Very Long Baseline experiment with a Super Neutrino Beam Brookhaven National Laboratory

Presented to the
NuFact04, Osaka University

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For the Brookhaven Neutrino Working Group

References:
Phys Rev D 68, 012002 (2003)
Talks at BNL-UCLA Neutrino Super Beam Workshop
M. Diwan's talk at APS Super Beam Study Group Meeting
B. Viren's talk at UNO Collaboration Meeting (April '04)

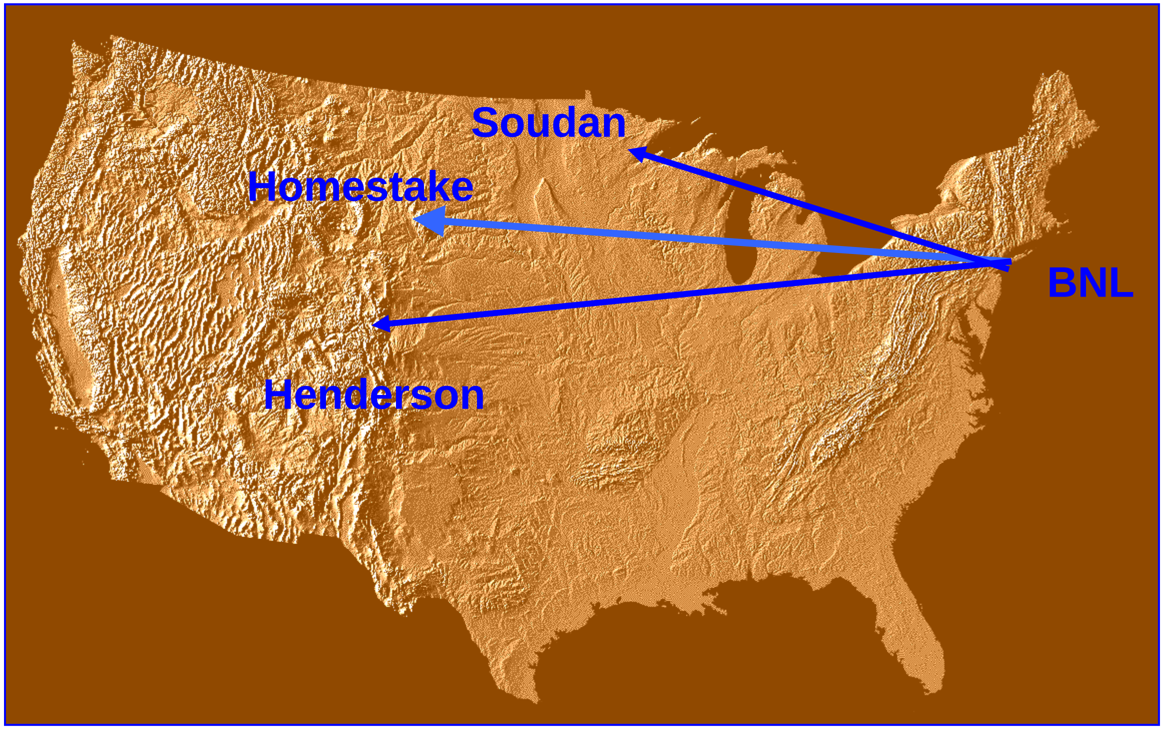
Physics Goals of the Very Long Baseline Neutrino Program

We introduce a plan to provide the following goals in a ***single facility***:

- precise determination of the oscillation parameters Δm_{32}^2 and $\sin^2 2\theta_{23}$
- detection of the oscillation of $\nu_\mu \rightarrow \nu_e$ and measurement of $\sin^2 2\theta_{13}$
- measurement of $\Delta m_{21}^2 \sin^2 2\theta_{12}$ in a $\nu_\mu \rightarrow \nu_e$ appearance mode, can be made if the value of θ_{13} is zero
- verification of matter enhancement and the sign of Δm_{32}^2
- determination of the CP-violation parameter δ_{CP} in the neutrino sector

The use of a *single neutrino super beam source* and *half-megaton neutrino detector* will optimize the efficiency and cost-effectiveness of a full program of neutrino measurements. If the value of $\sin^2 2\theta_{13}$ happens to be larger than ~0.01, then all the parameters, including CP-violation can be determined in the VLB program presented here.

BNL → Homestake Super Neutrino Beam



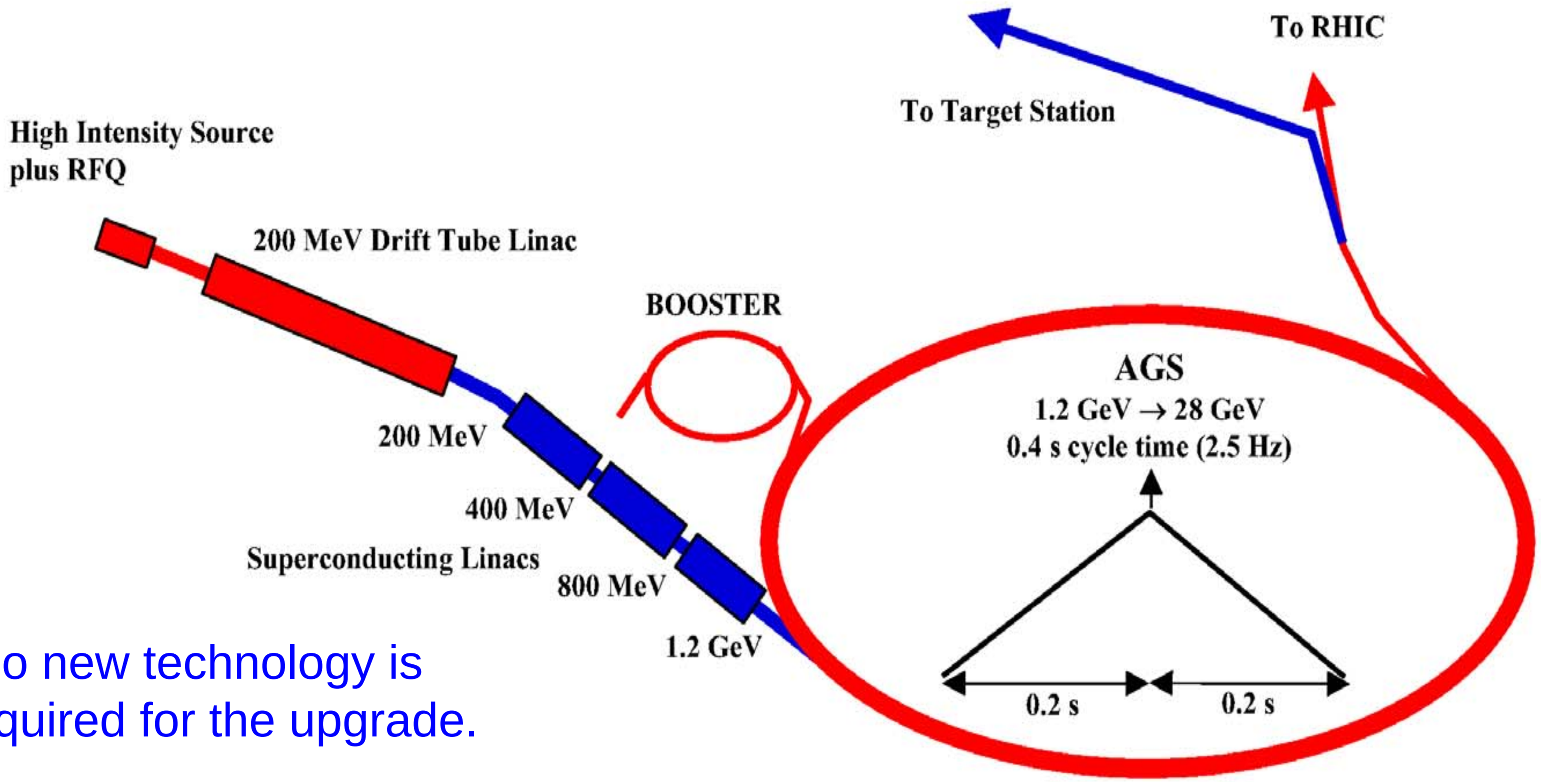
- The baseline design: BNL-Homestake 2540 km
- A potentially better site: BNL-Henderson 2767 km
- If the right detector (LAr) is build there: BNL-Soudan 1712 km

28 GeV protons, 1 MW beam power
500 kT Water Cherenkov detector
5×10^7 sec of running, Conventional Horn based beam

Flexibility to Handle Tomorrow's Physics

- At this point we do not know many of the critical parameters that describe the neutrino mixing sector.
  - The facility must be flexible to parameter changes so that it is not obsolete before it is built.
- The first phase is a wide-band ν beam that should measure 3-generation mixing with δ_{CP} at some precision.
  - 1 MW super beam with 0.5 Mton H_2O Č detector (or equivalent)
- Based on future knowledge of the mixing parameters, the running strategy can be adjusted.
  - Wide band anti-neutrino running with an upgrade to a 2 MW beam.
  - An off-axis ν beam with a narrower and lower energy spectrum to suppress background
    - The ability to have a 1° off axis beam is being designed into the facility.

AGS Target Power Upgrade to 1 MW



•No new technology is required for the upgrade.

- the *AGS Upgrade* to provide a source for the 1.0 MW Super Neutrino Beam
  Existing AGS is in red, Upgrades to the AGS are shown in blue.

•Increase AGS cycle time to 2.5 Hz, add 1.2 GeV Superconducting Linac instead of the booster.

AGS 1 MW Upgrade and SC Linac Parameters

Proton Driver Parameters

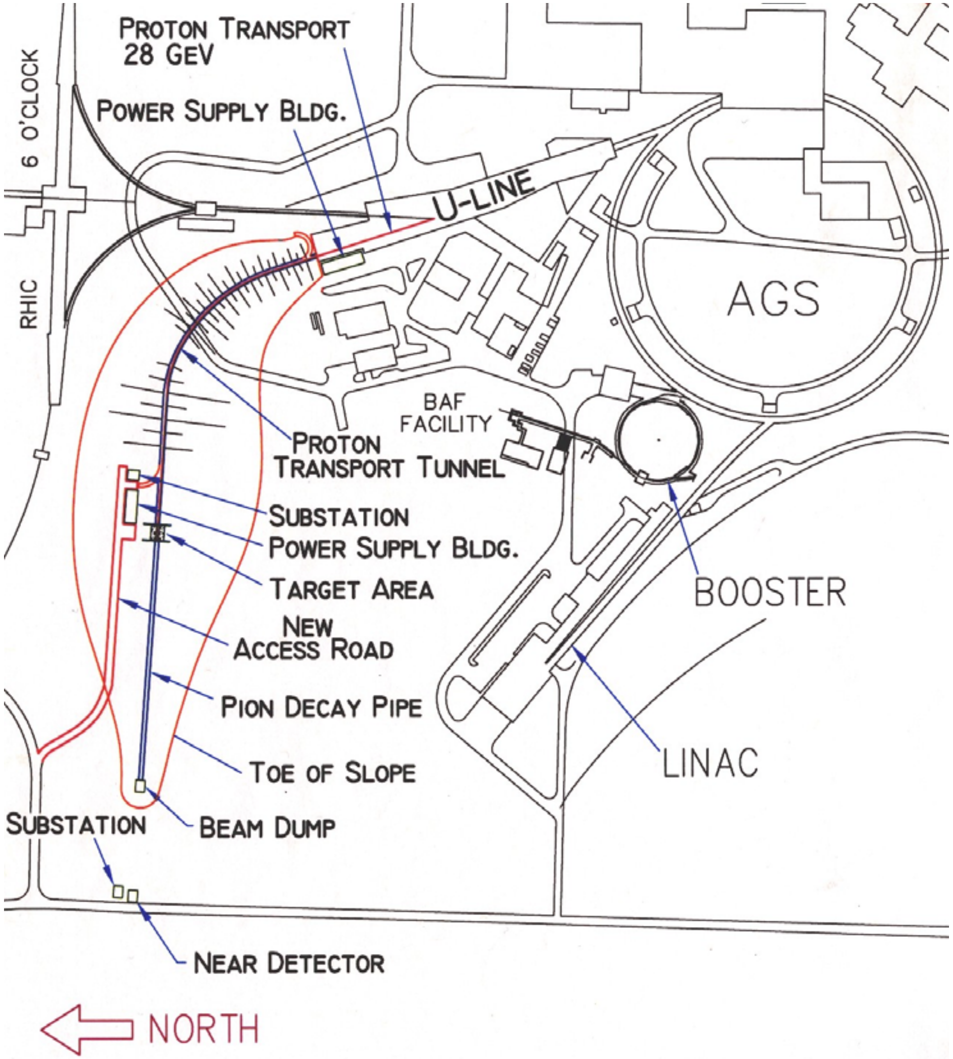
Item	Value
Total beam power	1 MW
Protons per bunch	0.4×10^{13}
Beam energy	28 GeV
Injection turns	230
Average beam current	38 mA
Repetition rate	2.5 Hz
Cycle time	400 ms
Pulse length	0.72 ms
Number of protons per fill	9.6×10^{13}
Chopping rate	0.75
Number of bunches per fill	24
Linac average/peak current	20/30 mA

