Long-Baseline Neutrino Experiment

Milind Diwan

for the LBNE Collaboration

ICFA Neutrino Panel, Paris
9 January, 2014

Long-Baseline Neutrino Experiment in US

LBNE configuration is:

- **A horn-produced broad-band beam with 60-120 GeV protons at 700 kw (upgradable to 2.3 MW) from FNAL.**
- **Planning change: 700 kw → 1.2 MW at LBNE start.**
- **A baseline of 1300 km towards the Sanford Underground Research Facility in Lead, South Dakota.**
- **A 35 kt fiducial volume liquid argon time projection chamber located at the 4850 ft level.**
- **A high resolution near detector at FNAL.**
- **This configuration will be achieved in a phased manner according to financial constraints.**

LBNE Science Collaboration

- **452 members, 82 institutions, 6 countries (Sept. 2013)**
- The collaboration has well-organized scientific and technical working groups.
- There is frequent communication with the funding agencies.

- 357 US + 95 non-US
  - 21% non-US; 26% of faculty/scientists
  - Significant growth since CD-1
  - We anticipate the collaboration to grow to 600-700 members.

Alabama
Alfenas
Argonne
Banaras Hindu
Boston
Brookhaven
Cambridge
Campinas
Catania
CBPF
Columbia
Chicago
Colorado
Colorado State
Columbia
Dakota State
Davis
Delhi
Drexel
Duke
Duluth
Feira de Santana
Fermilab
GSSI
Goias
Hawaii
HRI
IIT Guwahti
Indiana
Iowa State
Irvine
Kansas State
Kavli/IPMU-Tokyo
Lancaster
Lawrence Berkeley NL
Livermore NL
LNGS
London UCL
Los Alamos NL
Louisiana State
Manchester

Maryland
Michigan State
Milano
Milano Bicoca
Minnesota
MIT
Napoli
NGA
New Mexico
Northwestern
Notre Dame
Oxford
Padova
Panjab
Pavia
Pennsylvania
Pittsburgh
Princeton
Rensselaer
Rochester
Sanford Lab
Sheffield
SLAC
South Carolina
South Dakota
South Dakota State
SDSMT
Southern Methodist
Sussex
Syracuse
Tennessee
Texas, Arllington
Texas, Austin
Tufts
UCLA
Virginia Tech
Warwick
Washington
William and Mary
Wisconsin
Yale

Fort Collins, September 2013

LBNE Collaboration - Detail

	Faculty	Postdocs	Students	Engineers	Unknown	TOTAL
Brazil	8	1	-	-	-	9
India	8		-	-	-	8
Italy	27	10	-	-	-	37
Japan	1		-	-	-	1
UK	27	5	4	4	-	40
US	206	64	37	44	6	357
TOTAL	277	80	41	48	6	452
Non-US	71	16	4	4	0	95
Fraction non-US	26%	20%	10%	8%	0%	21%

The US intention is to create an international project at FNAL with these and additional partners. The partnerships are likely to extend to the accelerator complex at FNAL. The collaboration will be appointing an International Advisory Group soon.

We expect considerable growth as further discussions take place.

Scientific Priorities

- **LBNE design follows these priorities**
  - ➡ **CP violation in the neutrino sector**
  - ➡ **CP phase measurement regardless of its value.**
  - ➡ **Neutrino mass hierarchy determination.**
  - ➡ **Determination of θ_{23} octant and precision parameter measurements.**
  - ➡ **Precision tests of 3-flavor neutrino model.**
  - ➡ **Atmospheric neutrino measurements (confirmation of mass ordering with independent data)**
  - ➡ **Nucleon decay**
  - ➡ **Supernova burst neutrinos**
  - ➡ **As a very capable near detector will be needed, it is recognized that it could have a synergistic scientific program of precision neutrino and weak interaction physics.**

} comprehensive program with beam neutrinos

Experimental Strategy

- **Our experimental focus is on $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$anti-ν_e with superb particle identification and energy resolution, as this channel is most suitable for current neutrino beam and detector technologies.**

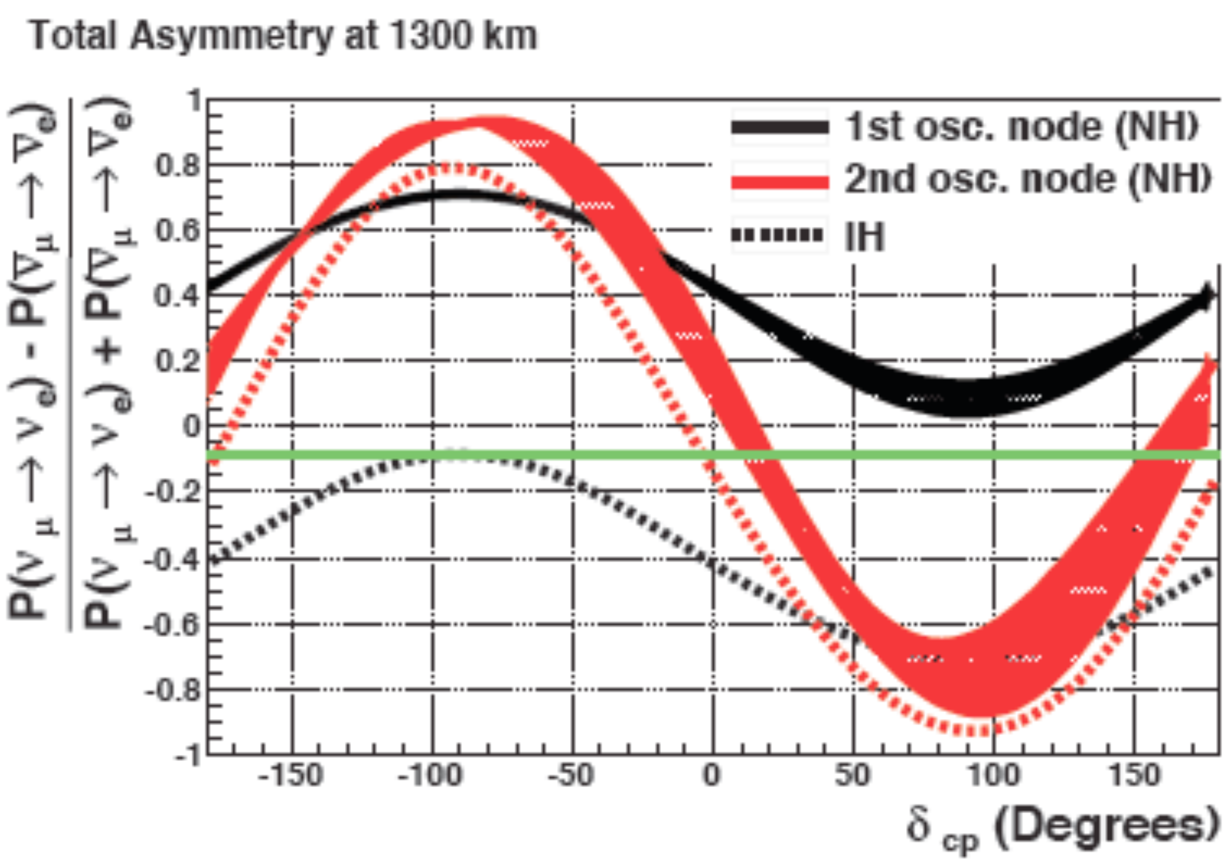
- **The measured neutrino mixing parameters in the 3-flavor framework suggest that the CP asymmetry will be <30% (first max) and therefore >1000 events are needed.**

