Very long baselines with a superbeam

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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.

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

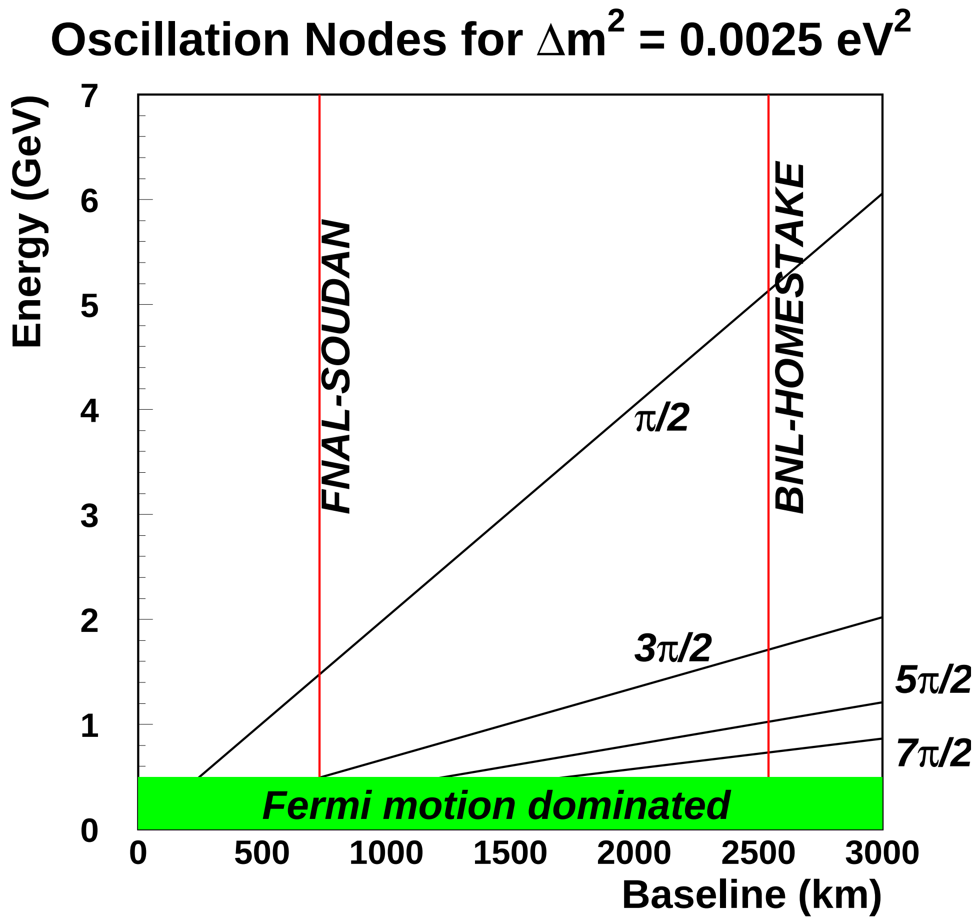
$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= | < \nu_b|\nu_a(t) > |^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned} \quad (2)$$

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 ($0.5 \rightarrow 8$ GeV).
- $\Delta m^2 \approx 0.0025 eV^2$: Baseline > 2000 km.

Neutrino Physics: the difficult stuff

Bill Marciano, hep-ph/0108181

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_1c_3 & s_1c_3 & s_3e^{-i\delta} \\ -s_1c_2 - c_1s_2s_3e^{i\delta} & c_1c_2 - s_1s_2s_3e^{i\delta} & s_2c_3 \\ s_1s_2 - c_1c_2s_3e^{i\delta} & -c_1s_2 - s_1c_2s_3e^{i\delta} & c_2c_3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{3}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) \quad = \quad & 4(s_2^2 s_3^2 c_3^2 + J_{CP} \sin\Delta_{21}) \sin^2 \frac{\Delta_{31}}{2} \\ & +2(s_1s_2s_3c_1c_2c_3^2 \cos\delta - s_1^2s_2^2s_3^2c_3^2) \sin\Delta_{31} \sin\Delta_{21} \\ & +4(s_1^2c_1^2c_2^2c_3^2 + s_1^4s_2^2s_3^2c_3^2 - 2s_1^3s_2s_3c_1c_2c_3^2\cos\delta \\ & \quad - J_{CP}\sin\Delta_{31}) \sin^2\frac{\Delta_{21}}{2} \\ & +8(s_1s_2s_3c_1c_2c_3^2\cos\delta - s_1^2s_2^2s_3^2c_3^2) \sin^2\frac{\Delta_{31}}{2} \sin^2\frac{\Delta_{21}}{2} \end{aligned} \tag{4}$$

No matter effects in above formula

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

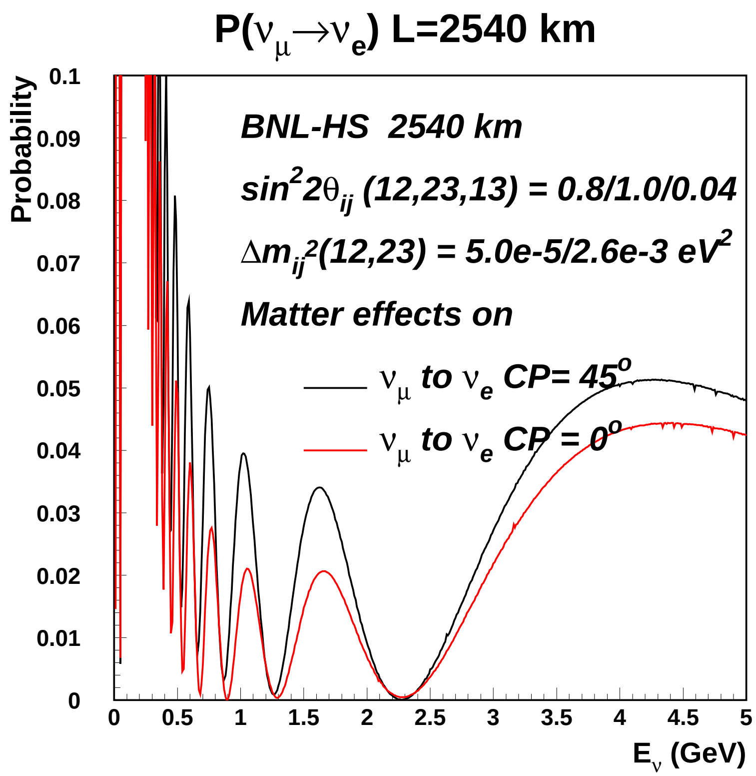
$$J_{CP} \equiv s_1 s_2 s_3 c_1 c_2 c_3^2 \sin\delta \tag{5}$$

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

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

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

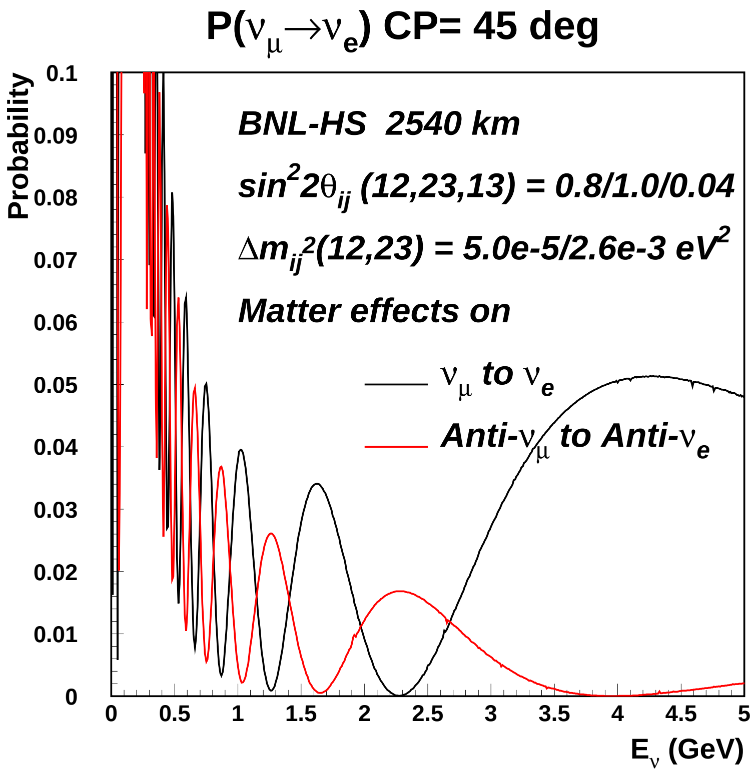
$$A \simeq \frac{J_{CP} \sin\Delta_{21}}{s_2^2 s_3^2 c_3^2} \simeq \frac{2 s_1 c_1 c_2 \sin\delta}{s_2 s_3} \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right) \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}(\Delta^2_{21}) \tag{12b}$$



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)



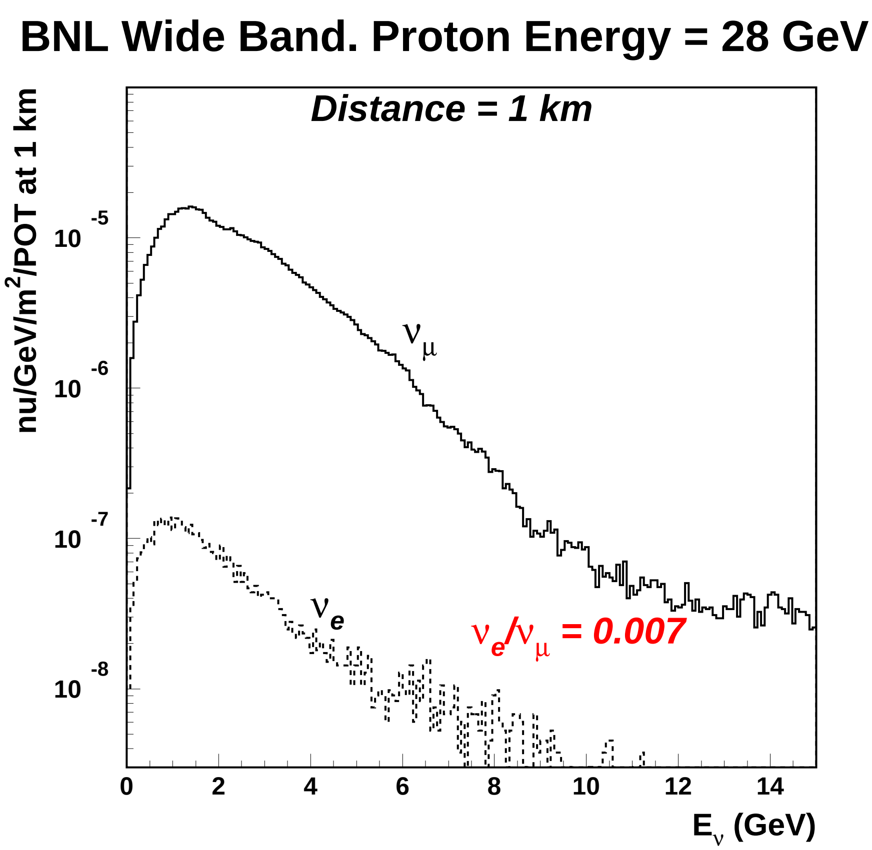
Compare Neutrino to Antineu.

- $0.5 - 1$ 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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

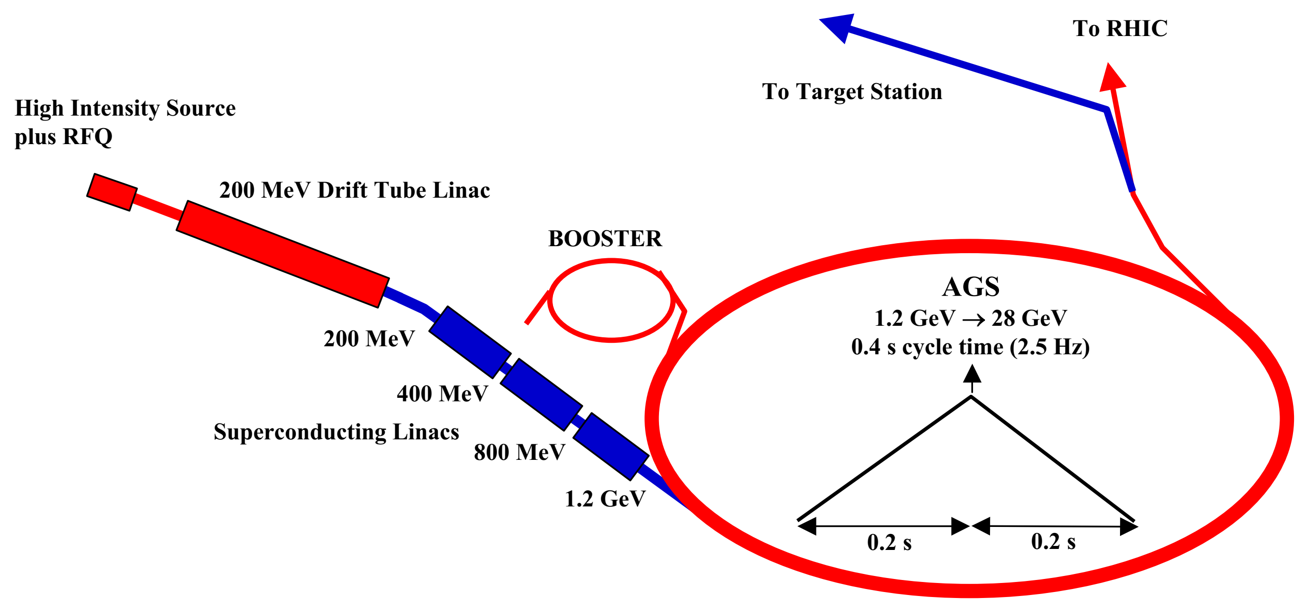
  It will be good to do it all in same experiment with only neutrino beam (no antineutrino).



