

Very long baselines with a superbeam

# Very long baselines with a superbeam

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Jan 30, 2003

FOR BNL Neutrino Working Group.

Wide Band Conventional Beam from BNL to the  
Homestake Laboratory.

## 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:  $2.981 \pm 0.008$  active types
  - Limits on sterile neutrinos from solar, atmospheric results.
  - Big Bang Nucleosynthesis: 3 active neutrinos.

## Neutrino Physics: Oscillations

Assume a  $2 \times 2$  neutrino mixing matrix.

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

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

Sufficient to understand most of the physics:

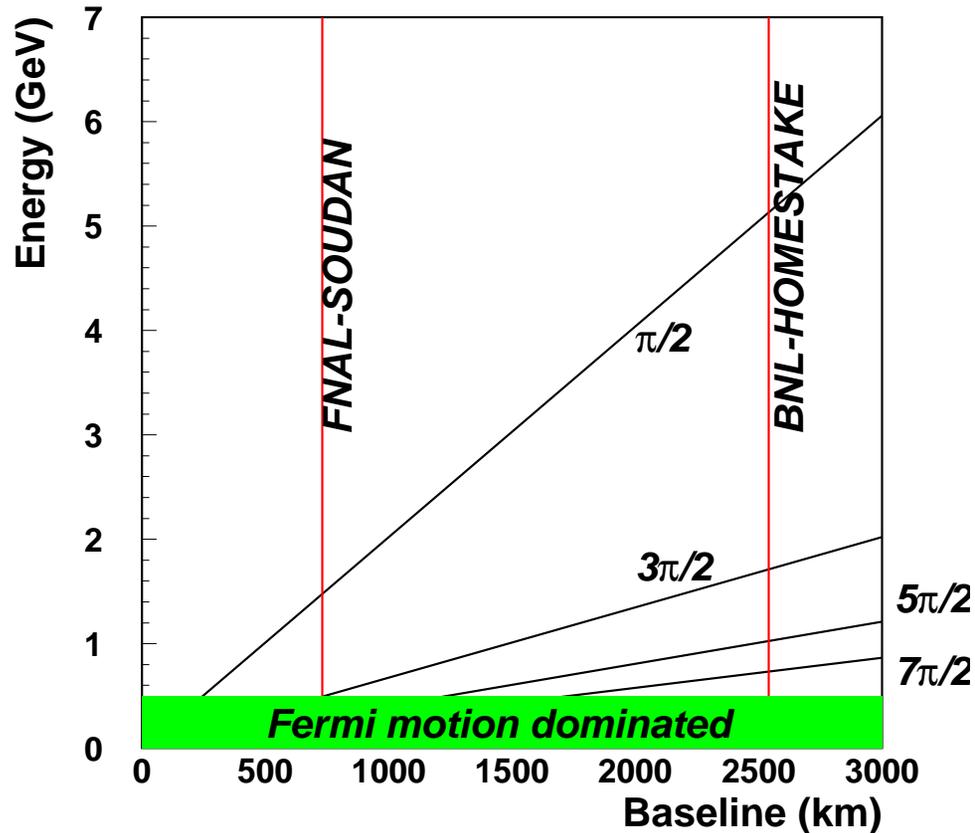
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

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

Oscillation nodes at  $\pi/2, 3\pi/2, 5\pi/2, \dots$  ( $\pi/2$ ):

$$\Delta m^2 = 0.003eV^2, E = 1GeV, L = 412km .$$

## Oscillation Nodes for $\Delta m^2 = 0.0025 \text{ eV}^2$



- 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).
- $\Delta m^2 \approx 0.0025 \text{ eV}^2$ : Baseline  $> 2000 \text{ km}$ .

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# Neutrino Physics: $3 \times 3$ Formulation

Bill Marciano, hep-ph/0108181

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (3)$$

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

# Neutrino Physics: the difficult stuff

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

No matter effects in above formula

$$\Delta_{31} \equiv \Delta m_{31}^2 L / 2E_\nu$$

$$\Delta_{21} \equiv \Delta m_{21}^2 L / 2E_\nu$$

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

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

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

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

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

## $\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula

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

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

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

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

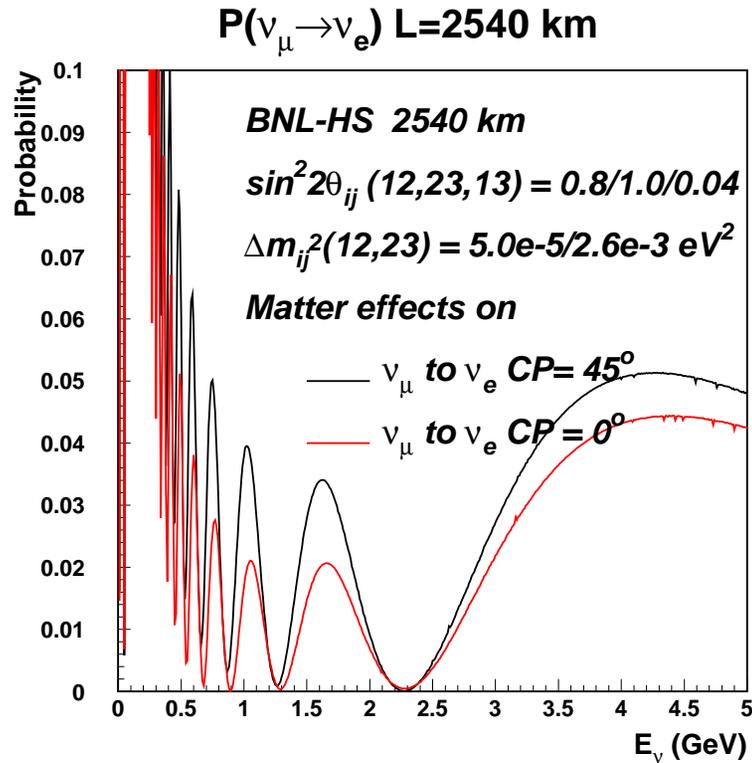
$$\hat{A} \approx 7.6 \times 10^{-5} \times (D/gm/cm^3) \times (E_\nu/GeV)/(\Delta m_{31}^2/eV^2),$$

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

- 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.
- Last term is almost independent of  $\Delta m_{31}^2$  and is purely dominated by the solar  $\Delta m_{21}^2$

Notice that the term with  $\sin \delta_{CP}$  is linear in  $\Delta m_{21}^2$  and in  $\sin 2\theta_{13}$  as well as  $L$ , the baseline.

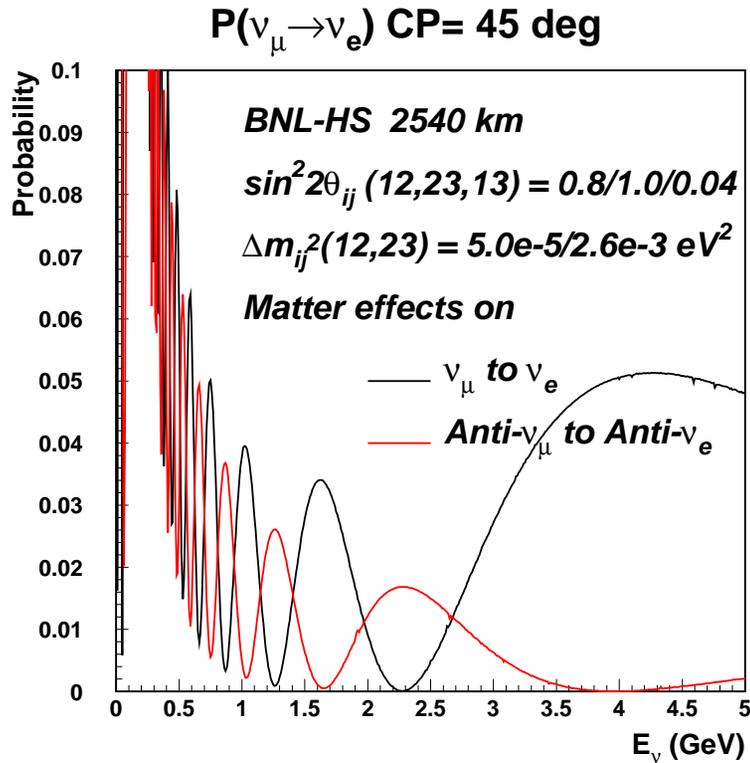
Implies that the resolution on CP should be independent of  $\sin 2\theta_{13}$  as well as  $L$ . And should get better if  $\Delta m_{21}^2$  is larger.



### General Features

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

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



Compare Neutrino to Antineu.

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

## 4 GOALS OF NEUTRINO OSCILLATION PHYSICS

- Precise determination of  $\Delta m_{32}^2$  and  $\sin^2 2\theta_{23}$  and definitive observation of oscillatory behavior.
- Detection of  $\nu_\mu \rightarrow \nu_e$  in the appearance mode. If  $\Delta m_{\nu_\mu \rightarrow \nu_e}^2 = \Delta m_{32}^2$  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  $\Delta m_{32}^2$ ; 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).

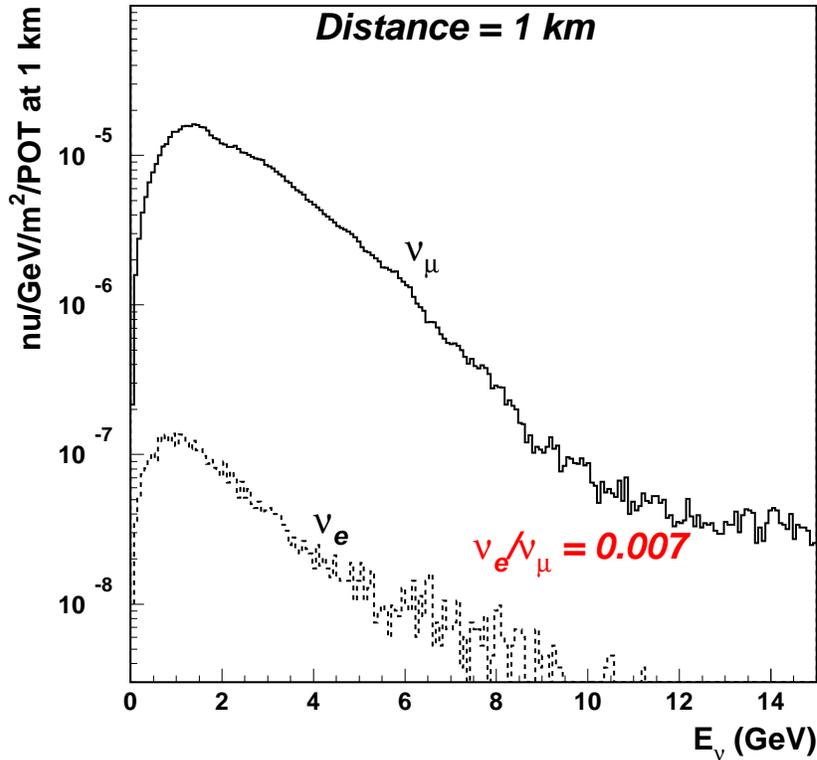
## Summary of our study

- 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  $\Delta m_{32}^2$
  - $< 1\%$  resolution on  $\sin^2 2\theta_{23}$
  - Sensitivity to  $\sin^2 2\theta_{13} > 0.005$  over a wide range of  $\Delta m_{32}^2$
  - Sensitivity to CP violation.
  - Sign of  $\Delta m_{32}^2$  over a wide range of parameters.
  - Measurement of  $\Delta m_{21}^2$  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  $\nu_e$  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.

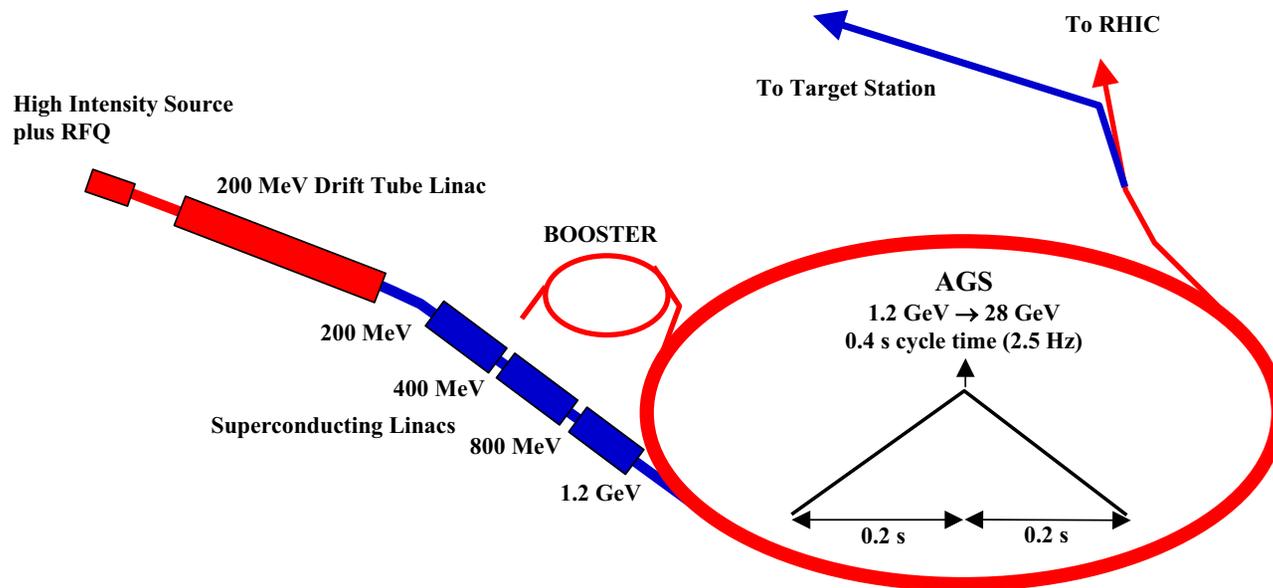
### BNL Wide Band. Proton Energy = 28 GeV



