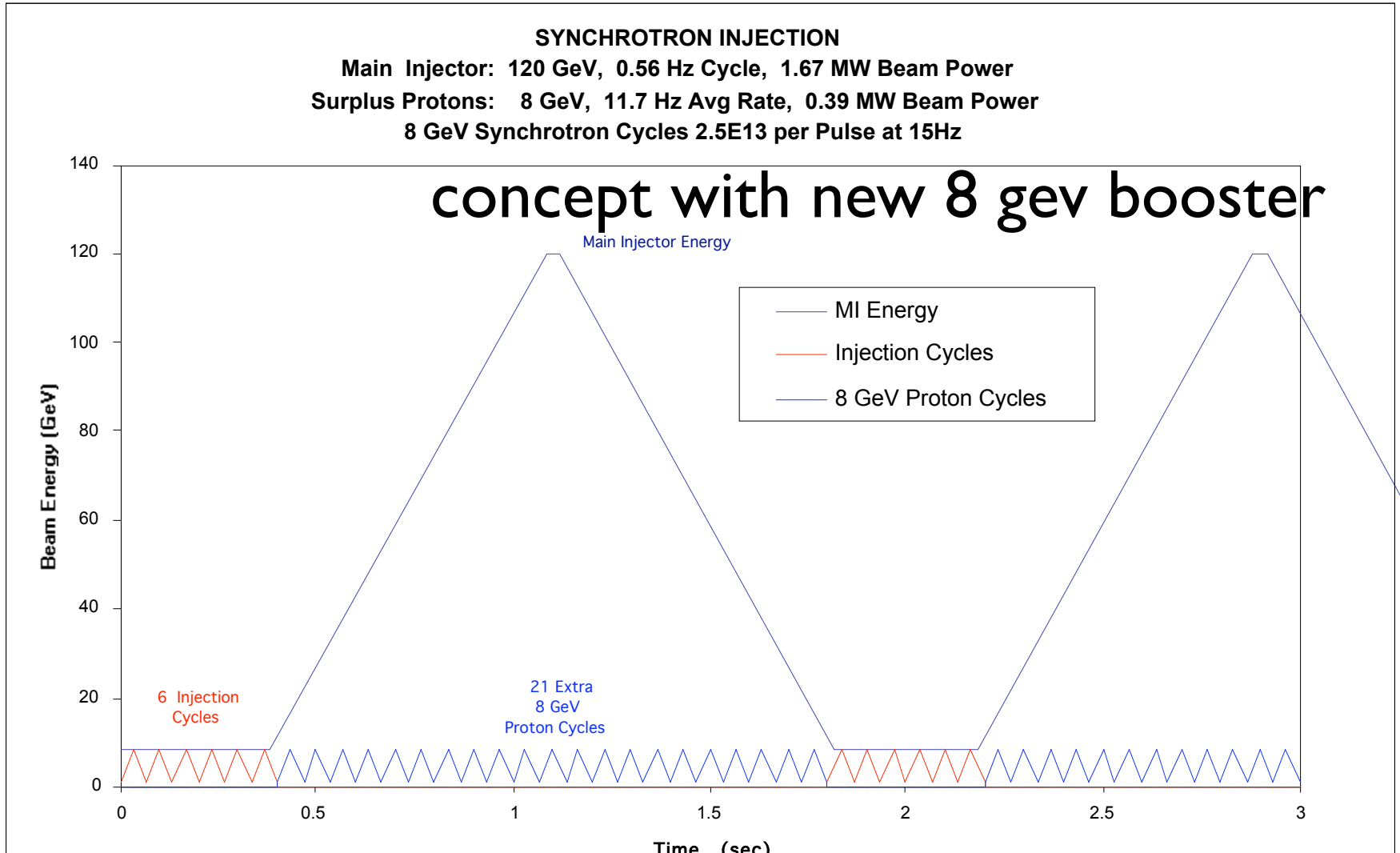
2) filling time: 0.6s → 1ms
   replace booster:
   extend warm linac 200 MeV
   new SC linac 1 GeV

3) Work continues to goto 1.5 or 2 MW.

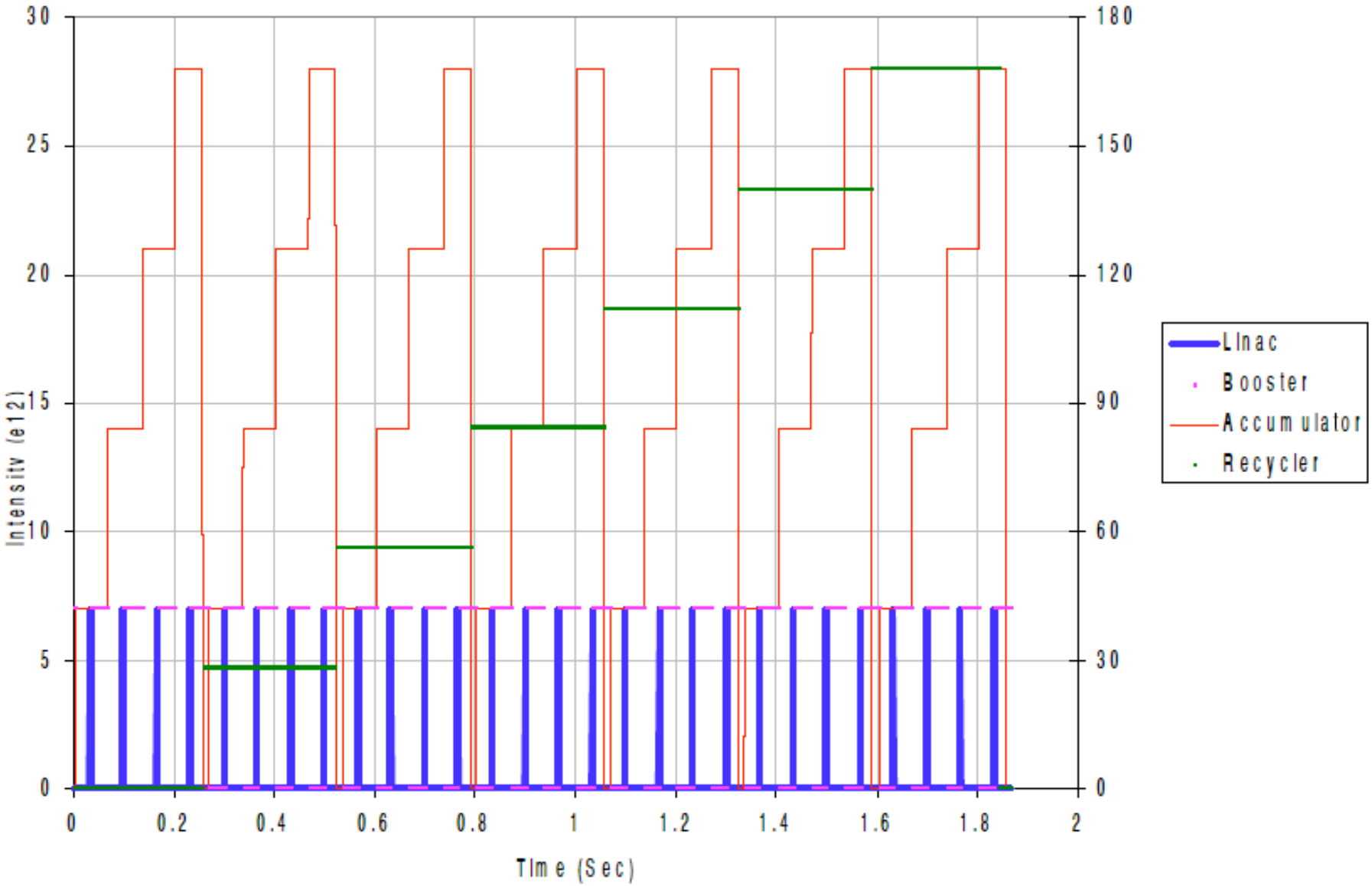
4) Experimental work on 1 MW carbon-carbon target.

D. McGinnis concept to get 1.1 MW at 120 GeV under $100M

- After the collider program concludes, the present antiproton production complex can be converted into a multi-stage proton accumulator for injection into the Main Injector.
  - Debuncher ->Wide Aperture Booster

