Very long baselines with a superbeam

Milind Diwan

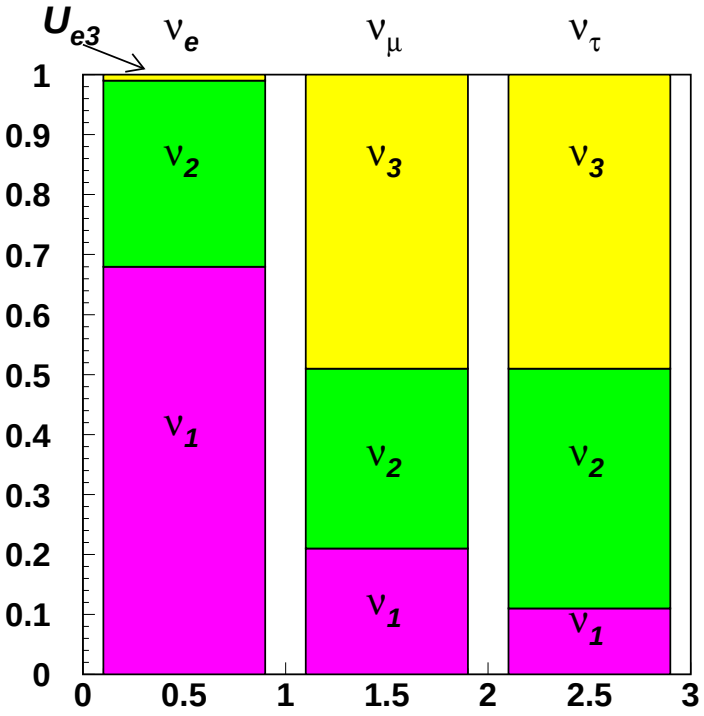
FOR BNL Neutrino Working Group.

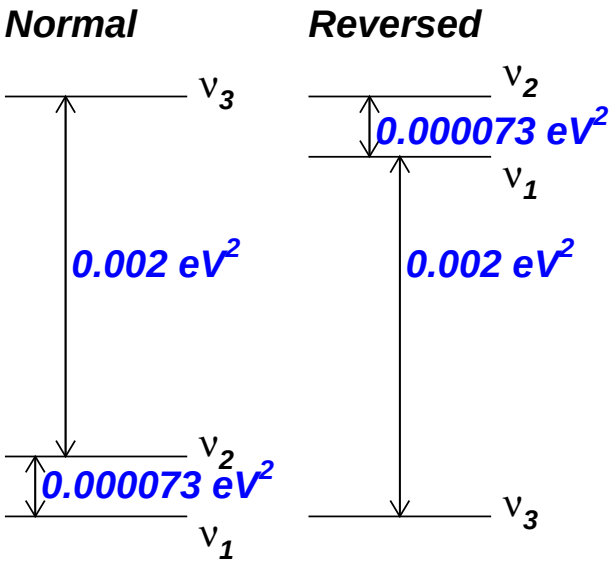
December 1, 2003

University of California, Los Angeles

Wide Band Conventional Beam from BNL to the Homestake Laboratory.

Big Picture





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

Neutrino Physics so far

- Evidence for Neutrino flavor change
  - Atmospheric neutrinos: SuperK
  - Solar: SNO, All previous radio-chemical measurements.
  - KamLAND: Confirm the solar LMA solution.
  - Limits on parameters from many accelerator and reactor exp.
  - LSND: To be addressed by mini-boone.
- Direct Neutrino mass
  - Oscillations: Neutrinos definitely have mass.
  - Tritium beta-decay: < 2.8 eV.
  - Double beta decay: mass < 0.3 eV if Majorana.
  - Astrophysics: Large Scale Structure < 1 eV.
- Number of Neutrinos
  - Z width: 2.981 ± 0.008 active types
  - Limits on sterile neutrinos from solar, atmospheric results.
  - Big Bang Nucleosynthesis: 3 active neutrinos.

Neutrino Physics: Oscillations

Assume a 2×2 neutrino mixing matrix.

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad (1)$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \rightarrow \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned} \quad (2)$$

Sufficient to understand most of the physics:

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

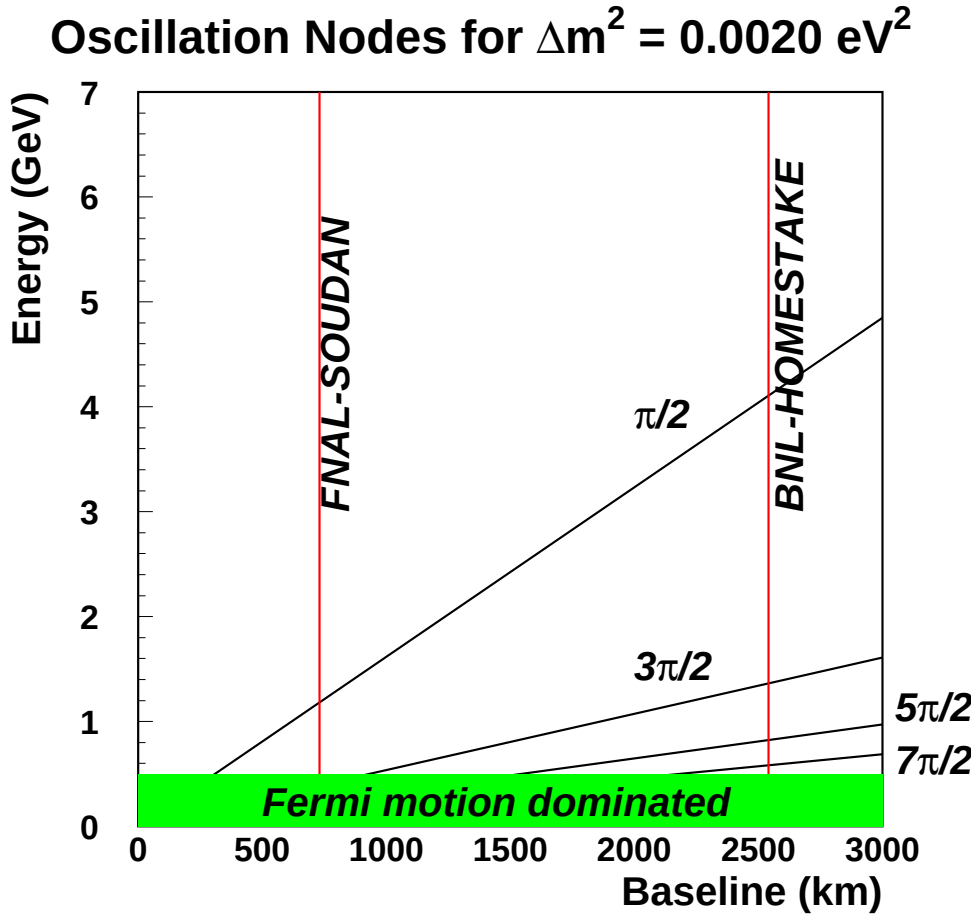
$$P(\nu_a \rightarrow \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, ...$ $(\pi/2)$:
$\Delta m^2 = 0.002 eV^2$, $E = 1 GeV$, $L = 618 km$.

Very long baselines with a superbeam

Matter Effect

Milind Diwan



- Large effects: Multiple oscillation nodes.
- Low cross section at low energies
- Fermi motion limits resolution at low energies: wide band beam ($0.5 \rightarrow 8$ GeV).
- $\Delta m^2 \approx 0.002 eV^2$: Baseline > 2000 km.

Neutrino Physics: 3×3 Formulation

Bill Marciano, hep-ph/0108181

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{4}$$

Neutrino Physics: the difficult stuff

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \quad = \quad & 4(s_2^2 s_3^2 c_3^2 + J_{CP} \sin\Delta_{21}) \sin^2 \frac{\Delta_{31}}{2} \\
& +2(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin\Delta_{31} \sin\Delta_{21} \\
& +4(s_1^2 c_1^2 c_2^2 c_3^2 + s_1^4 s_2^2 s_3^2 c_3^2 - 2 s_1^3 s_2 s_3 c_1 c_2 c_3^2 \cos\delta \qquad (5) \\
& \quad - J_{CP} \sin\Delta_{31}) \sin^2 \frac{\Delta_{21}}{2} \\
& +8(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{21}}{2}
\end{aligned}
$$

No matter effects in above formula

$$
\begin{aligned}
\Delta_{31} \quad &\equiv \quad \Delta m^2_{31} L/2E_\nu \\
\Delta_{21} \quad &\equiv \quad \Delta m^2_{21} L/2E_\nu
\end{aligned}
$$

$$J_{CP} \equiv s_1 s_2 s_3 c_1 c_2 c_3^2 \sin\delta \tag{6}$$

$$A \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \tag{7}$$

To leading order in Δ_{21} (assumed to be small), one finds

$$P(\nu_\mu \to \nu_e) \simeq 4 s_2^2 s_3^2 c_3^2 \sin^2 \frac{\Delta_{31}}{2} + \mathcal{O}(\Delta_{21})$$

$$A \simeq \frac{J_{CP} \sin\Delta_{21}}{s_2^2 s_3^2 c_3^2} \simeq \frac{2 s_1 c_1 c_2 \sin\delta}{s_2 s_3} \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2}\right) \frac{\Delta m_{31}^2 L}{4E_\nu} + \mathcal{O}(\Delta_{21}^2)$$

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

Approximate formula (Lindener, Huber et al.)

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

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

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

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

$$\hat{A} = 2VE/\Delta m^2_{31}$$

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}

Some Observations

If performing an appearance experiment ($\nu_\mu \rightarrow \nu_e$) or ($\nu_e \rightarrow \nu_\mu$) around $\pi/2$ node then

a) Difficult to avoid matter effect at accelerator energies.

b) Any reasonble accelerator based experimental setup has sizable contribution from all 4 effects

Matter effect or mass hierarchy

θ_{13}

δ_{CP}

Δm^2_{21}

c) To distentangle must have several data points on the oscillation curve (different L or E).

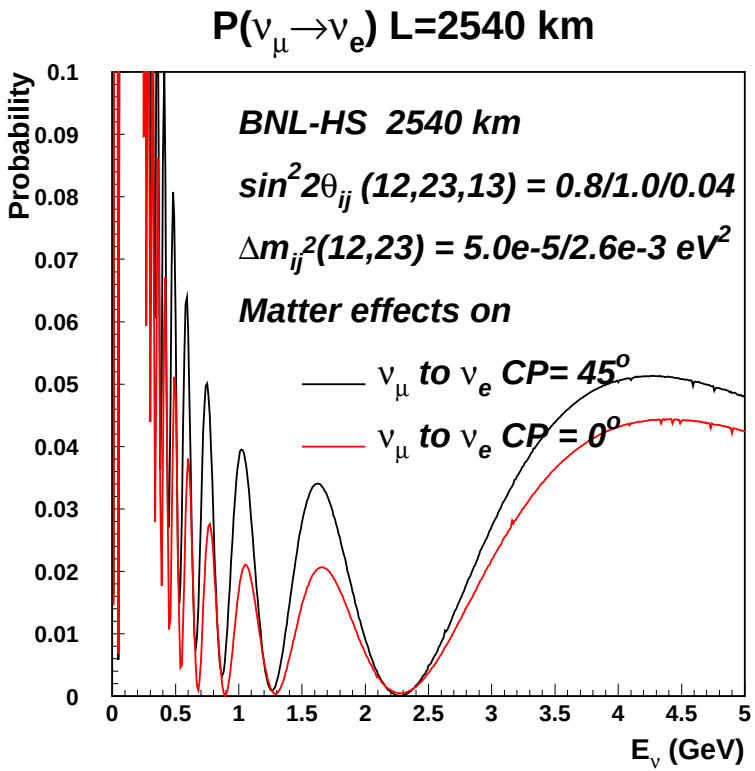
Scaling Laws for CP Measurement

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}.
- $R_{CP} \propto \Delta m^2_{21}$. Better CP resolution for higher Δm^2_{21}.
- For given resolution on δ_{CP} detector size is independent of L.

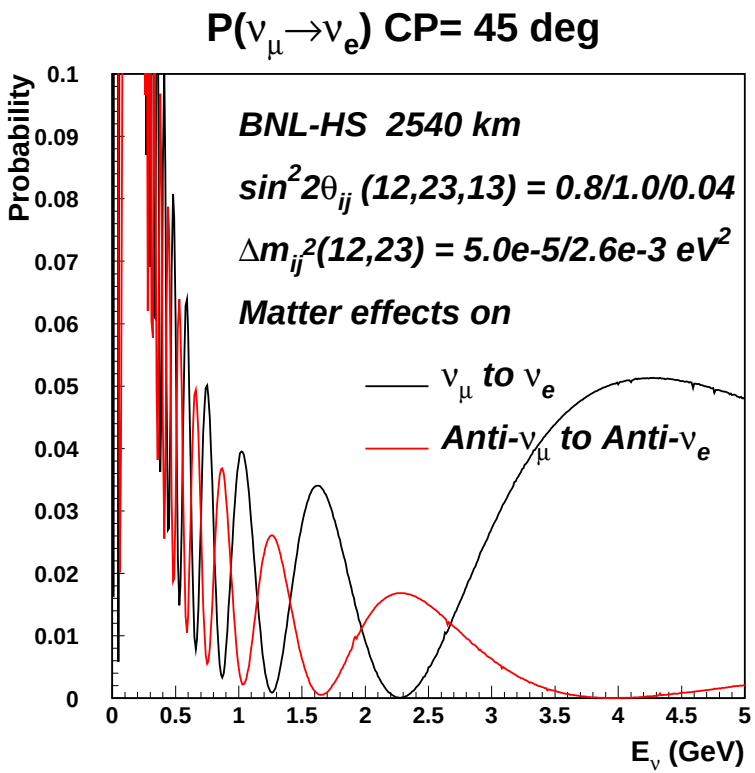


General Features

- $0.5-1$ GeV: Δm^2_{12} (LMA) region.
- $1-3$ GeV: CP large effects region
- $>$ 3 GeV: Matter enhanced (ν_μ), suppressed $(\bar{\nu}_\mu)$. $(\Delta m^2_{32} > 0)$ Region.

Exact numerical calculation

e.g. I. Mocioiu and R. Shrock, Phys. Rev. D62, 053017 (2000), JHEP 0111, 050 (2001)



Compare Neutrino to Antineu.

- $0.5 - 1$ GeV: Δm^2_{12} (LMA) region.
- $1 - 3$ GeV: CP region
- $>$ 3 GeV: Matter enhanced (ν_μ), suppressed $(\bar{\nu}_\mu)$. $(\Delta m^2_{32} > 0)$ Region.

4 GOALS OF NEUTRINO OSCILLATION PHYSICS

- Precise determination of Δm^2_{32} and $\sin^2 2\theta_{23}$and definitive observation of oscillatory behavior.
- Detection of $\nu_\mu \to \nu_e$ in the appearance mode. If $\Delta m^2_{\nu_\mu \to \nu_e} = \Delta m^2_{32}$ then $|U_{e3}|^2 (= \sin^2 \theta_{13})$ is non-zero.
- Detection of the matter enhancement effect in $\nu_\mu \to \nu_e$. Sign of Δm^2_{32}; i.e. which neutrino is heavier.
- Detection of CP violation in neutrino physics. Phase of $|U_{e3}|$ is CP violating and causes asymmetry in the rates $\nu_\mu \to \nu_e$ versus $\bar{\nu}_\mu \to \bar{\nu}_e$.

  It will be good to do it all in same experiment with only neutrino beam (no antineutrino).

Summary of our study

- Baseline of > 2000 km with wide band conventional beams are the next step in accelerator neutrino physics.
- Extraordinary, large physical effects will be seen in such an experiment.
- Very good sensitivity to neutrino properties.
  - $< 1\%$ resolution on Δm^2_{32}
  - $< 1\%$ resolution on $\sin^2 2\theta_{23}$
  - Sensitivity to $\sin^2 2\theta_{13} > 0.005$ over a wide range of Δm^2_{32}
  - Sensitivity to CP violation.
  - Sign of Δm^2_{32} over a wide range of parameters.
  - Measurement of Δm^2_{21} in LMA region.
- Requires new thinking on how to build a beam and a detector. But experiment is technically feasible.

Comments

- Important ideas here are:

  Long baseline to achieve large effects

  Low energy wide band beam to get spectra

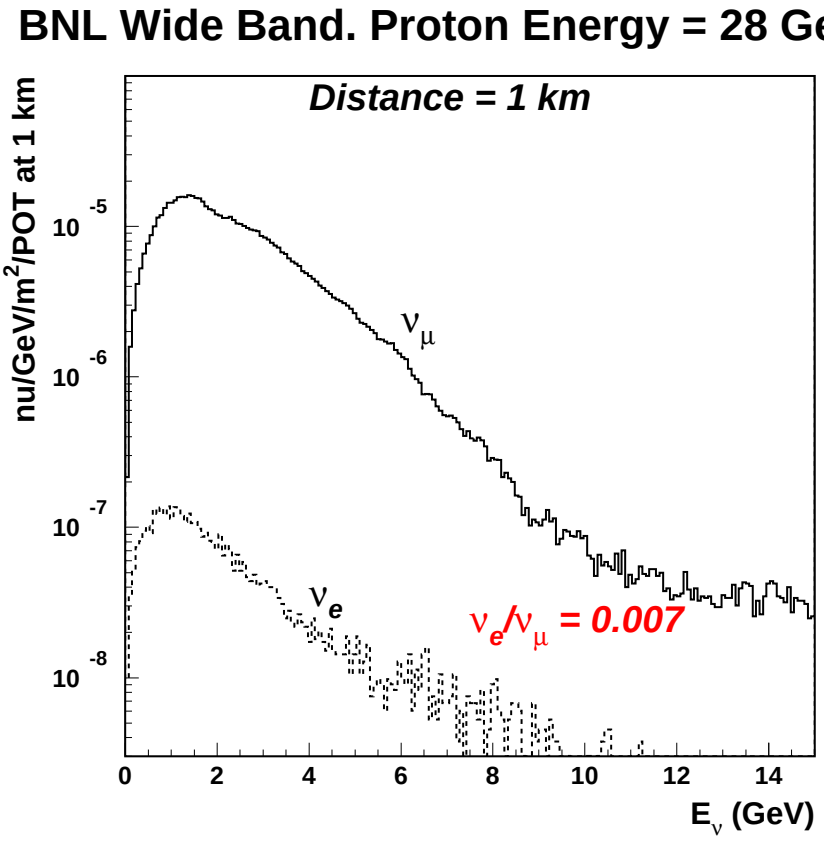
  Beam is wide band, but low energy to make low backgrounds to ν_e appearance signature.

