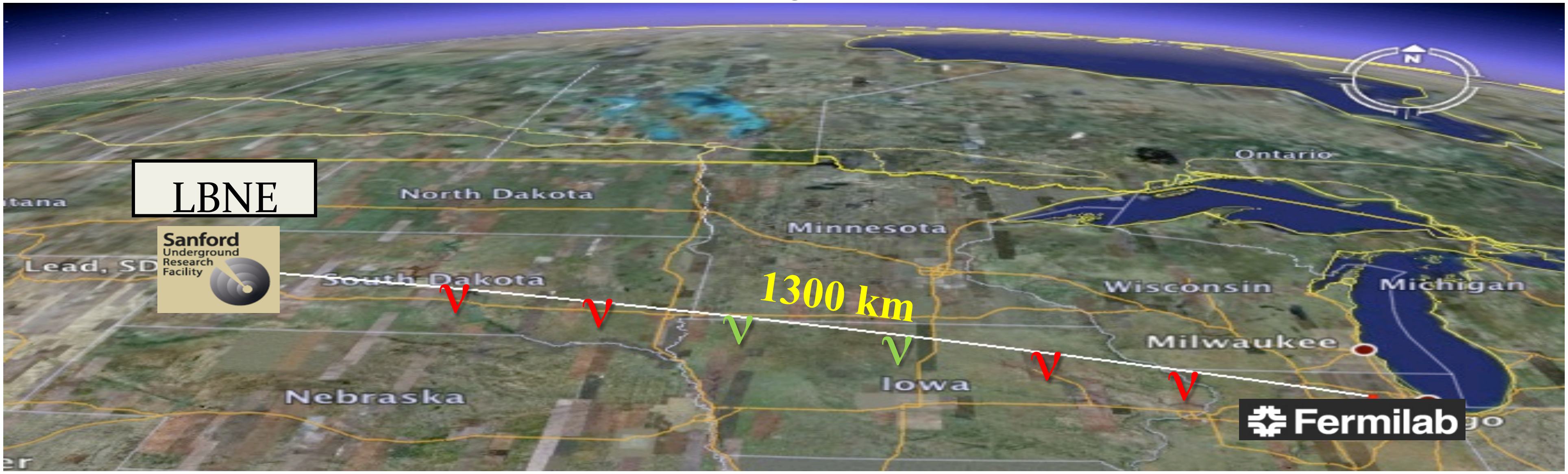
The **L**ong-**B**aseline **N**eutrino **E**xperiment Project

LBNE: Status and Outlook

Jon Urheim, Indiana University,
Representing the LBNE Collaboration

LBNE Information session
Friday 08:30 Rm 542

16th Lomonosov Conference
22 August 2013



Outline

- Scientific Motivation
- LBNE is…
  - Technical Summary
  - Science Collaboration
- Staging the Experiment
  - Background
  - Goal for initial phase
- Oscillation Parameter Sensitivities
  - With a 10 kt Liquid Argon TPC Far Detector (LBNE10)
  - With the full LBNE and with Project X
- LBNE Beam and Far Detector
- Project Status
- Underground Science
  - Proton Decay
  - Super Nova Burst Neutrinos
  - Atmospheric Neutrinos
- Near Detector Physics

Acknowledgements:
- M. Diwan
- J. Strait
- R. Wilson
- M. Bishai
- LBNE Physics Analysis Group
- LBNE Scientists, Engineers & Tech

Assumptions for this Talk

- Assuming this audience knows well already the phenomenology of neutrino oscillations, considering 3-flavor mixing, namely:
  - given observed disappearance of ν_e's from the sun (& to KamLand from distant reactors), controlled by θ_{12} and Δm^2_{sol}, and
  - given observed disappearance of atmospheric and beam ν_μ's, (nominally, osc'ns to ν_τ), controlled by by θ_{23} and Δm^2_{atm},
  - a subdominant $\nu_\mu \rightarrow \nu_e$ oscillation should exist at the Δm^2_{atm} scale, controlled by θ_{13}, and affected by matter effects with a sign that depends on the (unknown) mass hierarchy, and by the unknown CP-odd phase δ, where interference effects can lead to CP asymmetries
- Assuming this audience knows well the basic principle of operation of the LArTPC detector technique. (see talks by Erditato & Varanini)

Scientific Motivation fo


Scientific Opportunities with the Long-Baseline Neutrino Experiment

July 30, 2013

The LBNE Collaboration

arXiv:1307.7335v1 [hep-ex] 28 Jul 2013

- **CP Violation in neutrino sector**
  - Key ingredient for baryon asymmetry of the universe?
- **Neutrino Mass Hierarchy**
  - With pattern of mixings & Dirac vs. Majorana nature, crit
- **Testing the Three-Flavor Paradigm**
  - Precision measurements of oscillation parameters
  - New physics -> non-standard interactions, sterile neutri
  - Precision neutrino interaction studies (near detector)
- **Observation of Nucleon Decay**
  - Grand Unification
- **Neutrino Astrophysics**
  - Supernova ν burst flux and energy spectrum
- **These science goals have been embraced by US community / DOE**
  - Review panel (P5, NAS etc.) reports over many years have led to priorities for US HEP program: **LBNE recognized as centerpiece of US "intensity frontier" program**

Further details: "Science Opportunities w/ LBNE," arXiv:1307.7335.

LBNE is …

Alabama
Argonne
Boston
Brookhaven
Cambridge
Catania
Columbia
Chicago
Colorado
Colorado State
Columbia
Dakota State
Davis
Drexel
Duke
Duluth
Fermilab
Hawaii
Indian Group
Indiana
Iowa State
Irvine
Kansas State
Kavli/IPMU-Tokyo
Lawrence Berkeley NL
Livermore NL
London UCL
Los Alamos NL
Louisiana State
Maryland
Michigan State
Minnesota
MIT

- 372 members, 61 institutions, 5 countries (April 2013)
- Applications from 16 institutions and >50 members being prepared or submitted
- Co-spokespersons Milind Diwan (BNL), Bob Wilson (CSU)

Fermilab, March 2013

NGA
New Mexico
Northwestern
Notre Dame
Oxford
Pennsylvania
Pittsburgh
Princeton
Rensselaer
Rochester
Sanford Lab
Sheffield
SLAC
South Carolina
South Dakota
South Dakota State
SDSMT
Southern Methodist
Sussex
Syracuse
Tennessee
Texas, Arlington
Texas, Austin
Tufts
UCLA
Virginia Tech
Washington
William and Mary
Wisconsin
Yale

LBNE is…

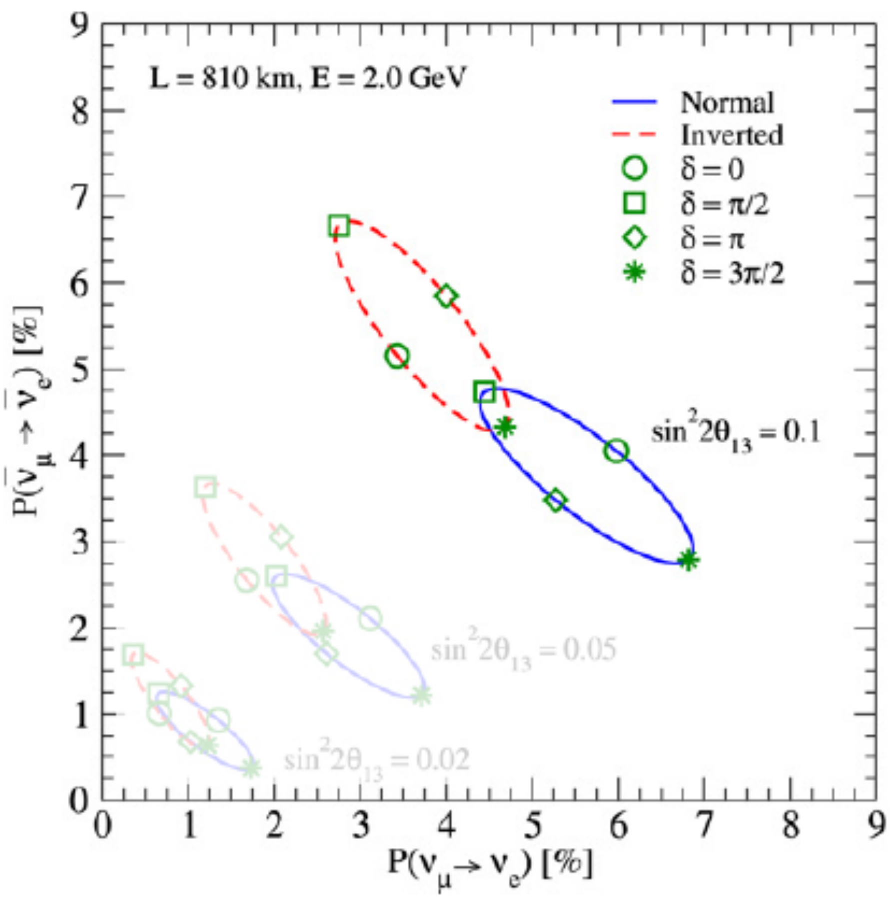
- **A new neutrino beam at Fermilab**
  - 700 kW, 60 – 120 GeV proton beam, 2.3 MW capable beam line
- **A near (neutrino) detector complex on the Fermilab site**
- **A 1300-km baseline: Fermilab to SURF**** – nearly optimal for oscillation physics
- **A 34-kt Liquid Argon TPC, located underground at SURF** (4850' overburden)

- **An optimized-cost/time-effective path to the science**
  - macroscopic θ_{13} means δ_{CP} is accessible
- **The conceptual design for LBNE as defined above…**
  - Completed a successful CD-1 Fermilab Director's Review (March 2012)
  - Has been subject to considerable scrutiny for cost and schedule
  - Estimated cost (July 2012): ~ US**$ 1.5 B** (incl. contingency & escalation)

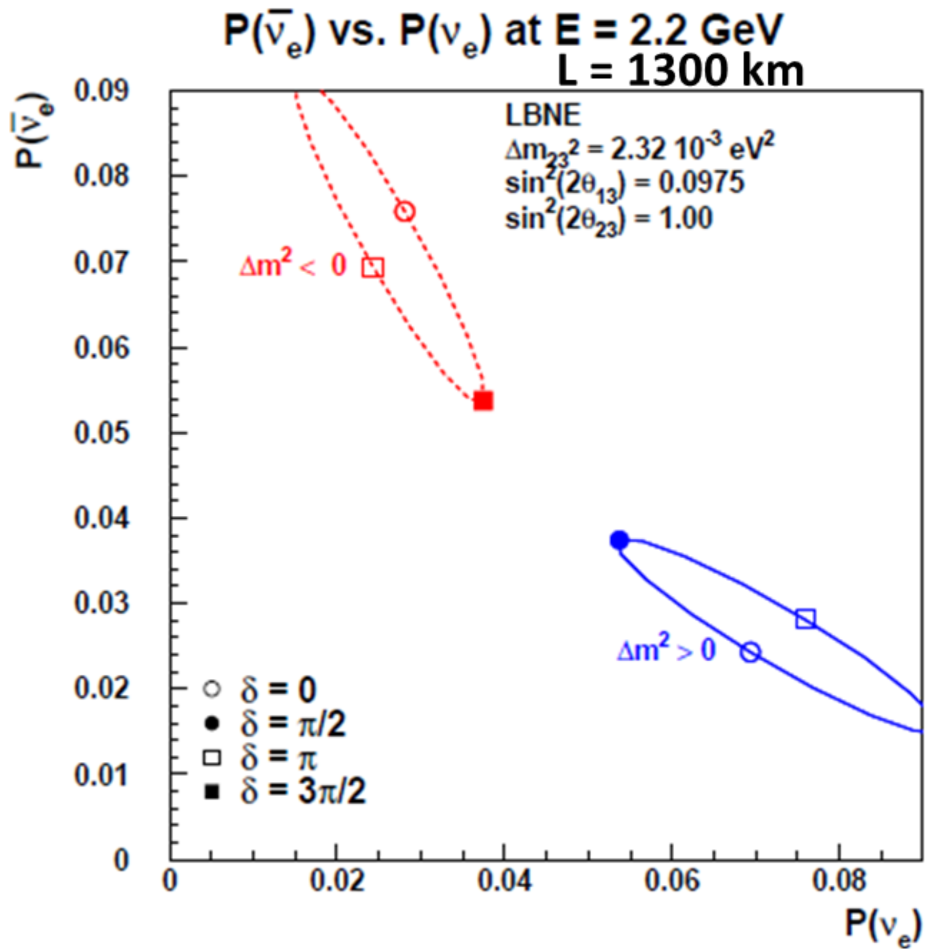
**SURF = Sanford Underground Research Facility (formerly known as DUSEL) @ Homestake Mine, Lead SD

LBNE CPV Principle of Operation

NOvA Baseline 810 km



LBNE Baseline 1300 km

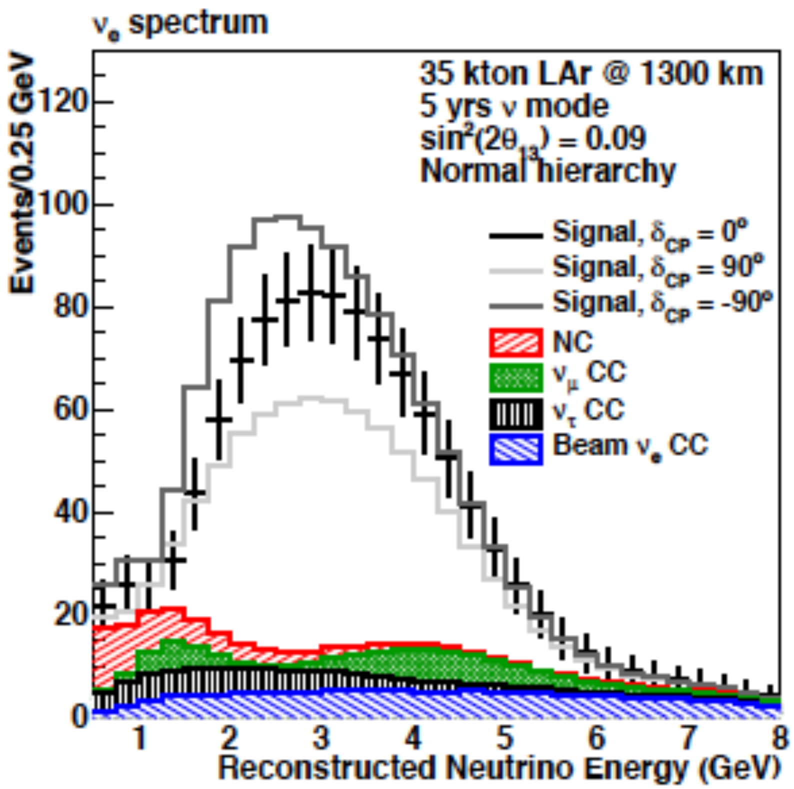


LBNE CPV Principle of Operation

L. Whitehead

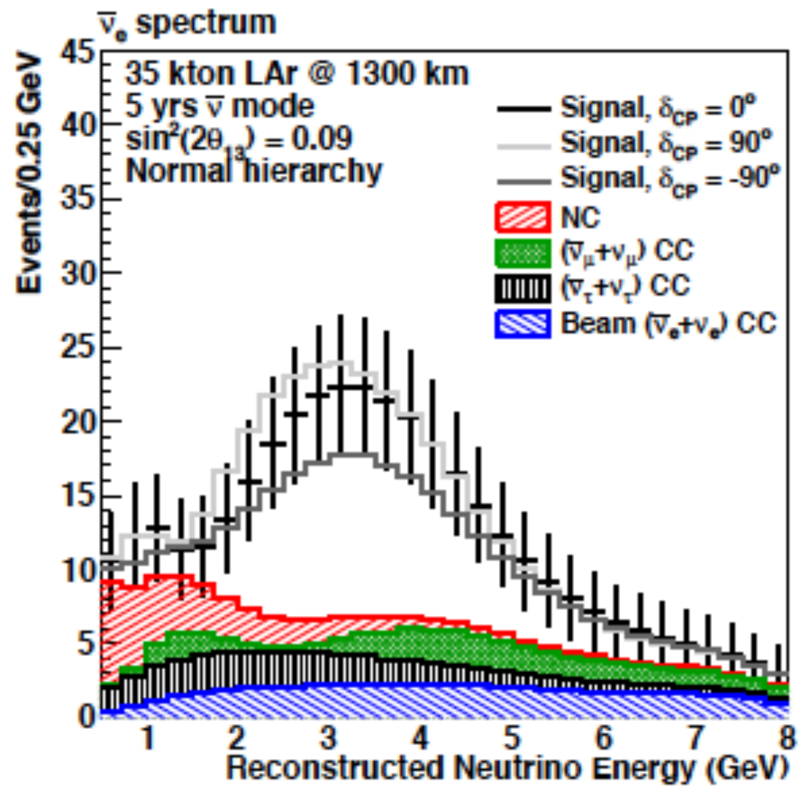
For illustration showing only the Normal Hierarchy case

ν (5 yrs @ 700 kW)



750 evts (330 IH)

$\bar{\nu}$ (5 yrs @ 700 kW)

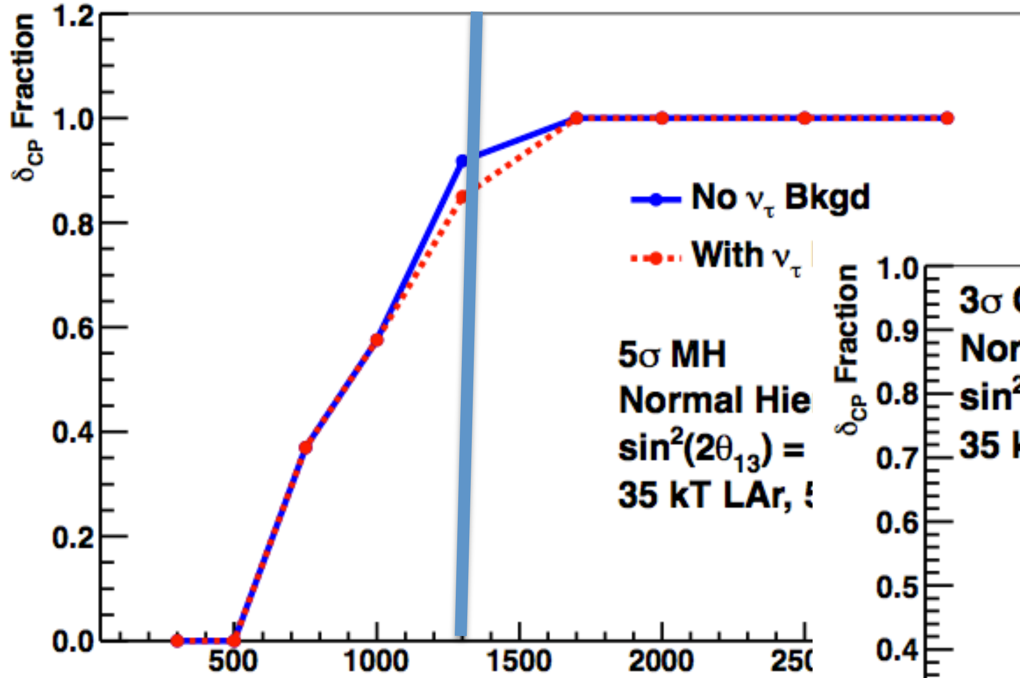


180 evts (272 IH)

