The Long-Baseline Neutrino Experiment

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Mary Bishai
Brookhaven National Laboratory
LBNE Project Scientist

August 25, 2014

Outline

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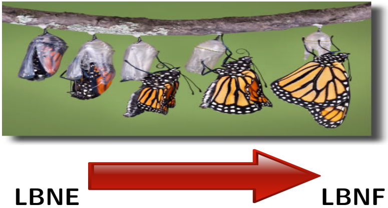
2. Scientific Objectives
3. Project History and Status
   - Near Site
   - Far Site
4. Physics Performance
   - ν oscillations
   - Underground Physics
5. Summary

Opening Remarks

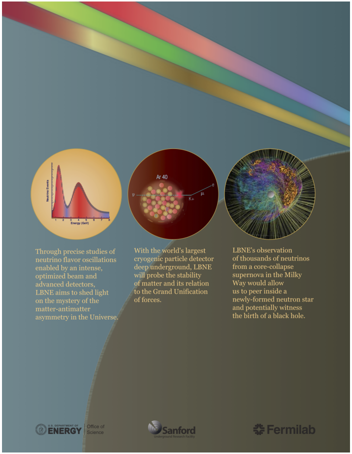
- **The LBNE project was conceived after the 2008 US Particle Physics Project Prioritization Panel (P5) recommended** *a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector at the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab*.
- **P5 is an** *advisory* **subpanel reporting to the High Energy Physics Advisory Panel (HEPAP) which reports to the US funding agencies DOE & NSF.**
- **The 2014 P5 issued the following recommendations:** *The U.S. will host a world-leading neutrino program that will have an optimized set of short- and long-baseline neutrino oscillation experiment, and its long-term focus is a reformulated venture referred here as the Long Baseline Neutrino Facility (LBNF). The Proton Improvement Plan-II (PIP-II) project at Fermilab will provide the needed neutrino physics capability*

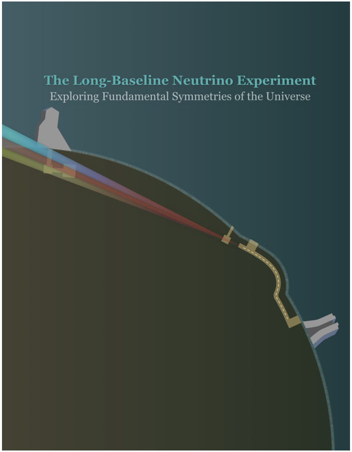


In this presentation I will talk only about the status of LBNE

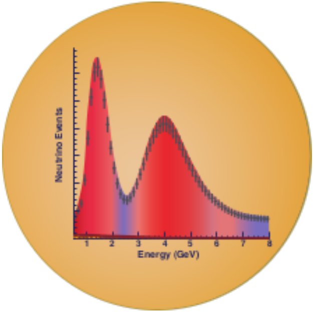
The Science of LBNE

The LBNE Science Program is described in detail in arxiv:1307.7335:



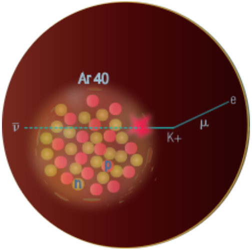


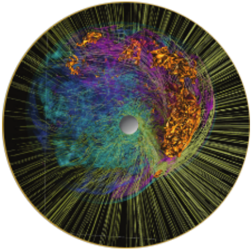
Scientific Objectives of LBNE



1. **precision measurements of the parameters that govern $\nu_\mu \to \nu_e$ oscillations; this includes precision measurement of the third mixing angle θ_{13}, measurement of the charge-parity (CP) violating phase δ_{CP}, and determination of the neutrino mass ordering (the sign of $\Delta m^2_{31} = m^2_3 - m^2_1$), the so-called mass hierarchy**
2. **precision measurements of the mixing angle θ_{23}, including the determination of the octant in which this angle lies, and the value of the mass difference, —Δm^2_{32}—, in $\nu_\mu \to \nu_{e,\mu}$ oscillations**

Scientific Objectives of LBNE





3. **search for proton decay, yielding significant improvement in the current limits on the partial lifetime of the proton (τ/BR) in one or more important candidate decay modes, e.g., $p \to K^+\overline{\nu}$**

4. **detection and measurement of the neutrino flux from a core-collapse supernova within our galaxy, should one occur during the lifetime of LBNE**