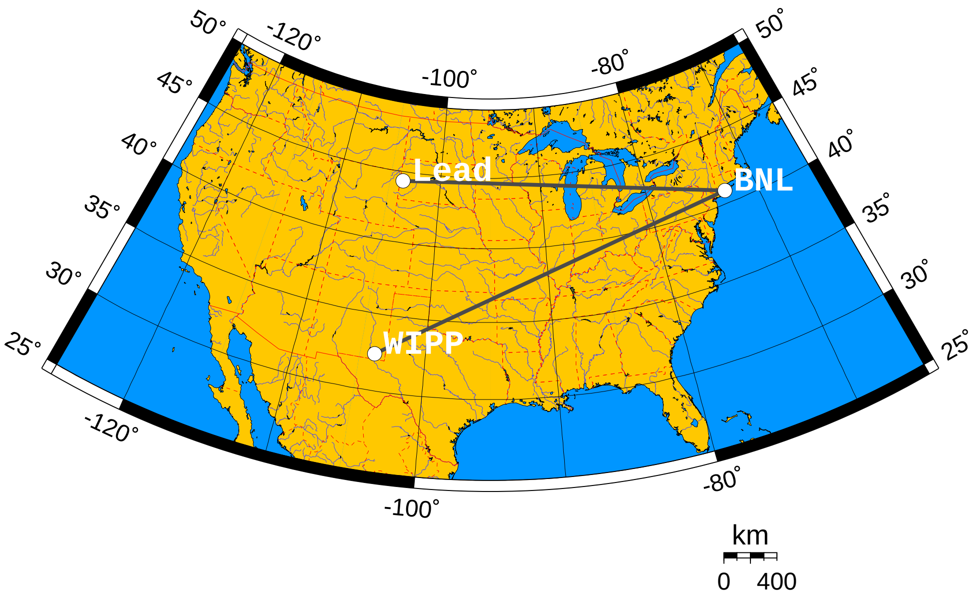
- New design spans 0.5-6 GeV
- Low ν_e background 0.7%
  0.0073 ± 0.0014 (E734 1986).
- Low background from high energies (NC and ν_τ for ν_e)
- 200 m decay tunnel
- Graphite target embedded in horn
- Target cooling achievable for 1 MW

The Accelerator

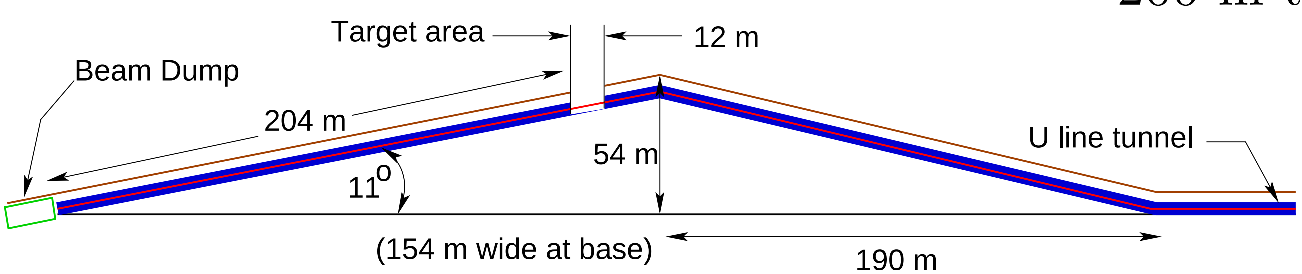
- Conceptually simple upgrade. No magic. Cost $\sim \$100M$.
- Run 28 GeV AGS at 2.5 Hz to get 1 MW.
- Need faster proton source: Super Conducting LINAC at 1.2 GeV
- Current: $7 \times 10^{13} ppp$ at 0.5 Hz => LINAC: $10^{14} ppp$ at 2.5 Hz.



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.

Neutral Current Events Neutrinos

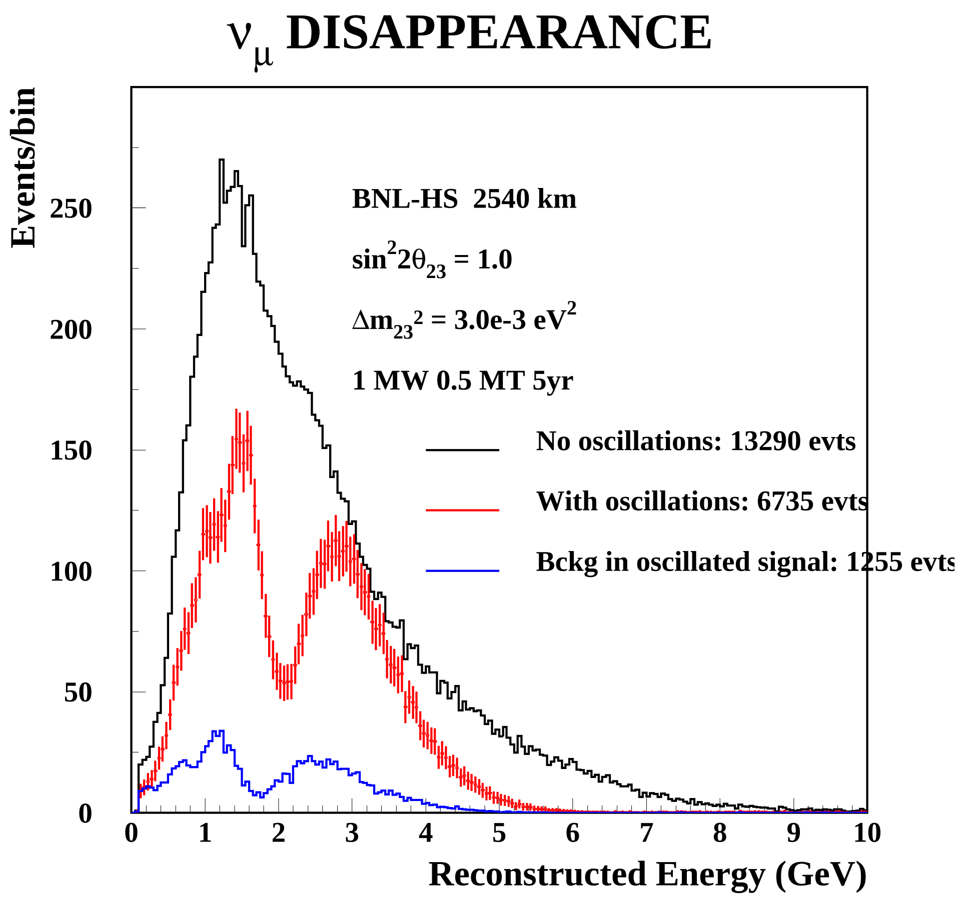
Assume 1 MW, 500 kT Fiducial, 5×10^7 sec running. (1.22×10^{22} Protons at 28 GeV.)

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.

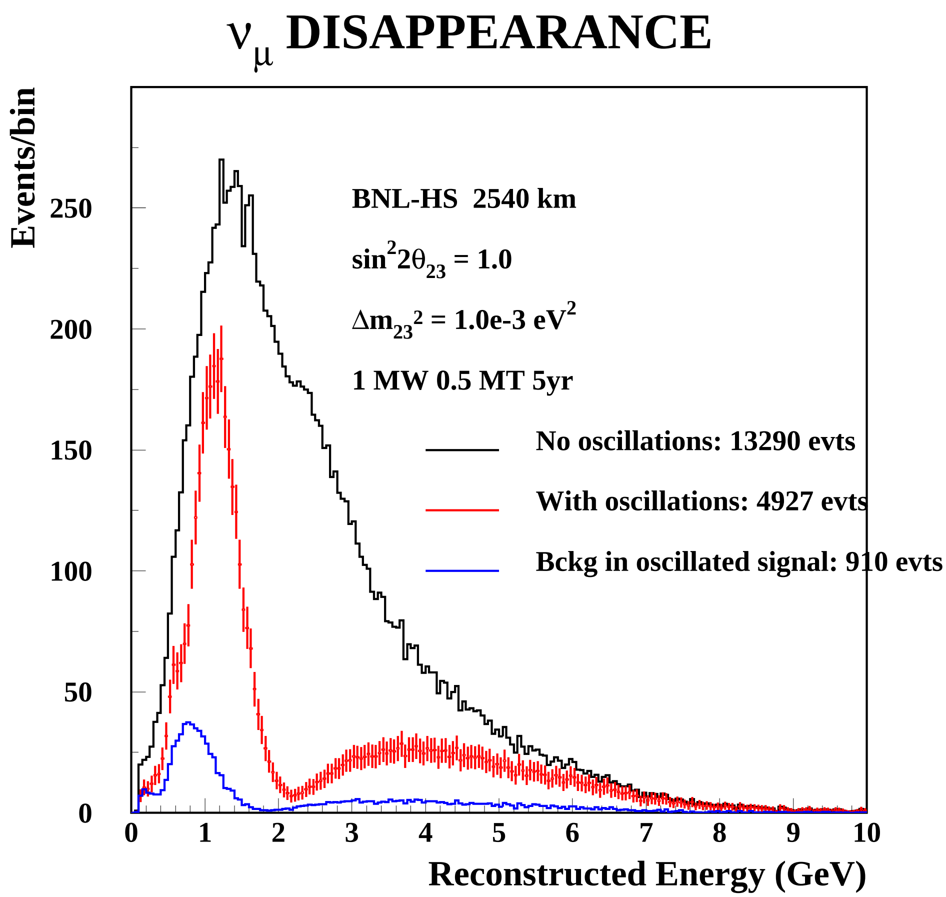
Both single and multi-pi event rate display the same tendency to fall rapidly with energy.



Node pattern provides high Δm^2_{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



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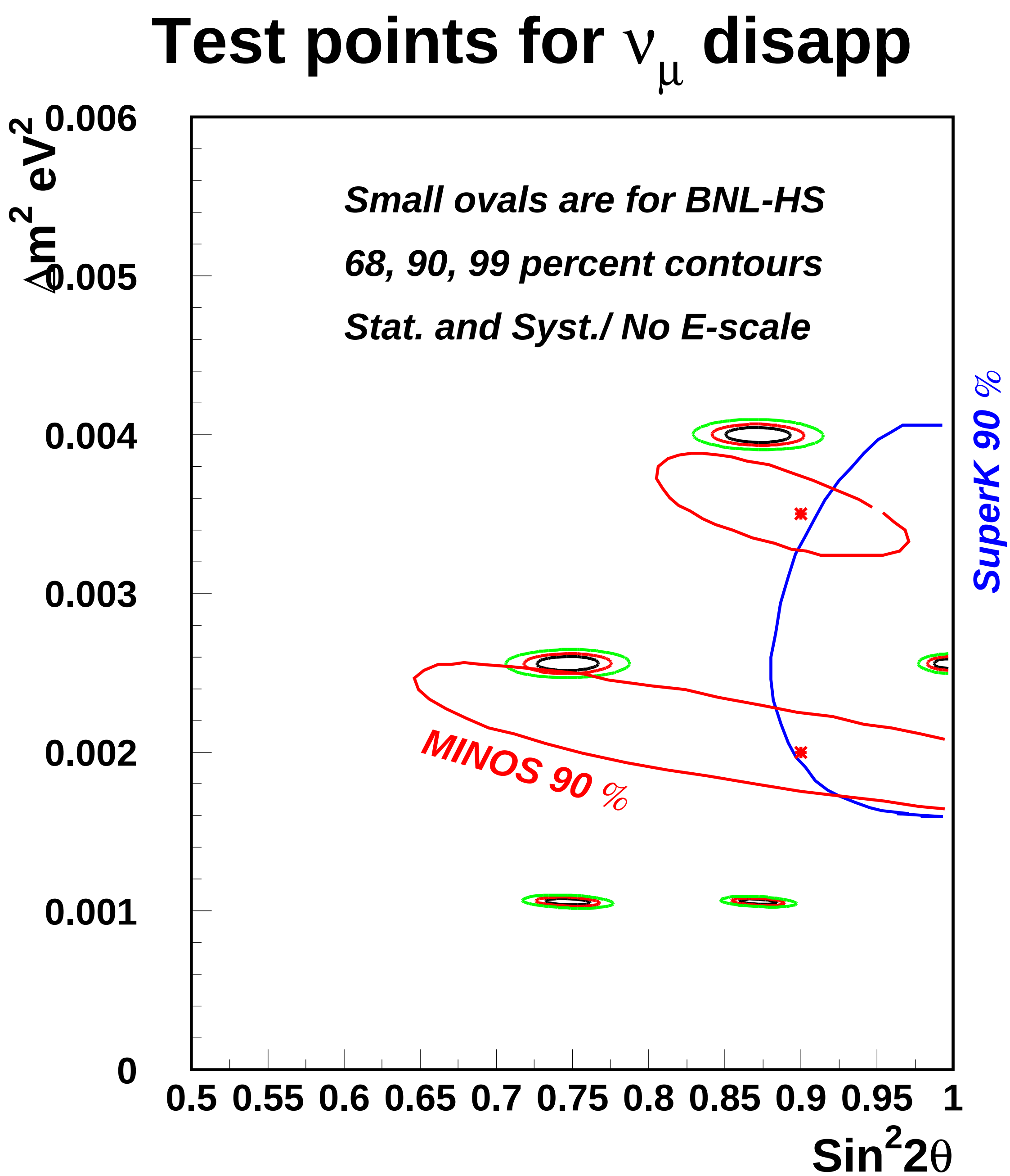
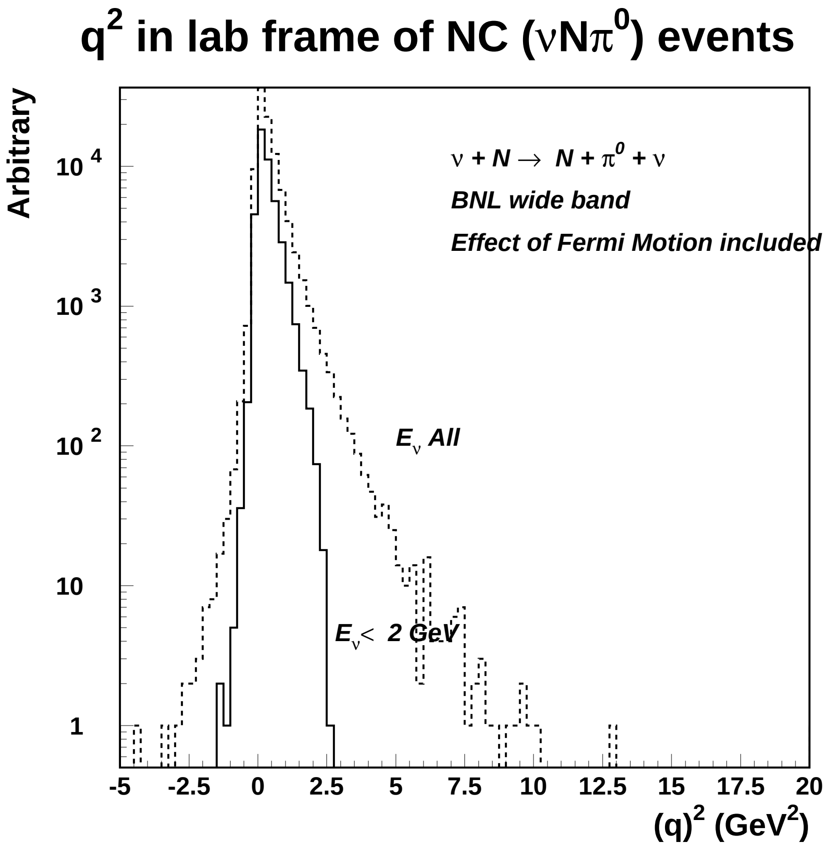

