Future Opportunities in Long Baseline Oscillation Physics

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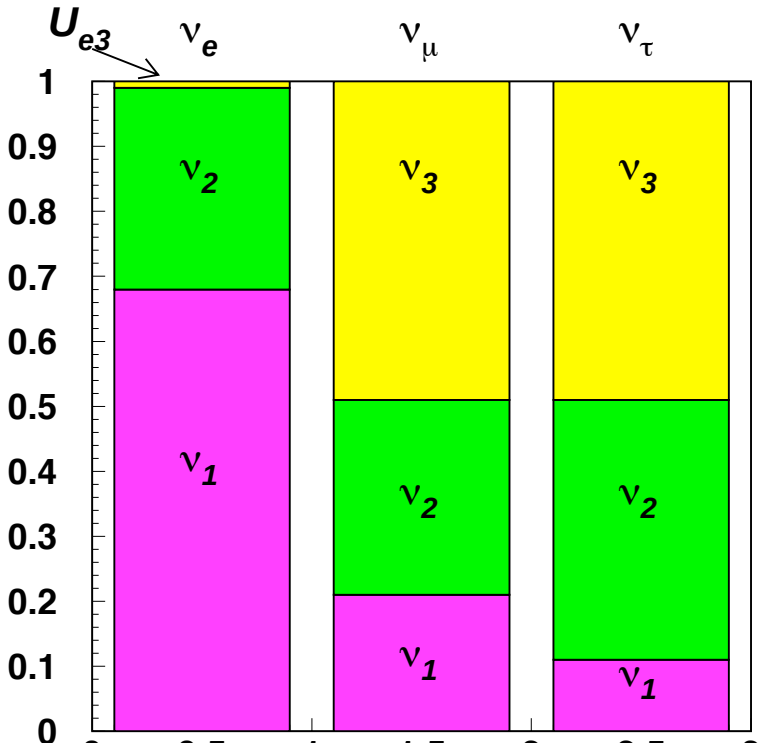
HUSEF topical workshop

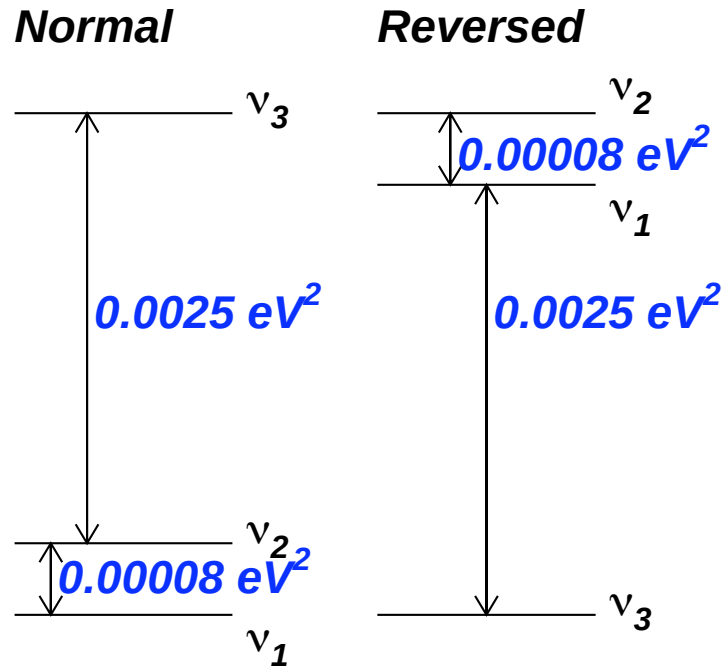
11/18/2005

Outline of talk

- Concept of very long baseline
- Possibilities in USA
  - Unique situation with DUSEL
- The backgrounds issue
- comparisons to NOVA, T2KK
- 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:

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

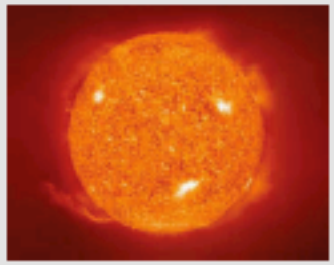
CP phase

no matter effects

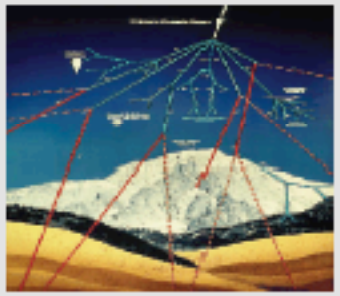
Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$.

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

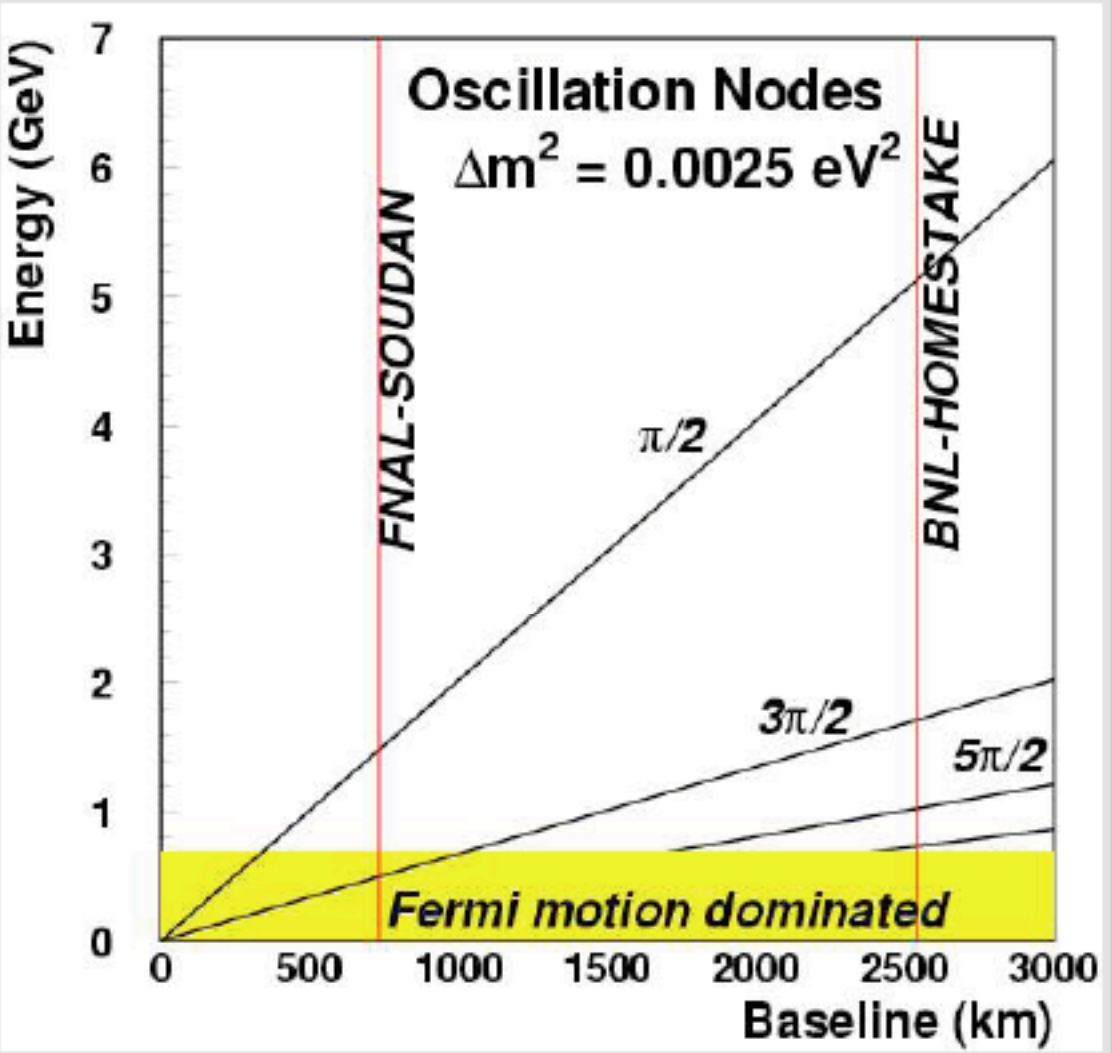
Why Very Long Baseline?