Choice of Far Detector Site / Baseline

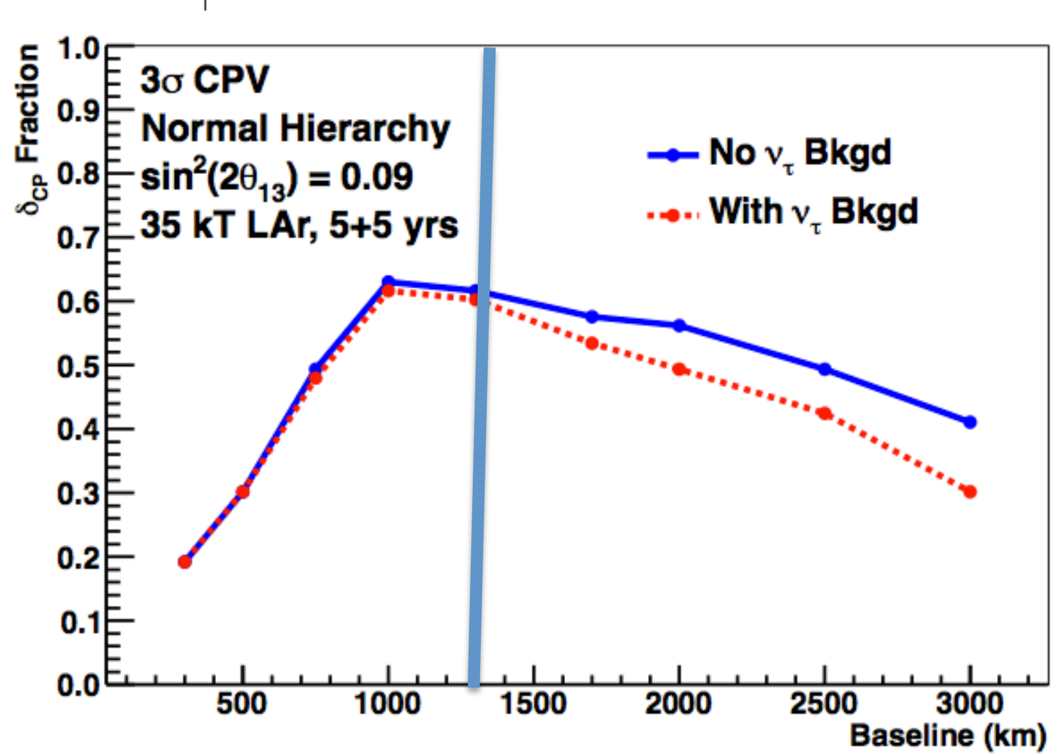
M. Bishai

Mass Hierarchy Sensitivity at > 5σ



1300 km

CPV Sensitivity at > 3σ



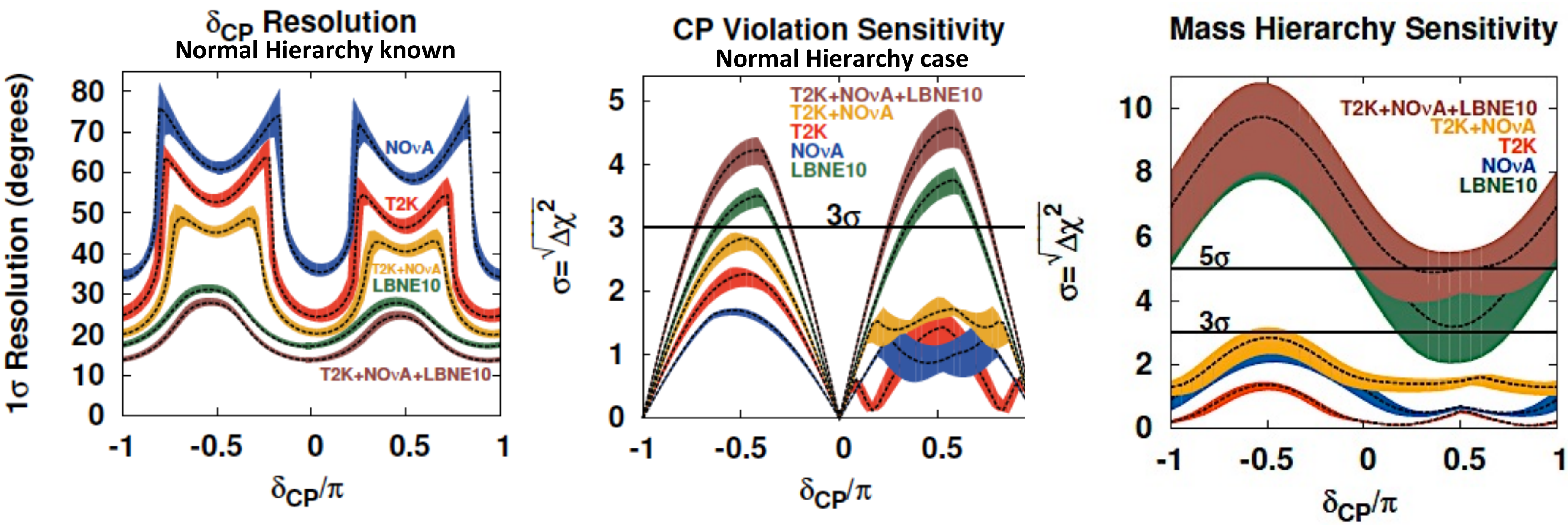
Staging the Experiment

- March 2012 DOE asked us to stage LBNE construction; an external review panel considered reconfiguration options including different far sites (including existing MINOS and NOvA sites)
  - We accepted the recommendation to proceed with emphasis on the most important aspects: 1300 km baseline, a site with infrastructure to support a massive underground detector (at SURF) and a full capability beam
- December 2012: CD-1 approval for $867M first phase DOE funding
  - We have completed an extensive cost/schedule for 10 kt LAr far detector (LBNE10) on the surface but the design is **not** fixed
  - ***CD-1 approval explicitly allows for scope change enabled by new partners with additional resources***
- **First phase goal:** *greater than 10 kt* far detector *underground* and a *full capability near detector*
- There is progress towards international partnerships

Even **LBNE10** would be a **Major Advance…**

PRELIMINARY Sensitivity Metrics

M. Bass



Bands: 1σ variations of θ_{13}, θ_{23}, Δm_{31}^2 (Fogli et al. arXiv:1205.5254v3)

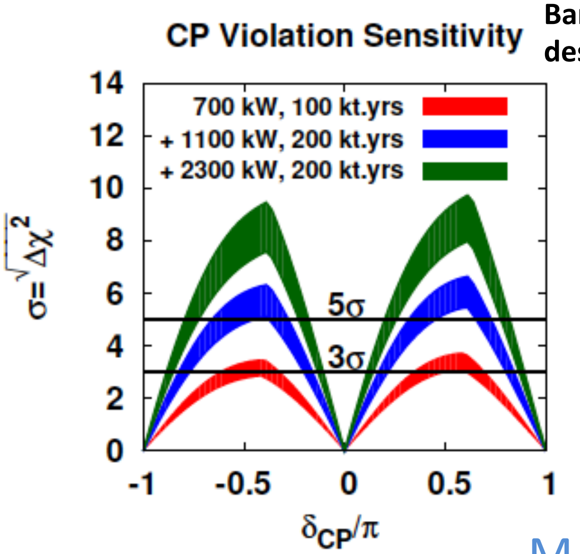
T2K 750 kW x 5 yr ν

NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$)

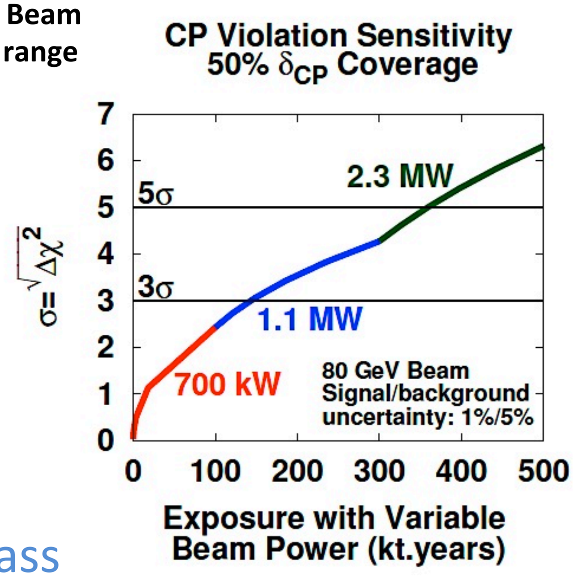
LBNE10 (80 GeV*) 700 kW x (5 yr ν + 5 yr $\bar{\nu}$)

… and it would lay the groundwork for …

Full LBNE + Project X = **Fully-Awesome**



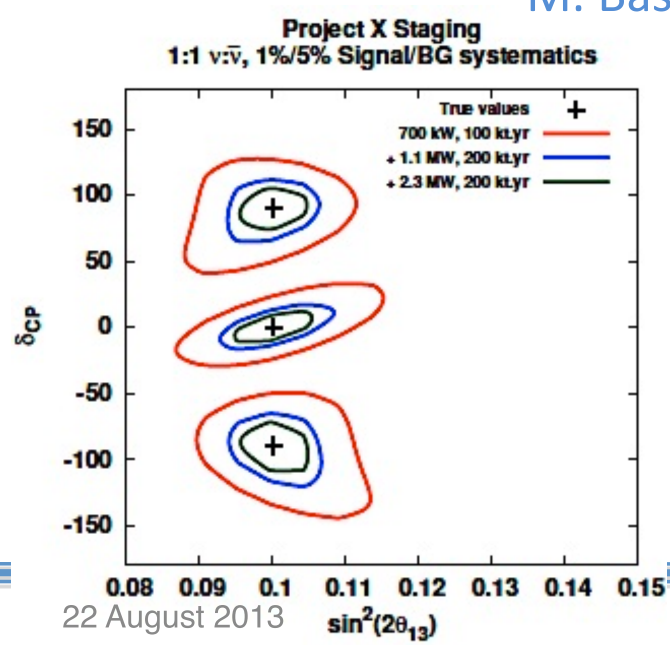
Bands: Beam design range

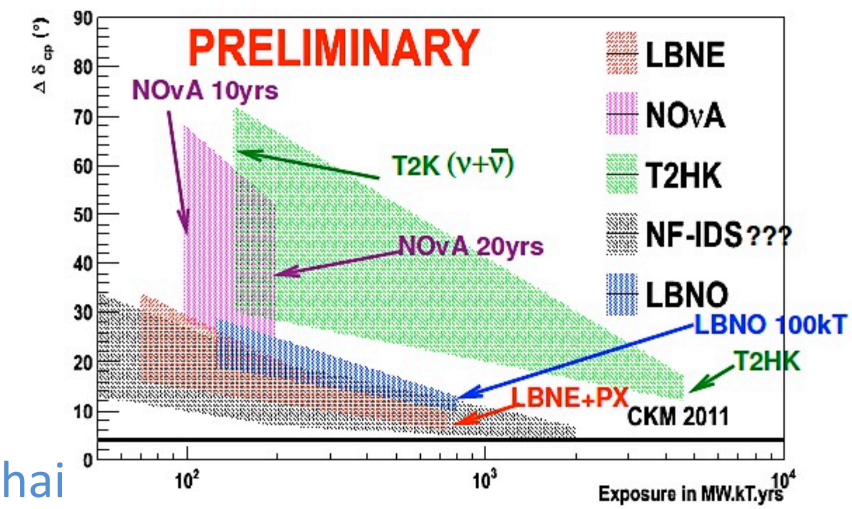


M. Bass

PRELIMINARY

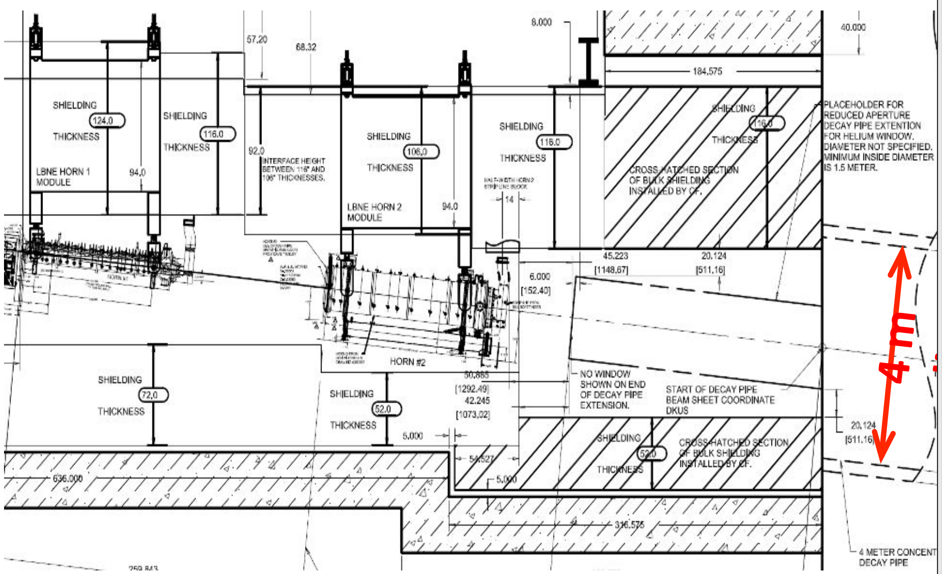
Sensitivity Metrics



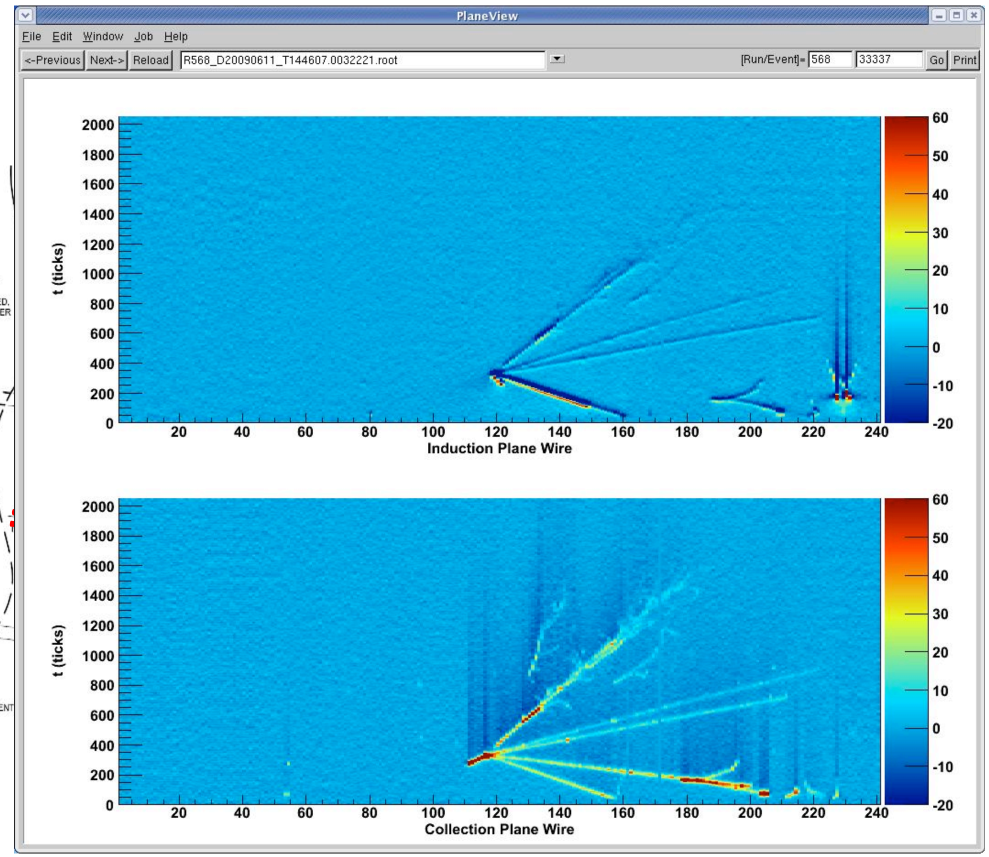


M. Bishai

LBNE Beam and Far Detector



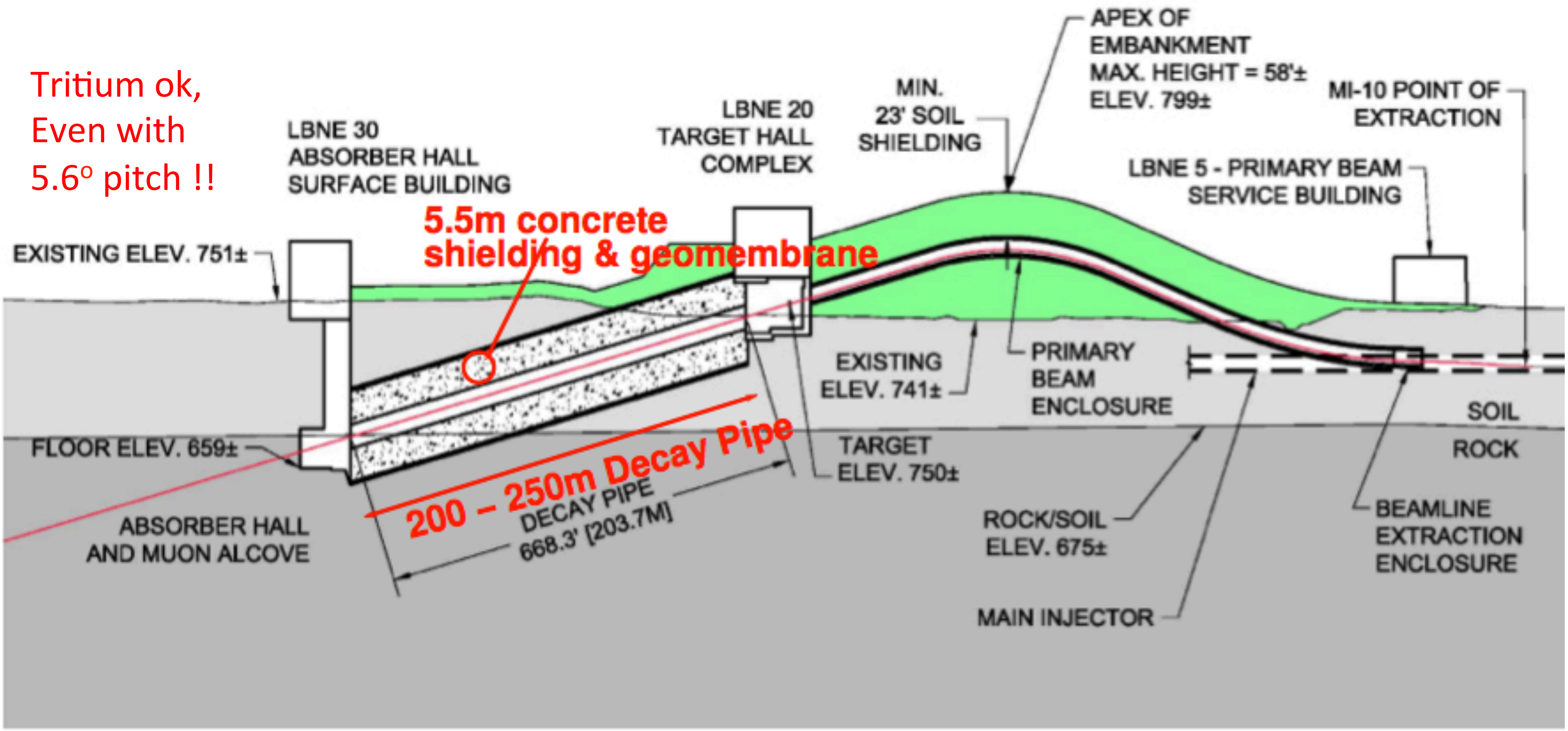
Target Hall, horns, decay pipe



NuMI neutrino event in ArgoNeuT

LBNE Beam Line

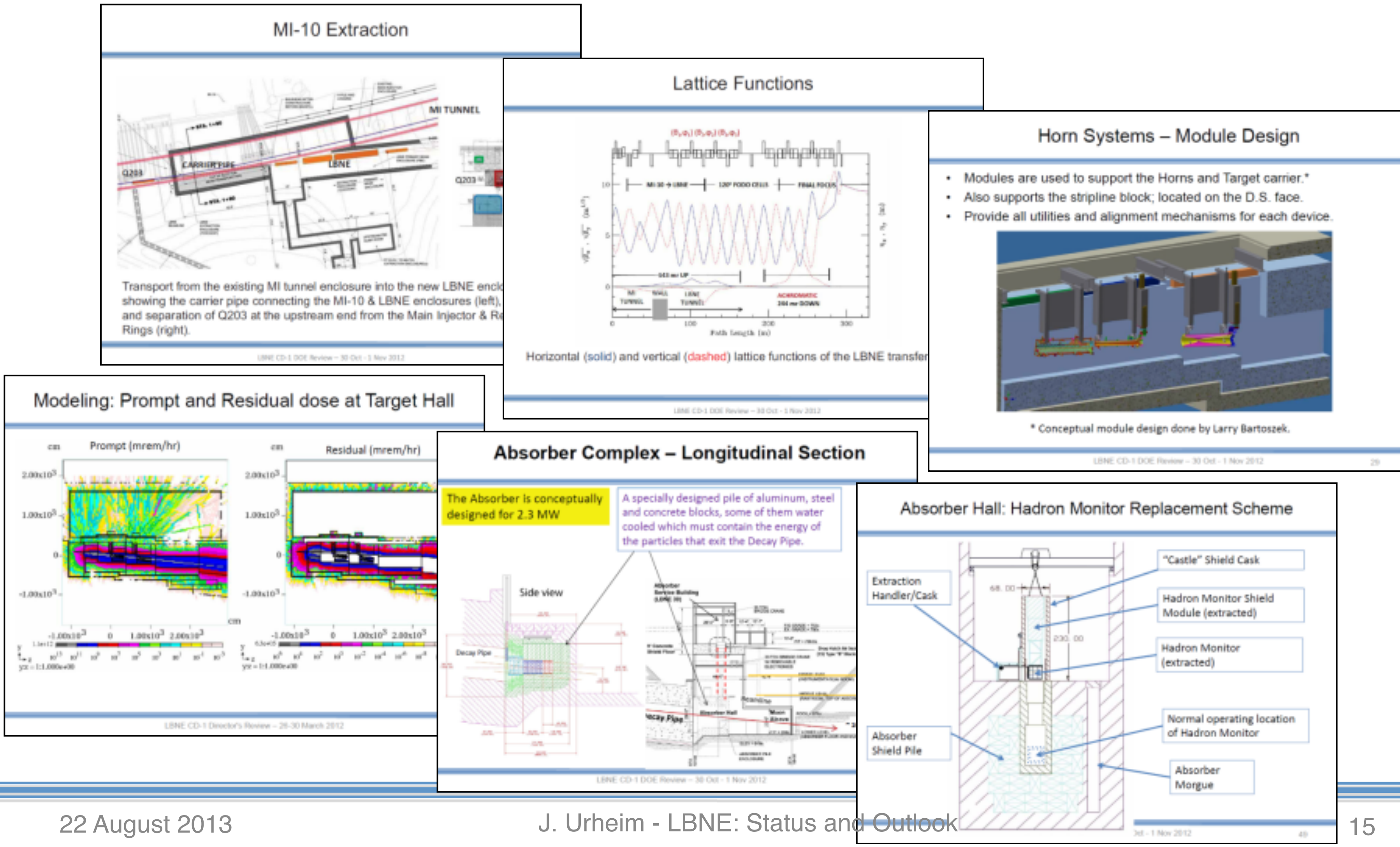
Novel 'beam-on-a-hill' layout, designed for 60-120 GeV @ 2.3 MW