- Important difference between quark-matrix and neutrino-matrix

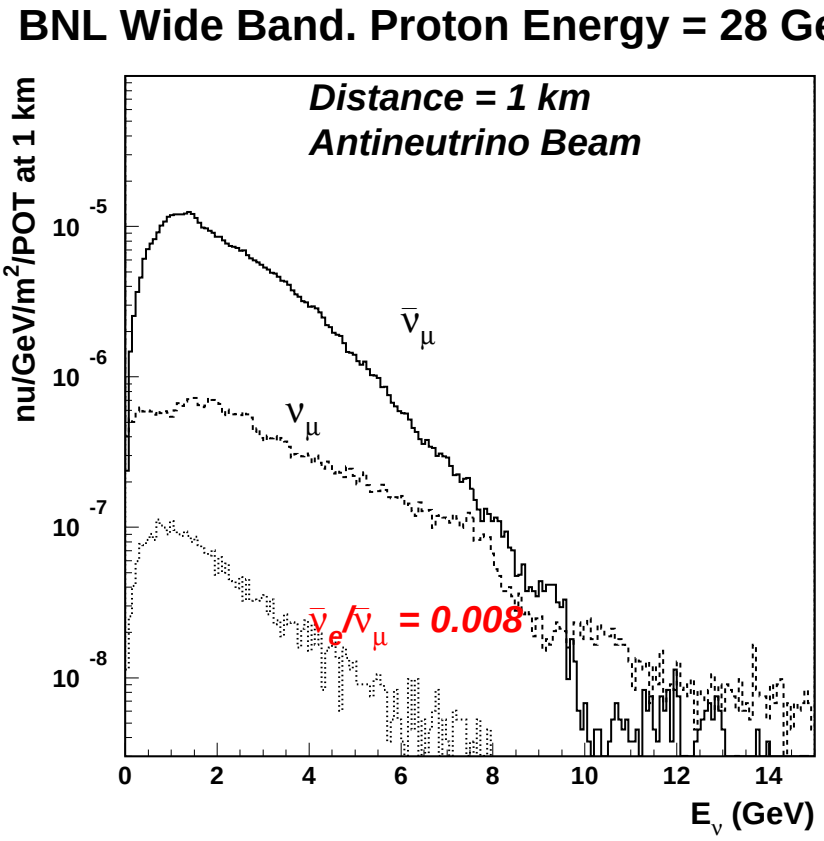
  Neutrino oscillation effects are exactly calculable for any given set of parameters. (including matter)

  For quarks we often need complex tools such as CHPT and Lattice to connect CKM-matrix to physical phenomena.

- It makes sense to make a neutrino oscillation experiment with large effects even if they are sensitive to multiple parameters.



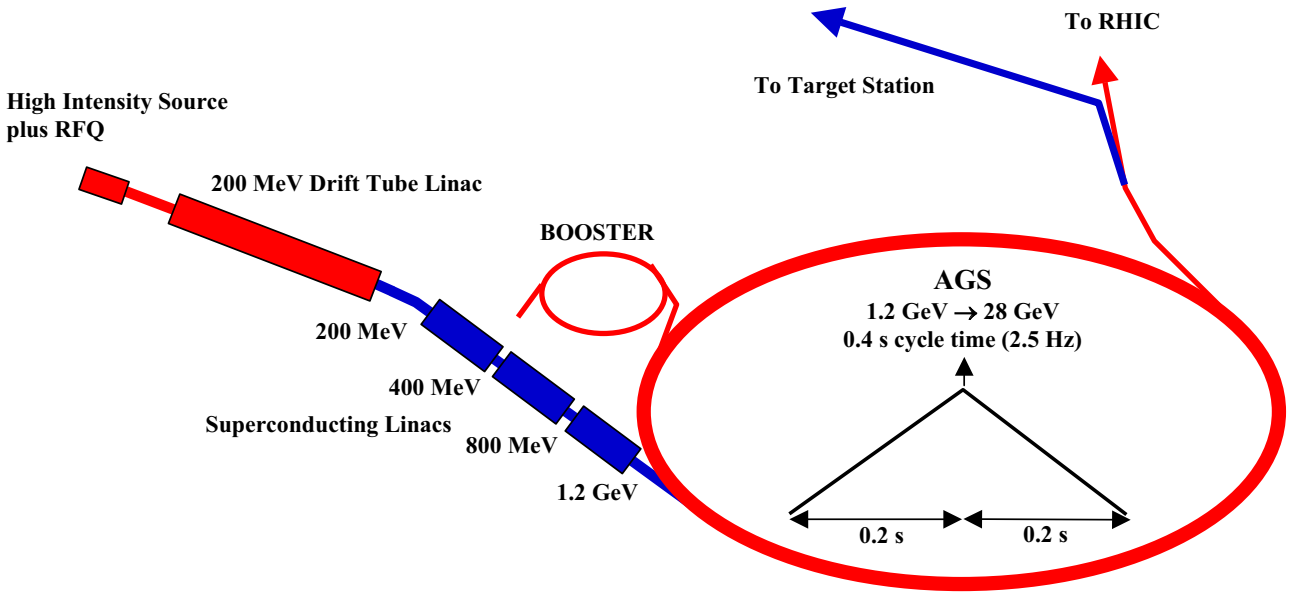
- New design spans 0.5-6 GeV
- Low ν_e background 0.7%
  0.0073 ± 0.0014 (E734 1986).
- Low background from high energies (NC and ν_τ for ν_e)
- 200 m decay tunnel
- Graphite target embedded in horn
- Target cooling achievable for 1 MW



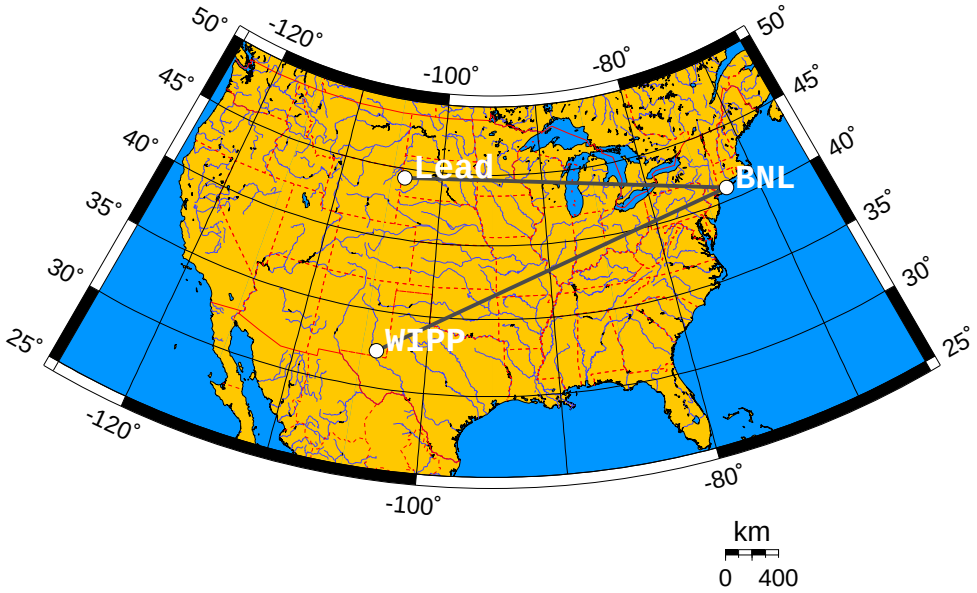
- Antineutrino beam has larger neutrino contamination.
- Will need to go to 2 MW to get statistics equal to neutrino.

The Accelerator

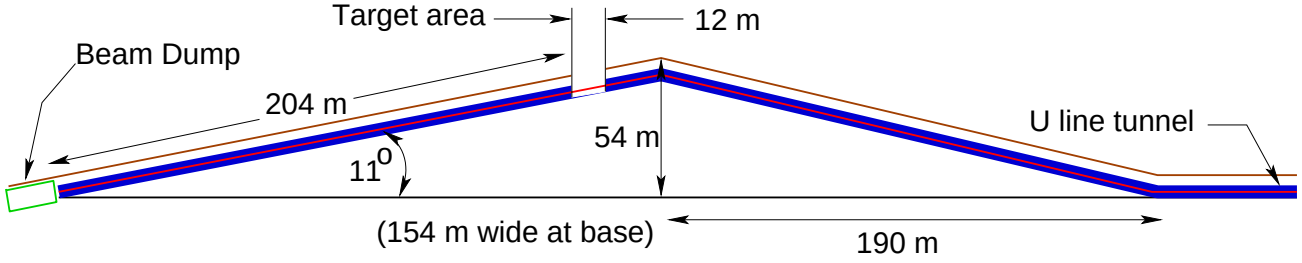
- Conceptually simple upgrade. No magic.
- Run 28 GeV AGS at 2.5 Hz to get 1 MW.
- Need faster proton source: Super Conducting LINAC at 1.2 GeV
- Current: $7 \times 10^{13} ppp$ at 0.5 Hz => LINAC: $10^{14} ppp$ at 2.5 Hz.



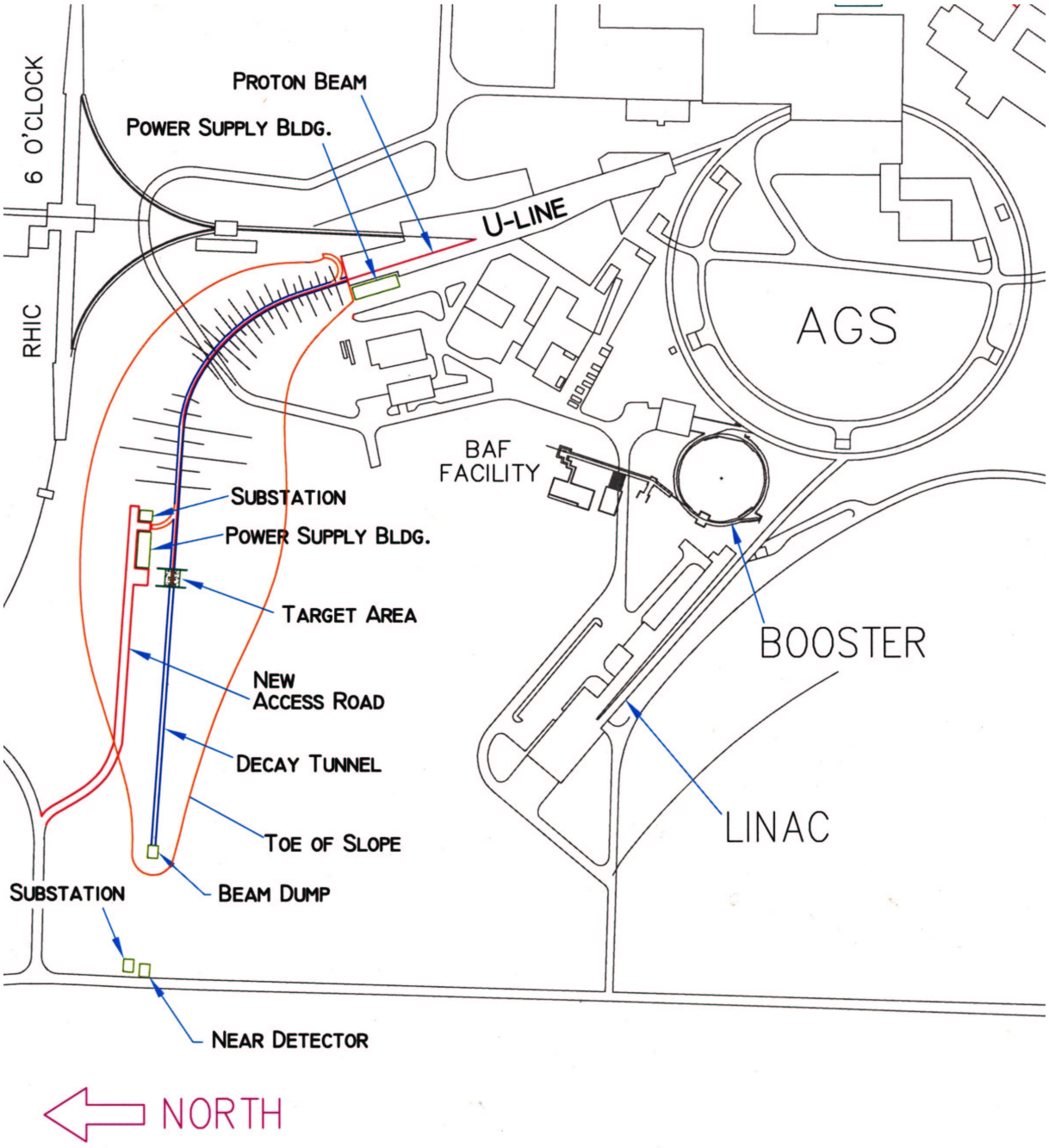
Beam on the Hill



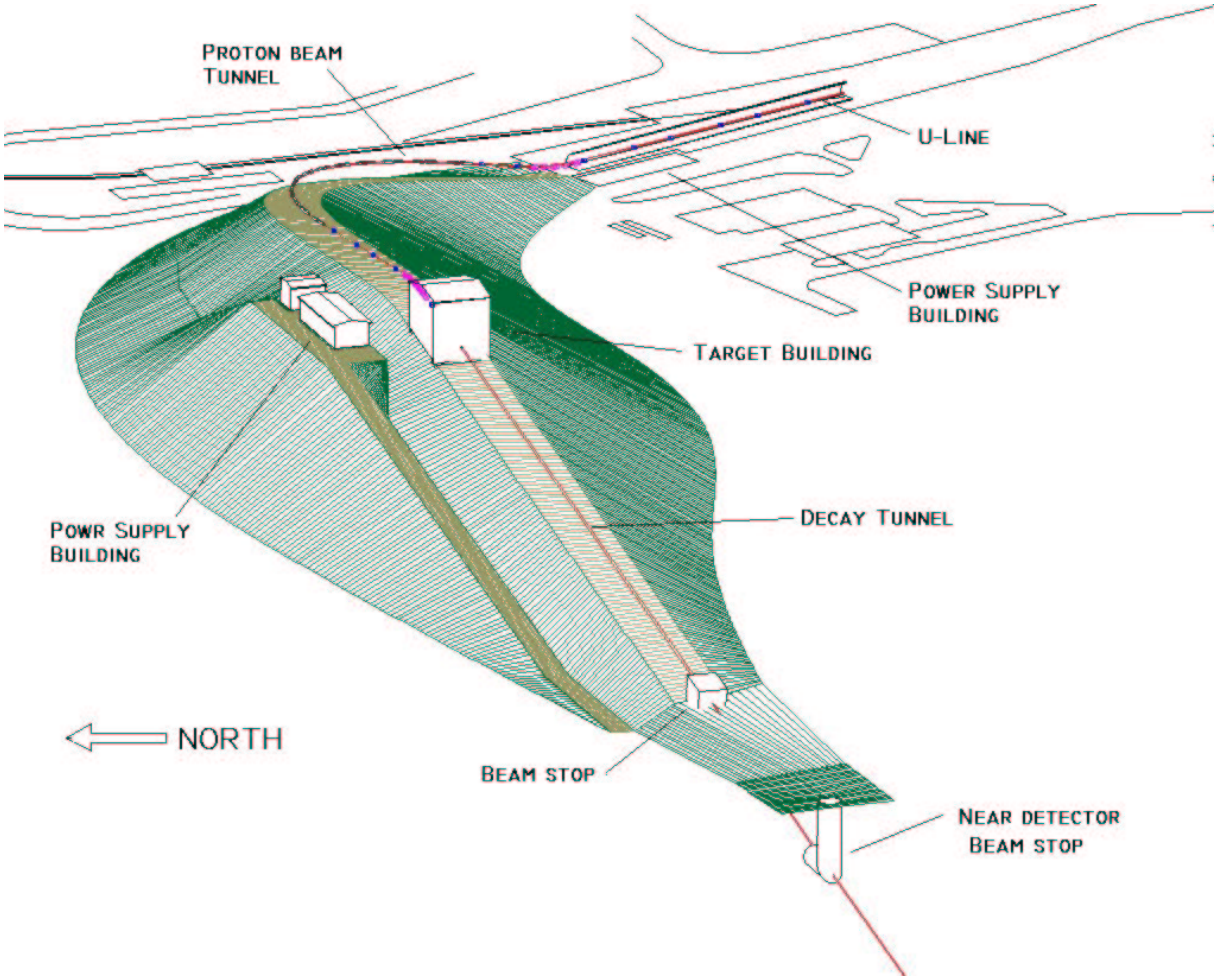
- BNL-Lead 2540km
  BNL-Wipp: 2880km
- Avoids water table.
- Hills are inexpensive: highway ramps.



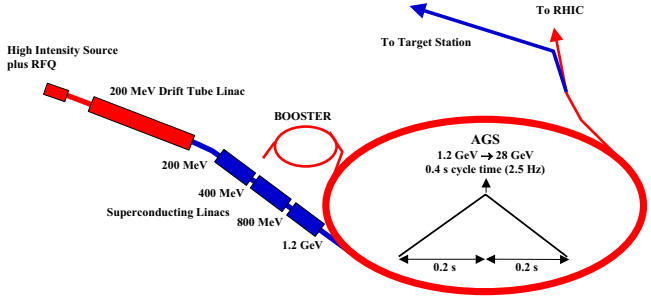
Beam Layout

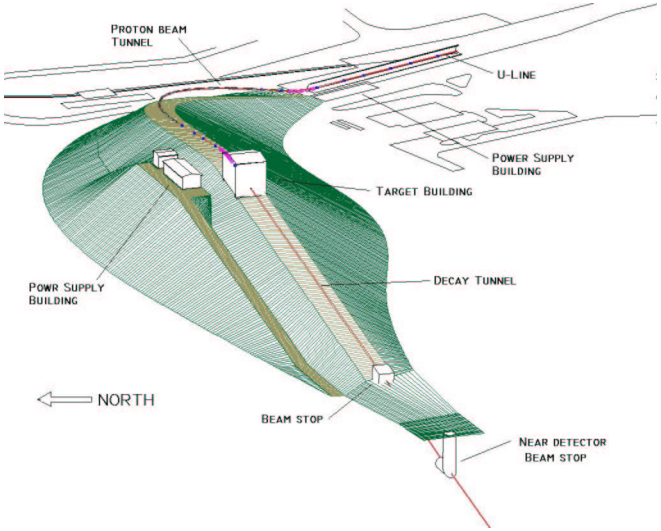

6 O'CLOCK
RHIC
PROTON BEAM
POWER SUPPLY BLDG.
U-LINE
AGS
BAF
FACILITY
SUBSTATION
POWER SUPPLY BLDG.
TARGET AREA
NEW
ACCESS ROAD
DECAY TUNNEL
TOE OF SLOPE
BEAM DUMP
BOOSTER
LINAC
SUBSTATION
NEAR DETECTOR
NORTH

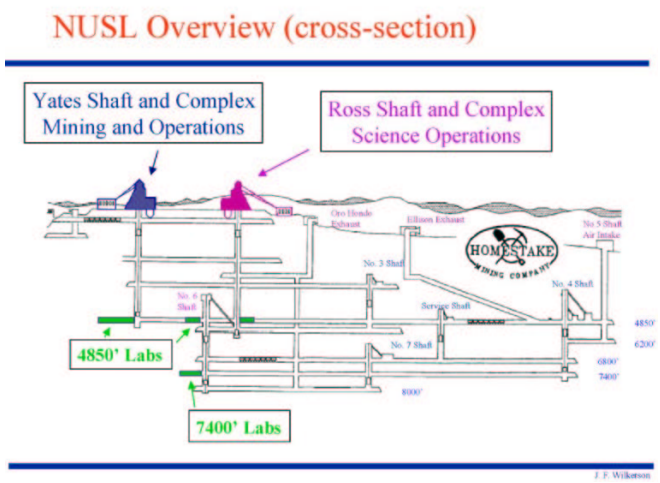
Beam 3d

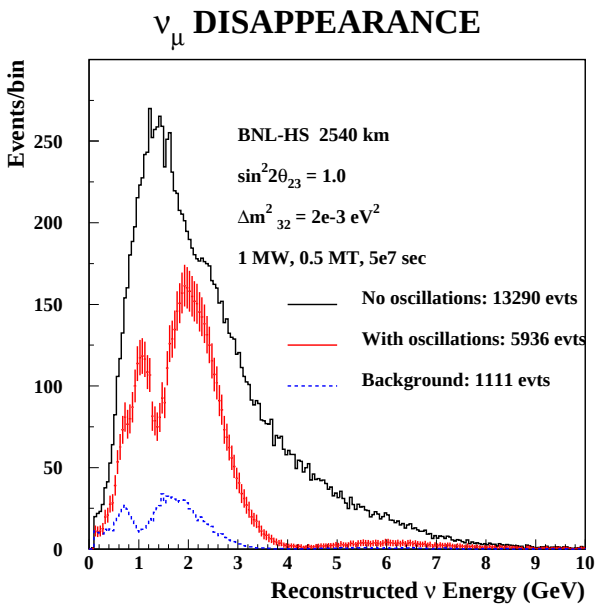

PROTON BEAM TUNNEL
U-LINE
POWER SUPPLY BUILDING
TARGET BUILDING
DECAY TUNNEL
POWR SUPPLY BUILDING
NORTH
BEAM STOP
NEAR DETECTOR BEAM STOP

1 MW beam - 2540 km - 500 kT detector









Very long baselines with a superbeam

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Event Rates with Neutrinos

Assume 1 MW, 500 kT Fiducial, 5×10^7 sec running. (1.22×10^{22} Protons at 28 GeV.)