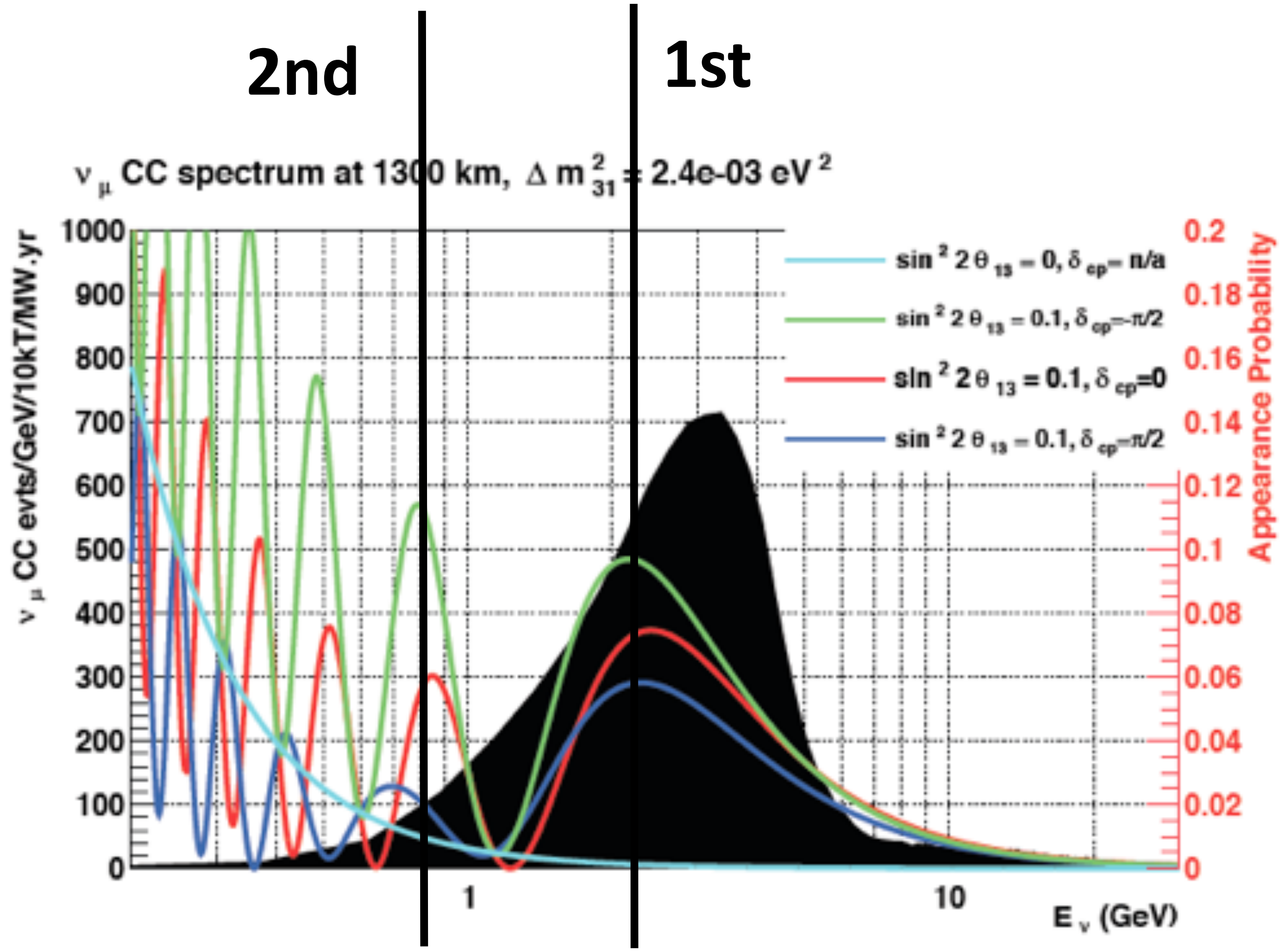
- **World-wide studies have concluded that beams with 1-2 MW of power at high energies and unprecedented large far detector fiducial mass is needed regardless of baseline to achieve above statistics.**

- **A baseline of >1000 km and a broad-band beam are needed for a comprehensive experiment with sensitivity to CP asymmetry, mass ordering and spectral shape.**

- **Detector must have sufficient overburden to allow sensitivity to nucleon decay and supernova.**

Neutrino Asymmetries



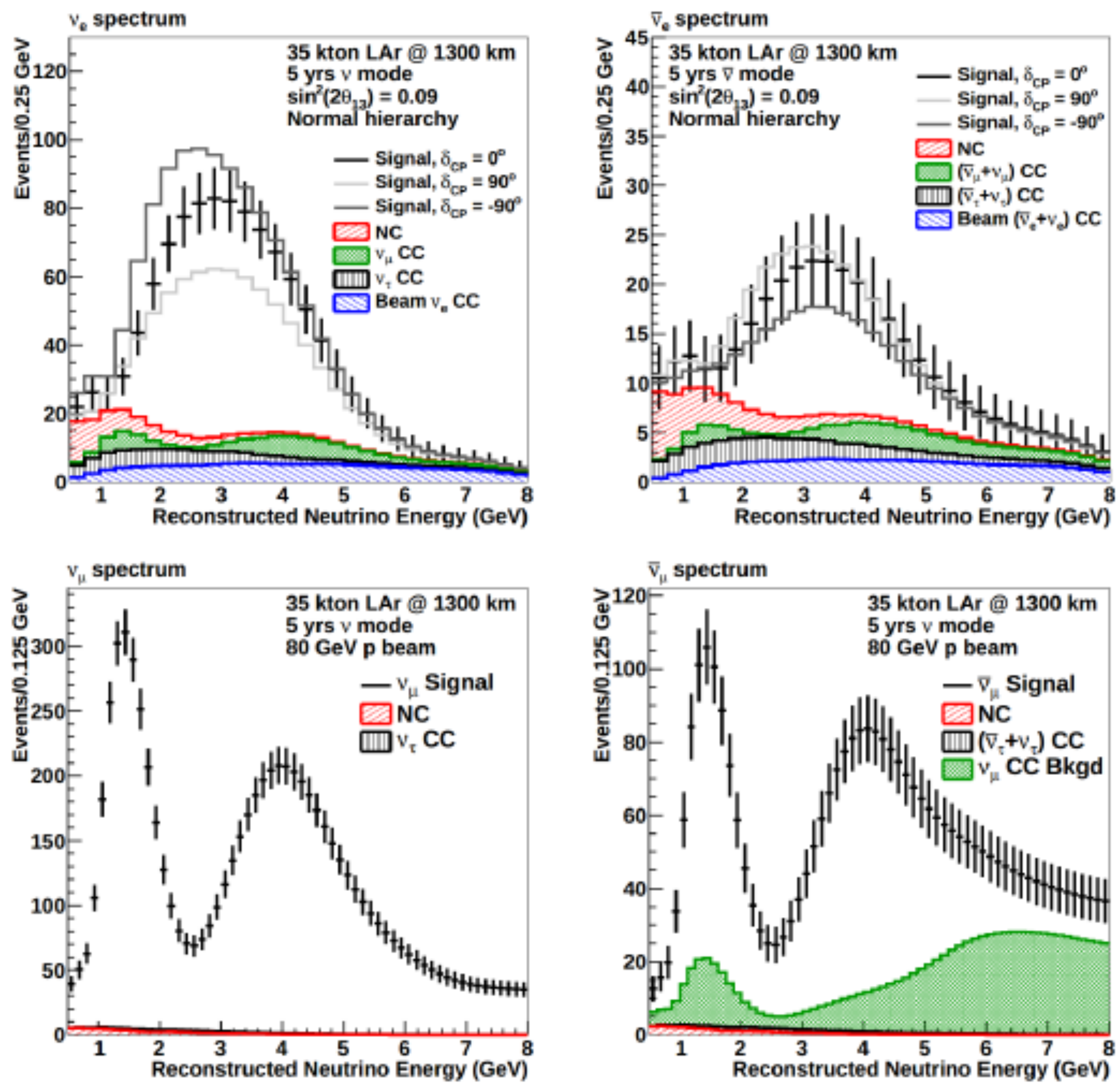


- **At 1300 km the events from 1st and 2nd maximum (and in-between) can measure the asymmetries from both CP and matter effect.**
- **With sufficient statistics all ambiguities can be resolved. We need ~1000-2000 events with good resolution.**
- **The requirement for statistics and low systematics is difficult and common for all proposals.**

Event rate and spectra expectation.