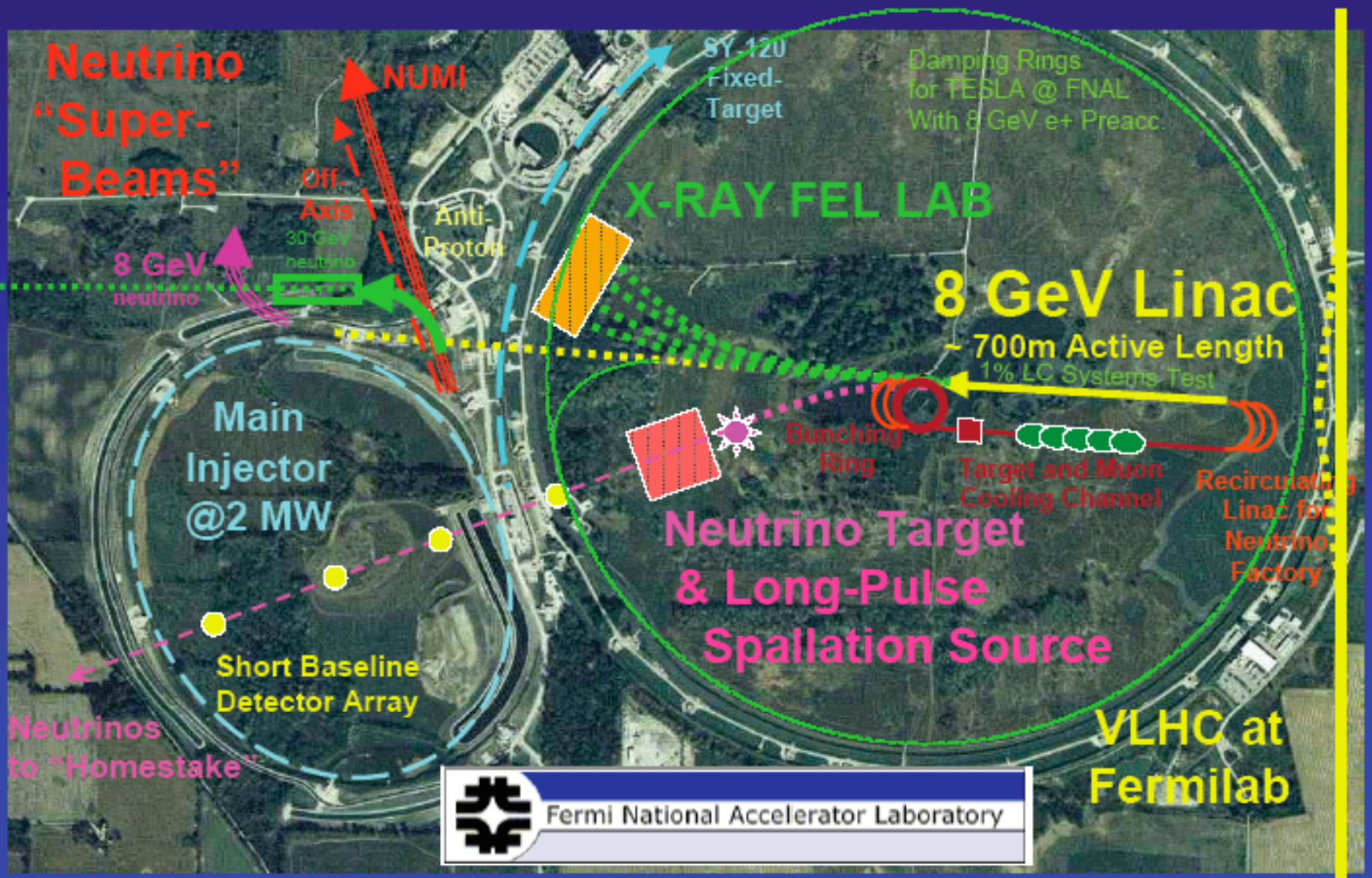


Multi-stage Proton Accumulator Production Cycle

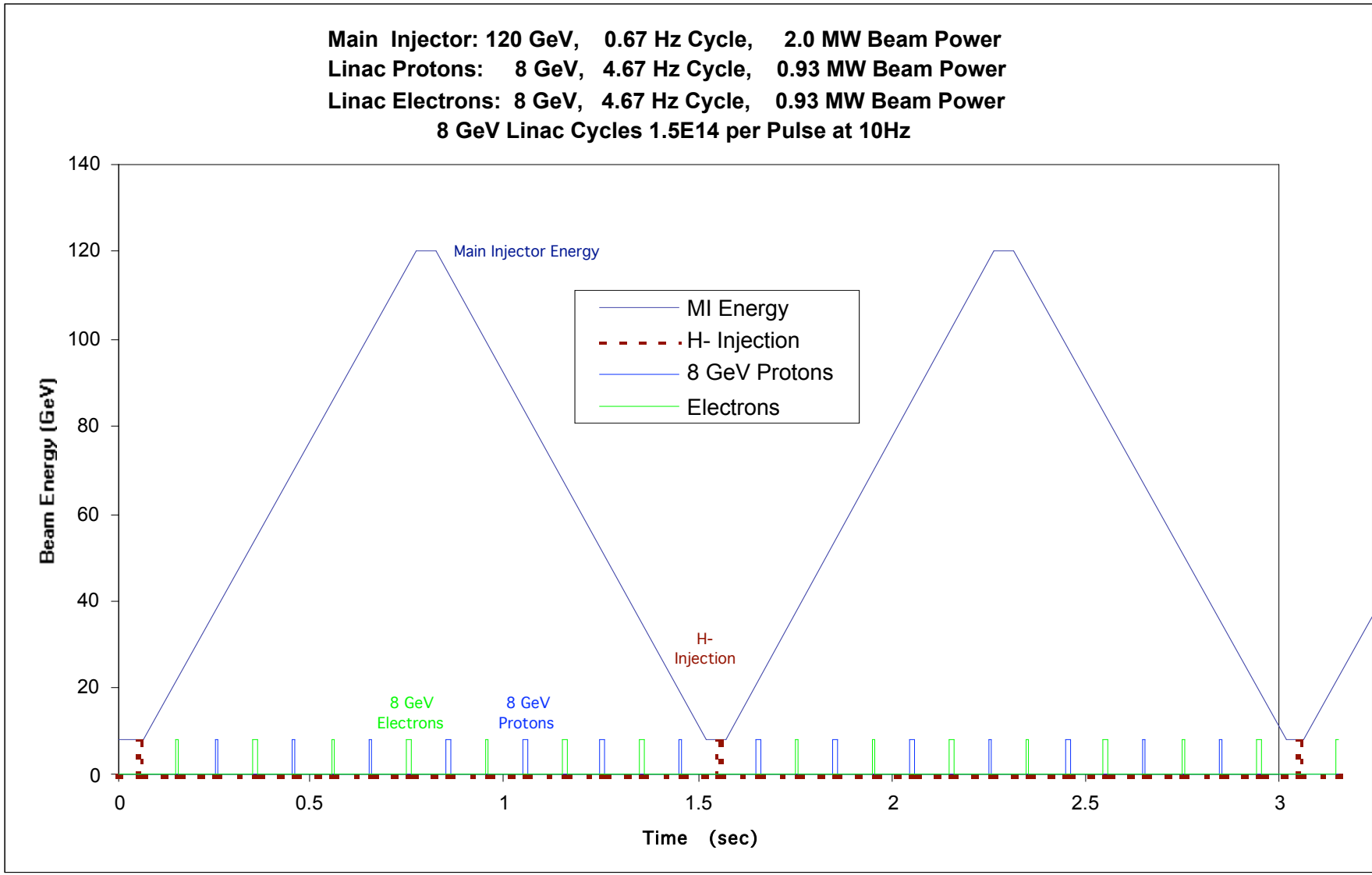


8 GeV Superconducting Linac

With X-Ray FEL, 8 GeV Neutrino & Spallation Sources, LC and Neutrino Factory



120 GeV Main Injector Cycle with 8 GeV Linac, e- and P



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	--

Event rates

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 using Miniboone data	2188 CC 850 NC
NOVA(810)	30kT	2X0.65MW@120	~20000 CC ~6000 NC

5 X 10^7 sec of running assumed

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

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

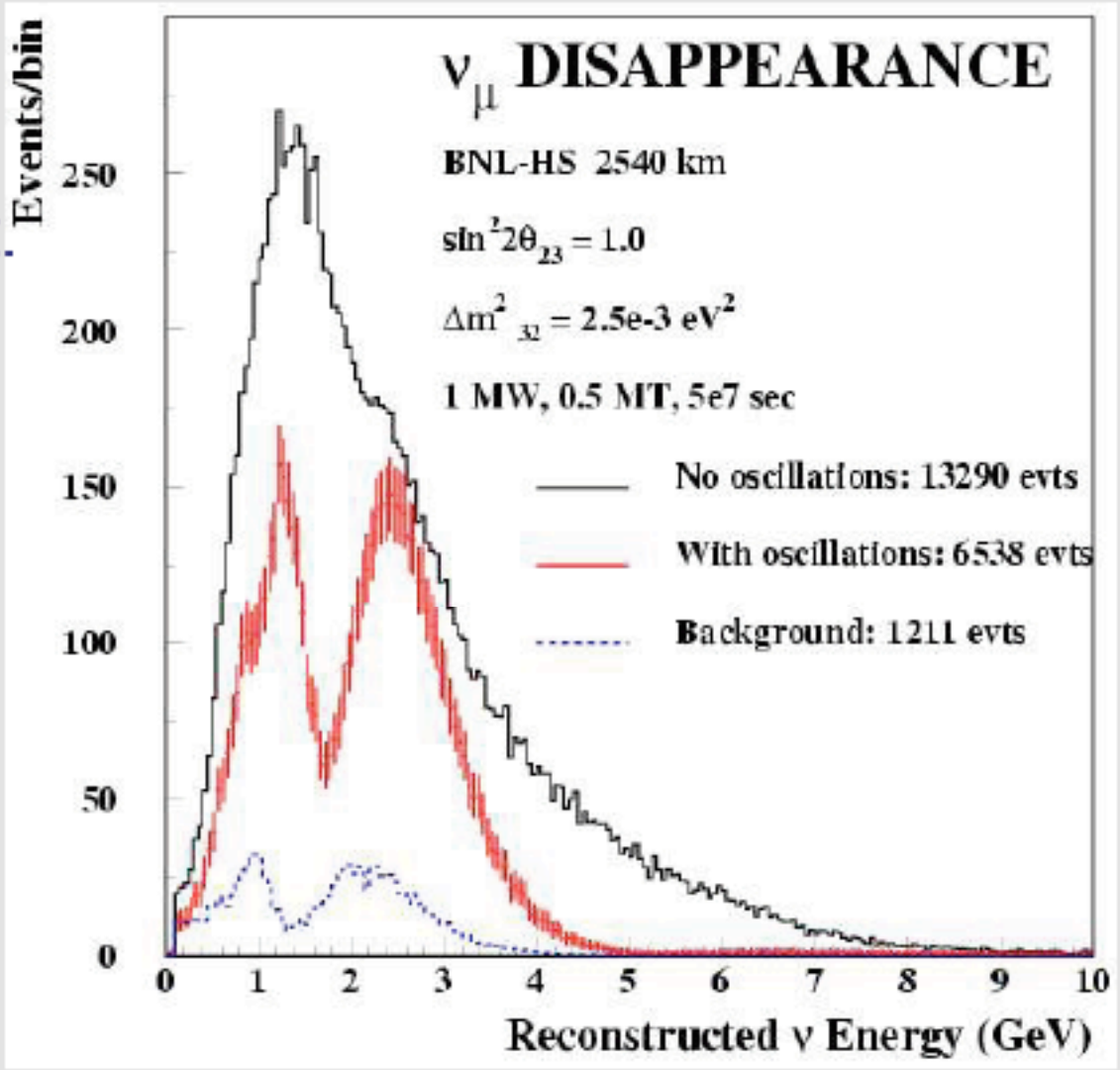
- NC kinematics favors a falling spectrum. Background is pushed to low energies.
- Currently we are assuming that we use only the cleanest events. eff. < 20 %. Large fraction of CC events could be used if detector can be finer grained.
- No hardware enhancements assumed for water Cherenkov detector so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

ν_μ disappearance

neutrino running:

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



anti-neutrino running:

same as ν but with
2MW beam

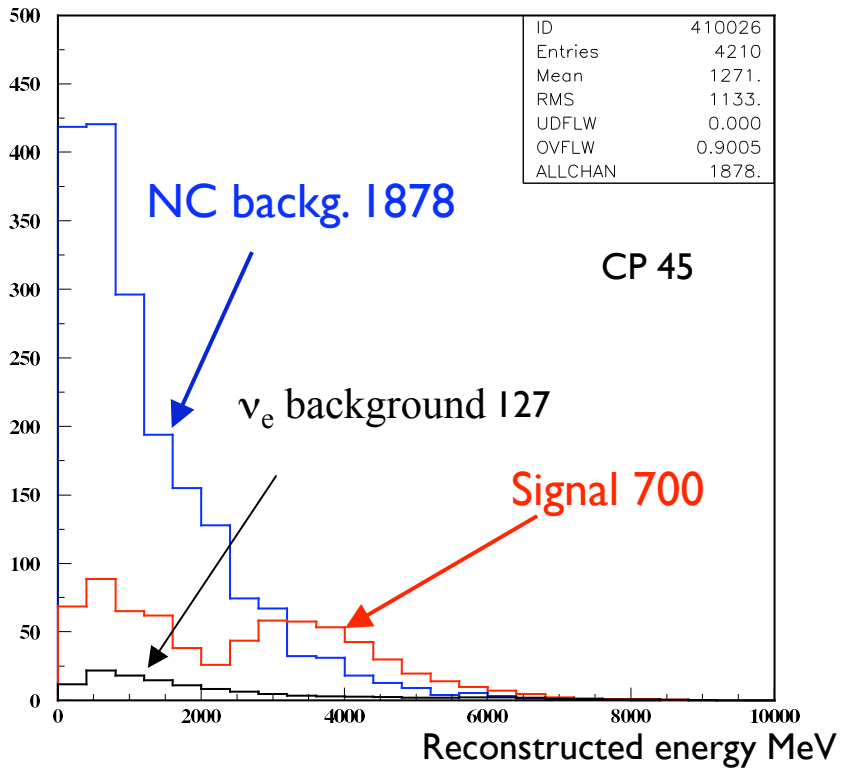
including anti-ν running:

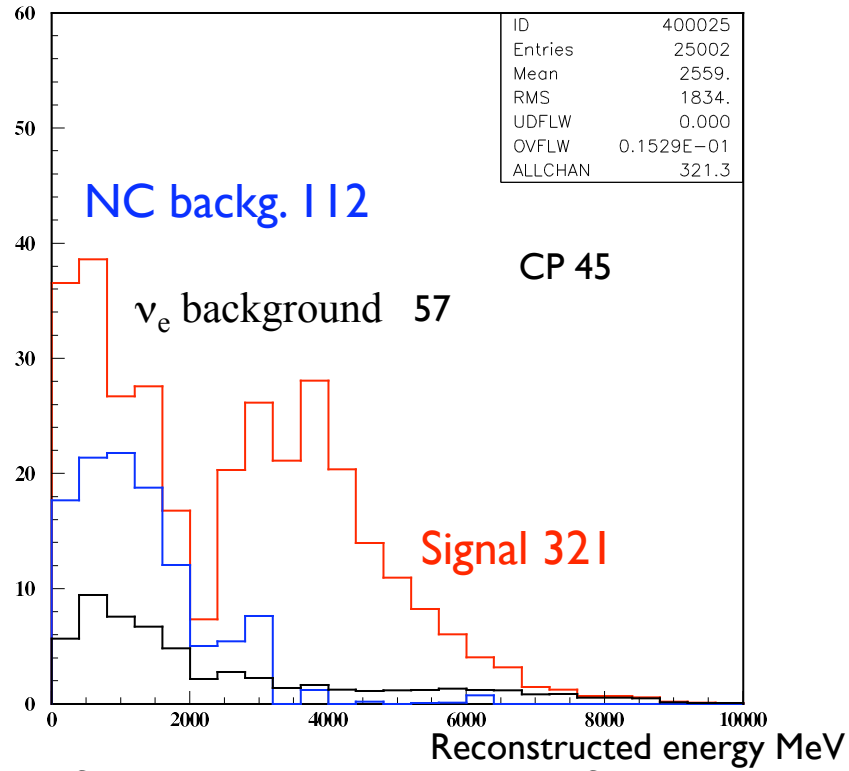
- CPT test possible
- errors below 1% achievable

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°





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:

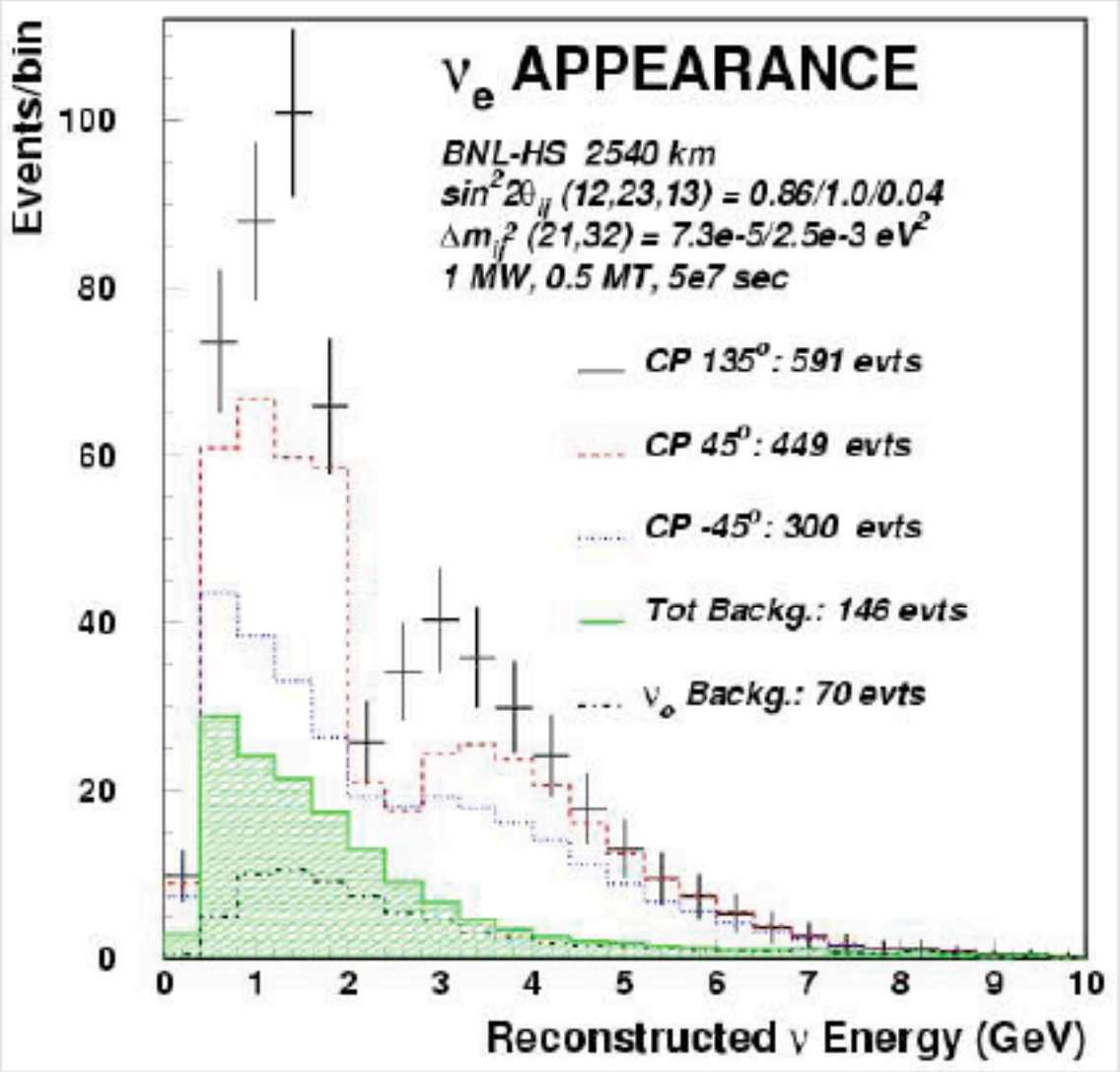
- beam ν_e
- NC ν_μ

neutrino running:

measure $\sin^2 2\theta_{13}$ and δ_{CP}
for $\sin^2 2\theta_{13} > 0.01$
resolve mass hierarchy

