Very long baselines with a superbeam

Milind V. Diwan

Brookhaven National Laboratory

Neutrinos and New Physics

Stony Brook, 2002

FOR BNL Neutrino Working Group.

Wide Band Conventional Beam from BNL to the Homestake Laboratory.

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_{12} 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.

Neutrino Physics: the simple stuff

Assume a 2×2 neutrino mixing matrix.

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

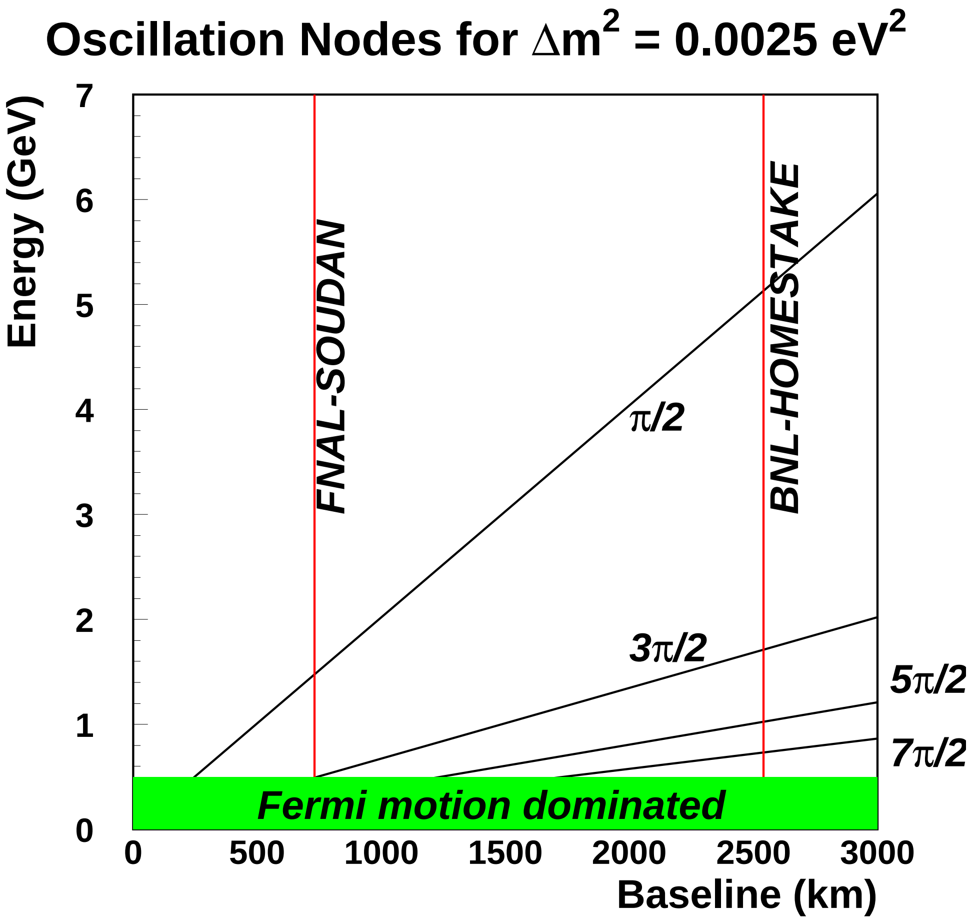
$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned} \quad (2)$$

Sufficient to understand most of the physics:

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

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

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, ...$ ($\pi/2$):
$\Delta m^2 = 0.003 eV^2$, $E = 1 GeV$, $L = 412 km$.



- Large effects: Multiple oscillation nodes.
- Fermi motion limits resolution at low energies: wide band beam $(0.5 \rightarrow 8 \text{ GeV})$.
- $\Delta m^2 \approx 0.0025 eV^2$: Baseline > 2000 km.

Neutrino Physics: the difficult stuff

Bill Marciano, hep-ph/0108181

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_1 c_3 & s_1 c_3 & s_3 e^{-i\delta} \\ -s_1 c_2 - c_1 s_2 s_3 e^{i\delta} & c_1 c_2 - s_1 s_2 s_3 e^{i\delta} & s_2 c_3 \\ s_1 s_2 - c_1 c_2 s_3 e^{i\delta} & -c_1 s_2 - s_1 c_2 s_3 e^{i\delta} & c_2 c_3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{3}$$

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

No matter effects in above formula

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

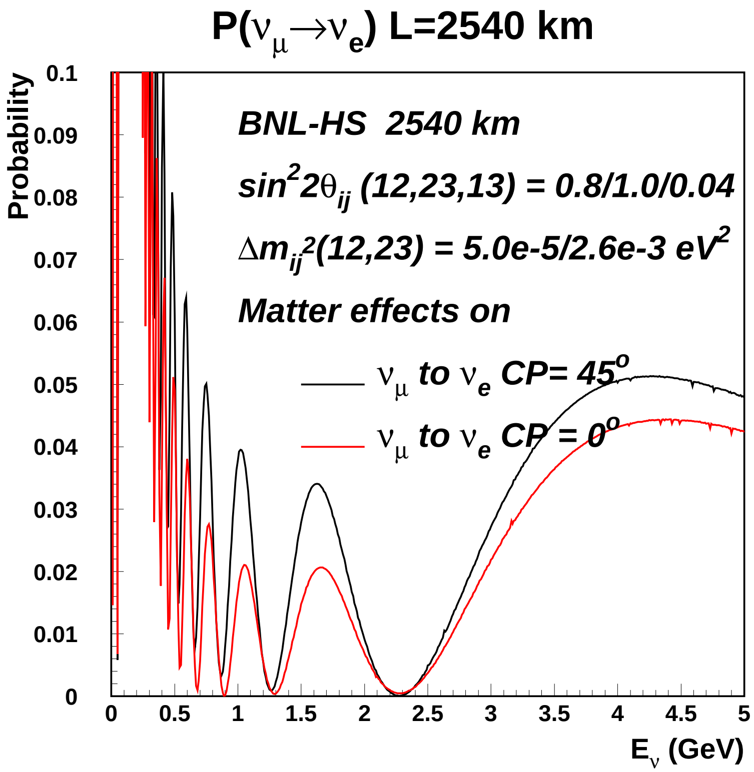
$$J_{CP} \equiv s_1 s_2 s_3 c_1 c_2 c_3^2 \sin\delta \tag{5}$$

$$A \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \tag{6}$$

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

$$P(\nu_\mu \to \nu_e) \simeq 4 s_2^2 s_3^2 c_3^2 \sin^2 \frac{\Delta_{31}}{2} + \mathcal{O}(\Delta_{21}) \tag{12a}$$

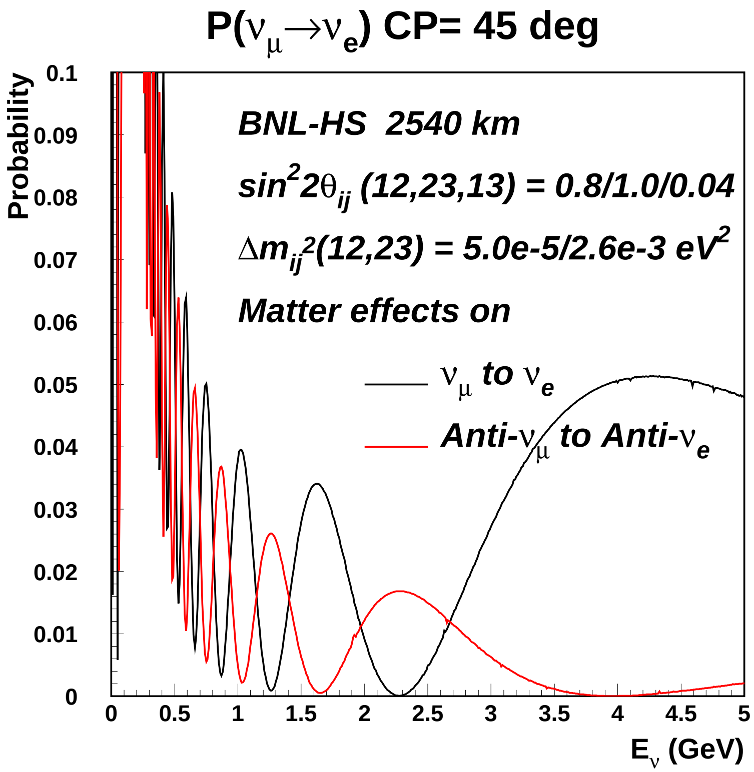
$$A \simeq \frac{J_{CP} \sin\Delta_{21}}{s_2^2 s_3^2 c_3^2} \simeq \frac{2 s_1 c_1 c_2 \sin\delta}{s_2 s_3} \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right) \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}(\Delta^2_{21}) \tag{12b}$$



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.

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



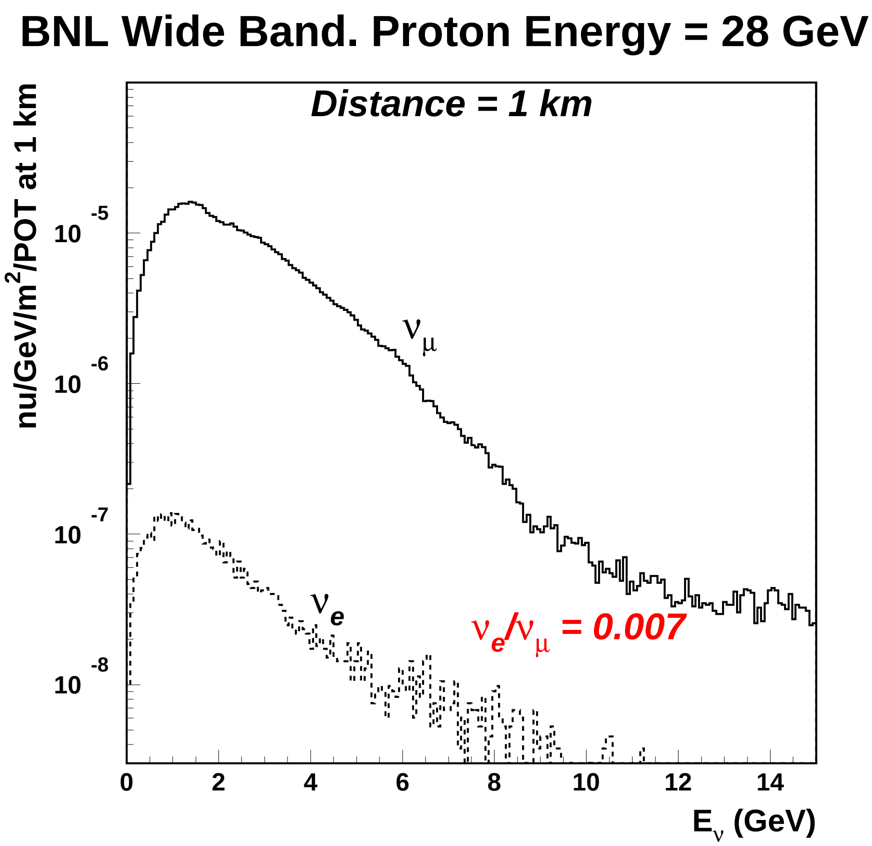
Compare Neutrino to Antineu.

- $0.5 - 1$ 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 $\nu_\mu \rightarrow \nu_e$ in the appearance mode. If $\Delta m^2_{\nu_\mu \rightarrow \nu_e} = \Delta m^2_{32}$ then $|U_{e3}|^2 (= \sin^2\theta_{13})$ is non-zero.
- Detection of the matter enhancement effect in $\nu_\mu \rightarrow \nu_e$. 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 $\nu_\mu \rightarrow \nu_e$ versus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

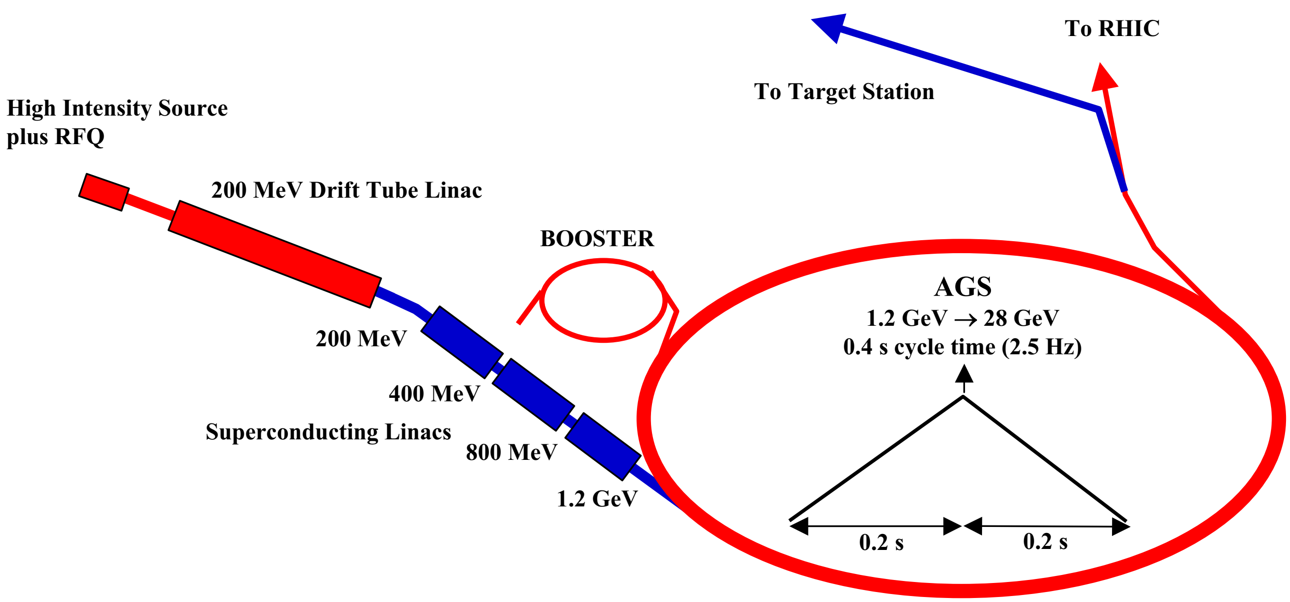
  It will be good to do it all in same experiment with only neutrino beam (no antineutrino).



