The FNAL-BNL joint study on Long Baseline Neutrinos

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BROOKHAVEN NATIONAL LABORATORY

NUSAG Charge

Address APS Study's recommendation for a next generation neutrino beam and detector configurations

U.S. Department of Energy
and the
National Science Foundation

March 3, 2006

Professor Eugene Beier
Co-Chair, NuSAG
University of Pennsylvania
209 South 33rd Street
Philadelphia, PA 19104

Professor Peter Meyers
Co-Chair, NuSAG
Princeton University
306 Jadwin Hall
Princeton, NJ 08544

Dear Professors Beier and Meyers:

We would like to thank you and the Neutrino Scientific Assessment Group (NuSAG) for your timely and thoughtful responses to the initial questions that were posed to you, concerning neutrinoless double beta decay, reactor experiments and accelerator-based experiments to determine fundamental neutrino properties. They have already been very useful and will help us put together a strong US program in neutrino physics.

We would now like your group to address the APS Study's recommendation for a next-generation neutrino beam and detector configurations. Assuming a megawatt class proton accelerator as a neutrino source, please answer the following questions for accelerator-detector configurations including those needed for a multi-phase off-axis program and a very-long-baseline broad-band program. This assessment will be used as one of the key elements to guide the direction and timeline of such a possible next generation neutrino beam facility.

In your assessment, NuSAG should look at the scientific potential of the facility, the timeliness of its scientific output, and its place in the broad international context. Specifically:

- **Scientific potential:** What are the important physics questions that can be addressed at the envisioned neutrino beam facility?
- **Associated detector options:** What are the associated detector options which might be needed to fully realize the envisioned physics potentials? What are the rough cost ranges for these detector options?
- **Optimal timeline:** What would be the optimal construction and operation timeline for each accelerator-detector configuration, taking the international context into account?
- **Other scientific considerations:** What other scientific considerations, such as results from other neutrino experiments, will be important in order to optimally determine the design parameters? What would be additional important physics questions that can be addressed in the same detector(s)?

The DOE and the NSF would like a preliminary draft of your report by December 2006, with a final version by February 2007.

- **What are the physics questions to be addressed?**
- **What are the detector options needed to realize the physics? Rough Costs?**
- **What is the optimal construction and operation timeline?**
- **What would be additional important physics questions that can be addressed by the same detector?**

FNAL-BNL Joint Study

The Chairs: Sally Dawson (BNL) and Hugh Montgomery (FNAL).

Advisory Committee: Franco Cervelli (INFN) Milind Diwan (BNL); co-leader, Maury Goodman (ANL), Bonnie Fleming (Yale), Karsten Heeger (LBL), Takaaki Kajita (Tokyo), Josh Klein (Texas), Steve Parke (FNAL), Gina Rameika (FNAL); co-leader

The Charge: Compare the neutrino oscillation physics potential of (report to NuSAG by Oct. 2006):

1) A broad-band proposal using either an upgraded beam of around 1 MW from the current Fermilab accelerator complex or a future Fermilab Proton Driver (PD) neutrino beam aimed at a DUSEL-based detector. Compare these results with those previously obtained for the BNL VLBNO program.

2) Off-Axis next generation options using a 1-2 MW neutrino beam from Fermilab and a liquid argon detector at either DUSEL or as a second detector for the NOVA experiment.

Status: Documents at http://nwg.phy.bnl.gov/~diwan/nwg/fnal-bnl/

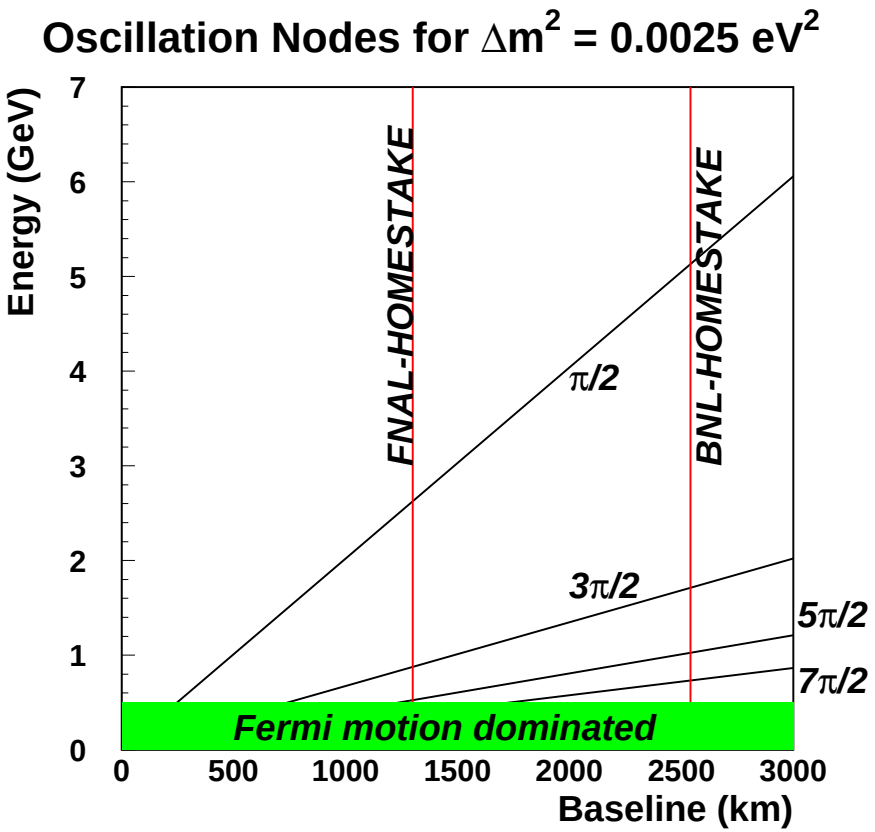
Experimental goals

Goals of the FNAL-BNL study:

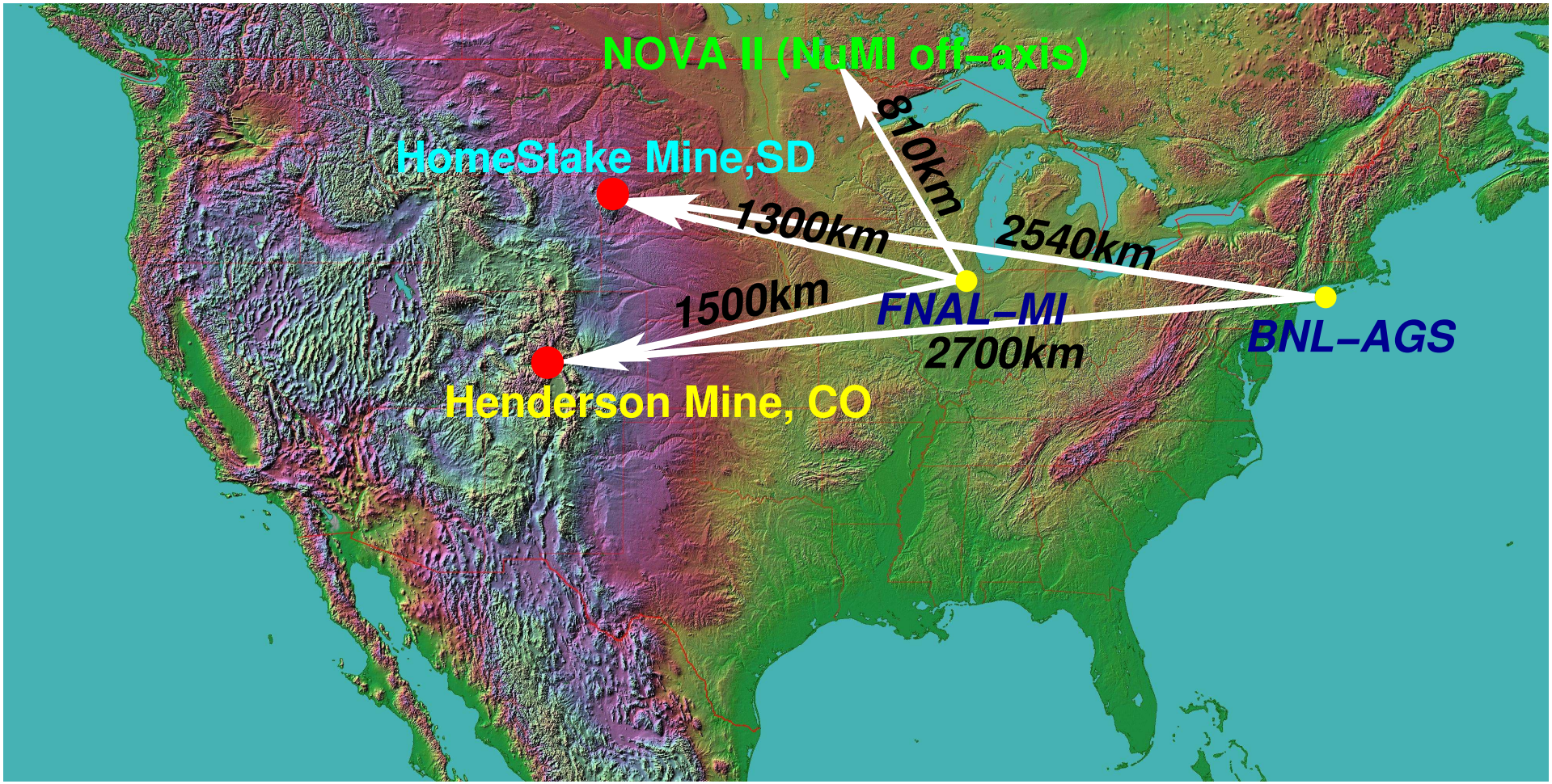
Verify oscillation behaviour by observing multiple nodes. Multiple nodes = higher precision

Longer flight paths = larger matter effects for resolving mass hierarchy and increasing sensitivity to new physics.

Better S/B for CP violation (δ_{cp}) measurements. Flux $\sim L^{-2}$, CP asymmetry $\sim L \Rightarrow$ sensitivity to CPV is independent of L (hep-ph/0108181).



EXPERIMENTAL SPECIFICATIONS



Beam Options/Baselines

The following beam options and baselines are considered:

Off axis beams using the existing 120 GeV NuMI beamline at FNAL to sites at 810km.

A 28 GeV on-axis Wide-Band Beam (WBB) beam from the BNL AGS to DUSEL sites at 2540 and 2700 km.

A newly designed on-axis ≤ 120 GeV Wide Band Low Energy (WBLE) beam and beamline from the FNAL MI to DUSEL sites at 1300km and 1500km.

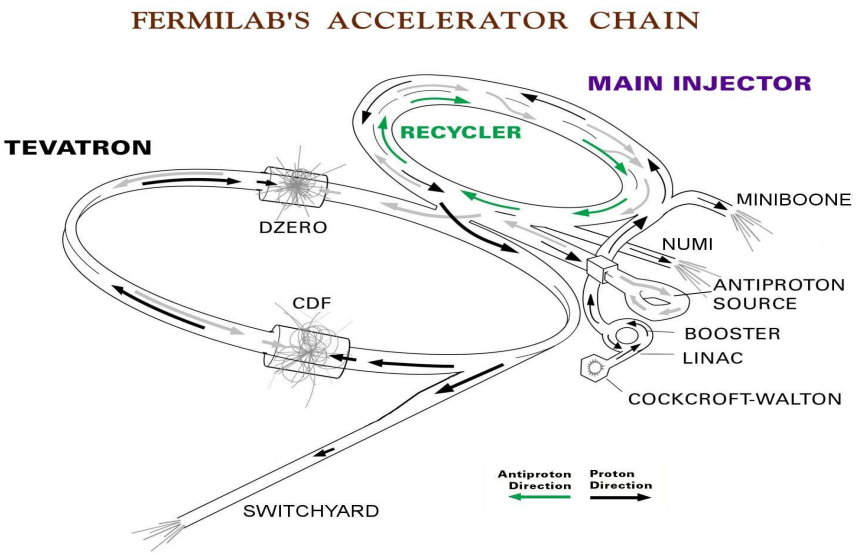
For the current study we will concentrate on beam options from FNAL

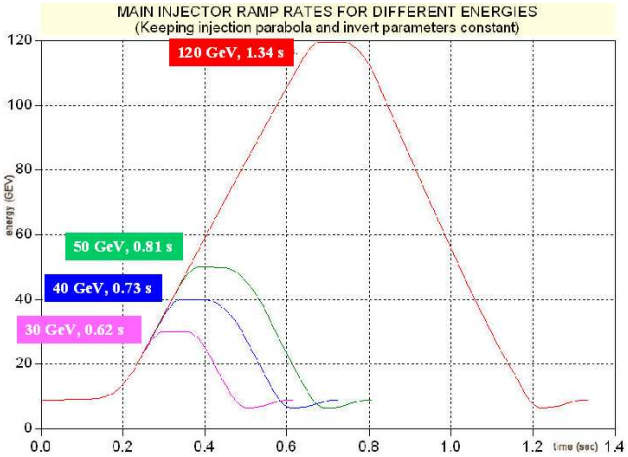
FNAL Beam Specs: E & Power

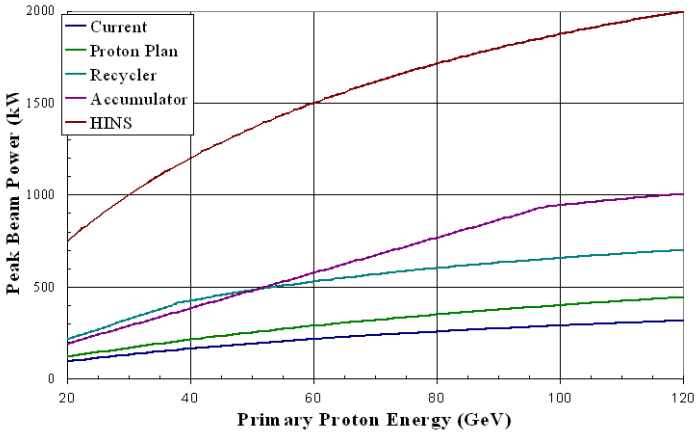
Incremental upgrades possible

(no proton driver):

Use the existing recycler and anti-proton accumulator to store protons from the 8 GeV 15 Hz Booster during the MI cycle then inject to MI bringing intensity up to $6 \times 10^{13} p/$spill.



