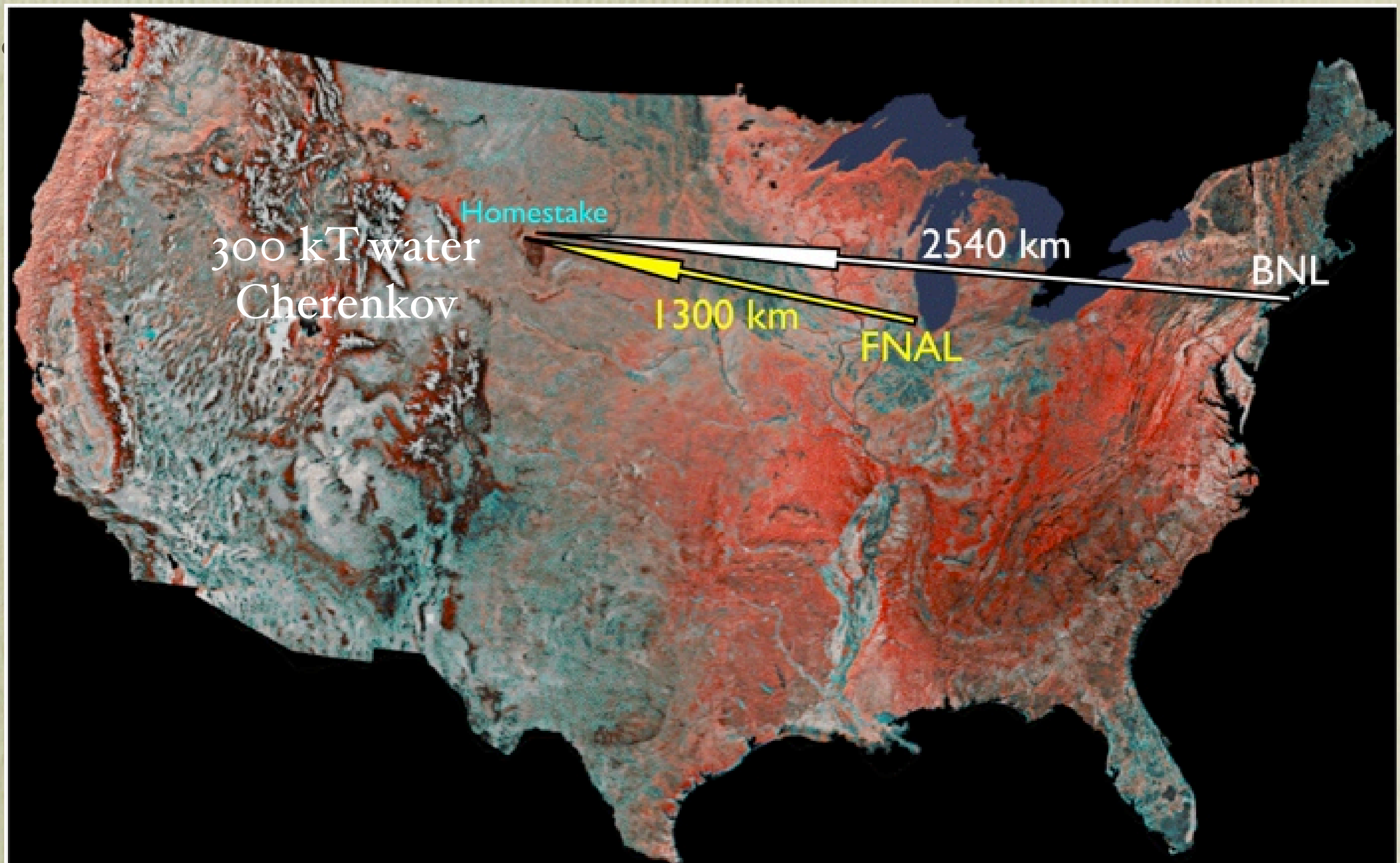
FNAL to DUSEL long baseline experiment

- Milind Diwan (BNL, USA) 9/12/2008 NNN08 conference in Paris



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Outline

- Physics considerations.
  - Strategy, Rate, Sensitivity, Detector Performance calculations.
- Technical summary of the project.
  - Intensity/Beam/Detector design considerations.
- Recent progress on organization.
  - Collaboration, schedule, funds, meetings.

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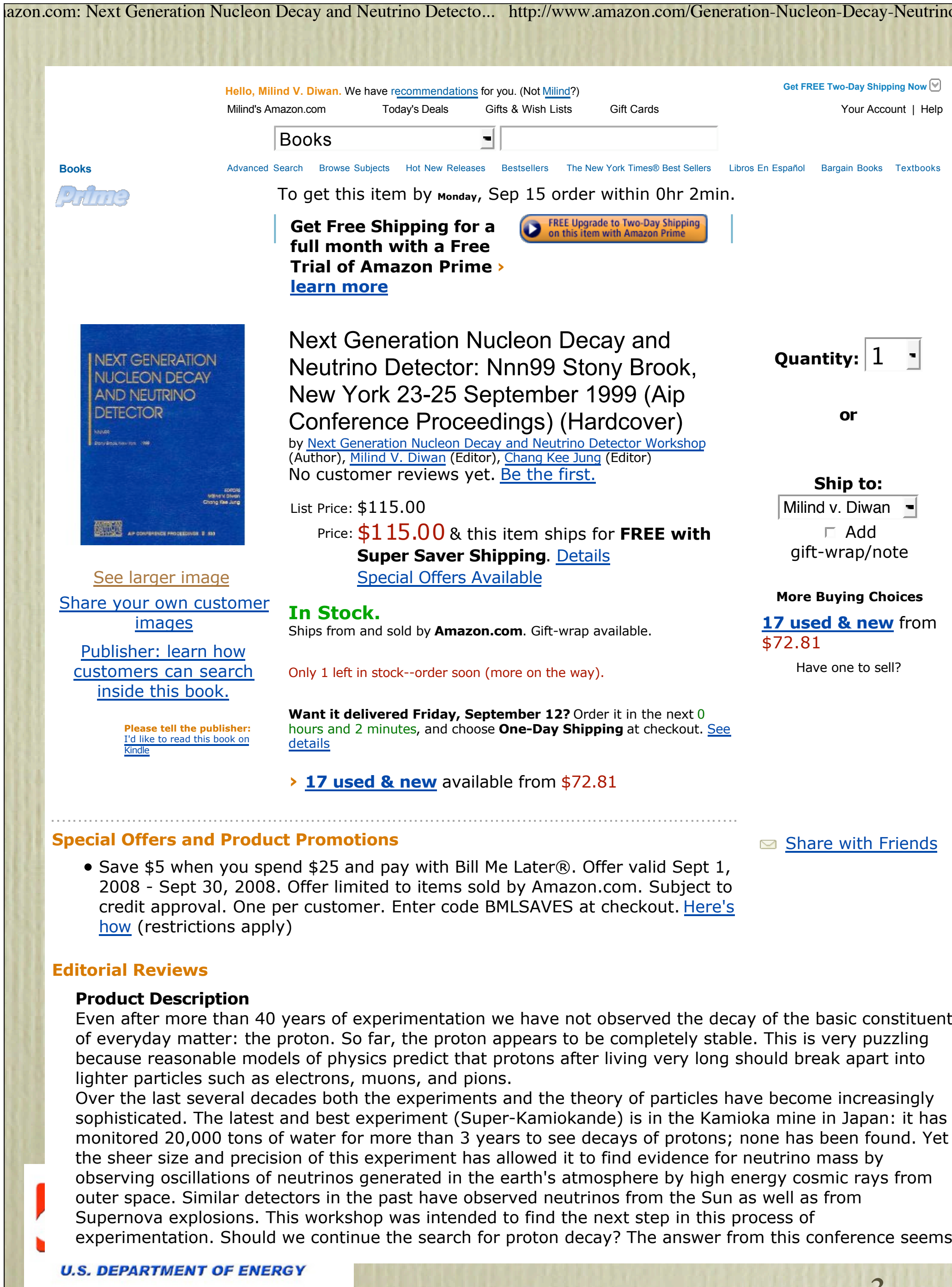

azon.com: Next Generation Nucleon Decay and Neutrino Detecto... http://www.amazon.com/Generation-Nucleon-Decay-Neutrino-Detect..

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Next Generation Nucleon Decay and Neutrino Detector: Nnn99 Stony Brook, New York 23-25 September 1999 (Aip Conference Proceedings) (Hardcover)

by Next Generation Nucleon Decay and Neutrino Detector Workshop (Author), Milind V. Diwan (Editor), Chang Kee Jung (Editor)

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Editorial Reviews

Product Description

Even after more than 40 years of experimentation we have not observed the decay of the basic constituent of everyday matter: the proton. So far, the proton appears to be completely stable. This is very puzzling because reasonable models of physics predict that protons after living very long should break apart into lighter particles such as electrons, muons, and pions.
Over the last several decades both the experiments and the theory of particles have become increasingly sophisticated. The latest and best experiment (Super-Kamiokande) is in the Kamioka mine in Japan: it has monitored 20,000 tons of water for more than 3 years to see decays of protons; none has been found. Yet the sheer size and precision of this experiment has allowed it to find evidence for neutrino mass by observing oscillations of neutrinos generated in the earth's atmosphere by high energy cosmic rays from outer space. Similar detectors in the past have observed neutrinos from the Sun as well as from Supernova explosions. This workshop was intended to find the next step in this process of experimentation. Should we continue the search for proton decay? The answer from this conference seems

Genesis

- Detector needs a neutrino beam, but what distance ? Why bother with longer distances than the first maximum ?

Marciano: hep-ph/0108181- Extra Long Baseline Neutrino Oscillations and CP violation

Diwan, et al.: hep-ex/0211001, hep-ex/0305105, hep-ex/0407047, PRD 68, 012002 (2003), hep-ex/0608023, etc.

Barger, et al., US long baseline study (FNAL-BNL study): arXiv:0705.4396 http://nwg.phy.bnl.gov/fnal-bnl

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Phenomenology of $\nu_\mu \to \nu_e$

The Mixing Matrix

$$
U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\text{Atmospheric}} \times \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{\text{Cross-Mixing}} \times \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Solar}}
$$

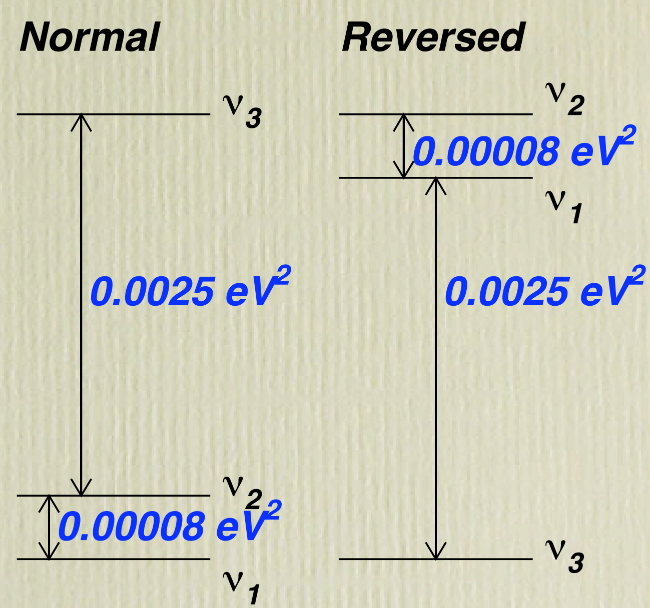
$$
\times \underbrace{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{Majorana } \cancel{CP} \text{ phases}}
$$

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

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

δ would lead to $P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$. $\cancel{CP}$

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~15000km

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

Approximate formula (M. Freund)

matter effect ~E

~7500 km
no CPV.
magic bln

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

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.