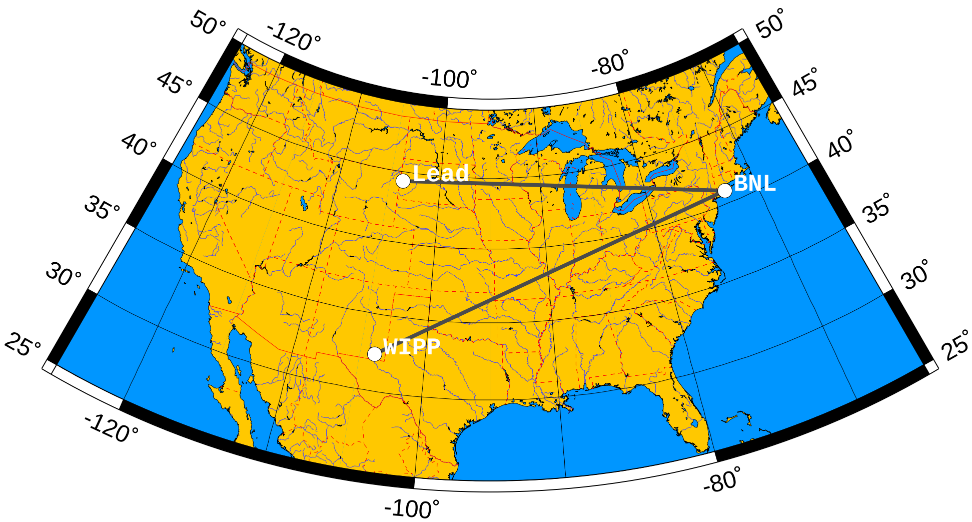
- New design spans 0.5-6 GeV
- Low ν_e background 0.7%
  0.0073 ± 0.0014 (E734 1986).
- Low background from high energies (NC and ν_τ for ν_e)
- 200 m decay tunnel
- Graphite target embedded in horn
- Target cooling achievable for 1 MW

The Accelerator

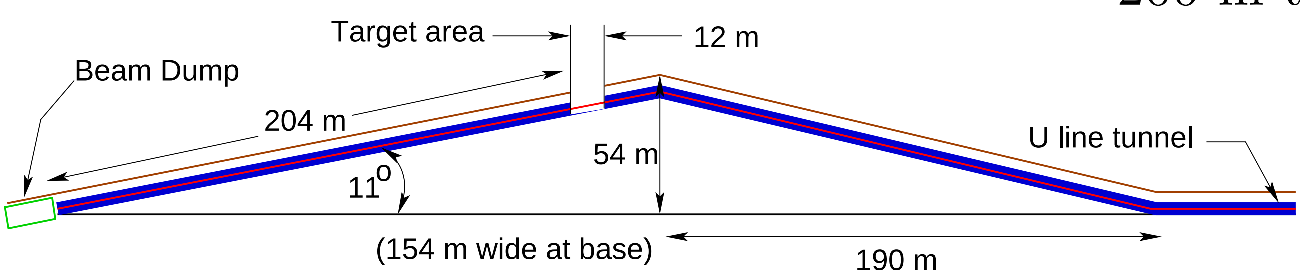
- Conceptually simple upgrade. No magic. Cost $\sim \$100M$.
- Run 28 GeV AGS at 2.5 Hz to get 1 MW.
- Need faster proton source: Super Conducting LINAC at 1.2 GeV
- Current: $7 \times 10^{13} ppp$ at 0.5 Hz => LINAC: $10^{14} ppp$ at 2.5 Hz.



Beam on the Hill



- BNL-Lead 2540km
  BNL-Wipp: 2880km
- Avoids water table.
- Hills are inexpensive: highway ramps.
- Total cost $35 M for 200 m tunnel.



Event Rates with Neutrinos

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

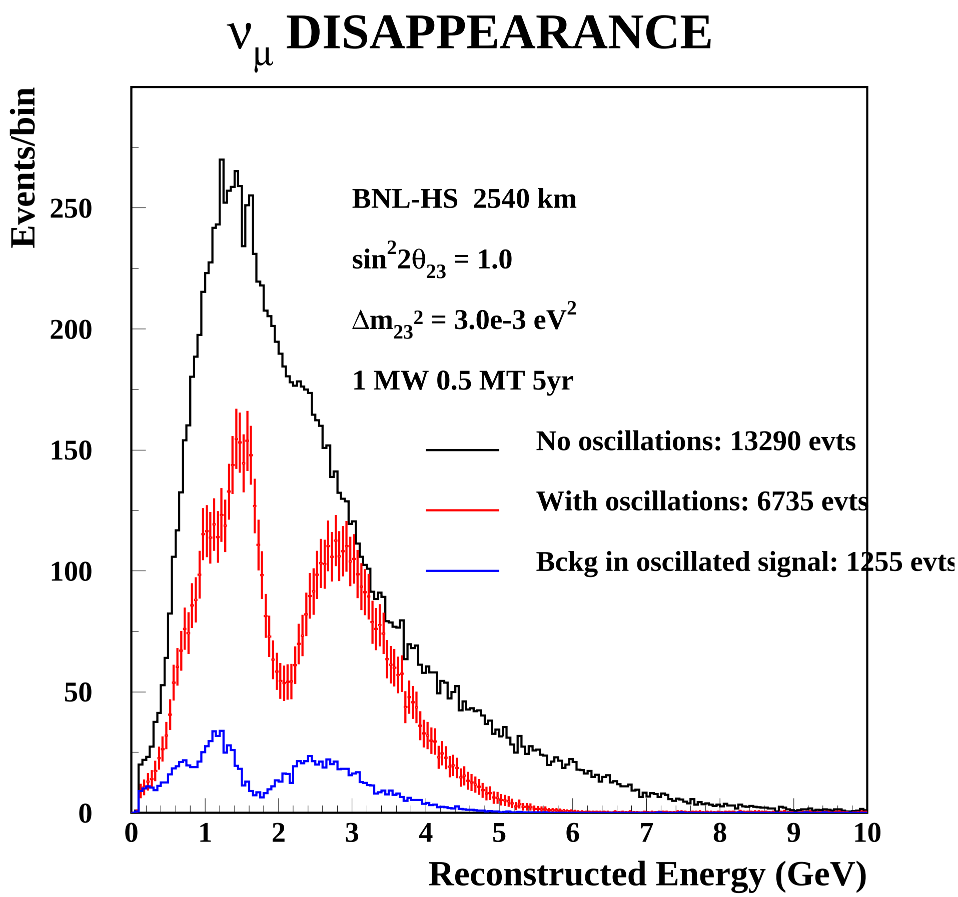
Assume Water Cerenkov detector (with ∼10% PMT coverage)

CC $\nu_\mu + N \rightarrow \mu^- + X$	51800
NC $\nu_\mu + N \rightarrow \nu_\mu + X$	16908
CC $\nu_e + N \rightarrow e^- + X$	380
QE $\nu_\mu + n \rightarrow \mu^- + p$	11767
QE $\nu_e + n \rightarrow e^- + p$	84
CC $\nu_\mu + N \rightarrow \mu^- + \pi^+ + N$	14574
NC $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$	3178
NC $\nu_\mu + O^{16} \rightarrow \nu_\mu + O^{16} + \pi^0$	574
CC $\nu_\tau + N \rightarrow \tau^- + X$ (if all $\nu_\mu \rightarrow \nu_\tau$)	319

Backgrounds to clean (QE) events SMALL

NC dominated by elastic and single π.

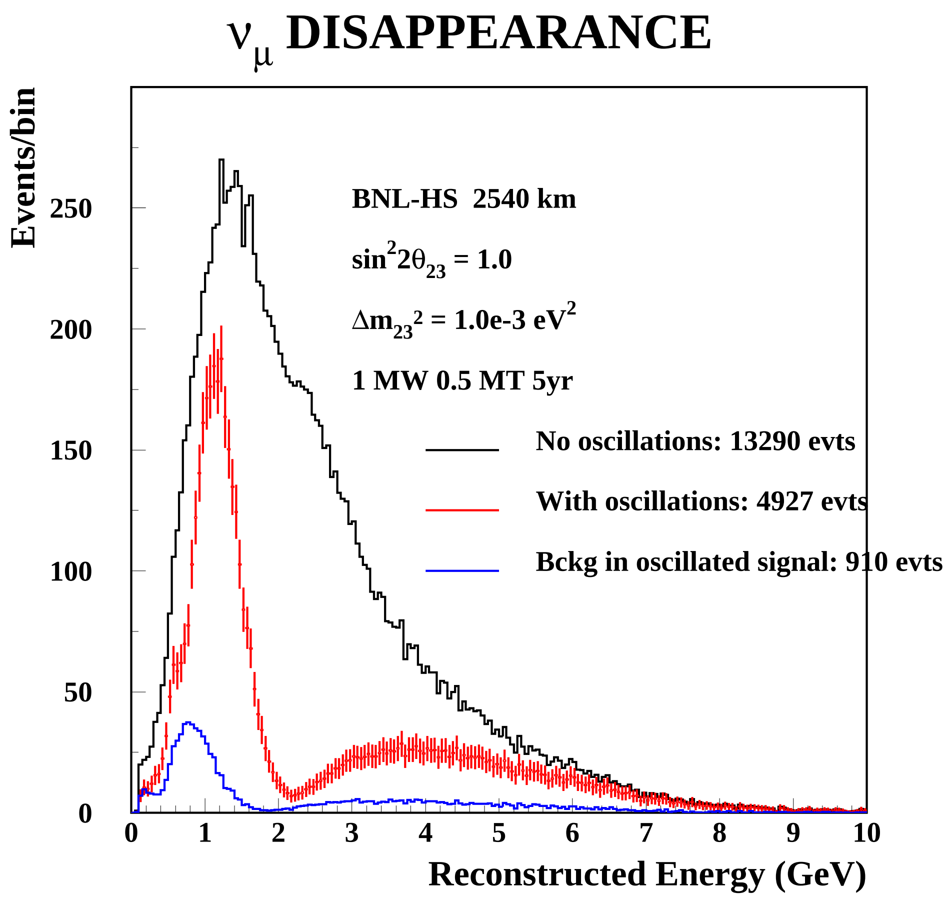
Low τ production.



Node pattern provides high Δm_{23}^2 resolution.
Energy calibration is very important.