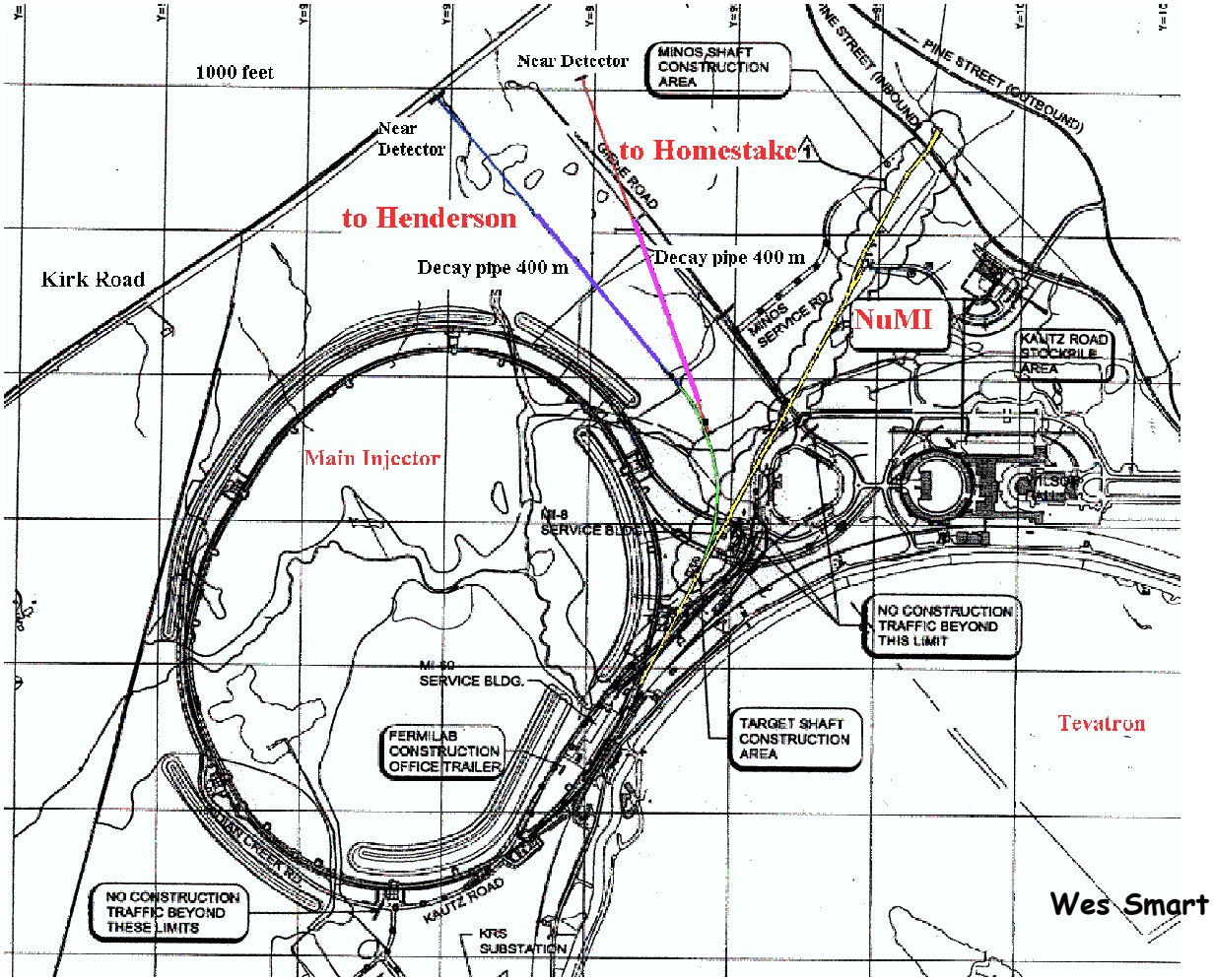




"Fermilab Proton Projections for Long-Baseline Neutrino Beams," Robert Zwaska for the SNuMI planning group, July 17, 2006. FNAL-Beams-DOC-2393

DUSEL Beamline Siting at FNAL

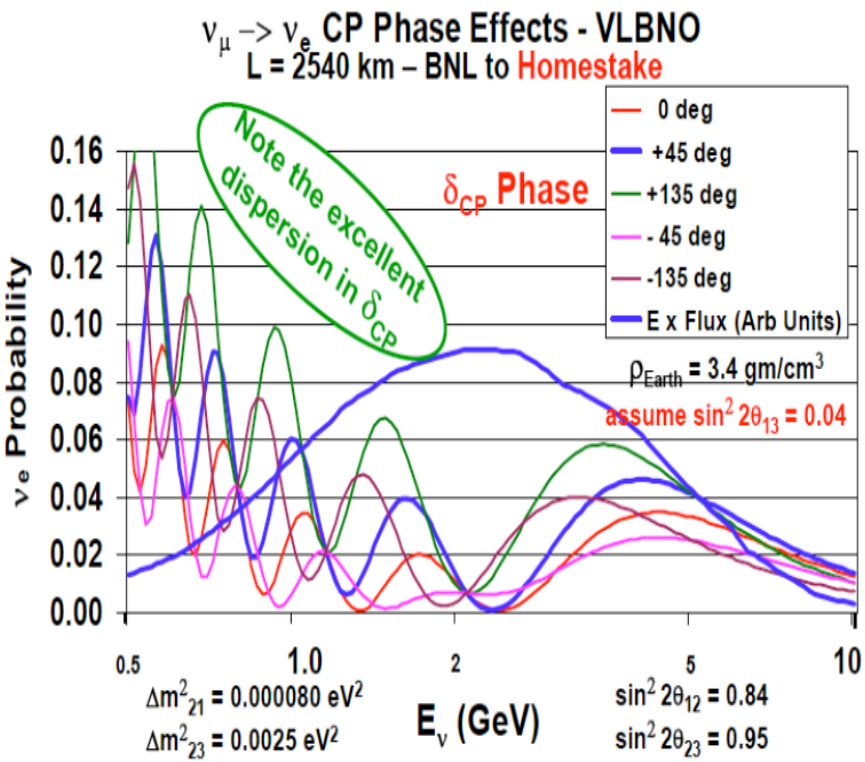
Greg Bock, Dixon Bogert, Wes Smart (FNAL)



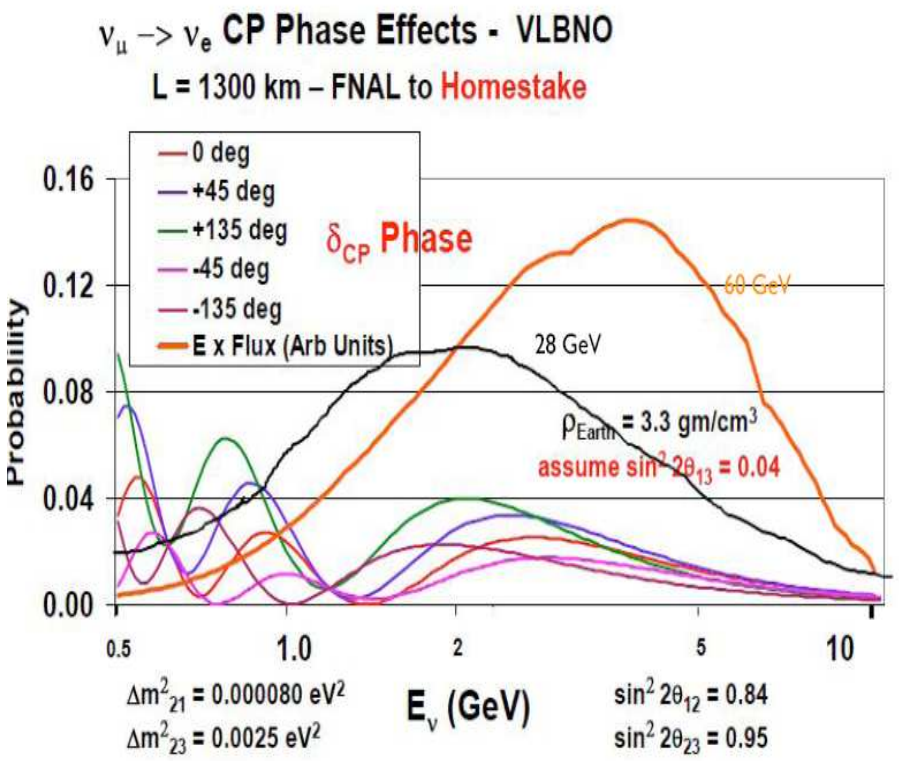
Beamlines to DUSEL can accomodate a decay tunnel with $L \leq 400$m on-site

WBLE Beam Design Requirements

The design specifications of a new WBLE beam based at the Fermilab MI are driven by the physics of $\nu_\mu \rightarrow \nu_e$ oscillations.



L = 2500 km



L = 1300 km

WBLE Beam Specs $L = 1300$ km

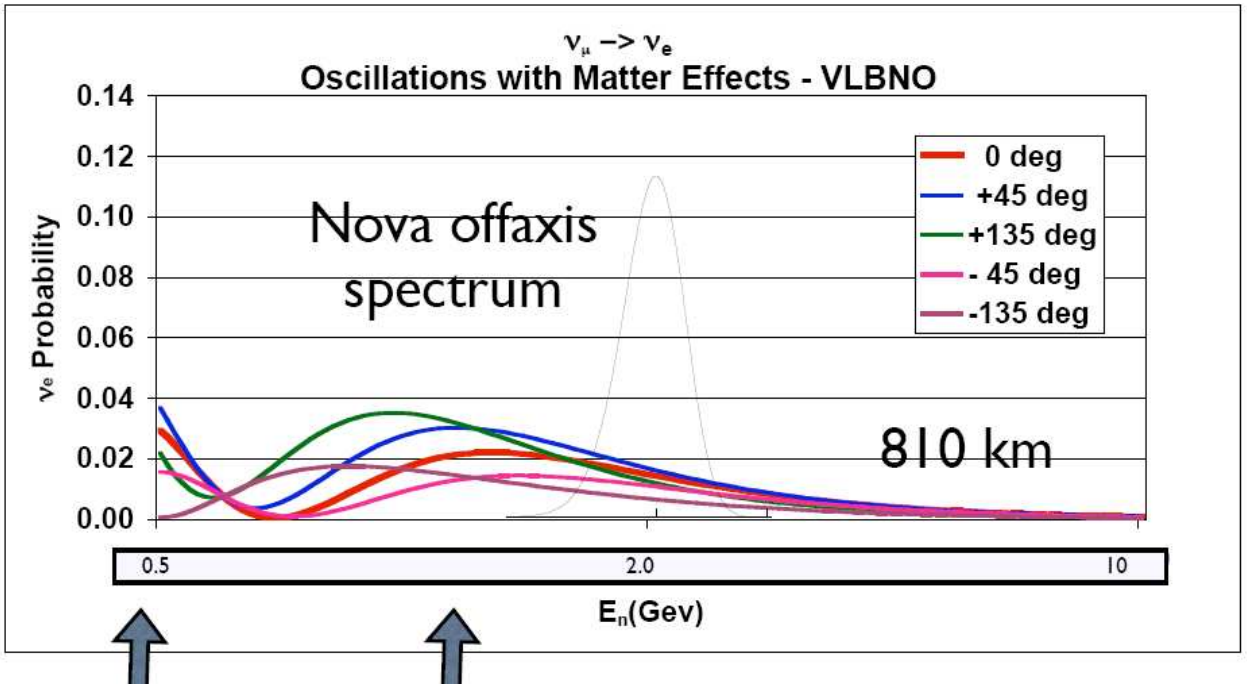
1. We require the maximal possible neutrino fluxes to encompass at least the 1st and 2nd oscillation nodes, the maxima of which occur at 2.4 and 0.8 GeV respectively.

2. Since neutrino cross-sections scale with energy, larger fluxes at lower energies are desirable to achieve the physics sensitivities using effects at the 2nd oscillation node and beyond.

3. To detect $\nu_\mu \to \nu_e$ events at the far detector, it is critical to minimize the neutral-current feed-down contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is no sensitivity to the oscillation parameters is highly desirable.

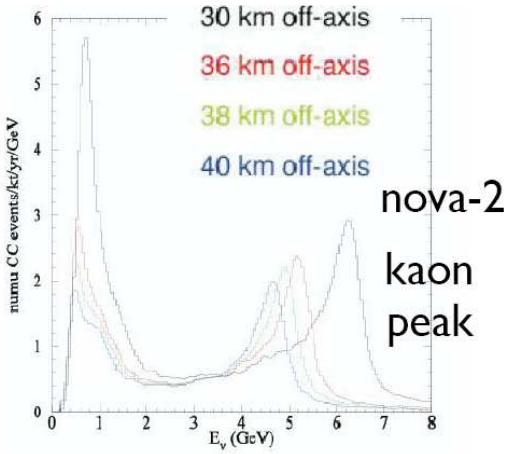
4. The irreducible background to $\nu_\mu \to \nu_e$ appearance signal comes from beam generated ν_e events, therefore, a high purity ν_μ beam with negligible ν_e contamination is required.

Off-axis Beam Specs at $L = 810$ km



Second NOVA detector positioned at a larger off-axis angle to access 2nd oscillation maximum at ~ 0.5 GeV.

Need excellent NC background rejection for backgrounds from higher energy kaon peak.



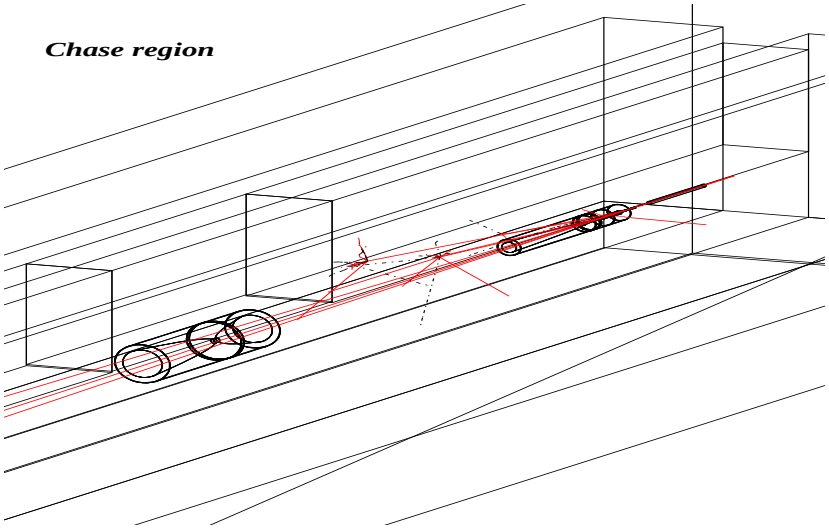
BEAMLINE DESIGN/SIMULATIONS

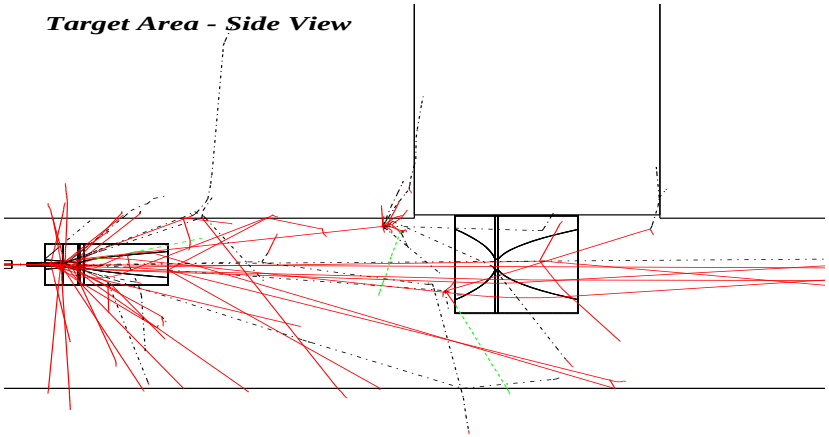
”Target System for a Long Baseline Neutrino Beam,” N. Simos, H. Kirk, J. Gallardo, S. Kahn, N. Mokhov. June 26, 2006.