Test points for ν_μ disapp
Δm^2 eV^2
0.006
0.005
0.004
0.003
0.002
0.001
0
0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1
$\sin^2 2\theta$
Small ovals are for BNL-HS
68, 90, 99 percent contours
Stat. and Syst./ No E-scale
MINOS 90 %
SuperK 90 %

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 $\nu_\mu \rightarrow \nu_e$



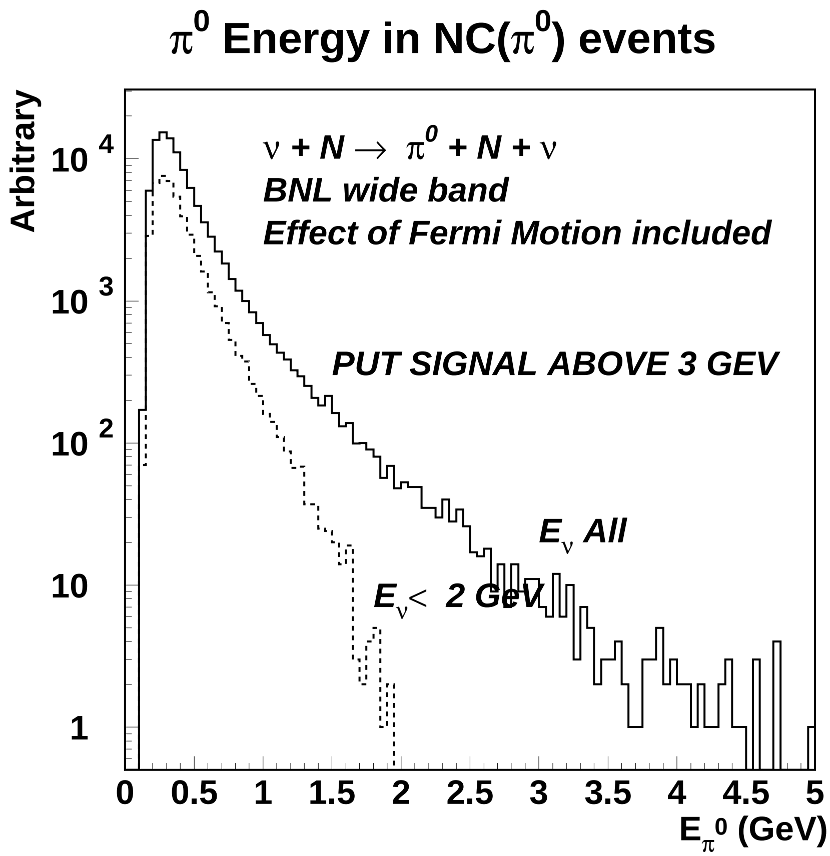
$q^2 = (p'_N + p'_\pi) - p_N.$

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

General feature of all neutral current processes:

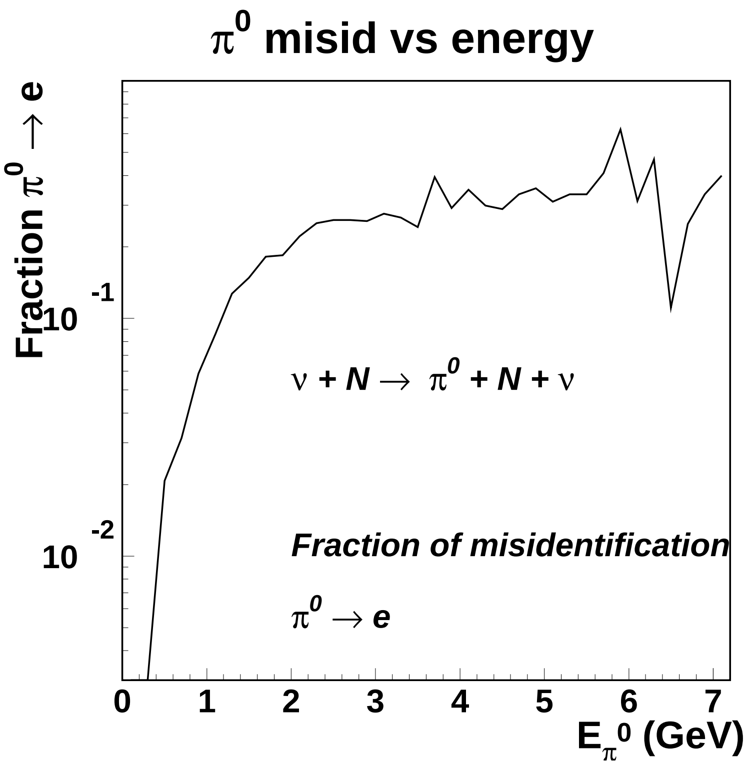
Low q^2 or low hadronic energy in final state independent of neutrino energy.

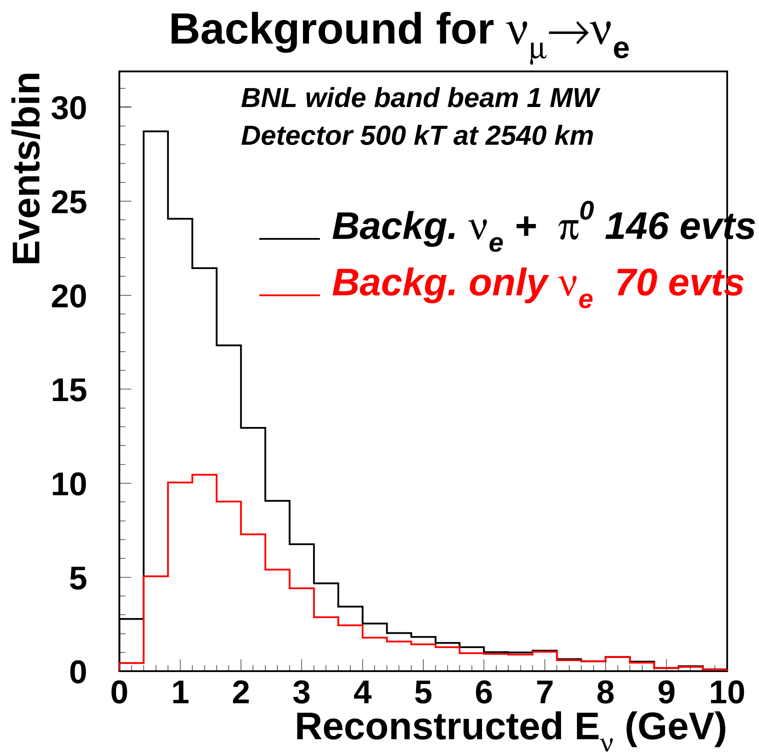
NC π^0 background for $\nu_\mu \rightarrow \nu_e$



- 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.