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

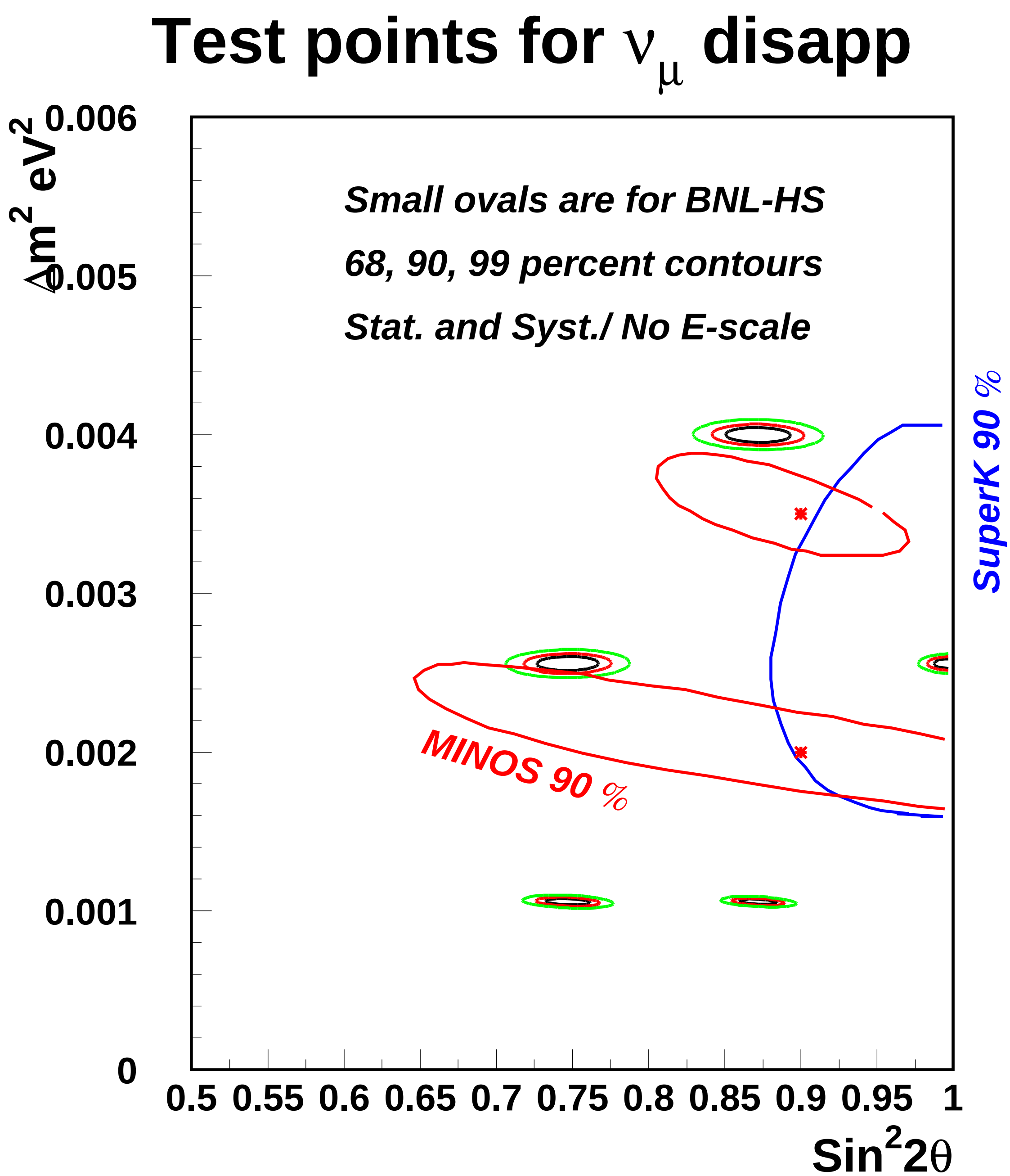
Background shape can be measured independently
Minimum systematics in ν_μ and $\bar{\nu}_\mu$ comparison



Node pattern provides high Δm^2_{23} resolution.
Energy calibration is very important.

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

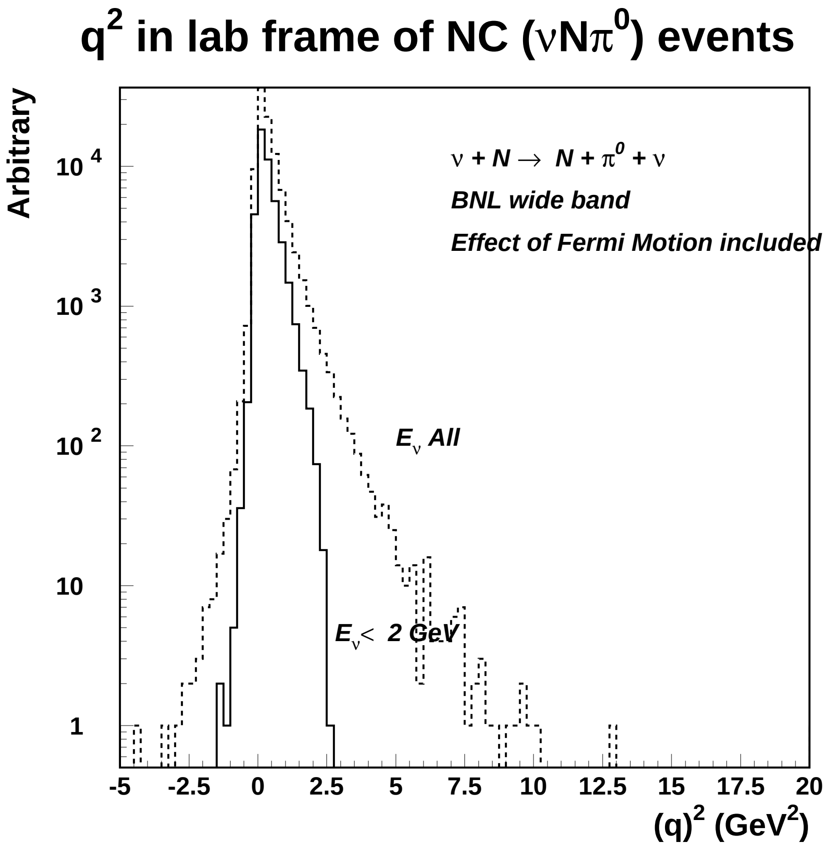
Background shape can be measured independently
Minimum systematics in ν_μ and $\bar{\nu}_\mu$ comparison


Test points for ν_μ disapp
Δm^2 eV^2
0.006
0.005
0.004
0.003
0.002
0.001
0
0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1
Sin^{2}2θ
Small ovals are for BNL-HS
68, 90, 99 percent contours
Stat. and Syst./ No E-scale
SuperK 90 %
MINOS 90 %

Measurement of Δm^2_{23}

- 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.

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



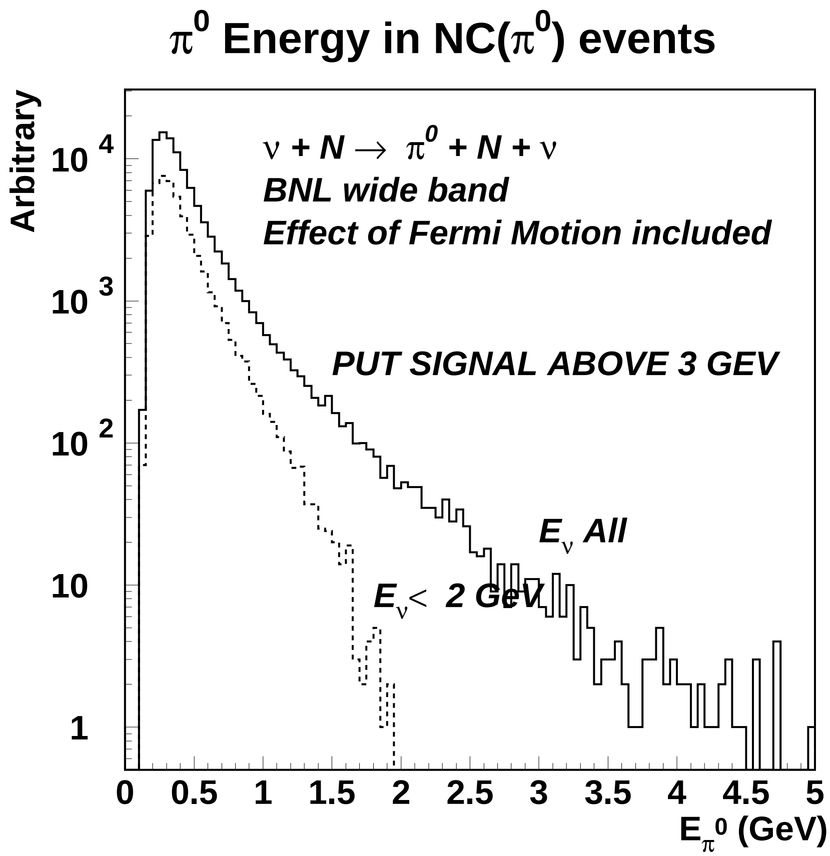
$q^2 = (p'_N + p'_\pi) - p_N.$

$p_N = (0, 0, 0, m_N)$ At rest nucleon.

General feature of all neutral current processes:

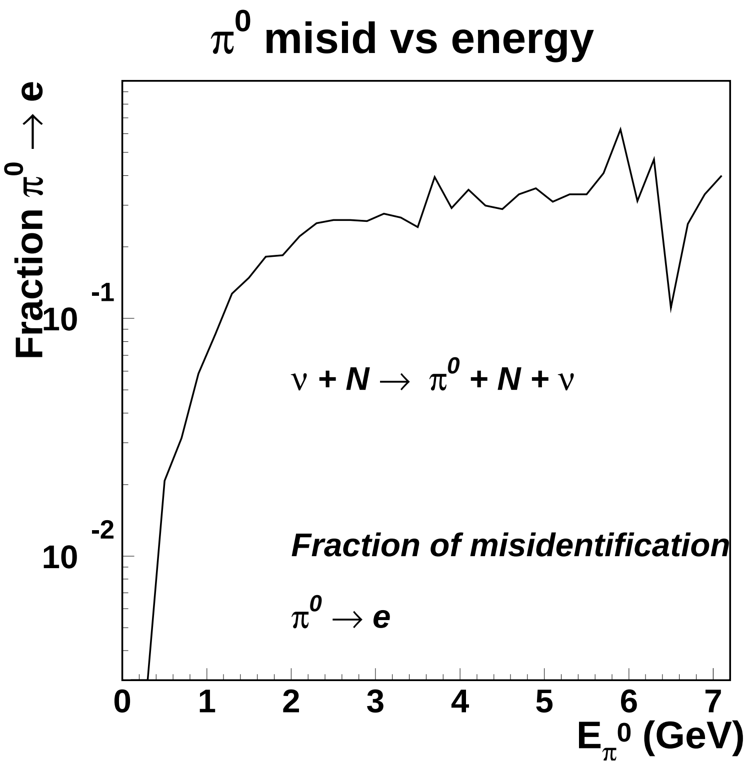
Low q^2 or low hadronic energy in final state independent of neutrino energy.

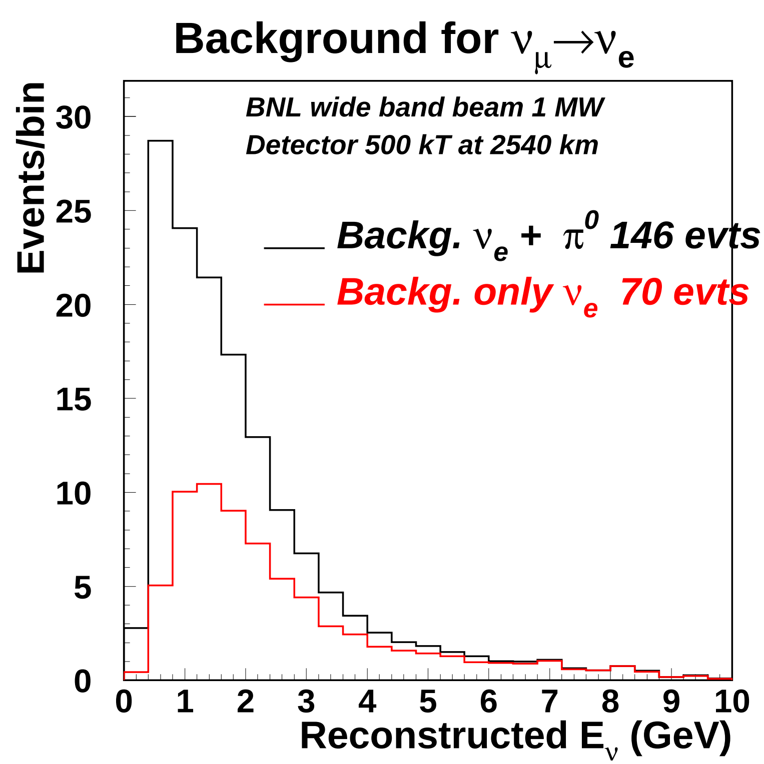
NC π^0 background for $\nu_\mu \rightarrow \nu_e$



- 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.