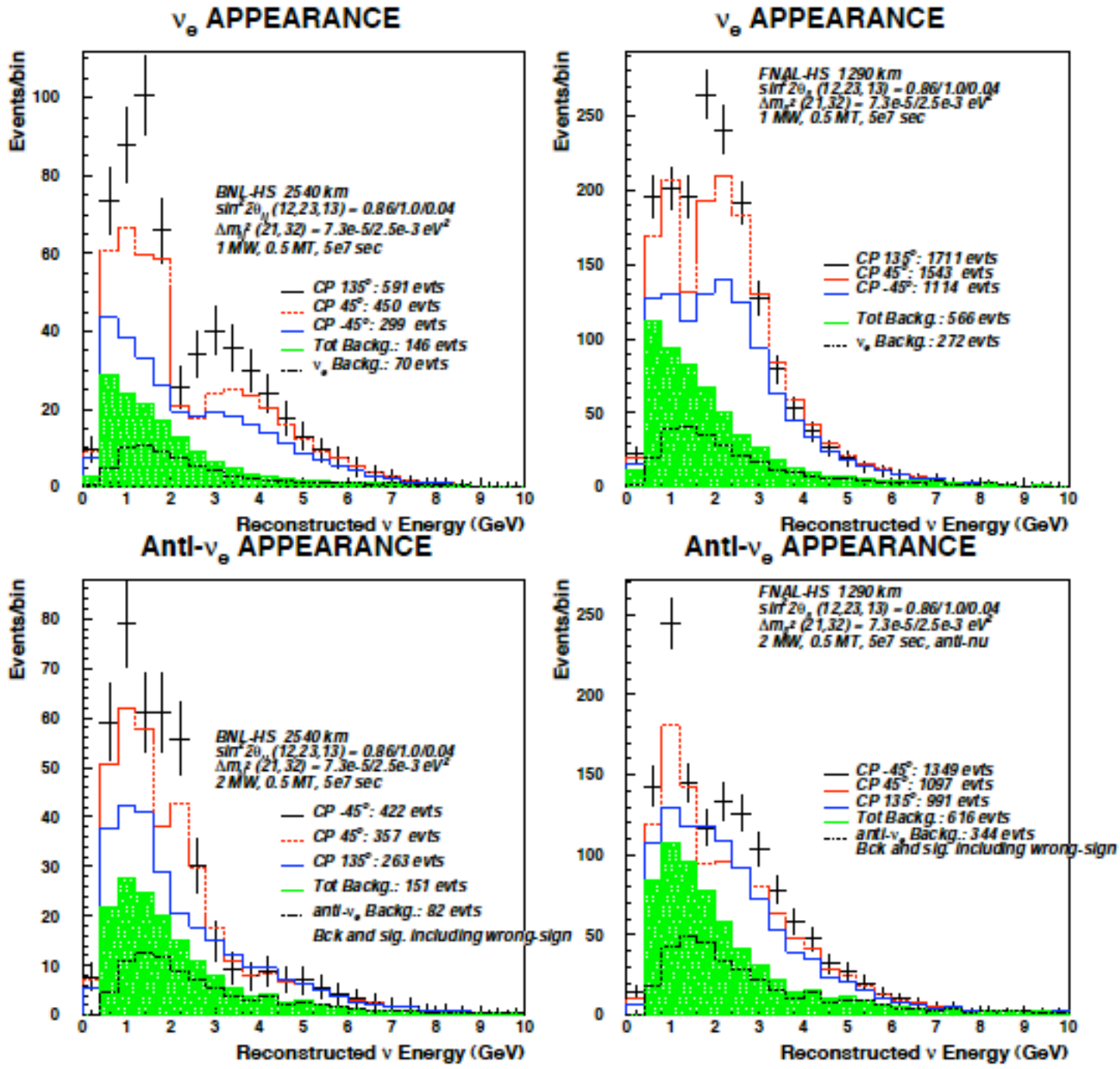
include anti-neutrino run:

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

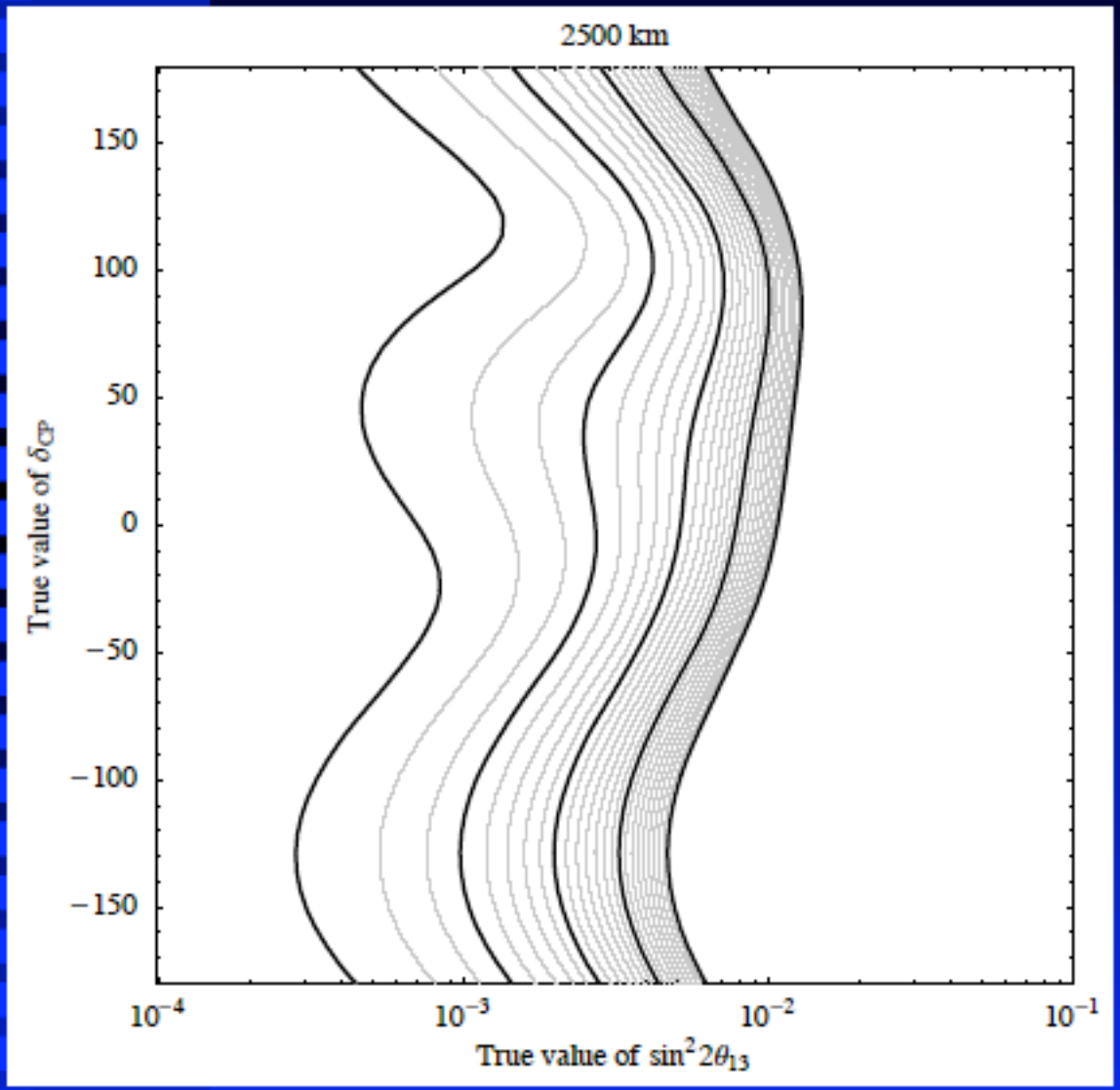


if $\sin^2 2\theta_{13}$ too small → δ_{CP} measurement not possible

observation ν_e appearance possible through solar term

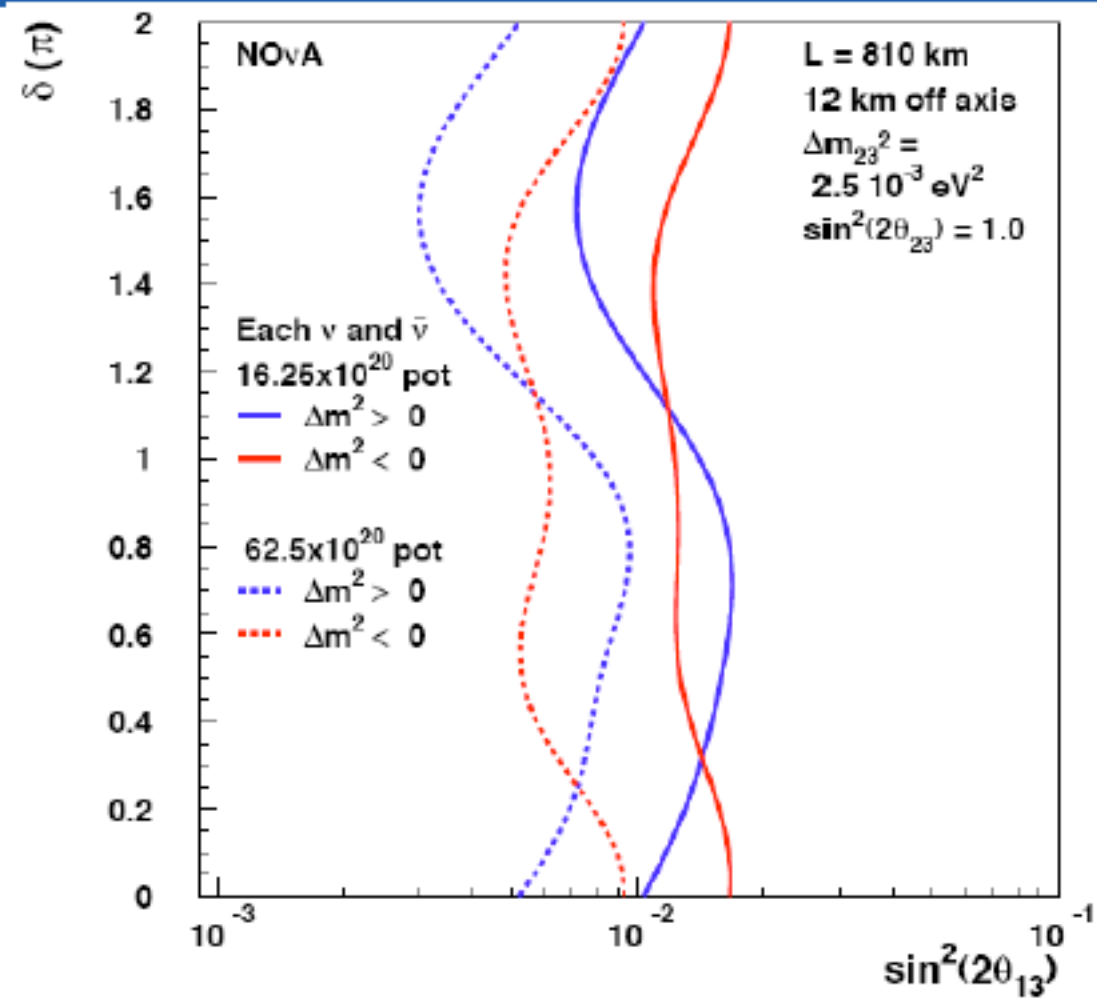

ν_e APPEARANCE
Events/bin
BNL-HS 2540 km
$\sin^2 2\theta_{\mu e}$ (12,23,13) = 0.86/1.0/0.04
Δm^2 (21,32) = 7.3e-5/2.5e-3 eV^2
1 MW, 0.5 MT, 5e7 sec
CP 135°: 591 evts
CP 45°: 450 evts
CP -45°: 299 evts
Tot Backg.: 146 evts
ν_e Backg.: 70 evts
Reconstructed ν Energy (GeV)
ν_e APPEARANCE
Events/bin
FNAL-HS 1290 km
$\sin^2 2\theta_{\mu e}$ (12,23,13) = 0.86/1.0/0.04
Δm^2 (21,32) = 7.3e-5/2.5e-3 eV^2
1 MW, 0.5 MT, 5e7 sec
CP 135°: 1711 evts
CP 45°: 1543 evts
CP -45°: 1114 evts
Tot Backg.: 566 evts
ν_e Backg.: 272 evts
Reconstructed ν Energy (GeV)
Anti-ν_e APPEARANCE
Events/bin
BNL-HS 2540 km
$\sin^2 2\theta_{\mu e}$ (12,23,13) = 0.86/1.0/0.04
Δm^2 (21,32) = 7.3e-5/2.5e-3 eV^2
2 MW, 0.5 MT, 5e7 sec
CP -45°: 422 evts
CP 45°: 357 evts
CP 135°: 263 evts
Tot Backg.: 151 evts
anti-ν_e Backg.: 82 evts
Bck and sig. including wrong-sign
Reconstructed ν Energy (GeV)
Anti-ν_e APPEARANCE
Events/bin
FNAL-HS 1290 km
$\sin^2 2\theta_{\mu e}$ (12,23,13) = 0.86/1.0/0.04
Δm^2 (21,32) = 7.3e-5/2.5e-3 eV^2
2 MW, 0.5 MT, 5e7 sec, anti-nu
CP -45°: 1349 evts
CP 45°: 1097 evts
CP 135°: 991 evts
Tot Backg.: 616 evts
anti-ν_e Backg.: 344 evts
Bck and sig. including wrong-sign
Reconstructed ν Energy (GeV)

Discovery of θ_{13}



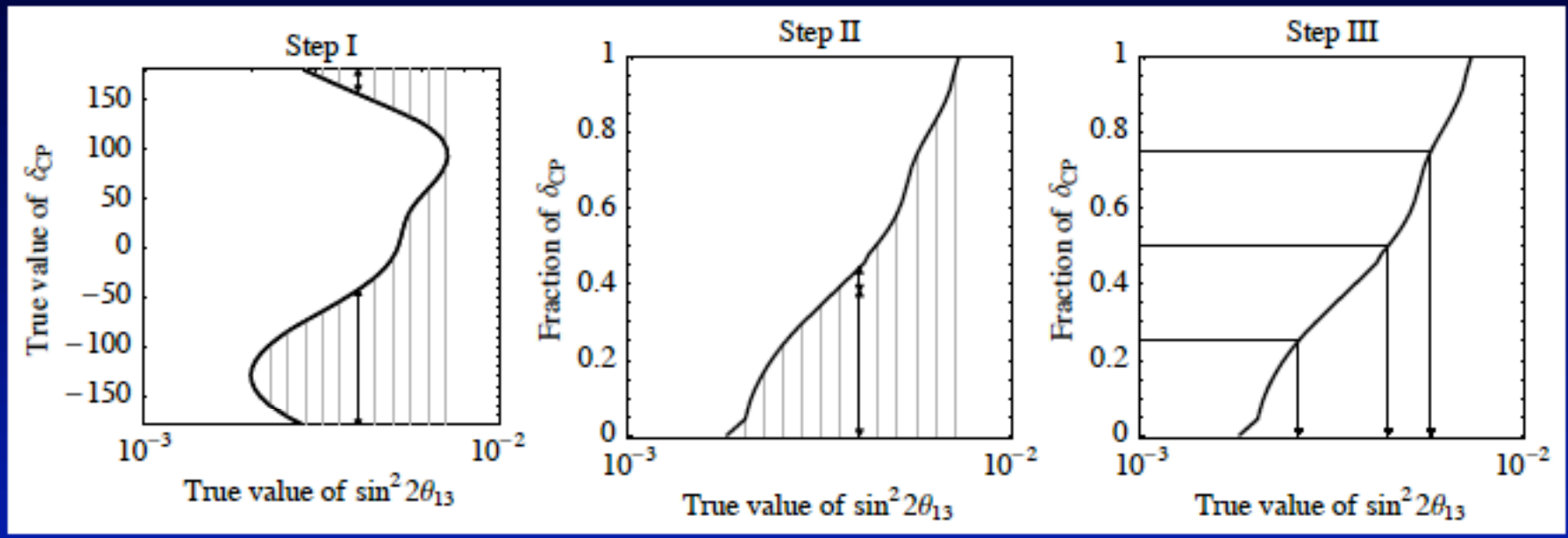
- simulate data for δ and $\theta_{13} \neq 0$
- try to fit them with $\theta_{13} = 0$
- repeat the fit for the wrong hierarchy
- take the smallest χ^2

3 σ Sensitivity to $\theta_{13} \neq 0$
Comparison with Proton Driver

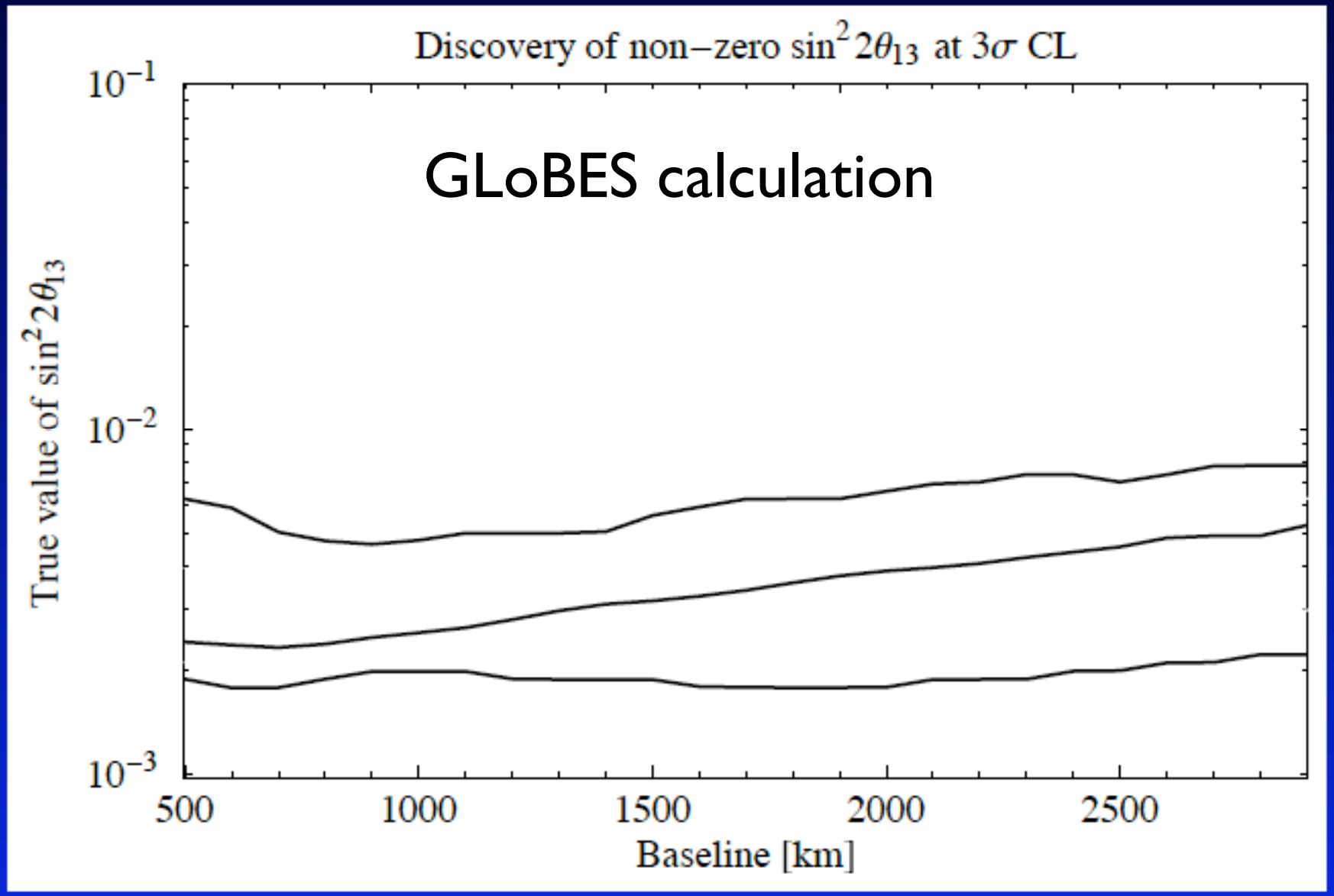


2.5 yr each ν and $\bar{\nu}$ run

CP fraction



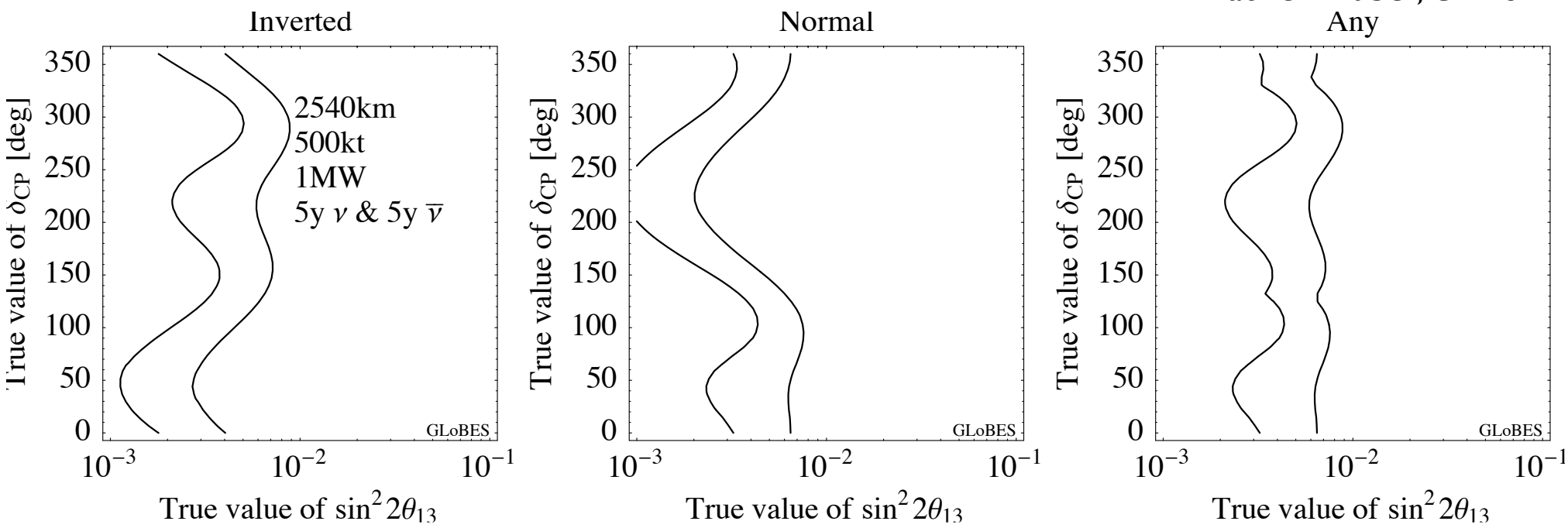
- reduces 2D plot to 3 points
- allows unbiased comparison
- allows risk assessment
- CPF = 1, worst case – guaranteed sensitivity
- CPF =0, best case