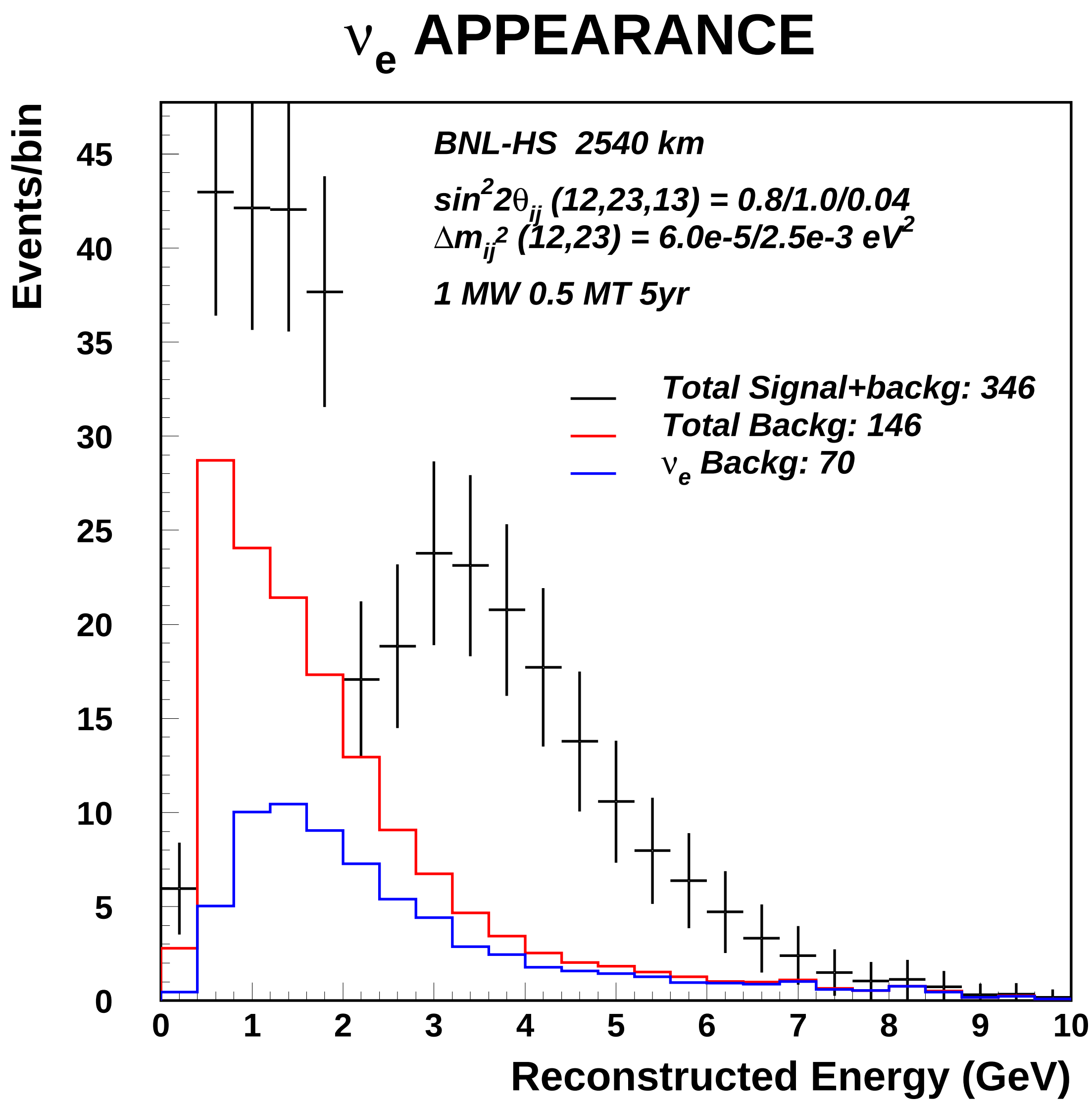
$\nu_\mu \to \nu_e$ All background





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

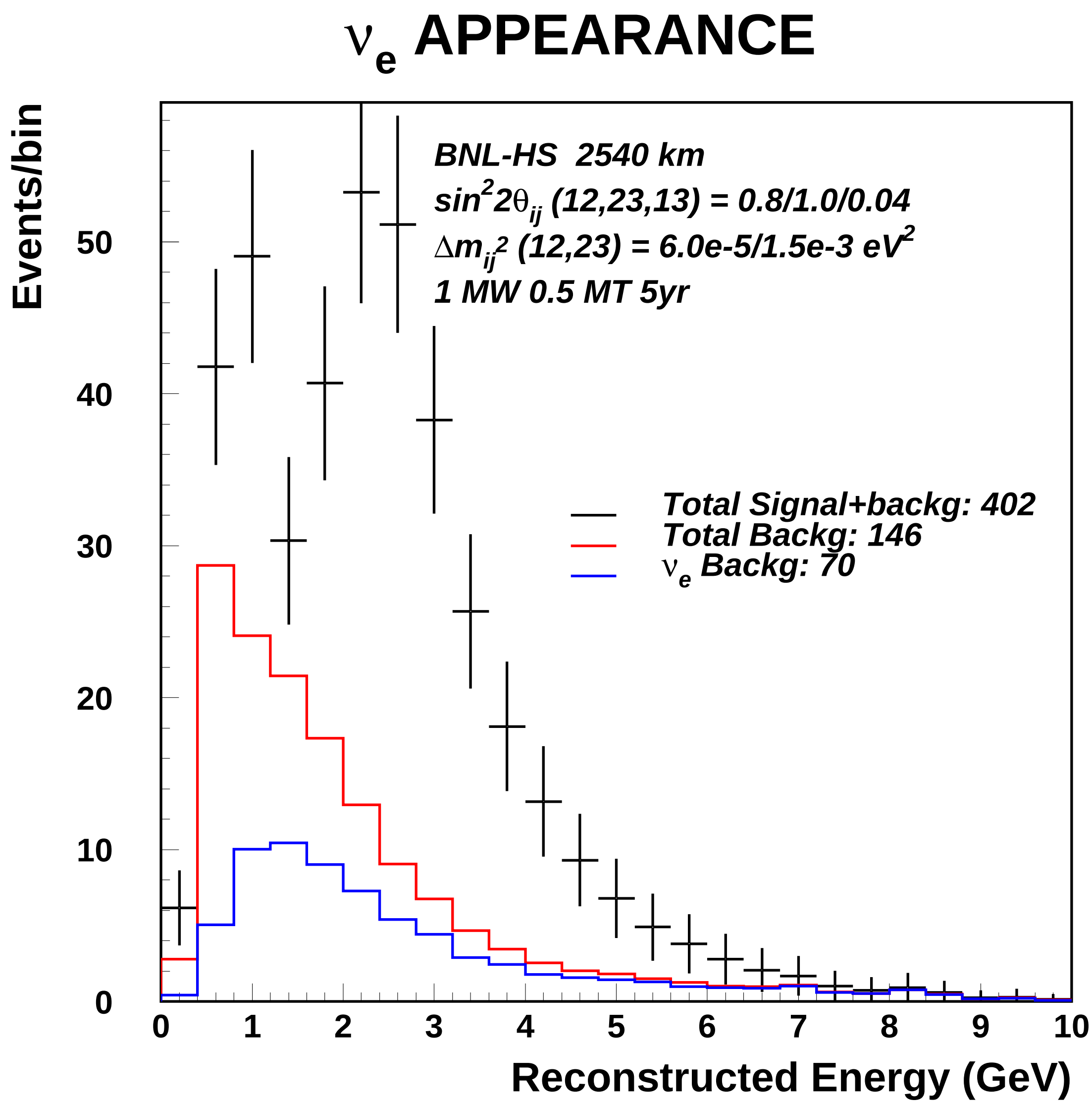


$\Delta m^2_{23} = 0.0025 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

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

Matter effects included.

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

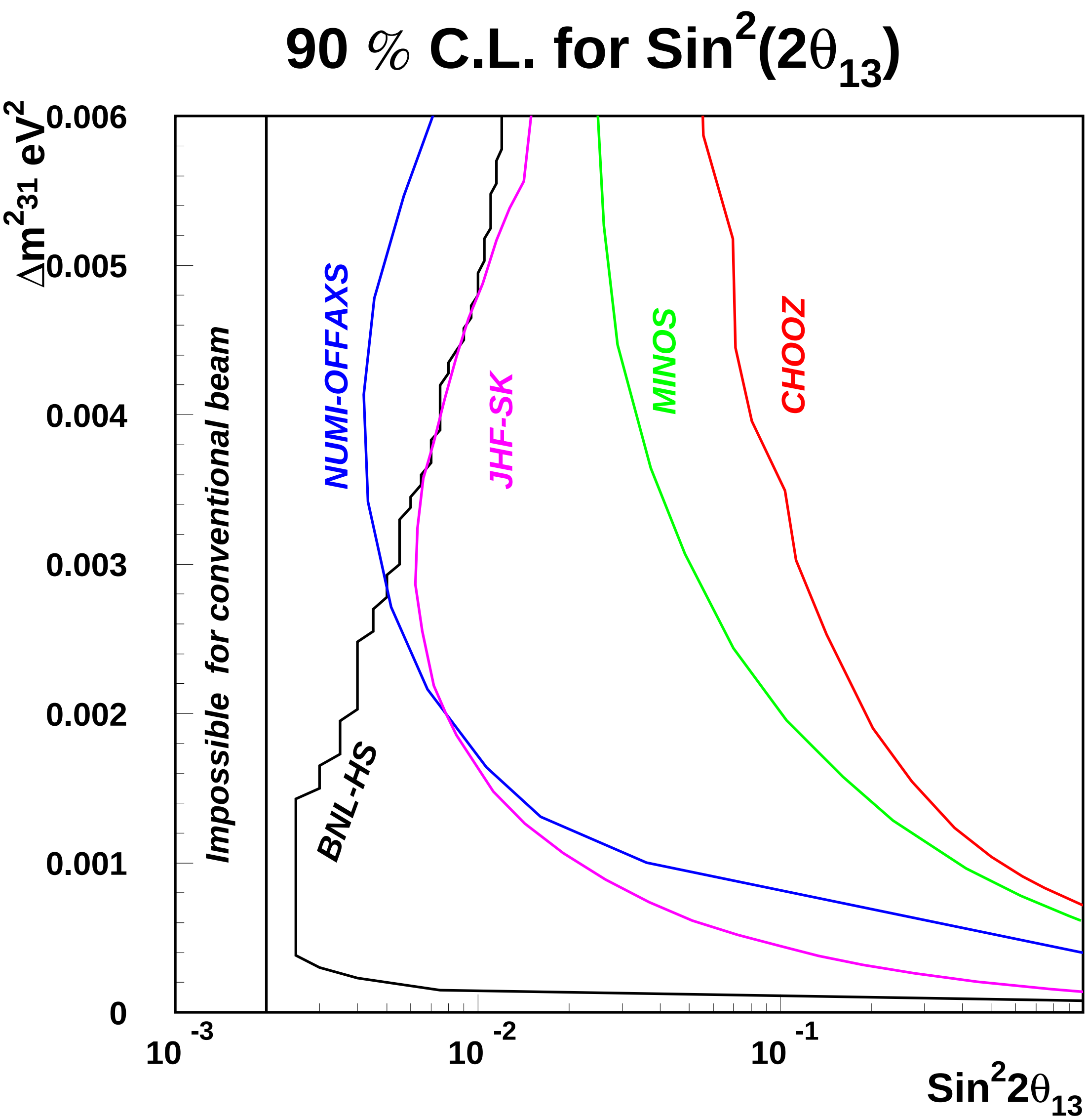


$\Delta m_{23}^2 = 0.0015 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

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

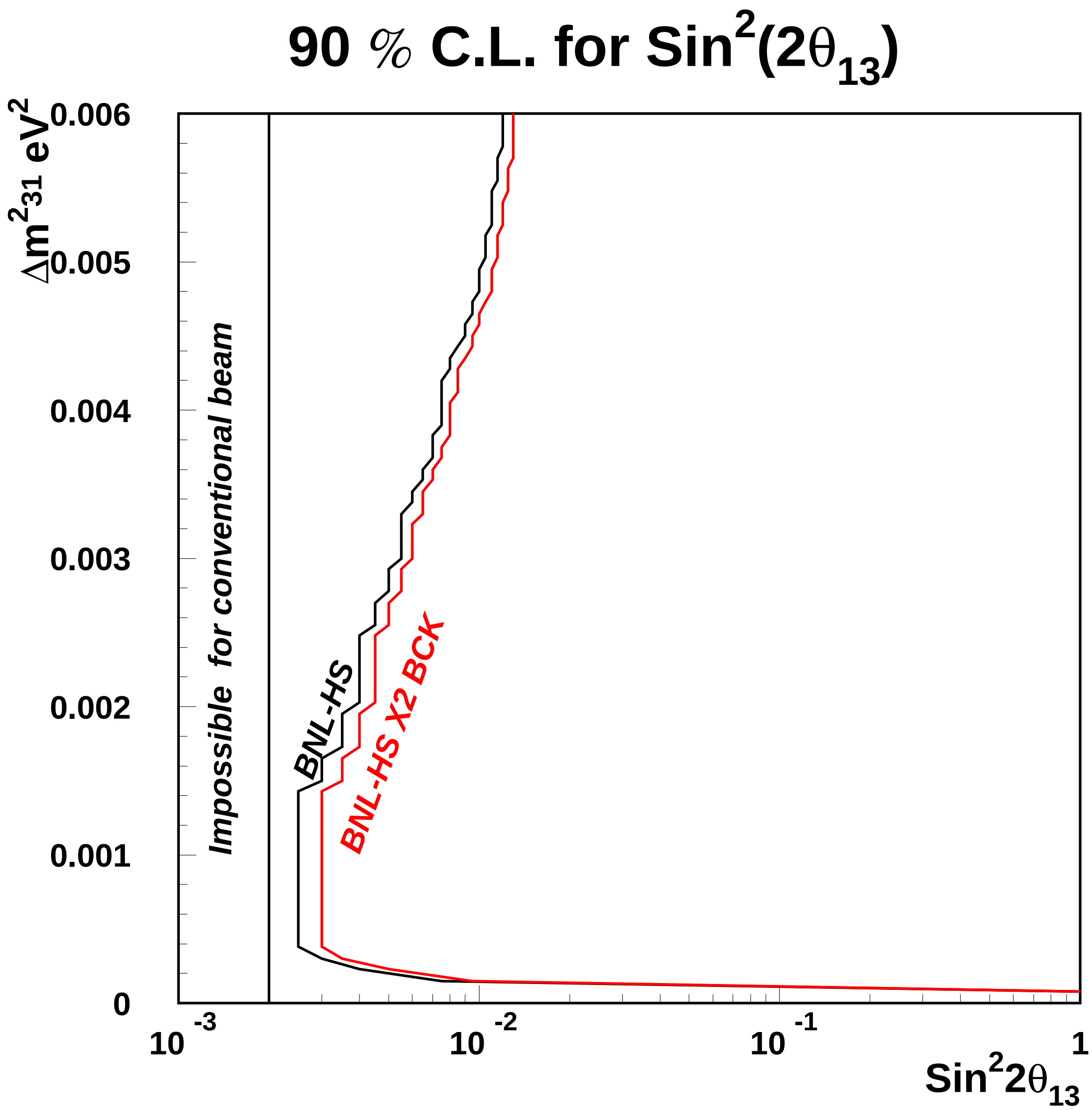
Matter effects included.

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

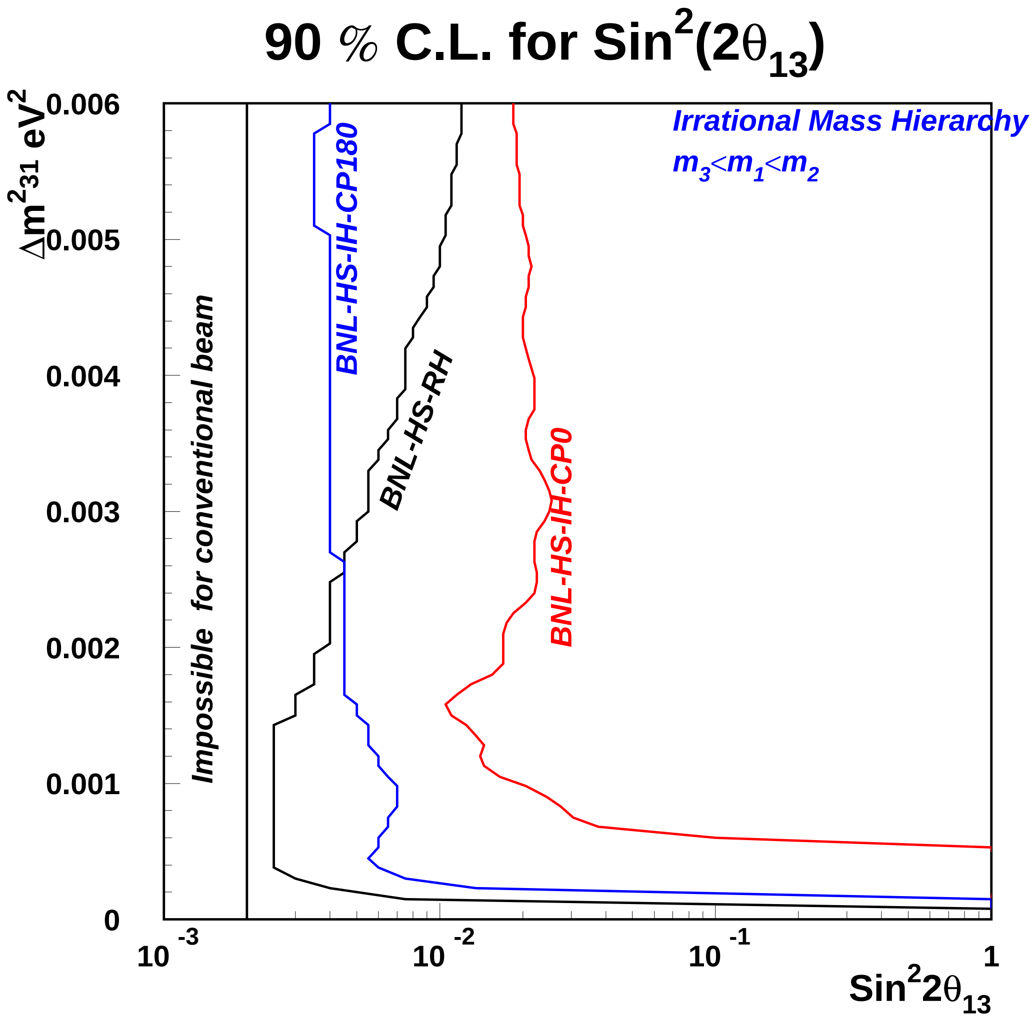
Improvement from 0.12 to 0.005 at 0.0025 eV^2.