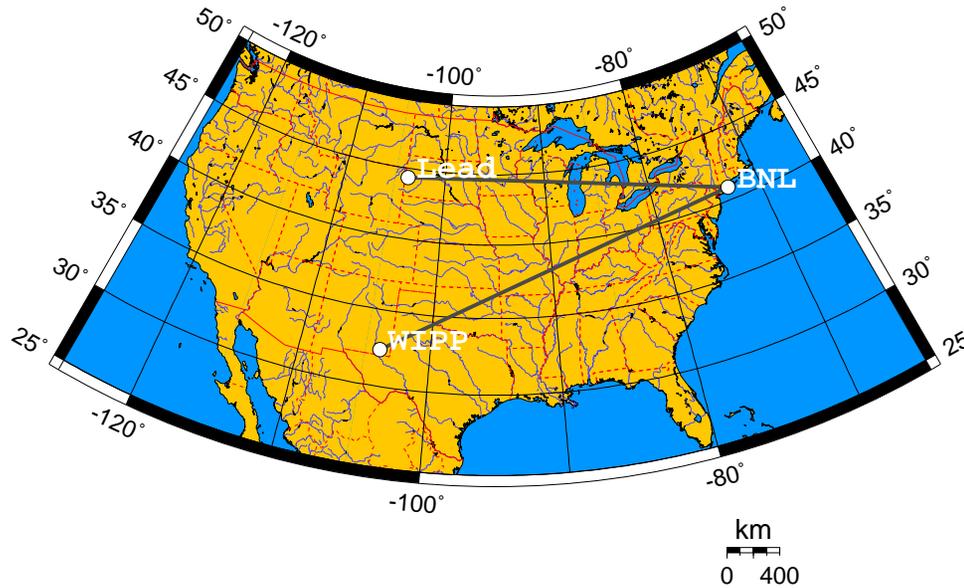
- New design spans 0.5-6 GeV
- Low  $\nu_e$  background 0.7%  
 $0.0073 \pm 0.0014$  (E734 1986).
- Low background from high energies (NC and  $\nu_\tau$  for  $\nu_e$  )
- 200 m decay tunnel
- Graphite target embedded in horn
- Target cooling achievable for 1 MW

# The Accelerator

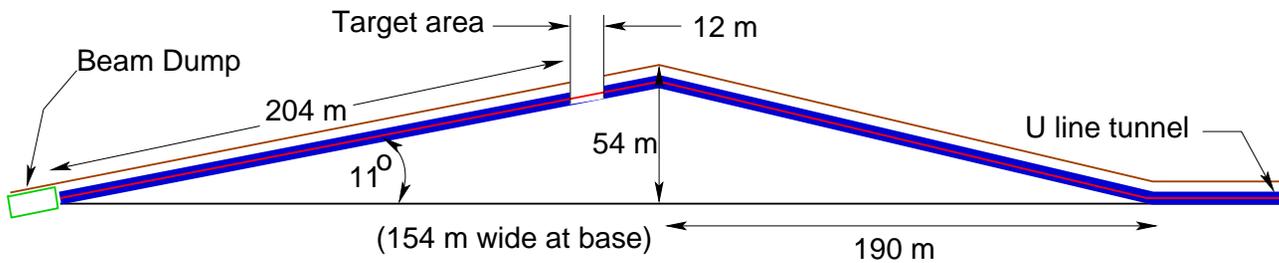
- Conceptually simple upgrade. No magic. Cost  $\sim$  \$100M.
- Run 28 GeV AGS at 2.5 Hz to get 1 MW.
- Need faster proton source: Super Conducting LINAC at 1.2 GeV
- Current:  $7 \times 10^{13} ppp$  at 0.5 Hz  $\Rightarrow$  LINAC:  $10^{14} ppp$  at 2.5 Hz.



# Beam on the Hill

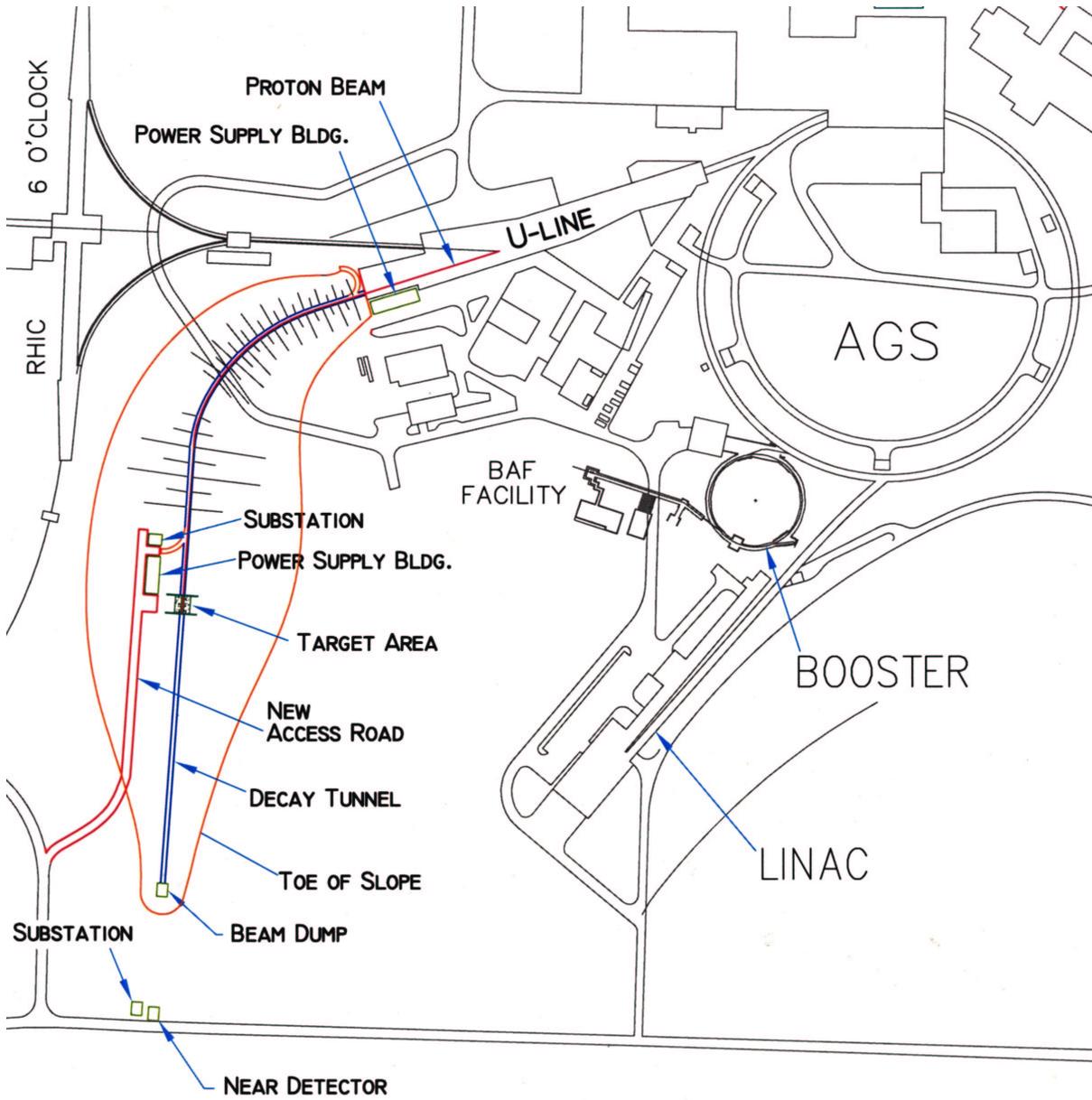


- BNL-Lead 2540km  
BNL-Wipp: 2880km
- Avoids water table.
- Hills are inexpensive:  
highway ramps.
- Total cost \$35 M for  
200 m tunnel.



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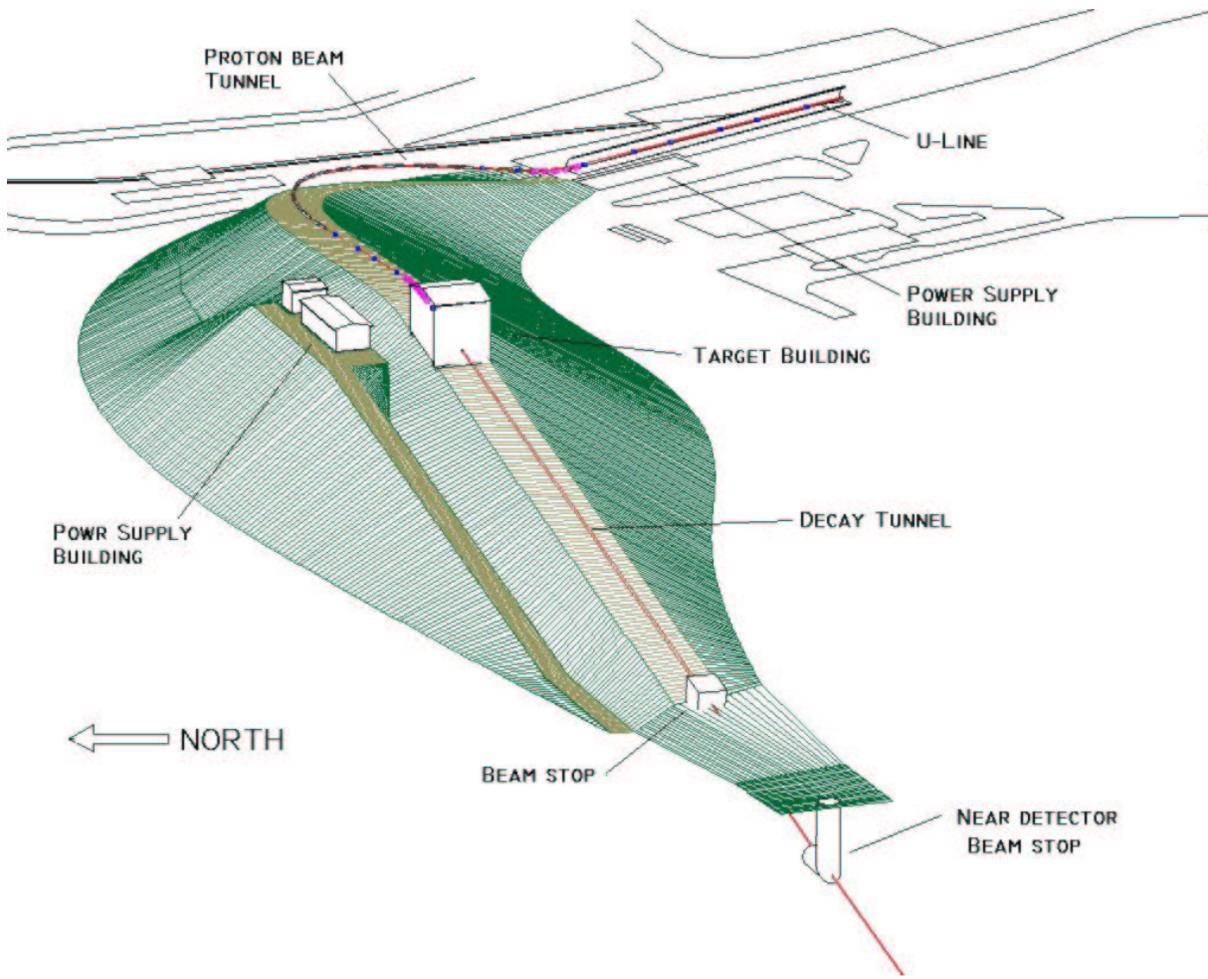
# Beam Layout



← NORTH

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# Beam 3d



## Event Rates with Neutrinos

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

Assume Water Cerenkov detector (with  $\sim 10\%$  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  $\pi$ .

Low  $\tau$  production.

## Neutral Current Events Neutrinos

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

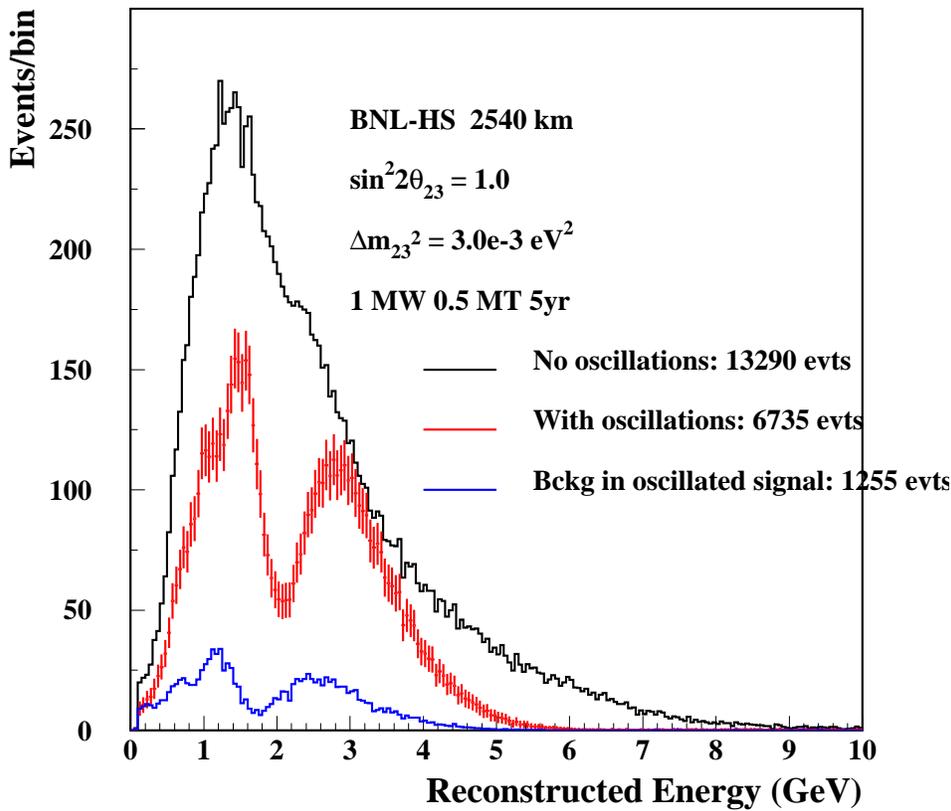
Assume Water Cerenkov detector (with  $\sim 10\%$  PMT coverage)

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

Multiple pion events should be suppressed better than single  $\pi^0$  events.