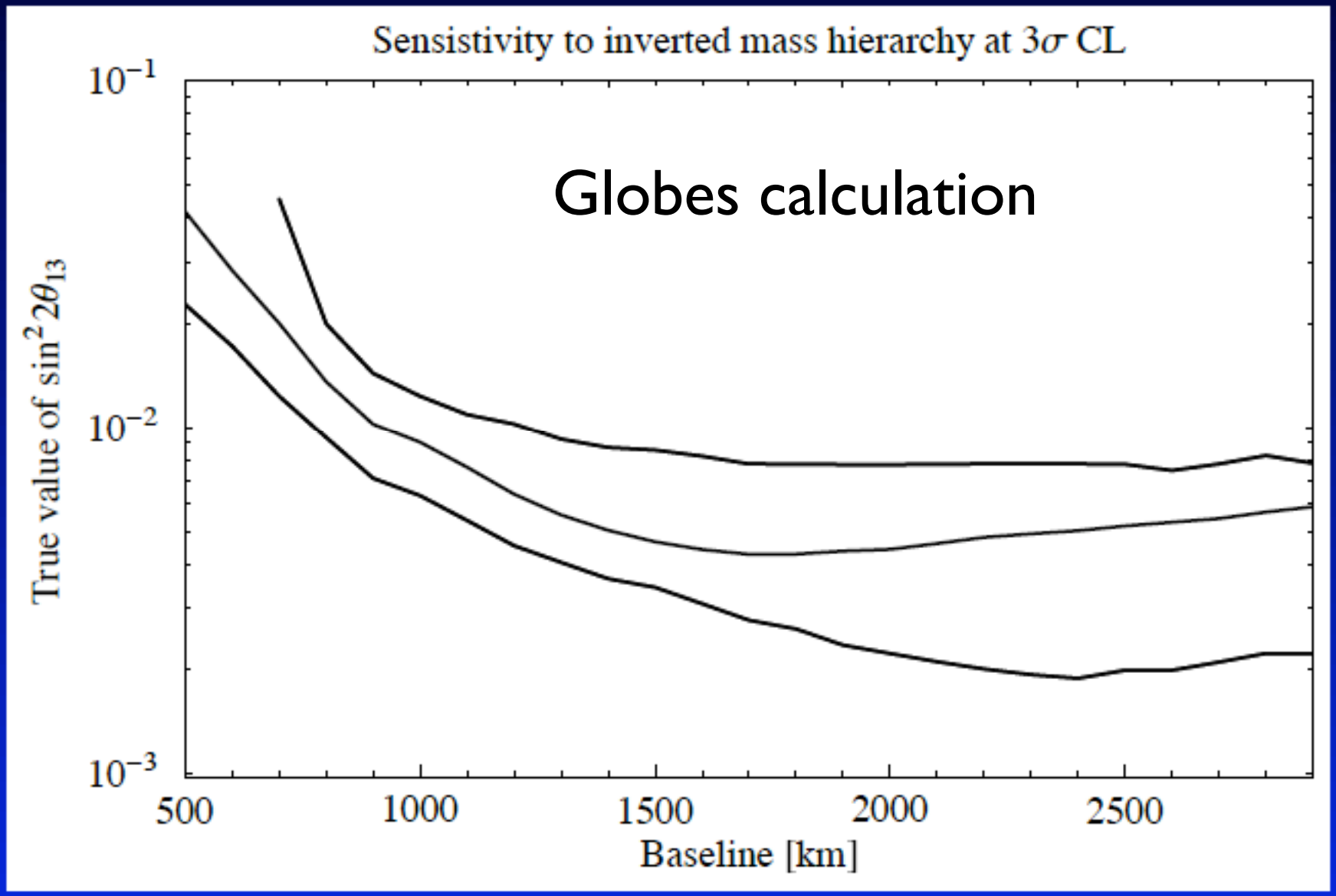
- weak baseline dependence

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

Patrick Huber, UWis

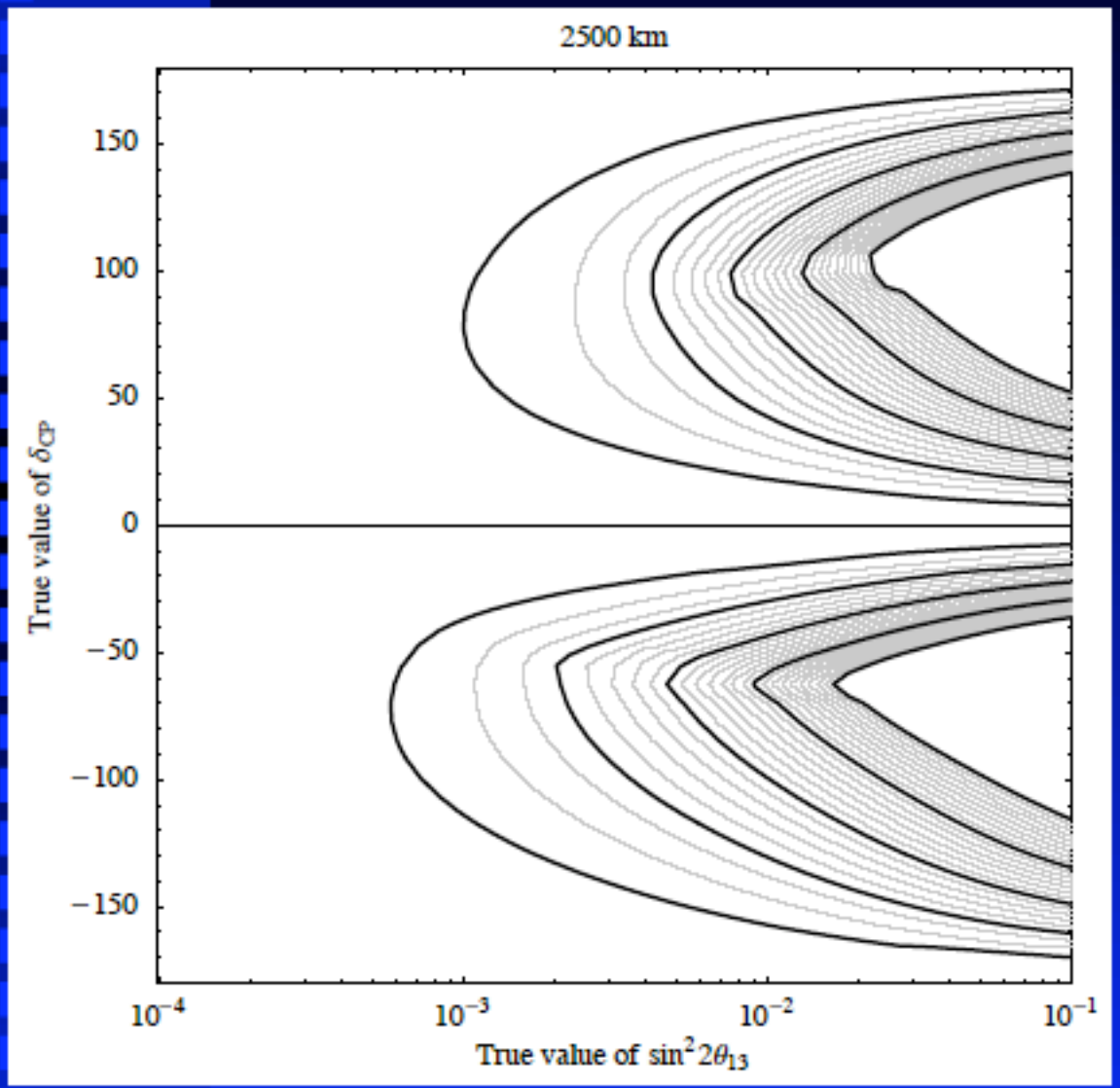


- Includes correlations and errors on all parameters including earth's density. 10% bckg uncertainty.
- As parameters improve this plot gets better.
- Entire range of delta is covered.