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



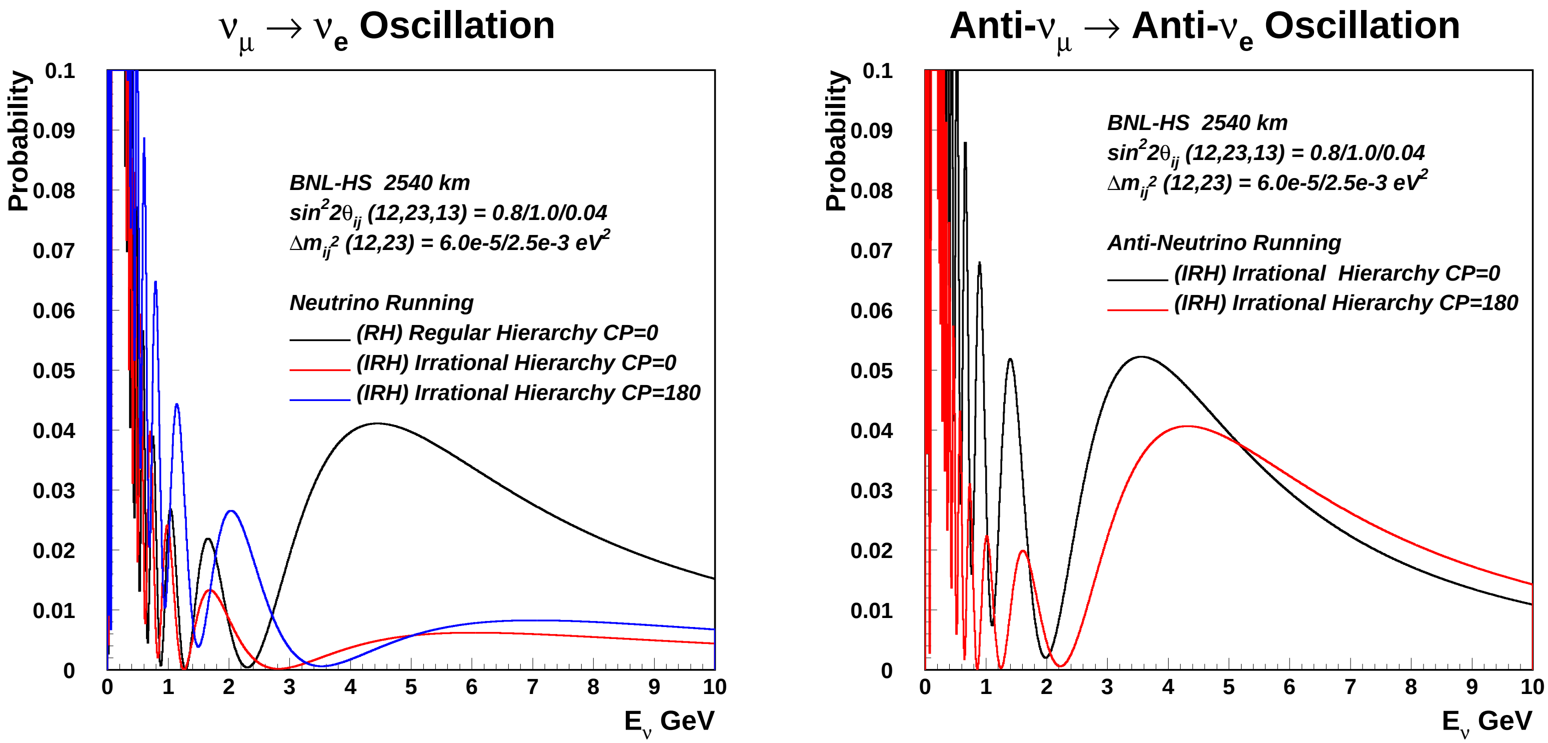
Regular Mass hierarchy: $m_3 > m_2 > m_1$ (RH)

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

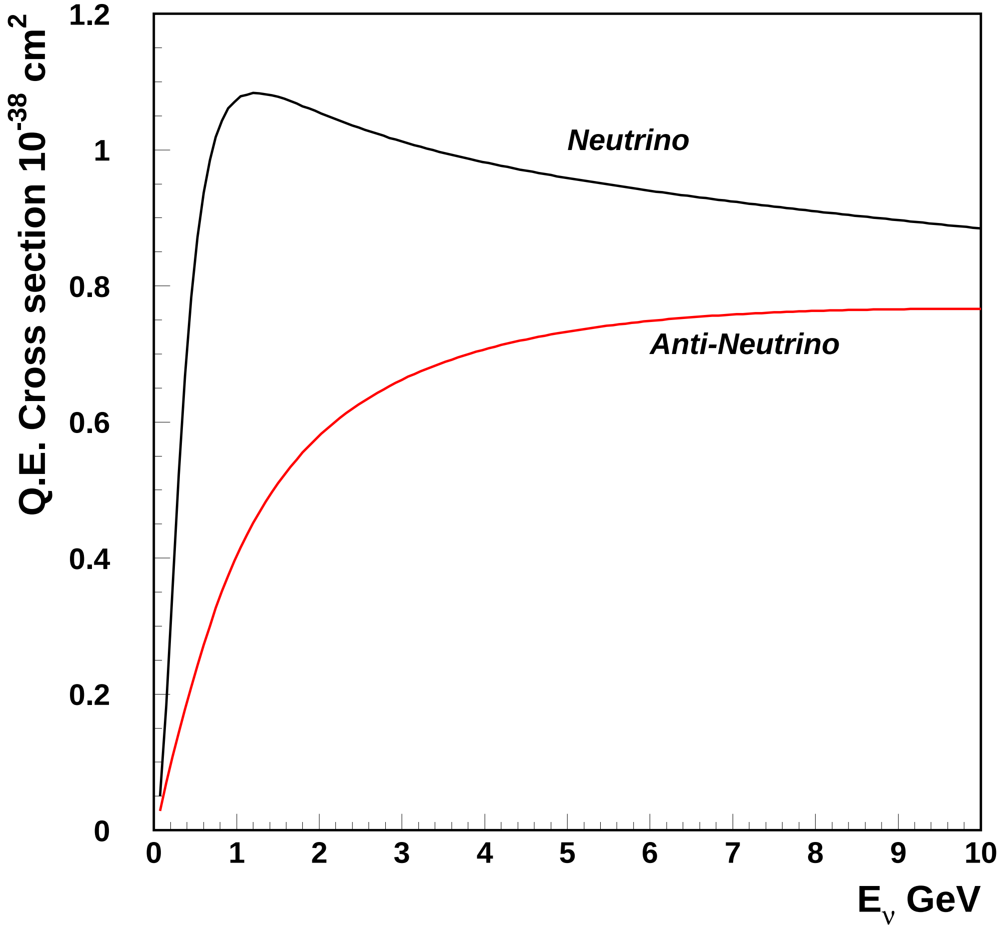
Irrational Mass hierarchy: $m_2 > m_1 > m_3$ (IH)
RVH is ruled out if Solar LMA is the correct solution.

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

Mass Hierarchy Anti-neutrinos

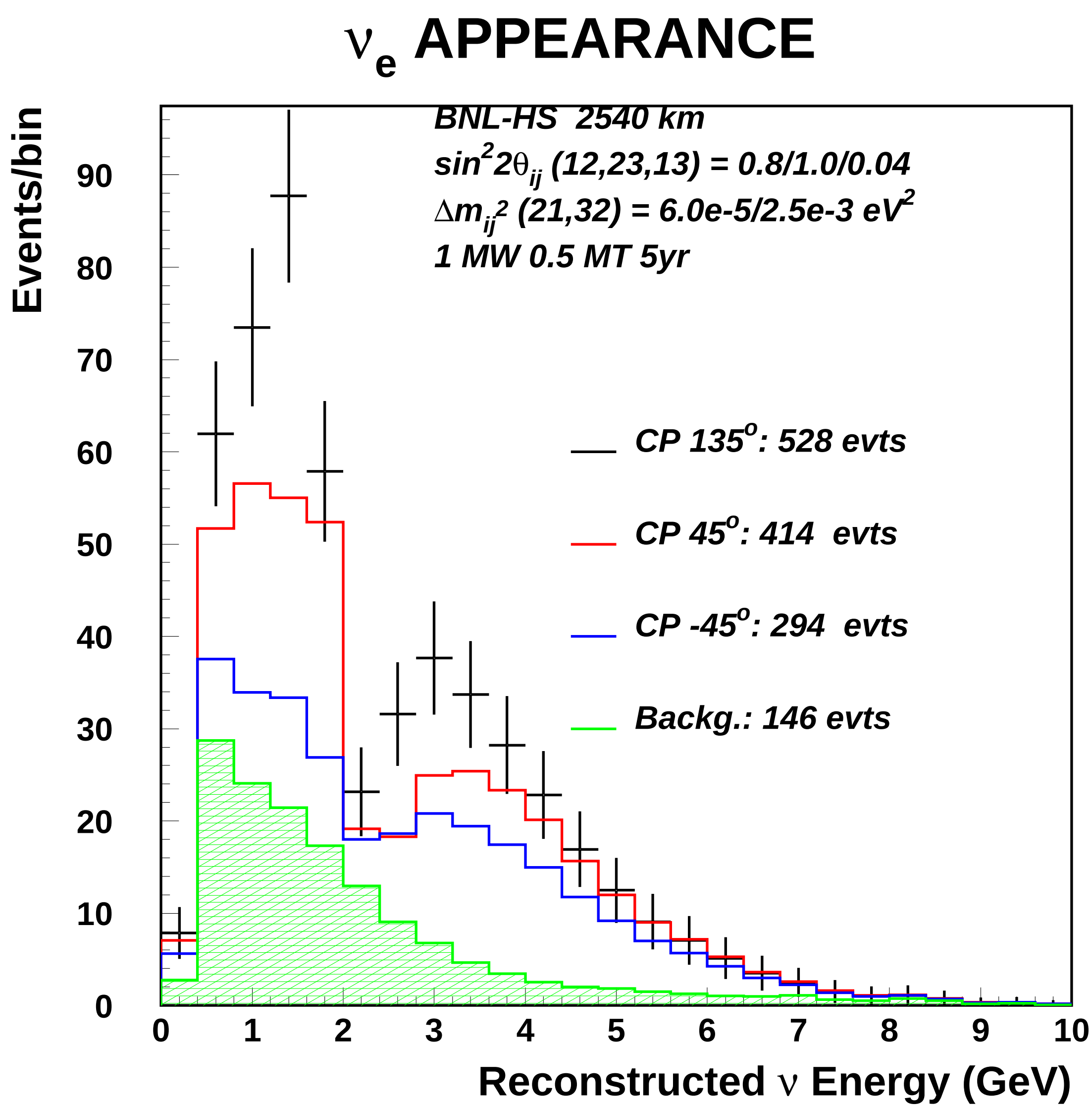


Quasielastic cross section



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

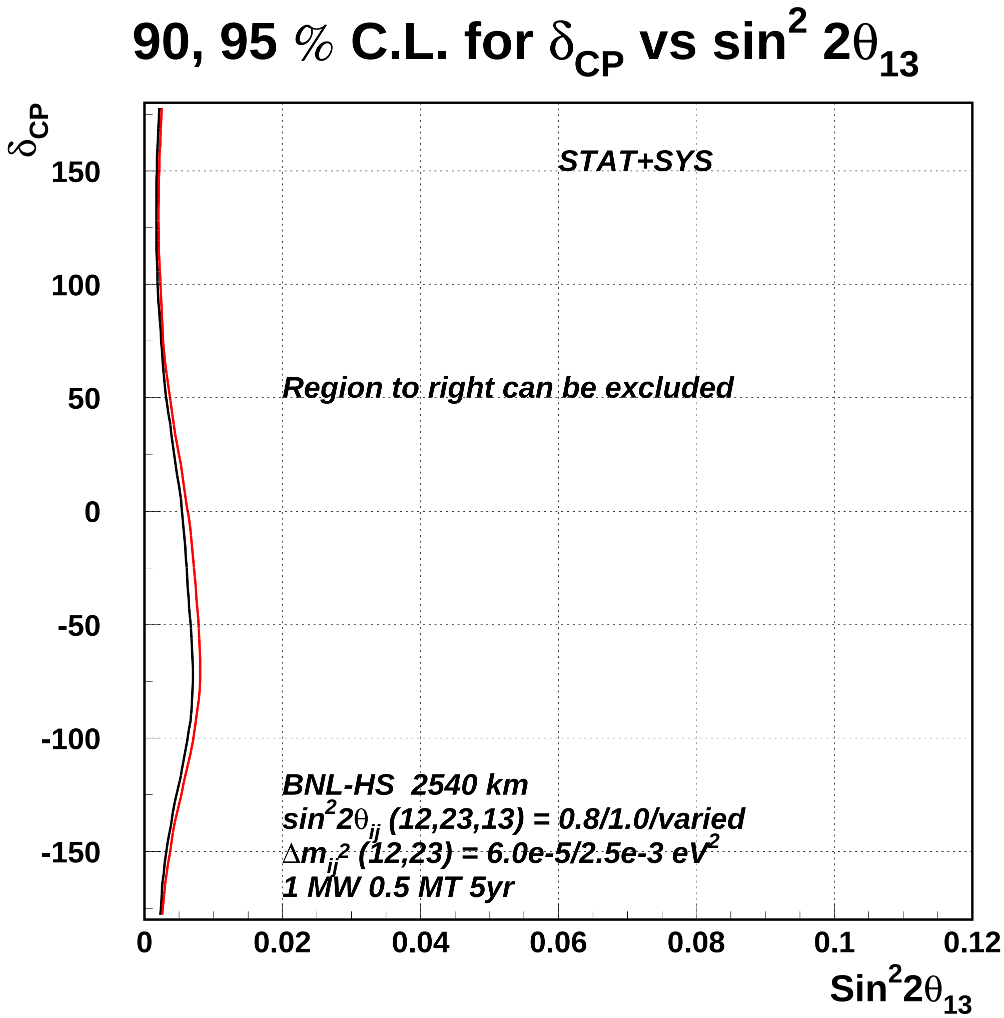
δ_{CP} Measurement. BNL-to-HS, 2540 km, 1 MW, 500kT, 5×10^7 sec



CP parameter can be determined from only neutrino data.