Assume Water Cerenkov detector.

CC $\nu_\mu + N \to \mu^- + X$	51800 (15160)
NC $\nu_\mu + N \to \nu_\mu + X$	16908 (5770)
CC $\nu_e + N \to e^- + X$	380 (103)
QE $\nu_\mu + n \to \mu^- + p$	11767 (5934)
QE $\nu_e + n \to e^- + p$	84 (40)
CC $\nu_\mu + N \to \mu^- + \pi^+ + N$	14574 (4200)
NC $\nu_\mu + N \to \nu_\mu + N + \pi^0$	3178 (1156)
NC $\nu_\mu + O^{16} \to \nu_\mu + O^{16} + \pi^0$	574 (202)
CC $\nu_\tau + N \to \tau^- + X$ (depends on Δm^2)	$\sim$ 110 (20)

Backgrounds to clean (QE) events SMALL

NC dominated by elastic and single π.

Low τ production.

Anti-neutrino rate in (brackets) for 1 MW. Neutrino contamination additional.

Neutral Current Events Neutrinos

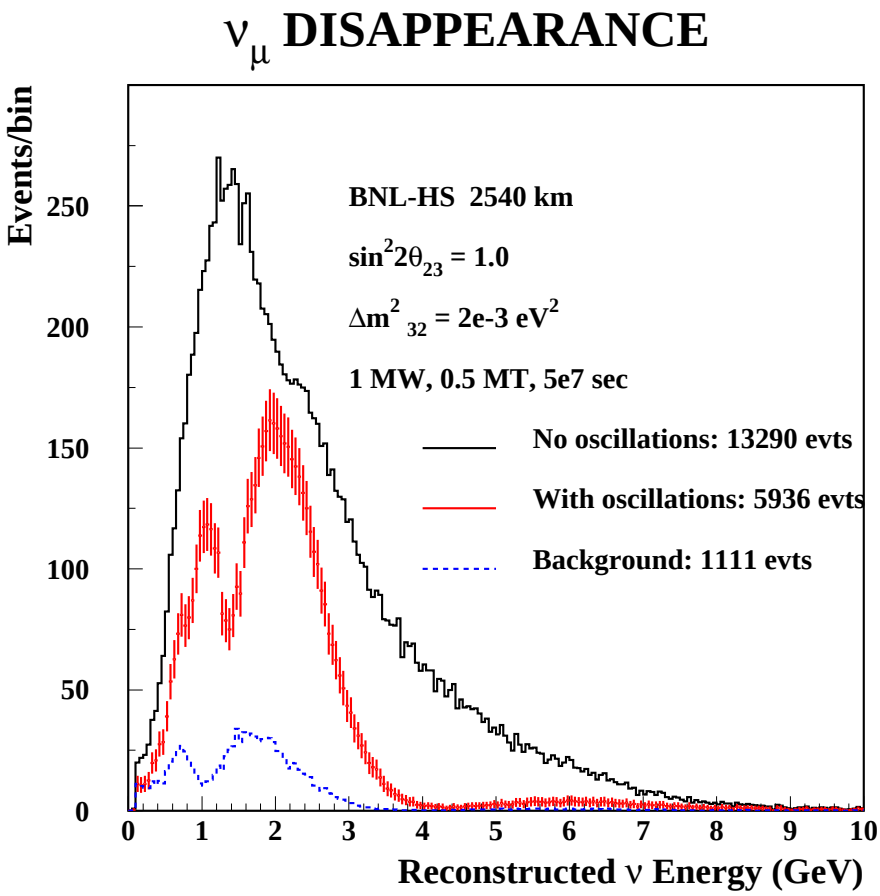
Assume 1 MW, 500 kT Fiducial, 5×10^7 sec running. (1.22×10^{22} Protons at 28 GeV.)

Assume Water Cerenkov detector (with ∼10% PMT coverage)

NC $\nu_\mu + N \rightarrow \nu_\mu + X$	16908
Single π^0	3700
Single $\pi^\pm$	3500
$\nu + n \rightarrow \nu + n$	2000
$\nu + p \rightarrow \nu + p$	2000
Multi-pi (0 π^0)	2900
Multi-pi ($\geq$ 1 π^0)	2900

Multiple pion events should be suppressed better than single π^0 events.

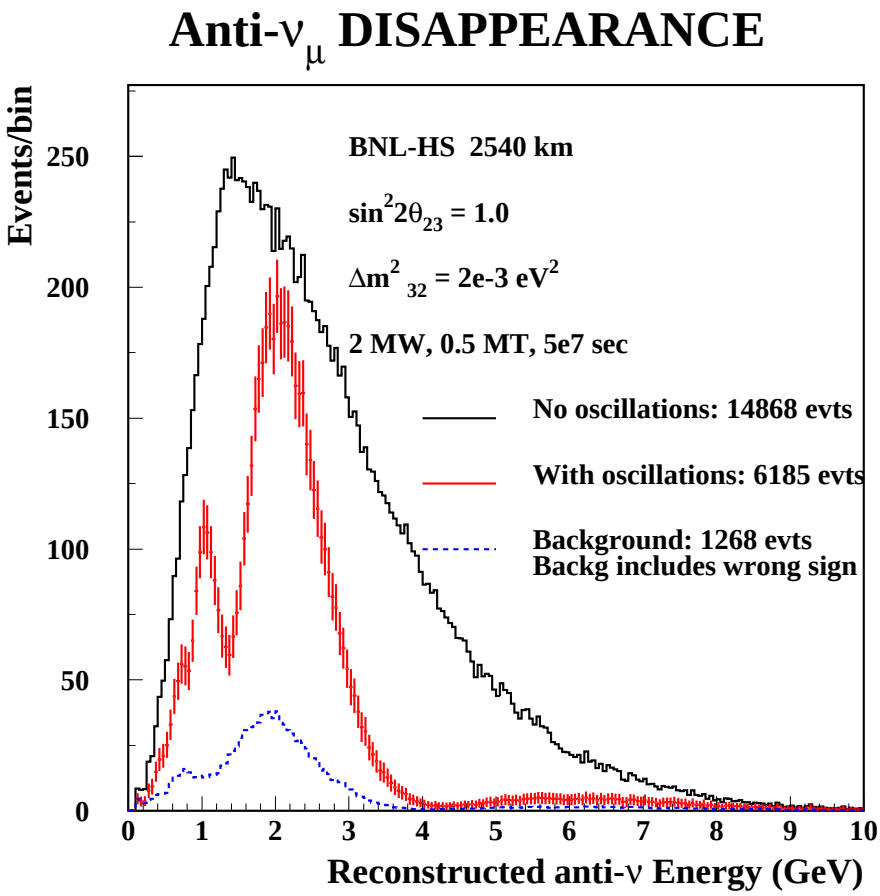
Both single and multi-pi event rate display the same tendency to fall rapidly with energy.



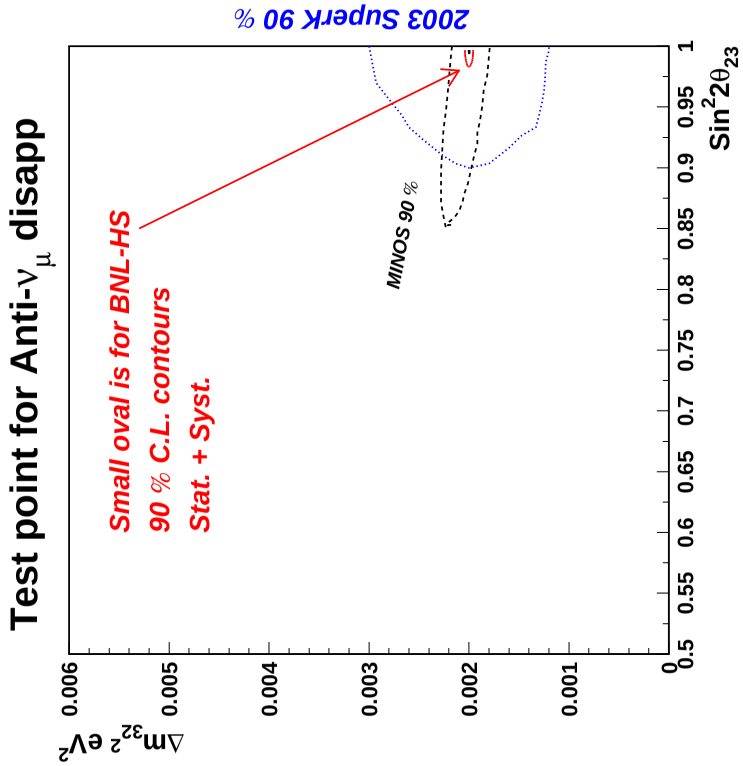
Node pattern provides high Δm^2_{32} resolution.
Energy calibration is very important.

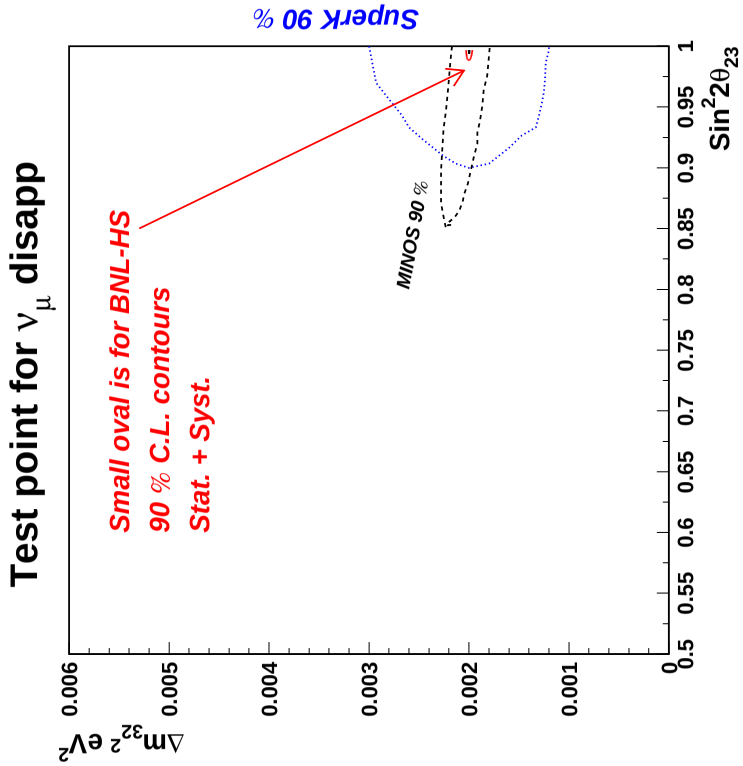
Flux normalization not important for measurement of $\sin^2 2\theta_{23}$

Background shape can be measured independently
Minimum systematics in ν_μ and $\bar{\nu}_\mu$ comparison



For anti-neutrinos low energy nodes have less statistics because of cross section.

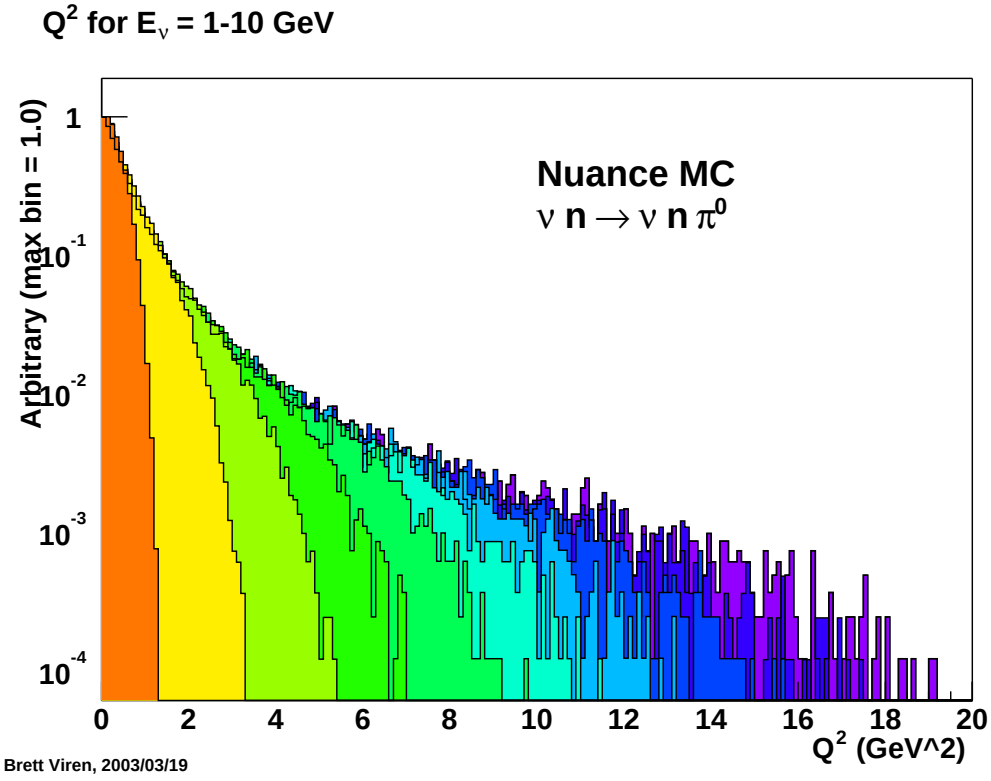

Test point for Anti-ν_μ disapp
Small oval is for BNL-HS
90 % C.L. contours
Stat. + Syst.
MINOS 90 %
2003 Superk 90 %
Δm^2_{32} eV^2
$Sin^2 2\theta_{23}$


Test point for ν_μ disapp
Small oval is for BNL-HS
90 % C.L. contours
Stat. + Syst.
MINOS 90 %
Superk 90 %
Δm^2_{32} eV^2
$Sin^2 2\theta_{23}$

Measurement of Δm^2_{32}

- Little dependence on systematic errors on resolution, backgrounds, energy linearity, or normalization.
- Ultimate resolution on Δm^2 depends on energy calibration. For perfect energy calibration $\pm 0.7\%$ possible.
- Energy calibration at $< 1\%$ in 1-5 GeV region needed.
- Can exclude $\sin^2 2\theta_{23} < 0.99$ at 90% C.L. Could be better with accurate background subtraction.
- No need of near detector for this measurement. Even a 10% systematic error on normalization does not bother measurement.
- neutrino-antineutrino comparison free of most systematics (even cross section) because of nodal pattern. Possible to measure difference in Δm^2_{32} of $< 1\%$.

NC π^0 background for $\nu_\mu \rightarrow \nu_e$

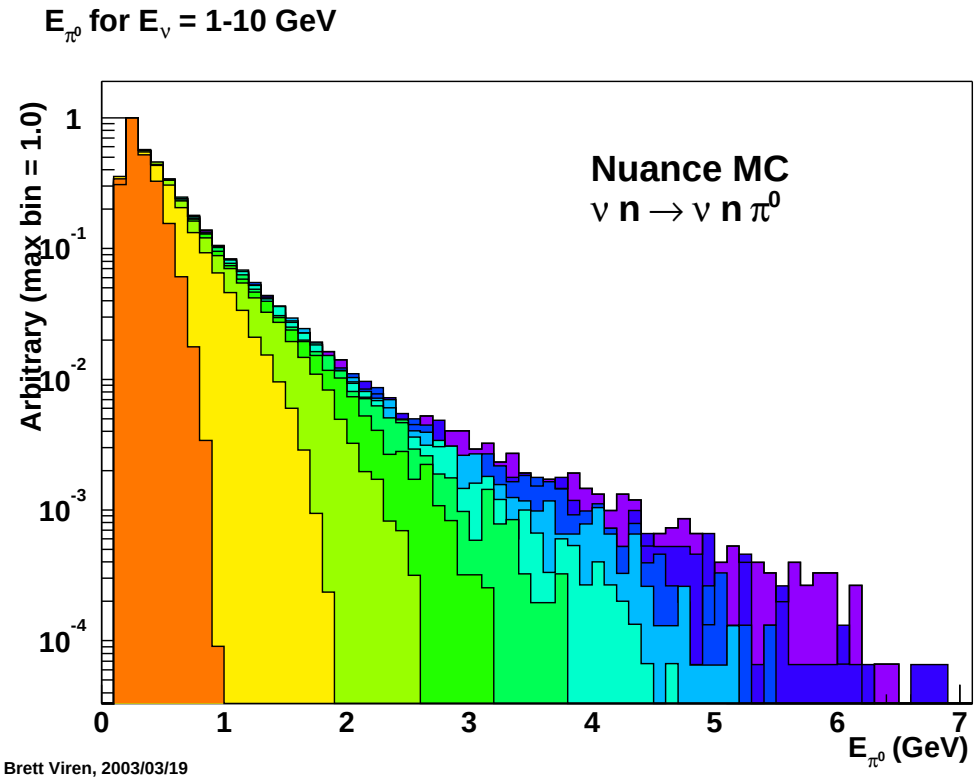


$$q^2 = (p'_N + p'_\pi) - p_N .$$

General feature of all neutral current processes:

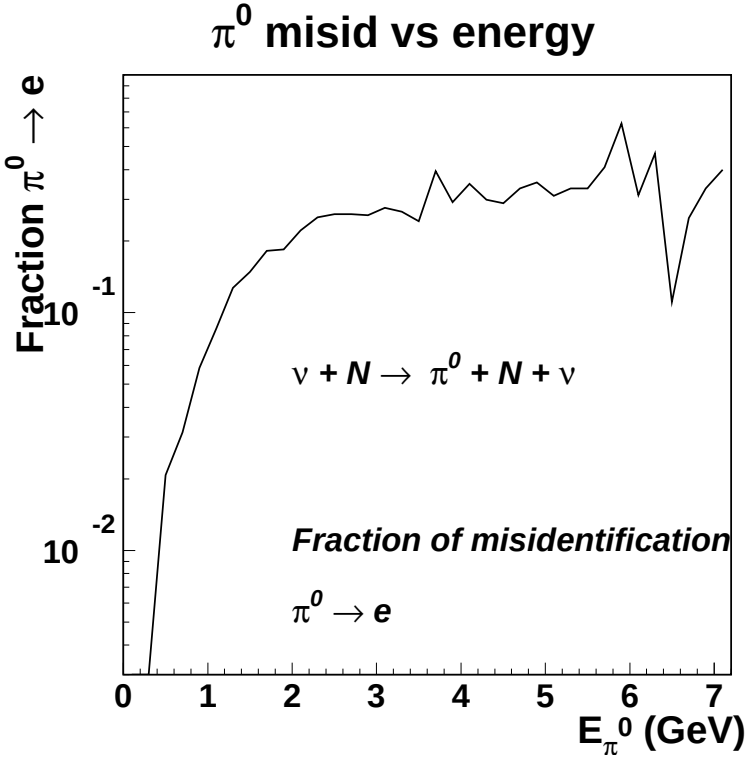
Low q^2 or low hadronic energy in final state independent of neutrino energy.