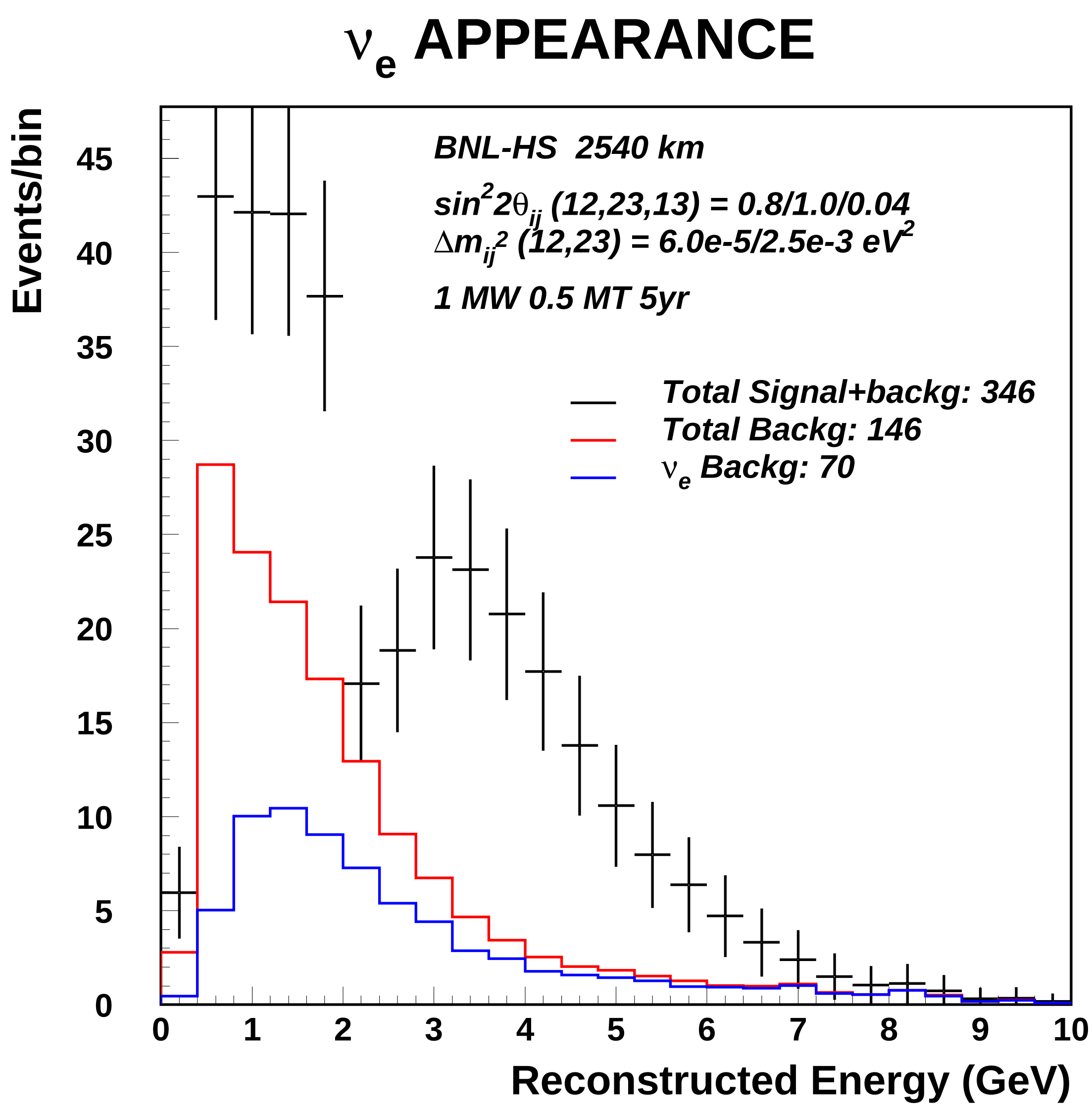
$\nu_\mu \rightarrow \nu_e$ All background





- 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 $\sin^2 2\theta_{13}$

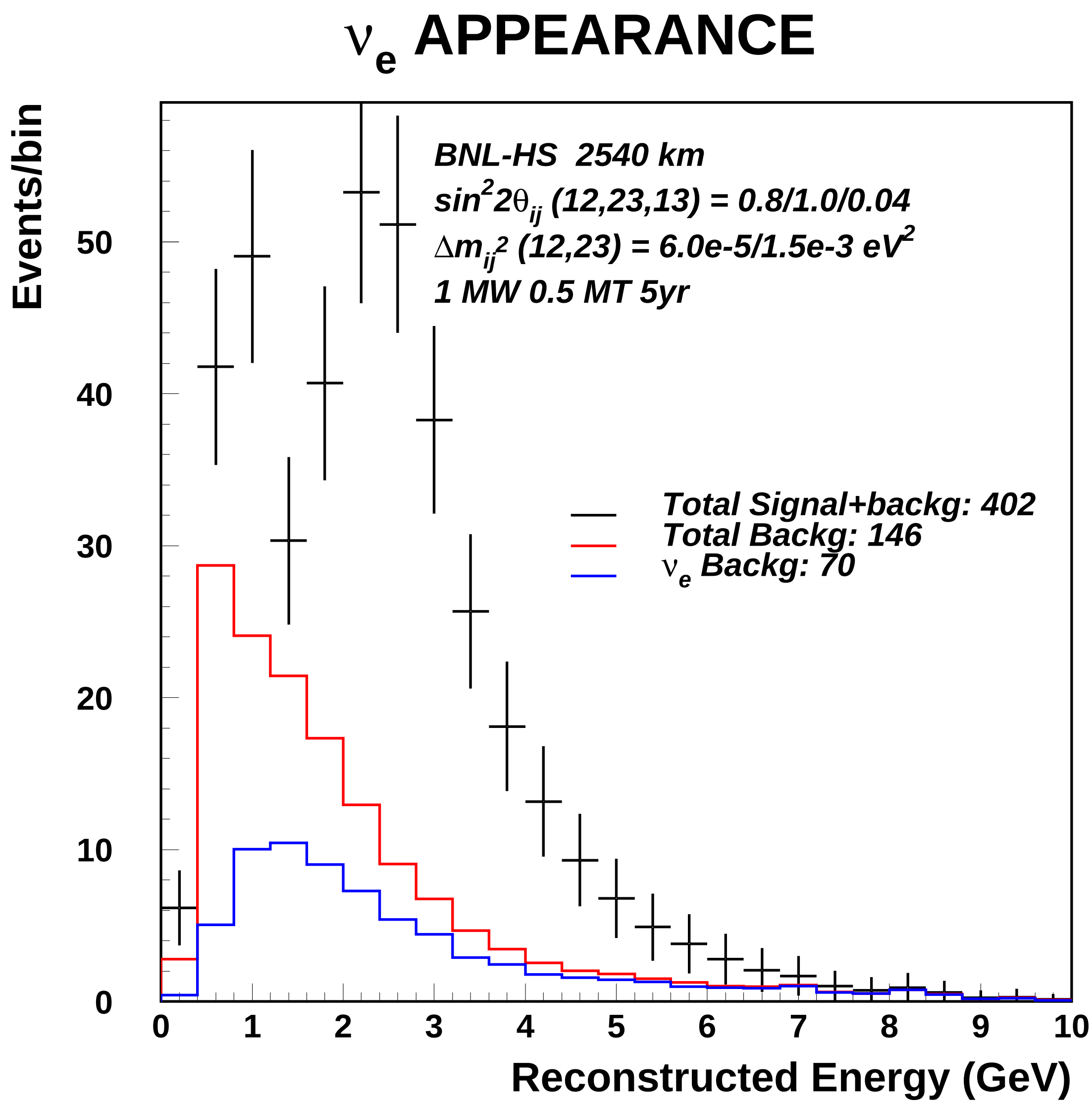


$\Delta m^2_{23} = 0.0025 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

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

Matter effects included.

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

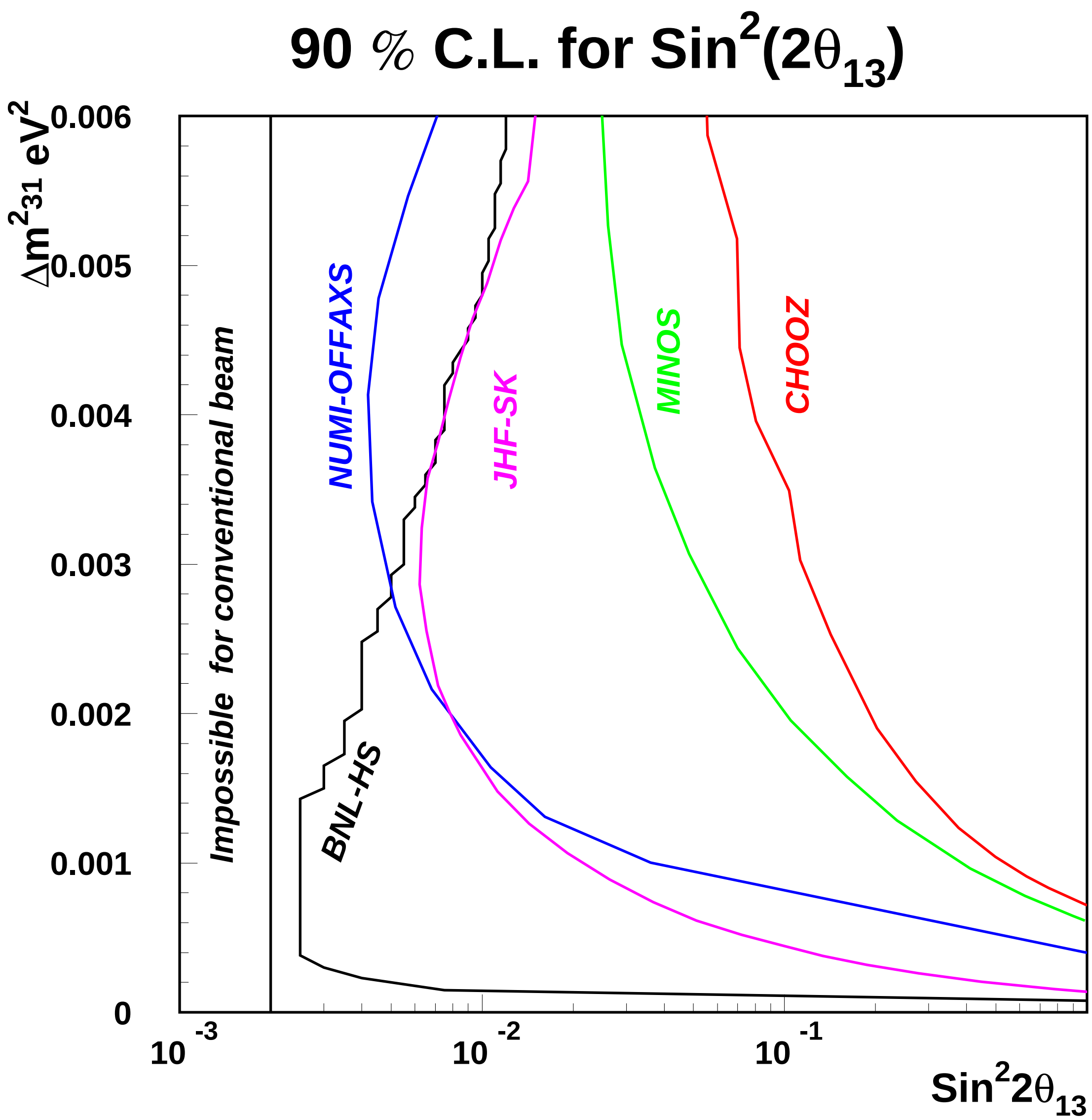


$\Delta m^2_{23} = 0.0015 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

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

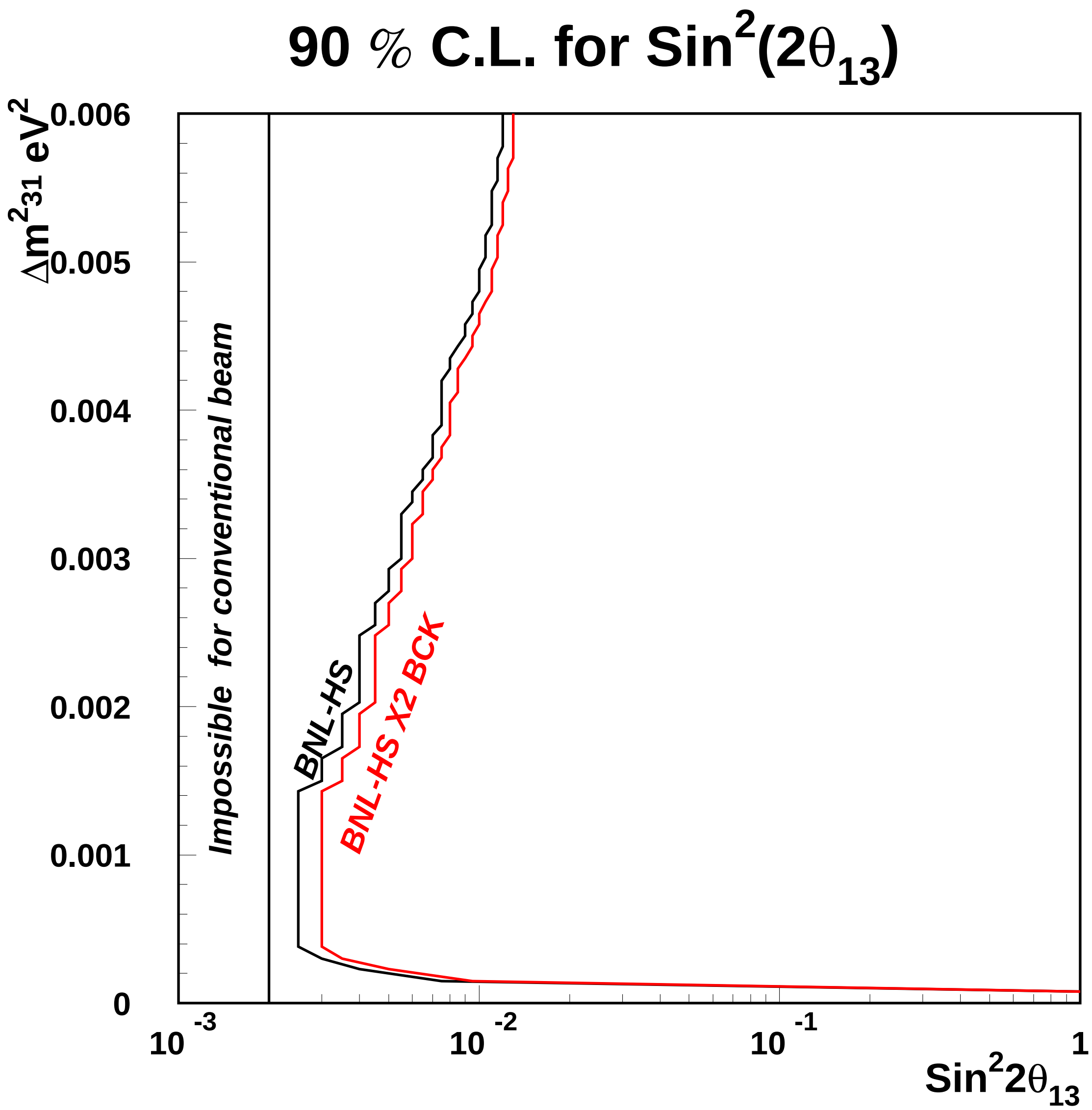
Matter effects included.