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

## $\nu_\mu$ DISAPPEARANCE

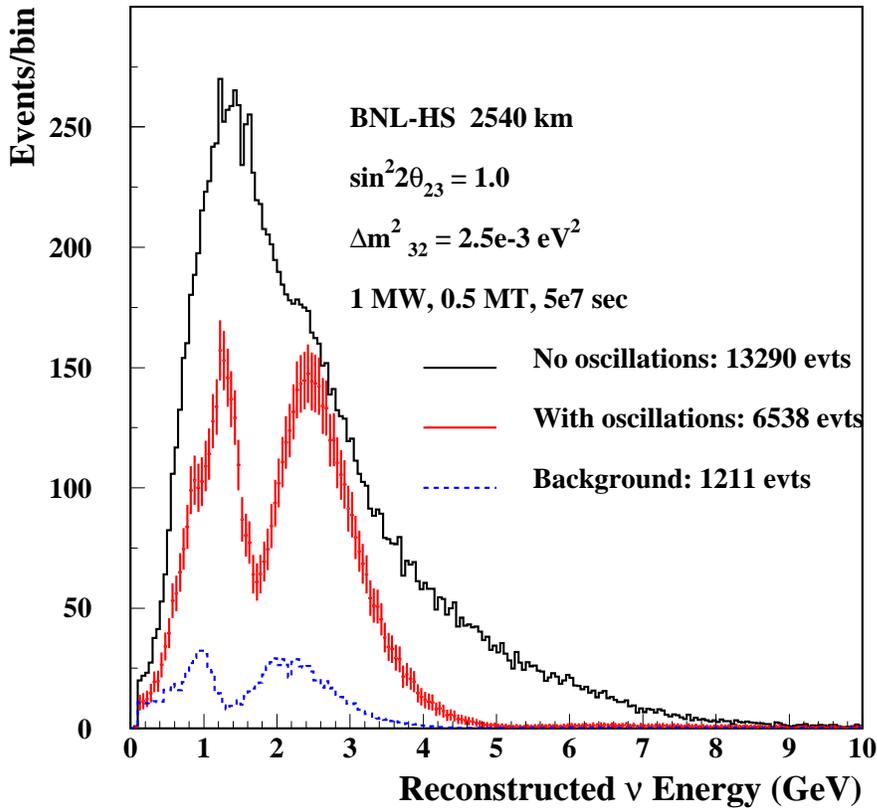


Node pattern provides high  $\Delta m_{23}^2$  resolution.  
Energy calibration is very important.

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

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

## $\nu_\mu$ DISAPPEARANCE

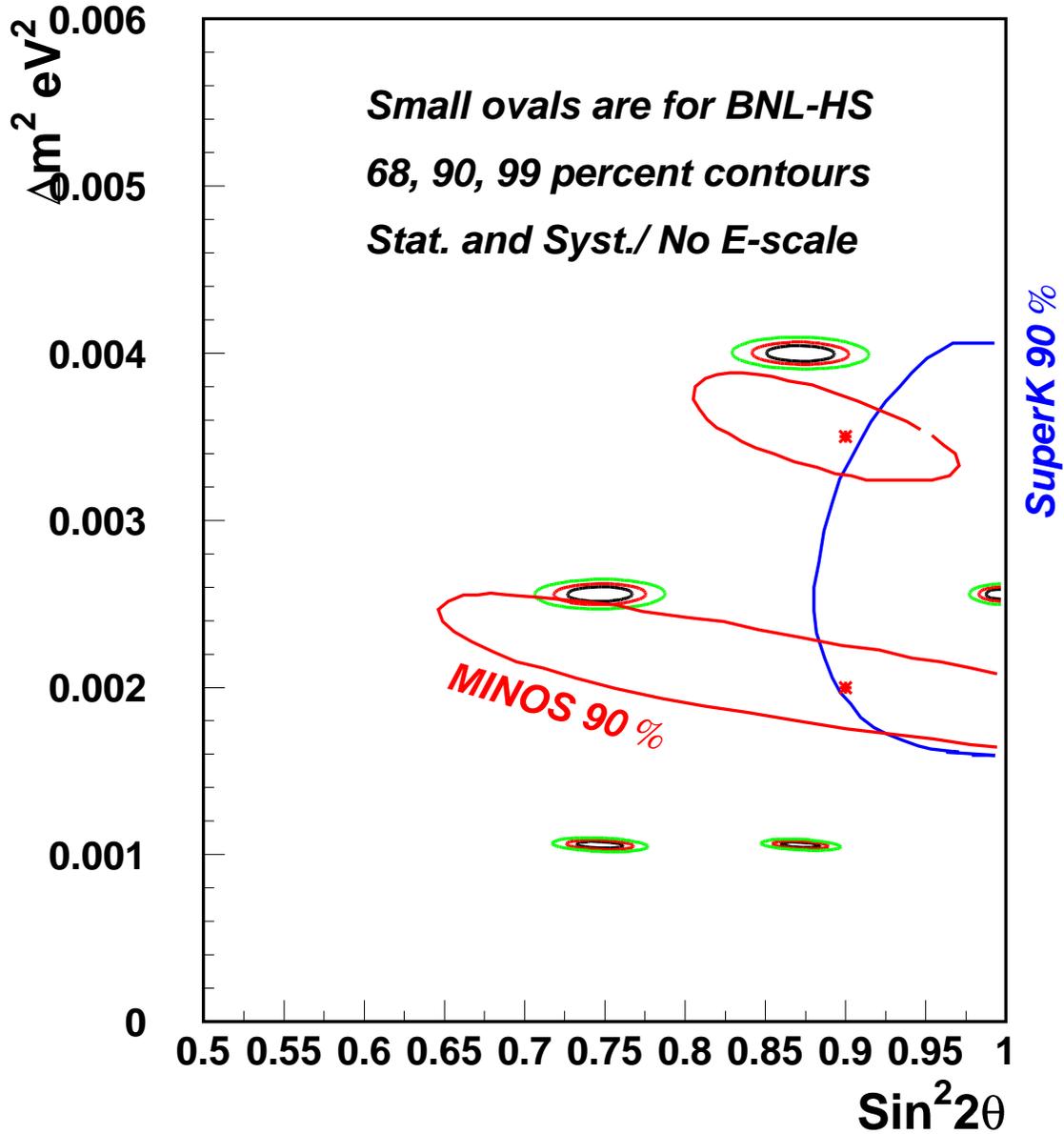


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Minimum systematics in  $\nu_\mu$  and  $\bar{\nu}_\mu$  comparison

# Test points for $\nu_\mu$ disapp

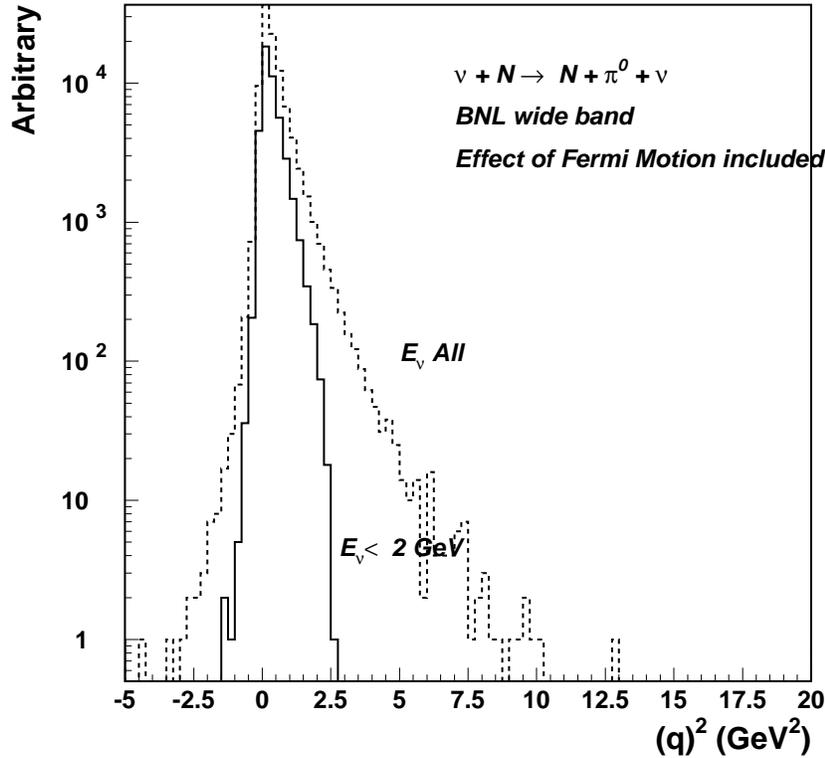


## Measurement of $\Delta m_{32}^2$

- Little dependence on systematic errors on resolution, backgrounds, energy linearity, or normalization.
- Ultimate resolution on  $\Delta m^2$  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 $\pi^0$ background for $\nu_\mu \rightarrow \nu_e$

$q^2$  in lab frame of NC ( $\nu N \pi^0$ ) events



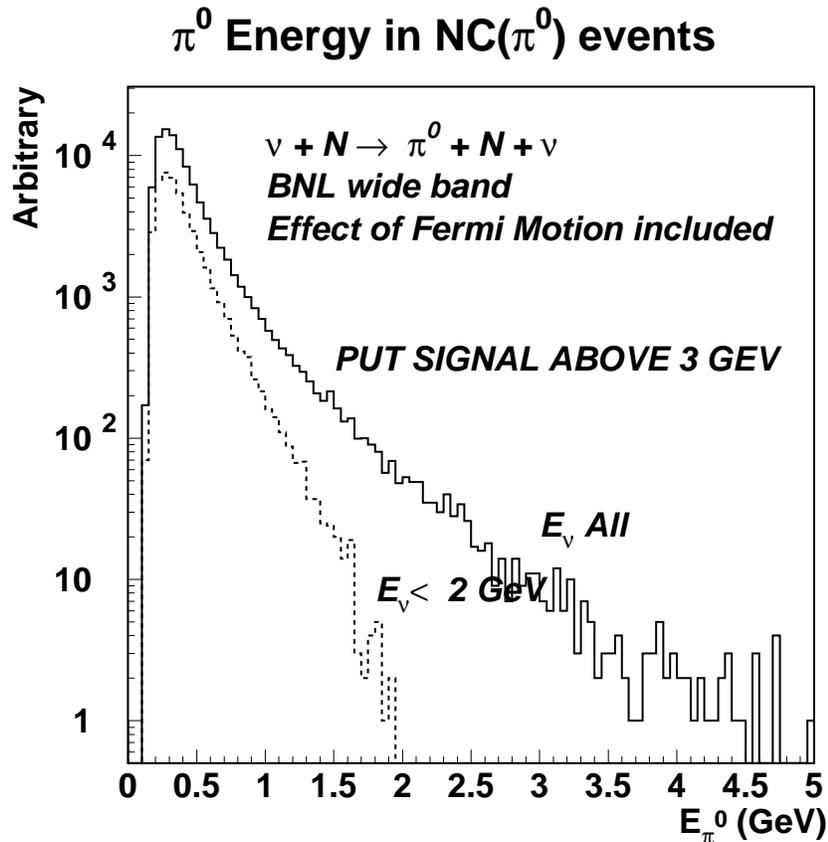
$$q^2 = (p'_N + p'_\pi) - p_N.$$

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

General feature of all neutral current processes:

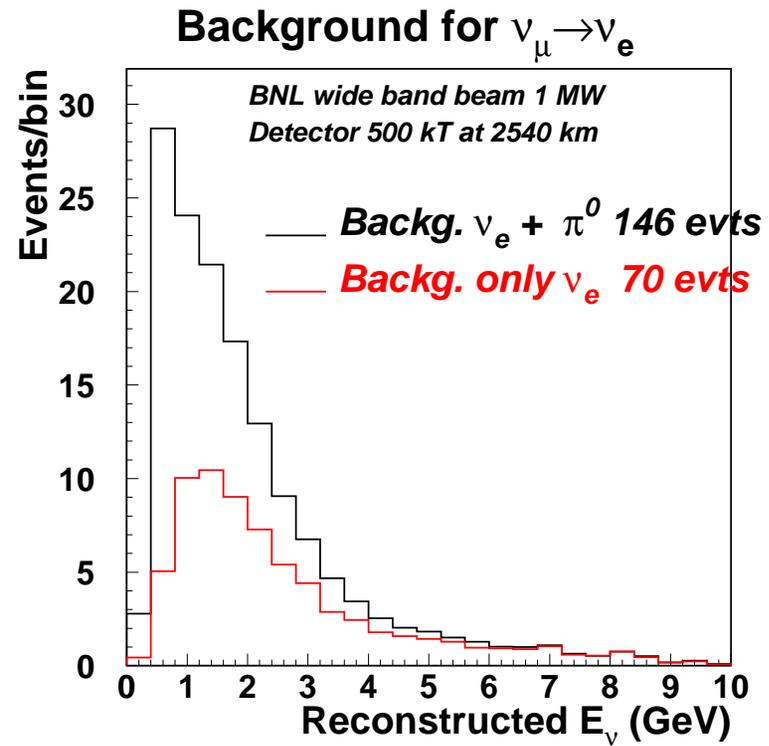
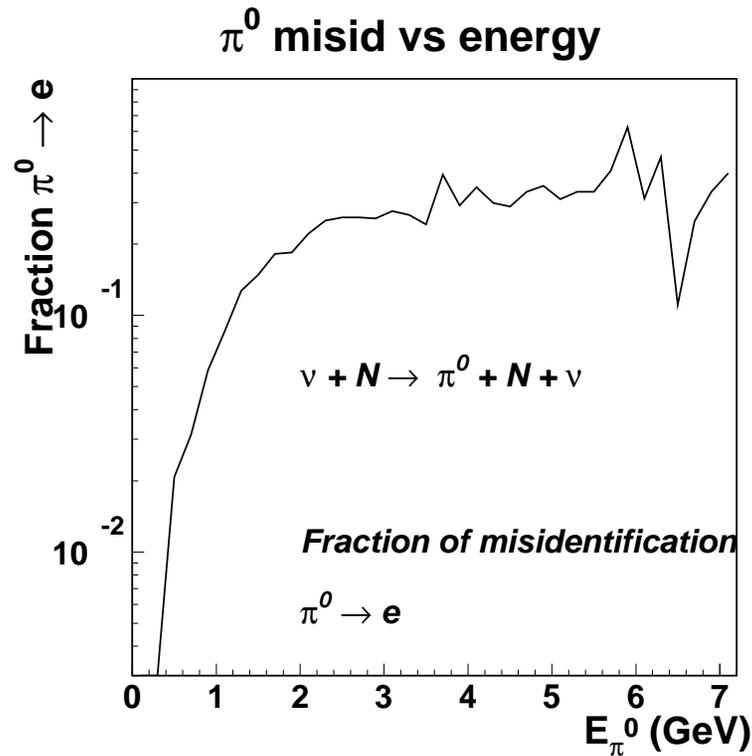
Low  $q^2$  or low hadronic energy in final state independent of neutrino energy.