“Simulation of a Wide-band Low-Energy Neutrino Beam for Very Long Baseline Neutrino Oscillation Experiments,” M. Bishai, J. Heim, C. Lewis, A. D. Marino, B. Viren, F. Yumiceva, July 20, 2006

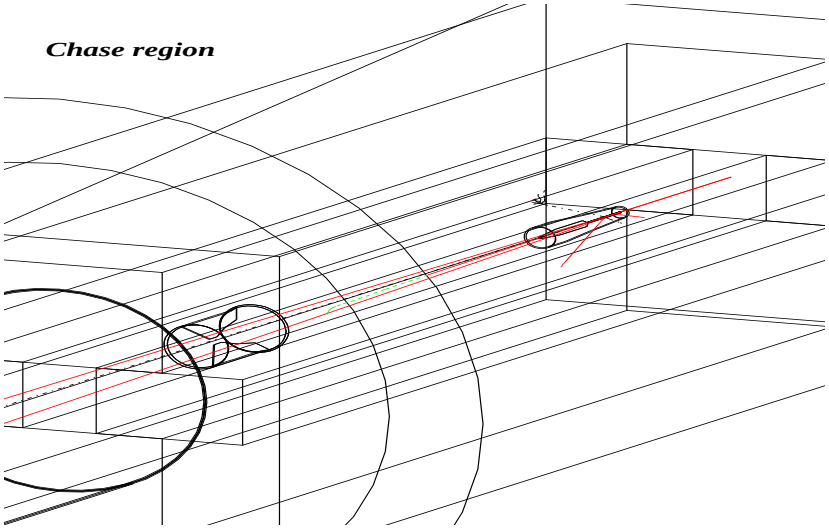
NuMI/WBLE simulation

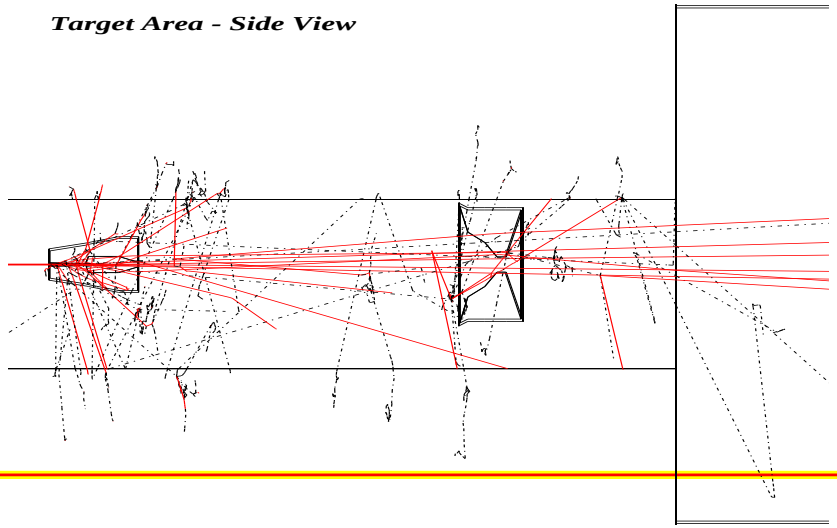
NuMI horns/target with 120 GeV p+



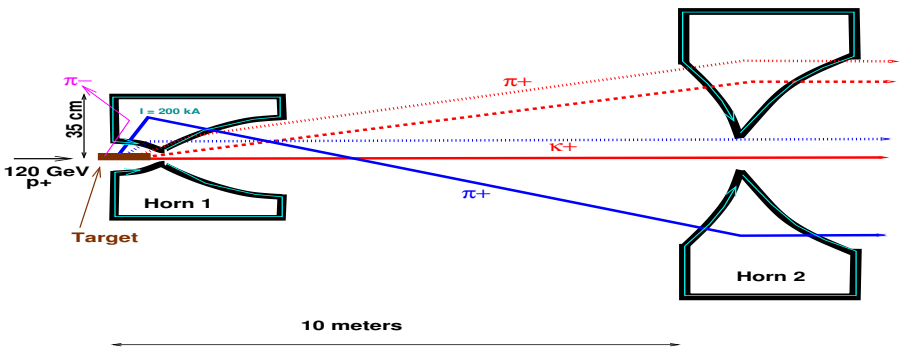


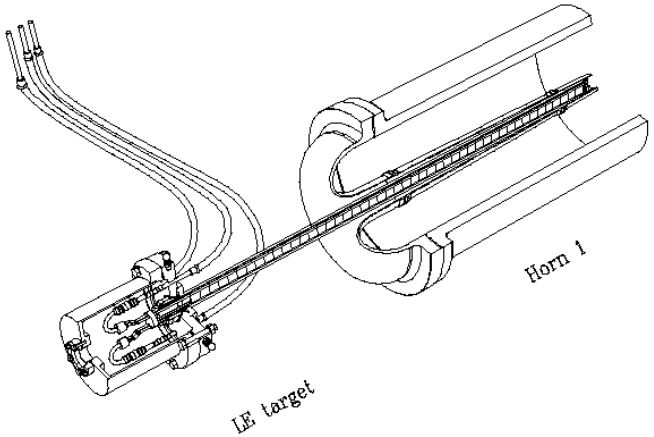
WBLE horns/target with 120 GeV p+

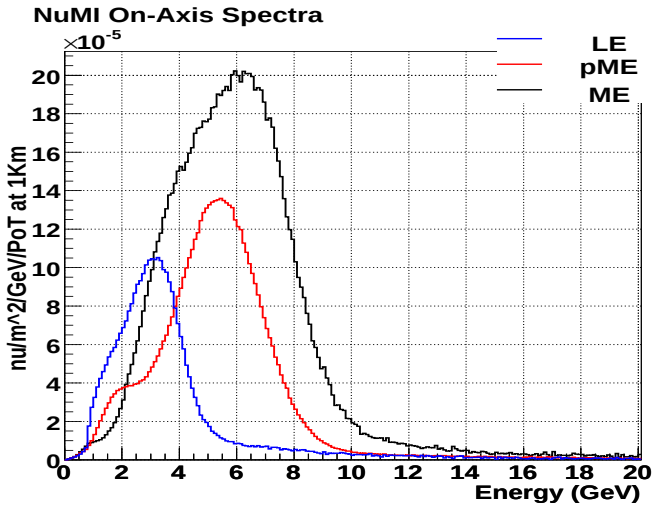


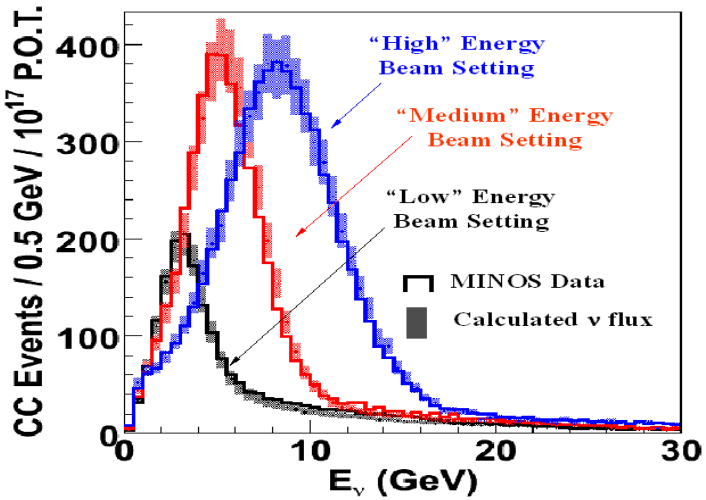


NuMI Beam Spectra







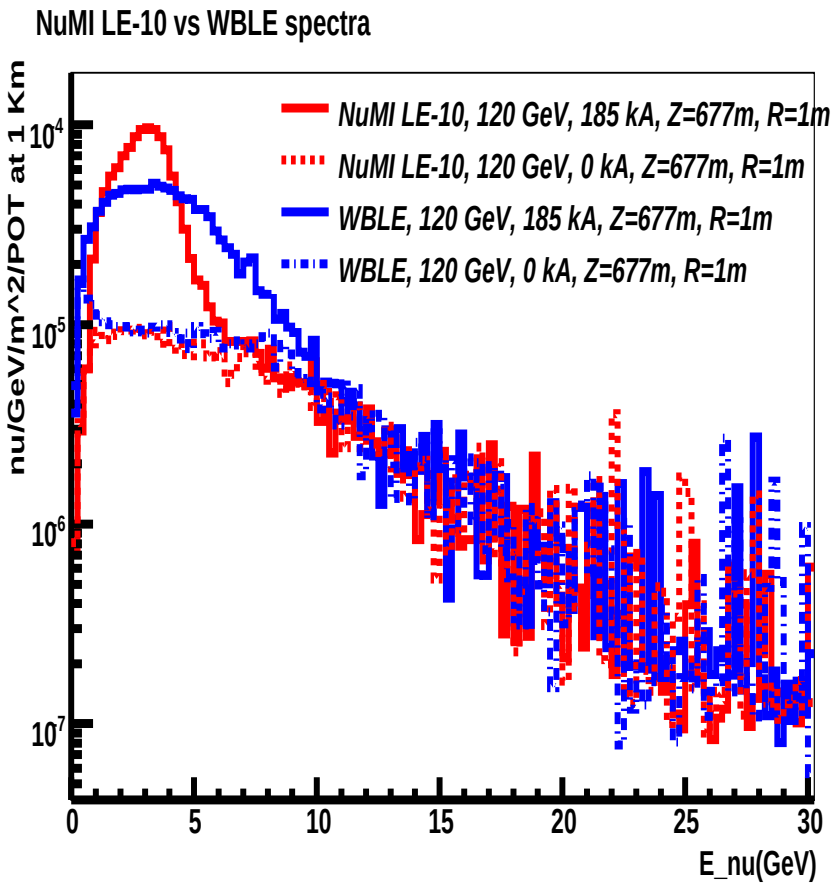


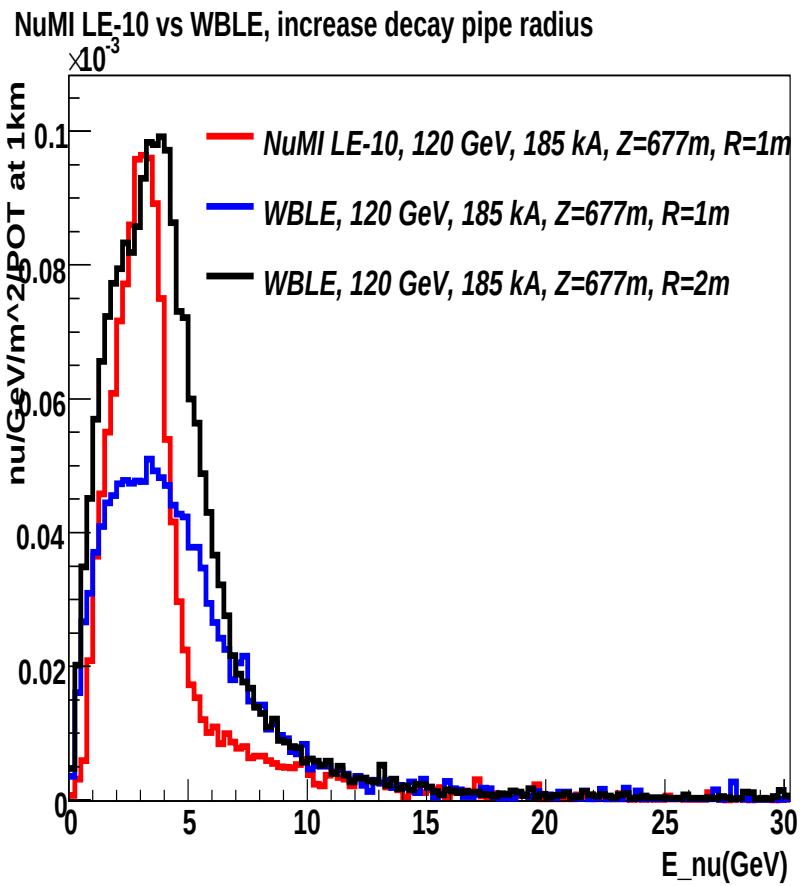
Target 45cm into Horn 1 (LE), -100cm from LE (pME), -250cm from LE (pHE)

-100 cm from LE and Horn 2 moved 3m further down (ME)

NuMI LE vs WBLE

R and Z refer to the geometry of the decay volume which is cylindrical.



