The US Long Baseline Neutrino Experiment Study - 1

Plenary Meeting of the International Design Study for the Neutrino Factory, CERN, Mar 29-31, 2007

Mary Bishai (BNL)

mbishai@bnl.gov

BROOKHAVEN NATIONAL LABORATORY

U.S. Long Baseline ν 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):

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 (Water Cerenkov and/or Liquid Argon). [this talk]

2) Off-Axis next generation options using a 1-2 MW neutrino beam from Fermilab and a liquid argon detector as a second detector for the NOVA experiment. [Niki Saoulidou's talk]

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

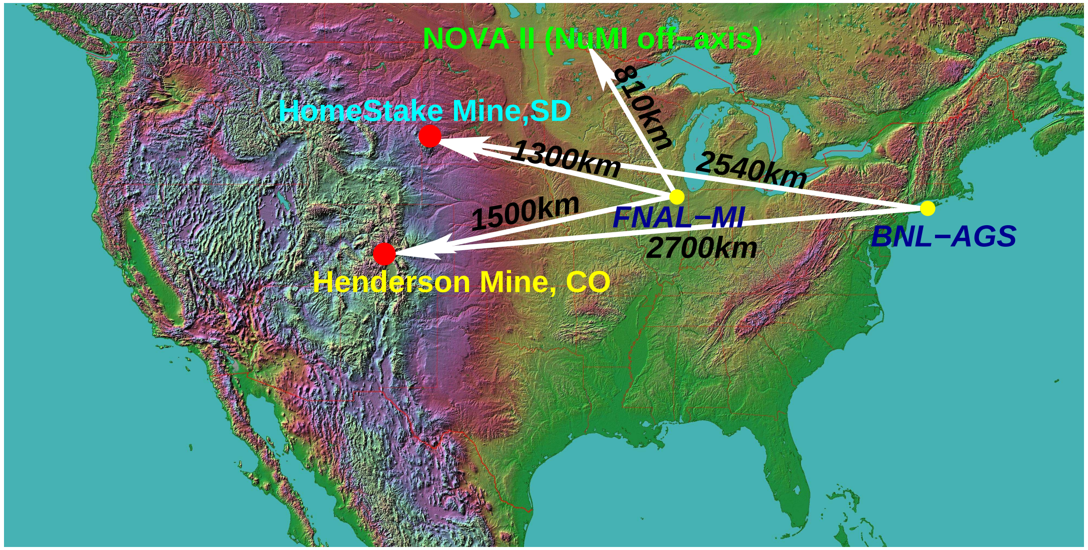
BEAM SPECIFICATIONS AND DESIGNS

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

”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

Beam Options/Baselines



The following beam options and baselines are considered:

Off axis beams using the 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.

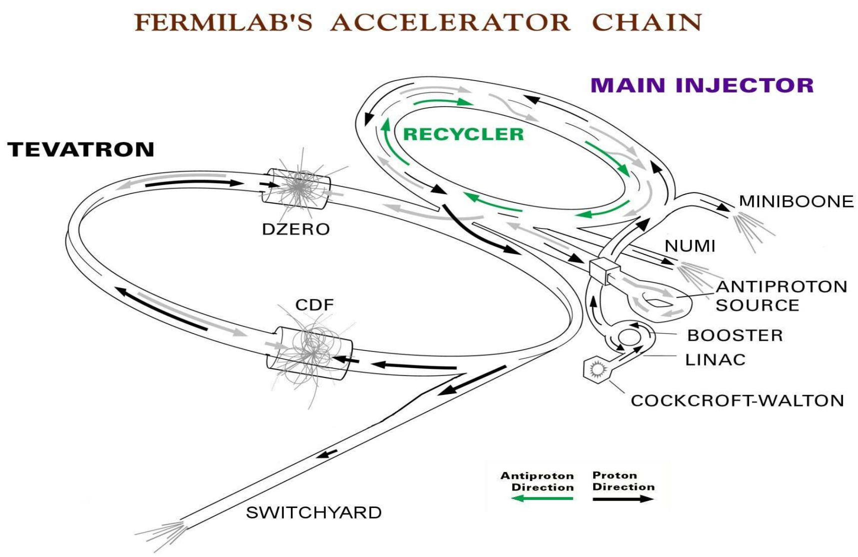
For the current study we will concentrate on beam options from FNAL

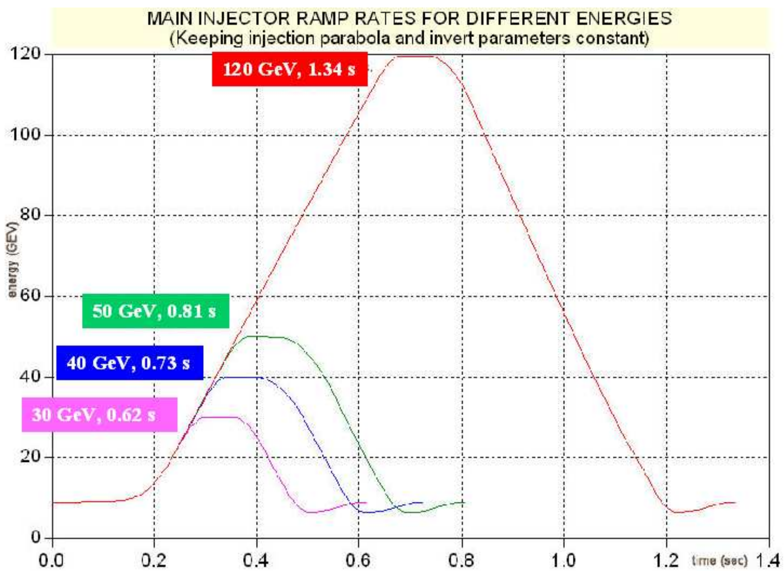
FNAL Beam Specs: E & Power

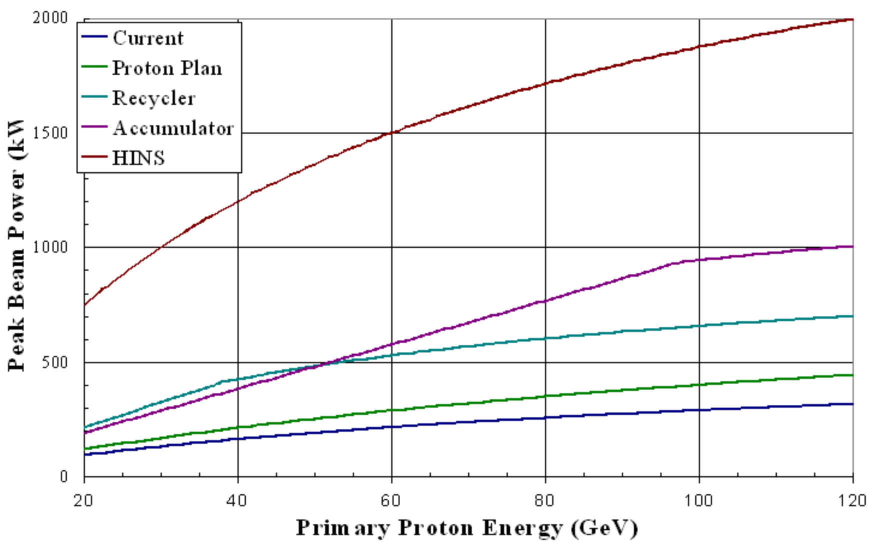
Incremental upgrades possible

(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.

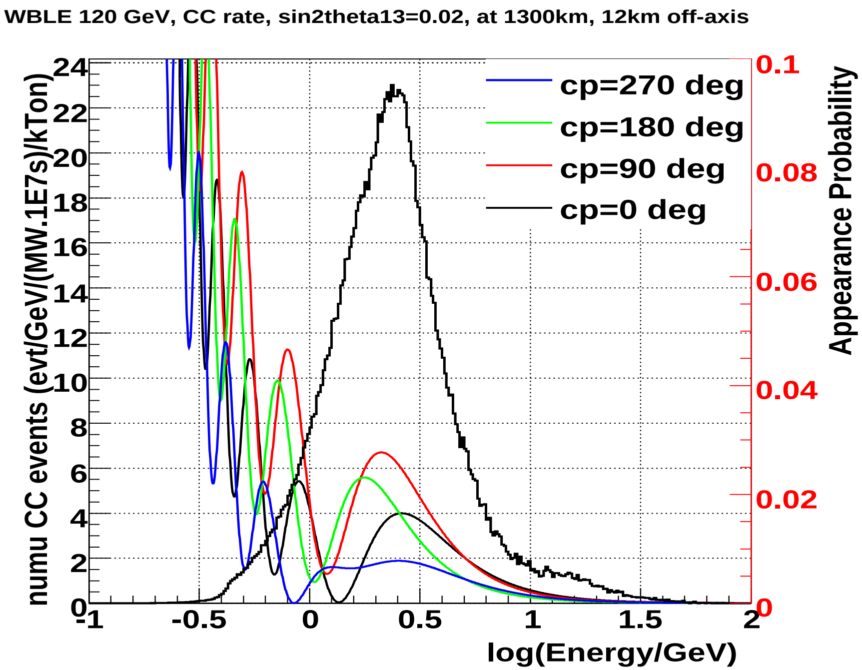






WBLE Beam Design Requirements

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 = 1300 km

Requirements:

-Maximal possible neutrino fluxes to encompass the 1st and 2nd oscillation nodes, with maxima at 2.4 and 0.8 GeV.

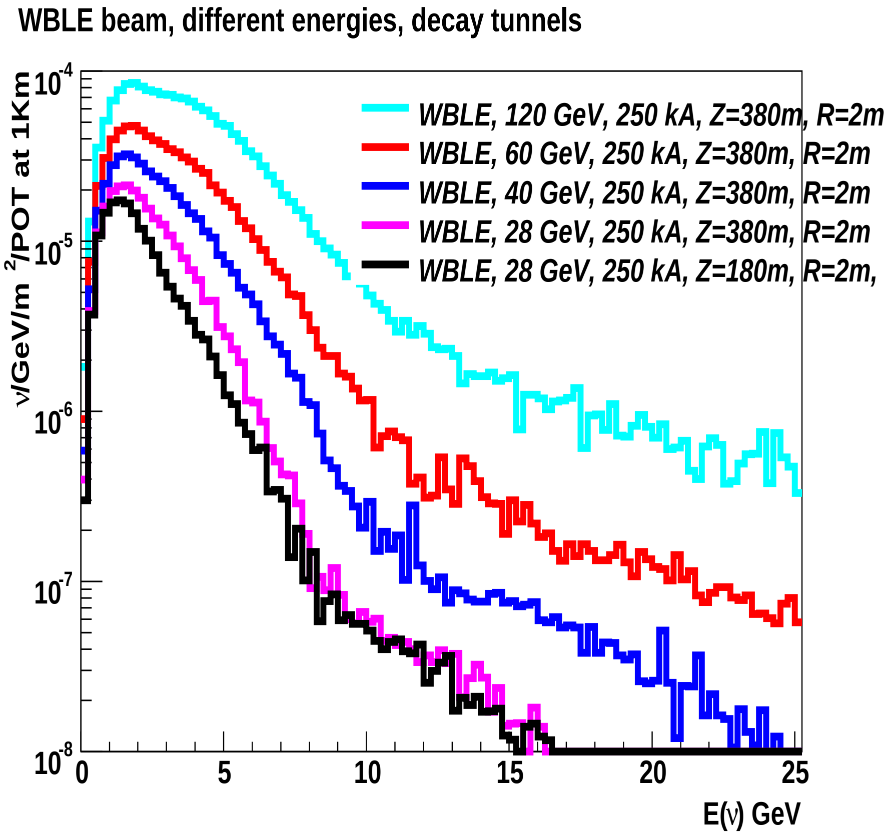
-High purity ν_μ beam with negligible ν_e

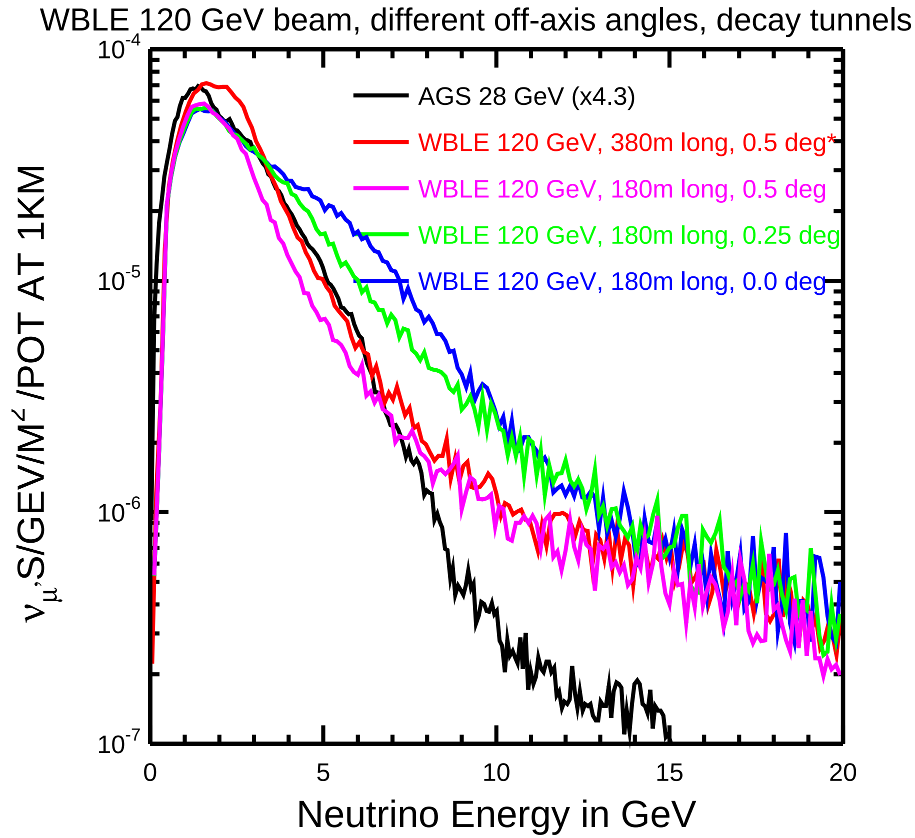
-Minimize the neutral-current feed-down contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is no sensitivity to the oscillation parameters is highly desirable.

WBLE Beam Spectra for VLBNO

Decay pipe radius chosen to be 2m = the maximum that can be accomodated in FNAL rock with concrete shielding for a MW class beam.