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

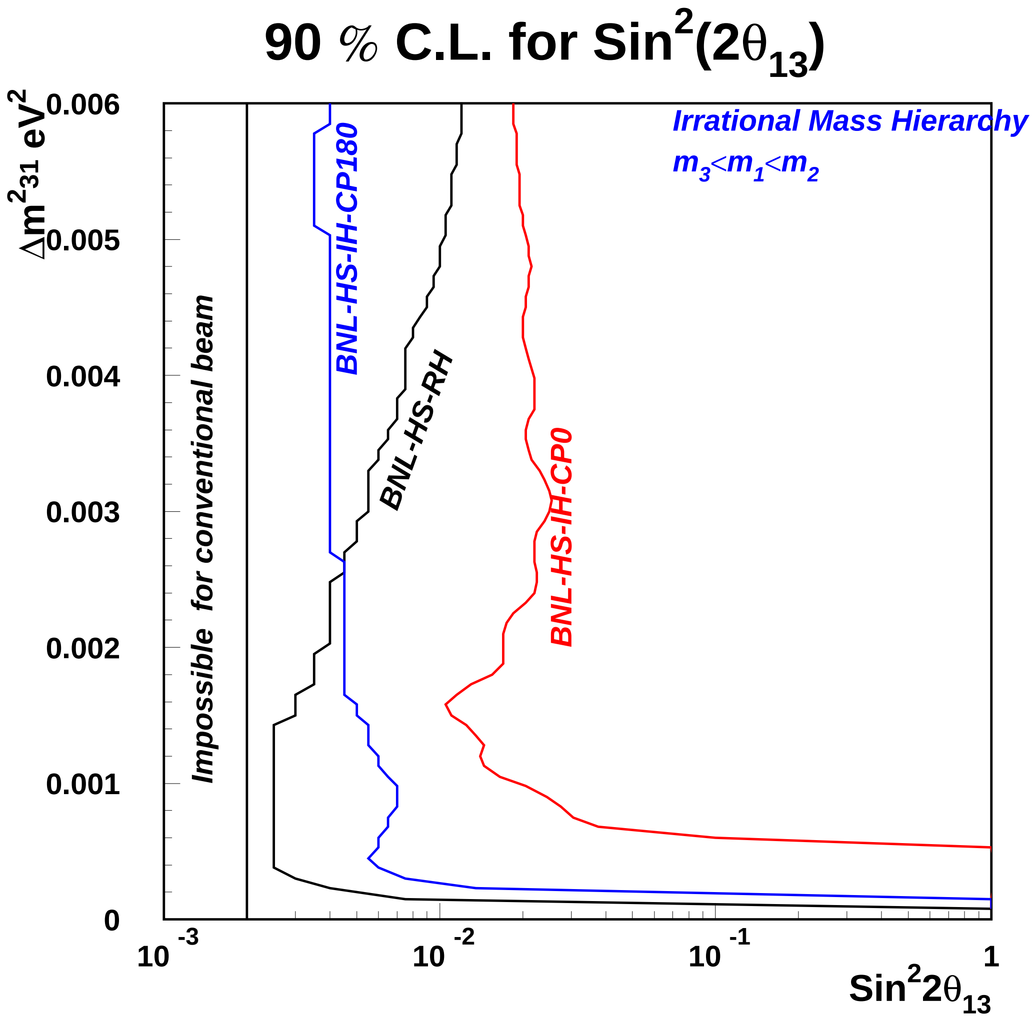
Improvement from 0.12 to 0.005 at 0.0025 eV^2.

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.

Mass Hierarchy



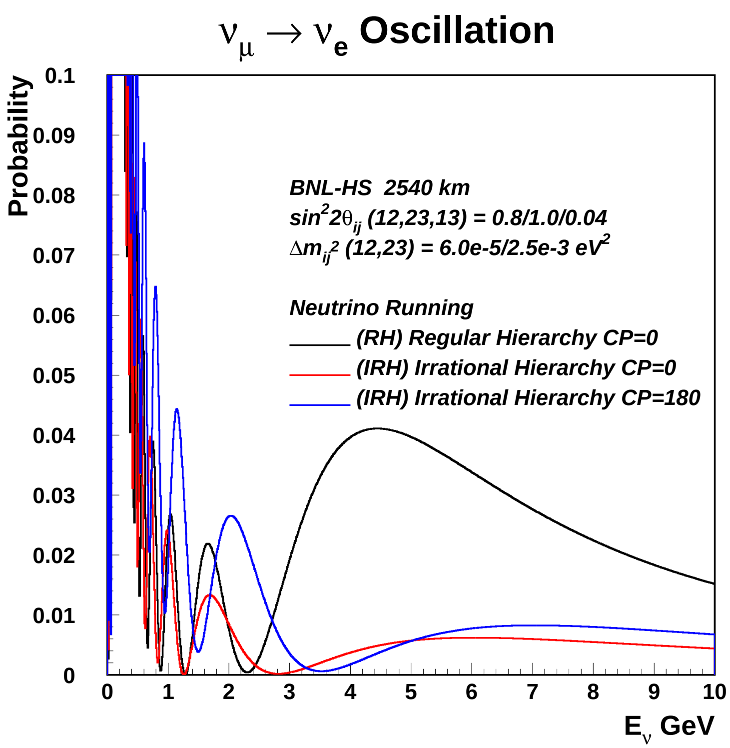
Regular Mass hierarchy: $m_3 > m_2 > m_1$ (RH)

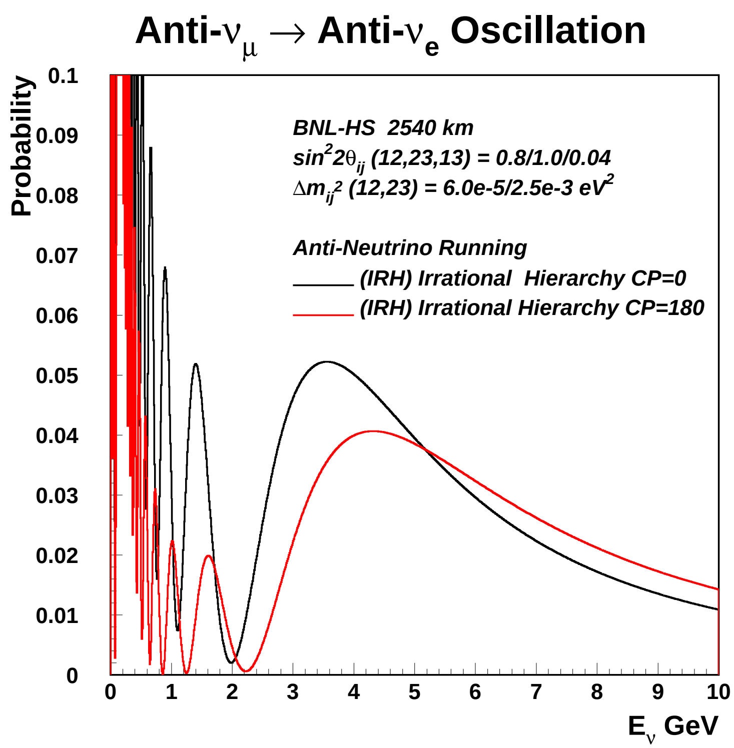
Reversed Mass hierarchy: $m_1 > m_2 > m_3$ (RVH)

Irrational Mass hierarchy: $m_2 > m_1 > m_3$ (IH)
RVH is ruled out if Solar LMA is the correct solution.

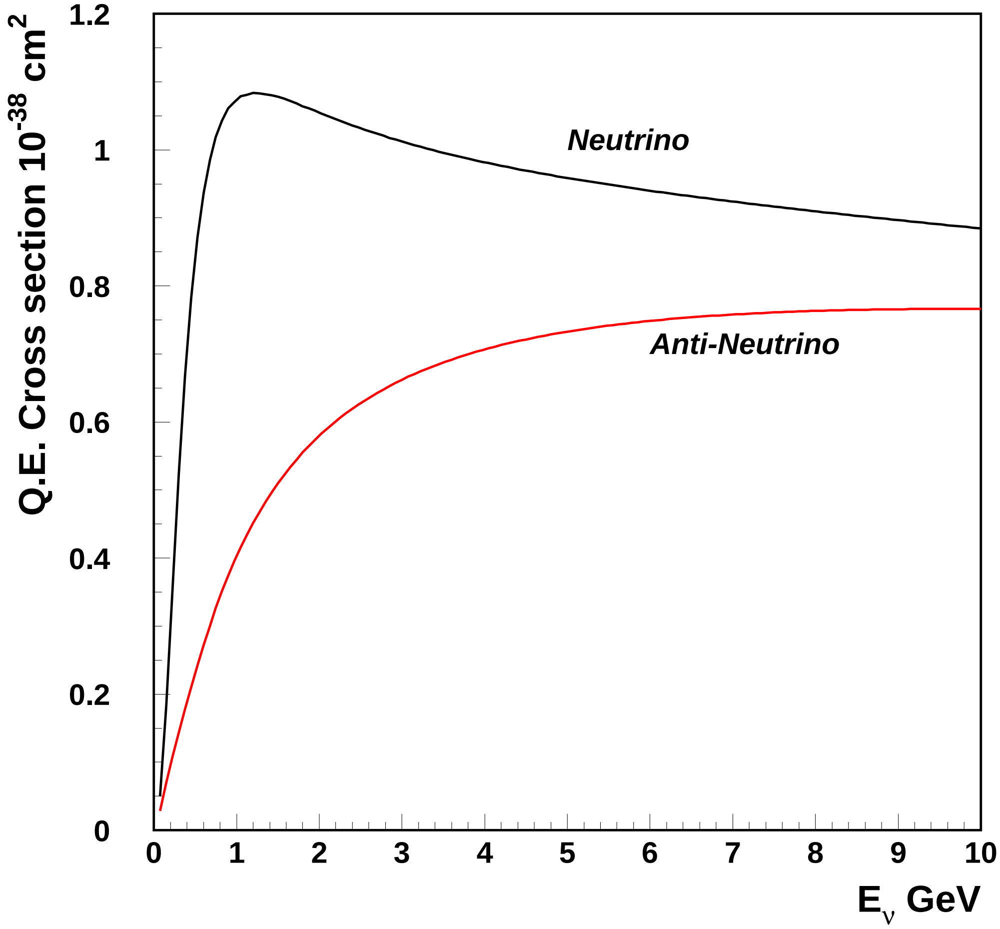
We would need to run Anti-neutrino beam to fully explore IH.