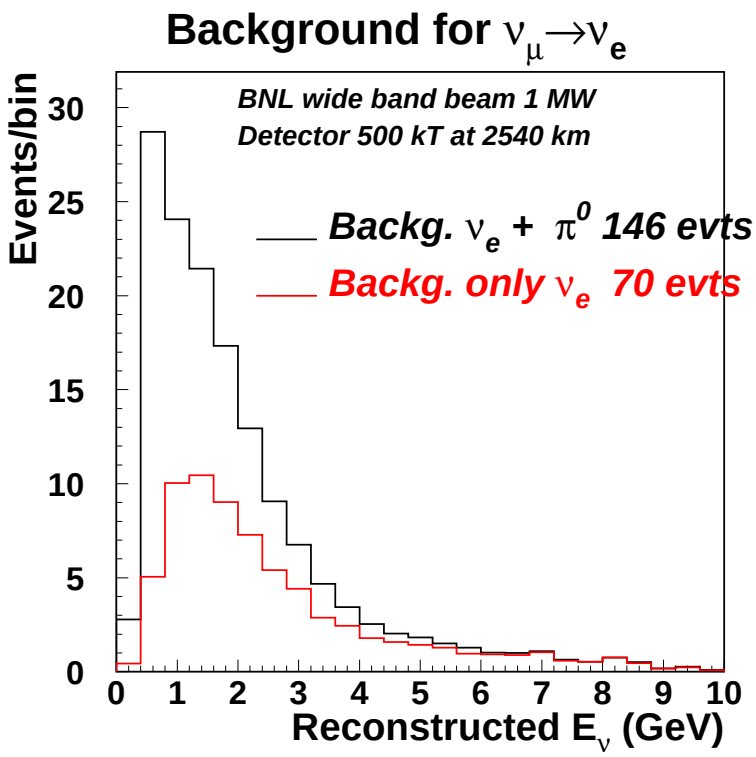
NC π^0 background for $\nu_\mu \rightarrow \nu_e$



- The NC energy distribution is independent of ν-energy except the kinematic limit.
- In $\nu_\mu N \rightarrow \nu_\mu N \pi^0$ events all energy ν produce peak at the same energy except the tail.
- For a very long baselines and wide band beam ν_e signal will be above 3 GeV with little π^0 background.

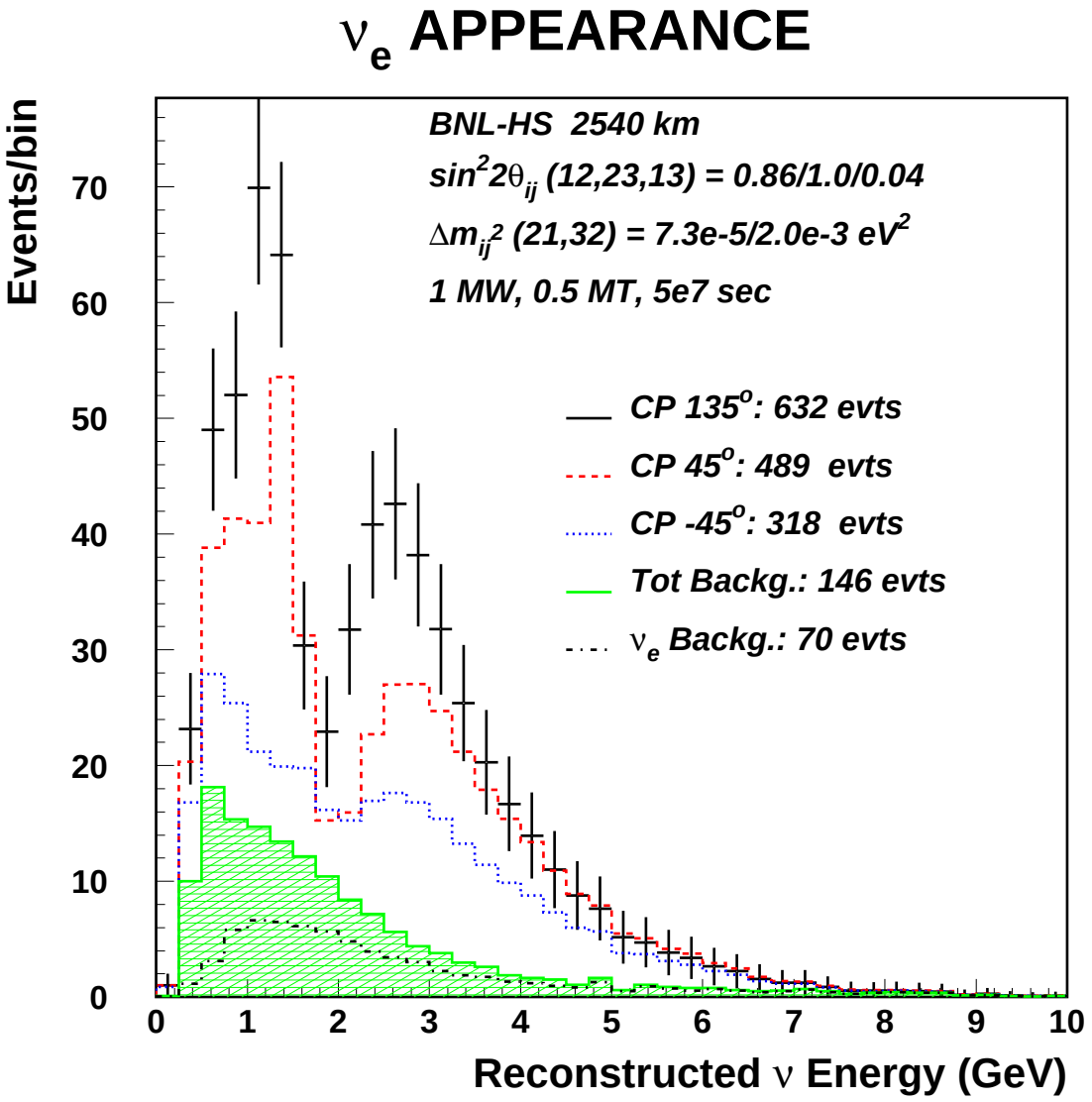
$\nu_\mu \rightarrow \nu_e$ All background





- Background includes $\nu N \pi^0$ and Coherent $\nu O^{16} \pi^0$.
- Efficiency for signal is $\sim 80\%$
- For $E_\nu < 2GeV$ $N_{\pi^0} : N_{\nu_e} :: 59 : 35$
- For $E_\nu > 2GeV$ $N_{\pi^0} : N_{\nu_e} :: 17 : 35$

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

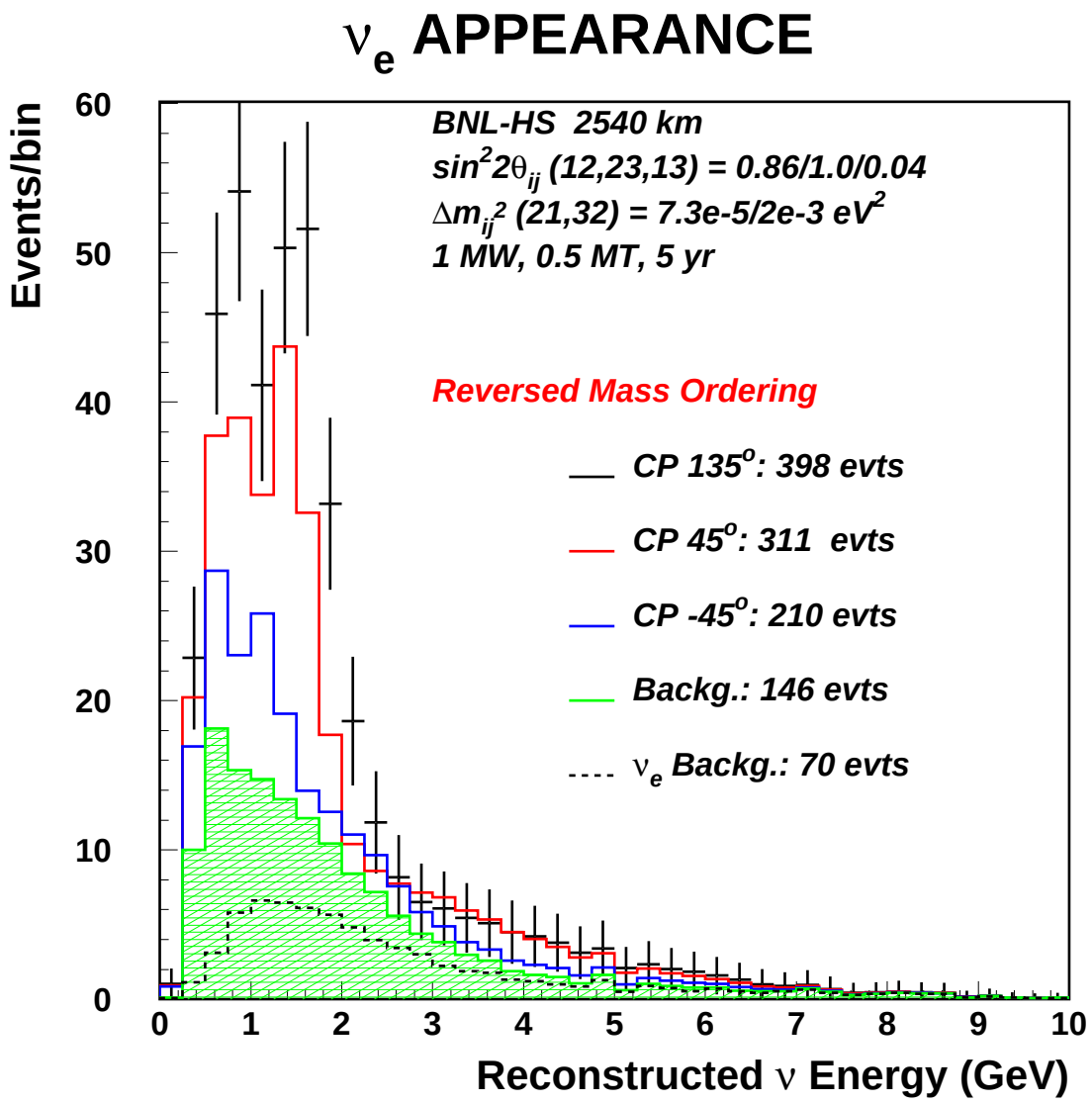


$\Delta m^2_{32} = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

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

Matter effects included.

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

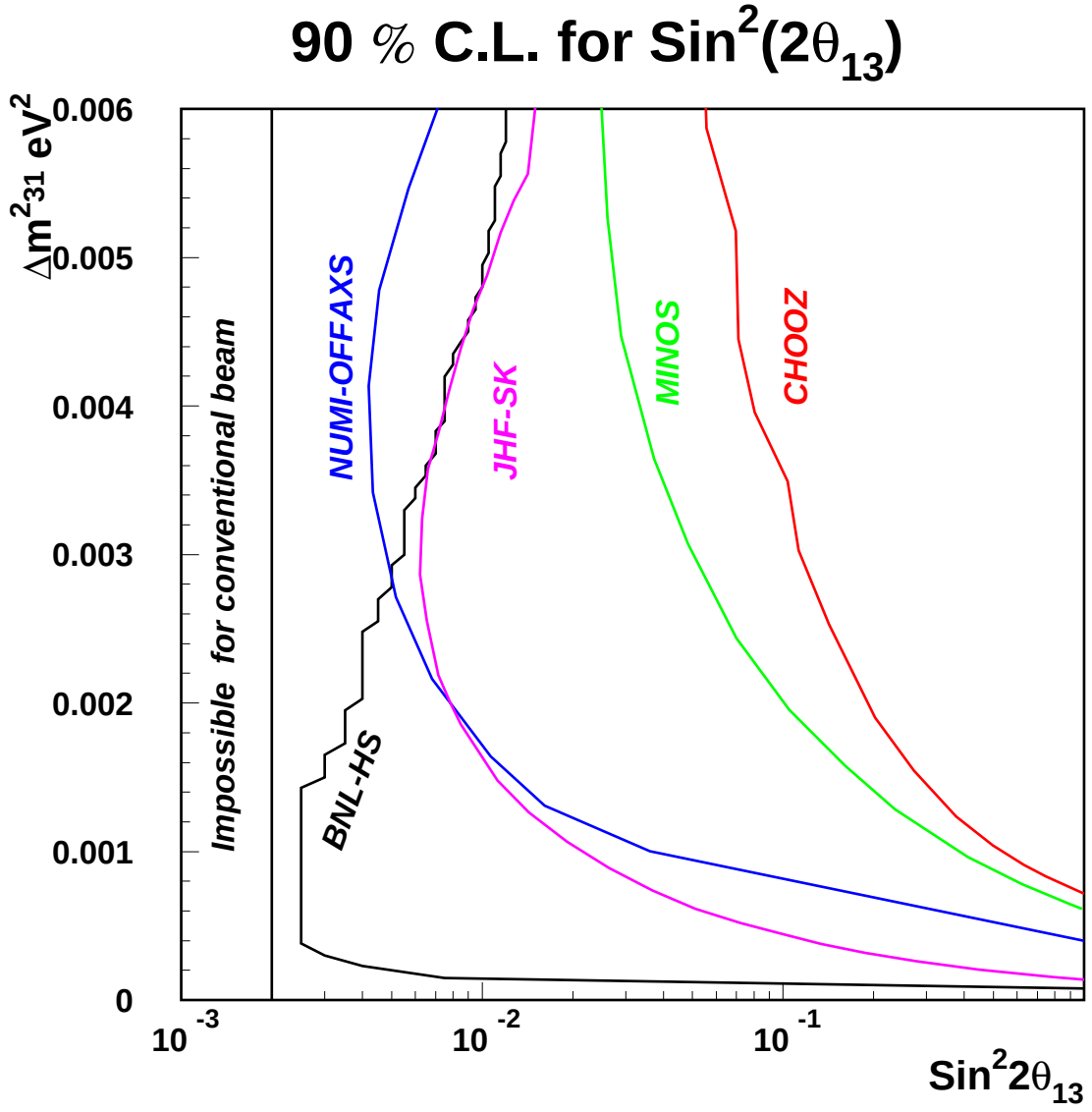


$\Delta m^2_{32} = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

Reversed Mass Hierarchy

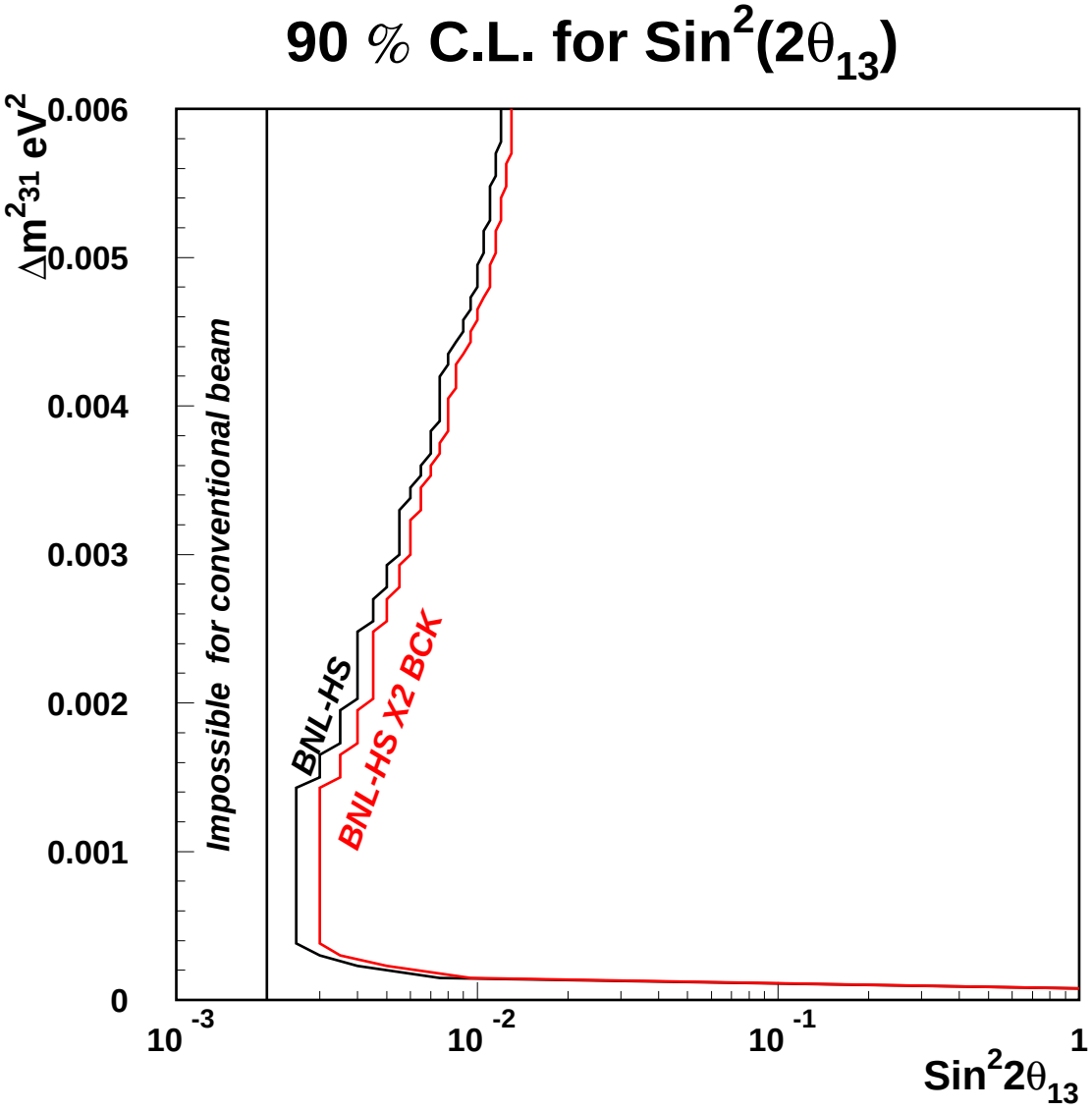
Matter effects included.

