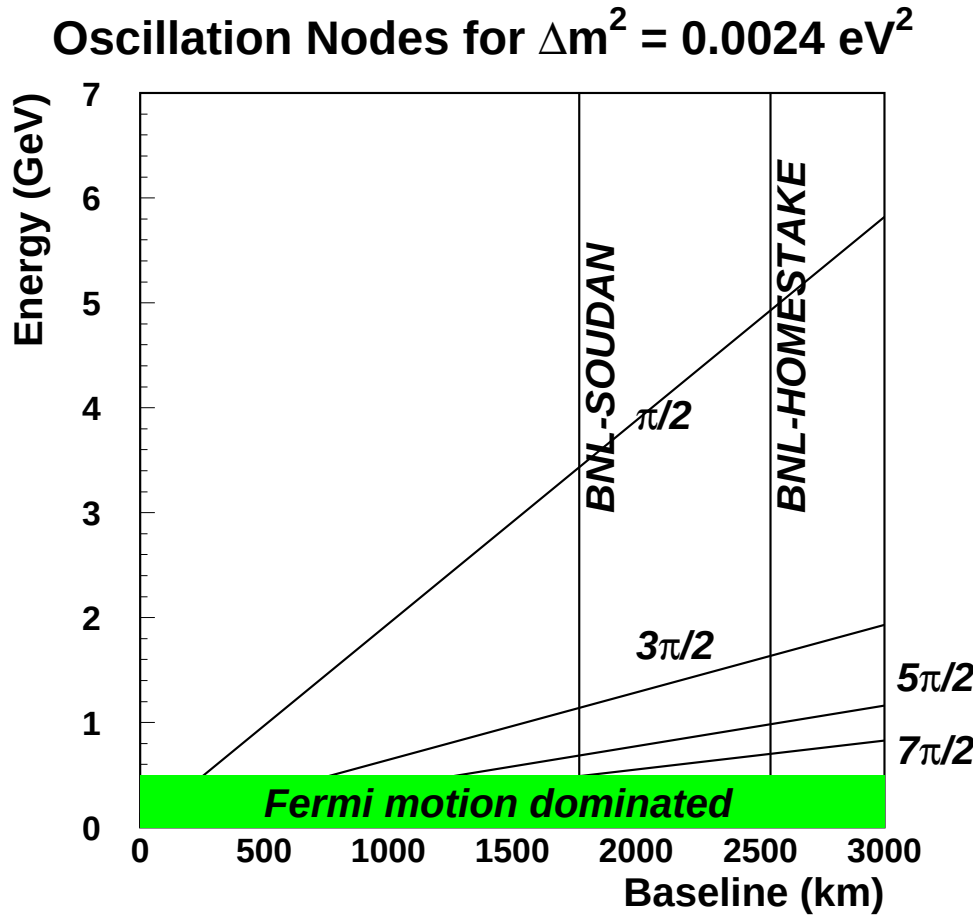
Very Long Baseline Scenarios

Milind Diwan March 2, 2004 Superbeam study

- A next generation large detector at a national underground facility with a powerful neutrino beam and very long baseline.
- Unique, and broad range of physics.
- Ability to over-constrain the neutrino mixing sector. (3-generation mixing: δ_{CP} can be measured without running both polarities)
- This talk on Flexibility:
  - Not affected if parameters change.
  - Go off-axis for better detector performance.
  - Change running strategy if physics emphasis changes.

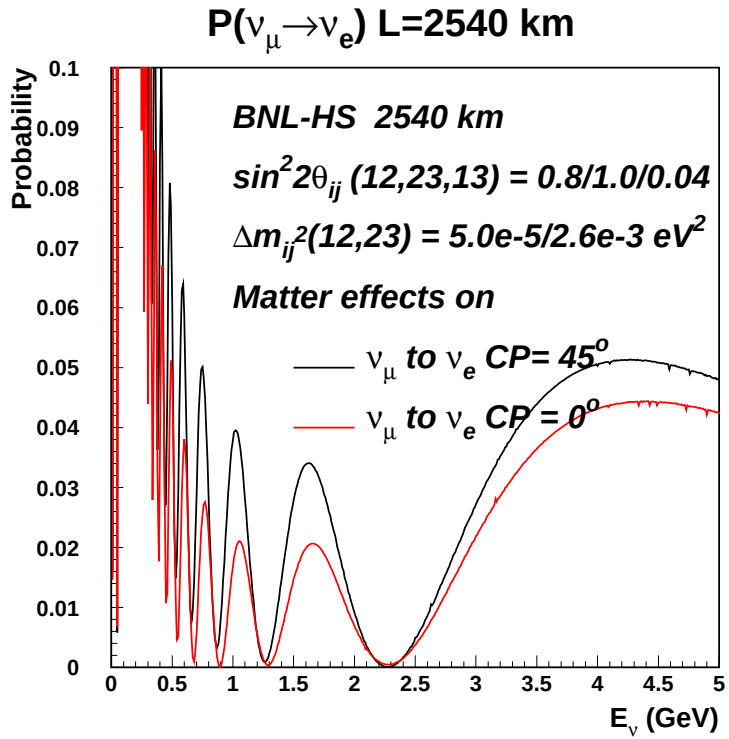
- Large effects: Multiple oscillation nodes.
- Low cross section at low energies
- Fermi motion limits resolution at low energies:
- $\Delta m^2 \approx 0.0024 eV^2$: Baseline $\sim$ 2000 km.



BNL strategy for leptonic CP violation

General Features

- $0.5-1$ GeV: Δm^2_{21} (LMA) region.
- $1-3$ GeV: CP large effects region
- >3 GeV: Matter enhanced (ν_μ), suppressed $(\bar{\nu}_\mu)$. $(\Delta m^2_{32} > 0)$.



Using neutrinos alone make fit to spectrum to extract δ_{CP}.

Full implementation: wide band beam over very long distance.

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

Approximate formula (Lindener, Huber et al.)

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

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

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

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

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

Resolving Parameters with $\nu_\mu \longrightarrow \nu_e$

Assume $L > 2000km$, wide band beam

Δm^2_{32}, Δm^2_{21}, θ_{12} well known.

3 neutrino generations. $\Uparrow$ = large change $\uparrow$ = small change

		$\sin^2 2\theta_{13} > 0$	$\Delta m^2_{32}(> 0, < 0)$	$\delta_{CP} = (\pi/4, -\pi/4)$	$\theta_{23}(< \pi/4, > \pi/4)$
ν	0 – 1.2 GeV	$\uparrow$	$-$, $-$	$\uparrow$, $\downarrow$	$\Uparrow$, $\Downarrow$
	1.2 – 2.2 GeV	$\uparrow$	$-$, $-$	$\Uparrow$, $\Downarrow$	$\downarrow$, $\uparrow$
	$>$ 2.2 GeV	$\uparrow$	$\Uparrow$, $\Downarrow$	$\uparrow$, $\downarrow$	$\downarrow$, $\uparrow$
$\bar{\nu}$	0 – 1.2 GeV	$\uparrow$	$-$, $-$	$\downarrow$, $\uparrow$	$\Uparrow$, $\Downarrow$
	1.2 – 2.2 GeV	$\uparrow$	$-$, $-$	$\Downarrow$, $\Uparrow$	$\downarrow$, $\uparrow$
	$>$ 2.2 GeV	$\uparrow$	$\Downarrow$, $\Uparrow$	$\downarrow$, $\uparrow$	$\downarrow$, $\uparrow$

Scaling Laws for CP Measurement

Effect of δ_{CP} compared to first term in appearance.

$R_{CP} \equiv$ Second term divided by First Term.

$$R_{CP} \propto \sin\delta_{CP} \frac{\Delta m^2_{21} L}{4E} \frac{1}{\sin 2\theta_{13}}$$

- $R_{CP} \propto 1/E$. Matter effect only at high E.
  Allows separation of matter effect and CP effect.
- $R_{CP} \propto L$. Event rate $\propto 1/L^2$.
  Statistical merit indep. of L for same sized detector.
- $R_{CP} \propto 1/\sin 2\theta_{13}$. Electron event rate $\propto \sin^2 2\theta_{13}$.
  Statistical merit indep. of θ_{13}.
- $R_{CP} \propto \Delta m^2_{21}$. Better CP resolution for higher Δm^2_{21}.
- For given resolution on δ_{CP} detector size is independent of L.

Running schemes and event rates

1 MW, $5 \times 10^7 sec$, Neutrino Running.

- Standard: Wideband beam to 500 kT detector at Homestake (2540 km) with strong background rejection.