Mass Hierarchy Anti-neutrinos



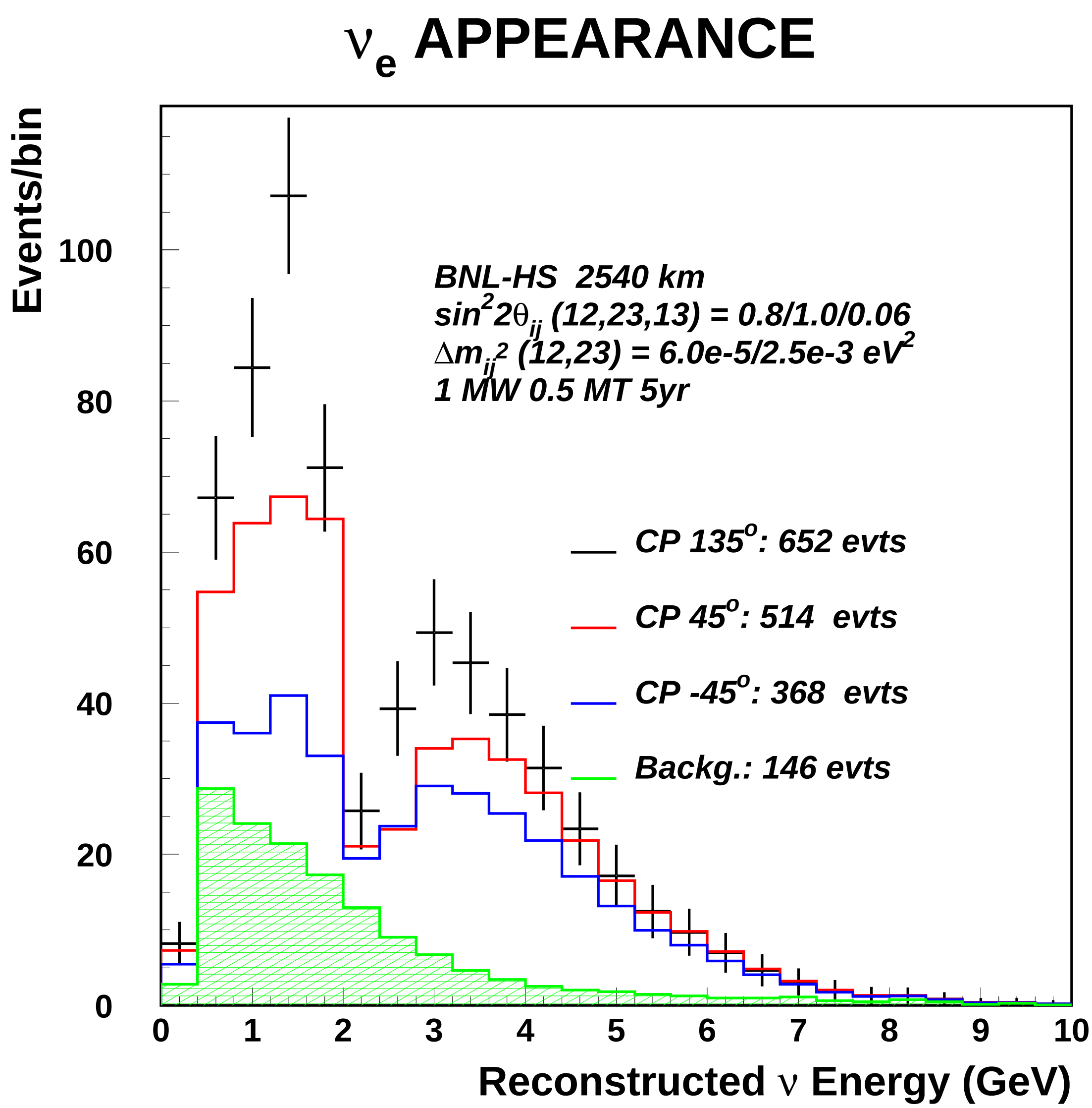


Quasielastic cross section



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

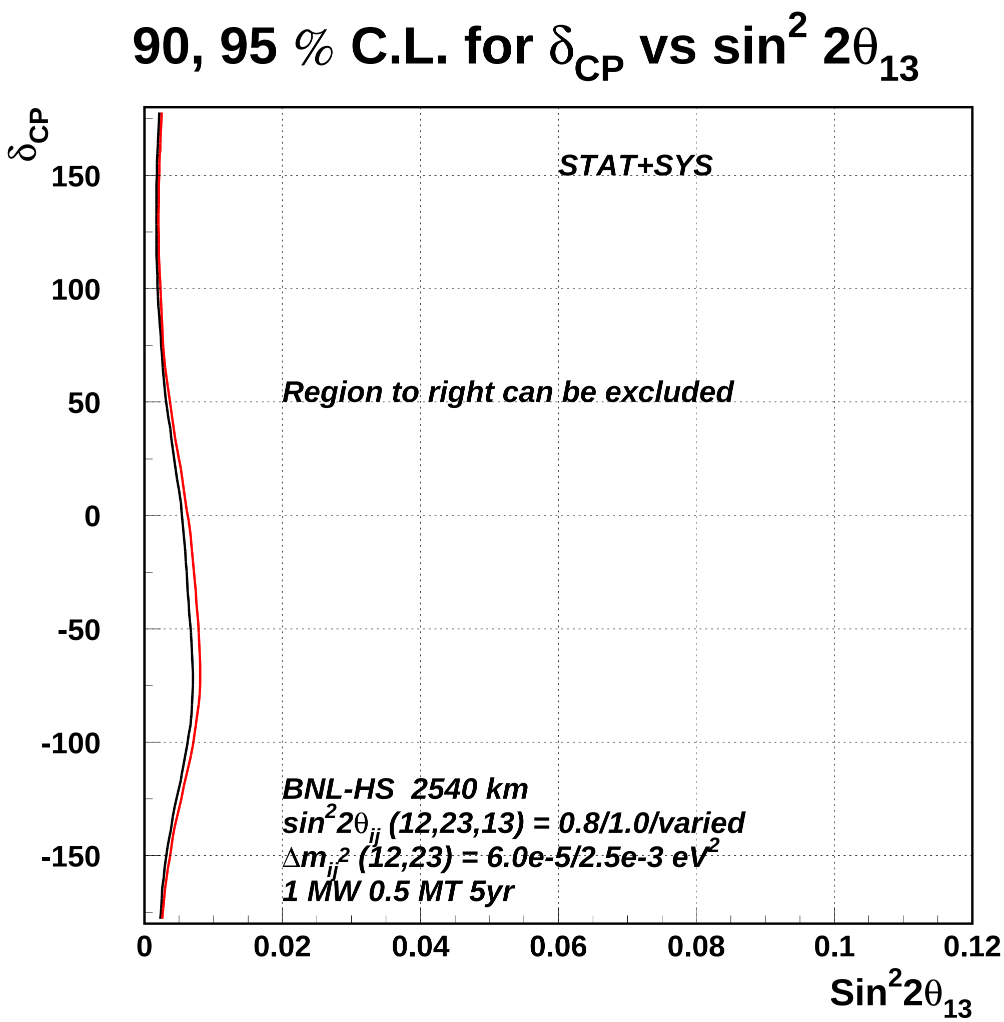
δ_{CP} Measurement. BNL-to-HS, 2540 km, 1 MW, 500kT, 5×10^7 sec



CP parameter can be determined from only neutrino data.

Good background subtraction can help.

Measurement of $\delta_C P$; Confidence Levels

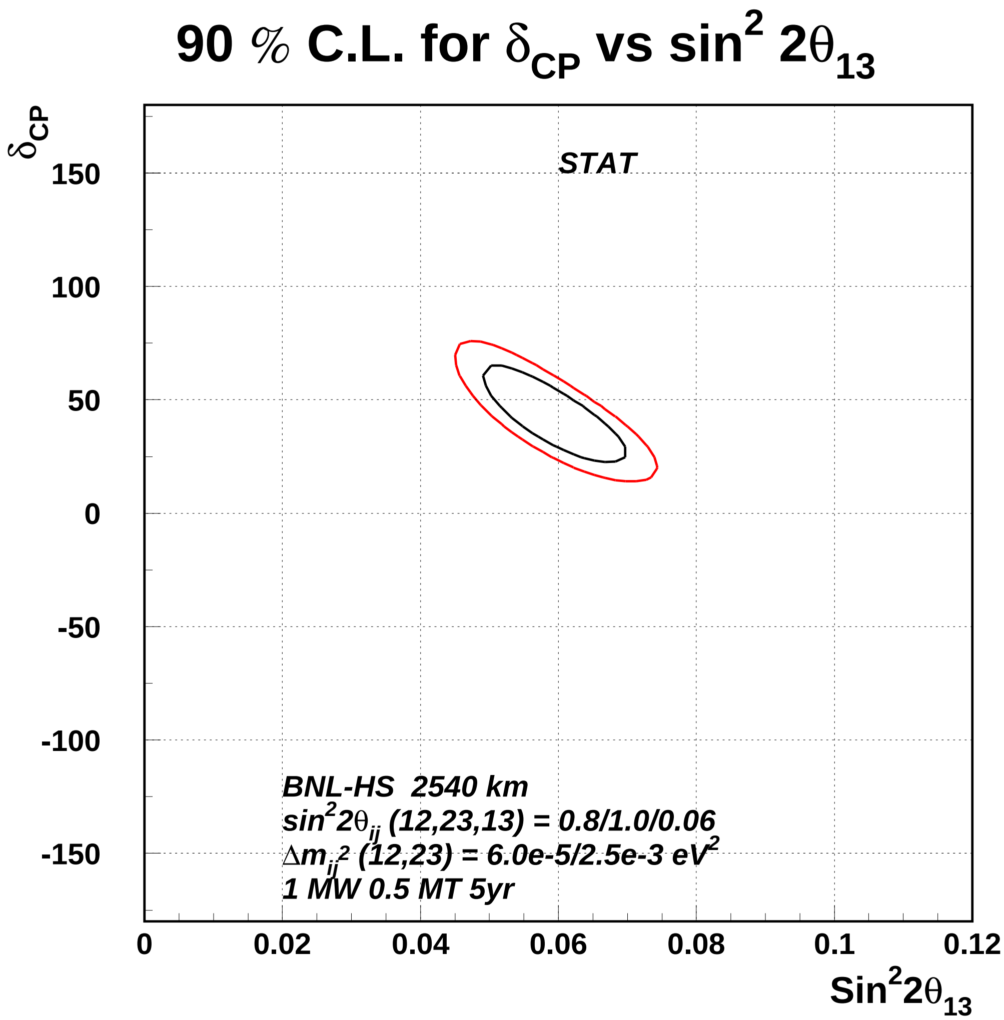


$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

The region on the right hand side of curve can be excluded at 95% C.L.

Measurement of $\delta_{CP} = 45^o$



No Systematic error

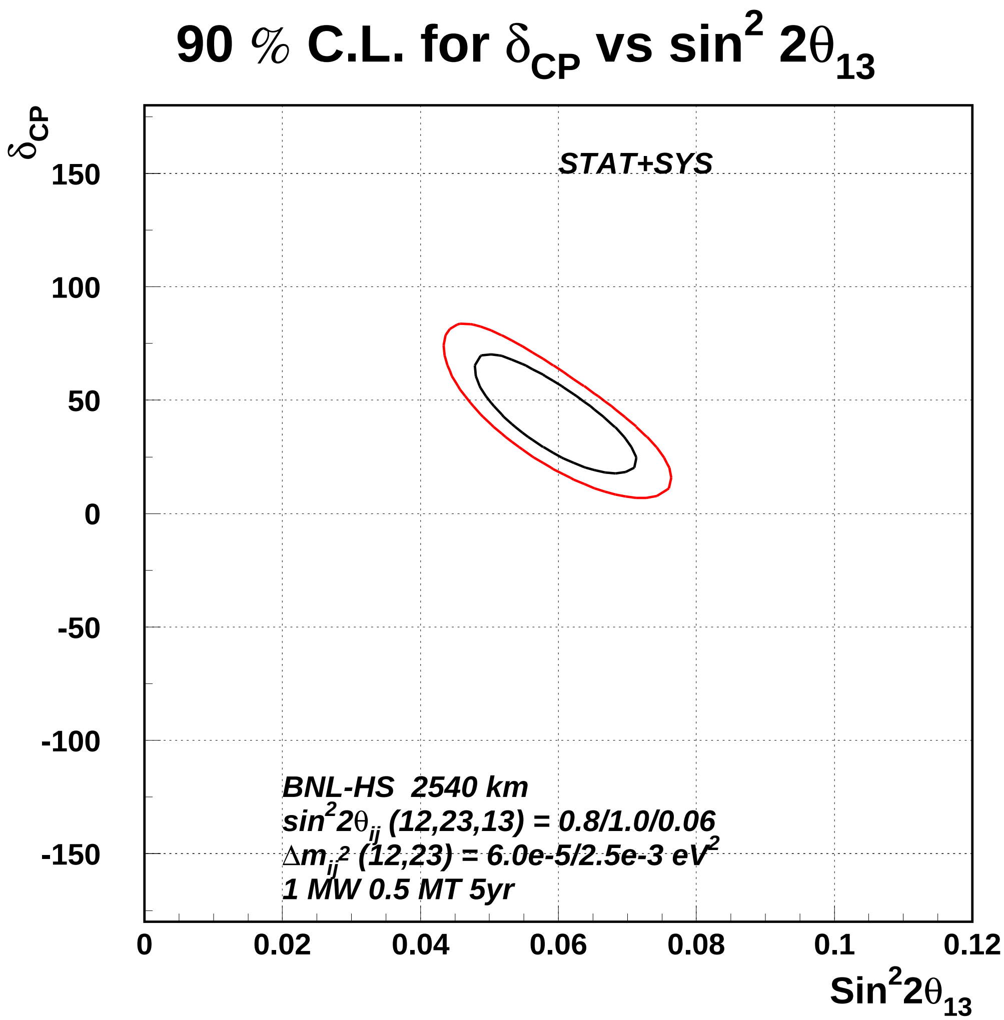
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

$\delta_{CP} = 45^o$, $\sin^2 2\theta_{13} = 0.06$

68%, and 90% C.L.

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



Systematic error of 10% on backg.