Assumptions:
35 kt LArTPC
1.2 MW operation at 80 GeV.
~3 yrs for each polarity.
Normal Hierarchy
δ_{CP}= 0
Rest of the parameters are at best fit from 2012

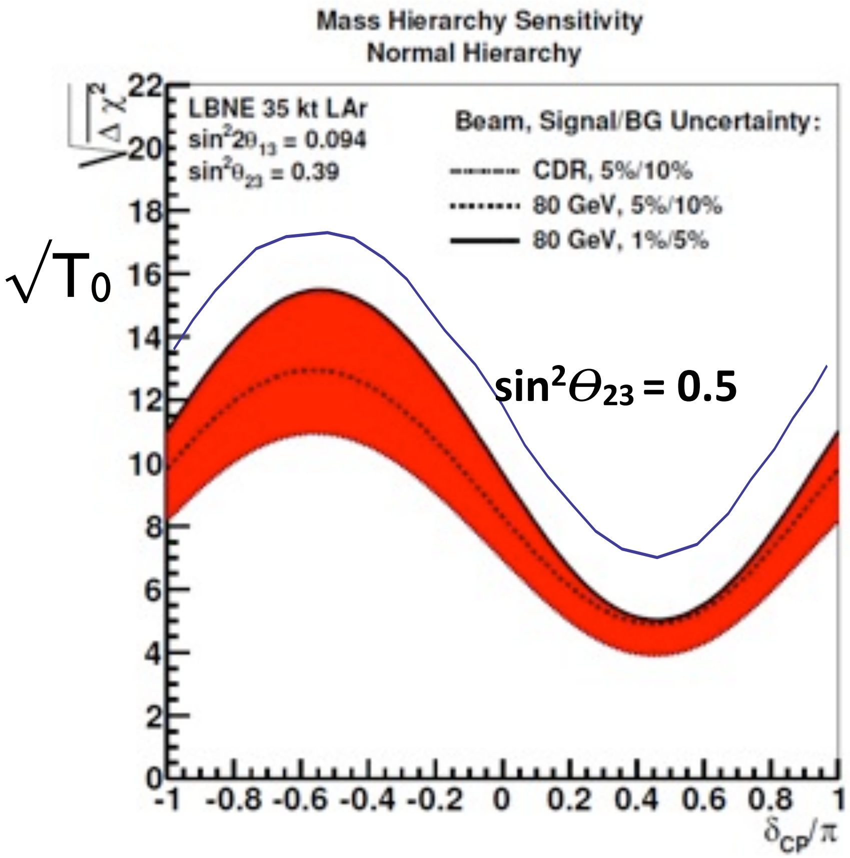
80 GeV Beam	ν mode	$\bar{\nu}$ mode
Signal: $\nu_e + \bar{\nu}_e$	777	189
BG: NC	67	39
BG: $\nu_\mu + \bar{\nu}_\mu$ CC	84	39
BG: Beam $\nu_e + \bar{\nu}_e$	147	81
BG: $\nu_\tau + \bar{\nu}_\tau$ CC	49	32

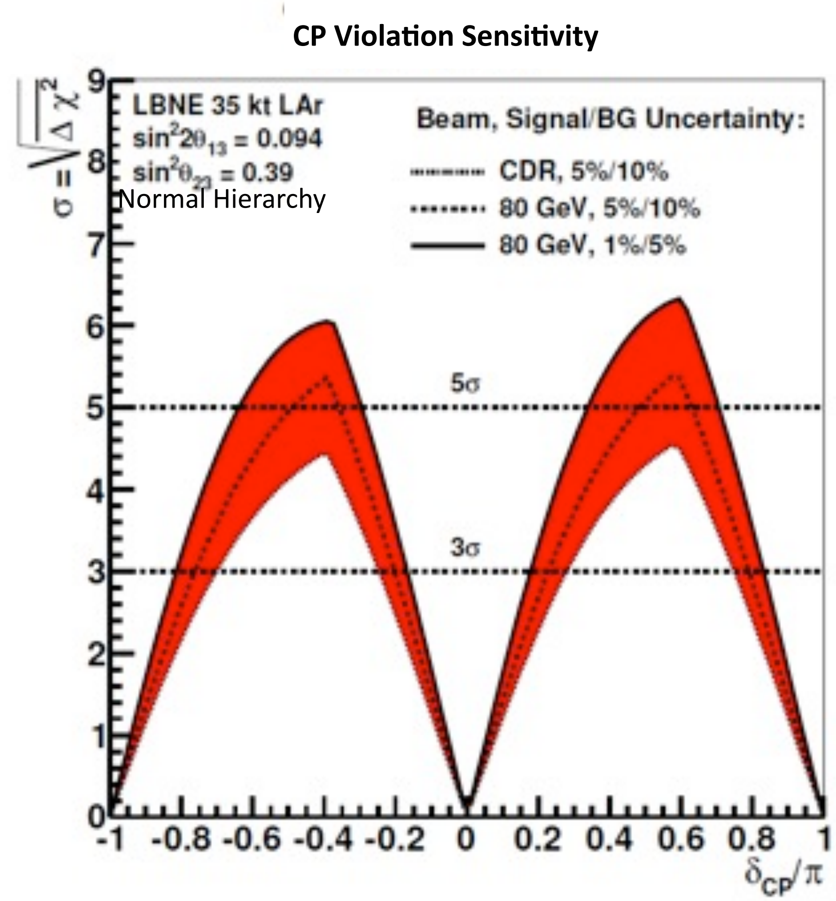


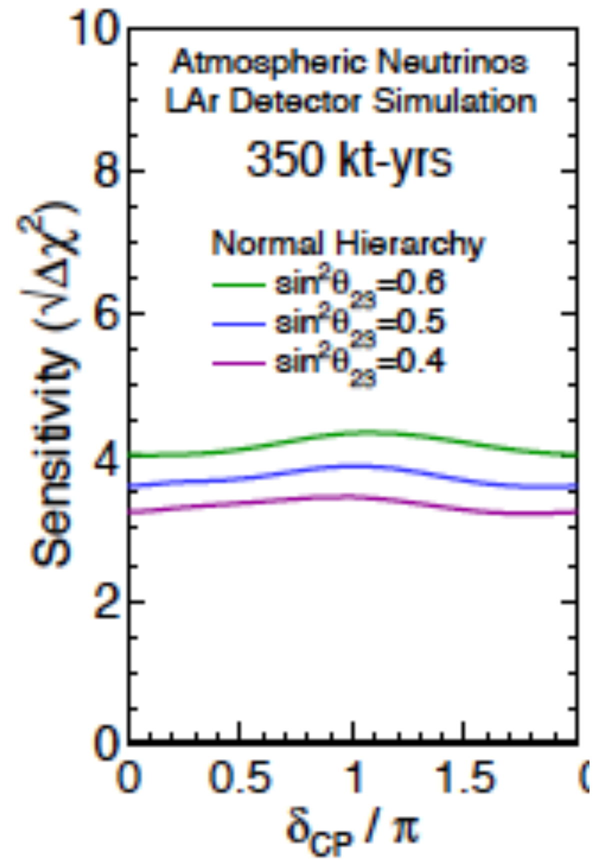
- **At 1300 km full oscillation structure is visible in the energy spectrum. A combined spectral fit provides unambiguous parameter sensitivity in a single experiment.**