Siting restrictions at FNAL $\Rightarrow$ decay pipe is $\lesssim$ 400 m in length





GEANT 3.21 simulation of wide-band horns+decay pipe, with FLUKA '05 for target hadro-production.

Based on NuMI simulation which matches observed MINOS event rate to 10% in 0 - 7 GeV range

ν_e Appearance Rates

$\Delta m^2_{21,31} = 8.6 \times 10^{-5}, 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{12,23} = 0.86, 1.0$

		$\nu_\mu \longrightarrow \nu_e$ rate				$\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ rates			
(sign of Δm^2_{31})	$\sin^2 2\theta_{13}$	δ_{CP} deg.							
		0°	-90°	180°	+90°	0°	-90°	180°	+90°
NuMI LE beam tune at 810km, per 100kT. MW. 10^7s									
15 mRad off-axis (NOνA)		Beam ν_e = 43*				Beam $\bar{\nu}_e$ = 17*			
(+)	0.02	76	108	69	36	20	7.7	17	30
(-)	0.02	46	77	52	21	28	14	28	42
50 mRad off-axis		Beam ν_e = 11*				Beam $\bar{\nu}_e$ = 3.4*			
(+)	0.02	5.7	8.8	5.1	2.2	2.5	1.6	0.7	3.3
(-)	0.02	4.2	8.0	5.7	2.0	2.3	2.2	0.8	3.6
WBLE 120 GeV beam at 1300km, per 100kT. MW. 10^7s									
9 mRad off-axis		Beam ν_e = 47**				Beam $\bar{\nu}_e$ = 17**			
(+/-)	0.0	14	N/A	N/A	N/A	5.0	N/A	N/A	N/A
(+)	0.02	87	134	95	48	20	7.2	15	27
(-)	0.02	39	72	51	19	38	19	33	52

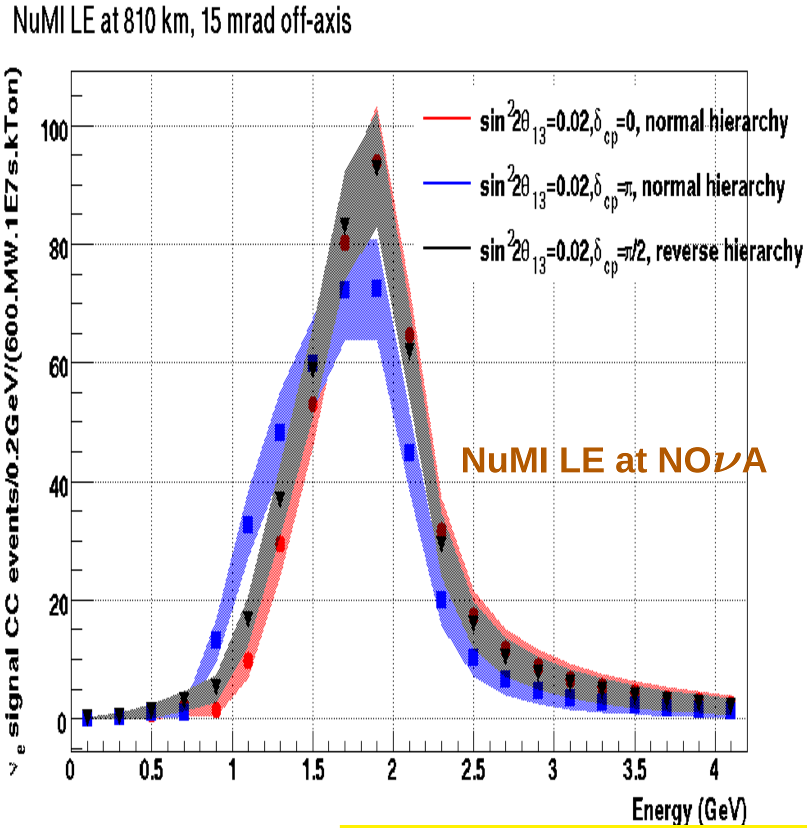
* = 0-3 GeV ** = 0-5 GeV, 1 MW. 10^7s = 5.2×10^{20} POT at 120 GeV, 1yr $= 1.7 \times 10^7 s$

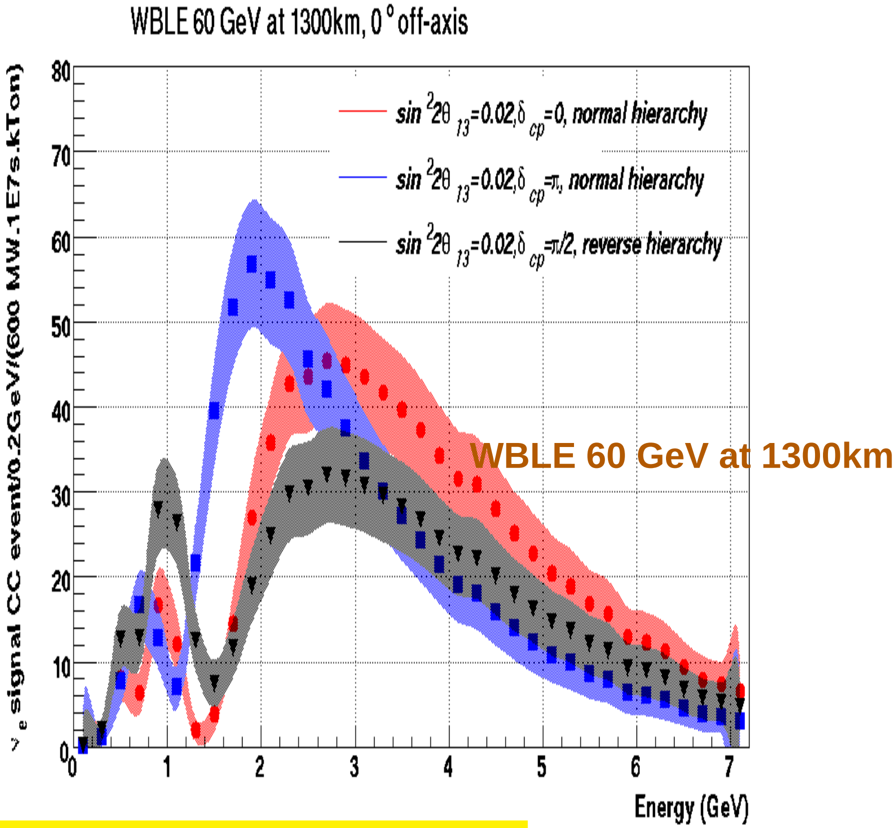
ν_e Appearance Spectra

—- $\sin^2 2\theta_{13} = 0.02, \delta_{cp} = 0$, normal hierarchy

—- $\sin^2 2\theta_{13} = 0.02, \delta_{cp} = \pi$, normal hierarchy

—- $\sin^2 2\theta_{13} = 0.02, \delta_{cp} = -\pi/2$, reverse hierarchy





Spectral information = resolves degeneracies

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

“T2KK Project & Likelihood study”. Fanny Dufour, FNAL-BNL VLB workshop, September 16, 2006

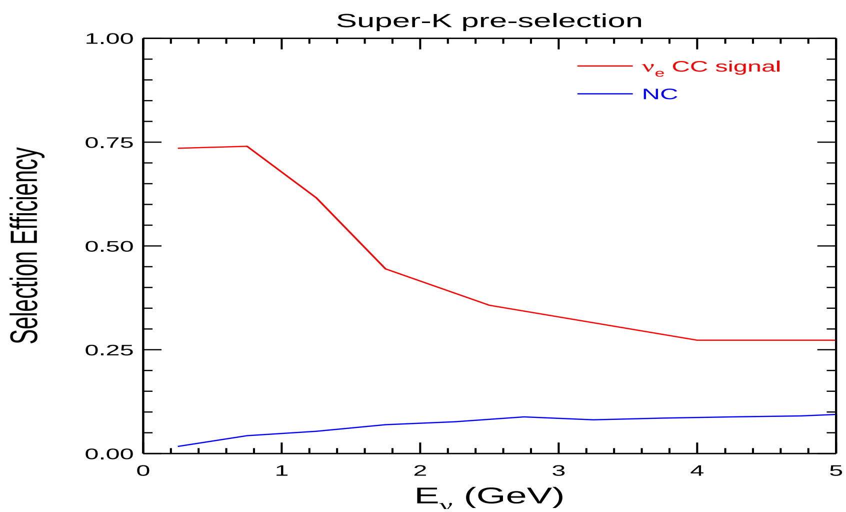
”Monte Carlo study of a liquid Ar time projection chamber for long baseline neutrino experiments.” A. Curioni, August 10, 2006.

www-larptc.fnal.gov/LBStudy_LAr/2006LB.html

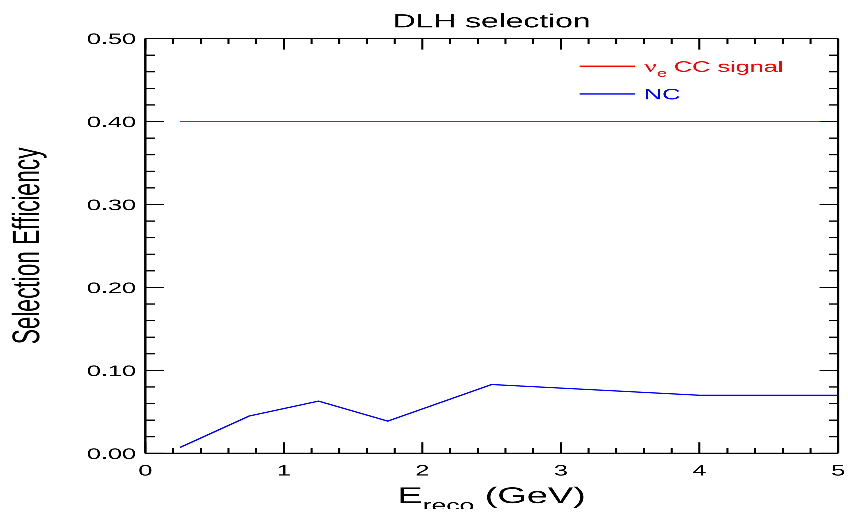
Water Cerenkov Simulation

The ν_{atm} GEANT simulation of SuperKamiokande is used.

An π^0 reconstruction algorithim called “Pattern Of Light Fit” is used as input to a likelihood (DLH) analysis to reconstruct $\pi^0 \rightarrow \gamma\gamma$ by looking for the 2nd ring. Independent studies by Chiaki Yanagisawa for FNAL-DUSEL WBB and Fanny Dufour for T2KK produce similar efficiency for signal and background.



Standard Super-K pre-selection efficiencies



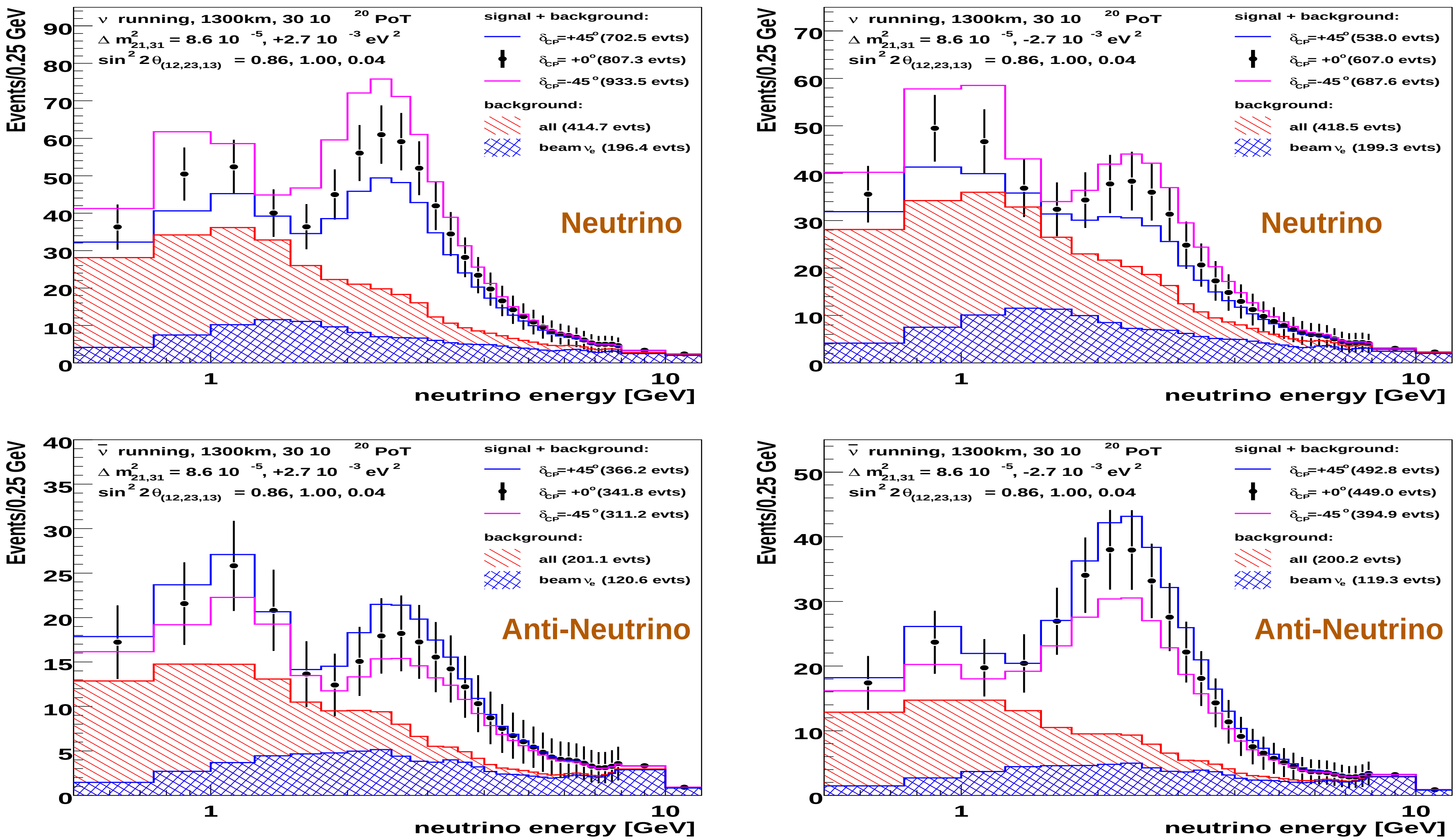
DLH selection efficiencies (Chiaki Y.)

WCe. energy dependent efficiencies and smearing implemented in GLoBeS.