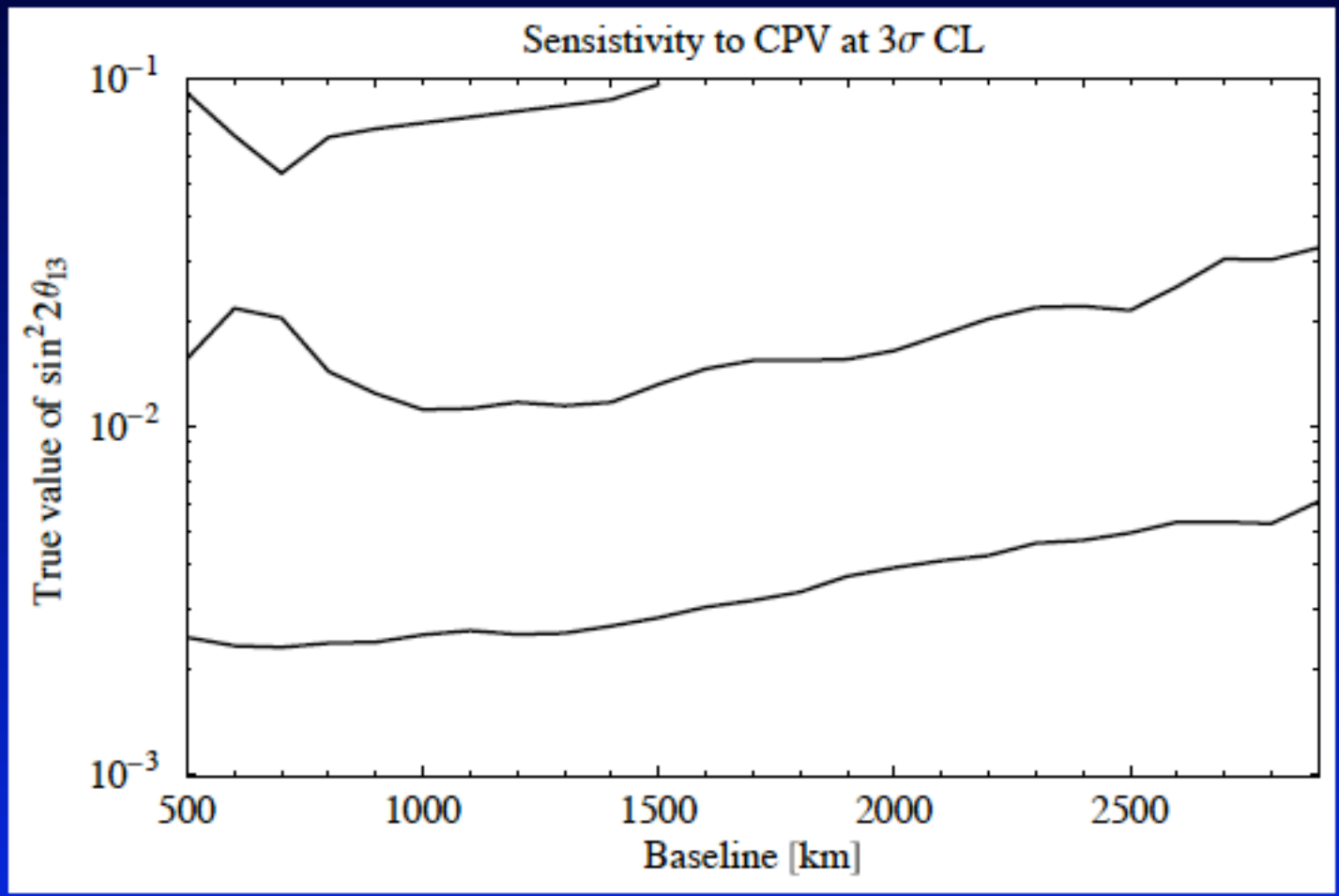
- long baselines are clearly favored

Discovery of CP violation



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

Baseline dependence



- baselines between 1000 and 2000 km are very similar

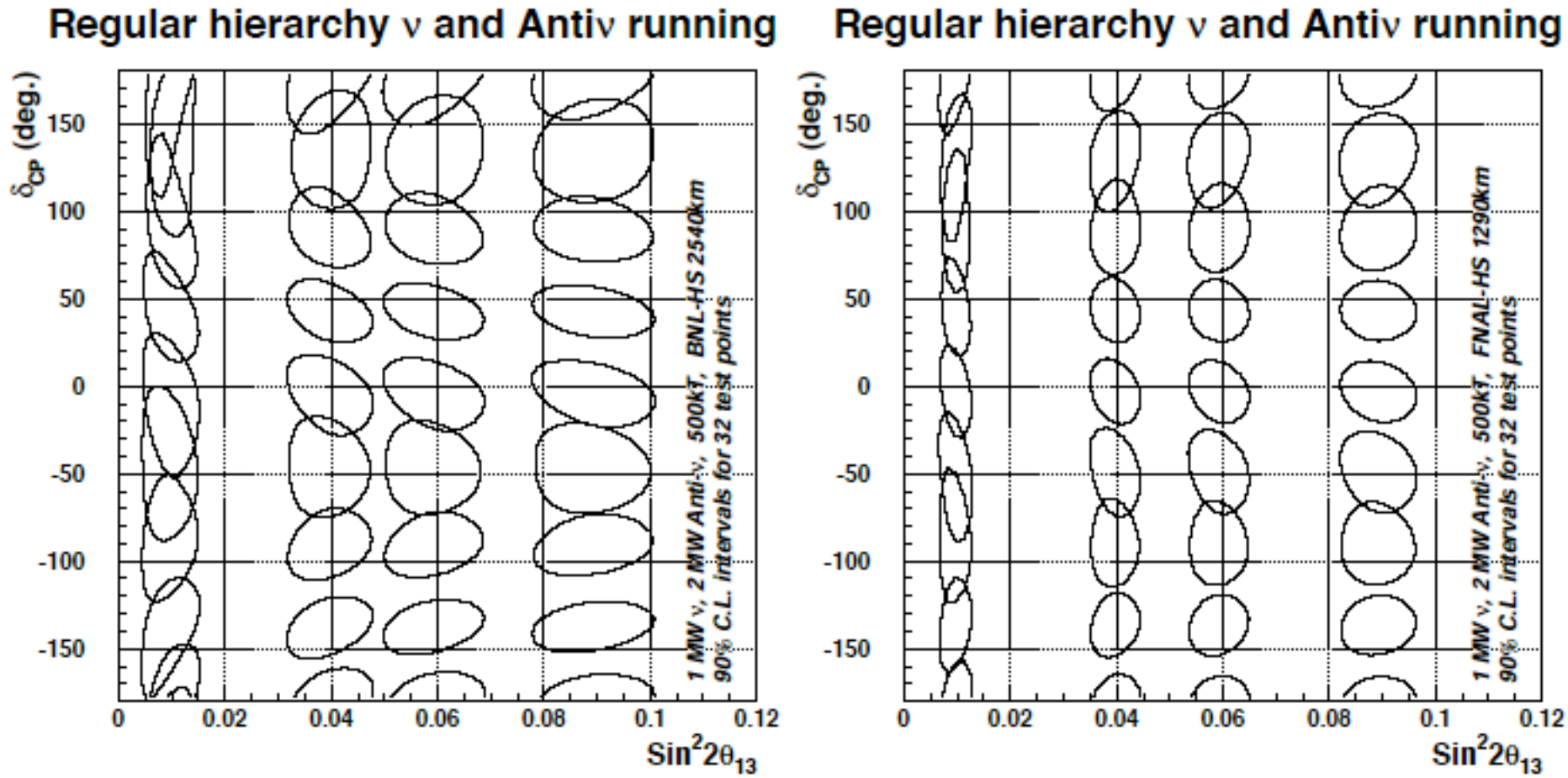
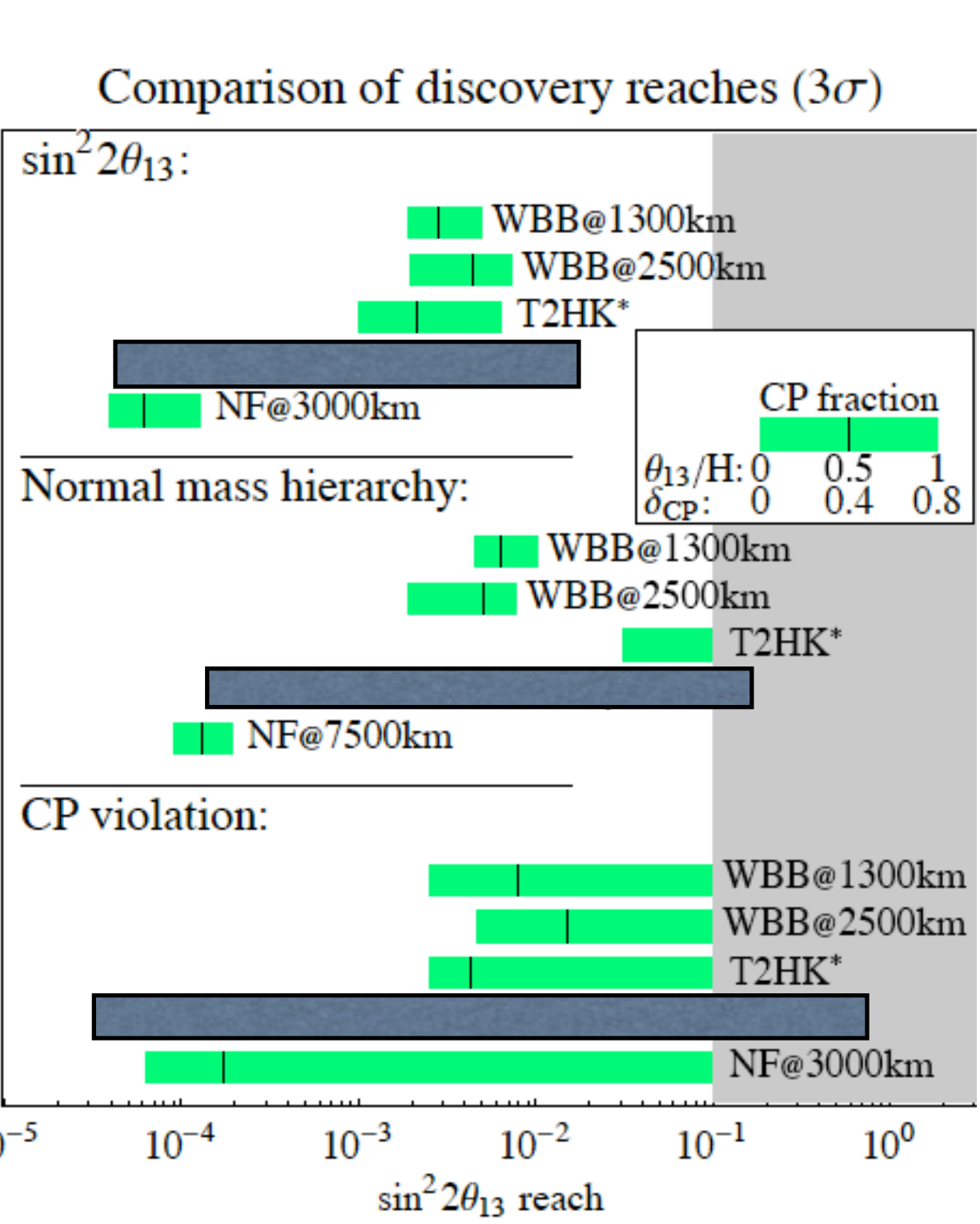
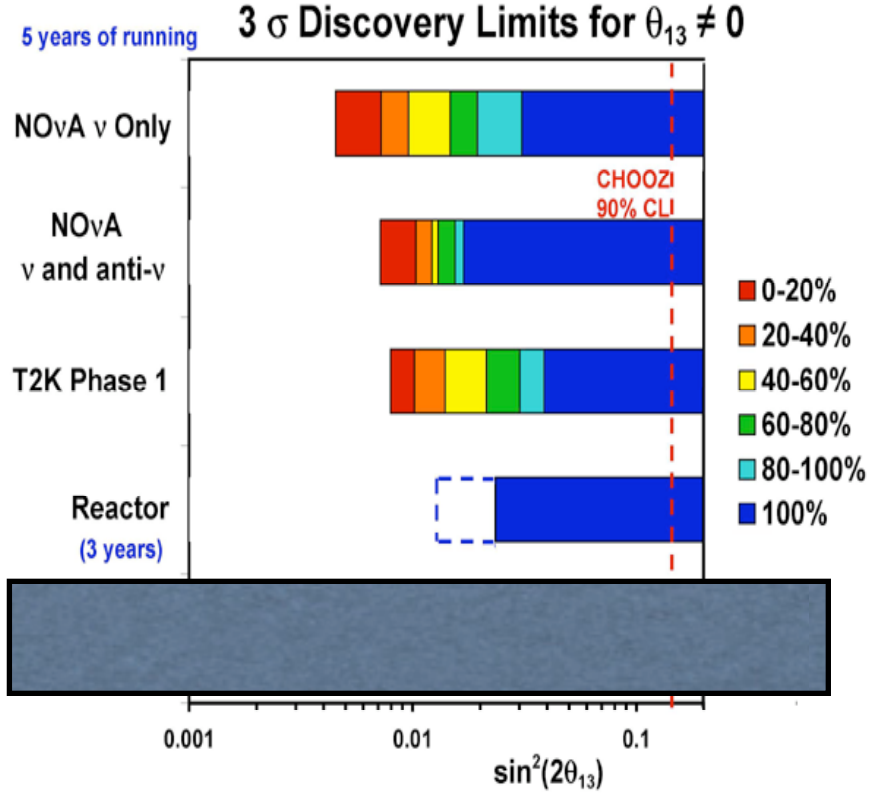
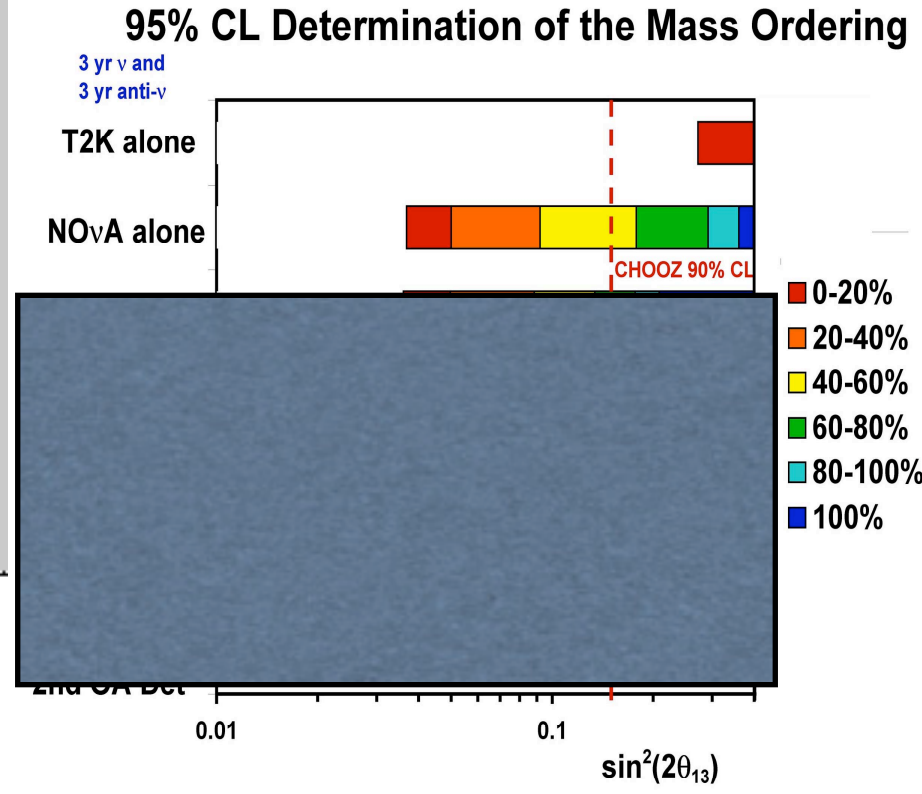