Cost (CD-1): ~ 390M in AY$, incl. conv. facilities & 30% contingency

LBNE Neutrino Beam at Fermilab
700 kW operation, upgradeable to 2.3 MW

Slide courtesy J. Strait



Highly-Capable Near Detector System on the Fermilab Site

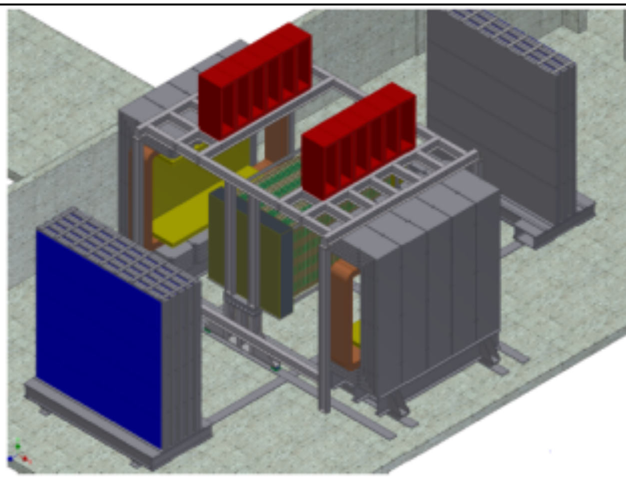
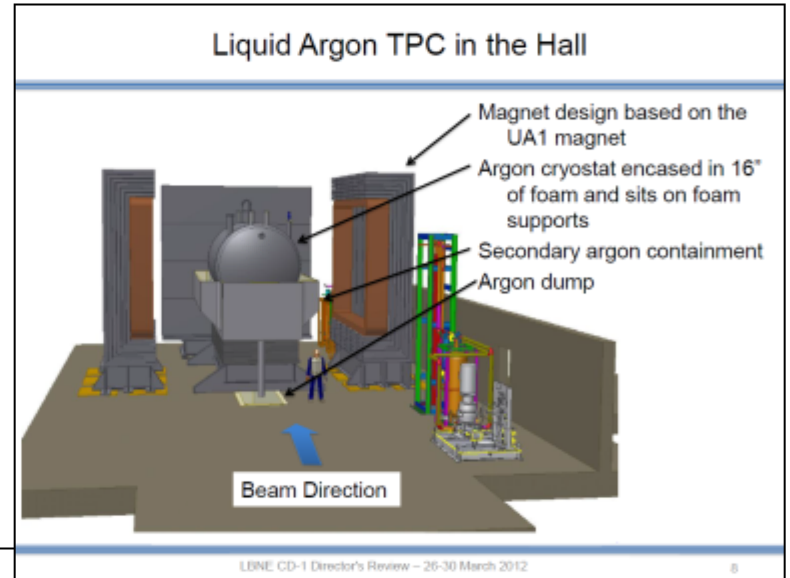


Figure 4–19: Schematic drawing of the FGT in the Near Detector Hall with the magnet opened up to show the STT, ECAL, and MuID



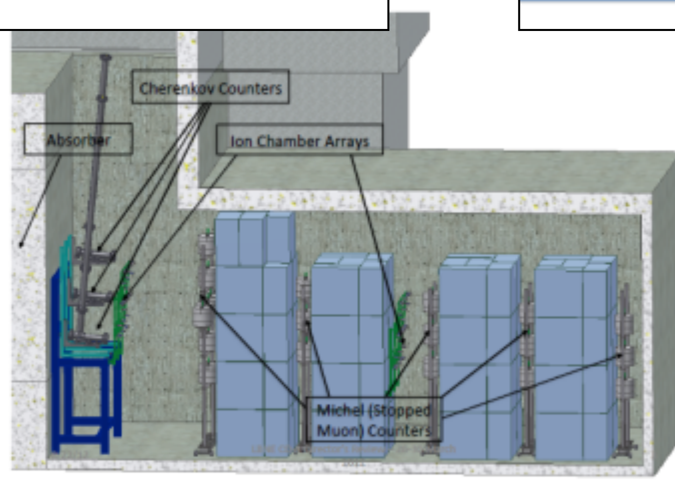
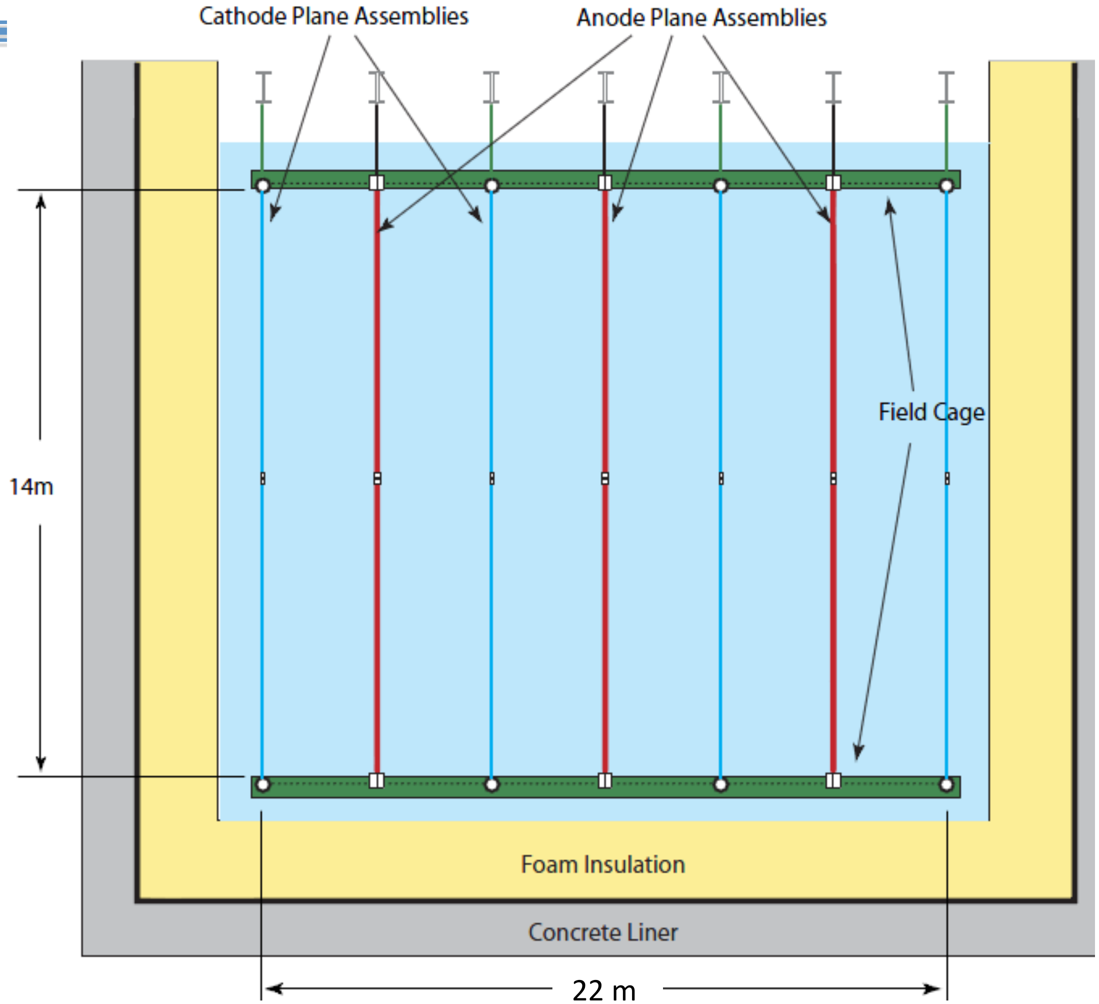


Figure 1–4: A model of the three muon monitor systems placed downstream of the absorber, in the muon alcove.

LBNE LArTPC Design Considerations

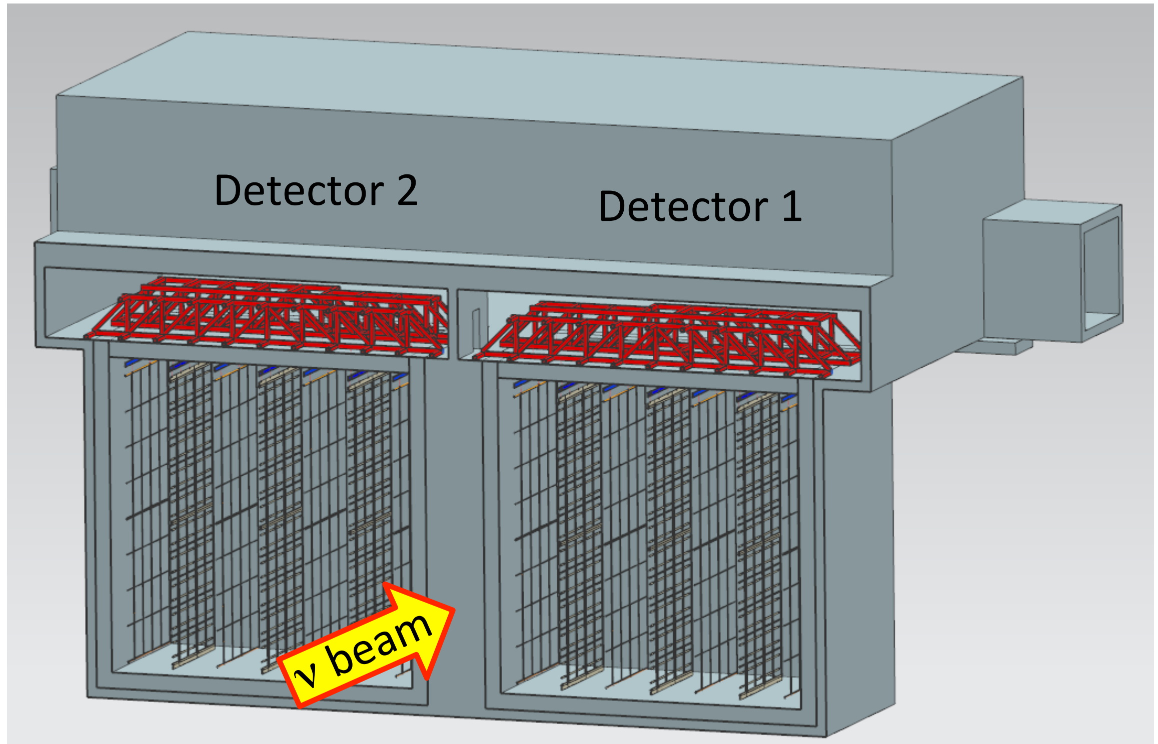
- Key Guidelines
  - Scalable
  - Components transportable via road / shaft access
  - Fully active
  - Scalable
  - Large continuous LAr volume (better volume / surface area)
  - Inexpensive construction
  - Reliable mechanical structure
  - **and Scalable !**



17-kt "module" (1 of 2) for 34-kt full LBNE
Alternating Anode and Cathode Planes
2 x 7m high; 18 x 2.5m long; 6 x 3.7 m wide cells

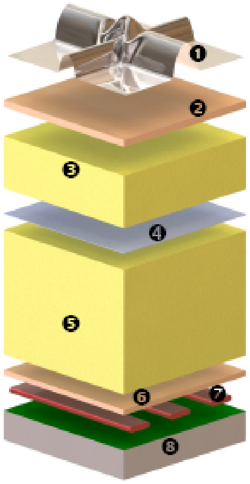
"LBNE10" Liquid Argon TPC Far Detector

- Key Features:
  - 13 kt (active) / 10 kt (fiducial)
  - Two modules (cryostats)
  - "Membrane" style cryostat w/ passive insulation
  - Modular TPC: Anode wire plane assemblies (APA's) and cathode plane assemblies (CPA's) hung from rails along cryostat roof.
  - Submerged CMOS electronics mounted on APA frames
  - Scintillation photon detectors
  - **FULL LBNE Far Detector is just a scaled-up version of this !!**

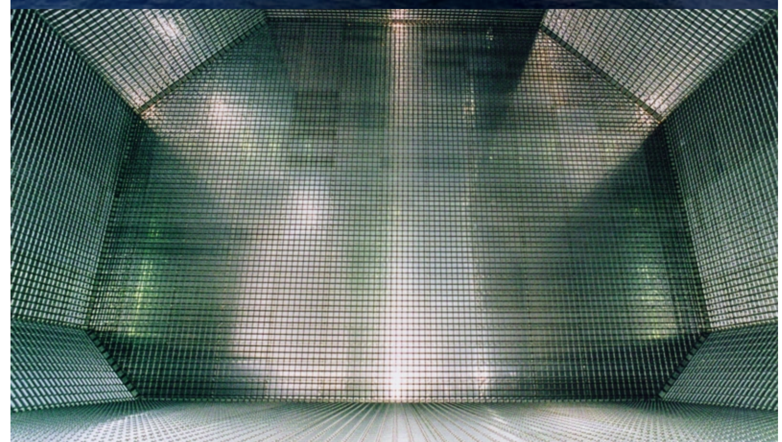


Alternating Anode and Cathode Planes
2.3 m drift

Membrane Cryostat Technology

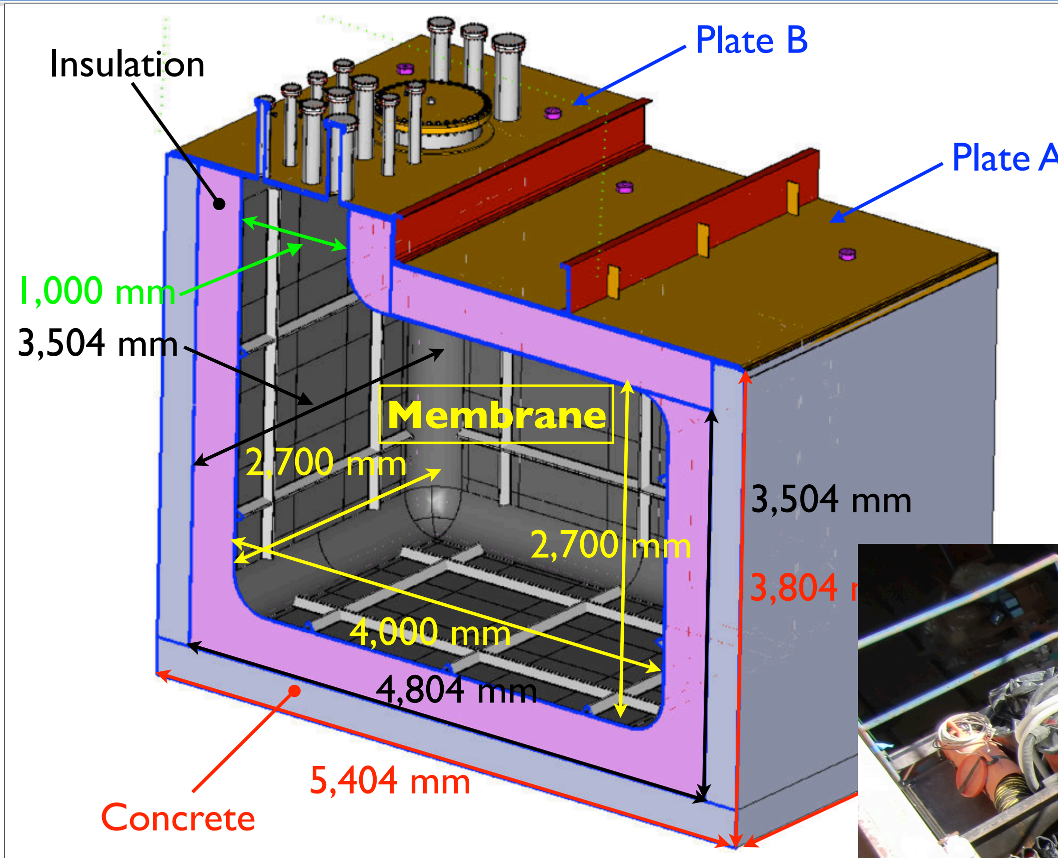


1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Concrete covered with moisture barrier



Below: 35t prototype: SS membrane vessel constructed at FNAL, Fall 2012

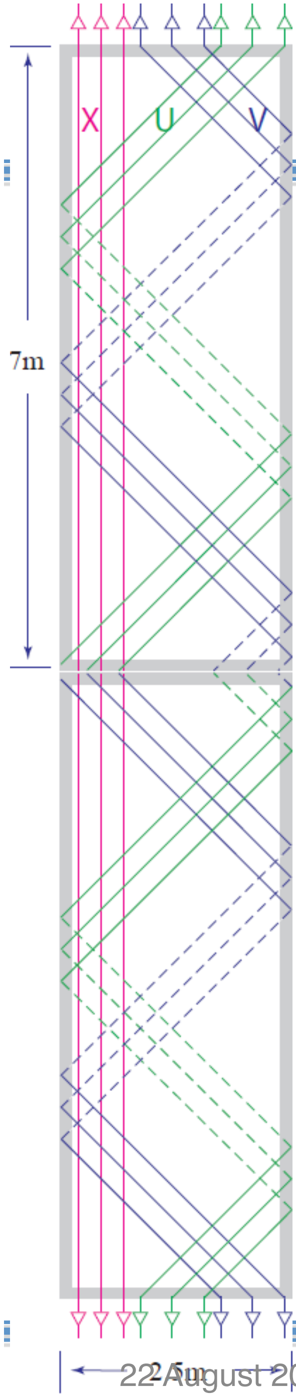
LBNE 35-ton Prototype Membrane Cryostat



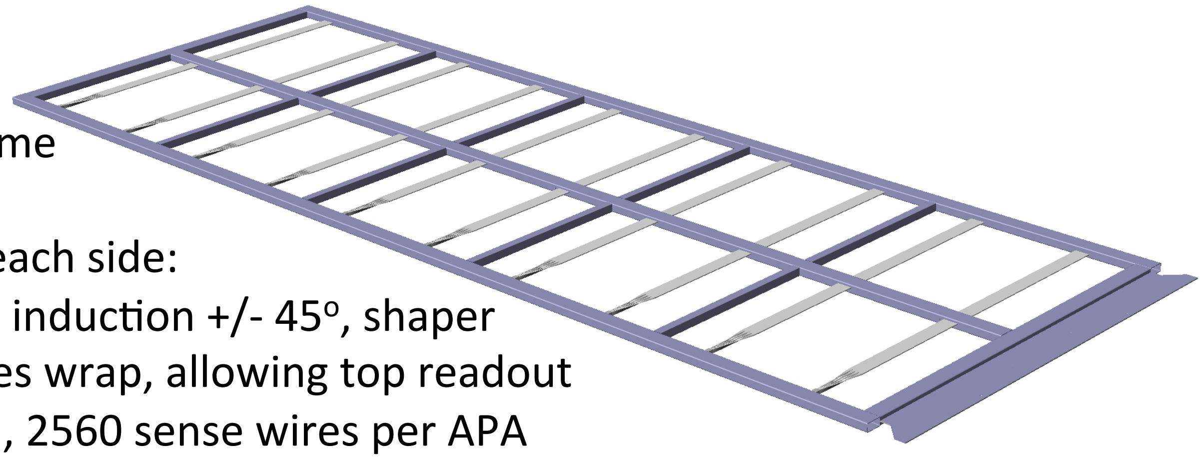
FNAL R&D program has demonstrated attainment of needed Argon purity w/o evacuation in a conventional (cylindrical) 30-ton tank (LAPD).