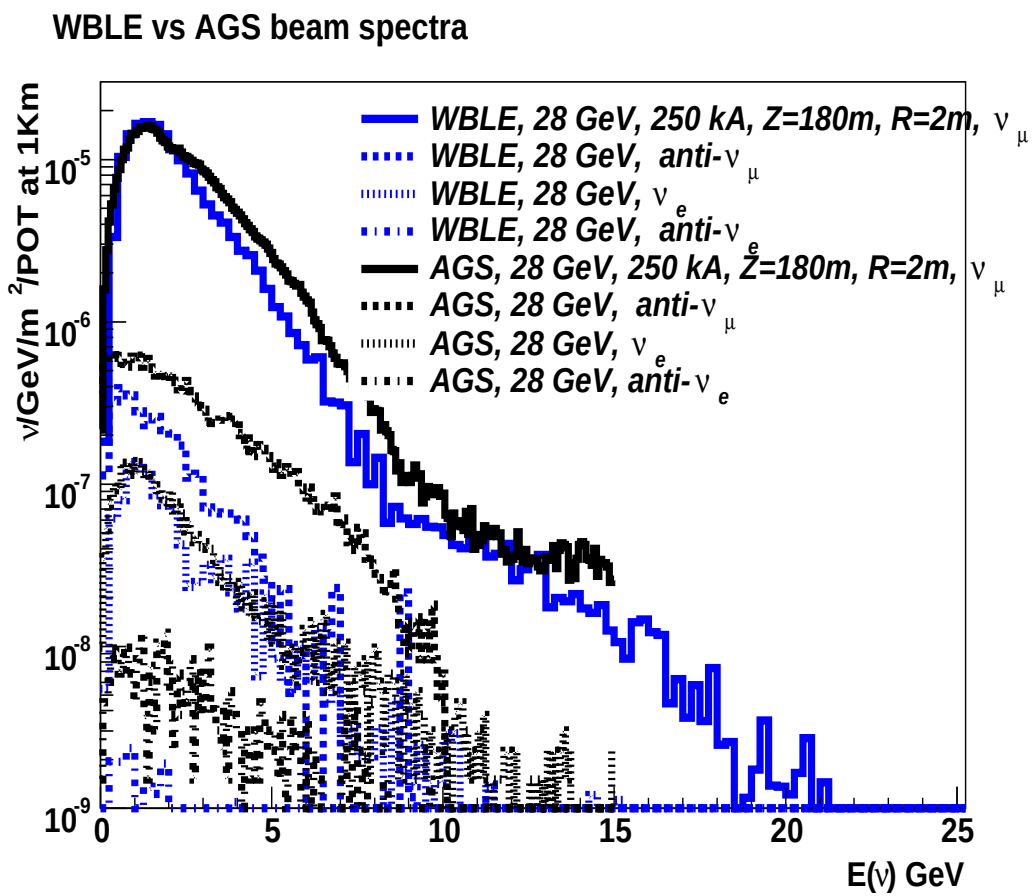


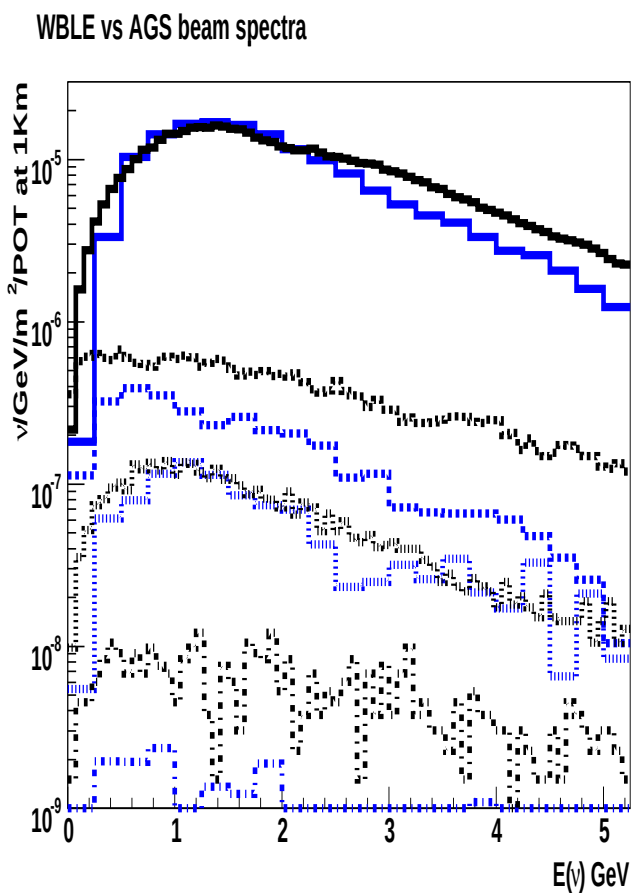
1m radius decay pipe **increase to 2m radius**

Larger diameter decay pipe = more flux at low E.

WBLE/BNL-Beam comparison

The current estimates of the physics sensitivities of a wide band on-axis long baseline experiment used a simulation of 28 GeV beam with the same horn design as described previously.



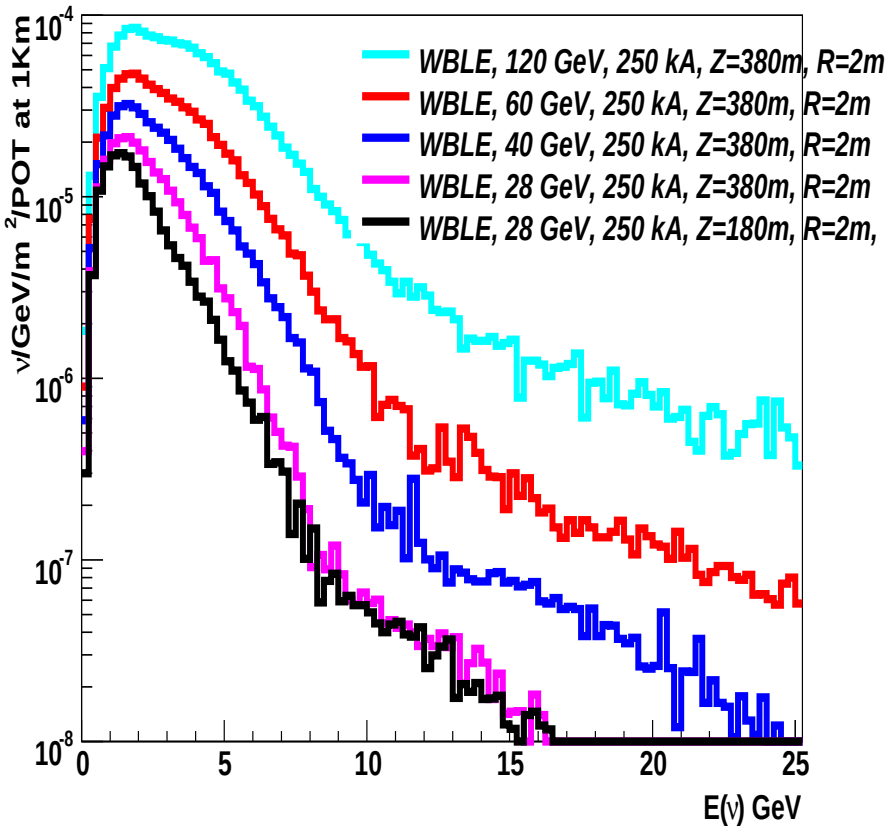


WBLE Beam Spectra for VLBNO

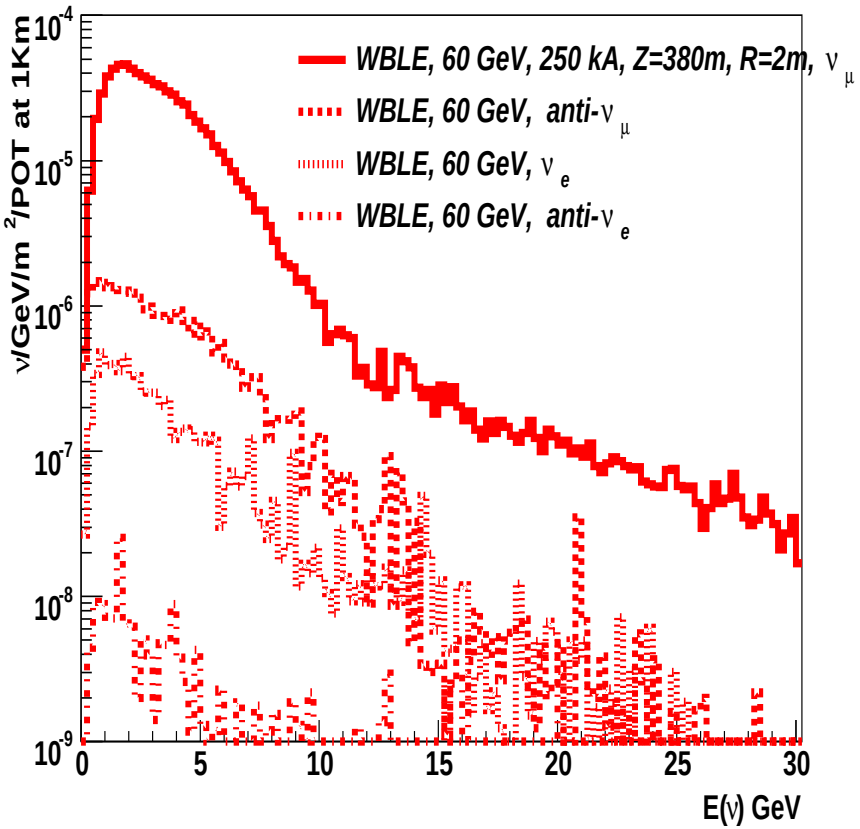
Decay pipe radius chosen to be 2m.

Siting restrictions $\Rightarrow$ decay pipe is $\leq$ 400 m in length

WBLE beam, different energies, decay tunnels



WBLE spectra at 60 GeV



INTERACTION RATES

”Event Rates for Off Axis NuMI Experiments,” B. Viren, June 8, 2006. BNL-76869-2006-IR. hep-ex/0608059.

Interaction Rates (No Osc.)

Beam Scenario	Decay Pipe (radius,length)	Total ν_μ CC rate /(10^{20} pot.kT)	Total ν_μ CC rate /(MW.kT.10^7s)	Total ν_μ QE rate /(MW.kT^{H_2O}.10^7s)
At a distance of 735 km				
NuMI LE-10 on-axis	(1m,677m)	82	427	56
At a distance of 810 km				
‘ NuMI ME on-axis	(1m,677m)	248	1290	
NuMI ME 6km o.a.	(1m,677m)	71.6	372	
NuMI ME 12km o.a.	(1m,677m)	18.1	94	
NuMI ME 30km o.a.	(1m,677m)	1.84	9.57	
NuMI ME 40km o.a.	(1m,677m)	0.86	4.47	
At a distance of 1300 km				
WBLE 120 GeV on-axis	(2m,380m)	44	228	27.4
WBLE 60 GeV	(2m,380m)	16	164	25.1
WBLE 40 GeV	(2m,380m)	7.6	120	21.5
WBLE 28 GeV	(2m,380m)	3.6	80	17.3
WBB 28 GeV (BNL)	(2m,180m)	3.5	78	16.2

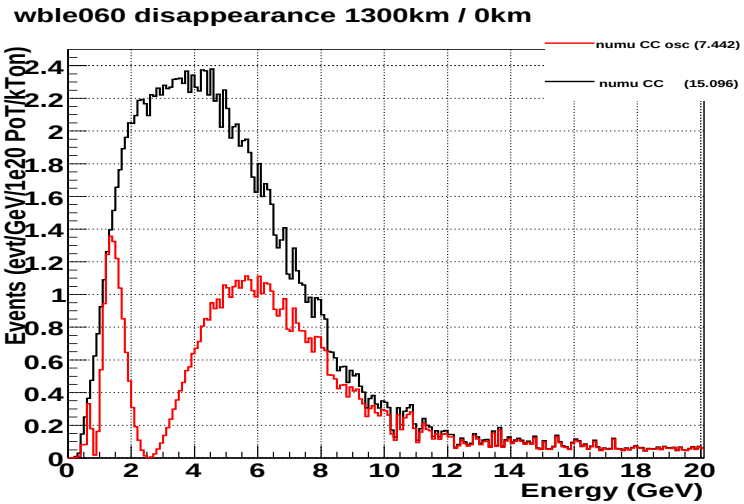
ν_μ Disappearance Rates

NO DETECTOR MODEL.

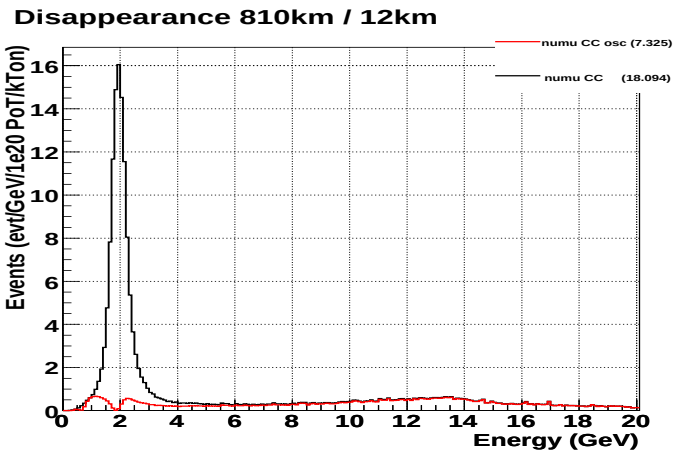
-ν_μ CC no osc.

-ν_μ CC with osc.