observe multiple nodes in oscillation pattern

☞ less dependent on flux normalization

neutrino travels larger distance through earth

larger matter effects



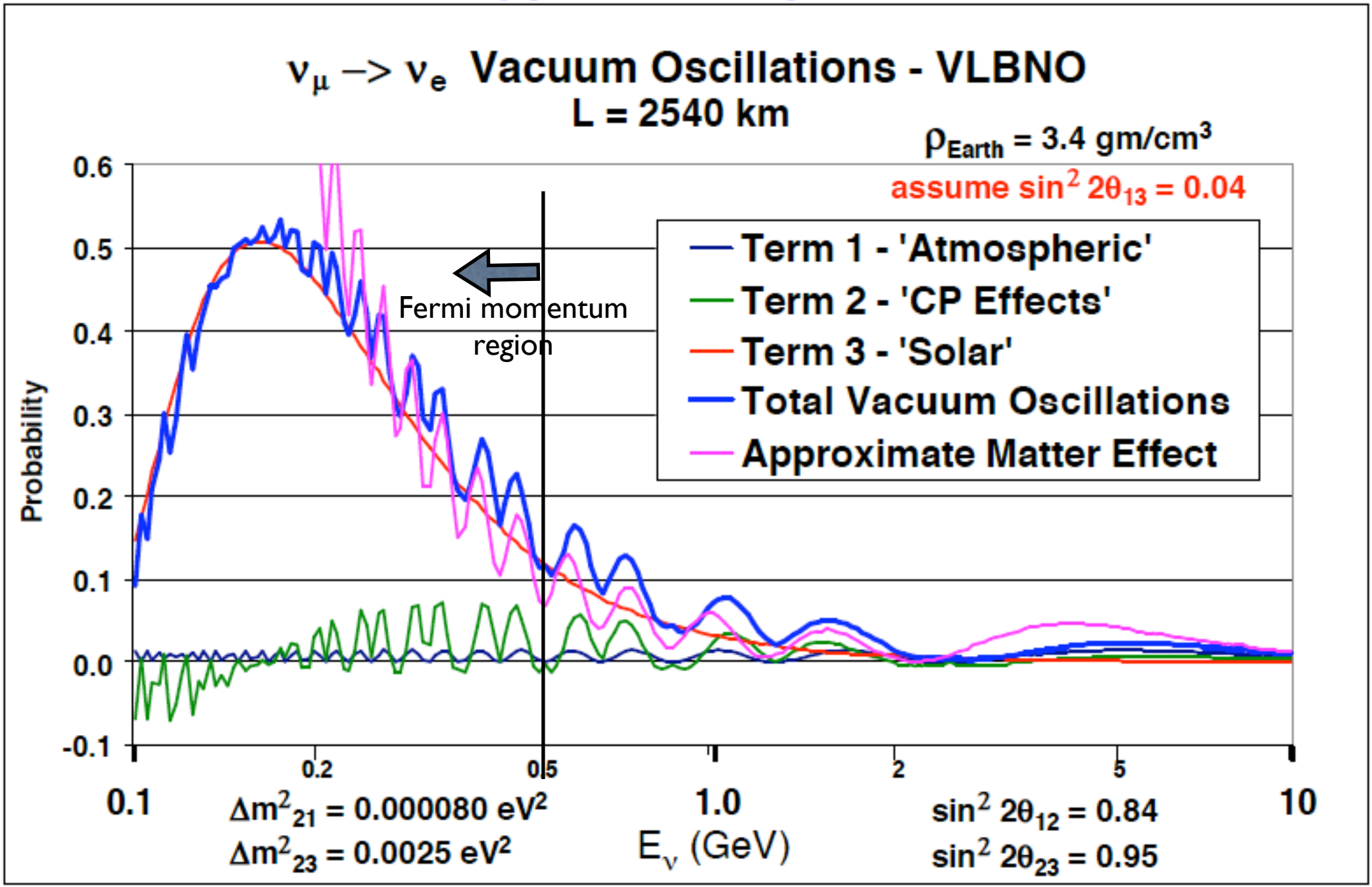
flux ~ L^{-2}: lower statistics

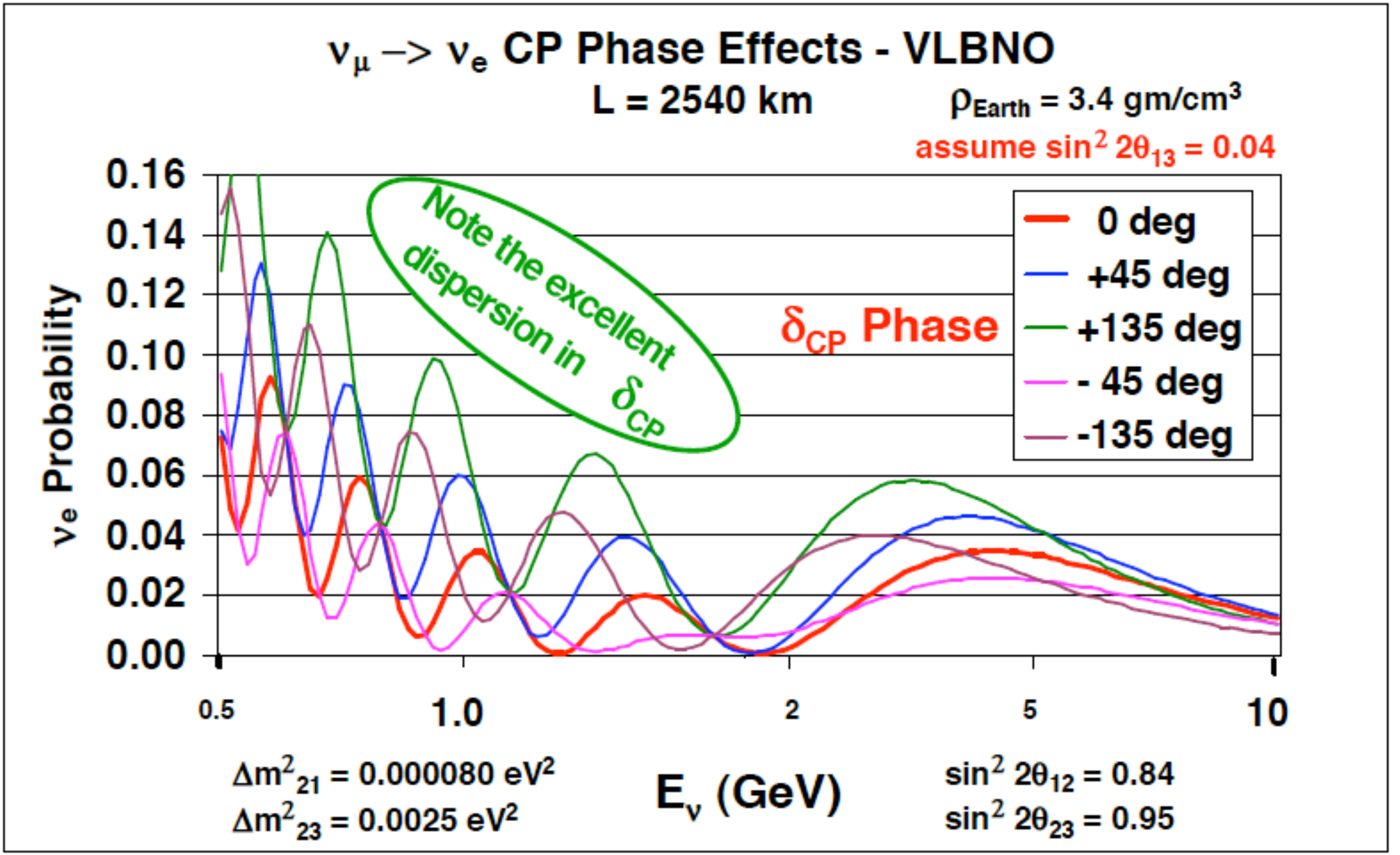
but: CP asymmetry ~ L

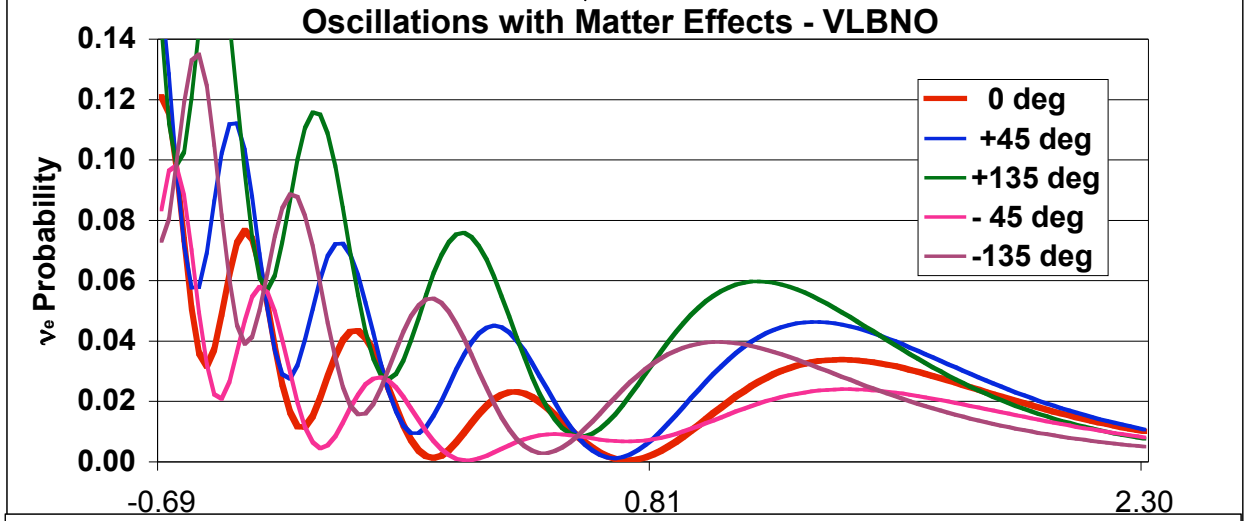
sensitivity to δ_{CP} independent of distance!

better S:B

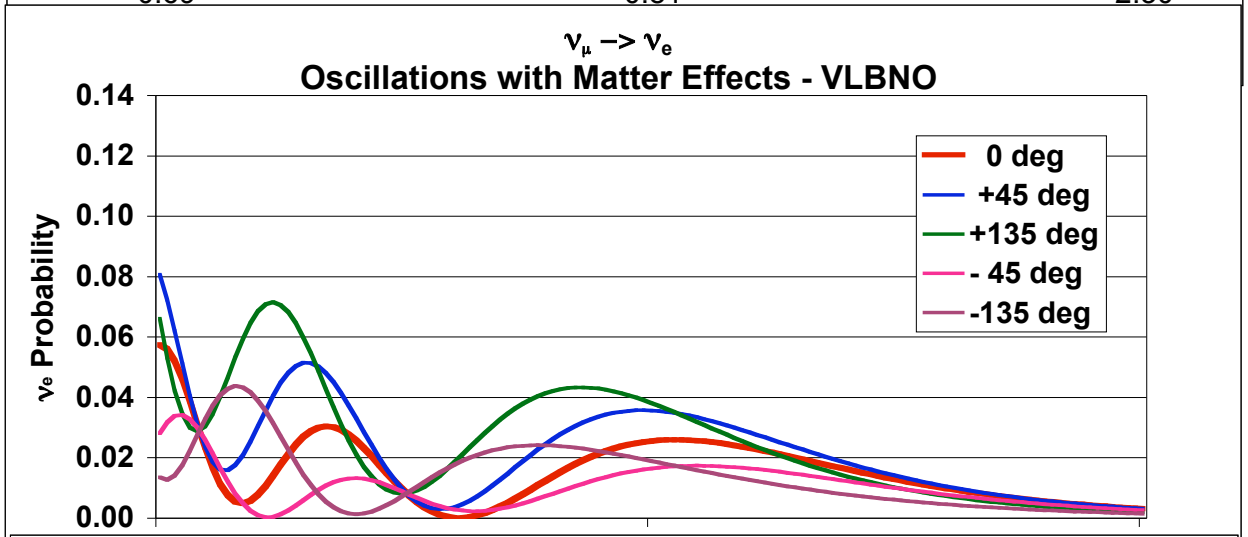
(Marciano hep-ph/0108181)


$\nu_\mu \rightarrow \nu_e$ Vacuum Oscillations - VLBNO
L = 2540 km
ρ_{Earth} = 3.4 gm/cm^3
assume $\sin^2 2\theta_{13} = 0.04$
Term 1 - 'Atmospheric'
Term 2 - 'CP Effects'
Term 3 - 'Solar'
Total Vacuum Oscillations
Approximate Matter Effect
Fermi momentum region
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
$\Delta m^2_{21} = 0.000080$ eV^2
$\Delta m^2_{23} = 0.0025$ eV^2
E_ν (GeV)
$\sin^2 2\theta_{12} = 0.84$
$\sin^2 2\theta_{23} = 0.95$

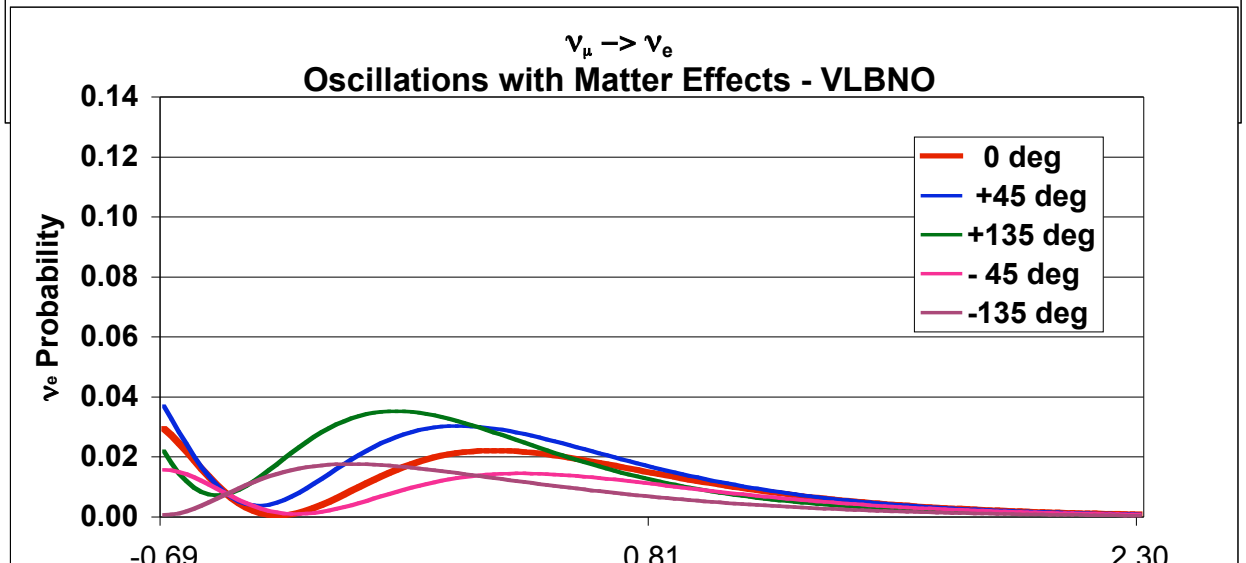

$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - VLBNO
L = 2540 km
ρ_{Earth} = 3.4 gm/cm^3
assume $\sin^2 2\theta_{13} = 0.04$
Note the excellent dispersion in δ_{CP}
δ_{CP} Phase
0 deg
+45 deg
+135 deg
- 45 deg
-135 deg
ν_e Probability
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.5
1.0
2
5
10
$\Delta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



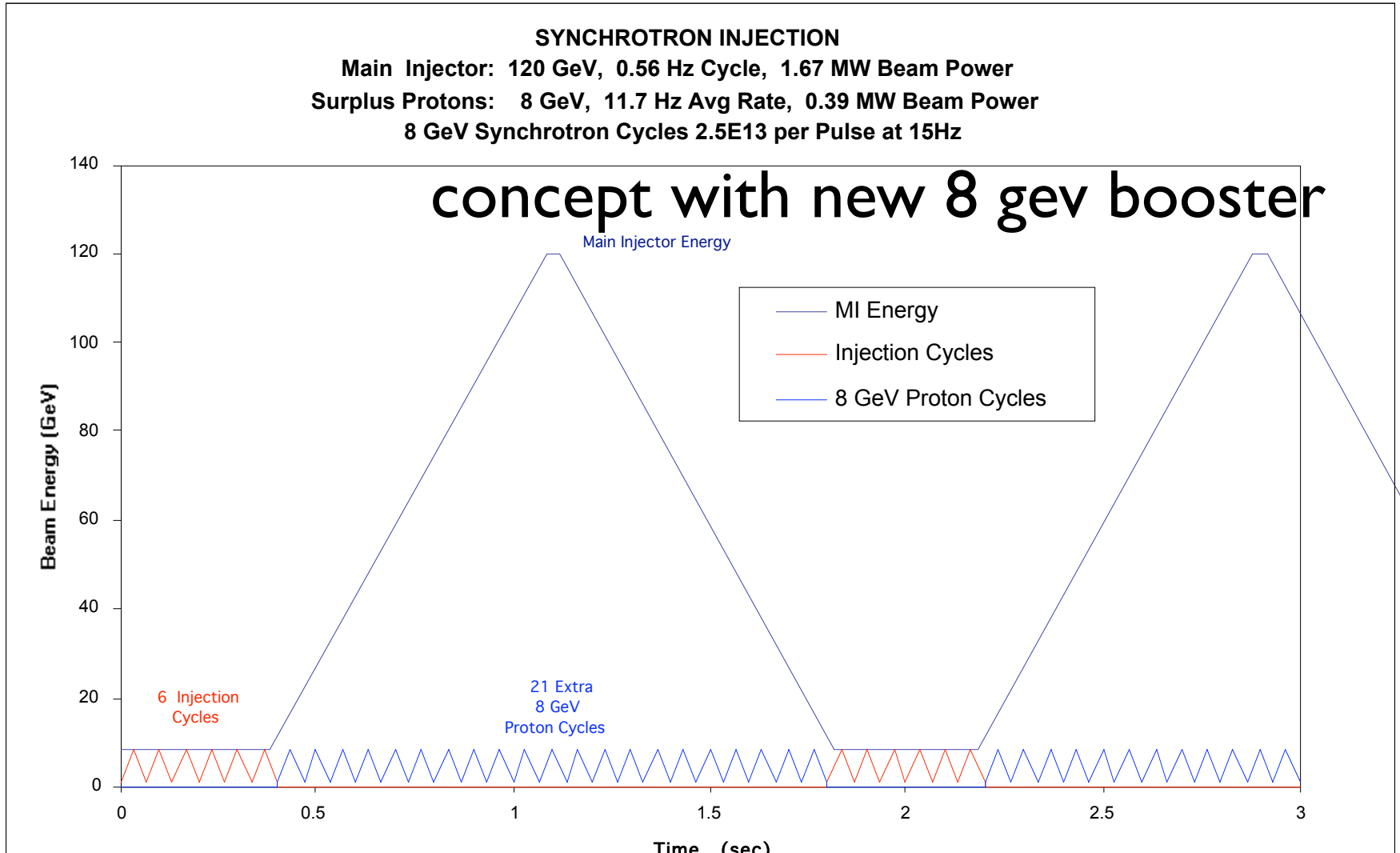
810 km

US possibilities for beam

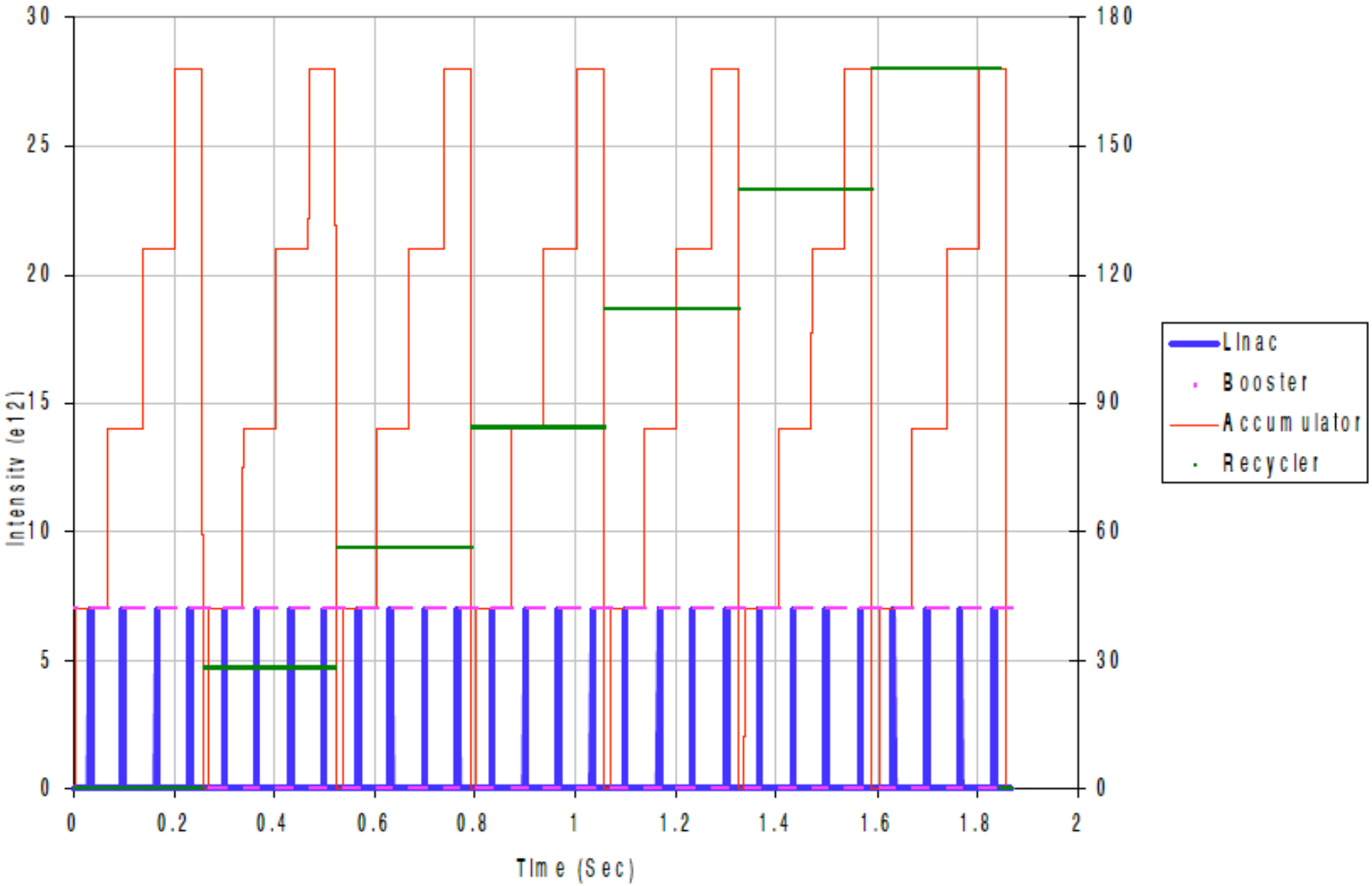
Source	Proton beam energy	Proton beam power
FNAL MI (McGinnis upgrade)	Ep=8-120GeV	1-2 MW X (Ep/120GeV)
FNAL MI (with 8GeV LINAC)	Ep=8-120 GeV	2 MW @ any Ep
BNL-AGS (upgrade 2.5- 5 Hz)	Ep=28 GeV	1-2 MW