The LBNE Scientific Collaboration

2014 census: 518 collaborators, 137 non-US, 381 US

History of the LBNE Project

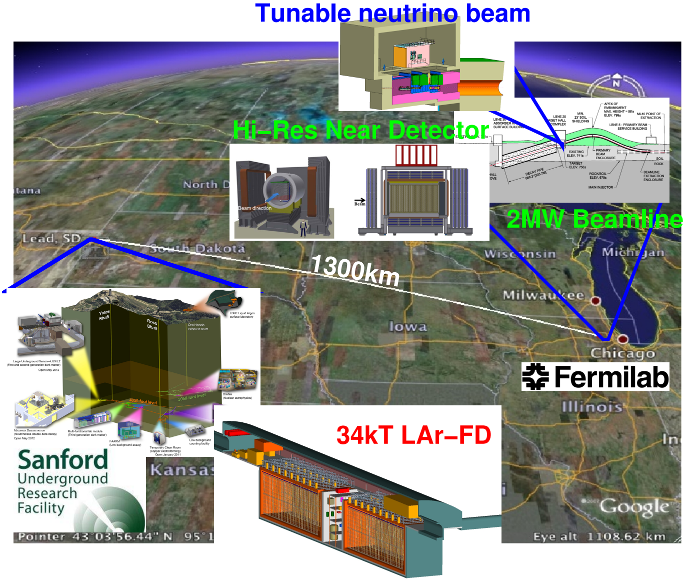
- **1960's - 2000 The Homestake neutrino detector discovers the "solar neutrino problem" $\rightarrow$ SNO,SuperK $\rightarrow$ neutrino oscillations $\rightarrow$ 2002 Nobel Prize to Ray Davis**
- **October 2004: Conceptual design report for "The AGS Super Neutrino Beam Facility" is issued by BNL group.** **BNL 28 GeV 1MW $\xrightarrow{2540\text{km}}$ W. Cerenkov at Homestake Mine.**
- **2005-2007 NSF S1-4 process selects site for underground laboratory with LBν experiment as a flagship. Many sites considered. Homestake mine, now a dedicated scientific facility under development by the state of South Dakota with *significant state and private funding* is chosen as the DUSEL site.**
- **2004-2008: Multiple studies conducted with Fermilab and BNL as neutrino source and baselines: 735 $\rightarrow$ 2540km. Successful launch of NuMI/MINOS. 2008 P5 recommends long-baseline neutrino experiment as a *core component of US program*.**
- **2010: DOE issues a *Misson Need statement (CD0)* for a long-baseline neutrino experiment with a baseline $>$ 1000km. LBNE project is formed with Fermilab as ν source**

History of the LBNE Project

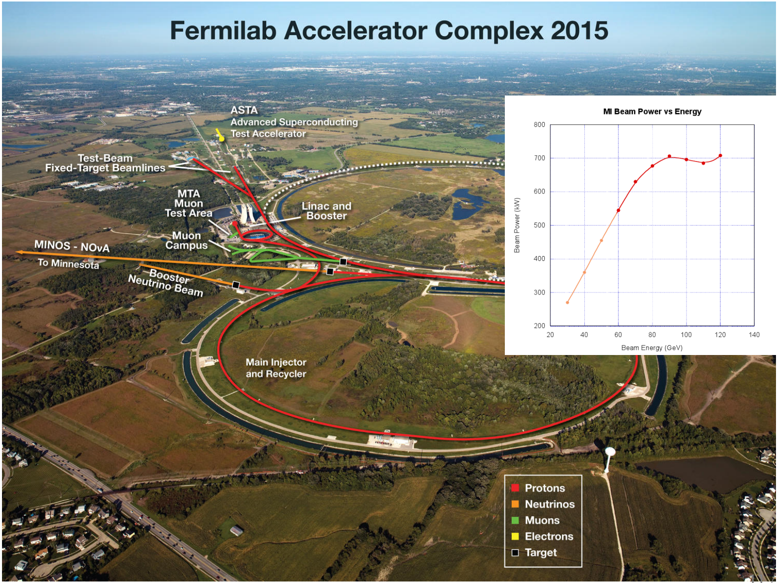
- **December, 2010: NSF decides not to develop DUSEL.**
- **March 2012: Fermilab Directors Review of a complete Conceptual Design for long-baseline experiment 120 GeV 700kW-2MW Fermilab $\xrightarrow{1300\text{km}}$ 34kton LArTPC at the 4850-ft level of the Sanford Underground Research Facility (SURF) in the former Homestake Mine. Alternative sites from NSF process were considered and discarded.**
- **April - December 2012: LBNE is reconfigured as a phased program. Conceptual design of first phase is approved (CD1) with initial funding of 867M US$ with a surface 10kton detector.**
- **Summer 2013: Surface option is discarded. DOE funding and CD1 to be applied to an initial phase with a near detector and 10kton LArTPC underground at 4850-ft that is to be realized with other domestic and international partnerships.**
- **Aug 2014: Preliminary underground site investigation complete.**

LBNF is now being formulated as a more ambitious international long-baseline neutrino project based at Fermilab.