→ Now test LBNE-style construction:

- Will do purity tests in 35t membrane prototype (Phase-I) later this year
- Will test prototype TPC components in late 2014.



The TPC Anode Plane Assembly

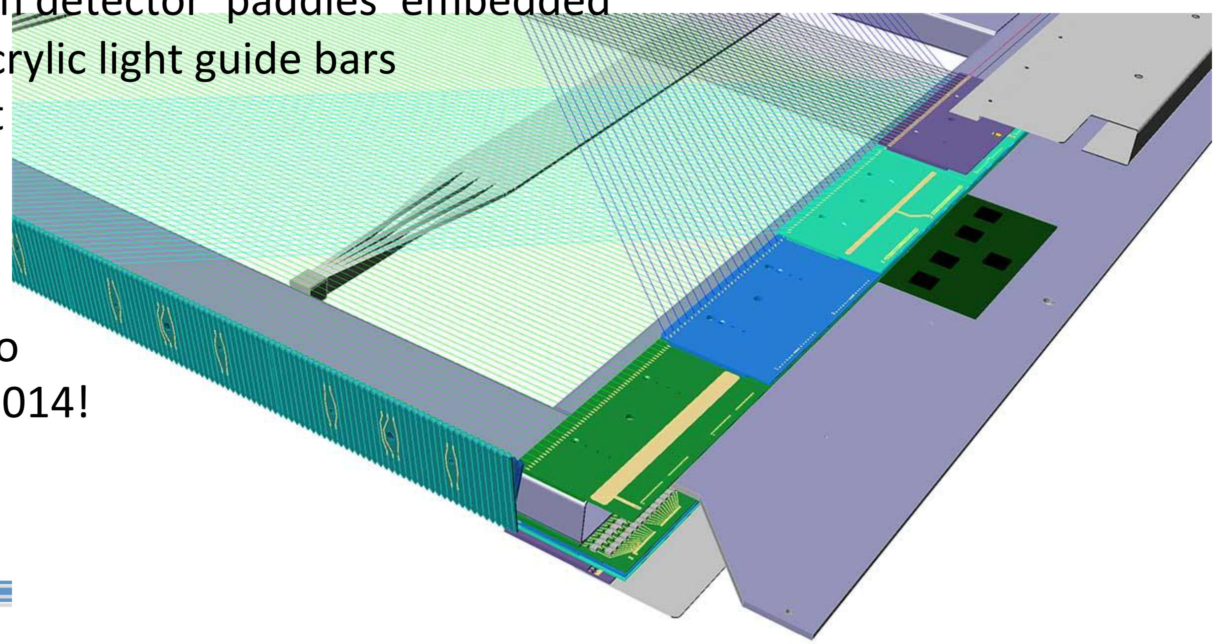


Key features:

- SS 304 channel frame

- Four wire planes, each side:
  - collection, 2 x induction +/- 45^{o}, shaper
  - induction wires wrap, allowing top readout
  - ~4.5mm pitch, 2560 sense wires per APA
  - CMOS front-end/ADC asics on FEBs on frame

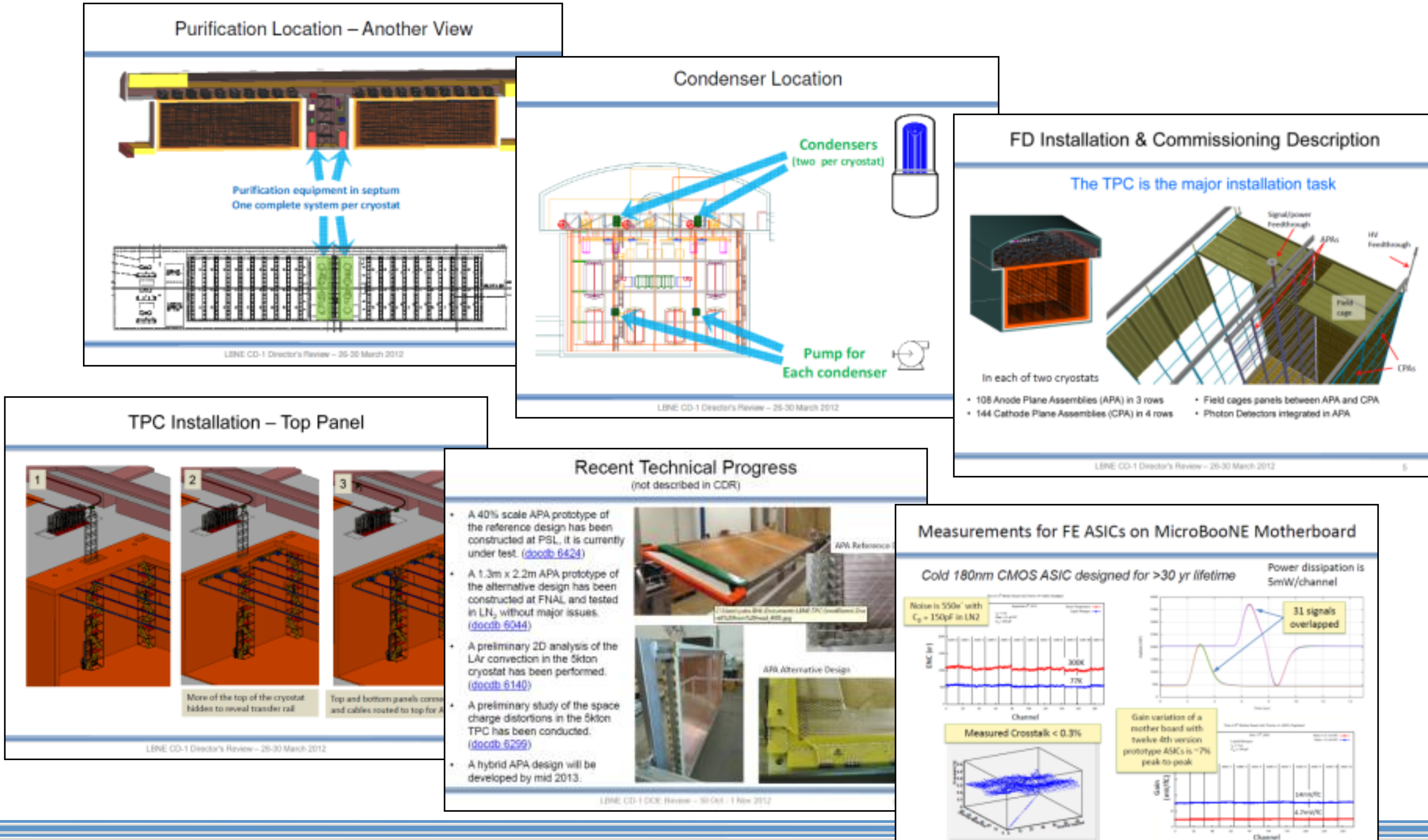
- Scintillation photon detector 'paddles' embedded
  - wls-coated acrylic light guide bars
  - SiPM readout



- Prototoypes will go into 35t vessel in 2014!

34 kt LAr Far Detector @ 4300 mwe Depth, 1300 km baseline

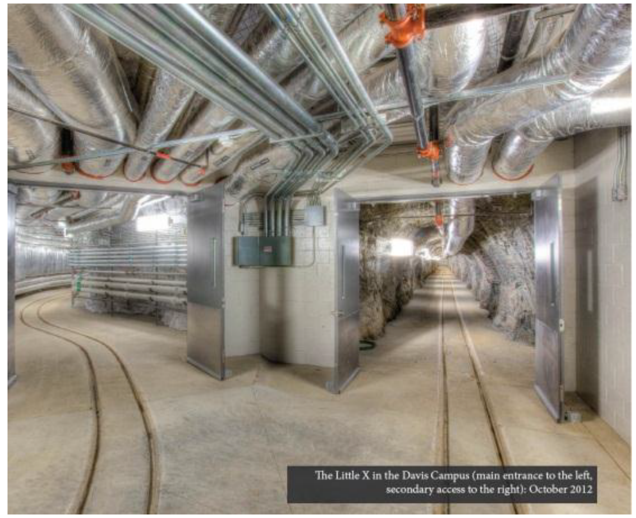
Slide courtesy J. Strait

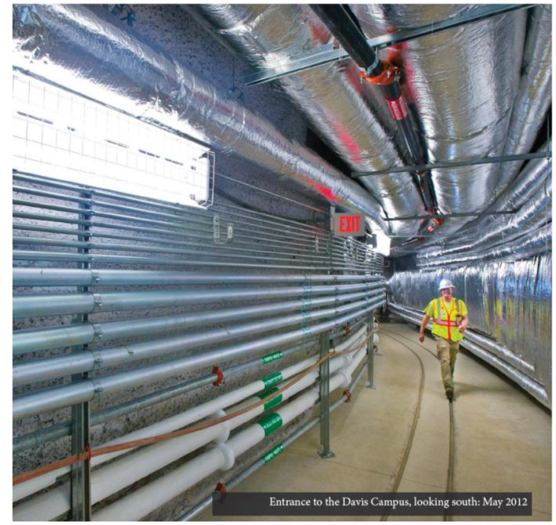


Sanford Underground Research Facility (Homestake) Facilities at 4300 mwe depth

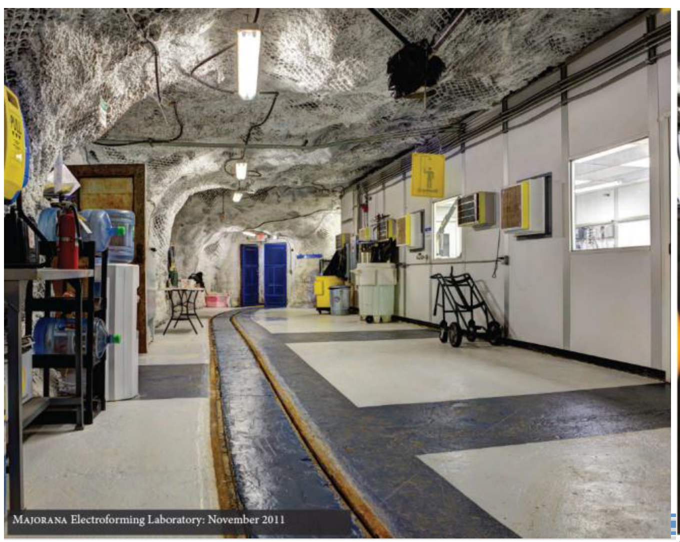
Slide courtesy J. Strait

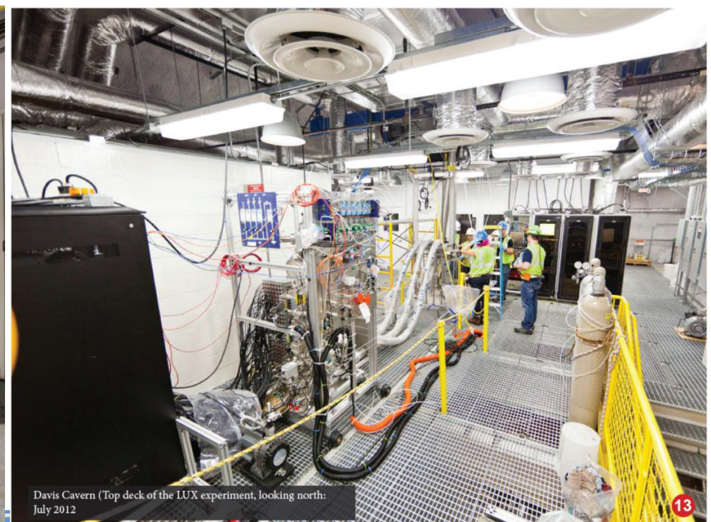

MAJORANA detector assembly room: December 2012


The Little X in the Davis Campus (main entrance to the left, secondary access to the right): October 2012



Entrance to the Davis Campus, looking south: May 2012

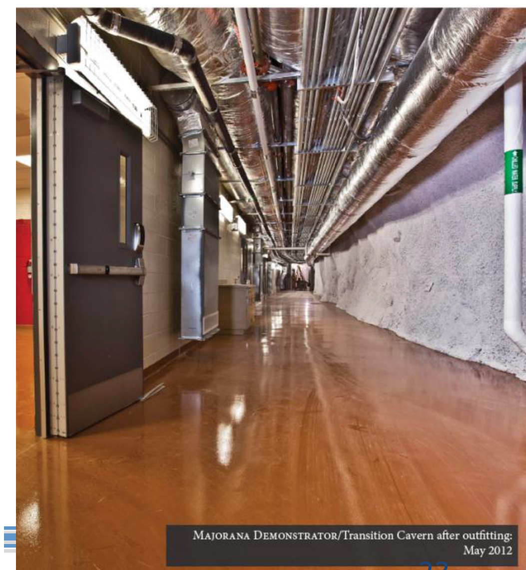

MAJORANA Electroforming Laboratory: November 2011


Davis Cavern (Top deck of the LUX experiment, looking north: July 2012

13

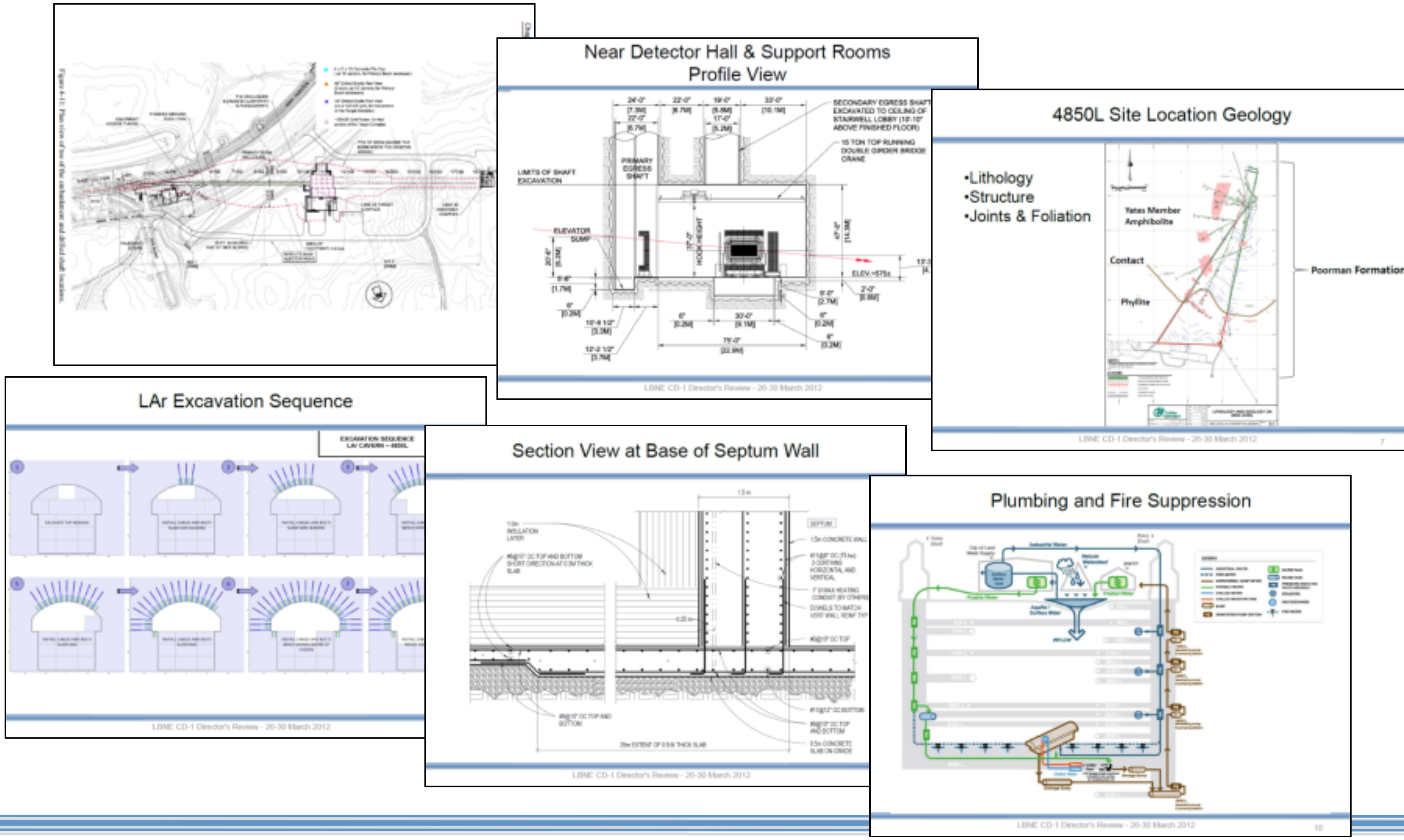
South Dakota Science and Technology Authority