CP asymmetry grows as
th13 becomes smaller

Scientific strategy

- The Study: A very large detector <u>and</u> an intense beam needed for the next steps for θ_{13}, mass ordering, and CP violation from the standard 3-generation scenario.

- The Study: Program should have broad physics capability: nucleon decay, supernova detection, astrophysical neutrinos.

- Conventional wisdom: Experimental set up with a large matter effect, such as for 1300 km, is more sensitive to possible new physics.

- For neutrino mixing the experiment must have internal redundancy to check 3-gen CP violation and get hints of new physics if they are there.

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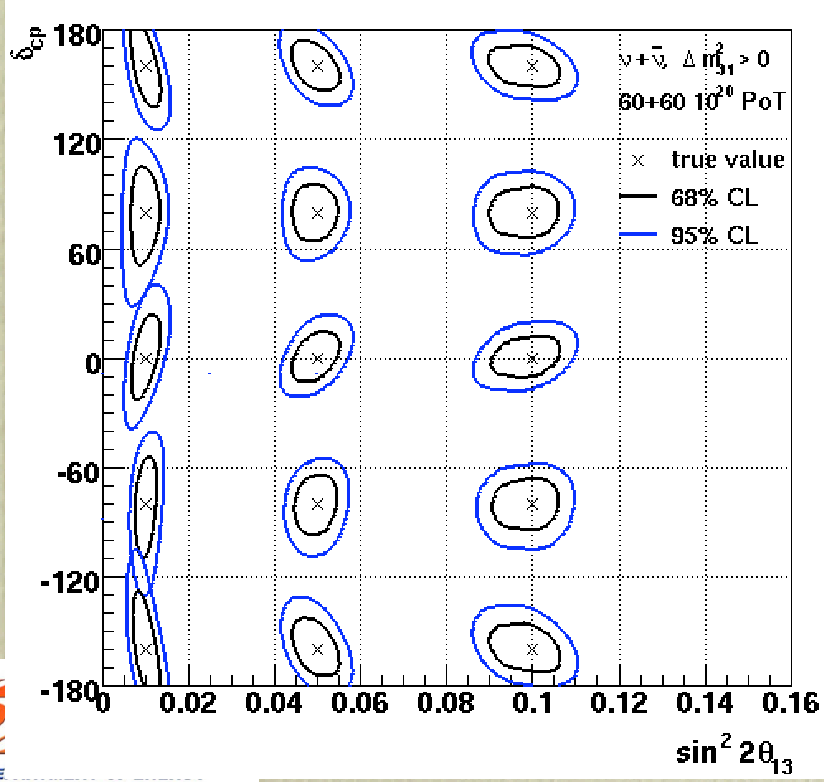
Technical issues

- Program should lead to measurement of 3-generation parameters without ambiguities. (recall: CP measurement is approximately independent of θ13). Need large detector independent of θ13 value.
- A broad band beam is needed to get spectral information to resolve ambiguities. Spectrum down to 0.5 GeV important.



300 kT water Cherenkov detector @DUSEL
Measurement of CP phase and $\sin^2 2\theta_{13}$ at several points. All ambiguities and mass hierarchy are resolved.

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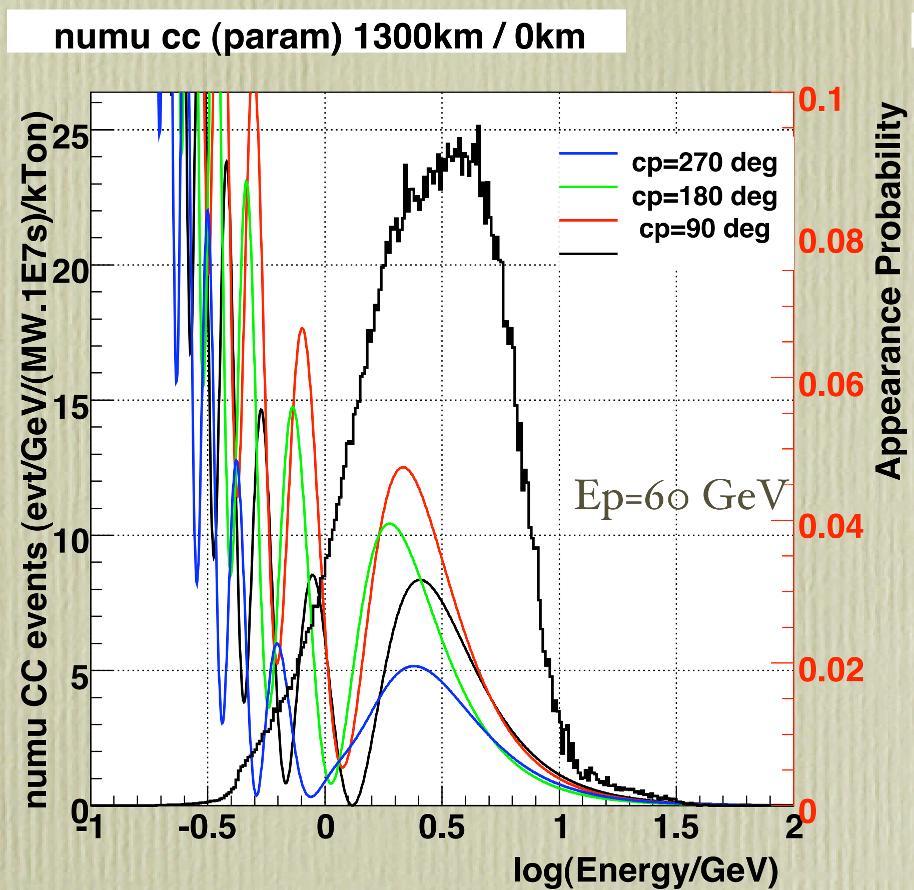
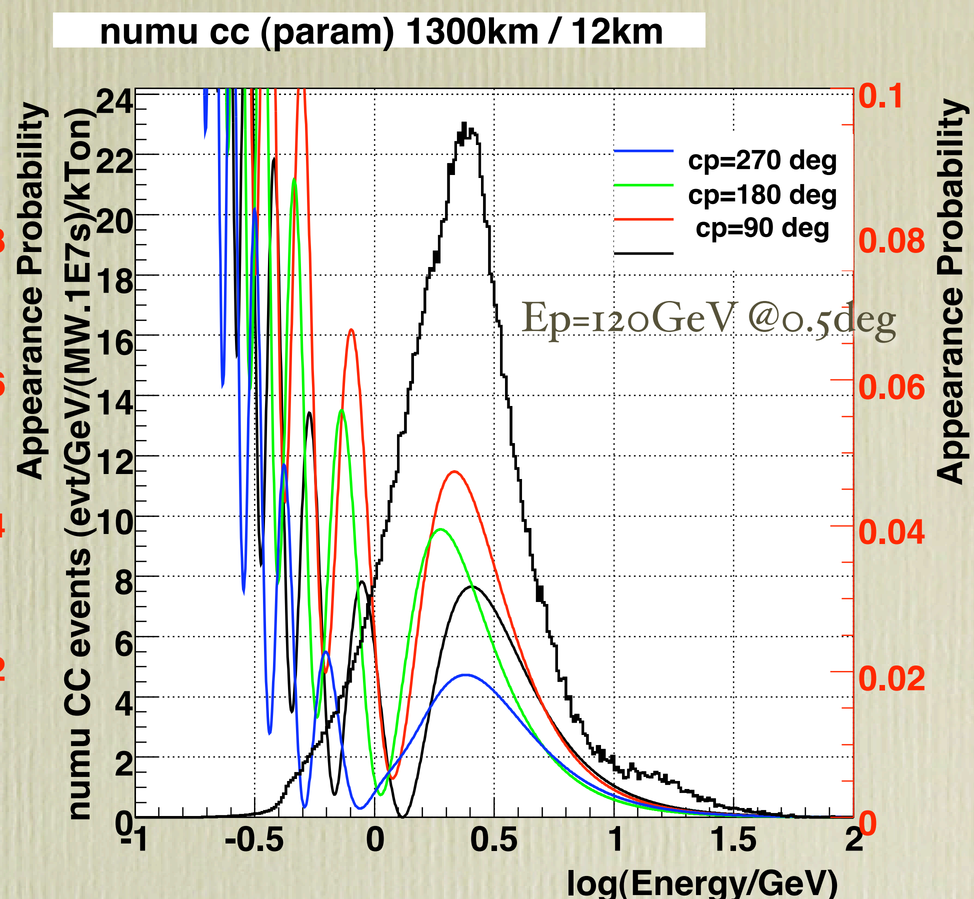
Spectra FNAL to DUSEL (WBLE:wide band low energy)





- 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

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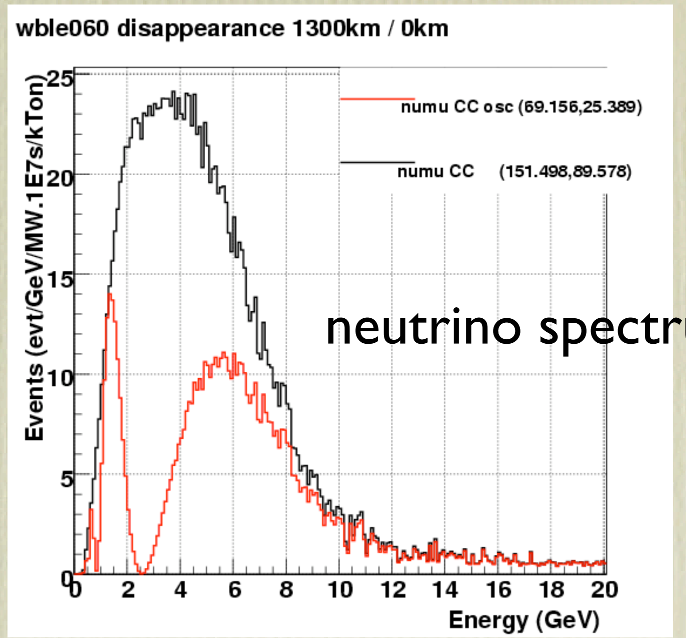
Event rate

Evt rate: 1 MW for 3 yrs ★

Event type	300kT, 120 GeV 0.5 deg.	300kT, 60 GeV 0 deg.
Numu CC no osc	161820	272693
Numu CC with osc	68220	124479



neutrino spectrum

High precision $\sin^2 2\theta_{23}$, Δm^2_{32}

- Important (esp. $\theta_{23} \sim 45$ deg.) with possibility of new physics.
- Either 120 GeV or 60 GeV beam can be used: two oscillation nodes.
- Measurement dominated by systematics (see hep/0407047) (~1%)

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★ yr~2×10^7 sec

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

5.2e20 POT @ 120 GeV

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

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

δ_{CP}

	$sgn(\Delta m^2_{31})$	0 deg	+90 deg	180 deg	-90 deg	nue backg
WBLE NU (1300km)	+	87	48	95	134	47
WBLE NU (1300km)	-	39	19	51	72	
WBLE ANU (1300km)	+	20	27	15	7.2	17
WBLE ANU (1300km)	-	38	52	33	19	