Measurement of $\sin^2 2\theta_{13}$ 90% C.L.



Distinctive signature with multiple oscillations above 0.001 eV^2

Measurement of $\sin^2 2\theta_{13}$ 90% C.L. high Bckg.



Assume that the neutral current background is higher by factor of 2 over the entire spectrum.

Measurement of $\sin^2 2\theta_{13}$ 90% C.L.

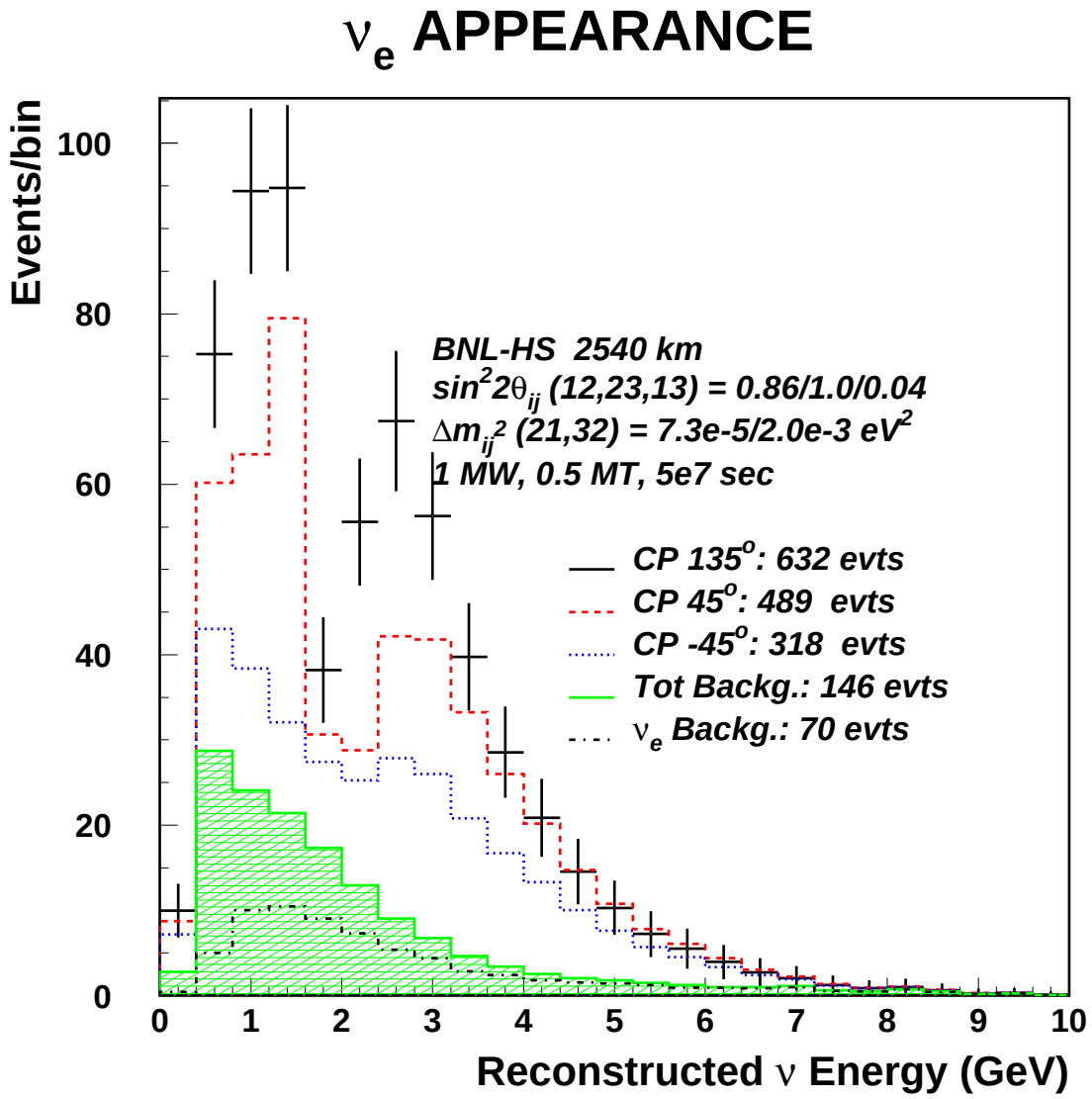
BNL-HS(2540 km) good sensitivity to $\sin^2 2\theta_{13}$.

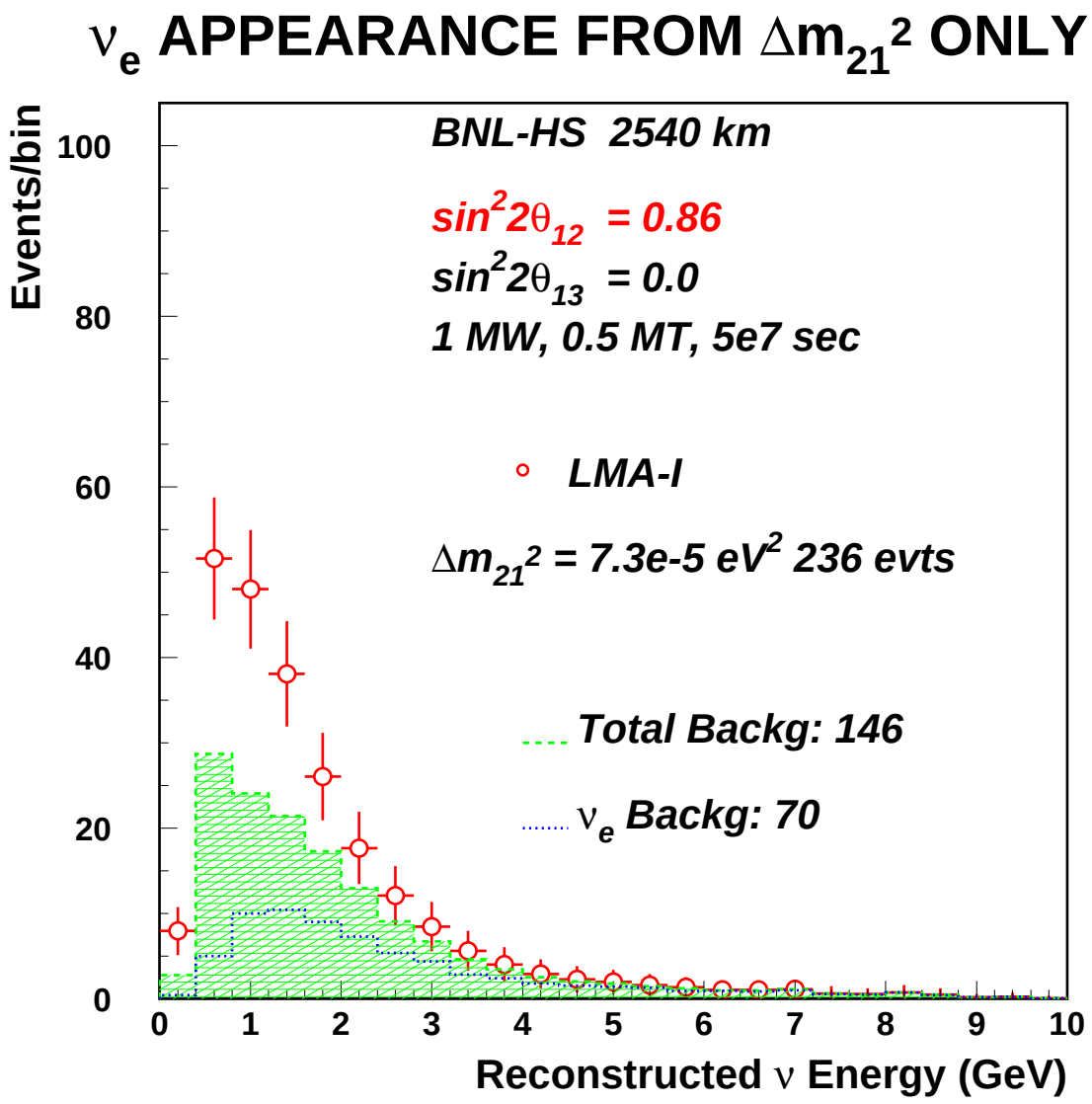
Improvement from 0.12 to 0.005 at 0.0025 eV^2.

Signal very distinctive above 0.001 eV^2.

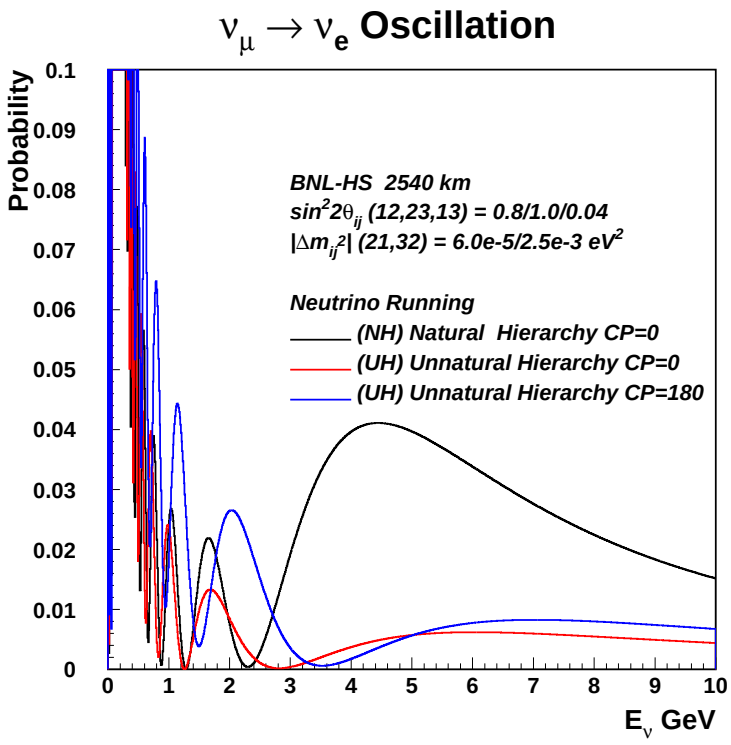
Need harder beam to improve sensitivity above 0.004 eV^2.

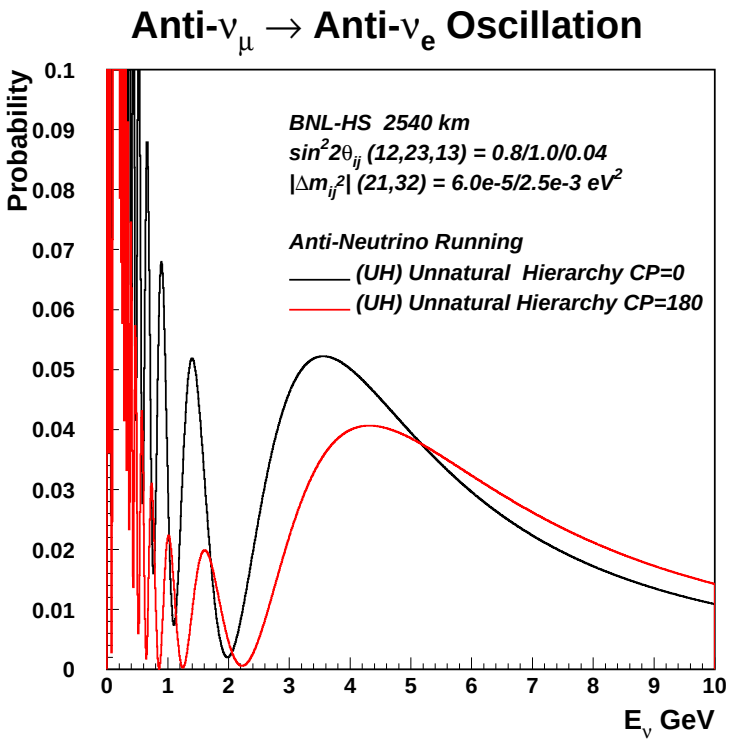
No experiment can go below $\sin^2 2\theta_{13} \approx 0.002$ with horn focussed beam due to systematic error on instrinsic ν_e background.


ν_e APPEARANCE
Events/bin
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
10
Reconstructed ν Energy (GeV)
BNL-HS 2540 km
$\sin^2 2\theta_{ij}$ (12,23,13) = 0.86/1.0/0.04
Δm^2_{ij} (21,32) = 7.3e-5/2.0e-3 eV^2
1 MW, 0.5 MT, 5e7 sec
CP 135^o: 632 evts
CP 45^o: 489 evts
CP -45^o: 318 evts
Tot Backg.: 146 evts
ν_e Backg.: 70 evts

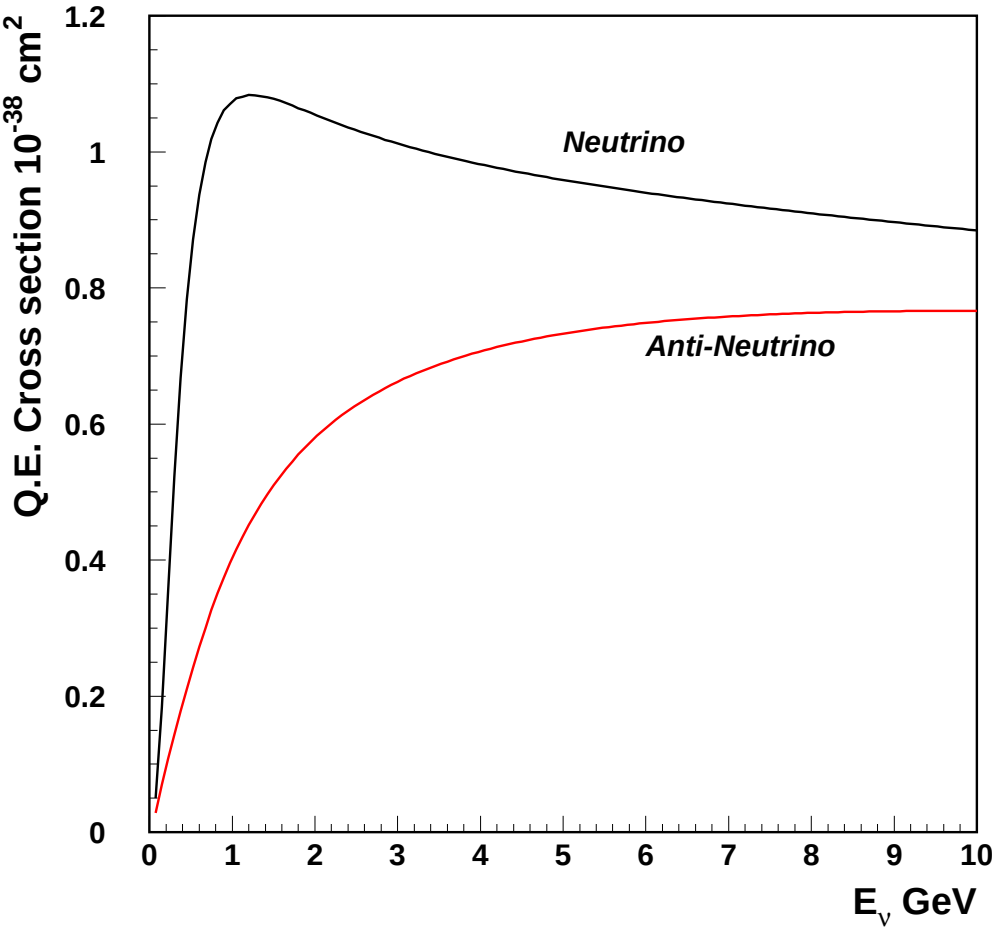

ν_e APPEARANCE FROM Δm_{21}^2 ONLY
BNL-HS 2540 km
$\sin^2 2\theta_{12}$ = 0.86
$\sin^2 2\theta_{13}$ = 0.0
1 MW, 0.5 MT, 5e7 sec
LMA-I
Δm_{21}^2 = 7.3e-5 eV^2 236 evts
Total Backg: 146
ν_e Backg: 70
Events/bin
Reconstructed ν Energy (GeV)
0
20
40
60
80
100
0
1
2
3
4
5
6
7
8
9
10

Mass Hierarchy Anti-neutrinos



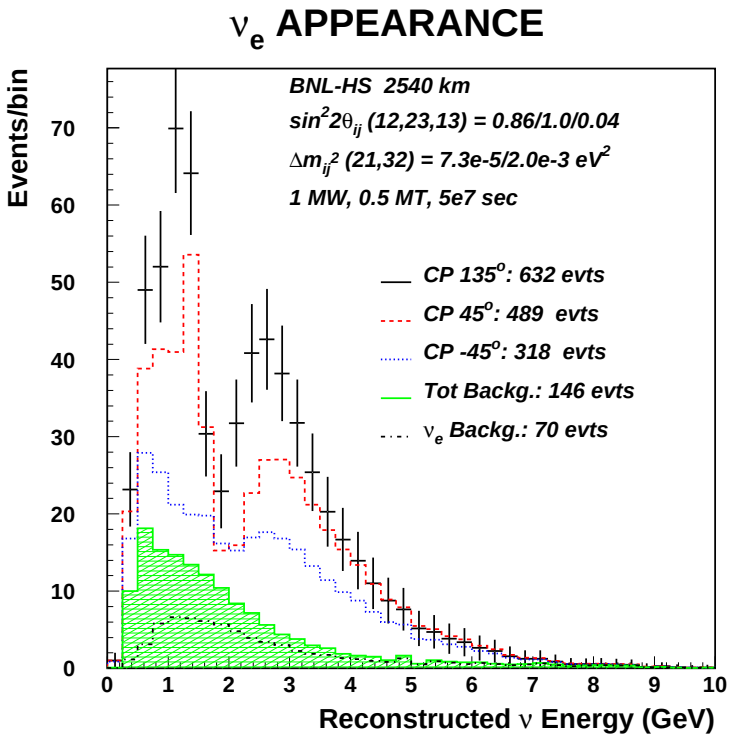


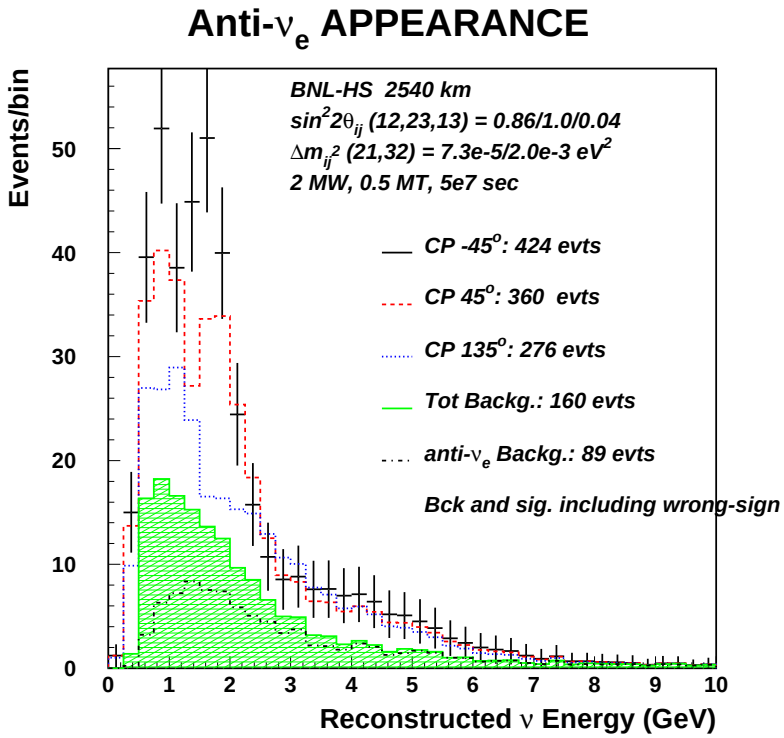
Quasielastic cross section



An experiment searching for signal at high energies may not need much more anti-neutrino running than neutrino running.