# NC $\pi^0$ background for $\nu_\mu \rightarrow \nu_e$



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

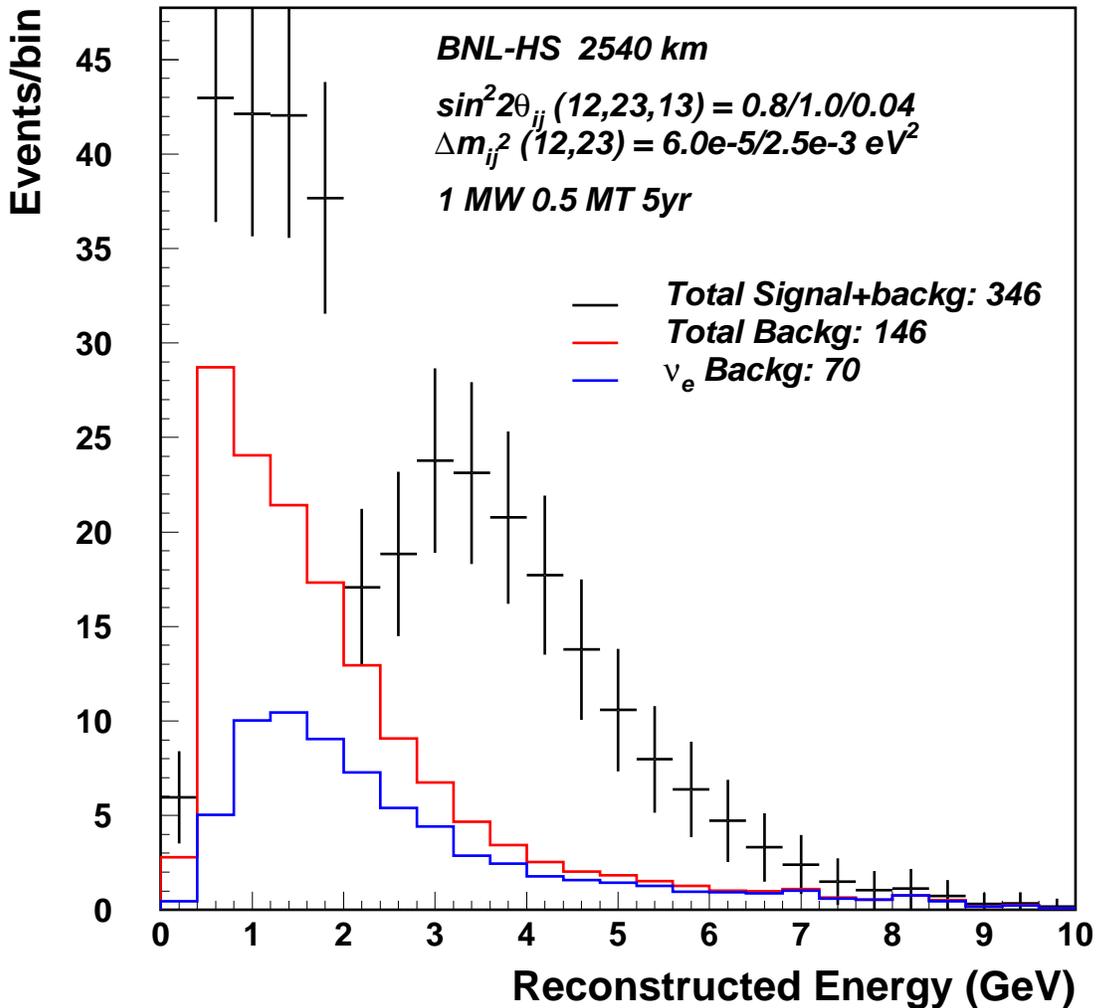
# $\nu_\mu \rightarrow \nu_e$ All background



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

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

## $\nu_e$ APPEARANCE



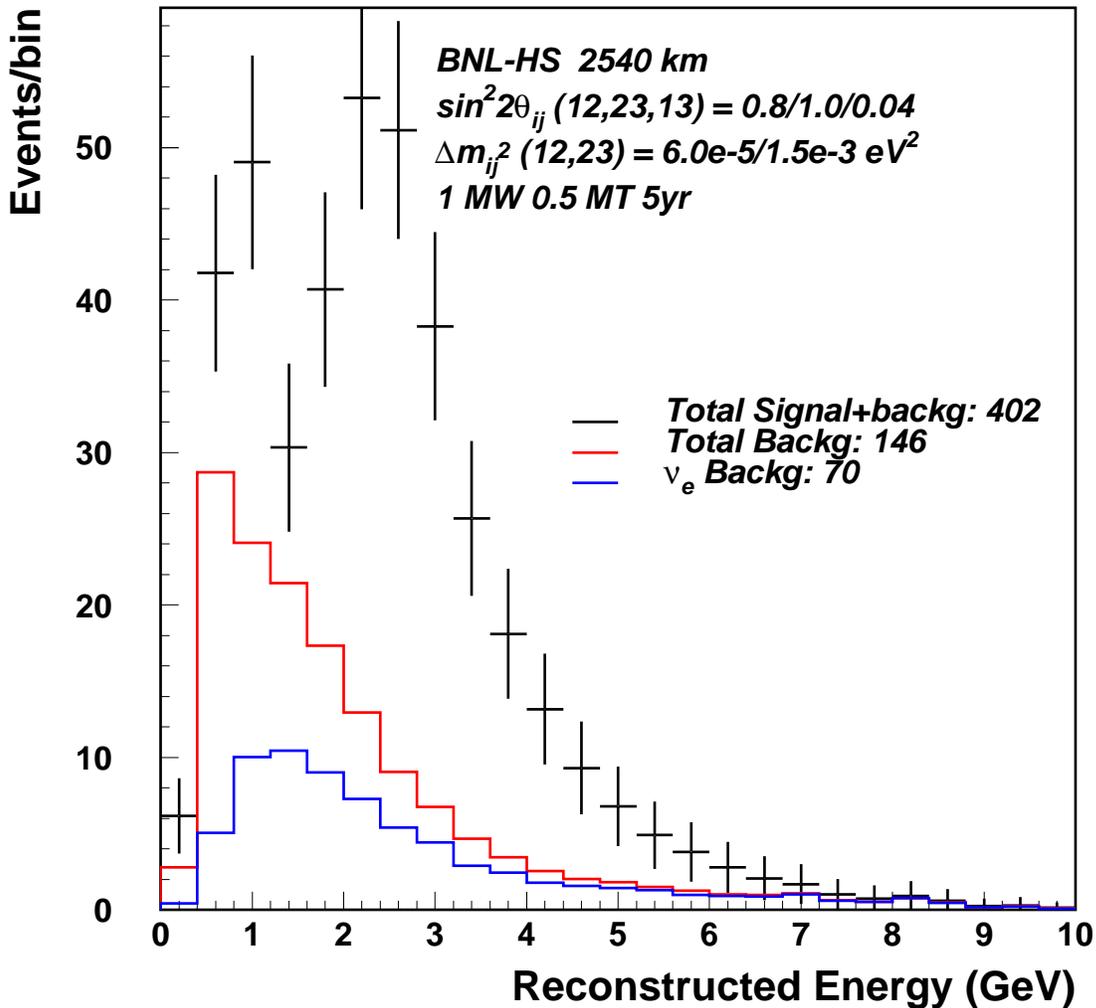
$$\Delta m_{23}^2 = 0.0025 \text{ eV}^2, \sin^2 2\theta_{13} = 0.04.$$

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

Matter effects included.

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

## $\nu_e$ APPEARANCE

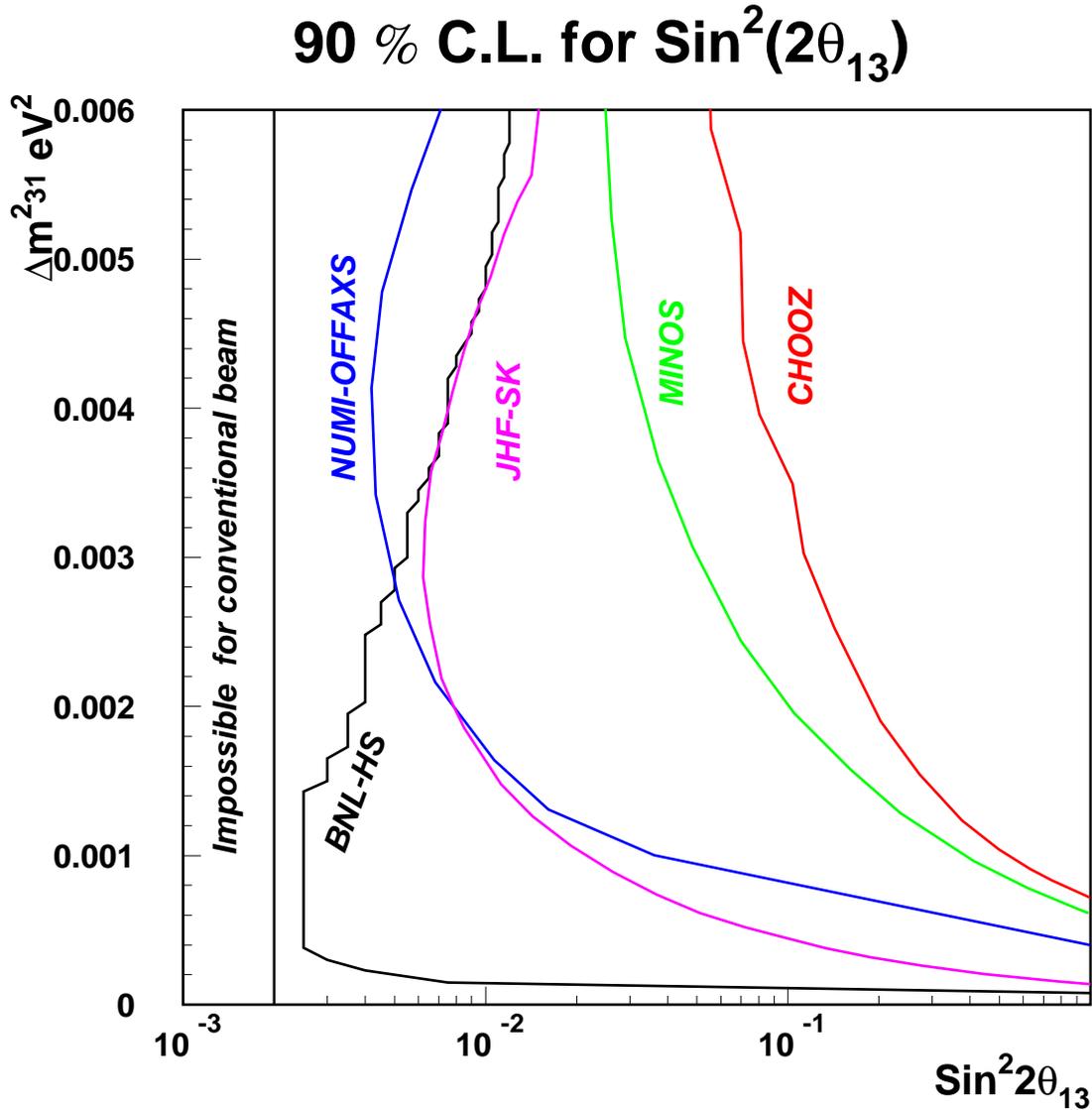


$$\Delta m_{23}^2 = 0.0015 \text{ eV}^2, \sin^2 2\theta_{13} = 0.04.$$

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

Matter effects included.