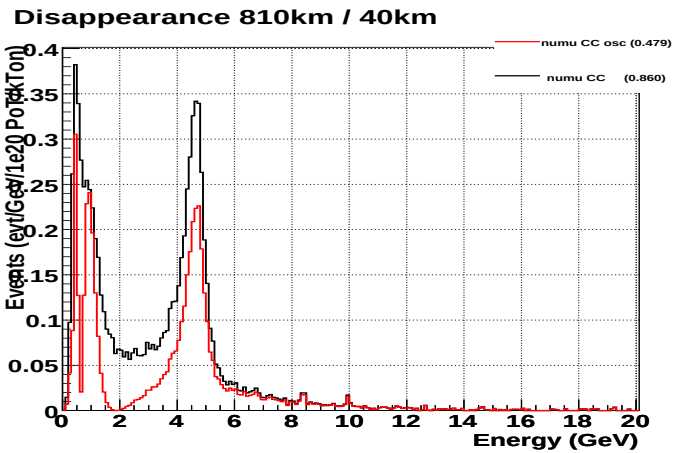
WBLE 60 GeV, 1300 km on-axis



NOVA Detector 1 810 km



NOVA Detector 2 810 km



Off-axis ν_e Appearance Rates

$$\sin^2 2\theta_{13} = 0.04$$

-NC π^0 from NUANCE

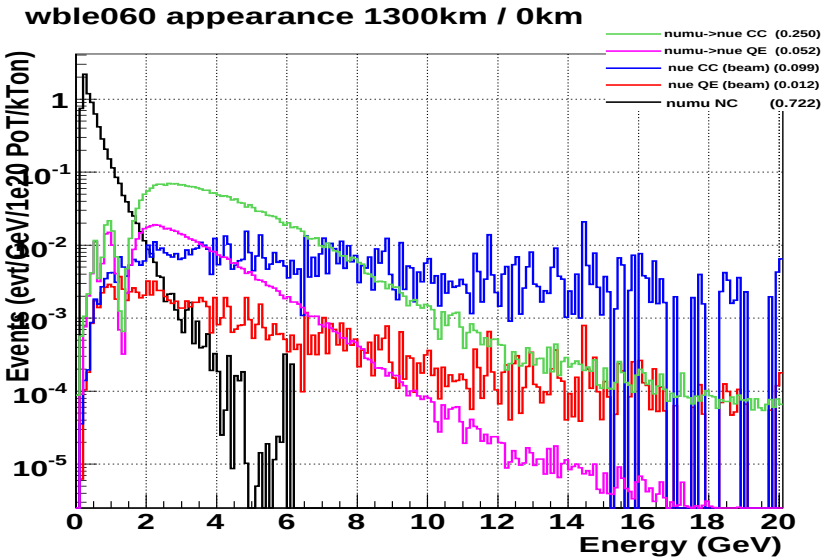
-CC $\nu_\mu \rightarrow \nu_e$

-QE $\nu_\mu \rightarrow \nu_e$

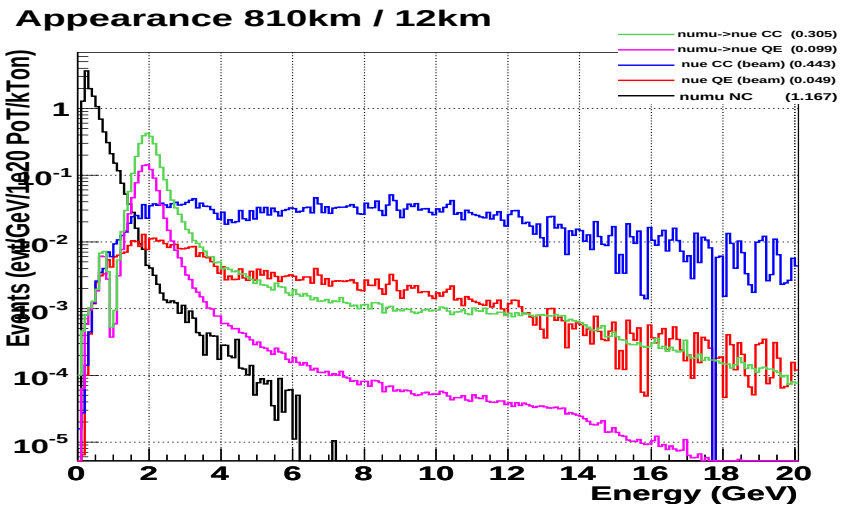
-CC beam ν_e

-QE beam ν_e

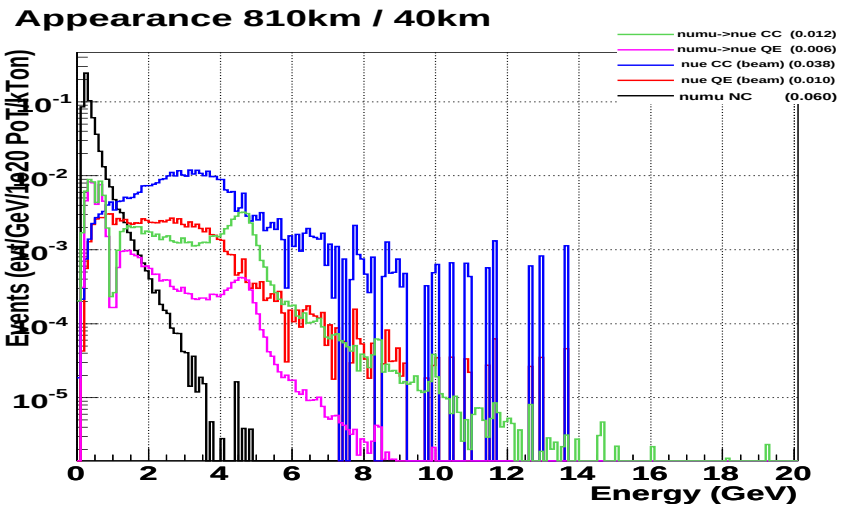
WBLE 60 GeV, 1300 km



NOVA D1 810 km



NOVA D2 810 km



FAR DETECTOR DESIGN/SIMULATIONS

”Background Rejection Study in a water Cherenkov detector,” C. Yanagisawa, C. K. Jung, P.T. Le, B. Viren, July 18, 2006

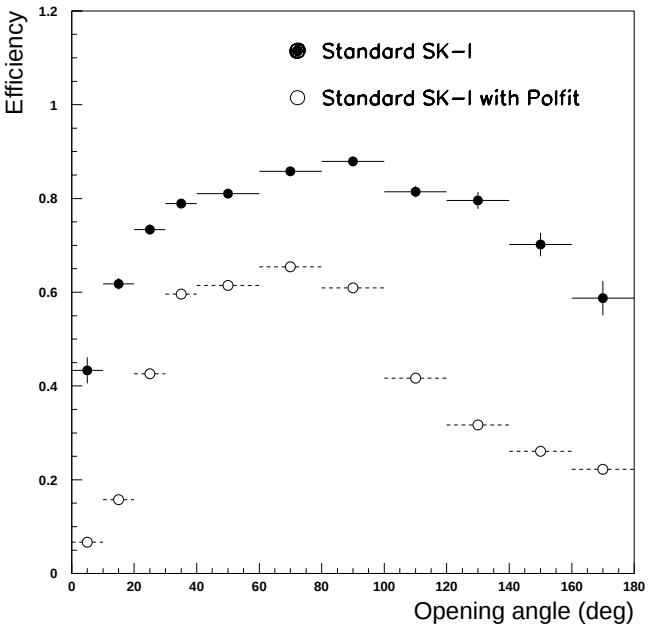
”Monte Carlo study of a liquid Ar time projection chamber for long baseline neutrino experiments.” A. Curioni, August 10, 2006.

Water Cerenkov Simulation

The full GEANT simulation of the SuperKamiokande detector is used with 40% PMT coverage.

- **The atmospheric neutrino spectrum used in the Super-K simulation is reweighed to match the expected flux from the 28 GeV WBB at a baseline of 1480 (FNAL-Henderson) and 2540km (BNL-Homestake).**
- **An π^0 reconstruction algorithim called "Pattern Of Light Fit" has been developed that enhances the default Super-K π^0 finder.**