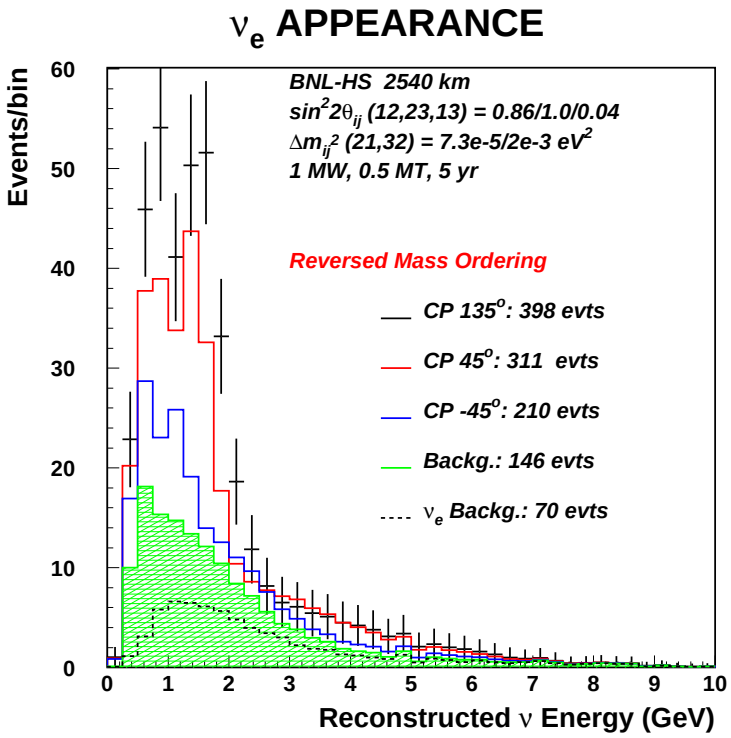
Running for $\sin^2 2\theta_{13}$

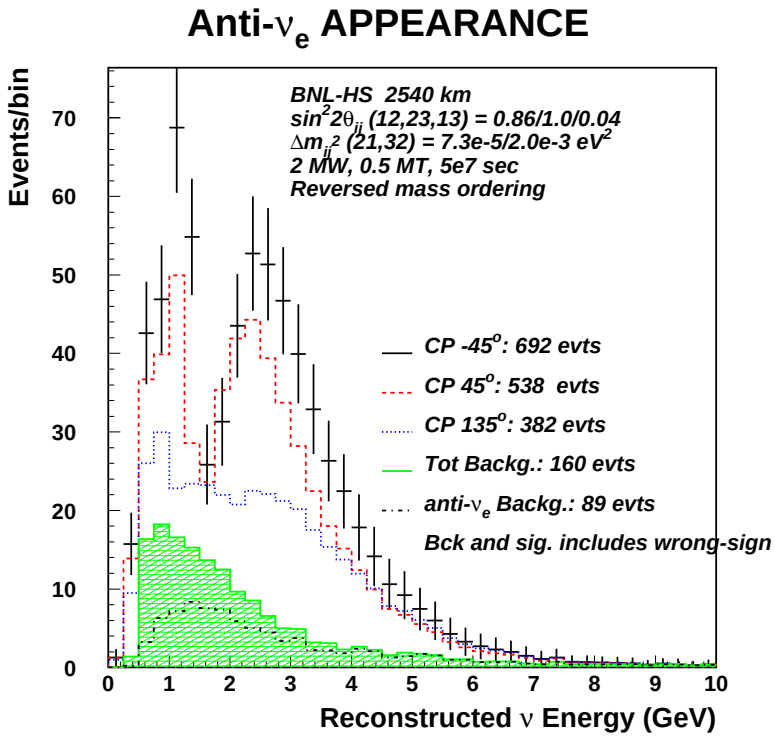




$\Delta m^2_{32} = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$. Assume normal mass hierarchy. $m_3 > m_2 > m_1$ Matter effects included.

Running for $\sin^2 2\theta_{13}$



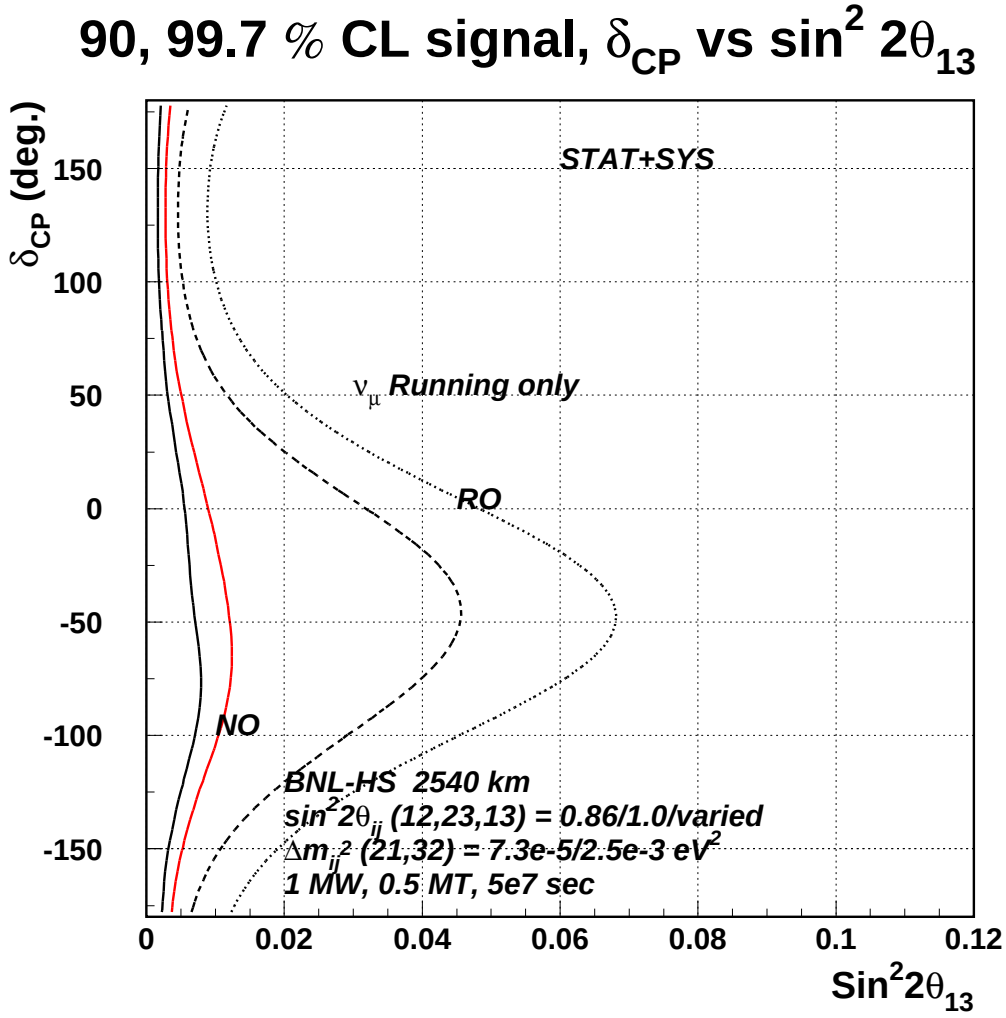


$\Delta m^2_{32} = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

Reversed Mass Hierarchy

Matter effects included.

Mass Hierarchy



Natural Mass hierarchy: $m_3 > m_2 > m_1$ (NO)

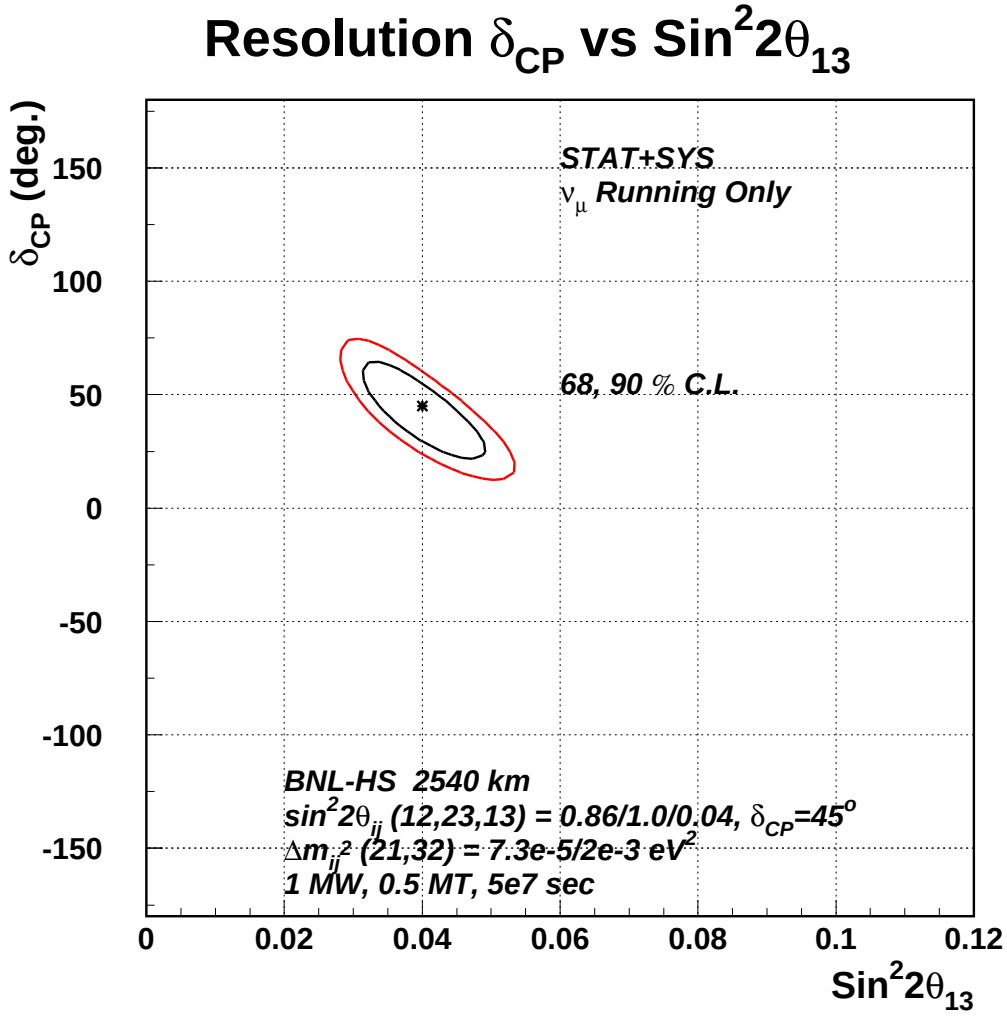
Reversed Mass hierarchy: $m_1 > m_2 > m_3$ (RO)

Unnatural Mass hierarchy: $m_2 > m_1 > m_3$ (RO)

$m_1 > m_2$ is ruled out if Solar LMA is the correct solution.

We would need to run Anti-neutrino beam to fully explore RO.

Measurement of $\delta_{CP} = 45^o$ No anti-neutrino running.



Systematic error of 10% on backg.

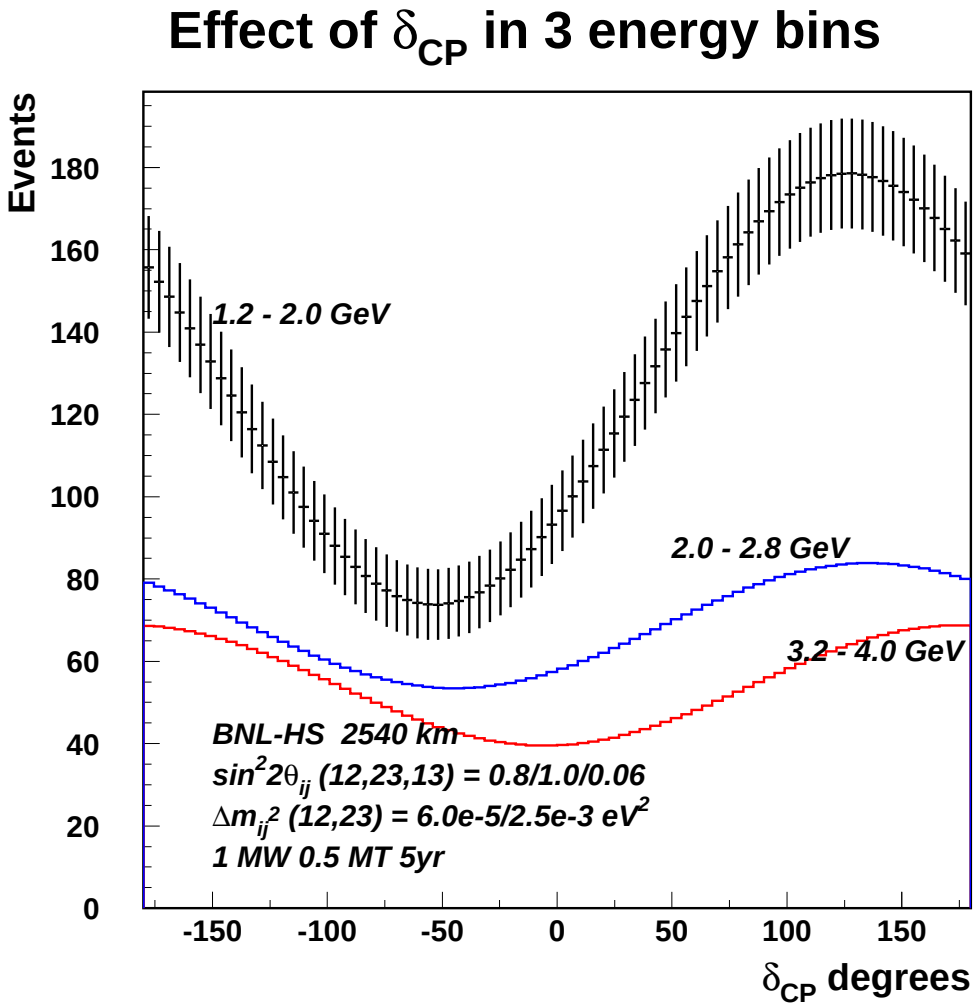
$\Delta m^2_{21} = 7.3 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2 \times 10^{-3} eV^2$

$\sin^2 2\theta_{12} = 0.86$, $\sin^2 2\theta_{23} = 1.0$

$\delta_{CP} = 45^o$, $\sin^2 2\theta_{13} = 0.04$

68%, and 90% C.L.

Effect of δ_{CP} on the spectrum.



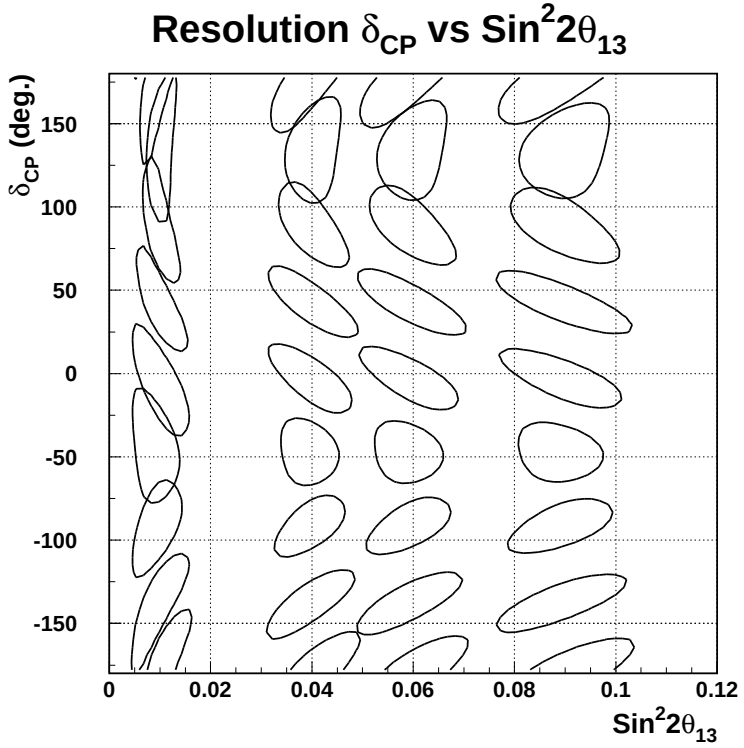
Event rate in 3 energy bins.

