# Very long baselines with a superbeam

Milind V. Diwan

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.

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

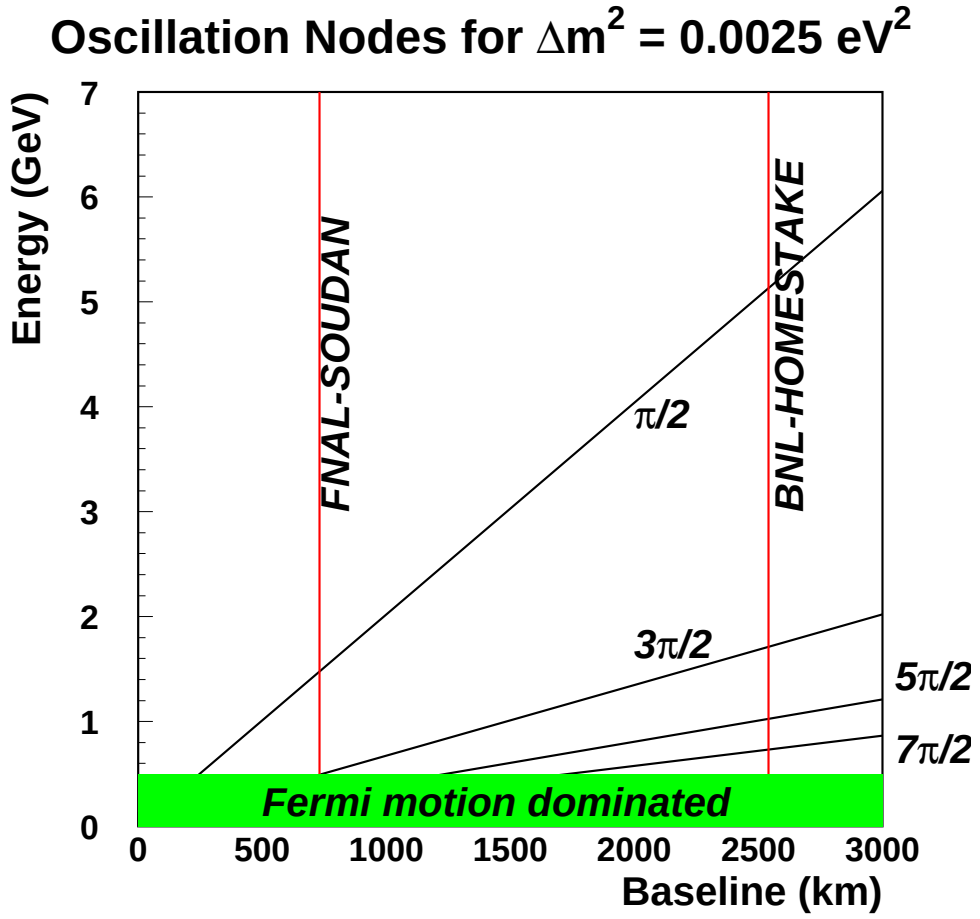
$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned} \quad (2)$$

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




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

Very long baselines with a superbeam

# Neutrino Physics: $3 \times 3$ Formulation

Bill Marciano, hep-ph/0108181

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

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

# 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 $\Delta_{21}$ (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

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

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

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

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

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

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

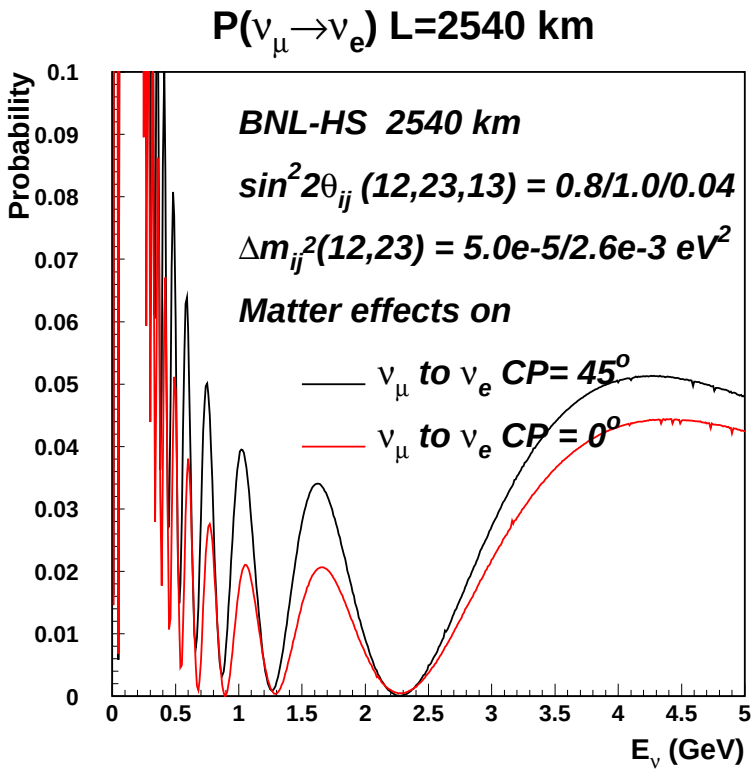
$\hat{A} = \approx 7.6 \times 10^{-5} \times (D/gm/cm^3) \times (E_\nu/GeV)/(\Delta m^2_{31}/eV^2)$,

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

Notice that the term with $\sin \delta_{CP}$ is linear in $\Delta m^2_{21}$ 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 $\Delta m^2_{21}$ is larger.

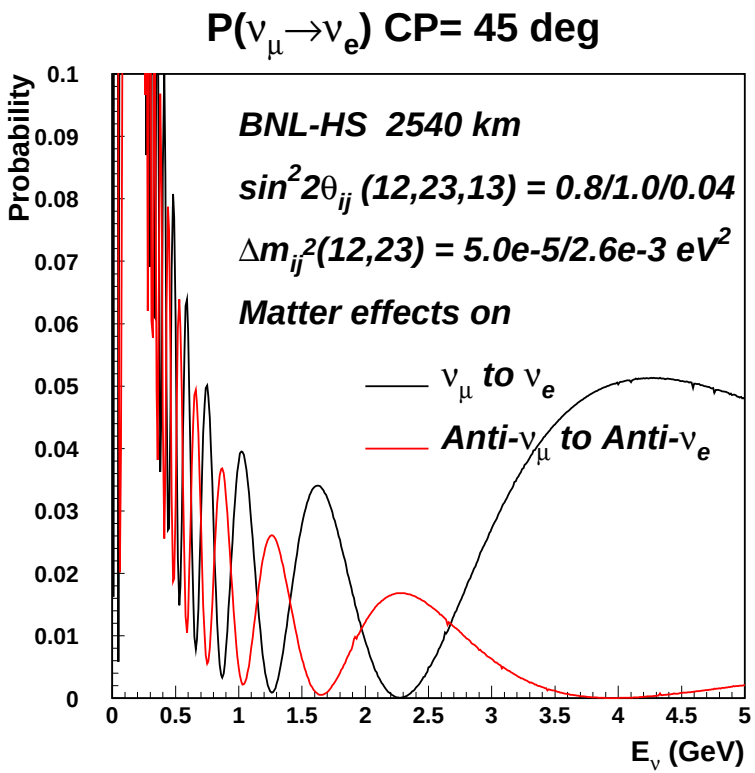



General Features

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

# 4 GOALS OF NEUTRINO OSCILLATION PHYSICS

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

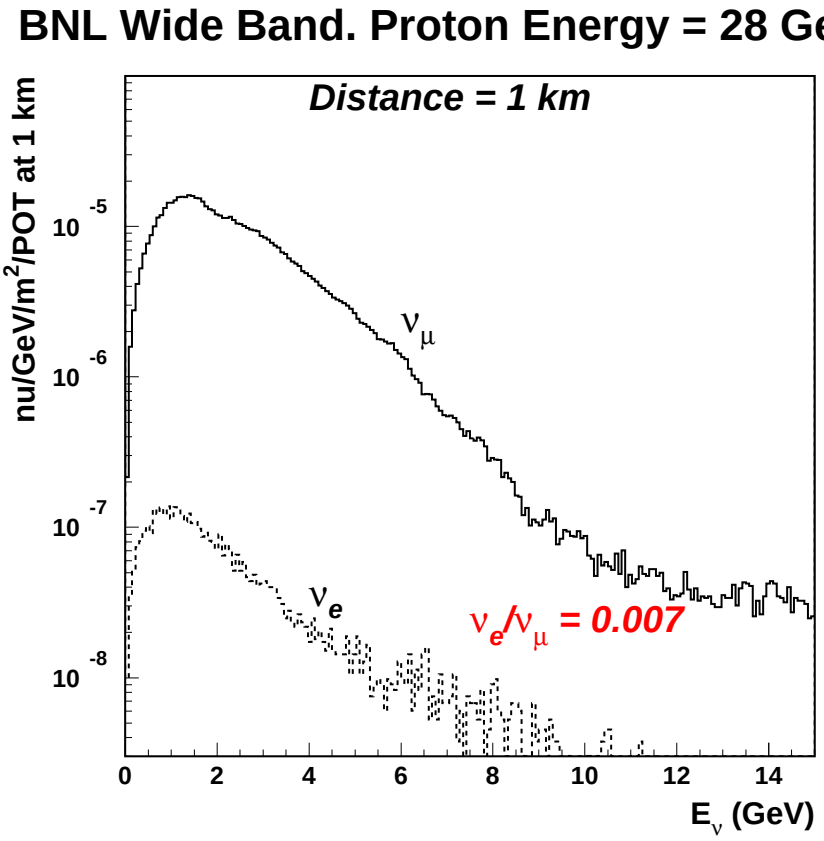
  Beam is wide band, but low energy to make low backgrounds to $\nu_e$ appearance signature.

- 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.

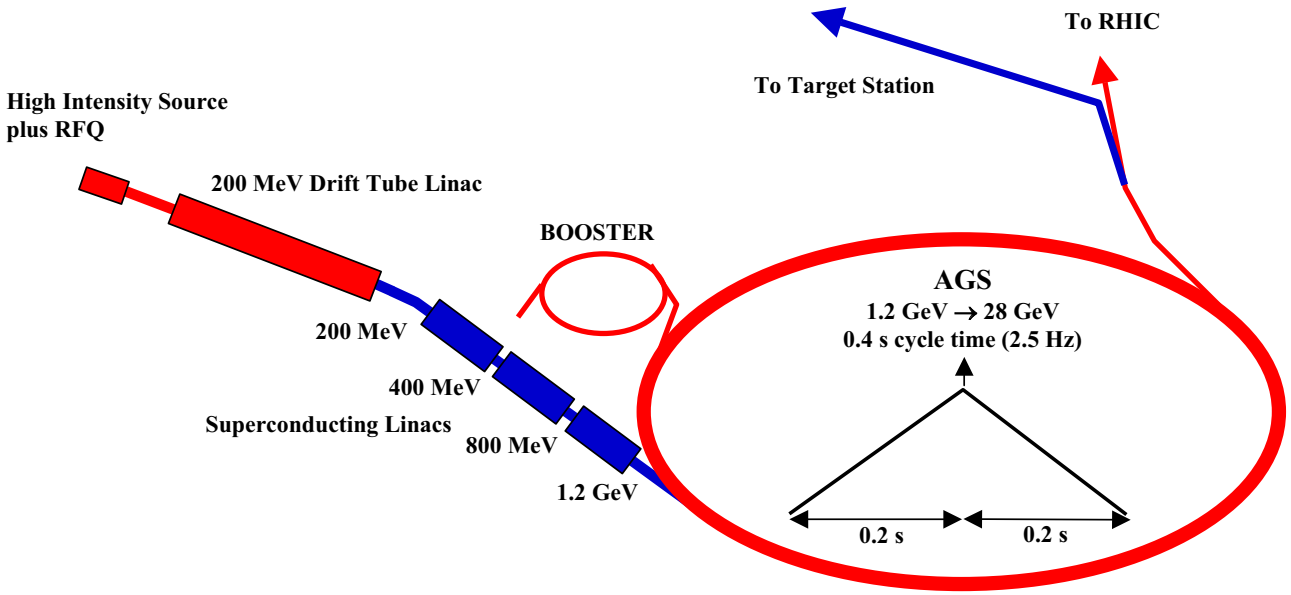
- It makes sense to make a neutrino oscillation experiment with large effects even if they are sensitive to multiple parameters.




- 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

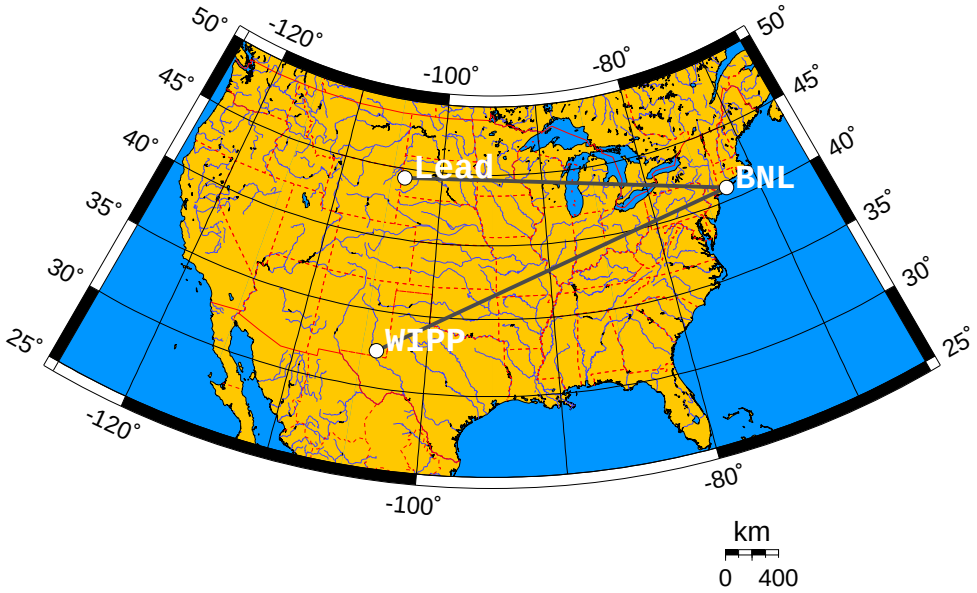
# The Accelerator

- 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 => LINAC: $10^{14} ppp$ at 2.5 Hz.