GLoBeS ν_e Appearance Spectra

$\sin^2 2\theta_{13} = 0.04$, **300kT WCe.** , **WBLE 120 GeV, 1300km, 30E20 POT.**

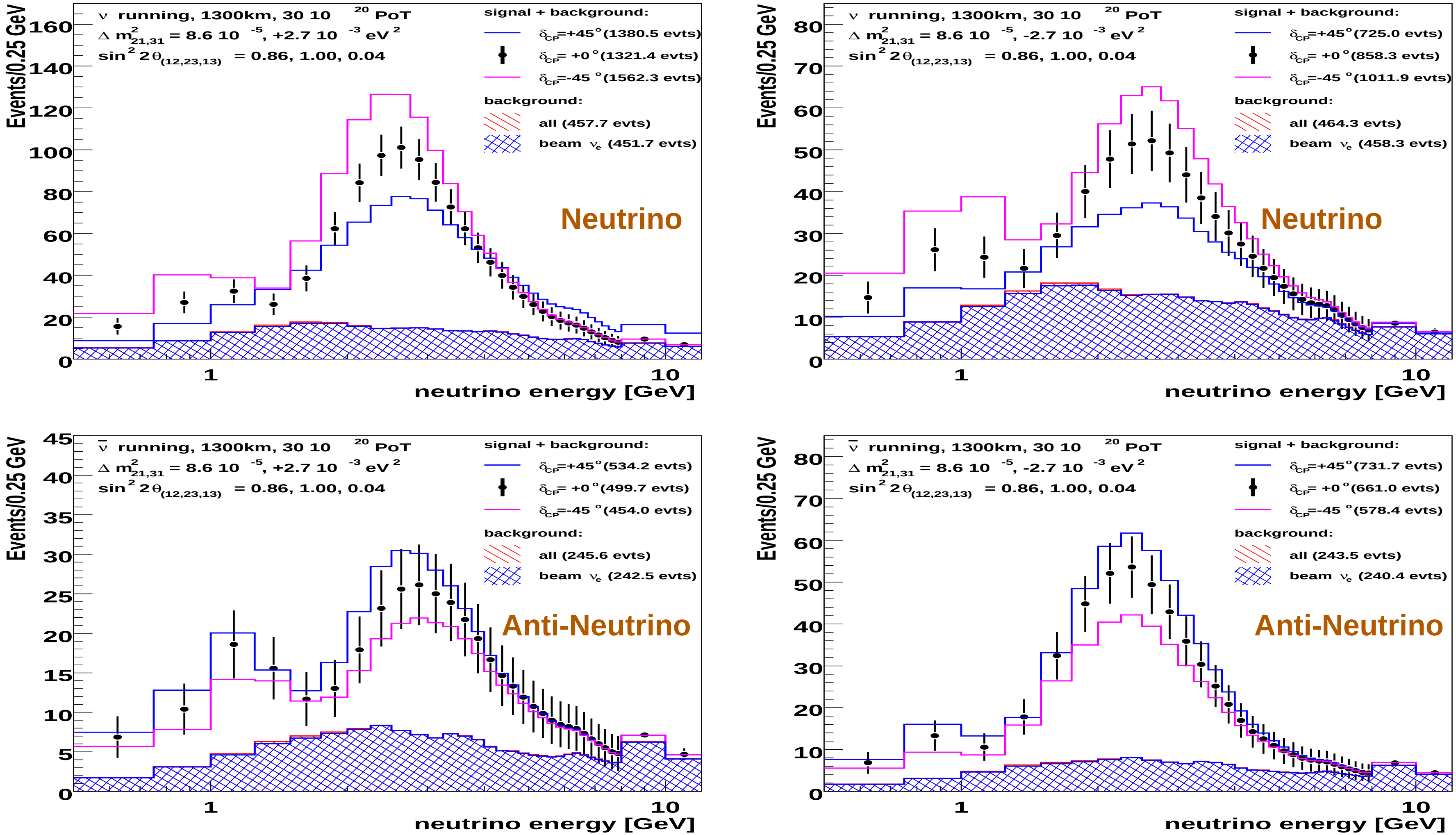
Normal hierarchy $(-\delta_{cp} = -45^\circ, -\delta_{cp} = +45^\circ)$ **Reversed hierarchy**



GLoBeS ν_e Appearance Spectra

$\sin^2 2\theta_{13} = 0.04$, **100kT LAr.** , **WBLE 120 GeV, 1300km, 30E20 POT.**

Normal hierarchy $(-\delta_{cp} = -45^\circ, -\delta_{cp} = +45^\circ)$ **Reversed hierarchy**



LAr simulation: 80% efficiency for ν_e CC, $\sigma(E)_{QE} = 5\%.\sqrt{(E)}$, $\sigma(E)_{CC} = 20\%.\sqrt{(E)}$

PHYSICS SENSITIVIES

V. Barger, M. Dierckxsens, M. Diwan, P. Huber, C. Lewis, D. Marfatia, B. Viren, Jul 17, 2006

hep-ph/0607177,BNL-76797-2006-JA

V. Barger, P. Huber, D. Marfatia and W. Winter Mar 4, 2007 hep-ph/0703029

Estimating Sensitivities

Matrix parameters used & systematic uncertainties:

-$\Delta m^2_{21,31} = 8.6 \times 10^{-5}(5\%), 2.7 \times 10^{-3}$ eV^2 (uncertainty determined from fit to disappearance mode) -$\sin^2 2\theta_{12,23} = 0.86(5\%), 1.0$(uncertainty determined from fit to disappearance mode) -Matter density (5%) -Background (10%)

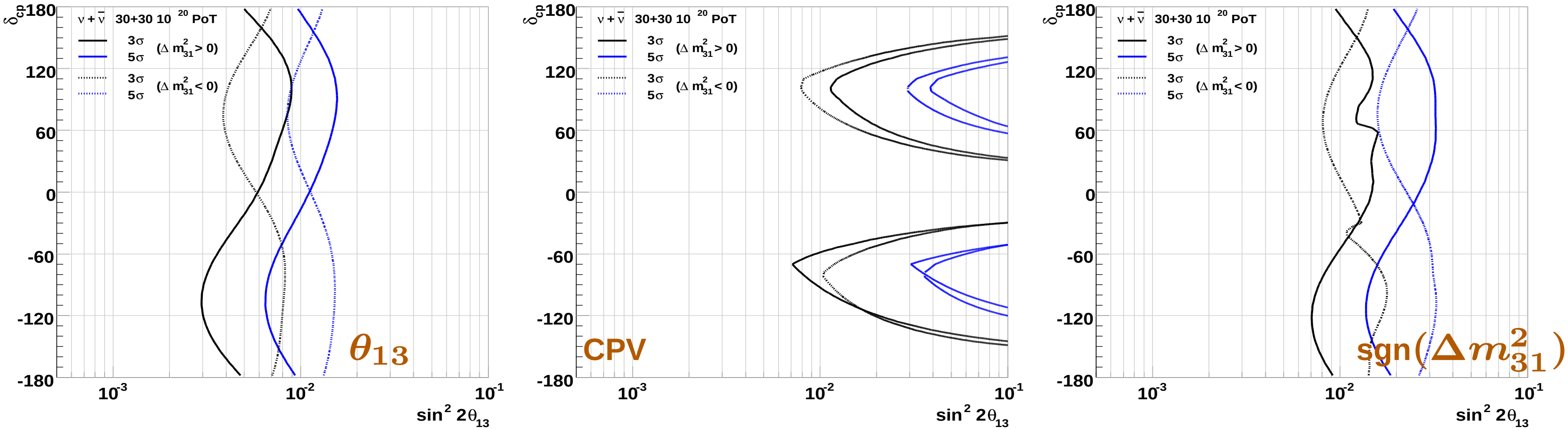
Determining θ_{13} sensitivity: Fit the appearance spectrum generated for a particular θ_{13}, δ_{cp} to the oscillation hypothesis with $\theta_{13} = 0$. Mass hierarchy is fixed.

CP-violation sensitivity: Fit the appearance spectrum to the oscillation hypothesis with $\delta_{cp} = 0$ and π. Take the worst χ^2.
θ_{13} is allowed to float in the fit. Mass hierarchy is fixed.

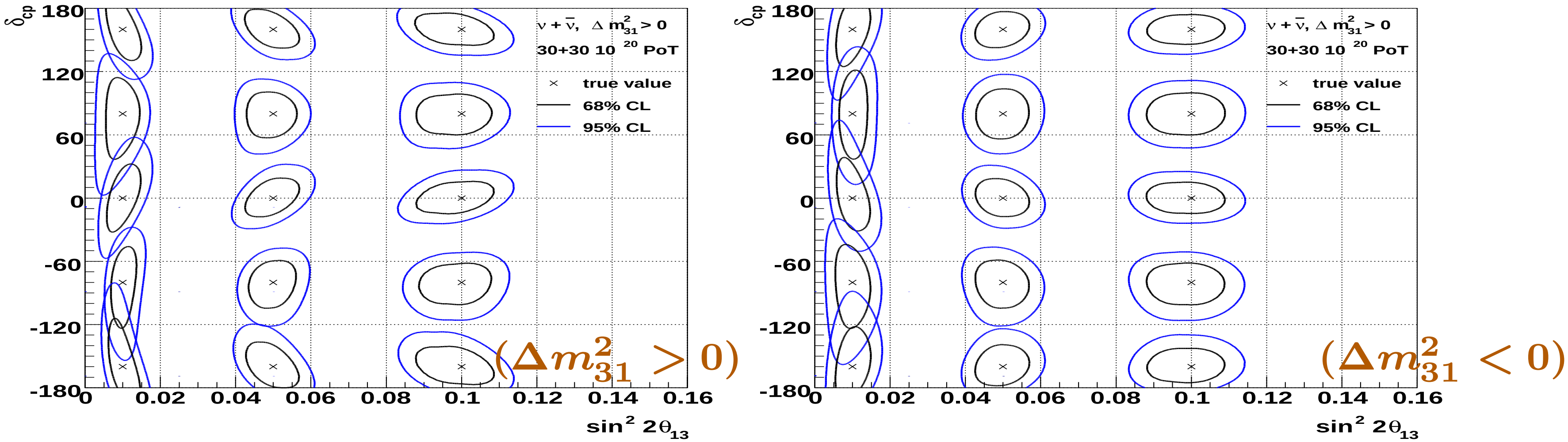
sign(Δm^2_{31}): Fit the appearance spectrum to the oscillation hypothesis with the opposite mass hierarchy.
BOTH θ_{13} and δ_{cp} are allowed to float in the fit.

WBLE to DUSEL (1300km)

Discovery potential (—5σ —3σ). WCe. 300 kT, 1.2 MW, 6yrs:

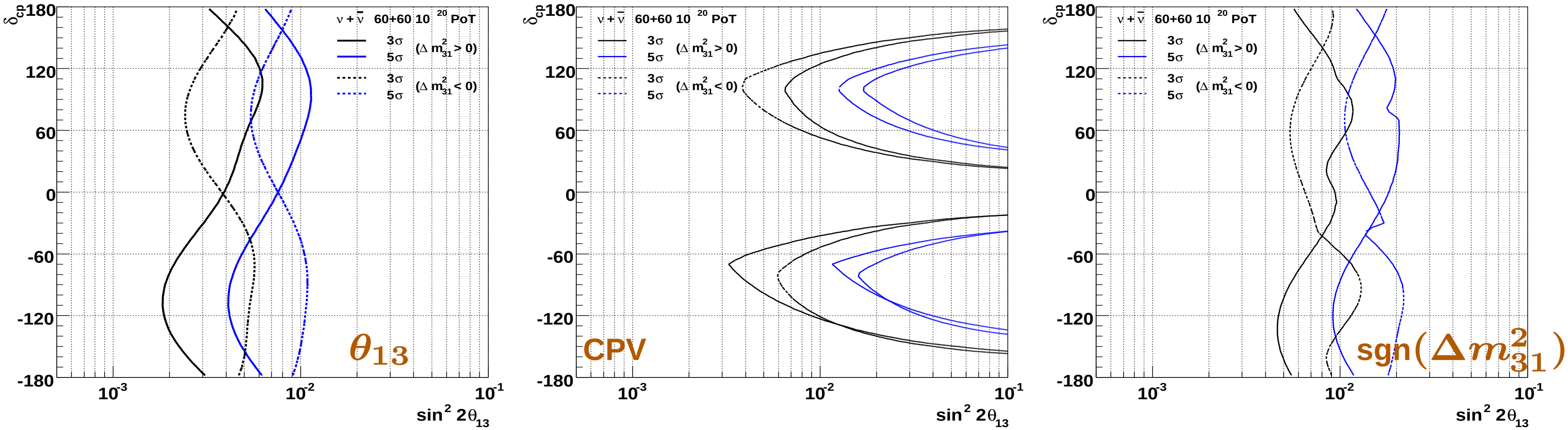


Measurement (—95% CL —68% CL) :

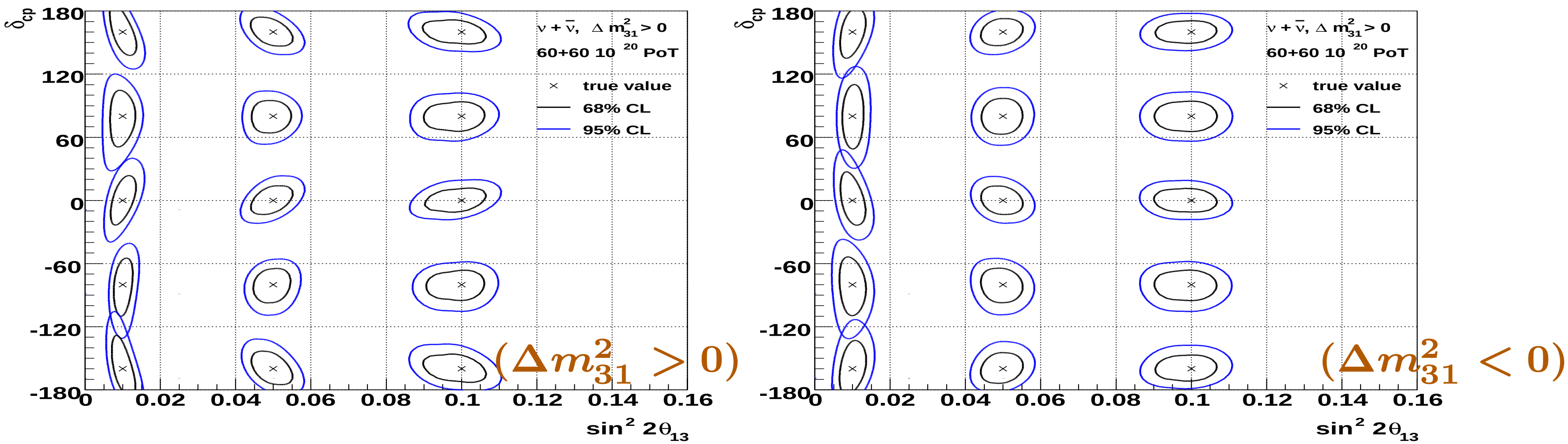


WBLE to DUSEL (1300km)