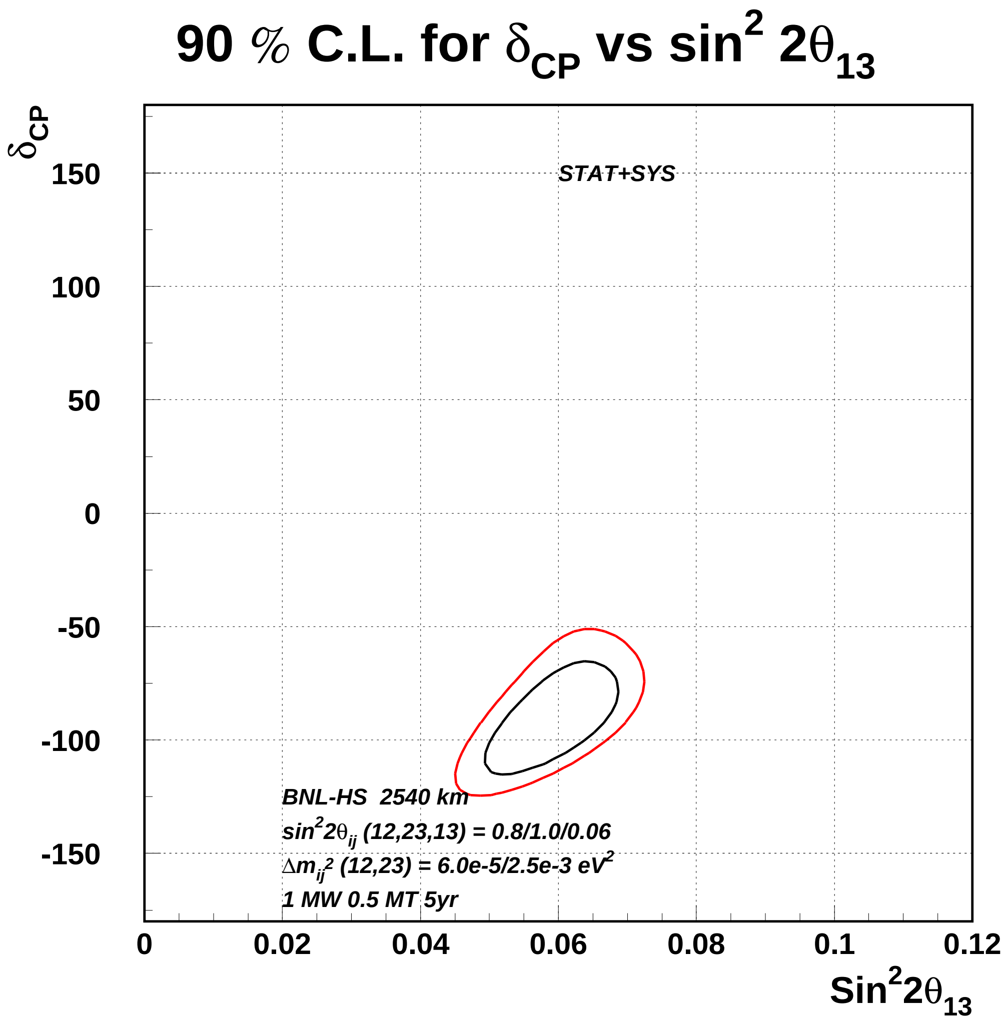
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

$\delta_{CP} = 45^o$, $\sin^2 2\theta_{13} = 0.06$

68%, and 90% C.L.

Measurement of $\delta_{CP} = -90^o$



Systematic error of 10% on backg.

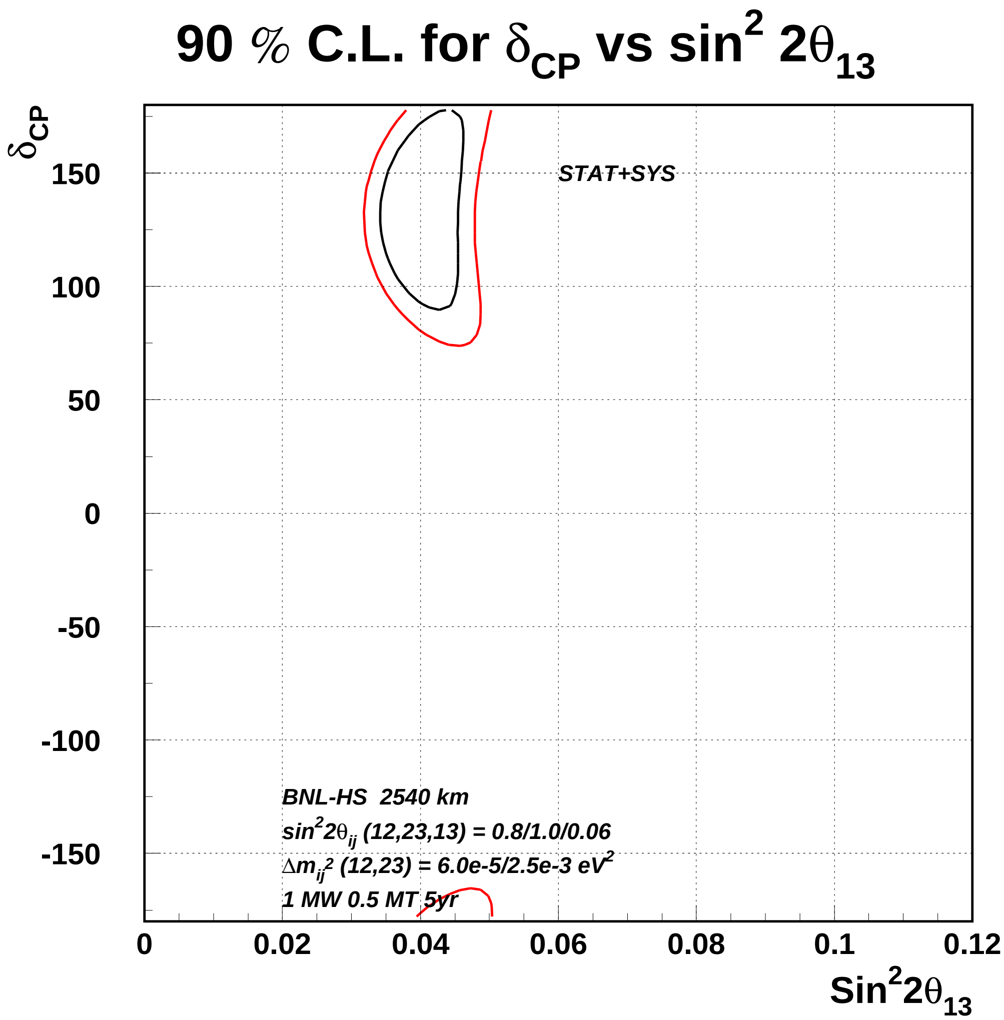
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

$\delta_{CP} = -90^o$, $\sin^2 2\theta_{13} = 0.06$

68%, and 90% C.L.

Measurement of $\delta_{CP} = 135^o$



Systematic error of 10% on backg.

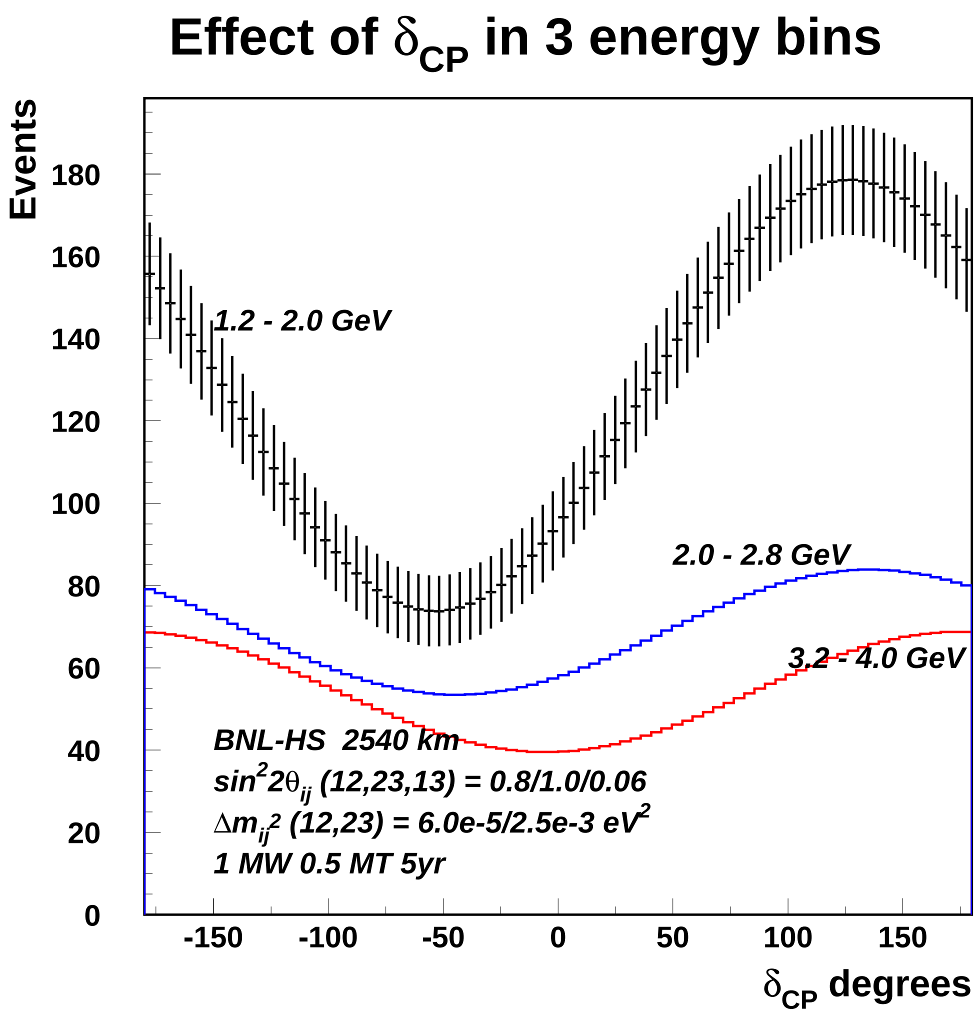
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

$\delta_{CP} = 135^o$, $\sin^2 2\theta_{13} = 0.06$

68%, and 90% C.L.

Effect of δ_{CP} on the spectrum.



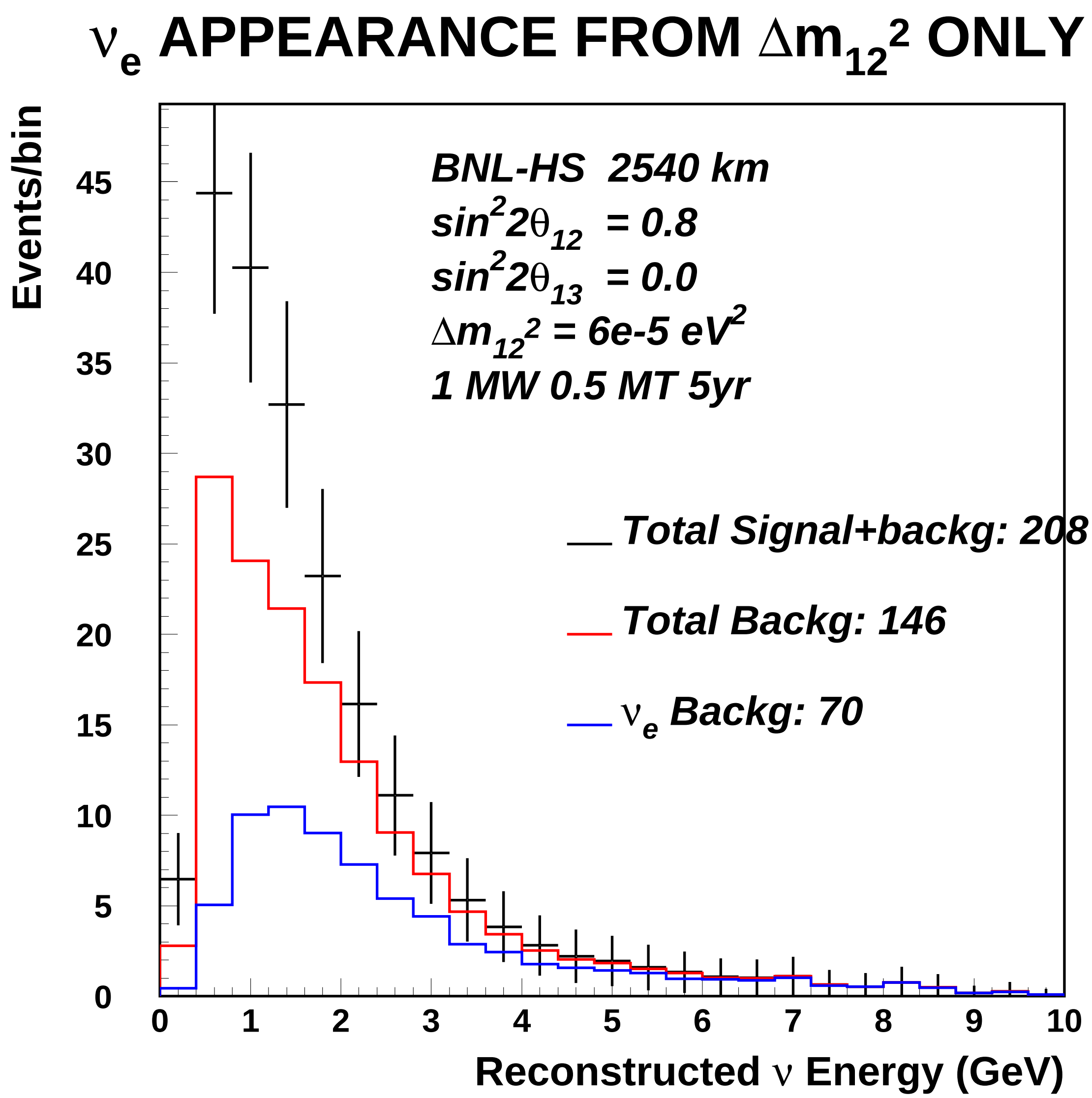
Event rate in 3 energy bins.