Sensitivity

median sensitivity to reject IH







Exposure 245 kt.MW.yr

1.2 MW x 35 kt x(3ν+3$\overline{\nu}$) yr

Parameter sensitivity to $\sin^2\Theta_{23}$ = 0.39 → 0.5

- **For NH versus IH hypothesis testing, following PDG two-hypothesis testing formalism, we find that α = β < 0.13% to be a sufficient criteria. These are probabilities of either rejecting the correct hierarchy or accepting the wrong one, respectively, for the worst case assumptions on parameters.**
- **LBNE will produce two independent checks on hierarchy (beam and ATM nus) with median sensitivity > 36 (beam) or >9 (atmospheric).**

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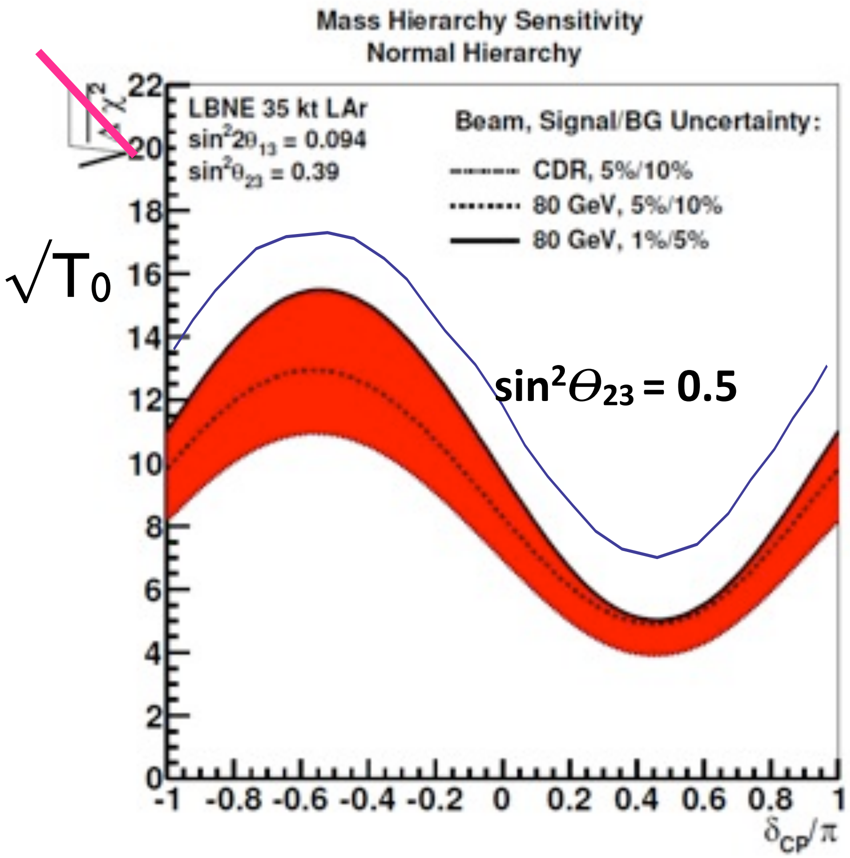