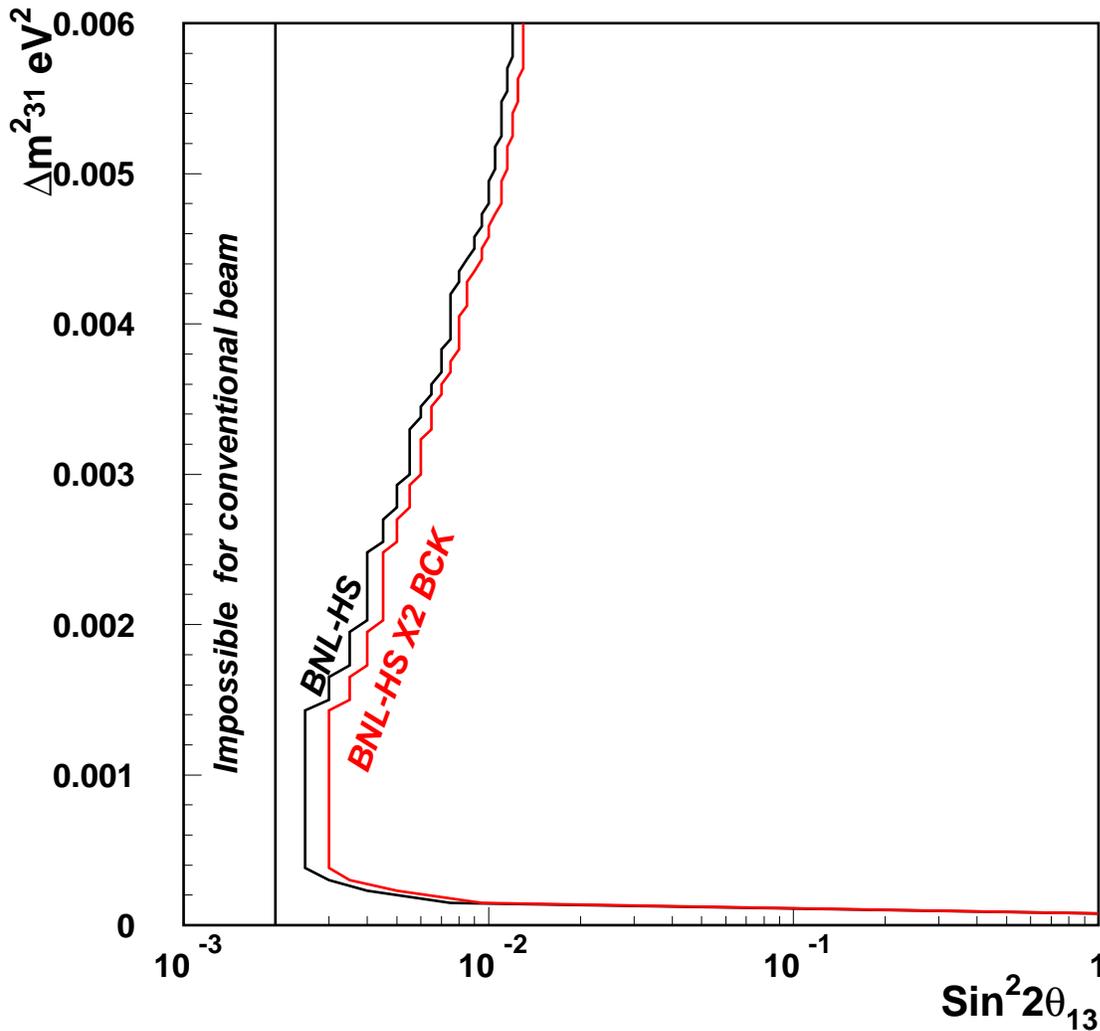
# Measurement of $\sin^2 2\theta_{13}$ 90% C.L.



Distinctive signature with multiple oscillations above  $0.001 \text{ eV}^2$

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

## 90 % C.L. for $\text{Sin}^2(2\theta_{13})$



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  $0.0025 eV^2$ .

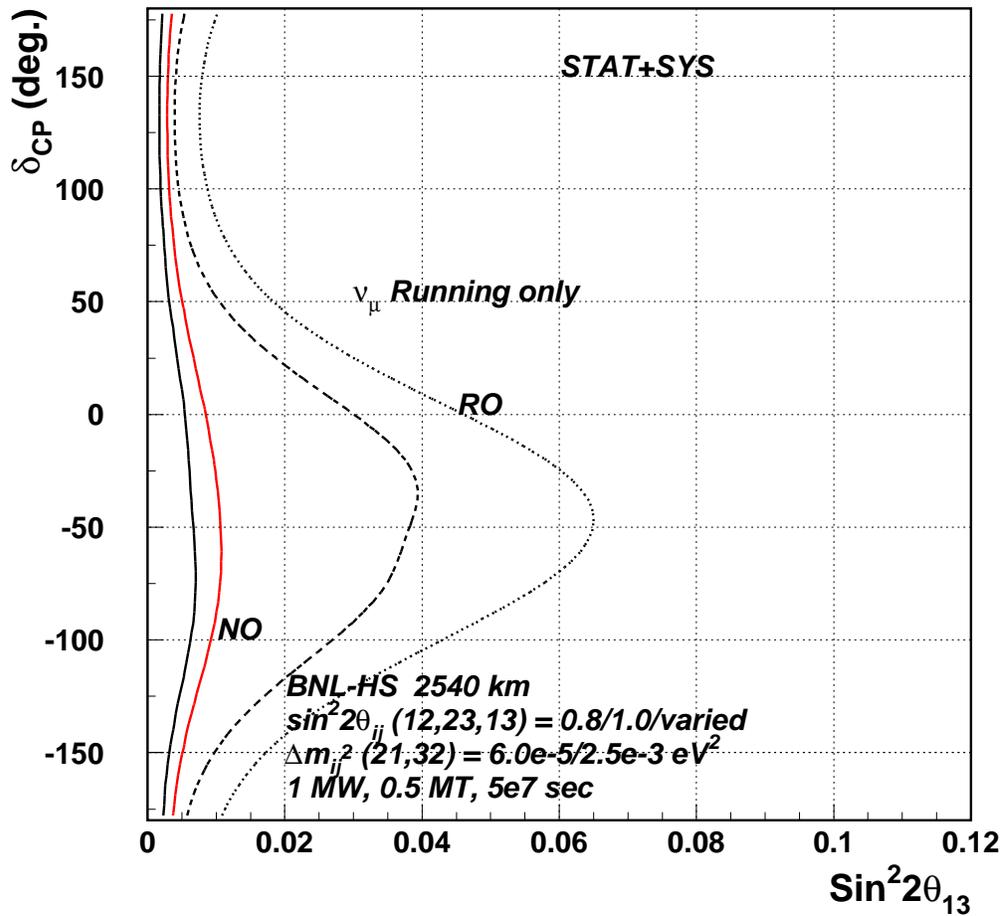
Signal very distinctive above  $0.001 eV^2$ .

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 intrinsic  $\nu_e$  background.

# Mass Hierarchy

90, 99.7 % CL signal,  $\delta_{CP}$  vs  $\sin^2 2\theta_{13}$



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

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

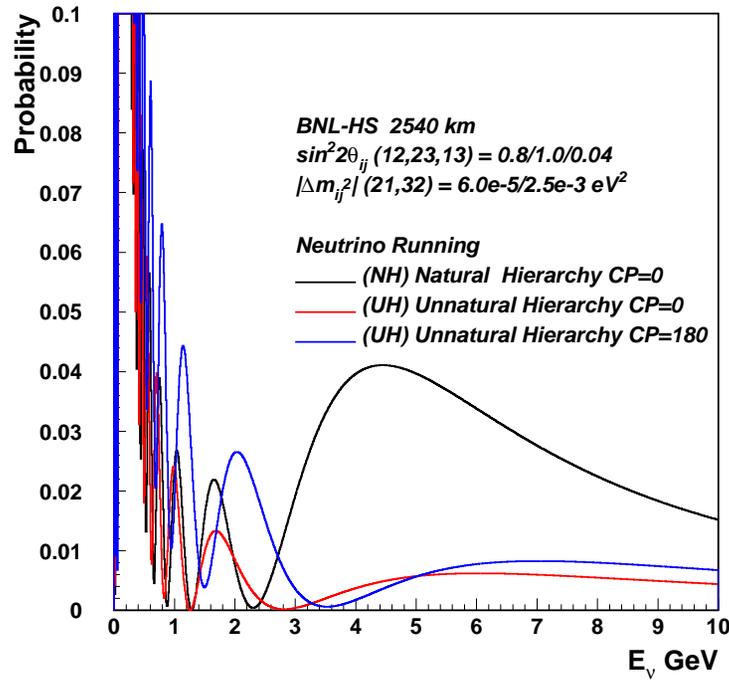
Unnatural Mass hierarchy:  $m_2 > m_1 > m_3$  (RO)

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

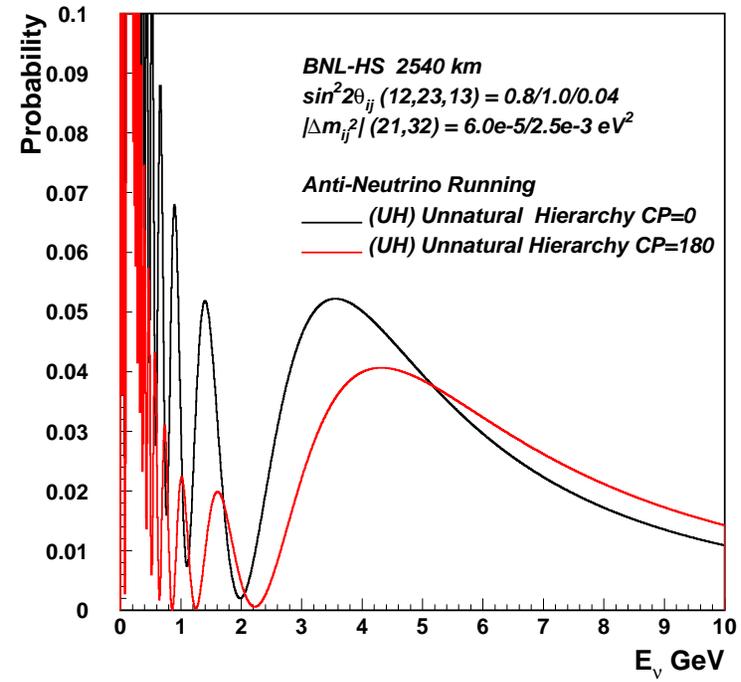
We would need to run Anti-neutrino beam to fully explore RO.