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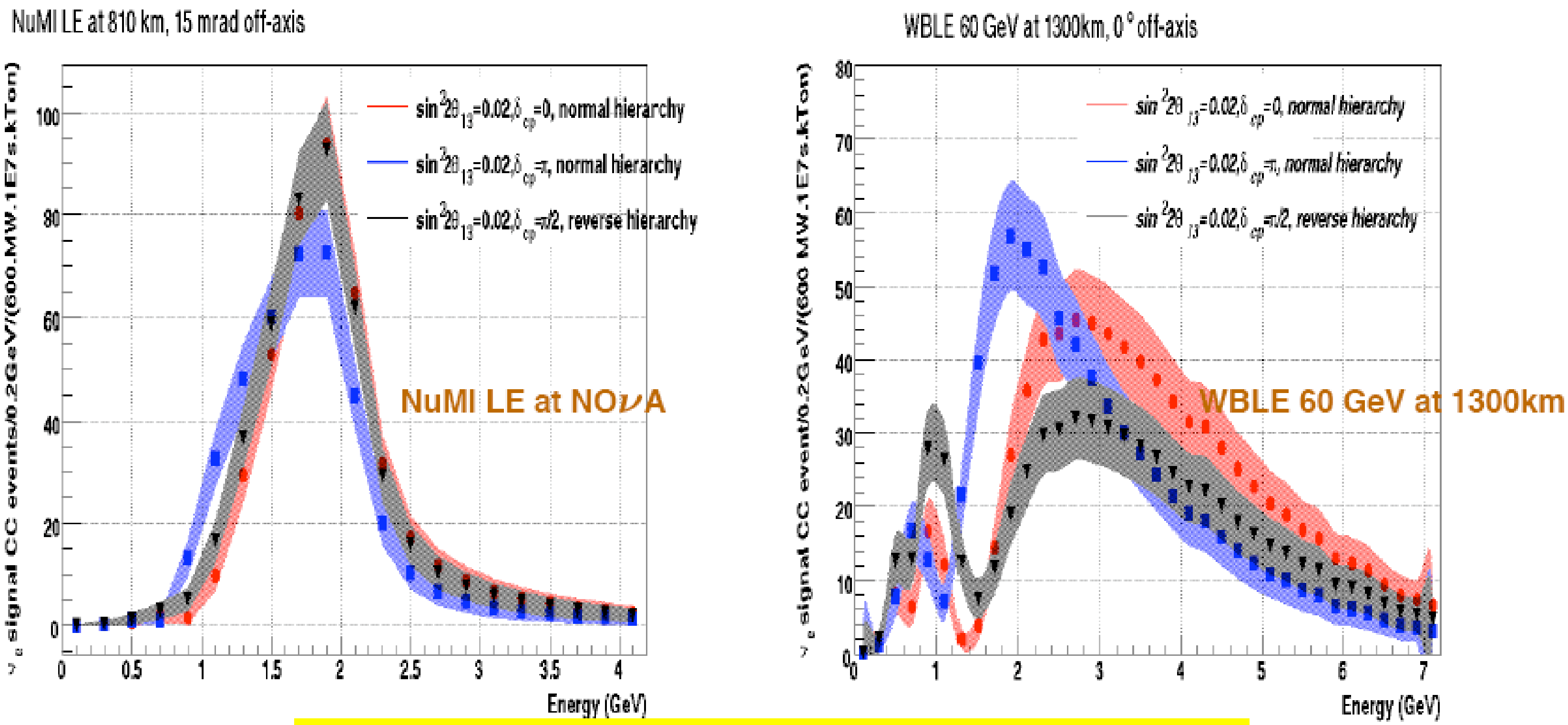
ν_e Appearance Spectra

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

Who is afraid of θ_{13} ?

$\sin^2 2\theta_{13}$	Events 0CP, (+)	Frac. diff. wrt (-)	Frac. diff. wrt 90CP
0.02	141	0.59	0.45
0.1	607	0.55	0.23

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}

The key experimental factor

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

Detector design considerations.

- Need ~100kT of fiducial mass with good efficiency. Much larger if lower 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

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

Cosmic rate in 50m h/dia detector in 10 μs for 10^7 pulses

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.

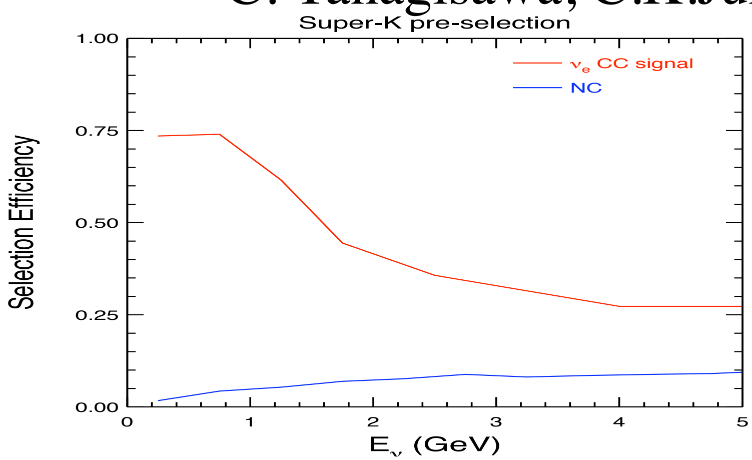
=> fully active fine grained detector.

Water Cerenkov Simulation

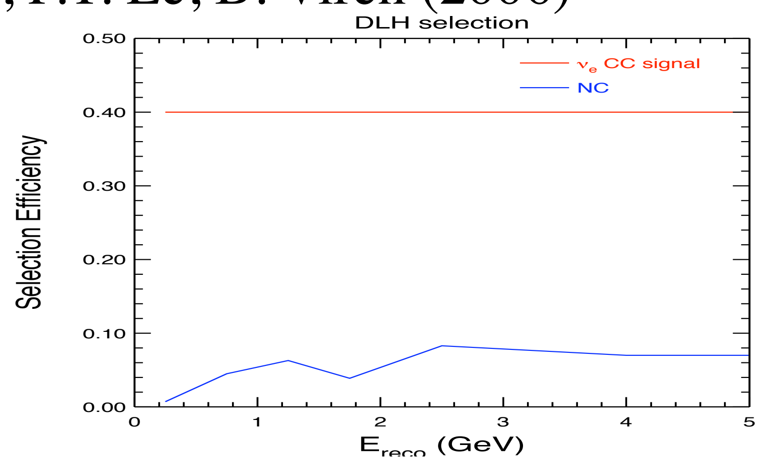
The ν_{atm} GEANT simulation of SuperKamiokande is used.

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.**

C. Yanagisawa, C.K.Jung, P.T. Le, B. Viren (2006)



Standard Super-K pre-selection efficiencies



DLH selection efficiencies (Chiaki Y.)

WCe. energy dependent efficiencies and smearing implemented in GLoBeS.