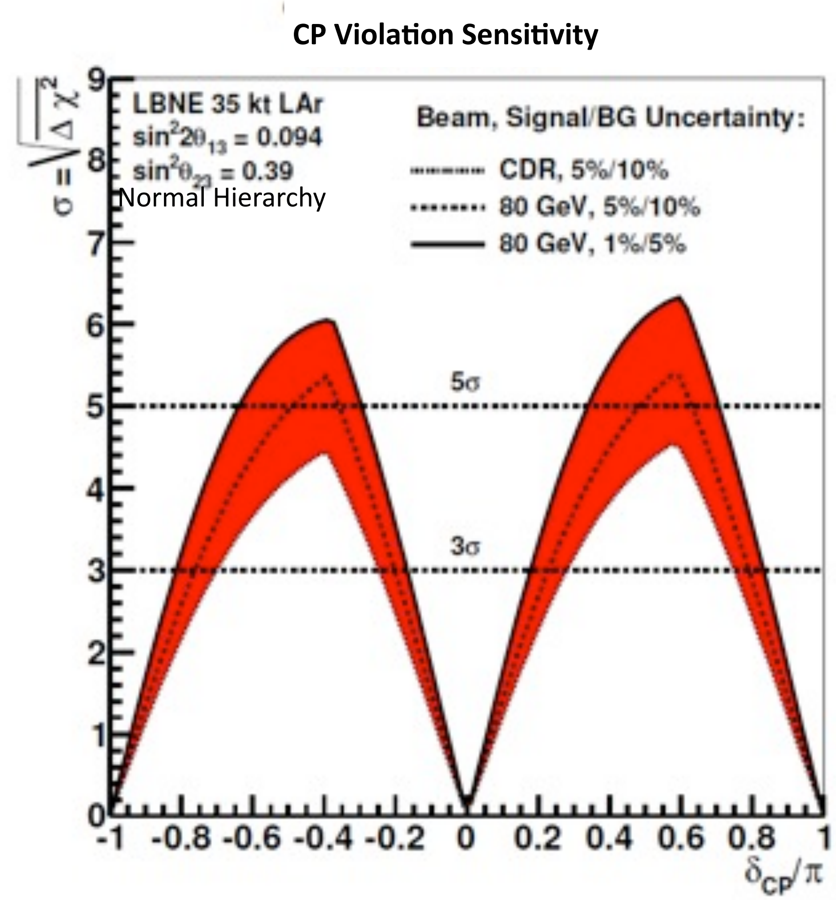

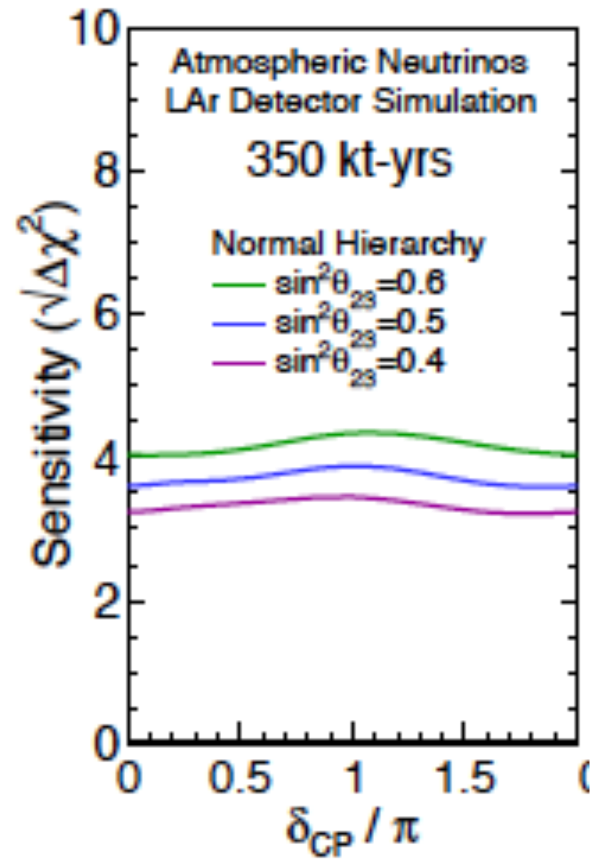

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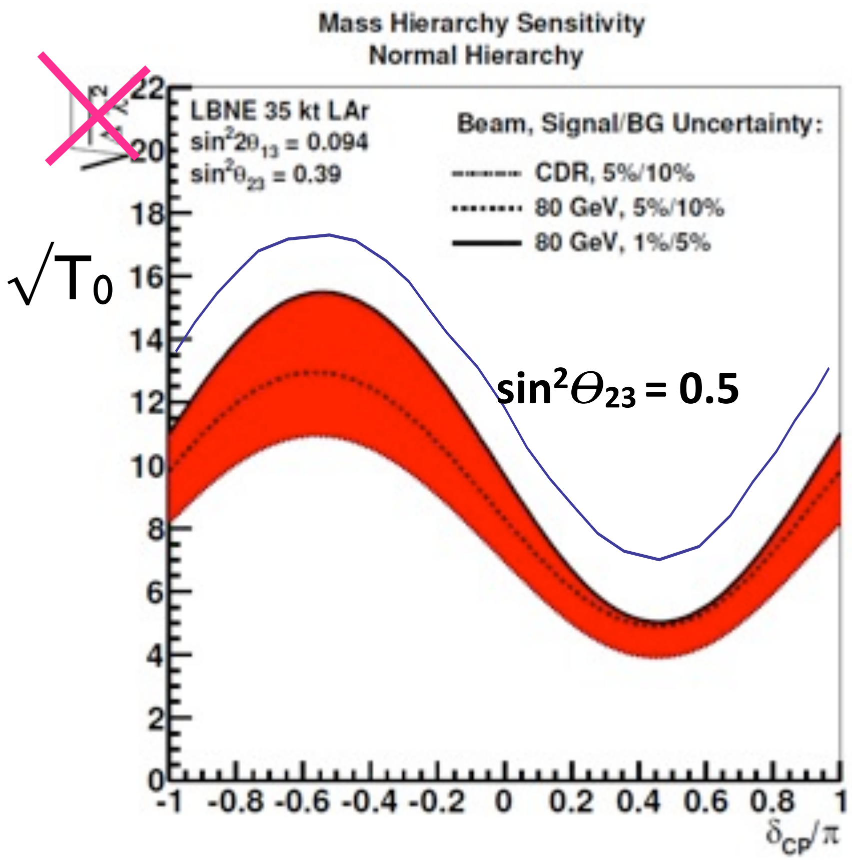