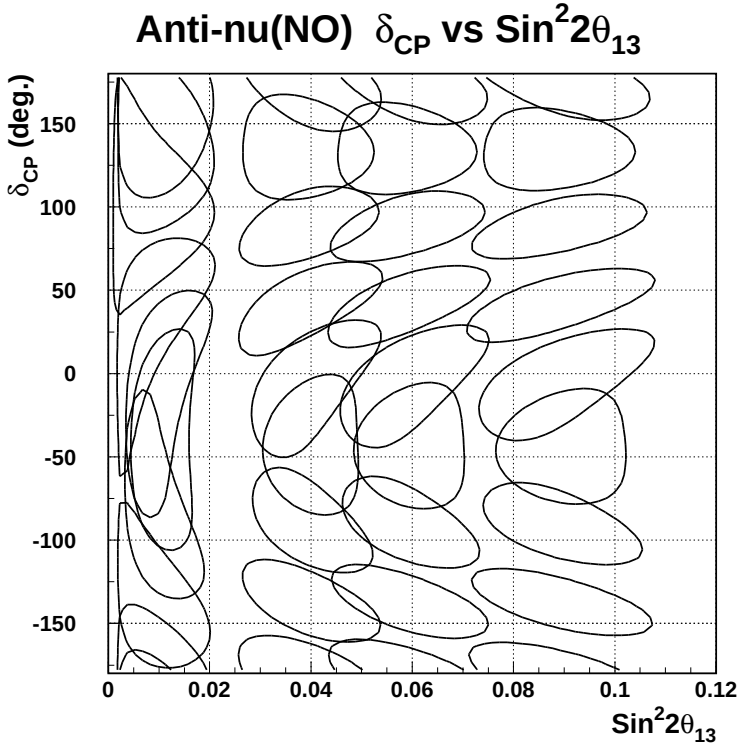
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

$\sin^2 2\theta_{12} = 0.8$, $\sin^2 2\theta_{23} = 1.0$

$\sin^2 2\theta_{13} = 0.06$

Error on δ_{CP} vs $\sin^2 2\theta_{13}$

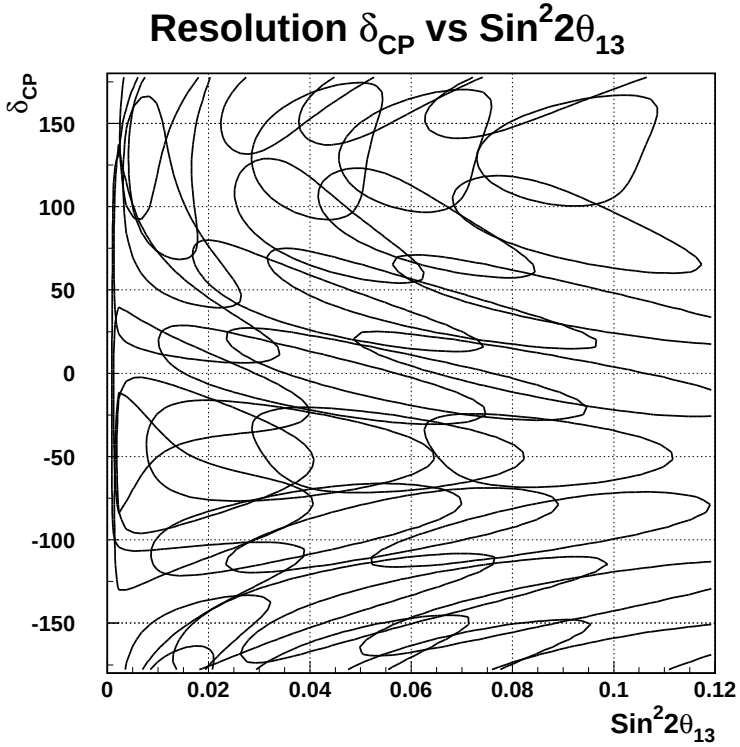


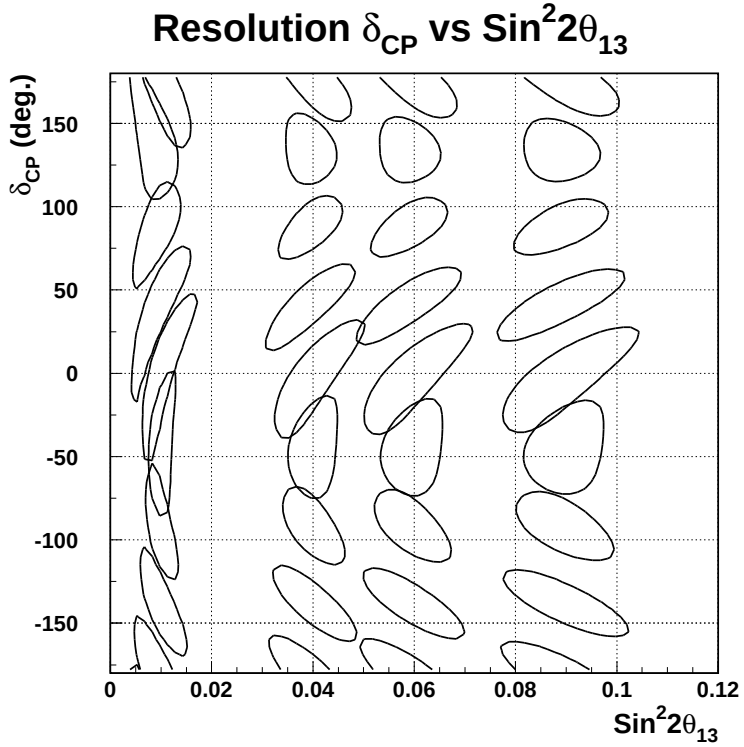


$\Delta m^2_{21} = 7.3 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2 \times 10^{-3} eV^2$

$\sin^2 2\theta_{12} = 0.86$, $\sin^2 2\theta_{23} = 1.0$

Error on δ_{CP} vs $\sin^2 2\theta_{13}$



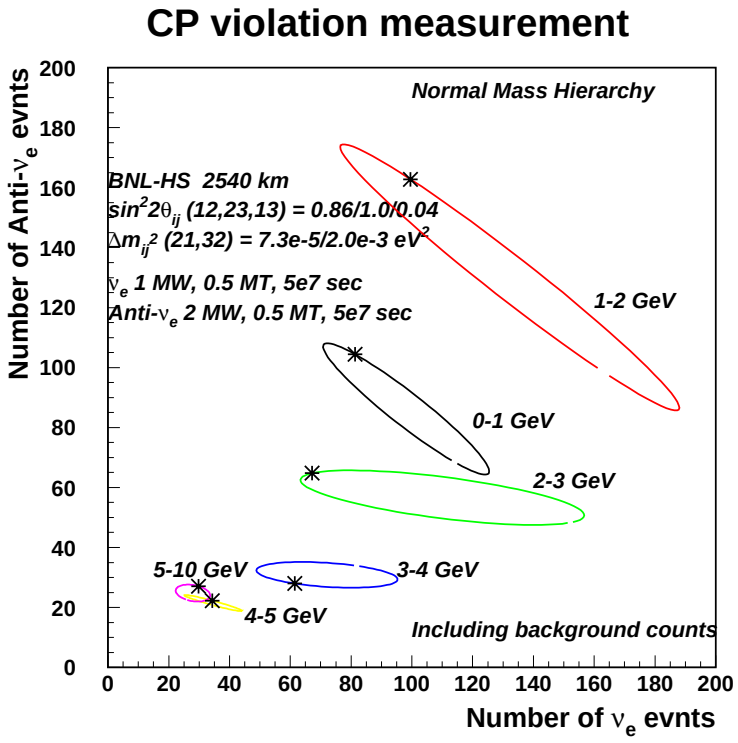


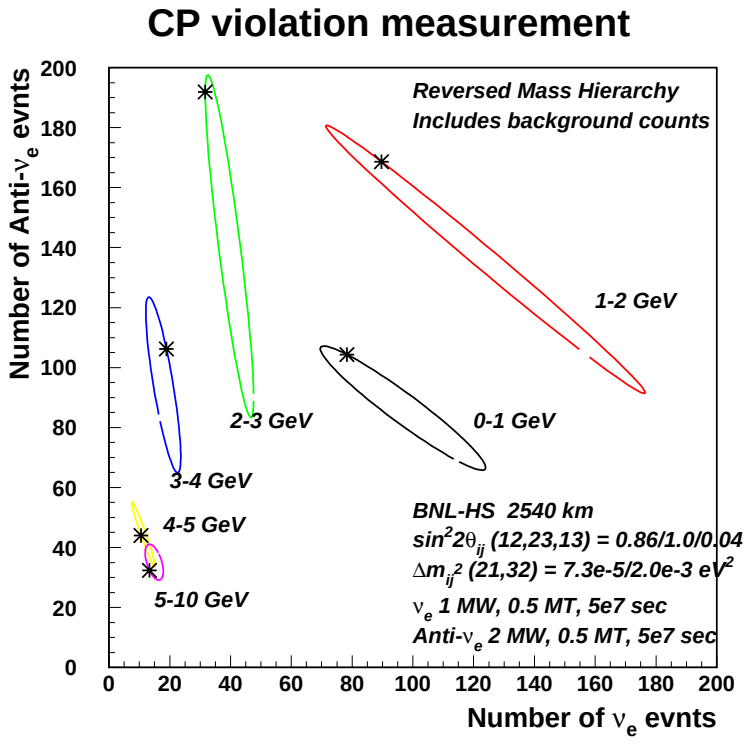
Reversed hierarchy.

$\Delta m^2_{21} = 7.3 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2 \times 10^{-3} eV^2$

$\sin^2 2\theta_{12} = 0.86$, $\sin^2 2\theta_{23} = 1.0$

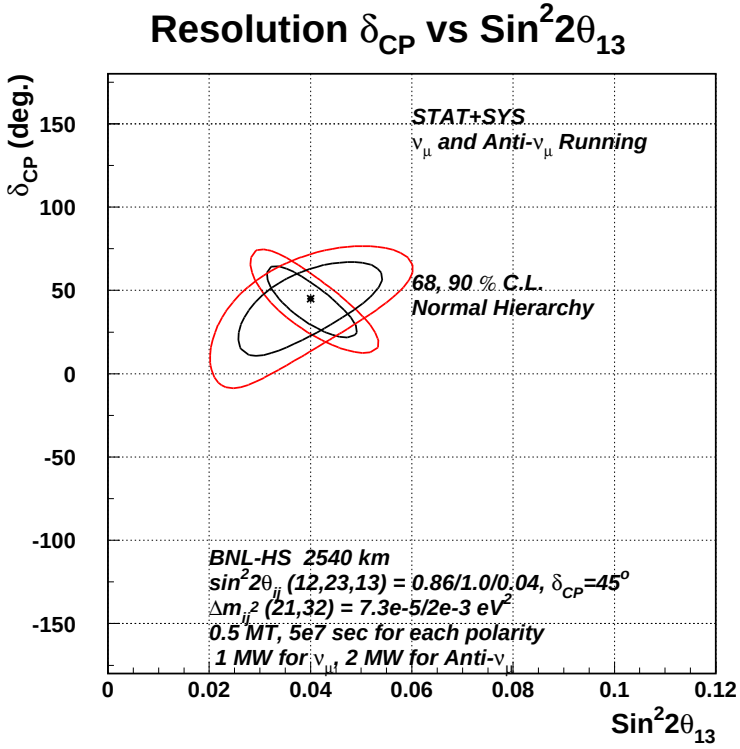
Combining Neutrino and Antineutrino

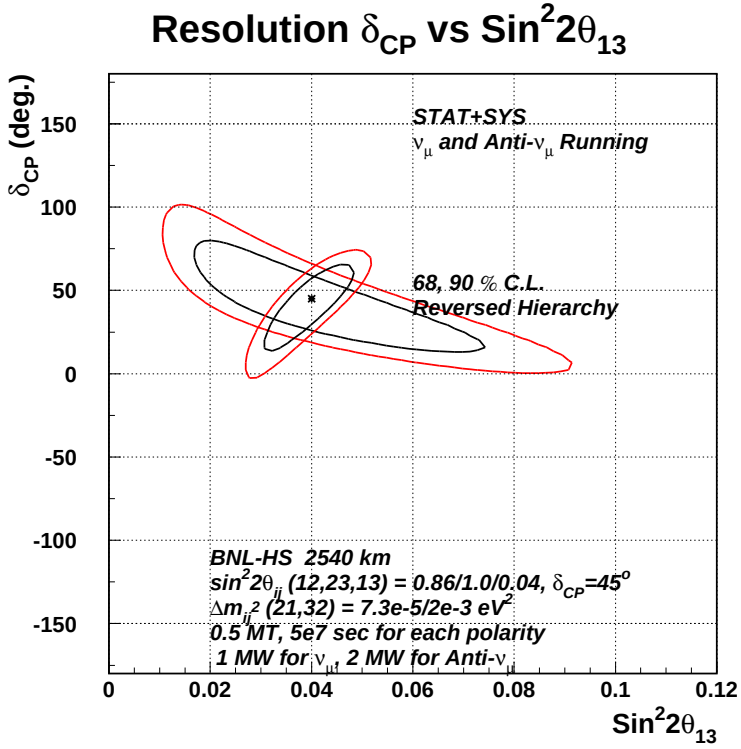




Note: No experiment can avoid matter effect. Explicit demonstration of CP violation must rely on a detailed fit to both neutrino and anti-neutrino data.

CP with Neutrino and Antineutrino

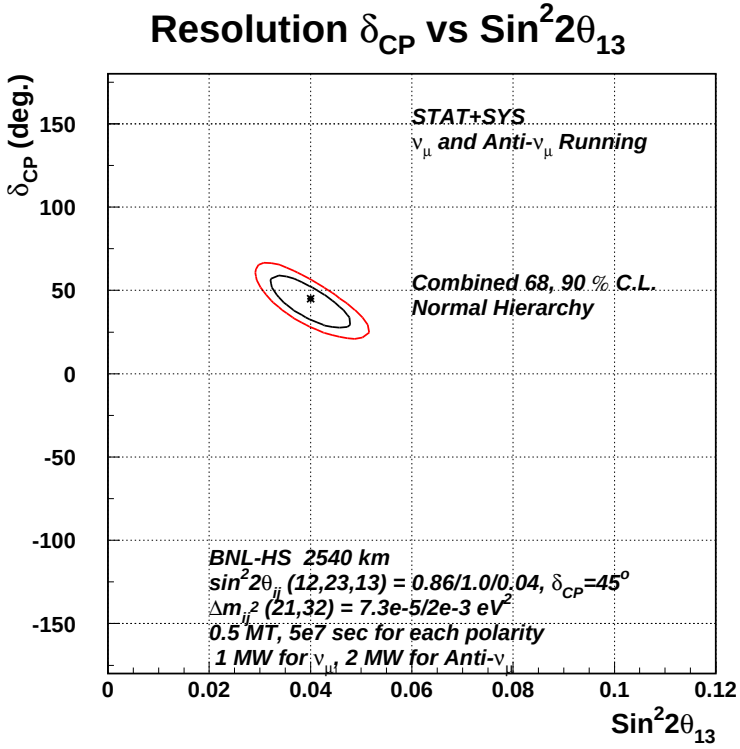


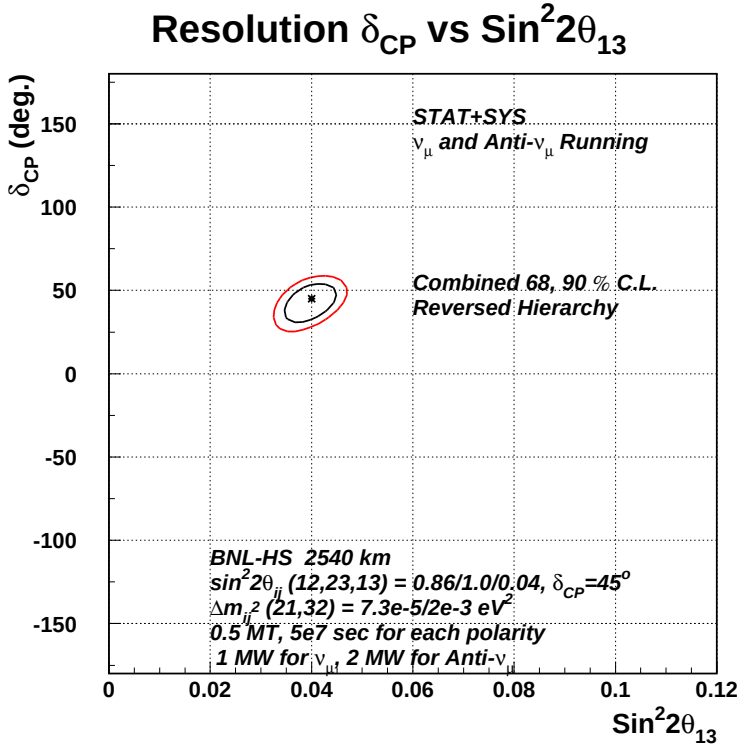


Very long baselines with a superbeam

Milind Diwan

CP with Neutrino and Antineutrino

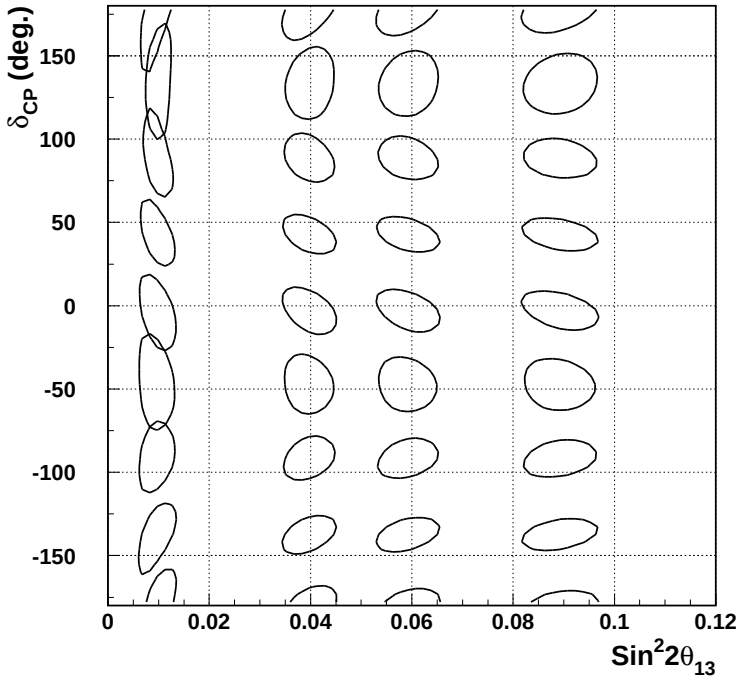




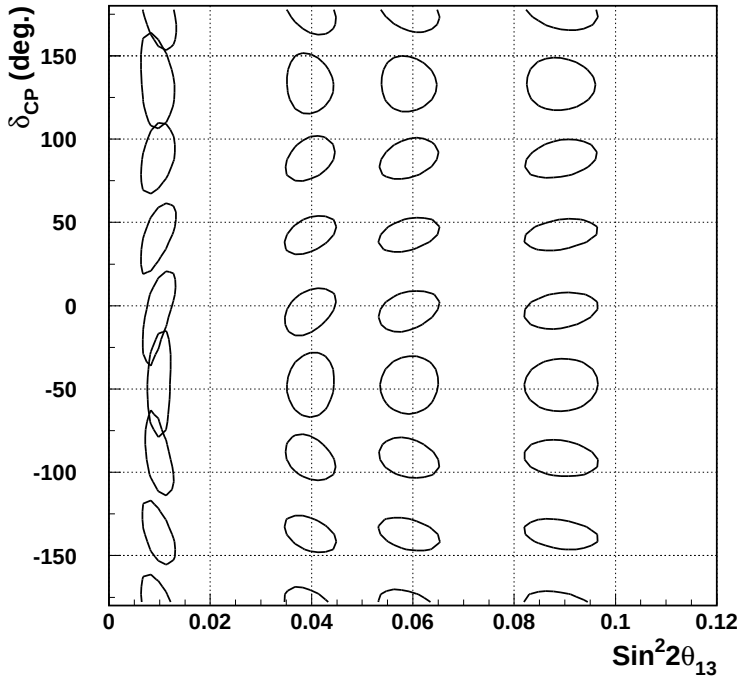
Very long baselines with a superbeam

CP with Neutrino and Antineutrino

Regular hierarchy $\nu\upsilon$ and Anti$\nu\upsilon$ running

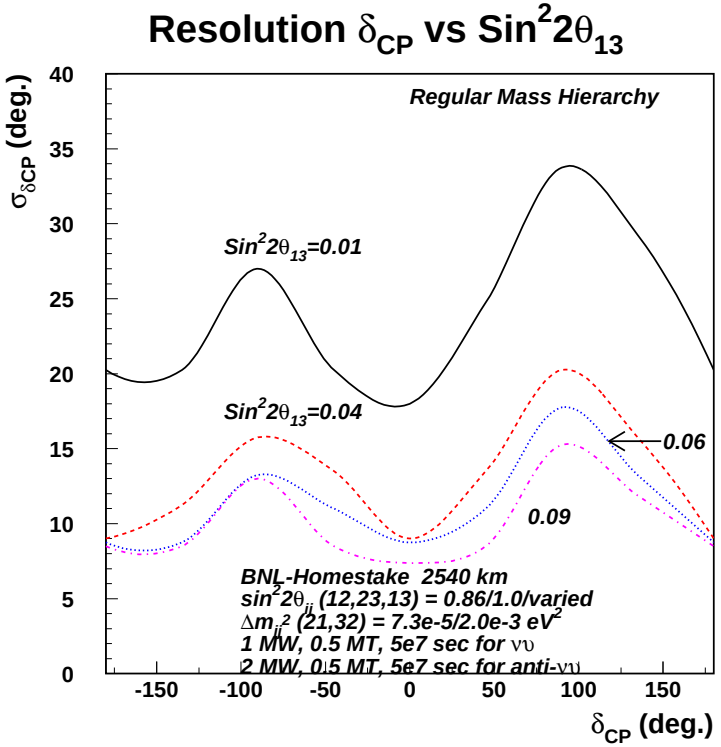


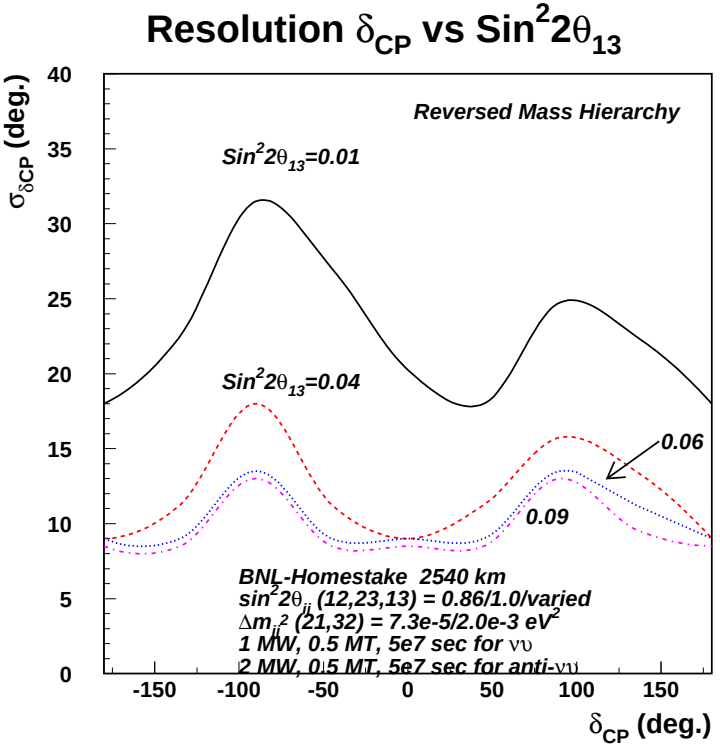
Reversed hierarchy $\nu\upsilon$ and Anti$\nu\upsilon$ running