Figure 7: *90% confidence level error contours in* $\sin^2 2\theta_{13}$ *versus* δ_{CP} *for statistical and systematic errors for 32 test points. This simulation is for combining both neutrino and anti-neutrino data. Left is for BNL-HS and right is for FNAL-HS. We assume 10% systematic errors for this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


Comparison of discovery reaches (3σ)
$\sin^2 2\theta_{13}$:
WBB@1300km
WBB@2500km
T2HK*
NF@3000km
CP fraction
θ_{13}/H: 0 0.5 1
δ_{CP}: 0 0.4 0.8
Normal mass hierarchy:
WBB@1300km
WBB@2500km
T2HK*
NF@7500km
CP violation:
WBB@1300km
WBB@2500km
T2HK*
NF@3000km
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
$\sin^2 2\theta_{13}$ reach


5 years of running
3 σ Discovery Limits for $\theta_{13} \neq 0$
NOνA ν Only
NOνA
ν and anti-ν
T2K Phase 1
Reactor
(3 years)
CHOOZ
90% CL
0-20%
20-40%
40-60%
60-80%
80-100%
100%
0.001
0.01
0.1
$\sin^2(2\theta_{13})$


95% CL Determination of the Mass Ordering
3 yr ν and
3 yr anti-ν
T2K alone
NOνA alone
CHOOZ 90% CL
0-20%
20-40%
40-60%
60-80%
80-100%
100%
0.01
0.1
$\sin^2(2\theta_{13})$

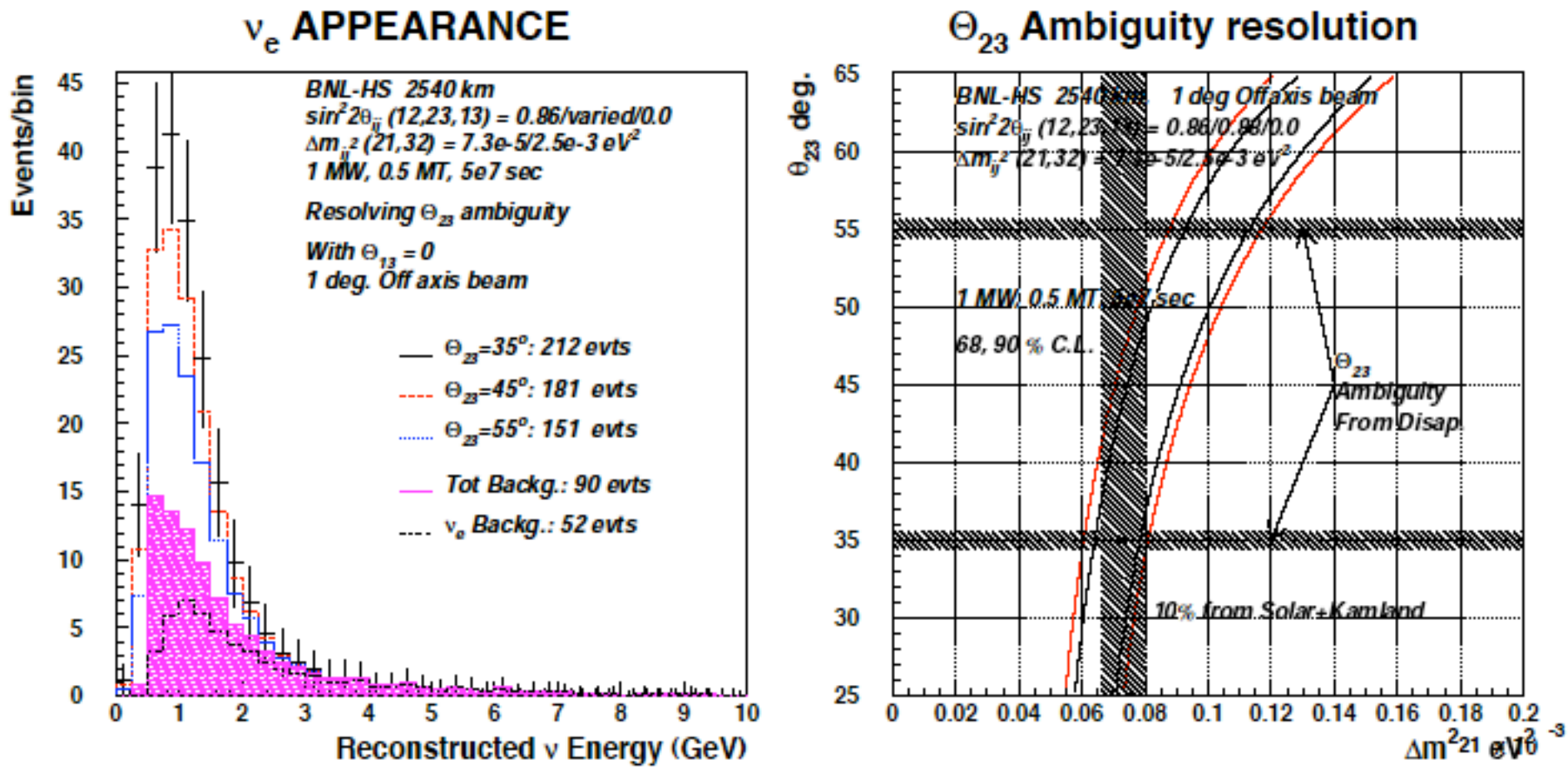


Figure 8: *Expected spectrum of electron neutrinos (left) for* $\theta_{13} = 0$ *and other assumed parameters indicated in the figure. The right hand side shows the resolution of the* $\theta_{23} \rightarrow \pi/2 - \theta_{23}$ *ambiguity using the measurement of* $\sin^2 2\theta_{23}$ *from disappearance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

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. (Did not talk about this physics)
- 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.