# Mass Hierarchy Anti-neutrinos

$\nu_\mu \rightarrow \nu_e$  Oscillation

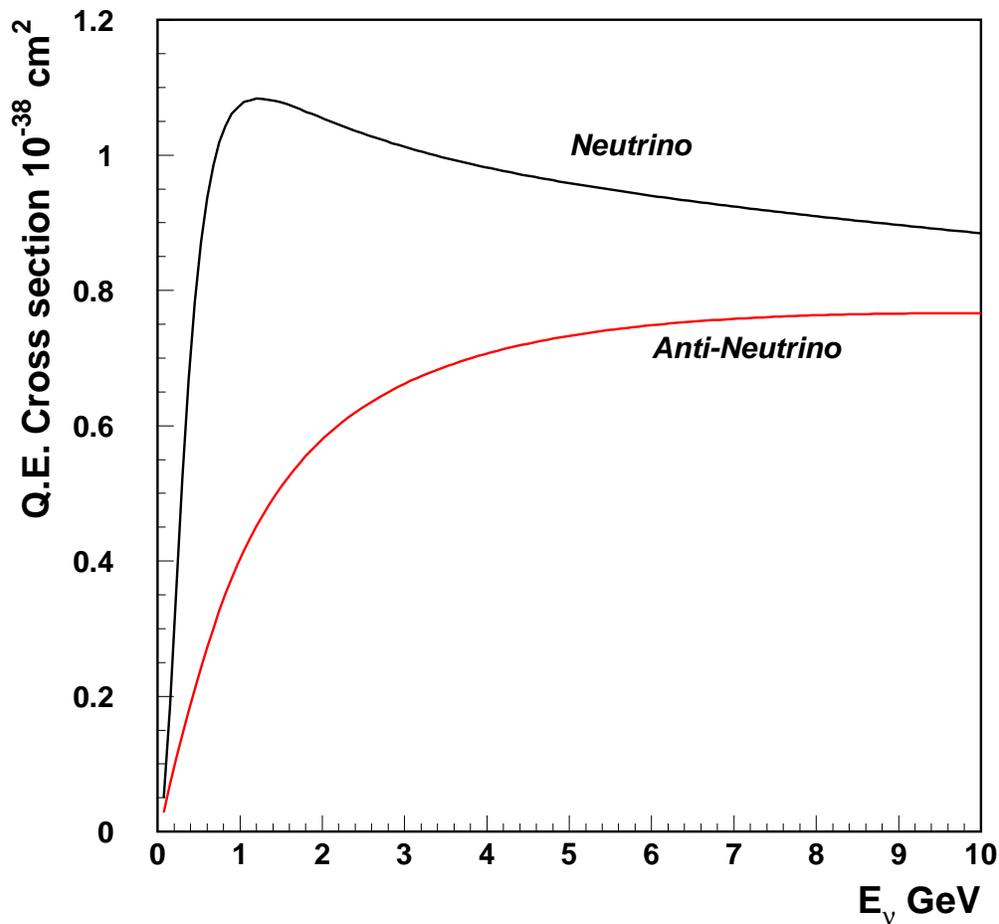


Anti- $\nu_\mu \rightarrow$  Anti- $\nu_e$  Oscillation



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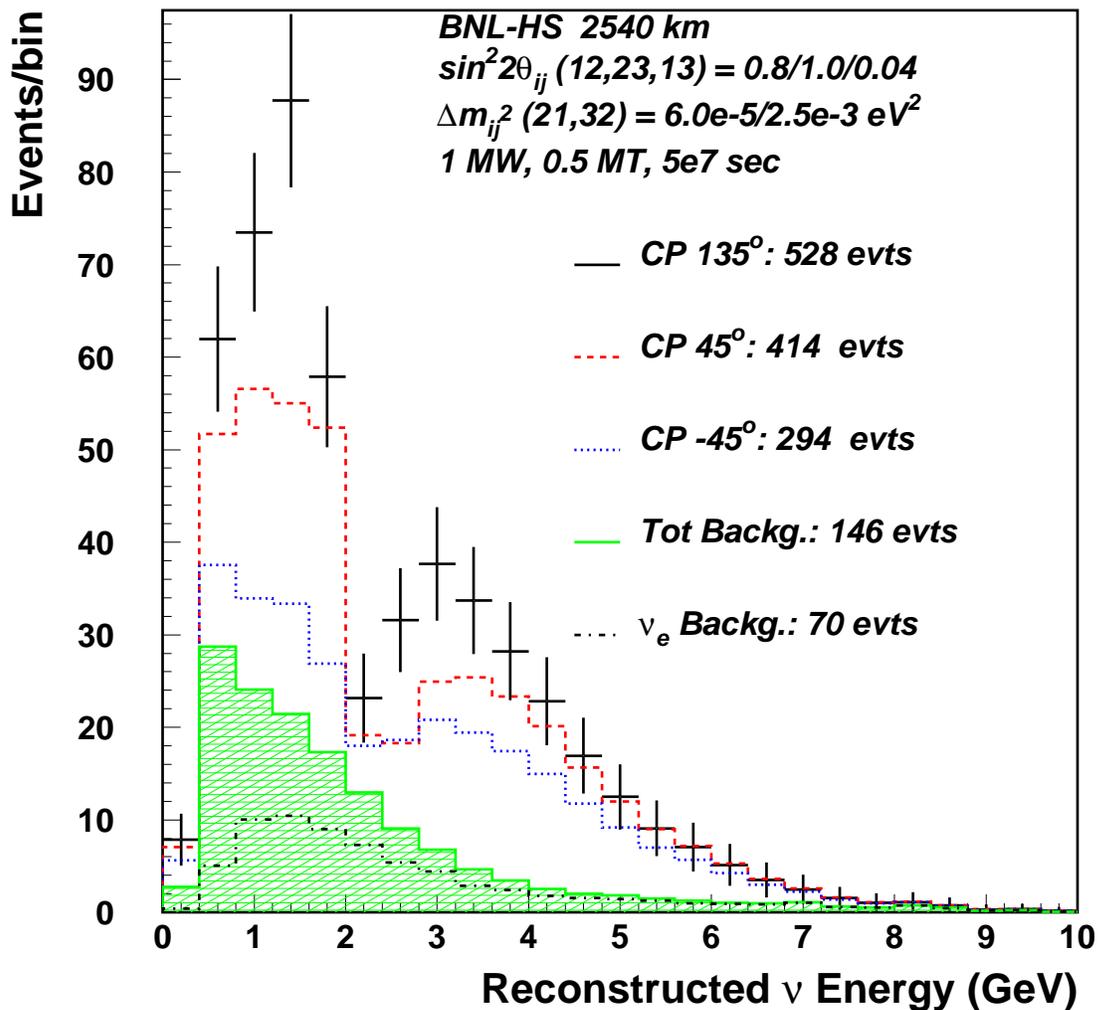
## Quasielastic cross section



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

# $\delta_{CP}$ Measurement. BNL-to-HS, 2540 km, 1 MW, 500kT, $5 \times 10^7$ sec

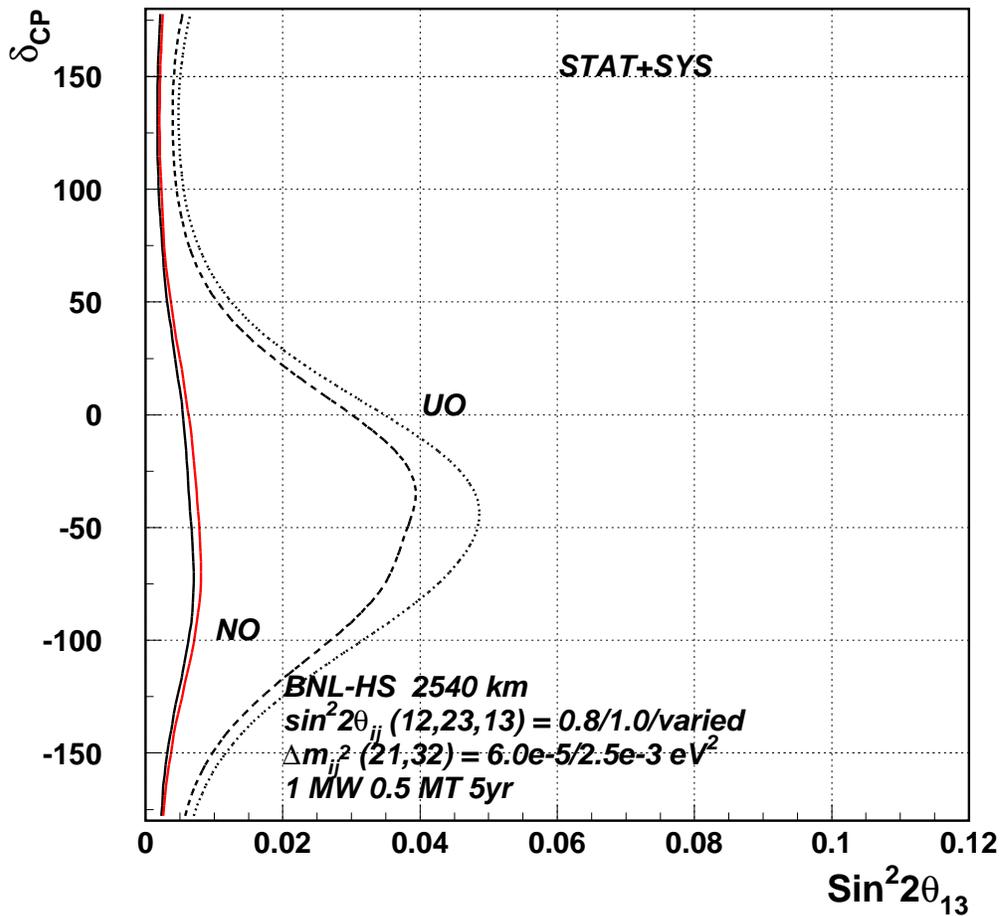
## $\nu_e$ APPEARANCE



CP parameter can be determined from only neutrino data.  
Good background subtraction can help.

# Measurement of $\delta_{CP}$ ; Confidence Levels

90, 95 % CL signal,  $\delta_{CP}$  vs  $\sin^2 2\theta_{13}$



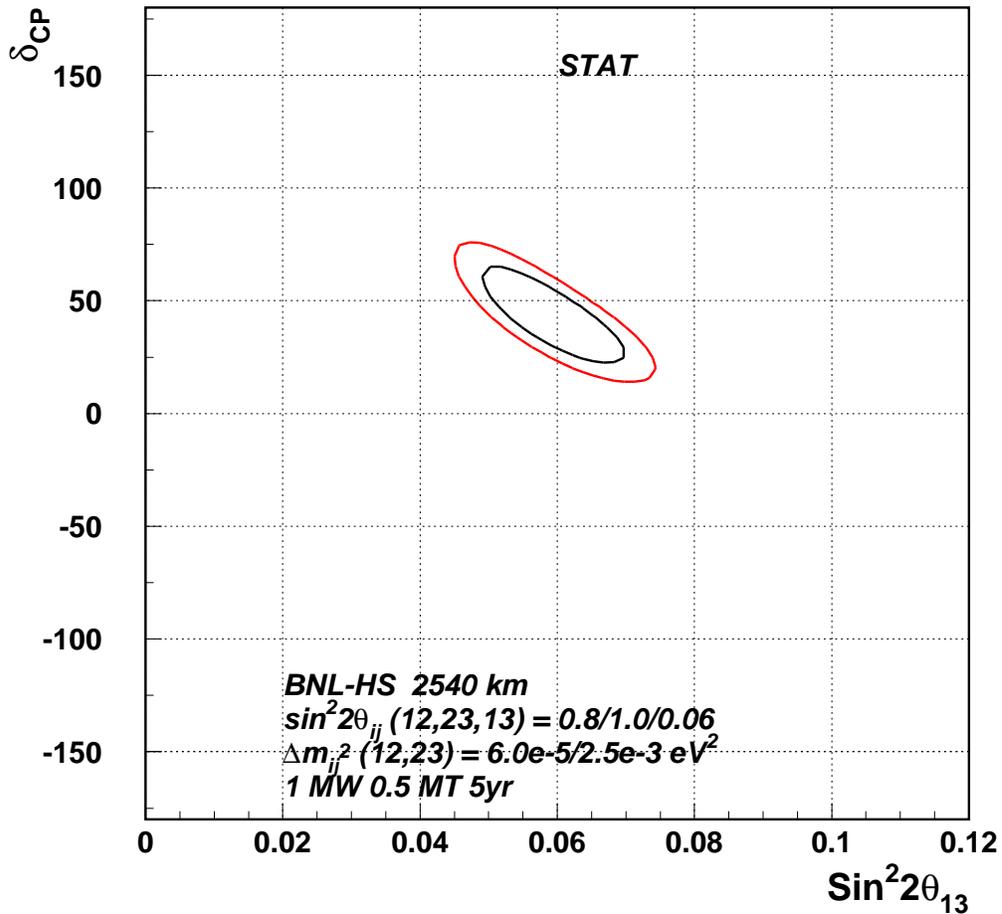
$$\Delta m_{21}^2 = 6 \times 10^{-5} eV^2, \Delta m_{31}^2 = 2.5 \times 10^{-3} eV^2$$

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

The region on the right hand side of curve can be excluded at 95% C.L. for NO and UO.

# Measurement of $\delta_{CP} = 45^\circ$

## 90 % C.L. for $\delta_{CP}$ vs $\sin^2 2\theta_{13}$



No Systematic error

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

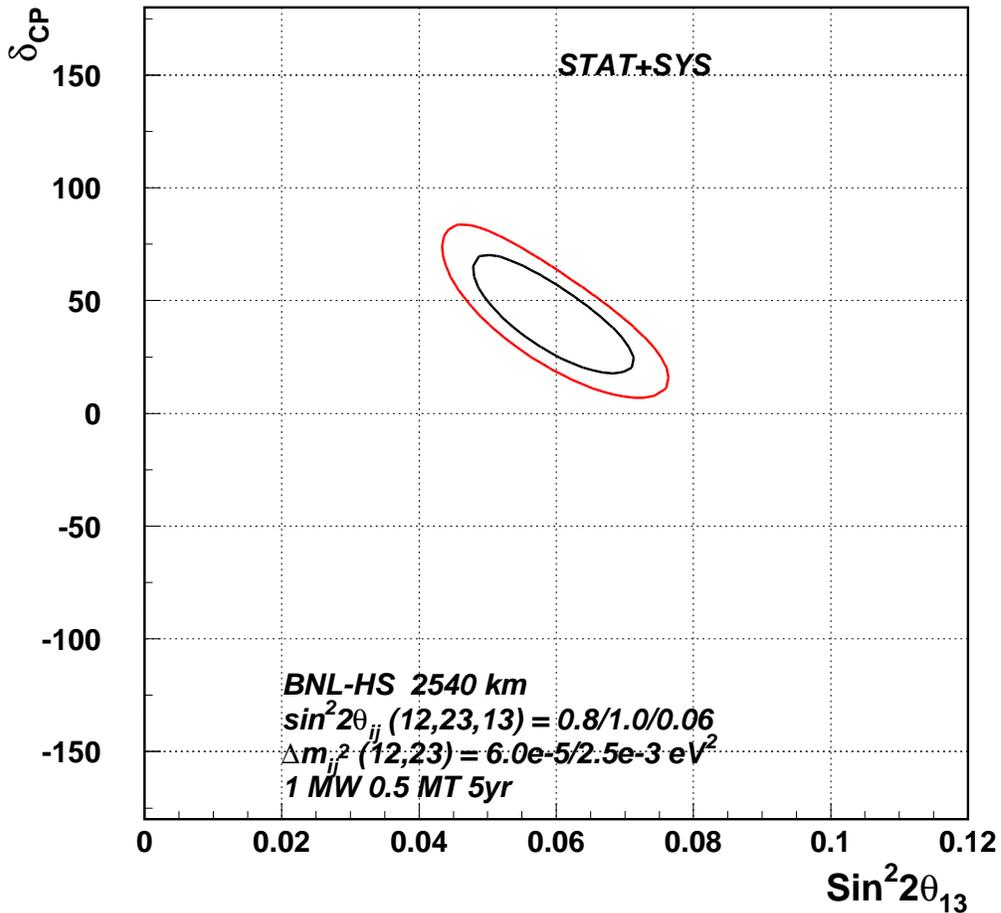
$$\sin^2 2\theta_{12} = 0.8, \sin^2 2\theta_{23} = 1.0$$

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

68%, and 90% C.L.

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

**90 % C.L. for  $\delta_{CP}$  vs  $\sin^2 2\theta_{13}$**



Systematic error of 10% on backg.

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

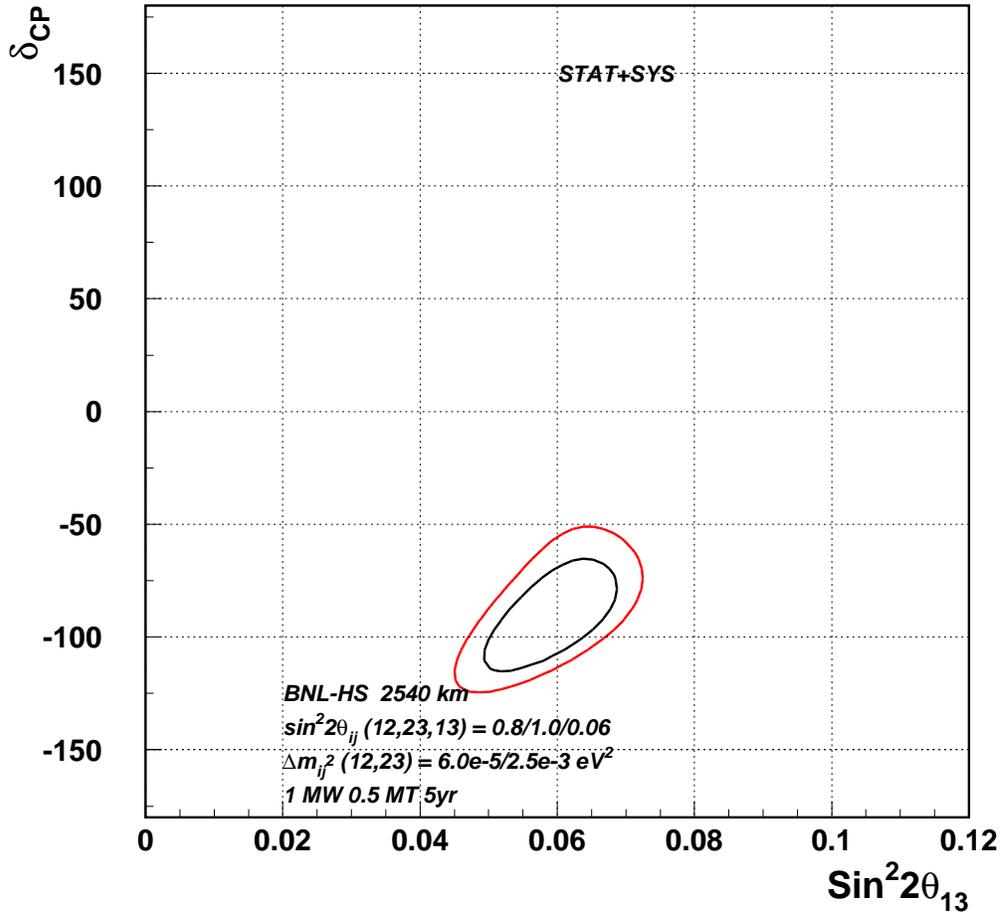
$$\sin^2 2\theta_{12} = 0.8, \sin^2 2\theta_{23} = 1.0$$

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

68%, and 90% C.L.