The LBNE Project



The Fermilab Accelerator Complex J-P. Delahaye presentation on 25/8



Proton Improvement Plan -II

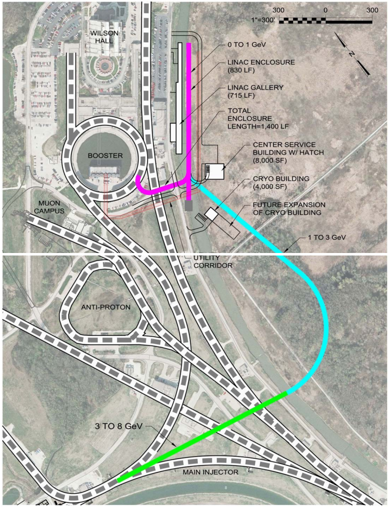
Upgrades to the Fermilab linac would increase proton yield from the complex. PIP-II replaces upstream portion of linac feeding into 8 GeV Booster:

1.03 MW at 60 GeV
1.07 MW at 80 GeV
1.20 MW at 120 GeV

PIP-II strongly endorsed by P5

Further upgrades (——, ——) would replace booster and inject directly into MI from 5-6 GeV

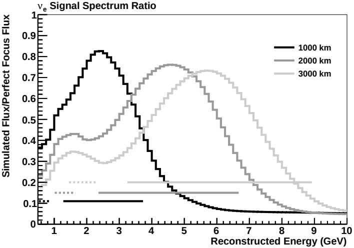
2.0 MW at 60 GeV
2.3 MW at 120 GeV



Optimal Baseline from Fermilab

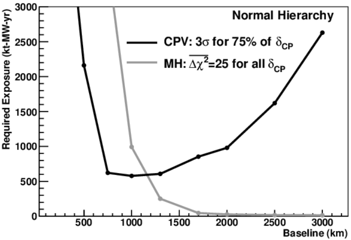
A study using (1) MI 120 GeV beam (2) tuned NuMI focusing (3) optimized decay channel geometry (4) off-axis angle, at each baseline is carried out to determine the optimal baseline from Fermilab (arxiv 1311:0212)

Tuned NuMI focusing



Exposure needed

($\sin^2\theta_{23} = 0.39, \sin^2 2\theta_{13} = 0.09$)



A 1300km baseline is optimal for CP violation, resolution of δ_{cp}, independent measurement of θ_{13}.
1300km is sufficient to resolve the mass hierarchy with a sensitivity of $\geq \Delta\bar{\chi}^2 = 25$ for the *worst case* values of $\sin^2\theta_{23}, \delta_{CP}$

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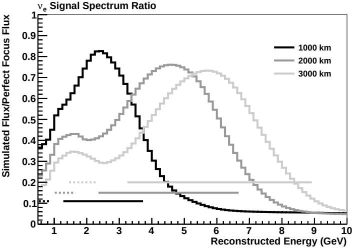

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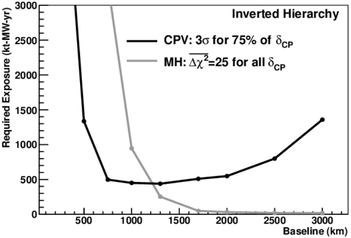

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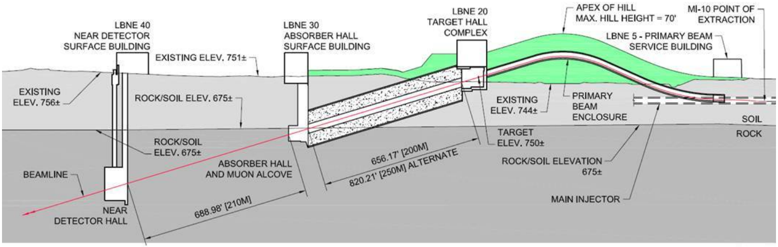
The LBNE Beamline

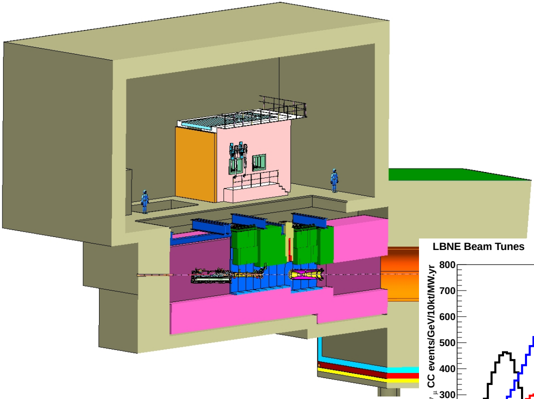
Novel concept beam-on-a-hill reduces cost.

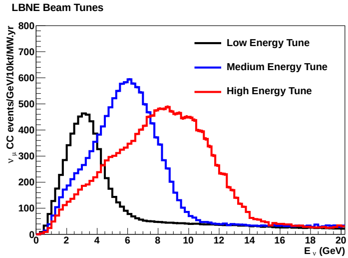


Primary proton beamline: extracts 60-120 GeV designed for 1.2MW upgradable to 2.3MW
Targetry/focusing: uses NuMI horn design now being upgraded to operate at 230 kA, updated NuMI graphite target design partially inserted into first horn. New Be target design under consideration
Decay pipe: 4m in diameter, 200-250m in length, Helium filled. 5.5m thick shielding using geo-membrane..