Lead, South Dakota


MAJORANA DEMONSTRATOR/Transition Cavern after outfitting: May 2012

Civil Engineering for Beam, Near Detector and Deep Far Detector

Slide courtesy J. Strait

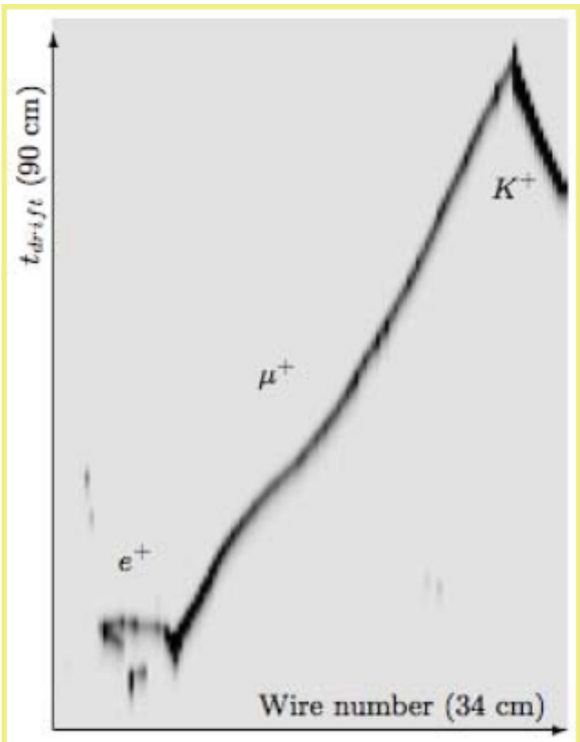


LBNE Design Status

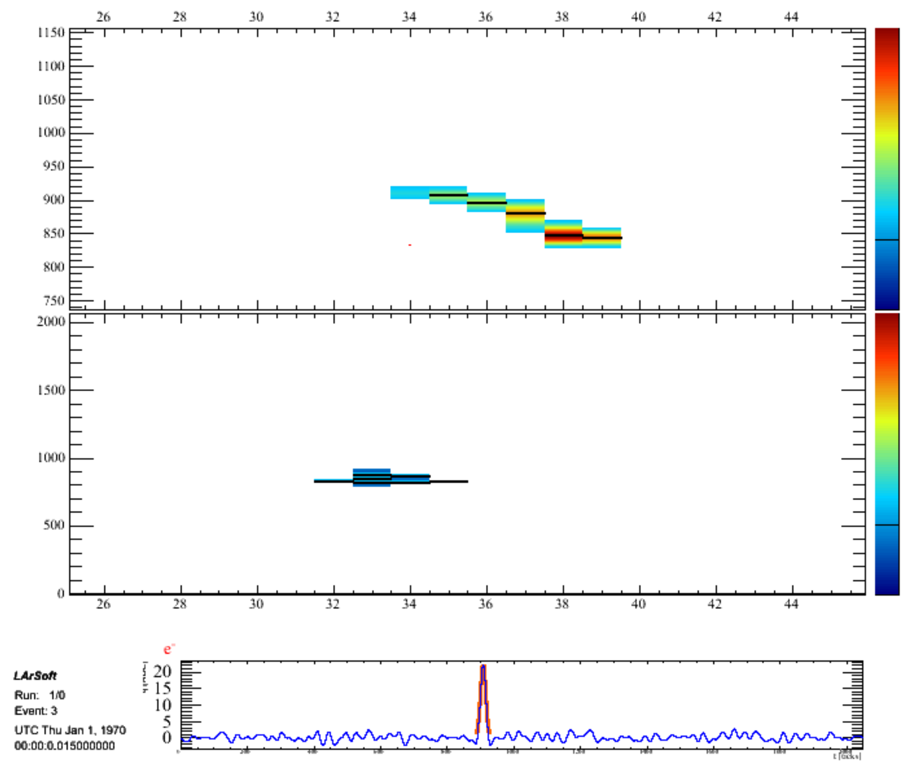
LBNE has a well-developed design for the complete project:

- Neutrino beam at Fermilab for 700 kW operation, upgradeable to 2.3 MW
- Highly-capable near neutrino detector on the Fermilab site
- 34 kt fiducial mass LAr far detector at
  - A baseline of 1300 km
  - A depth of 4300 m.w.e. at the Sanford Underground Research Facility (SURF) in the former Homestake Mine in Lead, South Dakota

Underground Science with LBNE

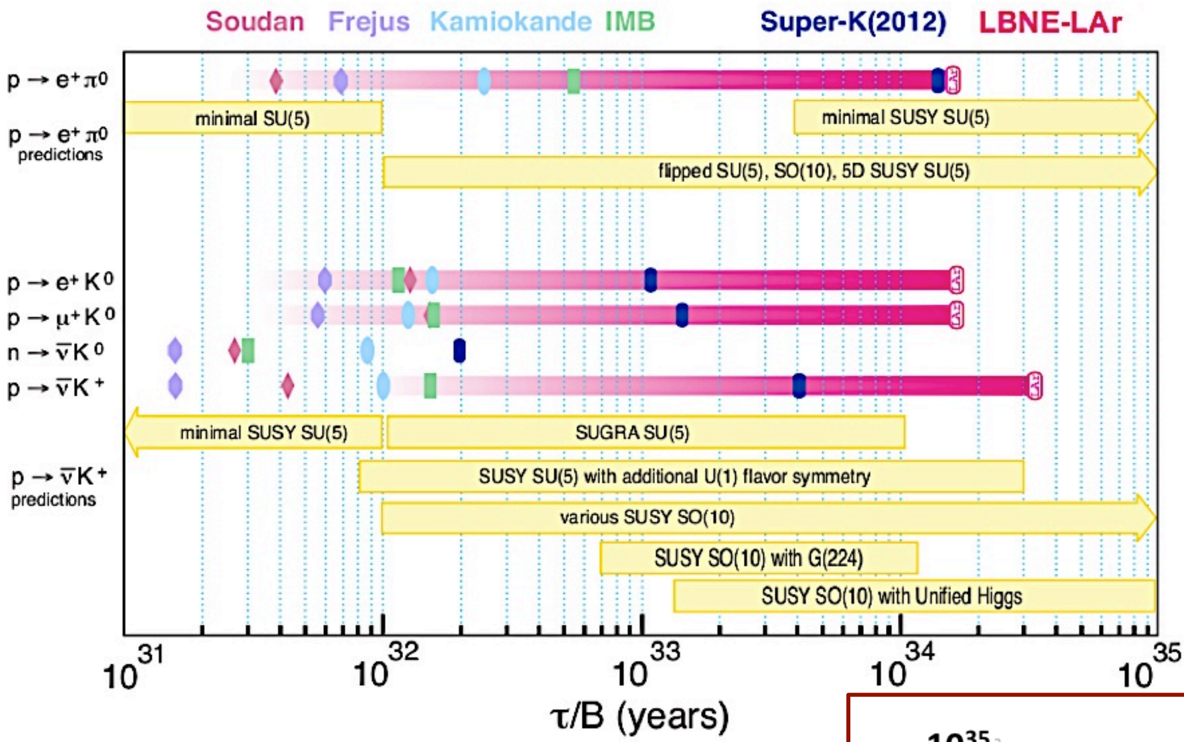


Simulated $p \rightarrow K^+ \overline{\nu}$ decay



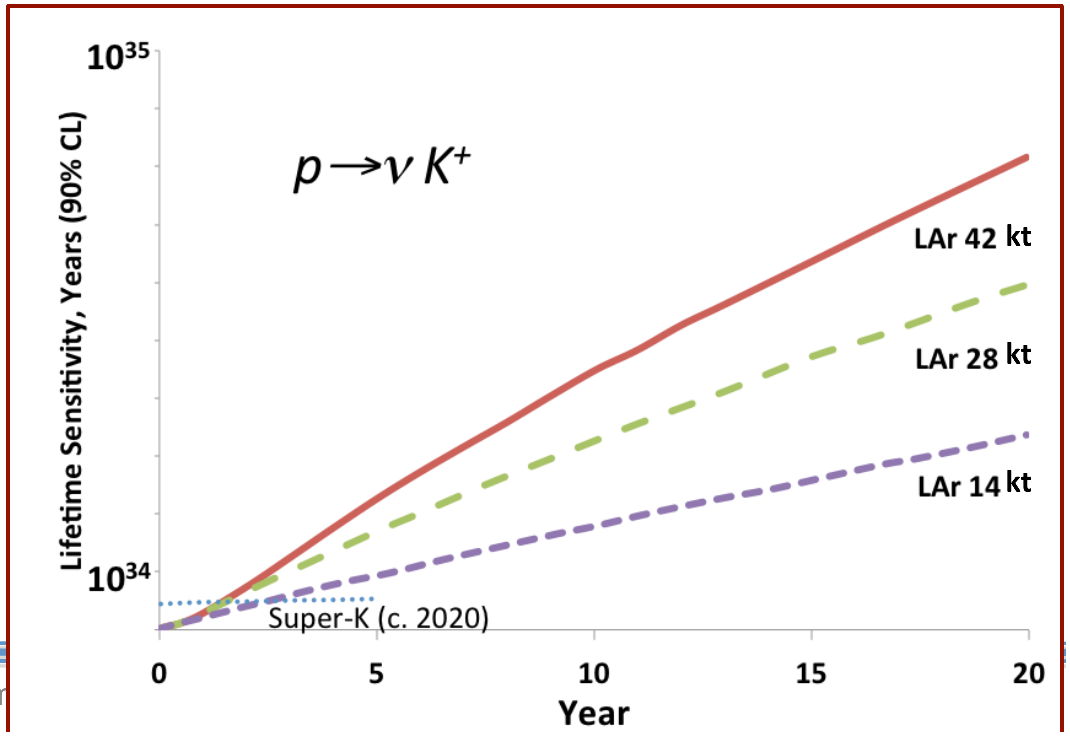
Simulated 10 MeV Supernova ν

Nucleon Decay



E. Kearns

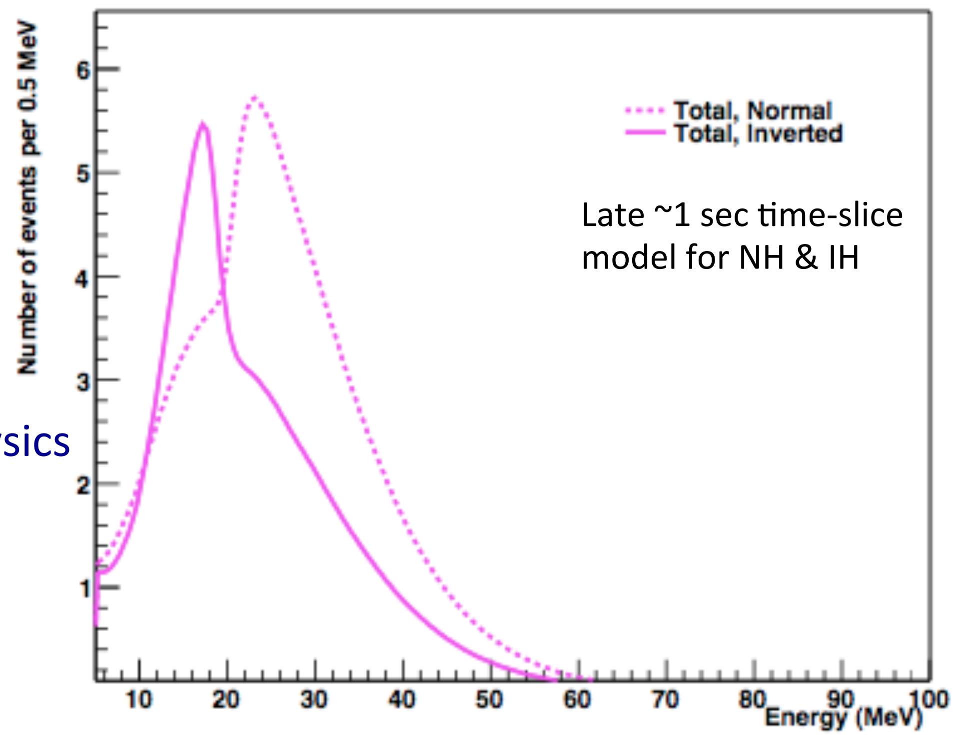
- LAr has high efficiency for SUSY-favored decay modes
- High spatial precision and energy resolution enable reconstruction of many potential decay modes



Supernova Neutrino Burst Detection

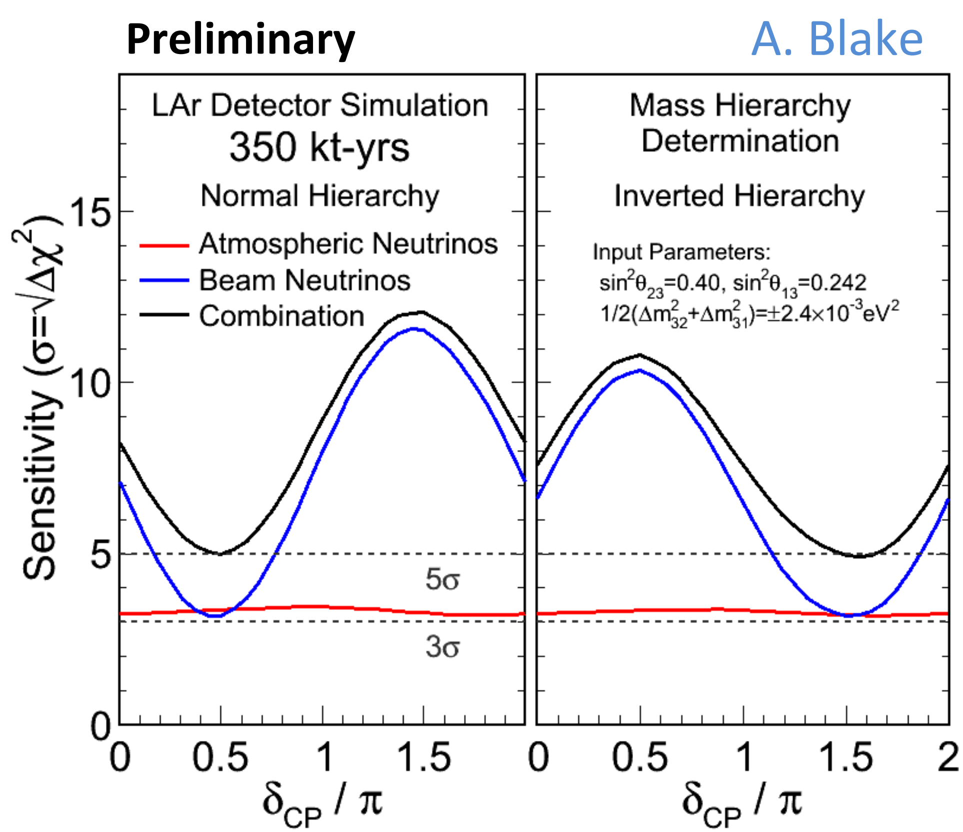
Channel	Events, "Livermore" model	Events, "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2308	2848
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	2798	3160

- SN at galactic core (10 kpc) – several 1000 interactions in 34 kt LAr in 10's of seconds
- Complementary to Water Cherenkov
- Fantastic for particle physics and astrophysics (c.f. SN1987A ~dozen events significance)



Atmospheric Neutrinos

- Large range of energy and baseline
- Independent determination of mass hierarchy
  - (adds significance to beam data)
- θ_{23} octant sensitivity
- Searches for new physics
- Nu-e sensitivity complementary to water Cherenkov detectors (anti-nu-e)



Preliminary analysis (not based on GLOBES) shows:
- **excellent agreement w/ Globes-based beam data senstivities**
- **considerable enhancement to beam-only sensitivities w/ atm ν's**

Summary

- **LBNE represents an optimized, realizable approach to the "precision era" of neutrino oscillation and underground physics**
  - Baseline is long enough, **and** short enough for practical considerations (beam line)
  - Detector technology gives high precision, **and** is easily scalable to large masses
  - Broad, exciting physics program, **and** robust to future developments in the field

- **DOE has approved (CD-1) an initial phase at reduced scope relative to full LBNE…**
  - LBNE10 will do physics while maintaining key full-scope elements (beam line/baseline)
- **…but is receptive/encouraging of scope restoration w/ additional partners, and…**
- **…global conditions are conducive for participation from international partners**

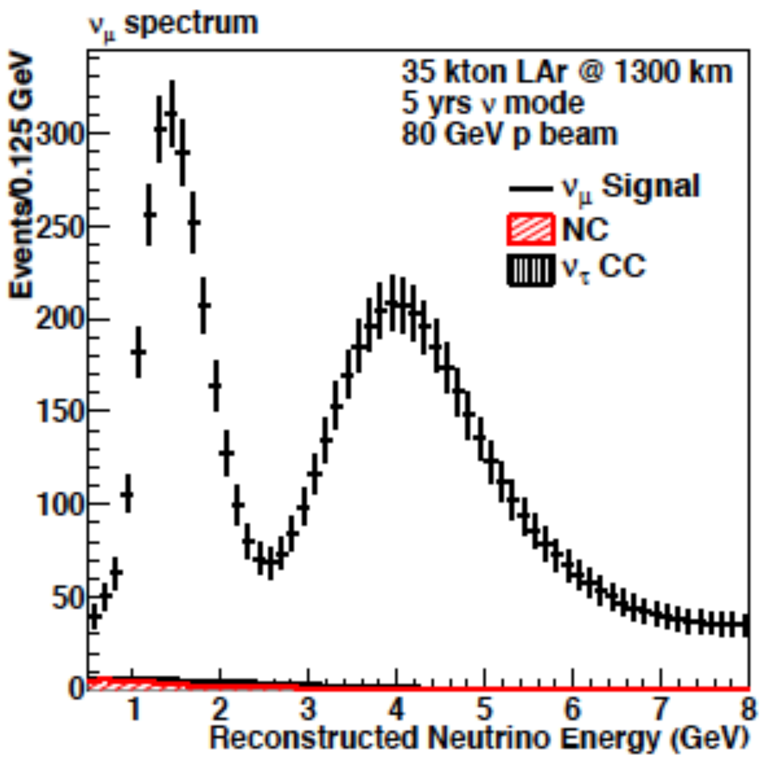
- **Challenges / novel aspects of beam line & detector will advance the field, and provide excellent opportunities for young scientists.**

Additional Material

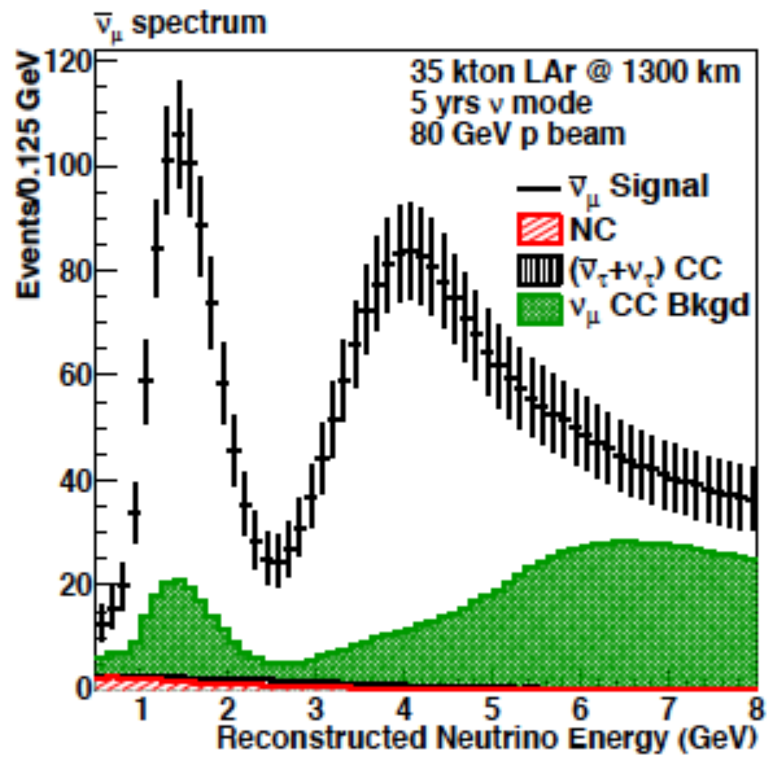
LBNE Charged-current ν_μ Event Samples

L. Whitehead

Samples for charged-current ν_μ disappearance studies (700kW beam)