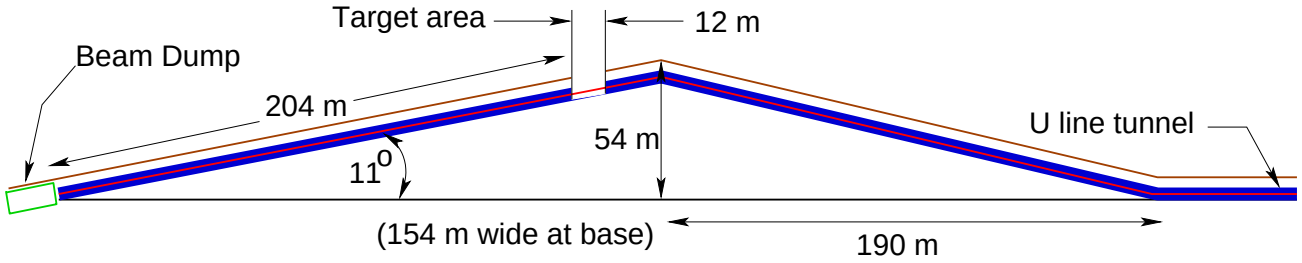



Very long baselines with a superbeam

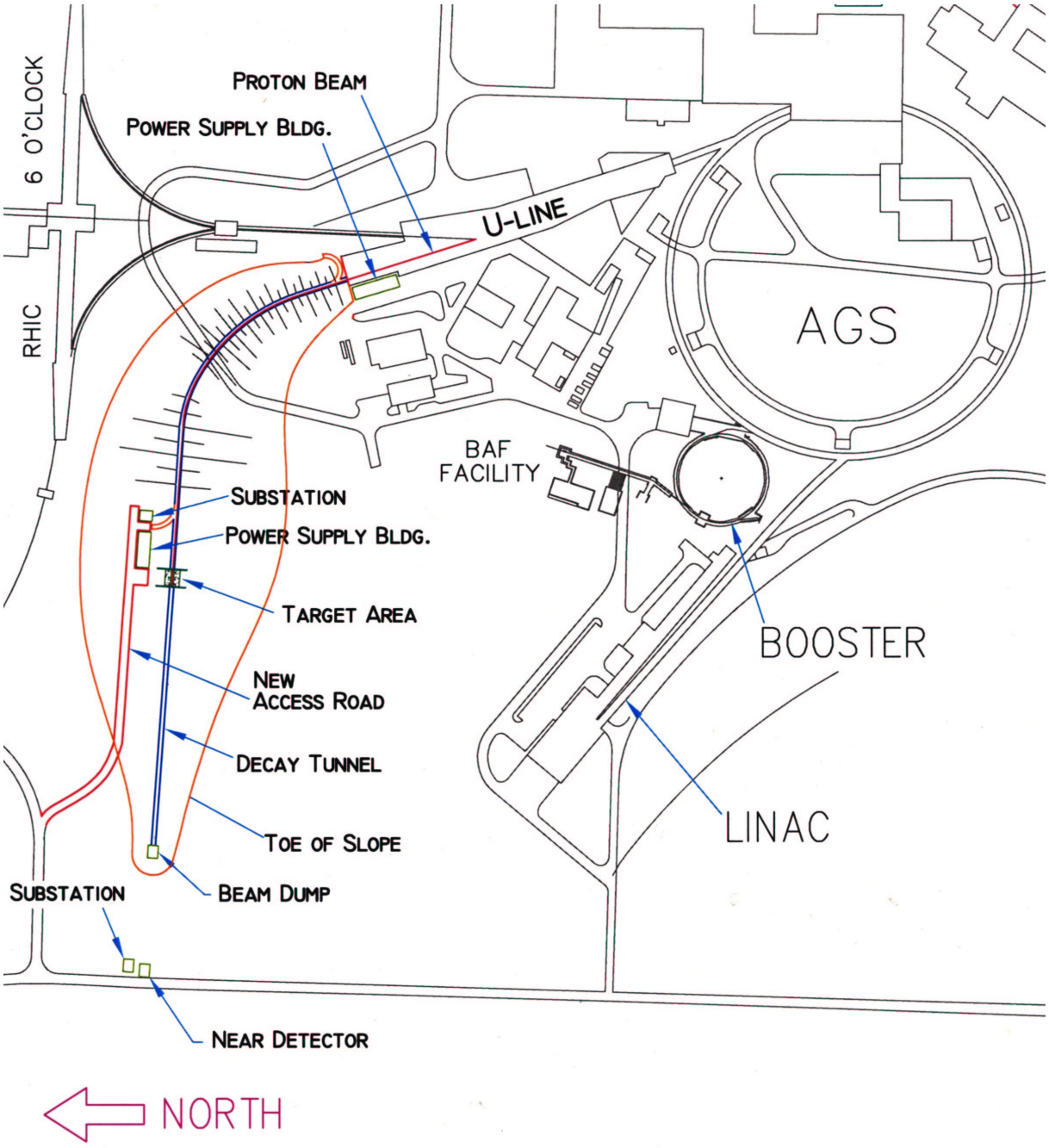
# Beam on the Hill



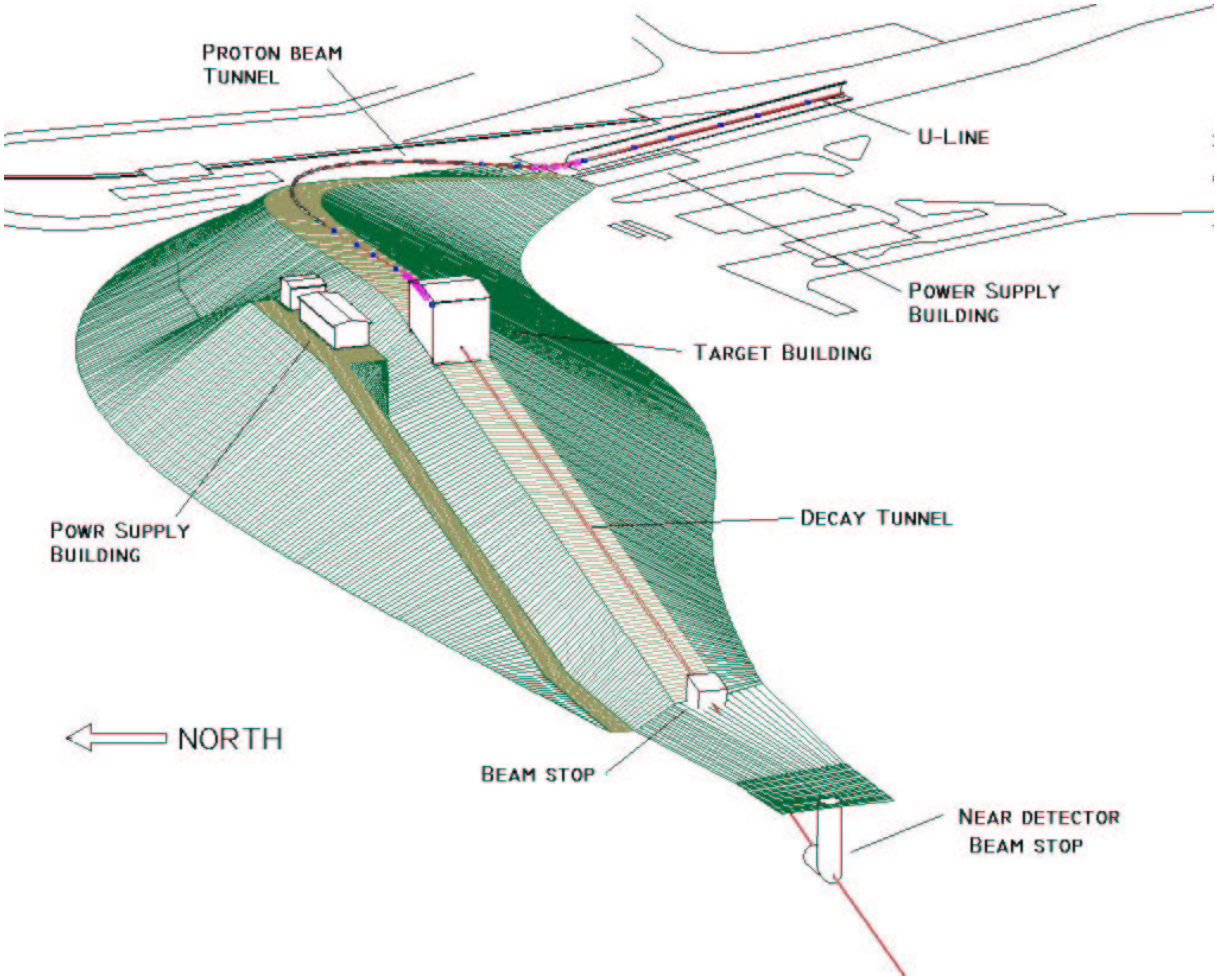

- BNL-Lead 2540km
  BNL-Wipp: 2880km
- Avoids water table.
- Hills are inexpensive: highway ramps.
- Total cost \$35 M for 200 m tunnel.



# 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

# 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 ~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

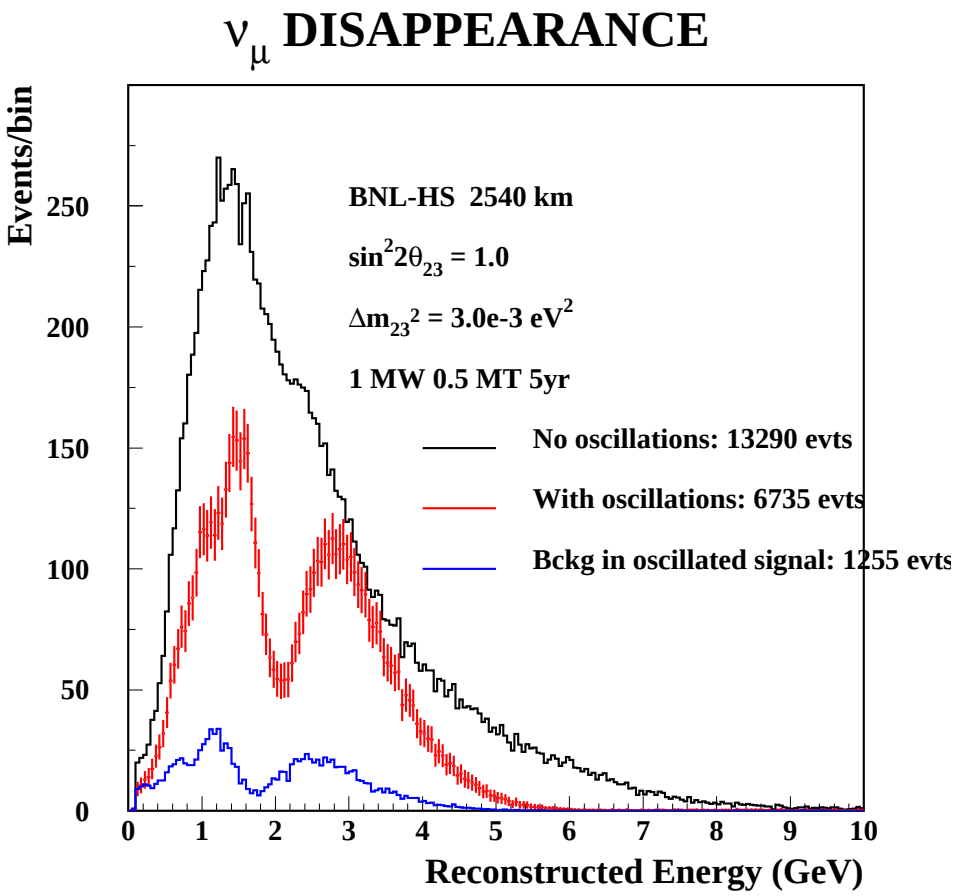
Assume 1 MW, 500 kT Fiducial, $5 \times 10^7$ sec running. ($1.22 \times 10^{22}$ Protons at 28 GeV.)

Assume Water Cerenkov detector (with ~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.

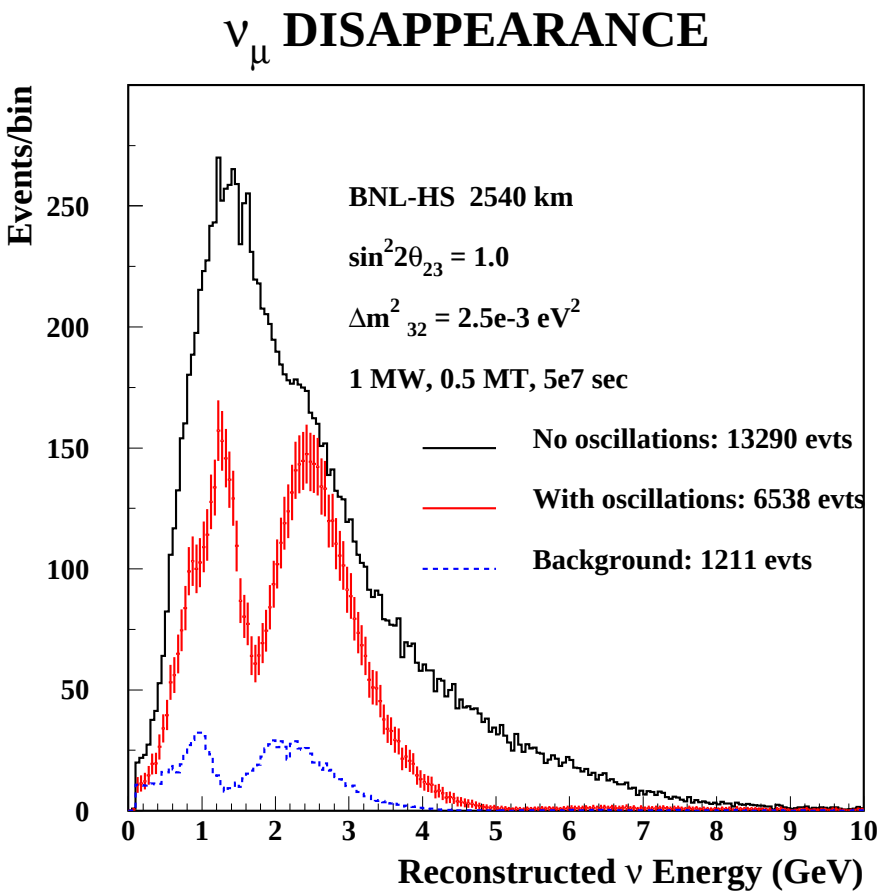
Both single and multi-pi event rate display the same tendency to fall rapidly with energy.