The LBNE Beamline

Advanced conceptual design of target chase using upgraded tunable NuMI targetry/focusing:

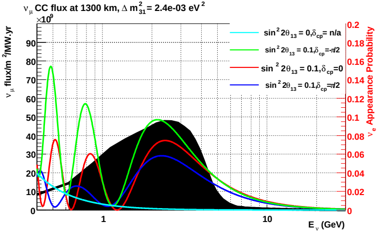




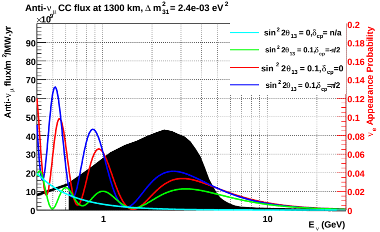
The LBNE Beamline

Optimized beam: 80 GeV, Be target 84cm long -25cm from Horn 1, NuMI horns 230kA, 6.6m apart, 6m* x 250m He filled DP:

Forward horn current



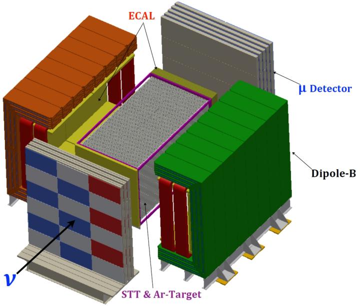
Reverse horn current



Experiment *details*	Baseline km	ν_μ unosc. CC	ν_μ osc. CC	ν_e beam CC	ν_μ NC	$\nu_\mu \to \nu_\tau$ CC	$\nu_\mu \to \nu_e$ CC $\delta_{CP} = -\frac{\pi}{2}$,	0,	$\frac{\pi}{2}$
LBNE LE	1,300								
80 GeV, 1.2 MW									
1.5 × 10²¹ POT/year									
50 kt · year ν		12721	4339	108	3348	156	605	480	350
50 kt · year $\bar{\nu}$		4248	1392	34	1502	48	51	86	106
LBNE ME	1,300								
120 GeV, 1.2 MW									
1 × 10²¹ POT/year									
50 kt · year ν		19613	12317	72	5808	686	435	399	293

* **Negligible difference with 4m diameter (~ 2% increase in LE flux).**

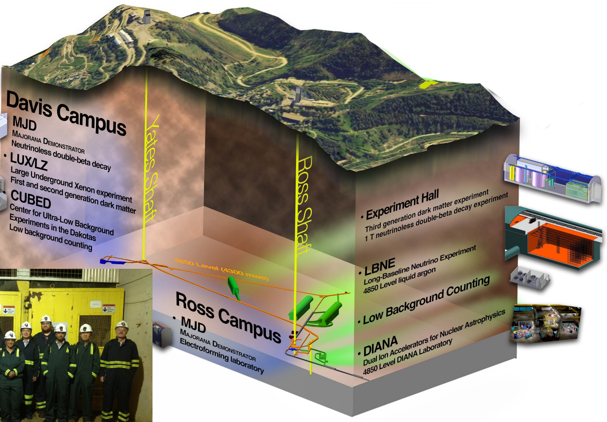
The Near Detector



Performance Metric	Value
Vertex resolution	0.1 mm
Angular resolution	2 mrad
E_e resolution	5%
E_μ resolution	5%
$\nu_\mu/\overline{\nu}_\mu$ ID	Yes
$\nu_e/\overline{\nu}_e$ ID	Yes
$NC\pi^0/CCe$ rejection	0.1%
$NC\gamma/CCe$ rejection	0.2%
$NC\mu/CCe$ rejection	0.01%

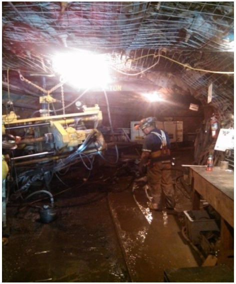
Parameter	Value
STT detector volume	$3 \times 3 \times 7.04$ m^3
STT detector mass	8 tons
Number of straws in STT	123,904
Inner magnetic volume	$4.5 \times 4.5 \times 8.0$ m^3
Targets	1.27-cm thick argon ($\sim$ 50 kg), water and others
Transition radiation radiators	2.5 cm thick
ECAL X_0	10 barrel, 10 backward, 18 forward
Number of scintillator bars in ECAL	32,320
Dipole magnet	2.4-MW power; 60-cm steel thickness
Magnetic field and uniformity	0.4 T; < 2% variation over inner volume
MuID configuration	32 RPC planes interspersed between 20-cm thick layers of steel