Good background subtraction can help.

Measurement of $\delta_C P$; Confidence Levels

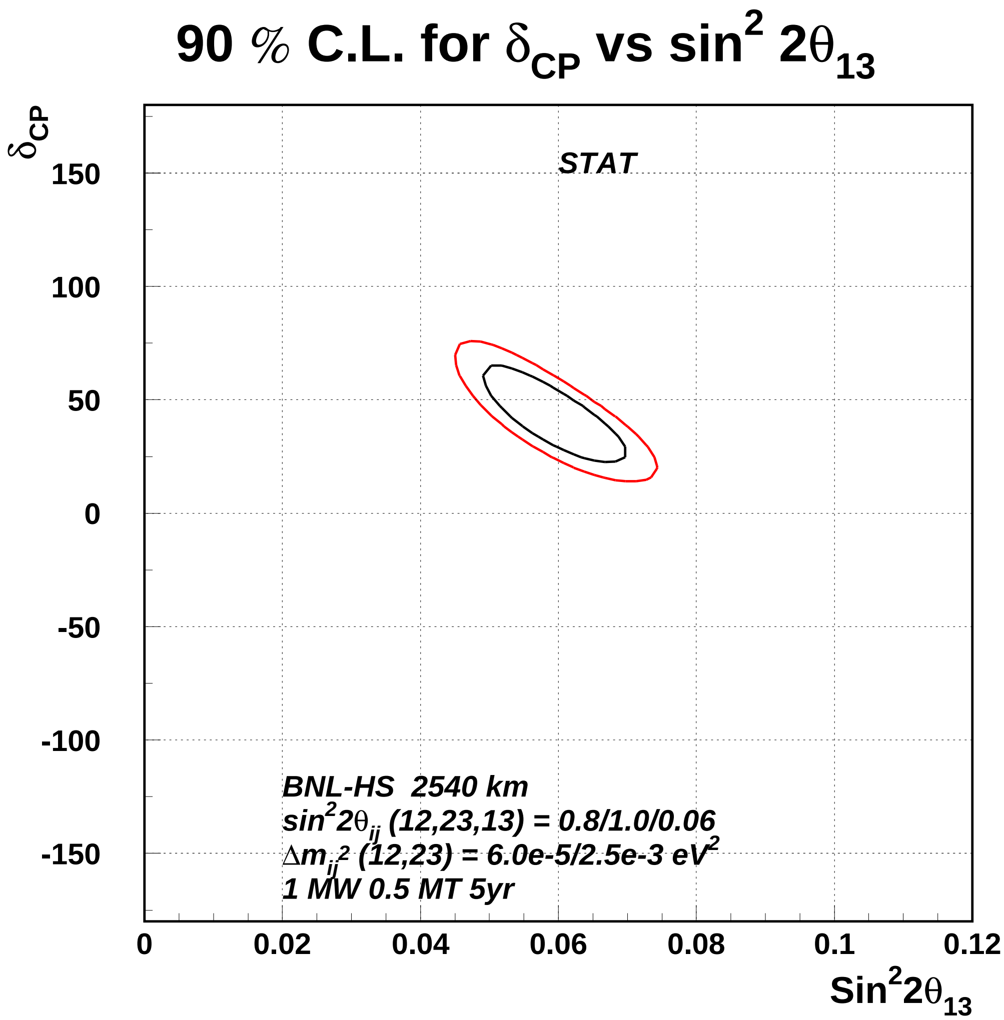


$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

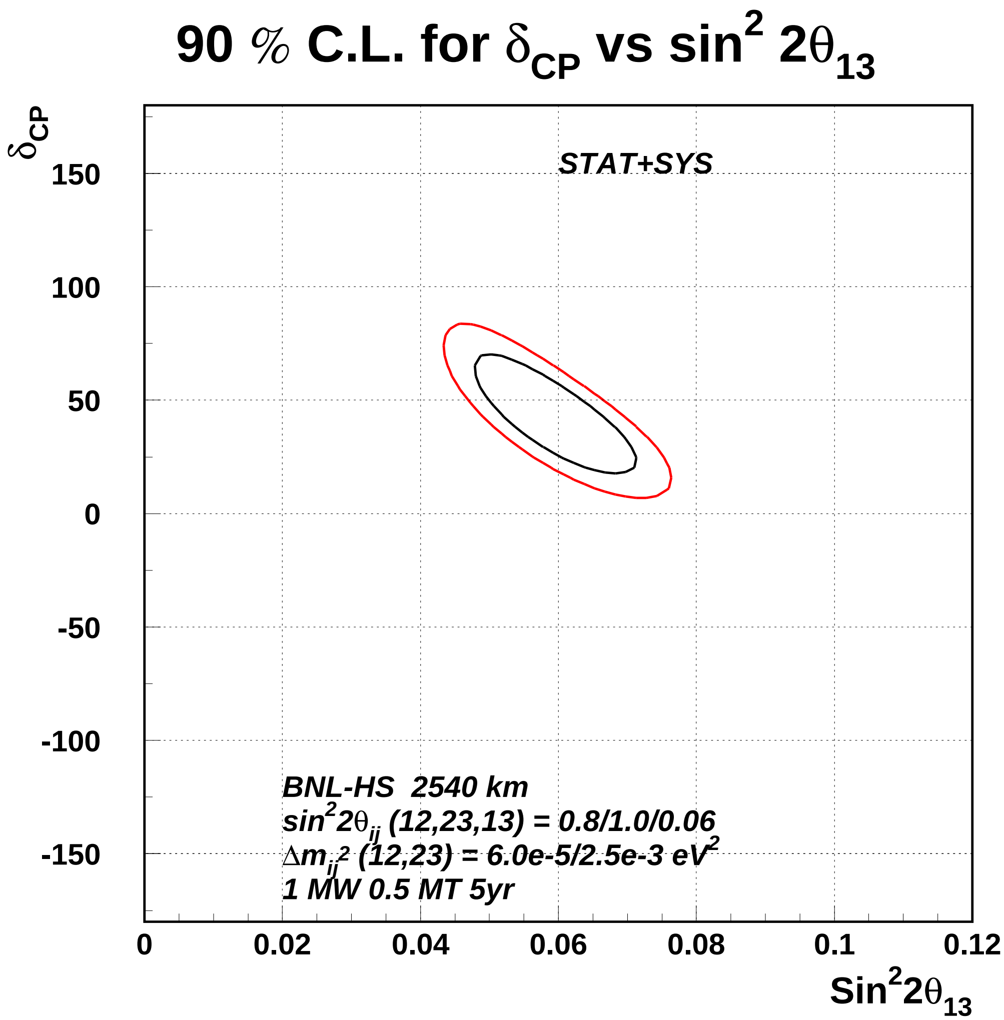
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

68%, and 90% C.L.

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



Systematic error of 10% on backg.

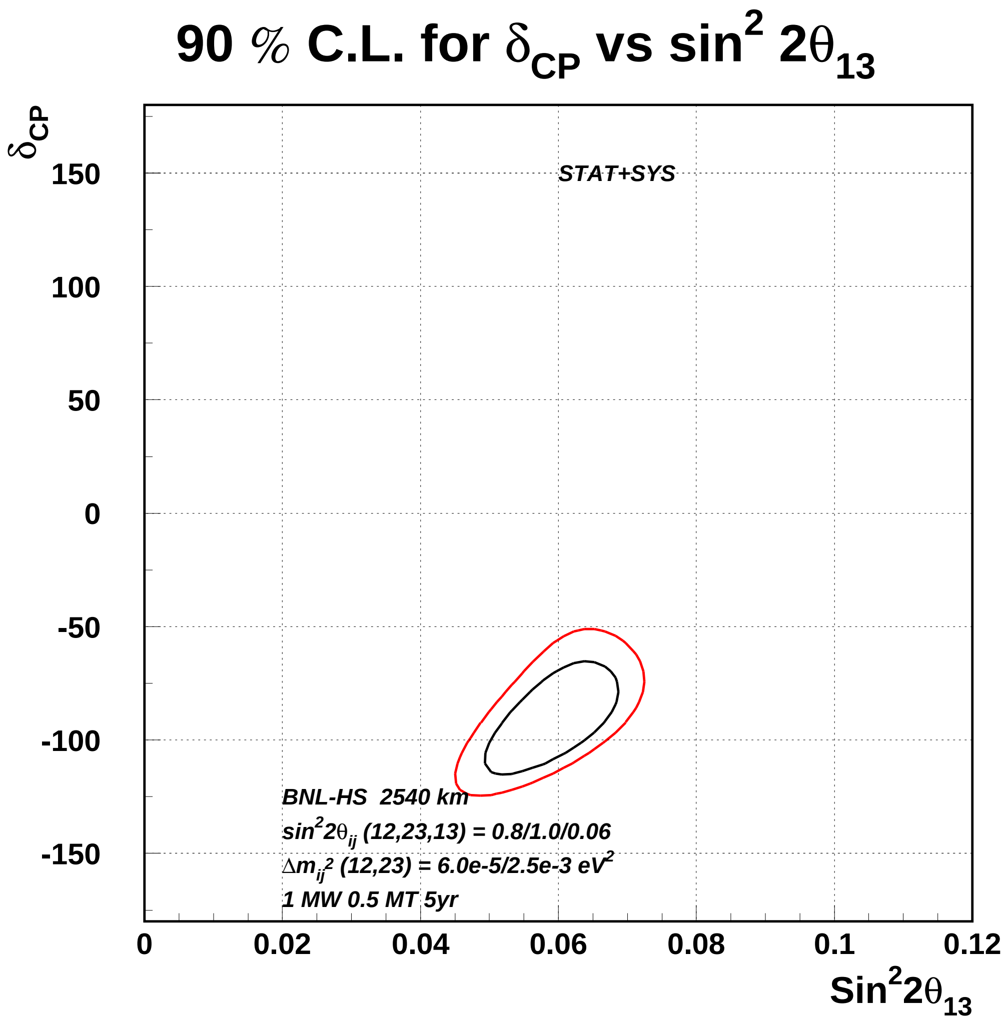
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

68%, and 90% C.L.

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



Systematic error of 10% on backg.

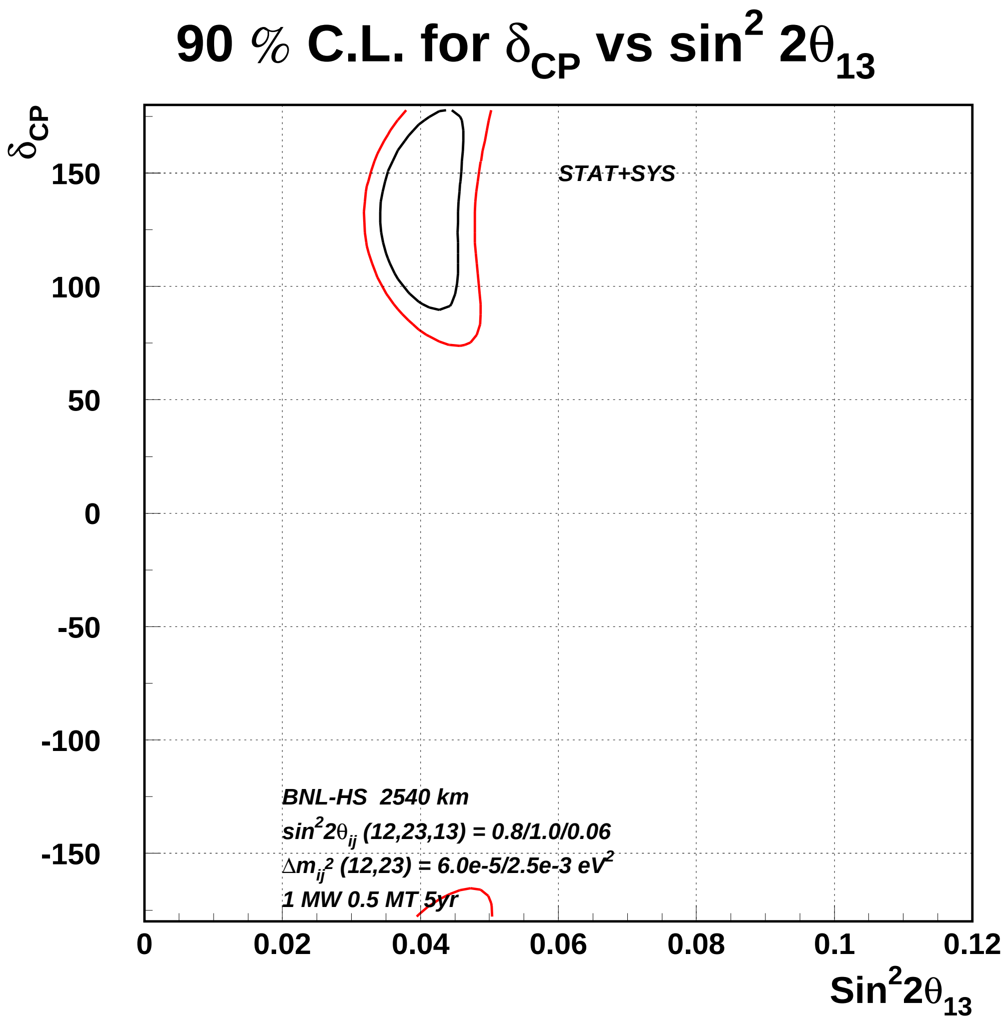
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

68%, and 90% C.L.