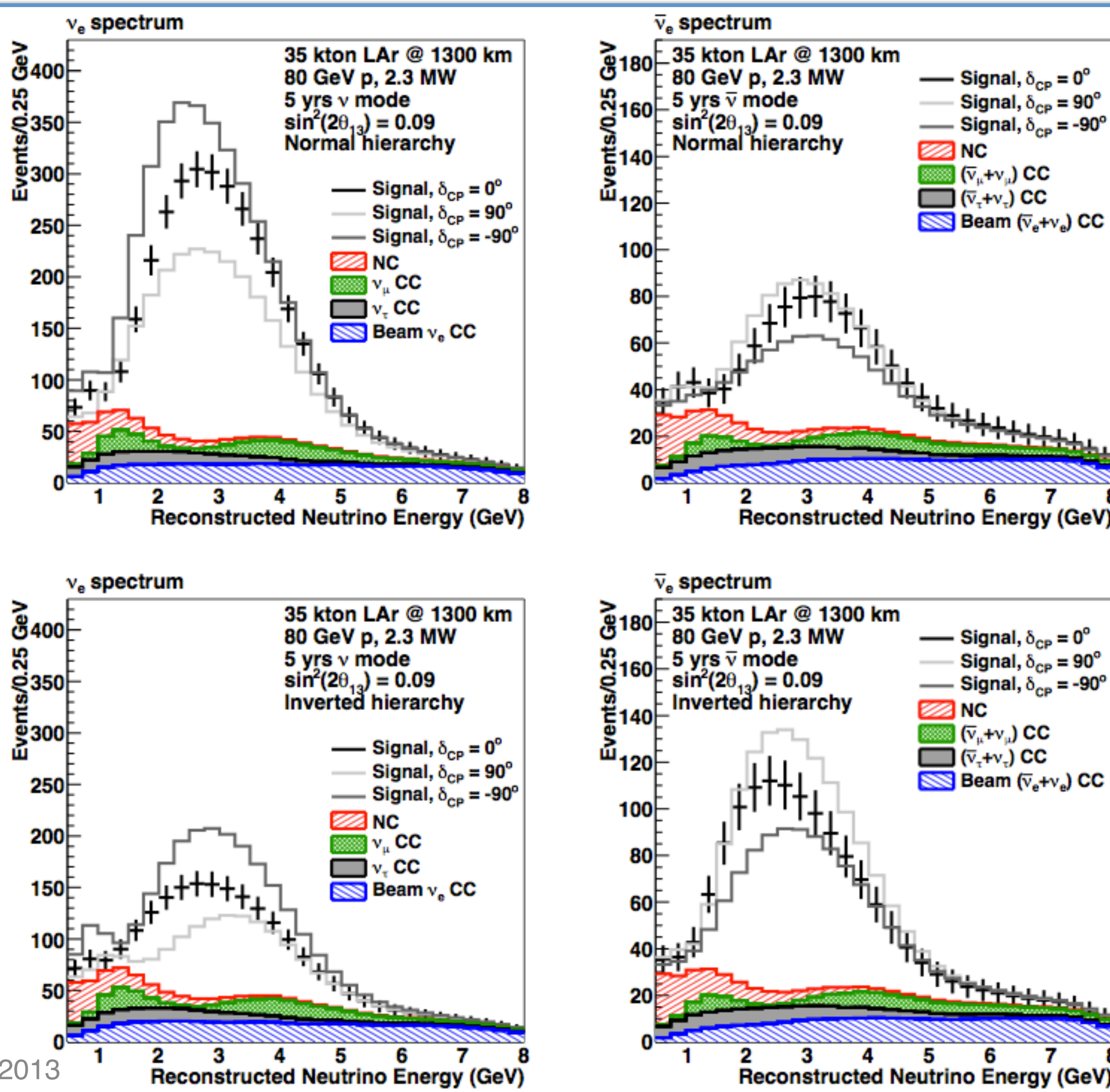
w/o osc'ns: 20,000
after osc'ns: 7,000



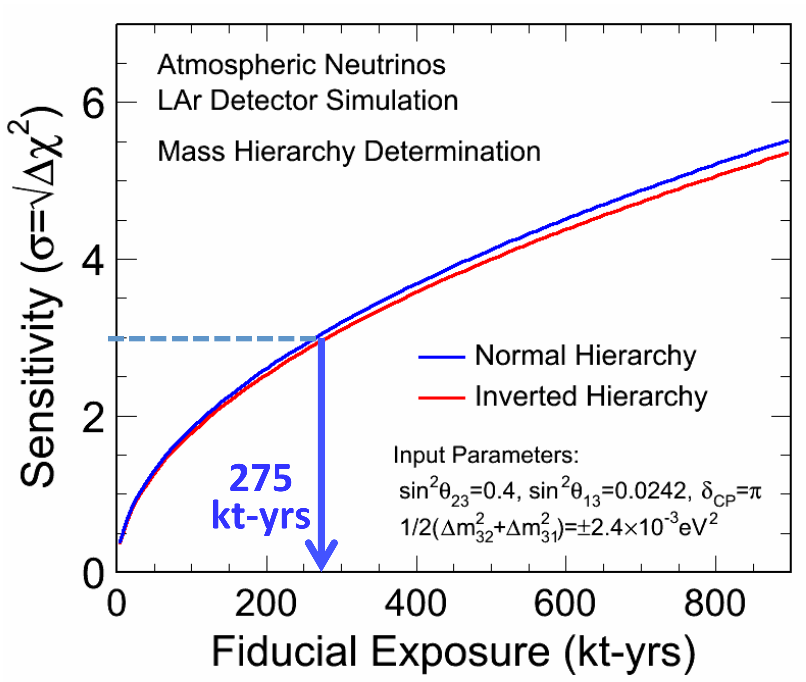
w/o osc'ns: 6,700
after osc'ns: 2,200

ν_e appearance signals, 35kt, 2.3 MW, 5+5yrs

L. Whitehead

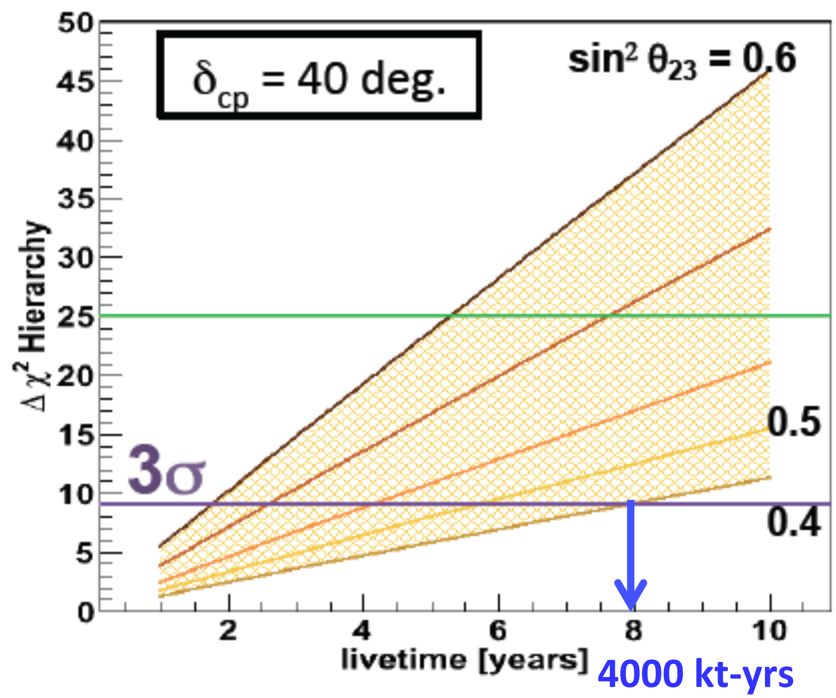


Atmospheric Neutrinos



LBNE MH Sensitivity

(H. Gallagher + A. Blake*)



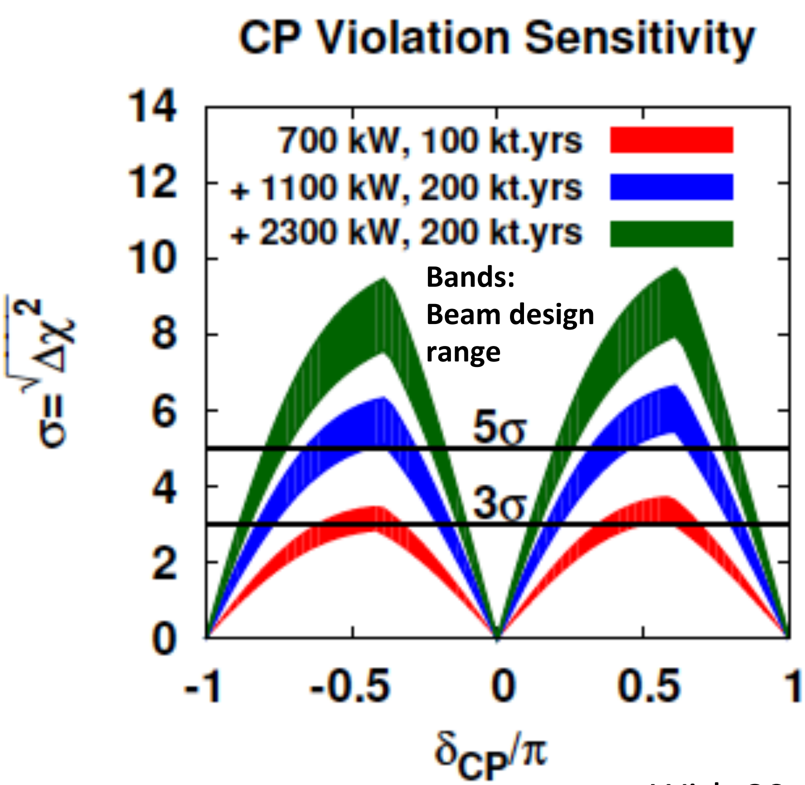
HyperK MH Sensitivity

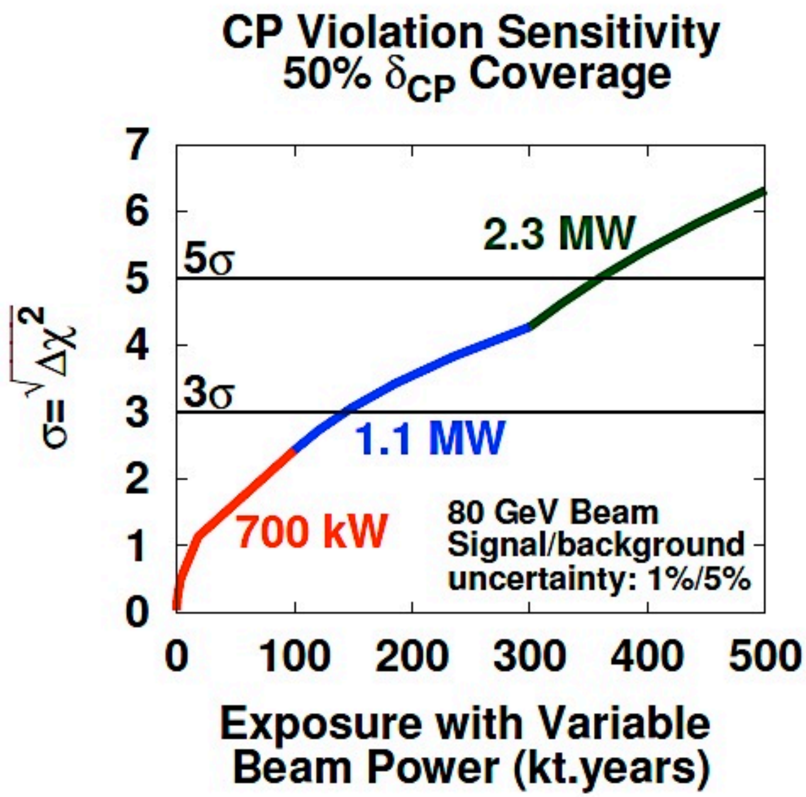
(C. Walter*)

- **HyperK and LBNE have comparable sensitivity to the MH with atmospheric neutrinos!**
- LBNE's higher resolution of event energy and direction makes up for smaller mass.

*ISOUPs, May 2013

LBNE + Project X (1.1-2.3 MW) = Comprehensive Global Science Program





With 80 GeV MI protons source

- Long-range program in tandem with near detector neutrino interactions and non-accelerator physics

Complete Design of LBNE was Independently Reviewed and Found to be Sound

Issued April 23, 2012

Fermilab

Final Rep

Director's Independe
Design and CD-1 Rea
of the LBNE I

March 26-30,

Director's Independent Conceptual Design and CD-1 Readi
March 26-30, 2012

Issued April 23, 2012

Executive Summary

This Director's review was designed to elicit the assembled committee's opinion on two primary questions. The first focus of the review was to perform an independent Conceptual Design review of the LBNE project to verify that the design is technically adequate, and should achieve the Project's scientific goals. The second focus was to perform a CD-1 Readiness review, with a focus on the project's cost, schedule, management, and ES&H.

The committee finds that the Conceptual Design for the LBNE project is sound, and should achieve the Project's scientific goals. Our determination is that the level of technical detail across the entire breadth of the LBNE project is sufficient to address the question of overall capability to achieve the scientific goals, as appropriate for this stage of the project. There are a number of components of the project that have advanced well beyond the conceptual stage.

The committee is confident that the LBNE project can be ready for a CD-1 review on the time scale given to the committee, the summer of 2012, if issues related to the funding profile and the resulting schedule are resolved. The management systems and documentation for the project are appropriate for a CD-1 review.

However…

- Last year US funding agency (DOE) asked us to stage LBNE construction and gave us a budget of $867M for the first phase
  - They also encouraged us to develop new partnerships to maximize the scope of the first stage.
- We chose to proceed with emphasis on the most important aspects of the experiment: 1300 km baseline and the full capability beam
  - With just the DOE budget, the far detector would be 10 kt LAr TPC at the surface.
- An external review panel recommended this phase 1 configuration.
- DOE approved "CD-1" in December 2012 for this phase-1 scope.
- *Our plan continues to be to build the full scope originally planned, and are working with domestic and international partners to make the first phase as close as possible to the original goal.*

DOE CD-1 Approval Document

lbne-doc-6681

Critical Decision 1
Approve Alternative Selection and Cost Range
of the
Long Baseline Neutrino Experiment (LBNE) Project
(Line Item Project 11-SC-40)
at the
Fermi National Accelerator Laboratory and
Sanford Underground Research Facility
Office of High Energy Physics
Office of Science

Purpose

The purpose of this paper is to document the review and approval by the DOE Office of Science Energy Systems Acquisition Advisory Board-equivalent for Critical Decision 1 (CD-1) "Approve Alternative Selection and Cost Range" for the Long Baseline Neutrino Experiment (LBNE) Project at the Fermi National Accelerator Laboratory (Fermilab) and Homestake Mine

Critical Decision 1, Approve Alternative Selection and Cost Range for the LBNE Project

Approval

Based on the information presente din this document and at the ESAAB review, I approve Critical Decision 1, Approve Alternative Selection and Cost Range for the Long Baseline Neutrino (LBNE) Project.

William Brinkman, Acquisition Executive
Director, Office of Science

12/10/12
Date

Tailoring of the scope definition prior to CD-2 to enhance scientific capabilities may also be considered. The physics opportunities offered by the beam from Fermilab and the long baseline may attract the support of other agencies both domestic and international. Contributions from such other agencies offer alternative funding scenarios that could enhance the science capabilities of the Project. If additional domestic or international funding commitments are secured sufficiently prior to CD-2, the DOE LBNE Project baseline scope could be refined before CD-2 to include scope opportunities such as a Near Neutrino Detector complex at Fermilab or an underground location at SURF for the far detector.

the neutrino mass states, would not be obtained, compromising the ability to understand the matter-antimatter asymmetry and resulting dominance of matter in the universe.

To meet the scientific and technical objectives for the LBNE experiment, the following draft key performance parameters have been developed.

http://lbne2-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=6681;filename=LBNE%20CD-1%20appr.pdf

Goal for LBNE Phase 1

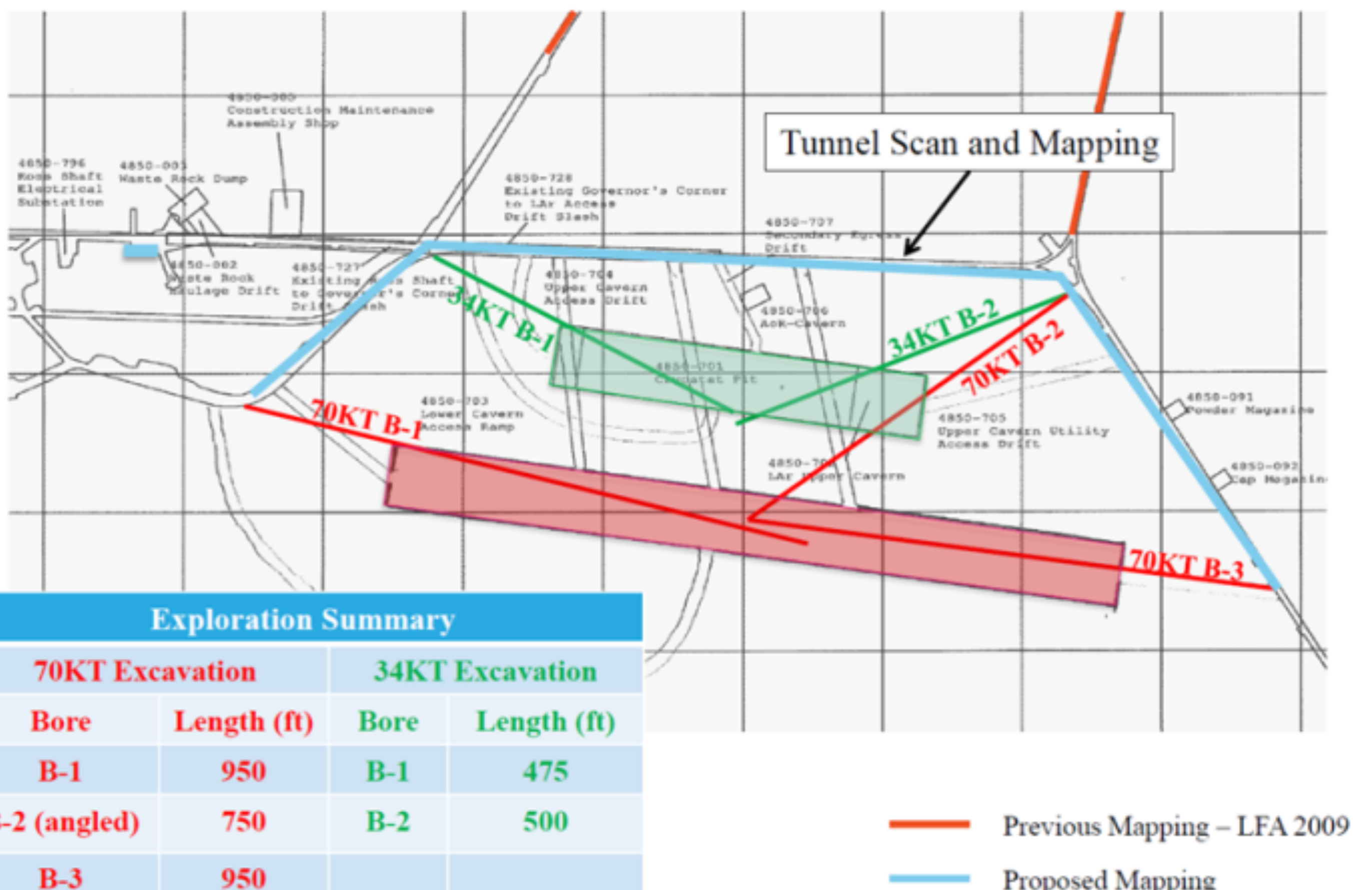
- Together with additional partners, build:
  - Neutrino beam for 700 kW, upgradeable to 2.3 MW
  - Highly-capable near neutrino detector
  - >10 kt fiducial mass LAr far detector at
    A baseline of 1300 km
    A depth of 4300 m.w.e.
- The world-wide community can build upon the substantial investment planned by the US to make LBNE a world facility for neutrino physics, astrophysics, and searches for non-conservation of baryon number.

Together we can do more than we can do separately.

Planning for Underground Location

- We have launched geotechnical investigation of the LBNE detector site at the 4850 level, which is on critical path.

Conceptual 4850 LBNE Exploration Program

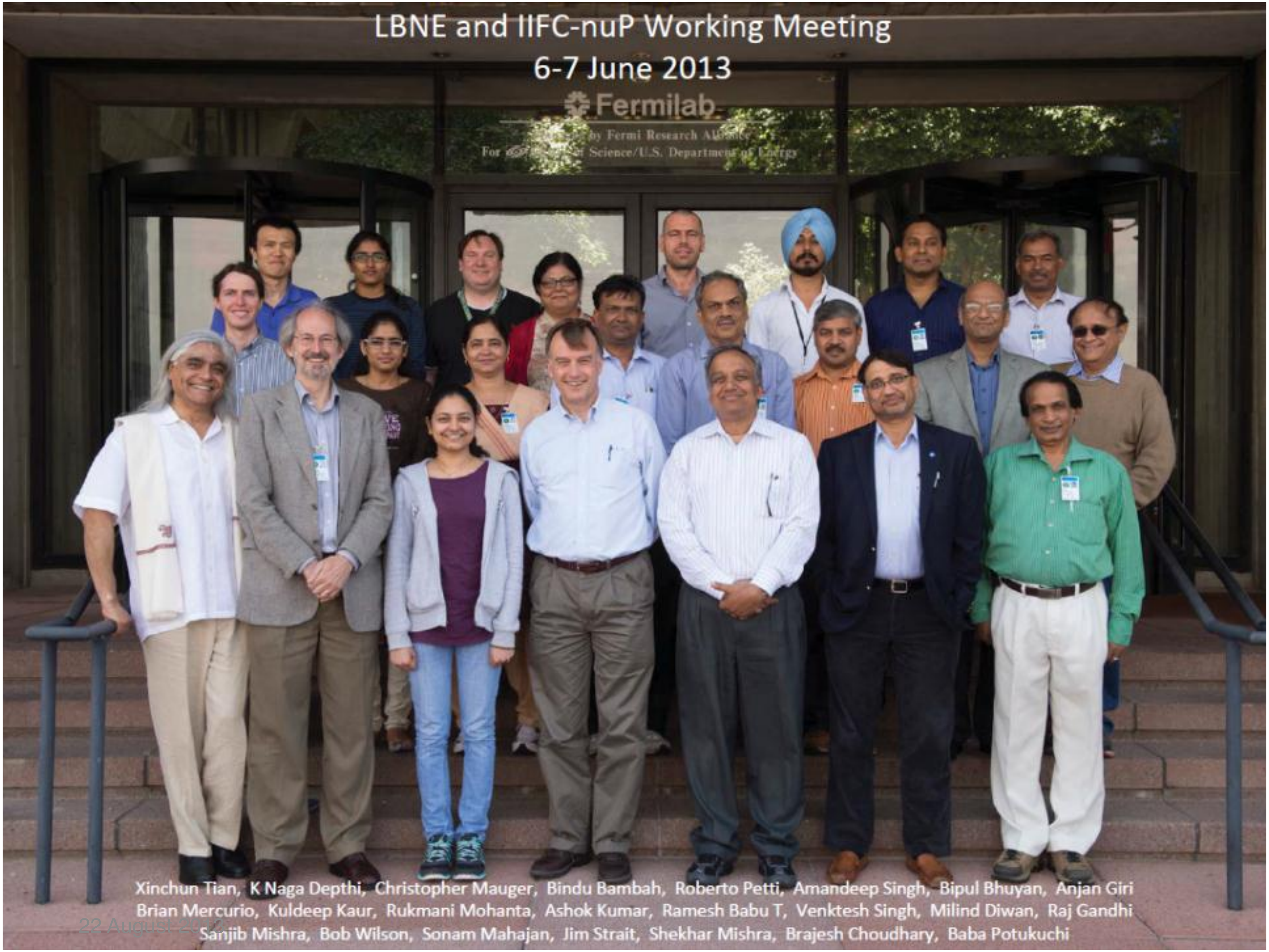


Exploration Summary

70KT Excavation		34KT Excavation	
Bore	Length (ft)	Bore	Length (ft)
B-1	950	B-1	475
B-2 (angled)	750	B-2	500
B-3	950		

International Discussions

- We are in discussion with a number of potential non-US partners, both physics groups and funding agencies, in:
  - Brazil
  - India
  - Italy
  - UK
- LBNE and LAGUNA-LBNO have established a working group to explore joining forces
- Italian ICARUS groups in the process of joining LBNE
- We have initiated preliminary discussions with:
  - CERN
  - Dubna
- We are hoping to engage others potential partners:
  - Japan
  - China
  - Additional countries in the Americas, Asia and Europe
- Also exploring how to engage domestic US funding agencies beyond the DOE


LBNE and IIFC-nuP Working Meeting
6-7 June 2013
Fermilab
Xinchun Tian, K Naga Depthi, Christopher Mauger, Bindu Bambah, Roberto Petti, Amandeep Singh, Bipul Bhuyan, Anjan Giri
Brian Mercurio, Kuldeep Kaur, Rukmani Mohanta, Ashok Kumar, Ramesh Babu T, Venktesh Singh, Milind Diwan, Raj Gandhi
Sanjib Mishra, Bob Wilson, Sonam Mahajan, Jim Strait, Shekhar Mishra, Brajesh Choudhary, Baba Potukuchi


Joint ICARUS-LBNE Meeting
Padova, 17-18 June 2013
Paola Sala, Claudio Montanari, Marzio Nessi, Filippo Varanini, Francesco Pietropaolo, Bob Wilson, David Montanari, Tom Junk, Alberto Guglielmi, Mauro Mezetto
Alberto Scaramelli, Renato Potenza, Carlo Rubbia, Jim Strait, Enzo Bellini, Guang Meng, Sandro Centro, Elaine McCluskey, Jim Stewart, Bagdat Baibussinov
Russ Rucinski, Daniele Dequal, Christian Farnese, Jon Urheim, Chiara Vignoli, Milind Diwan, Angela Fava, Alfredo Cocco, Maurizio Bonesini

European Strategy and CERN

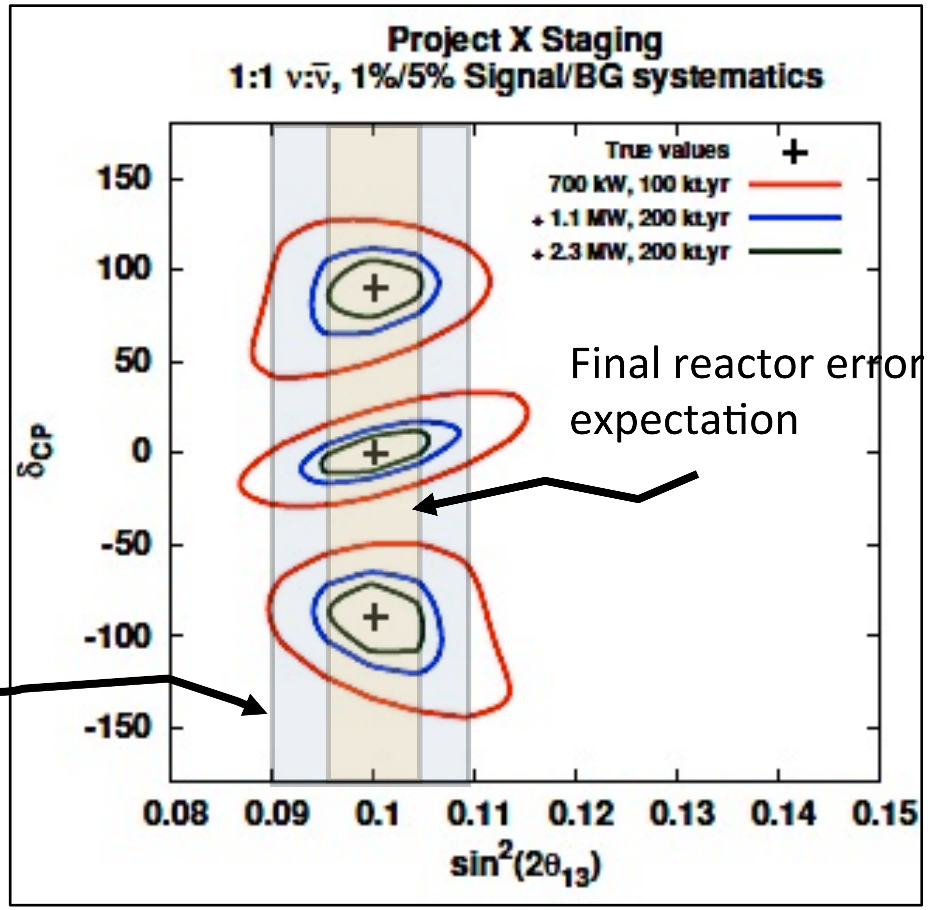
European Strategy for Particle Physics:

Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.

CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

- Formally adopted at the special European Strategy Session of the Council in Brussels on 30 May 2013.
- The role of CERN will be key. The next step is for CERN to establish a platform from which European groups can participate in long-baseline physics.

LBNE + Project X (1.1-2.3 MW) = Comprehensive Global Science Program



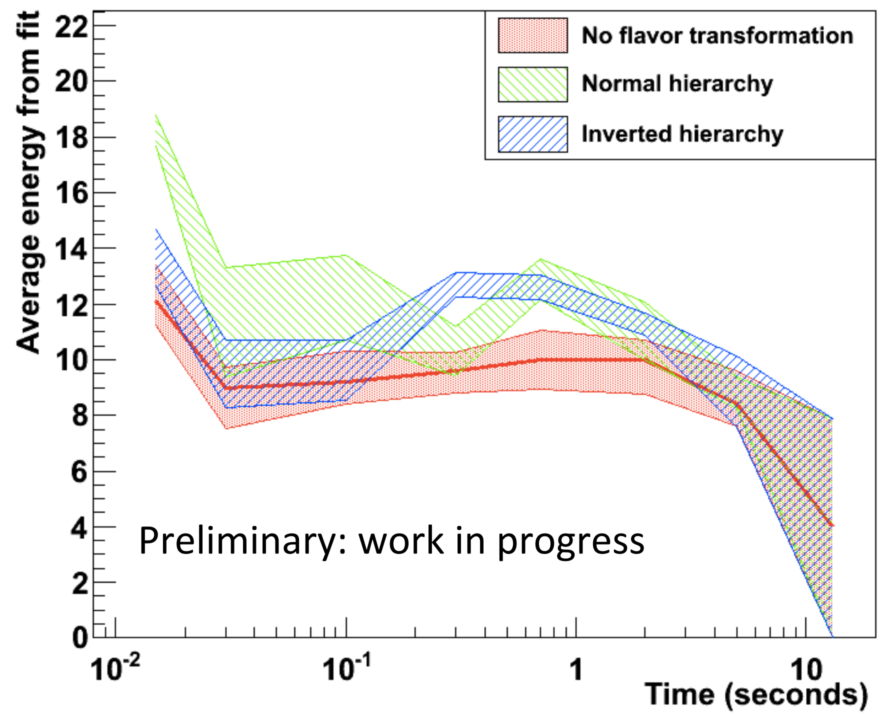
Final reactor error expectation

Current reactor error

Supernova Burst Neutrinos

- When a star's core collapses ~99% of the gravitational binding energy of the proto-neutron star goes into ν's
- SN at galactic core $\Rightarrow$ 1000's interactions in 20 kt LArTPC in tens of seconds (ν_e detection complementary to WCD)
- **SN 1987A observation of ~20 events → ~800 publications!**

Measuring SN ν_e temperature vs. time

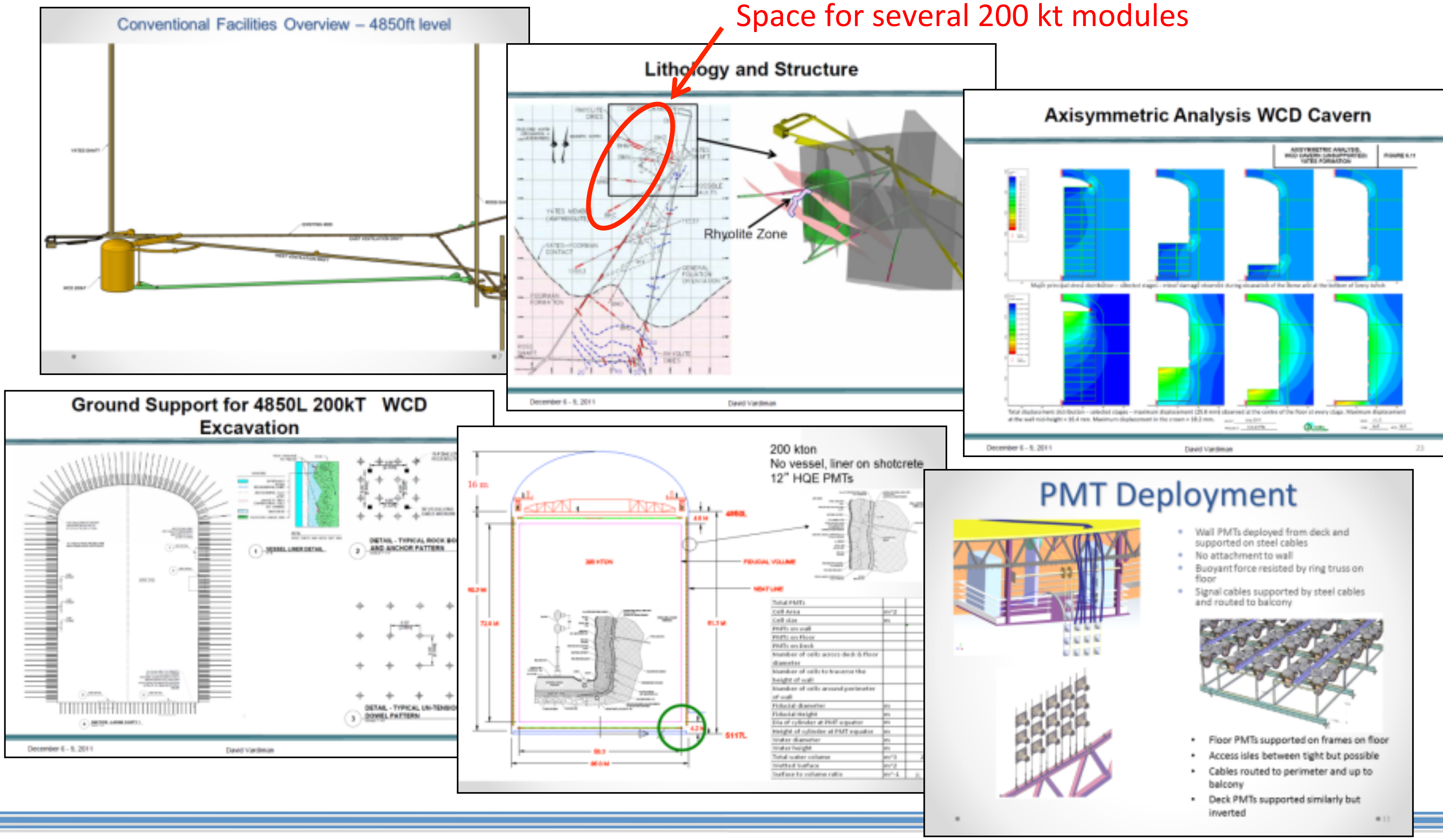


- 10 kpc spectra from A. Friedland/JJ Cherry/H. Duan smeared w/ SNOwGLoBES response, fit to pinched thermal spectrum
- Based on Keil, Raffelt, Janka spectra, astro-ph/0208035, w/ collective oscillations (NH & IH)

And …. we also have a design for a 200 kt (fiducial) Water Cherenkov Detector

Slide courtesy J. Strait

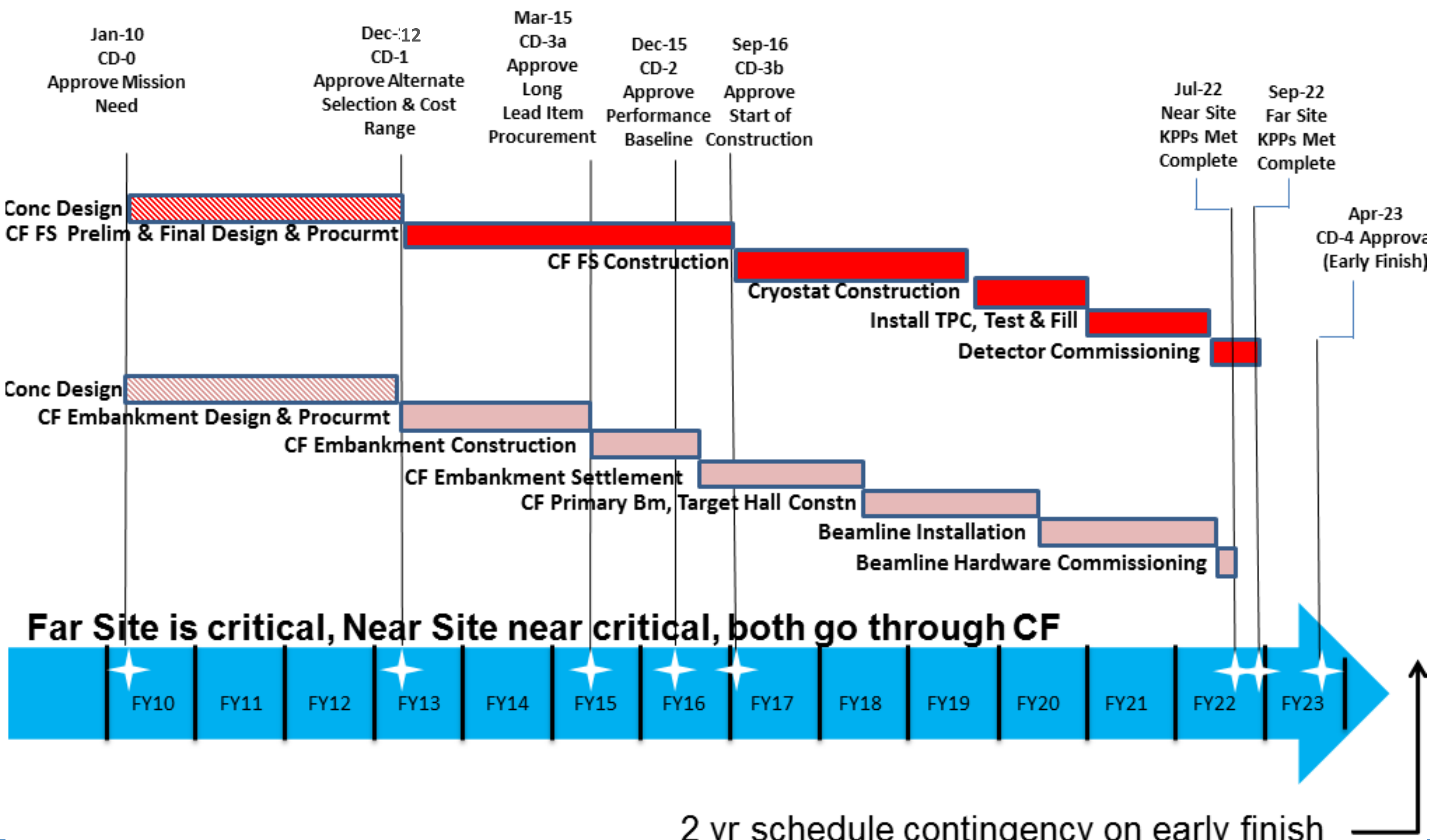
Space for several 200 kt modules



DOE Critical Decisions

• CD-0 ("Mission Need") approves the need for the project.	Jan 2010
• CD-1 ("Alternative Selection and Cost Range") approves overall design, cost and schedule.	Dec 2012 (*for phase 1*)
• CD-2 ("Performance Baseline") approves the precise technical design, cost and schedule.	*Early 2017*
• CD-3A ("Approve Long-Lead Item Procurements") approves early start of selected parts of the project.	*Early 2016*
• CD-3 ("Start of Construction") approves the start of construction.	*Late 2017*
• CD-4 ("Project Completion") approves transition to operations.	*2023*

LBNE DOE Schedule (CD-1 Review)



Cold Front-end Electronics Considerations

- Large TPC → many channels, many time samples

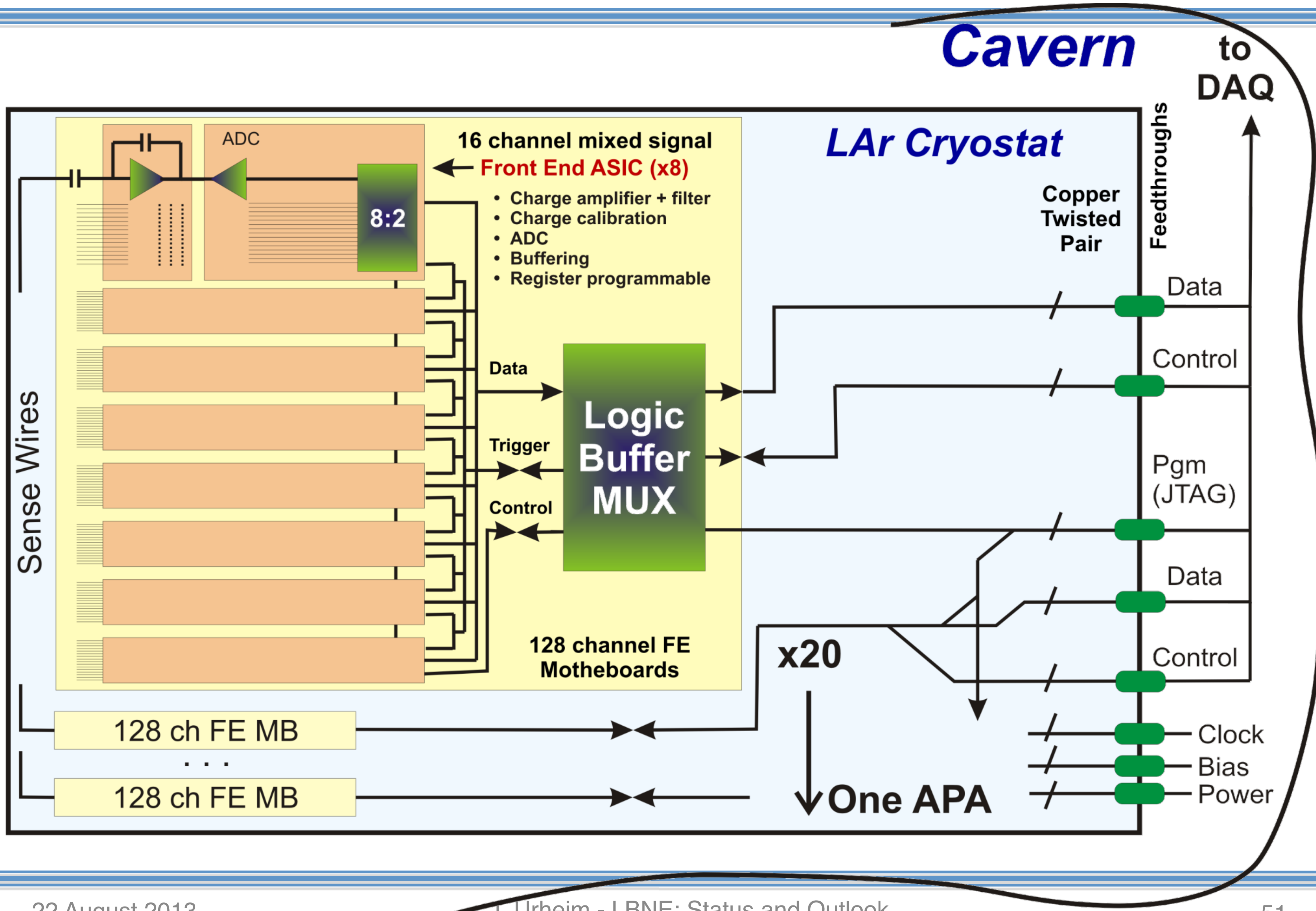
- One goal is to minimize number of penetrations & size of cable plant
  - Limit challenge of running many long cables from bottom APA modules
  - Limit possible sources of impurity in the gas (ullage)
  - Limit heat load at penetrations; keep ullage gas cold & ~uniform in temperature.