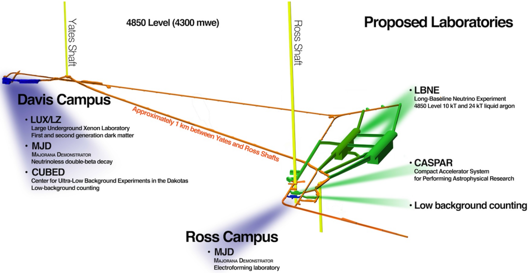
The Sanford Underground Research Facility



Experimental facility operated by the state of South Dakota. LUX (dark matter) and Majorana ($0\nu2\beta$) demonstrator operational expts at 4850-ft level. Chosen as site of G2 dark matter experiment

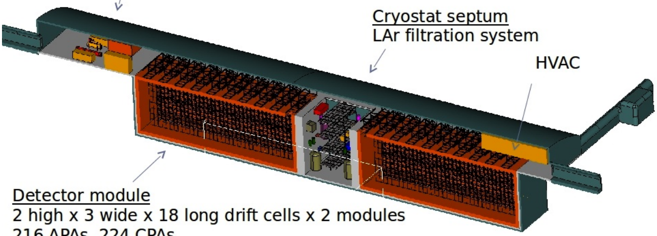
LBNE Underground Site Investigation Status





Preliminary underground site investigation of possible cavern locations at the Ross Campus with sizes up to 70 kton is now complete. Cavern design is ready to proceed *based on the final detector design agreed upon by the reformulated collaboration*.

The Far Detector: 34kton single-phase LArTPC

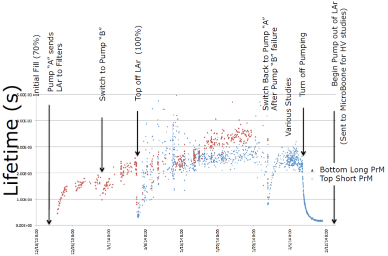


Parameter	Value
Total/Active/Fiducial Mass	50/40/34 kt
Number of Detector Modules (Cryostats)	2
Drift Cell Configuration within Module	3 wide × 2 high × 18 long drift cells
Drift Cell Dimensions	2 × 3.7 m wide (drift) × 7 m high × 2.5 m long
Detector Module Dimensions	22.4 m wide × 14 m high × 45.6 m long
Anode Wire Spacing	~5 mm
Wire Planes (Orientation from vertical)	Grid (0°), Induction 1 (45°), Induction 2 (-45°) Collection (0°)
Drift Electric Field	500 V/cm
Maximum Drift Time	2.3 ms

Final LArTPC design TBD by LBNF collaboration

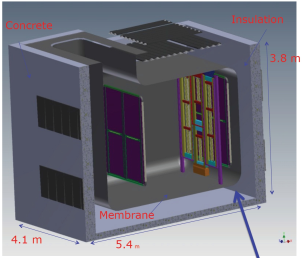
35-ton Prototype Detector

Phase I

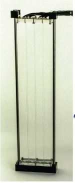


Liquid recirculation purification

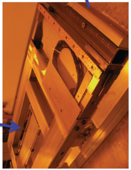
Phase II



The 35-ton LarTPC Prototype

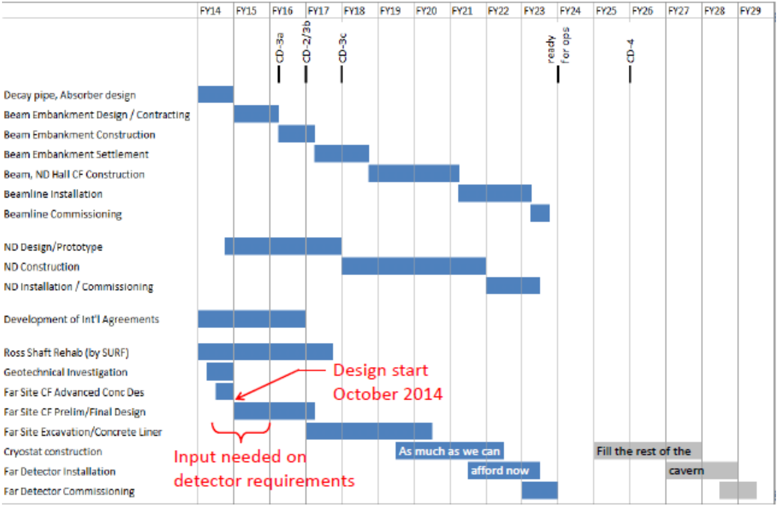


One (of 4) photon detector designs to be tested (CSU, IU, LBNL, LSU)