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

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

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

Measurement of Δm^2_{12}

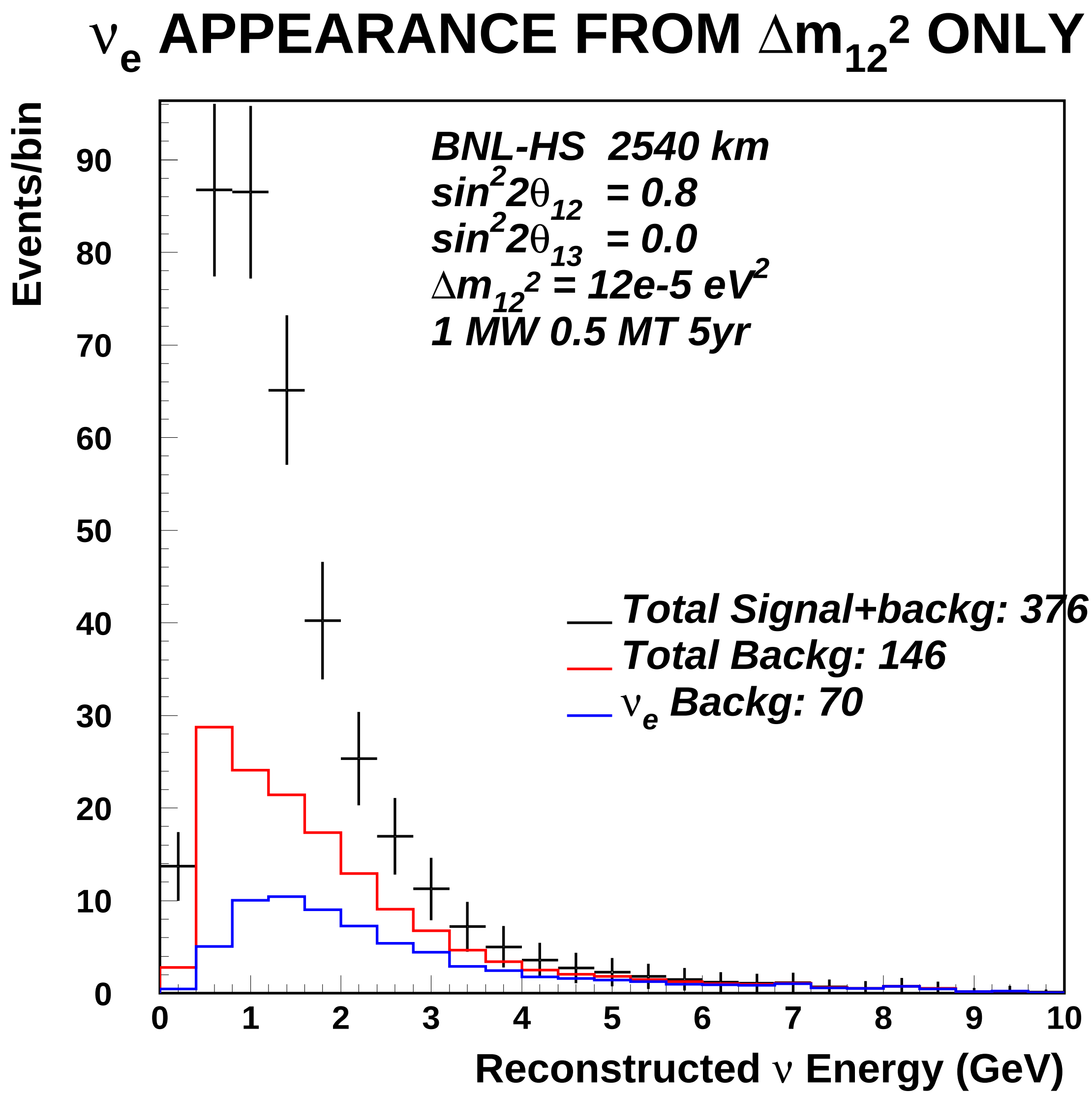


$\theta_{13} = 0$, $\Delta m^2_{12} = 6 \times 10^{-5} eV^2$

Excess of ~ 50 events. Must know background

Recall $\sin^2(1.27 \Delta m^2_{12} 2540\ km/1\ GeV) = 0.037$

Measurement of Δm^2_{12}

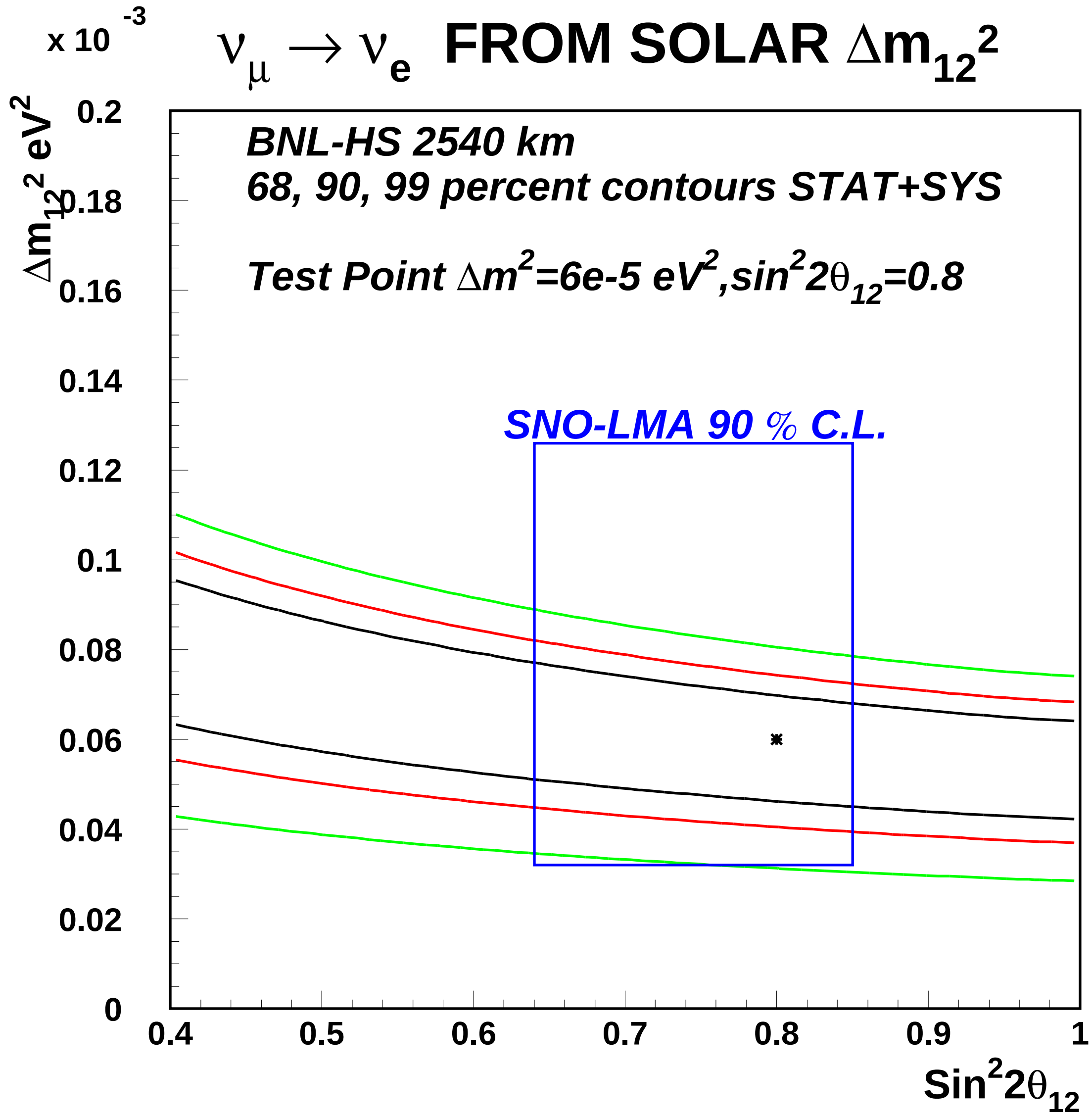


$\theta_{13} = 0$

$\Delta m^2_{12} = 12 \times 10^{-5} ev^2$

Excess of $\sim$ 230 events. Unmistakable.

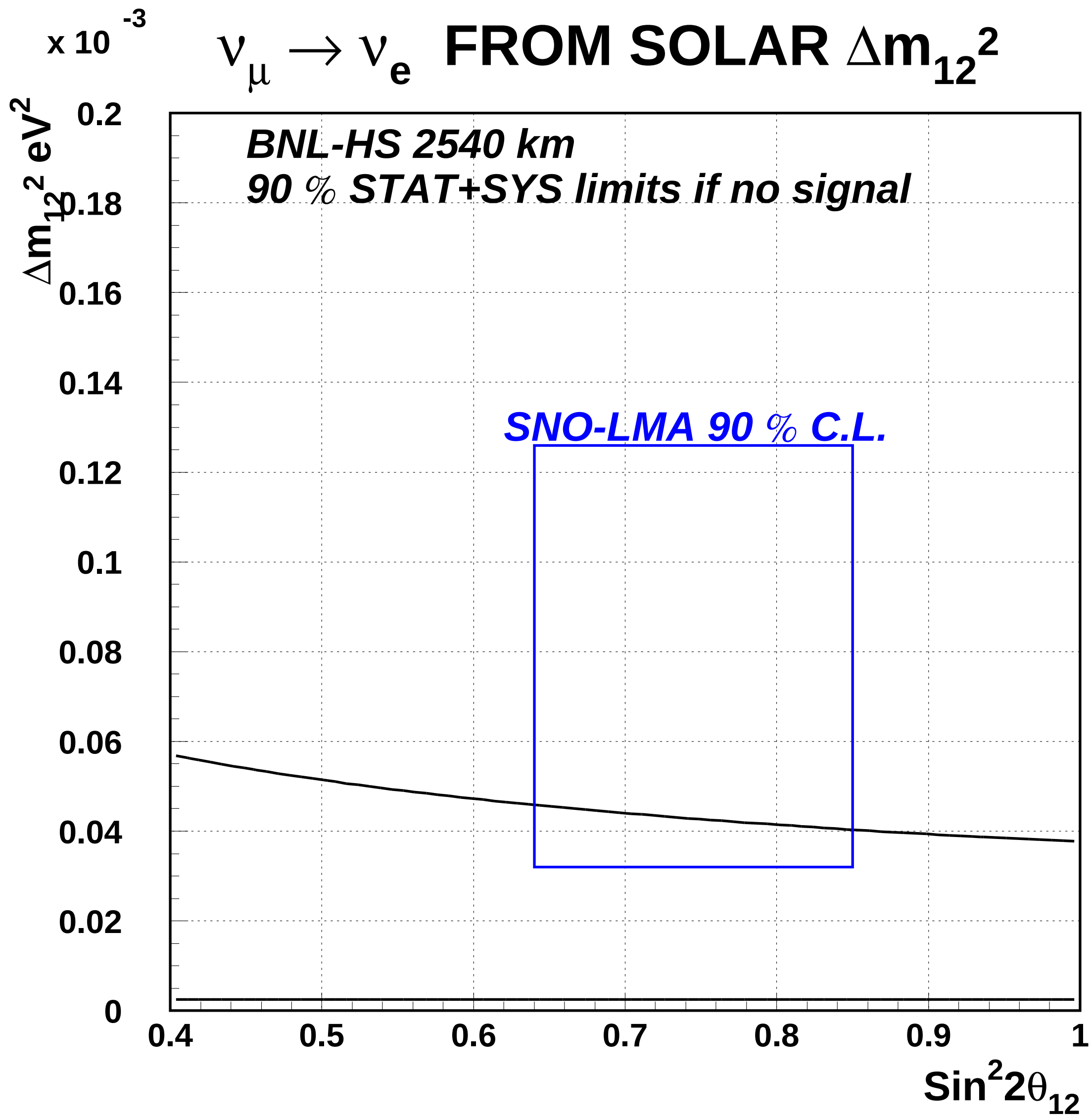
Measurement of Δm^2_{12}



Independent $\sim 15\%$ measurement of Δm^2_{12}

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

Limit on Δm^2_{12} 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_{23} from disappearance and definitive signal of oscillations.
- From the measured Δm^2_{23} 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_{12} 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_{12} 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_{12} , 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_{12} 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_{12}	$\sin^2 2\theta_{13}$ 90 % C.L.	δ_{CP}
$\Delta m^2_{32} > 0.001$	$< 1\%$	$\sim 1\%$	$\pm 15\%$	~ 0.005	
$\Delta m^2_{32} > 0.001$ $\sin^2 2\theta_{13} > 0.01$	$< 1\%$	$\sim 1\%$	$\pm 15\%$	± 0.01	$\pm 25^o$
$\Delta m^2_{32} > 0.001$ $\sin^2 2\theta_{13} < 0.01$	$< 1\%$	$\sim 1\%$	$\pm 15\%$	No Measure.	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_{12} and CP. (Near Detector)

What is Next ?

Study will be published shortly.

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

Anti-neutrino sensitivity. Hierarchy determination.

Parameter correlations.

Background determination with near det.

- The experiment is technically feasible.
  Direct costs.

  AGS upgrade, Hill, Proton transp., horns, decay tunnel: $\sim \$150M$

  Detector: \$300 M for 10% PMT coverage.

  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.