π^0 reconstruction efficiency



WC ν_e Appearance Spectra

WBB 28 GeV, 2500 MW.kT.10^7s

$\sin^2 2\theta_{13} = 0.04$, **1480 km baseline**

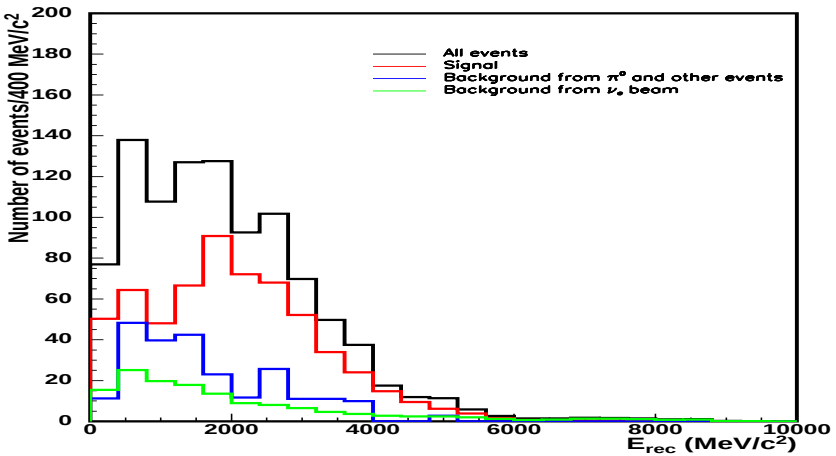
-All events

-Signal $\nu_\mu \rightarrow \nu_e$

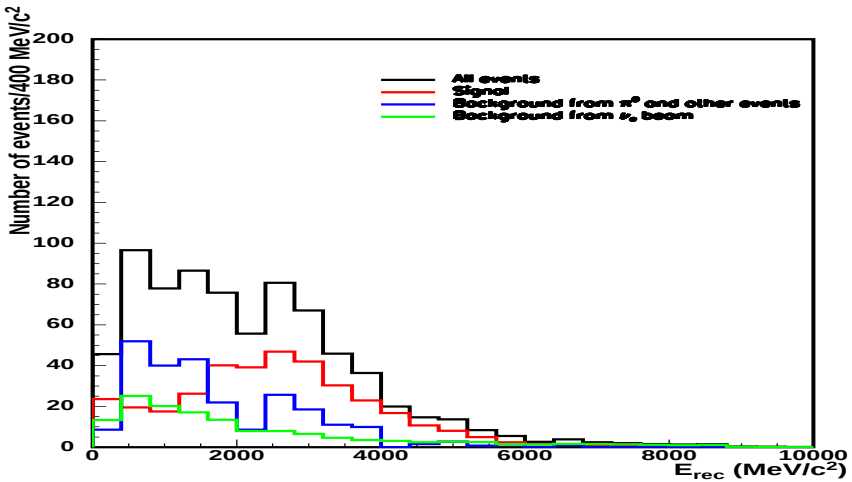
-NC π^0 bkgd

-Beam ν_e

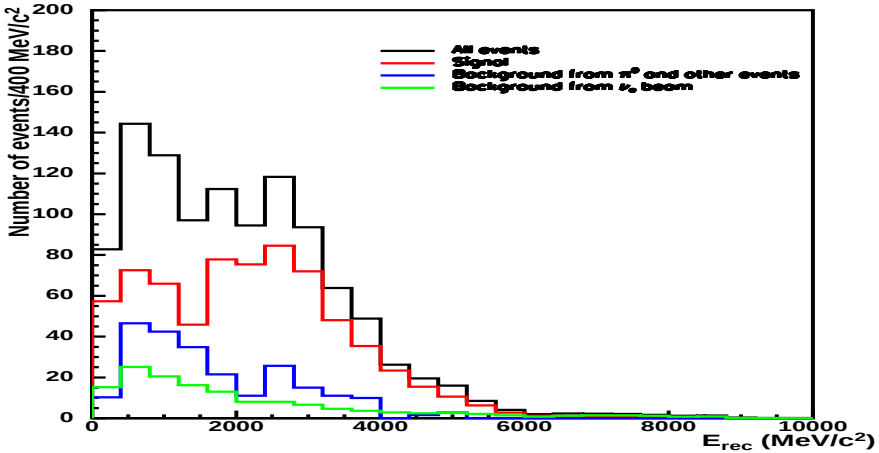
$\delta_{cp} = 0^0$



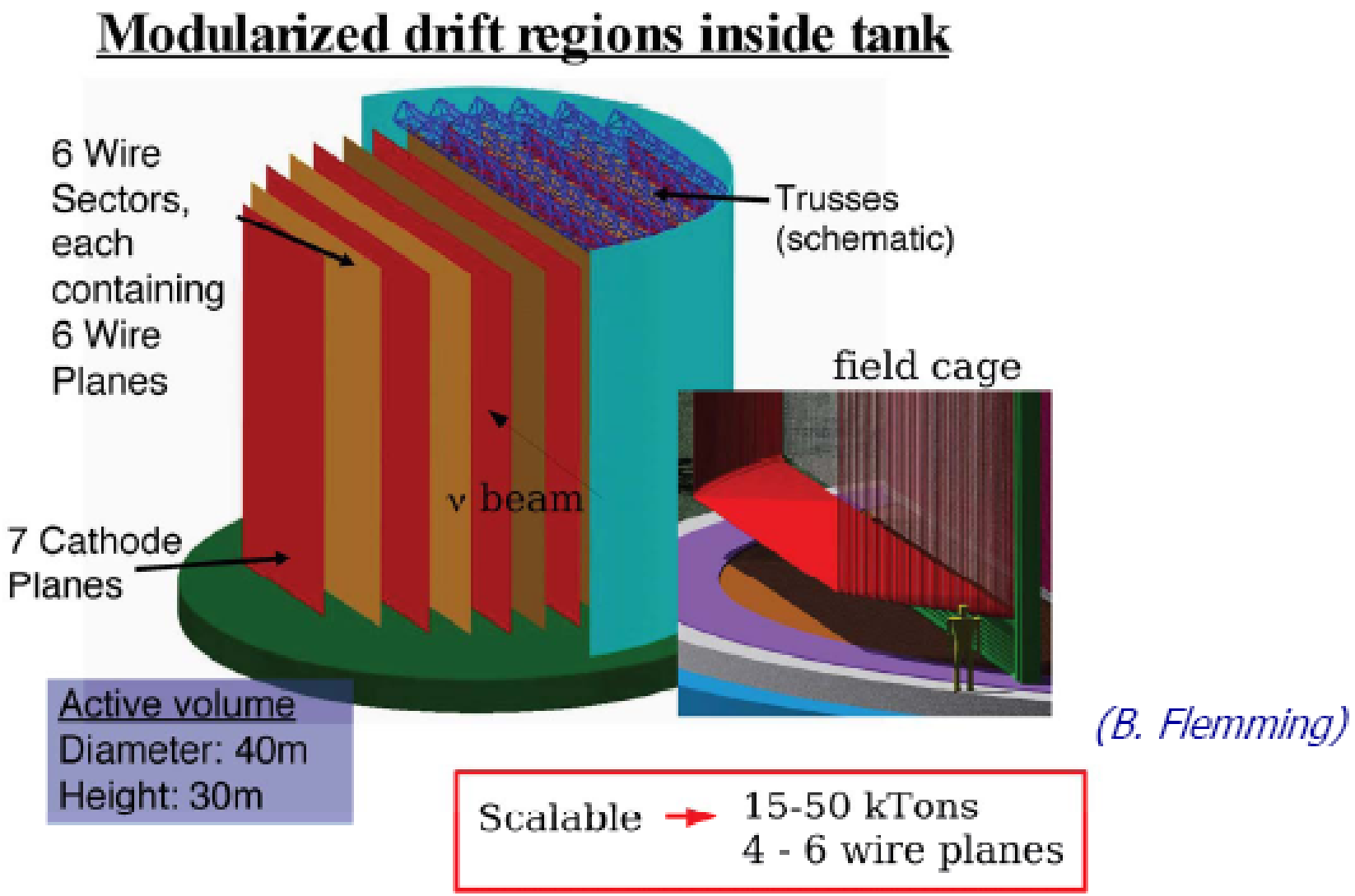
$\delta_{cp} = -45^0$



$\delta_{cp} = +45^0$

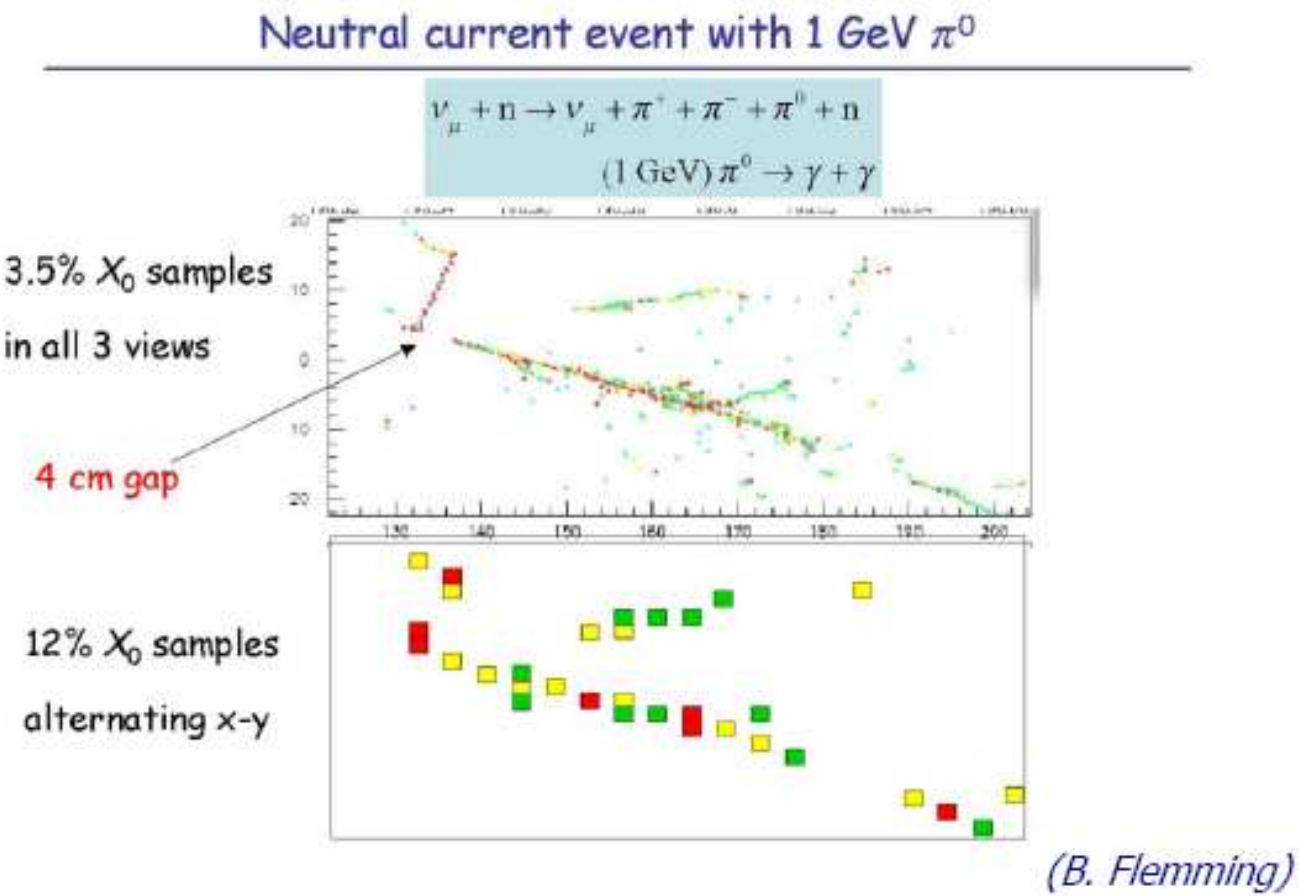


Liquid Argon Design



(B. Flemming)

Liquid Argon Simulations



Handscanning indicates good π^0 rejection.

ν_μ QE event reconstruction in MC.

PHYSICS SENSITIVIES

” V. Barger, M. Dierckxsens, M. Diwan, P. Huber, C. Lewis, D. Marfatia, B. Viren, Jul 17, 2006 hep-ph/0607177

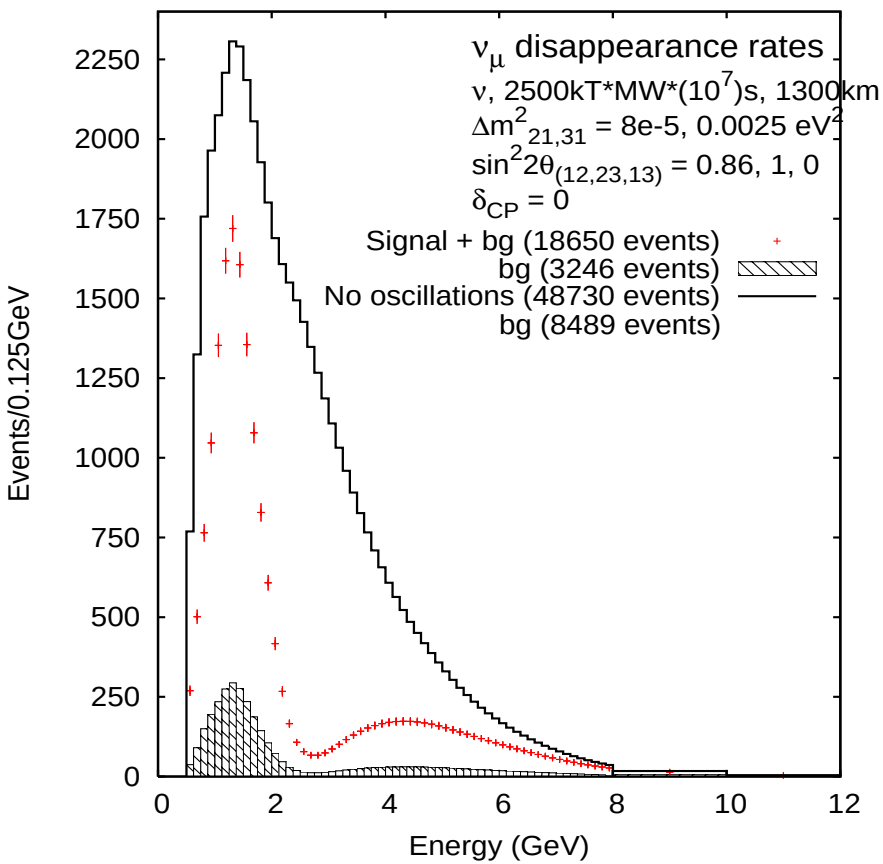
for a local copy BNL-76797-2006-JA

WBLE ν_μ Disappearance Spectra

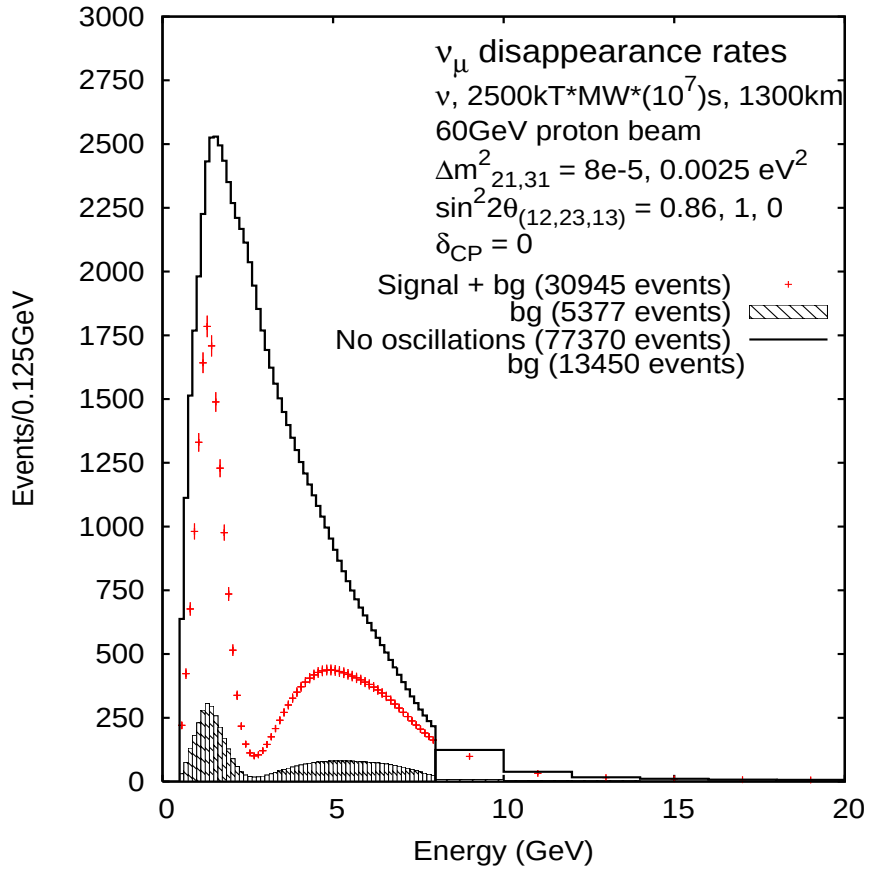
Parameterized Water Cerenkov Model in GLoBES.

1300km at 2500 MW.kT.10^7s.

WBB 28 GeV



WBLE 60 GeV

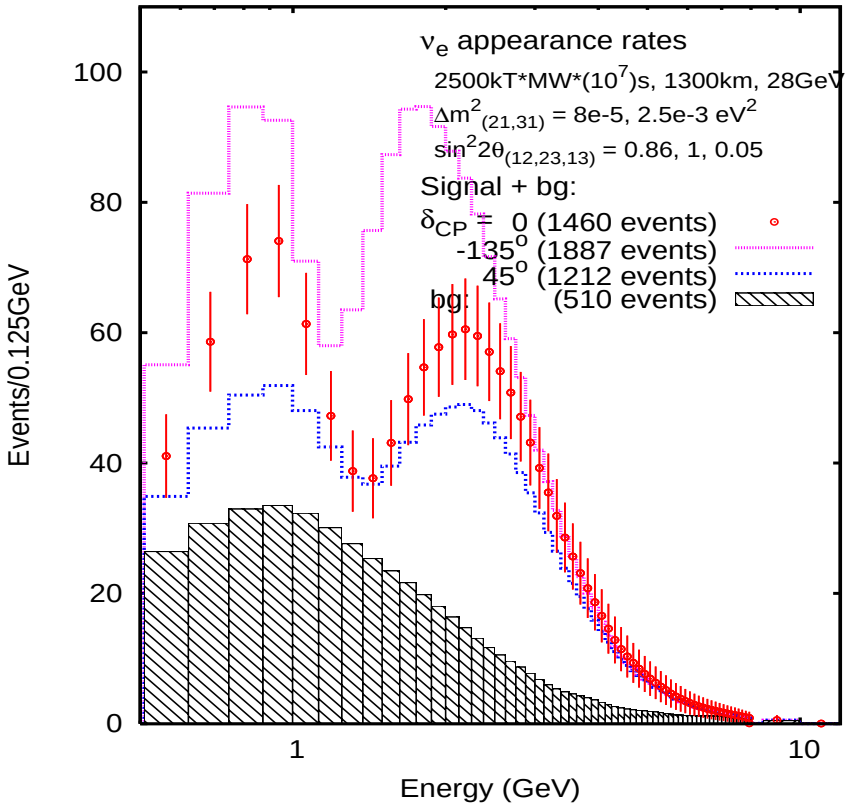


WBLE ν_e Appearance Spectra

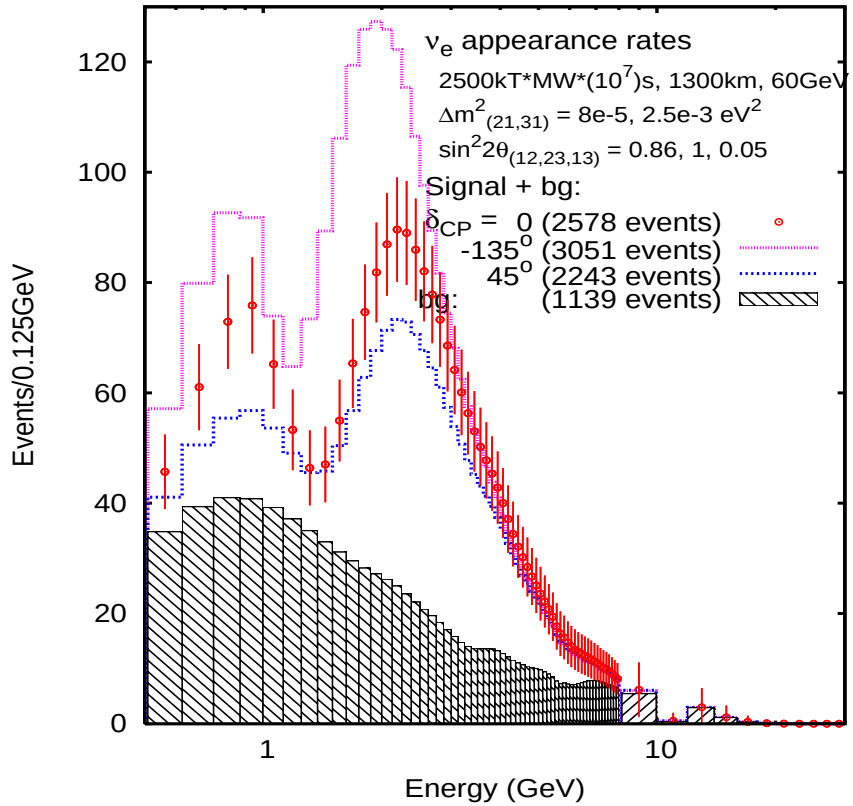
Parameterized Water Cerenkov Model in GLoBES.

