Report of the US long baseline neutrino experiment study

Milind Diwan
Brookhaven National Laboratory

I am grateful for the opportunity to give this talk. I first want to thank the CDF collaboration and the CDF speaker who gave up this time for this presentation.

6/29/2007

Friday Wine and Cheese Seminar at Fermilab

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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

April 5, 2006

Milestone: Presentation to the FNAL PAC, March 29. 2007 http://nwg.phy.bnl.gov/fnal-bnl

PAC acknowledged our efforts

Final report released May 2007 arXiv:0705.4396

Fermilab-0801-AD-E
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Report of the US long baseline neutrino experiment study

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NUSAG Charge

March 3, 2007

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:

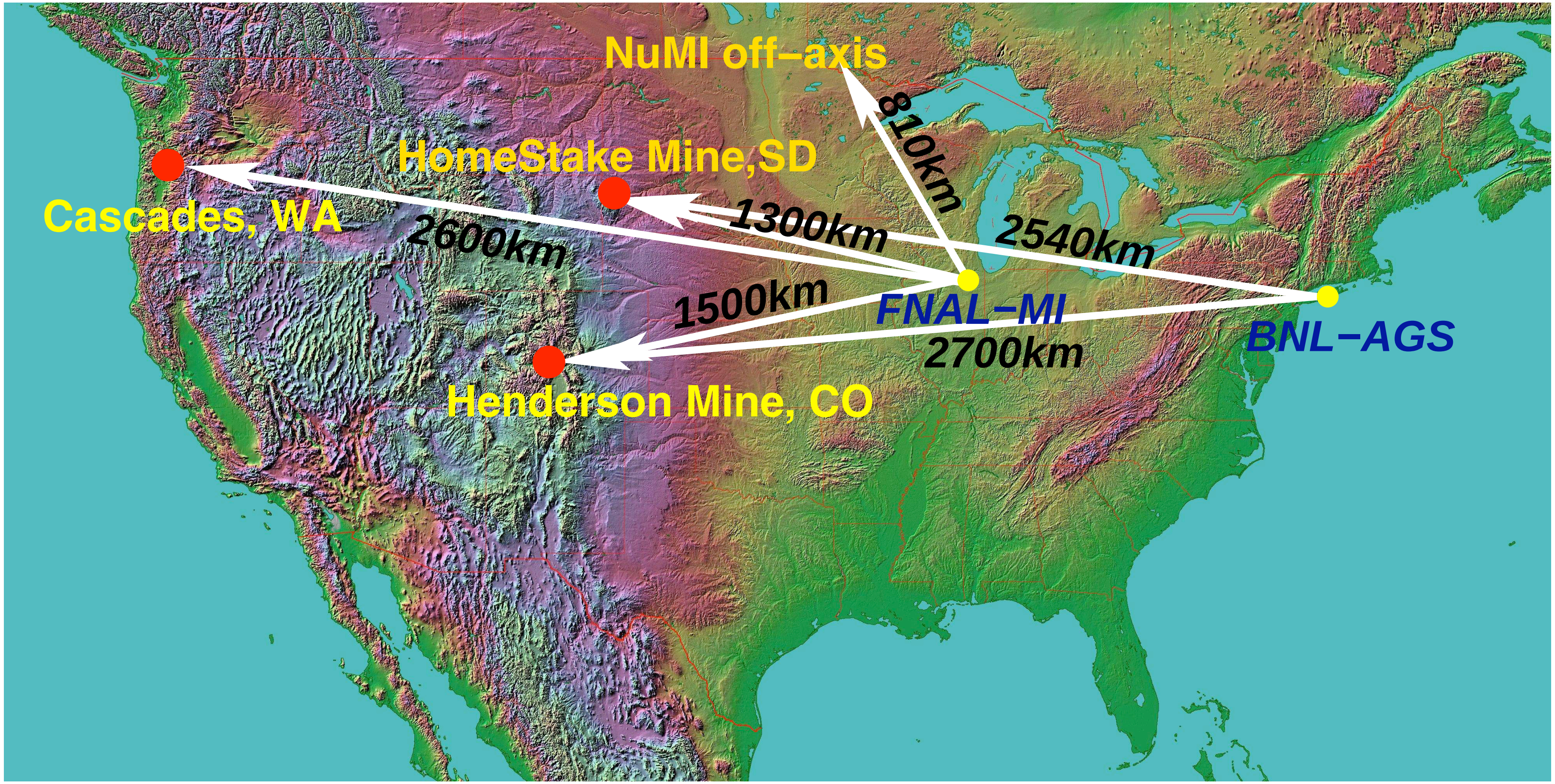
- **Scientific potential:** What are the important physics questions that can be addressed at the envisioned neutrino beam facility?
- **Associated detector options:** What are the associated detector options which might be needed to fully realize the envisioned physics potentials? What are the rough 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 [illegible] other [illegible] experiments, will be important in order [illegible] optimally determine the [illegible] parameters? What would be additional important physics questions that can be addressed in the same detector(s)?

The [illegible] NSF would like a preliminary draft of your report by December 2006, with a final version [illegible] 2007.

Final report due to HEPAP on July 12

- **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?**

NuSAG requested input from US LBν Study to address APS recommendation



Options

- Existing 120 GeV NuMI beam with an off-axis site.
- 28 GeV BNL-AGS Wide band beam over 2500 km.
- New on-axis 40-120 GeV FNAL-MI Wide Band Low Energy (WBLE) beam to DUSEL @ 1300-2700 km

Science to be addressed with very large detectors and the beam

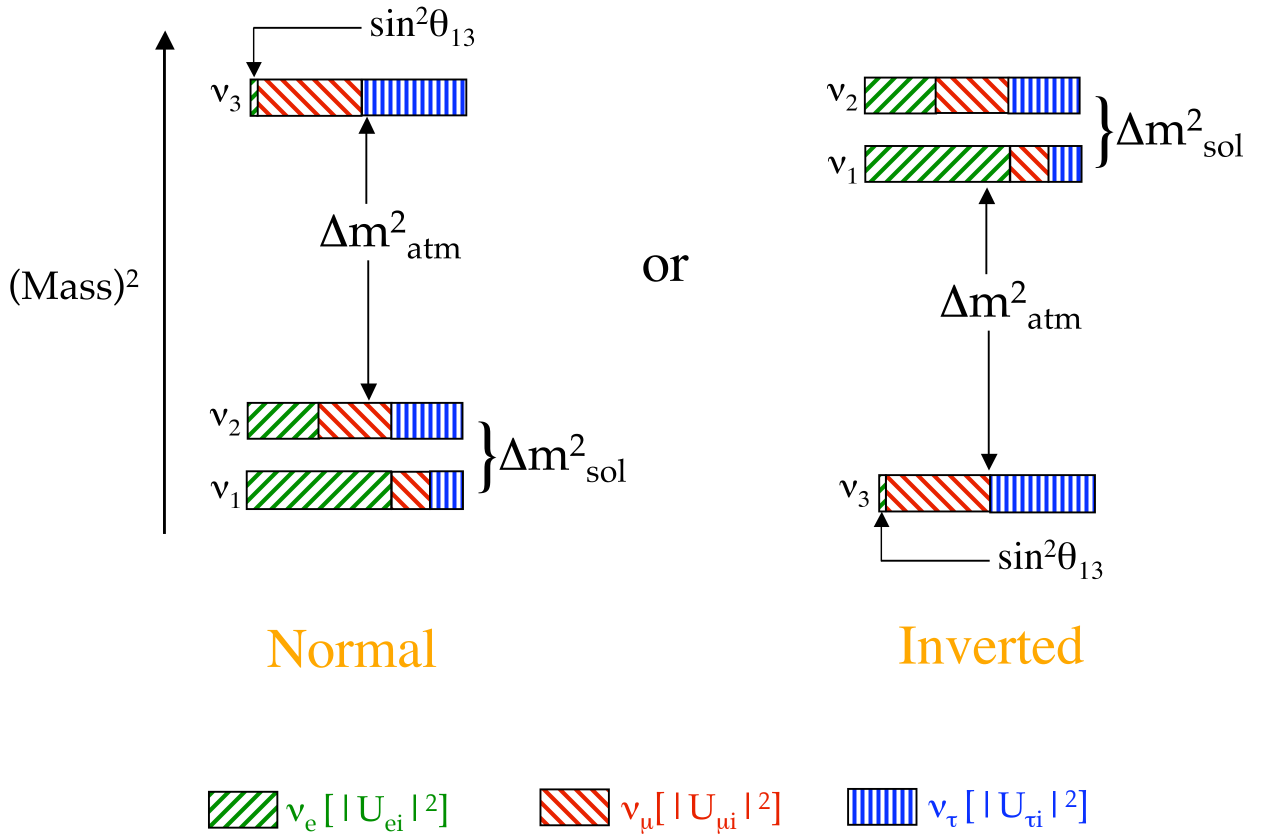
- Neutrino Oscillations.
  - ★ What is the size of θ_{13} ?
  - ★ What is the ordering of Neutrino masses?
  - ★ Do Neutrinos violate the CP symmetry?

Importance θ_{13}

- There is little guidance on the size of θ_{13} but a small value is mathematically highly unlikely given the largeness of other mixing angles. A result such as $\sin^2 2\theta_{13} < 0.01$ could be a clue to some new symmetry.

Mass ordering

The spectrum, showing its approximate flavor content, is



- If found to be inverted, direct link to the GUT scale.
- If inverted and Majorana then double beta decay at 10-20meV

Neutrino CP violation

- Convergence of many profound theoretical ideas and observations:
  - ★ The see-saw mechanism
  - ★ Majorana nature of neutrinos
  - ★ Leptogenesis <=> Baryogenesis

Other Science

- Nucleon decay
- Neutrino astrophysics

Nucleon decay

$$Rate = a^2 \times m_N^5 / M_G^4 \sim (10^{35} - 10^{36} years)^{-1}$$

$$M_G = 10^{16} GeV$$

- Almost accessible with next generation experiments ? May be ...
- Broad guidance: leading modes are
  - ★ nonsupersymmetric: $p \longrightarrow e^+\pi^0$; current limit 8×10^{33} yrs (SuperK)
  - ★ supersymmetric: $p \longrightarrow \bar{\nu} K^+$; current limit 2×10^{33} yrs (SuperK)

Neutrino astrophysics

- Galactic supernova: ~30000 $\bar{\nu}_e$ events/100kT of water with many types of events. ~few 1000 ν_e events in liquid argon,
- Diffuse (relic) supernova from z~1: 20-30 events above 10 MeV. Positive indication could be extra-ordinary.
- Solar neutrinos: day-night effect. Could collect 100000 events, need to measure 1-2% asymmetry.

Phenomenology of $\nu_\mu \rightarrow \nu_e$

The Mixing Matrix

Atmospheric — Cross-Mixing — Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

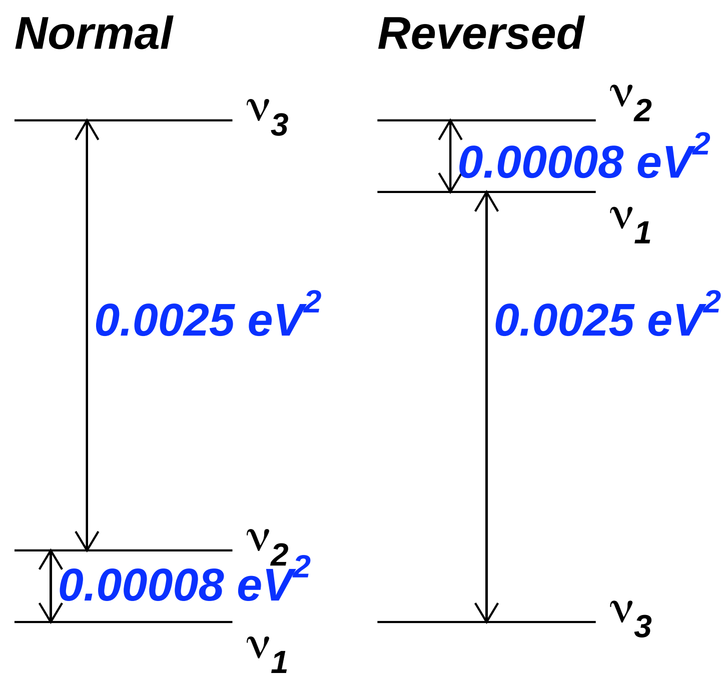
Majorana ~~CP~~ phases

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 10°$

δ would lead to $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$. ~~CP~~

mass-squares



Difference in mass squares: $(m_2^2 - m_1^2)$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$.

Solar : L~15000*km*

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

Approximate formula (M. Freund)

matter effect ~E

~7500 km
no CPV.
magic bln

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

CPV term
approximate
dependence
~L/E

solar term

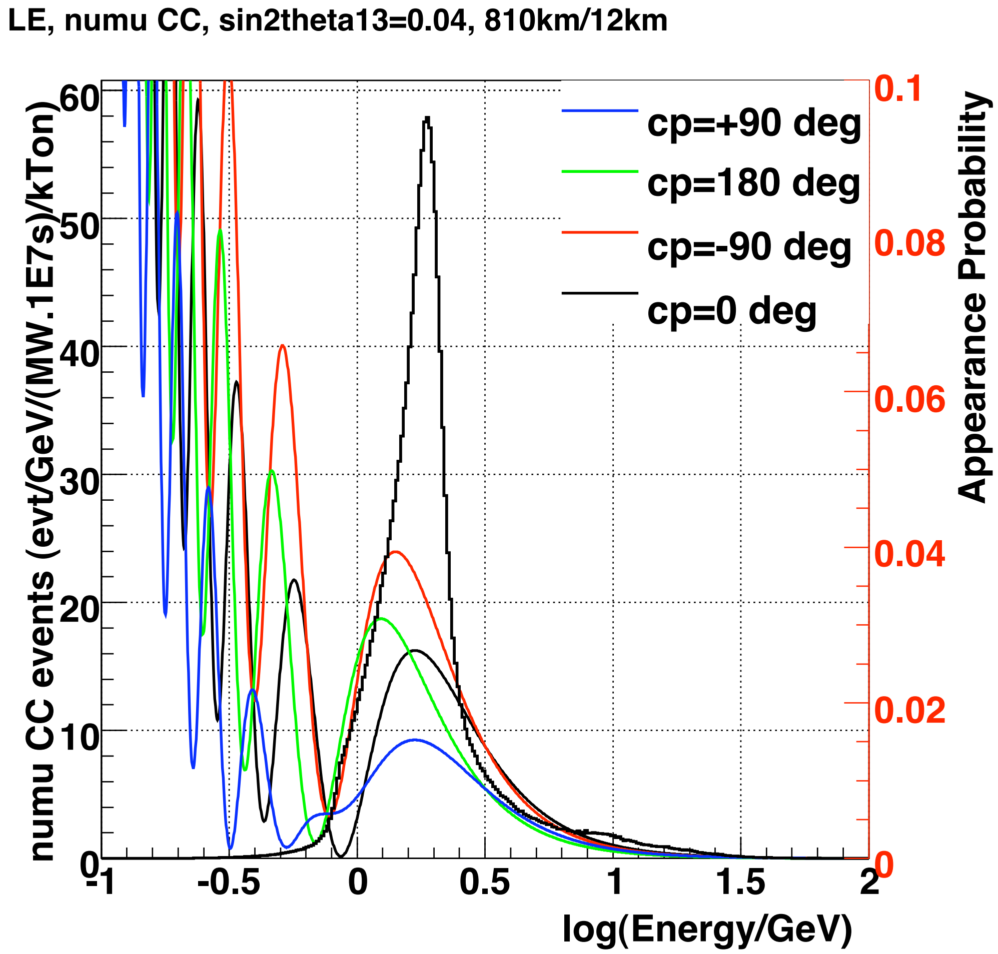
linear dep.