Discovery potential (— 5σ —3σ). WCe. 300 kT, 1.2 (2) MW, 12 (7) yrs:

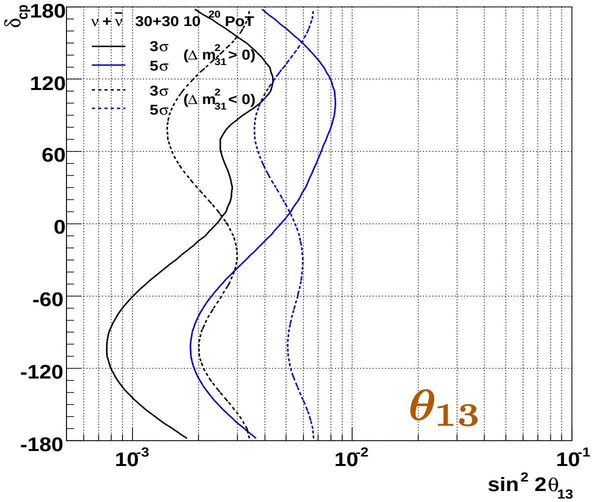


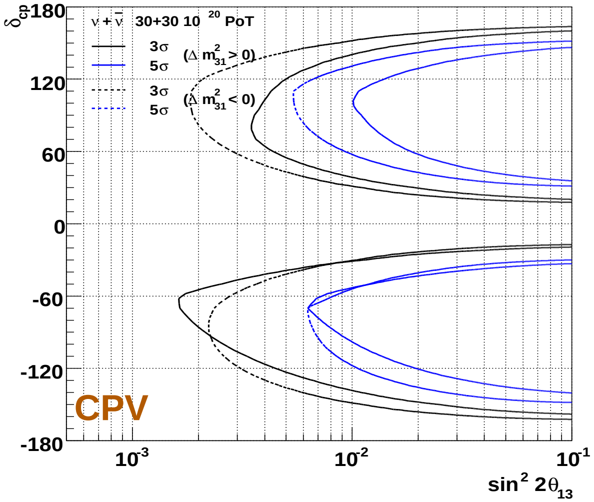
Measurement (—95% CL —68% CL) :

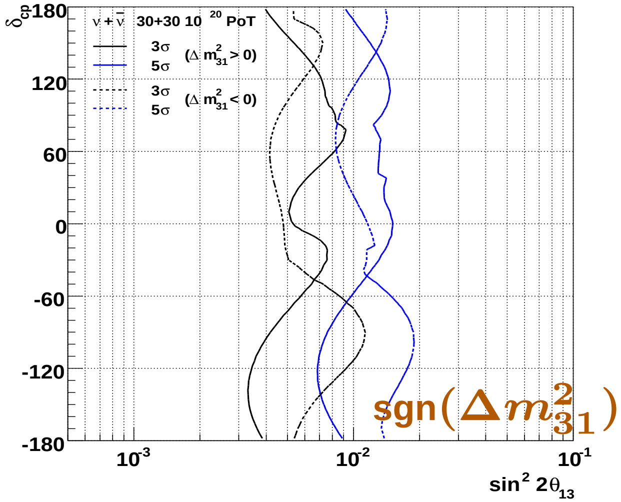


WBLE to DUSEL (1300km)

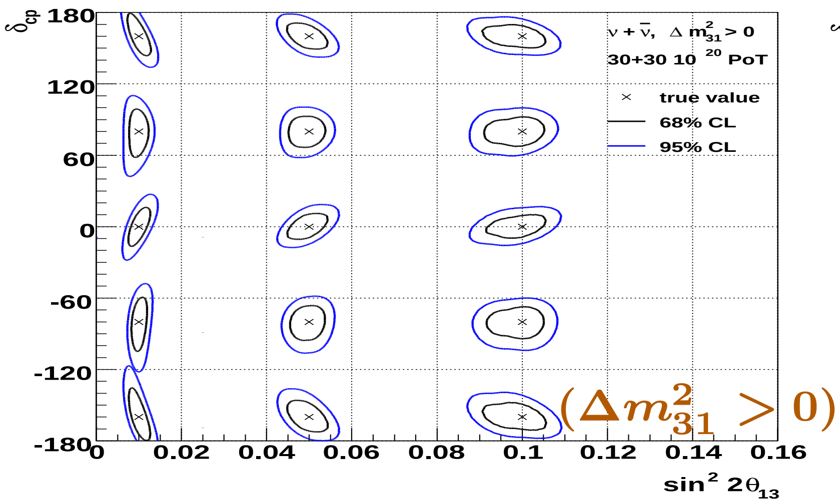
Discovery potential (— 5σ —3σ). LAr. 100 kT, 1.2 MW, 6yrs:

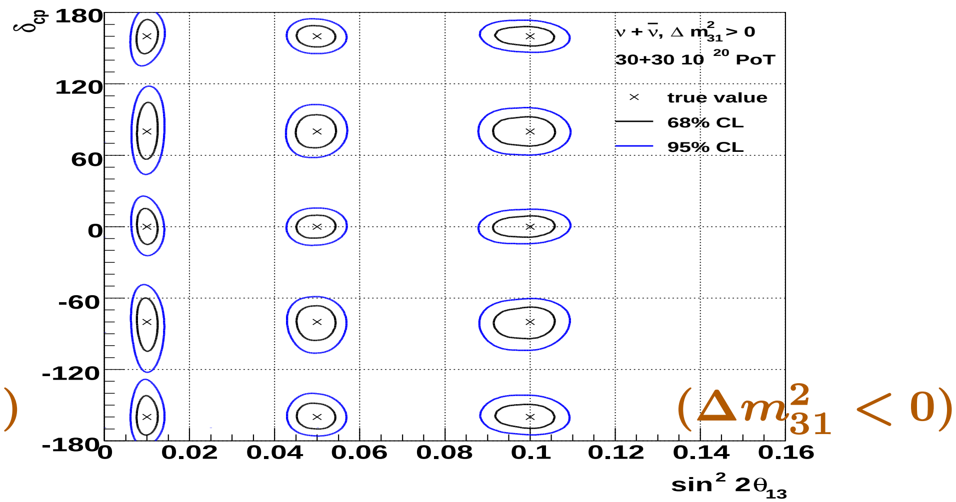






Measurement (—95% CL —68% CL) :





Milestones

- **Detailed study of different FNAL beam power scenarios**
- **Conceptual design of beamline to DUSEL from FNAL**
- **Detailed definition/simulation of a WBLE beam from FNAL complete.**
- **Detailed simulation of ν_e signal and backgrounds in a Water Cerenkov detector complete.**
- **MC for LAr under development. Performance is based on eye scanning with a narrow band beam.**
- **Physics sensitivities using a FNAL based WBLE beam to DUSEL with a 300kT WC and 100 kT LArTPC computed.**
- **Preliminary cost, timelines for building a modularized 300 kT Water Cerenkov detector at Homestake Mine produced (for discussion).**

First draft of the study report is in preparation.

FOR FURTHER DISCUSSION

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?**

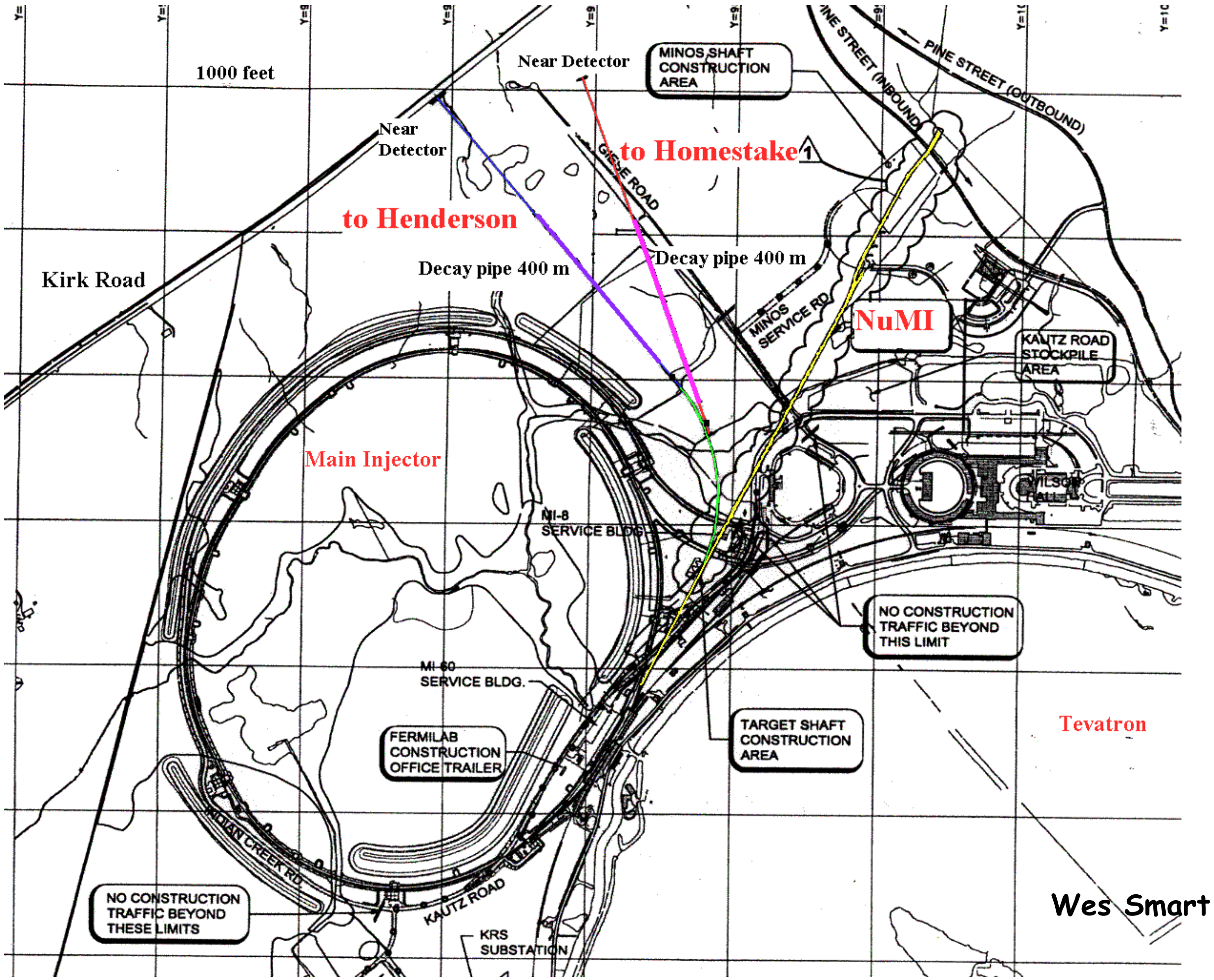
BEAMLINE DESIGN/SIMULATIONS

”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

DUSEL Beamline Siting at FNAL

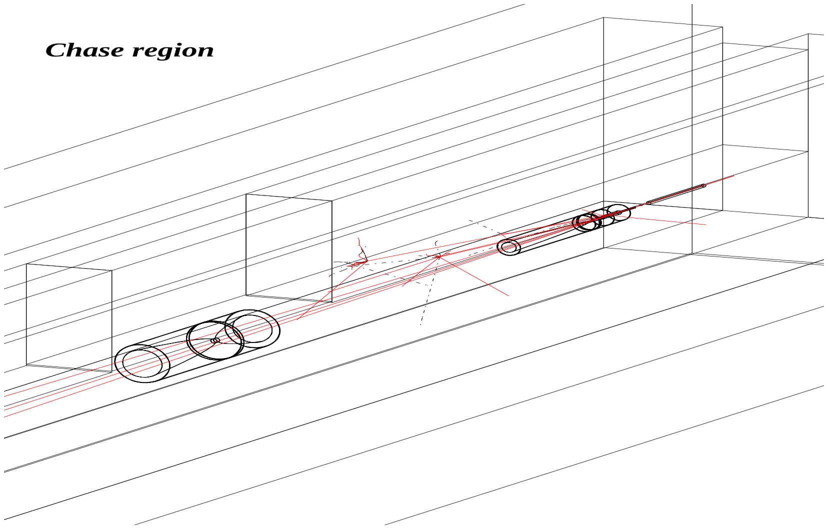
Greg Bock, Dixon Bogert, Wes Smart (FNAL)

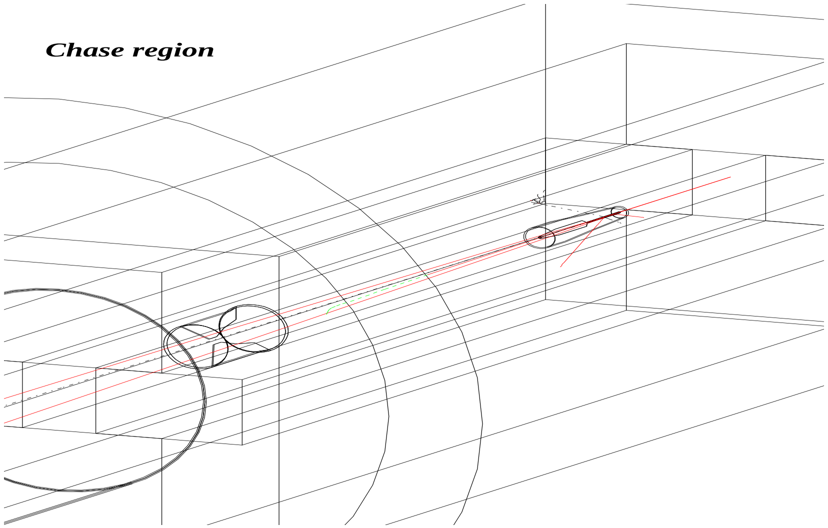


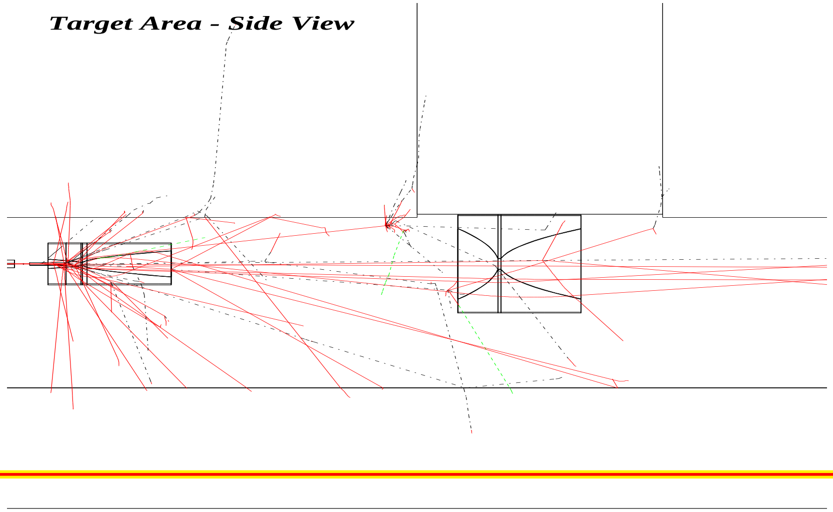
Beamlines to DUSEL can accomodate a decay tunnel with $L \leq 400$m on-site