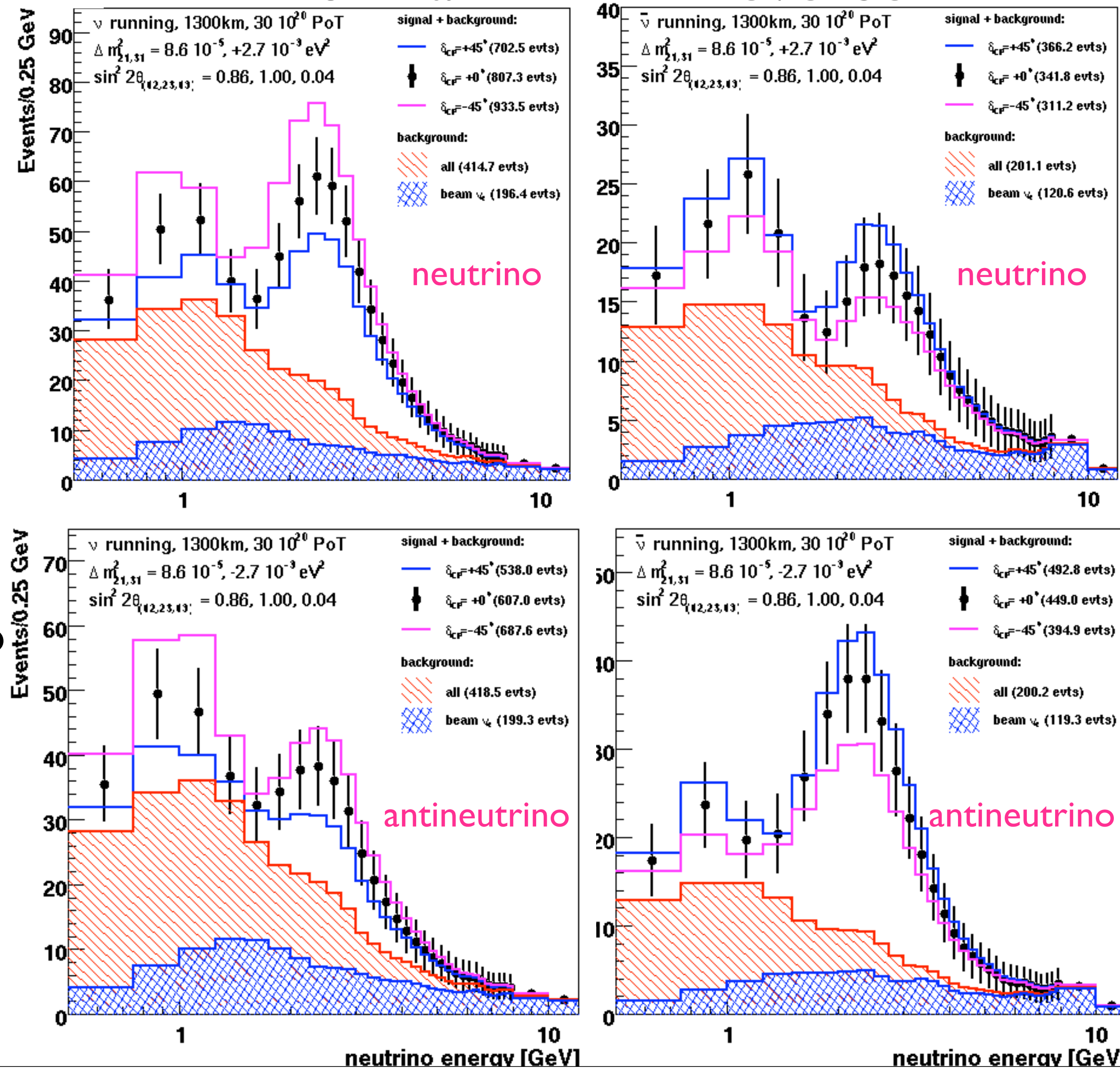
Electron neutrino appearance spectra

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

Normal Reversed



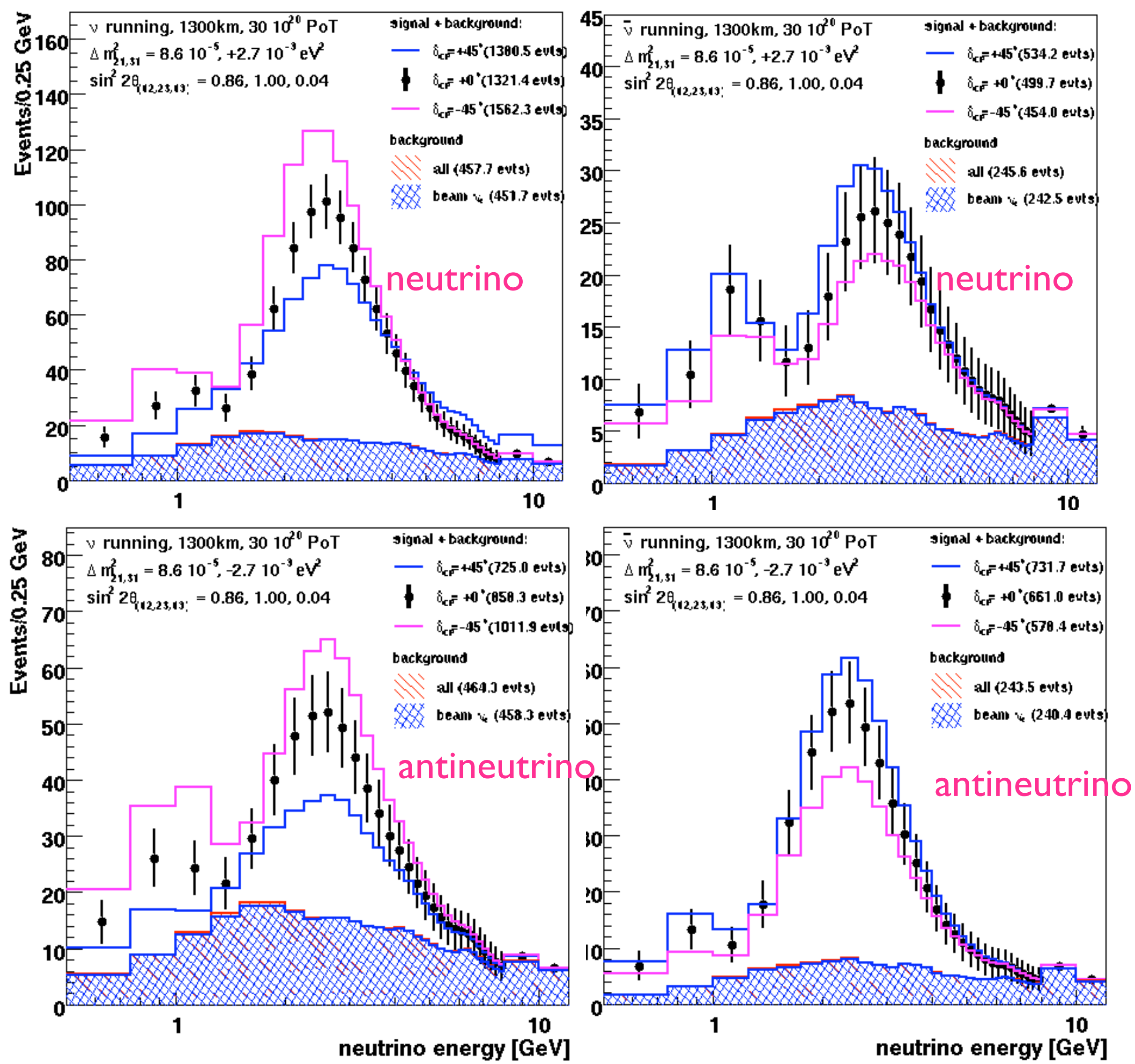
Electron neutrino appearance spectra

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

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

Normal Reversed

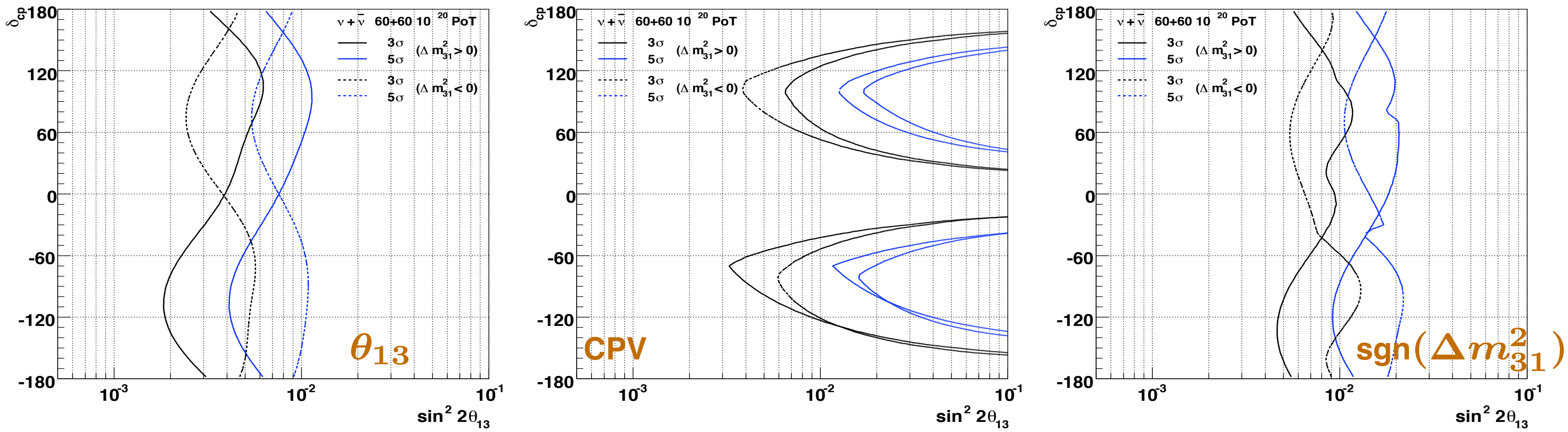
- LAR assumptions
- 80% efficiency on electron neutrino CC events.
- sig(E)/E = 5%/sqrt(E) on quasielastics
- sig(E)/E = 20%/sqrt(E) on other CC events



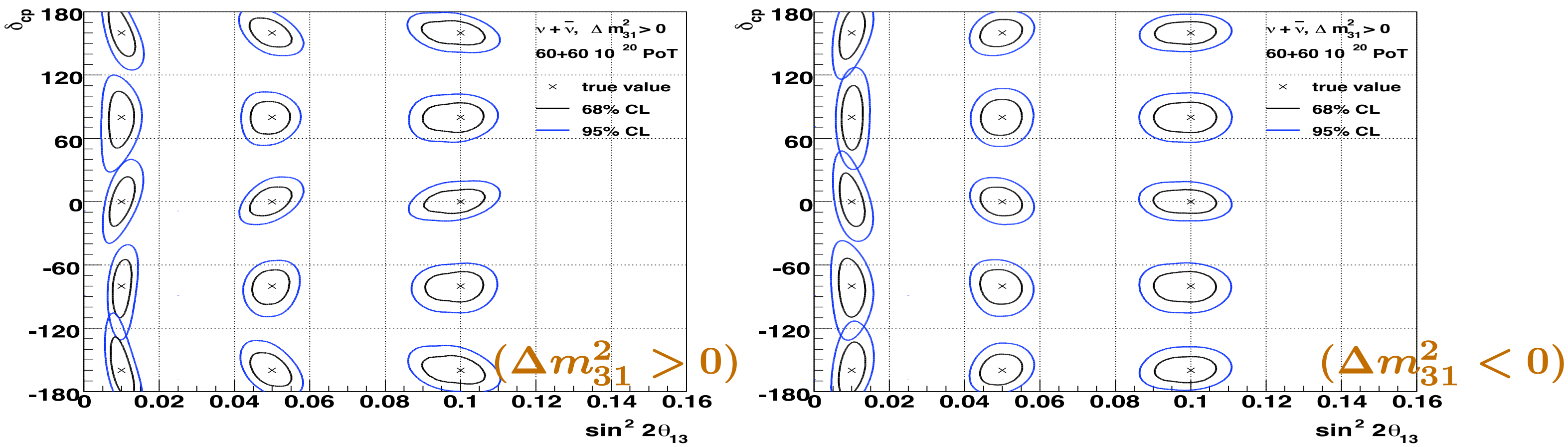
Spectra and sensitivity is the work of M. Bishai, Mark Dierckxsens, Patrick Huber + many helpers

WBLE FNAL to DUSEL (1300km)

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



Measurement (—95% CL —68% CL) :



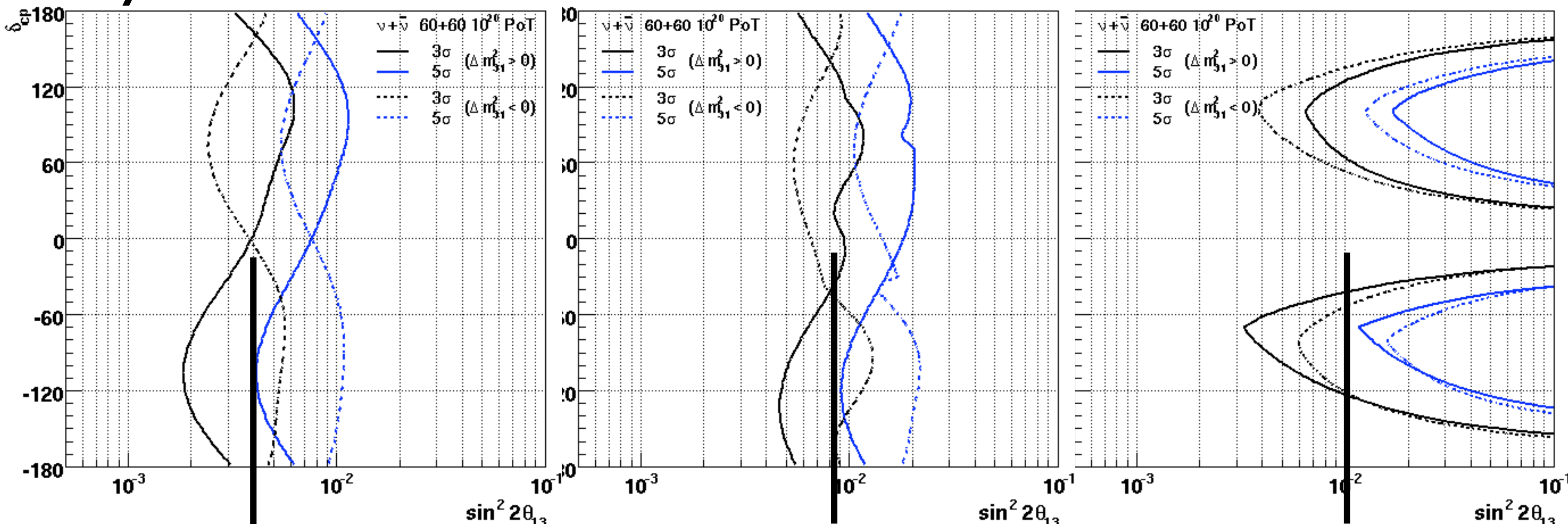
WBLE to DUSEL(1300km) 3sig, 5sig discovery regions.

300 kT WCh

60 10^20 POT for each nu and anu

Stat+syst

th13 | mass ordering | CP violation



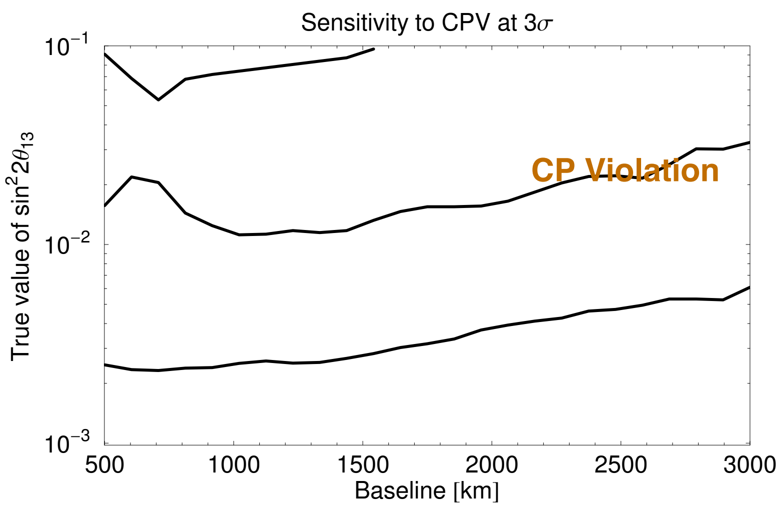
0.004 | 0.008 | 0.01

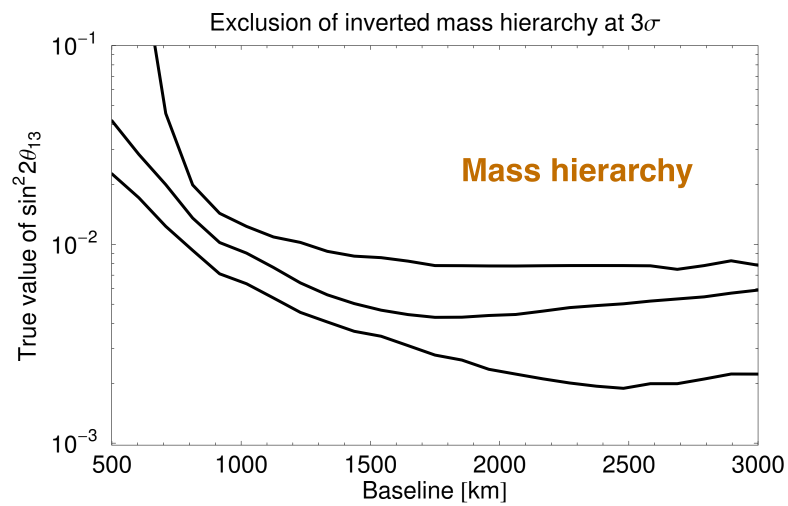
CP Fraction: Fraction of the CP phase (0-2pi) covered at a particular confidence level.

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

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

This calculation needs to be updated, but is generically correct.

FNAL beam to DUSEL

- New working group formed coordinated by Jeff Appel.
- http://beamdocs.fnal.gov
- Program development public documents.
- Currently examining lessons from the NuMI project.

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Neutrino Beam Requirements*

- The maximal possible neutrino fluxes to encompass at least the 1st and 2nd oscillation nodes, which occur at 2.4 and 0.8 GeV respectively
- 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
- To detect $\nu_\mu \rightarrow \nu_e$ at the far detector, it is critical to minimize the neutral-current contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is little sensitivity to the oscillation parameters is highly desirable
- The irreducible background to $\nu_\mu \rightarrow \nu_e$ appearance signal comes from beam generated ν_e events, therefore, a high purity ν_μ beam with as low as possible ν_e contamination is required

***From "Simulation of a Wide-Band Low-Energy Neutrino Beam for Very Long Baseline Neutrino Oscillation Experiments", Bishai, Heim, Lewis, Marino, Viren, Yumiceva*

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The general concept to date

- The present extraction of the Main Injector into the NuMI primary beam-line will be used.
- An additional tunnel will be constructed starting from the approximate location of the NuMI lower Hobbit door, at the end of the carrier tunnel, in order to transport the proton beam to the west.
- The radius of curvature of the tunnel bending west will be similar to the Main Injector curvature which will enable protons with energies up to 120 GeV to be steered along the bend using conventional magnets
- The target hall length is ≤ 45 m.
- A decay tunnel length of up to 400 m can be accomodated on the site assuming the near detector is 300m from the end of the decay pipe.
- The low energy neutrino flux can be enhanced by increasing the decay pipe radius. A radius of ~2 m would be desirable.
- For a ~2MW beam the concrete shielding needed around the decay pipe will be ~2.5m

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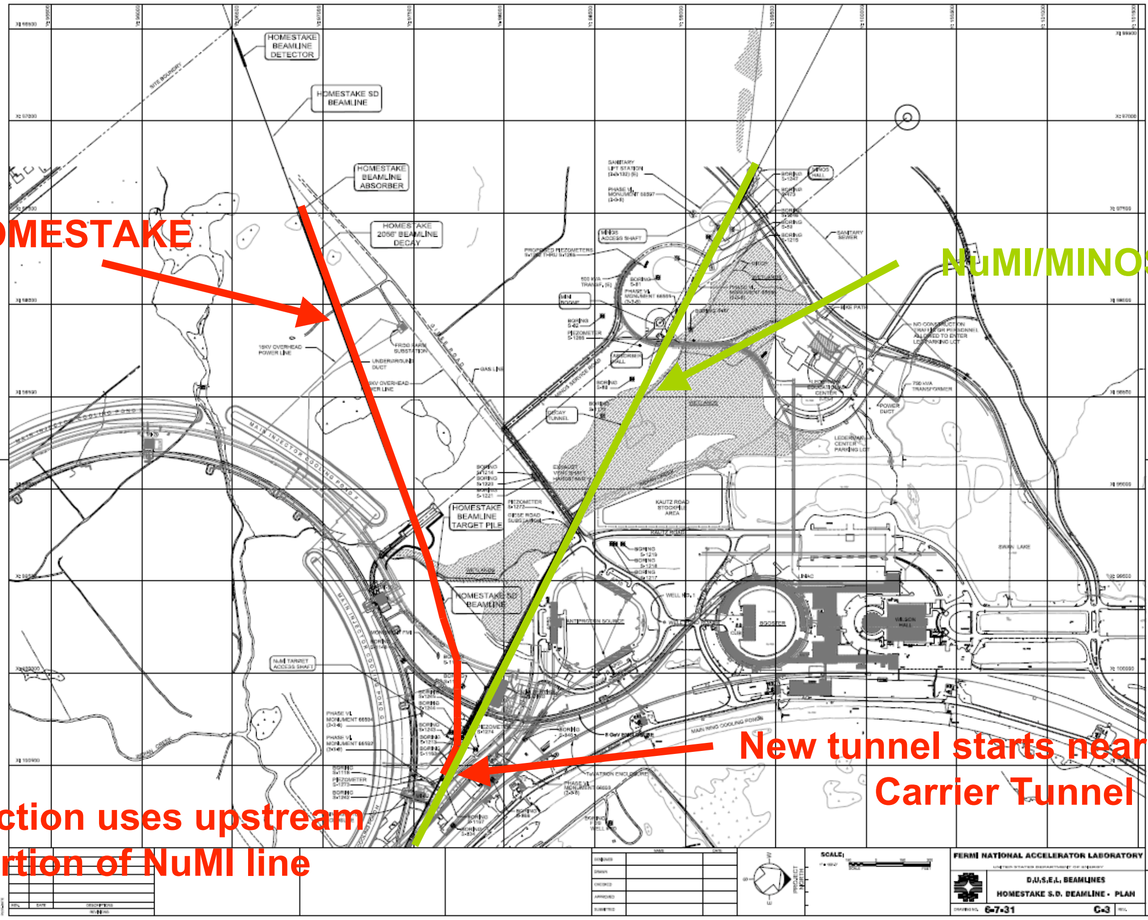
NuMI/Homestake DUSEL Beam

Location of the Homestake Beamline



Homestake/DUSEL Neutrino Beam

3

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NuMI/Homestake DUSEL Beam

Second Elevation View of the Homestake Beamline

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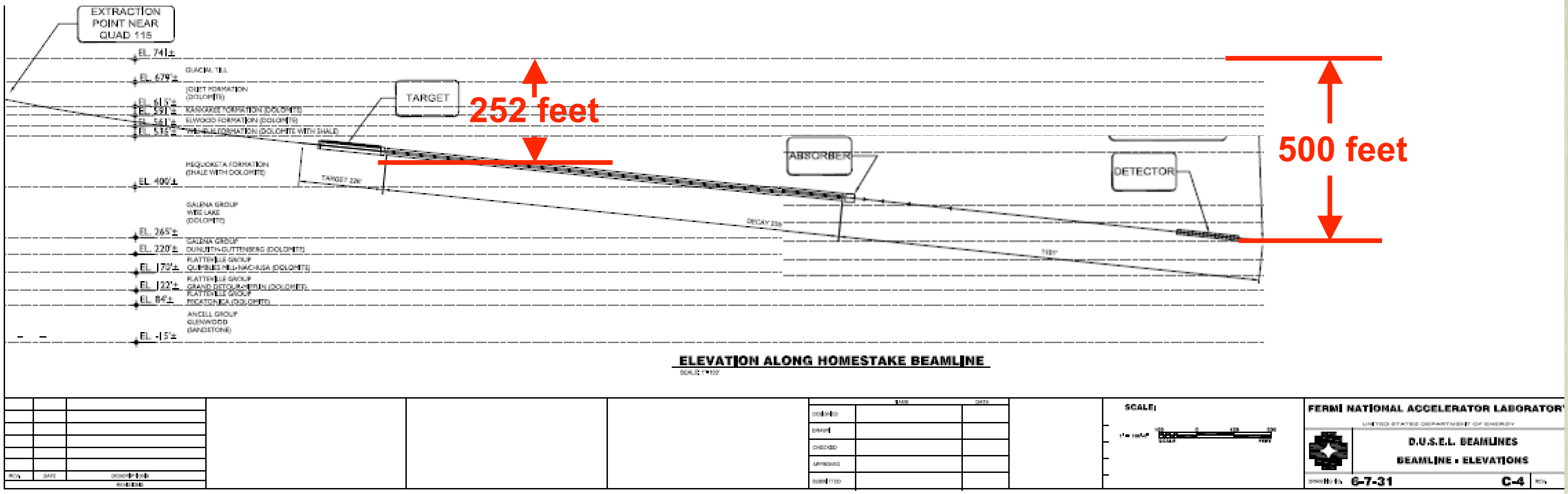
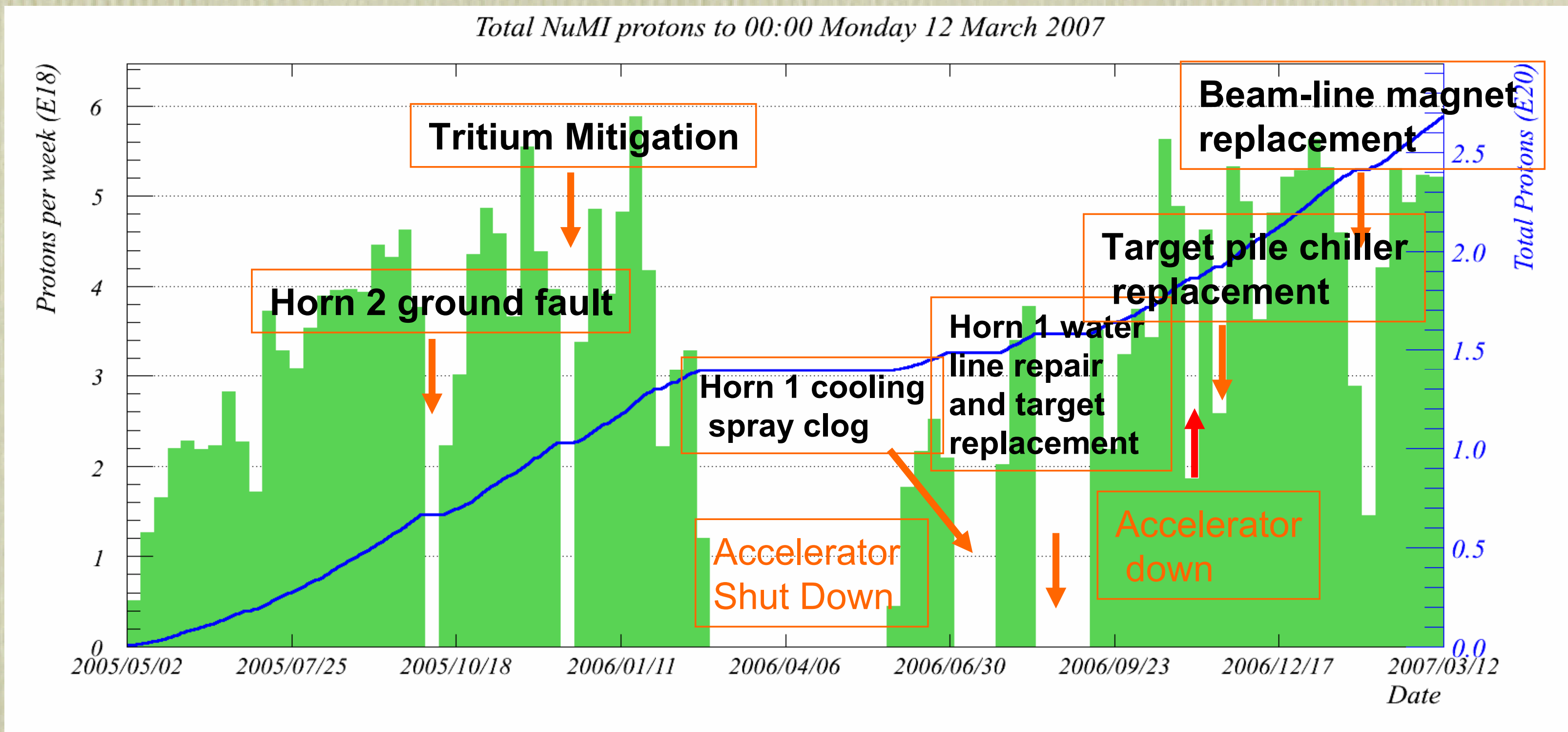


This elevation view of the Homestake Beamline (-5.84^{o}) is drawn with the decay pipe limited to 400m. This shortens the beamline by 741 feet, and lifts The detector hall (and shaft) by about 75 feet (500 feet deep). Overall, this configuration will be cheaper to build and is probably adequate.

NuMI Performance - POT/week



We need exposures that are >10 times higher for FNAL-to-DUSEL

NuMI knowledge base is excellent

Up (513) and down (83) days 5/1/05 – 3/22/07

86% / 74% efficiency excluding / including sched. shutdown

Days	Description (**non-recurring)		Long term corrective action
513	Up for beam		
95	Accelerator scheduled down		
25	Horn cooling spray clog **		Check valves, filters on skids
14	Horn water line repair		Eliminate braze on spares
14	Target motion frozen		Graphalloy bushing on spare
10	Horn ground fault		Pin feet, float modules
8	Tritium mitigation **		Condensate sys./dehumidifiers
6	Replace NuMI beam-line magnet		
4	Replace accelerator magnet		
2	Replace pile chiller compressor		New hot spare chiller unit

NuMI Extraction from MI

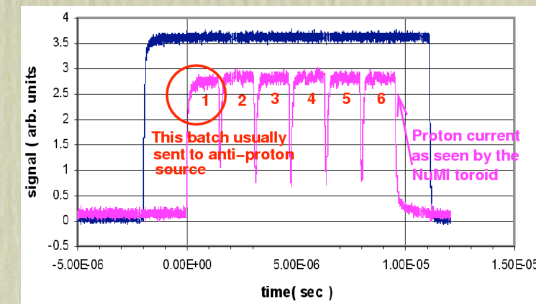
The MI accepts up to 6 proton batches ($\sim\ 5 \times 10^{12} p/$batch) at 8 GeV from the Booster, accelerates $8 \rightarrow 120$ GeV in ~ 1.5 s. MI cycle types:

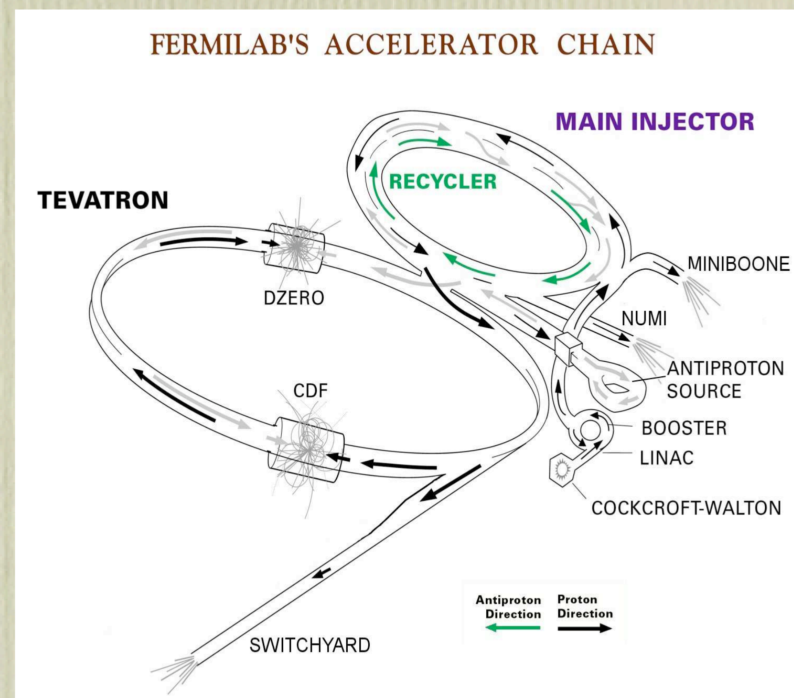
NuMI only: Every 1.9 seconds. Batches 1-6 $\longrightarrow$ NuMI in 10 μ s

Mixed mode: Every 2.4-4 seconds. Batch "1" (2 merged Booster batches "slip stacked" at 8×10^{12} p) $\longrightarrow$ $\bar{p}$ source. Batches 2-6 $\longrightarrow$ NuMI in 8 μ s.

Tevatron store cycles: Once per day (~ 2 hrs). 150 GeV $p \longrightarrow$ Tevatron and $\bar{p}$ from Pbar source accelerated to 150 GeV and injected into Tevatron.

Batch structure as measured in NuMI beamline

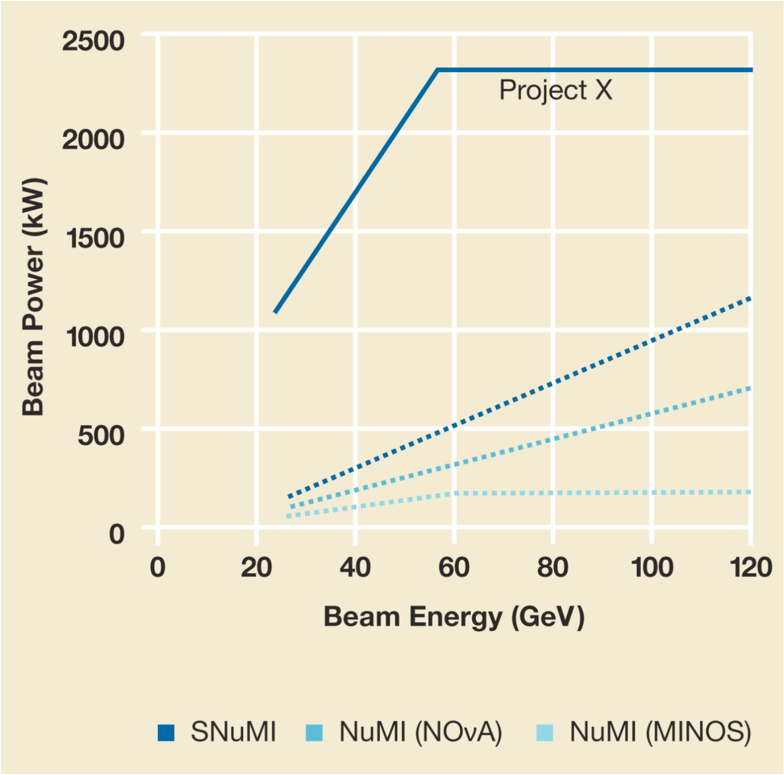




	Protons (10^{12})	Cycle time (sec)	Power (kw)
Current complex			
No improvements			
- Shared beam	25	2.4	200
- NuMI alone	30	2.0	280
Proton plan			
Slip-stacking			
-Shared beam	37	2.2	320
-NuMI alone	49	2.2	430
SNuMI -Recycler slip-stack; reduce cycle	49	1.33	700
SNuMI -Accumulator momentum stack;	82	1.33	1200
High Intensity Source 8 GeV SC LINAC injector (maj. upgrades to MI-RF)	150	1.33	2200

SNuMI: depends on the current booster

- 60 -120 GeV protons from the Main Injector fed by Project X



20-40x10^{20} POT/yr

10x10^{20} POT/yr

6x10^{20} POT/yr

3x10^{20} POT/yr

Recent sensitivity studies are being done for 120x10^{20} POT each ν and $\bar{\nu}$ (120 GeV)

$$POT(10^{20}) = \frac{1000 \times BeamPower(MW) \times T(10^7 s)}{1.602 \times E_p(GeV)}$$

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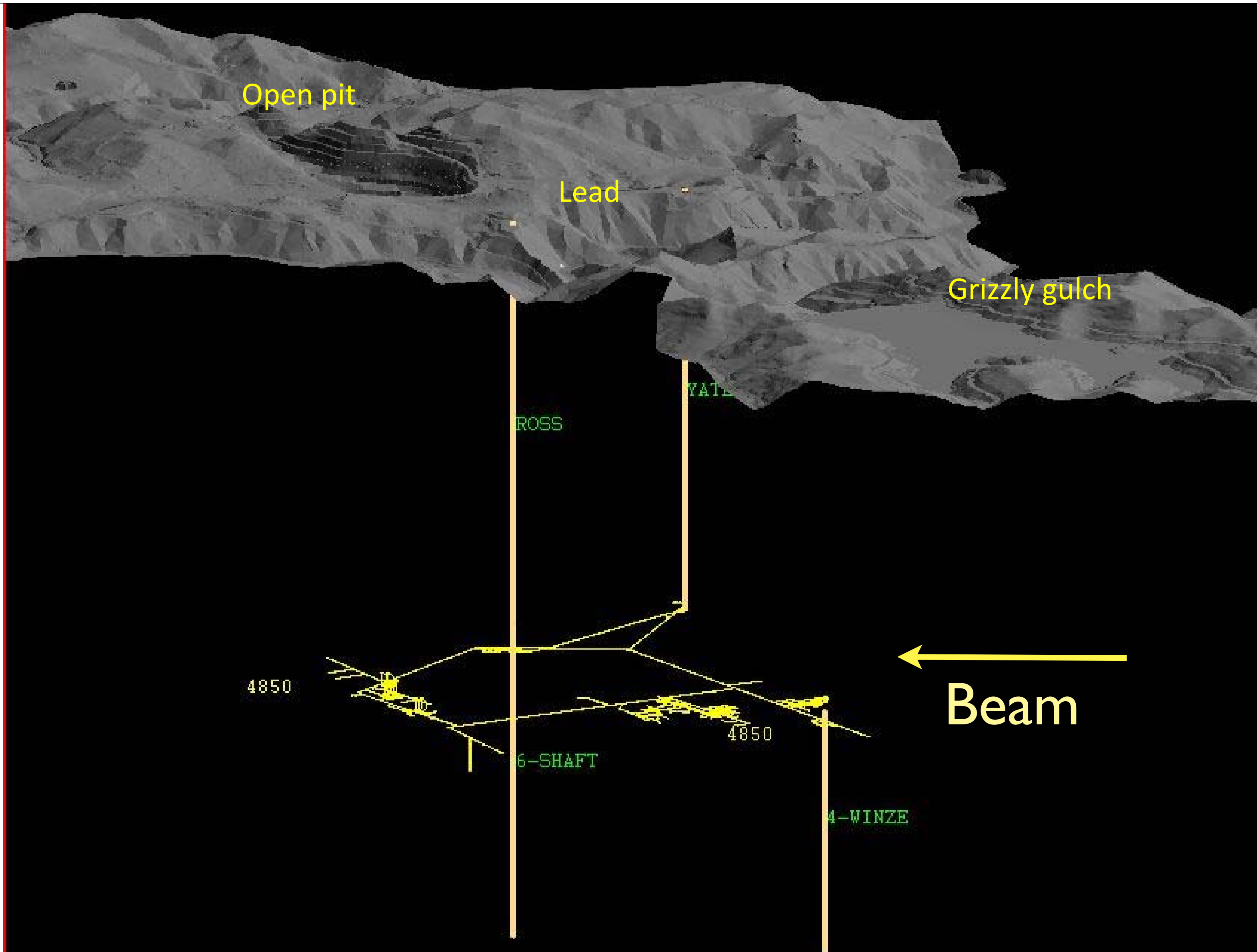


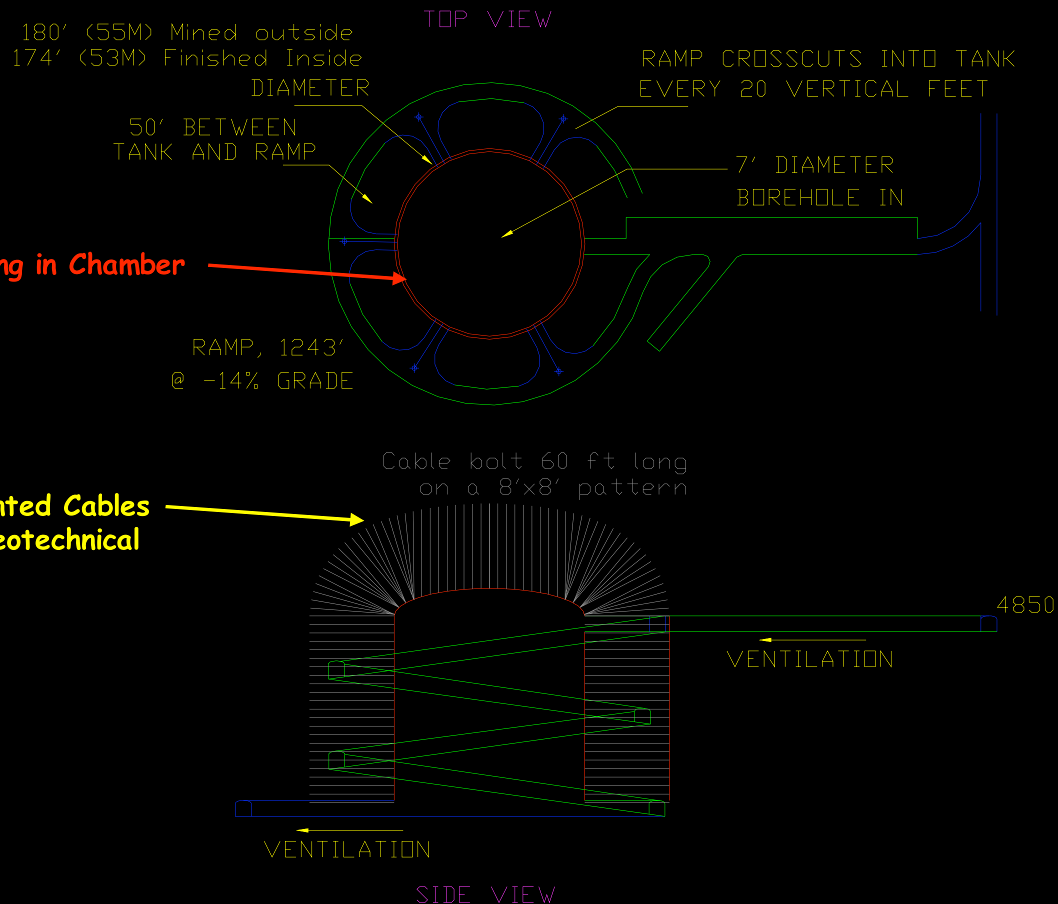
The Detector @ homestake

Megaton Modular Multi-Purpose Neutrino Detector

✓ Chamber Design

Controlled Blasting in Chamber

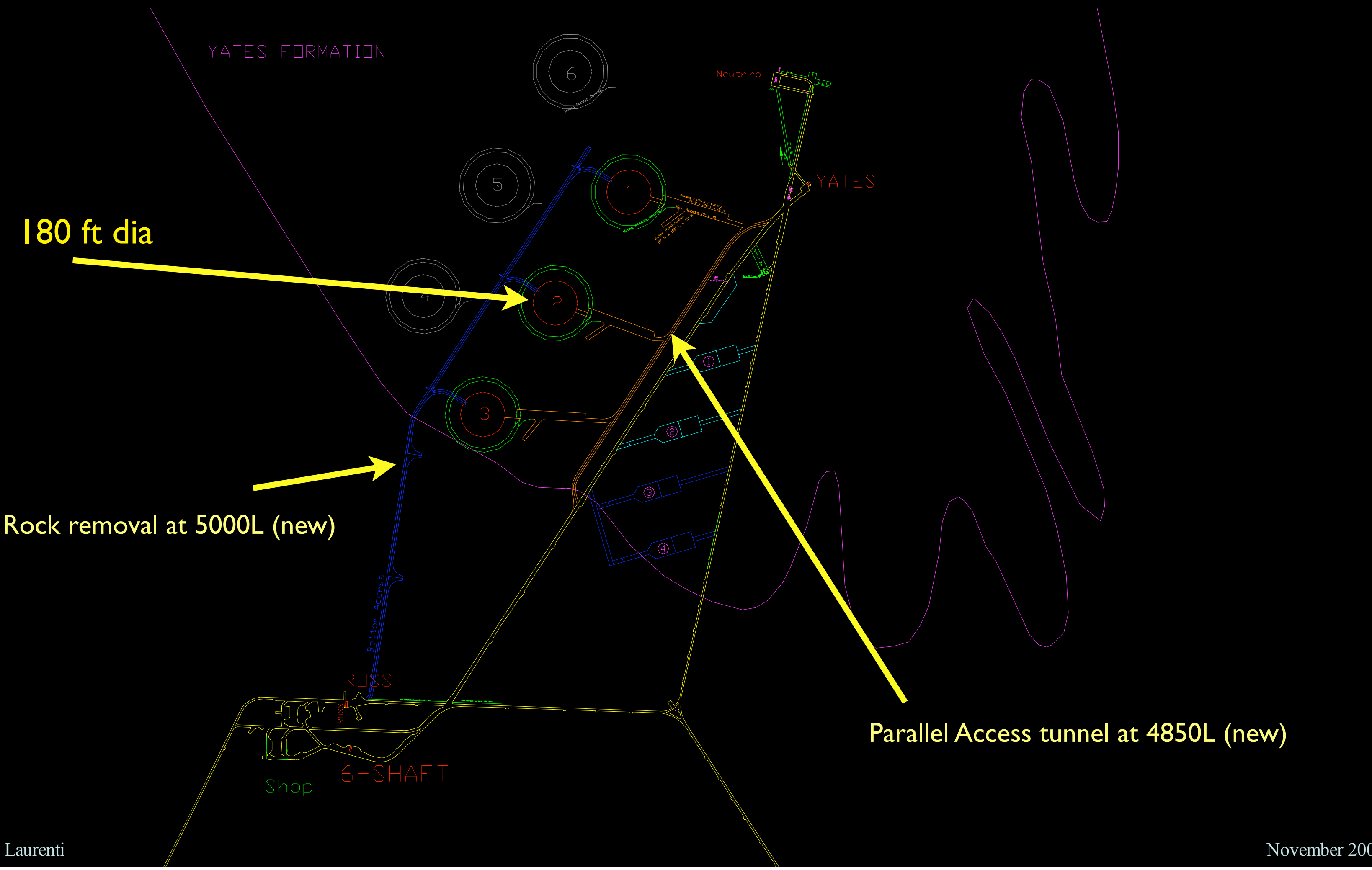
Could use Instrumented Cables for Engineering / Geotechnical Study



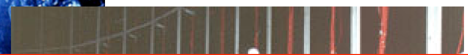
Megaton Modular Multi-Purpose Neutrino Detector

✓ **Modular Configuration**

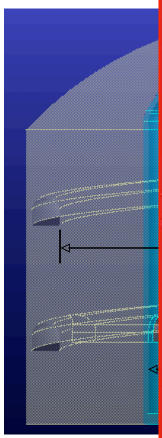
muon rate/cavern 0.1-0.3 Hz

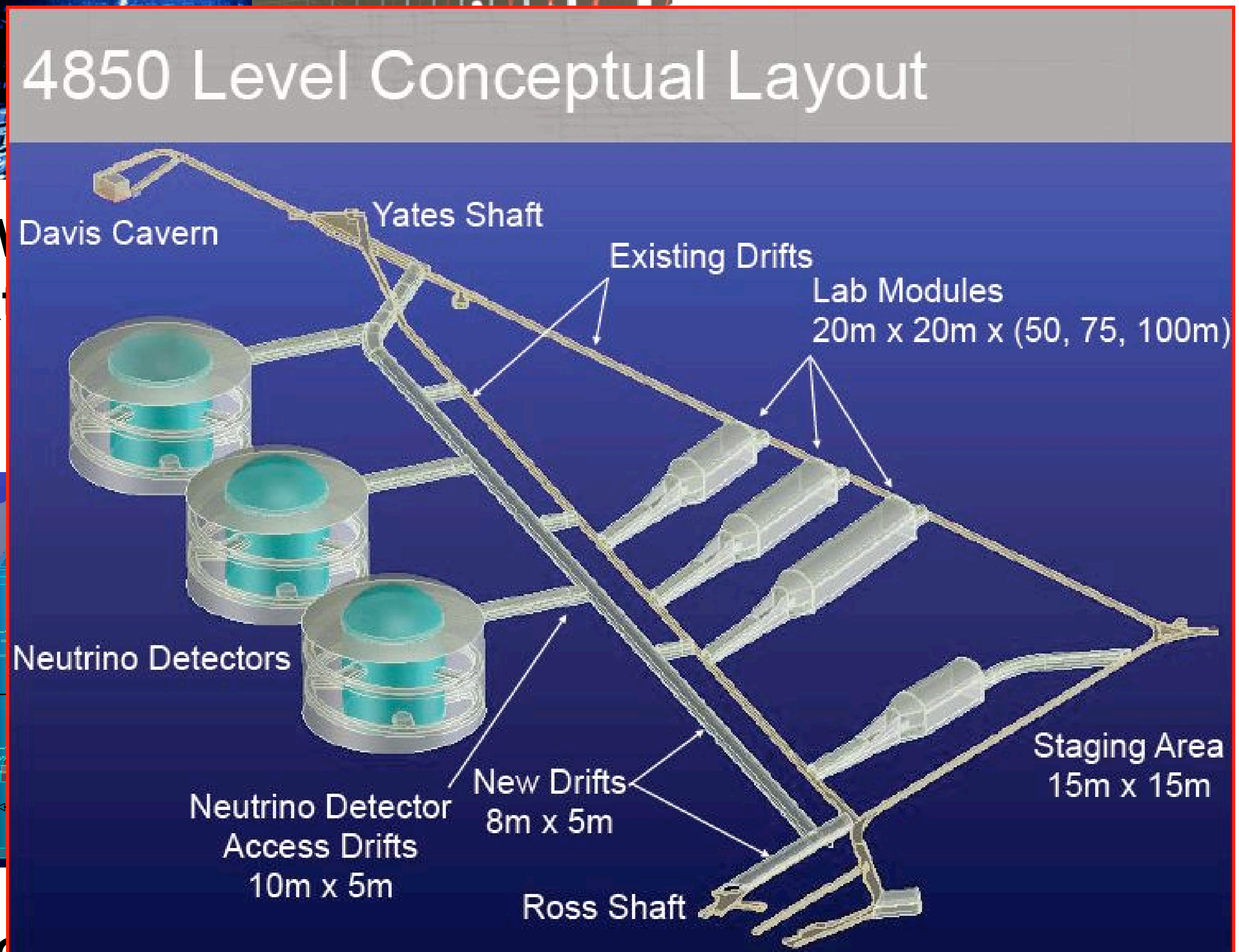


Water Cherenkov Detector



IM
3 k





1 mod

300 kT

Organization

- The beam and the water Cherenkov detector are an exercise in organization and planning.
- There have been 4 meetings of an interim executive board (more about this later)
- Two documents have been commissioned. (Depth paper and white paper)
- There have been several meetings at FNAL and Lead http://nwg.phy.bnl.gov/DDRD/cgi-bin/private/ListAllMeetings
- There is talk of forming an Institutional Board as quickly as possible so that the EB can be

