US Long Baseline Neutrino Experiment Study

Milind Diwan
Brookhaven National Laboratory

NNN-07 workshop, Hamamatsu
Oct 4, 2007

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Joint FNAL/BNL study

- Start Apr-06 in anticipation of physics urgency and DUSEL.
- Study also informed the NuSAG committee of US DOE
  - Chairs: Hugh Montgomery, Sally Dawson; 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 and ~10 documents from ~30 people on sensitivity, backgrounds, beam alternatives, etc.
  - Scope of work (http://nwg.phy.bnl.gov/fnal-bnl)
    - ★ Accelerator intensity
    - ★ Beamline feasibility (NuMI offaxis/ to DUSEL) and rates
    - ★ Detector feasibility/Prelim. Costs/Schedule/R&D plan
    - ★ Backgrounds/Sensitivity

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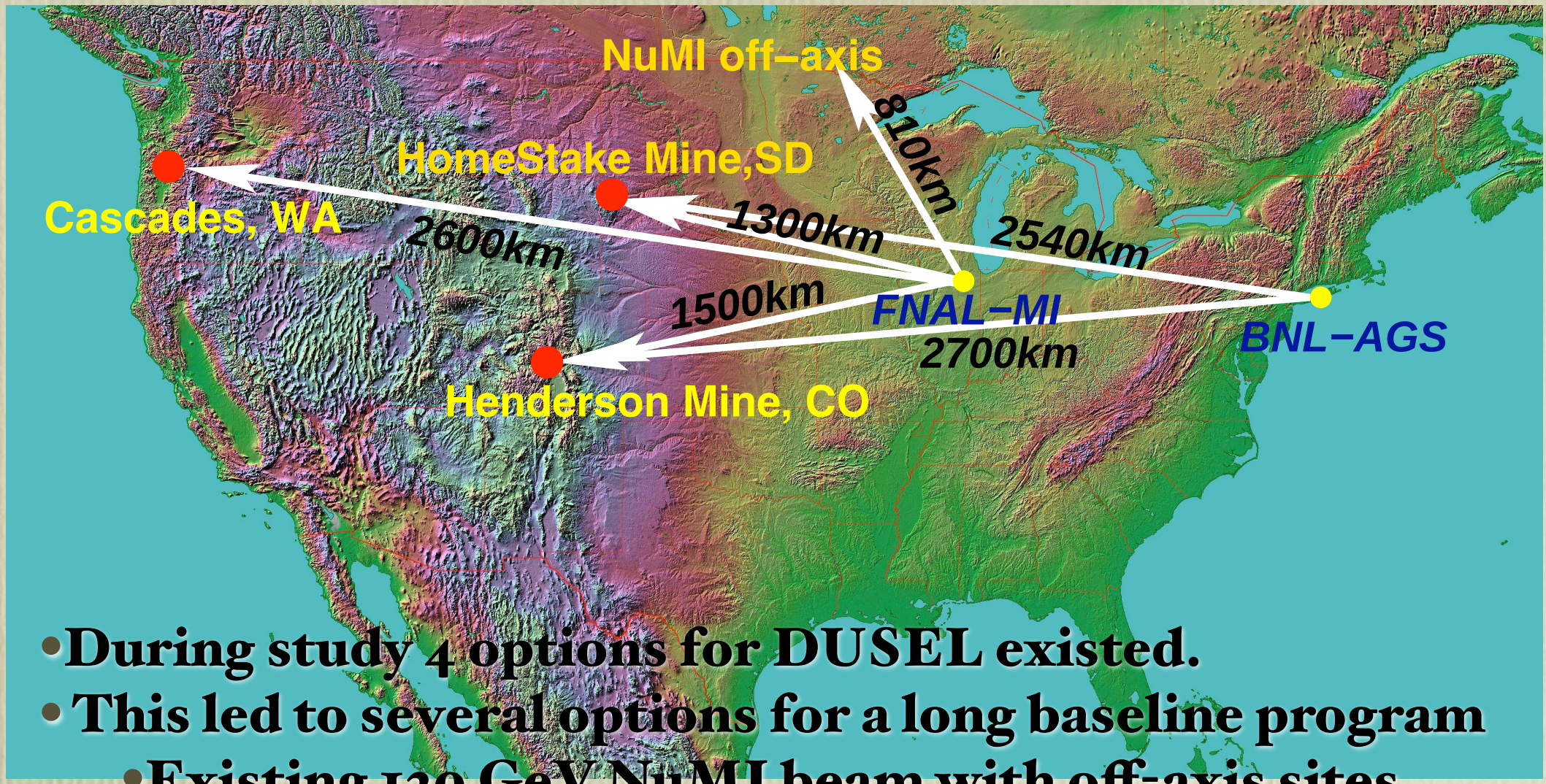
NSF DOE (HEP) DOE (NUCLEAR)

HEPAP : High Energy Physics Advisory Panel

NSAC : Nuclear Science Advisory Committee.

NuSAG: neutrino science advisory group



- During study 4 options for DUSEL existed.
- This led to several options for a long baseline program
  - Existing 120 GeV NuMI beam with off-axis sites
  - 28 GeV BNL-AGS beam over 2500 km
  - 40-120 GeV FNAL-MI Wide Band Low Energy (WBLE) beam to DUSEL 1300-2700 km.

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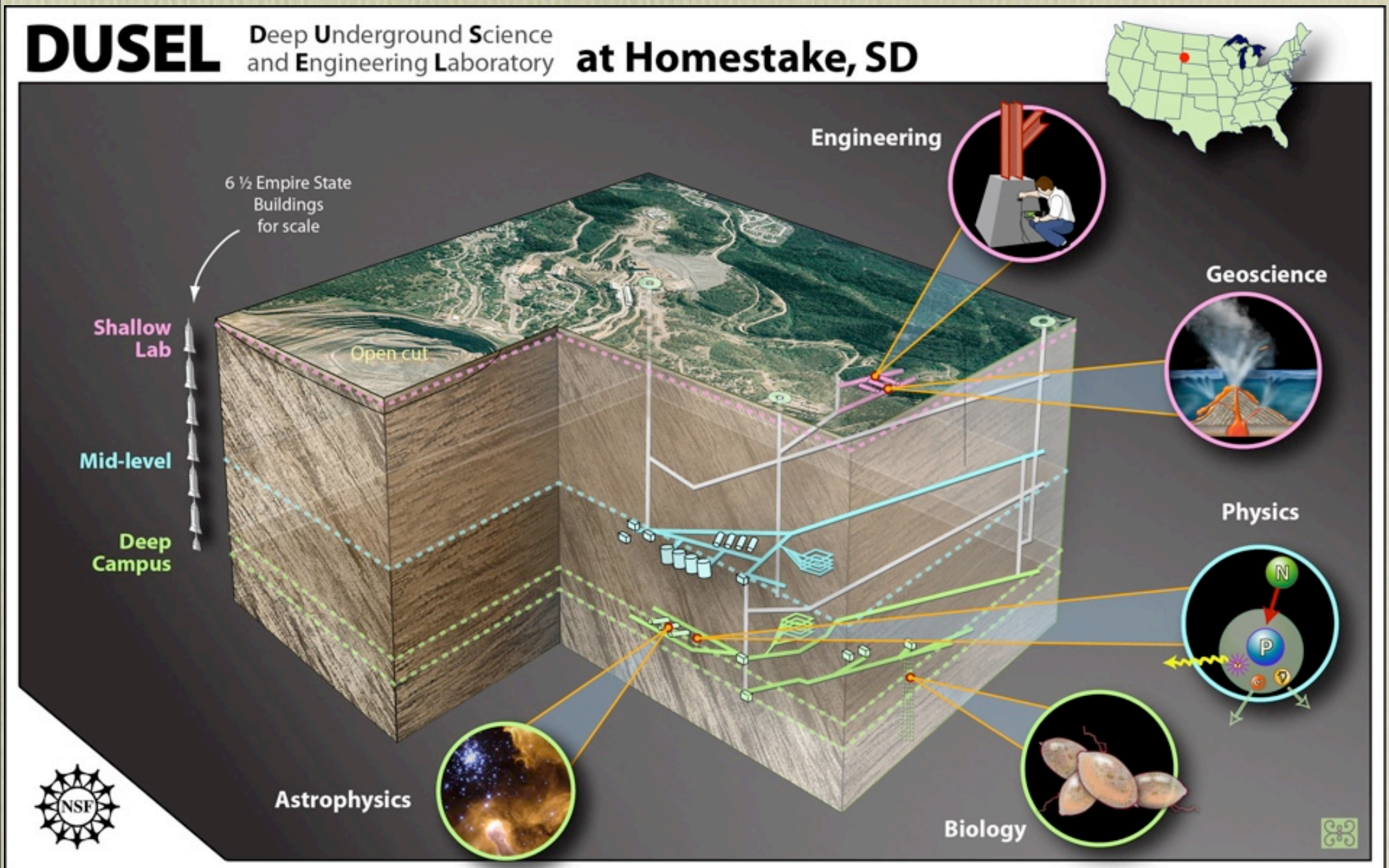

NSF site decision on advice from a 22 member unanimous panel. July 2007

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NSF: US national science foundation

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. (100kT LAR) could 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.

Proton Intensity at FNAL

	Now	Proton Plan	NOvA *	SNuMI	Project X	
Batch Intensity (8 GeV)	4.4×10^{12}	4.3×10^{12}	4.1×10^{12}	4.5×10^{12}	5.6×10^{13}	protons/pulse
Rep Rate	7	9	12	13.5	5	Hz
Protons/hour	1.1×10^{17}	1.4×10^{17}	1.8×10^{17}	2.2×10^{17}	1.0×10^{18}	
Main Injector batches	7	11	12	18	3	
MI batches to pbar target	2	2	0	0	0	
MI Cycle Time	2.4	2.2	1.33	1.33	1.4	sec
MI Beam Power (120 GeV)	176	338	710	1169	2314	kW
8 GeV Beam Power (available)	18	17	16 *	0	206	kW
Injection energy into 1st synchrotron	400	400	400	400	8000	MeV

From: FNAL Steering group report.

Beam from FNAL

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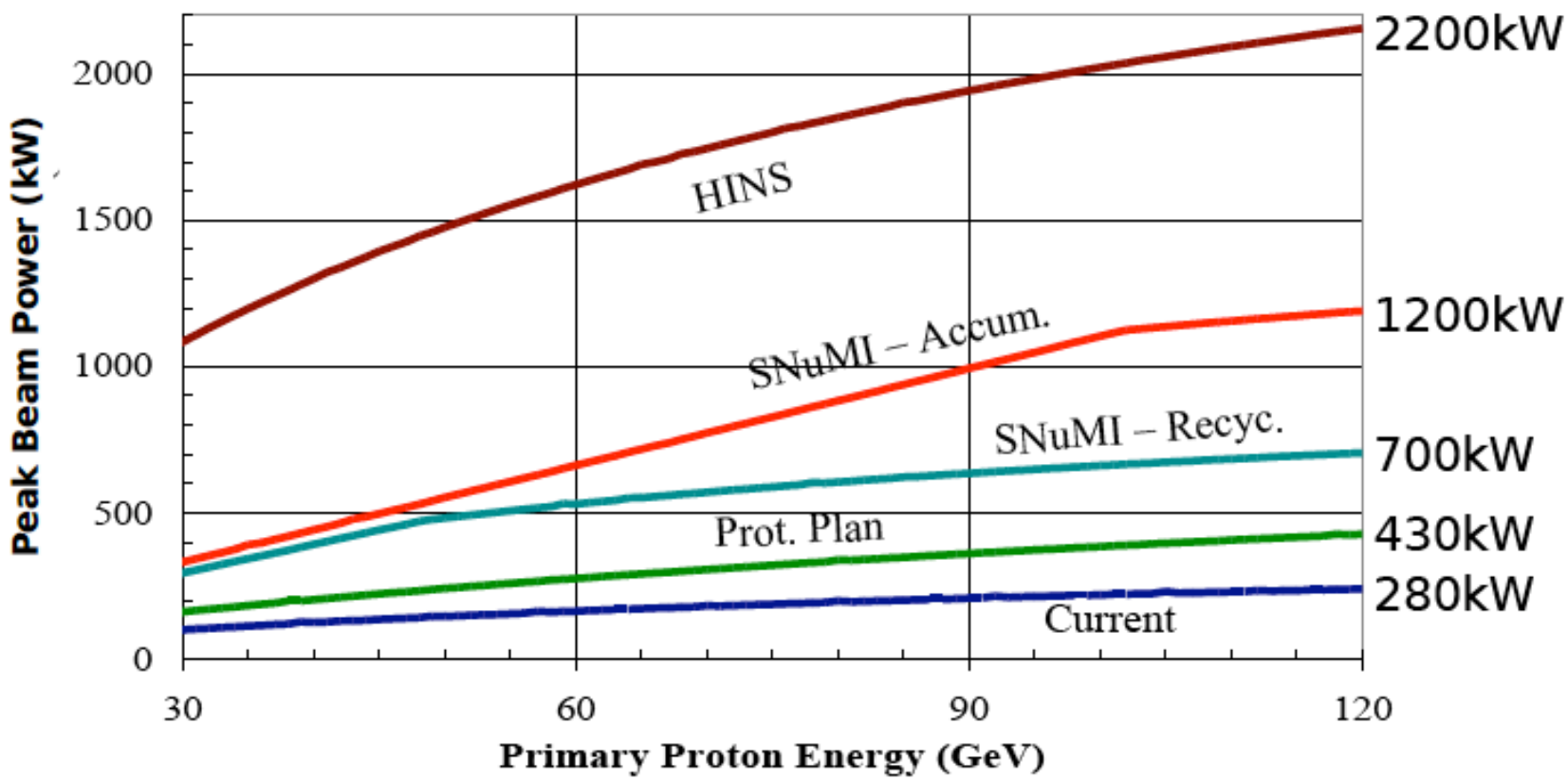
After Collider

Flexibility of proton energy:



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

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

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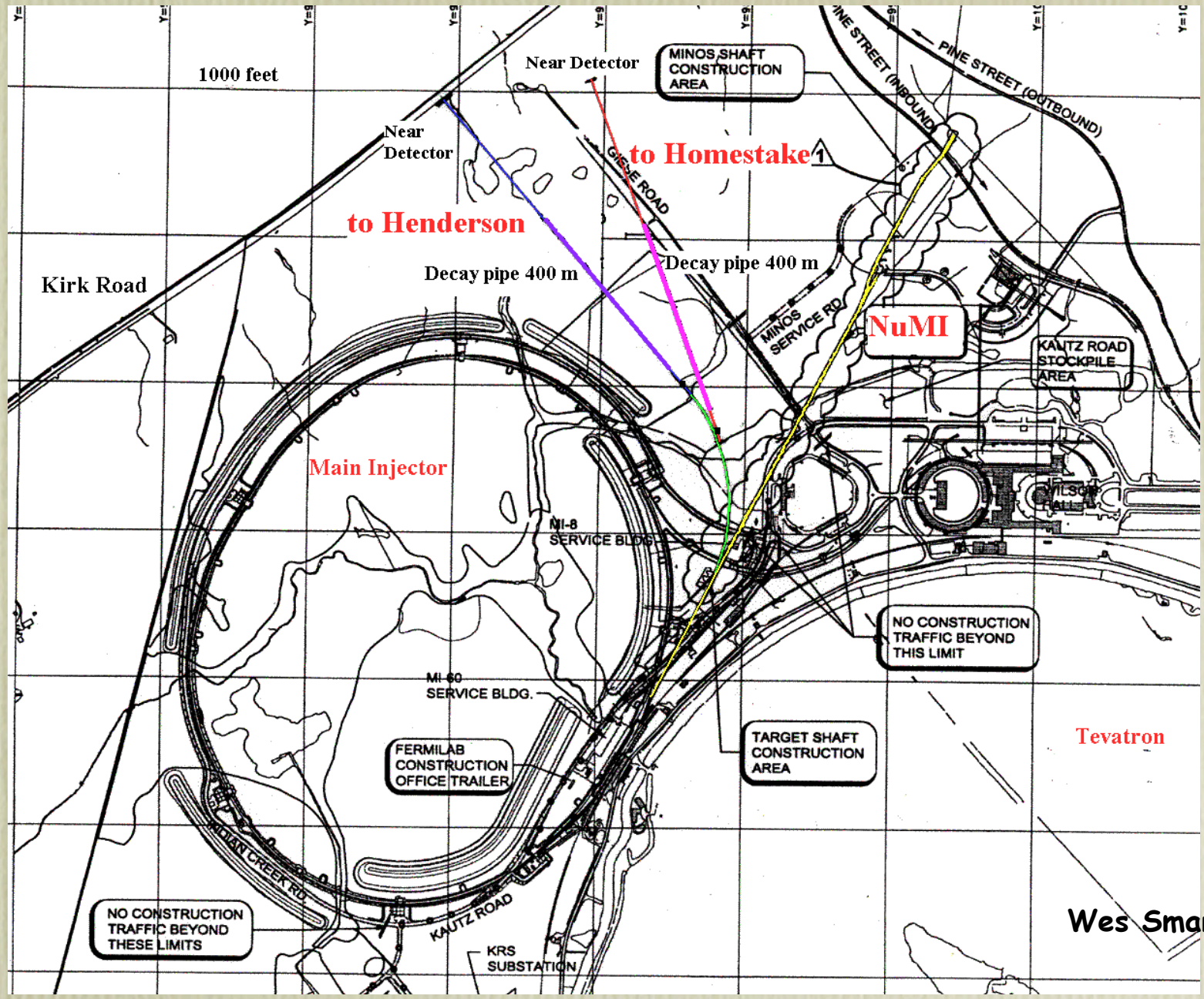

DUSEL beamline decay tunnel should be <400 m and >1.5 m radius

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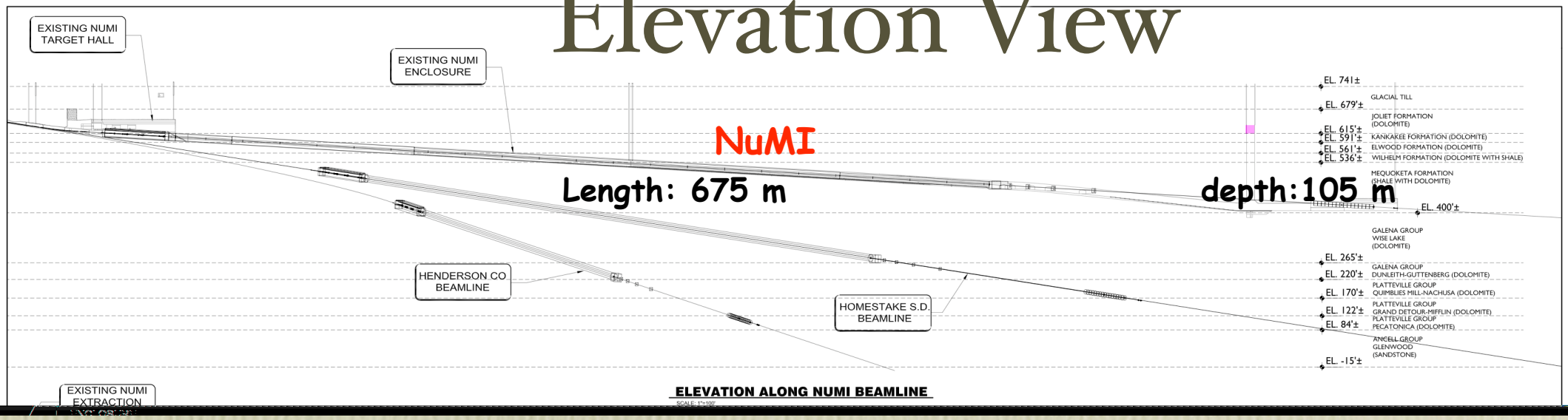
Elevation View



	Latitude	Longitude	Vertical angle from FNAL (deg)	Distance from FNAL (km)
Homestake	44.35	-103.77	-5.84	1289
Henderson	39.76	-105.84	-6.66	1495

- **Use the present extraction out of Main Injector into NuMI**
- **Second tunnel to transport protons west starts near lower Hobbit door in present line.**
- **Radius of curvature same as MI for 120 GeV using conventional magnets.**
- **New target station: R&D needed beyond 1 MW.**

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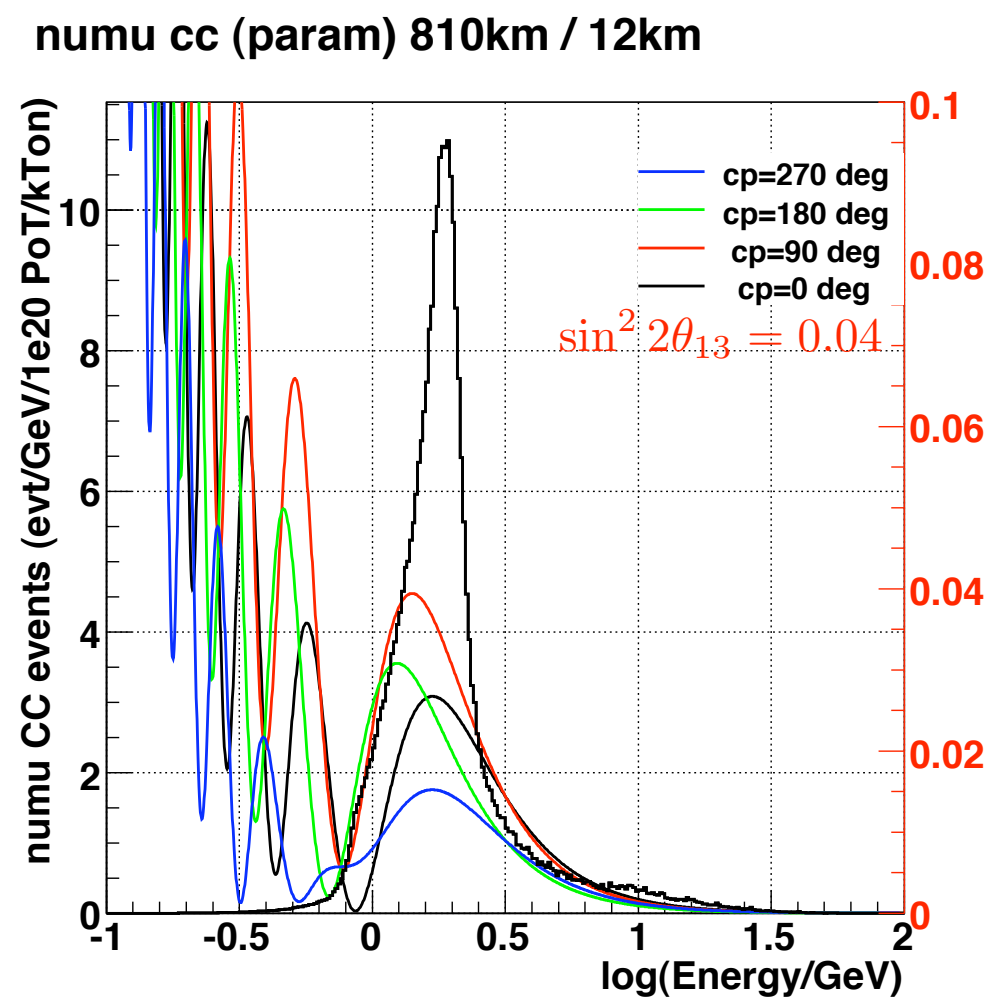
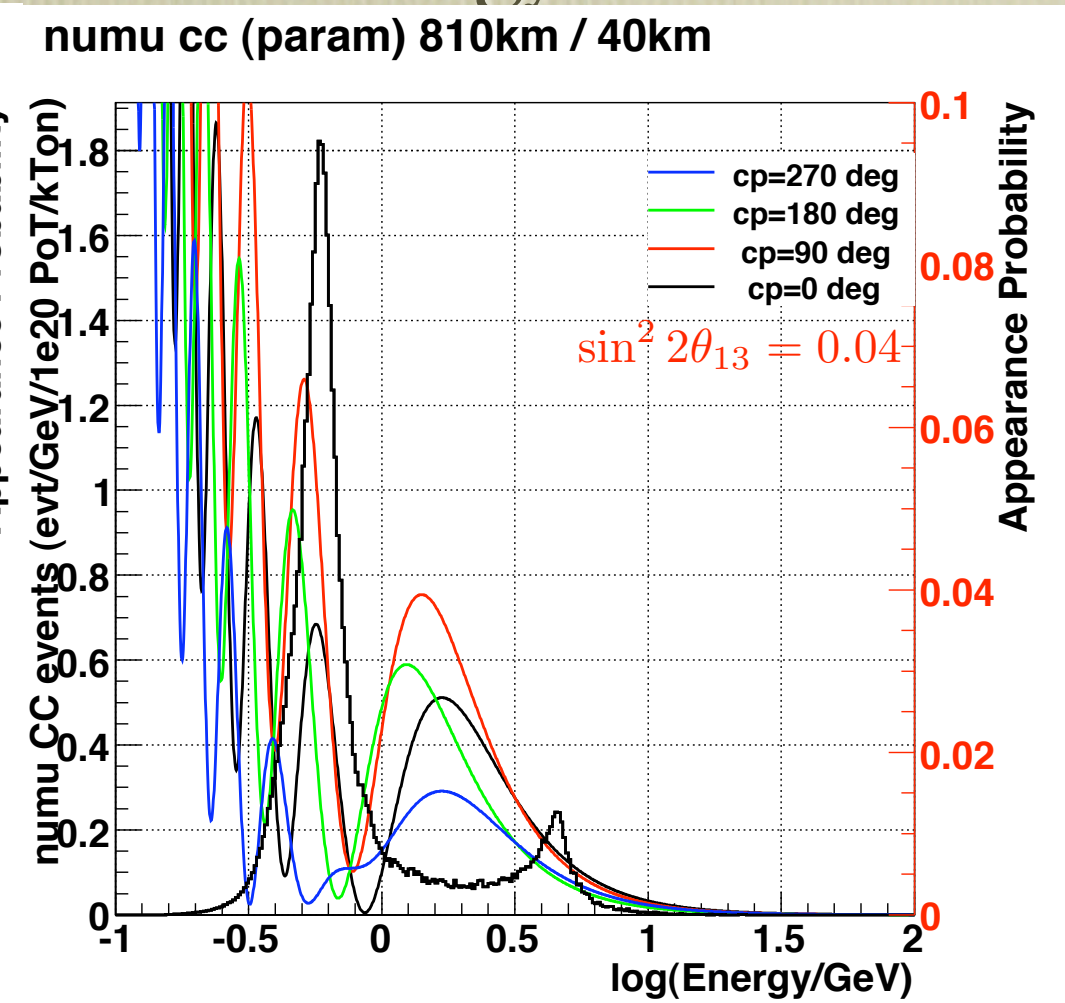
Spectra off-axis with Low Energy tune





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

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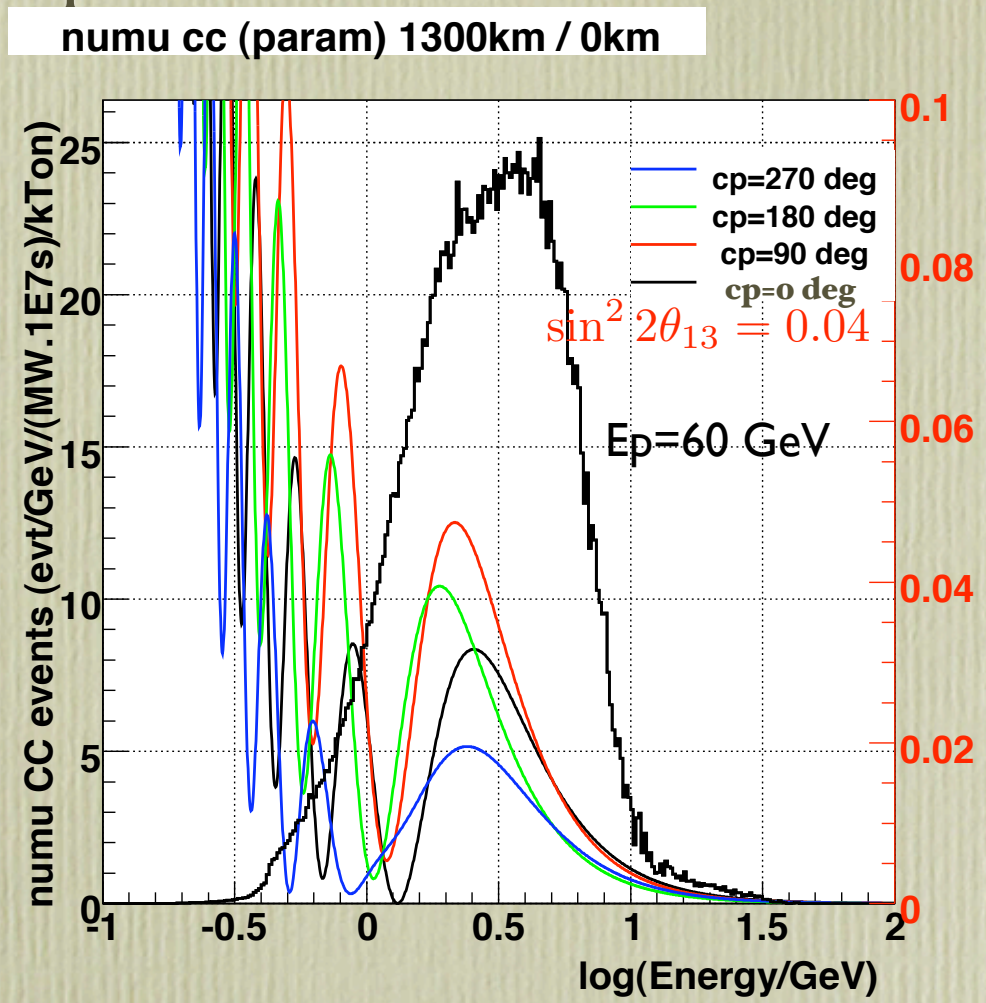
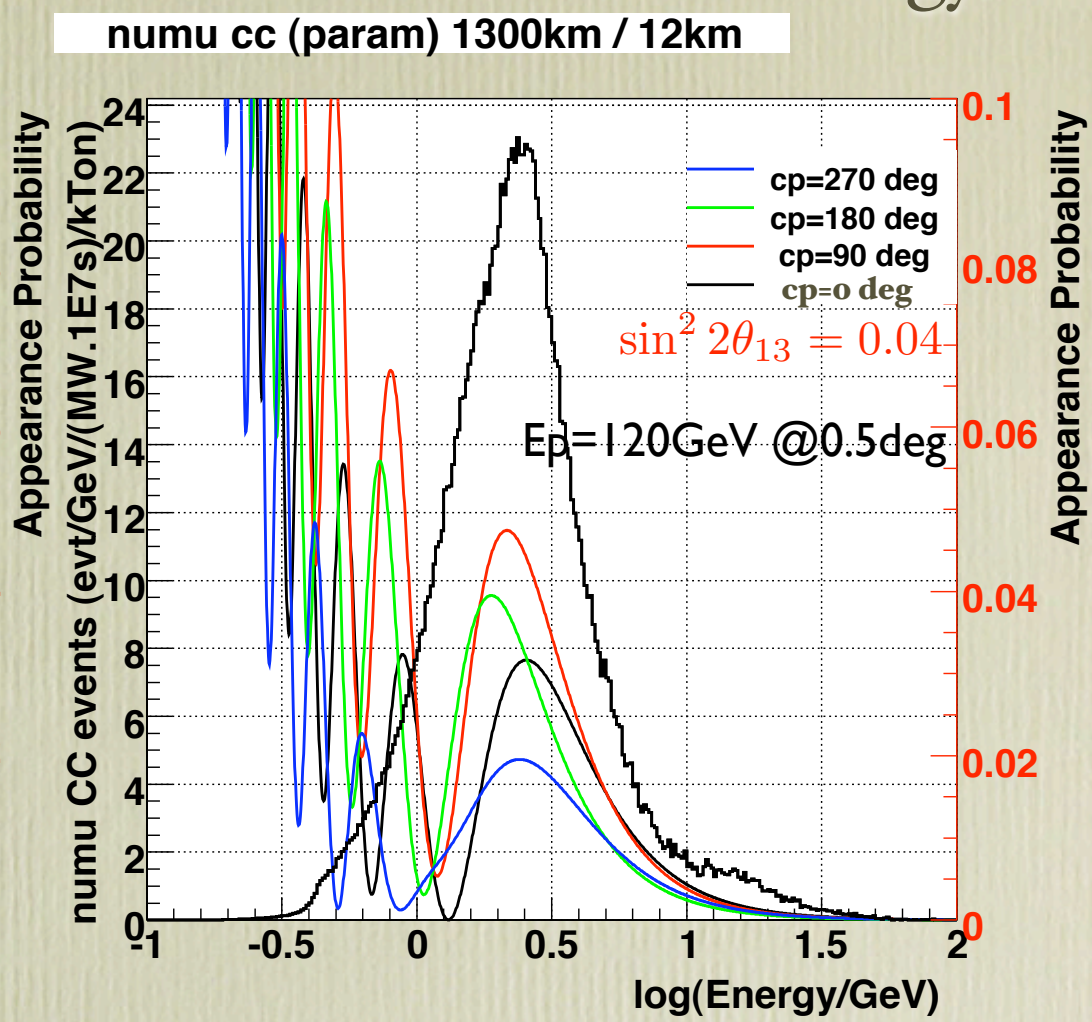
Spectra FNAL to DUSEL (WBLE: wide band low energy)





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

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

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$\nu_\mu \rightarrow \nu_e$ rate in 100kT*1MW*10^7 sec

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

δ_{CP}

	$sgn(\Delta m^2_{31})$	0 deg	+90 deg	180 deg	-90 deg
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

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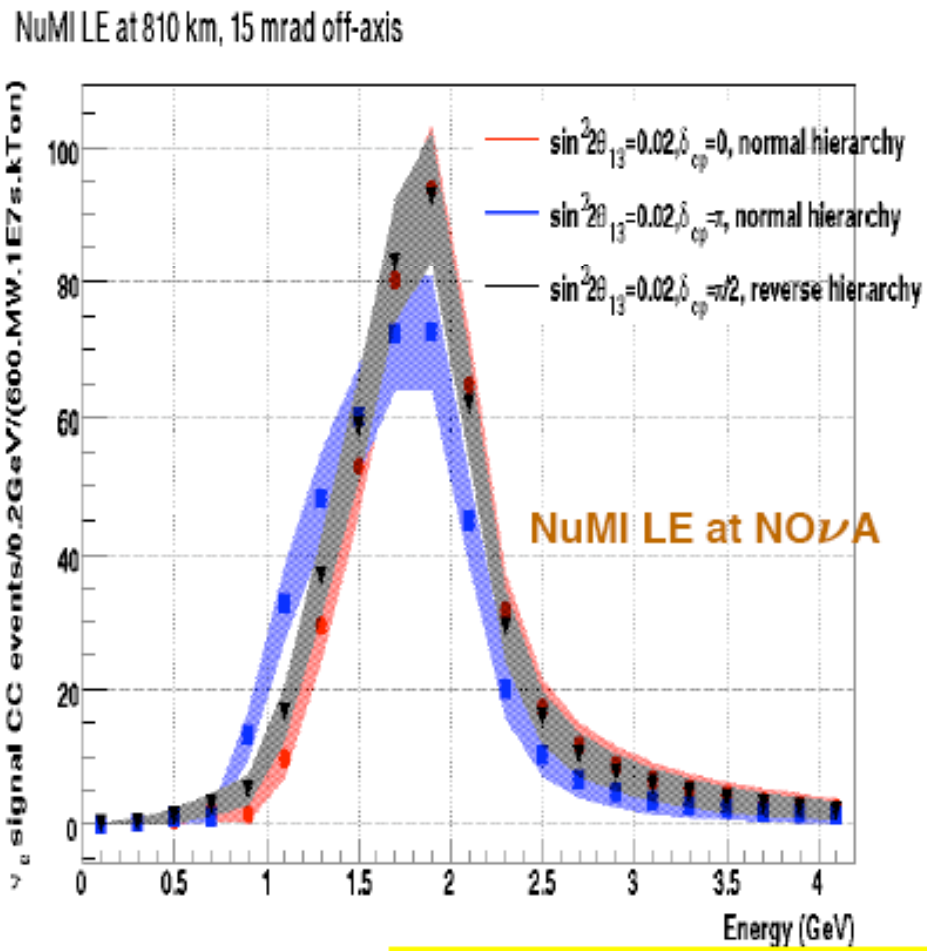
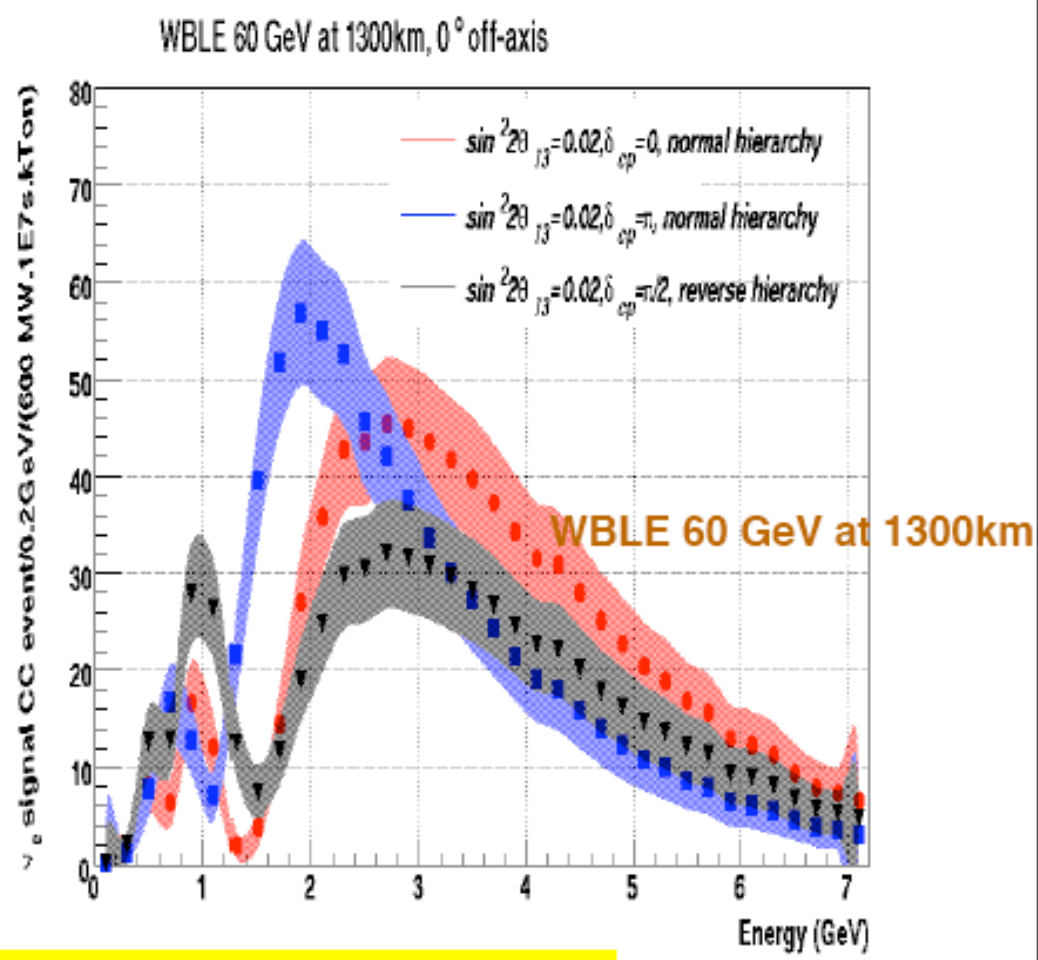
ν_e Appearance Spectra

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

$\sin^2 2\theta_{13}$	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*10^7sec
- Significance for CP violation is different from matter effect. For large θ_{13} it is only weakly dependent on θ_{13}

Detector design considerations

- Need ~100kT efficient mass
- Signal ~50events/year
- 100kT→ 50m∅ × 50m h
- Cosmic rate in 10μs for 10^7 pulses.
- If detector on surface need rejection of ~10^8 for muons and ~10^4 for photons ➢ fully active fine grained detector.

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

DUSEL

Detector technolgies

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. PMT R&D and costing in progress.
- Can be deployed deep scaled up: 50kT to fewX100kTon.
- MODEST DEVELOPMENT NEEDED FOR PROPOSAL.

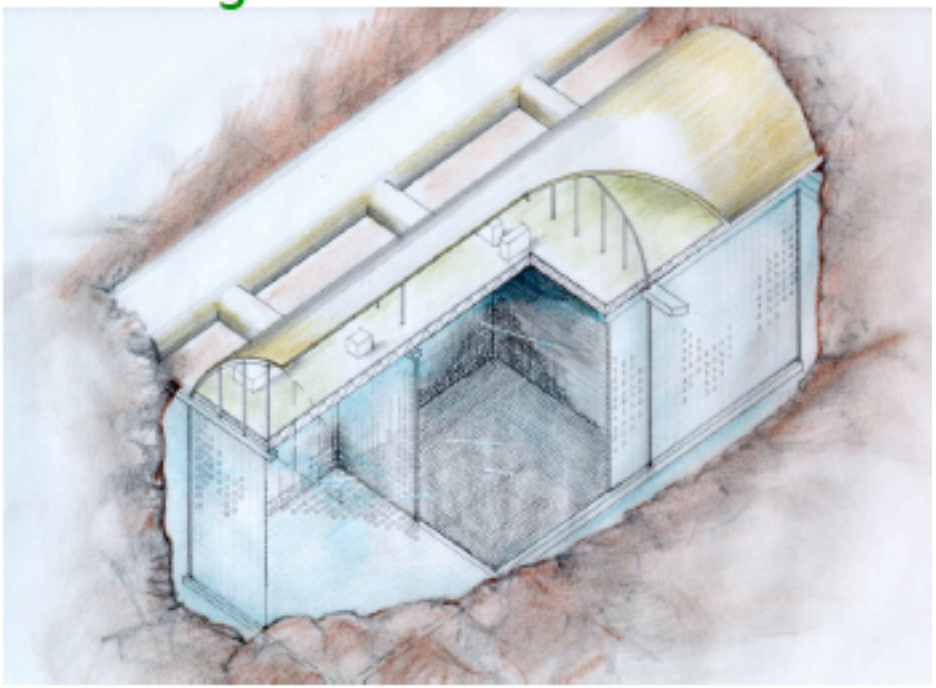
Liquid argon

- Substantial R&D needed to scale current 0.3 kT (ICARUS) to 100kT.
- Solution needed deep deployment. Can proton decay physics or other non-accelerator physics be done near 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:

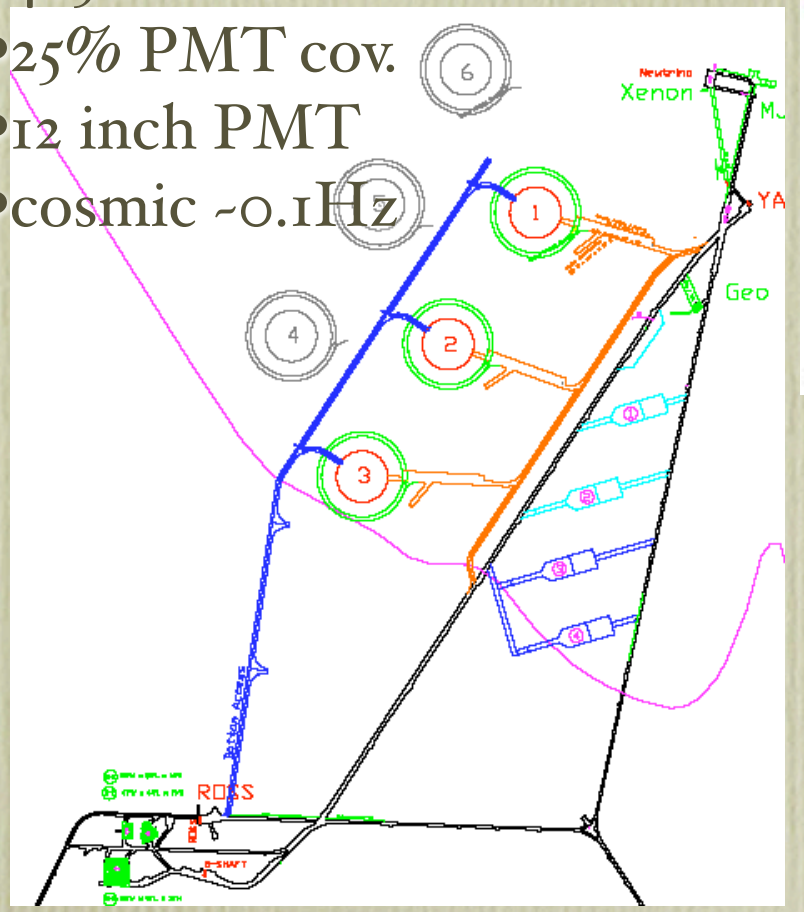
- 1 large cavern
- 3 optically separated modules of 60x60x60 m^3
- total mass 440 kT fiducial
- central module 40% PMT coverage (low E physics)
- outer modules 10% PMT coverage
- optional finer granularity: 20 or 13 inch tubes
- optimal depth 5400mwe (2500 feet)
- construction time: 10 years
- coarse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

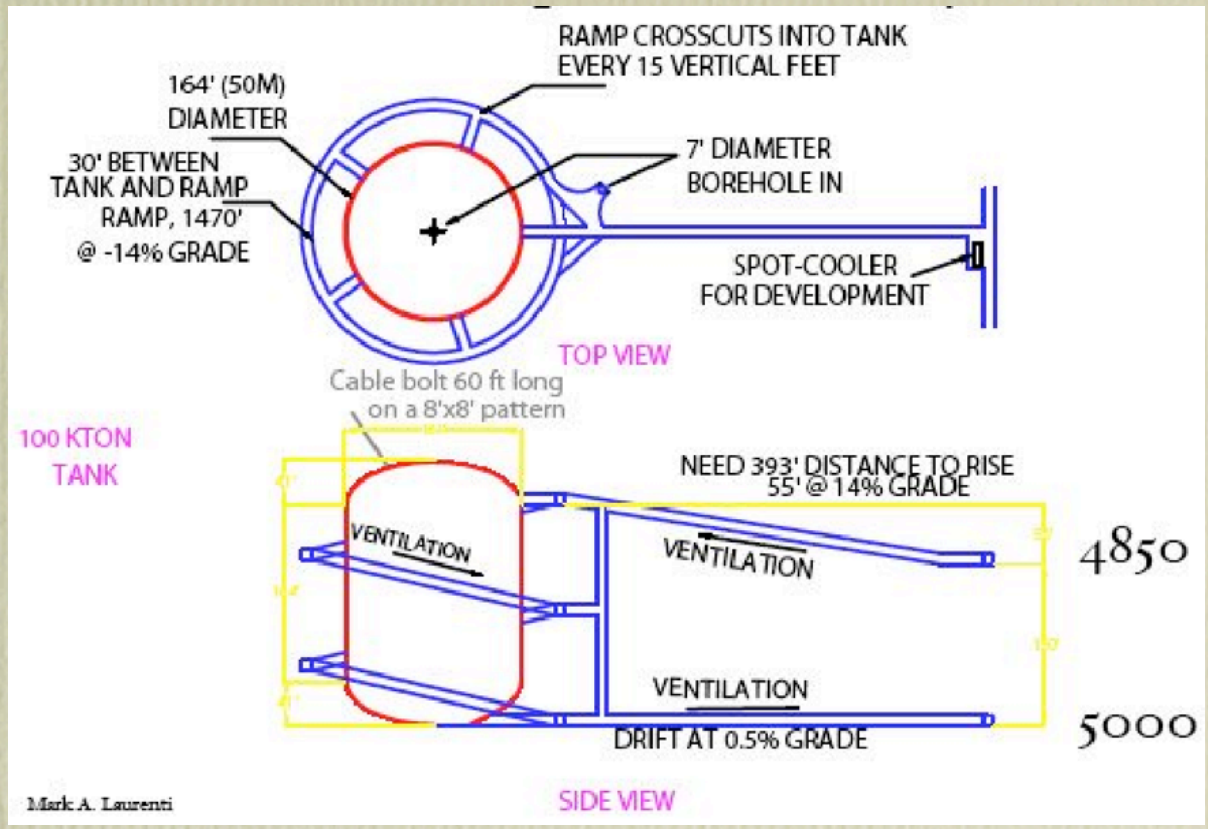


Detector at Homestake

Modular Detector

- ~53m dia/h
- 100kT fiducial
- 4850 mwe
- 25% PMT cov.
- 12 inch PMT
- cosmic ~0.1Hz





Studies ~50m cavity stable in HS rock

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

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

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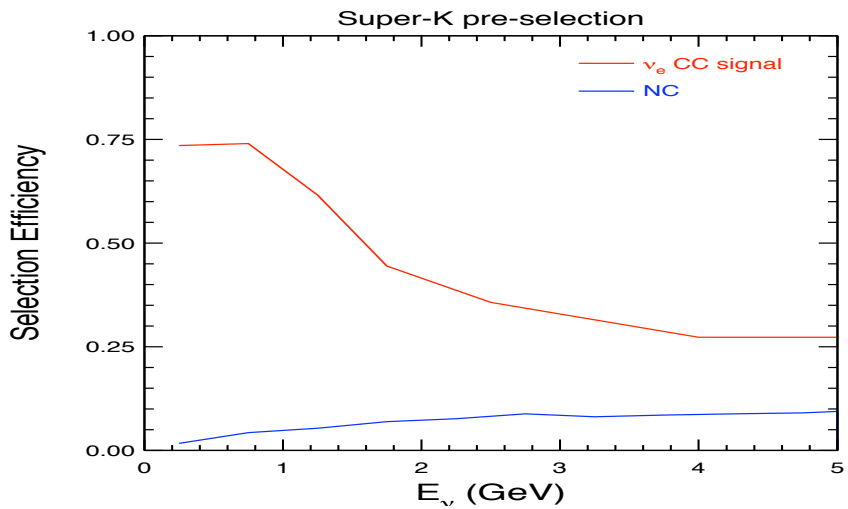
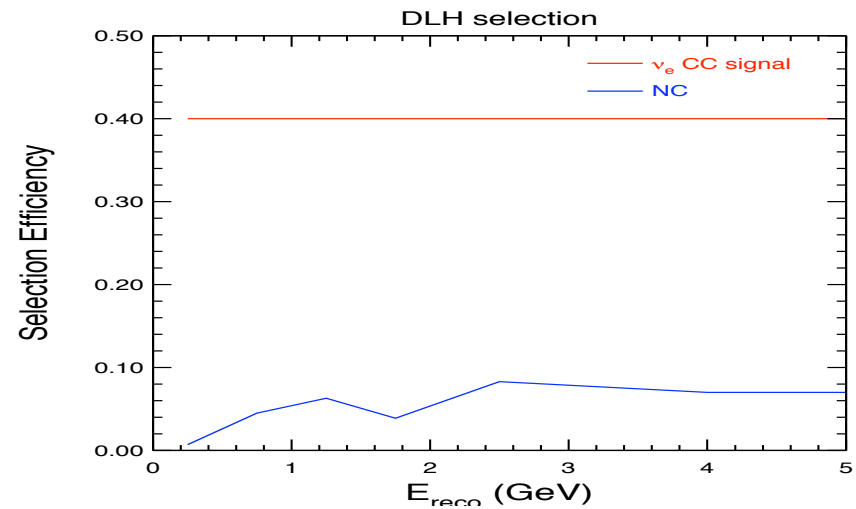
Water Cerenkov Simulation

The ν_{atm} 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.**





For total eff. and rej. multiply these plots together

Standard Super-K pre-selection efficiencies

DLH selection efficiencies (Chiaki Y.)

WCe. energy dependent efficiencies and smearing implemented in GLoBeS.

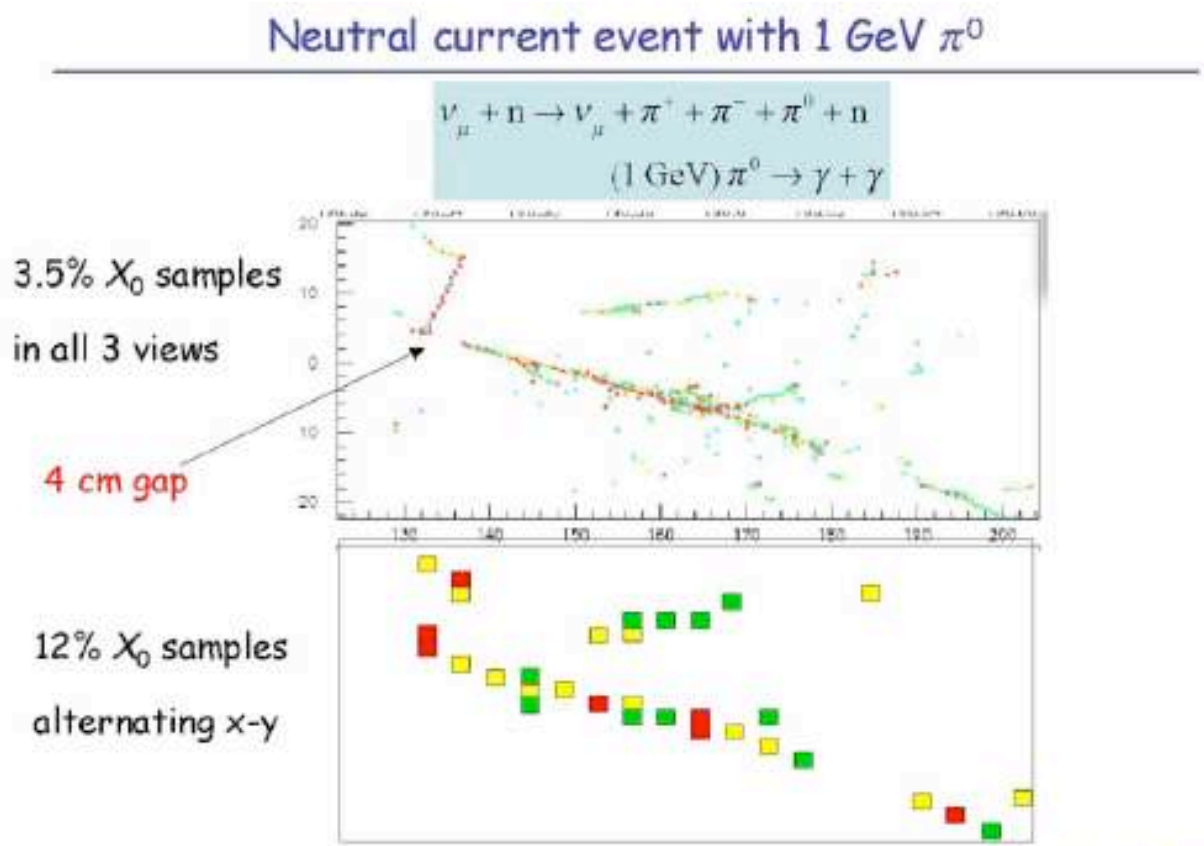
LARTPC

www-lartpc.fnal.gov

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

- 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.
- 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.

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.

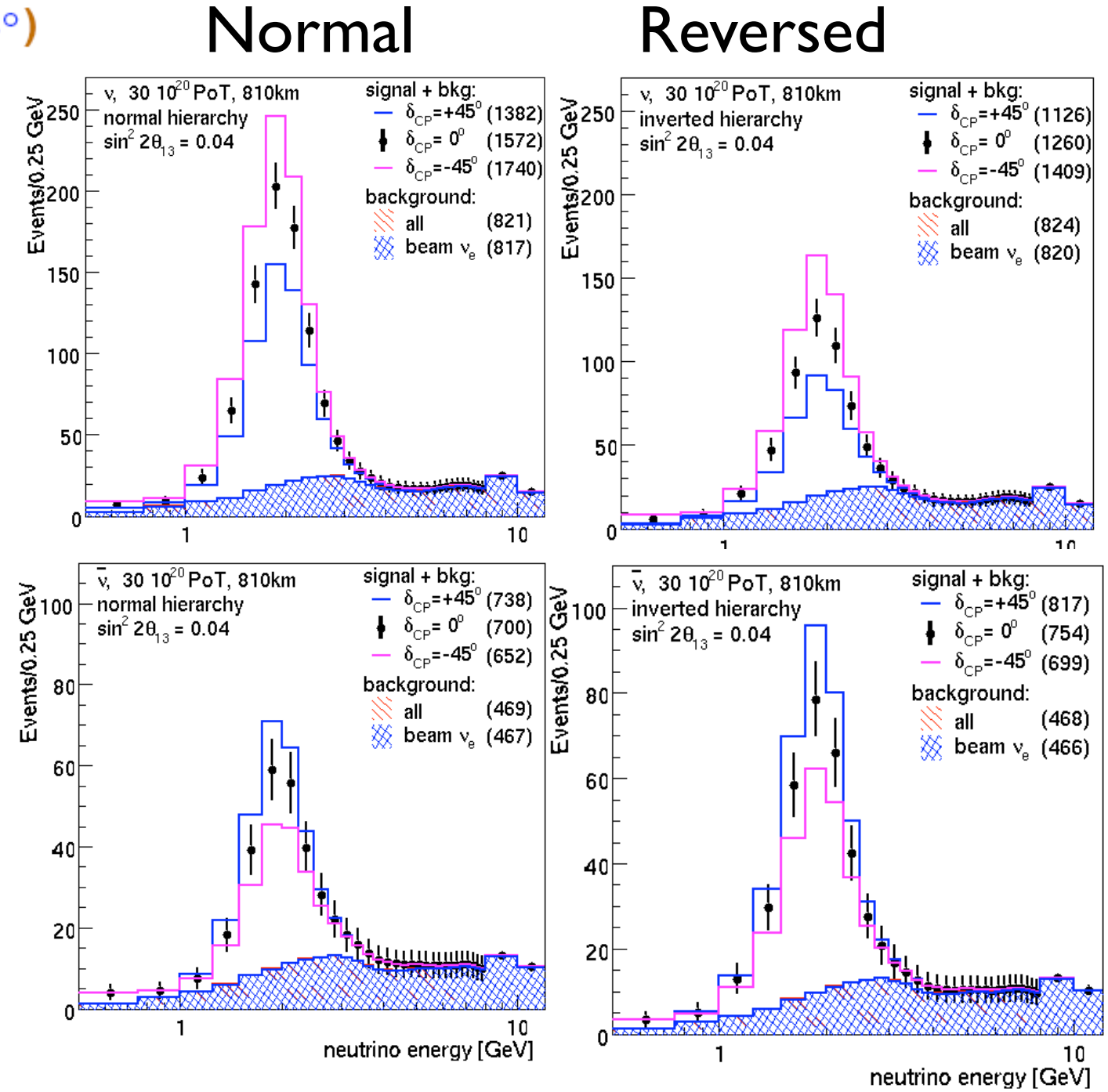
ν_μ QE event reconstruction in MC.

Electron neutrino appearance spectra

$\sin^2 2\theta_{13} = 0.04$, 100kT LAr. ,Numi120 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



Electron neutrino appearance spectra

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

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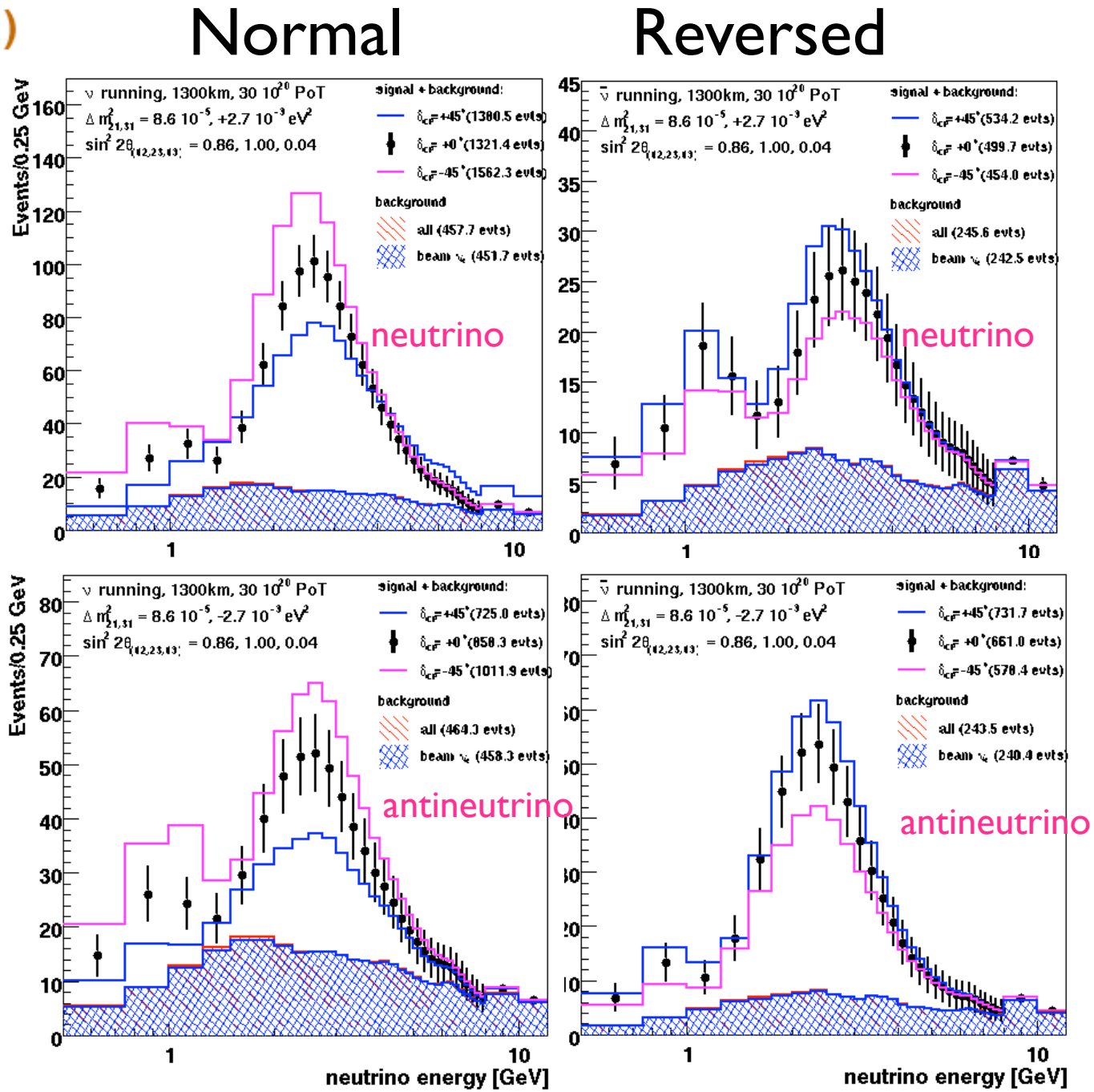
- 80% efficiency on electron neutrino CC events.
- sig(E)/E = 5%/sqrt(E) on quasielastics
- sig(E)/E = 20%/sqrt(E) on other CC events

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

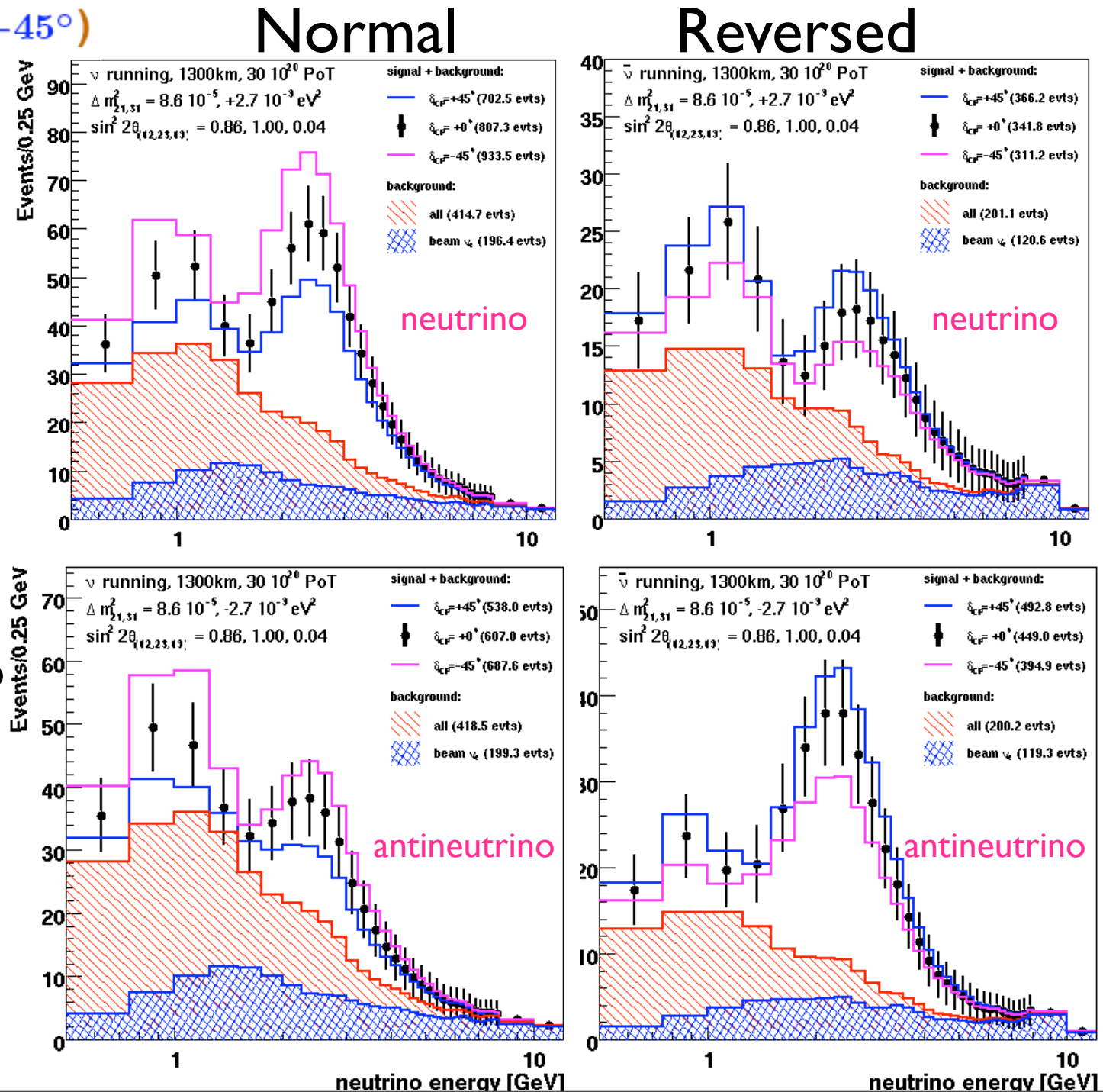


Electron neutrino appearance spectra

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

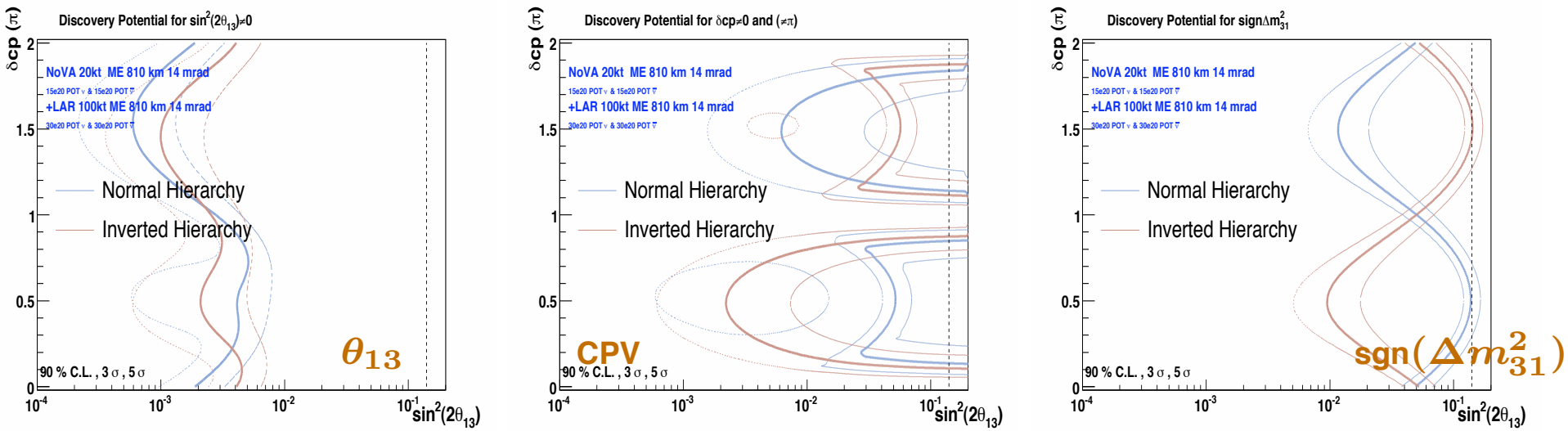
$(-\delta_{cp} = -45°, -\delta_{cp} = +45°)$

- 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.