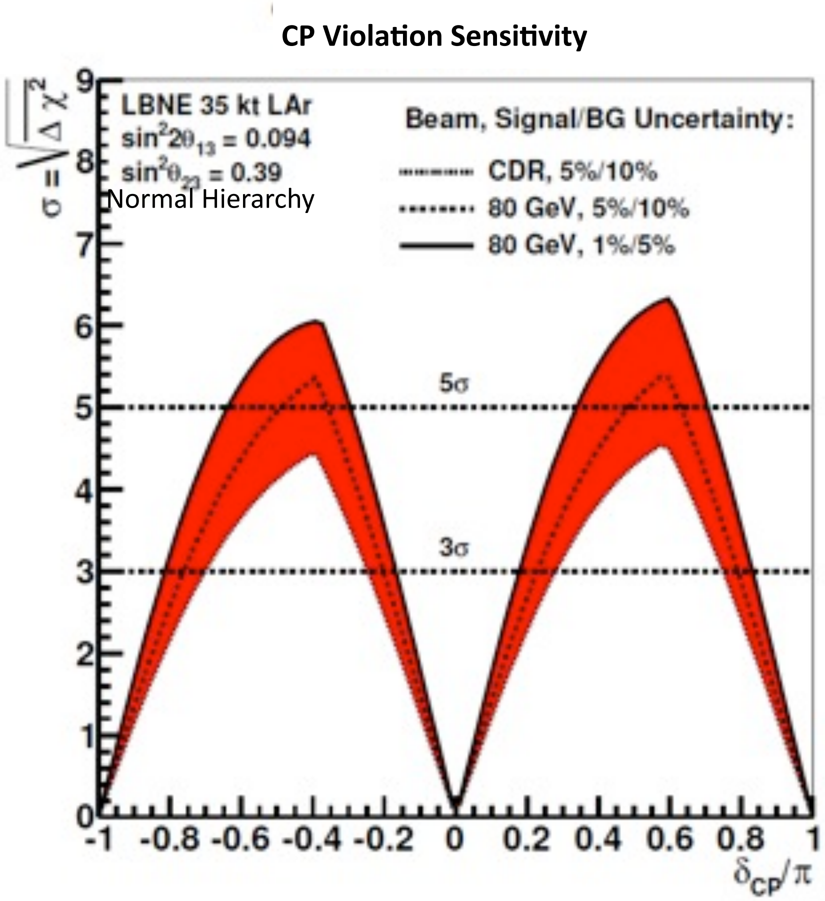

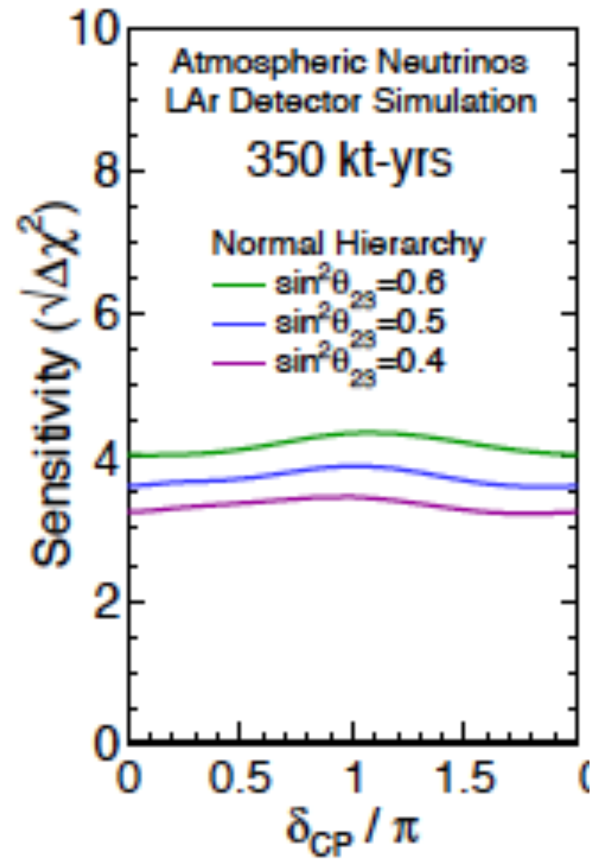

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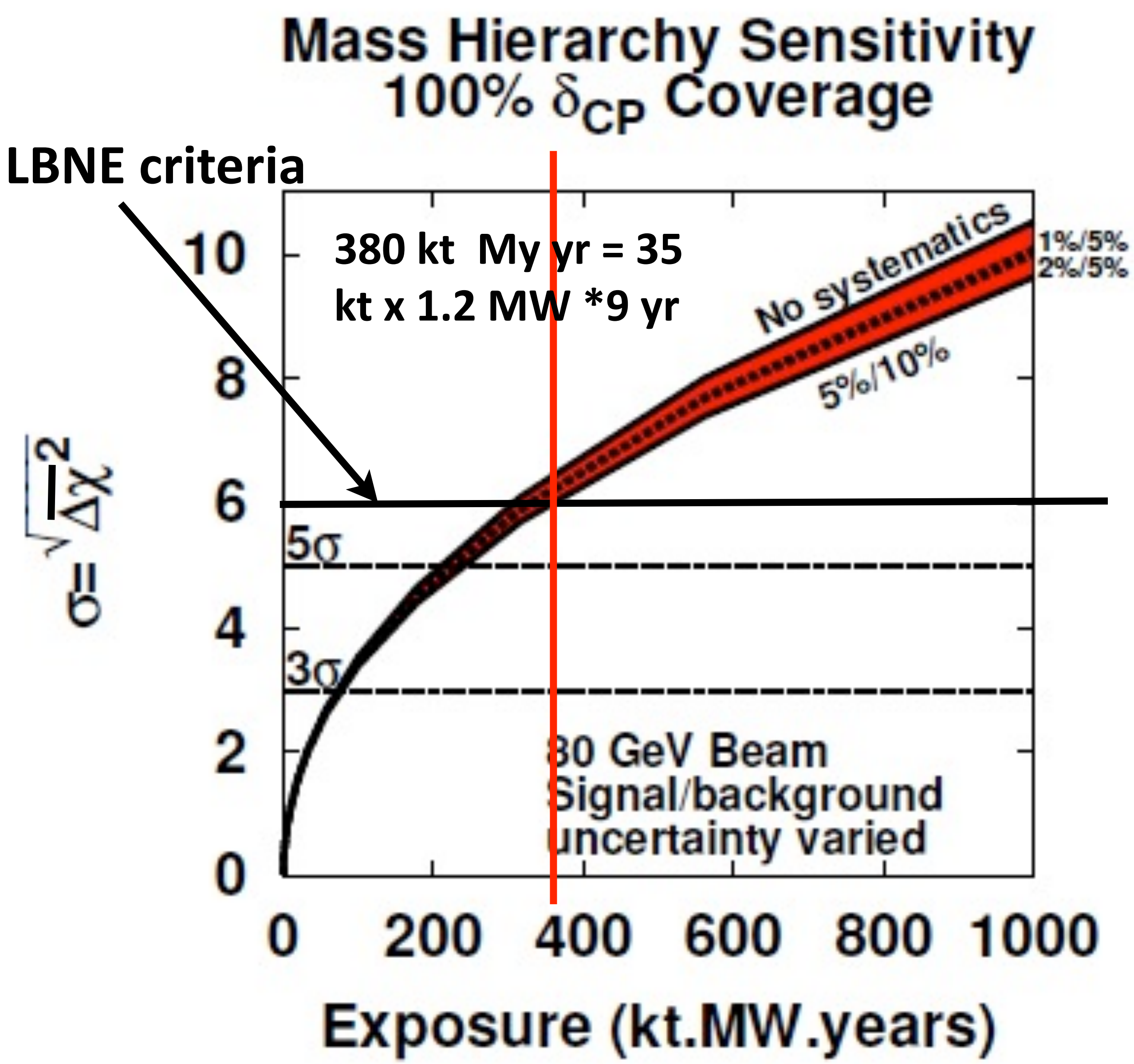
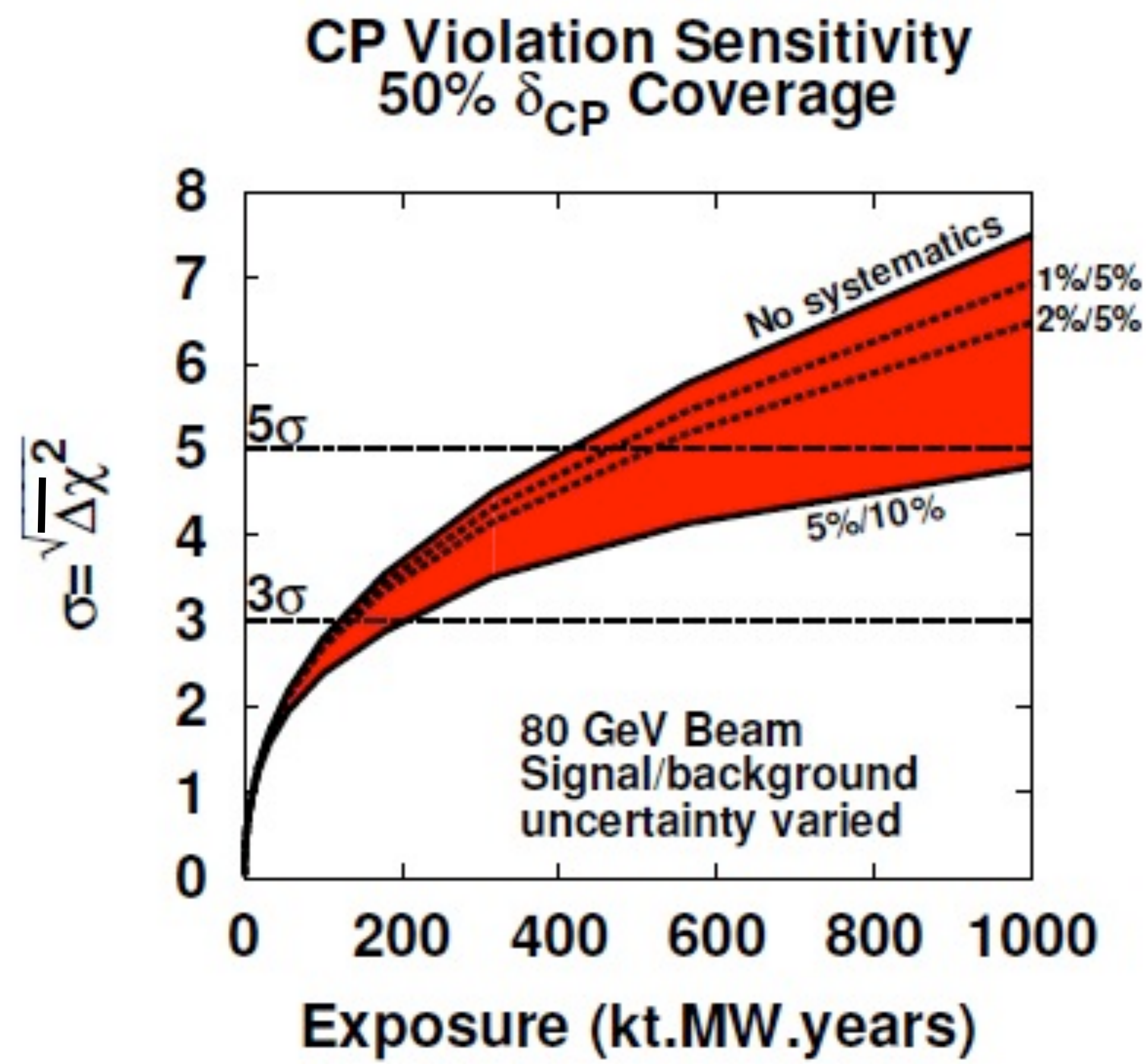
Impact of Normalization Uncertainties





- **All experiments aiming to measure CP violation need to reduce errors.**
- **The systematic precision is required to be better than the expected statistics at each stage of the experiment. High precision is needed after 200kt*MW*yr.**
- **MH relatively insensitive to systematics; but further study needed.**
- **MINOS appearance result has achieved better than 5%/5% systematics.**