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

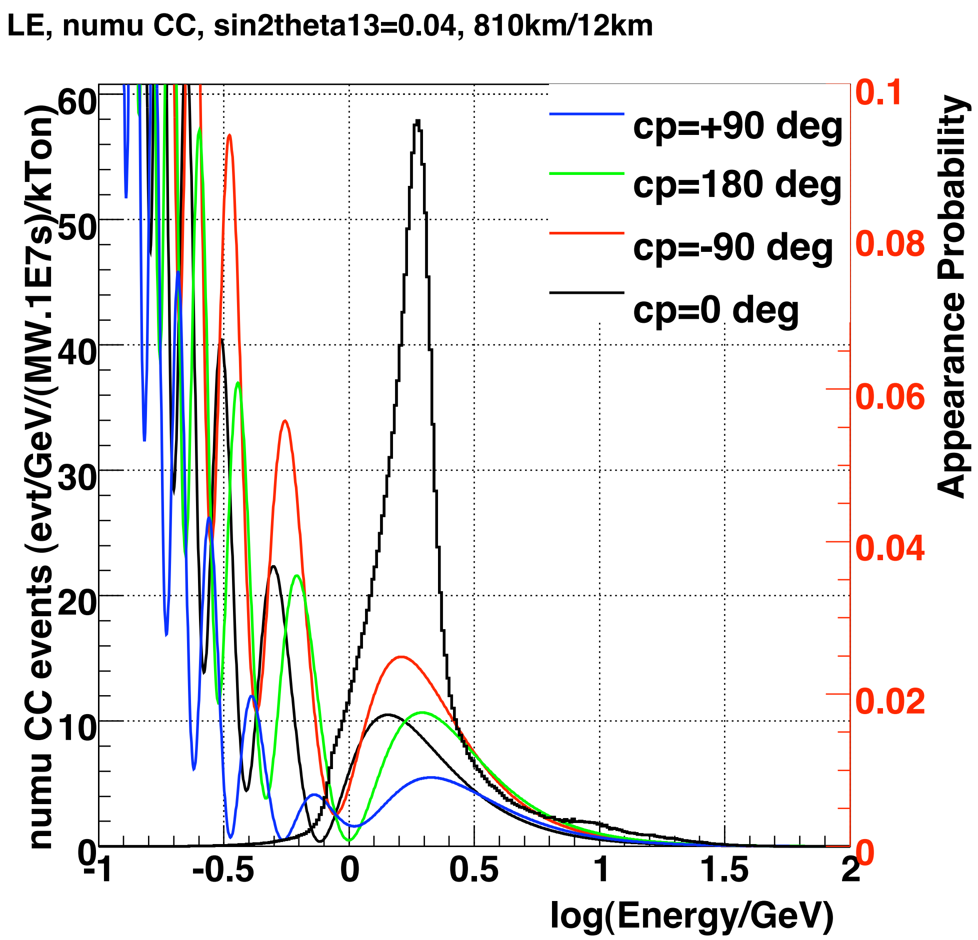
$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

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

$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11$ For Earth's crust.



LE, numu CC, sin2theta13=0.04, 810km/12km
numu CC events (evt/GeV/(MW.1E7s)/kTon)
Appearance Probability
cp=+90 deg
cp=180 deg
cp=-90 deg
cp=0 deg
log(Energy/GeV)



LE, numu CC, sin2theta13=0.04, 810km/12km
numu CC events (evt/GeV/(MW.1E7s)/kTon)
Appearance Probability
cp=+90 deg
cp=180 deg
cp=-90 deg
cp=0 deg
log(Energy/GeV)

Two approaches

No new beam, but restricted physics because of surface det.

- Off axis: Use existing NUMI beam. NOvA will be built ~10mrad offaxis for the first maximum. NOvA2(100kTLAR) will be built at either 10 mrad or 40 mrad for second maximum. Detectors will be on the surface. Combine the results to extract th13, mass hierarchy, and CPV.

New beam, but detector capable of Nucleon Decay

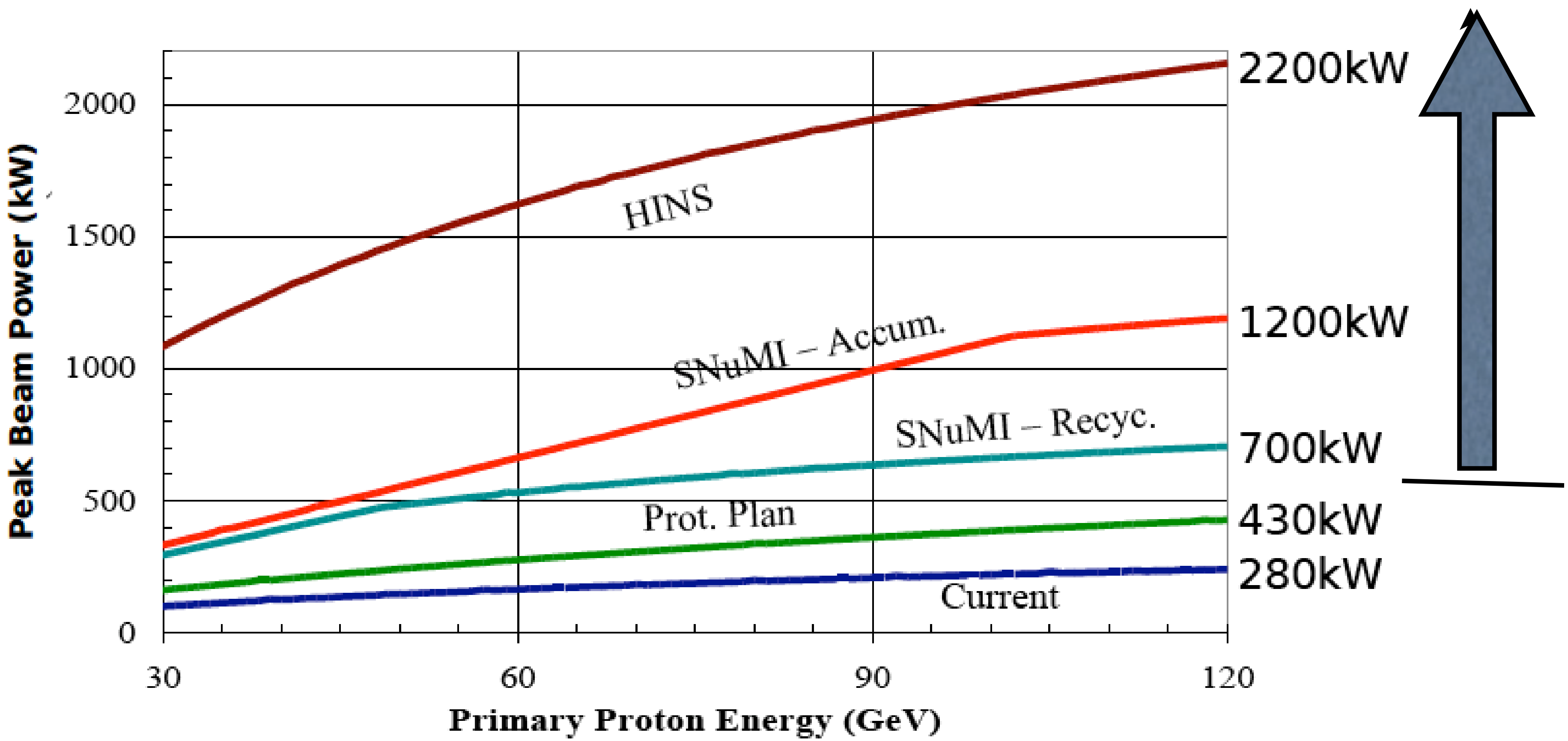
- Wide band Low Energy: Couple the long baseline program to a new deep underground laboratory (DUSEL). Site a large detector (~300kT if water Cherenkov or 100kT LAR) at approximately 5000 mwe. Build a new wide beam with a spectrum shaped to be optimum (0.5-6 GeV). Use detector resolution to extract multiple nodes.

- Concerns: event rate, NC background, resolution, parameter sensitivity, total cost and timeliness.

Beam from FNAL

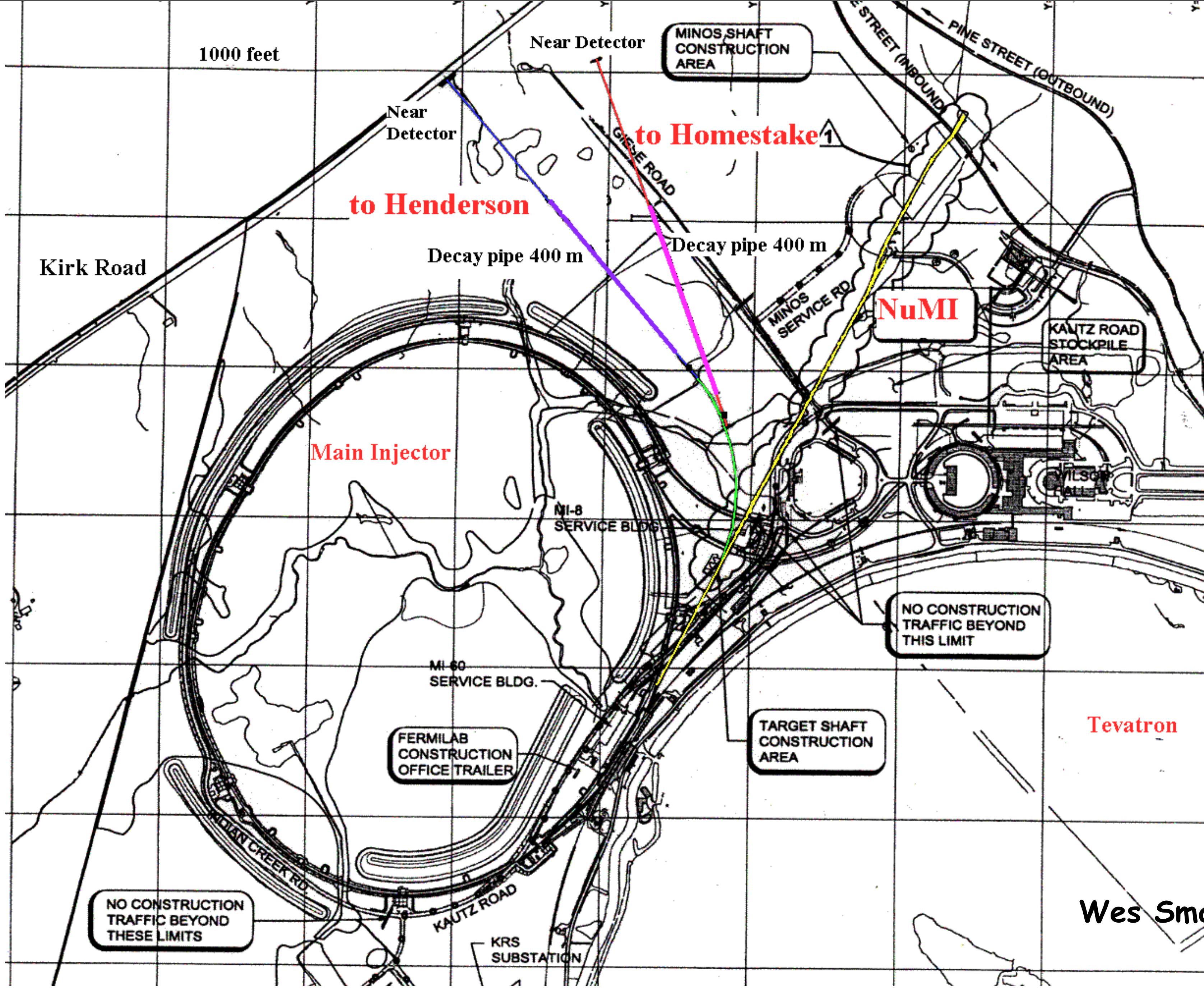
Flexibility of proton energy:

After Collider



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

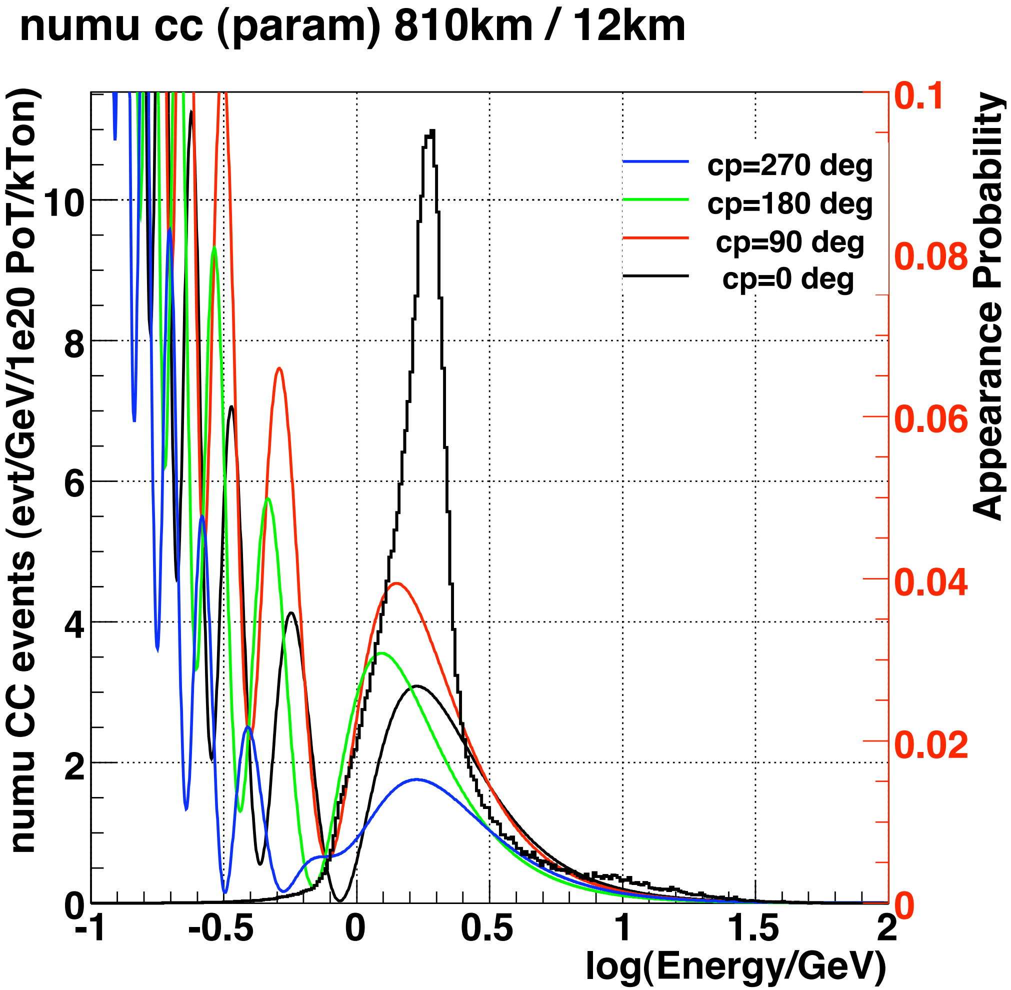
1MW*130 hrs/week*42 weeks = 10.2 10^{20}