- Also, importantly:
  - Limit analog signal cable runs → limit noise at the front-ends

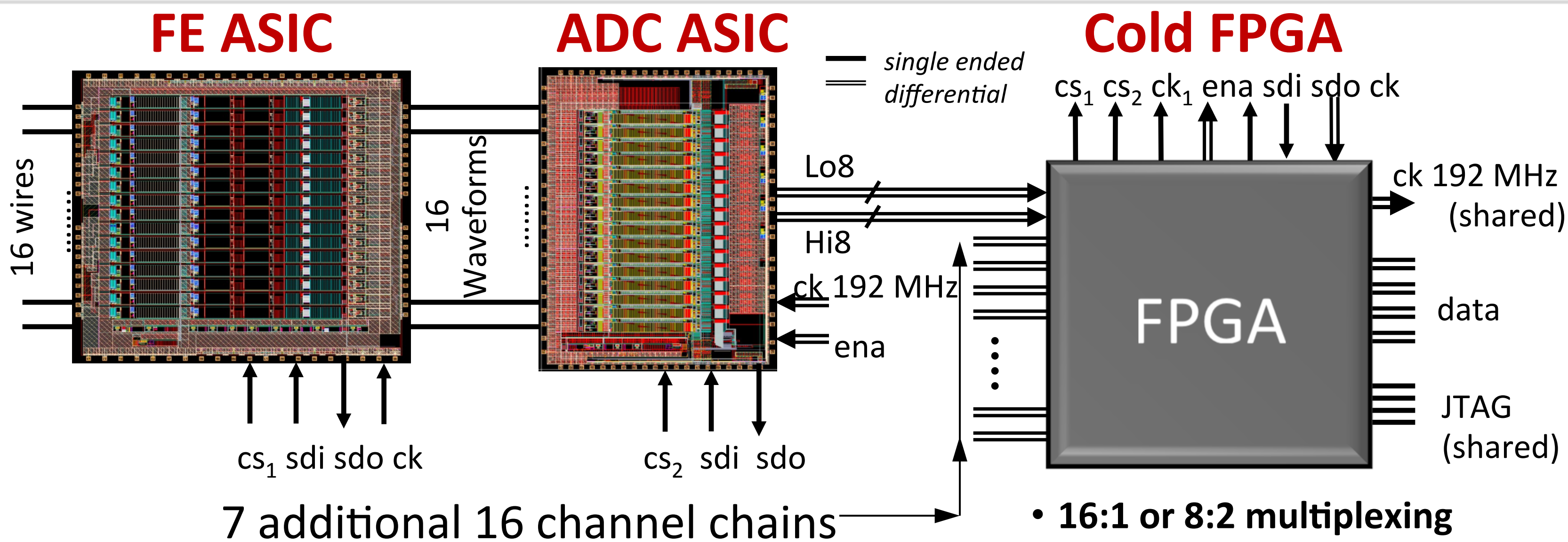
- Aided by good understanding of cyrogenic operation of electronics:
  - Most properties improve at lower temperatures
  - But long-term reliability of CMOS hampered by "hot carrier" effects, which get worse
  - With appropriate design rules + operation at reduced drain voltage, expected lifetimes are controllable

- Digitization at the front-end allows muxing and zero-suppression/compression + transmission of digital signals → fewer cables and less noise.

Proposed Block Diagram – Cold CMOS Electronics



Cold CMOS Electronics: 35t Phase II Prototype



- low-noise analog amplification
- programmable gain, shaping, coupling

- ADC 12-bit 2MS/s
- small buffer
- 2 x **8:1 multiplexing**

- **16:1 or 8:2 multiplexing** (total 128:1 or 64:2)
- timestamp
- compression
- zero suppression
- neighbor triggering

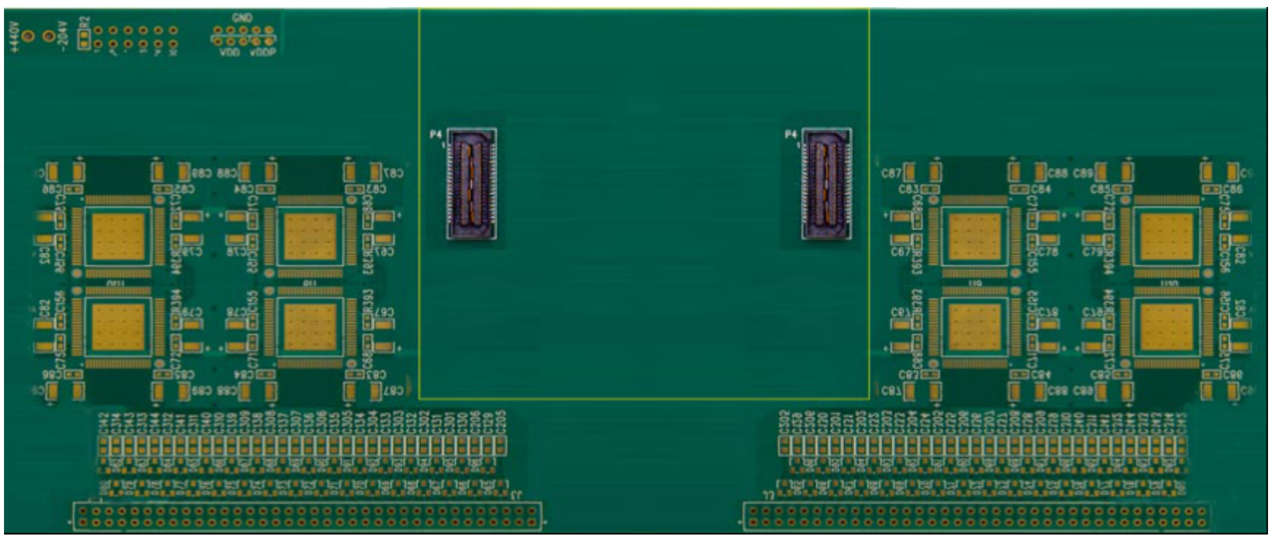
- **Developed at BNL**
- **Being used at MicroBooNE**

- **Developed at BNL**
- **in 3rd revision now**

- **Cold FPGA candidates found (power, lifetime, driving)**
- **Power regulators being studied**

Cold Electronics FE Motherboard (for 35ton)

Model of 128 channel front-end mother board with 8 FE ASICS, 8 ADC ASICs and connector for the FPGA mezzanine board



Schematic for 35t cold readout board drafted. Will start layout soon

Scintillation Photon Detection

- LAr is an excellent scintillator – O(10^4) 128-nm (VUV) photons emitted per MeV of energy deposition.

- Useful applications of detected signals for both surface & underground operations:
  - Signals are prompt (~6 ns & 1.5 μs components)
  - They provide complementary calorimetric info to ionization signal.

- On Surface:
  - Photon signal coincidence w/ beam spill → reject CR mu's

- Underground:
  - added CR mu rejection still useful, depending on depth
  - Photon signal provides trigger/t-zero for TPC for proton decay candidates
  - Helps with low-energy events, i.e., supernova ν's: trigger signal + t-zero for correction of ionization signal dE/dx

- But, detection at 128 nm is tricky…

Further challenges of photon system

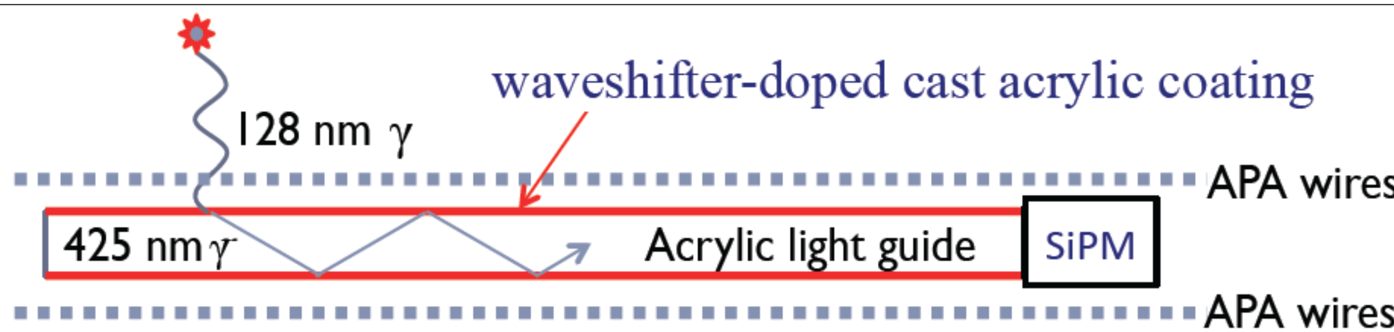
- Requirements:
  - Must have good coverage in large detector
  - Must not introduce dead space within TPC active volume
  - Must be inexpensive

- No sensors work at 128 nm. → Need to understand properties of wavelength shifters

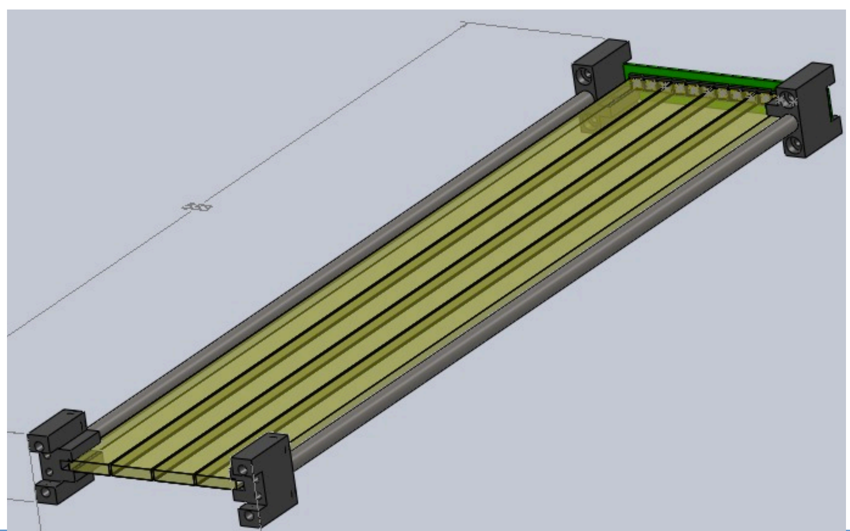
- → Limited number of options; deployment of large-area PMT coverage on walls of cryostat (as in ICARUS & MicroBooNE) is not likely to work so well.
  - Several ideas being pursued within LBNE, will talk a little about the one that is currently most advanced

WLS-coated Light-guide Paddle Concept

- Main idea (pioneered by MIT group for generic application):
  - Coat acrylic bar w/ wavelength shifting material (TPB, bis-MSB) to convert 128 nm → 425 nm
  - Capture 425 nm light in bar by total internal reflection, pipe to photo senser
  - Low profile of system fits in gap between wires mounted on the two sides of an APA
  - Four bars mount together to form a paddle; ~ 10 paddles per APA.



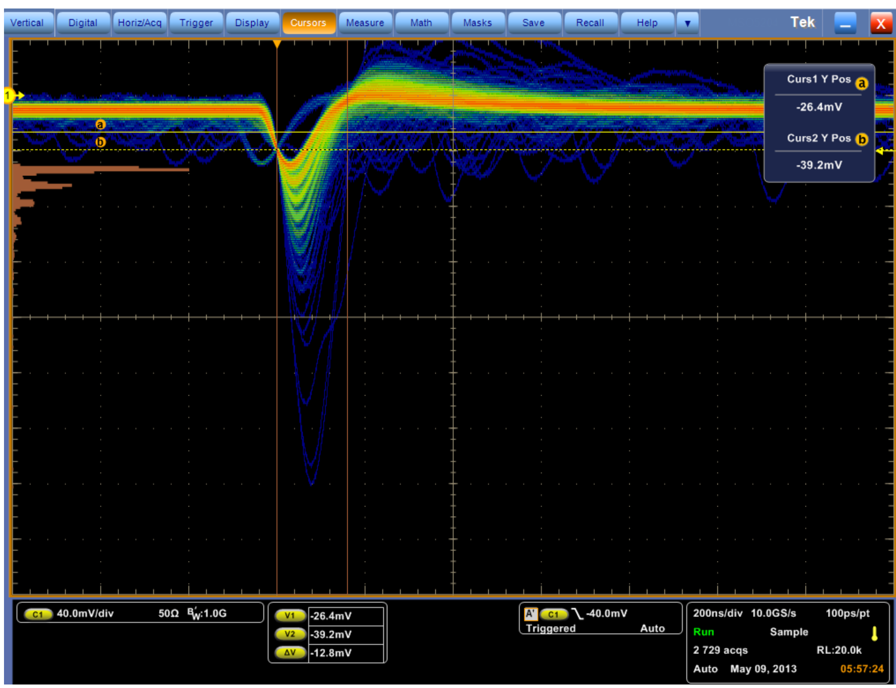
Bis-MSB coated cast acrylic
25 mm x 6 mm x 2.25 m bars
4 bars per paddle
SiPM readout



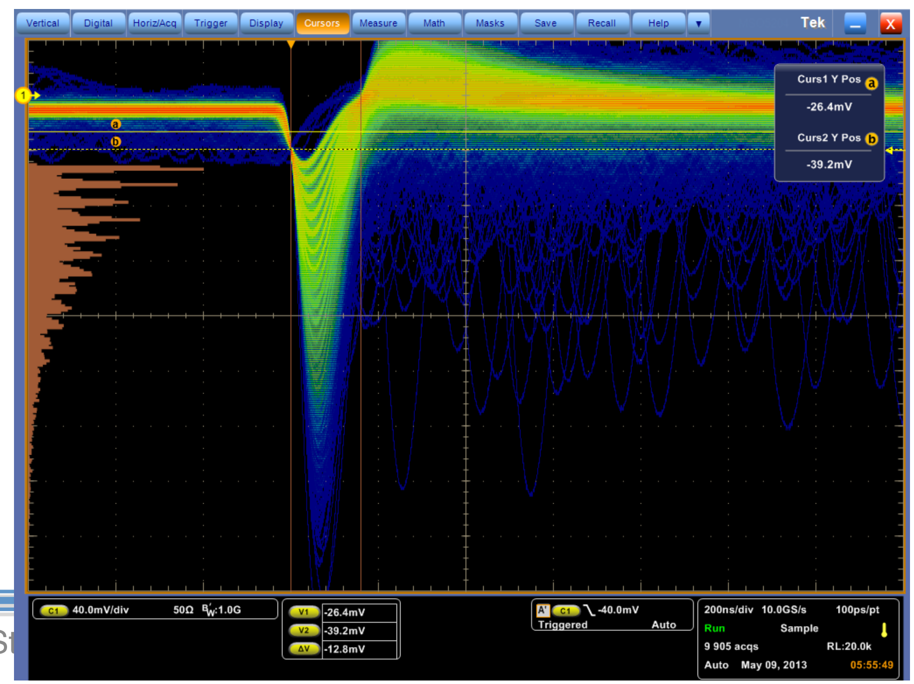
WLS-coated Light-guide Paddle Concept

- Progress to date (S. Mufson et al., Indiana U):
  - Identified bis-MSB as an inexpensive but effective WLS material
  - Have characterized absorption spectrum of bis-MSB & TPB w/ VUV monocrhomator
  - Have developed method of spraying / curing bars with bis-MSB or TPB
  - Have seen alpha's in LAr with PMT and SiPM (below) readout of bars
  - Have also seen cosmic rays → planning test of 50cm bars in large dewar at FNAL this fall
  - Plan to install bars in prototype APAs for 35ton Phase-II test in 2014

Alpha source turned away from bar



Alpha source turned toward bar



Near Detector Physics

- Characterize beam for Long-Baseline measurements
- Evidence for sterile neutrinos
- Large dataset for neutrino interaction studies

Production mode	1 x 10^{20} POT Rate/ton* of Ar
CC QE ($\nu_\mu n \to \mu^- p$)	50K
NC elastic ($\nu_\mu N \to \nu_\mu N$)	18K
CC resonant π^+ ($\nu_\mu N \to \mu^- N \pi^+$)	68K
CC resonant π^0 ($\nu_\mu n \to \mu^- p \pi^0$)	16K
NC resonant π^0 ($\nu_\mu N \to \nu_\mu N \pi^0$)	16K
NC resonant π^+ ($\nu_\mu p \to \nu_\mu n \pi^+$)	6.9K
NC resonant π^- ($\nu_\mu n \to \nu_\mu p \pi^-$)	6.0K
CC DIS ($\nu_\mu N \to \mu^- X$, $W > 2$)	69K
NC DIS ($\nu_\mu N \to \nu_\mu X$, $W > 2$)	24K
CC coherent π^+ ($\nu_\mu A \to \mu^- A \pi^+$)	3.9K
NC coherent π^0 ($\nu_\mu A \to \nu_\mu A \pi^0$)	2.0K
NC resonant radiative decay ($N^* \to N\gamma$)	0.11K
Inverse Muon Decay ($\nu_\mu e \to \mu^- \nu_e$)	12
$\nu_\mu e^- \to \nu_\mu e^-$	29
Other	42.6K
Total CC	236K
Total NC+CC	322K

* 120 GeV proton beam, 250 kA horn current,
2-m radius x 250-m decay pipe
No detector efficiency/acceptance