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



Systematic error of 10% on backg.

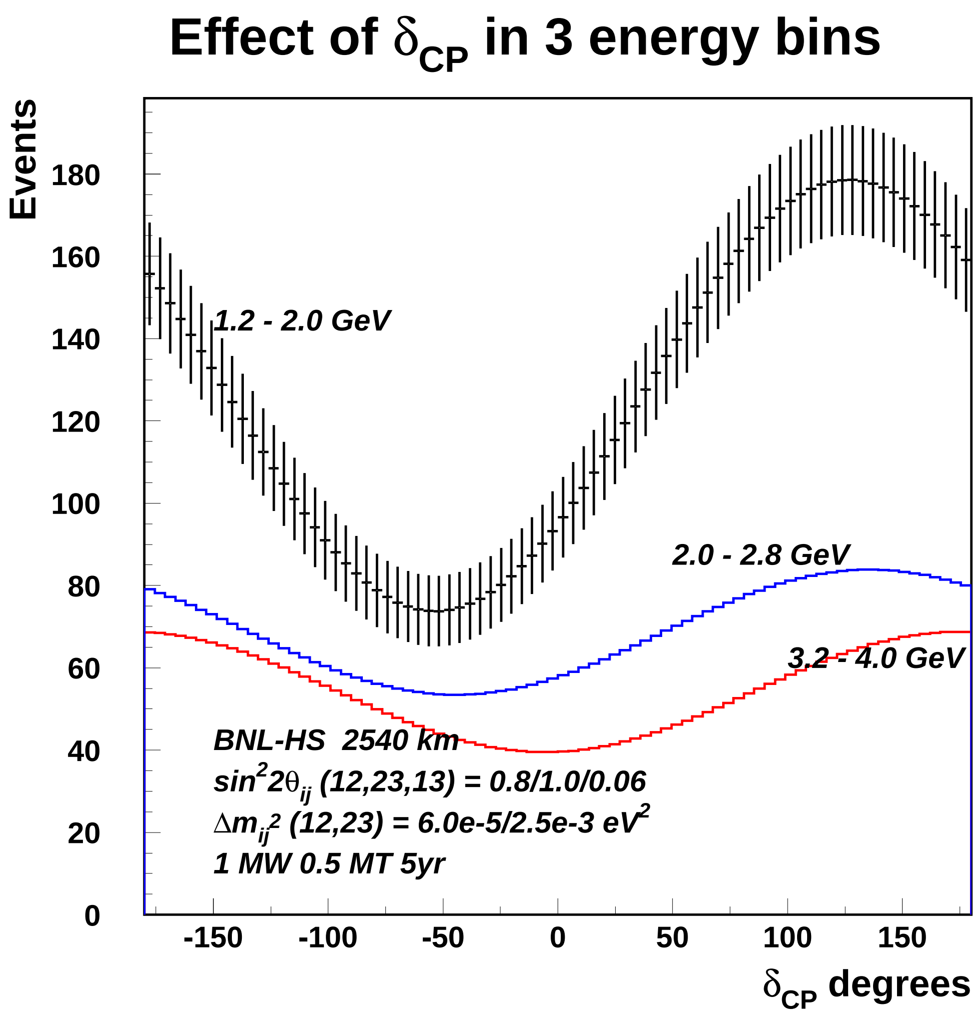
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

68%, and 90% C.L.

Effect of δ_{CP} on the spectrum.



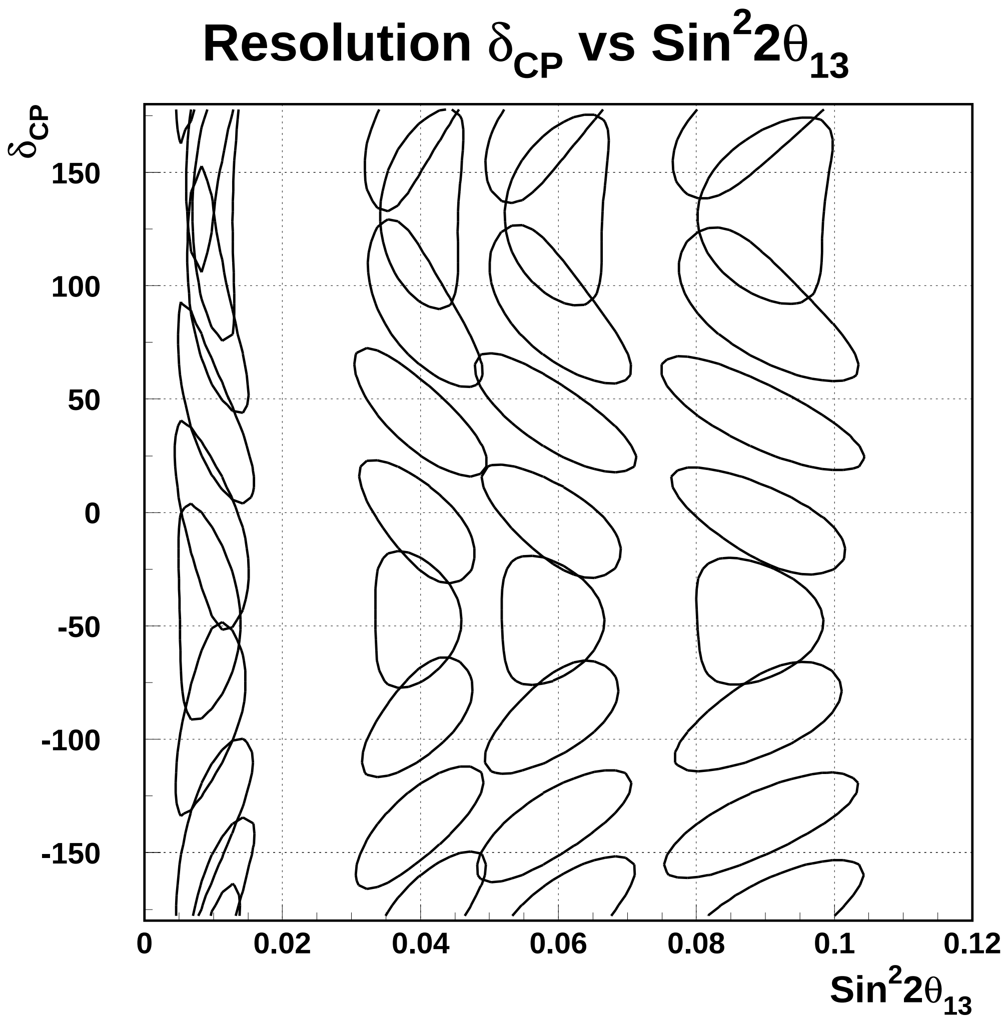
Event rate in 3 energy bins.

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

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

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

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

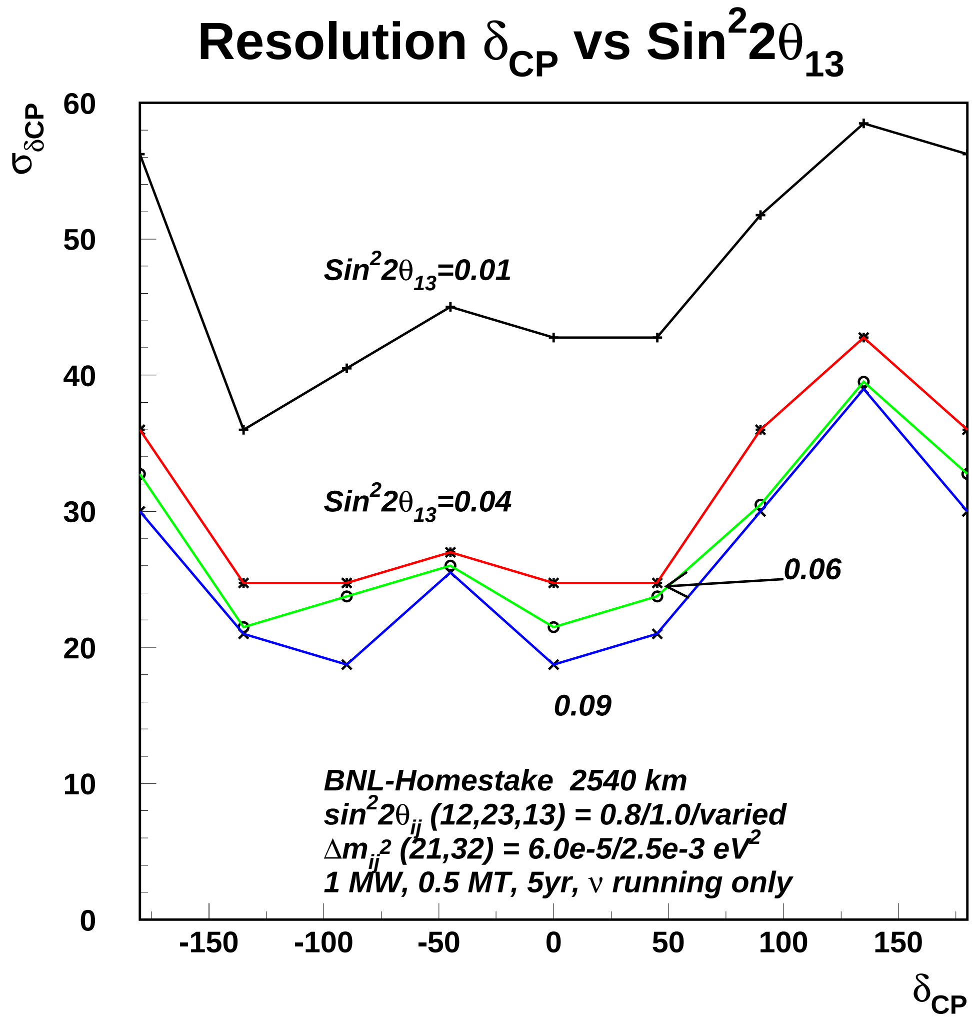


Assume all other parameters are well-known.

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

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

1 sigma error on δ_{CP} vs δ_{CP}

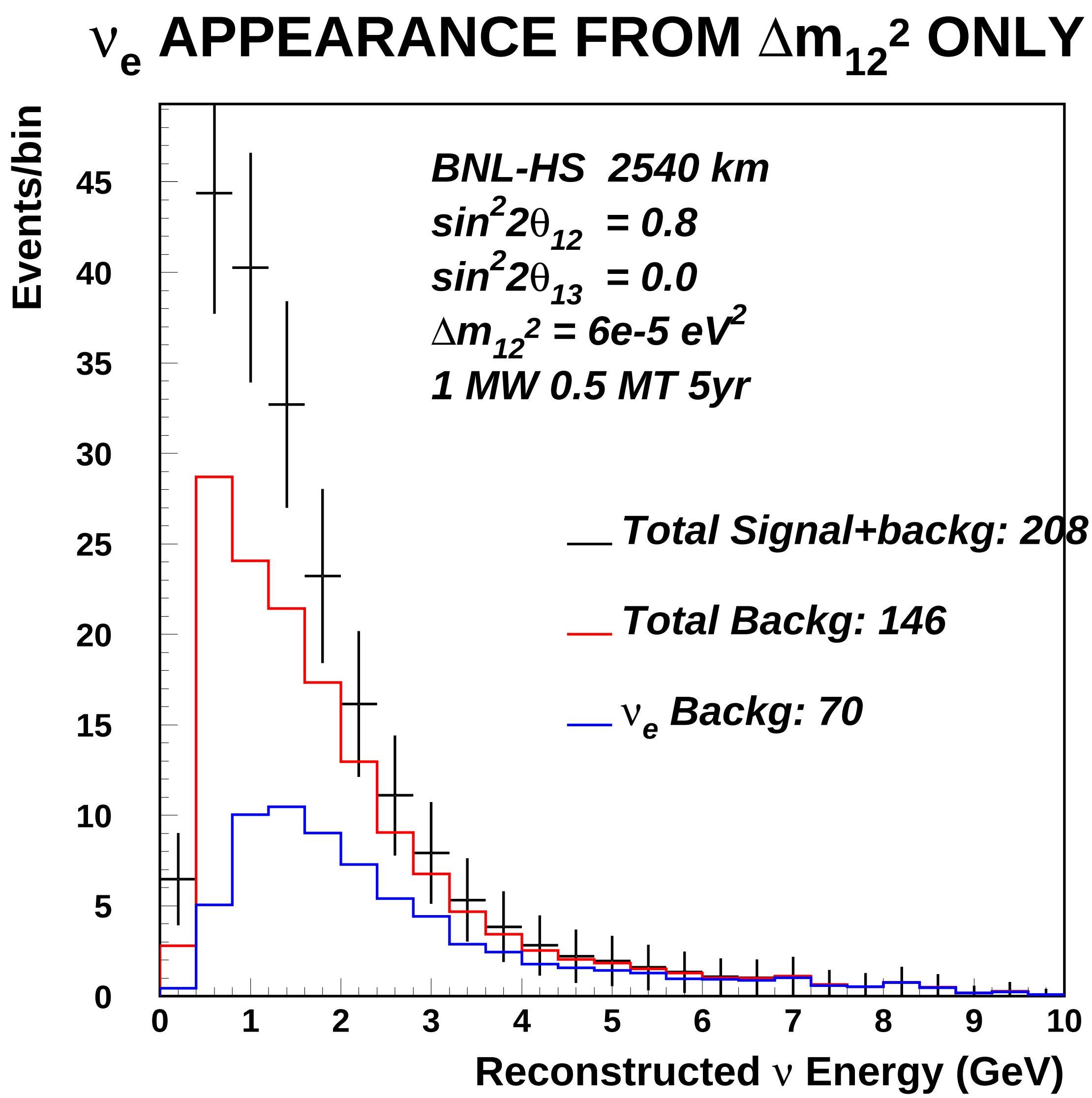


Full error from error contour. No knowledge of θ_{13} assumed, but all other parameters fixed.