Very long baselines with a superbeam

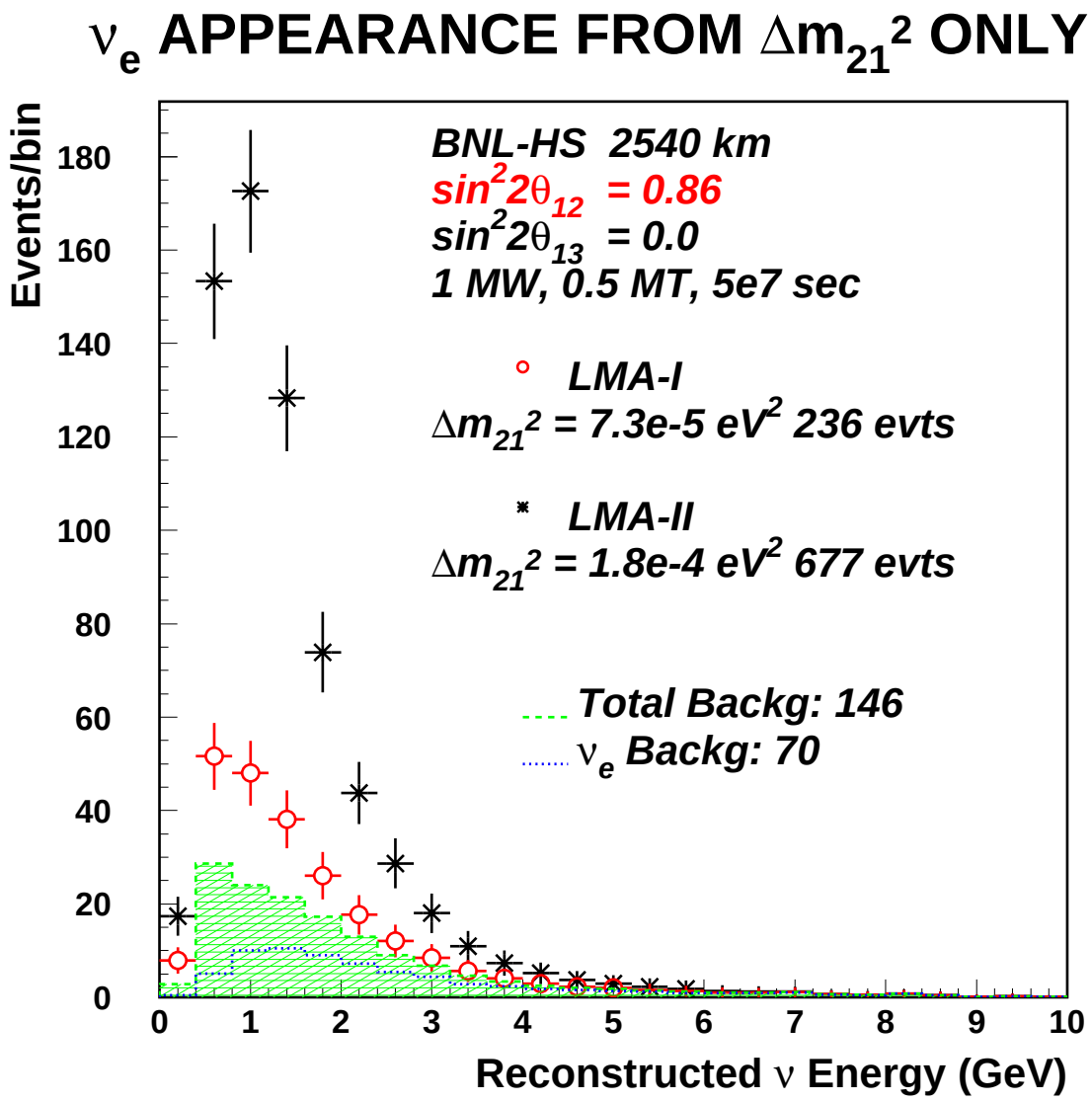
CP with Neutrino and Antineutrino





Milind Diwan

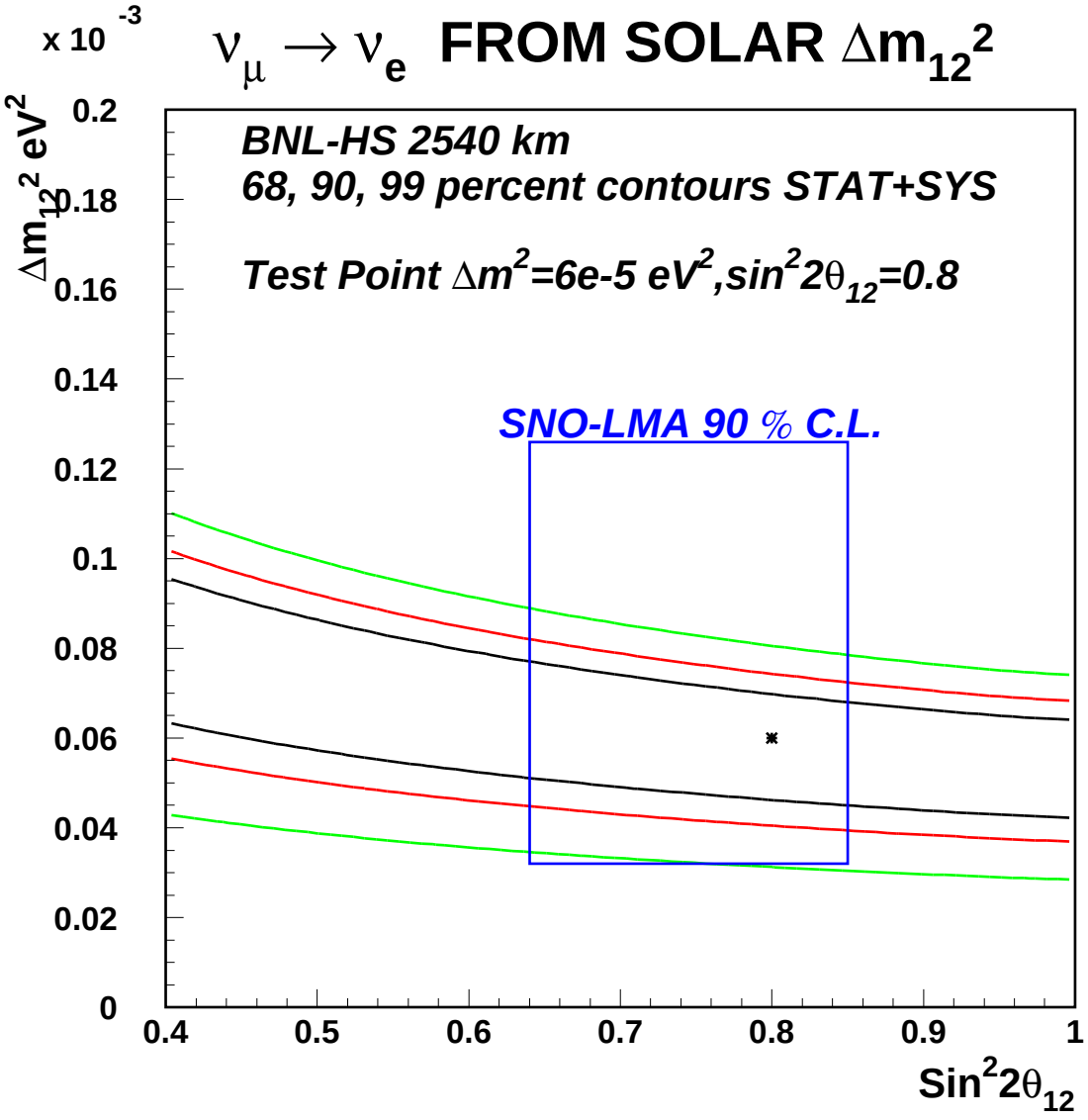
Measurement of Δm^2_{12}



$\theta_{13} = 0$, $\Delta m^2_{12} = 7.3 \times 10^{-5} eV^2$

Excess of ~ 90 events. Must know background

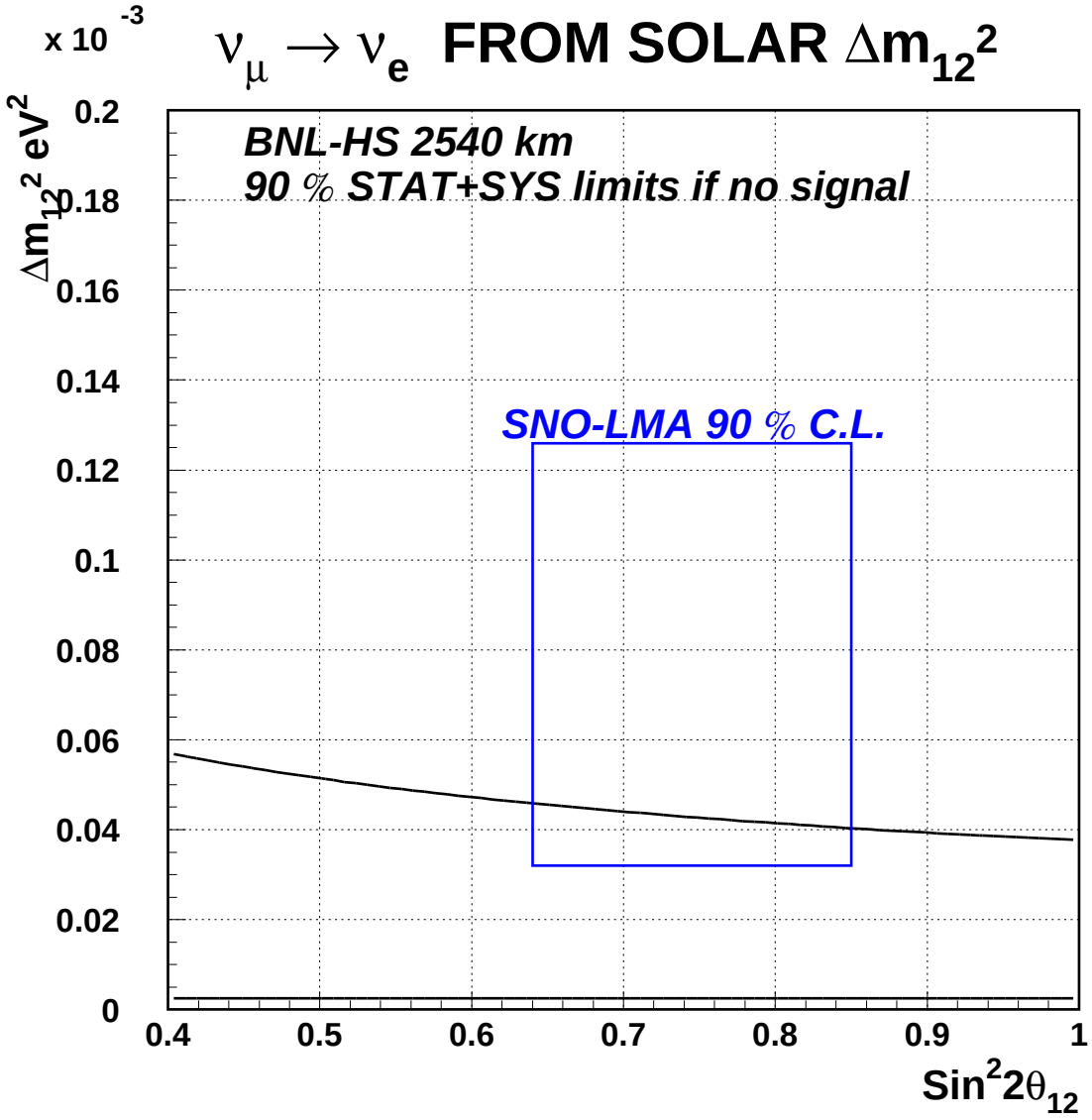
Measurement of Δm^2_{21}



Independent $\sim 15\%$ measurement of Δm^2_{21}

Needs $\sim 10\%$ error on backg. $=>$ near detector.

Limit on Δm^2_{21} vs $\sin^2 2\theta_{12}$



If no signal then a limit can be obtained that almost eliminates LMA.

Analysis Flow Chart

How the experiment will proceed:

- After 2 years of running get a very precise measurement of Δm^2_{32} from disappearance and definitive signal of oscillations.
- From the measured Δm^2_{32} predict the shape of the electron spectrum including matter effects.
- Do we have a peak in the electron spectrum at the expected energy ? Yes No
- NO: Either $\sin^2 2\theta_{13}$ too small or inverted mass hierarchy $\Delta m^2_{32} < 0$.
  - Get an independent measurement of Δm^2_{21} at about $\pm 15\%$.
  - Run with anti-neutrinos. (next next slide)
- YES: GREAT NEWS ! GOTO NEXT SLIDE.

- YES: There is a peak in the electron spectrum from the neutrino beam.
  - Use Δm^2_{21} from SNO and KAMLAND and make a fit to the spectrum for CP angle versus $\sin^2 2\theta_{13}$.
  - Accumulate more statistics and make a combined fit for Δm^2_{21} , δ_{CP} and θ_{13}.
  - Is the CP angle too small ? NO YES
- NO: Finished ! Still run antineutrinos for more precise δ_{CP}.
- YES: Run anti-neutrinos for more sensitivity on δ_{CP}.

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

- Running with anti-neutrinos if no peak in the electron spectrum from neutrinos

  Is there a peak in the electron spectrum from anti-neutrinos ? Yes No

  - Yes The mass hierarchy is inverted. Proceed to measure $\sin^2 2\theta_{13}$ and CP angle with anti-neutrinos.
  - No $\sin^2 2\theta_{13}$ is too small. Proceed to social work.

If inverted hierarchy;

measure both $\sin^2 2\theta_{13}$ and

δ_{CP}.
OR $\sin^2 2\theta_{13}$ is just too small for conventional beam.

Summary of our study

- Baseline of > 2000 km with wide band conventional beams are the next step in accelerator neutrino physics.
- Extraordinary, large physical effects will be seen in such an experiment.
- Very good sensitivity to neutrino properties.
  - $< 1\%$ resolution on Δm^2_{32}
  - $< 1\%$ resolution on $\sin^2 2\theta_{23}$
  - Sensitivity to $\sin^2 2\theta_{13} \sim 0.005$ over a wide range of Δm^2_{32}
  - Sensitivity to CP parameter $\pm 25^o$ with neutrinos alone.
  - Sign of Δm^2_{32} over a wide range.
  - Measurement of Δm^2_{21} at $\pm 15\%$
- The electron spectrum has a lot of physics. It can be extracted using some outside information on parameter.

Measurement matrix

Neutrino running only; Running: 5×10^7 sec.

Baseline: 2540 km; beam: 1 MW at 28 GeV; detector: 500 kT

	Δm^2_{32}	$\sin^2 2\theta_{23}$	Δm^2_{21}	$\sin^2 2\theta_{13}$ 90 % C.L.	δ_{CP}
$\Delta m^2_{32} > 0.001$ $\sin^2 2\theta_{13} > 0.01$	$< 1\%$	$\sim 1\%$	$\pm 15\%$	± 0.01	$\pm 25^o$
$\Delta m^2_{32} > 0.001$ $\sin^2 2\theta_{13} < 0.01$	$< 1\%$	$\sim 1\%$	$\pm 15\%$	Limit < 0.005	No Measure.

Not complete story, but an impression. Assume $m_3 > m_2 > m_1$.

Need good energy calibration for Δm^2_{32} ($\sim 100 MeV$ LINAC ?)
Need small error on backg. for Δm^2_{21} and CP. (Near Detector)

Some comments on detector

- Detector studies have started. Need more manpower.
- Water Cherenkov
  - 50 kT SuperK is existence proof.
  - Background rejection ? need another $\times$ 3 to 5 to reach level in this talk.
  - Additional imaging capability ?
- Liquid Argon TPC
  - 100 kT module never built.
  - Current size 300Ton.
  - Needs detailed simulations.
- Any other technology ?

What is Next ?

White paper: hep-ex/0211001

Short paper: hep-ph/0303081, published PRD68, 012002, 2003

Can we use events such as $\nu_e + N \rightarrow e^- + \pi^+ + N$?

Background determination with near det.

- The experiment is technically feasible.
  Direct costs.
  AGS upgrade, Hill, Proton transp., horns, decay tunnel: $\sim \$150M$
  This can be a staged program that starts with \$90 M at the AGS and \$150 M at Homestake for first critical results.
- The detector has applications far beyond accelerator neutrinos. And should have a very diverse and rich physics program.
  Detector: \$300 M for 10% PMT coverage ?
  If water Cherenkov cannot have the needed performance then what ?

Two possibilities

1) Increase AGS to 2 MW by going to 5 Hz operation

2) Make finer grain detector at 100 kT. Use all events.

Optimization of the detector and accelerator needs much more detailed simulation study.