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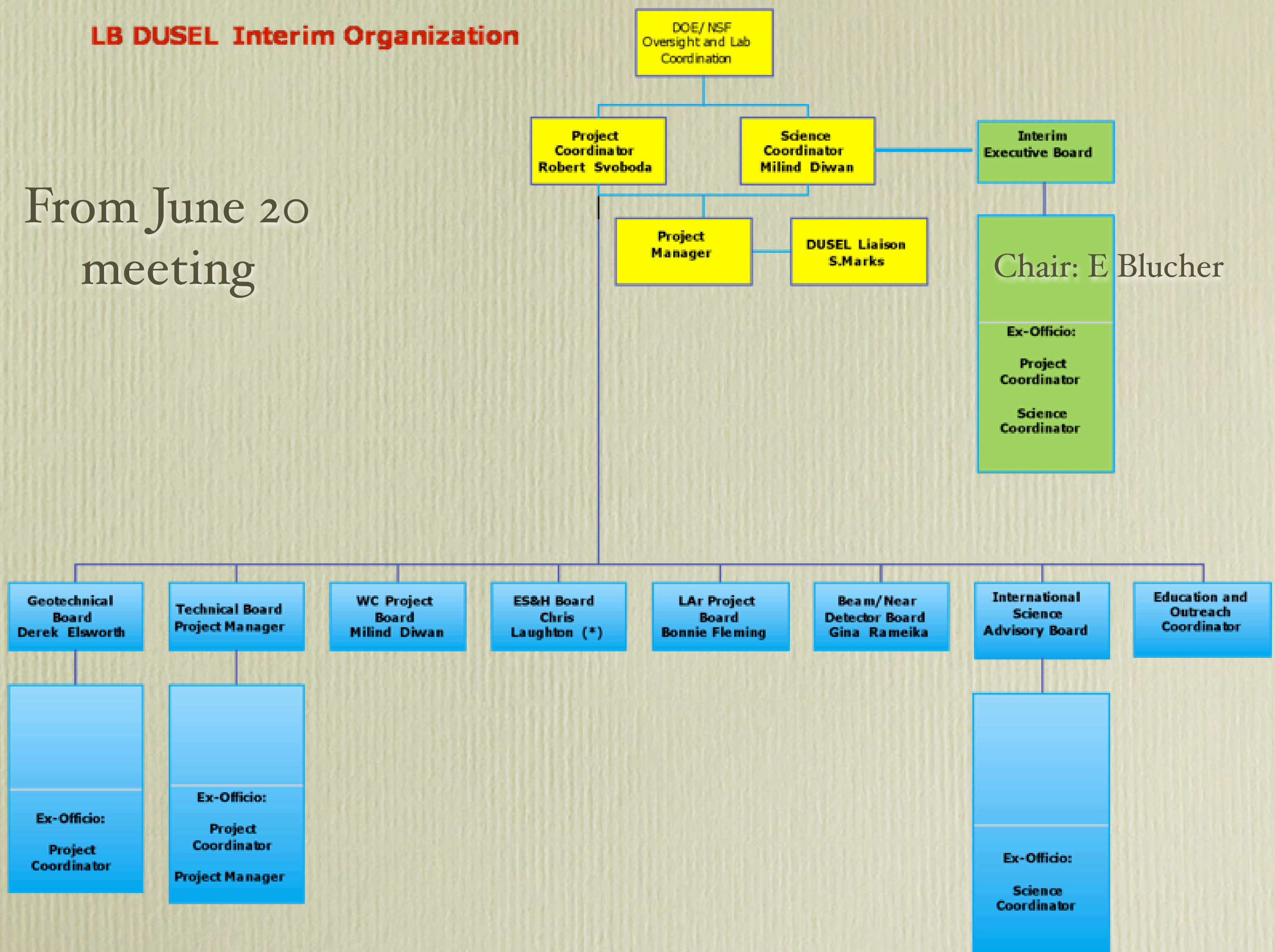
LB DUSEL Interim Organization

From June 20 meeting

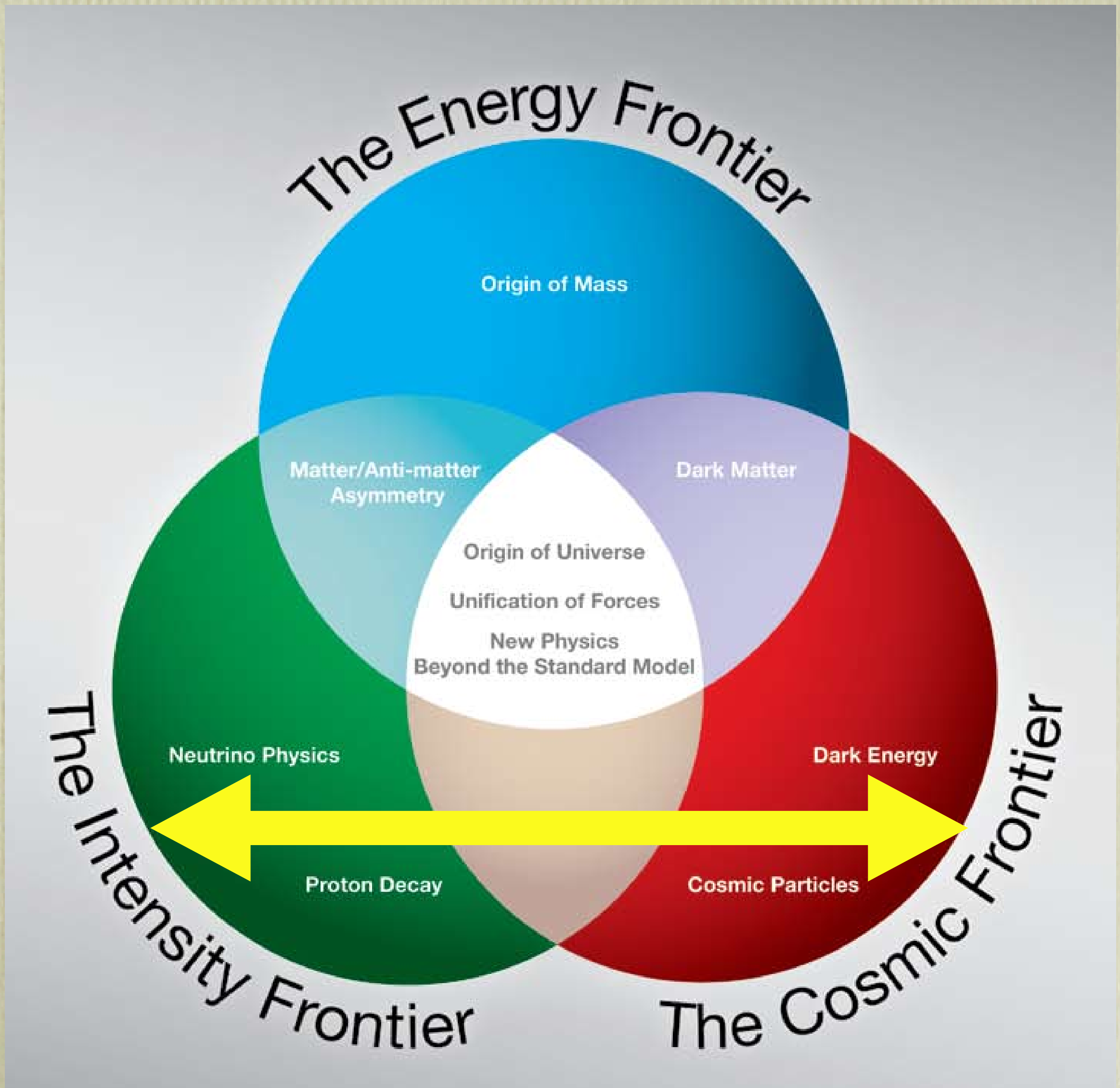


LB DUSEL Interest Group

- **ANL:** M.Goodman, M.Sanchez
- **Boston Univ.:** E.Kearns, J.Stone
- **BNL:** M.Bishai, M.Diwan, H.Chen, S.Hightower, D.Jaffe, de Geronimo , J.S.Kettell, F.Lanni, D.Lissauer, Makowiecki, J.Mead, D.W.Morse, T.Muller, V.Radeka, S.Rescia, Sondericker, J.B.Viren, B.Yu
- **Univ. of California, Davis:** M.Tripathi, R.Svoboda
- **Univ. of California, Irvine:** M.Smy, H.Sobel, M.Vagins
- **Univ. of California, Los Angeles:** D.Cline, H.Wang
- **Caltech:** R.McKeown
- **Univ. of Chicago:** E.Blucher, M. Dierckxsens
- **Colorado State Univ:** N.Buchanan
- **Drexel Univ.:** C.Lane
- **Duke Univ.:** K.Scholberg, C.Walter
- **FNAL:** J.Appel, L.Bugel, B.Choudhary, J.Hylen, C.Laughton,M.Martens, R.Plunkett, G.Rameika, R.Ray, R.L.Schmitt, D.Schmitz, P.Shanahan, R.Zwaska
- **Univ. Of Illinois, Urbana:** P.Kammel, C.Polly
- **Indiana Univ.:** C.Bower, M.D.Messier, S.Mufson, J.Musser, J.Urheim
- **INFN:** O.Palamara
- **Kansas State Univ.:** G.Horton-Smith
- **LBL:** J.R.Kadel, J.Siegrist
- **LLNL:** A.Bernstein, S.Dazeley
- **Louisiana State University:** T.Kutter
- **Univ. of Maryland:** G.Sullivan
- **Michigan State Univ.:** C.Bromberg
- **Univ. of Minnesota, Duluth:** A.Habig
- **Univ. of Minnesota:** M.Marshak, W.Miller
- **Univ. of Pennsylvania:** J.Klein, K.Lande
- **Princeton Univ.:** K.McDonald
- **Rensselaer Polytechnic Institute:** J.Napolitano
- **Univ. of Sussex:** E.Falk, J.Hartnell, S.Peeters
- **Univ. of Texas, Austin:** K.Lang, S.Kopp
- **Tufts Univ.:** T.Mann
- **William and Mary:** J.Nelson
- **Univ. of Wisconsin:** B.Balantekin, H.Band, K.Heeger, W.Wang
- **Yale:** B.Fleming, M.Soderberg

Incomplete list; needs international participation

Science



From 2008 P5 report

Complementary to the physics of the energy frontier

Size, neutrino beam intensity, distance: the next step in neutrino physics.

Size gives improved sensitivity to proton decay, our window to the unification of forces.

Depth and low background allows detection of neutrinos from present and past supernova at cosmological distances.

Very large increases to data from known natural neutrino sources: the Sun, and the atmosphere.

Funds

- P5 report and associated reports from various panels (NuSAG, NSF DUSEL selection panel, and others) very important.

- Initial guidance is CD0 in Dec. 2008 and CD1 in late 2009.

- This is to allow funds from DOE to flow.

- 4 avenues for funds: NSF regular, sep 2008, DUSEL R&D (due Dec 2008), DOE program money, NSF S4 money.

UDIG workshop

- Next workshop for the project (theory and experiment).
- Date: Oct. 16-17 at Brookhaven National Lab.
- Meeting of the collaboration: Oct. 14-15
- http://www.bnl.gov/udig

Conclusion

- A 300kT detector at a good depth is well justified for accelerator neutrino physics.
- If built in the USA it has unique and complementary physics capability in the world due the length of the baseline.
- A conventional beam from FNAL to Homestake lab. is going through an examination by a technical working group.
- Excellent sensitivity for θ_{13} and mass ordering and CP violation. Non-accelerator physics additional.
- The caverns built could house different technology: better PMTs, Liquid Scintillator, Liquid Argon ...