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

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

Measurement of Δm^2_{12}

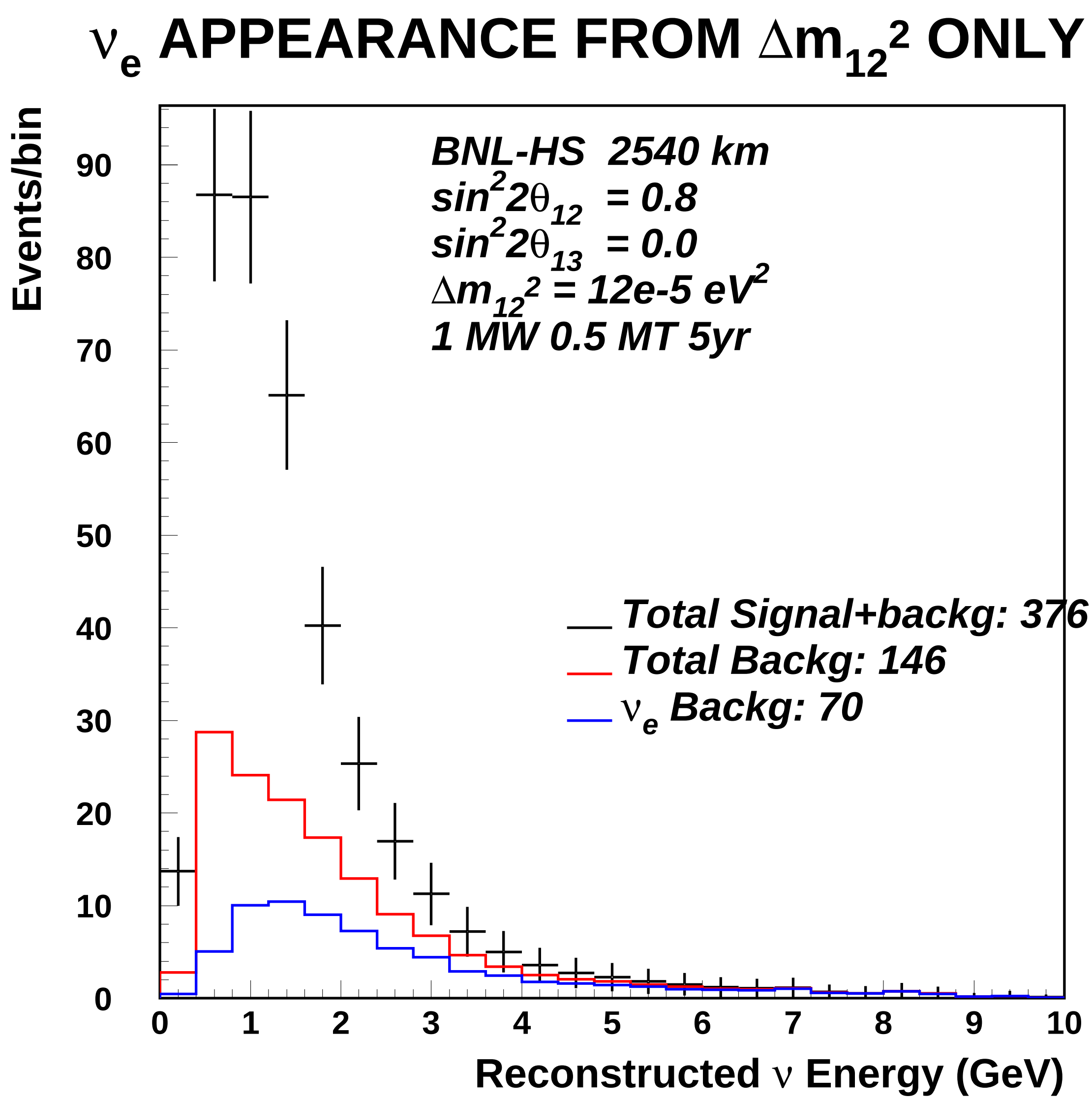


$\theta_{13} = 0$, $\Delta m^2_{12} = 6 \times 10^{-5} eV^2$

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_{12}^2

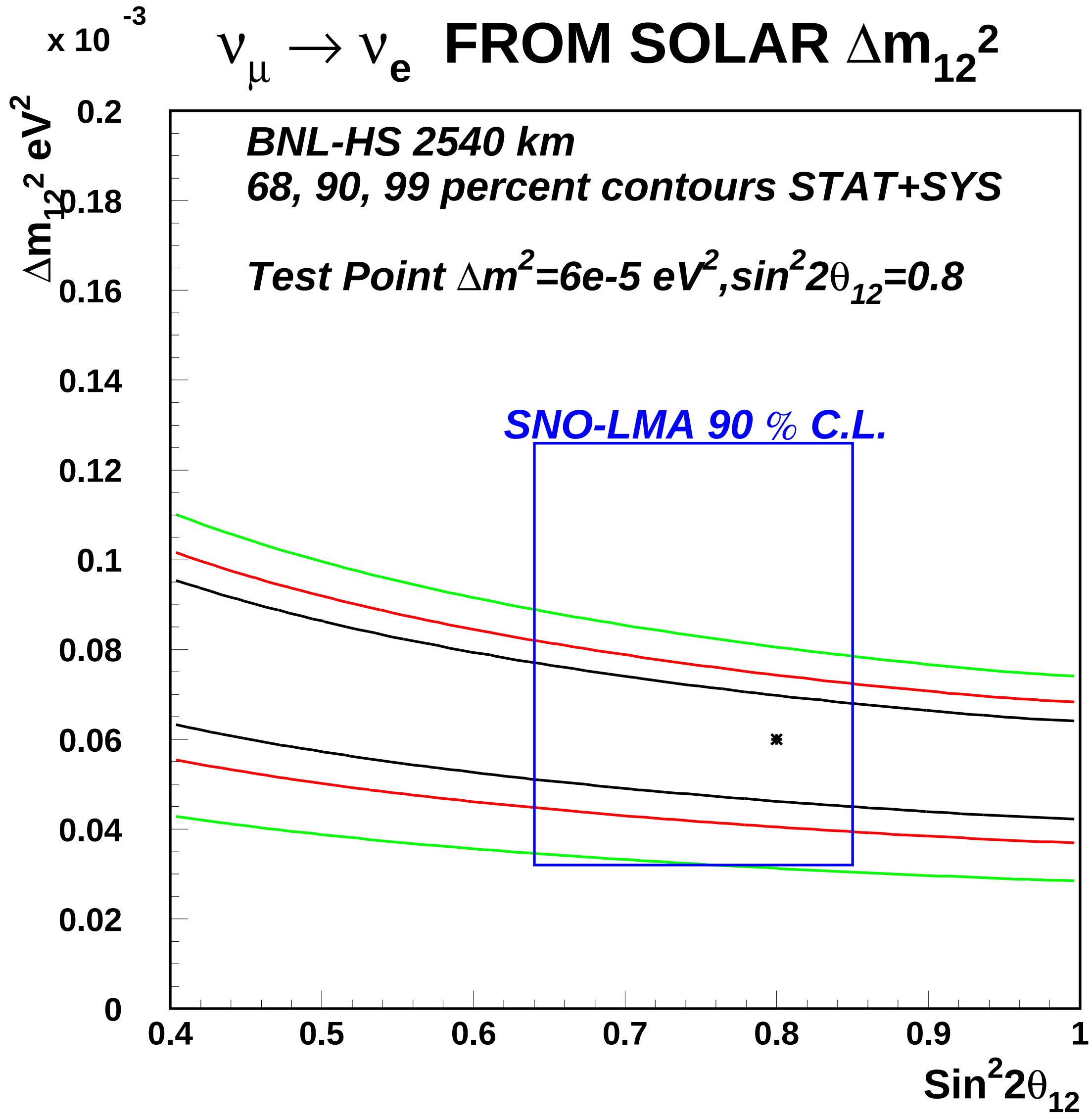


$\theta_{13} = 0$

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

Excess of $\sim$ 230 events. Unmistakable.

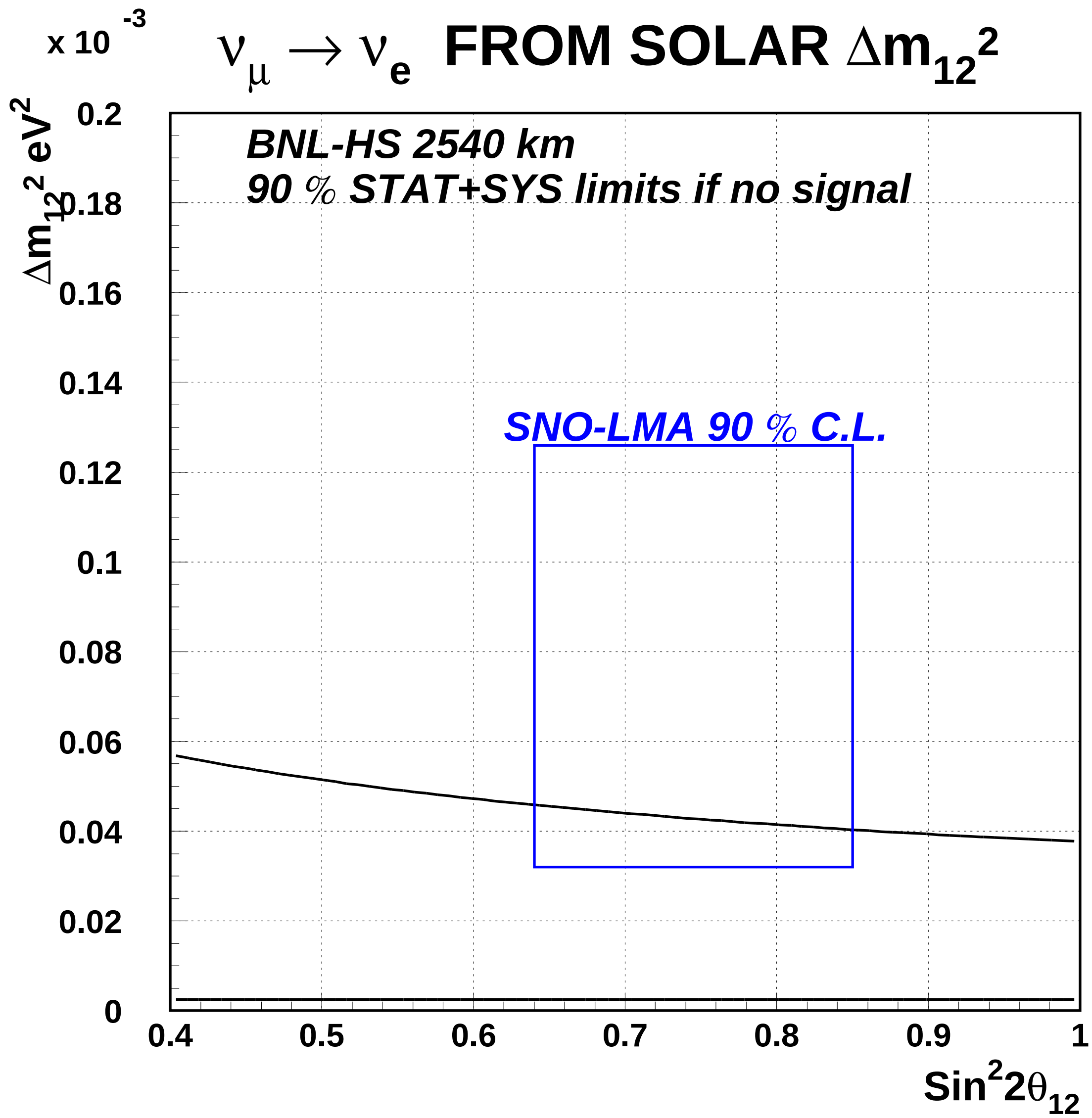
Measurement of Δm^2_{12}



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 ?

White paper has been sent to the community.

hep-ex/0211001

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.