Superconducting Linac Parameters

Linac Section	LE	ME	HE
Av Beam Pwr, kW	7.14	14.0	14.0
Av Beam Curr, mA	35.7	35.7	35.7
K.E. Gain, MeV	200	400	400
Frequency, MHz	805	1610	1610
Total Length, m	37.82	41.40	38.32
Accel Grad, MeV/m	10.8	23.5	23.4
norm rms ε, π mm-mr	2.0	2.0	2.0

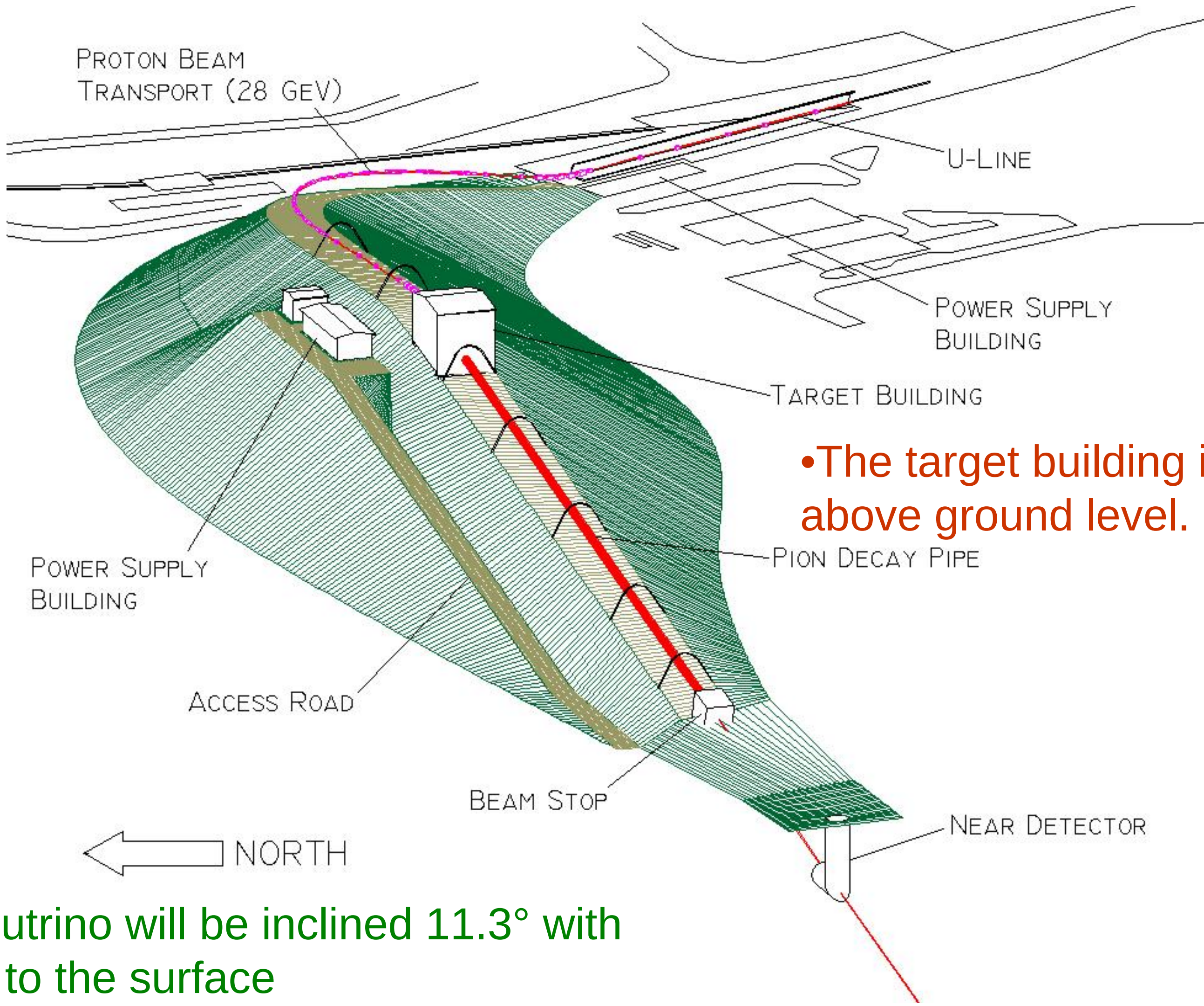
- This should provide 2.4×10^{20} protons per 10^7 seconds. (SSC year)
- We would want an eventual upgrade to 2 MW for $\bar{\nu}$ running.

Super Neutrino Beam Geographical Layout



- BNL can provide a *1 MW capable Super Neutrino Beam* for $104M FY03 (TEC) dollars
- the neutrino beam can aim at any site in the western U.S.; the Homestake Mine is shown here
- there will be no environmental issues if the beam is produced atop the hill illustrated here and the beam dumped well above the local water table
- construction of the Super Neutrino Beam is essentially de-coupled from AGS and RHIC operations

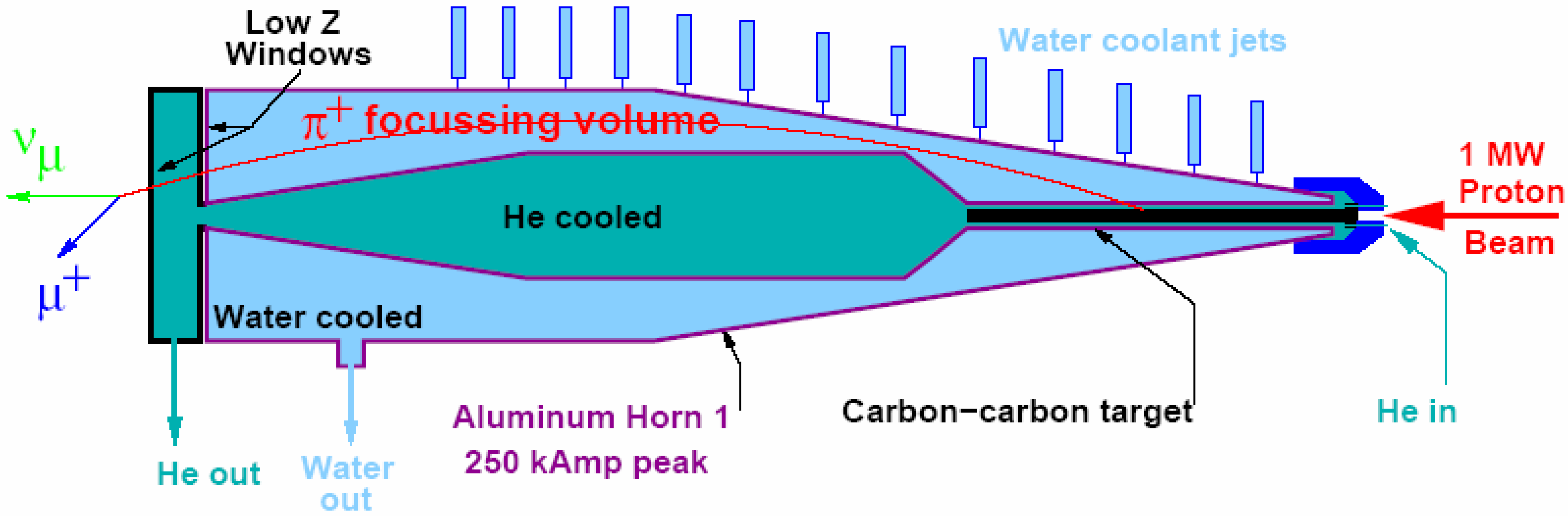
3-D Neutrino Super Beam Perspective



- The target building is 50 m above ground level.

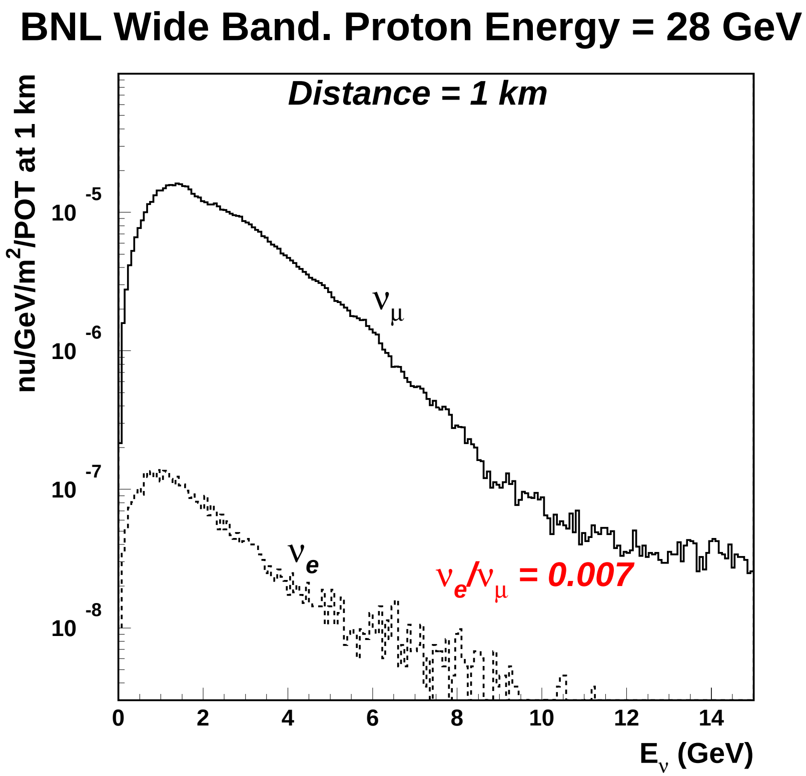
- The neutrino will be inclined 11.3° with respect to the surface

Target and 1st Horn



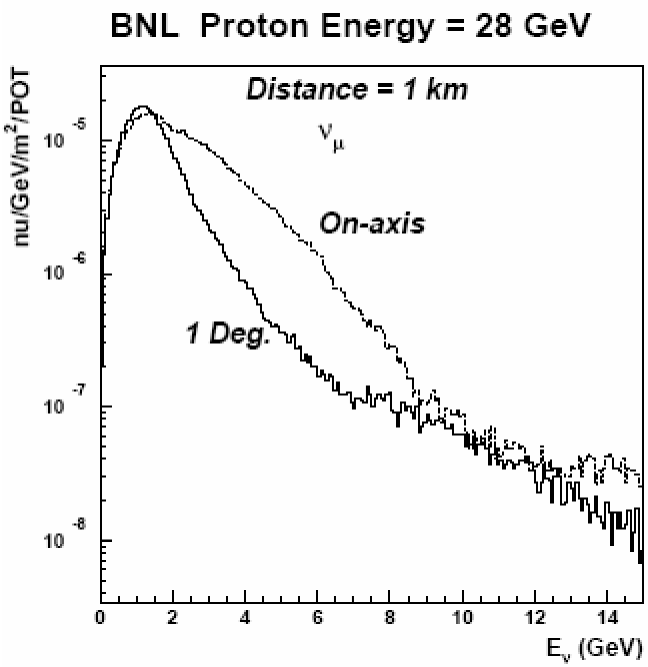
- Conventional pulsed, hadron focussing horns
- Baseline: carbon-carbon target, water + He cooling
- R&D underway with real experiments
- Collaboration with FNAL, JPARC, others

Wide Band Neutrino spectrum from AGS



- Proton energy 28 GeV
- 1 MW total power
- ~10^{14} proton per pulse
- Cycle 2.5 Hz
- Pulse width 2.5 mu-s
- Horn focused beam with graphite target
- 5×10^{-5} ν/m^2/POT @ 1km

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)

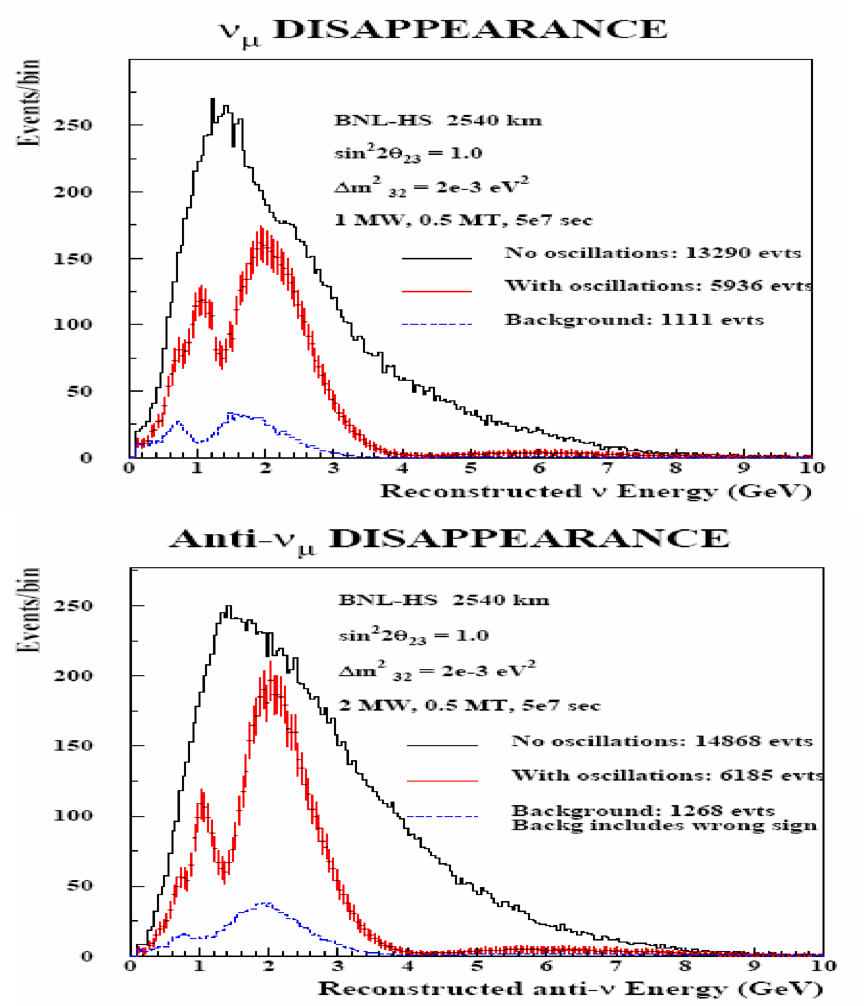
Event Rates Seen at the Far Detector

Channel	ν WB Events	$\bar{\nu}$ WB Events	ν 1° Off Axis Events
CC $\nu_\mu N \rightarrow \mu^- X$	51800	30050	18931
NC $\nu_\mu N \rightarrow \nu_\mu X$	18323	11540	7081
CC $\nu_e N \rightarrow e^- X$	380	106	265
QE $\nu_\mu n \rightarrow \mu^- p$	11767	11868	6462
QE $\nu_e n \rightarrow e^- p$	84	80	69
CC Single π	22053	11872	8445
NC Single π	7741	5057	2996
NC $\nu_\mu O^{16} \rightarrow \nu_\mu O^{16} \pi^0$	574	376	222
CC $\nu_\tau N \rightarrow \tau^- X$	110	40	50

- Non Oscillating event rates seen in a H_2O Č detector at the Homestake Lab assuming:
  - 1 MW source (2 MW for $\bar{\nu}$ running).
  - 500 kT fiducial volume
  - 5×10^7 sec running period with 1.22×10^{22} total 28 GeV protons.
- Backgrounds in the quasi-elastic channel are manageable:
  - ν_e beam contamination estimated at ~1% and can be measured.
  - NC single π^0. Needs to be demonstrated.

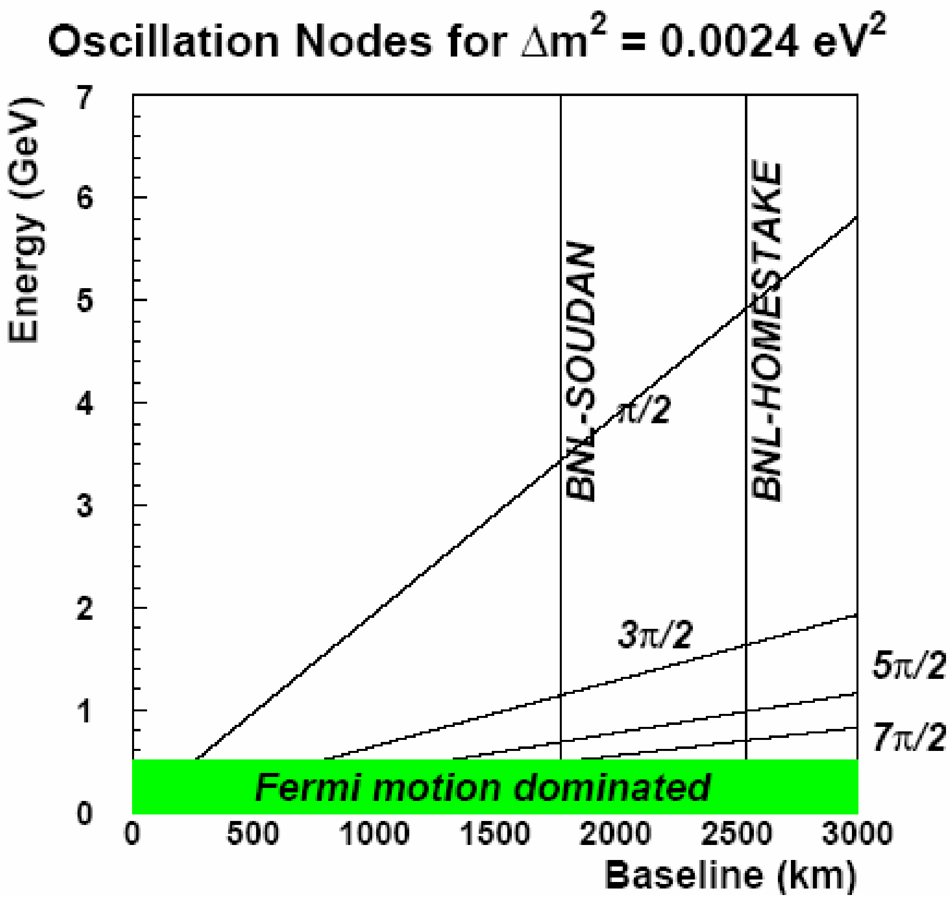
ν Disappearance with a Very Long Baseline

From the Quasi-elastic channel:



- Neutrino oscillations result from the factor $\sin^2(\Delta m_{32}^2 L/4E)$ modulating the ν_μ flux.
- The oscillation period is directly proportional to the distance and inversely proportional to the energy.
- With a very long baseline the actual oscillations are seen in the data as a function of E_ν.
- The multiple-node structure allows Δm_{32}^2 to be precisely measured by a wavelength rather than an amplitude ratio, reducing systematic errors.

Baseline Length and Neutrino Energy



- for a fixed phase angle, e.g. $\pi/2$, the ratio of distance to energy is fixed (see sloped lines in Figure)

  the useful neutrino energy range in a beam derived from a proton production source is restricted:

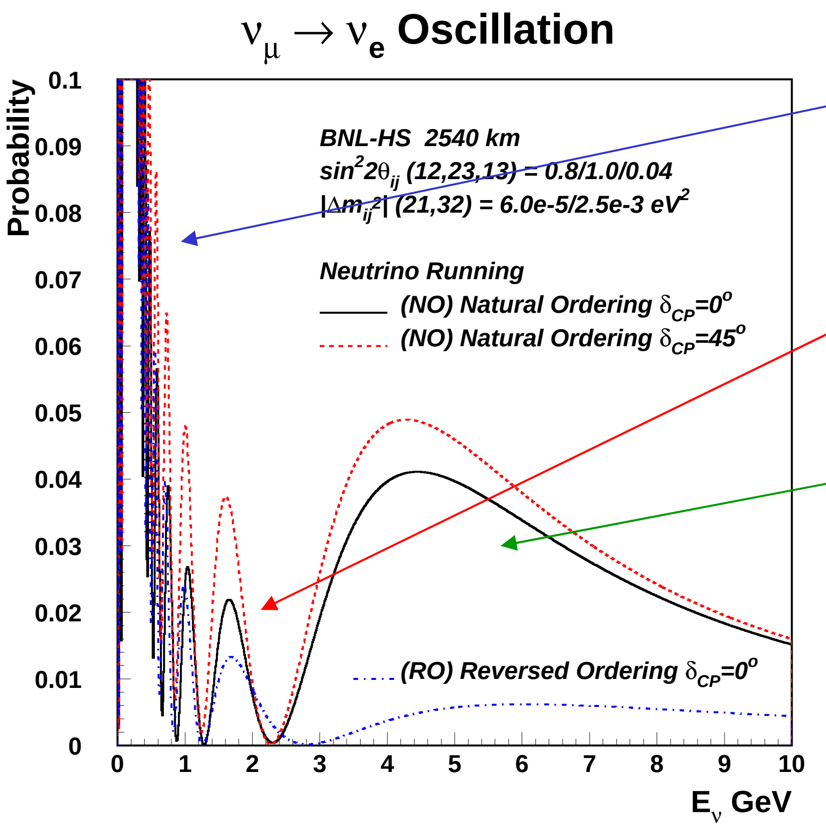
  below ~0.5 GeV by *Fermi mom.* in the target nucleus

  above ~8 GeV by *inelastic ν interactions* background

  these conditions prescribe a needed baseline of greater than *2000 km* from source to detector

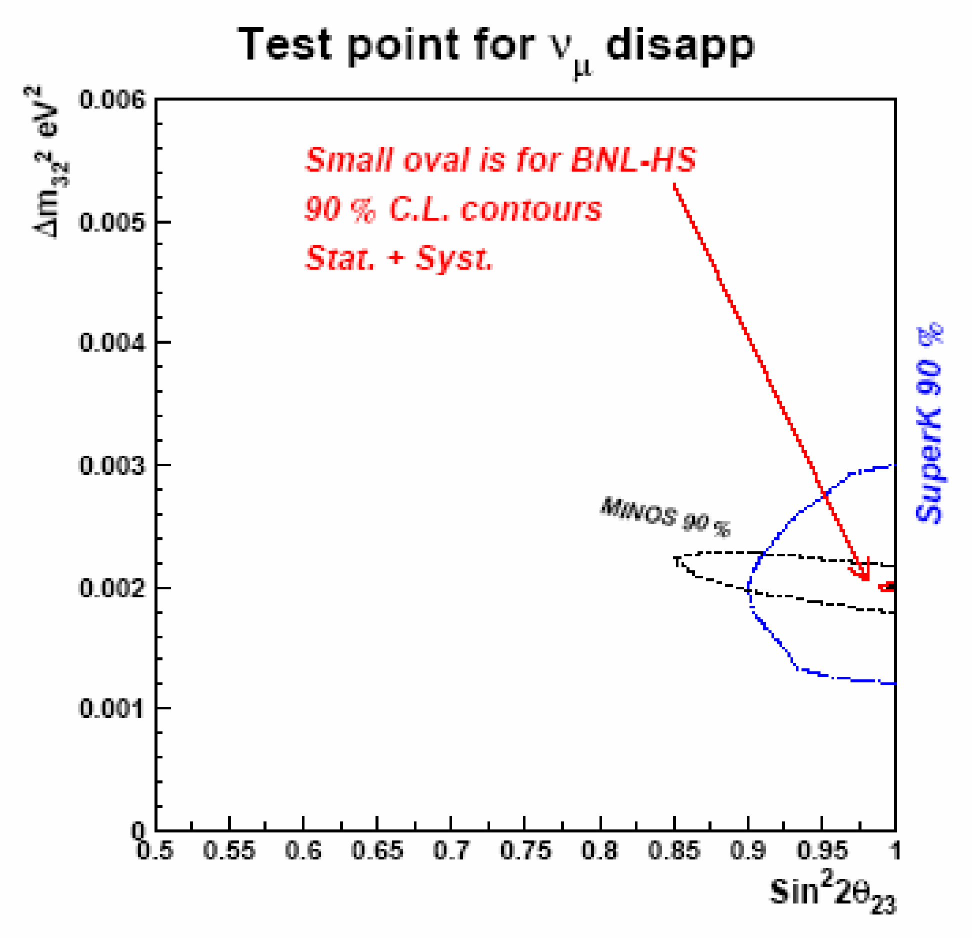
  by serendipity, the distance from BNL to the Homestake Mine in Lead, SD is 2540 km

Probability of $\nu_\mu \rightarrow \nu_e$ through earth



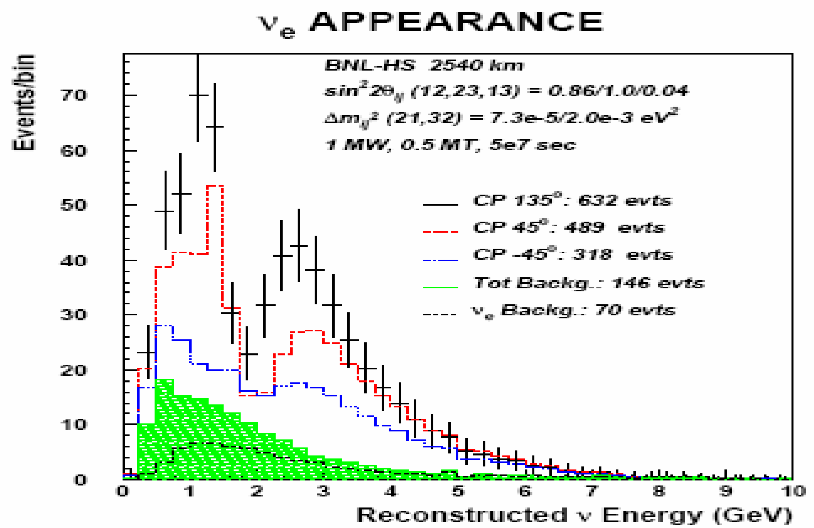
- Below 1.5 GeV: Δm^2_{21} contribution increases at low energy.
- 1-3 GeV : small matter effect, large CP effect.
- Above 3 GeV matter enhancement by about factor of 2.
- Very long baseline separates physics effects.

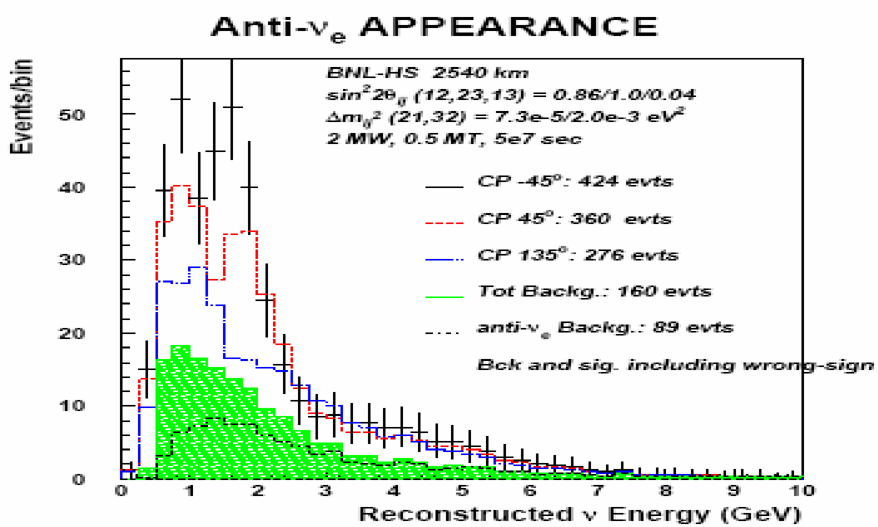
Very Long Baseline Application to Measurement of Δm_{32}^2



- Comparison of the precision of measuring Δm_{32}^2 between the following experiments:
  - BNL Very Long Baseline with 5 years running
  - Expected Minos results with planned 3 year running period.
  - Existing SuperK results.
- Do not expect better precision without a Neutrino Factory.

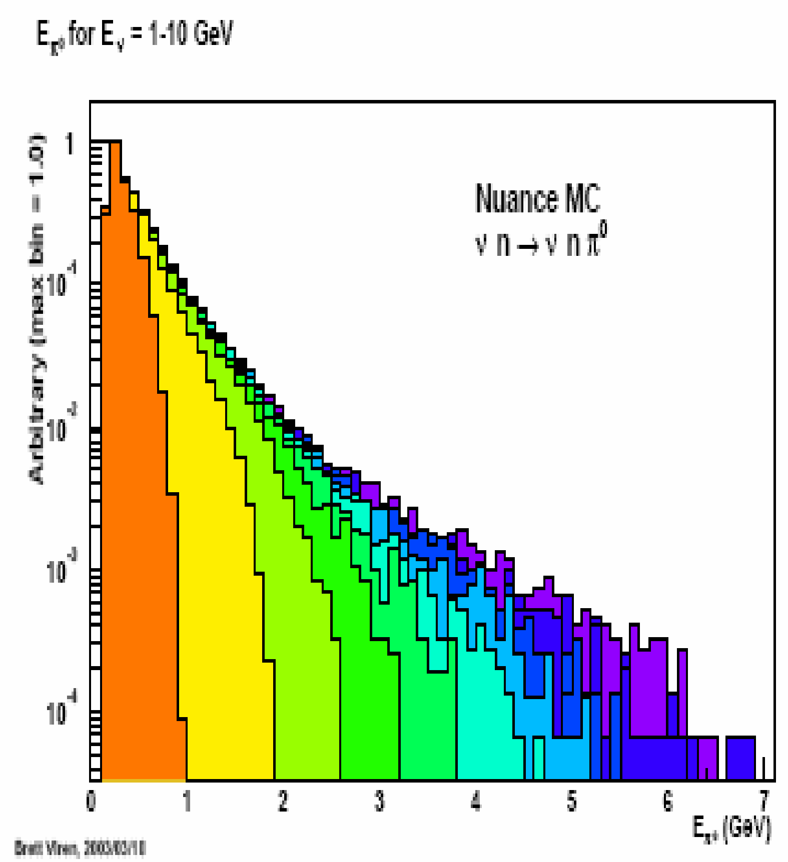
ν_e Appearance Measurements





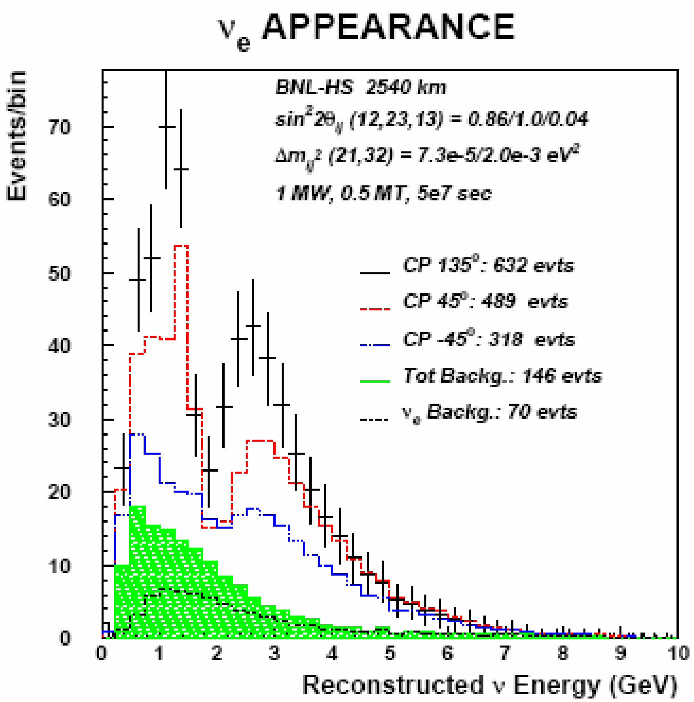
- • a direct measurement of the appearance of $\nu_\mu \rightarrow \nu_e$ is important;
  the VLB method competes well with
  any proposed super beam concept
- for values > 0.01, a measurement of $\sin^2 2\theta_{13}$ can be made (the current experimental limit is 0.12)
- for most of the possible range of $\sin^2 2\theta_{13}$, a good measurement of θ_{13} and the CP-violation parameter
  δ_{CP} can be made by the VLB experimental method

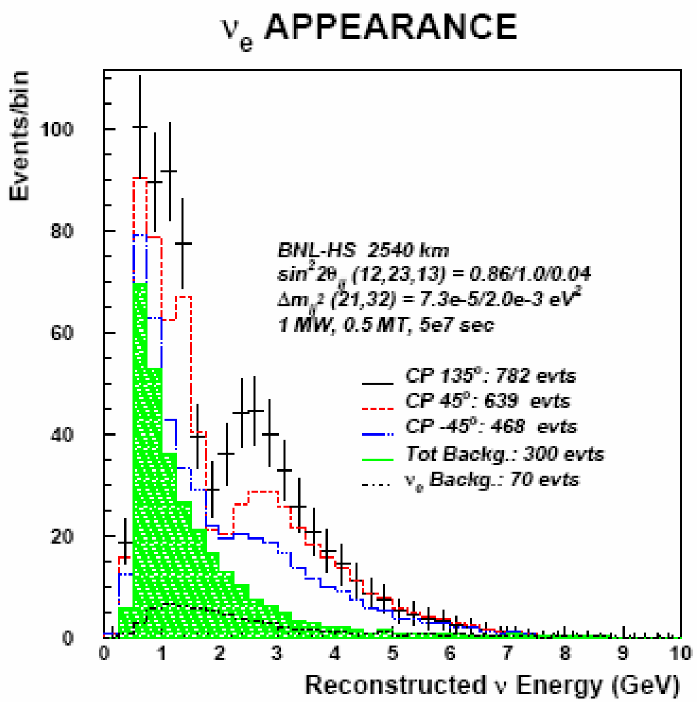
Backgrounds to ν_e Appearance Signal



- ν_e contamination in the beam coming from K_{e3} and μ decays.
  - This is expected to be ~1%.
  - The ν_e contamination will be well measured in the close-in detector.
- NC single π^0 events where the π^0 decay is sufficiently asymmetric that only one γ is seen and it is confused with an electron.
  - The peak in the $\nu N \rightarrow \nu N \pi^0$ distribution is independent of E_ν.
  - The $\nu N \pi^0$ distribution falls 2 orders of magnitude 2.5 GeV
  - The $\nu N \pi^0$ background should be manageable above ~2 GeV.
- We have attempted to evaluate background spectrum from not being able to resolve photons with less than 20° separation.
  - Large effect at lower energies
  - Some effect on disappearance
  - Some effect on appearance with E>2.5 GeV.

Worse background spectra





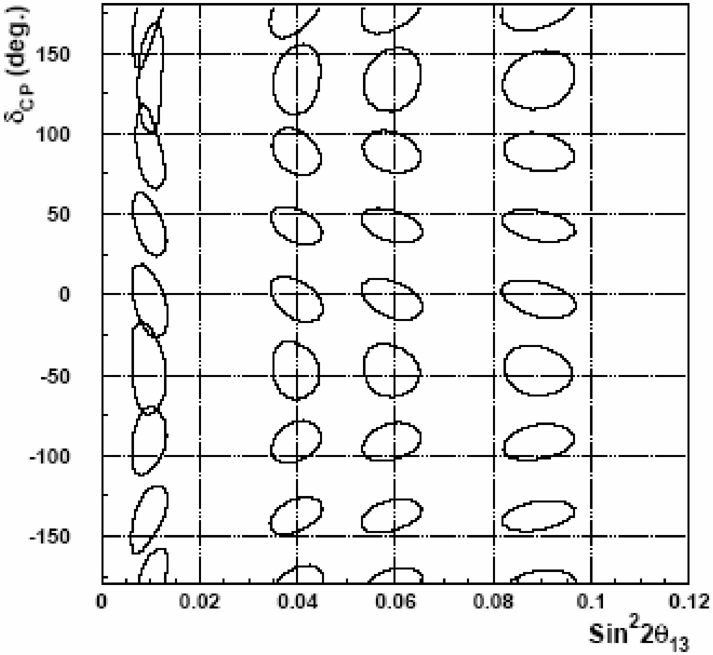
Left: strong rejection Right: weak rejection

Background is confined to lower node.

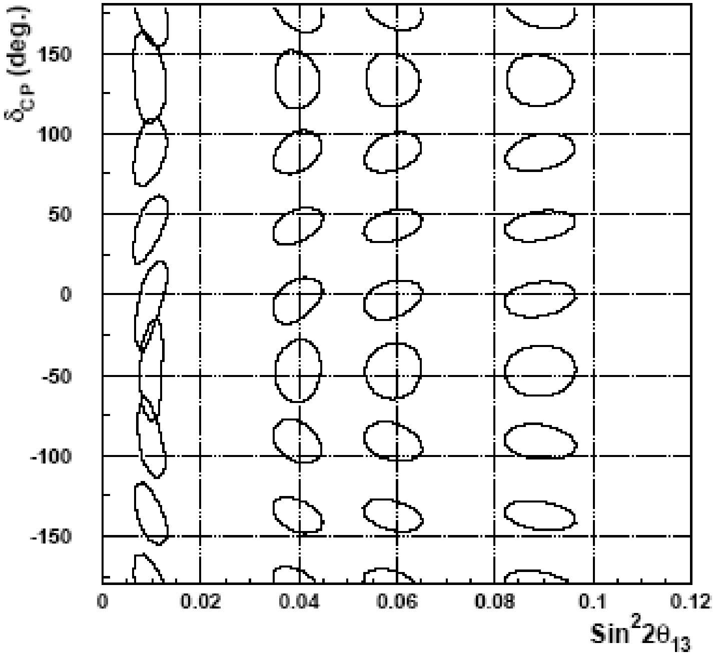
CP-violation Parameter

CP measurement after nu and anti-nu

Regular hierarchy νυ and Antiνυ running



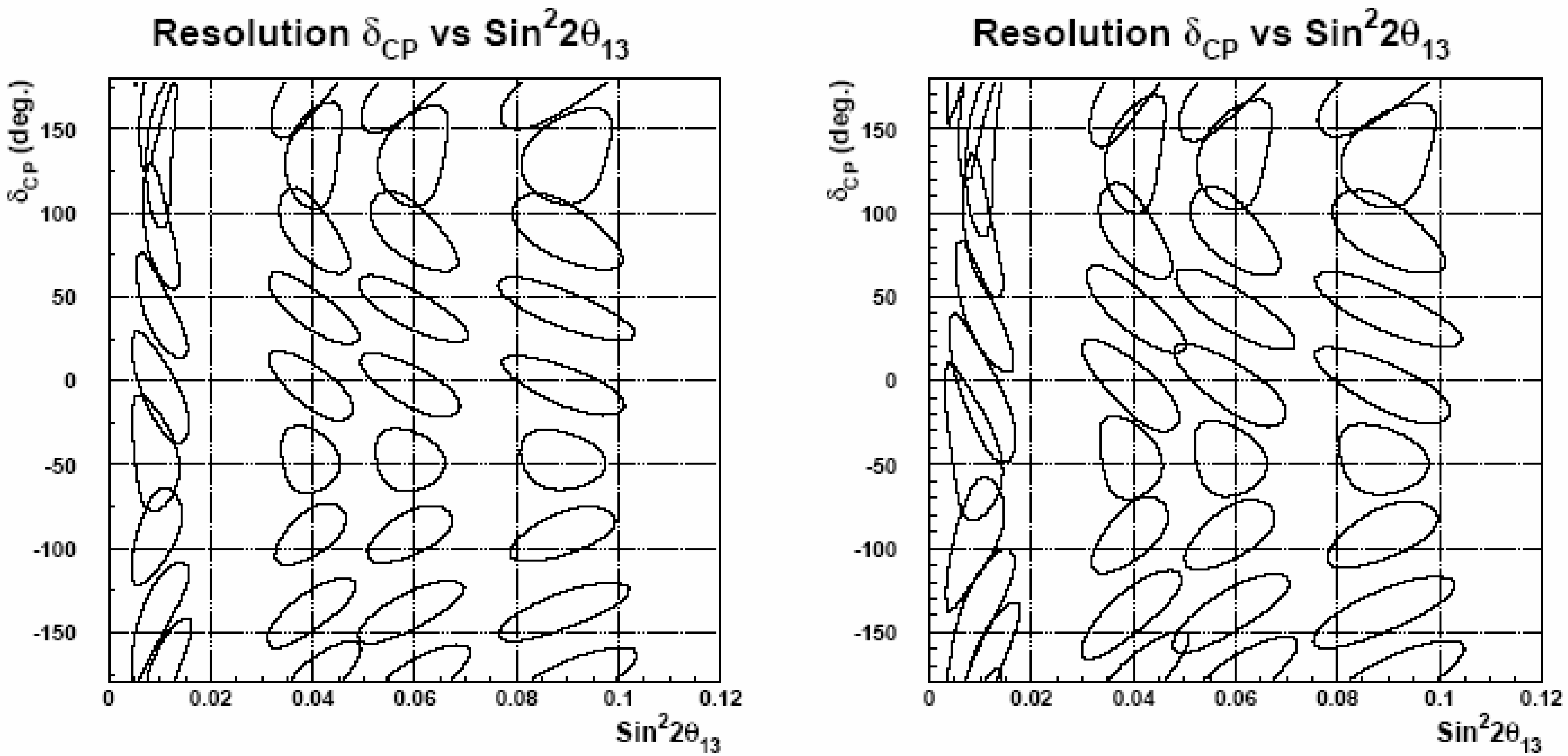
Reversed hierarchy νυ and Antiνυ running



Left: Regular mass hierarchy Right: reversed mass hierarchy.

No $\delta_{CP}/\sin^2 2\theta_{13}$ degeneracy, only the θ_{23} ambiguity is left.

Worse background CP-measurement



Left: strong rejection

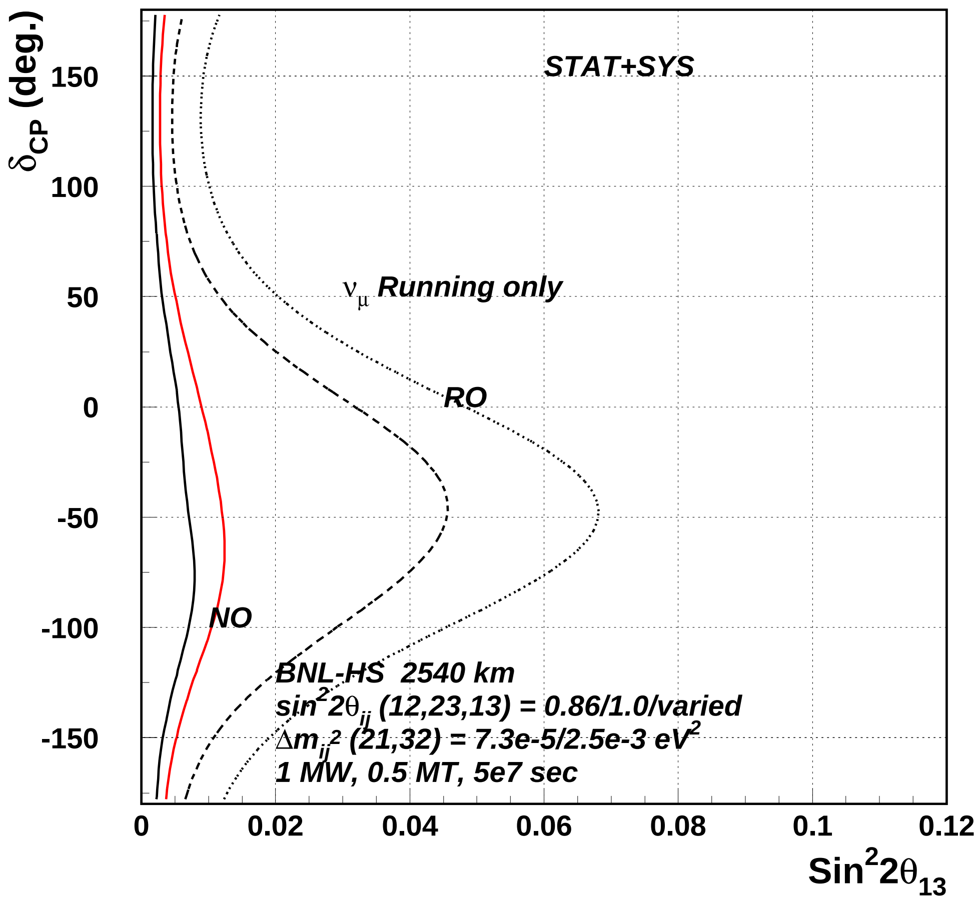
Right: weak rejection

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

Could one run off-axis to do better ? $\longrightarrow$

Possible limits on $\sin^2 2\theta_{13}$ versus δ_{CP}

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

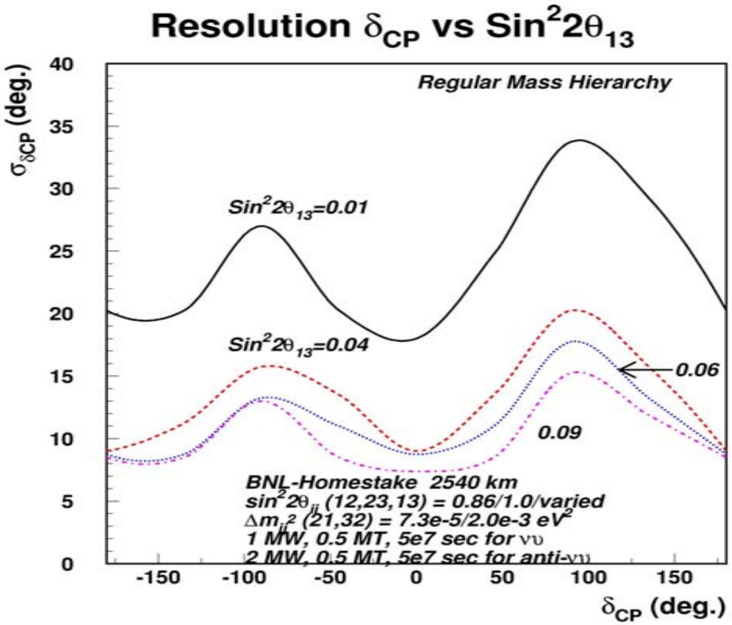


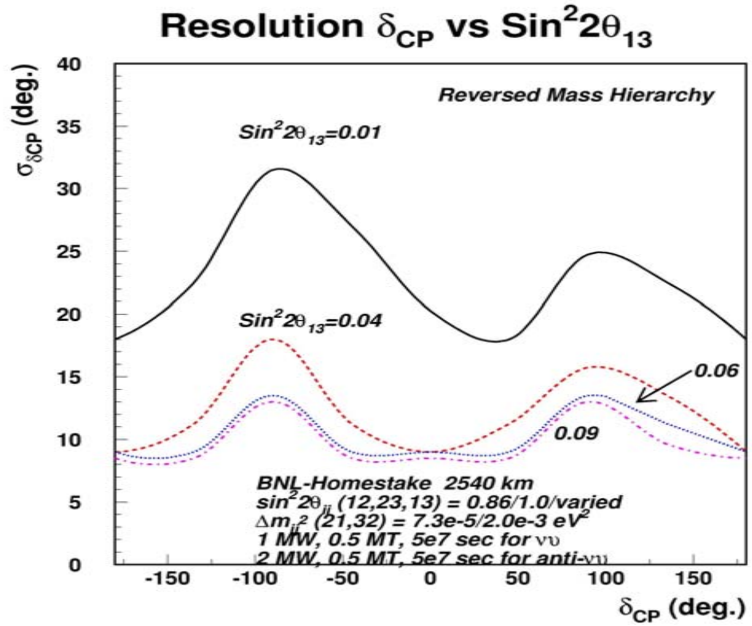
- **For normal mass ordering limit on $\sin^2 2\theta_{13}$ will be 0.005 for no CP**

Any experiment with horn focused beam is unlikely to do better.

- **If reversed mass ordering then need to run antineutrinos**

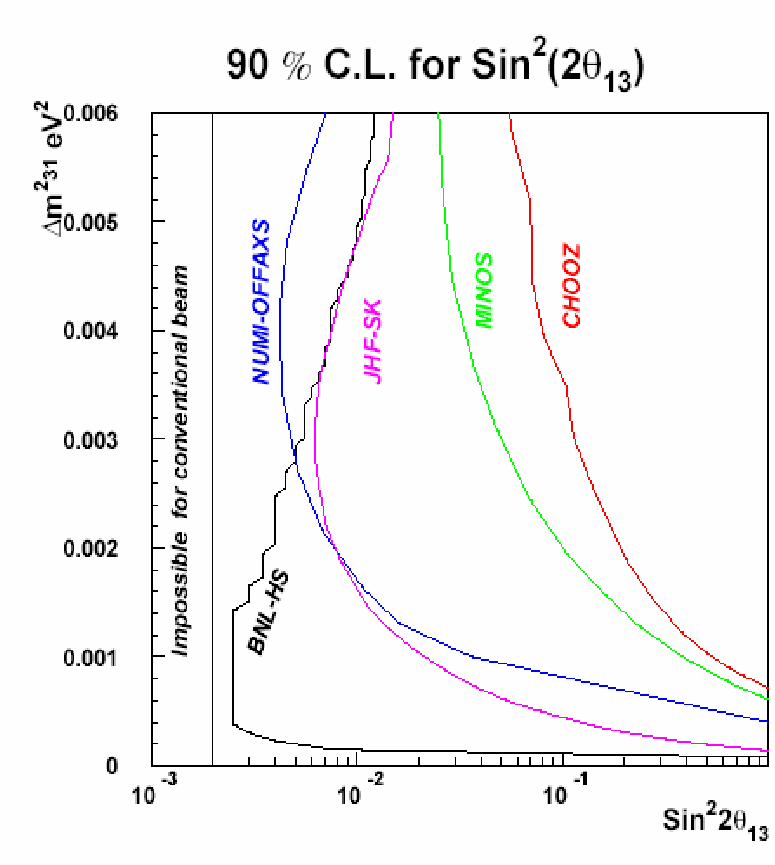
Resolution on CP phase





- Resolution gets better rapidly as Δm_{21}^2 becomes larger.
- Resolution of 20 deg as long as signal sufficiently above background.

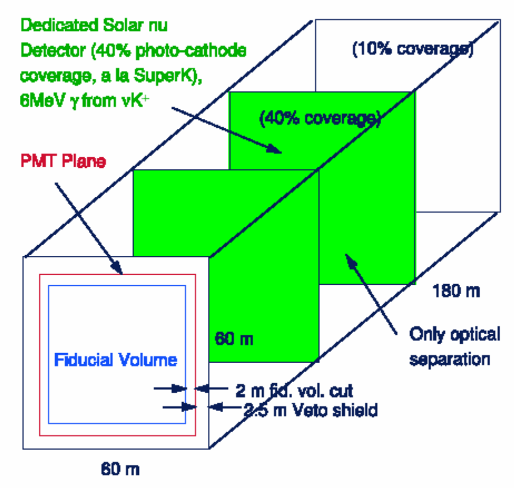
Sensitivity to $\mathrm{Sin}^2 2\theta_{13}$



- Figure shows expected 90% CL limits for $\sin^2 2\theta_{13}$ vs. Δm_{31} for various experiments.
- The BNL VLB will produce the best measurement of $\sin^2 2\theta_{13}$ before a Neutrino Factory.

Detector Choices

- The baseline choice for the far detector is H_2O Cherenkov similar to UNO.
  - This was done merely to permit calculations for our study with known parameters.
  - There are cost concerns for a 0.5 megaton detector. H_2O $\check{C}$ tends to be a cost effective approach to large detectors.
  - We need software improvements to increase π^0 rejection. (C. Yanagisawa, SUNY-SB)
- Possible focusing photo-detectors to give photon direction information.
  - Aqua-Rich type technology.
- Liquid Argon may be promising.
  - Very good resolution.
  - Very good sensitivity to e, γ should reduce NC π^0 background.
    - May be able to use 100kT because it is not restricted to quasi-elastic events.
  - It may not be as expensive as we thought.
    - Large Cryo liquid CH_4 commercially available.
    - Argon is cheap.

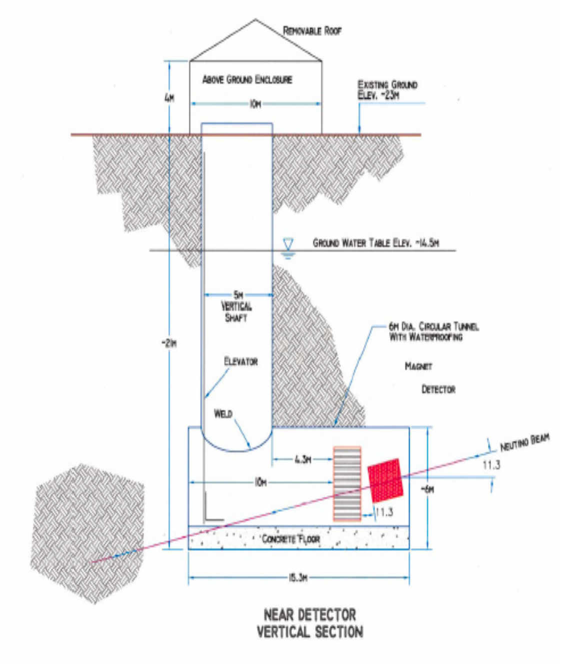


•It should be the community that designs the detector, not the laboratory.

•Your input (and work) is appreciated.

The Near Detector

- The close-in detector will be necessary to determine the composition of the beam.
  - It will see ~10^9 events during the running period.
    - Structure function physics.
  - It will provide a precise measurement of ν_e contamination in the beam.
    - It would be desirable to have a magnetic field to separate antineutrinos.
  - It would be desirable to have the similar technology as the far detector to cancel systematic effects such as pion reabsorption in the nucleus.
- The close-in detector will be located 285 m from the target.
  - The location is dictated be the steep beam incline to reach Homestake.
  - The neutrino source will not be a point source.
  - This is similar to the situation for the close detector at J-Parc.
  - Techniques to determine the far detector flux will have to be developed.



How Much Will This Cost?

AGS Upgrade & SC Linac	$156.8M	(C-AD staff, recent SNS and BNL experience)
Neutrino Beam Cost	61.7M	(C-AD/Phys. Dept. staff, recent BNL experience)
EDIA, Conting., Proj. G&A	150.0M	(BNL project experience and current rates)
Total Estimated Cost (TEC)	**$368.5M**	**(fully burdened)**
3 yrs R&D ($1M, 3M, 5M)	9.0M	(estimated *accelerator* R&D in FY04, 05, 06)
Pre-ops, starting in FY09	12.0M	(this would accomplish the needed pre-ops)
Total Project Cost (TPC)	**$389.5M**	**(fully burdened)**

These numbers are being revised

These estimates are provided in FY 2003 dollars and are for the *Accelerator and Super Neutrino Beam elements only*. These costs *do not* include the detector.

The basis of estimate comprises current costs that C-AD and BNL engineers and physicists derive from recent and ongoing BNL projects. The level of EDIA is scaled from recent BNL projects in HENP areas of DOE.

When Can We Have It?

- **The *technology* (not budget) *limited schedule* would comprise:**
  - **a 3-year R&D period (FY04-06)**
  - **a 5-year construction period (FY07-11)**
- **the *critical path* would definitely be the R&D:**
  - **to develop the *superconducting RF cavities***
  - **To develop the *RF power system*.**
  - **All the other systems would require less R&D time.**
- **There are *no novel or unproven technologies* in the accelerator and neutrino beam concept.**

Conclusions

- measurement of the *complete set of neutrino mass and mixing parameters* is very compelling for the advance of particle physics
- the *Very Long Baseline* method, utilizing a *1 MW Super Neutrino Beam* from BNL's AGS, coupled with a *half-megaton water Cerenkov detector* in the Homestake Mine in Lead, SD, offers a uniquely effective plan
- the half-megaton detector was not detailed in this presentation but we note that the UNO detector has all the properties needed for the VLB neutrino program and offers important and compelling physics beyond the neutrino oscillations work.

neutrino only running, low sensitivity to systematics,
high sensitivity to mass ordering, broad spectrum of physics.
We can decide at a later point to run anti-neutrinos to increase precision.

This plan received high marks from HEPAP facilities committee in February.

Backup Slides

There is no time to show these slides unless specific questions are asked.

- 1 degree off axis beam
- Breaking θ_{23} Degeneracy
- Liquid Ar at 1770 km

Separating Multiple Appearance Effects

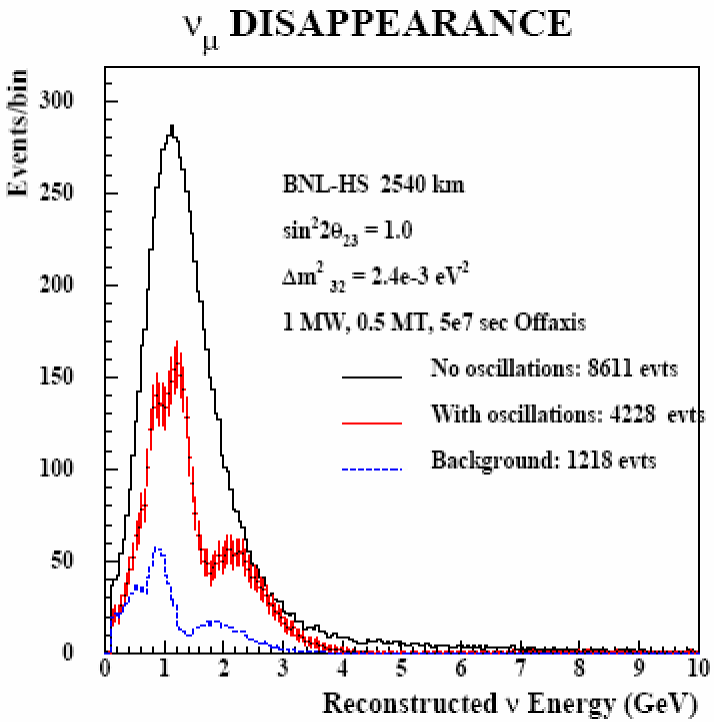
Many effects, but in different energy ranges:

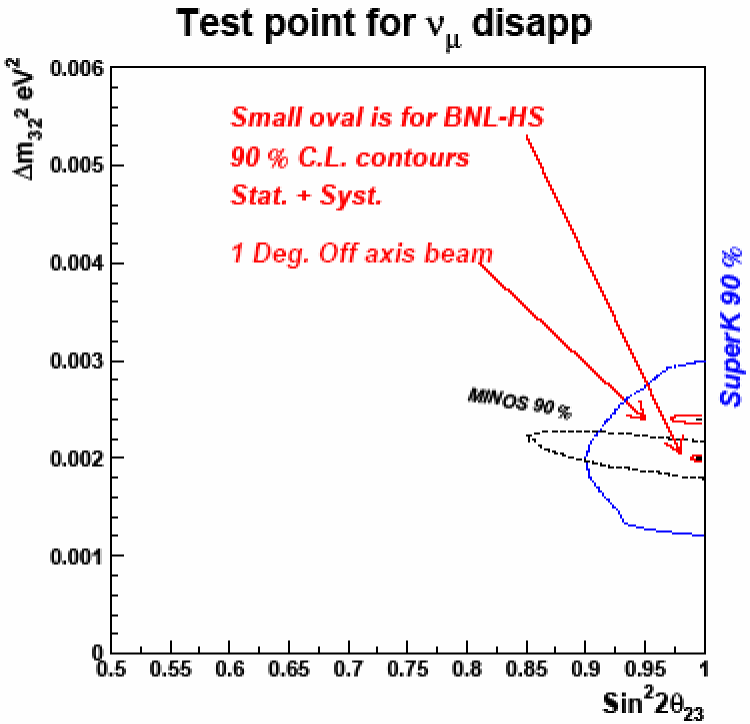
	energy (GeV)	$\sin^2 2\theta_{13}$ > 0	Δm^2_{32} $(> 0, < 0)$	$\delta_{CP} =$ $(\frac{\pi}{4}, -\frac{\pi}{4})$	θ_{23} $(< \frac{\pi}{4}, > \frac{\pi}{4})$
ν	0–1.2	$\uparrow$	$-, -$	$\uparrow, \downarrow$	$\Uparrow, \Downarrow$
	1.2–2.2	$\uparrow$	$-, -$	$\Uparrow, \Downarrow$	$\downarrow, \uparrow$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

(M.Diwan)

Brett Viren <bv@bnl.gov> UNO Collaboration Meeting 4/04

Disappearance with 1° Off-Axis Beam

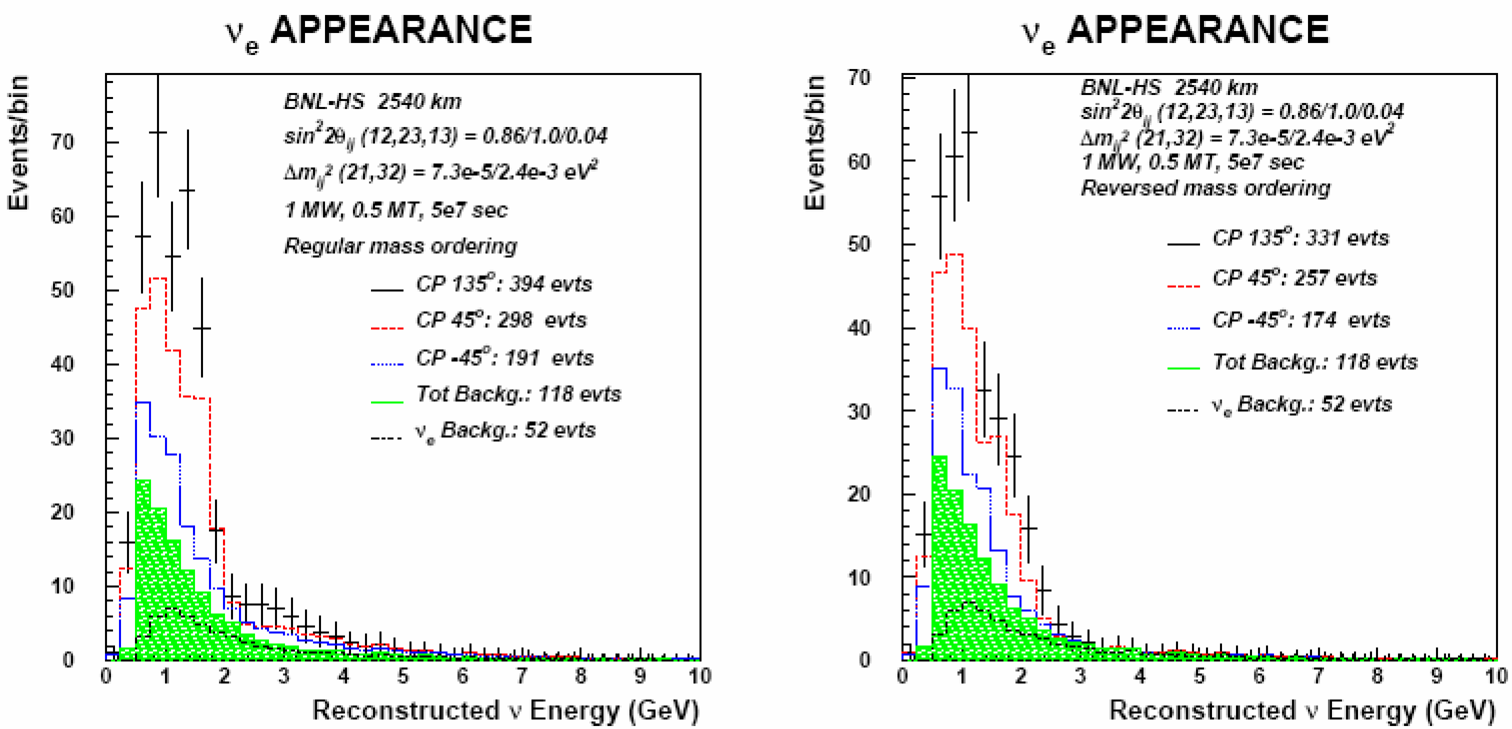




Lose one node, Resolution of $\sin^2 2\theta_{23}$ is reduced.

About factor of 3 worse compared to wide-band running.

Appearance with 1° Off-Axis Beam

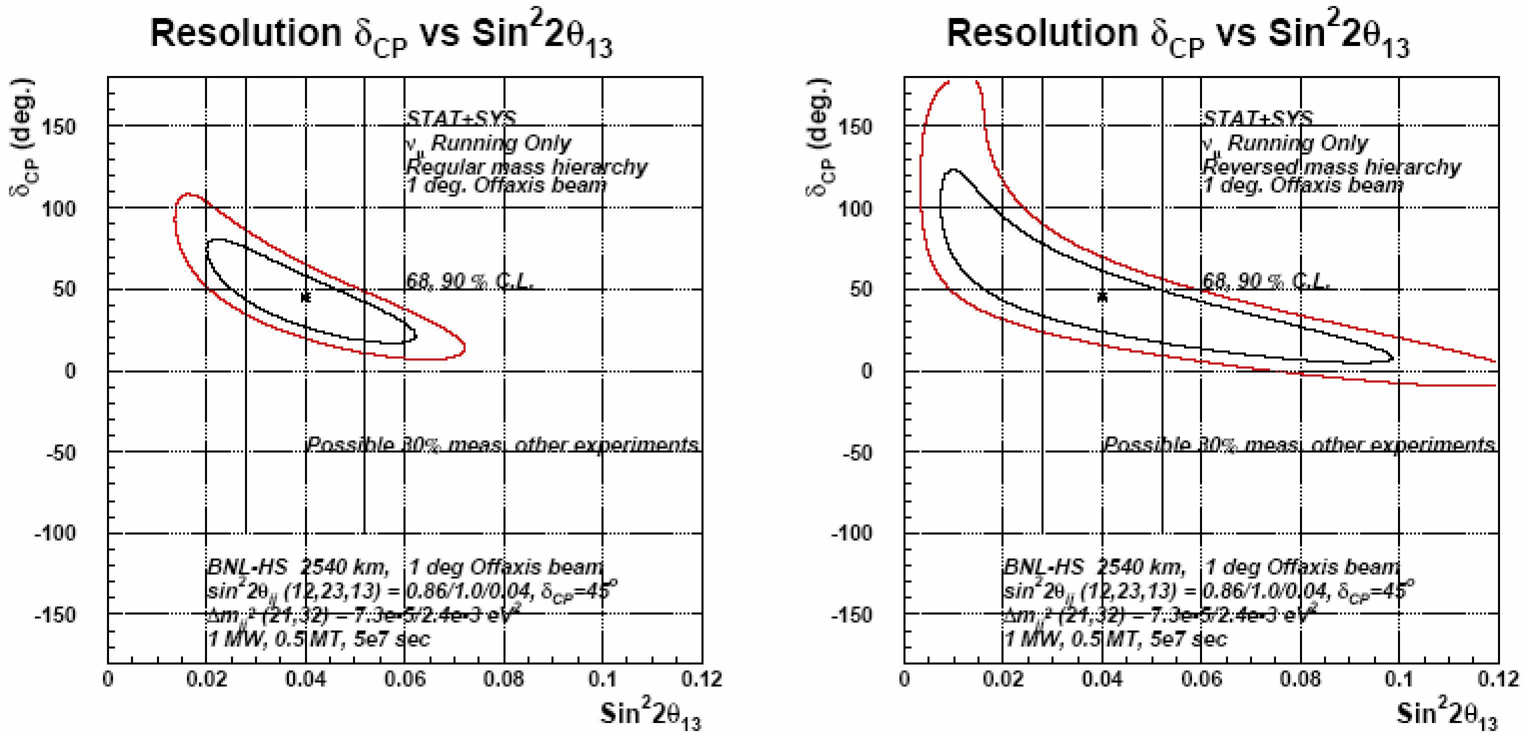


Left: normal mass hierarchy Right: reversed mass hierarchy

With weak background rejection reduce NC background by $\sim 3.5\times$ with 1° beam. Mass ordering discrimination worse.