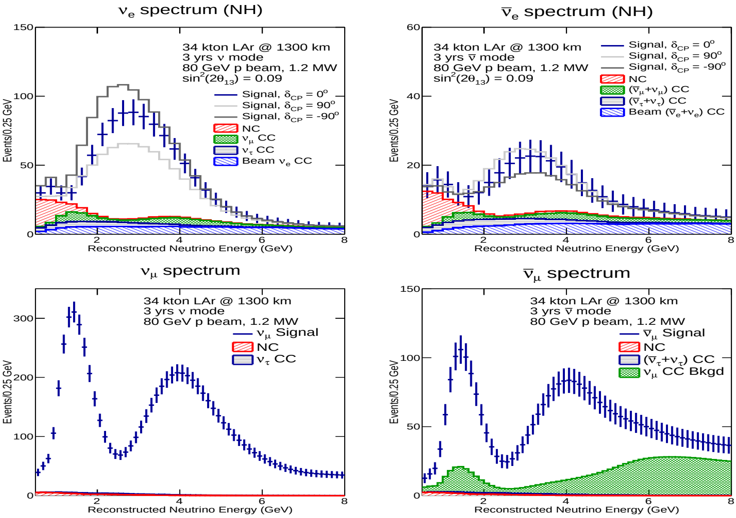
First (of 4) TPC planes - Apr 2014 (PSL at U. Wisc)

Technically Driven Schedule for International LBNE



Oscillation signals

Exposure: 34 kton, 3 ν + 3 $\bar{\nu}$ MW.yrs. 1MW.yr = 1×10^{21} p.o.t at 120 GeV. ($\sin^2 2\theta_{13} = 0.094$, $\sin^2 \theta_{23} = 0.39$, $\delta m^2_{31} = 2.47 \times 10^{-3}$ eV^2)



Simultaneous fit to all four samples to determine osc. params

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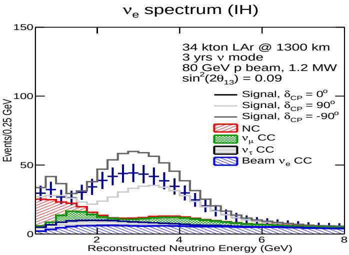

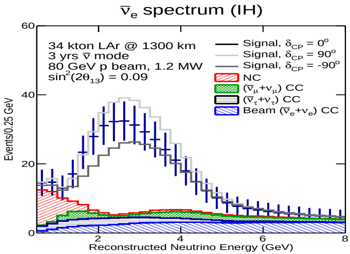

Event rates per 10 kton 3 MW.yr

Beam	Hierarchy	Signal Events	Background Events				
		$\nu_x/\bar{\nu}_x$ CC	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC	Total
$\nu_\mu \to \nu_{x=\mu}$ (disappearance)							
Neutrino	-	2056/96	23	N/A	-	18	41
Antineutrino	-	280/655	10	N/A	-	10	20
$\nu_\mu \to \nu_{x=e}$ (appearance)							
Neutrino	Normal	229/3	21	25	47	14	107
Neutrino	Inverted	101/5	21	25	49	17	112
Antineutrino	Normal	15/41	11	11	24	9	55
Antineutrino	Inverted	7/75	11	11	24	9	55

Current LBNE Systematics Estimates (see X. Tian WG2 presentation on 25/8)

Source of Uncertainty	MINOS Absolute/ν_e	T2K ν_e	LBNE ν_e	Comments
Beam Flux after N/F extrapolation	3%/0.3%	2.9%	2%	MINOS is normalization only. LBNE normalization and shape highly correlated between ν_μ/ν_e.
Detector effects				
Energy scale (ν_μ)	7%/3.5%	included above	(2%)	Included in LBNE ν_μ sample uncertainty only in three-flavor fit. MINOS dominated by hadronic scale.
Absolute energy scale (ν_e)	5.7%/2.7%	3.4% includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%/2.4%	1%	1%	Larger detectors = smaller uncertainty.
Neutrino interaction modeling				
Simulation includes: hadronization cross sections nuclear models	2.7%/2.7%	7.5%	$\sim$ 2%	Hadronization models are better constrained in the LBNE LArTPC. N/F cancellation larger in MINOS/LBNE. X-section uncertainties larger at T2K energies. Spectral analysis in LBNE provides extra constraint.
Total	**5.7%**	**8.8%**	**3.6 %**	**Uncorrelated ν_e uncertainty in full LBNE three-flavor fit = 1-2%.**

In combined fit, many correlated systematics cancel. Assume independent *uncorrelated* normalization systematics of 5%/10% on ν_μ sig/bkgd and 1-2%/5% on ν_e sig/bkgd.

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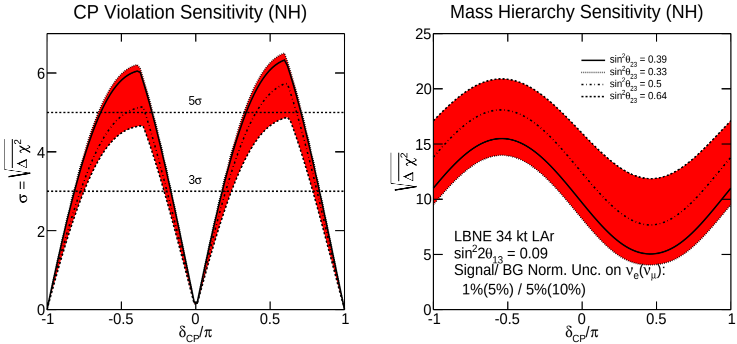
A FastMC has been developed to enable the estimation of detailed neutrino interaction and beam flux shape and normalization systematics. Studies are ongoing.