$\sin^2 2\theta_{13} = 0.05$ **1300km at 2500 MW.kT.**10^7**s.**

WBB 28 GeV



WBLE 60 GeV

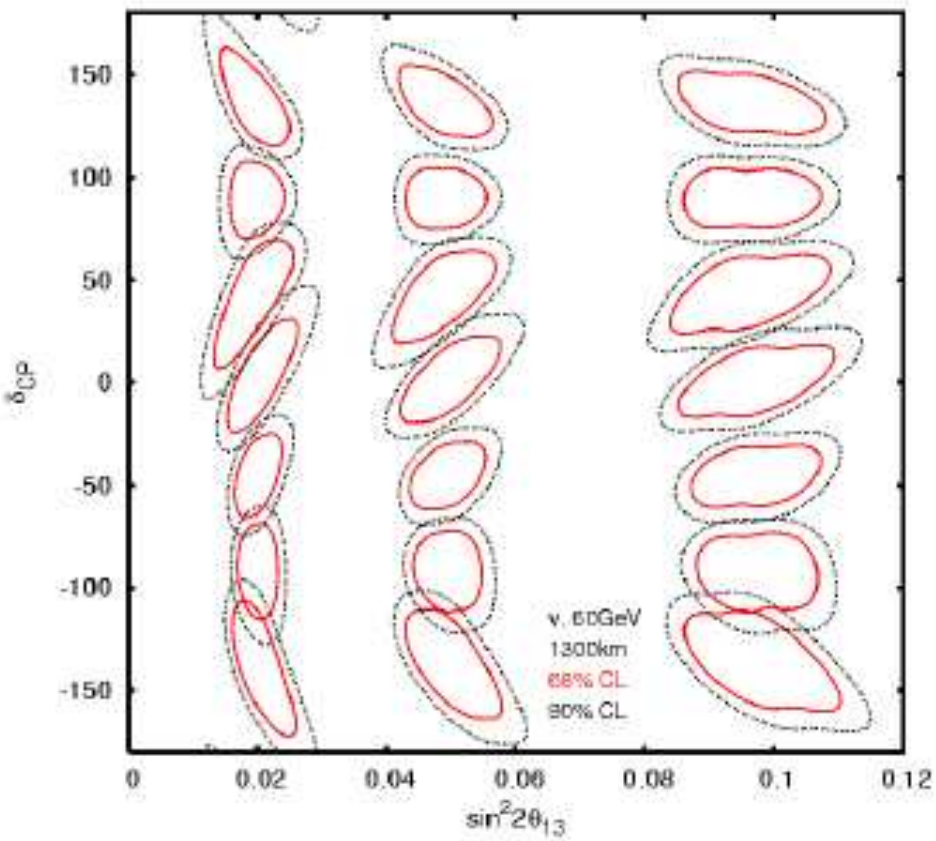


60 GeV WBLE and 28 GeV WBB = similar sensitivies

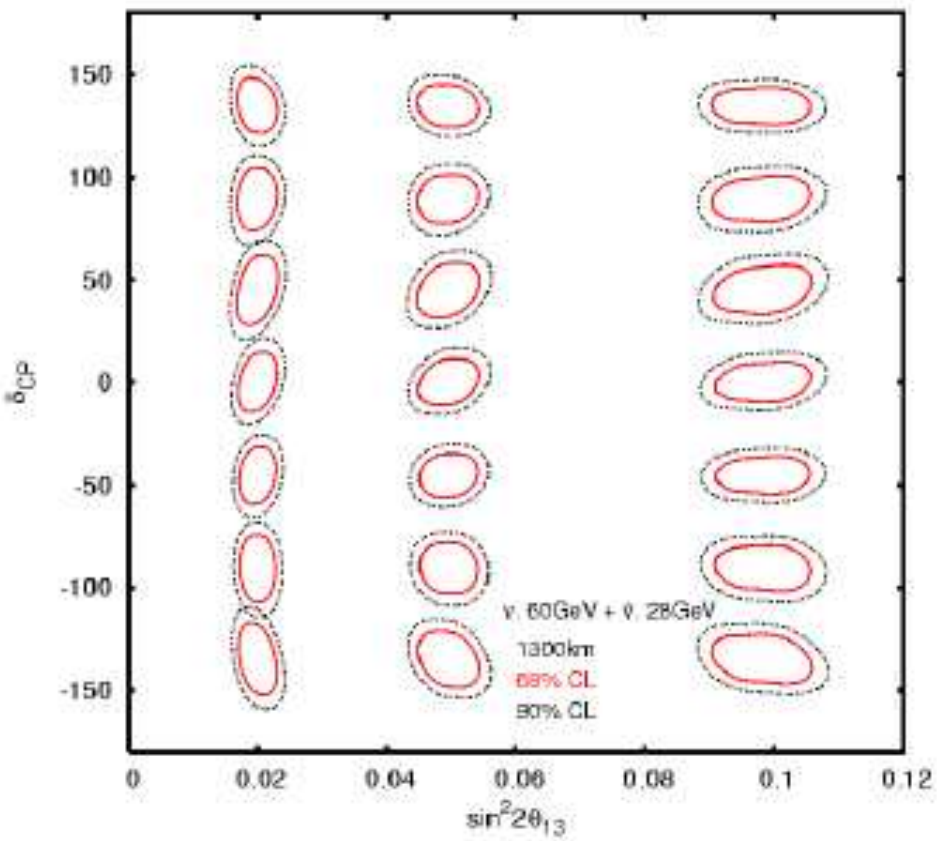
θ_{13} and δ_{cp}

WBLE 60 GeV and WBB 28 GeV, 1300km baseline, 2500 MW.kT.10^7s

60GeV – ν running only



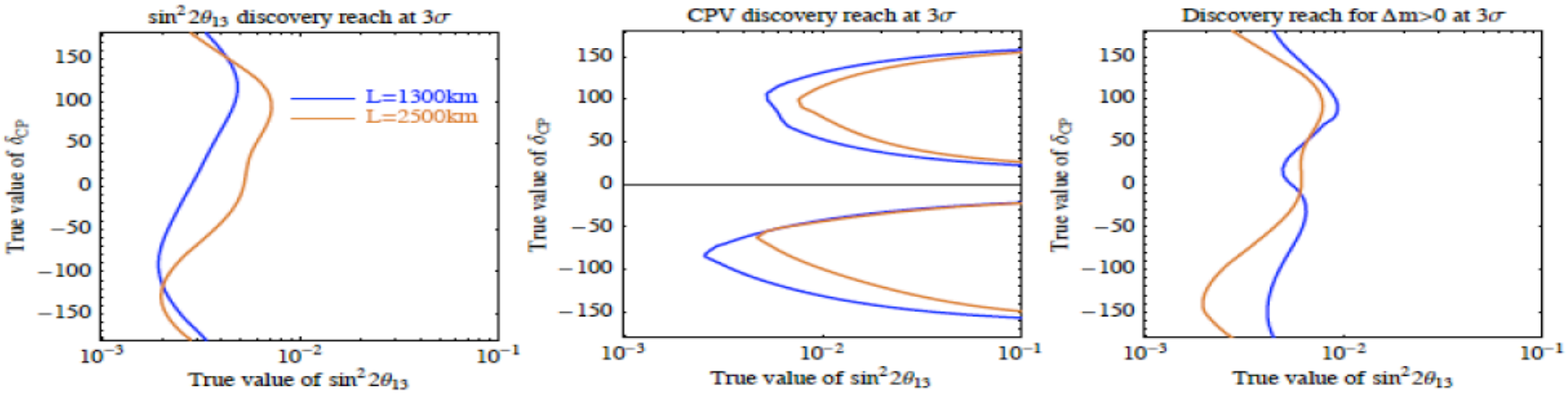
60 GeV ν + 28 GeV anti-ν



Discovery reaches

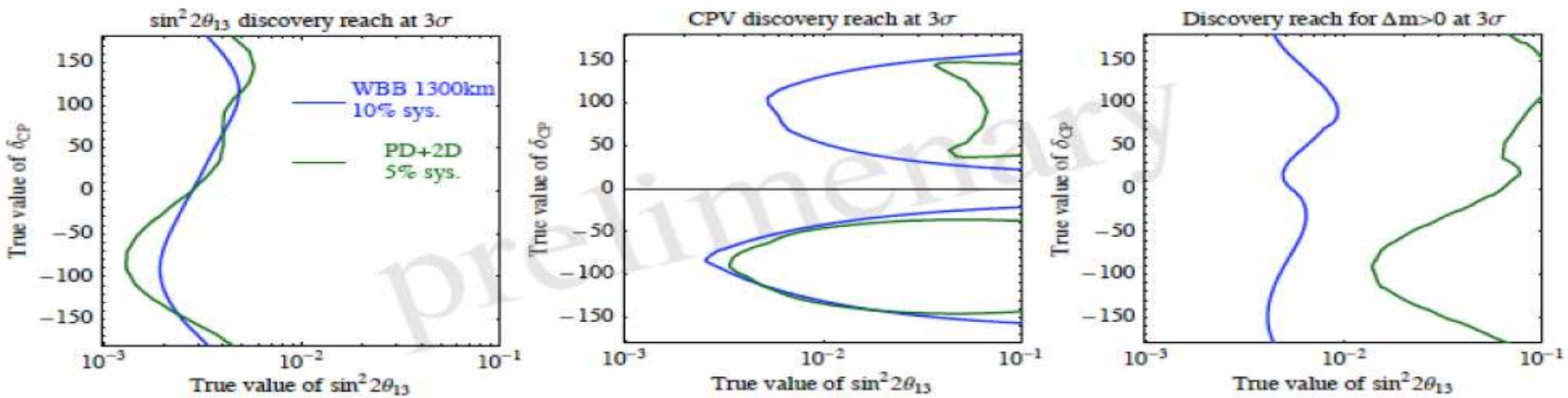
WBB 28 GeV, ν 2500 MW.kT.10^7s + same for $\bar{\nu}$. Water Cerenkov.

(300kT, 1MW beam, 8.4yrs)



NuMI off-axis (NOVA II), ν 1200 MW.kT.10^7s + same for $\bar{\nu}$, Water Cerenkov.

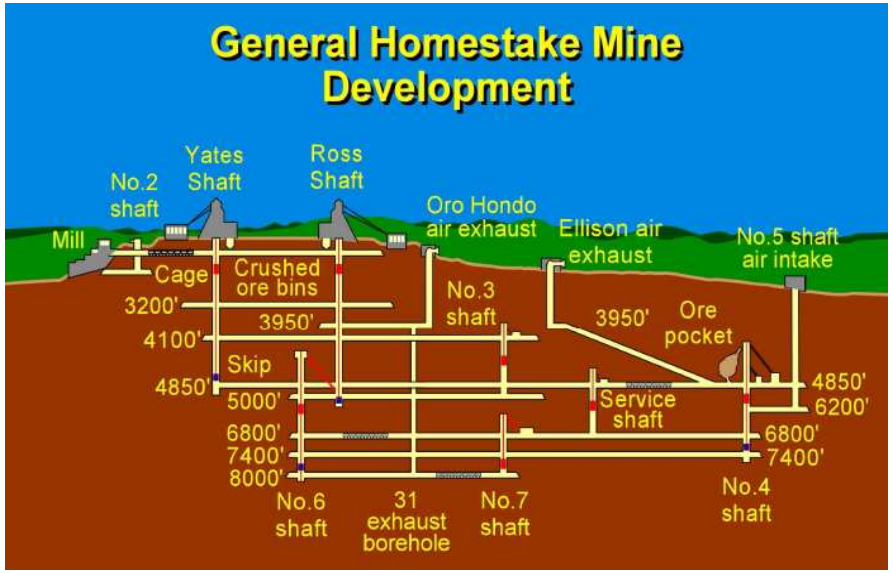
(25 kT D1+50 kT D2, 2MW beam, 12yrs if D1 and D2 run simultaneously.)

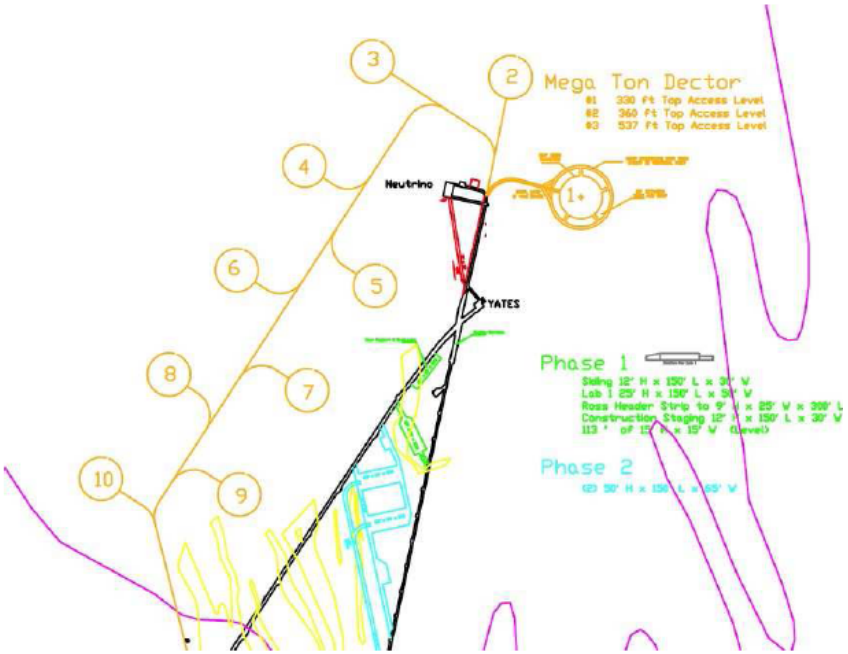


FAR SITE PRELIMINARY DESIGN,COST,SCHEDULE (Homestake Mine)

”Proposal for an Experimental Program in Neutrino Physics and Proton Decay in the Homestake Laboratory,” Collaboration: BNL, Brown University, UC/Berkeley, LBNL, University of Pennsylvania, Princeton University, UCLA, University of Wisconsin, University of Kansas, University of Colorado. July 12, 2006. BNL-76798-2006-IR