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

## 90 % C.L. for $\delta_{CP}$ vs $\sin^2 2\theta_{13}$



Systematic error of 10% on backg.

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

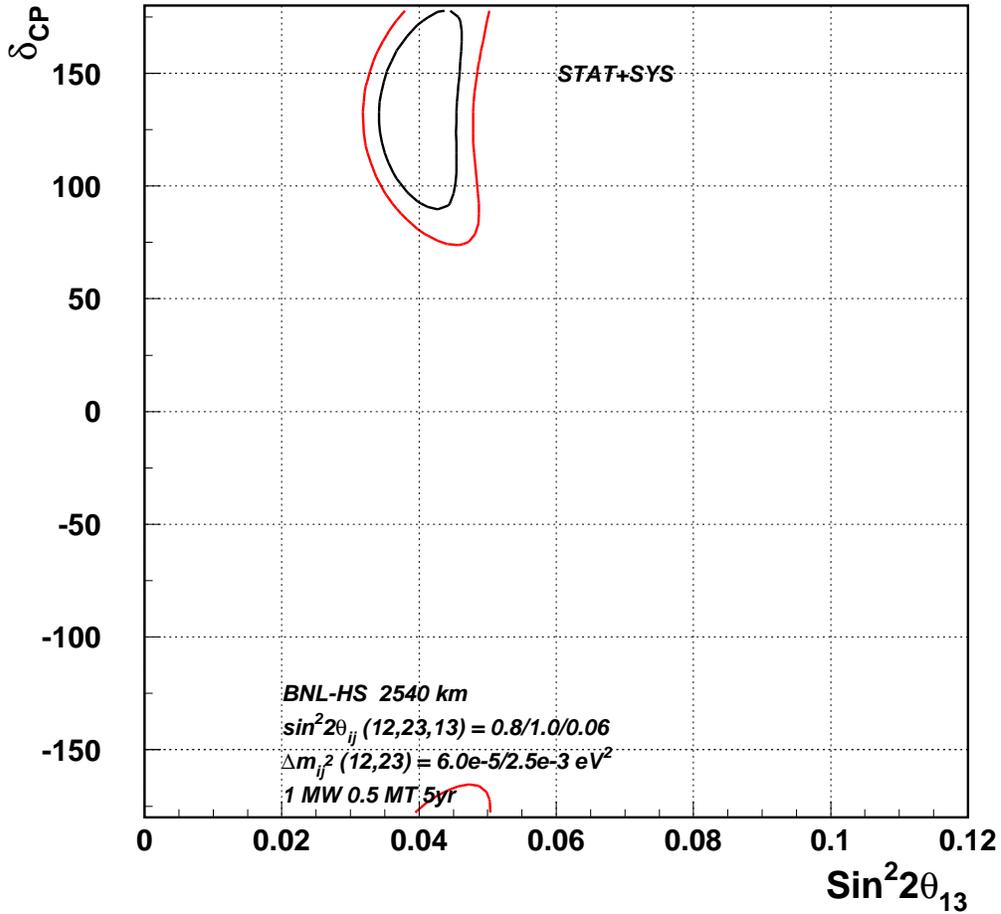
$$\sin^2 2\theta_{12} = 0.8, \sin^2 2\theta_{23} = 1.0$$

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

68%, and 90% C.L.

# Measurement of $\delta_{CP} = 135^\circ$

## 90 % C.L. for $\delta_{CP}$ vs $\sin^2 2\theta_{13}$



Systematic error of 10% on backg.

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

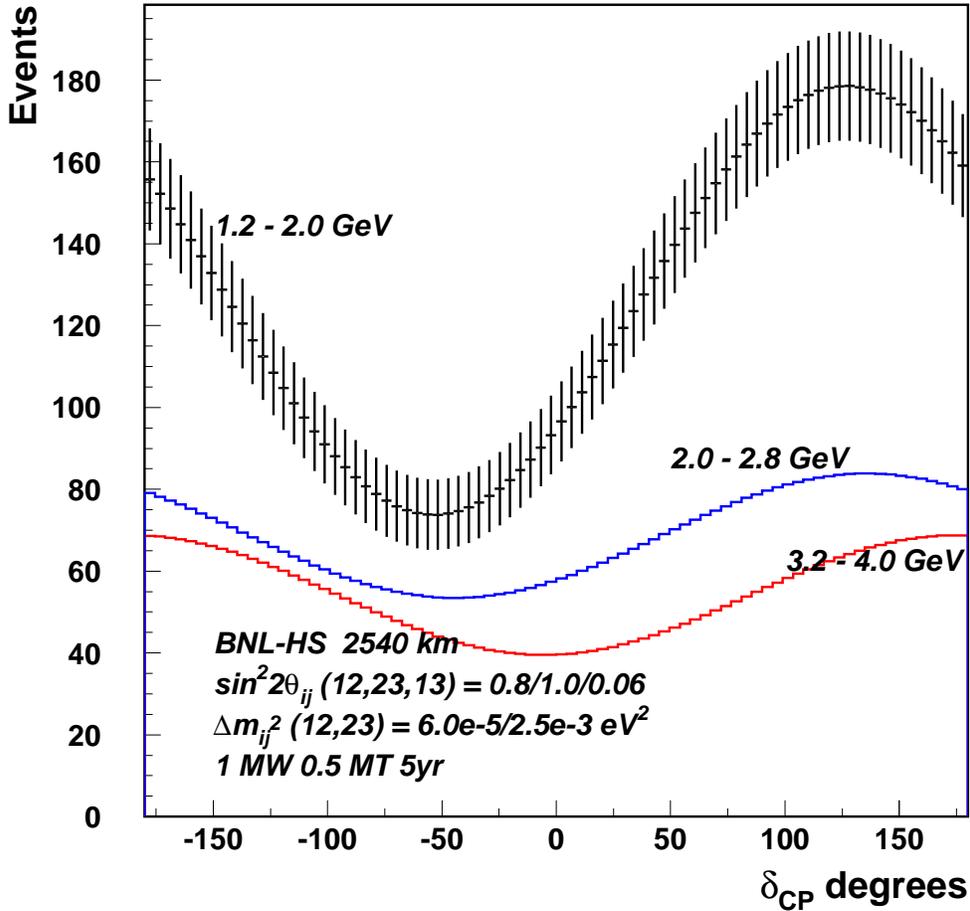
$$\sin^2 2\theta_{12} = 0.8, \sin^2 2\theta_{23} = 1.0$$

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

68%, and 90% C.L.

# Effect of $\delta_{CP}$ on the spectrum.

## Effect of $\delta_{CP}$ in 3 energy bins



Event rate in 3 energy bins.

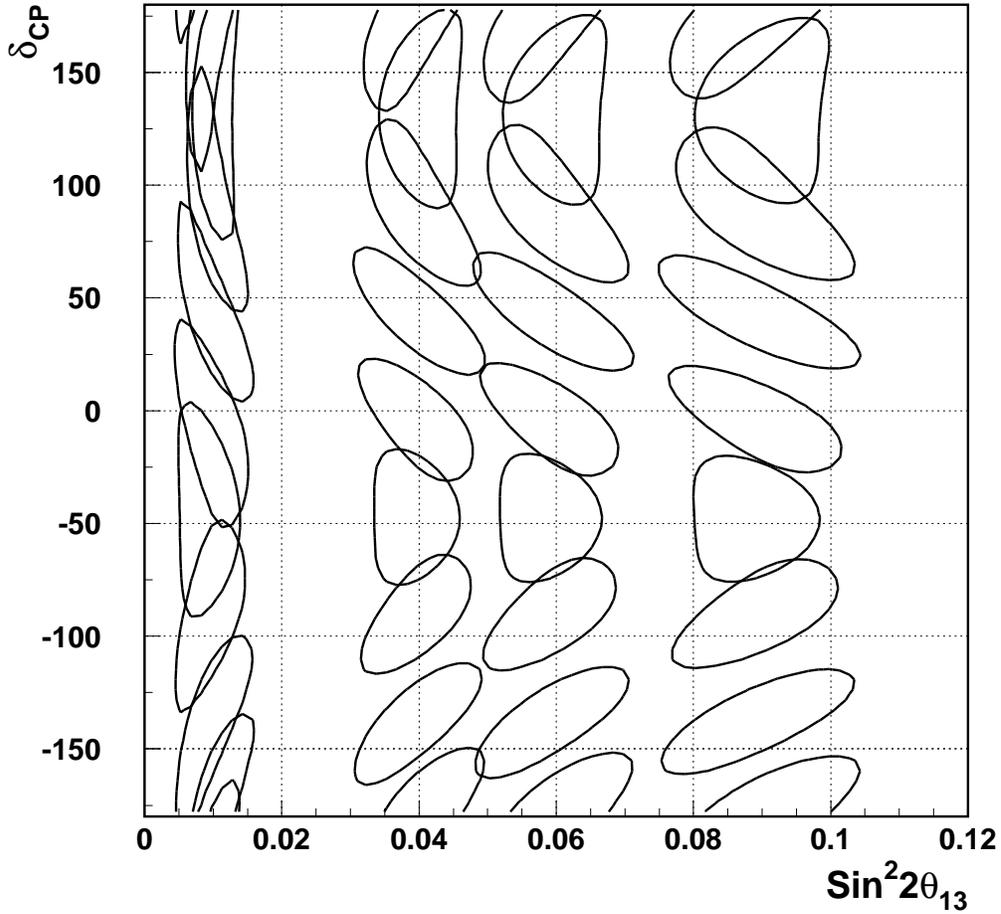
$$\Delta m_{21}^2 = 6 \times 10^{-5} eV^2, \Delta m_{31}^2 = 2.5 \times 10^{-3} eV^2$$

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

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

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

### Resolution $\delta_{CP}$ vs $\text{Sin}^2 2\theta_{13}$

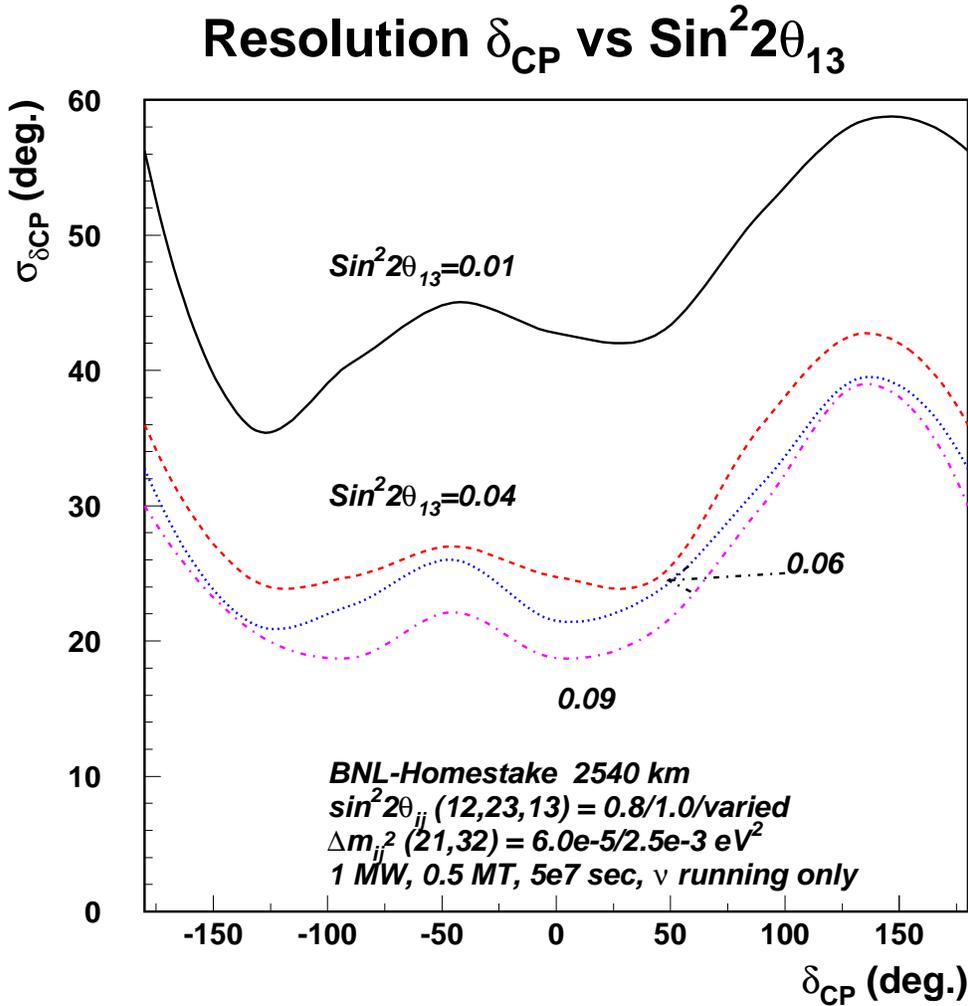


Assume all other parameters are well-known.