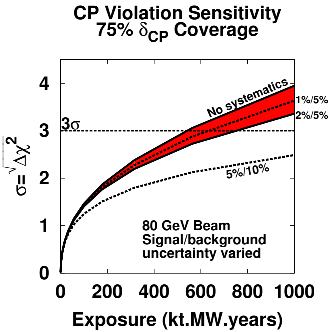
MH and CPV Sensitivities

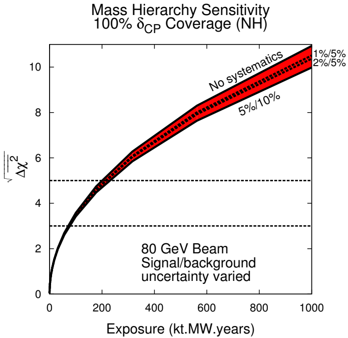


In LBNE with a 34-kton LArTPC operating for six years in a 1.2-MW beam ($\sin^2\theta_{23} = 0.39, \sin^2 2\theta_{13} = 0.09$):

- **The CPV sensitivity is $\geq 3, 5\sigma$ for 60%,35% of $\delta_{\rm CP}$.**
- **At the *worst sensitivity point* the MH $|\Delta\chi^2|$ value obtained in a typical data set will exceed 25, allowing LBNE on its own to rule out the incorrect mass ordering at a confidence level above $1 - 3.7 \times 10^{-6}$.**

Sensitivities with varying ν_e uncorrelated systematics

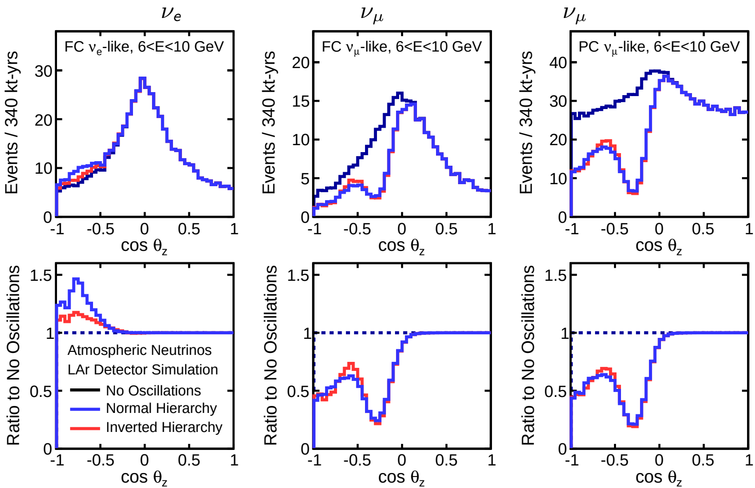




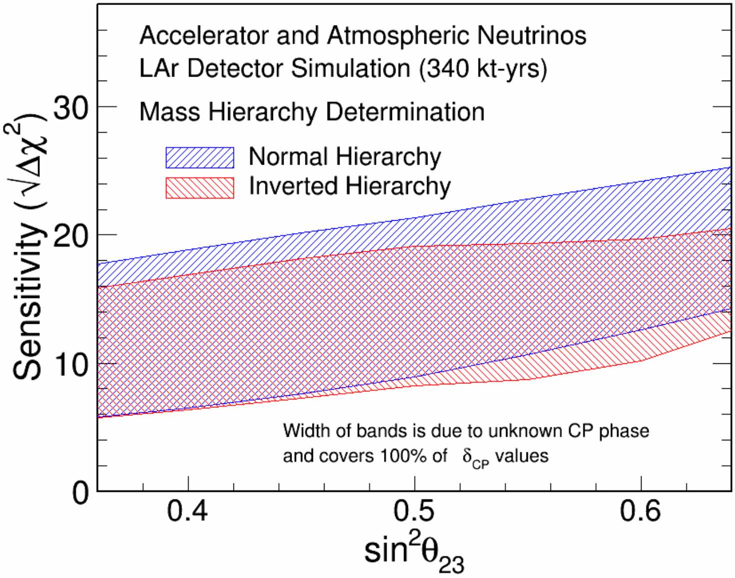
Systematic uncertainty	CPV Sensitivity δ_{CP} Fraction	$(\sqrt{\Delta\chi^2})$	Required Exposure
0 (statistical only)	50% δ_{CP}	3 σ	100 kt · MW · year
	50% δ_{CP}	5 σ	400 kt · MW · year
1%/5% (Sig/bkgd)	50% δ_{CP}	3 σ	100 kt · MW · year
	50% δ_{CP}	5 σ	450 kt · MW · year
2%/5% (Sig/bkgd)	50% δ_{CP}	3 σ	120 kt · MW · year
	50% δ_{CP}	5 σ	500 kt · MW · year
5%/10% (no near ν det.)	50% δ_{CP}	3 σ	200 kt · MW · year