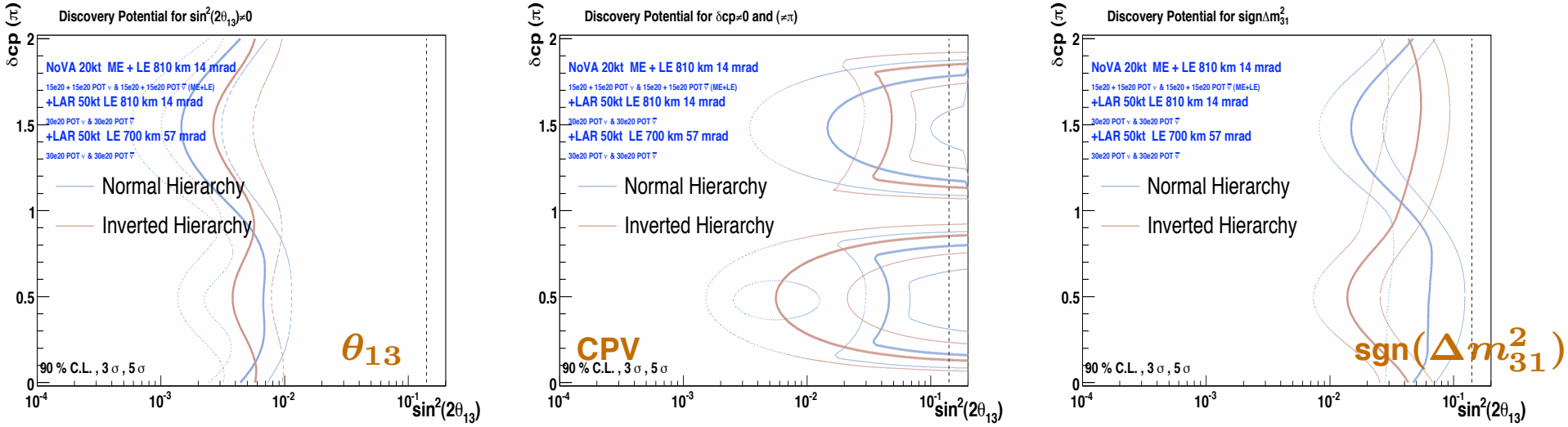


NuMI Off-axis

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



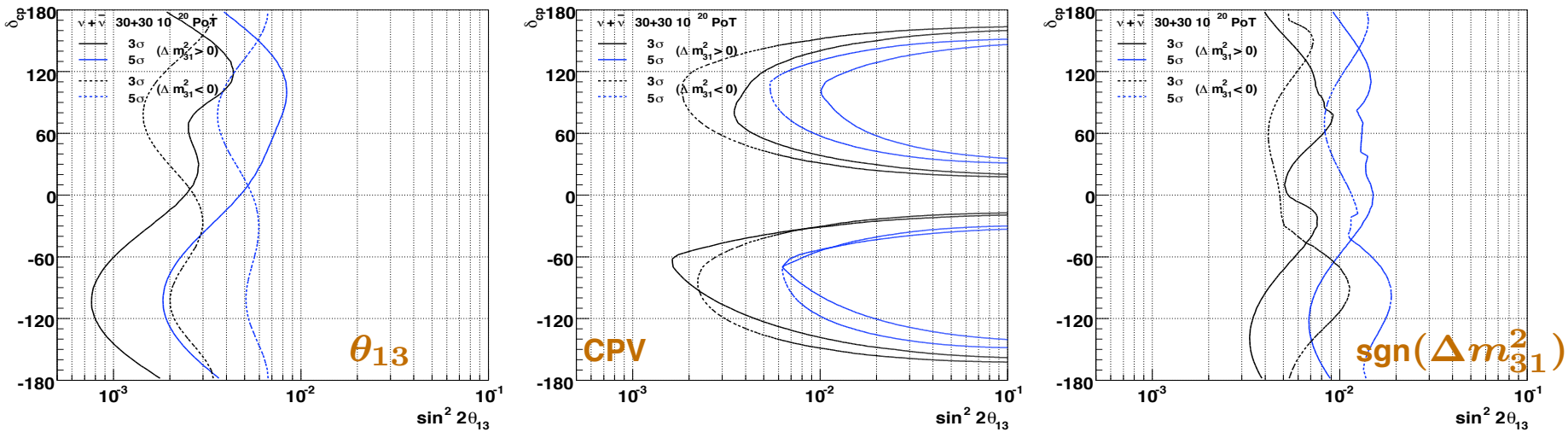
Discovery potential (90% C.L,3σ, 5σ) LAr. 2X50 kT at 700,810km , 1.2 MW, 6yrs:



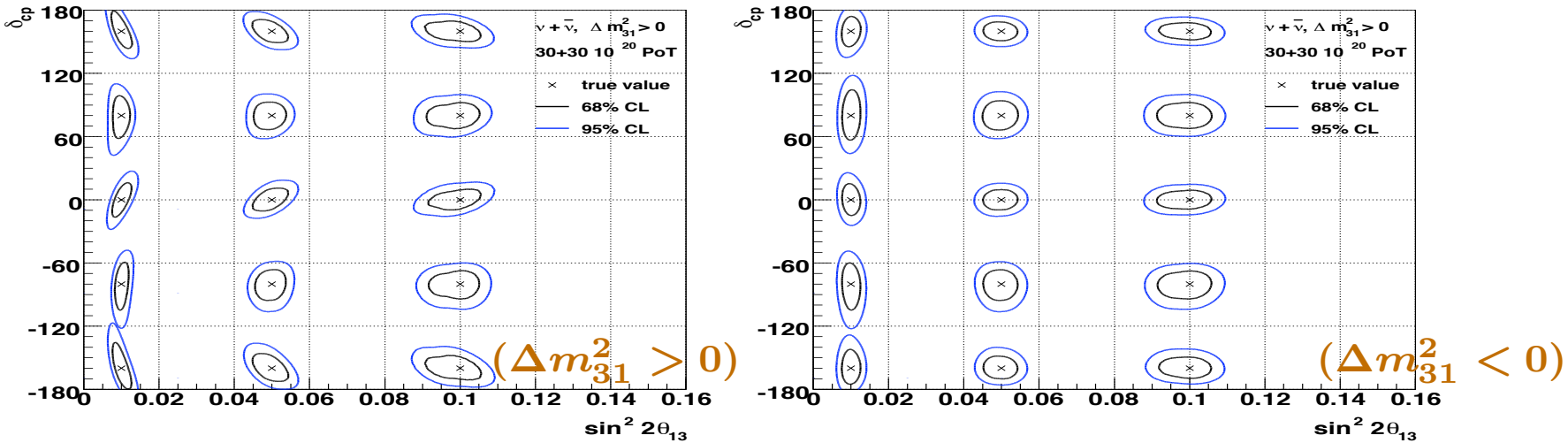
Niki Saoulidou

WBLE FNAL to DUSEL (1300km)

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

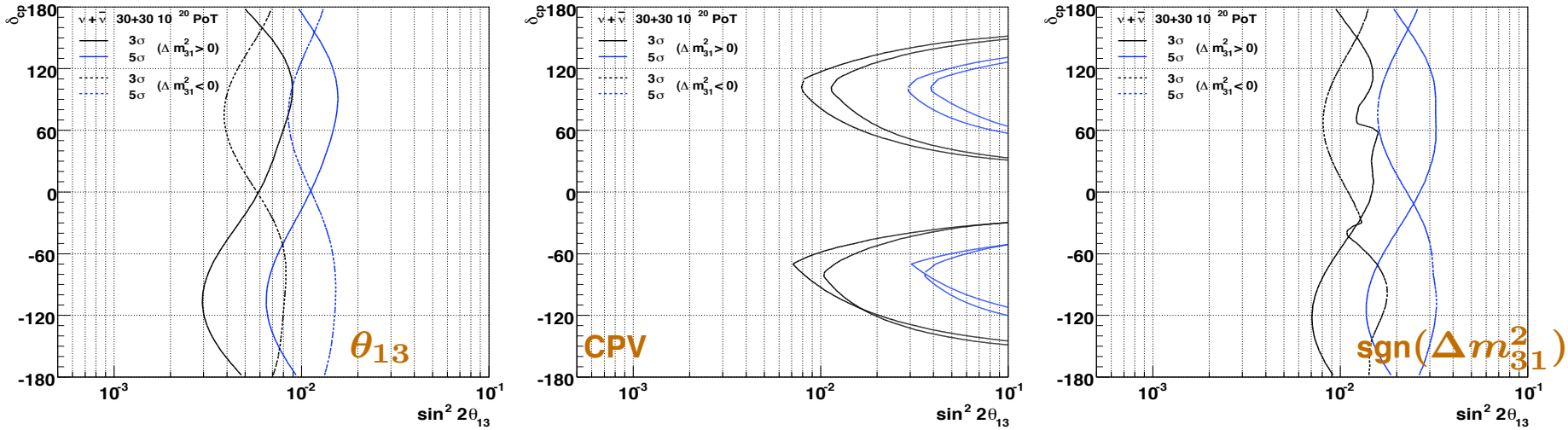


Measurement (—95% CL —68% CL) :

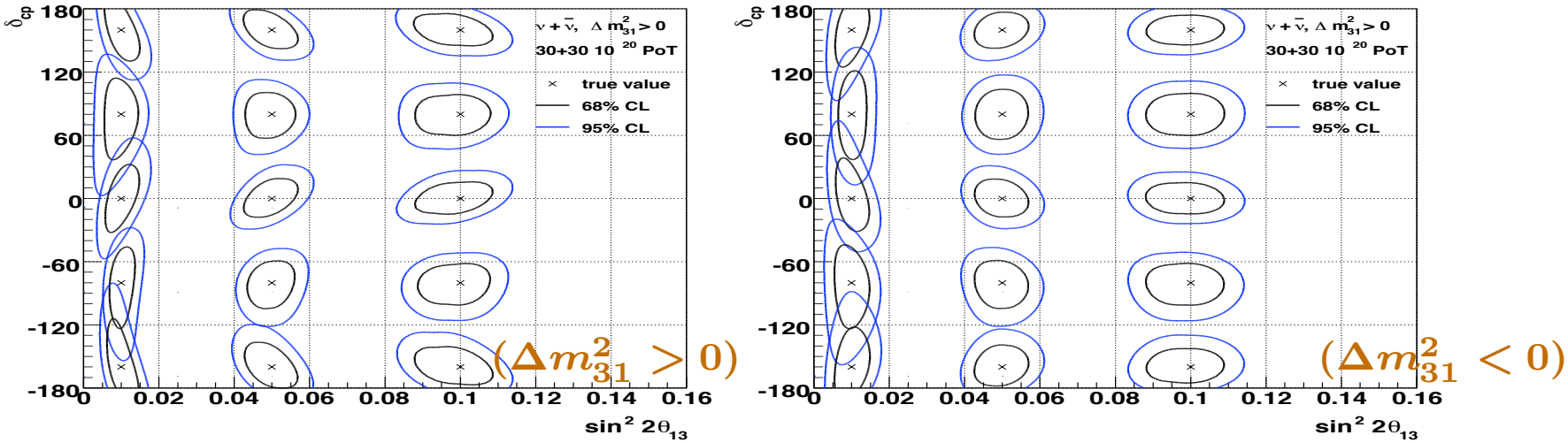


WBLE FNAL to DUSEL (1300km)

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

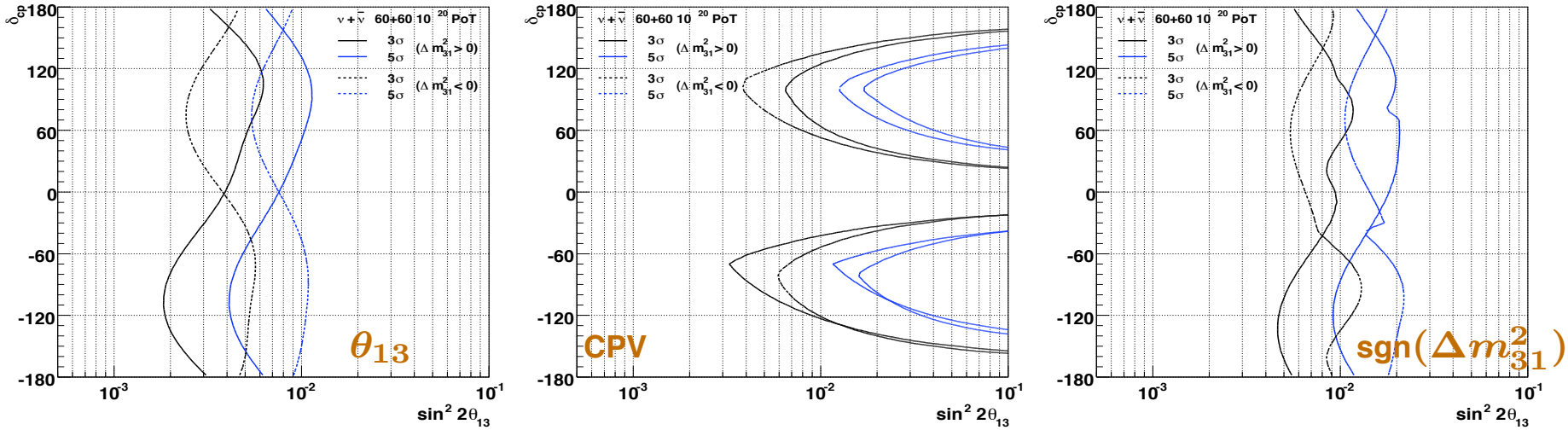


Measurement (-95% CL -68% CL) :

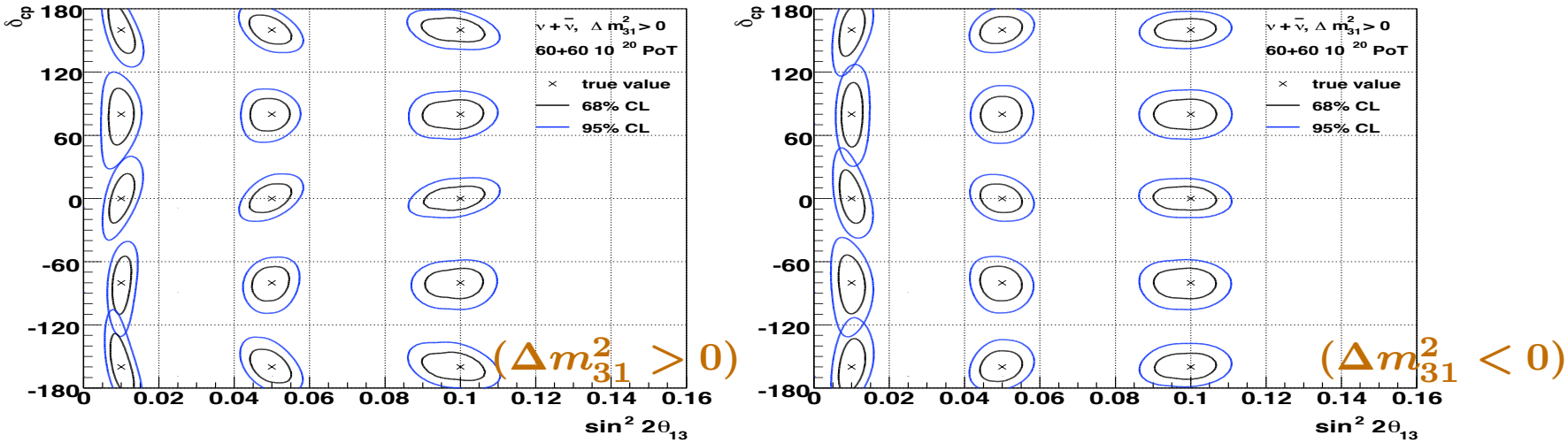


WBLE FNAL to DUSEL (1300km)

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



Measurement (—95% CL —68% CL) :



Sensitivity comparison

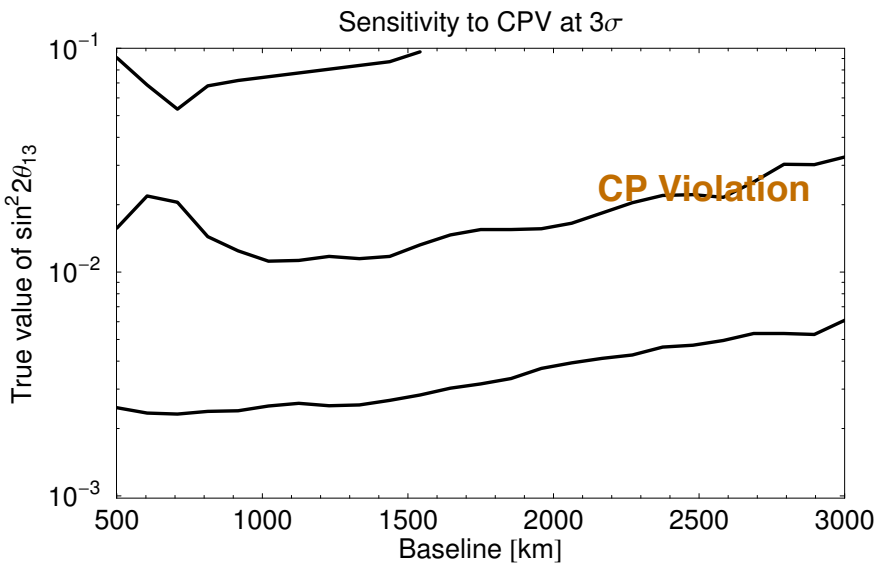
Comparison of the sensitivity reach of different long baseline experiments given as the value of $\sin^2 2\theta_{13}$ at which 50% of δ_{cp} values will have $\geq 3\sigma$ reach for the choice of mass hierarchy with worst sensitivity. Total exposure assumes equal amounts of ν and $\bar{\nu}$:

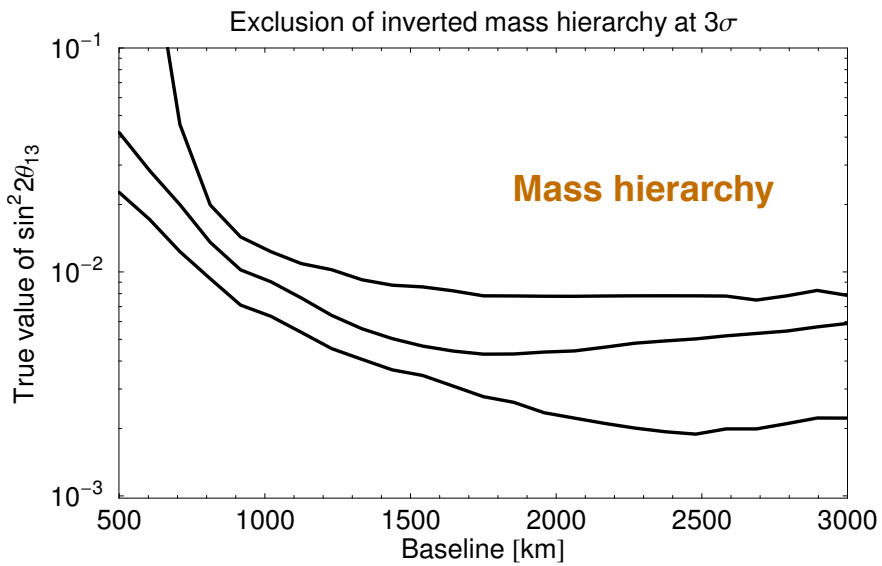
Beam	Baseline	Detector	Exposure (MW.yr*)	$\theta_{13} \neq 0$	CPV	$sign$ (Δm^2_{31})
NuMI ME, 0.9°	810 km	NOνA 20 kT	6.8	0.015	$>$ 0.2	0.15
NuMI ME, 0.8°	810 km	LAr 100 kT	6.8	0.002	0.03	0.05
NuMI LE, 0.8°, 3°,	810,700 km	LAr 2 $\times$ 50 kT	6.8	0.005	0.04	0.04
WBLE 120GeV, 0.5°	1300km	LAr 100 kT	6.8	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, but best results are obtained with a Wide Band beam to DUSEL at 1300 km.

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

NuSAG Recommendations

Recommendation 1. The US should prepare to proceed with a long baseline neutrino oscillation program to extend sensitivity to $\sin^2 2\theta_{13}$, to determine the mass ordering of the neutrino spectrum, and to search for CP violation in the neutrino sector. Planning and R&D should be ready for a technology decision and a decision to proceed when the next round of results on $\sin^2 2\theta_{13}$ becomes available, which could be as early as 2012. A review of the international program in neutrino oscillations and the opportunities for international collaboration should be included in the decision to proceed.

Recommendation 2. Research and development towards an intense, conventional neutrino beam suitable for these experiments should be supported. This R&D may be to support intensity upgrades to the existing NuMI beam, as well as development of a new beam directed towards DUSEL, which would likely employ the wide-band beam approach.

Recommendation 3. Research and development required to build a large water Cherenkov detector should be supported, particularly addressing questions of minimum required photocathode coverage, cost, and timescale.

Recommendation 4. A phased R&D program with milestones and using a technology suitable for a 50-100 kton detector is recommended for the liquid argon detector option. Upon completion of the existing R&D project to achieve purity sufficient for long drift times, to design low noise electronics, and to qualify materials, construction of a test module that could be exposed to a neutrino beam is recommended.