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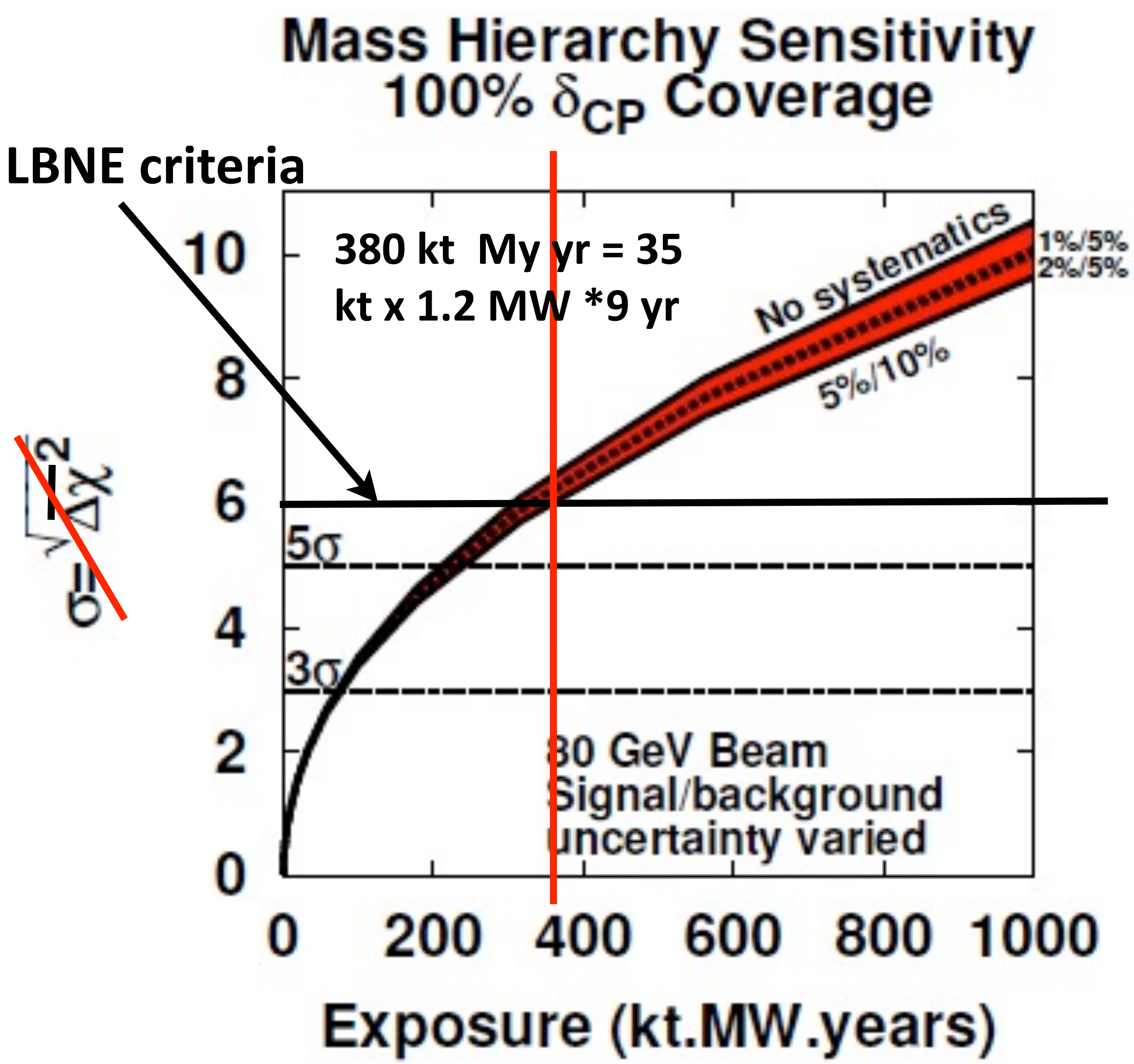