MH with Atmospheric Neutrinos

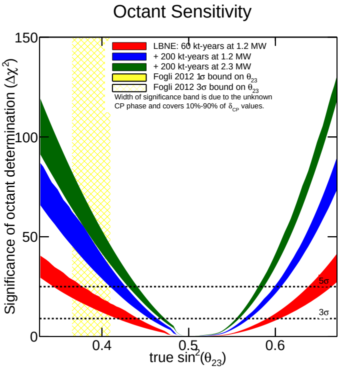
Spectra of fully contained (FC) and partially contained (PC) atmospheric $\nu_{\mu,e}$ ($6 < E_\nu < 10$ GeV) in a 34-kton LArTPC after 10 yrs.

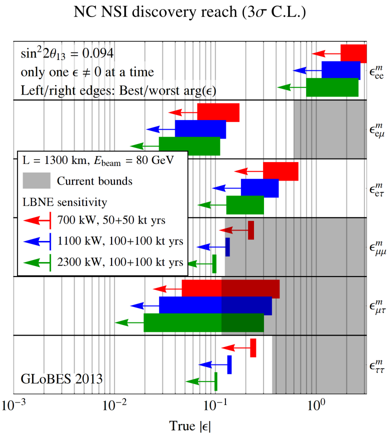


MH with Atmospheric Neutrinos



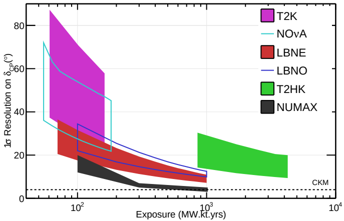
Octant and NSI



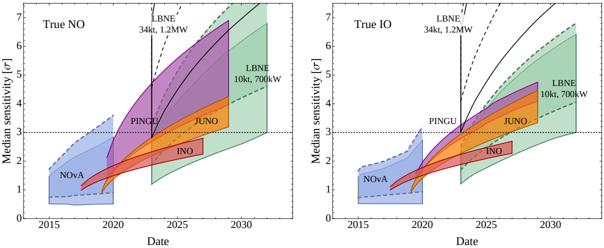


Comparison with other Experiments

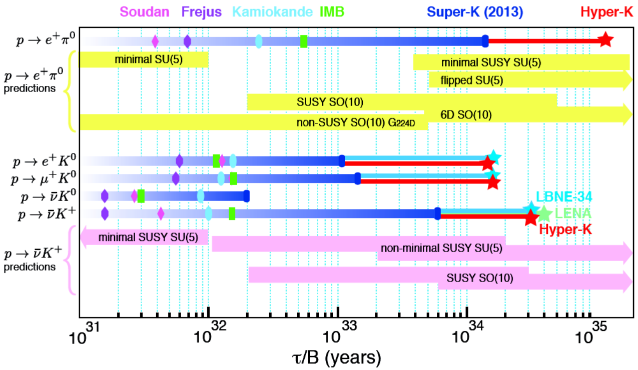
LBNE estimate of δ_{cp} resolution from public information:



Independent study of MH sensitivities: M. Blennow *et. al.* arxiv:1300.1822



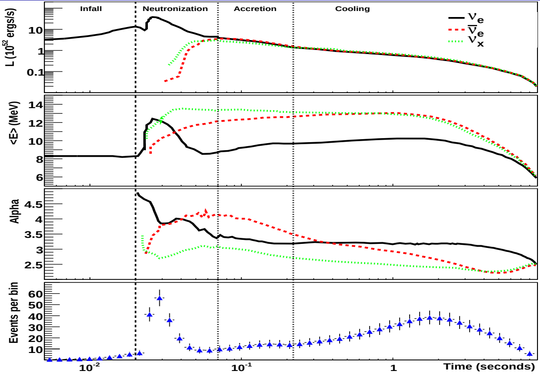
Proton Decay Sensitivities



Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8

LAr detectors are best for detecting proton decay modes with kaons in the final state.

Core-Collapse Supernova Signal



Event rates in a 34-kt LArTPC (10kpc):

Channel	Events *Livermore* model	Events *GKVM* model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2308	2848
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	2794	3160

LAr detectors are sensitive to the ν_e component of the core-collapse SN flux the primary component of the initial neutronization pulse.

LBNE Status Summary

- **The LBNE concept has developed over a decade, with extensive studies of site, technology, physics capabilities.**
- **P5 has endorsed the LBNE vision both in 2008 and 2014!**
- **A large, diverse international collaboration has developed and is continuing to expand.**
- **Designs are being developed incorporating ideas of all partners.** *Input from additional partners is welcome.*

The transmogrification of LBNE to LBNF is being conjured up. Process will become clearer in the coming months.