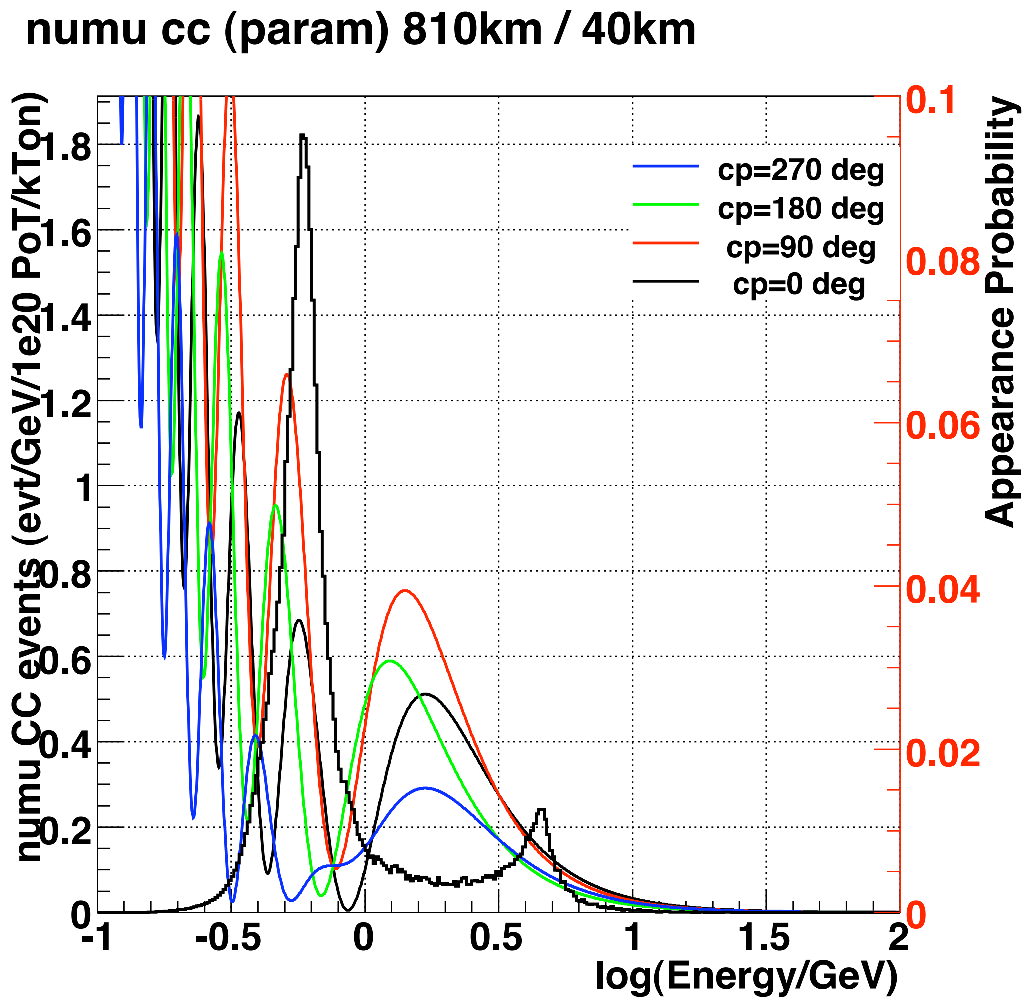


Bock, Bogert, Smart

DUSEL beamline <400 m, 2 m radius

off-axis spectra with LE tune

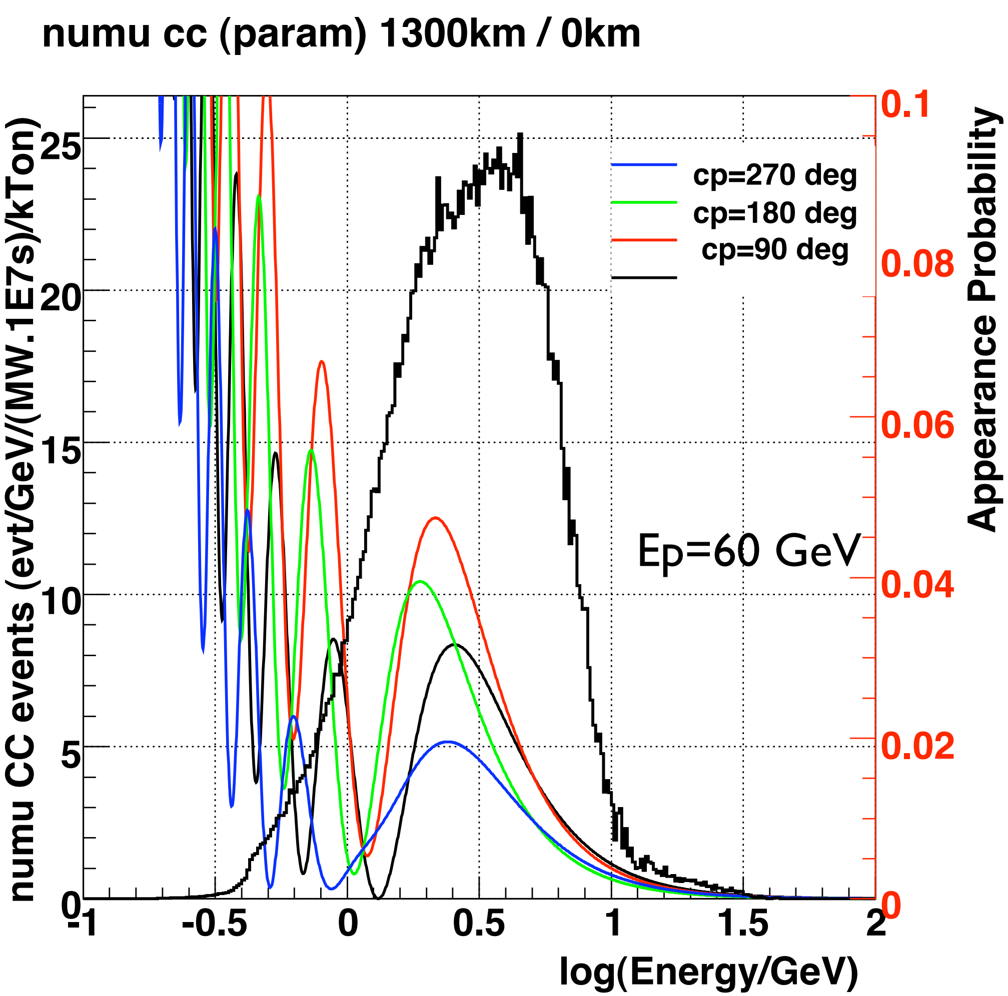


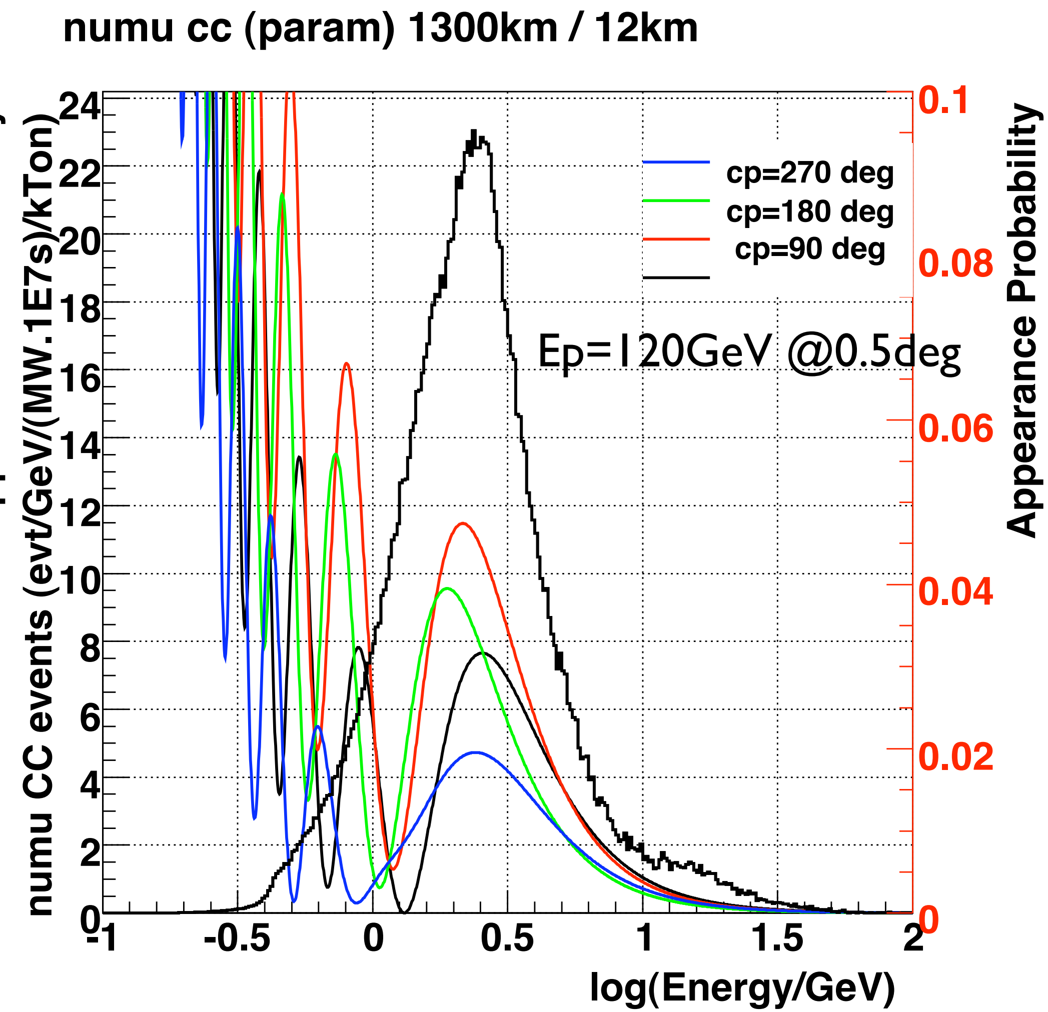


sin^22t13 =0.04

- 12 km (nova-I) CCrate: ~16.2 per (kT*10^20 POT)
- 40 km (nova-II)CCrate: ~1.0 per (kT*10^20 POT)

Spectra FNAL to DUSEL (WBLE:wide band low energy)





- 60 GeV at 0deg: CCrate: 14 per (kT*10^20 POT)
- 120 GeV at 0.5deg:CCrate: 17 per(kT*10^20POT)

Work of M. Bishai and B.Viren using NuMI simulation tools

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

$$\nu_\mu \longrightarrow \nu_e$$

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

$$\delta_{CP}$$

	$sgn(\Delta m^2_{31})$	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

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

$\sin^2 2\theta_{13}$	Events NuMI 12km 0CP, (+)	Frac. diff. wrt (-)	Frac. diff. wrt 90CP
0.02	76	0.25	0.36
0.1	336	0.23	0.15

Matter effect ↑ ↑ CP effect

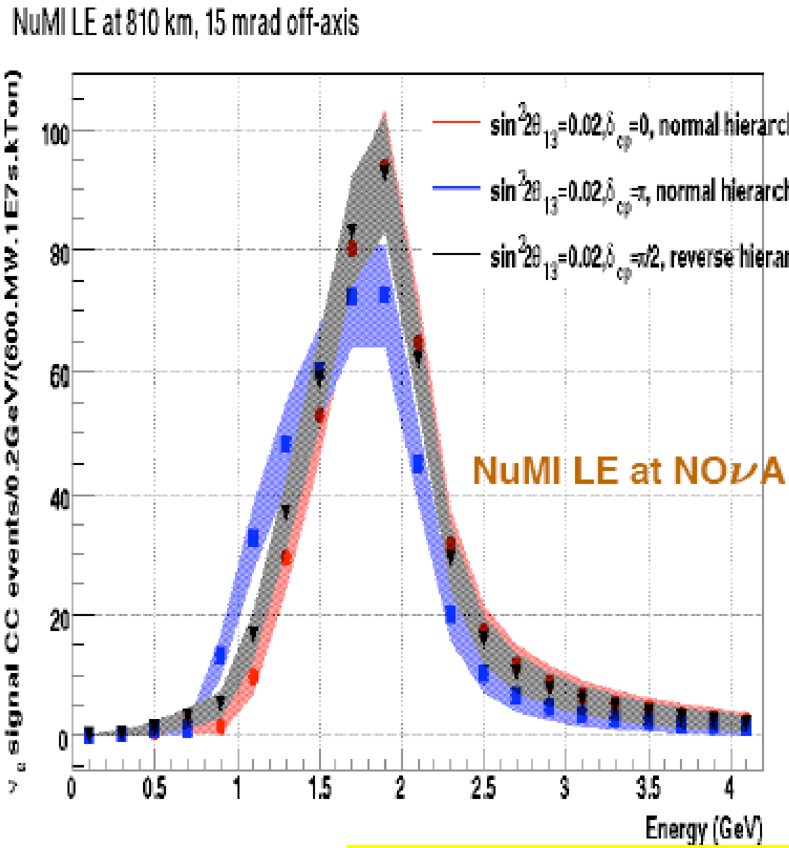
- Normalization: 1MW*100kT*10^7
- Significance for CP violation is different from matter effect. For large θ_{13} it is only weakly dependent on θ_{13}

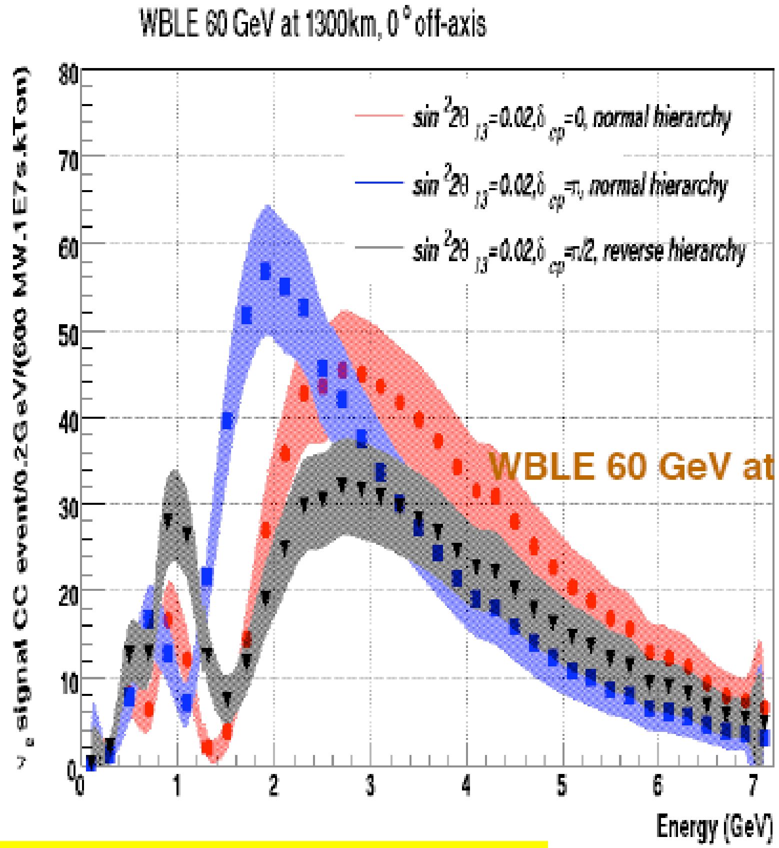
ν_e Appearance Spectra

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

The key experimental factor

- Huge (>100kT) detector with high efficiency.
- 2 MW beam helps, but need the above detector first.

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

- 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.

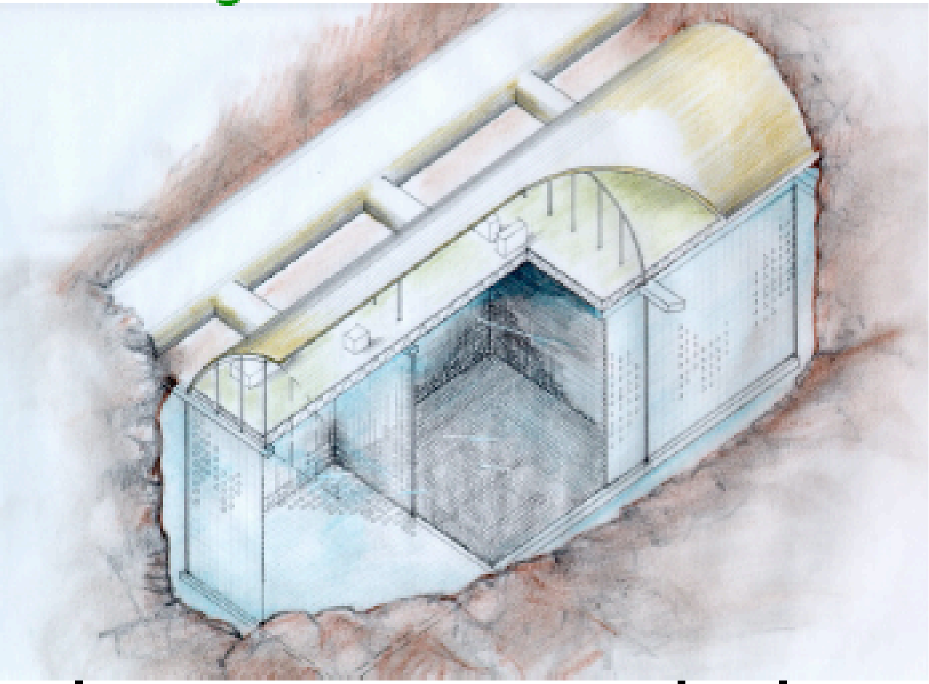
Liquid Argon

- 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. There is both risk and controversy if proton decay physics or other non-accelerator physics can be done on surface.
- Must demonstrate 10^8 rejection of cosmics as well as data rate capability.
- Aggressive successful R&D is needed to mount a proposal in 5 yrs.

Detector at Henderson

UNO detector:

- 1 large cavern
- 3 optically separated modules of 60x60x60 m^3
- total mass 440 kT fiducial
- central module 40% PMT coverage (low E physics)
- outer modules 10% PMT coverage
- optional finer granularity: 20 or 13 inch tubes
- optimal depth 5400mwe (2500 feet)
- construction time: 10 years
- coarse cost estimate scaling Super-K: $500M

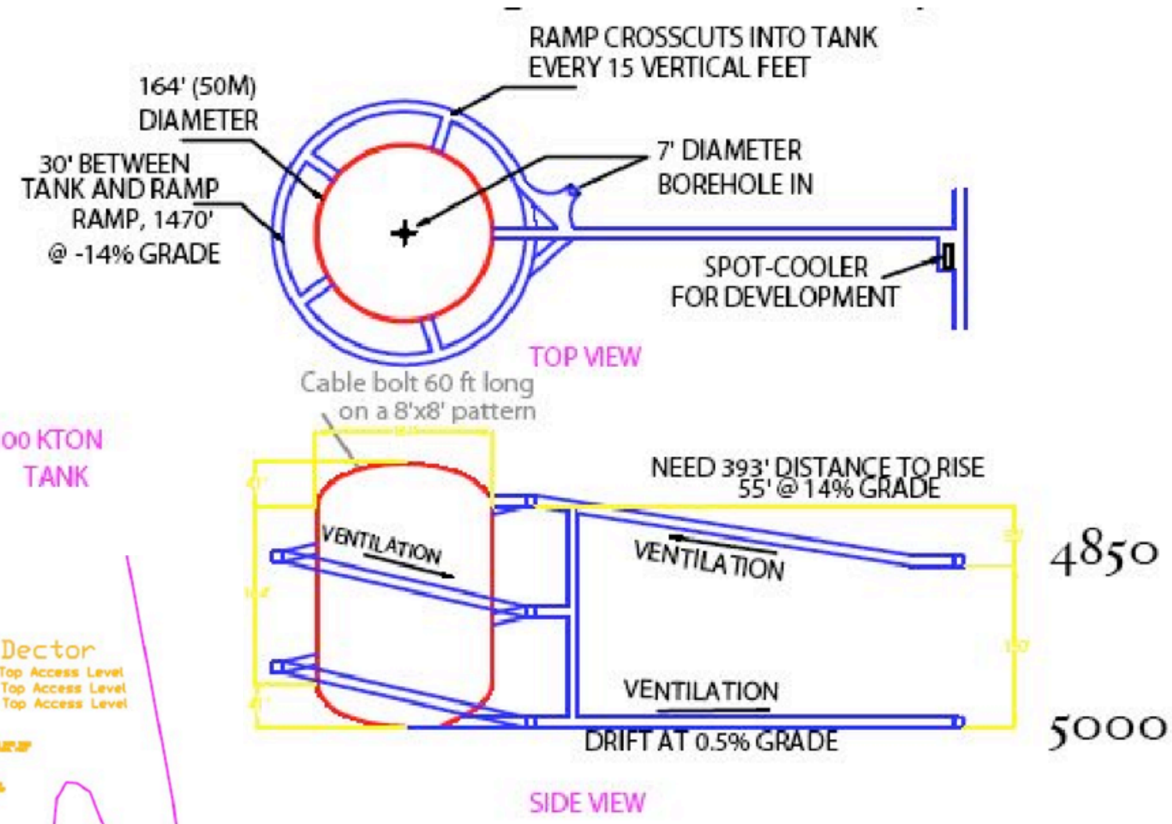


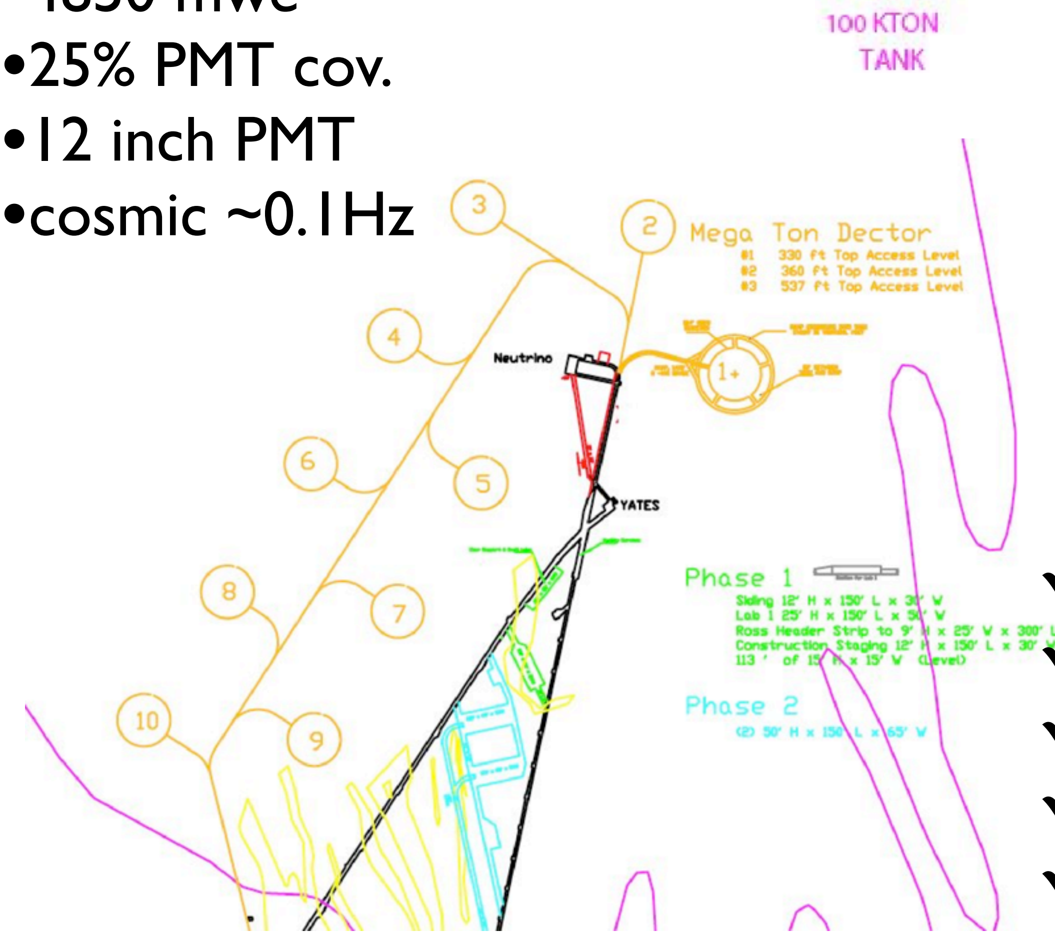
There is also an evolving concept to deploy such a detector in the Cascades site

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.

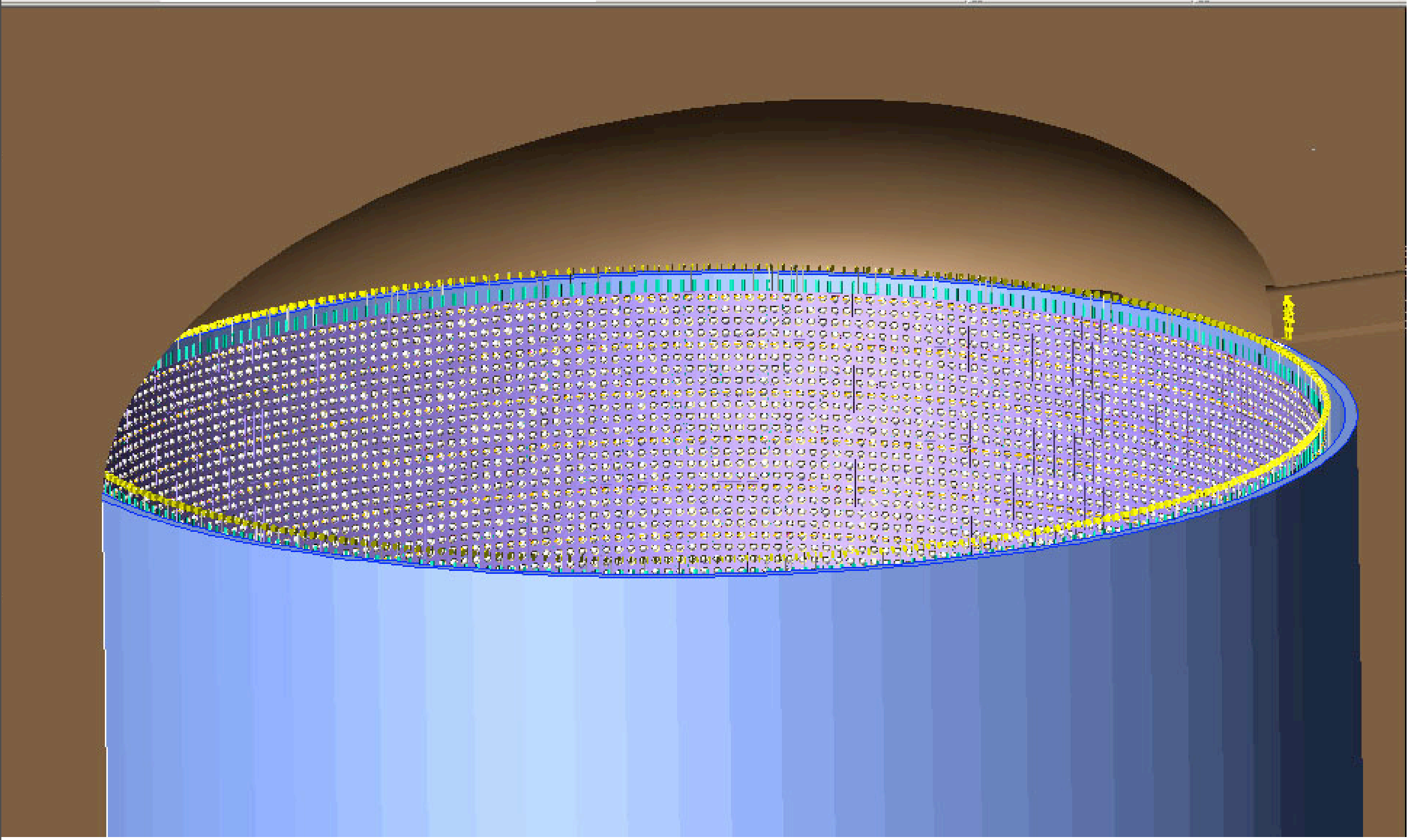
Fiducial vol depends on rock stability studies and PMT pressure rating.

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

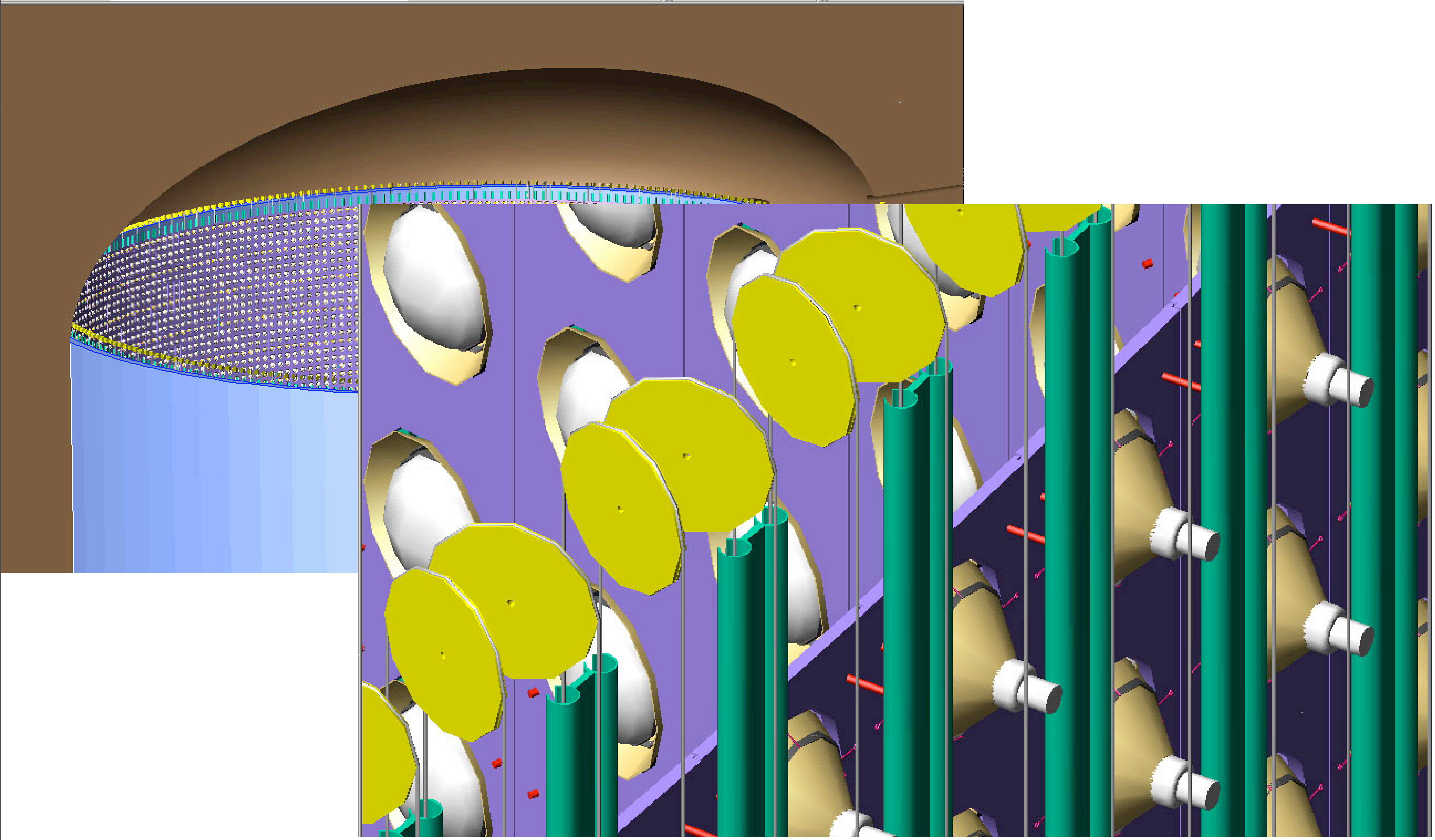
- Cost for 3 modules of ~100kT fiducial mass. 6 yrs to first 100kT, 8 yrs for full 300kT.
- Civil cost recently reviewed by RESPEC (consultants) and found to be consistent with other projects. (In addition, construction could be faster).
- Consultations with C. Laughton and Homestake on overhead factors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

Installation



Conceptual design for installation

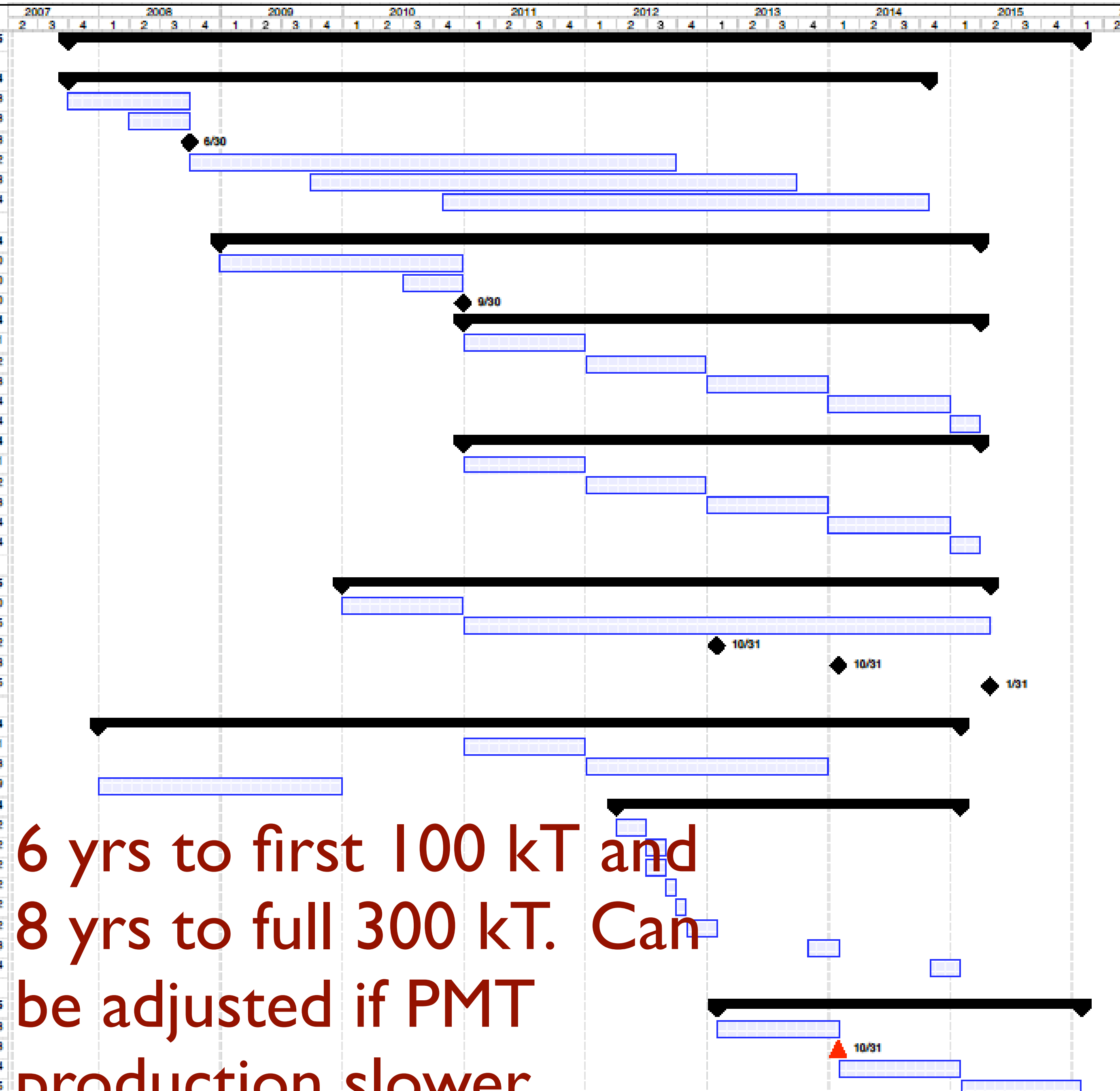
Installation



Conceptual design for installation

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

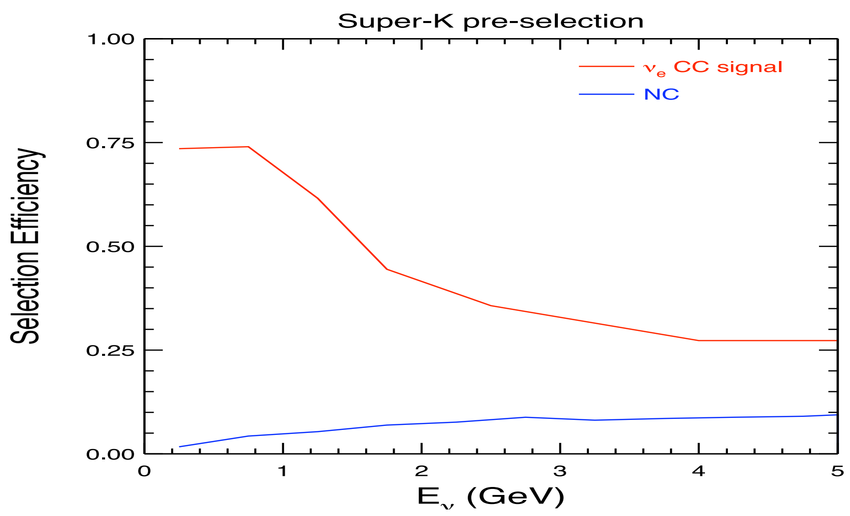


6 yrs to first 100 kT and 8 yrs to full 300 kT. Can be adjusted if PMT production slower.

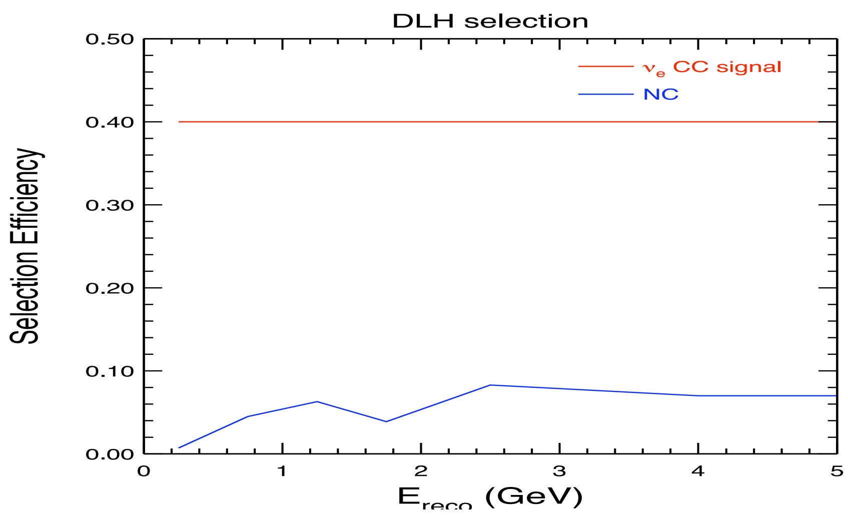
Water Cerenkov Simulation

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 $\pi^0 \to \gamma\gamma$ 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.

LARTPC

www-lartpc.fnal.gov

B. Fleming, D. Finley, S.Pordes, et al.

- Experience to date is with 600 ton ICARUS in Gran Sasso.
- There is now an active program at FNAL with links to many institutions.
- Very good progress.

- Key Challenge is in scale up from 0.6 kT to 100 kT
  - ★Must show long drift in industrial environment
  - ★Acquire signals on long, high capacity wires
  - ★Show surface data-rate capability
  - ★If underground need understanding of cost and safety issues.
  - ★Need to develop cost/schedule estimate.

start doing physics here!

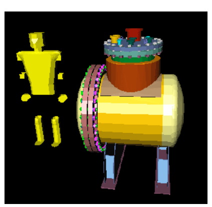
5 kton: sensitivity to mass hierarchy, increase sensitivity to θ_{13}

50-100 ktons: Search for CP Violation in neutrino sector

Possible FNAL sited experiments (50-1000 tons)

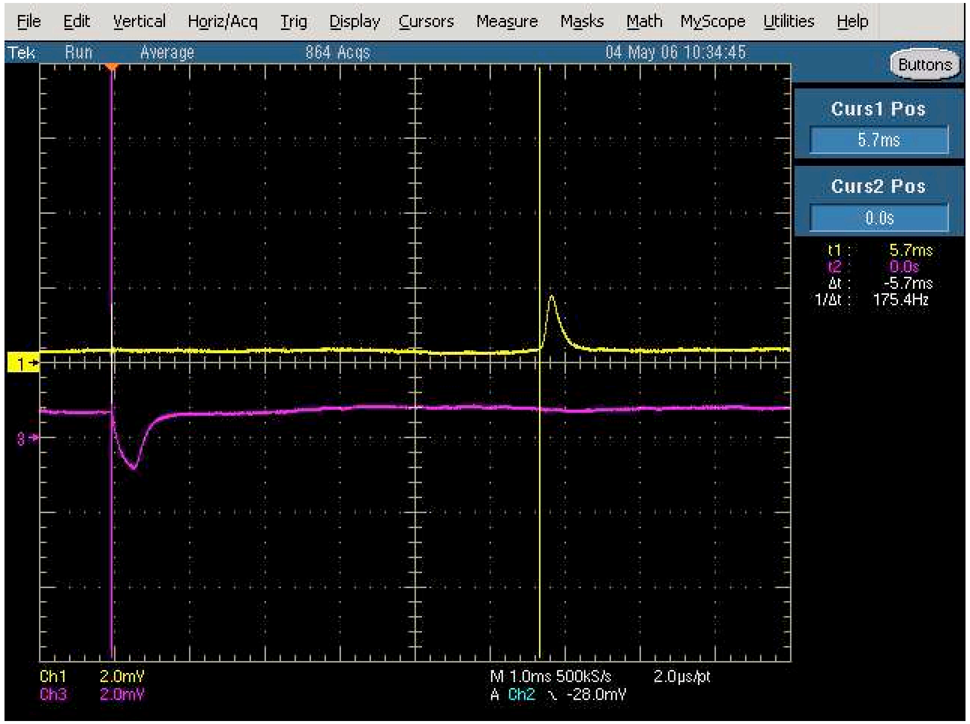
150 ton purity demonstration

test stands

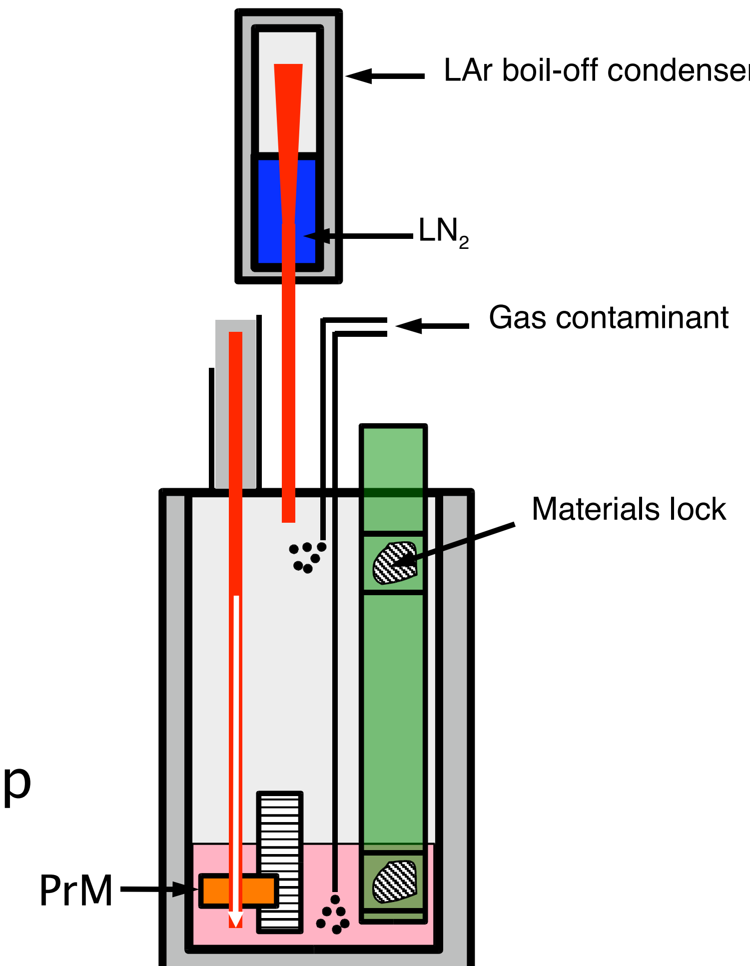


2007 2008-9 2013-15 201?

a 5.7 millisecond drift with the long PrM

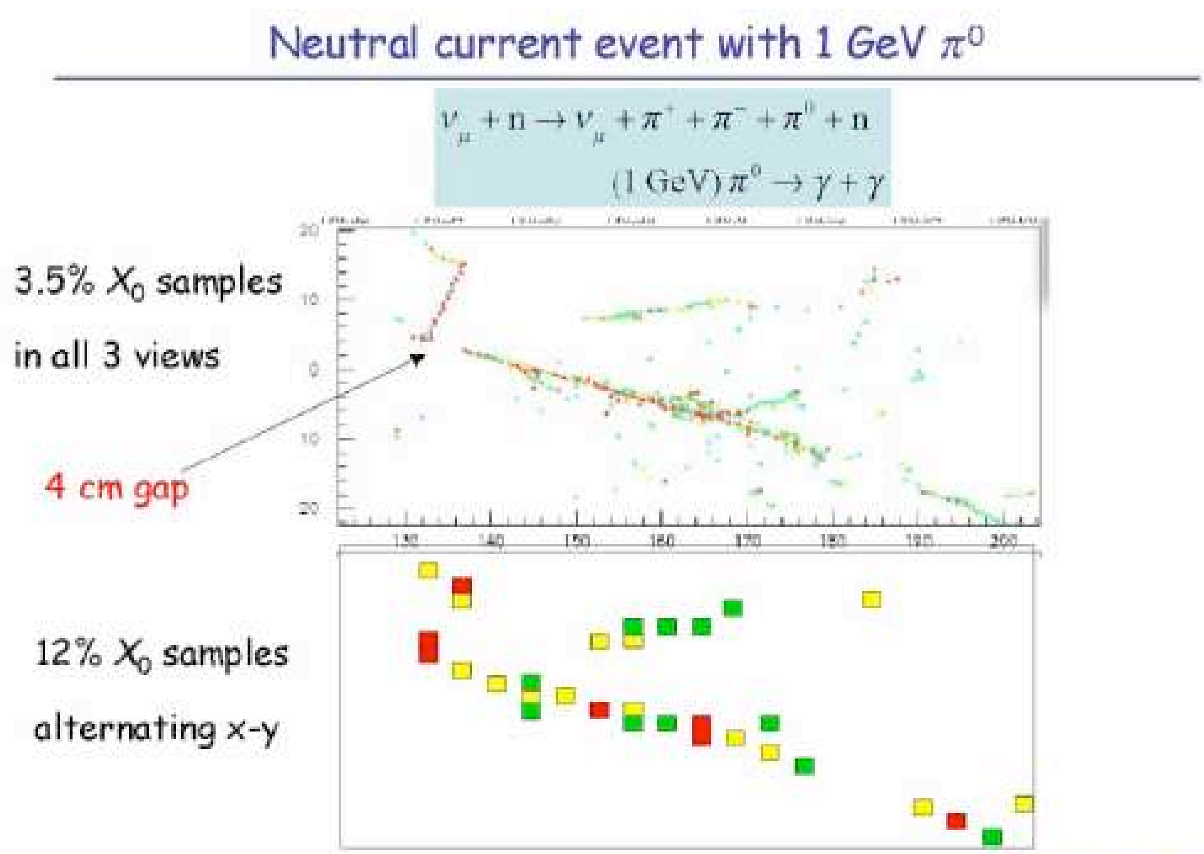


Lifetime Measurements:
> 8ms lifetimes achieved.
Example here: 5.7ms drift



Materials test station..
(new closed system cryostat)
Developing in-cryostat thermal pump

Liquid Argon Simulations



(B. Flemming)

- For the study we assume 80% efficiency for CC and complete rejection of NC indep. of beam energy.

Handscanning indicates good π^0 rejection.

ν_μ QE event reconstruction in MC.

LARTPC

www-lartpc.fnal.gov

B. Fleming, D. Finley, S.Pordes, et al.

- The LAR group has shown an advantage of about a factor 4 over a water Cherenkov detector of equal mass due to better background rejection. There is no easy automated event analysis, however.
- A 50 m high/dia tank on surface has 500 kHz of rate. LARTPC could take data around beamtime, but still need rejection of 10^8 on muons and 10^3-10^4 on gammas. This needs further work.
- To reach 100 kT, aggressive R&D path is needed including argon purity, industrial tank technology, readout geometry and signal/noise. First step : 1 kT before cost and schedule could be properly evaluated. Current scaling law is \$2.7M+\$0.3M/kT + \$1M/kTon (for LAR).
- Lower bound on 100 kT cost ~\$200M ?
- For $p \rightarrow K^+\nu$ decay mode depth might be needed simply for data rate, and most likely for background.
- Such a detector can be placed at either NuMI off-axis or DUSEL.

Electron neutrino appearance spectra

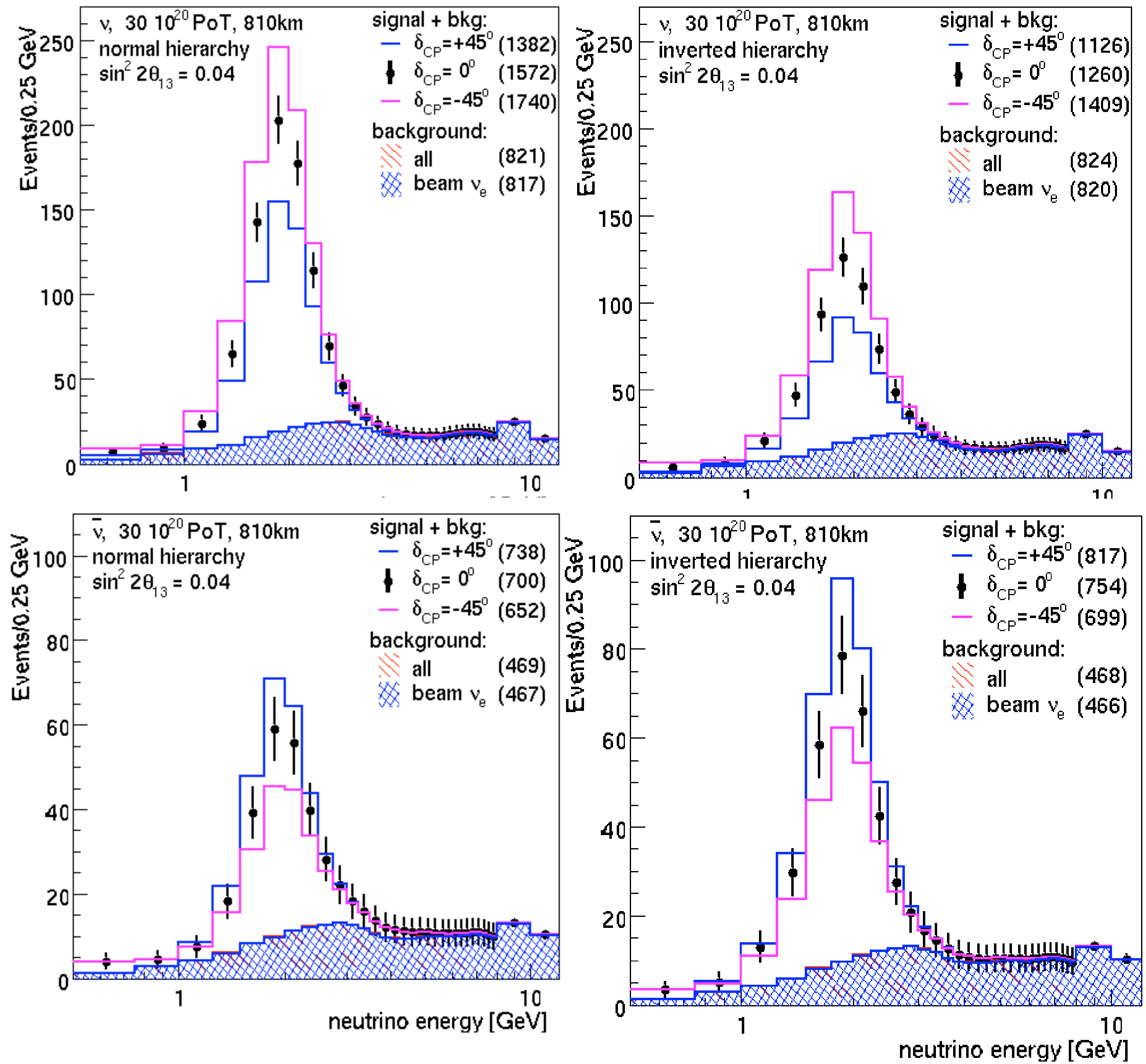
$\sin^2 2\theta_{13} = 0.04$, 100kT LAr. ,Numi120 GeV, 1300km, 30E20 POT.

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

Normal Reversed

- 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

Same performance for NuMI offaxis beam



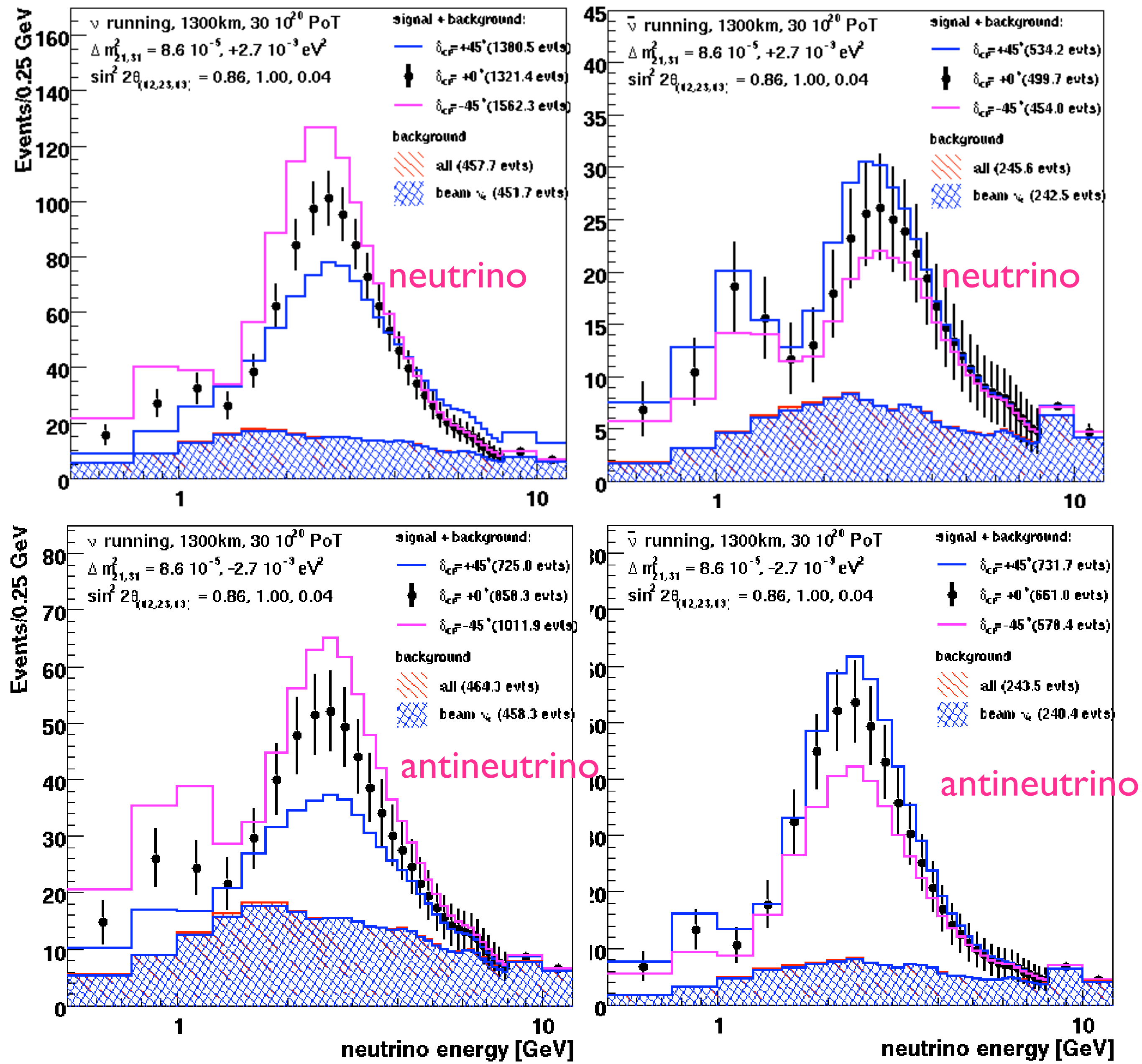
Electron neutrino appearance spectra

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

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

Normal Reversed

- 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



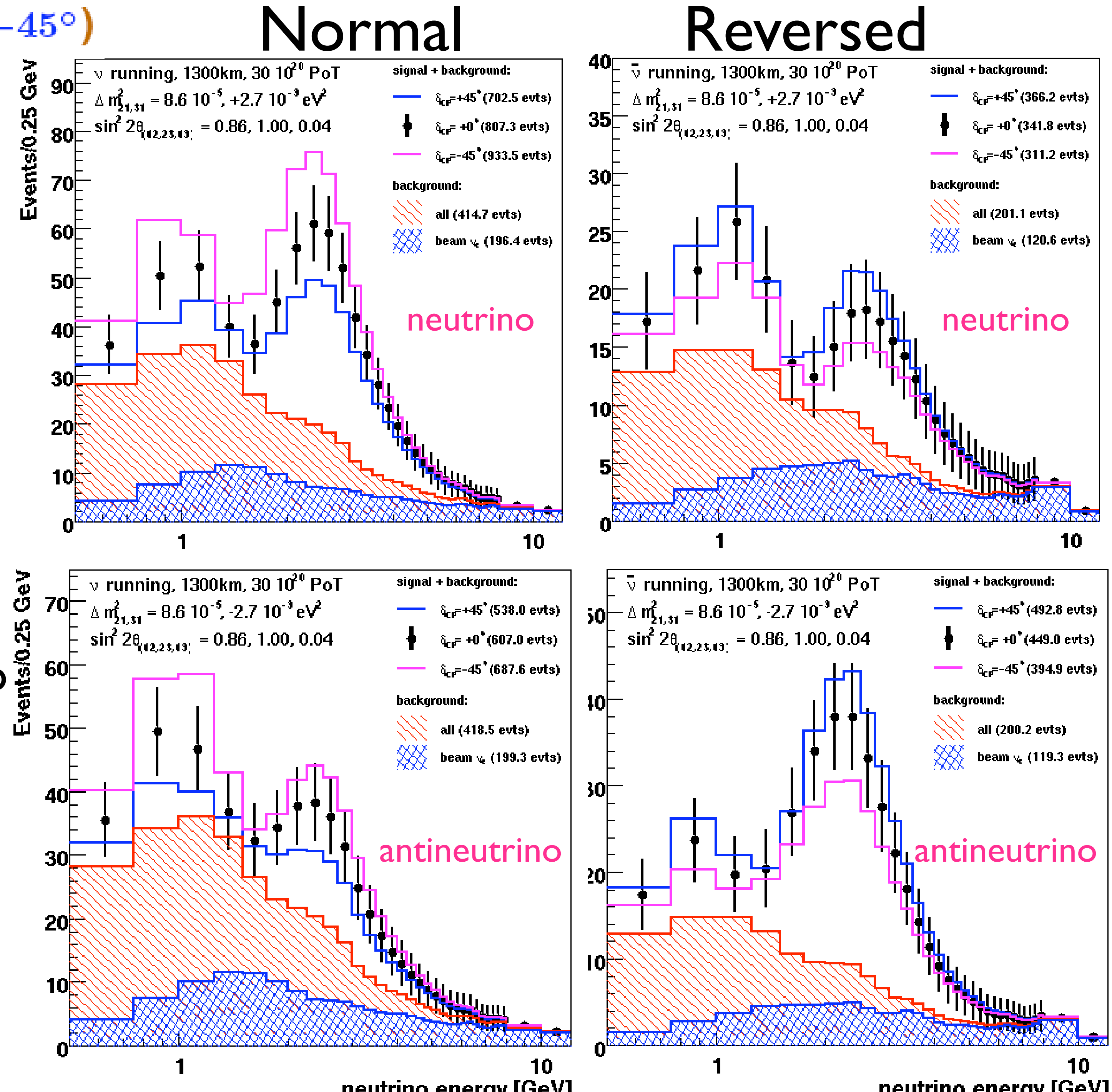
Spectra and sensitivity is the work of Mark Dierckxsens and Patrick Huber + many helpers

Electron neutrino appearance spectra

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

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

- 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.



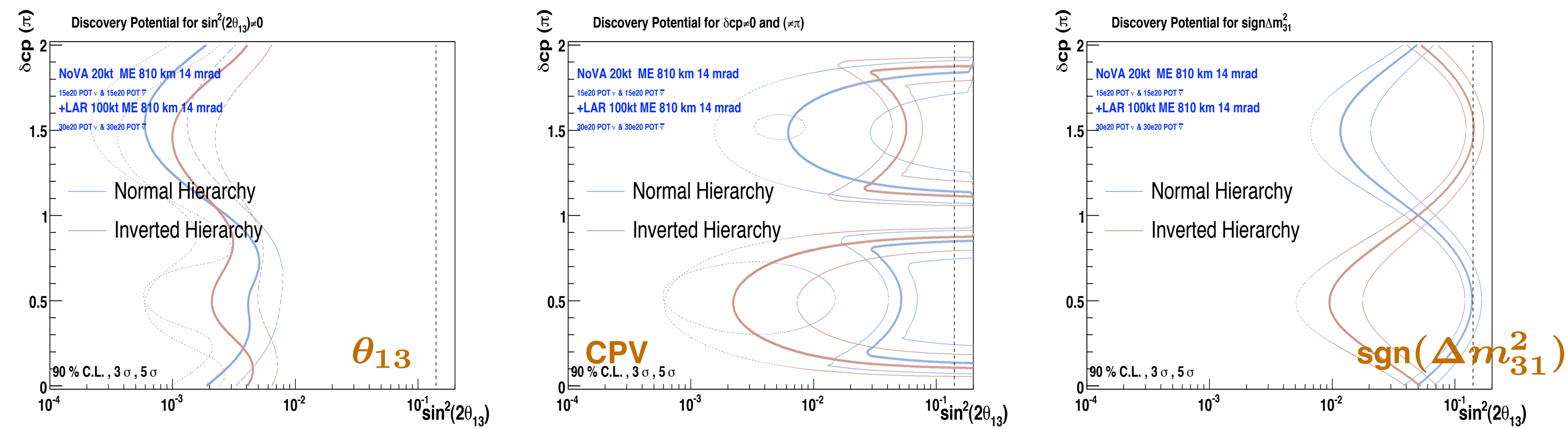
Choices

1. 100 kT LARTPC at the NOvA site at first maximum.
2. 50 kT LARTPC at NOvA site and another 50 kT at 3.3 deg.
3. 300 kT water Cherenkov at 1300 km in a wide band 0.5 deg. off-axis beam
4. 100 kT LARTPC at 1300 km in wideband 0.5 deg. off-ais beam.

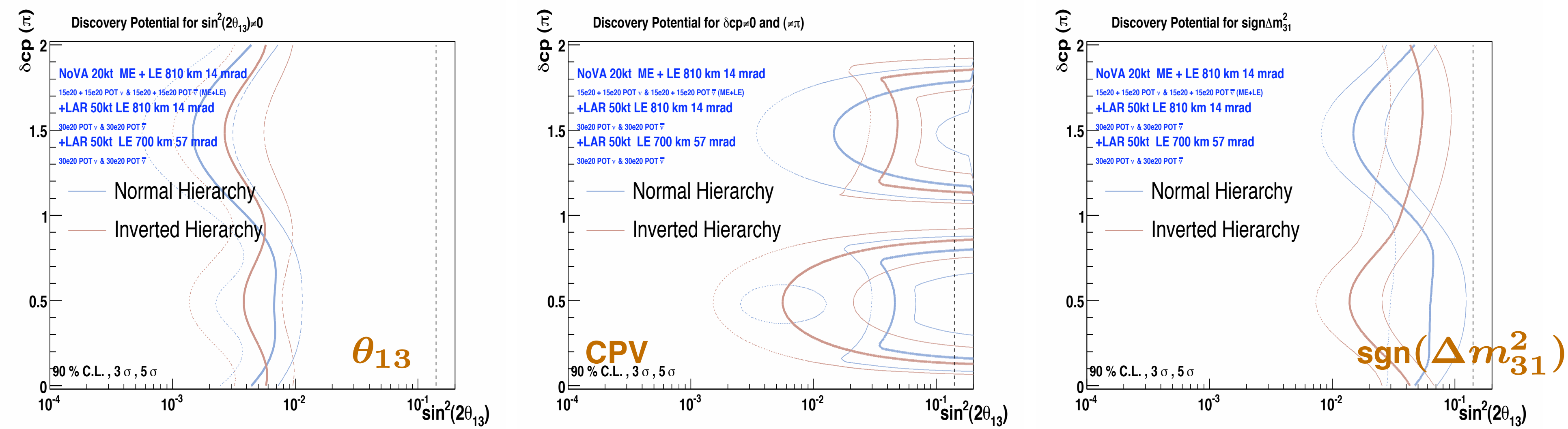
Use same number of protons 30e20 POT for nu and nubar

NuMI Off-axis

Discovery potential (90% C.L, 3σ, 5σ) LAr. 100 kT at 810km, 1.2 MW, 6yrs:



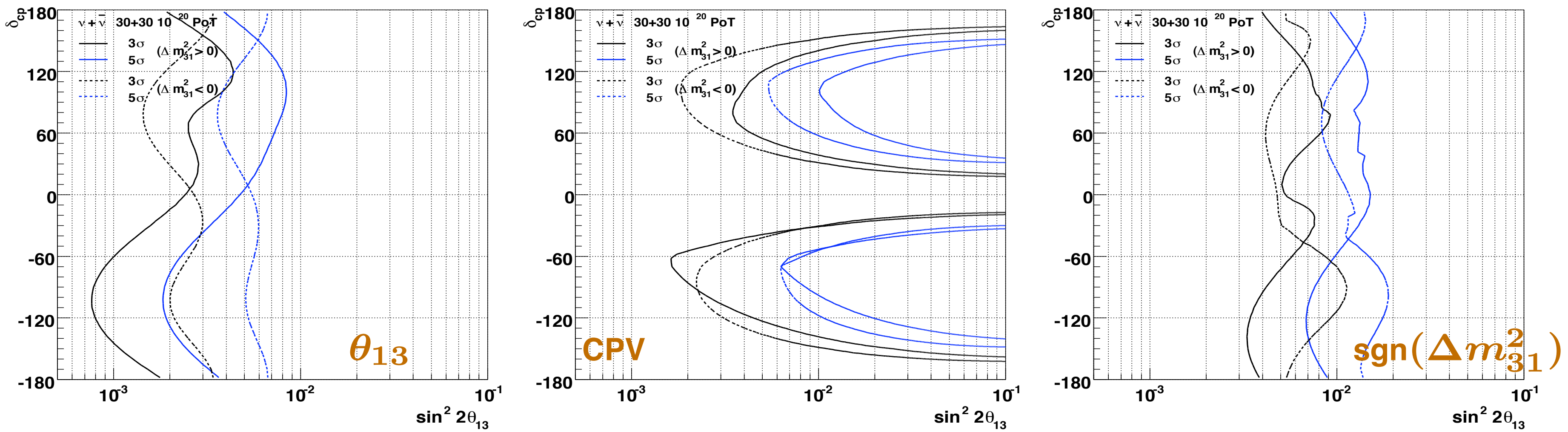
Discovery potential (90% C.L, 3σ, 5σ) LAr. 2X50 kT at 700,810km, 1.2 MW, 6yrs:



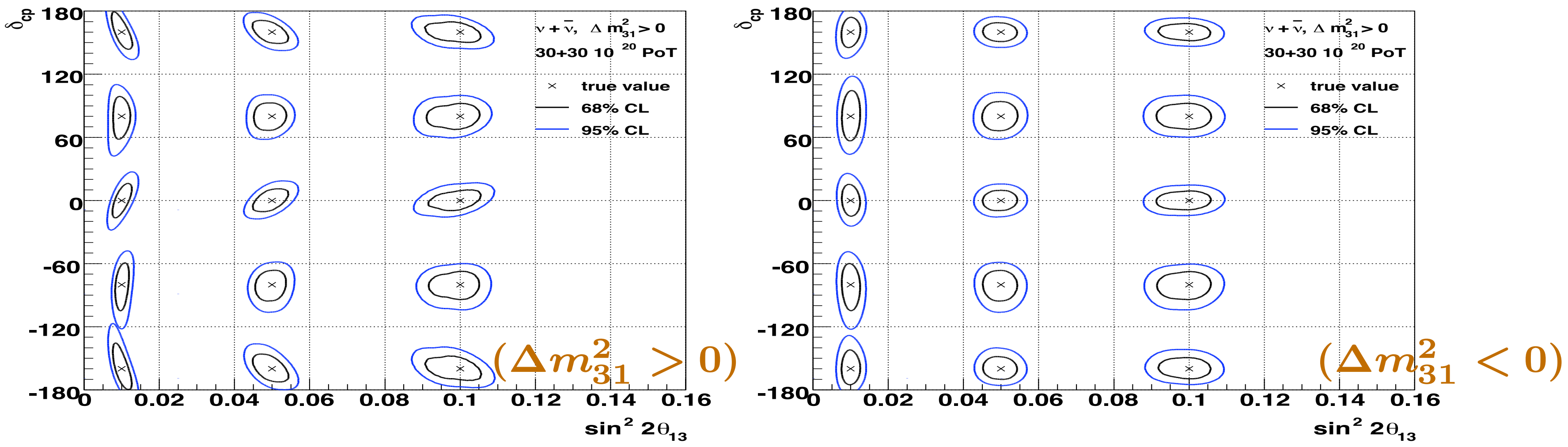
Niki Saoulidou

WBLE FNAL to DUSEL (1300km)

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

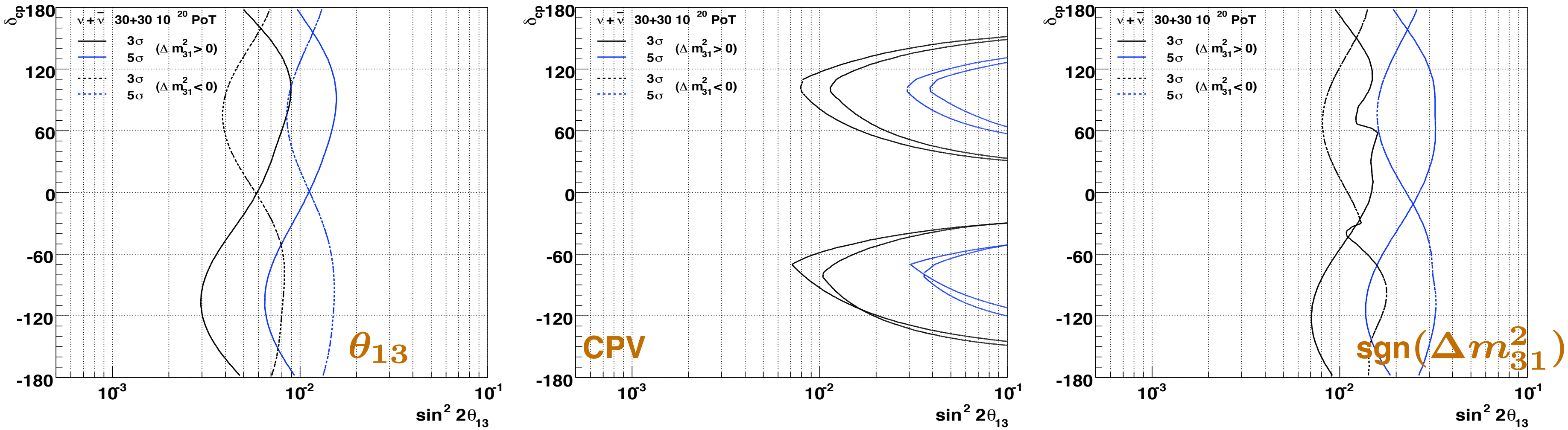


Measurement (—95% CL —68% CL) :

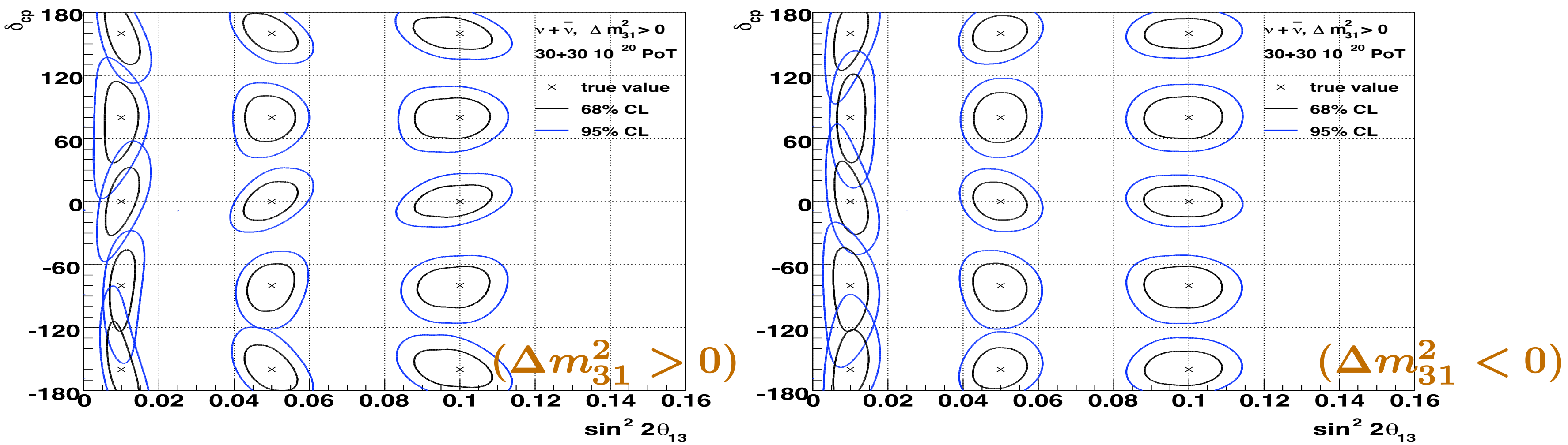


WBLE FNAL to DUSEL (1300km)

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

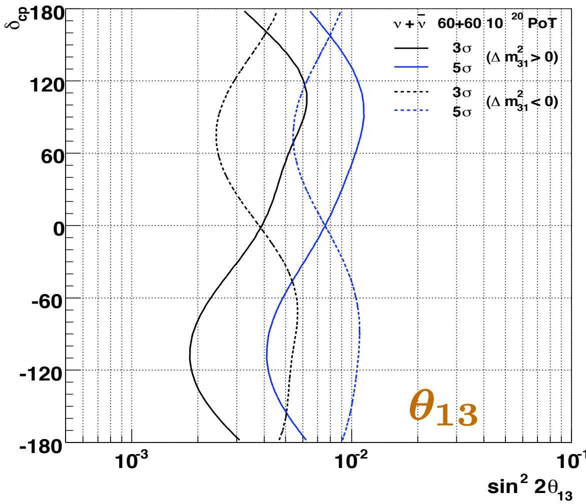


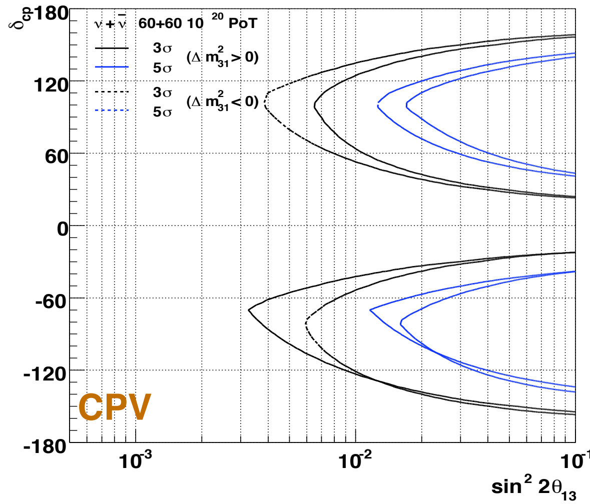
Measurement (—95% CL —68% CL) :

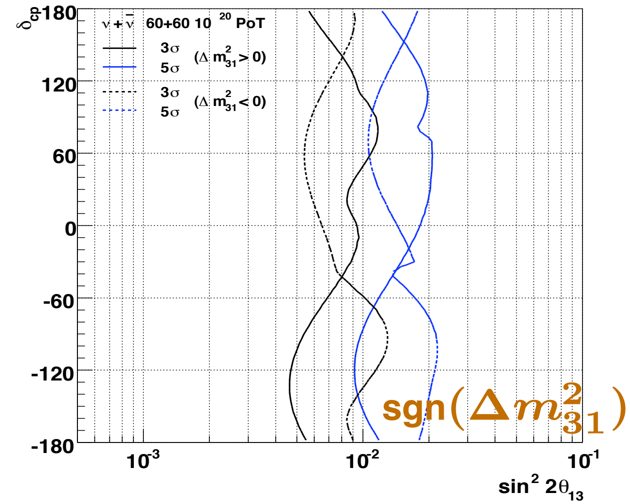


WBLE FNAL to DUSEL (1300km)

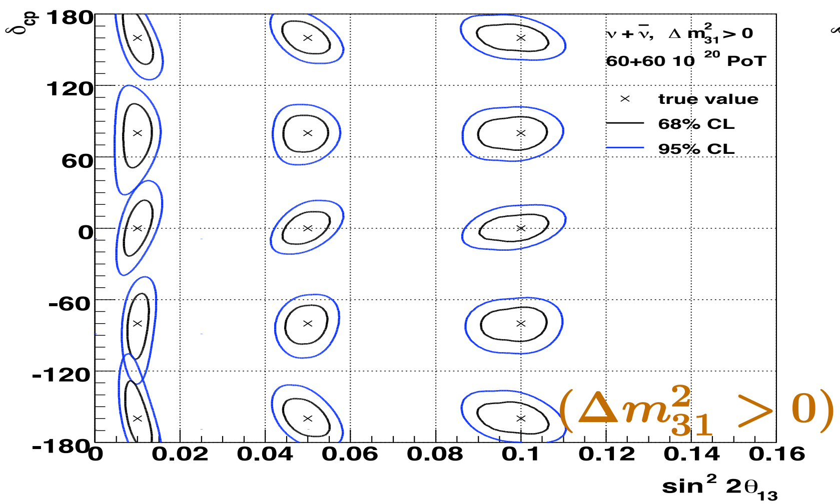
Discovery potential (— 5σ —3σ). WCe. 300 kT, 1.2 (2) MW, 12 (7) yrs:

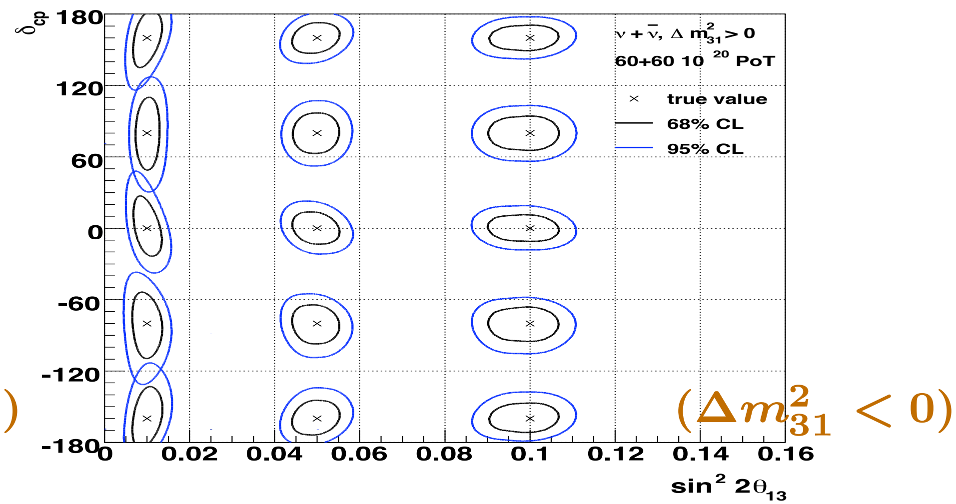






Measurement (—95% CL —68% CL) :





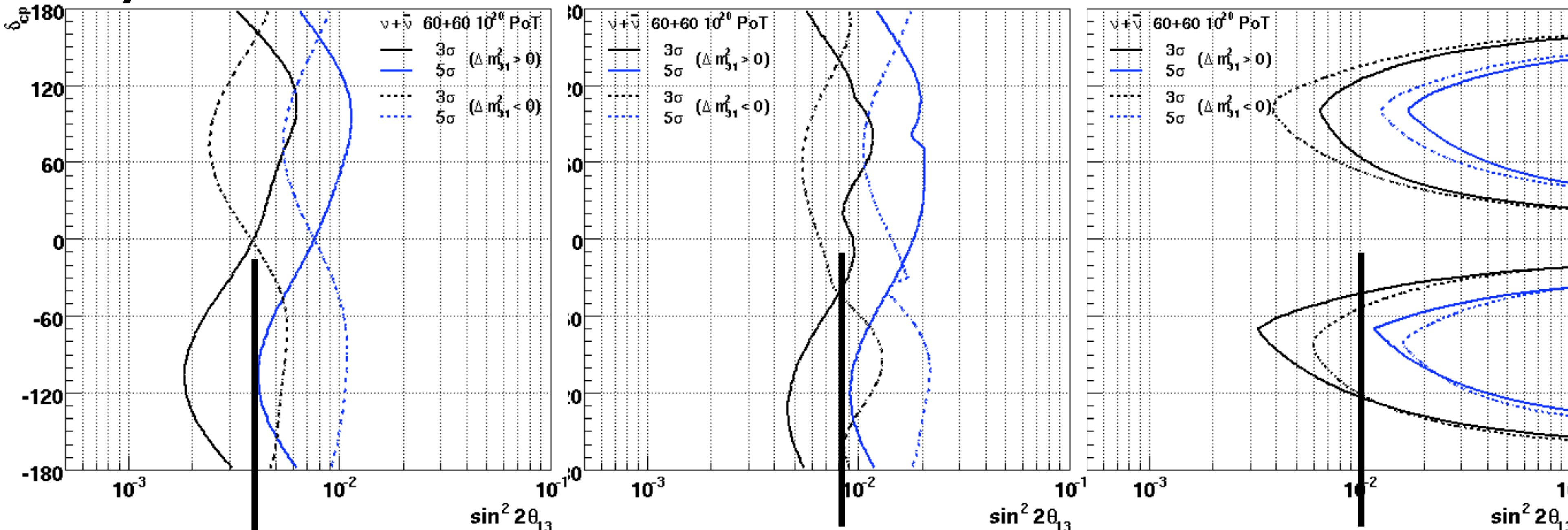
WBLE to DUSEL(1300km) 3sig, 5sig discovery regions.

300 kT WCh

60 10^20 POT for each nu and anu

Stat+syst

th13 | mass ordering | CP violation



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.

Sensitivity comparison

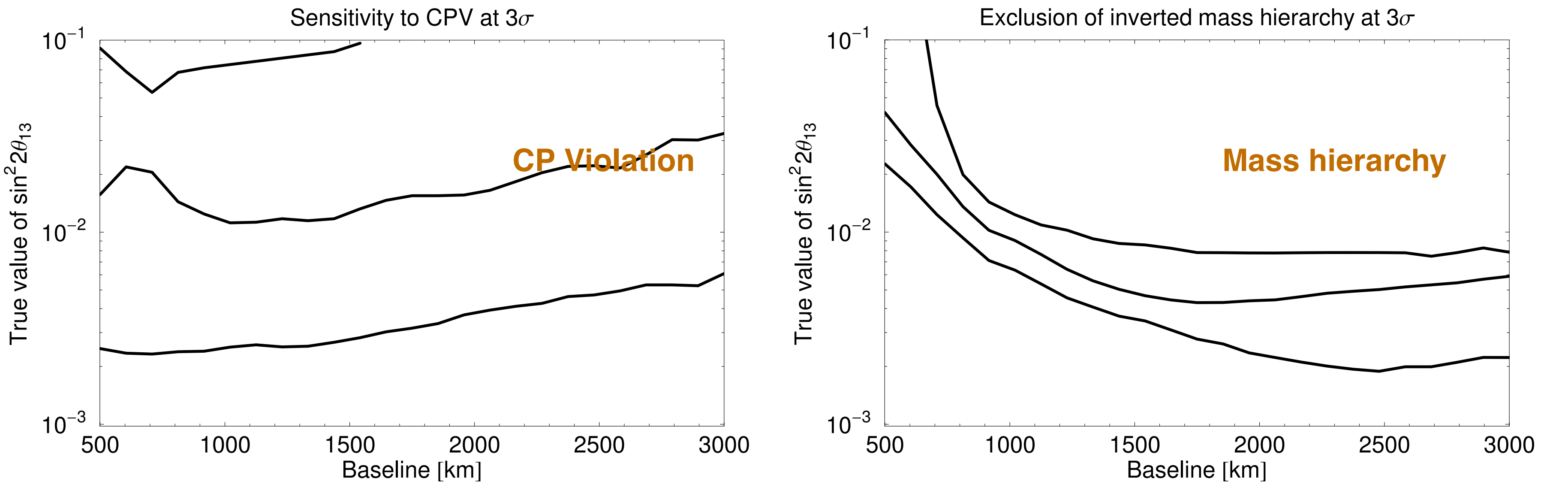
Comparison of the sensitivity reach of different long baseline experiments given as the value of $\sin^2 2\theta_{13}$ at which 50% of δ_{cp} values will have $\geq 3\sigma$ reach for the choice of mass hierarchy with worst sensitivity. Total exposure assumes equal amounts of ν and $\bar{\nu}$:

Beam	Baseline	Detector	Exposure (MW.yr*)	$\theta_{13} \neq 0$	CPV	$sign$ (Δm^2_{31})
NuMI ME, 0.9°	810 km	NOνA 20 kT	6.8	0.015	$>$ 0.2	0.15
NuMI ME, 0.8°	810 km	LAr 100 kT	6.8	0.002	0.03	0.05
NuMI LE, 0.8°, 3°,	810,700 km	LAr 2 $\times$ 50 kT	6.8	0.005	0.04	0.04
WBLE 120GeV, 0.5°	1300km	LAr 100 kT	6.8	0.0025	0.005	0.006
WBLE 120GeV, 0.5°	1300km	WCe 300 kT	6.8	0.006	0.03	0.011
WBLE 120GeV, 0.5°	1300km	WCe 300 kT	13.6	0.004	0.012	0.008

Some differences in calculations remain: 5% syst assumed for off-axis, 10% assumed for WBLE.

Physics sensitivity vs baseline

Using a broad-band beam with peak rate at 2 GeV and a parameterized water Cerenkov detector (V. Barger *et al.*. Phys. Rev. D 74, 073004 2006):



Minimum value of $\sin^2(2\theta_{13})$ for which the sensitivity is $> 3\sigma$

for (best,50%, worst) of δ_{cp} values

Best sensitivity is for baselines 1200 - 2500km

Beam to DUSEL

Pro

- Can use either detector technology.
- 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.
- Broader physics program includes proton decay and astrophysics.

Con

- Needs new beamline
- Coupled to DUSEL with uncertain timeline and funding.

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 science that requires depth.

Summary

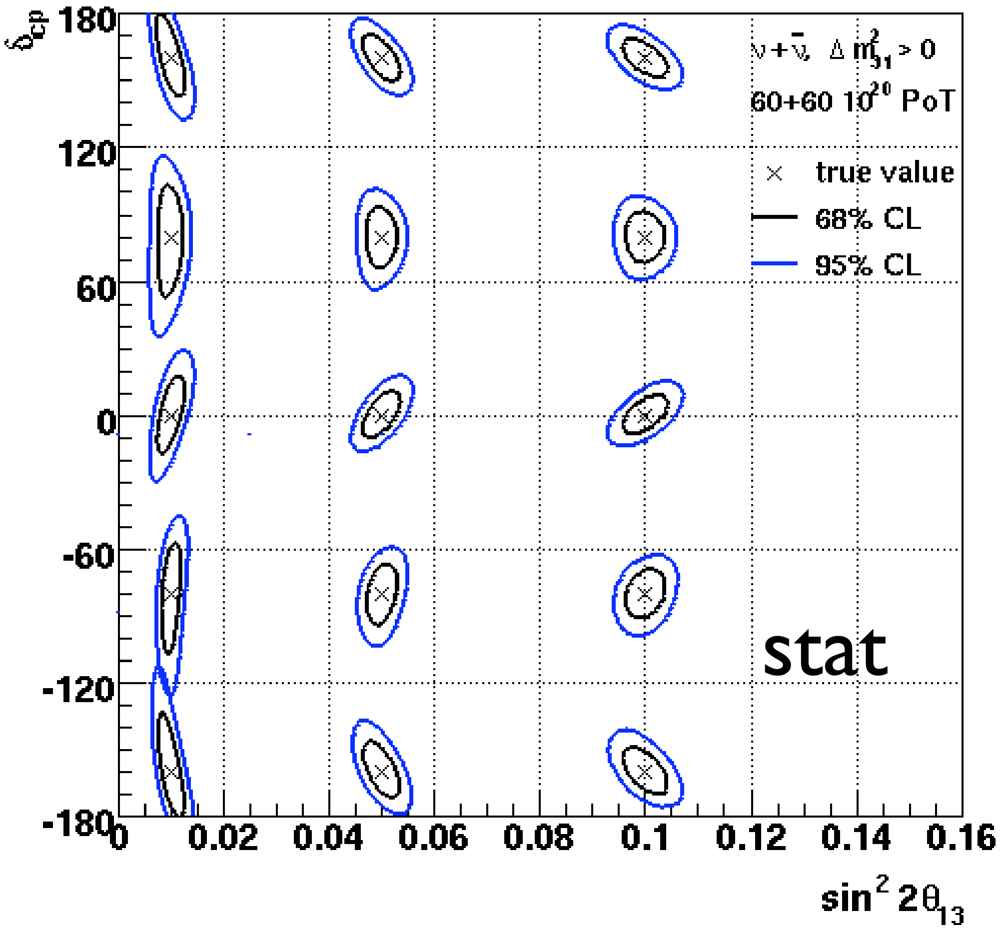
- CP violation in neutrinos should guide the Long baseline program in the future. Program is doable with known technology (water Cherenkov detector) and current accelerator intensity if nature co-operates.
- A very large detector ~100 kT efficient mass is needed to carry out the program. Megawatt proton source obviously helps.
- It is desirable that such a detector support a broad program including nucleon decay and neutrino astrophysics. This will require depth.

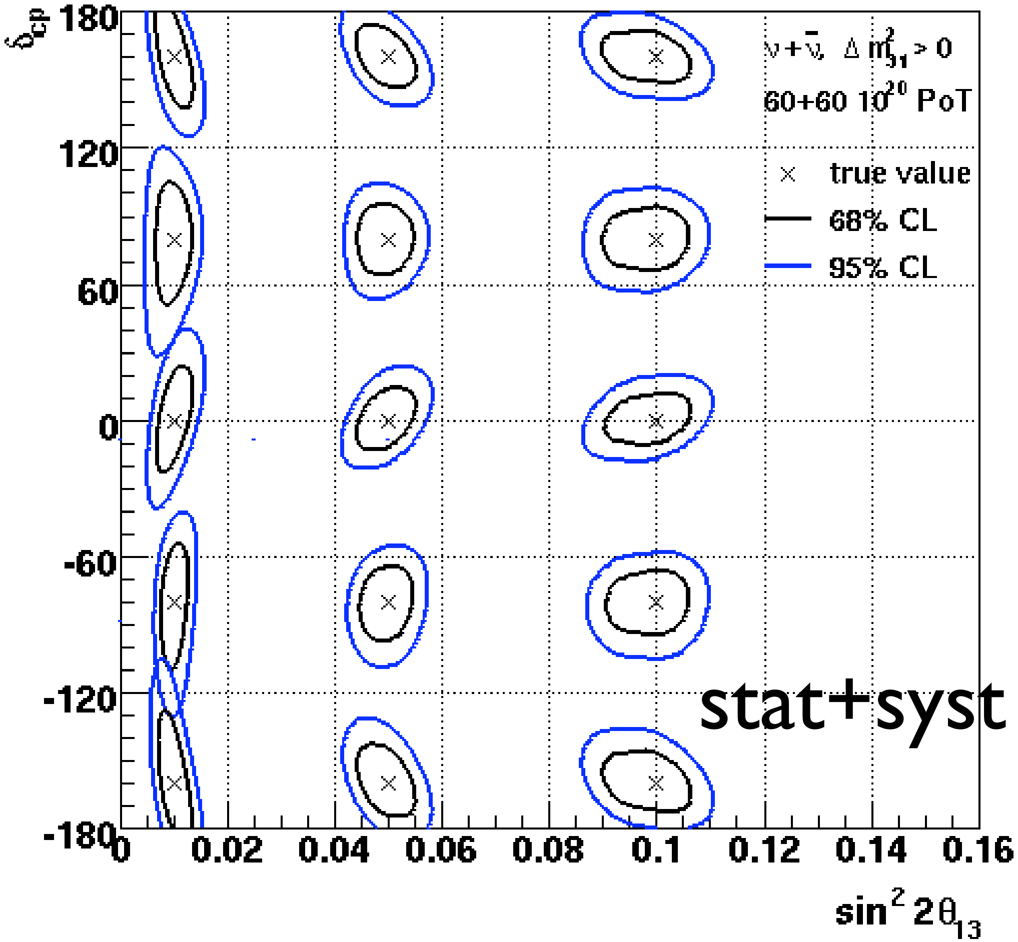
How do we get ready to launch this program in 5-6 yrs ?

Dependence of CP measurement on th13

WCC 1300 km 300kT

(—95% CL —68% CL)





Measurement of CP phase does not depend strongly on th13