  CC: 52000 NC: 18000 QE: 11800

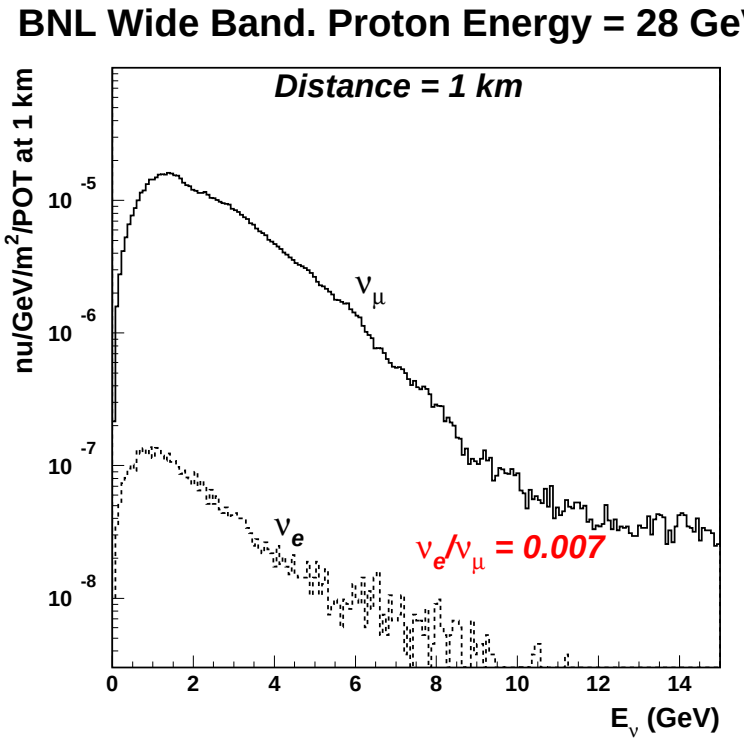
- Weak Backg. rej.: Wideband beam to 500 kT detector at Homestake (2540 km) with weak background rejection.

- Offaxis: 1 deg. Offaxis beam to 500 kT detector at Homestake (2540 km) with weak background rejection.

  CC: 19000 NC: 7100 QE: 6500

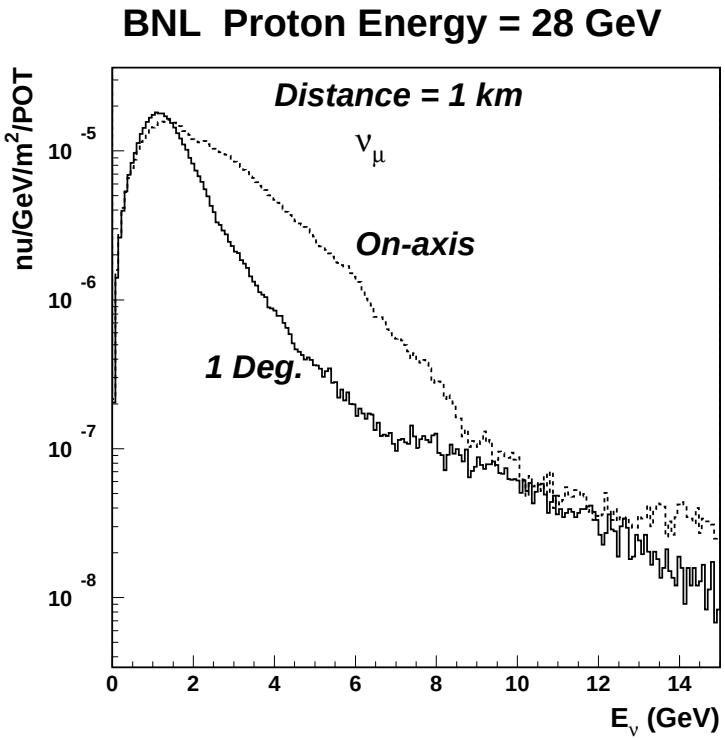
- Some comments on 50 kT Liquid Argon detector.

BNL on-axis



- Flux and contamination experimentally known
- 60 cm graphite target.
- 4 m diameter, 200 m long tunnel
- $5 \times 10^{-5}\ \nu/m^2/POT$ @ 1 km.
- 52000 CC, 17000 NC events (1MW, 2540 km, 0.5 MT, 5×10^7 sec)

1 deg. Off axis beam



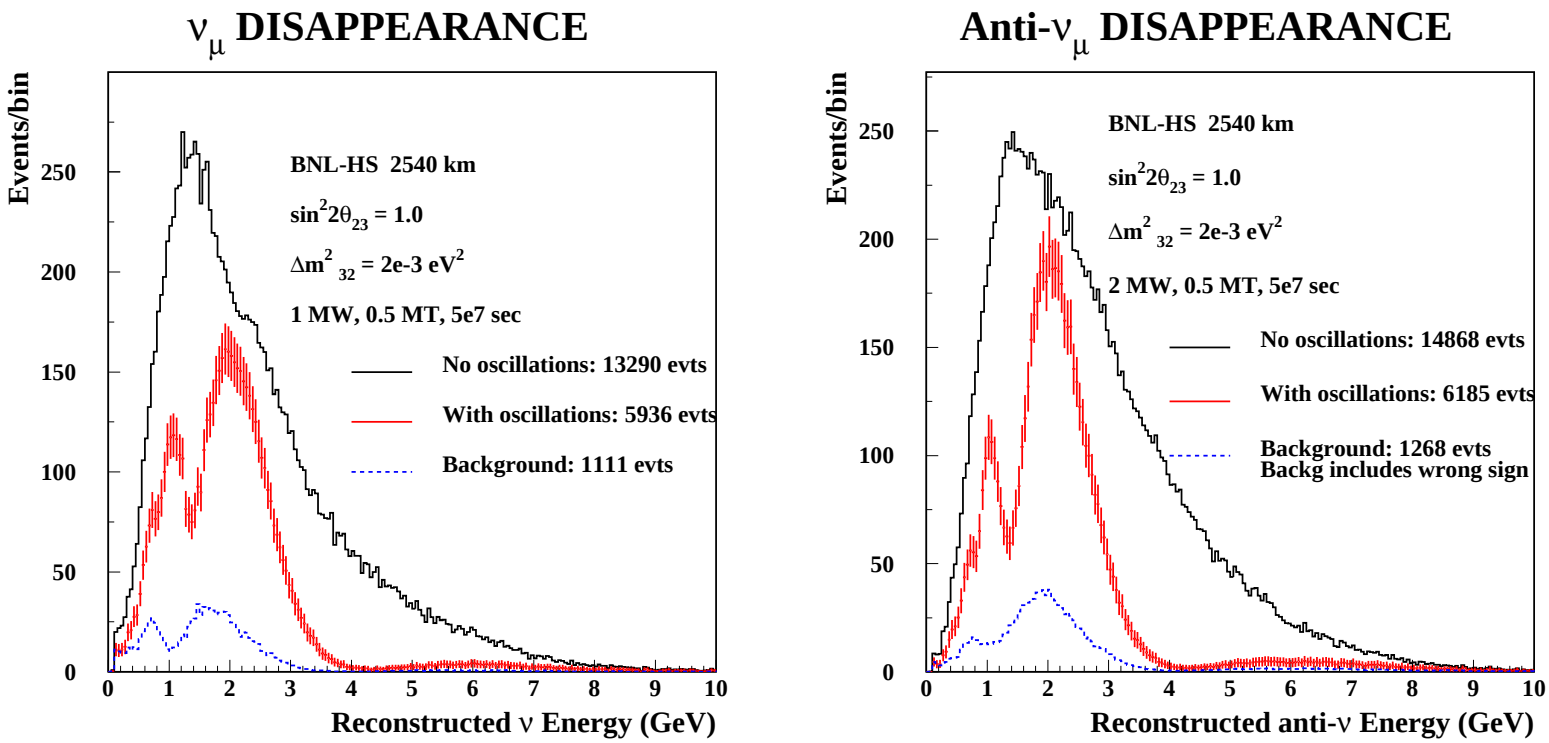
- Move target and horn by 1.3 m and rotate 1 deg.
- Same 4 m diameter, 200 m long tunnel
- Will need large beam dump
- 19000 CC, 7000 NC events (1MW, 2540 km, 0.5 MT, 5×10^7 sec)

Scenario No. 1 Wide band

1 MW, Neutrinos, 500 kT, L=2540km, $5 \times 10^7 sec$
2 MW, Anti-Neutrinos, 500 kT, L=2540km, $5 \times 10^7 sec$
Strong Background Rejection.

CC $\nu_\mu N \rightarrow \mu^- X$	51800 (30050)	NC $\nu_\mu N \rightarrow \nu_\mu X$	18323 (11540)
CC $\nu_e N \rightarrow e^- X$	380 (106)		
QE $\nu_\mu n \rightarrow \mu^- p$	11767 (11868)	NC elastic	4575 (3882)
QE $\nu_e n \rightarrow e^- p$	84 (80)		
CC Single π	22053 (11872)	NC Single π	7741 (5074)
CC Two π	10143 (3336)	NC Two π	3557 (1630)
CC $> 2\ \pi$	4882 (500)	NC $> 2\ \pi$	1729 (560)
CC $\nu_\tau N \rightarrow \tau^- X$	$\sim$ 110 (40)	(depends on Δm^2)	

Anti-neutrino rate (brackets) for 2 MW.
(Add Nu cont. to antinu rate: 7696 CC and 2600 NC.)

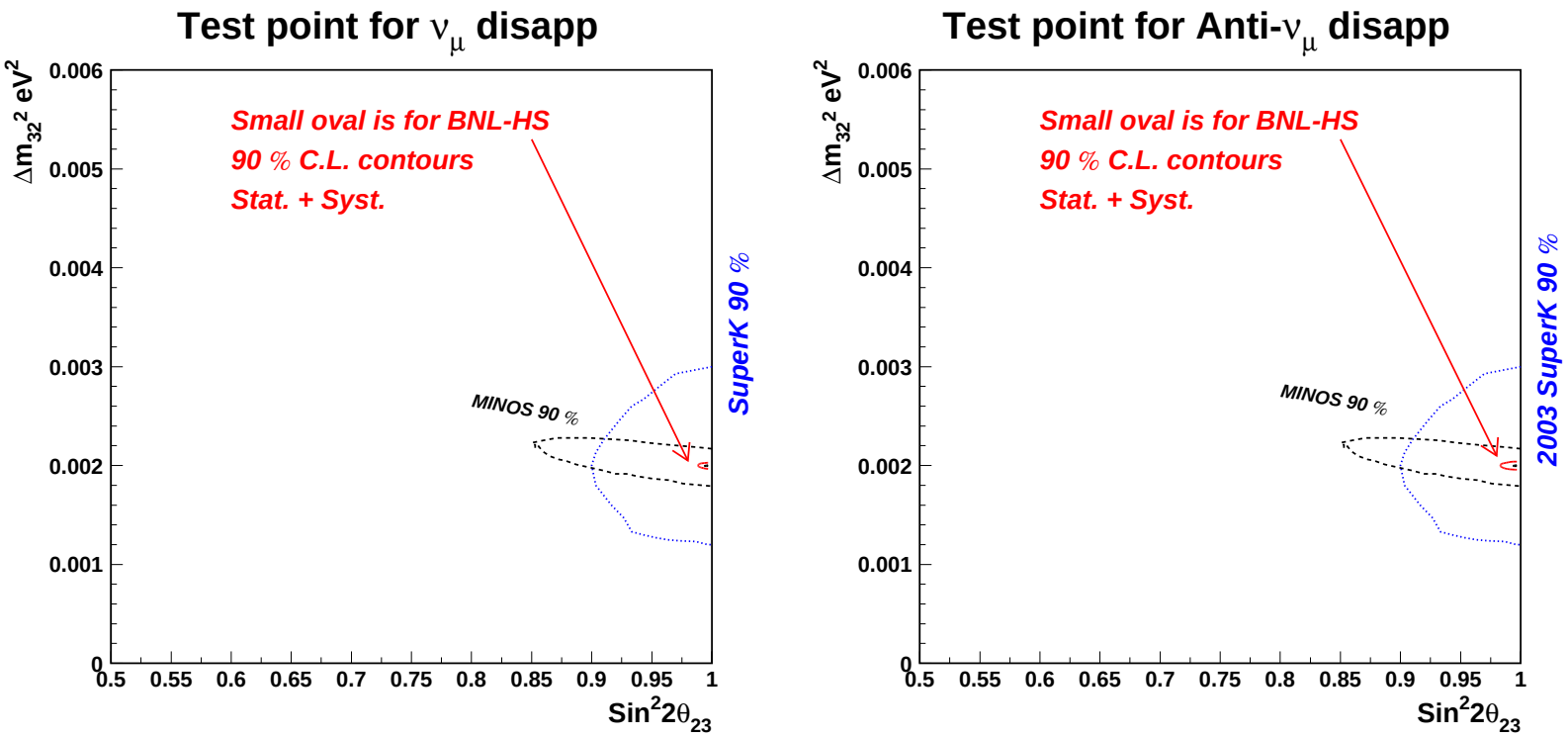


Node pattern provides high Δm^2_{32} resolution. Energy calibration is very important.

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

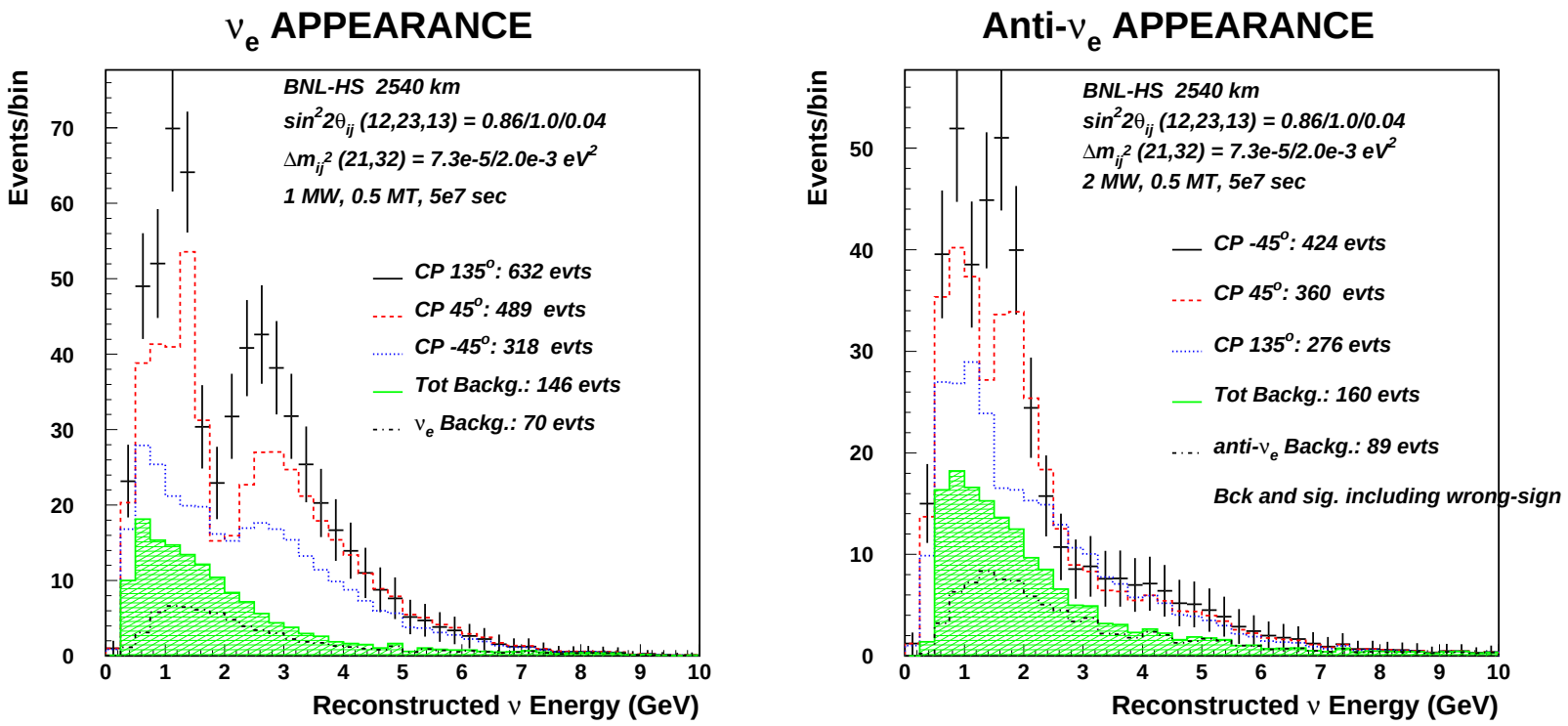
Minimum systematics in ν_μ and $\bar{\nu}_\mu$ comparison

Disappearance resolution, essential measurement of θ_{23}



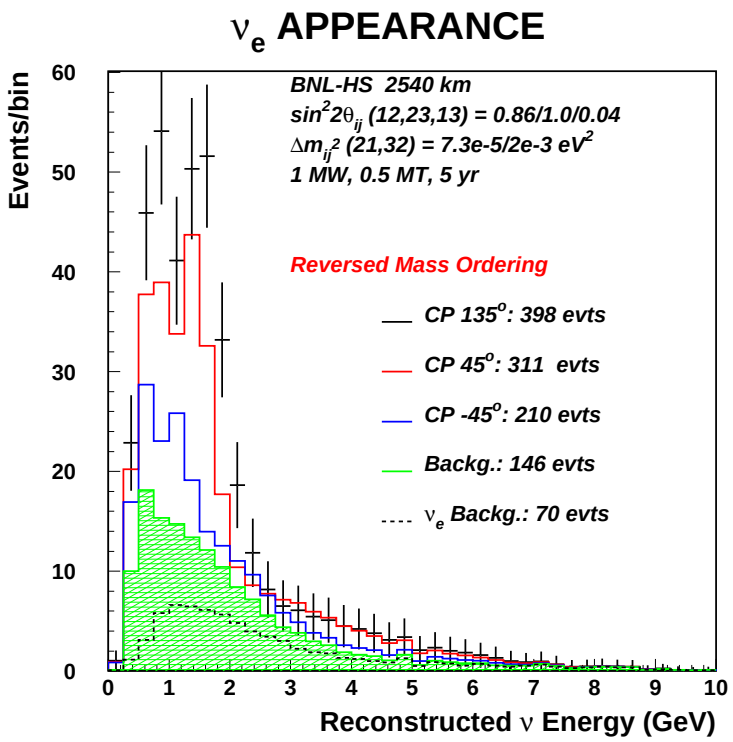
$\sim 1\%$ resol. on Δm^2_{32} and $\sin^2 2\theta_{23}$ over broad range. Understand detector energy scale to 1%. Robust against systematics.

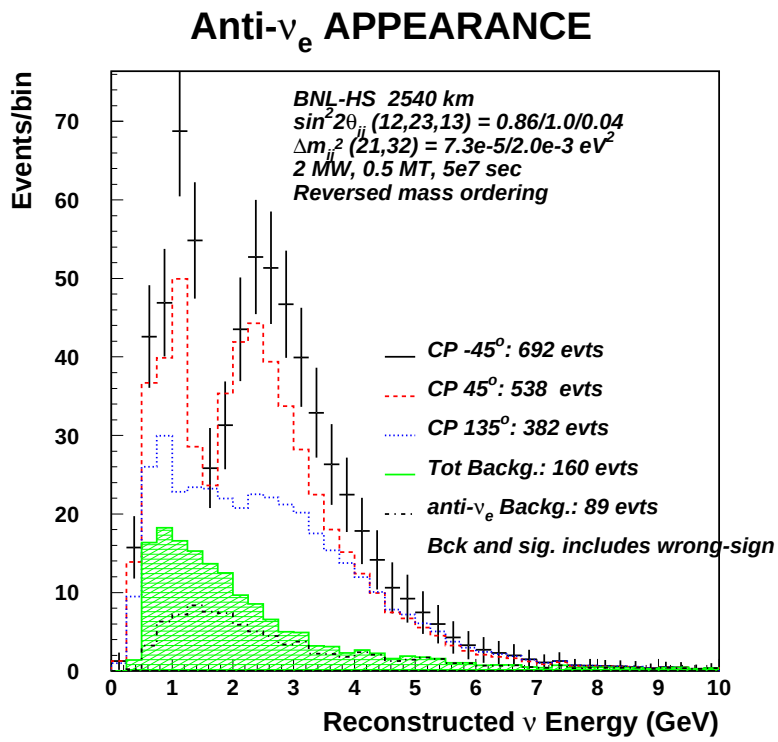
Running for $\sin^2 2\theta_{13}$



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

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



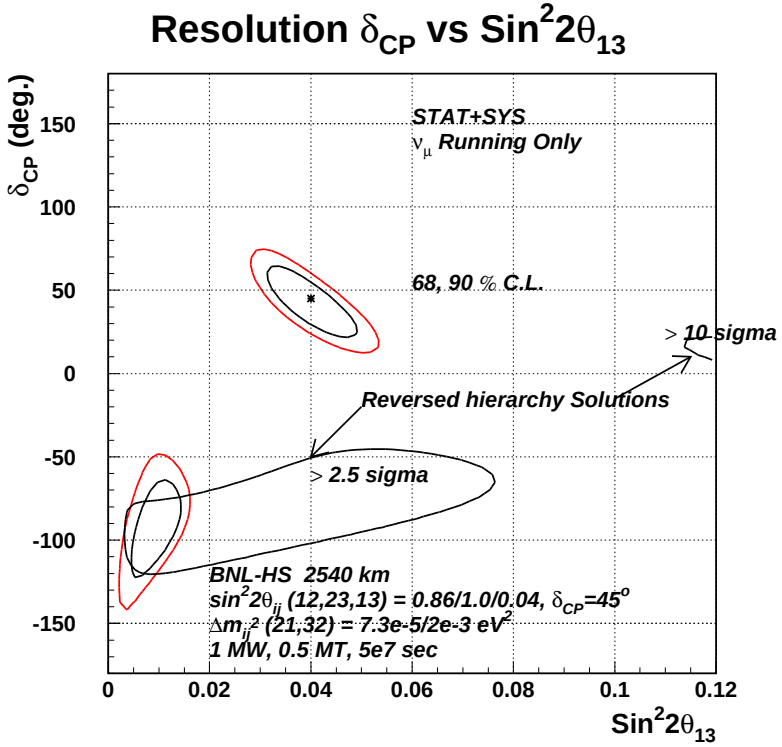


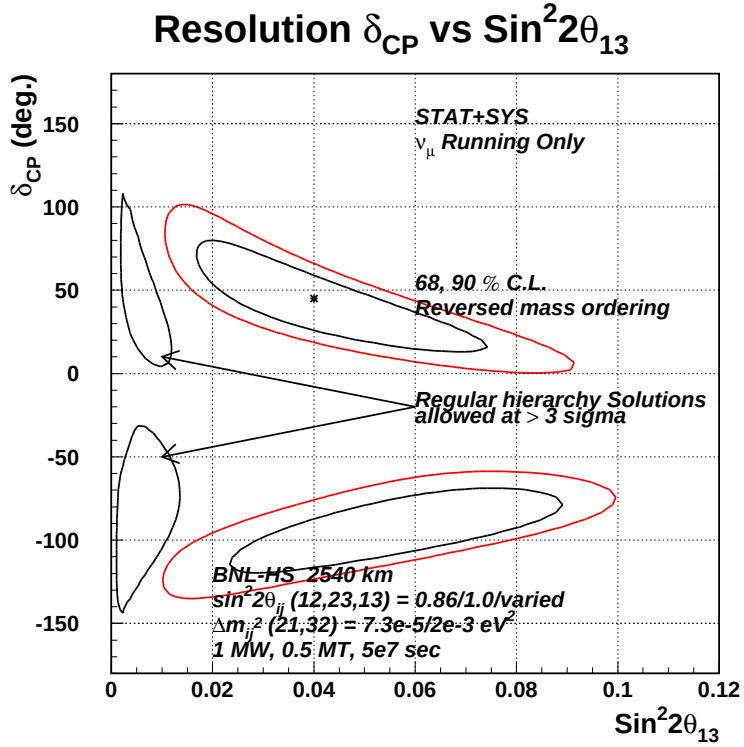
$\Delta m^2_{32} = 0.002 eV^2$, $\sin^2 2\theta_{13} = 0.04$.

Reversed Mass Hierarchy

Matter effects included.

Mass hierarchy after neutrino running

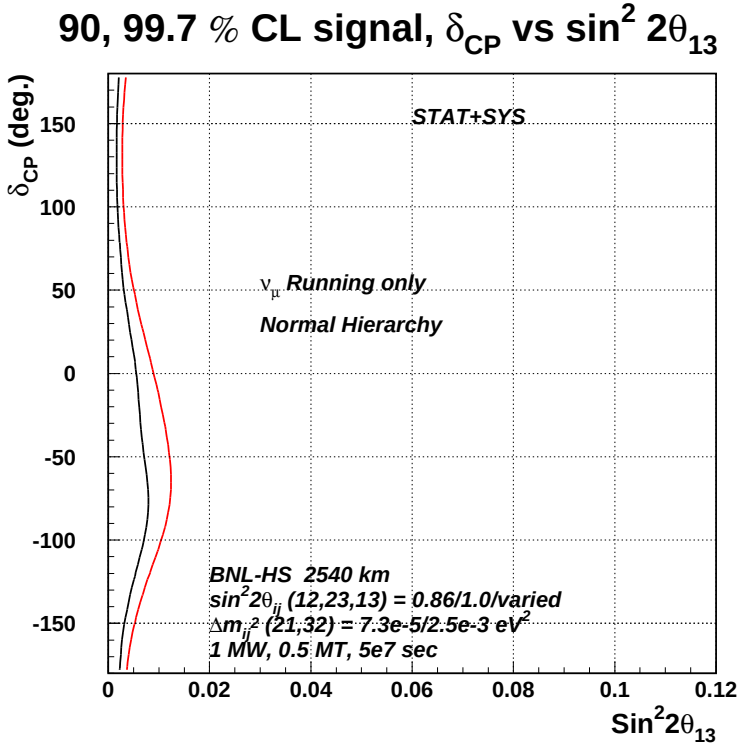


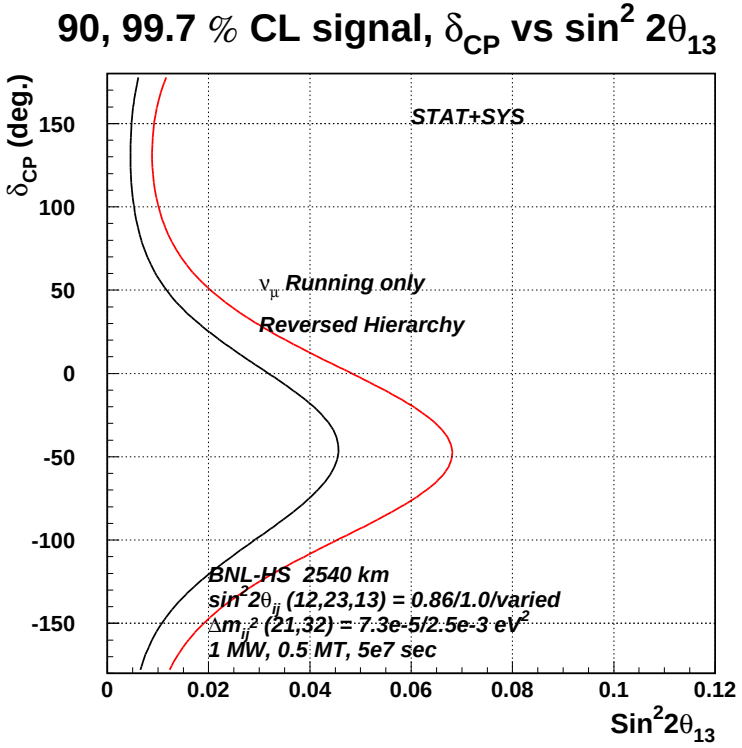


Left: Regular mass hierarchy Right: reversed mass hierarchy.

Mass hierarchy is resolved to 3 sigma with only neutrino running in large part of the parameter space.

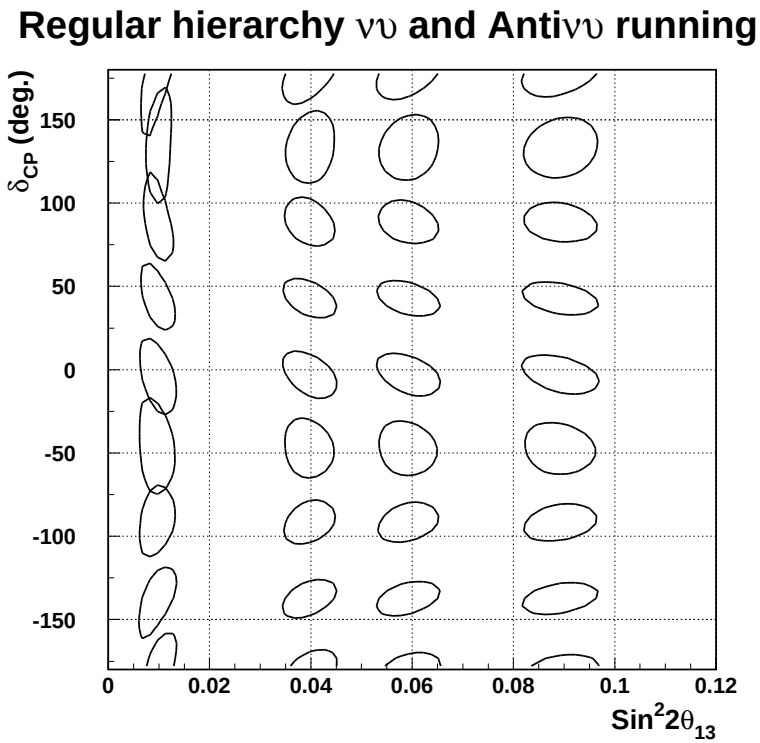
$\sin^2 2\theta_{13}$ sensitivity

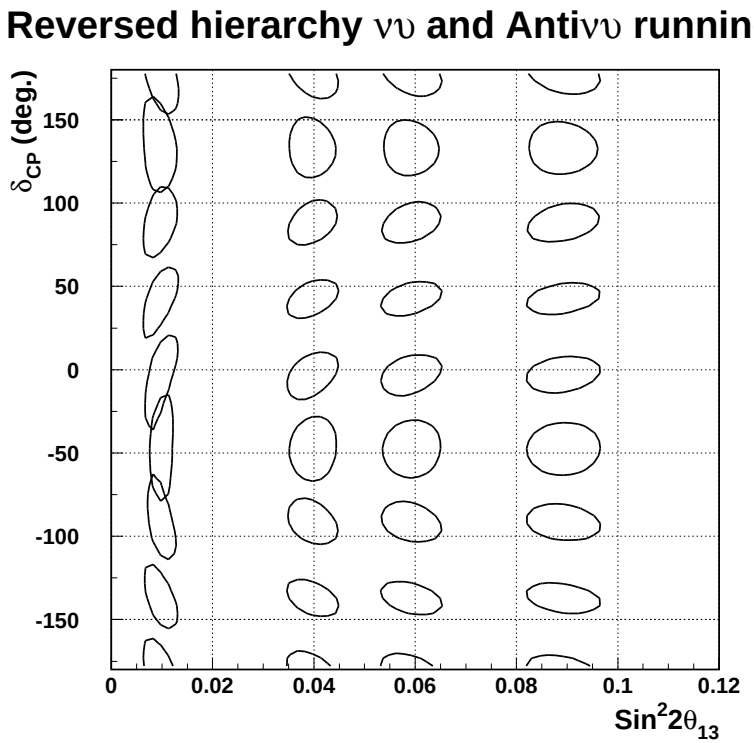




If reversed hierarchy and in the unlucky region, need to run anti-neutrinos.

CP measurement after nu and anti-nu





Left: Regular mass hierarchy Right: reversed mass hierarchy.

Only the θ_{23} ambiguity is left.

more about this later...

Scnenario 2. Background is worse

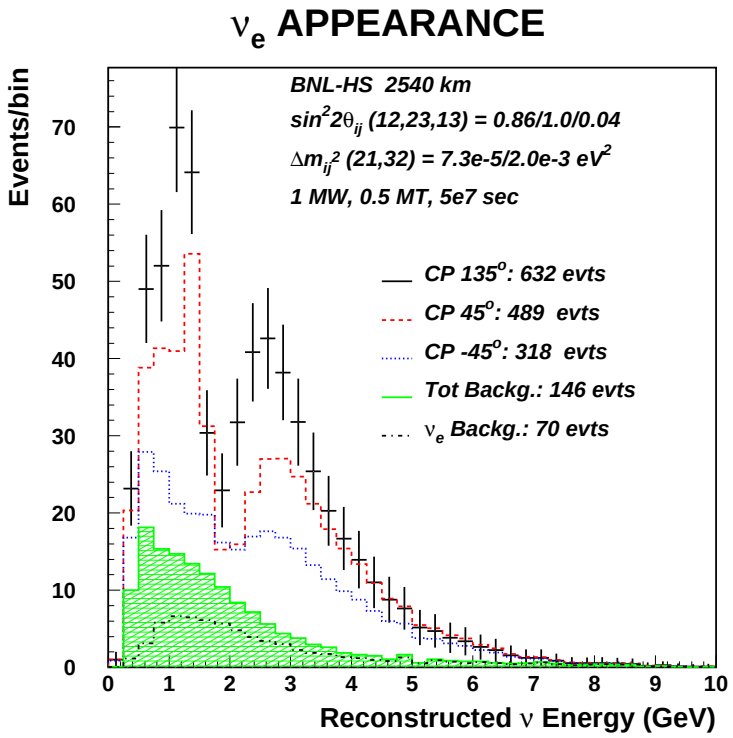
Same running conditions.

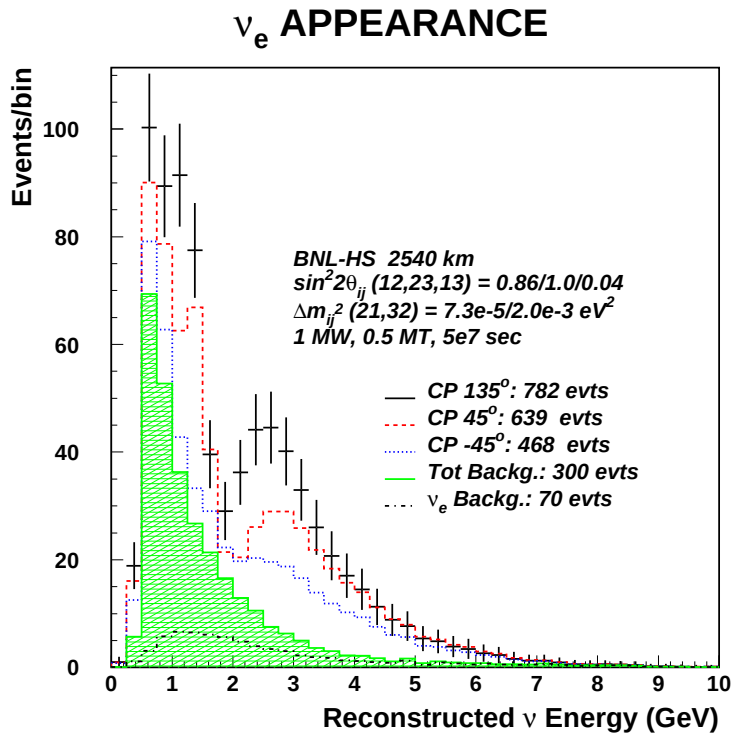
Particles within 20 deg. separation cannot be resolved.

- Some effect on disappearance.
- Some effect on appearance with $E > 2.5 GeV$.
- Large effect at lower energies.

Can background above 2-3 GeV be kept under control by shaping the beam spectrum ?

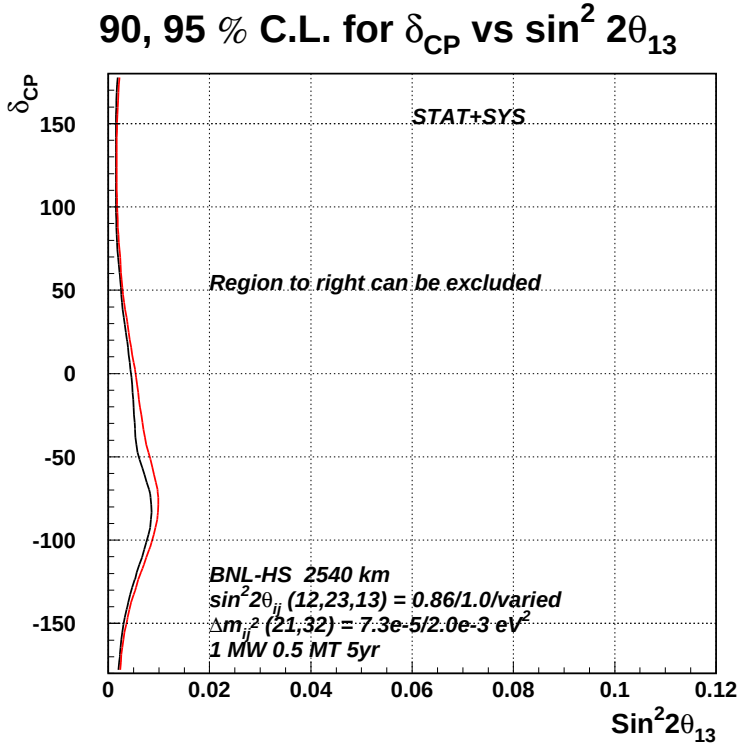
Worse background spectra

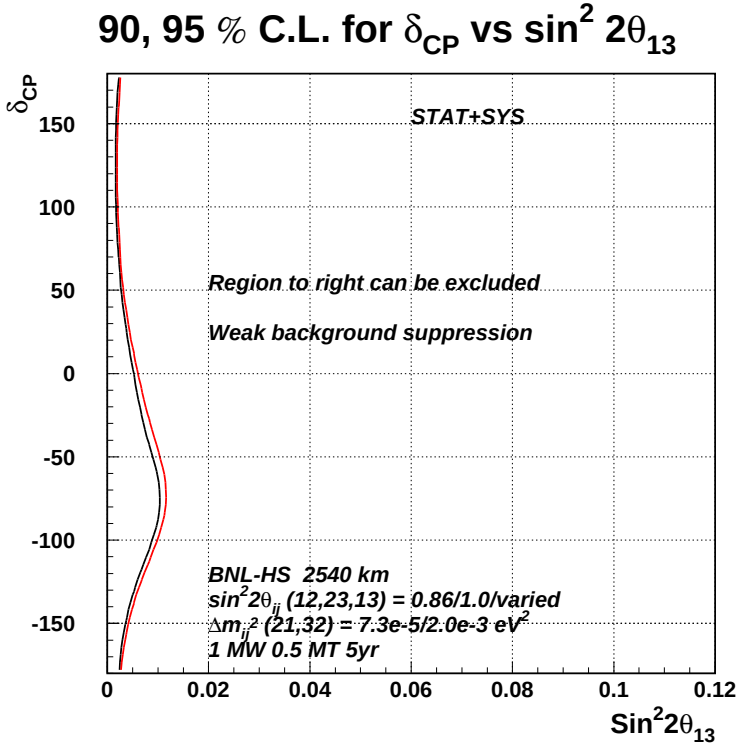




Left: strong rejection Right: weak rejection

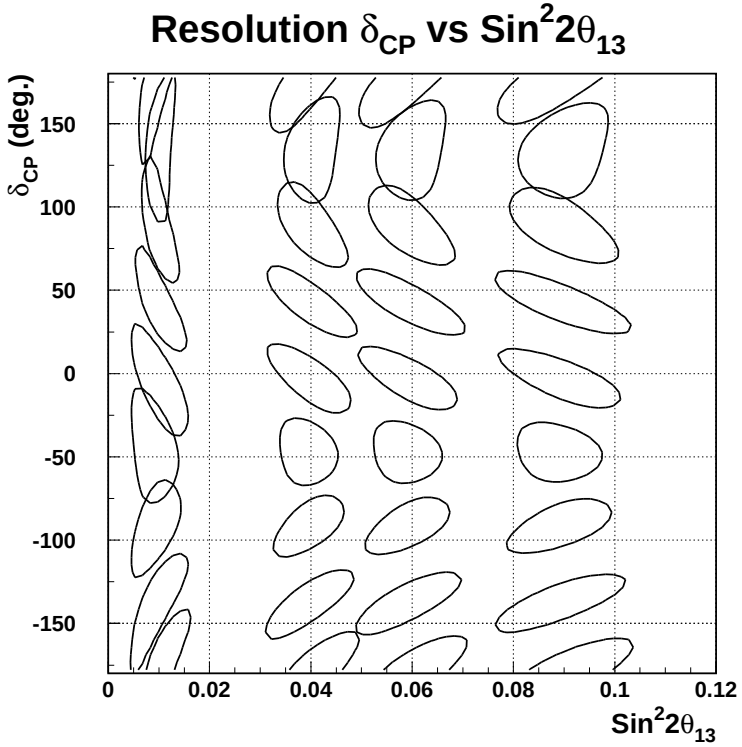
Worse background limit

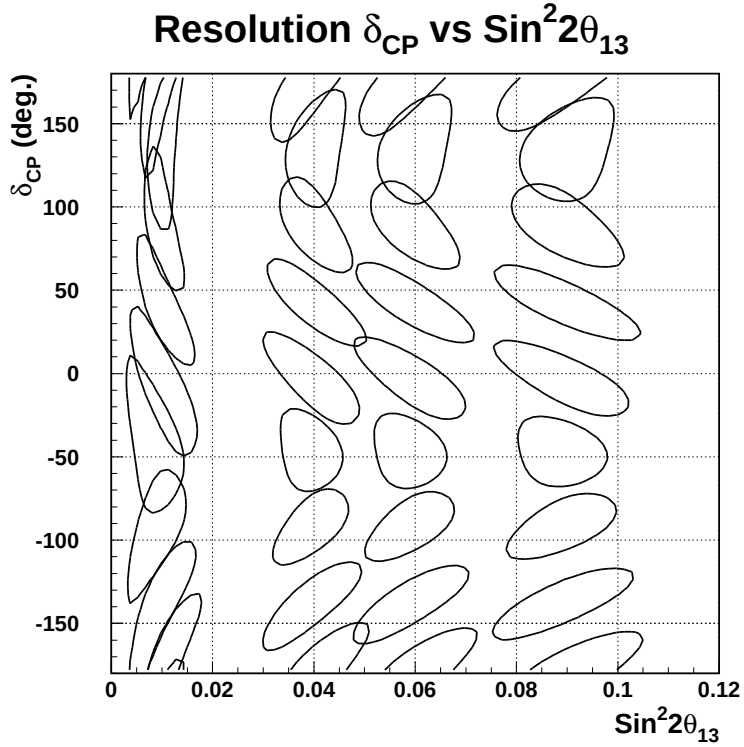




Left: strong rejection Right:weak rejection Limit affected by < 2:
Using knowledge of δm^2_{32} in extracting limit
Background is confined to lower node.

Worse background CP-measurement





Left: strong rejection Right: weak rejection

Worse background: δ_{CP} worse by $\sim 50\%$

Could one run off-axis to do better ?

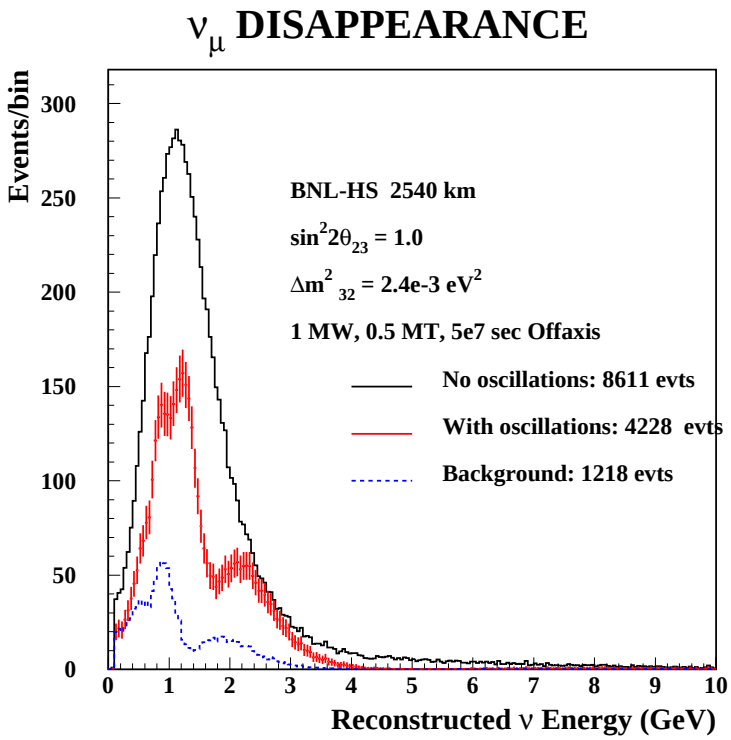
1 Deg. neutrino running

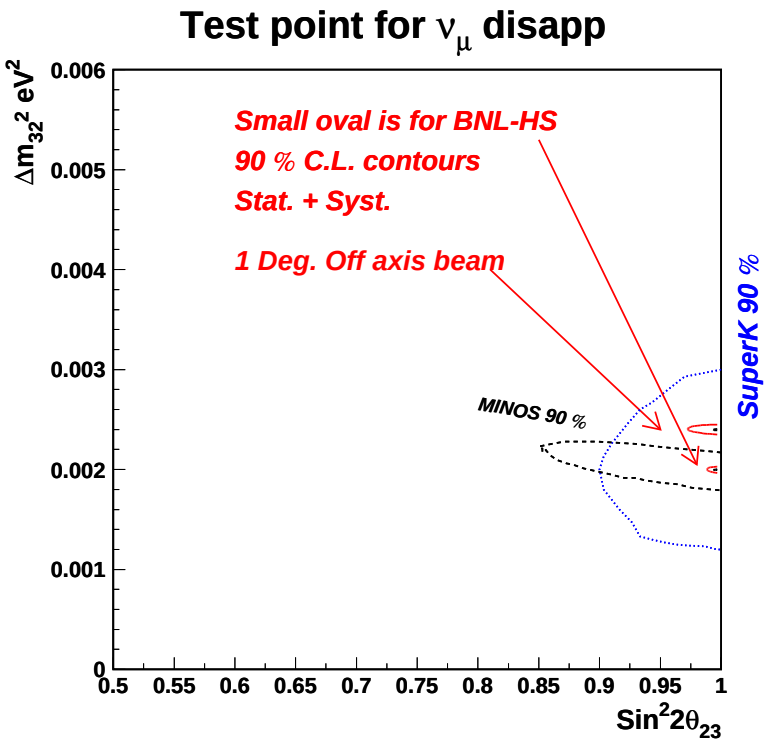
- Better backgrounds for ν_e detection.
- Refine CP measurement.
- Better measurement of θ_{23} and Solar parameters ?

1 MW, 500 kT, Neutrino running, $5 \times 10^7 sec$, 2540 km (1.22×10^{22} Protons at 28 GeV.)

	On axis	1 Deg. Off axis
CC/NC $\nu_\mu N \rightarrow lX$	51800/18323	18931/7081
CC $\nu_e N \rightarrow e^- X$	380	265
QE $\nu_\mu n \rightarrow \mu^- p$	11767	6462
QE $\nu_e n \rightarrow e^- p$	84	69
CC/NC Single π	22053/7741	8445/2996
CC/NC Two π	10143/3557	2394/814
CC $\nu_\tau N \rightarrow \tau^- X$	~ 110	50

1 deg. disappearance

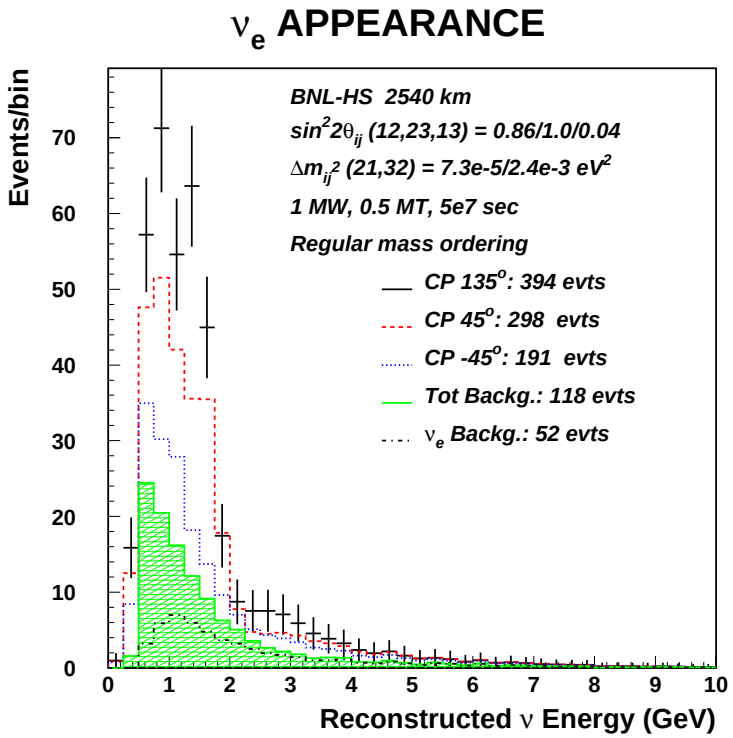


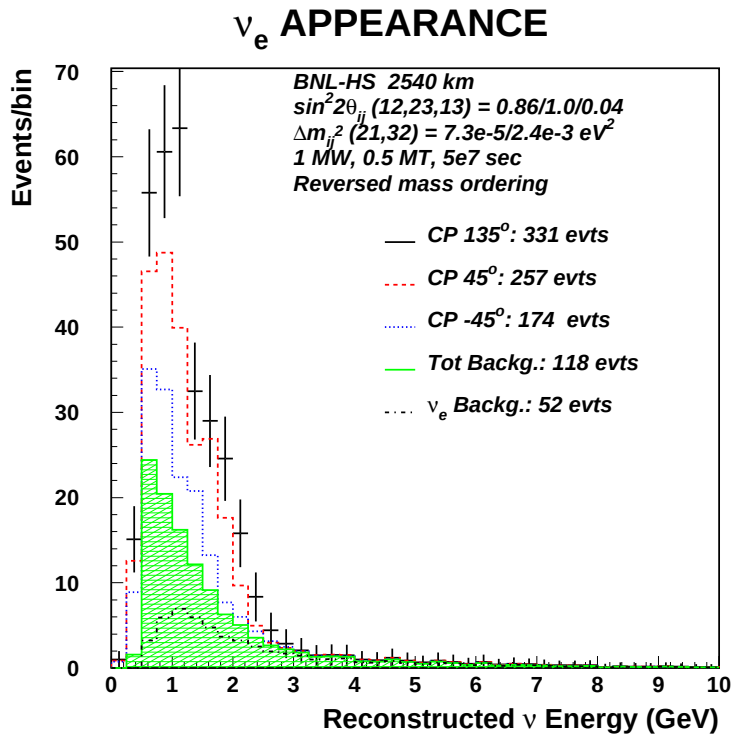


Loss of one node, Reduction in $\sin^2 2\theta_{23}$ resolution.

About factor of 3 compared to wide-band running.

1 deg. appearance





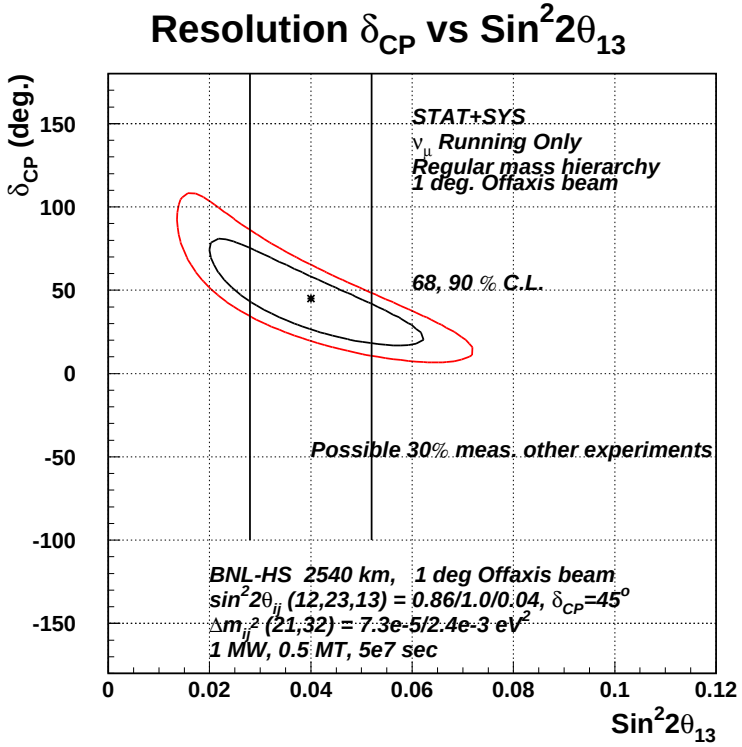
Left: regular mass ordering; Right: reversed mass ordering

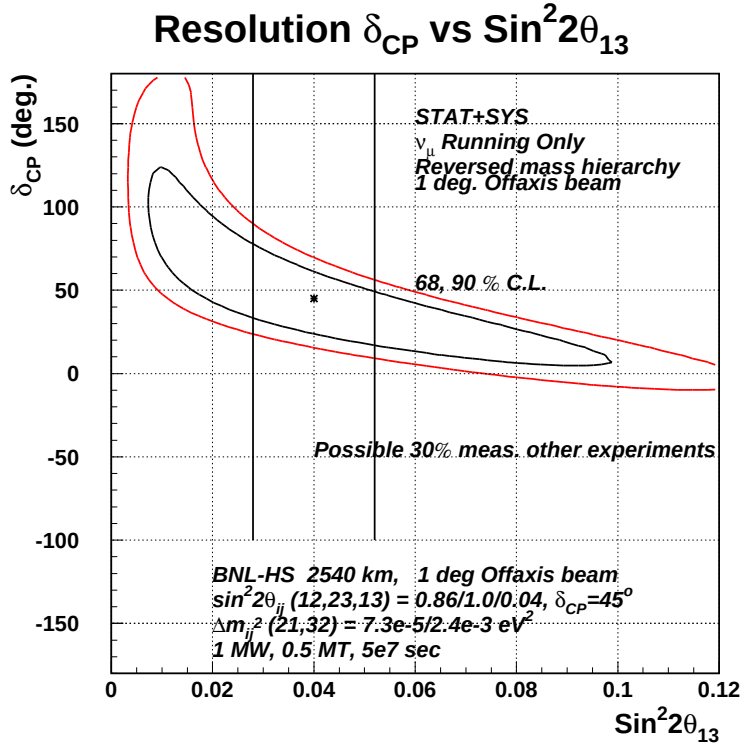
Assume weak background rejection

Obtain factor of ~ 3.5 in NC backg. due to 1 deg.

Mass ordering discrimination worse.

1 deg. CP measurement



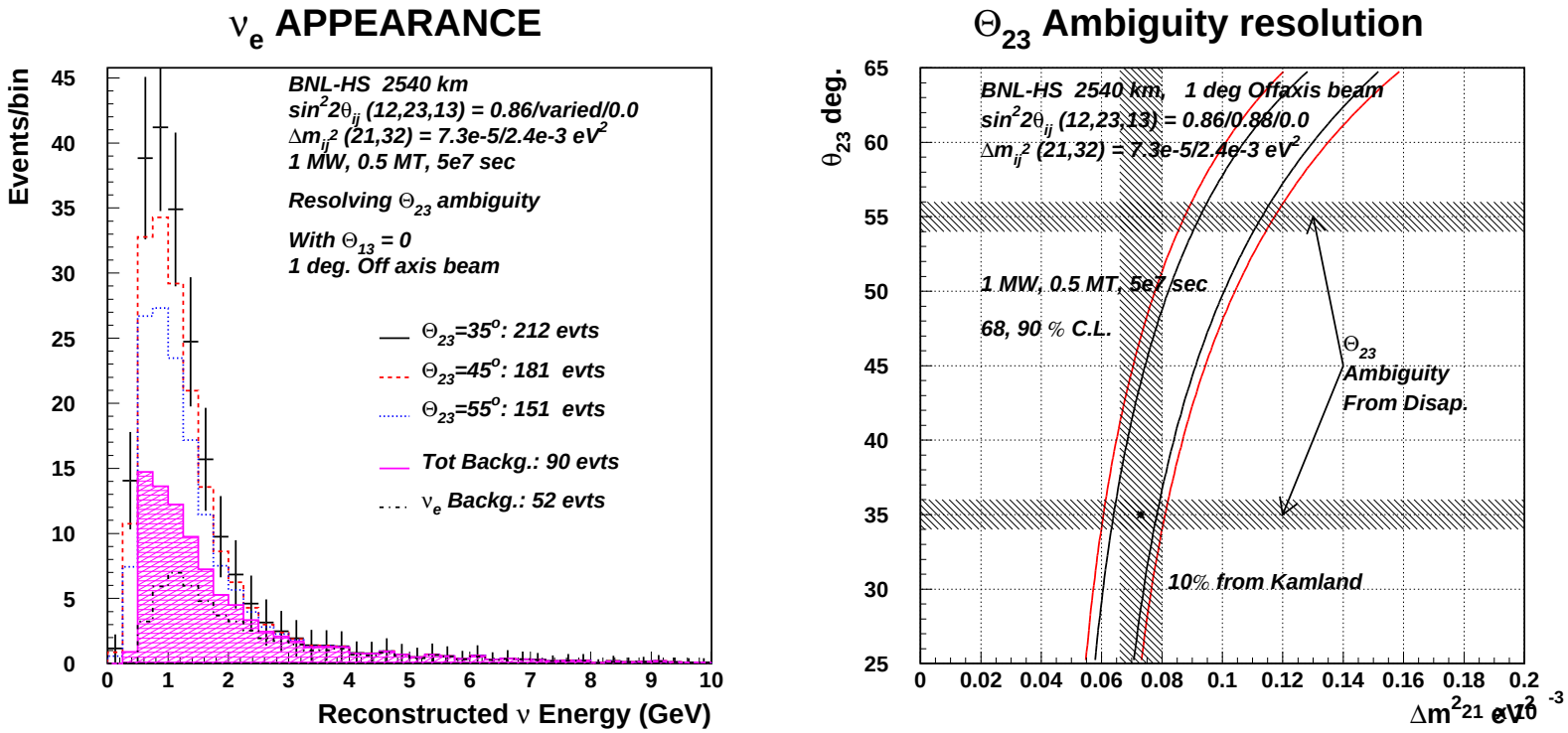


Left: regular mass ordering; Right: reversed mass ordering

Large CP vs. $\sin^2 2\theta_{13}$ correlation.

Will need separate measurment of $\sin^2 2\theta_{13}$.

1 deg. θ_{23} measurement



If $\sin^2 2\theta_{23} < 1.0$ then $\theta_{23} \rightarrow \pi/2 - \theta_{23}$ ambiguity.

Can be resolved with $\nu_\mu \rightarrow \nu_e$ at low energies.

Need strong backg. rej. and off-axis beam.

Use KAMLAND $\sin 2\theta_{12} \times \Delta m^2_{21}$ measurement.

On axis beam to LAR

1 MW, Neutrino running, $5 \times 10^7 sec$

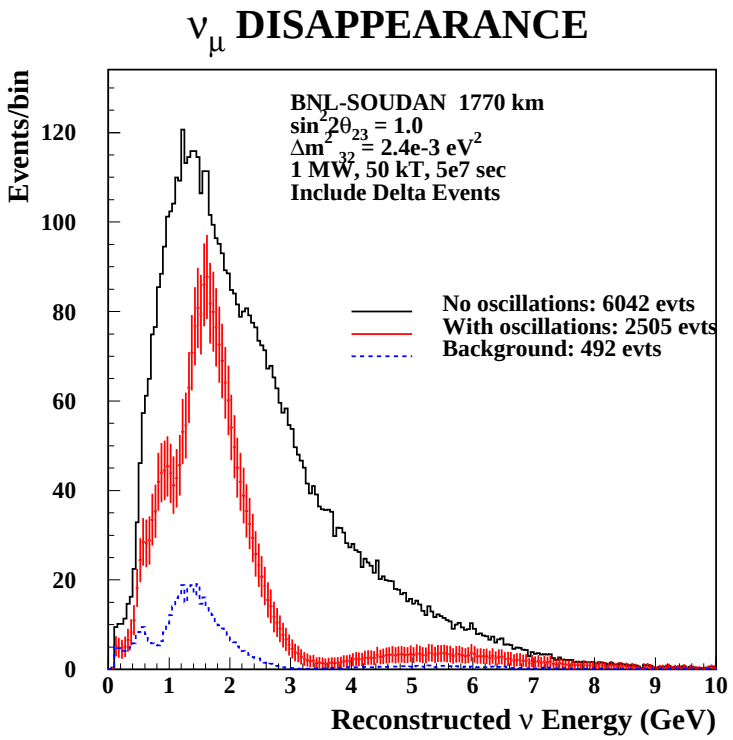
	0.5 MT 2540km H2O	50 kT 1770km LAR
CC/NC $\nu_\mu N \rightarrow lX$	51800/18323	12371/4240
CC $\nu_e N \rightarrow e^- X$	380	93
QE $\nu_\mu n \rightarrow \mu^- p$	11767	3372
QE $\nu_e n \rightarrow e^- p$	84	24
CC/NC Single π	22053/7741	5082/1783
CC/NC Two π	10143/3557	2535/825
CC $\nu_\tau N \rightarrow \tau^- X$	~ 110	25

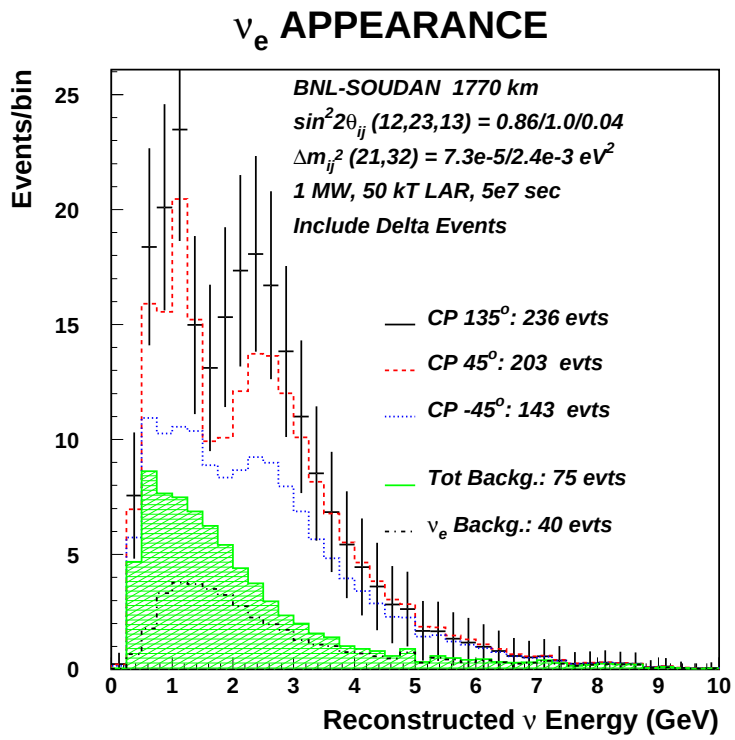
(Used slightly different spectra for two simulations)

Most physics preserved if event rate can be obtained.

Use all CC ? Go to 2 MW ?

LAR1770 disappearance, appearance





Only 2 nodes visible. Increase yield with delta production events.

Treat all $\nu_l p \to l^- \pi^+ n$ as if $\nu_l p \to \Delta^+ l^-$

Reduces resolution below 2 GeV.

Detector Requirements

- Fiducial Mass:
  - $>$ 500 kT if using only "clean" events.
    Also needed for proton decay and neutrino astrophysics.
  - $\sim$ 100 kT if fine grain and use all CC events.
    Selected proton decay modes still at the frontier.
- Threshold: $\sim$ 10 MeV, Dynamic range: contain 5 GeV μ
- Time res: few ns. Energy resolution: $\sim$ 10 %
- muon/electron discrimination: $<$ 1 %
- Pattern recognition:
  - 1, 2, 3 track separation
  - showering vs. multitrack separation.
  - need factor of 20-30 rejection capability around 1-2 GeV.
- Cost: 300 M$ – 1000 M$

Some comments on detector

- Need much more manpower for detector studies.
- Water Cherenkov
  - 50 kT SuperK is existence proof.
  - Background rejection ? (Yanagisawa)
    need another $\times 3 \rightarrow 5$
  - Additional imaging capability (Viren)
- Liquid Argon TPC
  - scale up to 100 kT module ?
  - Current size 300Ton.
  - Needs detailed simulations.
- Any other technology ?

Summary of studies

- Background:
  - Kinematic suppression of backg. above 2 GeV needs to be viable.
  - Could tolerate more background at lower energies by switching to 1 deg. beam if needed.
- 1 Deg. running:
  - Use to compliment the wide band running for CP.
  - Or to find $\nu_\mu \rightarrow \nu_e$ at even larger L/E
  - Could resolve θ_{23} ambiguity if needed.
- Liquid Argon:
  - Need at least 50 kT if large fraction of CC events can be used.
  - Could be closer (1720 km ?) and perform adequately for CP.

Conclusion

A next generation large detector at a national underground facility with a powerful neutrino beam and very long baseline.
Unique, and broad range of physics.

- Known Knowns: Δm^2_{32}, $\sin^2 2\theta_{23}$, measure better.
  Δm^2_{21} $\sin^2 2\theta_{12}$ constrain with appearance.
- Known Unknowns: θ_{13}, δ_{CP}, θ_{23} ambiguity.
  sign of Δm^2_{32} and matter effect
- Unknown Unknowns: Over-constrain the 3-generation mixing picture.