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

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

# 1 sigma error on $\delta_{CP}$ vs $\delta_{CP}$



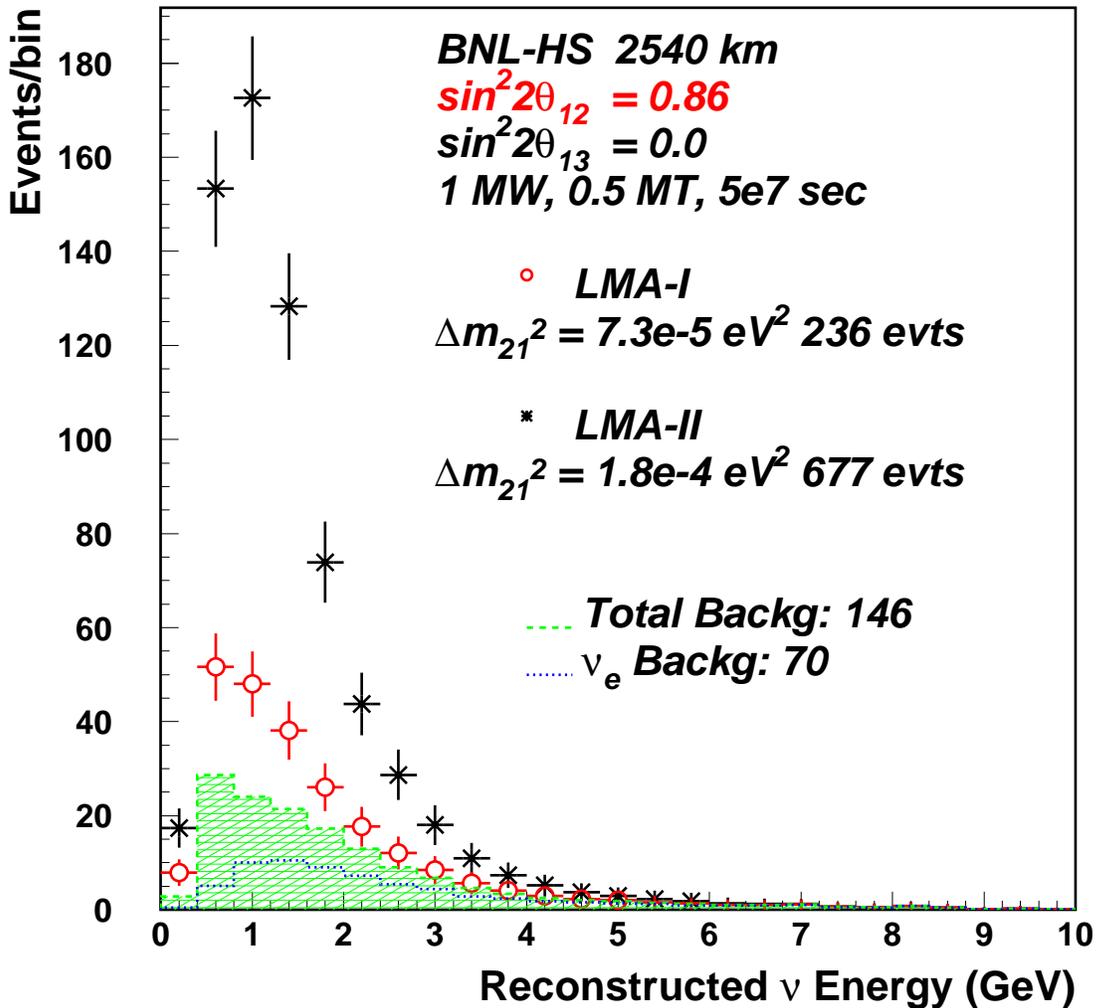
Full error from error contour. No knowledge of  $\theta_{13}$  assumed, but all other parameters fixed.

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

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

# Measurement of $\Delta m_{12}^2$

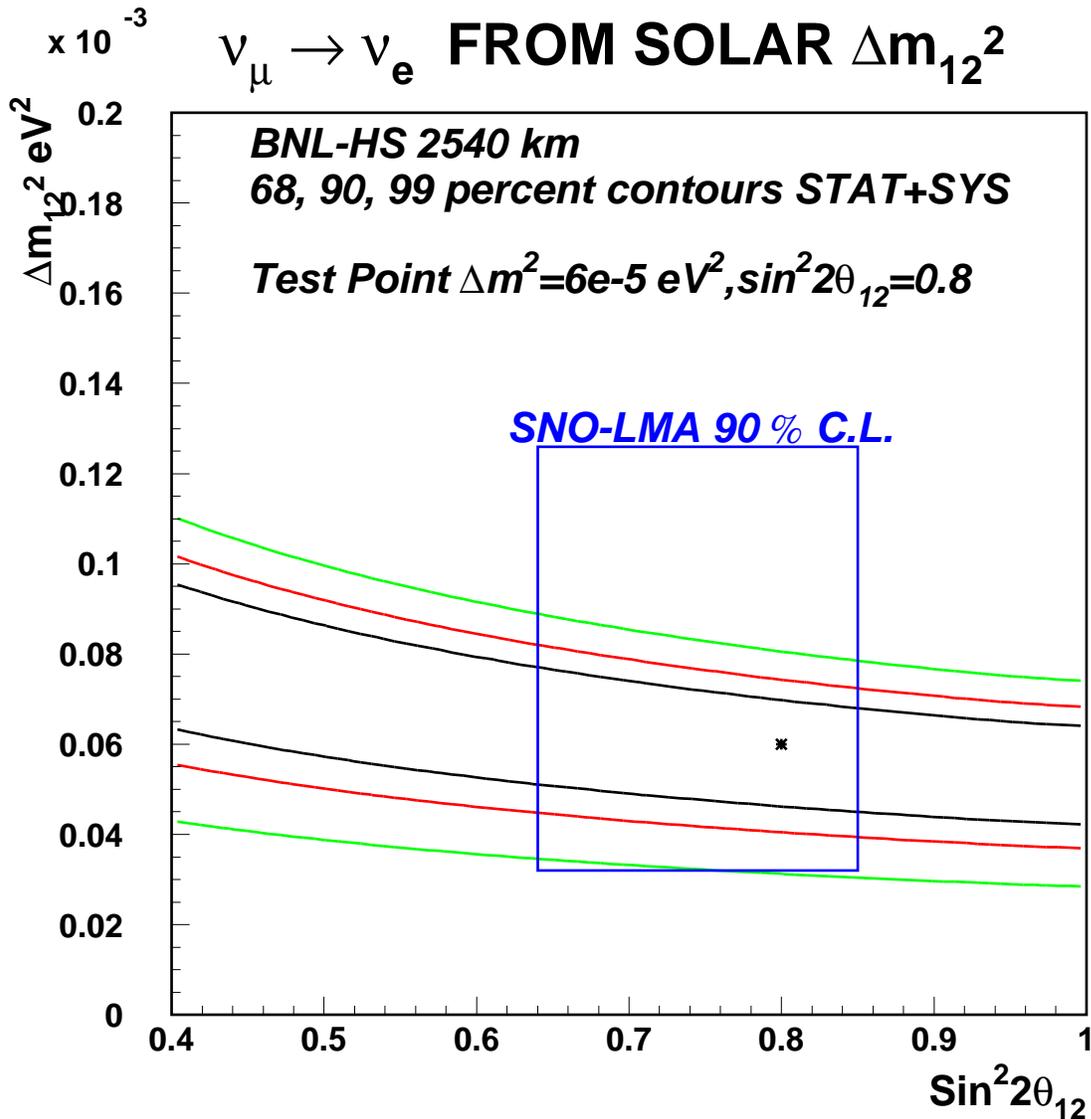
## $\nu_e$ APPEARANCE FROM $\Delta m_{21}^2$ ONLY



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

Excess of  $\sim 90$  events. Must know background

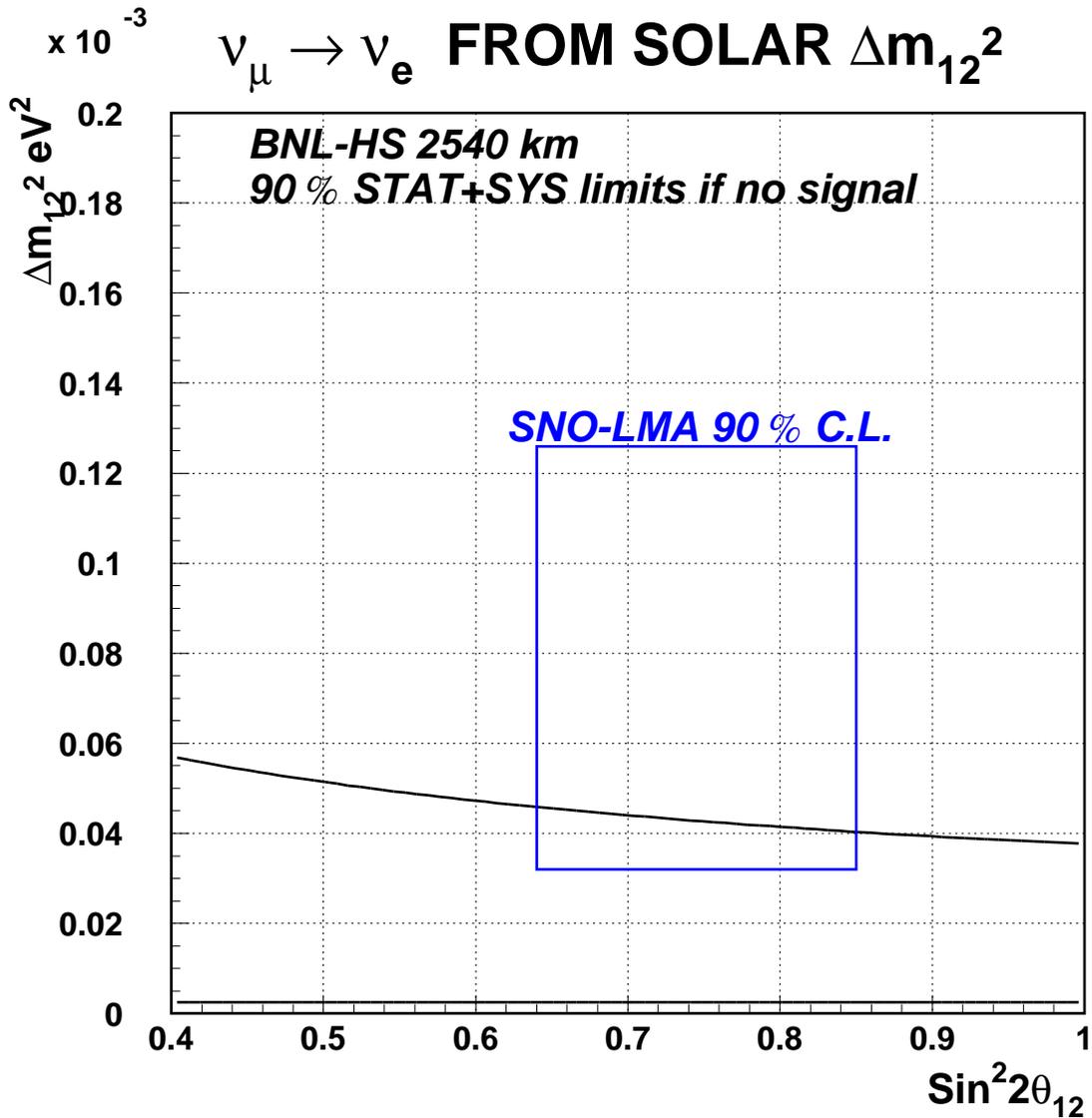
# Measurement of $\Delta m_{12}^2$



Independent  $\sim 15\%$  measurement of  $\Delta m_{12}^2$

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

# Limit on $\Delta m_{12}^2$ 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  $\Delta m_{23}^2$  from disappearance and definitive signal of oscillations.
- From the measured  $\Delta m_{23}^2$  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  $\Delta m_{32}^2 < 0$ .**
  - Get an independent measurement of  $\Delta m_{12}^2$  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  $\Delta m_{12}^2$  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  $\Delta m_{12}^2$ ,  $\delta_{CP}$  and  $\theta_{13}$ .
  - Is the  $CP$  angle too small? **NO YES**
- NO: Finished ! Still run antineutrinos for more precise  $\delta_{CP}$ .
- YES: Run anti-neutrinos for more sensitivity on  $\delta_{CP}$ .

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

- 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

$\delta_{CP}$ .

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  $\Delta m_{32}^2$
  - $< 1\%$  resolution on  $\sin^2 2\theta_{23}$
  - Sensitivity to  $\sin^2 2\theta_{13} \sim 0.005$  over a wide range of  $\Delta m_{32}^2$
  - Sensitivity to CP parameter  $\pm 25^\circ$  with neutrinos alone.
  - Sign of  $\Delta m_{32}^2$  over a wide range.
  - Measurement of  $\Delta m_{12}^2$  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:  $5 \times 10^7$  sec.

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

	$\Delta m_{32}^2$	$\sin^2 2\theta_{23}$	$\Delta m_{12}^2$	$\sin^2 2\theta_{13}$ 90 % C.L.	$\delta_{CP}$
$\Delta m_{32}^2 > 0.001$	$< 1\%$	$\sim 1\%$	$\pm 15\%$	$\sim 0.005$	
$\Delta m_{32}^2 > 0.001$ $\sin^2 2\theta_{13} > 0.01$	$< 1\%$	$\sim 1\%$	$\pm 15\%$	$\pm 0.01$	$\pm 25^\circ$
$\Delta m_{32}^2 > 0.001$ $\sin^2 2\theta_{13} < 0.01$	$< 1\%$	$\sim 1\%$	$\pm 15\%$	No Measure.	No Measure.

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

Need good energy calibration for  $\Delta m_{32}^2$  ( $\sim 100 \text{ MeV}$  LINAC ?)

Need small error on backg. for  $\Delta m_{12}^2$  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.