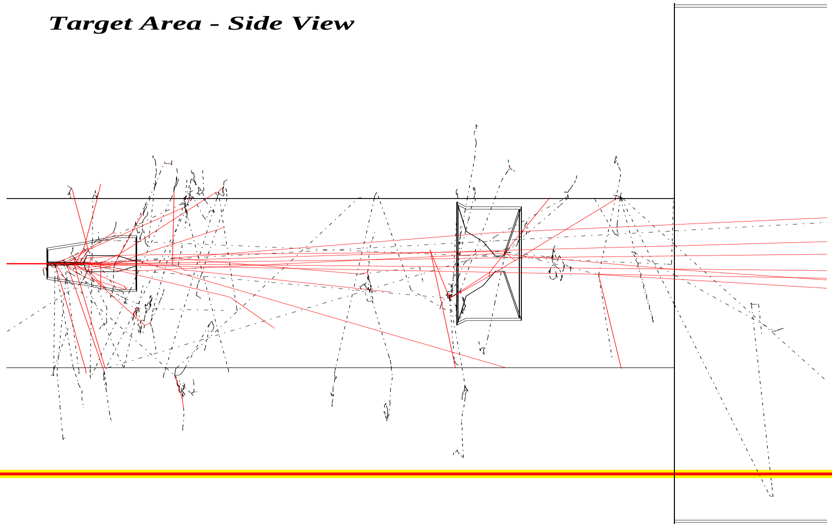
NuMI/WBLE simulation

NuMI horns/target with 120 GeV p+ **WBLE horns/target with 120 GeV p+**



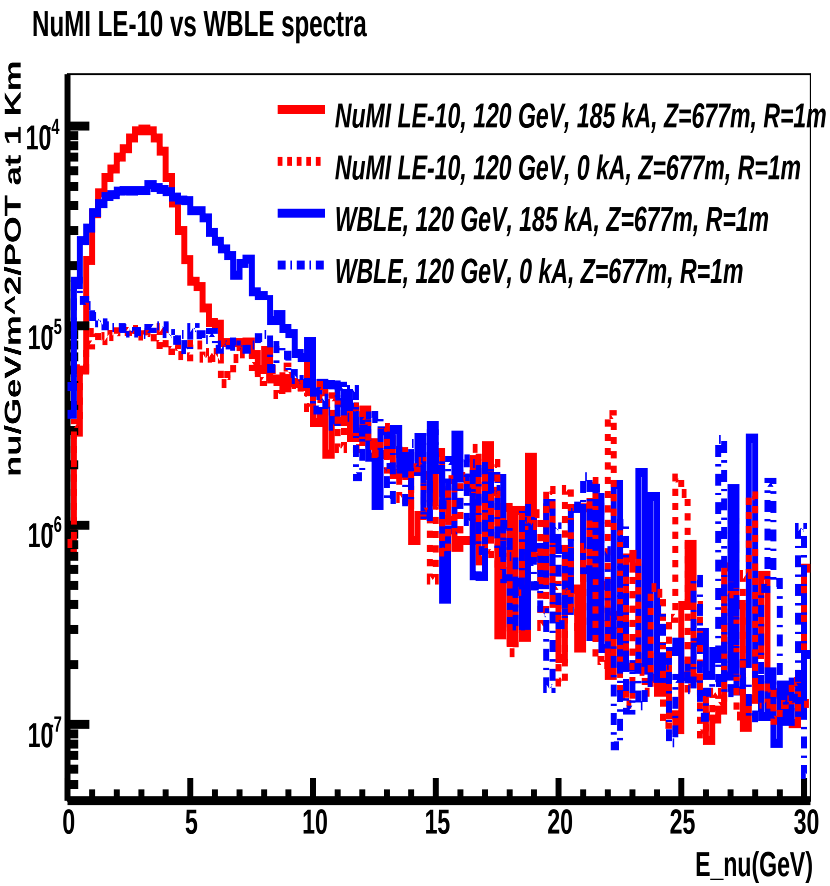




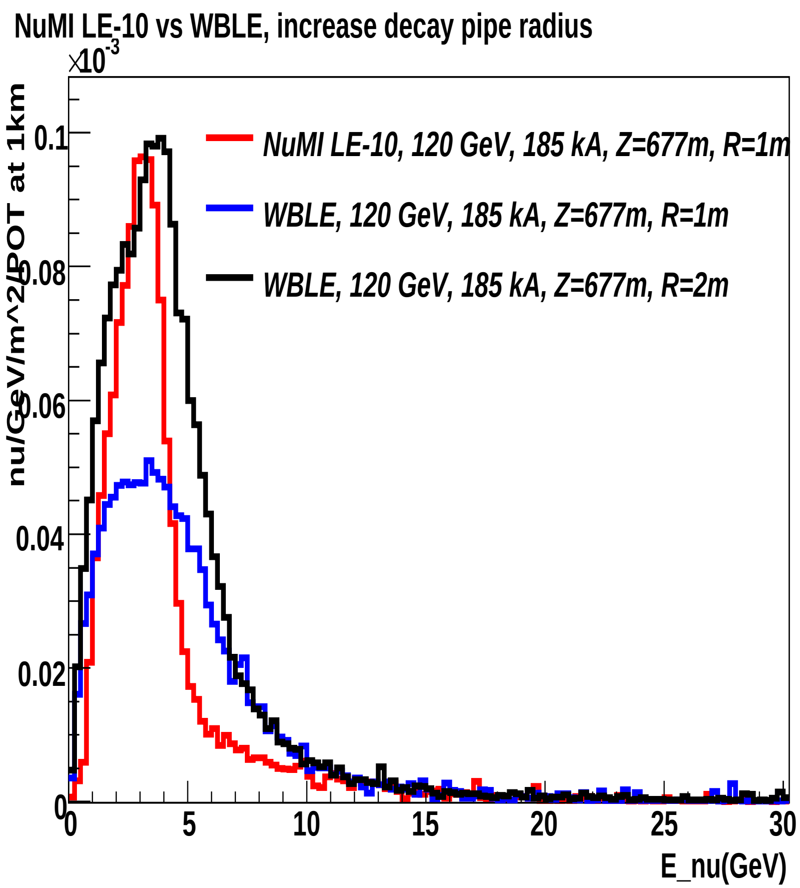


NuMI LE vs WBLE

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



1m radius decay pipe



increase to 2m radius

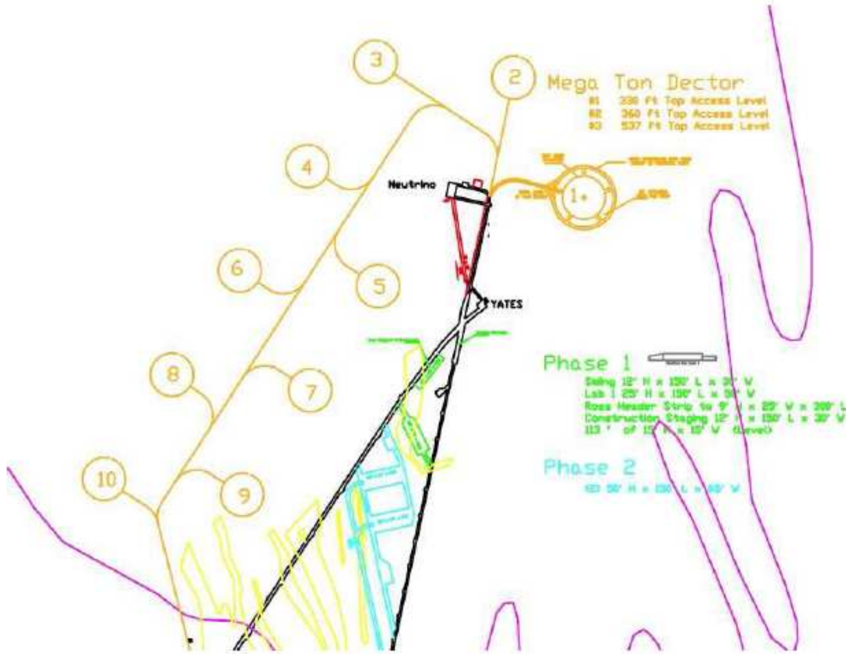
Larger diameter decay pipe = more flux at low E.

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

“Large Cavity Excavation”. William Pariseau (University of Utah), FNAL-BNL VLB workshop, September 16, 2006

Modularized Detectors at HS

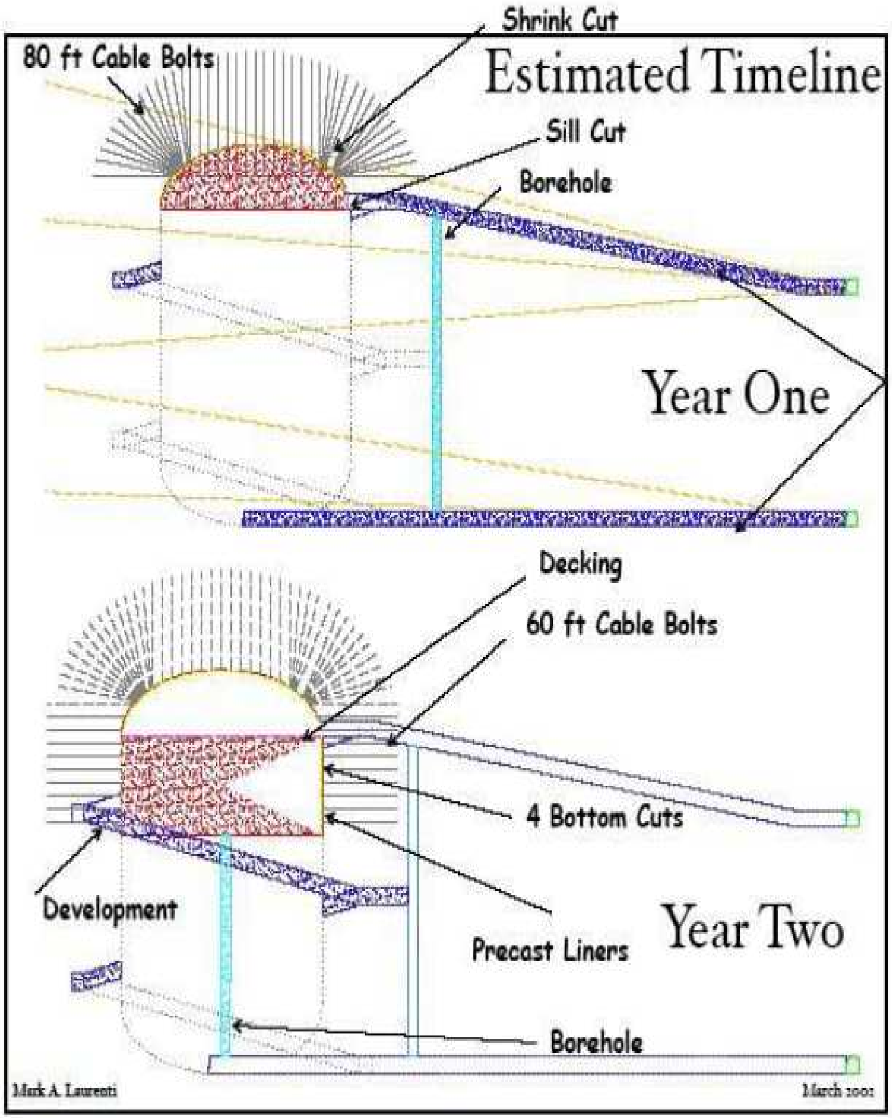


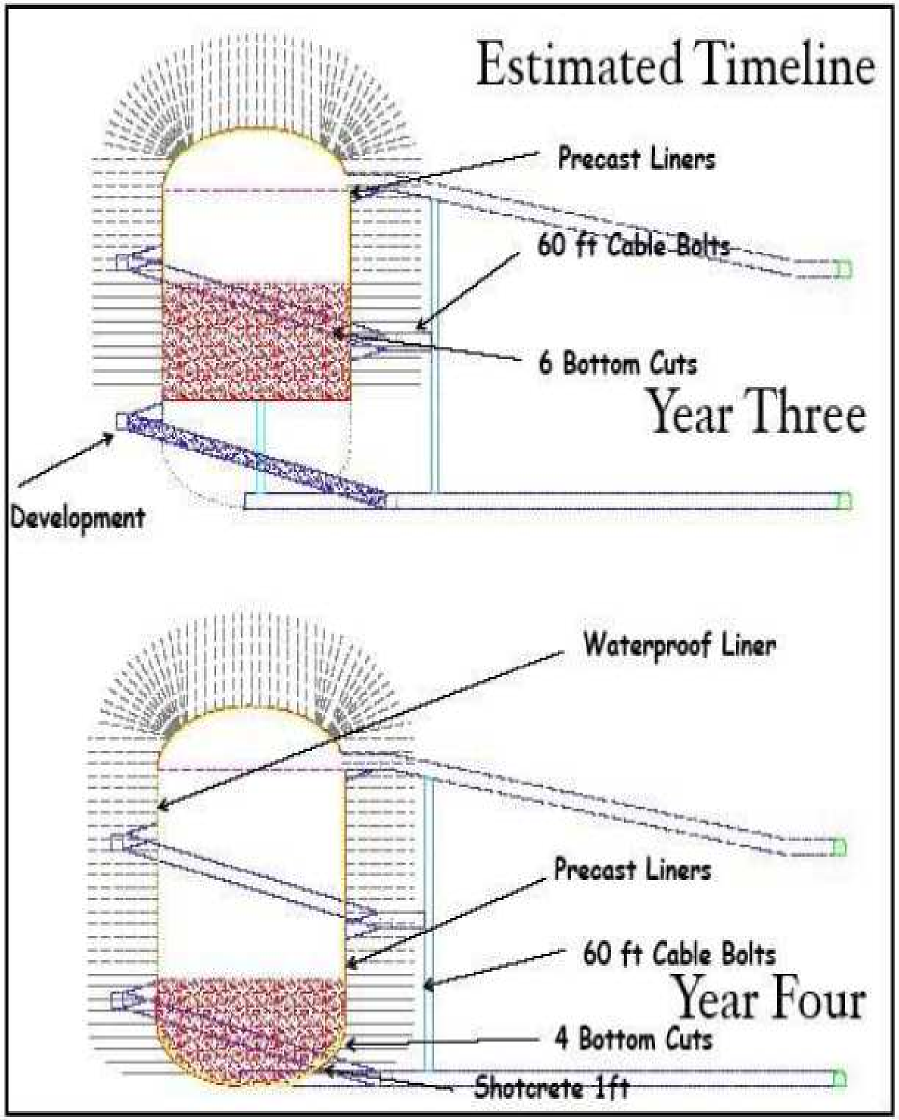
The detector system will be deployed in the 4850 ft level as seperate 100kT Water Cerenkov detector modules to allow a staged approach with potential for expansion.