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

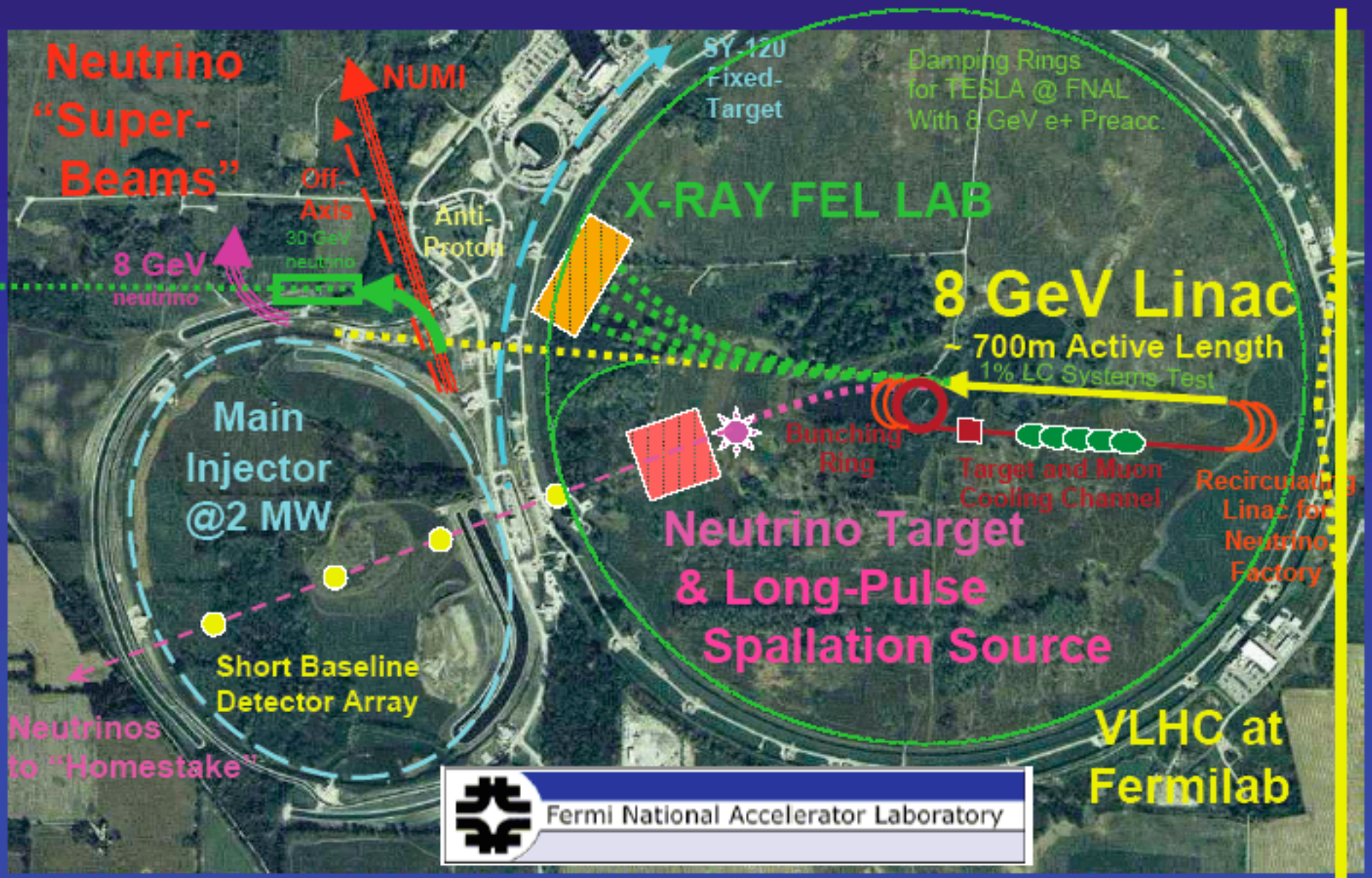


Multi-stage Proton Accumulator Production Cycle

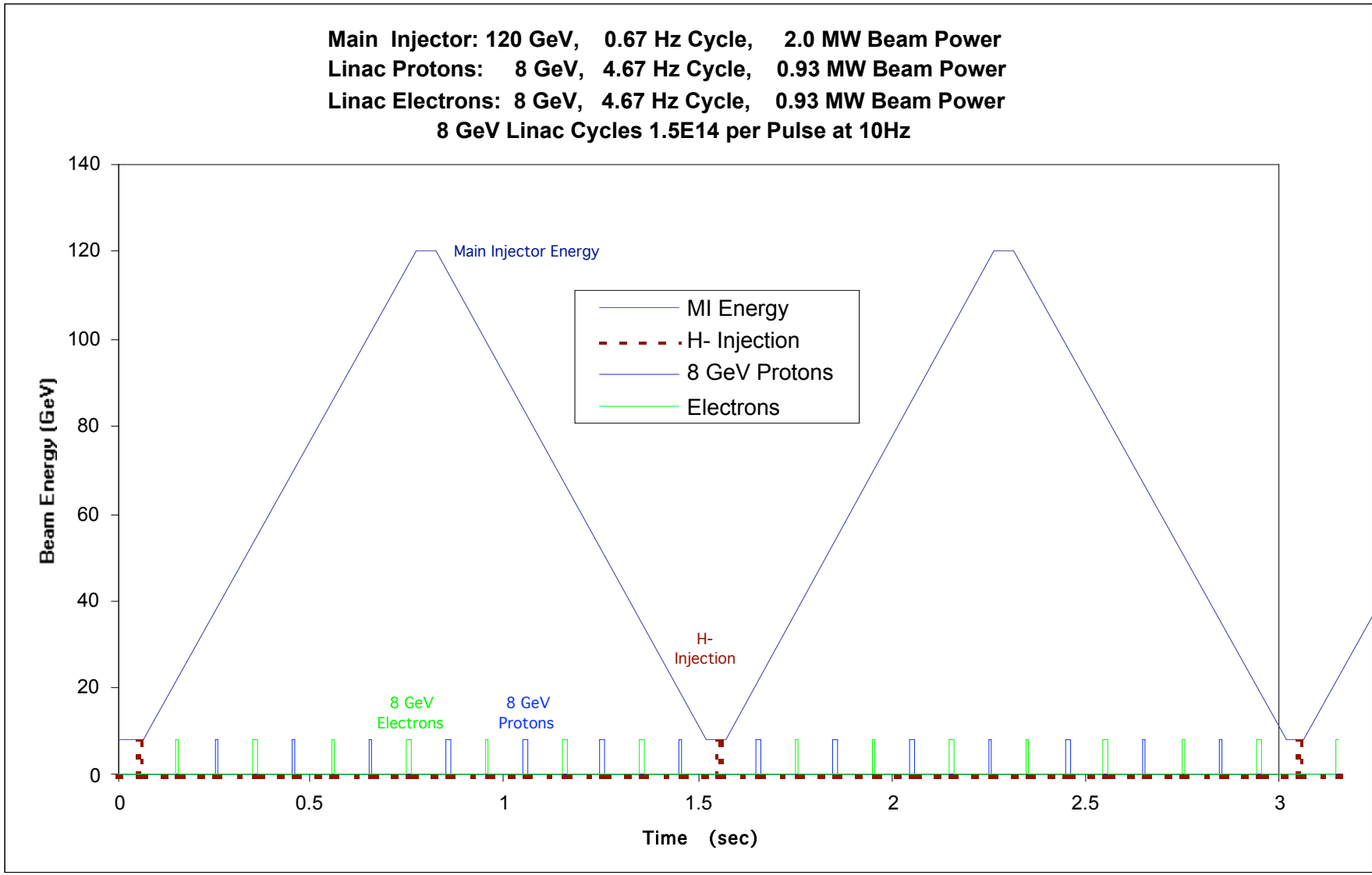


8 GeV Superconducting Linac

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	--

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 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

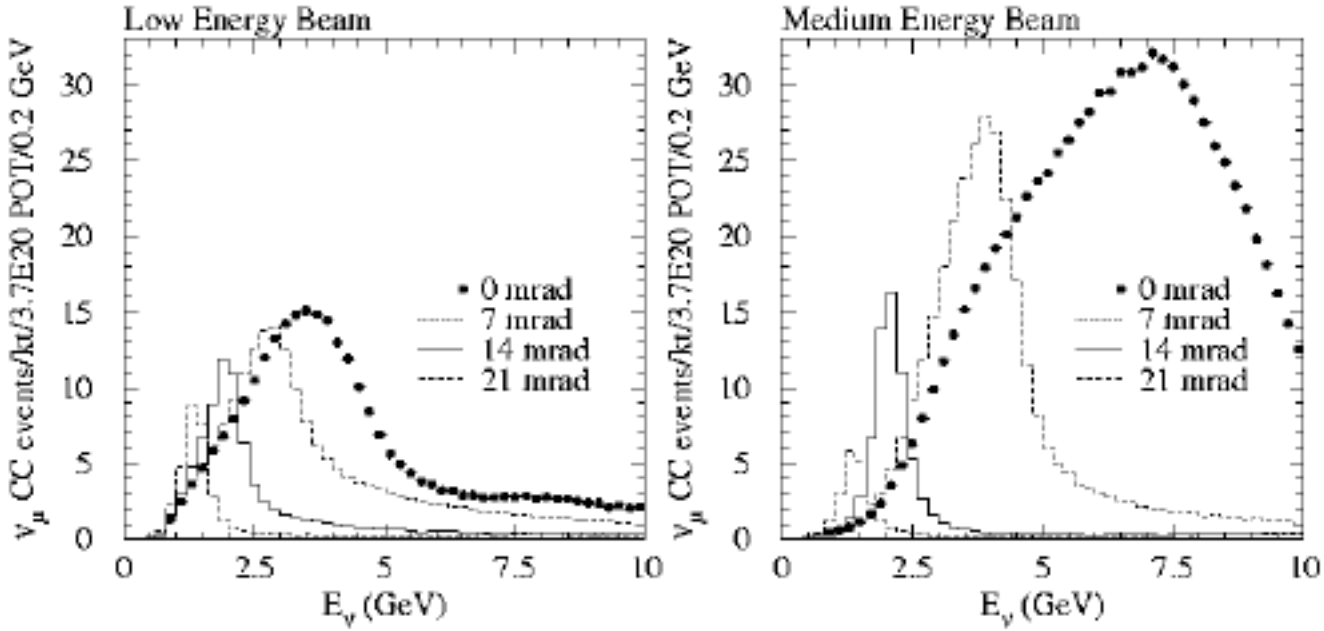
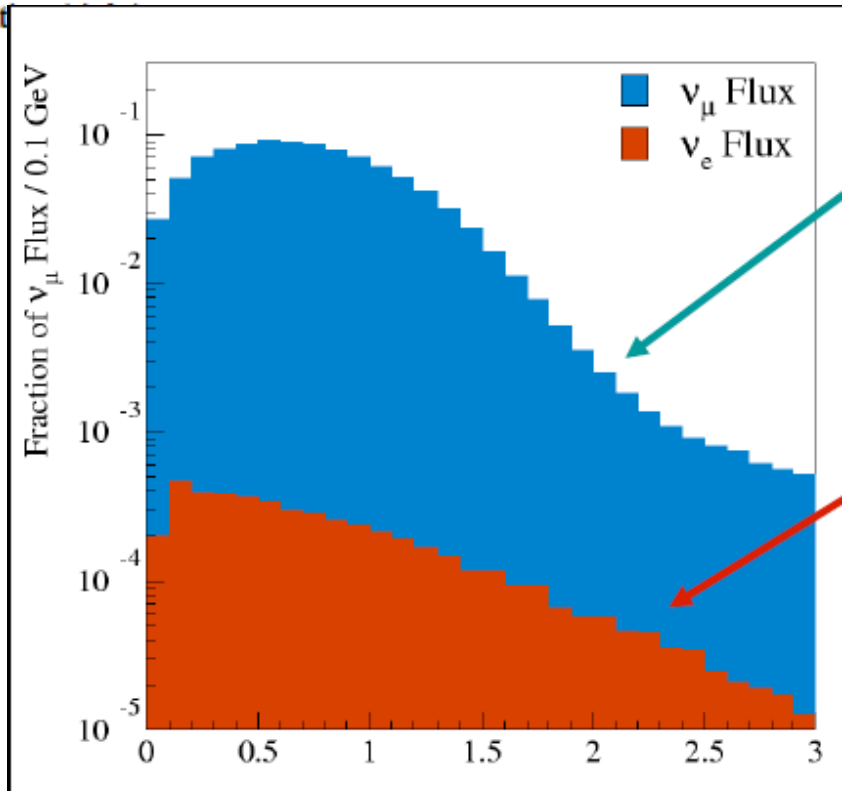


Fig. 4.4: CC ν_μ event rates expected under a no-oscillation hypothesis at a distance of 800 km from Fermilab and at various transverse locations for the NuMI low-energy beam configuration (left) and medium-energy beam configu-