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

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

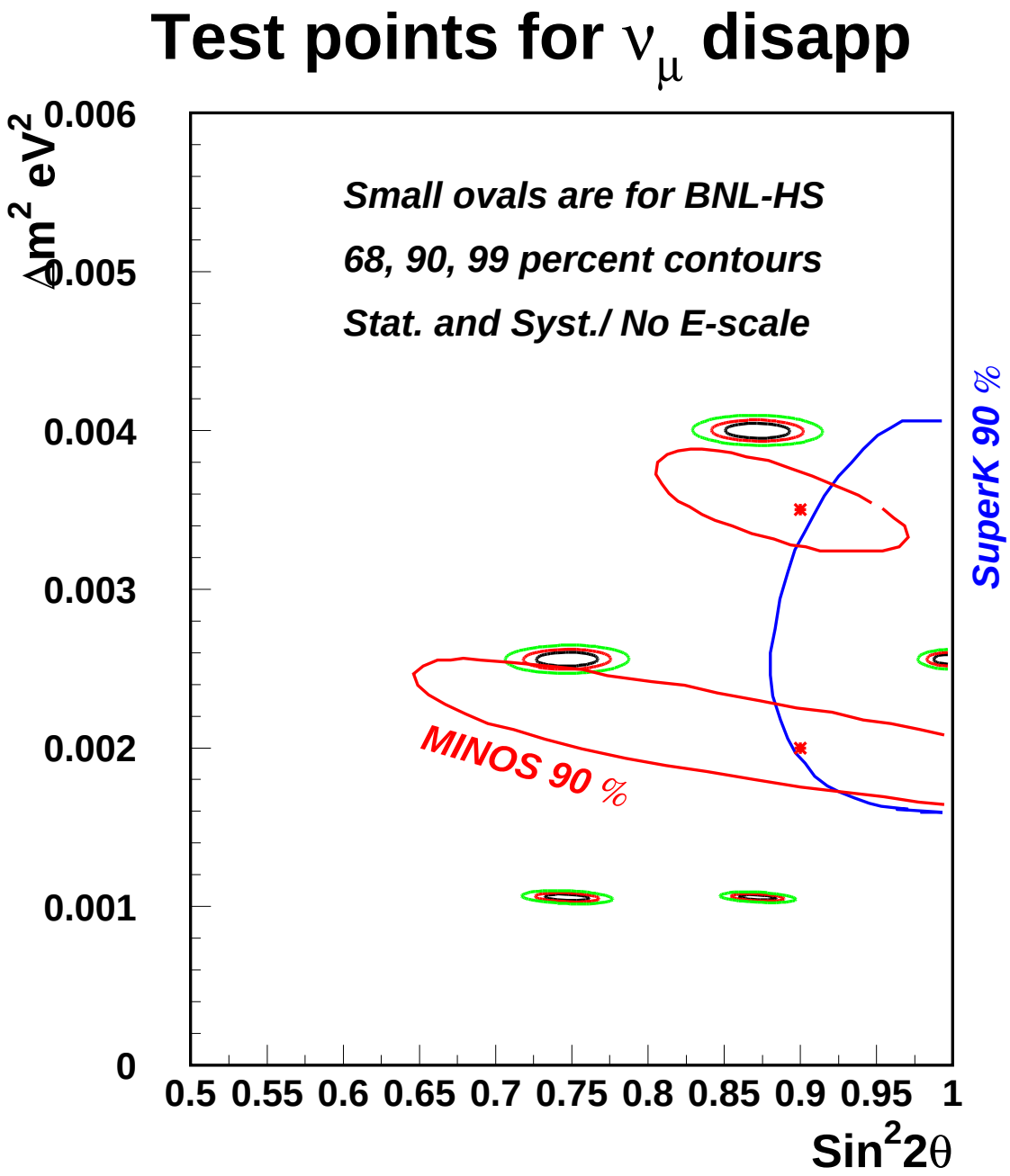
Background shape can be measured independently
Minimum systematics in $\nu_\mu$ and $\bar{\nu}_\mu$ comparison




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

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

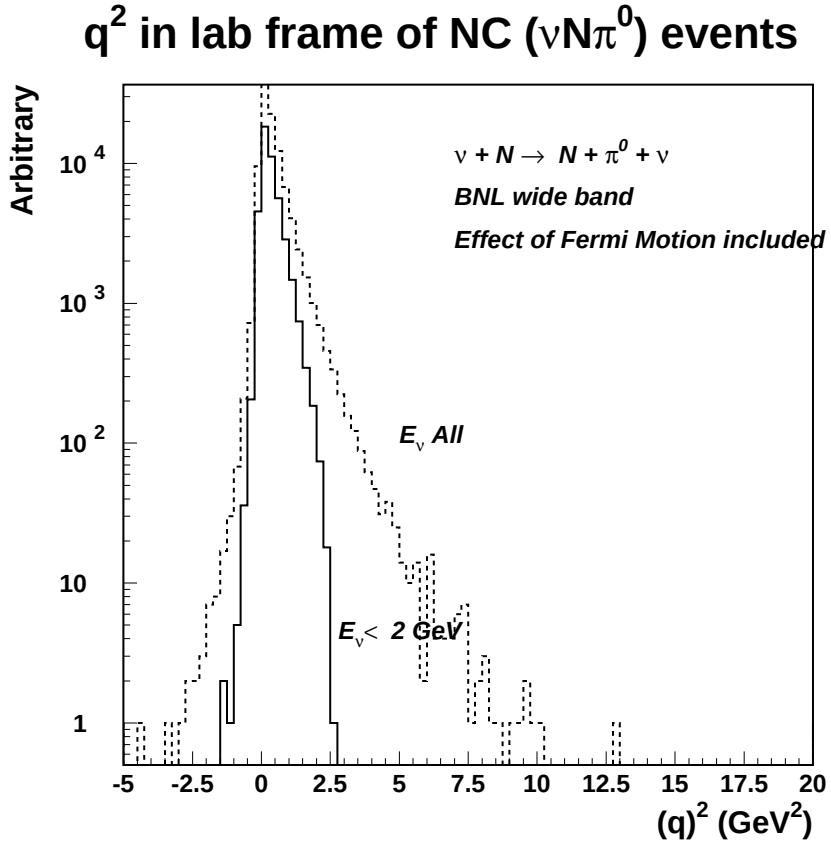
Background shape can be measured independently
Minimum systematics in $\nu_\mu$ and $\bar{\nu}_\mu$ comparison


Test points for $\nu_\mu$ disapp
Small ovals are for BNL-HS
68, 90, 99 percent contours
Stat. and Syst./ No E-scale
MINOS 90 %
SuperK 90 %
$\Delta m^2$ 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$

# Measurement of $\Delta m^2_{32}$

- 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 $\nu_\mu \to \nu_e$



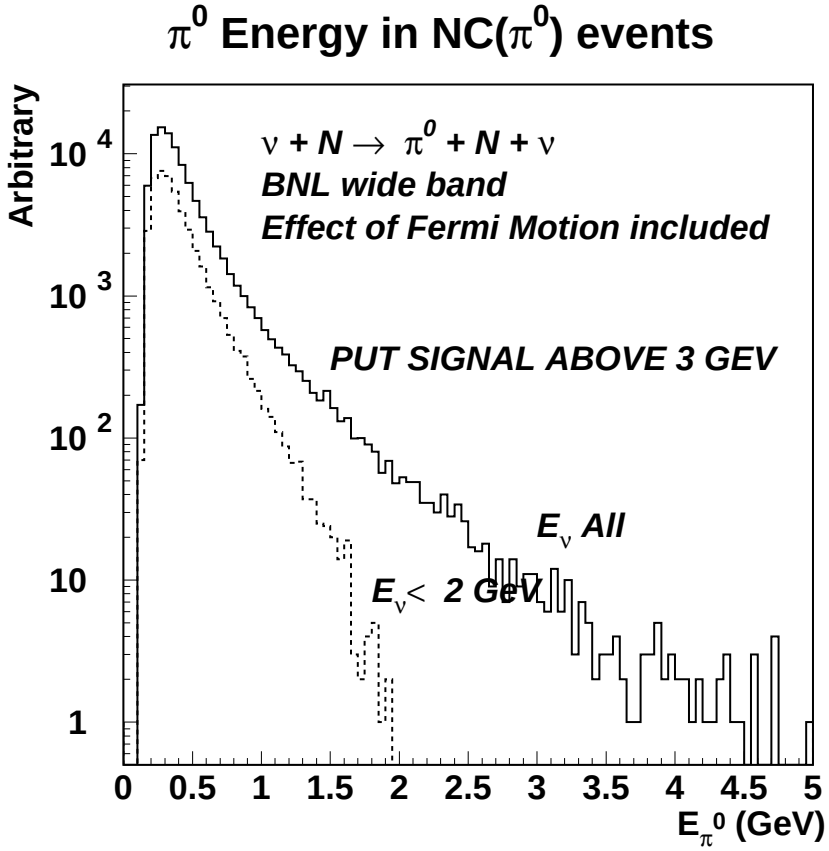

$q^2 = (p'_N + p'_\pi) - p_N$.

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

General feature of all neutral current processes:

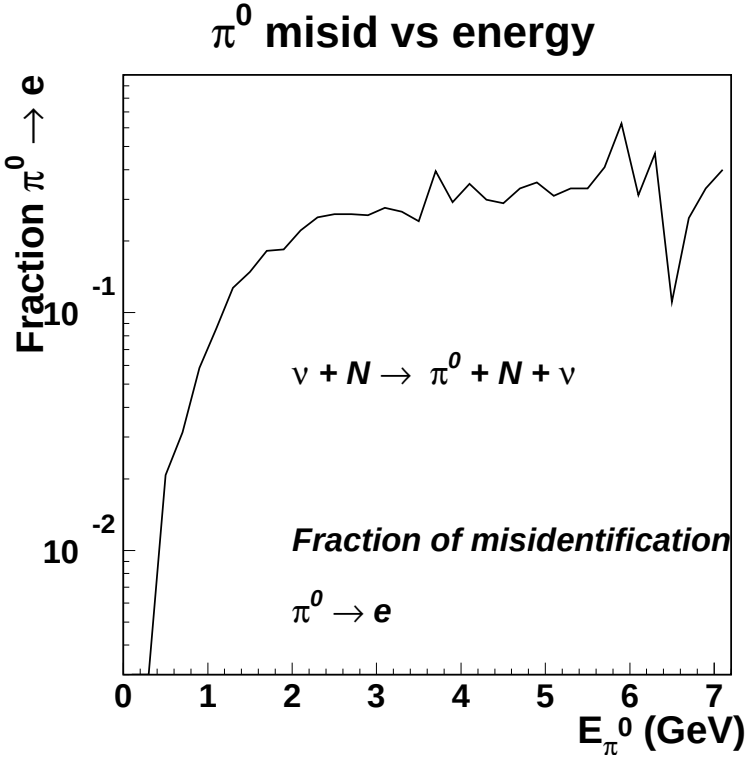
Low $q^2$ or low hadronic energy in final state independent of neutrino energy.

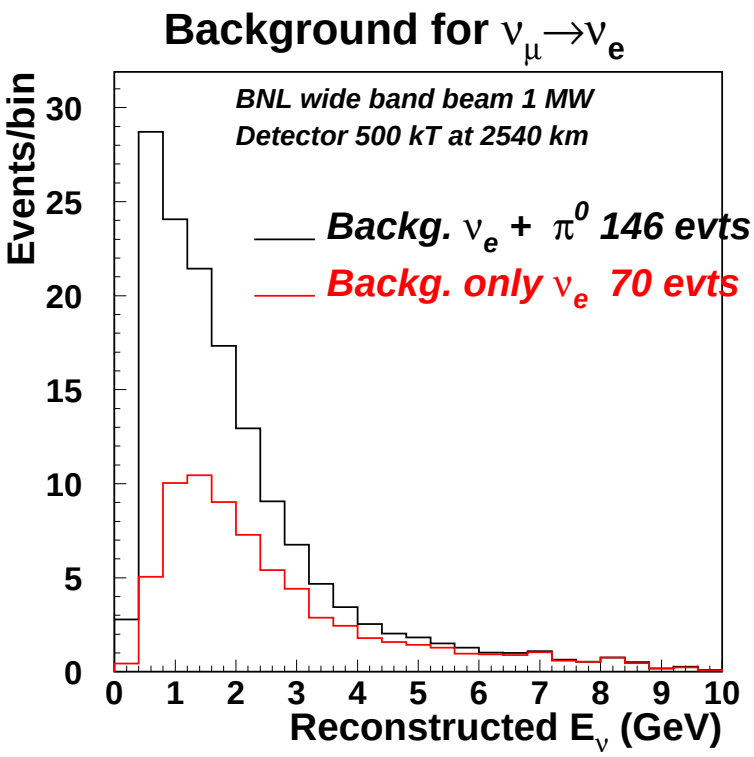
# NC $\pi^0$ background for $\nu_\mu \to \nu_e$




- The NC energy distribution is independent of $\nu$-energy except the kinematic limit.
- In $\nu_\mu N \to \nu_\mu N \pi^0$ 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.