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 (fiducial)

Construction costs for 3 caverns:

Cost Description	Amount
Labor/benefits	$19.3M
Minig equipment	$5.30M
Mining equipment operations	$4.55M
Supplies	$15.8M
precast concrete liner	$11.4M
Plastic liner	$0.79M
Outside contractor (bore holes)	$0.42M
Rock removal	$3.18M
Contingency	$18.2
Total for 3 chambers	$78.9

Detector costs

For 25% PMT coverage of 11,000m^2 using 8” PMTs. Extrapolated from SNO.

Cost Description	Amount
PMT+electronics	$171.3M
R&D,Water,DAQ, etc	$8.2M
Installation+testing	$35.7M
Contingency (non-civil)	$50.8M
Total detector cost (3 Modules)	$266.0M

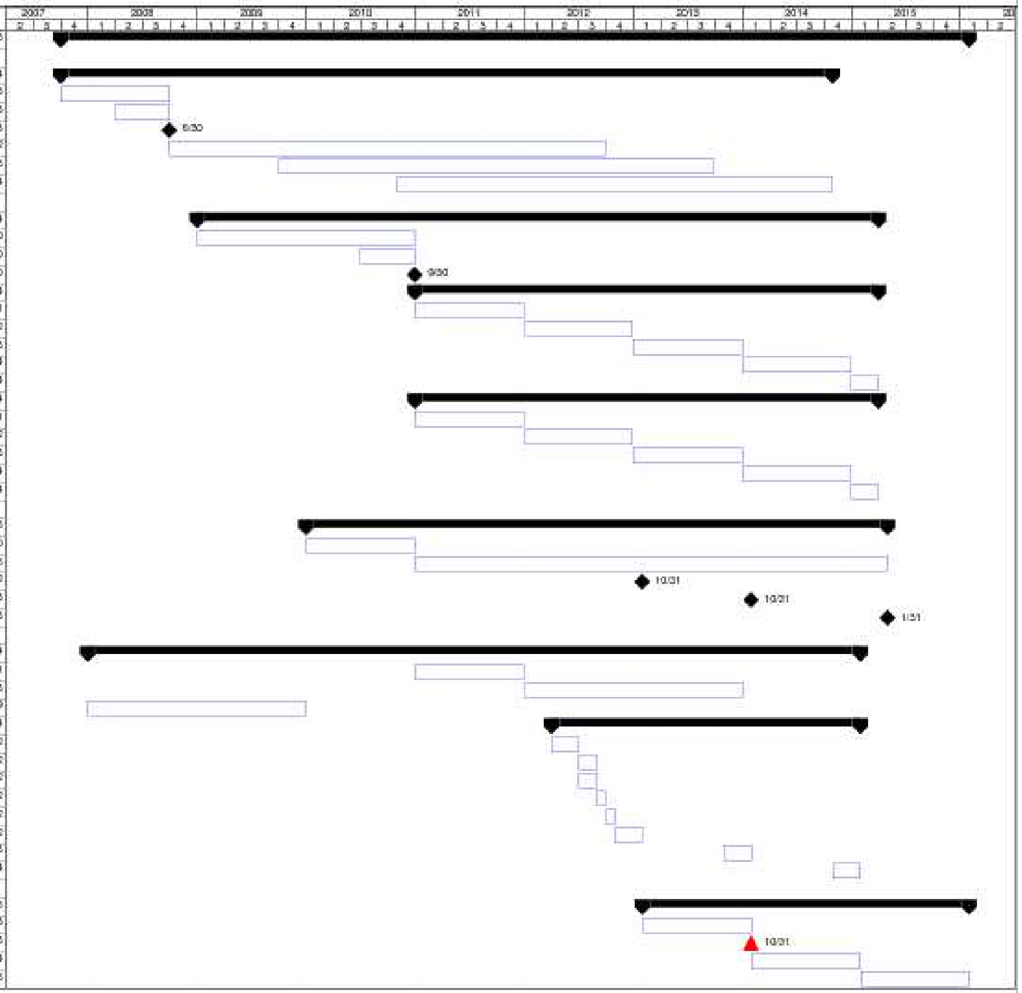
Total cost for 300kT (2007) : $345M

Costs DO NOT include managment overheads.

Overall Timeline

Long Baseline Neutrinos + PDK
Schedule No. 2

ID	Task Name	Start	Finish
1	Long Baseline Neutrinos + PDK	7/2/07	10/30/15
2			
3	Chamber Construction	7/2/07	7/30/14
4	Chamber R&D	7/2/07	6/30/08
5	Contract Process	1/1/08	6/30/08
6	Chamber Construction Contract Award	6/30/08	6/30/08
7	Module 1	7/1/08	6/29/12
8	Module 2	7/1/09	6/28/13
9	Module 3	8/2/10	7/30/14
10			
11	PMs	10/1/08	12/31/14
12	PM R&D	10/1/08	9/30/10
13	Contract Process	4/1/10	9/30/10
14	PMs Contract Award	9/30/10	9/30/10
15	Vendor 1	10/1/10	12/31/14
16	Qty 10,000 PMs	10/1/10	9/30/11
17	Qty 20,000 PMs	10/3/11	9/28/12
18	Qyt 20,000 PMs	10/1/12	9/30/13
19	Qty 20,000 PMs	10/1/13	9/30/14
20	Qty 5,000 PMs	10/1/14	12/31/14
21	Vendor 2	10/1/10	12/31/14
22	Qty 10,000 PMs	10/1/10	9/30/11
23	Qty 20,000 PMs	10/3/11	9/28/12
24	Qyt 20,000 PMs	10/1/12	9/30/13
25	Qty 20,000 PMs	10/1/13	9/30/14
26	Qty 5,000 PMs	10/1/14	12/31/14
27			
28	Testing	10/1/09	1/31/15
29	Test Facility	10/1/09	9/30/10
30	Testing of PMs	10/1/10	1/30/15
31	1st Module PMs ready for Installation	10/31/12	10/31/12
32	2nd Module PMs ready for Installation	10/31/13	10/31/13
33	Final Module PMs ready for Installation	1/31/15	1/31/15
34			
35	Other Equipment	10/1/07	10/31/14
36	Calibration Equipment R&D	10/1/10	9/30/11
37	Calibration Equipment	10/3/11	9/30/13
38	Development Labor	10/1/07	9/29/09
39	Water Purification	1/2/12	10/31/14
40	Purchase Order	1/2/12	3/30/12
41	Vendor	4/2/12	5/31/12
42	Shop Conversion	4/2/12	5/31/12
43	Install Water Systems (3 systems)	6/1/12	6/29/12
44	Test Water (to see if suitable)	7/2/12	7/31/12
45	Fill up 1st Chamber	8/1/12	10/31/12
46	Fill up 2nd Chamber	8/1/13	10/31/13
47	Fill up 3rd Chamber	8/1/14	10/31/14
48			
49	Installation	11/1/12	10/30/15
50	Module 1	11/1/12	10/31/13
51	Physics Turn-On	10/31/13	10/31/13
52	Module 2	11/1/13	10/31/14
53	Module 3	11/3/14	10/30/15



Page 1

Proposal Schedule 2_Jan 11 1/12/07

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

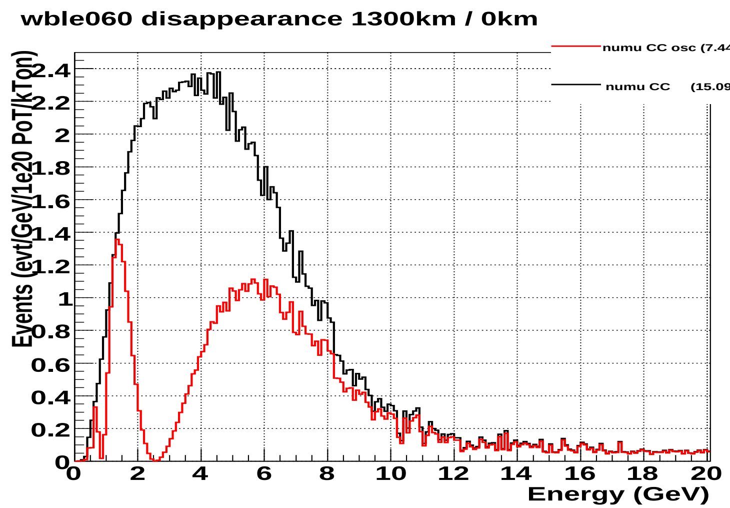
ν_μ Disappearance Rates

NO DETECTOR MODEL.

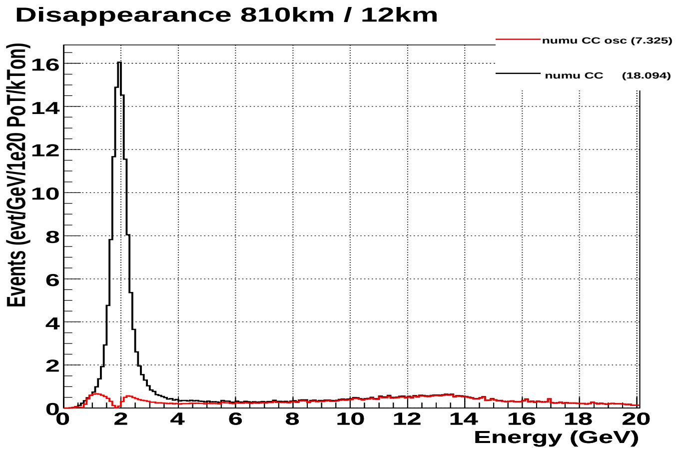
-ν_μ CC no osc.

-ν_μ CC with osc.

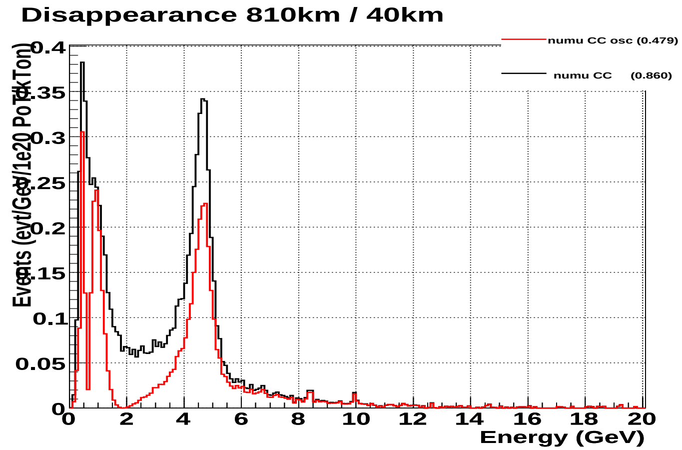
WBLE 60 GeV, 1300 km on-axis



NOVA Detector 1 810 km



NOVA Detector 2 810 km



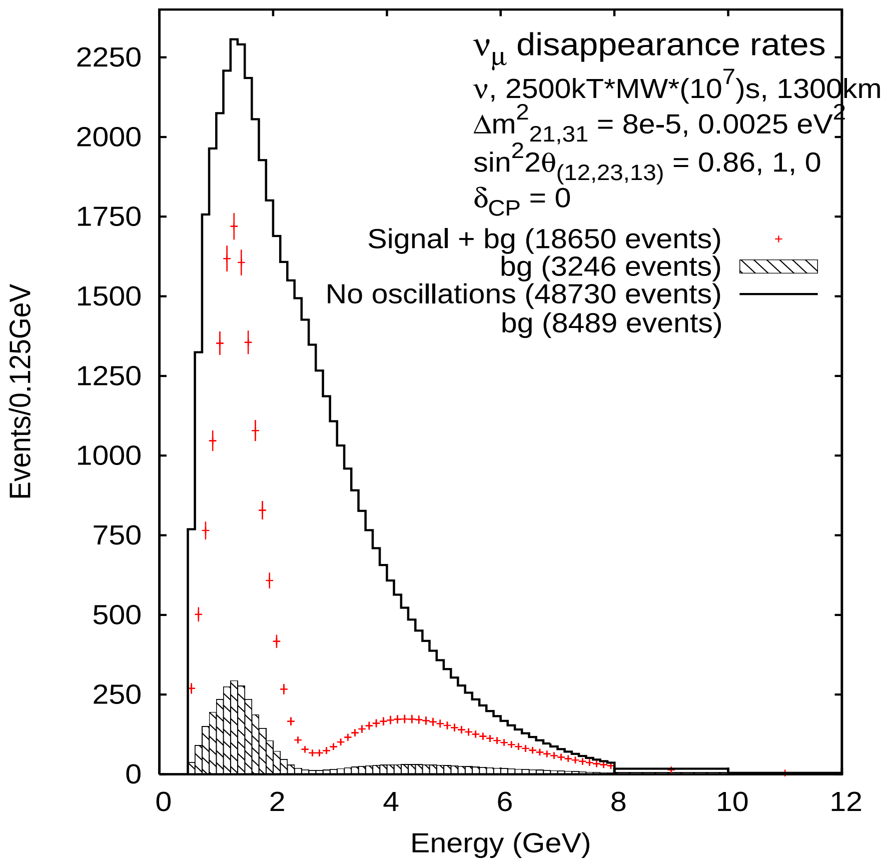
WBLE ν_μ Disappearance Spectra

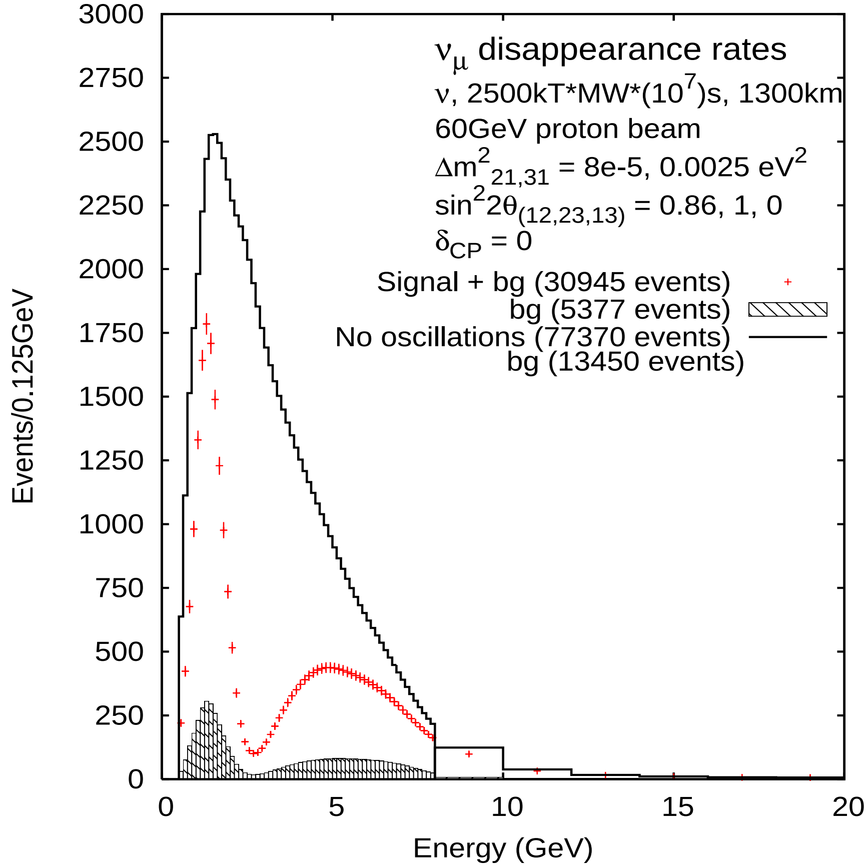
Parameterized WCe. Model in GLoBES.

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

WBB 28 GeV

WBLE 60 GeV



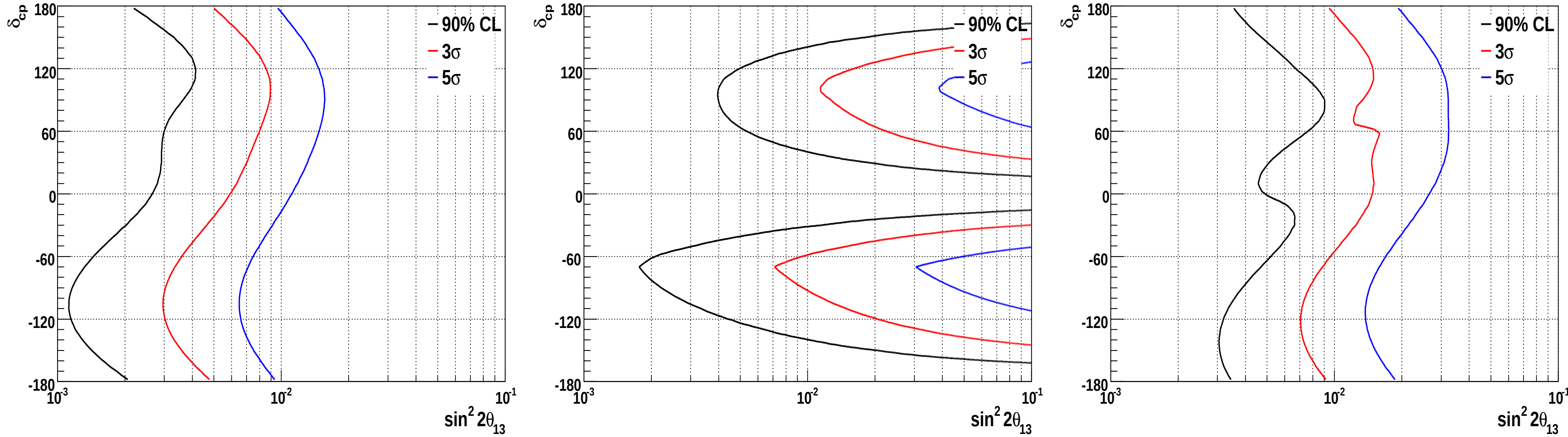


WCe. Background Composition

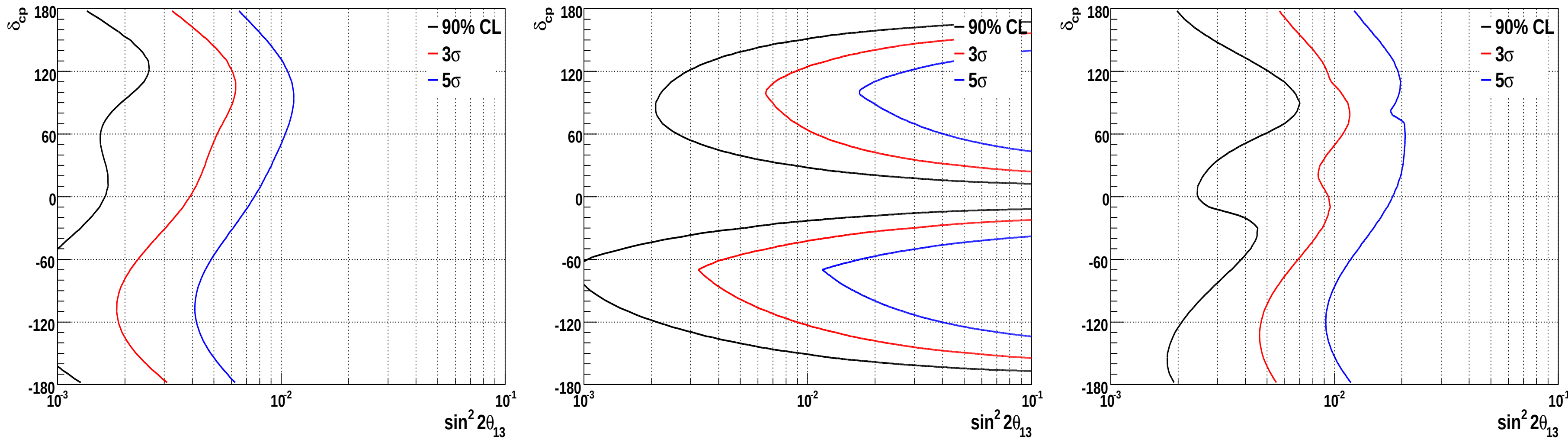
Interaction	E_{rec} range (GeV)					
Sig	0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-3.0	3.0-
CC QE	80%	78%	36%	53%	58%	55%
CC π^0	3%	3%	9%	5%	4%	5%
CC $\pi^\pm$	15%	15%	39%	30%	27%	27%
CC $n\pi$	1%	3%	14%	10%	9%	10%
CC others	0%	2%	4%	2%	5%	4%
Bkg 1	0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-3.0	3.0-
CC QE	7%	4%	1%	3%	0%	0%
CC π^0	0%	2%	6%	4%	0%	0%
CC $\pi^\pm$	5%	5%	0%	1%	1%	0%
CC $n\pi$	0%	0%	1%	6%	7%	1%
CC others	0%	0%	2%	0%	0%	0%
NC π^0	20%	54%	62%	50%	26%	0%
NC $\pi^\pm$	53%	9%	6%	0%	0%	0%
NC $n\pi$	0%	13%	5%	21%	62%	99%
NC others	15%	14%	16%	21%	1%	0%

WBLE to DUSEL (1300km) + WCe

$\nu\ 30 \times 10^{20}$ POT+ same for $\bar{\nu}$. WCe. 300 kT, 1.2 MW, 6yrs, normal.:

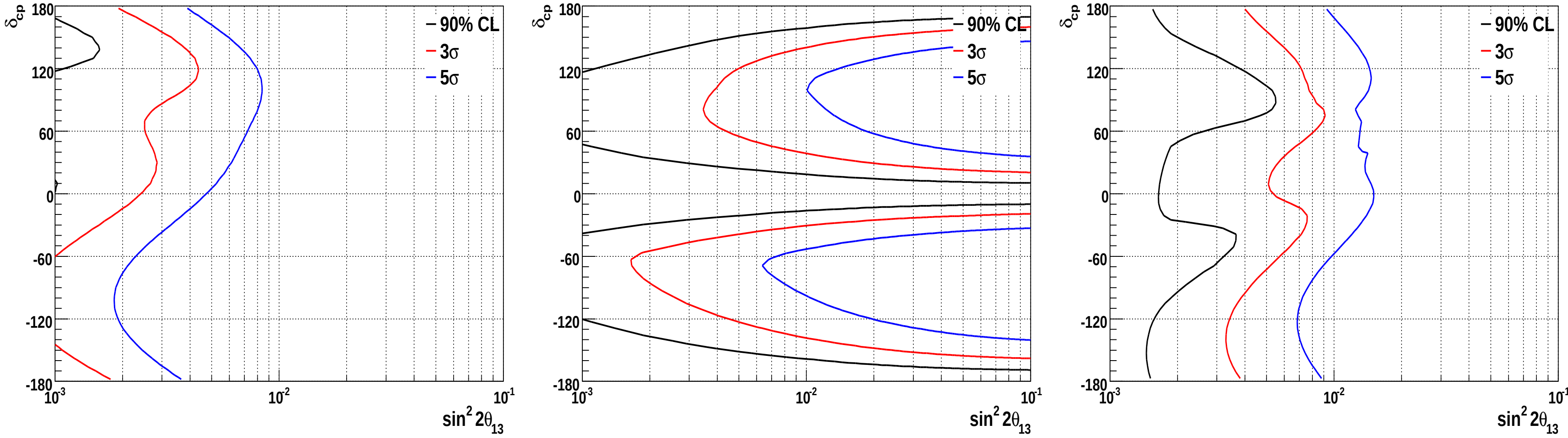


$\nu\ 60 \times 10^{20}$ POT+ same for $\bar{\nu}$. WCe. 300 kT, 1.2 (2) MW, 12 (7) yrs, normal:



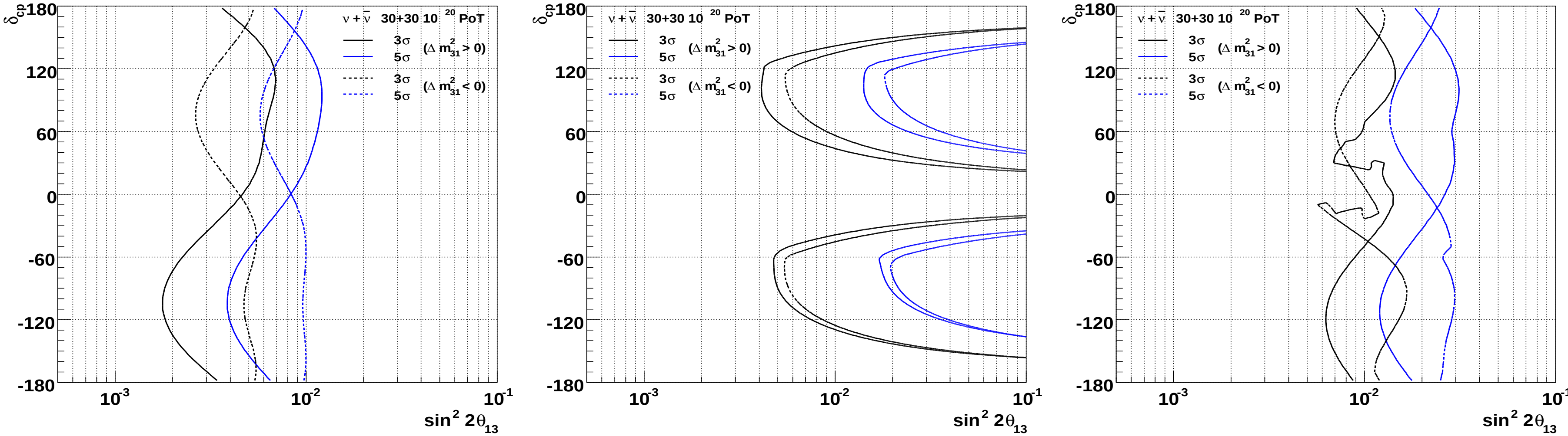
WBLE to DUSEL (1300km) + LAr

ν 30×10^{20} POT+ same for $\bar{\nu}$. LAr 100 kT, 1.2 MW beam, 6yrs, normal:

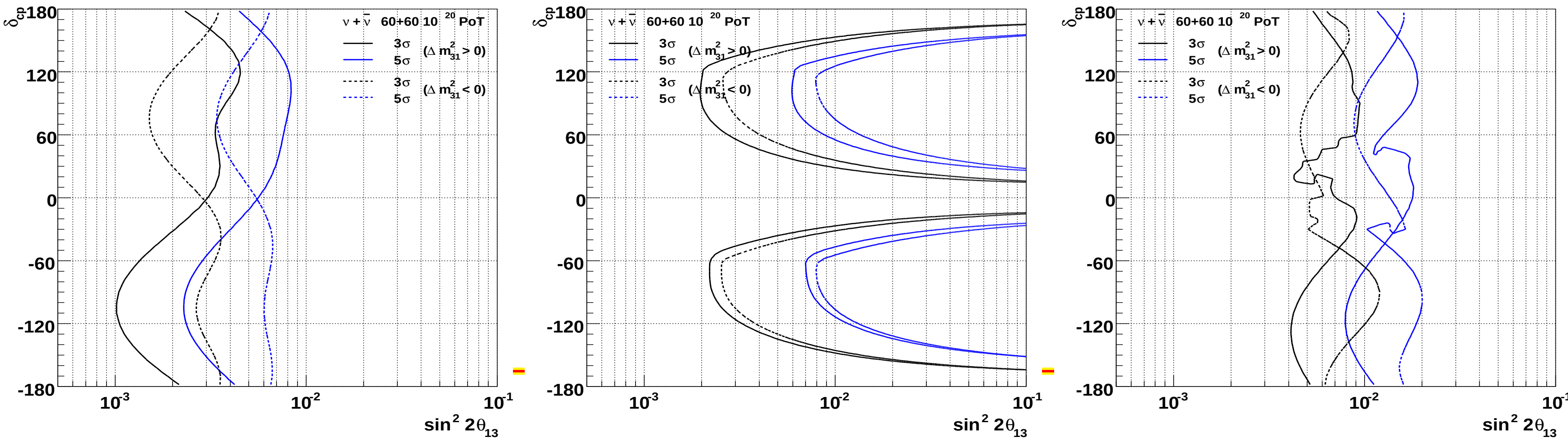


WBLE to DUSEL (1300km) + WCe

$\nu\ 30 \times 10^{20}$ POT+ same for $\bar{\nu}$. WCe. 300 kT, 1.2 MW, 6yrs, stat only:

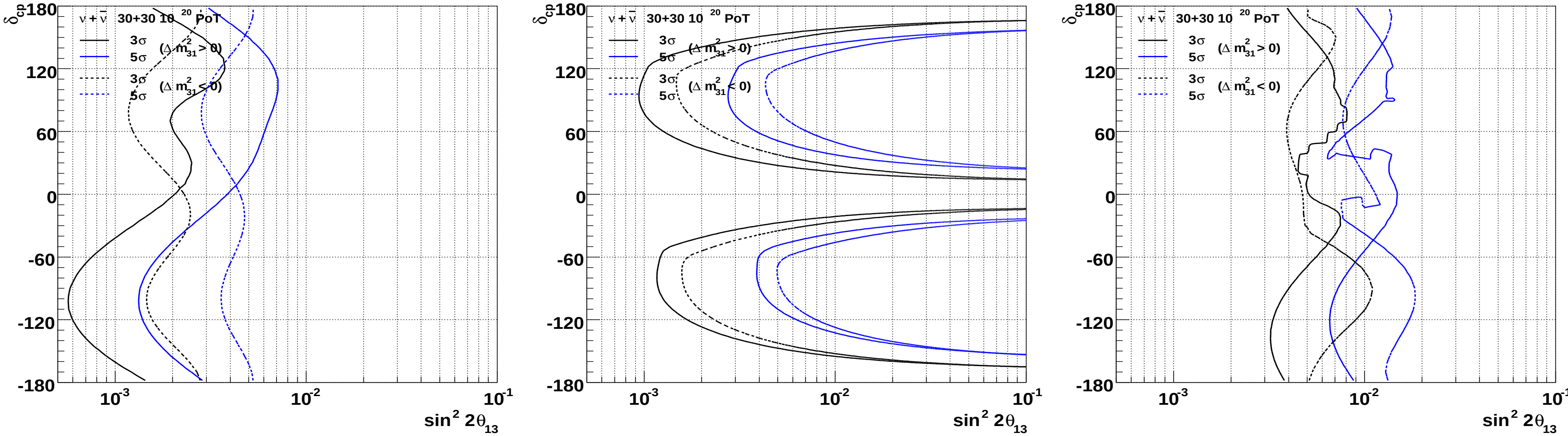


$\nu\ 60 \times 10^{20}$ POT+ same for $\bar{\nu}$. WCe. 300 kT, 1.2 (2) MW, 12 (7) yrs, stat only:

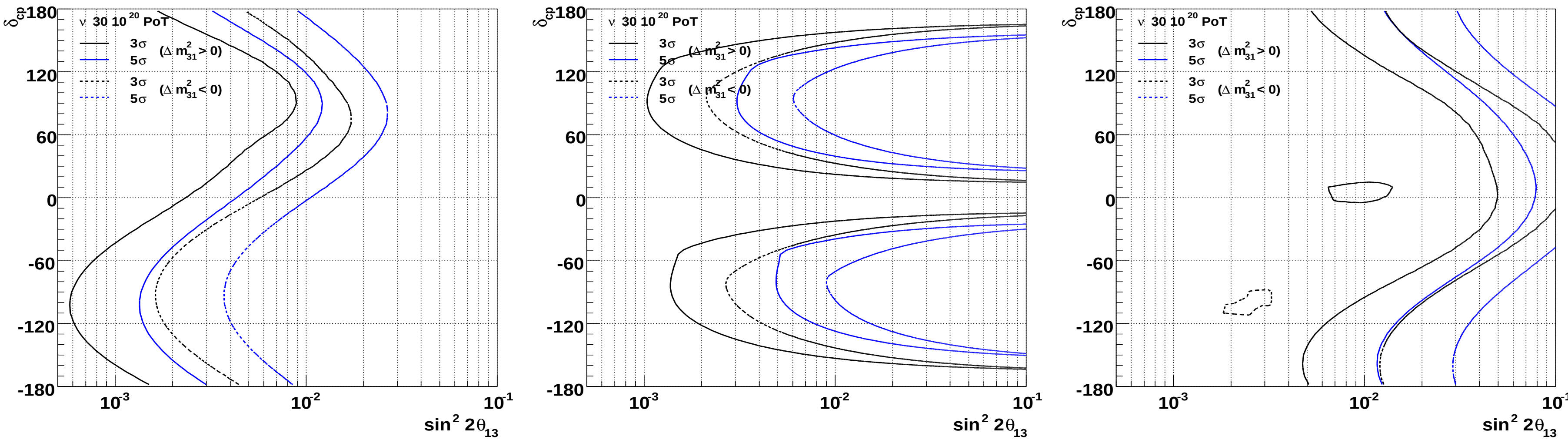


WBLE to DUSEL (1300km) + LAr

ν 30×10^{20} POT+ same for $\bar{\nu}$. LAr 100 kT, 1.2 MW beam, 6yrs, stat only:

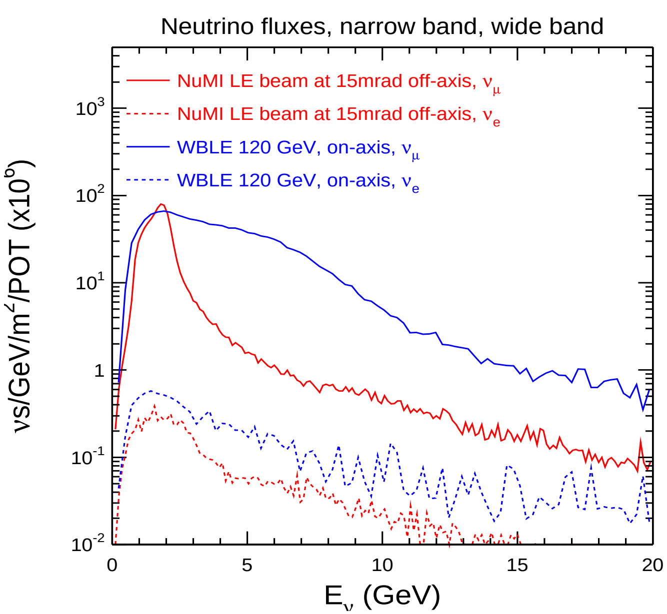


ν 30×10^{20} POT ONLY. LAr 100 kT, 1.2 MW beam, 3yrs, stat only:

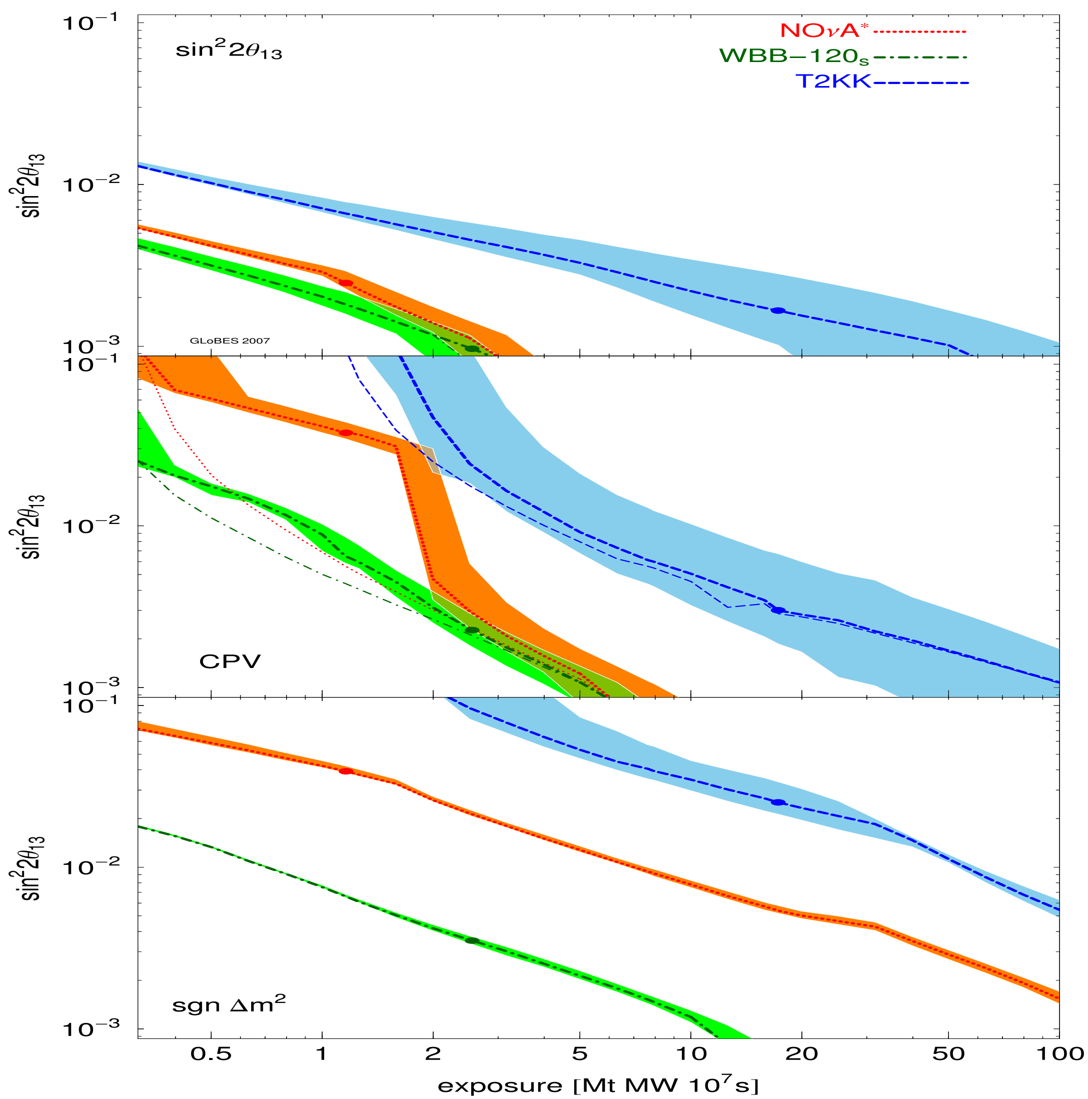


Physics Sensitivies - Compare

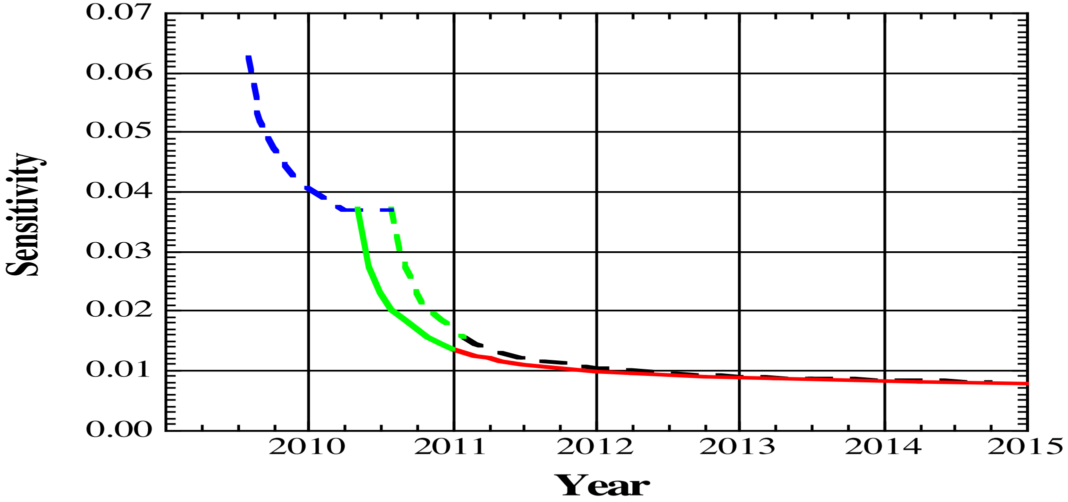
The potential physics reach from studies with the 120 GeV WBLE-DUSEL at 1300km using a LAr detector, the NOνA experiment and the T2KK experiment:*

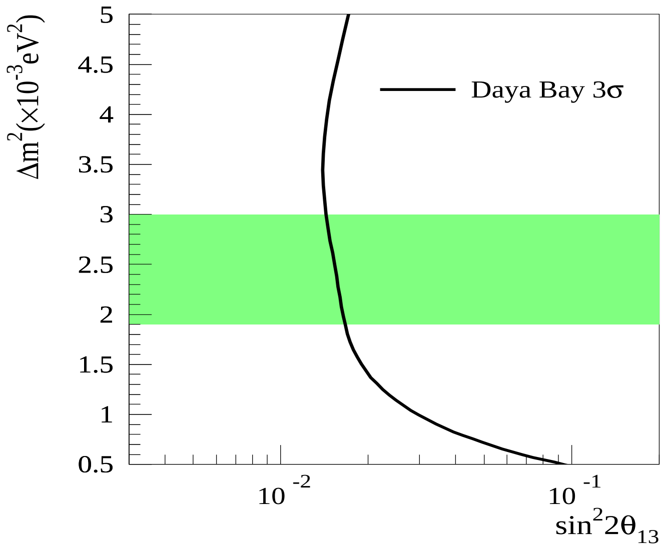


From hep-ph/0703029:



Daya Bay Sensitvitiy





Sensitivity reach at 90% CL

After 3 yrs of running

90% C.L. sensitivity limit for $\sin^2 2\theta_{13}$ at $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2 for different assumptions of detector related systematic uncertainties. 3 years running for each scenario:

Systematic Uncertainty Assumptions:	Baseline	Goal	Goal with swapping
90% C.L. Limit:	0.008	0.007	0.006