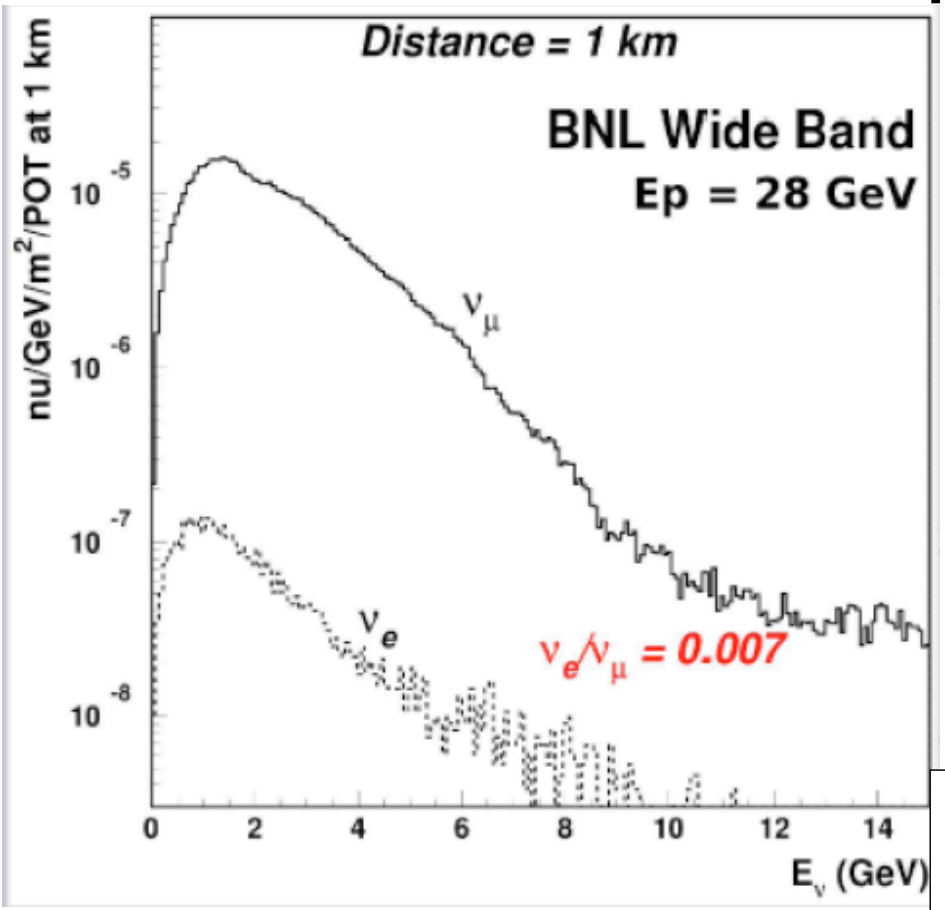


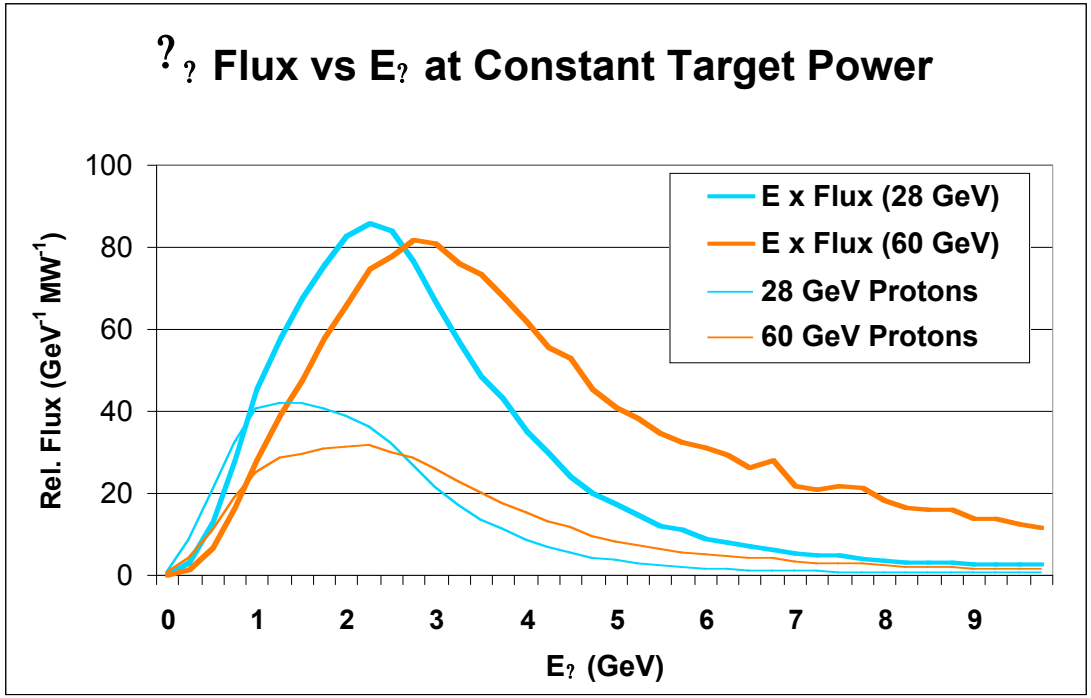
<E>~0.7

nue~0.001

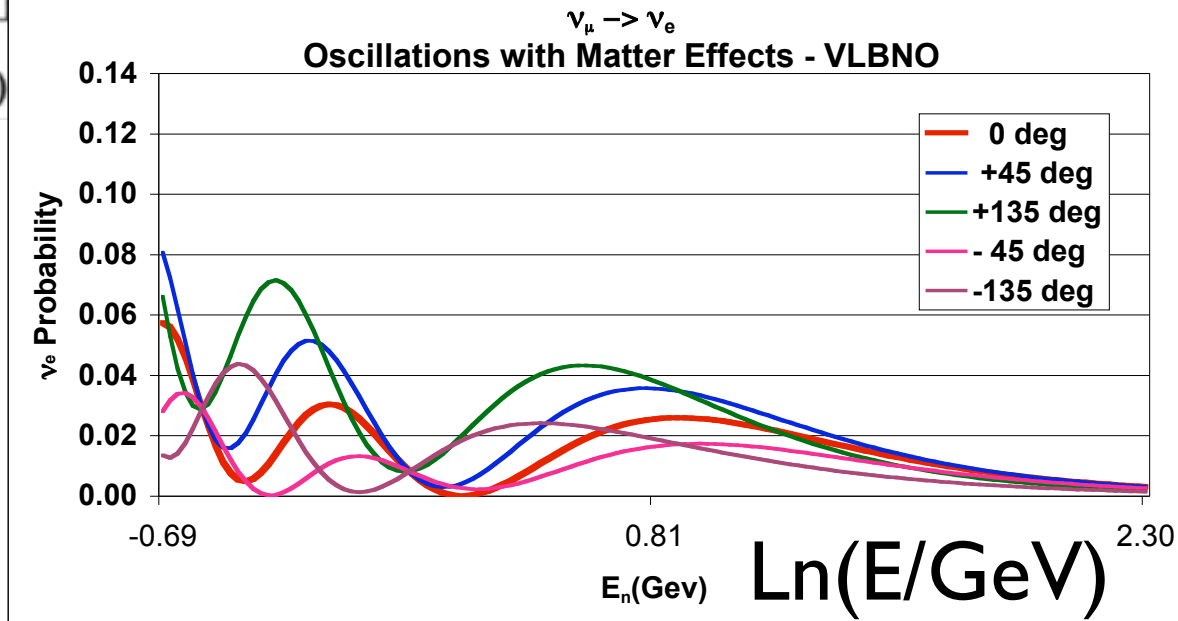
miniboone

Flux shapes for DUSEL





Using low E horn configuration and 200 m decay tunnel



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.

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

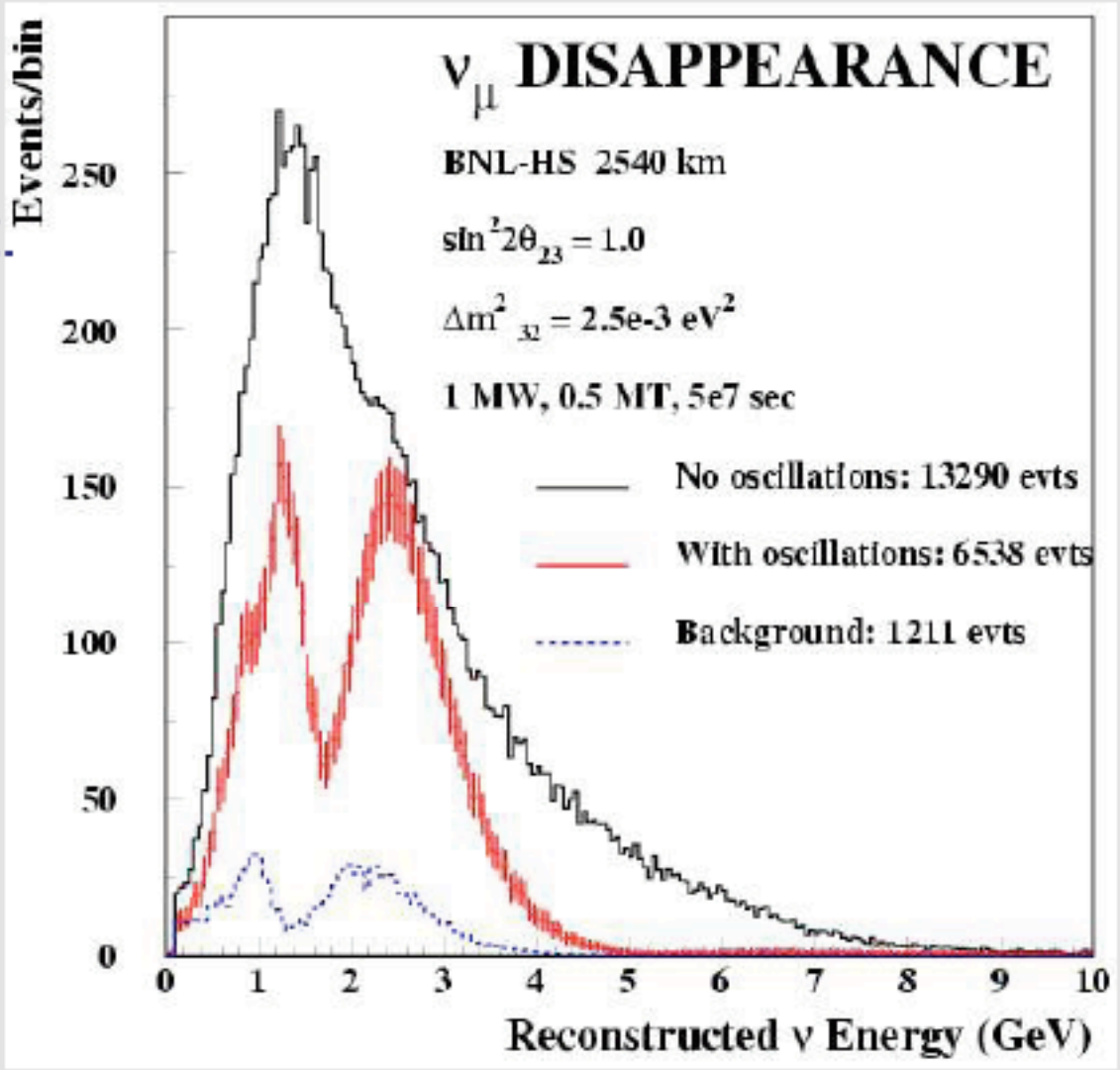
- NC kinematics favors a falling spectrum. Background is pushed to low energies.
- Currently we are assuming that we use only the cleanest events. eff. < 20 %. Large fraction of CC events could be used if detector can be finer grained.
- No hardware enhancements assumed for water Cherenkov detector so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

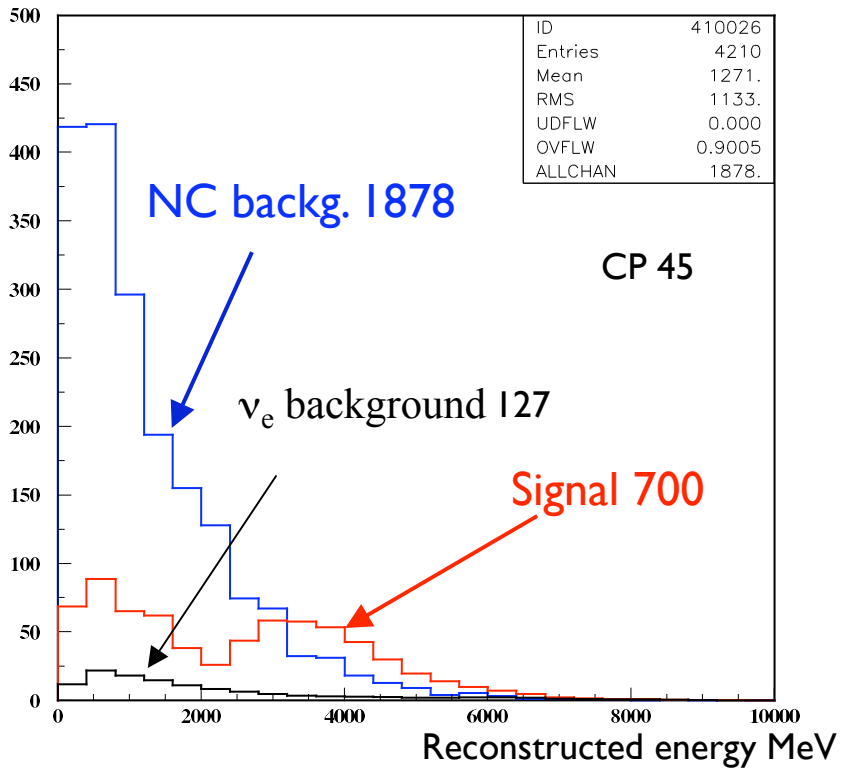
including anti-ν running:

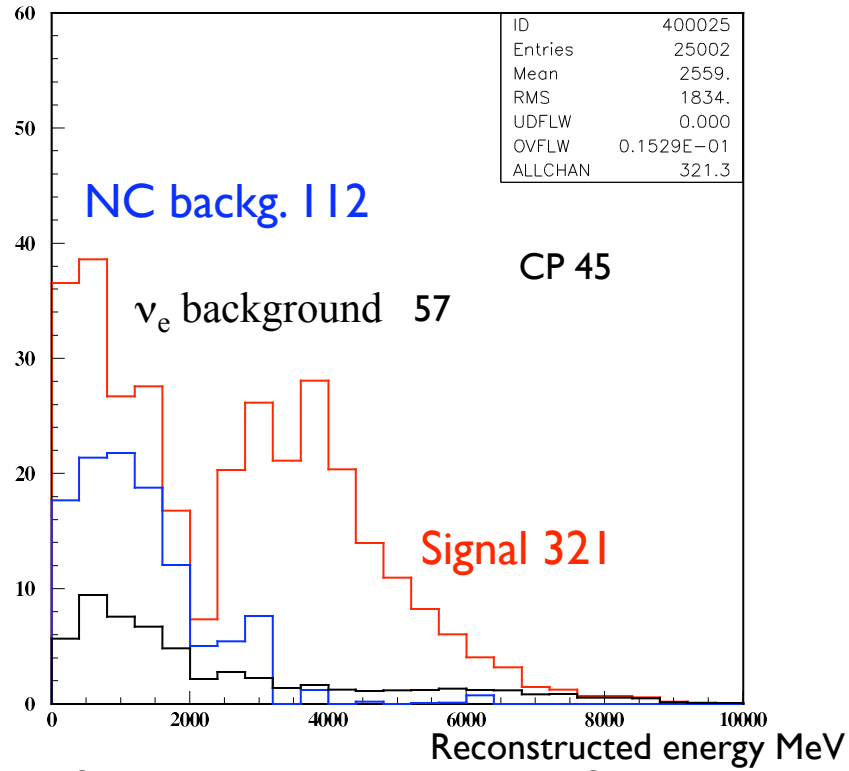
- CPT test possible
- errors below 1% achievable

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:

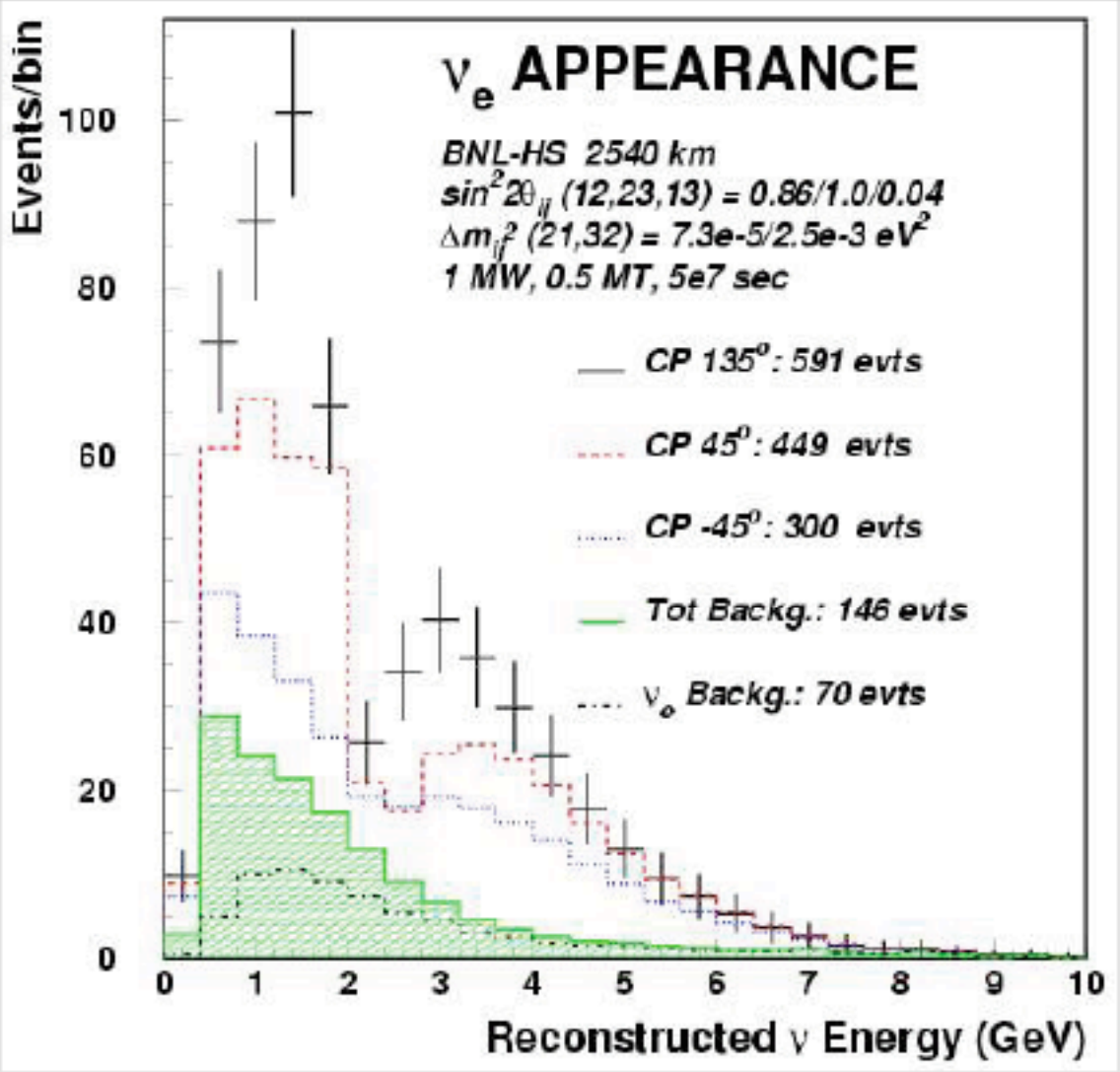
- beam ν_e
- NC ν_μ

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:

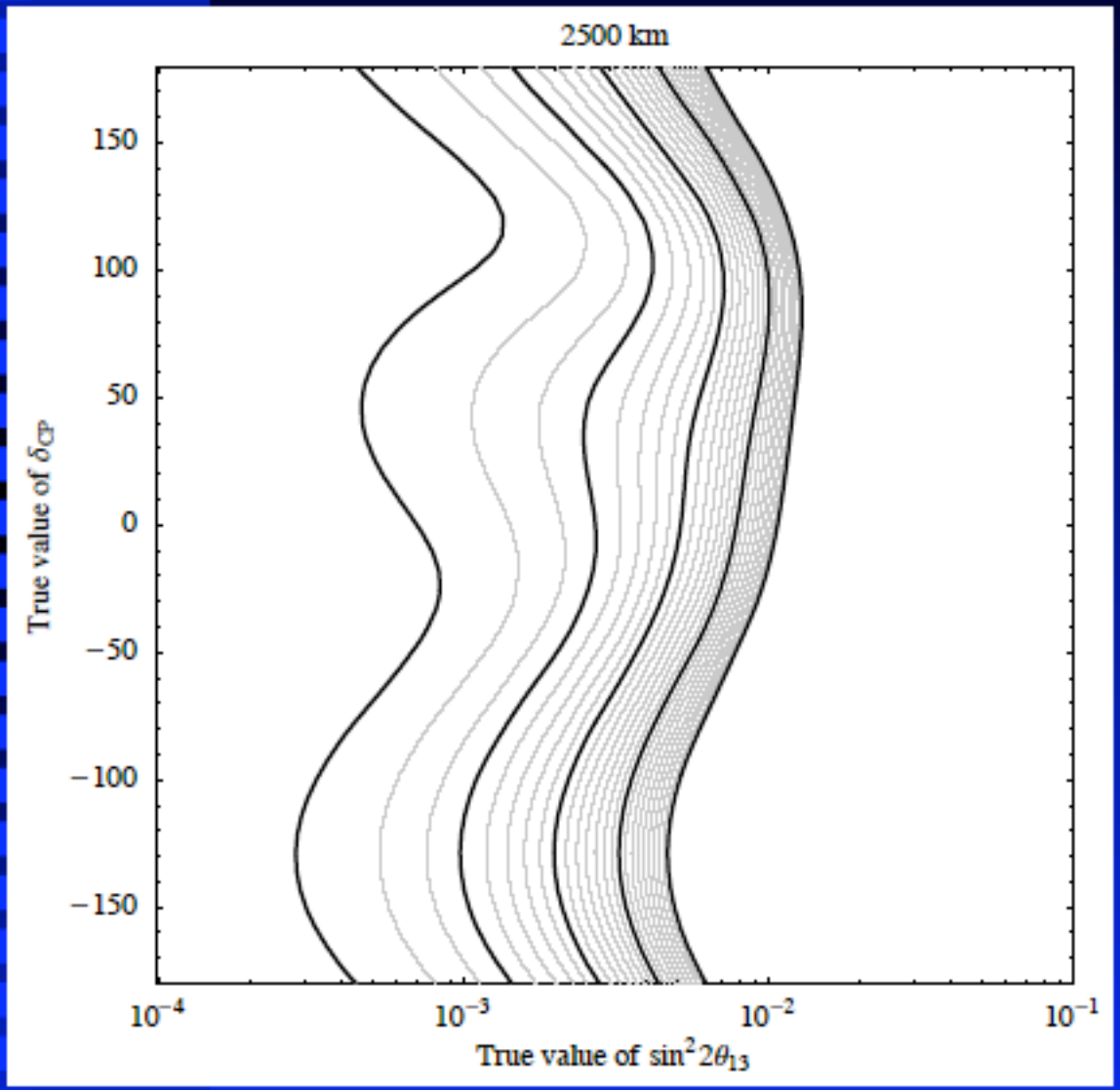
exclude $\sin^2 2\theta_{13} > 0.003$



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

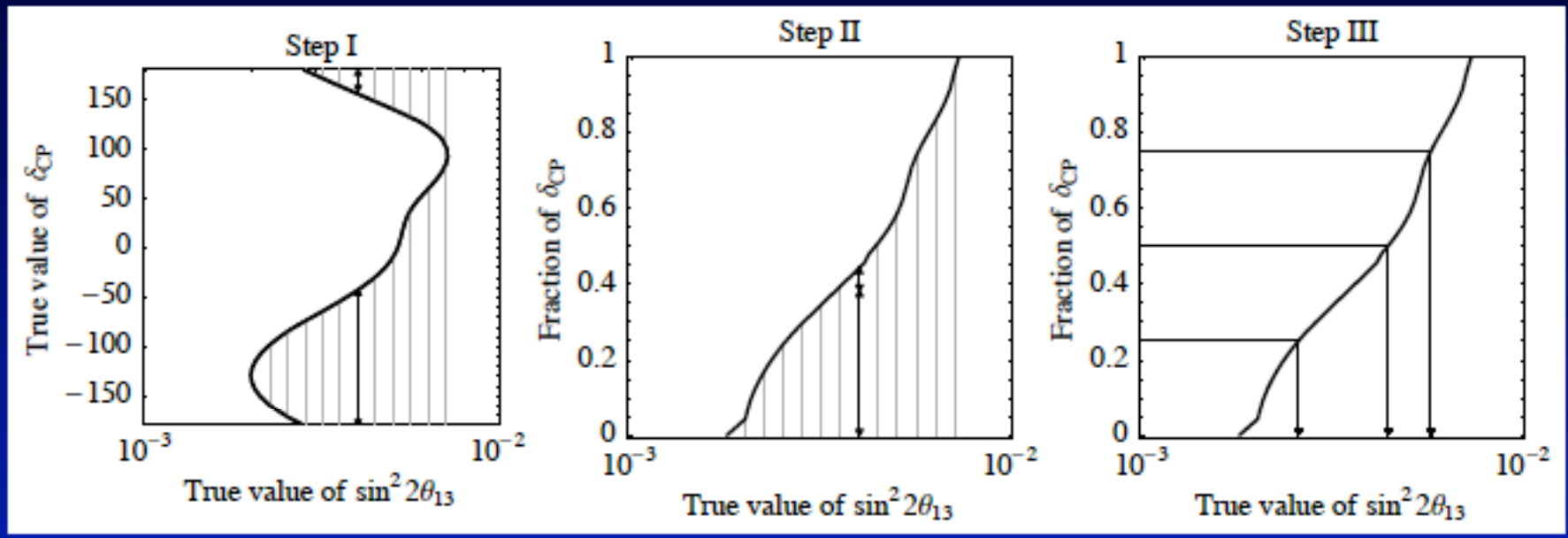
observation ν_e appearance possible through solar term

Discovery of θ_{13}

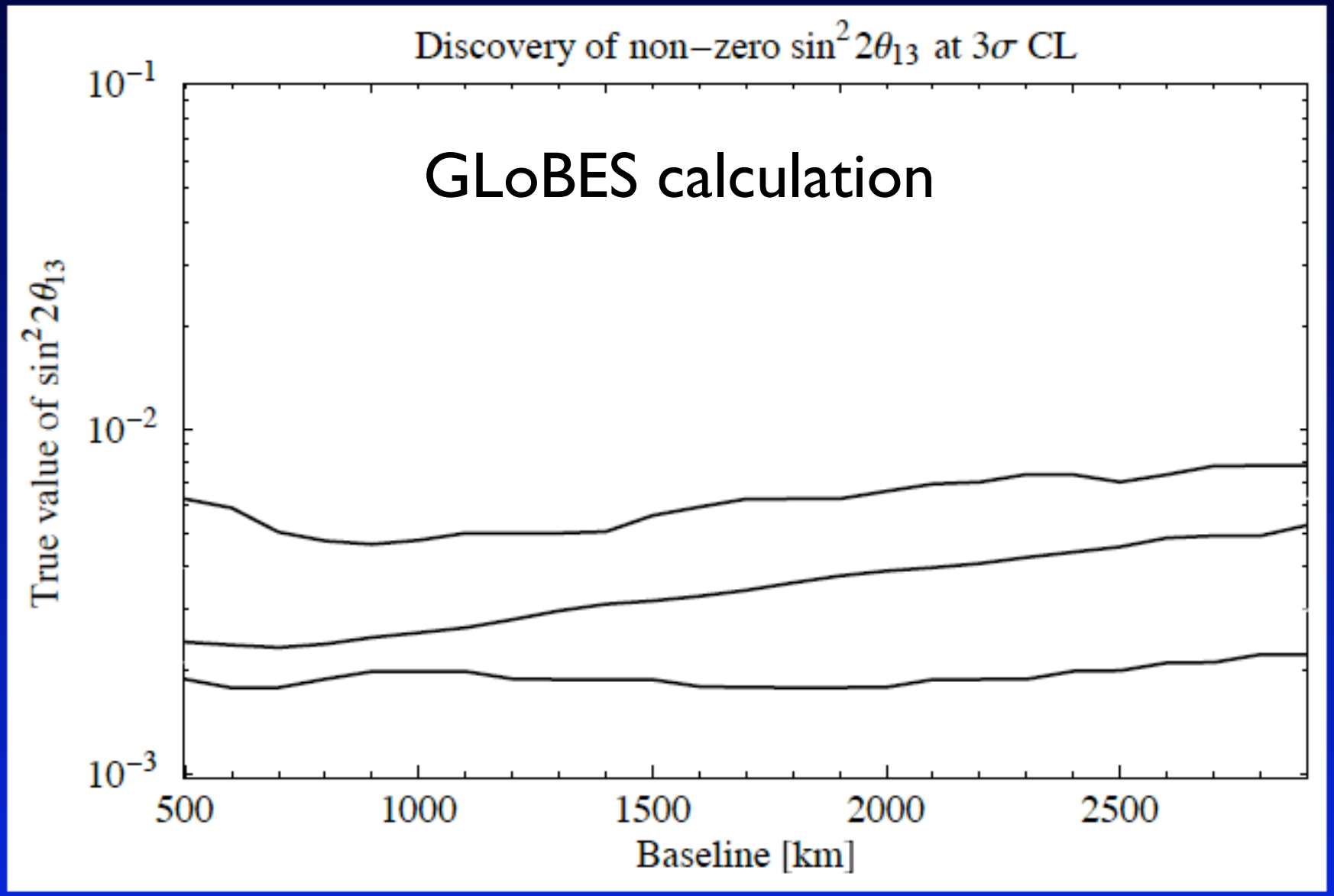


- simulate data for δ and $\theta_{13} \neq 0$
- try to fit them with $\theta_{13} = 0$
- repeat the fit for the wrong hierarchy
- take the smallest χ^2

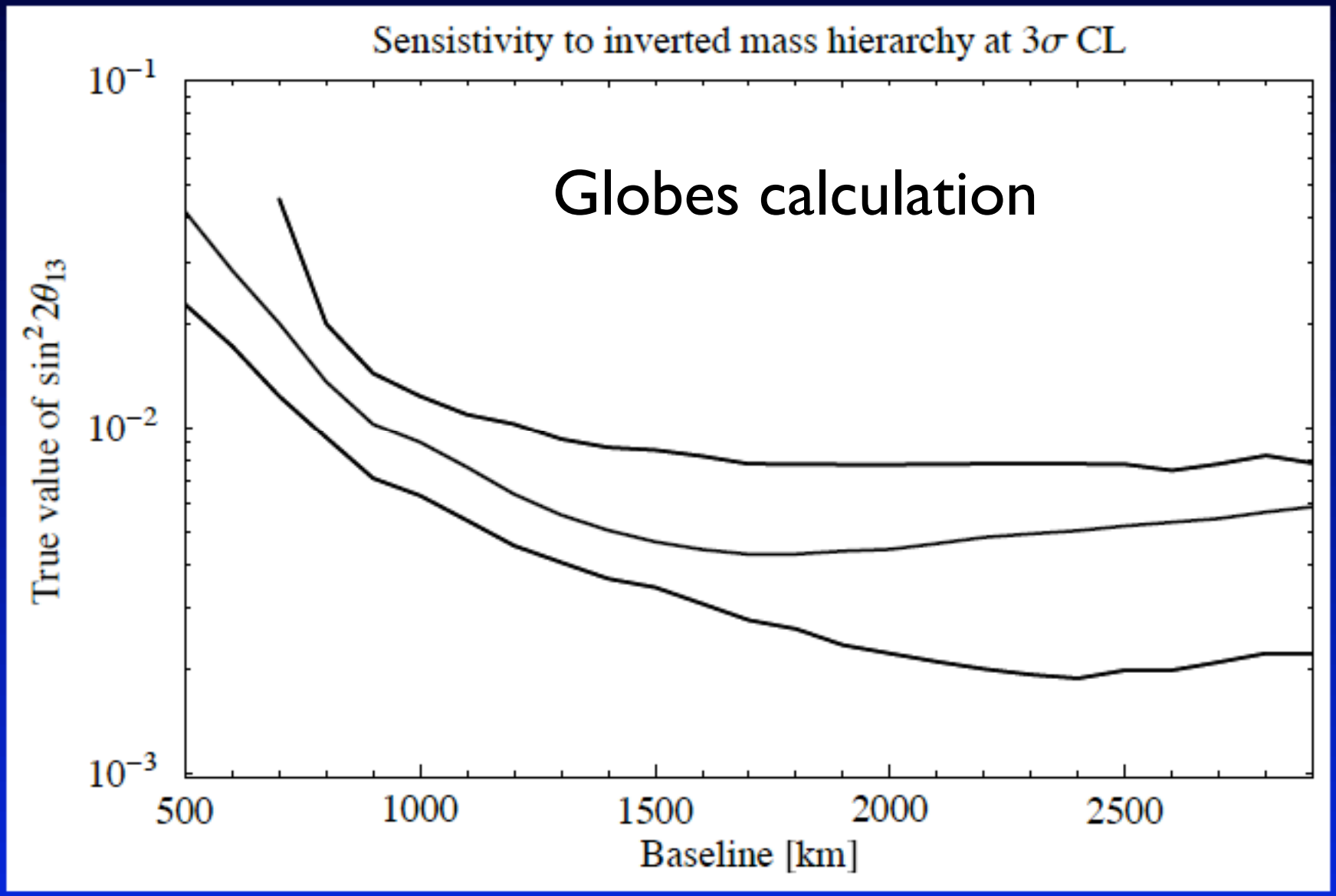
CP fraction



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

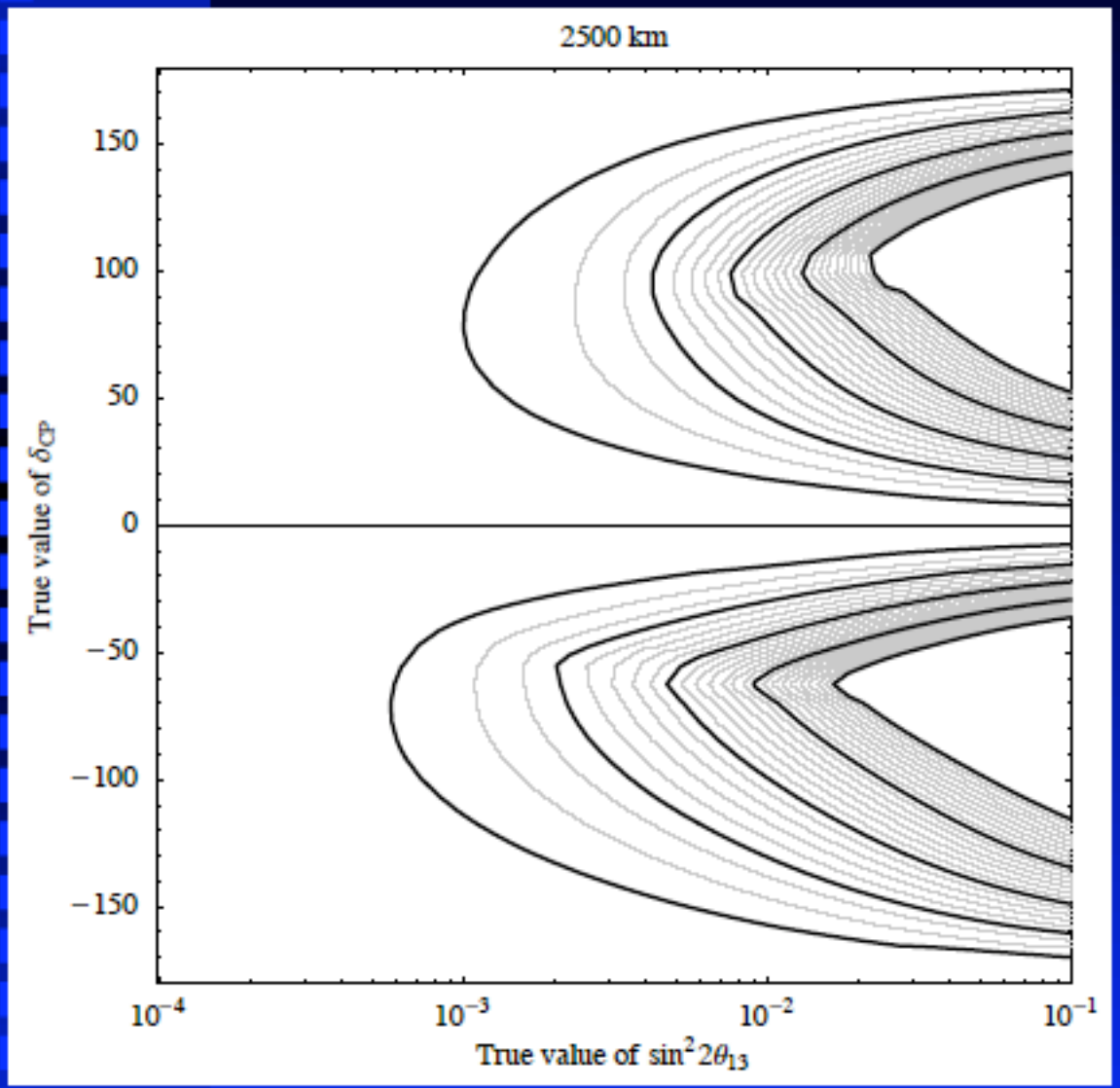


- weak baseline dependence



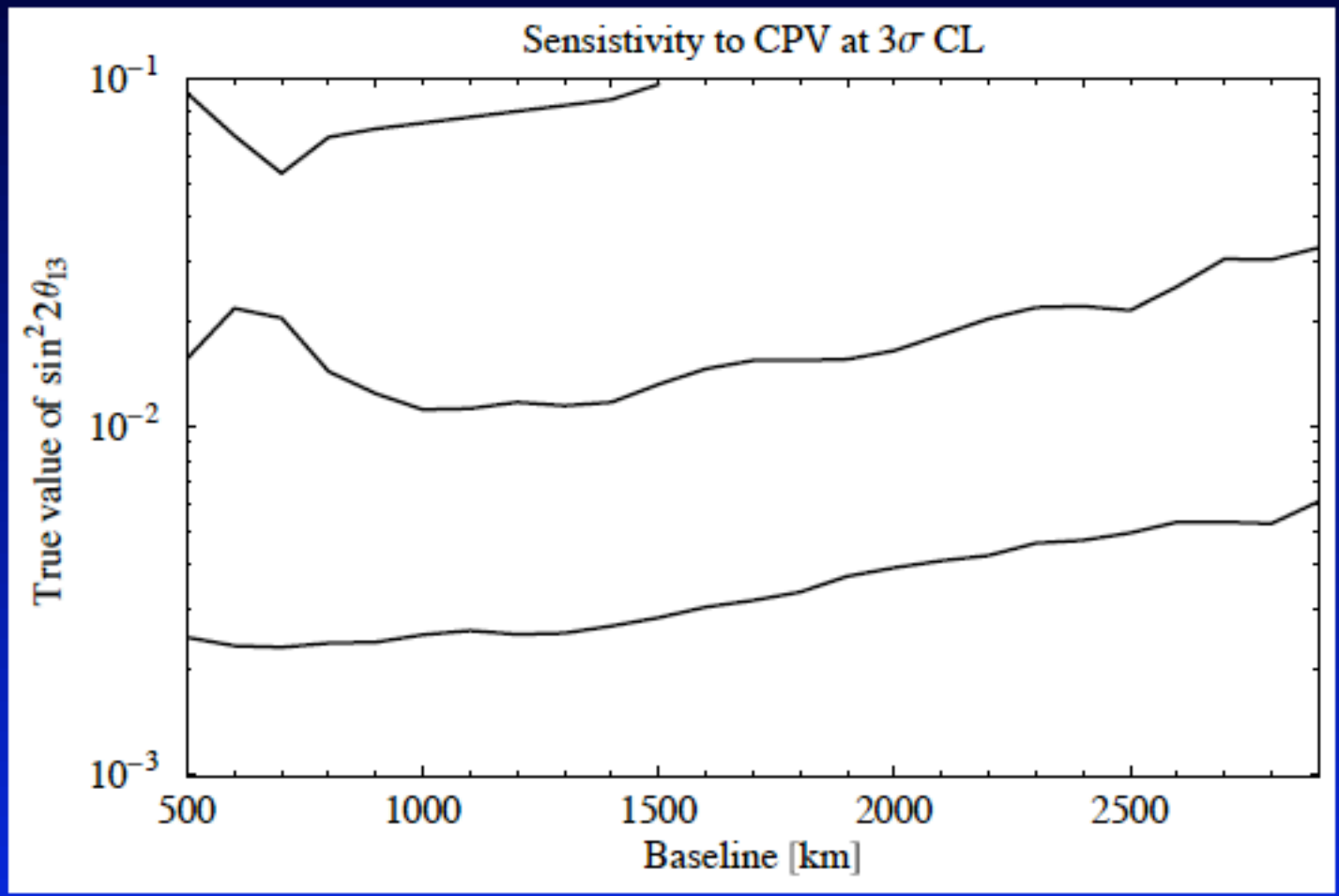
- long baselines are clearly favored

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

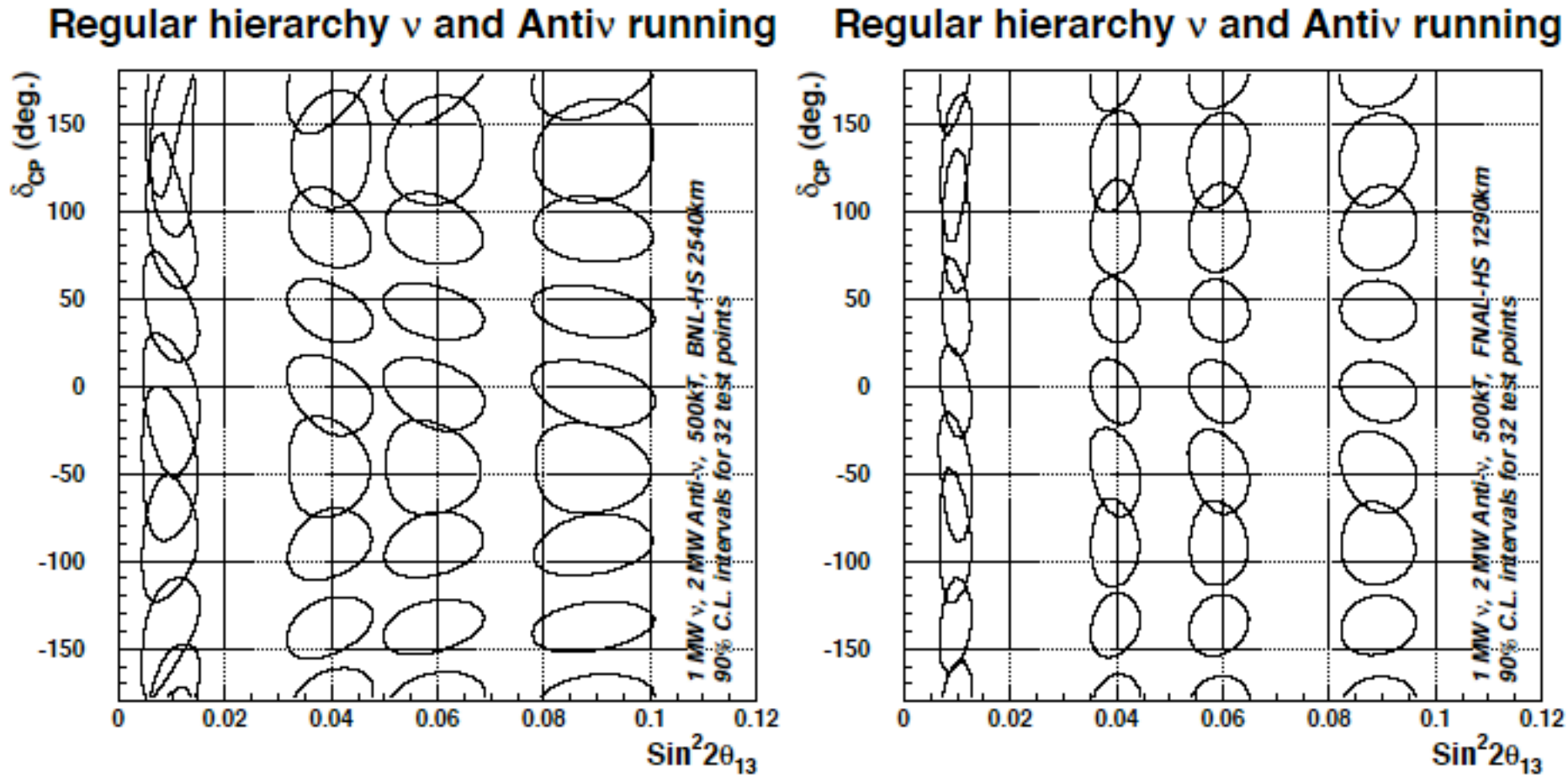
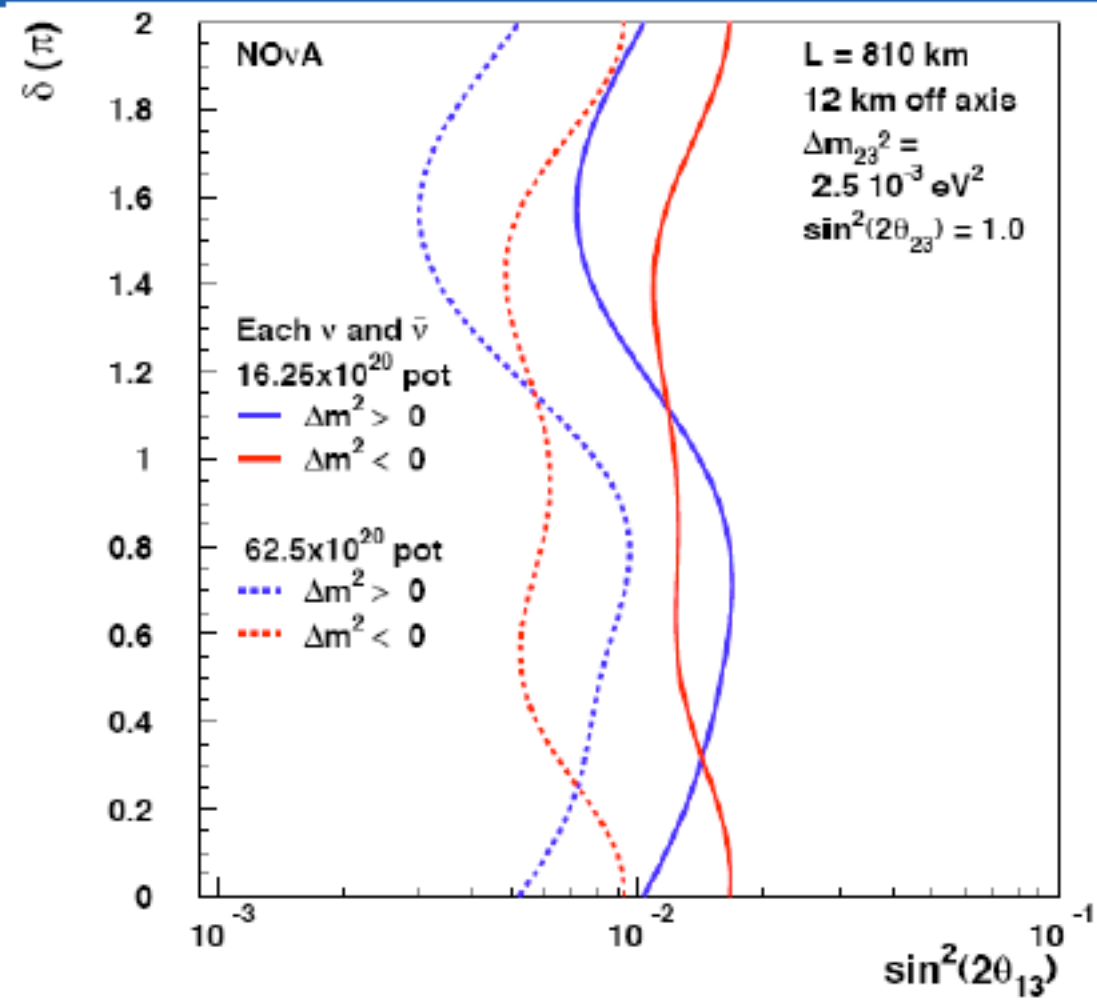
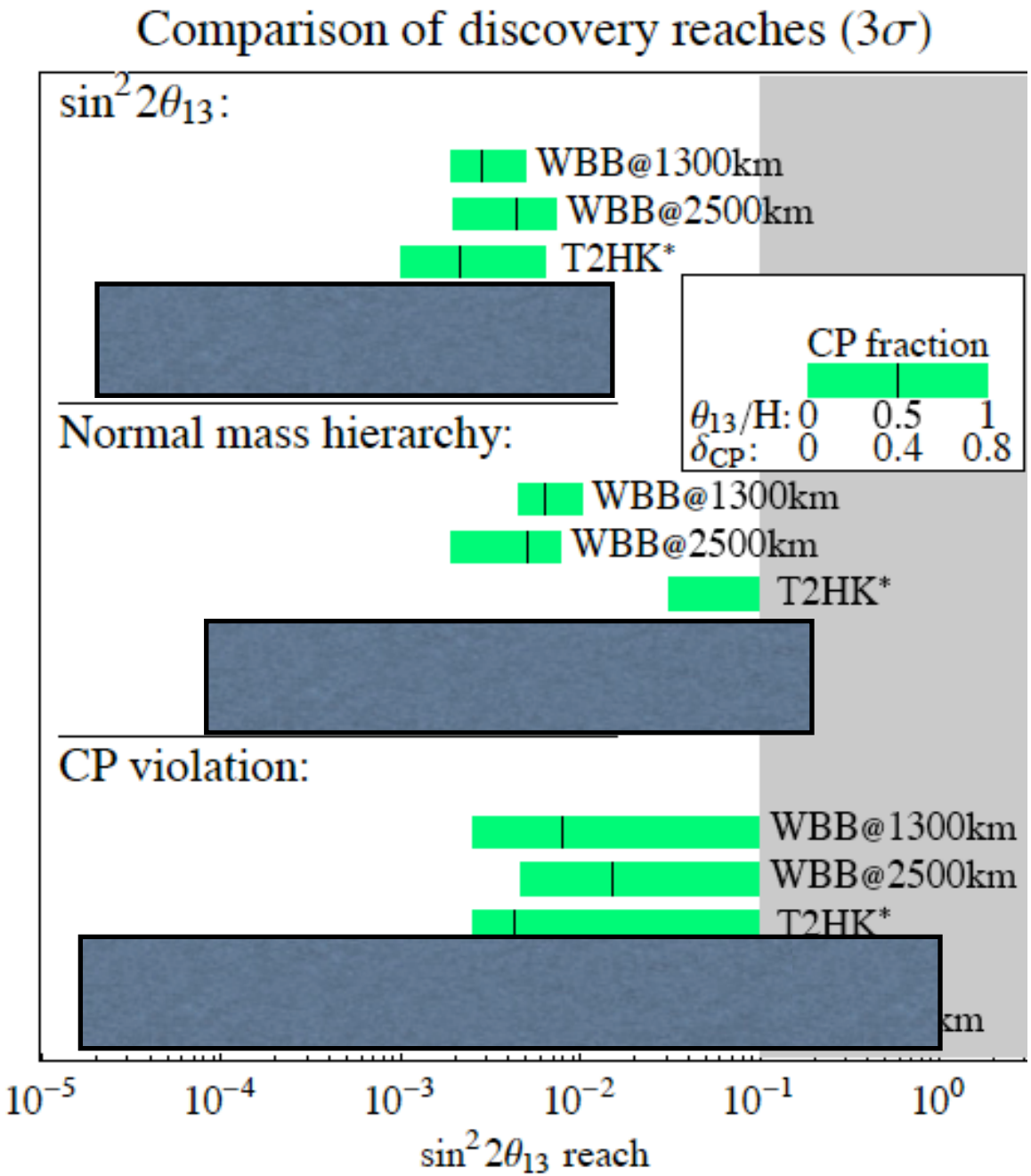


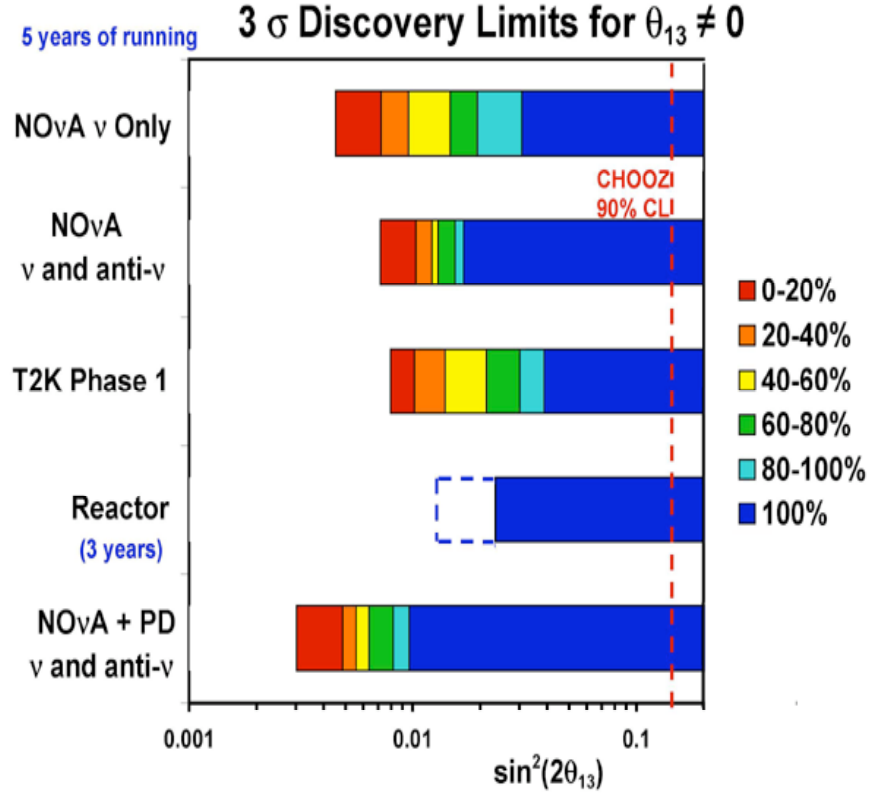
Figure 7: *90% confidence level error contours in* $\sin^2 2\theta_{13}$ *versus* δ_{CP} *for statistical and systematic errors for 32 test points. This simulation is for combining both neutrino and anti-neutrino data. Left is for BNL-HS and right is for FNAL-HS. We assume 10% systematic errors for this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

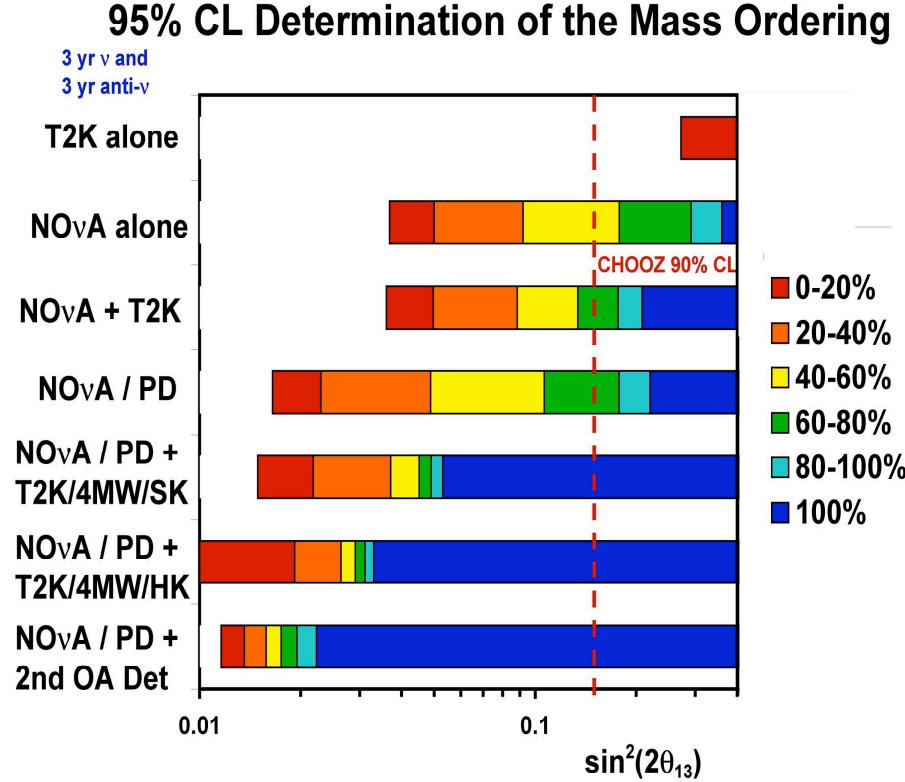
3 σ Sensitivity to $\theta_{13} \neq 0$
Comparison with Proton Driver



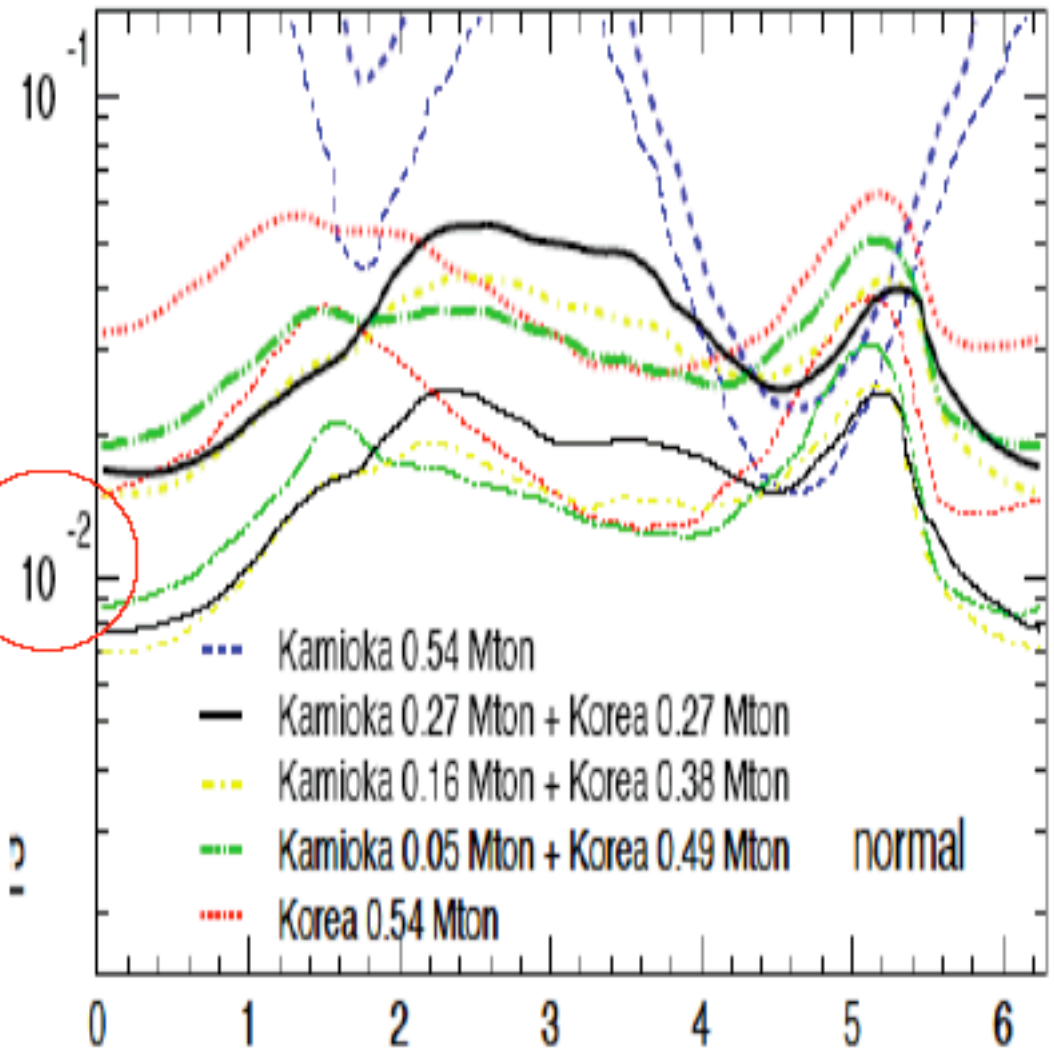
2.5 yr each ν and $\bar{\nu}$ run


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

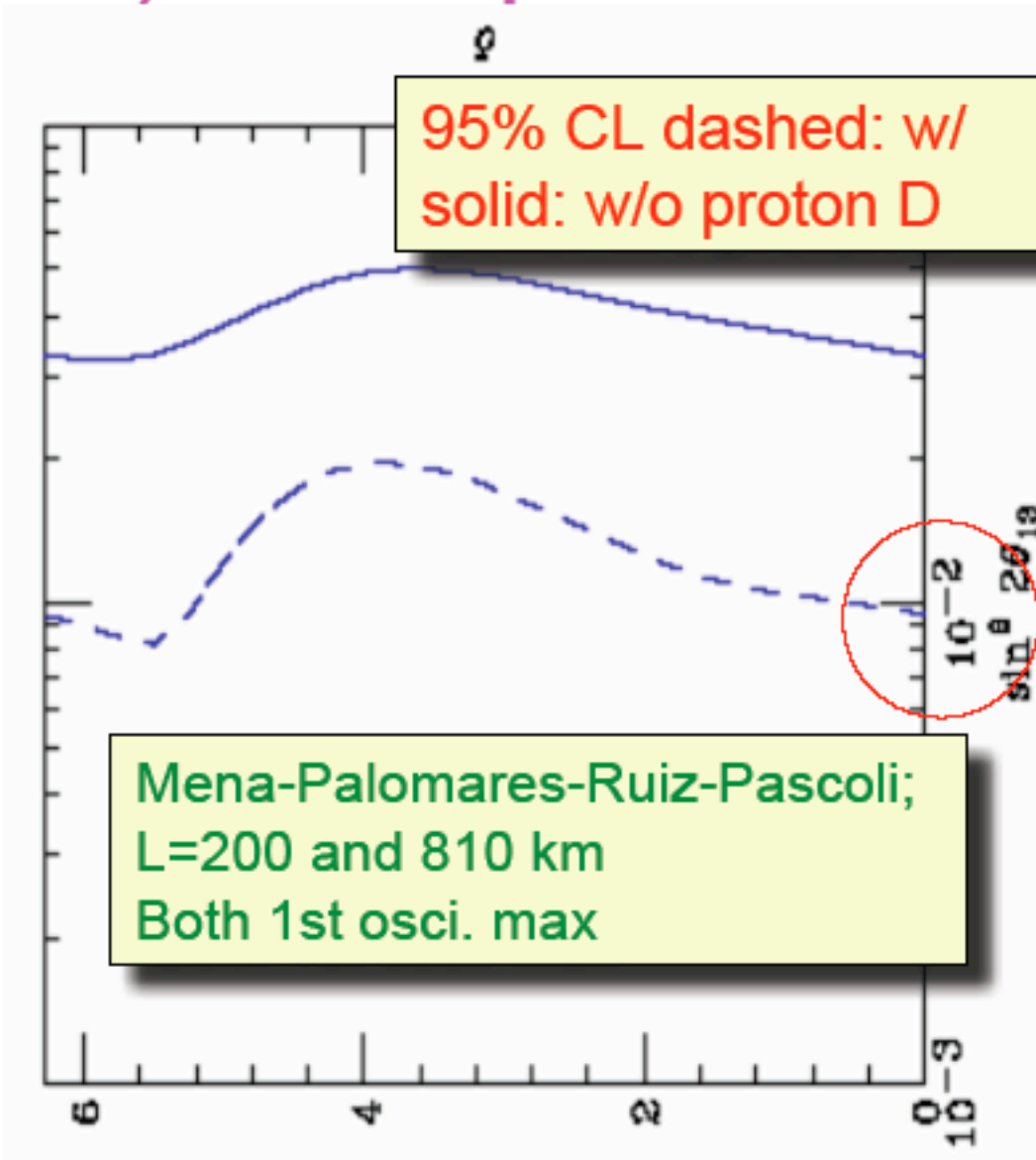

5 years of running
3 σ Discovery Limits for $\theta_{13} \neq 0$
NOvA ν Only
NOvA ν and anti-ν
T2K Phase 1
Reactor (3 years)
NOvA + PD ν and anti-ν
CHOOZ 90% CL
0-20%
20-40%
40-60%
60-80%
80-100%
100%
0.001
0.01
0.1
$\sin^2(2\theta_{13})$


95% CL Determination of the Mass Ordering
3 yr ν and 3 yr anti-ν
T2K alone
NOvA alone
NOvA + T2K
NOvA / PD
NOvA / PD + T2K/4MW/SK
NOvA / PD + T2K/4MW/HK
NOvA / PD + 2nd OA Det
CHOOZ 90% CL
0-20%
20-40%
40-60%
60-80%
80-100%
100%
0.01
0.1
$\sin^2(2\theta_{13})$

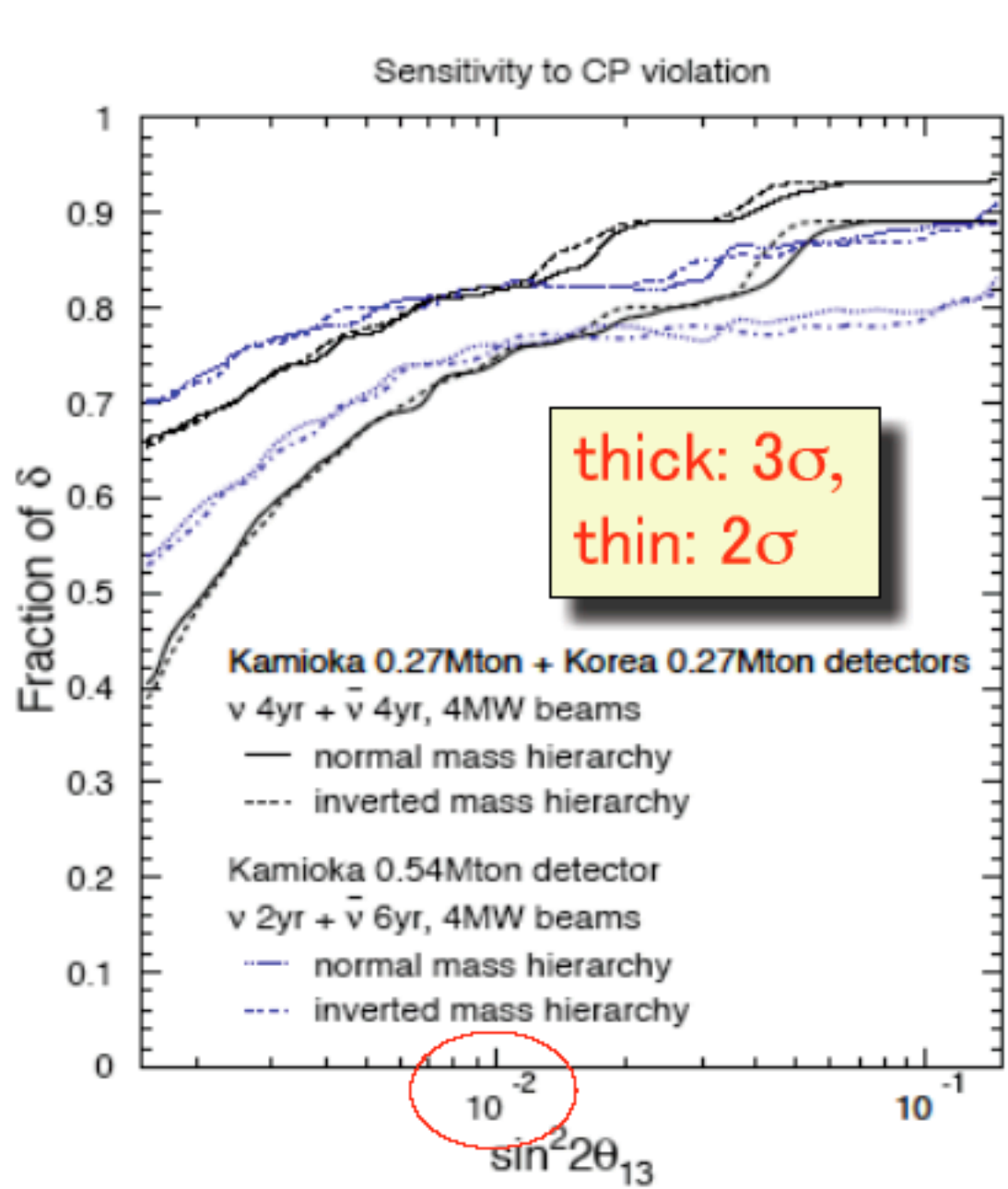
Sensitivity to mass hierarchy: T2K-II vs. (Kam+Korea) vs. super-Nνa

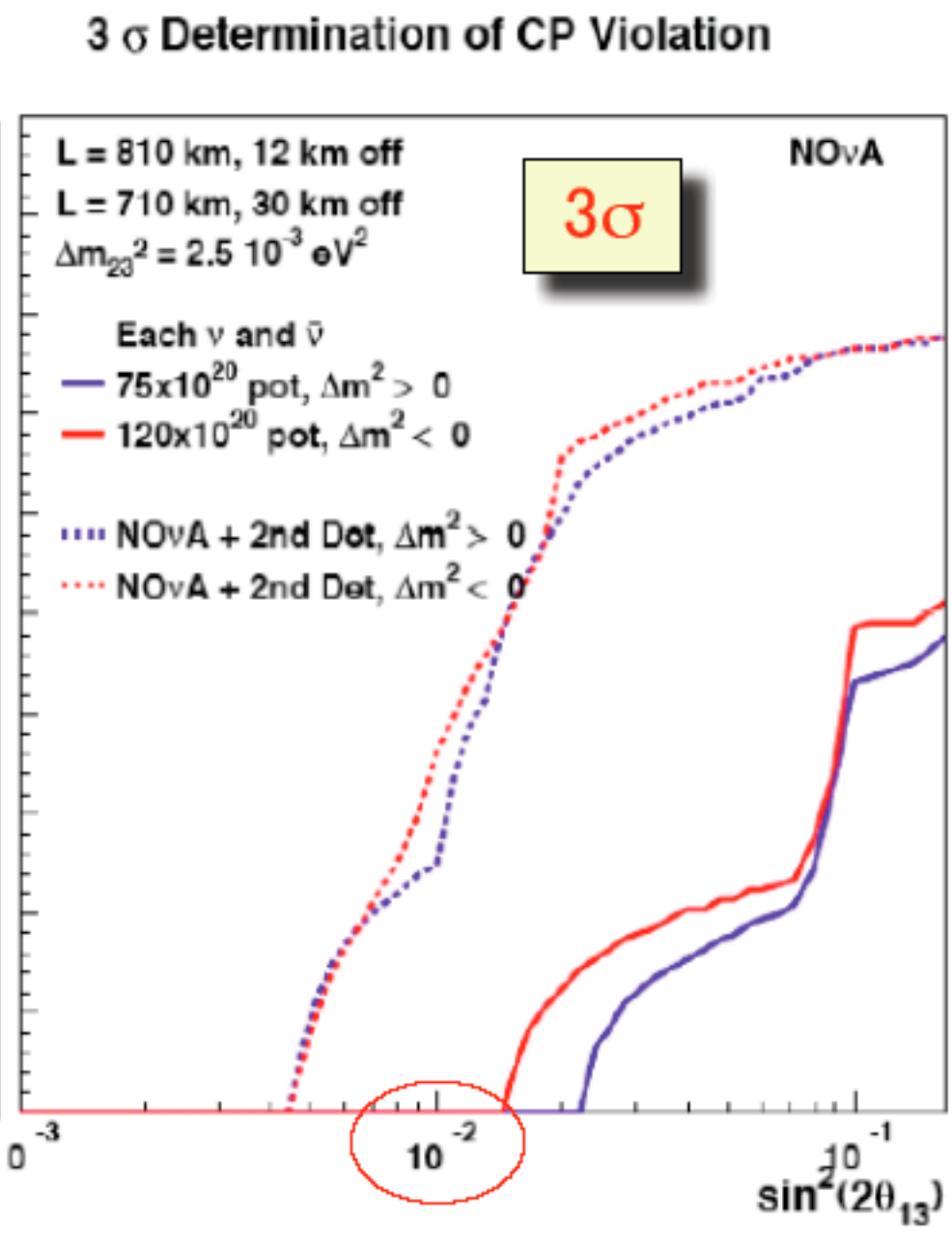


thick: 3σ,
thin: 2σ



Sensitivity to CP: T2K-II vs. (Kam+Korea) vs. Nνa





What needs to be examined for LOI

- 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.