Modularized Detectors at HS



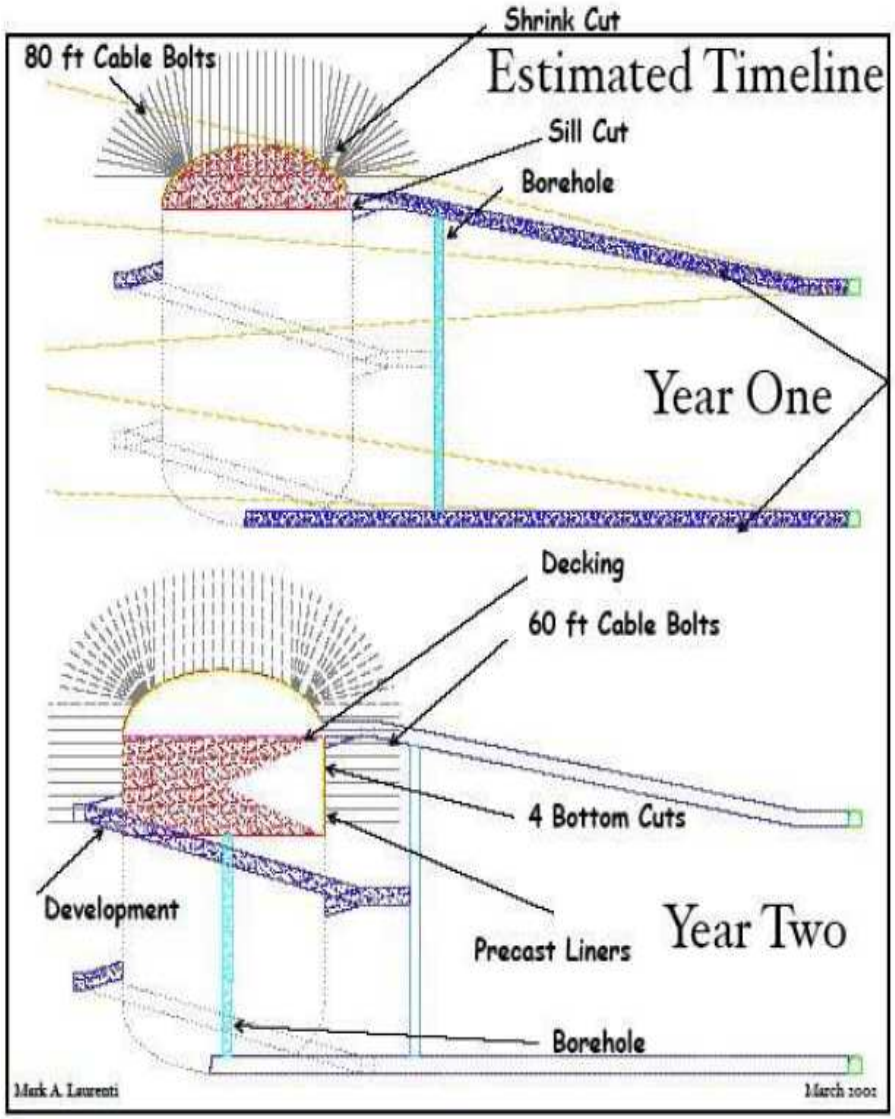


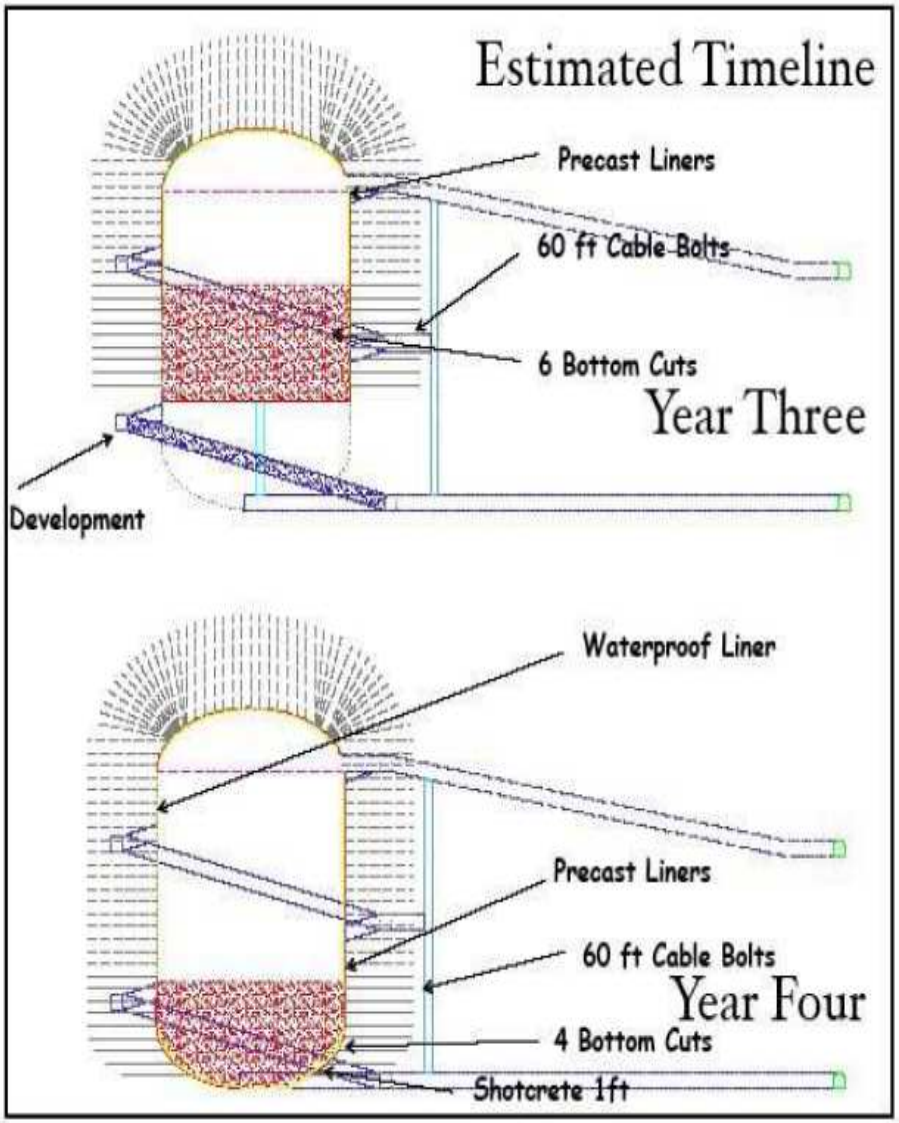
The detector system will be deployed in the 4850 ft level as seperate 100kT Water Cerenkov detector modules to allow a staged approach with potential for expansion.

The first modules will be located near the original cavern for the Ray Davis experiment.

Cavern Construction Timeline

Mark Laurenti, Chief Mine Engineer for Homestake till 2001





Cost Estimates for 300 kT

Construction costs for 3 caverns:

Table 3: Comparison of single chamber versus three chamber cost

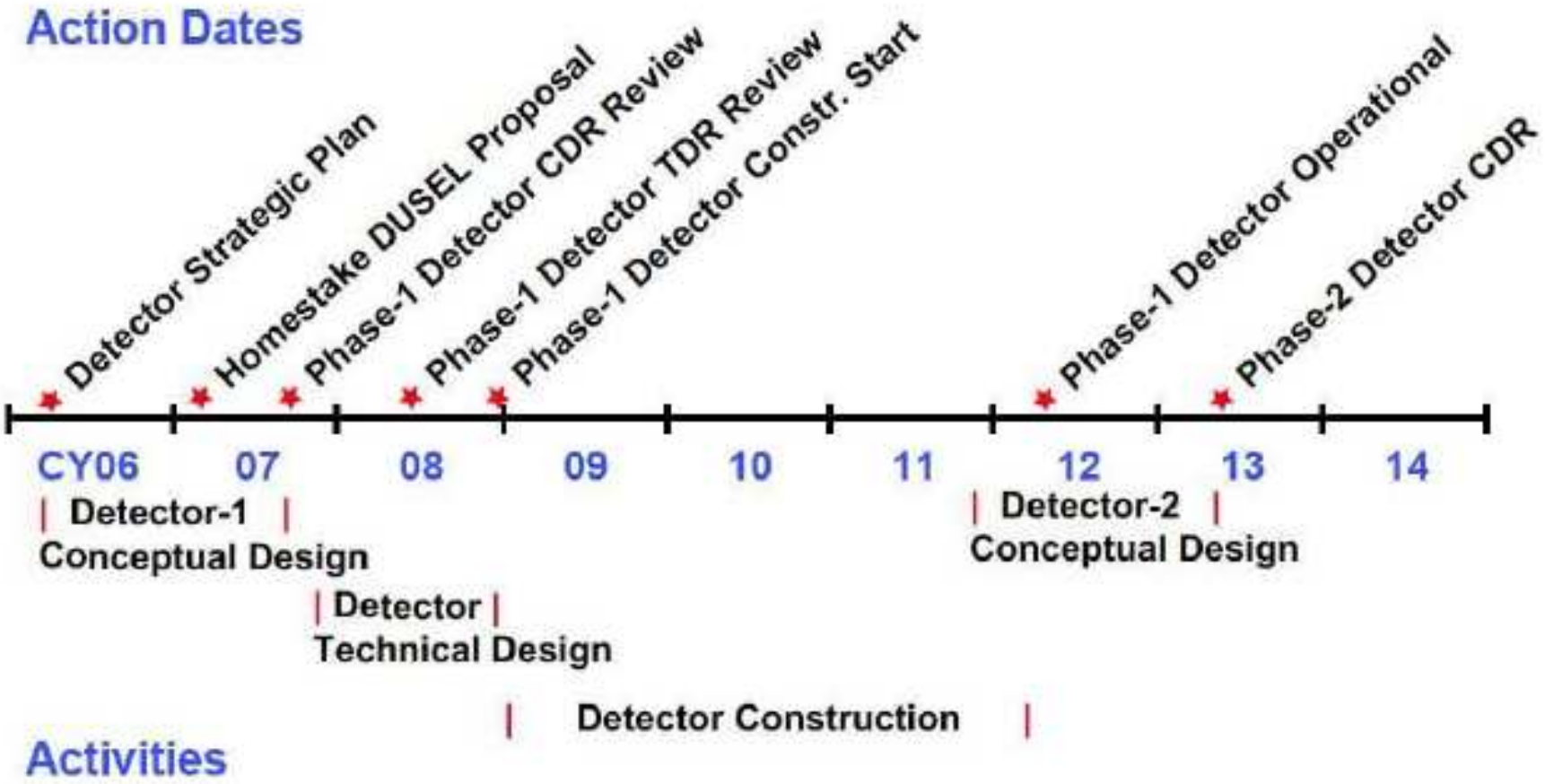
Estimated Costs ($MM)			
	# Of Chambers	1	3
Labor & Benefits		$5.51	$10.94
Mining and Construction			
Equipment Operation		$1.30	$3.89
Supplies		$4.51	$13.35
Precast Concrete Liner		$3.25	$9.75
Other (Outside Contractors)		$0.17	$0.52
30% Contingency		$4.40	$11.48
	TOTAL(2002)	$19.1	$49.93
	TOTAL(2007)	$29.1	$66.1

Costs of 3 detector modules:

Cost Description	Amount	Comment
Development	$3M	Extrapolated from SNO
Procurement/Module	$5M	Water purification, distributution, calibration
Production/Module	$62.1M	For 25% PMT coverage of 11,000 m^2
Total (3 Modules)	$242.7M	Includes 25% contingency

Total cost for 300kT (2007) : $308.8M

Overall Timeline



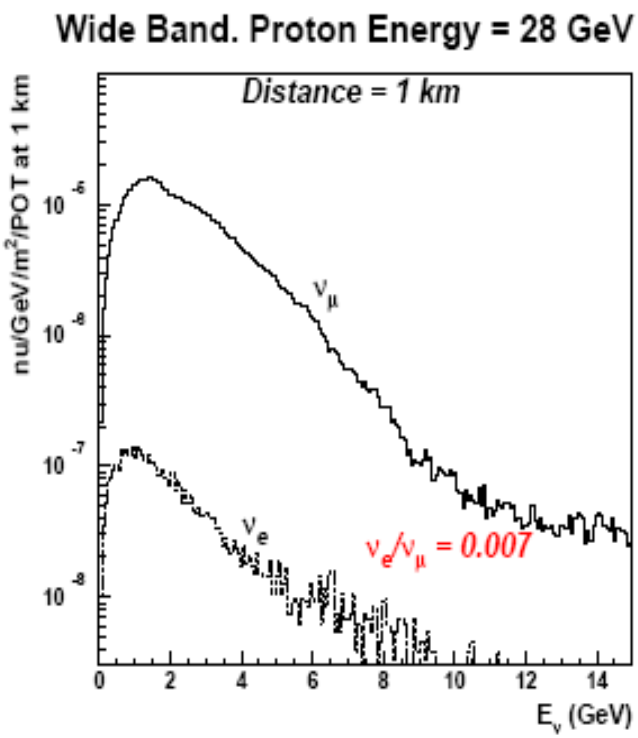
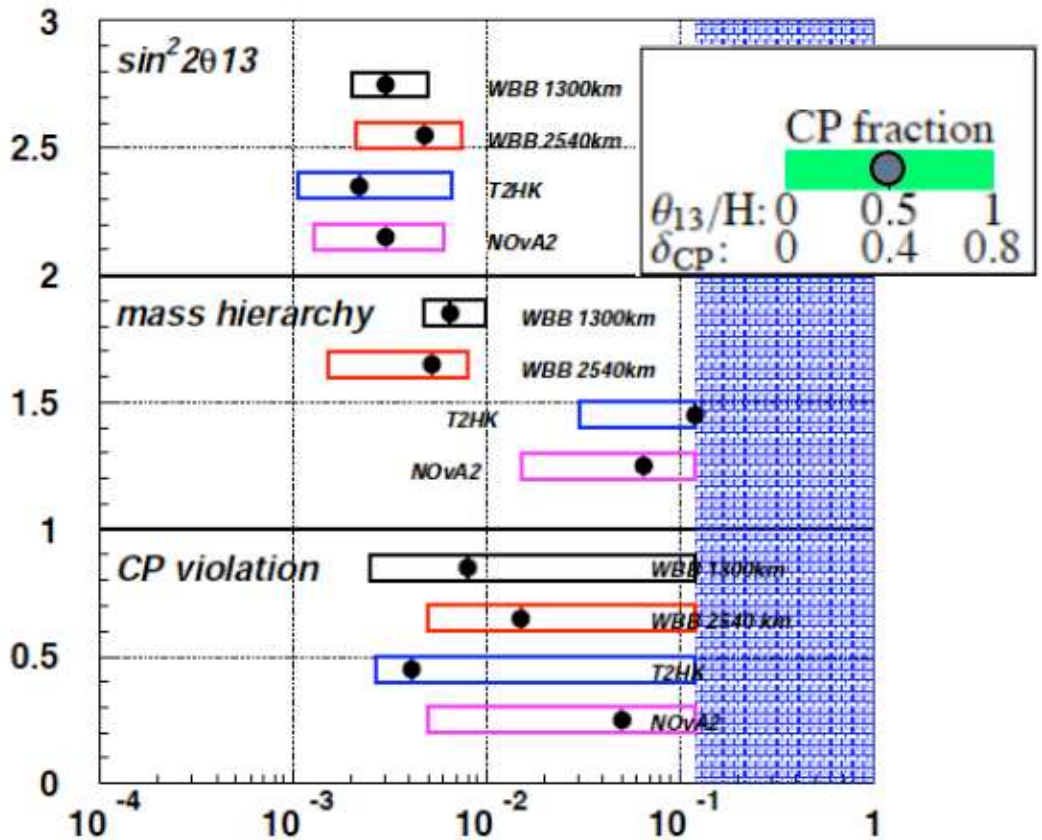
Milestones

- Detailed study of different FNAL beam power scenarios
- Conceptual design of beamline to DUSEL from FNAL
- Technical feasibility of a solid target for 1-2MW beam identified.
- Detailed definition/simulation of a WBLE beam from FNAL complete.
- Estimation of event and background interaction rates for on-axis WBLE beams and off-axis NuMI completed.
- Detailed simulation of on-axis event and background rates in a Water Cerenkov detector complete.
- Physics sensitivies using FNAL WBLE beam, NOVA II with Water Cerenkov detector simulation computed (no LAr detector model yet).
- Preliminary cost, timelines for building a 300 kT Water Cerenkov detector at Homestake produced.
- MC for LAr developed, automated reconstruction still being developed

BACKUP

Physics Sensitivies

The potential physics reach from previous studies with the 28 GeV Wide-Band 1-2 MW beam, 500kT Water Cerenkov, for both FNAL-DUSEL and BNL-DUSEL baselines - compared to other approaches:



From Patrick Huber, U. of. Wisconsin: