Report of the US long baseline neutrino experiment study

Milind Diwan
Brookhaven National Laboratory

4/17/2007

Talk to the BNL DOE review committee

Office of Science
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN
NATIONAL LABORATORY

FNAL/BNL study

- Chairs: Hugh Montgomery, Sally Dawson
- Advisory committee: F. Cervelli(INFN), M. Diwan(BNL), M. Goodman(ANL), B. Fleming(Yale), K. Heeger(LBL), T. Kajita (Tokyo), J. Klein(Texas), S. Parke(FNAL), R. Rameika(FNAL)
- Several small workshops were held last year.
- Many reports on physics sensitivity, backgrounds, and beam alternatives.
- Work of approximately 20-30 individuals at various levels.
- ~10 documents. ~2-3 publications could result

http://nwg.phy.bnl.gov/fnal-bnl/

Timescale:

The United States neutrino community is heavily engaged in operation and analysis of its existing program. On the other hand there are active discussions within advisory bodies and the agencies with a view to setting directions for future facilities inside the next year.

It would be desirable to see results of this **U.S. Long Baseline Neutrino Experiment Study** before October 2006, with a preliminary report by July 15, 2006.

U.S. Long Baseline Neutrino Experiment Study

Compare the neutrino oscillation physics potential of:

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

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.

Considerations of each should include:

i) As a function of θ_{13}, the ability to establish a finite θ_{13}, determine the mass hierarchy, and search for CP violation and, for each measurement, the limiting systematic uncertainties.

ii) The precision with which each of the oscillation parameters can be measured and the ability to therefore discriminate between neutrino mass models.

iii) Experiment Design Concepts including:

Optimum proton beam energy
Optimum geometries
Detector Technology
Cost Guesstimate

Milestone: Presentation to the FNAL PAC, March 29. 2007

http://nwg.phy.bnl.gov/fnal-bnl

PAC acknowledged our efforts

Report of the US long baseline neutrino experiment study

FNAL-numbers
BNL-numbers-IR

D. Bogert, D. Finley, C. Laughton, S. Pordes, A. Marchionni, R. Rameika, N. Saoulidou, R. Zwaska,[1] M. Bishai, M. Diwan, M. Dierckxsens, H. Kirk, N. Simos, W. Marciano, Z. Parsa, B. Viren,[2] C. Lewis,[3] C. Bromberg,[4] B. Flemming, A. Curioni,[5] C. K. Jung, C. Yanagisawa,[6] Fanny Dufour, E. Kearns,[7] T. Kirk, E. Zimmerman,[8] R. Wilson,[9] K. McDonald,[10] P. Huber, V. Barger,[11] K. Whisnant,[12] D. Marfatia,[13] K. Lande, A. K. Mann, R. Van Berg,[14] K. Lesko, W. Y. Lee,[15] M. Messier,[16] K. Whisnant,[12] W. Pariseau,[17] P. Litchfield, M. Marshak,[18] and R. Potenza[19]

[1]*Fermi National Accelerator Laboratory*
[2]*Brookhaven National Laboratory*
[3]*Columbia University*
[4]*Michigan State University*
[5]*Yale University*
[6]*State University of New York, Stonybrook*
[7]*Boston University*
[8]*University of Colorado*
[9]*Colorado State University*
[10]*Princeton University*
[11]*University of Wisconsin*
[12]*Iowa State University*
[13]*University of Kansas*
[14]*University of Pennsylvania*
[15]*Lawrence Berkeley National Laboratory*
[16]*Indiana University*
[17]*University of Utah*
[18]*University of Minnesota*
[19]*University Di Catania*

(Dated: April 16, 2007)

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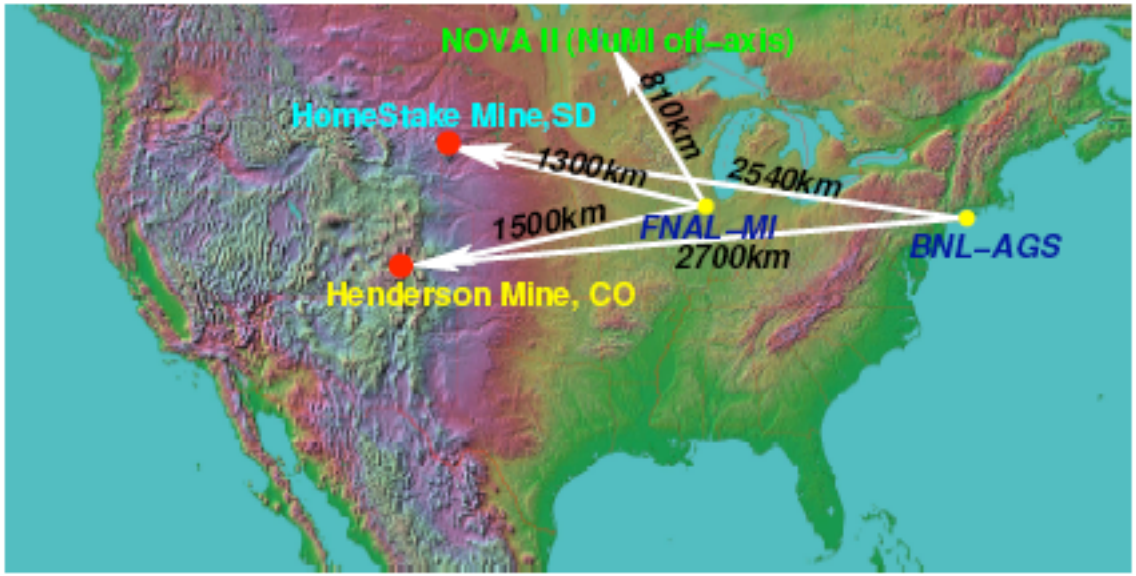
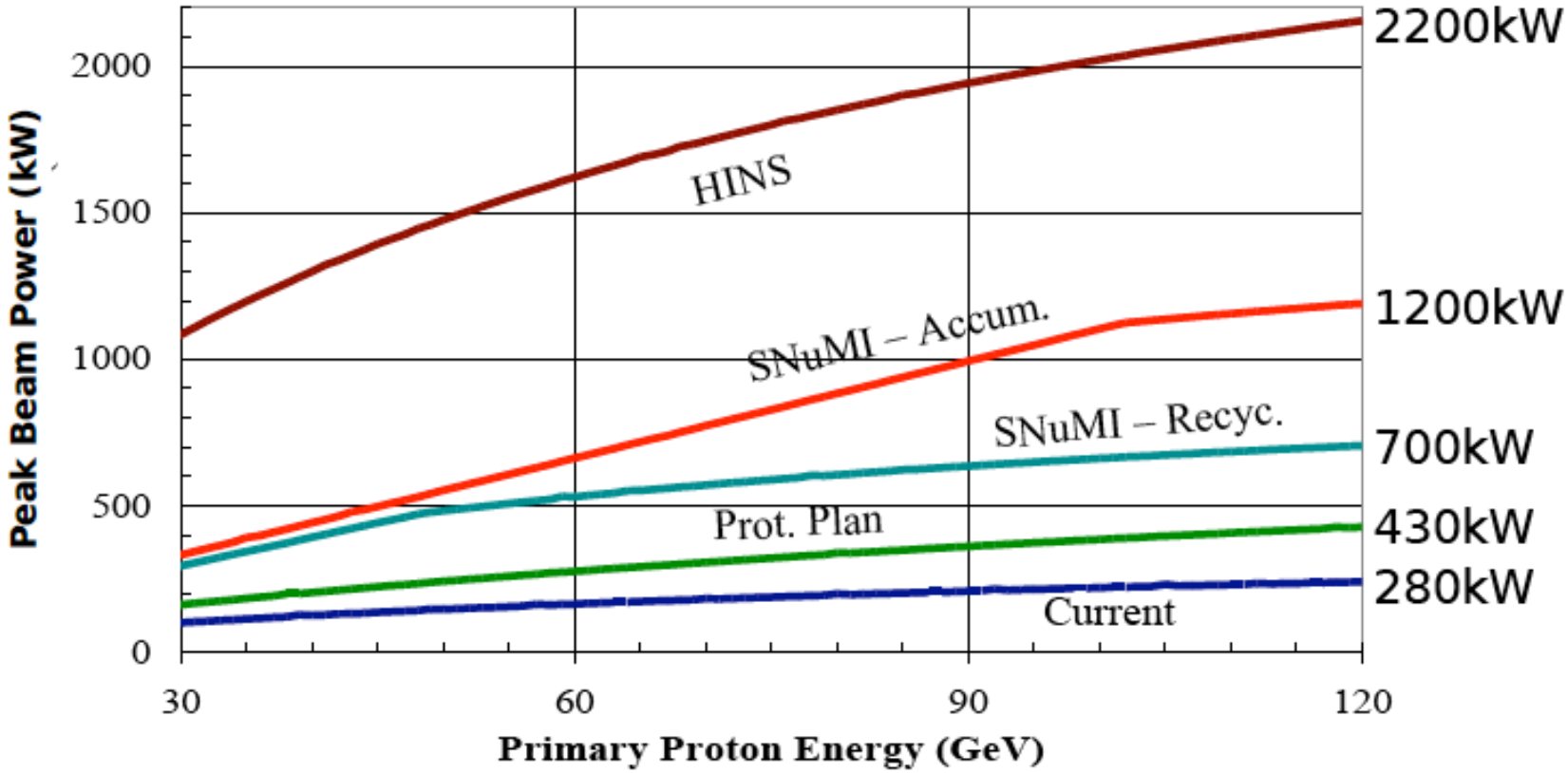


Beam from FNAL

Flexibility of proton energy:



$$1\ \mathrm{MW} * 10^{7}\ \mathrm{sec} = 5.2\ 10^{20}\ \ \mathrm{POT\ at\ 120\ GeV}$$

Key Event Rate in 100kT*MW*10^7

$$\nu_\mu \rightarrow \nu_e$$

$\Delta m^2_{21,31} = 8.6 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ $\sin^2 2\theta_{12,23} = 0.86, 1.0$ $\sin^2 2\theta_{13} = 0.02$

$$\delta_{CP}$$

	$sgn(\Delta m^2_{31})$	0 deg	+90 deg	180 deg	-90 deg
NuMI-15mrad (810km)	+	76	36	69	108
NuMI-15mrad (810km)	-	46	21	52	77
WBLE (1300km)	+	87	48	95	134
WBLE (1300km)	-	39	19	51	72

Detector design considerations.

- Need ~100kT of fiducial mass with good efficiency.
- At this mass scale cosmic ray rate becomes the driving issue for detector placement and design.

$\sin^2 2\theta_{13} = 0.02$

signal~50 evts/yr

Cosmic rate in 50m h/dia detector in $10\mu s$ for 10^7 pulses

Intime cosmics/yr	Depth (mwe)	
5×10^7	0	
4230	1050	
462	2000	
77	3000	
15	4400	DUSEL depth

If detector is placed on the surface it must have cosmic rejection for muons $\sim 10^8$ and for gammas $\sim 10^4$ beyond accelerator timing.

=> fully active fine grained detector.

Detector technologies

Water Cherenkov (Studied at BNL)

- Known, successful technology with wide dynamic range (5 MeV-50GeV).
- Can perform both p-decay, astrophysical sources, and accelerator nus.
- R&D on large caverns already in progress (part of this study).
- PMT R&D and costing in progress.
- Can be deployed deep scaled up: 50kT to fewX100kTon.
- MODEST DEVELOPMENT NEEDED FOR PROPOSAL.

Liquid Argon (Studied at FNAL)

- Substantial R&D needed to prove that 100kT can be built. (current size of ICARUS module is 0.3kT)
- There is no solution yet on how to deploy deep underground. Otherwise no proton decay physics or other non-accelerator physics can be done.
- Must demonstrate 10^8 rejection of cosmics (not done yet).
- TIME SCALES FOR R&D ARE STILL LONG

Beam to DUSEL

Pro

- Possible to put large detectors at depth with proven technology.
- Currently planned accelerator upgrade enough to get first physics because of detector size. But it is even more attractive with a Proton Driver
- Full energy spectrum for oscillation pattern and parameter measurement without ambiguities.
- There has been good progress in water Cherenkov pattern recognition.
- Broader physics program includes proton decay and astrophysics.

Con

- Needs new beamline
- Coupled to DUSEL with uncertain timeline and funding.
- Near detector cannot be water Cherenkov.

NUMI off-axis

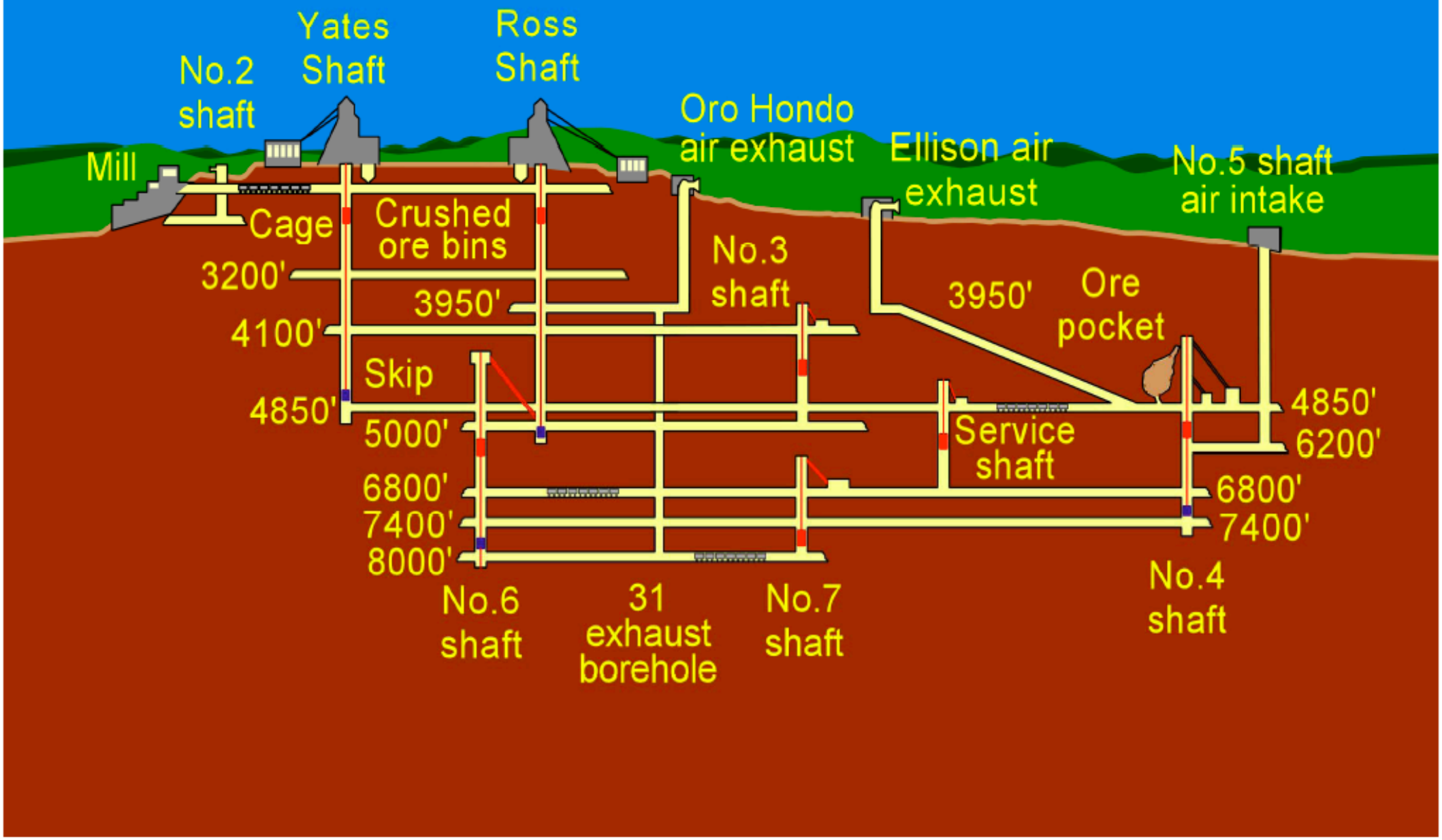
Pro

- Use existing beam !
- Use 12 km offaxis to lower neutrino energy to the oscillation region.
- Narrow band beam=> easier reconstruction/higher efficiency ?
- Additional benefit is reduction of beam tails and backgrounds from beam.
- Use same near detector.
- Incremental program (but each step $$)

Con

- Must be surface detector. Must use liquid Argon TPC to reject cosmics (not yet proven)
- Monochromatic nature of beam means strong correlations and ambiguities
- Must deploy another detector at another energy or baseline. Second max has 1/20 event rate (has background from higher energy Kaon neutrinos).
- Program cannot include nucleon decay and science that requires depth.

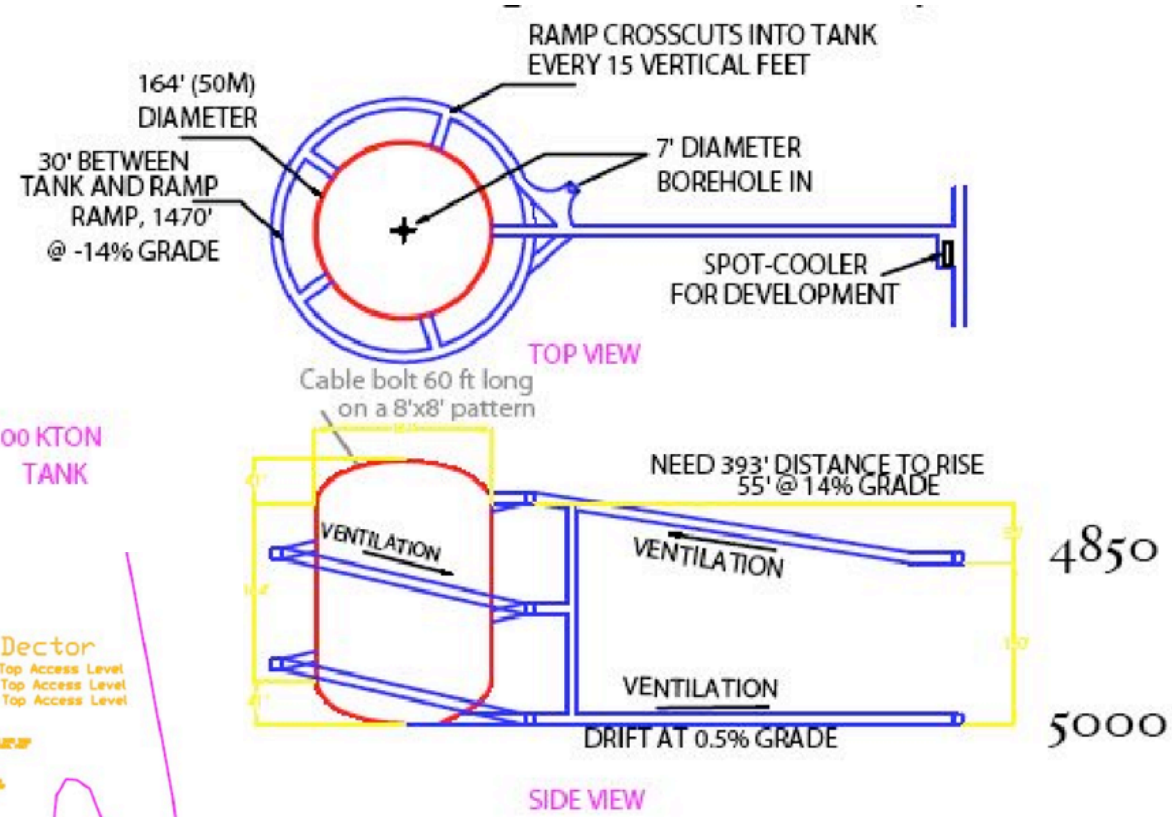
General Homestake Mine Development

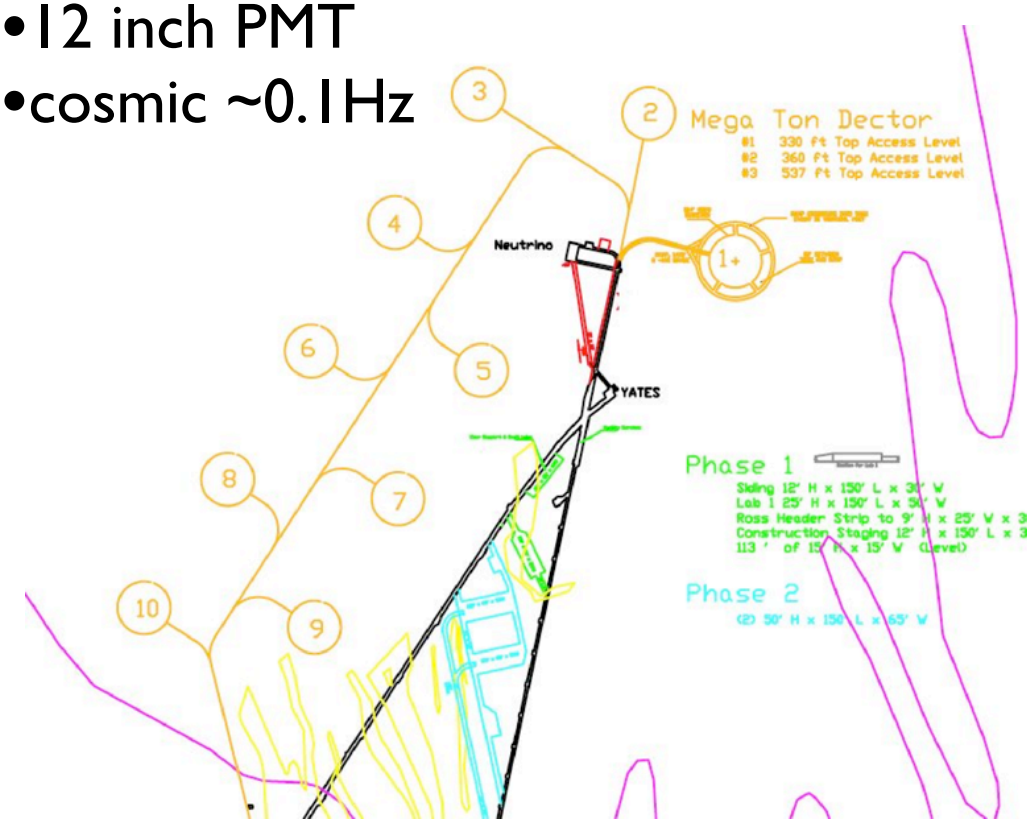


Detector at Homestake

Modular Detector

- ~50m dia/h
- 100kT fiducial
- 4850 mwe
- 25% PMT cov.
- 12 inch PMT
- cosmic ~0.1Hz



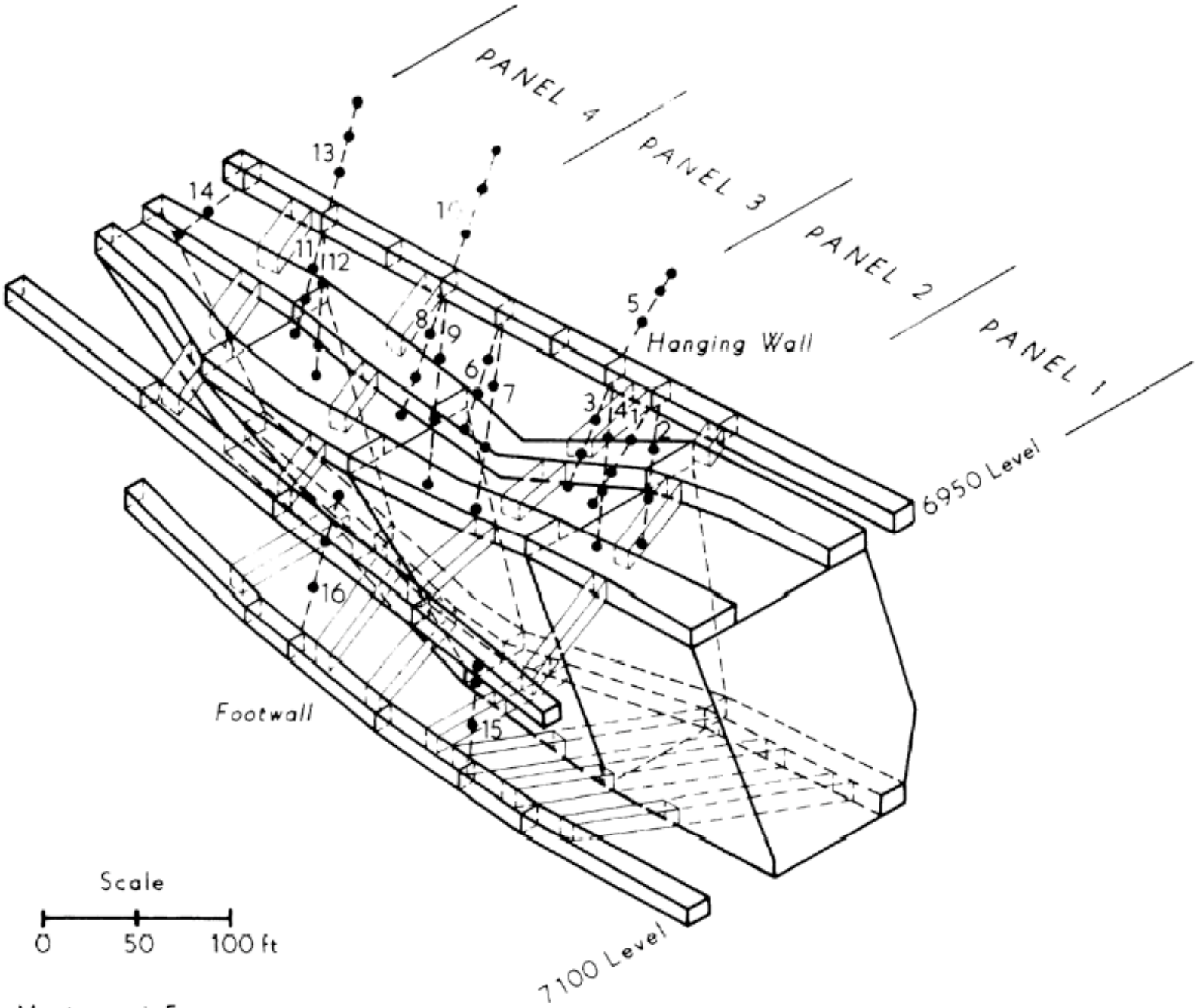


- ✓ Initial detector 3 modules
- ✓ Space can be planned for 10
- ✓ Cost estimate $115/module
- ✓ 6 yrs construction to first 100kT
- ✓ 8 yrs to full 300 kT.

Fiducial vol depends on rock stability studies and PMT pressure rating.

Why Homestake ?

- 100 yrs of operating experience
- 20 yrs of rock mechanics research.
- INITIAL STABILITY STUDY OF LARGE OPENINGS FOR THE NATIONAL UNDERGROUND SCIENCE LABORATORY AT THE HOMESTAKE MINE, LEAD, SD Doug Tesarik, Jeff Johnson, Karl Zipf, Jr., Kenneth Lande. NARMS - TAC 2002: Mining and Tunnelling Innovation and Opportunity, Vol. 1, pp 157-163 R. Hammah et al Eds.,Toronto, University of Toronto Press



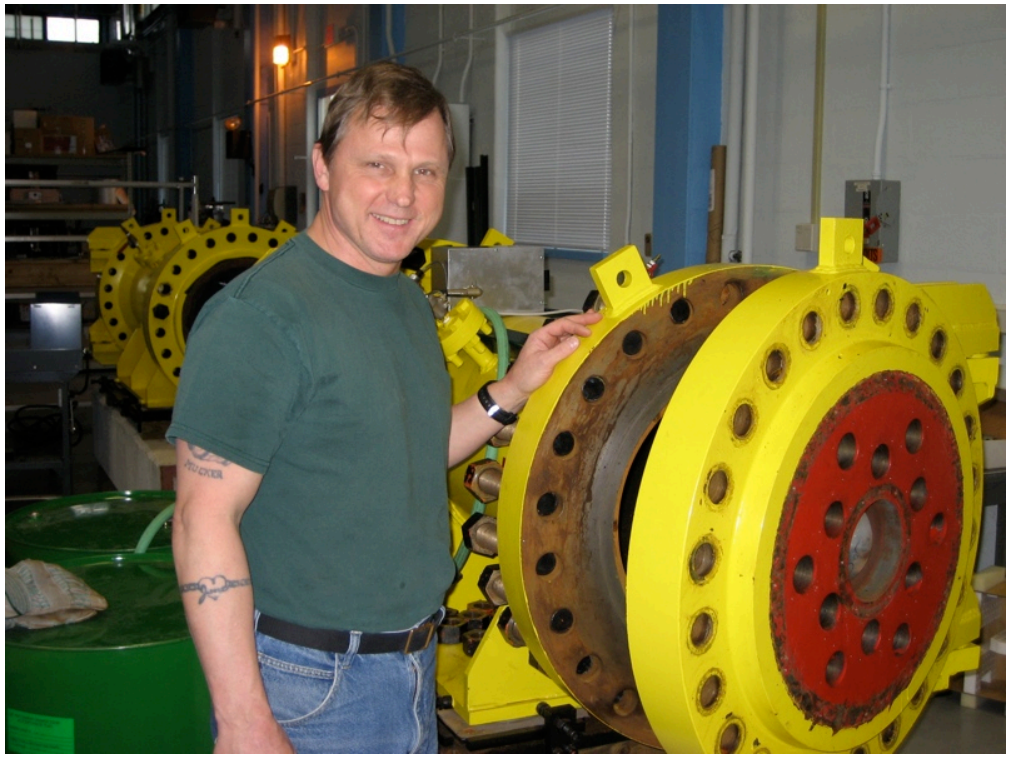
Bill Pariseau (University of Utah)

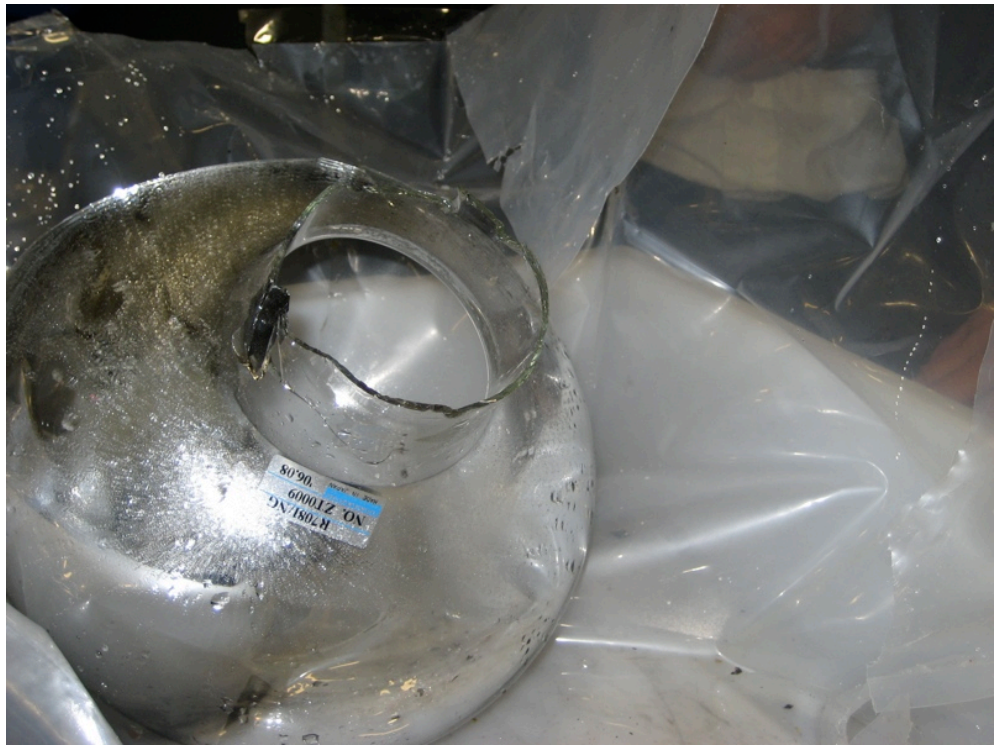
Summary cost ($FY07) for 300kT at Homestake

Cavity construction (30% contingency)	$78.9M
PMT+electronics	$171.3M
Installation+testing	$35.7M
R&D, Water, DAQ, etc.	$8.2M
Contingency(non-civil)	$50.8M
Total	$344.9M

- Cost for 3 modules of ~100kT fiducial mass. 6 yrs to first 100kT, 8 yrs for full 300kT.
- Civil cost recently reviewed by RESPEC (consultants) and found to be consistent with other projects. (In addition, construction could be faster).
- Consultations with C. Laughton and Homestake on overhead factors (not included in civil).

Pressure testing

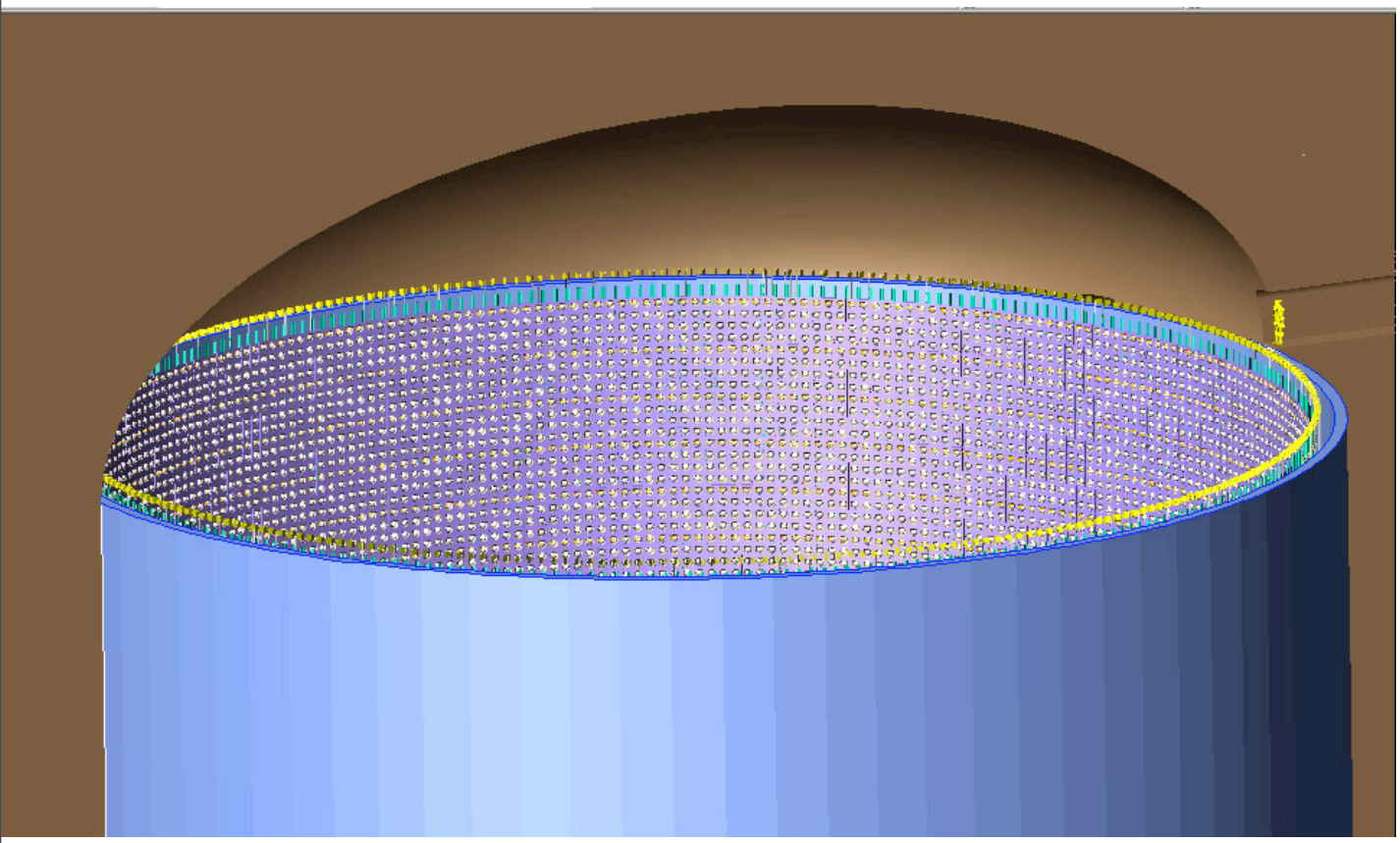




Have 32 phototubes from Hamamatsu (R7081). Getting 12inch tubes from other vendor. Pressure vessel from BNL. Evolving testing protocol.

Hamamatsu rating is ~7atm. Tested this tube until it broke at 148 psi (~10atm)

Installation



Conceptual design for installation

M.Diwan

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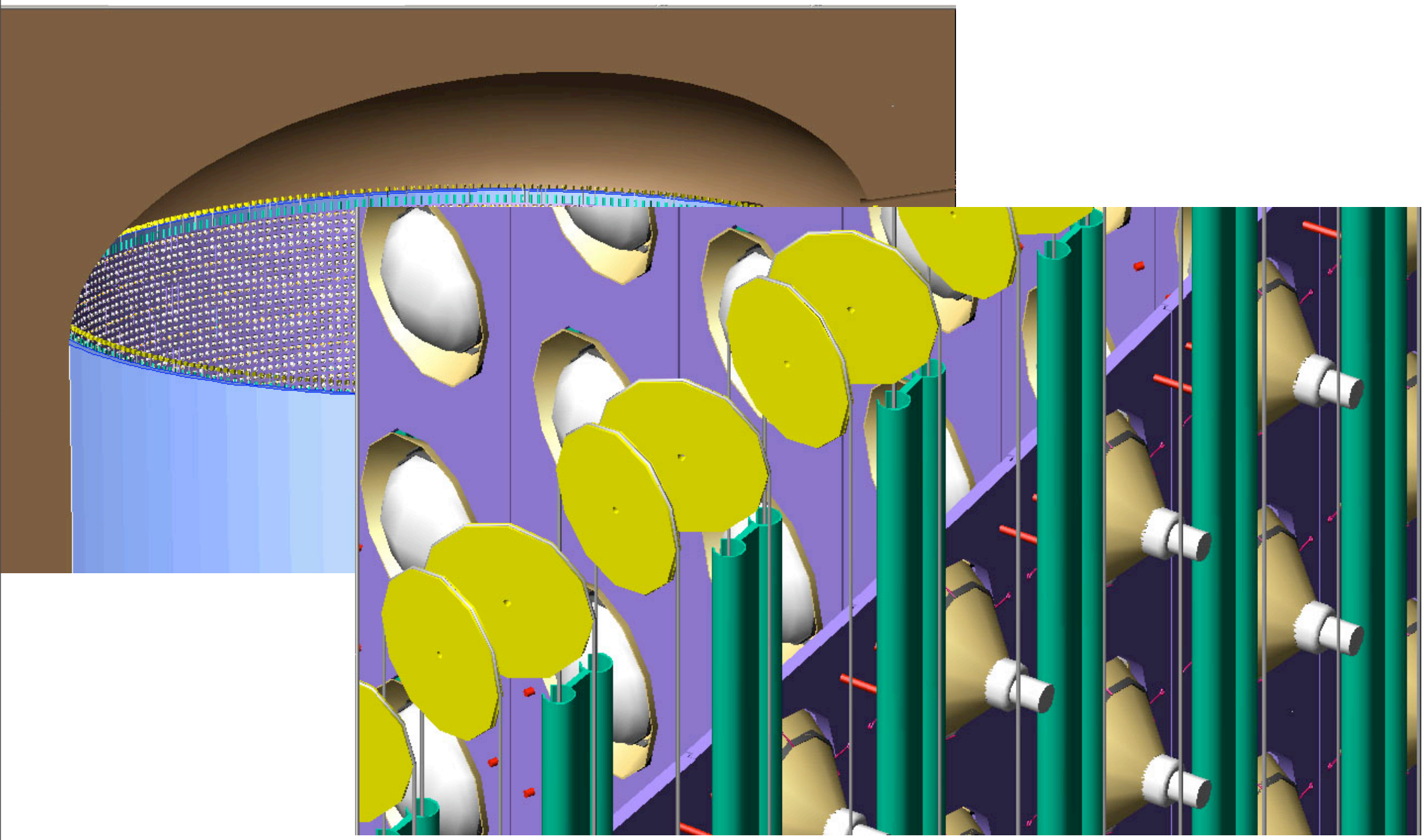
Installation



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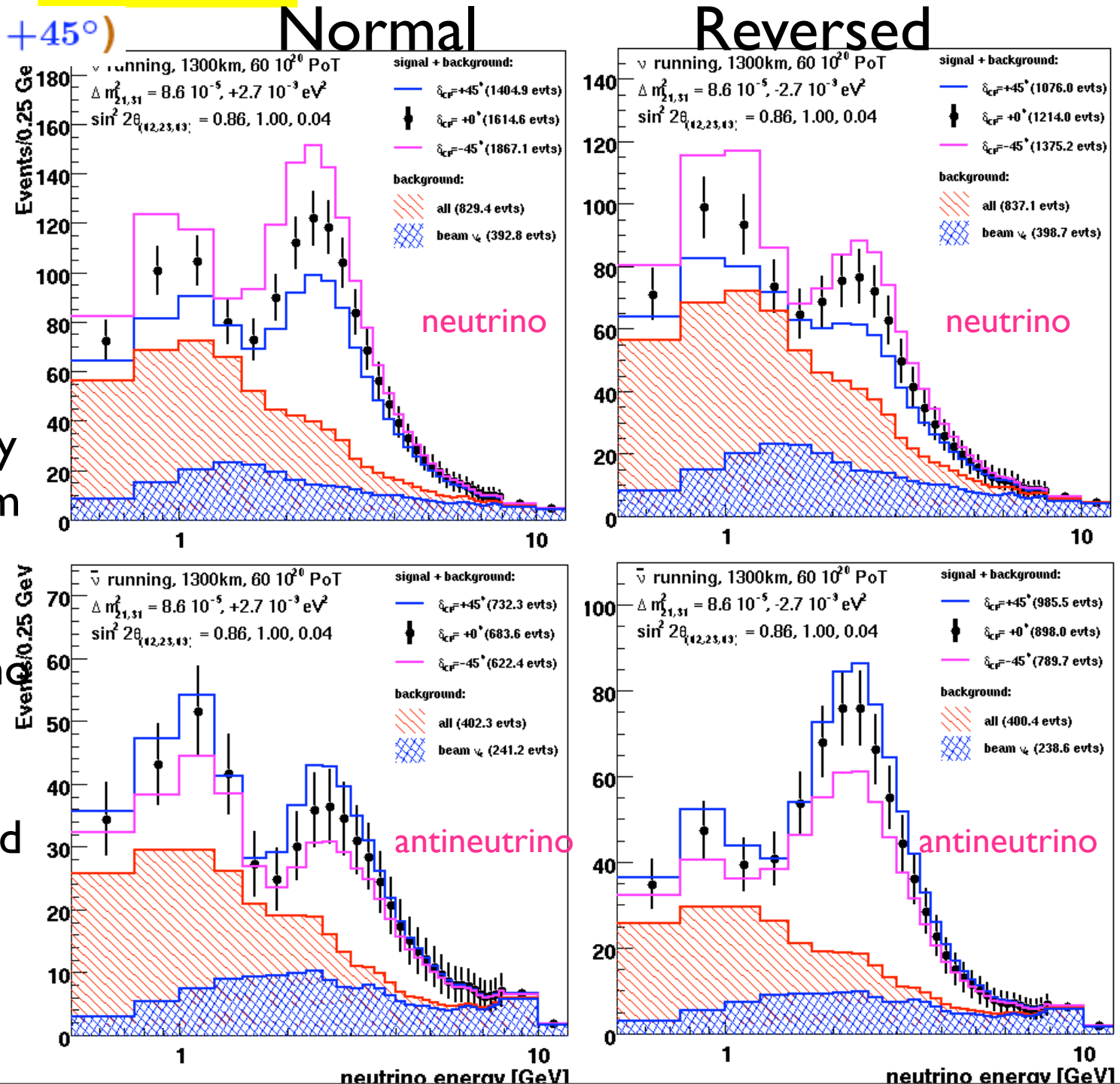
Electron neutrino appearance spectra

$\sin^2 2\theta_{13} = 0.04$, **300kT WCe.** , WBLE 120 GeV, 1300km, 60E20 POT.

$(-\delta_{cp} = -45°, -\delta_{cp} = +45°)$

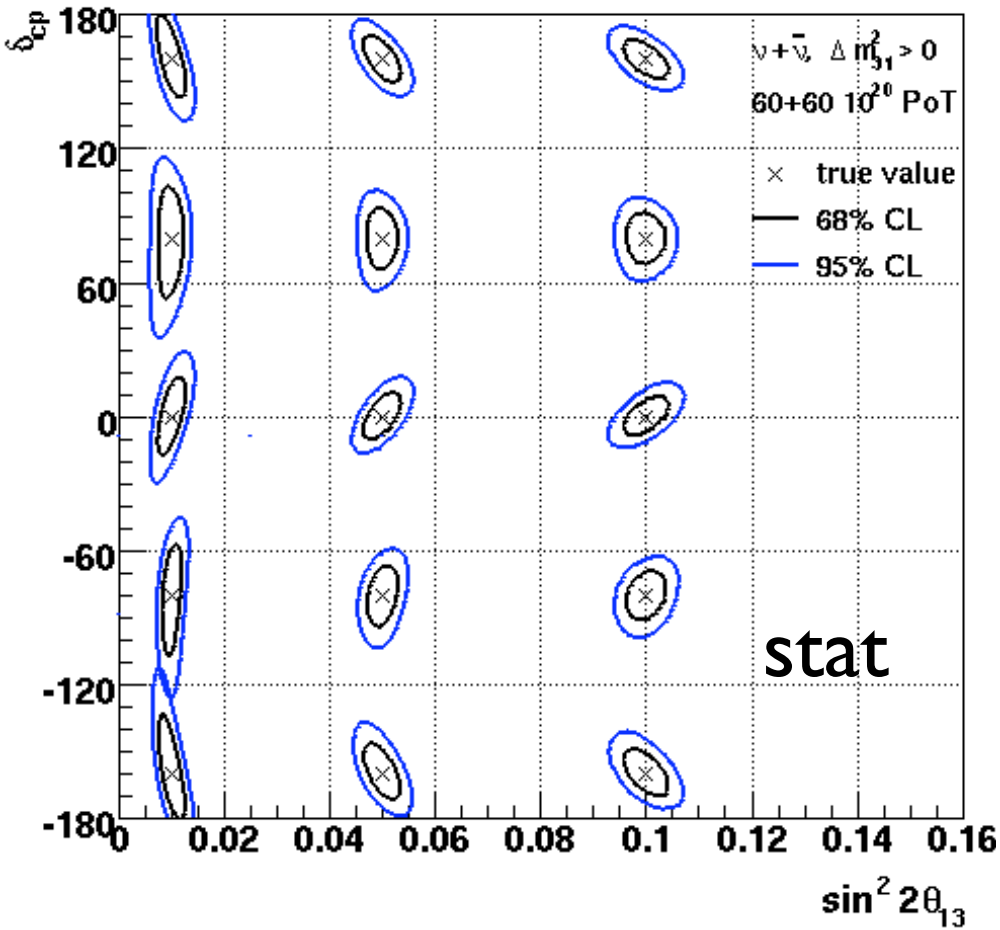
- All background sources are included.
- S/B ~ 2 in peak.
- NC background about same as beam nue backg.
- For normal hierarchy sensitivity will be from neutrino running.
- For reversed hierarchy anti-neutrino running essential.
- Better efficiency at low energies expected with higher PMT counts.

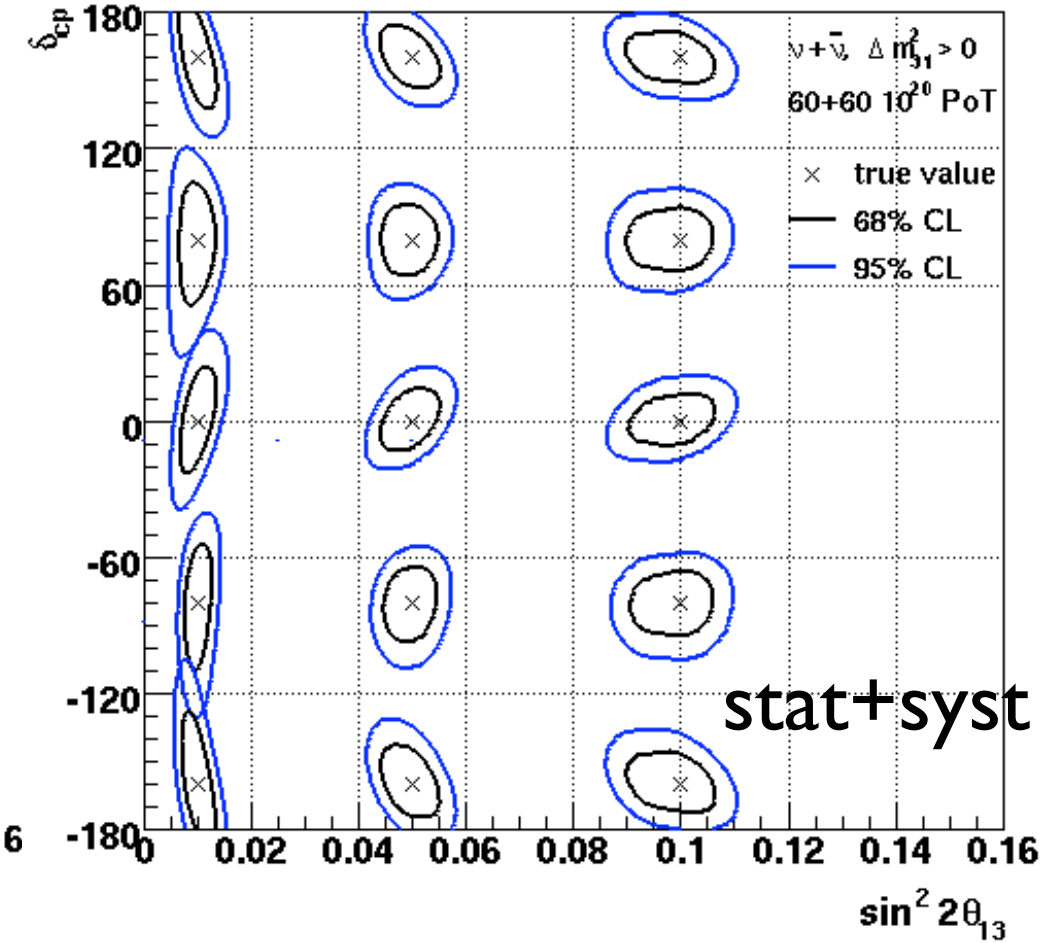


Dependence of CP measurement on th13

WCC 1300 km 300kT

(—95% CL —68% CL)





Measurement of CP phase does not depend strongly on th13

WBLE to DUSEL(1300km) 3sig, 5sig discovery regions.

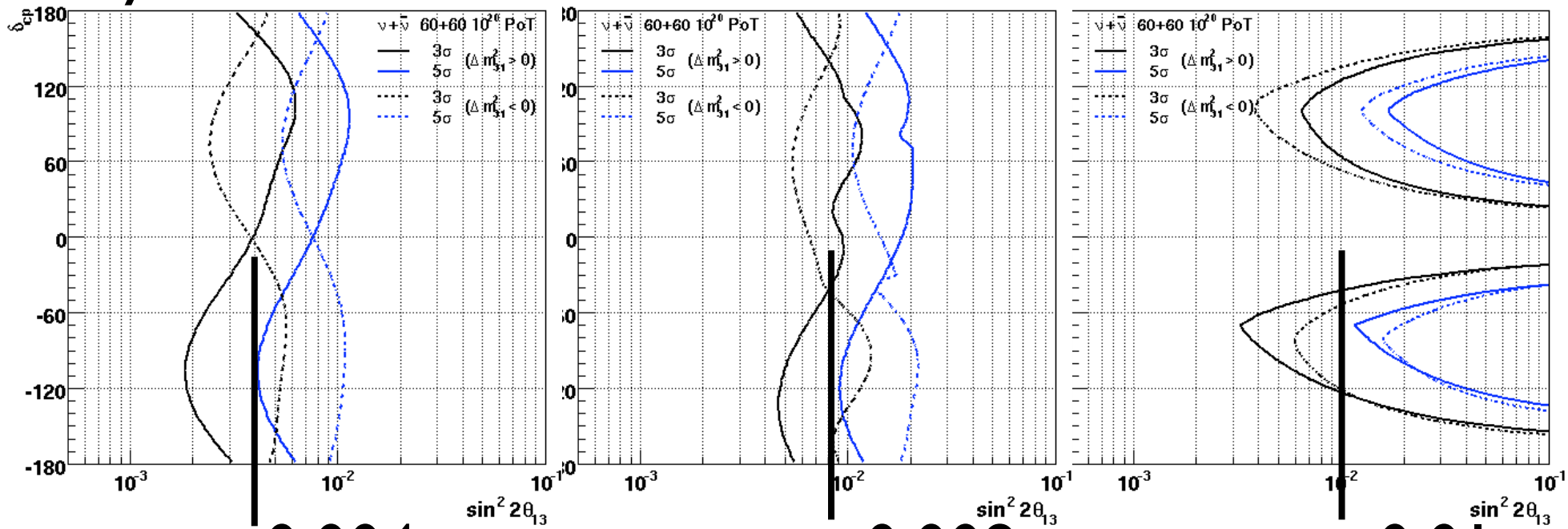
300 kT

60 10^20 POT for each nu and anu

WCh

th13 mass ordering CP violation

Stat+syst



0.004 0.008 0.01

CP Fraction: Fraction of the CP phase (0-2pi) covered at a particular confidence level.

Report the value of th13 at the 50% CP fraction.

Comparison

Beam	Baseline	Detector	Exposure (MW.yr*)	θ_{13}	CPV	$sgn(\Delta m^2_{31})$
NuMI ME, 0.9°	810 km	NOνA 20 kT	6.8	0.01	> 0.2	0.2
NuMI ME, 0.9°	810 km	LAr 100 kT	6.8	0.002	0.03	0.05
WBLE 120GeV, 0.5°	1300km	LAr 100 kT	6.8	0.002	0.005	0.006
WBLE 120GeV, 0.5°	1300km	WCC 300 kT	6.8	0.006	0.02	0.011
WBLE 120GeV, 0.5°	1300km	WCC 300 kT	13.6	0.004	0.01	0.008

TABLE VIII: Comparison of the sensitivity reach of different long baseline experiments. The sensitivity is given as the value of $\sin^2 2\theta_{13}$ at which 50% of δ_{cp} values will have $\geq 3\sigma$ reach. We assume equal amounts of ν and $\bar{\nu}$ running in the total exposure. * 1yr = 1.7×10^7 seconds.

How to proceed ?

- Proposal for a water Cherenkov detector at DUSEL after site selection. Support will be needed at modest level for proposal writing.
- We will continue more development. Support needed for geo-technical work and PMT development.

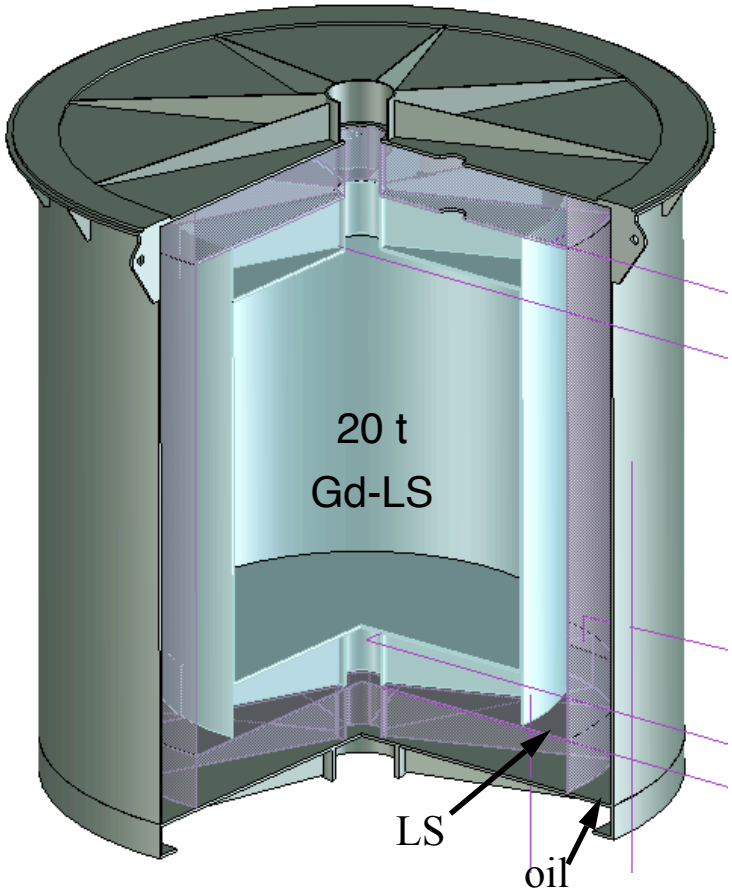
Development items:

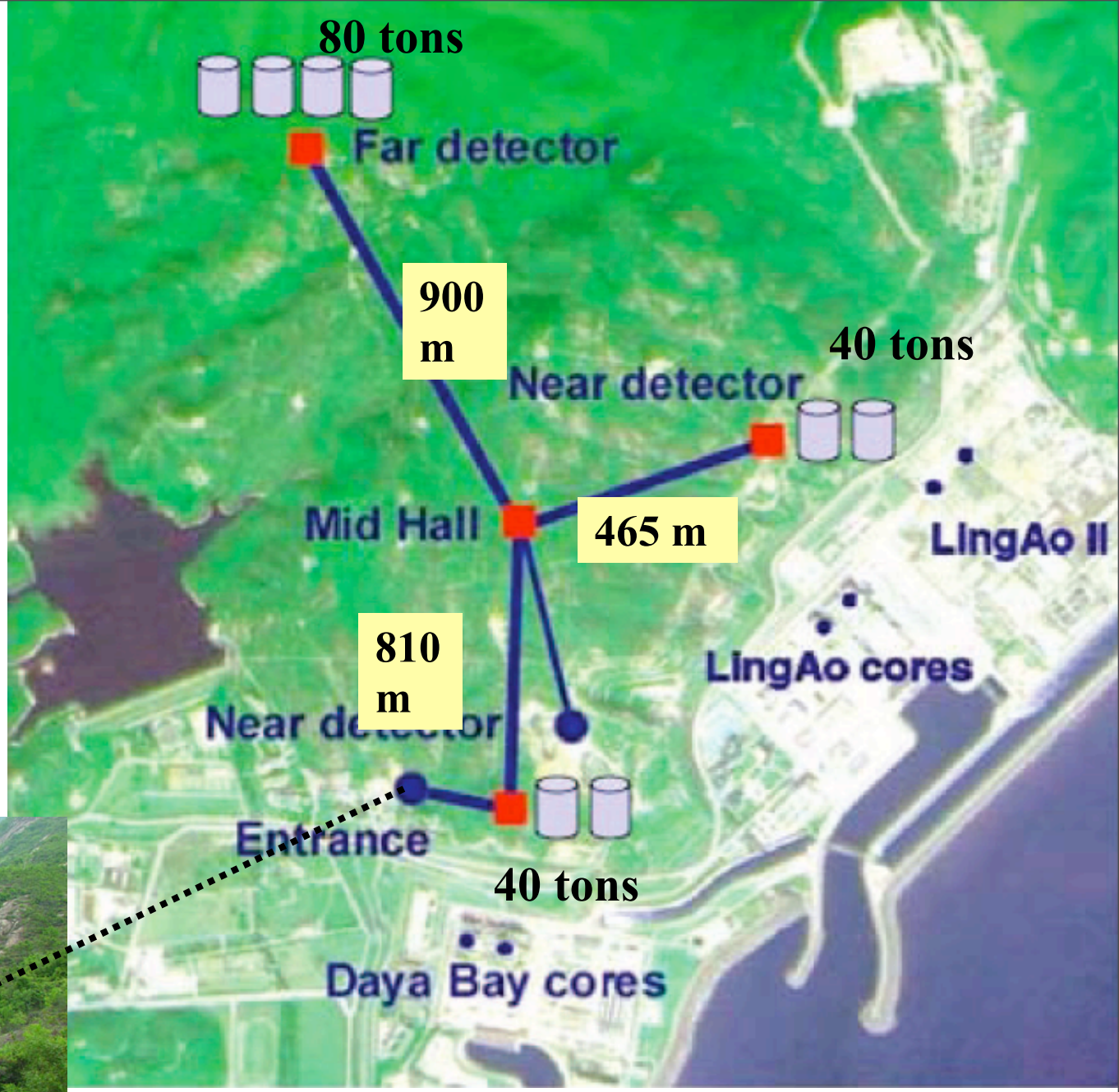
1) PMT pressure testing and development of 13" tube (in progress)
2) Geo-technical work on cavern stability (in progress at NIOSH)
3) Conceptual engineering for installation (in progress at BNL)
4) Simulations
5) Project development

$700k/yr for 2 yrs needed including university support

BNL neutrino physics effort

- We have three efforts that are overlapping, but focussed on the same physics.
- MINOS (running)
- Daya Bay (will be under construction)
- DUSEL based large detector (Proposed)

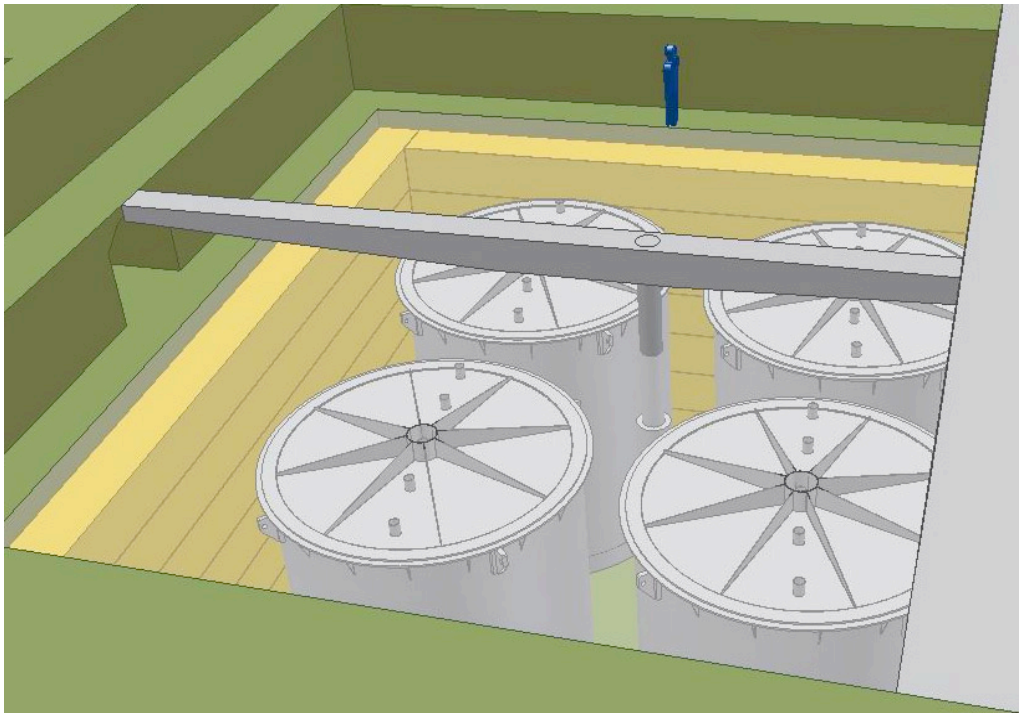

20 t
Gd-LS
LS
oil

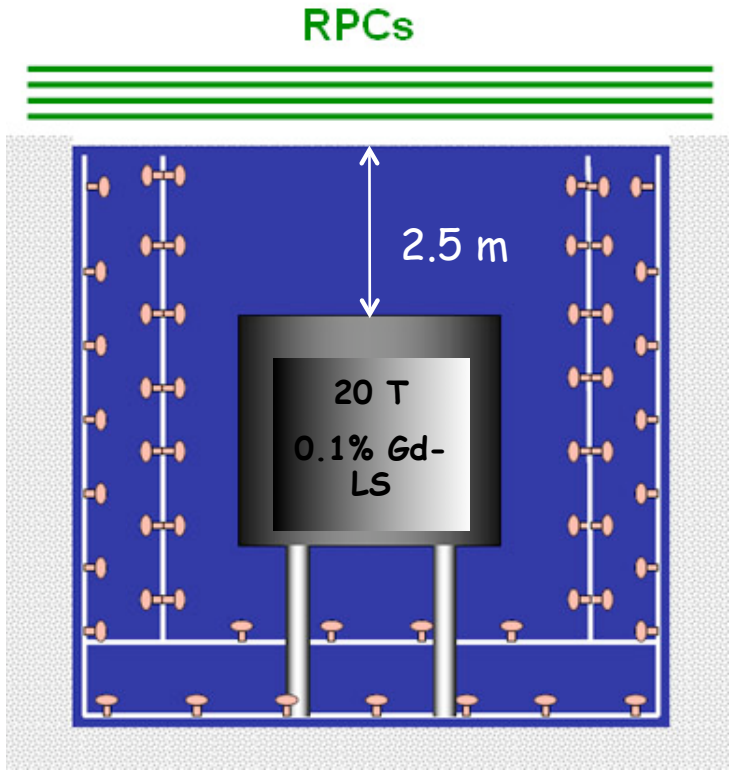

80 tons
Far detector
900 m
40 tons
Near detector
Mid Hall
465 m
LingAo II
LingAo cores
810 m
Near detector
Entrance
40 tons
Daya Bay cores

Entrance
portal

Daya Bay

Baseline Design





- **3 sigma Sensitivity to $\sin^2 2\theta_{13} \sim 0.01$ with no correlations to mass ordering or CP phase.**
- **Multiple anti-neutrino detector modules for side-by-side cross check**
- **Multiple muon tagging detectors:**
  - **Water pool as shield and Cherenkov counter**

Summary

- CP violation in neutrinos should guide the Long baseline program in the future. Program is doable with known technology (water Cherenkov detector) and current accelerator intensity.
- A MW class proton machine in the US remains well-motivated at if coupled to a capable large detector.
- A very large detector ~100 kT efficient mass is needed to carry out the program.
- For a broad program including nucleon decay and astrophysical neutrinos need depth >2000 mwe.
- Need modest resources to continue development or complete proposal. $700k/yr for 2 yrs.

Extra slides

- complete rate table
- spectra for signal
- spectrum expected for LAR 100kT@DUSEL

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		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

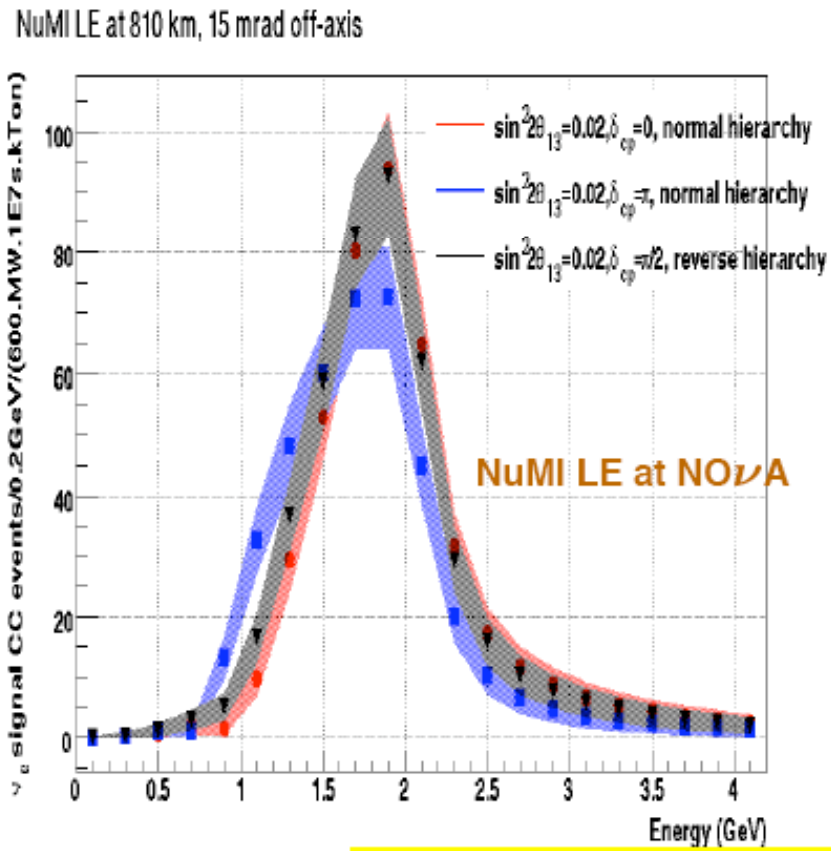
* = 0-3 GeV ** = 0-5 GeV, 1 MW. 10^7s = 5.2×10^{20} POT at 120 GeV

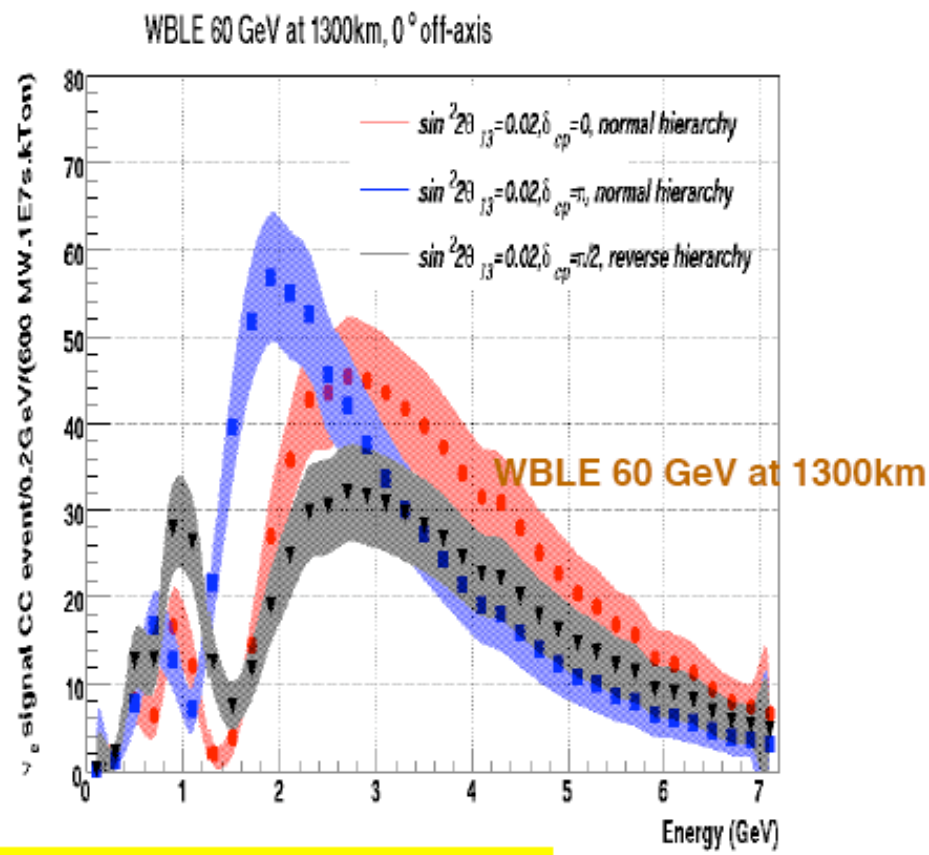
ν_e Appearance Spectra

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



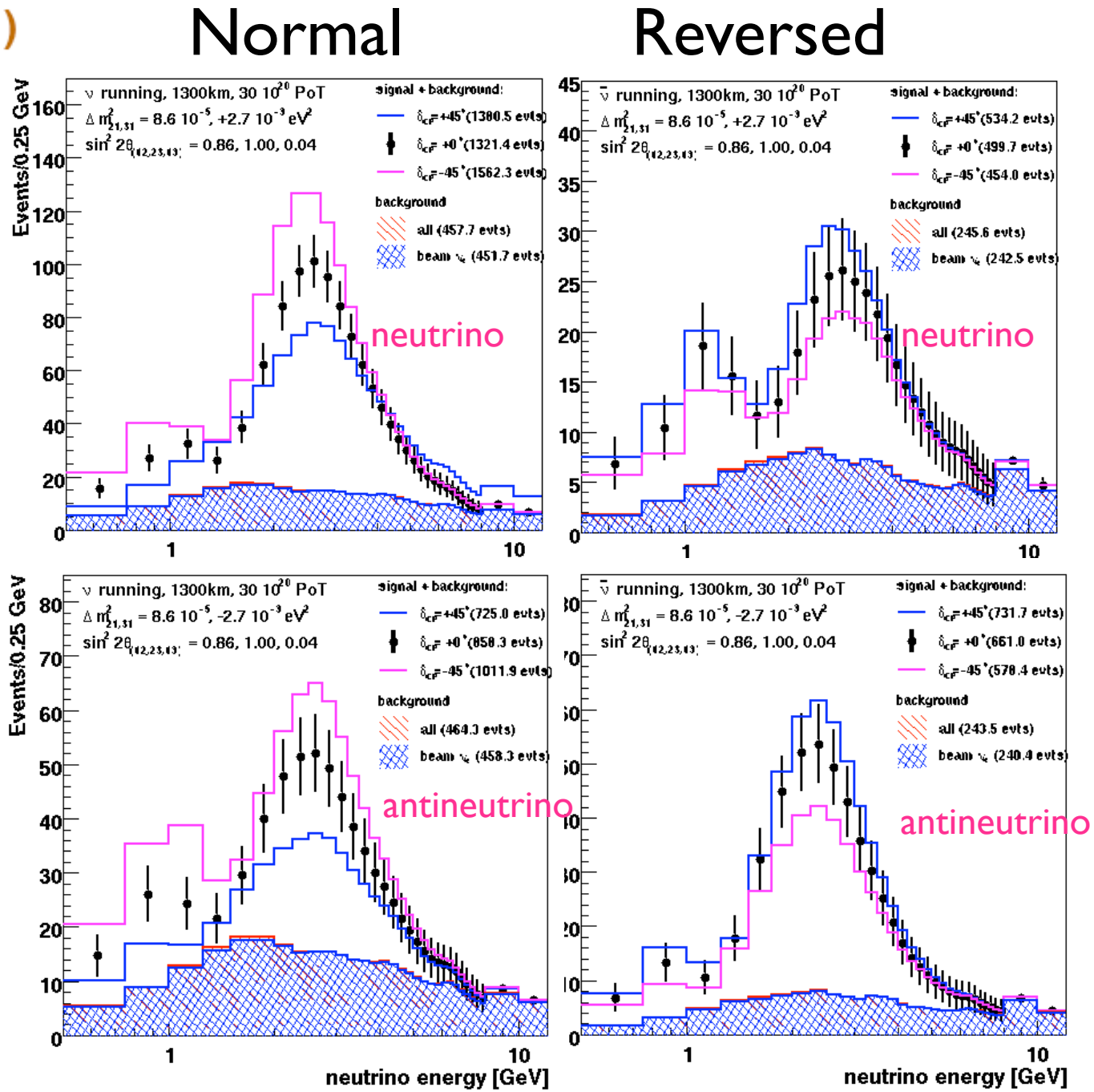


Spectral information = resolves degeneracies

Electron neutrino appearance spectra

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

$(-\delta_{cp} = -45°, -\delta_{cp} = +45°)$

- LAR assumptions
- 80% efficiency on electron neutrino CC events.
- sig(E)/E = 5%/sqrt(E) on quasielastics
- sig(E)/E = 20%/sqrt(E) on other CC events

Spectra and sensitivity is the work of Mark Dierckxsens and Patrick Huber + many helpers