Milind Diwan <diwan@bnl.gov> BNL/UCLA/APS workshop, 3/04

Measuring δ_{CP} with 1° Off-Axis Beam



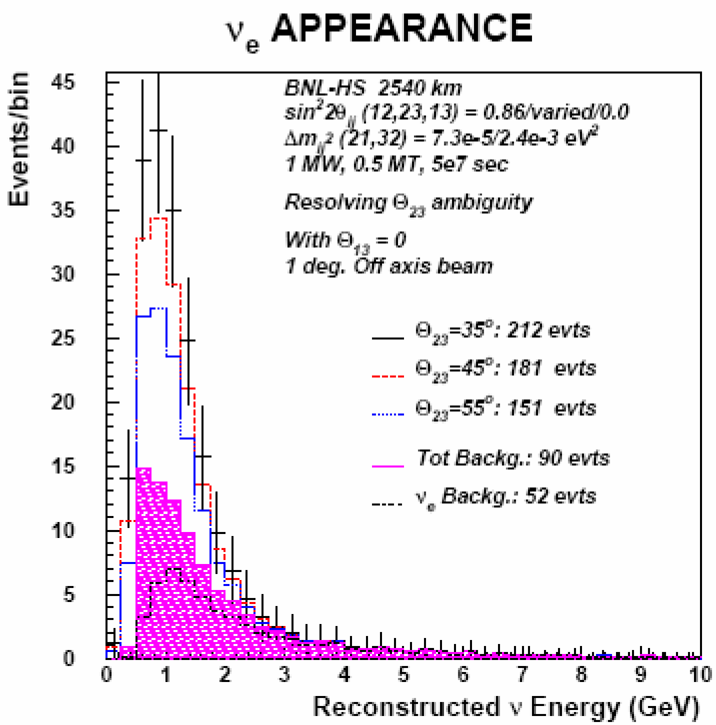
Left: normal mass hierarchy Right: reversed mass hierarchy

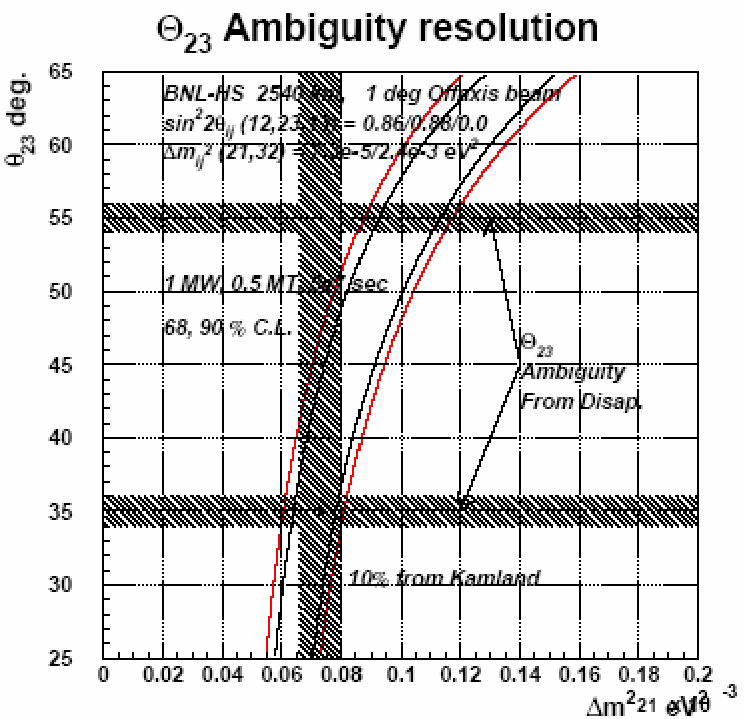
Large CP vs. $\sin^2 2\theta_{13}$ correlation. Needs separate measurement of $\sin^2 2\theta_{13}$.

Milind Diwan <diwan@bnl.gov> BNL/UCLA/APS workshop, 3/04

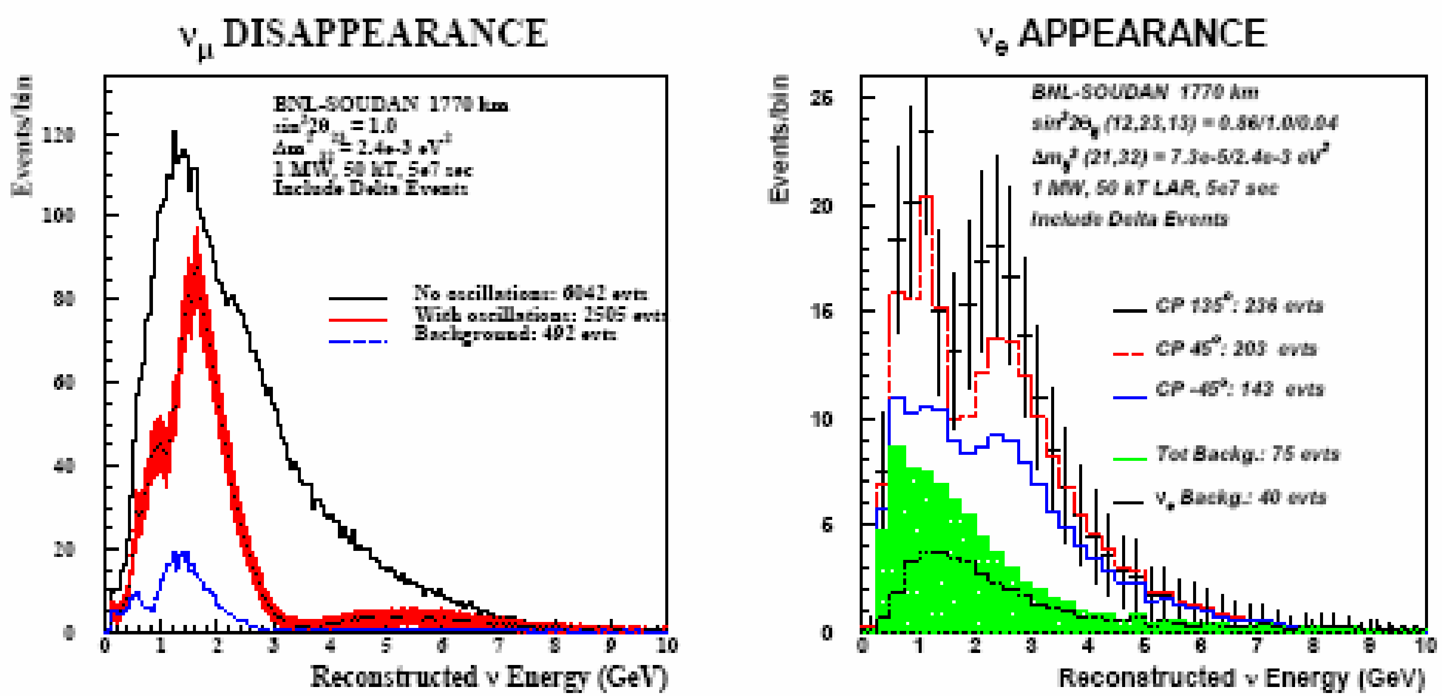
Break θ_{23} Degeneracy if Non-Maximal Mixing

Asside: with strong background rejection **and** off-axis beam **and** help from KamLAND (for δm^2_{21}), can measure θ_{23} (not just $\sin^2 2\theta_{23}$), thus breaking $\theta_{23} \to \pi/2 - \theta_{23}$ ambiguity.





With a Liquid Argon Detector at 1770 km

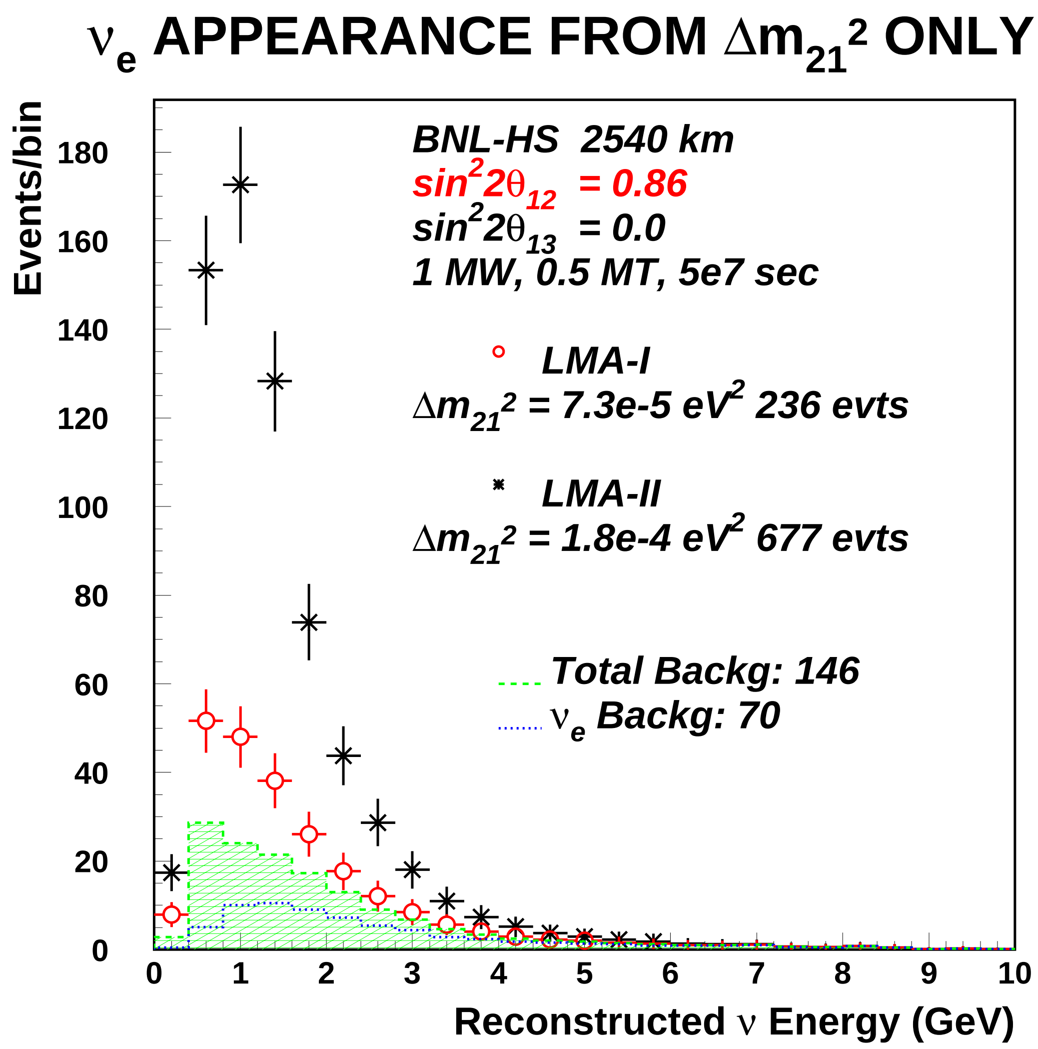


Only 2 nodes visible. Increase yield with delta production events.

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

Reduces resolution below 2 GeV.

ν_e Appearance Measurements if *no CP Violation*



- even if $\sin^2 2\theta_{13} = 0$, the current best-fit value of $\Delta m_{21}^2 = 7.3\times10^{-5}$ induces a ν_e appearance signal
- the size of the ν_e appearance signal above background depends on the value of Δm_{21}^2; the figure left indicates the range of possible measured values for the ν_e yields above background for various assumptions of the final value of Δm_{21}^2