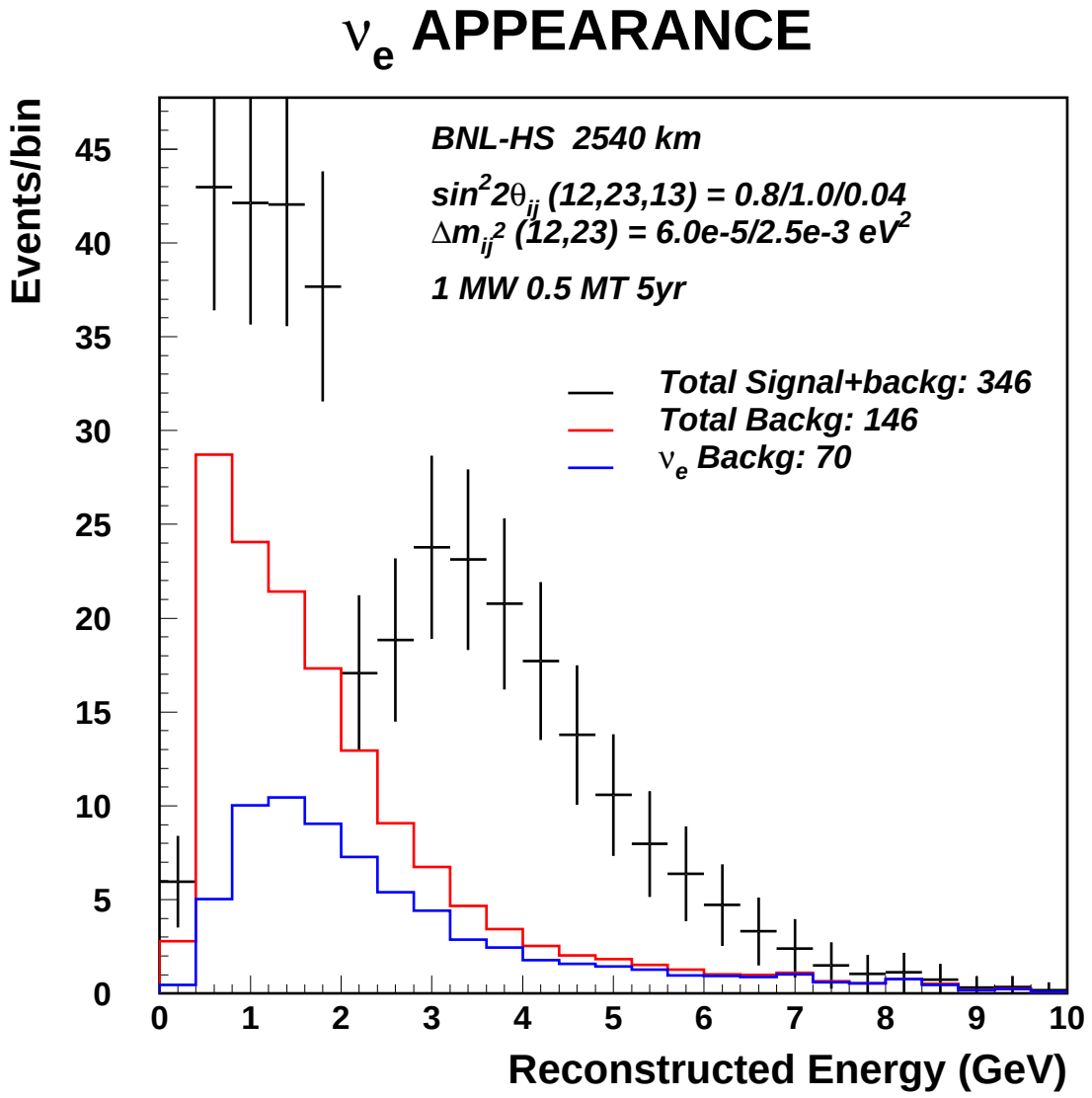
# $\nu_\mu \rightarrow \nu_e$ All background




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

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

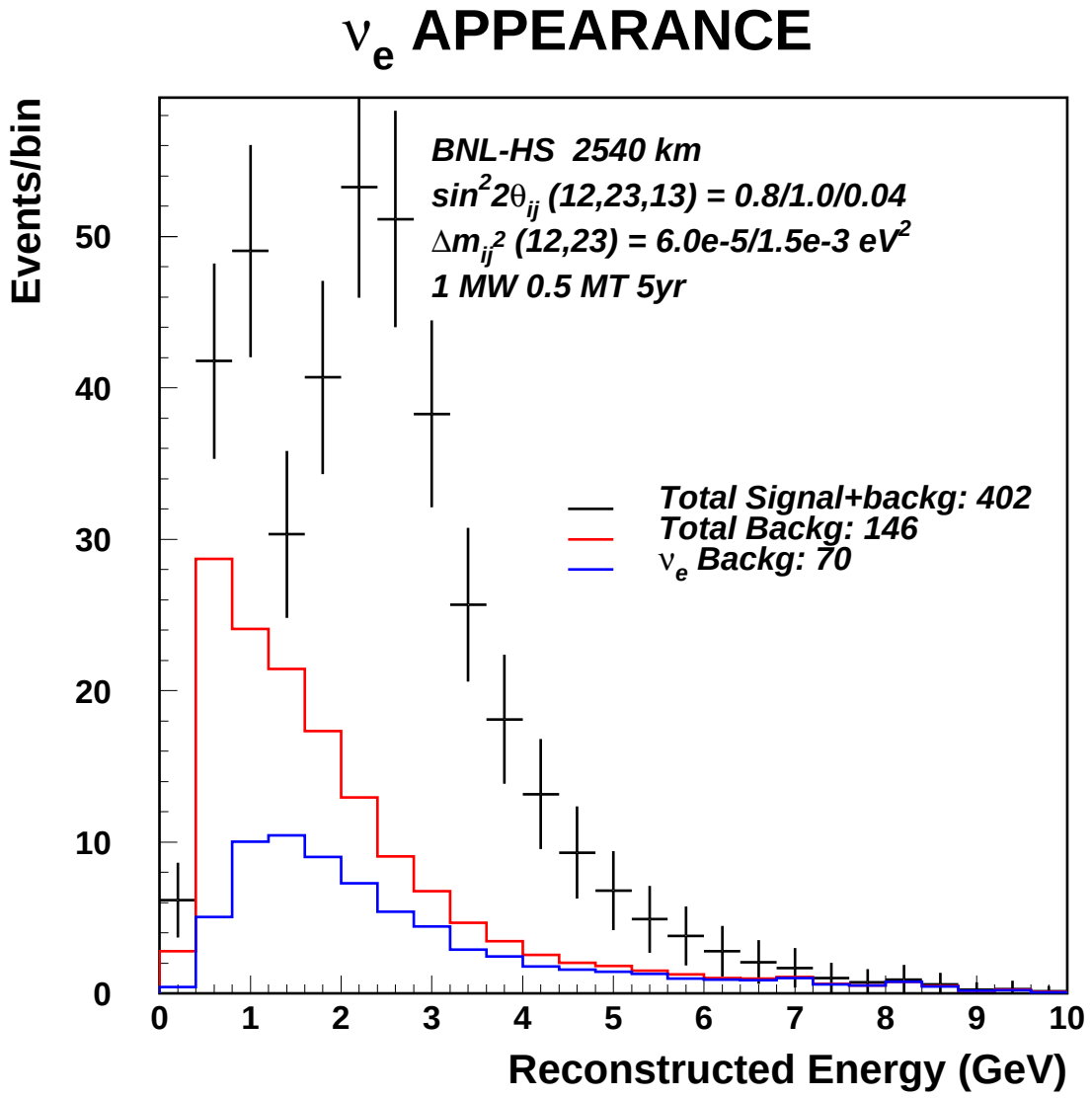



$\Delta m^2_{23} = 0.0025 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

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

Matter effects included.

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

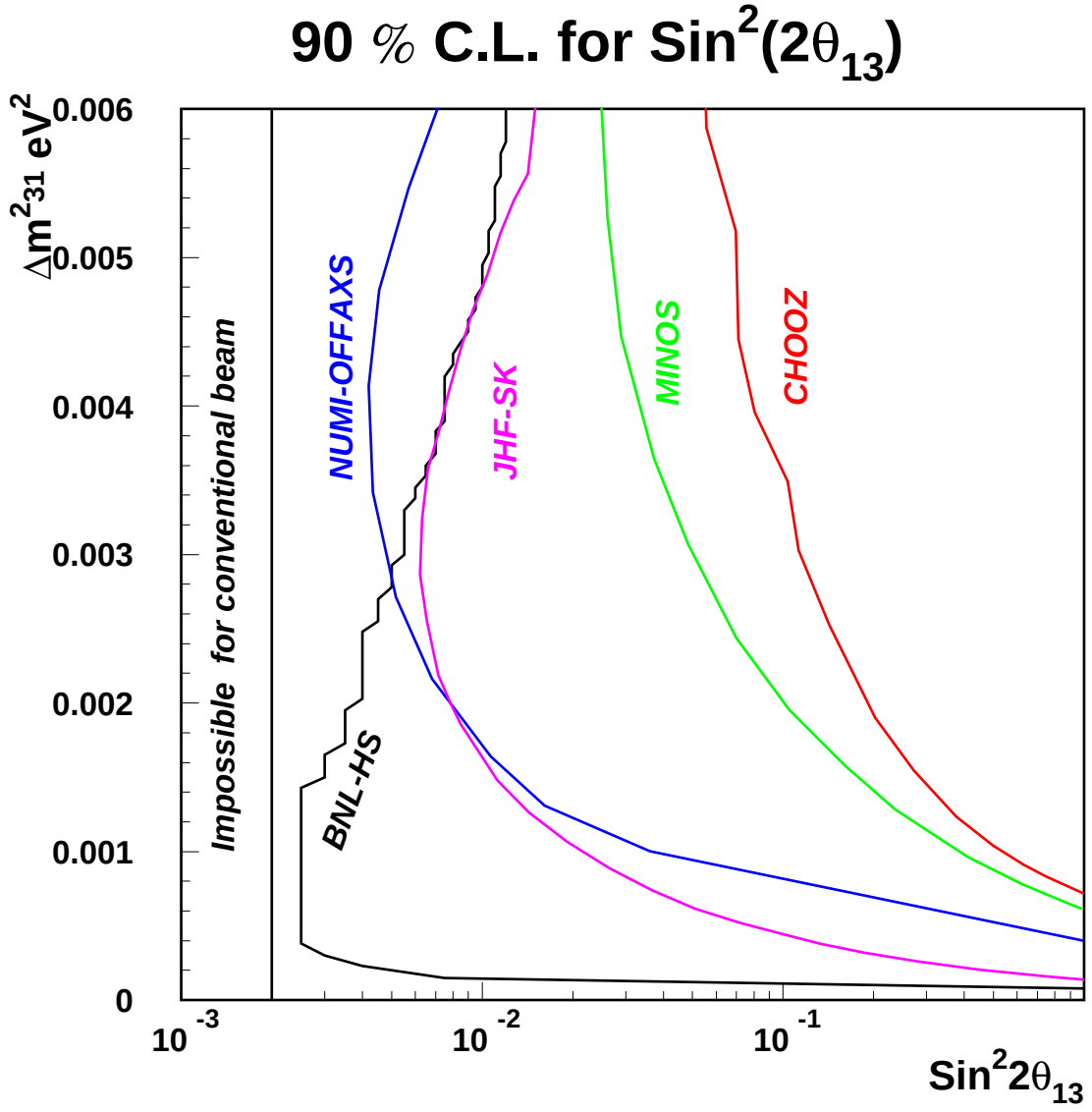



$\Delta m^2_{23} = 0.0015 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

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

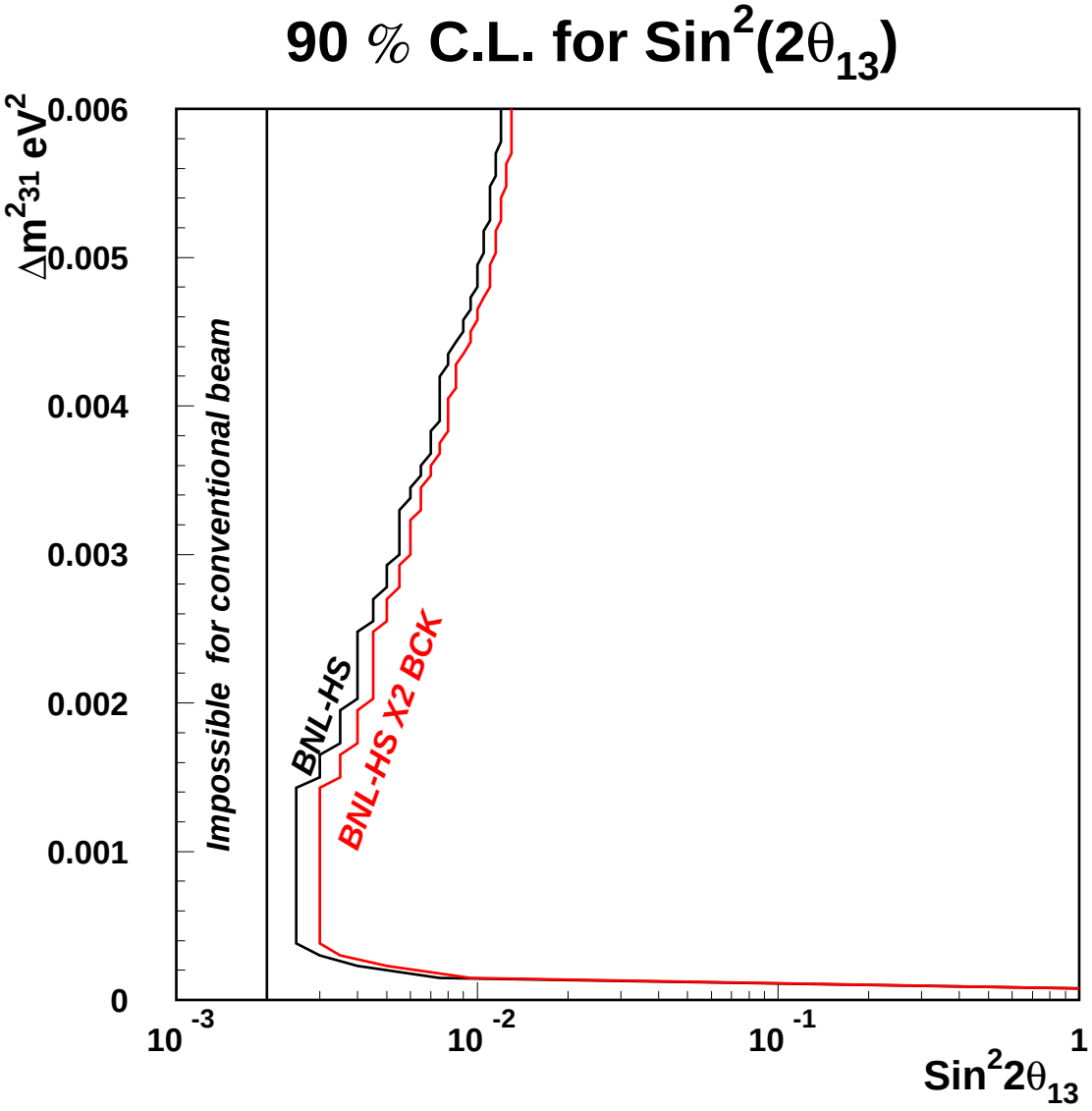
Matter effects included.

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

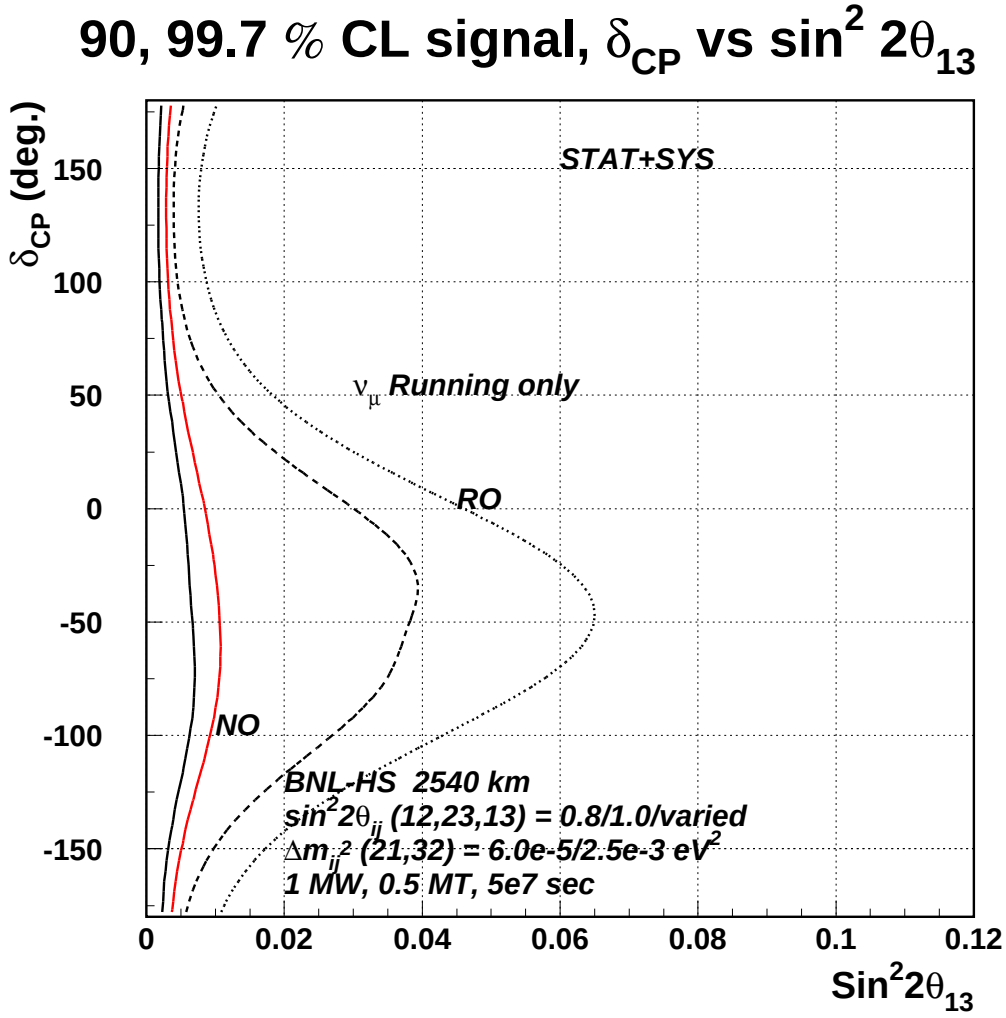
Improvement from 0.12 to 0.005 at 0.0025 $eV^2$.

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 $\nu_e$ background.

# Mass Hierarchy




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

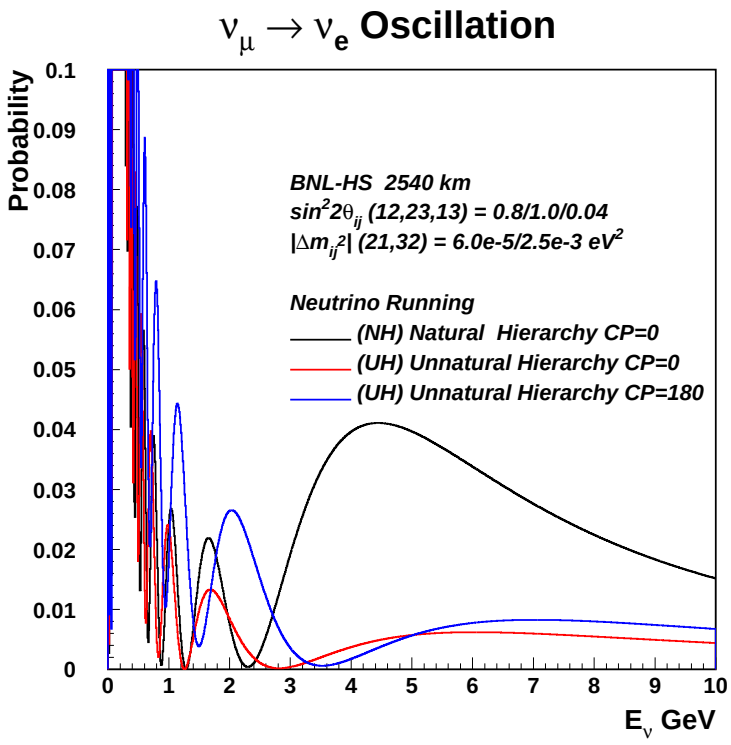
Reversed Mass hierarchy: $m_1 > m_2 > m_3$ (RO)

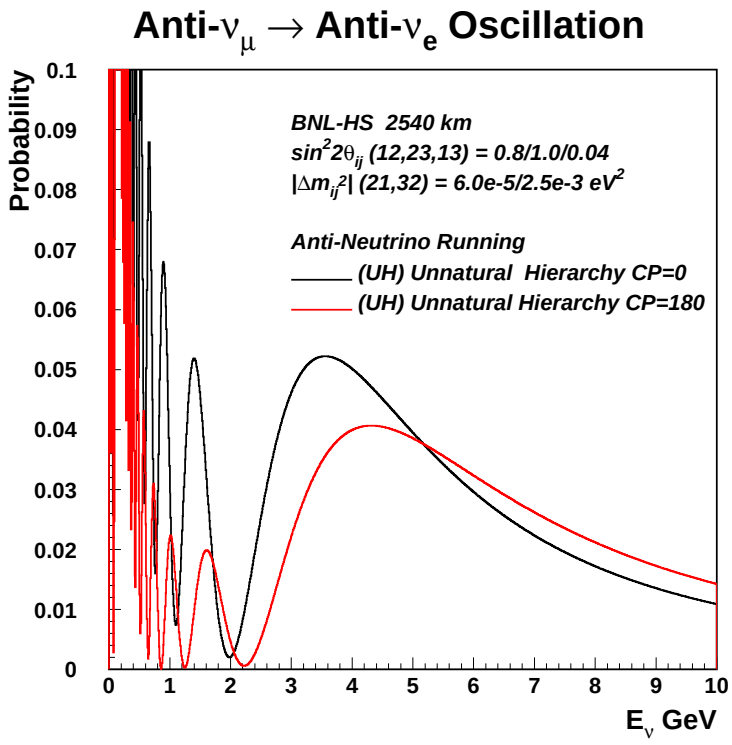
Unnatural Mass hierarchy: $m_2 > m_1 > m_3$ (RO)

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

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

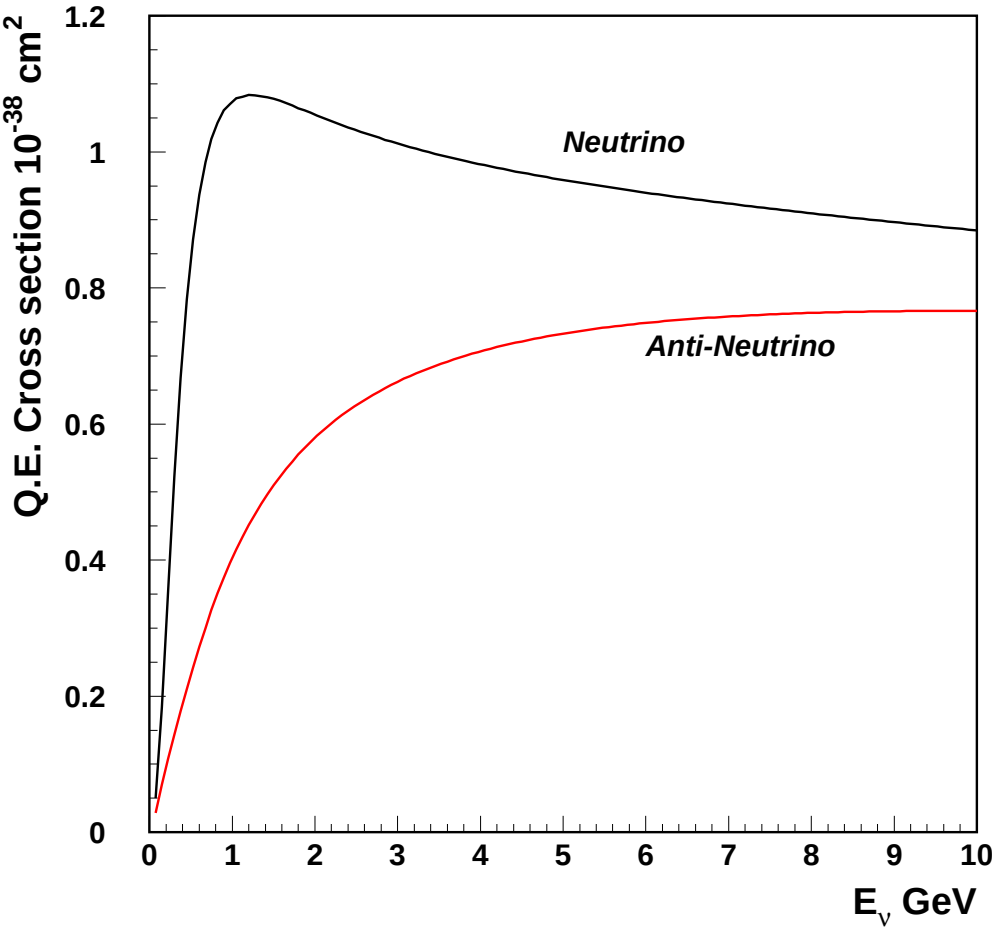
# Mass Hierarchy Anti-neutrinos



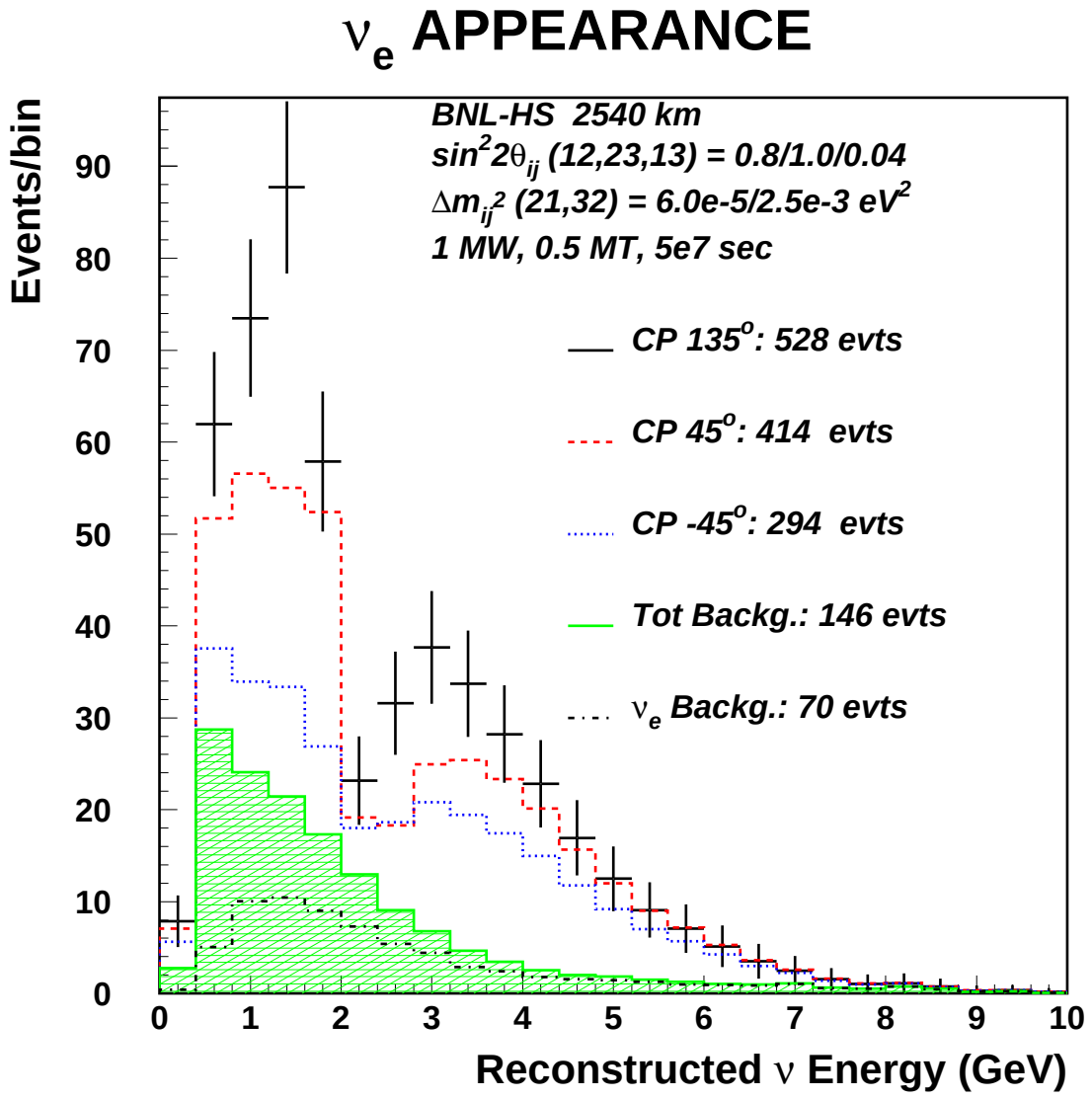

Very long baselines with a superbeam

# Quasielastic cross section




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

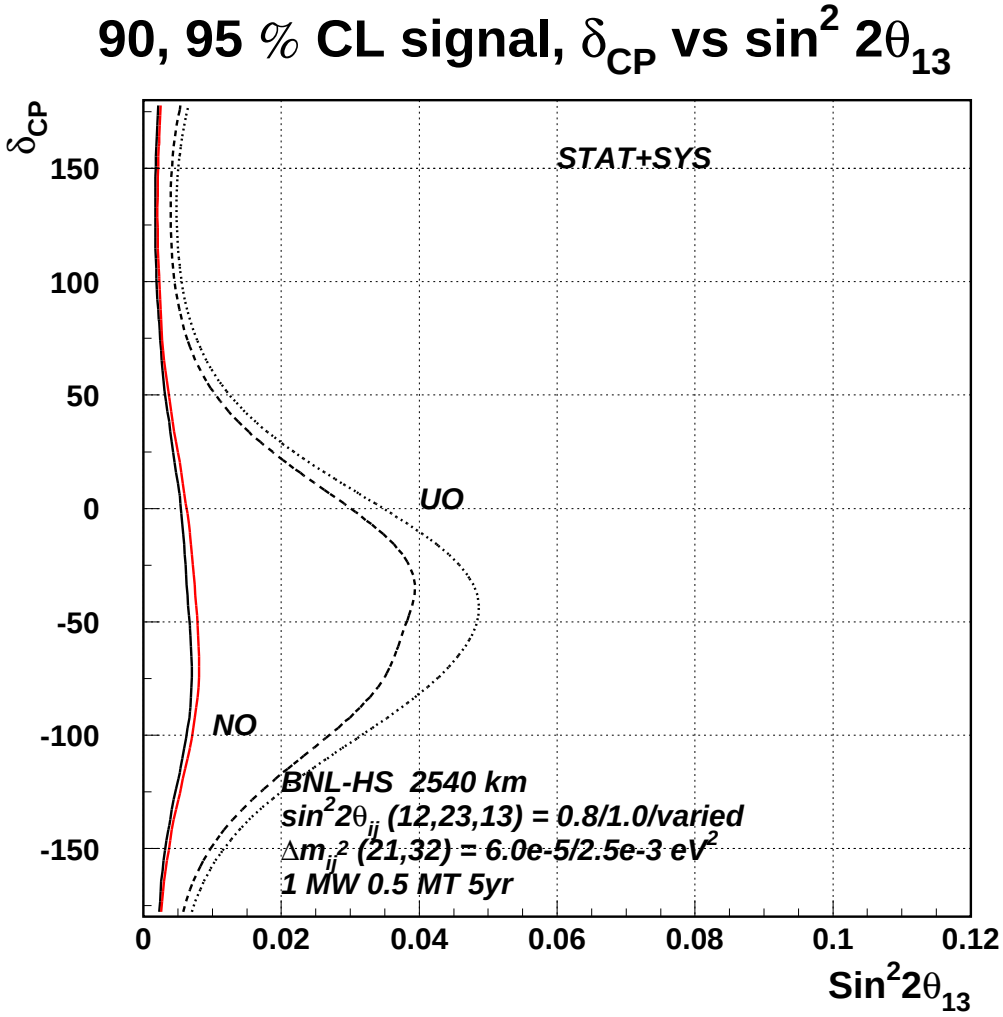
# $\delta_{CP}$ Measurement. BNL-to-HS, 2540 km, 1 MW, 500kT, $5 \times 10^7$ sec




CP parameter can be determined from only neutrino data.

Good background subtraction can help.

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

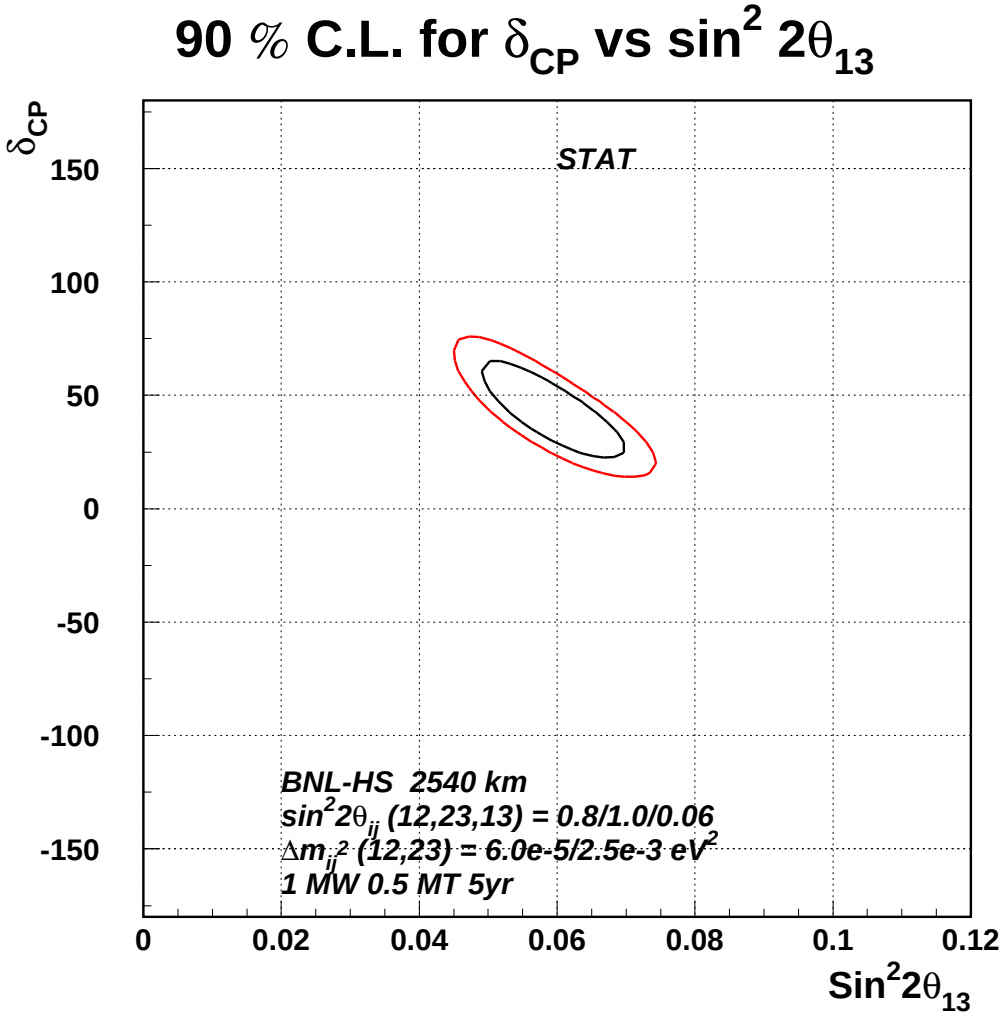



$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

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




No Systematic error

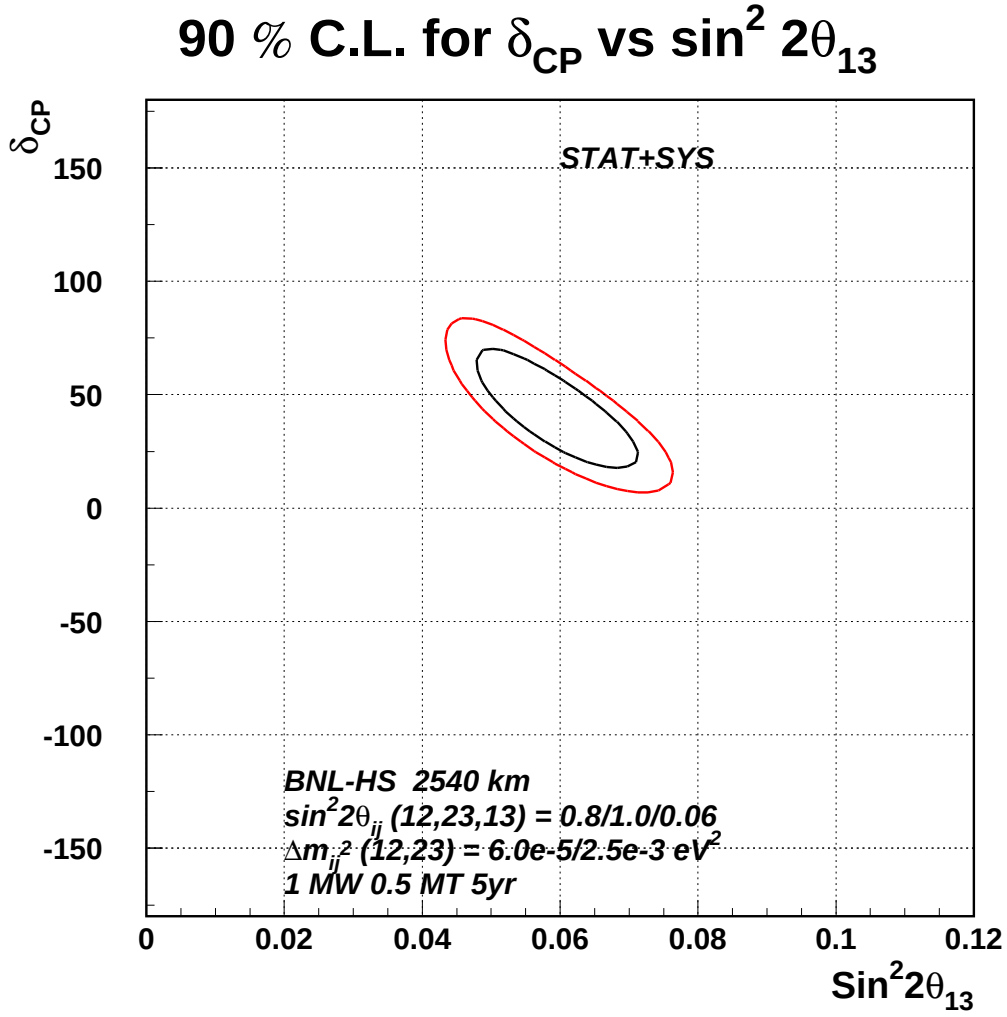
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

68%, and 90% C.L.

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




Systematic error of 10% on backg.

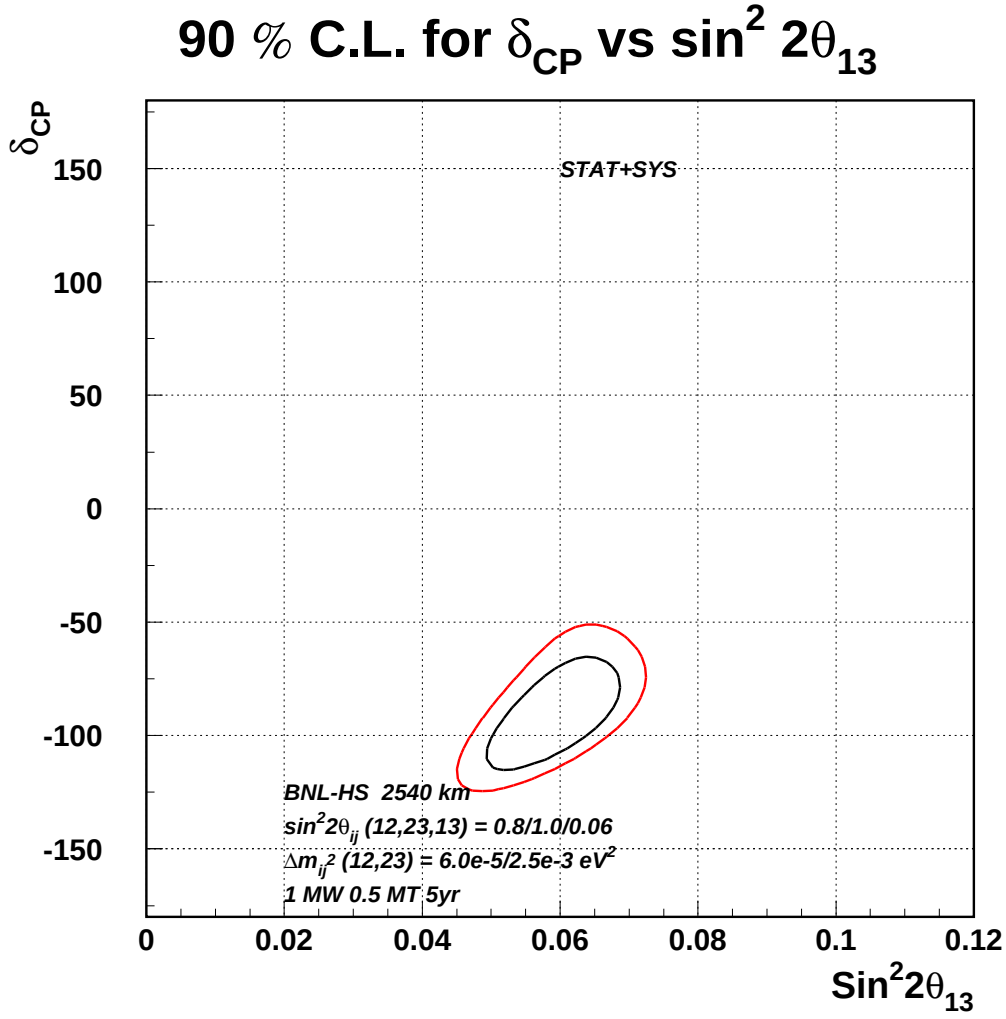
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

68%, and 90% C.L.

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




Systematic error of 10% on backg.

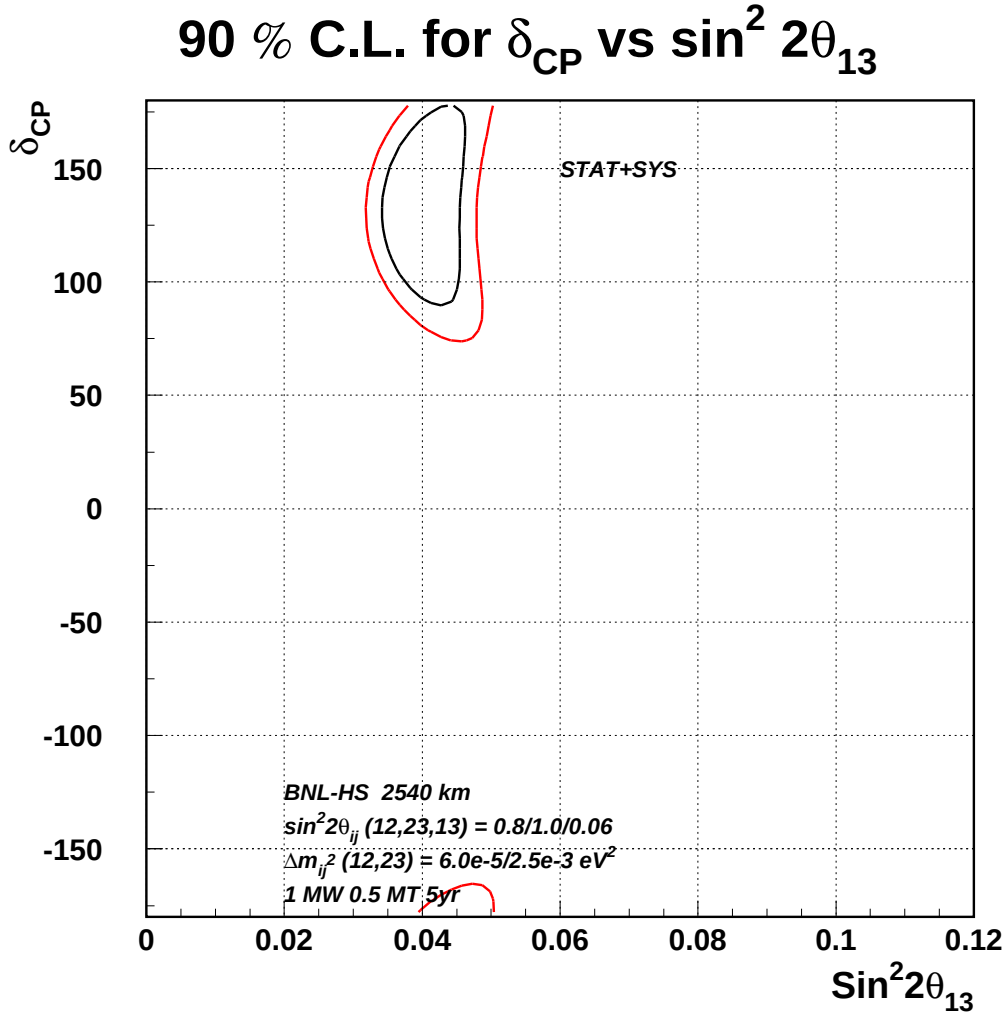
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

68%, and 90% C.L.

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




Systematic error of 10% on backg.

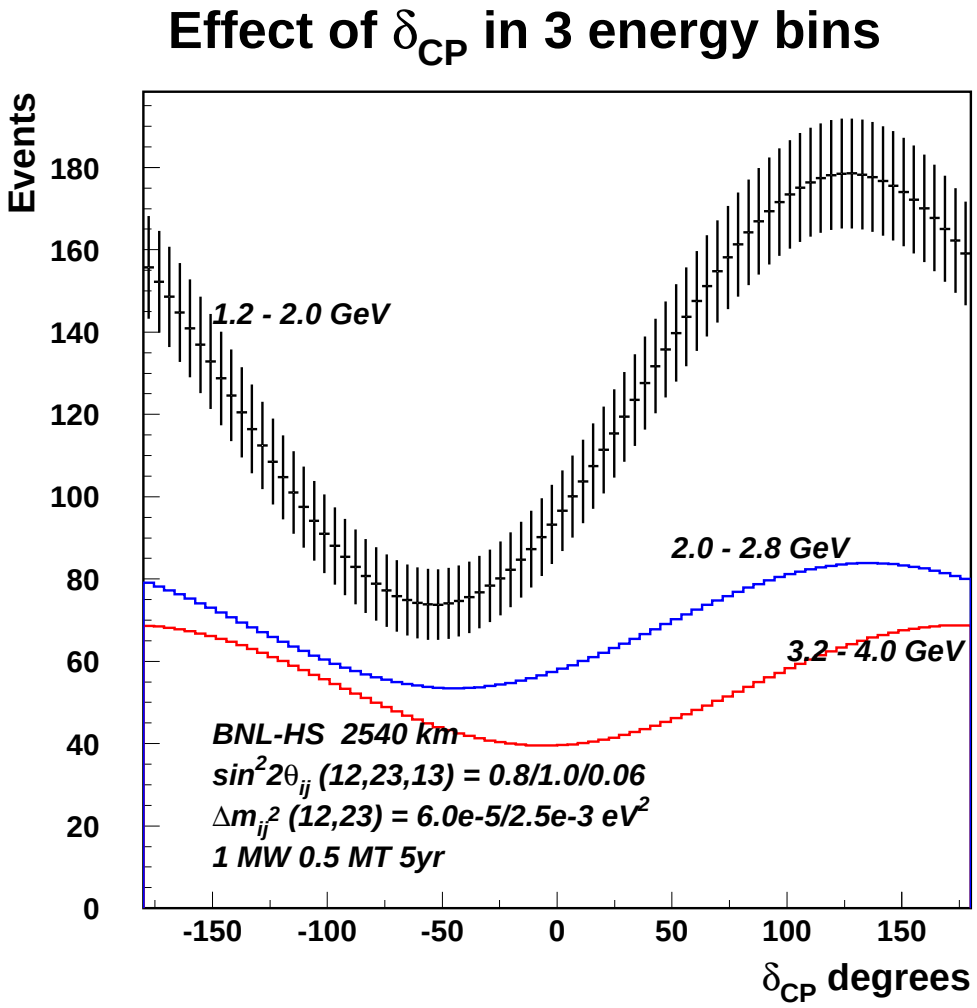
$\Delta m^2_{21} = 6 \times 10^{-5} eV^2$, $\Delta m^2_{31} = 2.5 \times 10^{-3} eV^2$

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

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

68%, and 90% C.L.

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



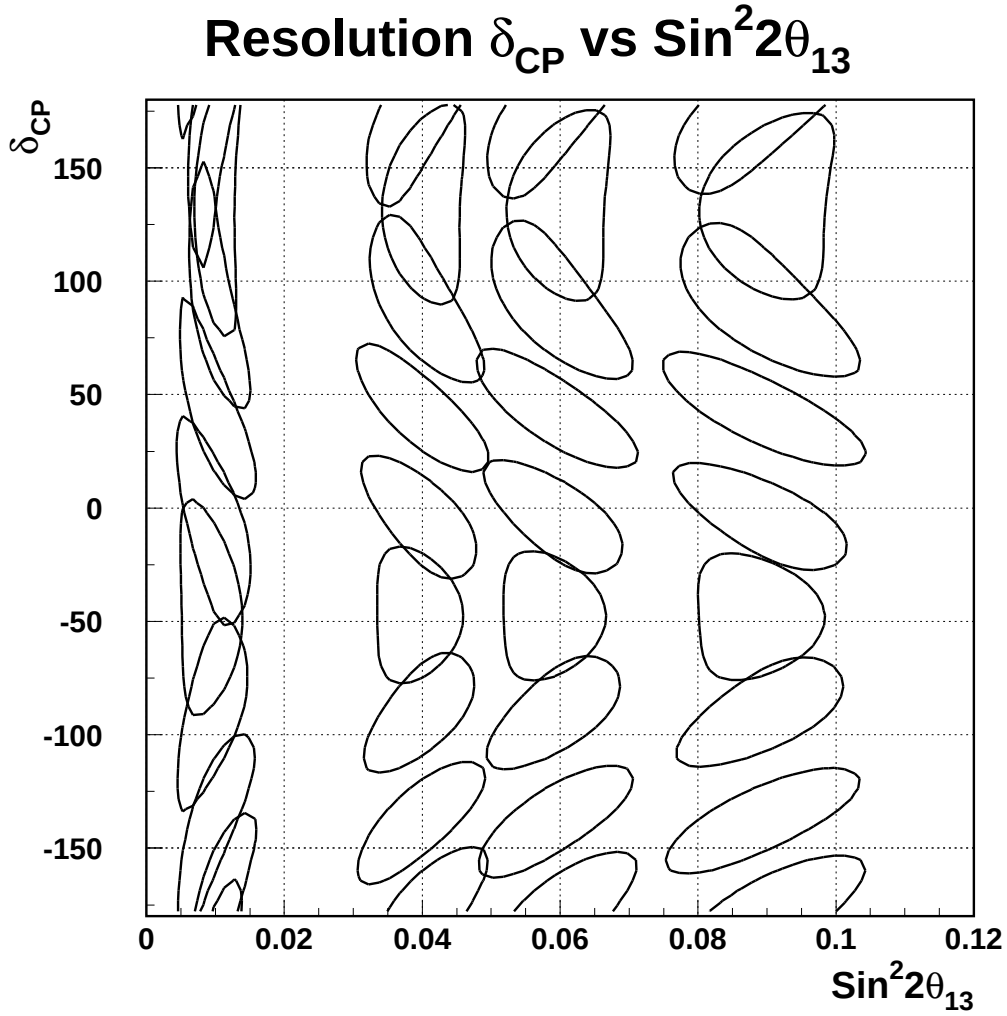

Event rate in 3 energy bins.

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

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

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

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

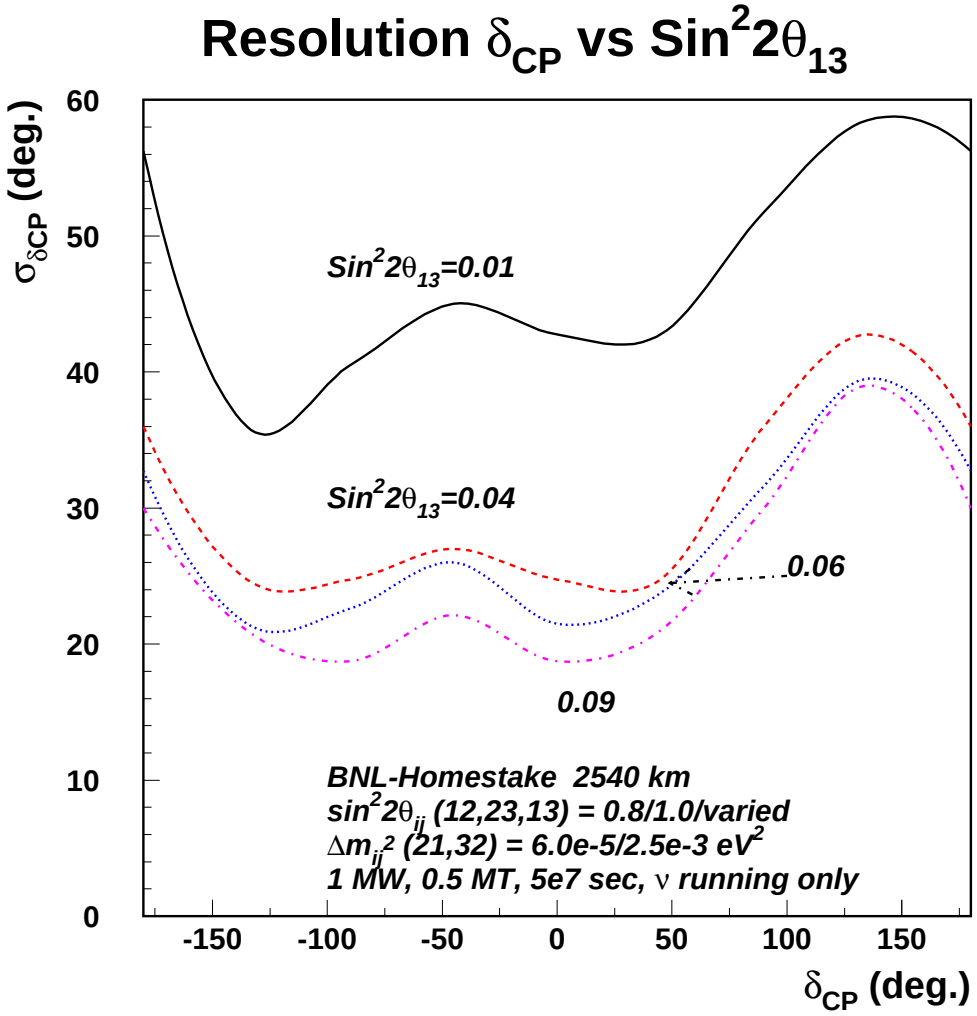



Assume all other parameters are well-known.

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

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

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

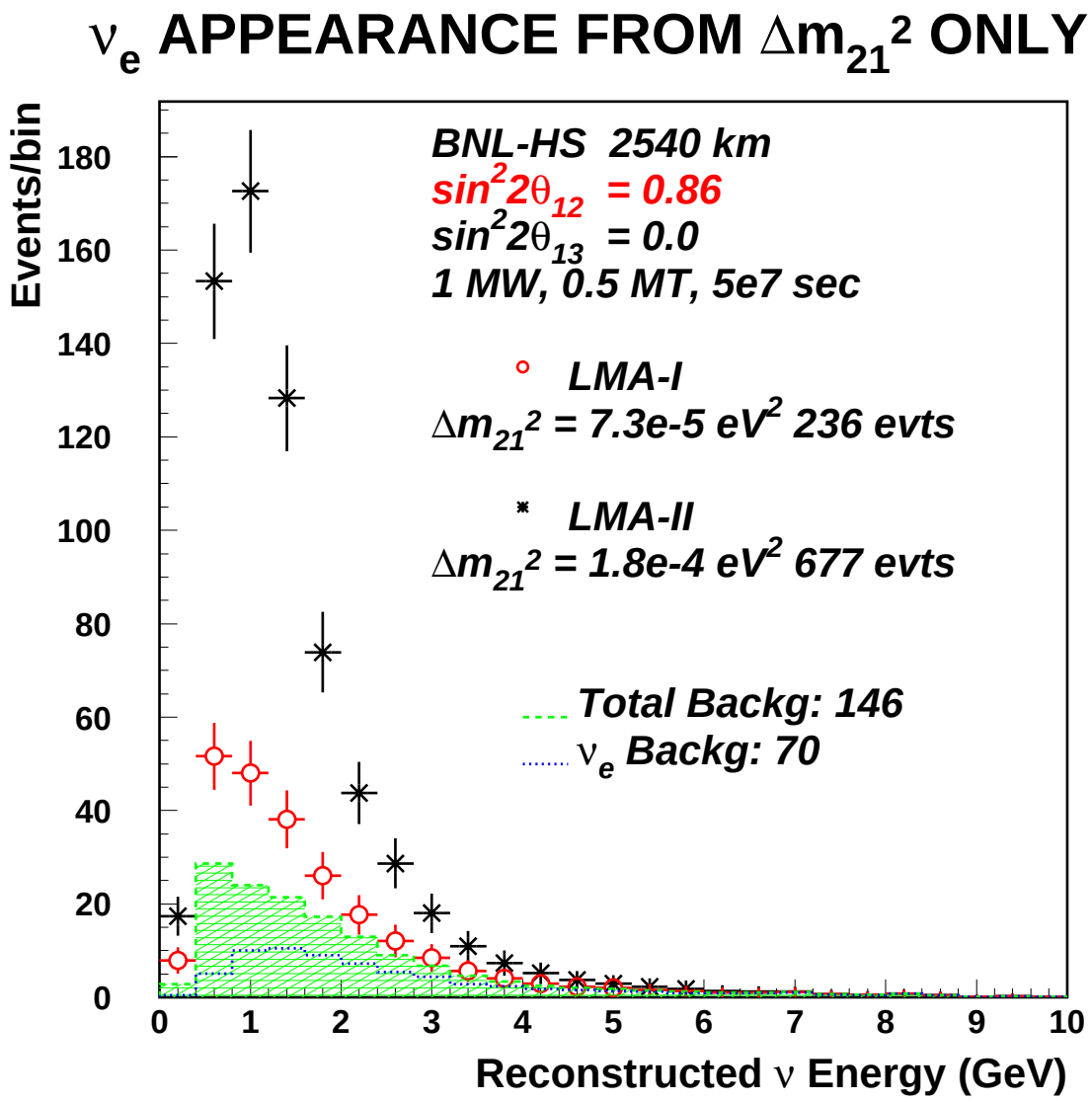



Full error from error contour. No knowledge of $\theta_{13}$ assumed, but all other parameters fixed.

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

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

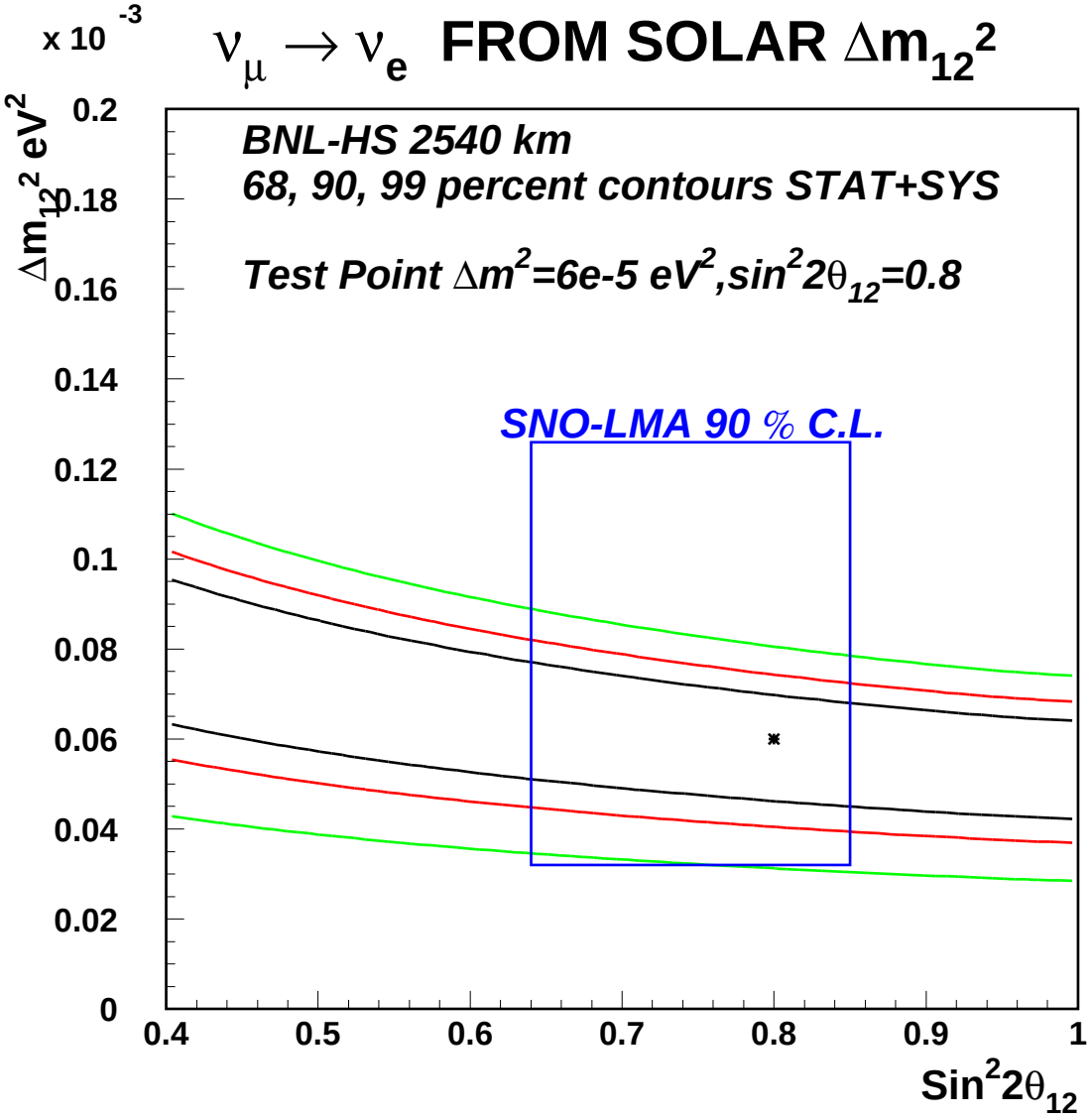
# Measurement of $\Delta m^2_{12}$




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

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

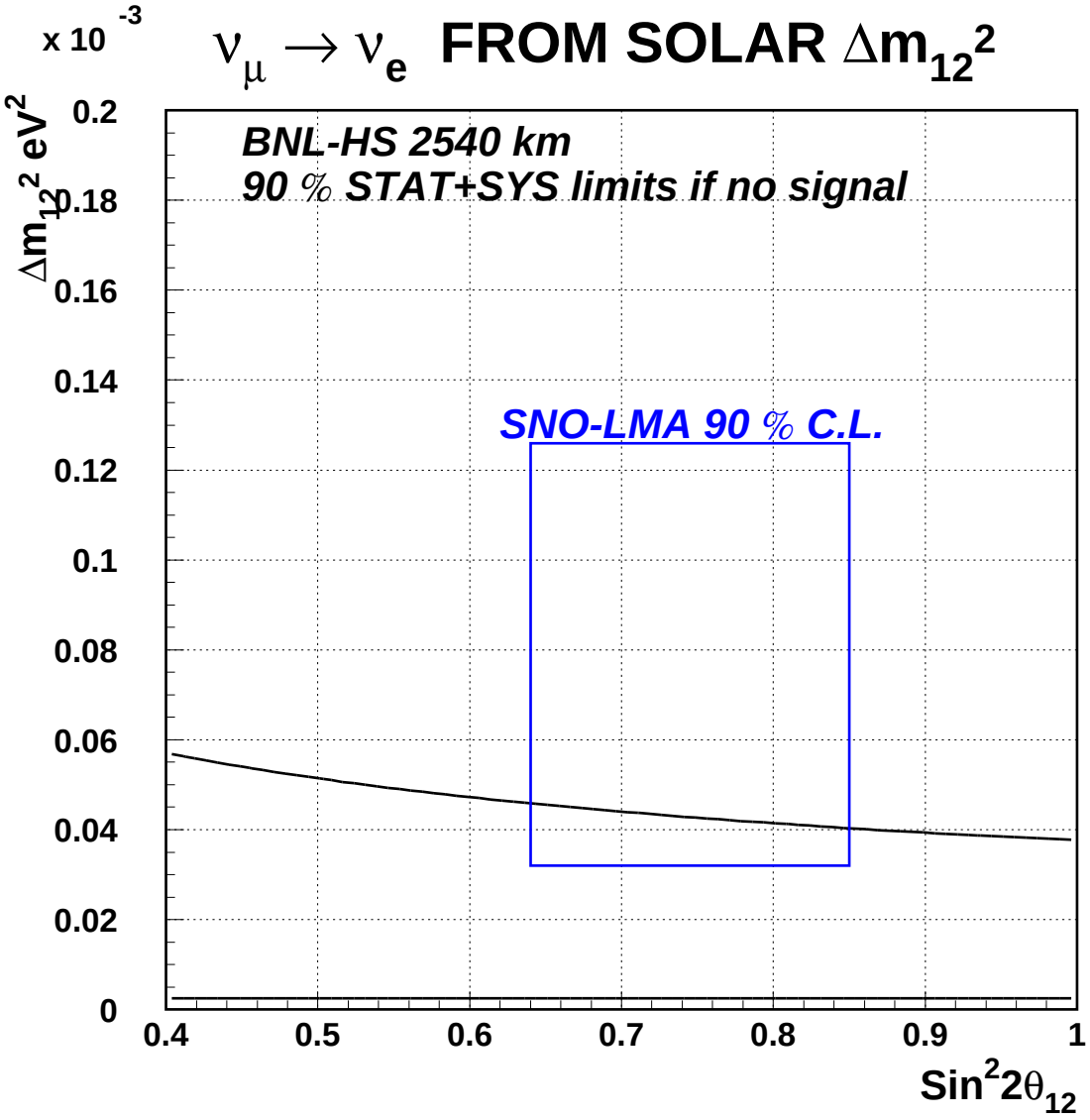
# Measurement of $\Delta m^2_{12}$




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

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

# Limit on $\Delta m^2_{12}$ 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 $\Delta m^2_{23}$ from disappearance and definitive signal of oscillations.
- From the measured $\Delta m^2_{23}$ 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 $\Delta m^2_{12}$ 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 $\Delta m^2_{12}$ 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 $\Delta m^2_{12}$ , $\delta_{CP}$ 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 $\Delta m^2_{32}$
  - $< 1\%$ resolution on $\sin^2 2\theta_{23}$
  - Sensitivity to $\sin^2 2\theta_{13} \sim 0.005$ over a wide range of $\Delta m^2_{32}$
  - Sensitivity to CP parameter $\pm 25^o$ with neutrinos alone.
  - Sign of $\Delta m^2_{32}$ over a wide range.
  - Measurement of $\Delta m^2_{12}$ 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: $5 \times 10^7$ sec.

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

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

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

Need good energy calibration for $\Delta m^2_{32}$ ($\sim 100 MeV$ LINAC ?)
Need small error on backg. for $\Delta m^2_{12}$ 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.