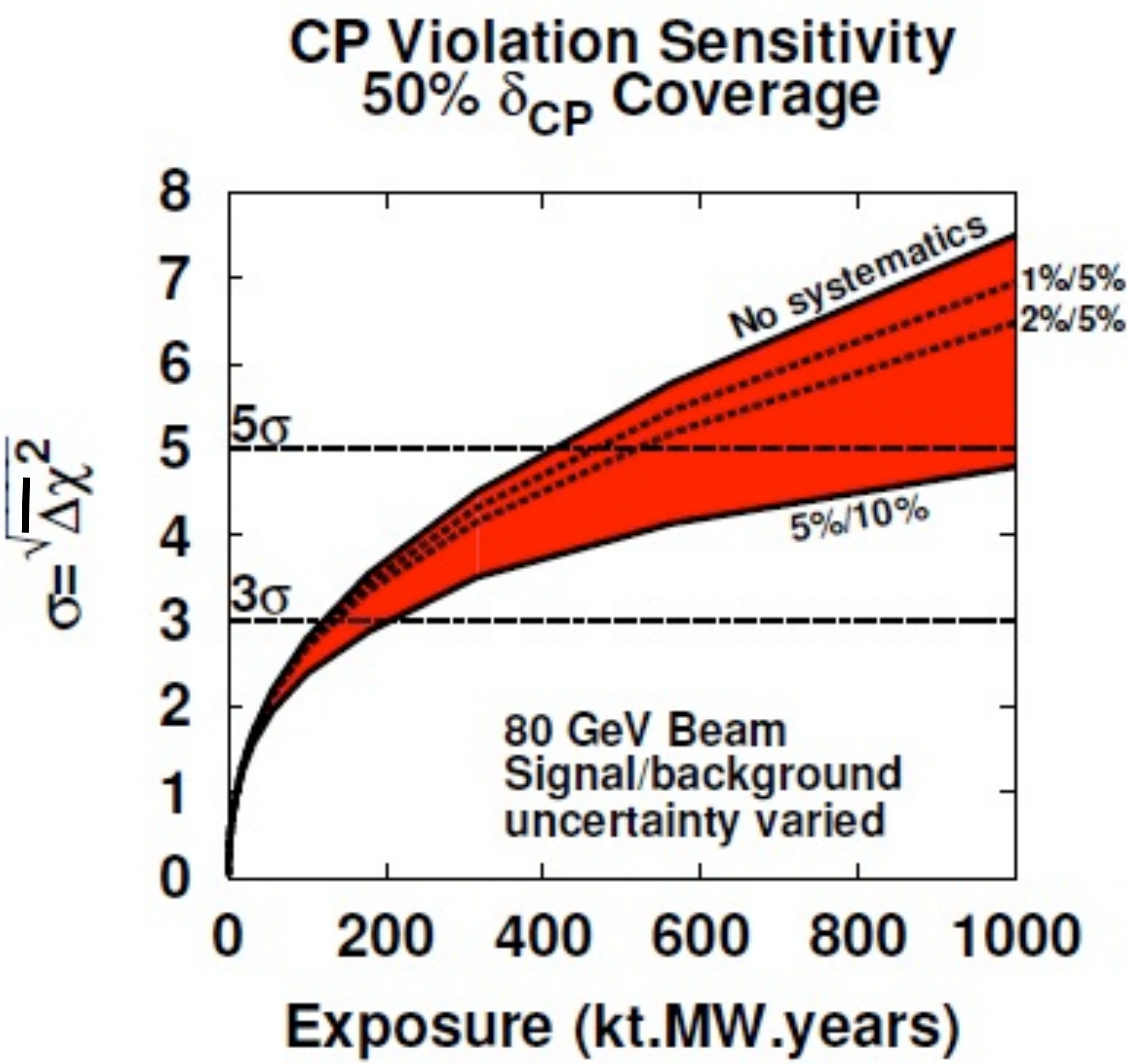

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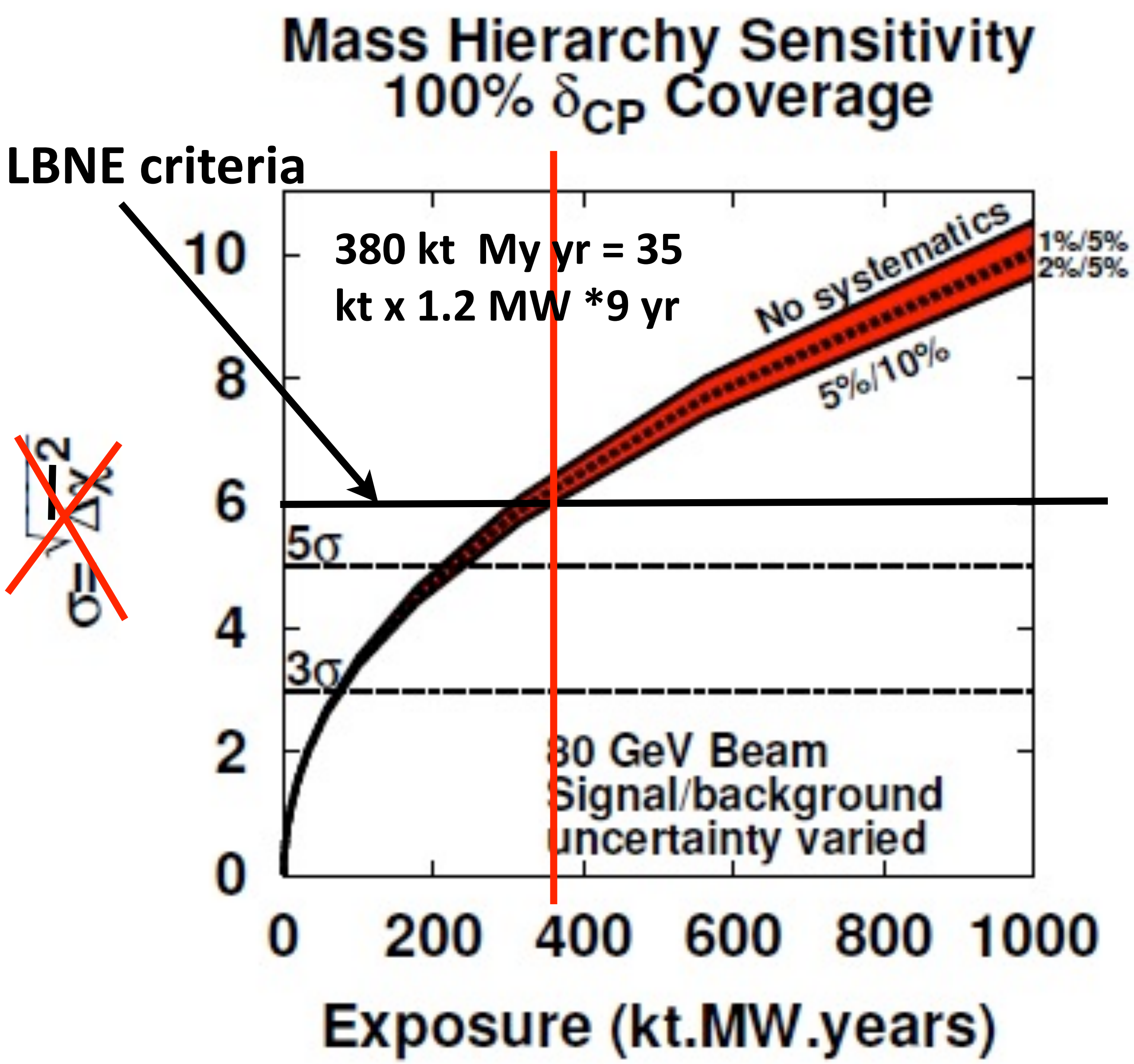

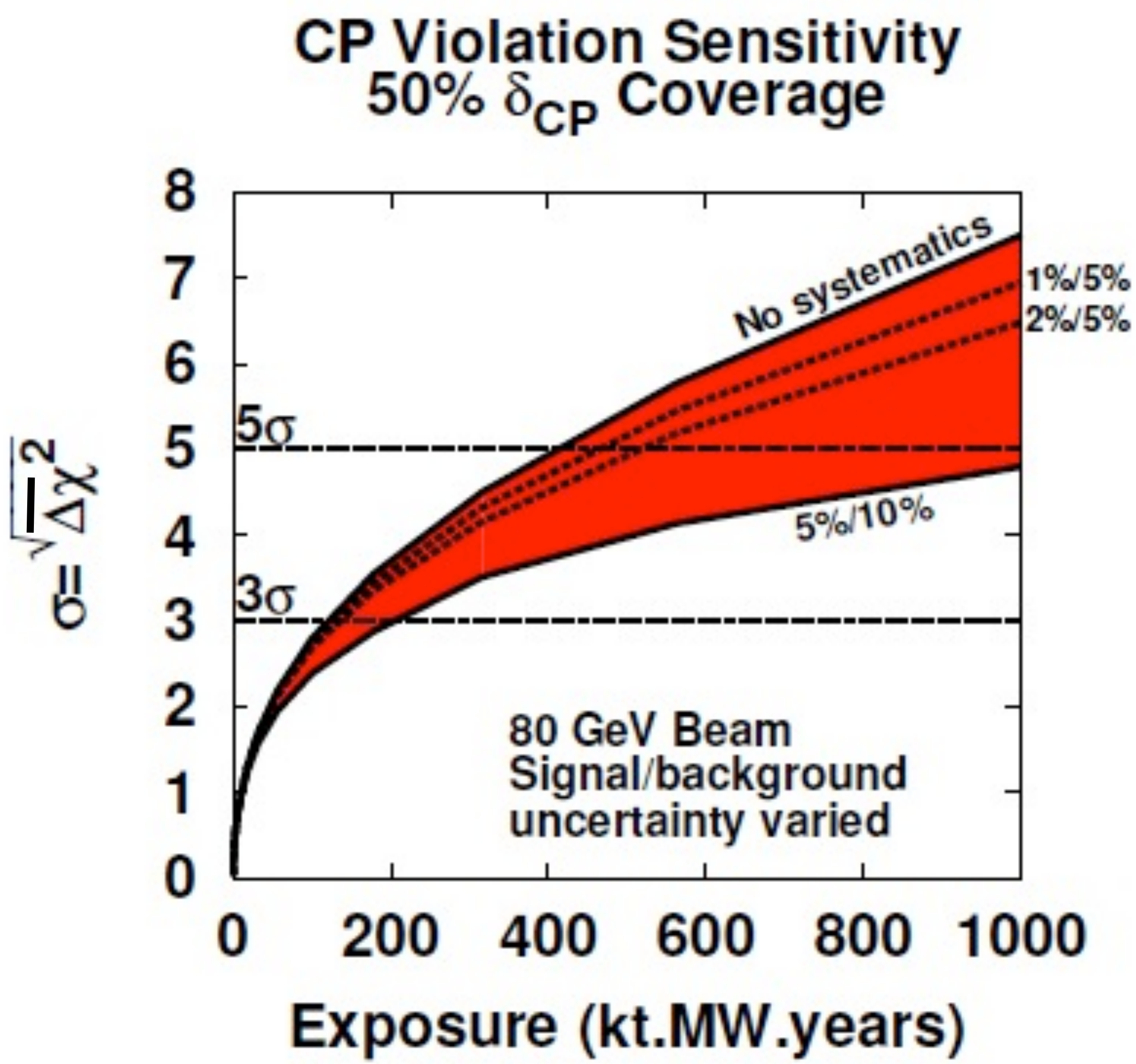

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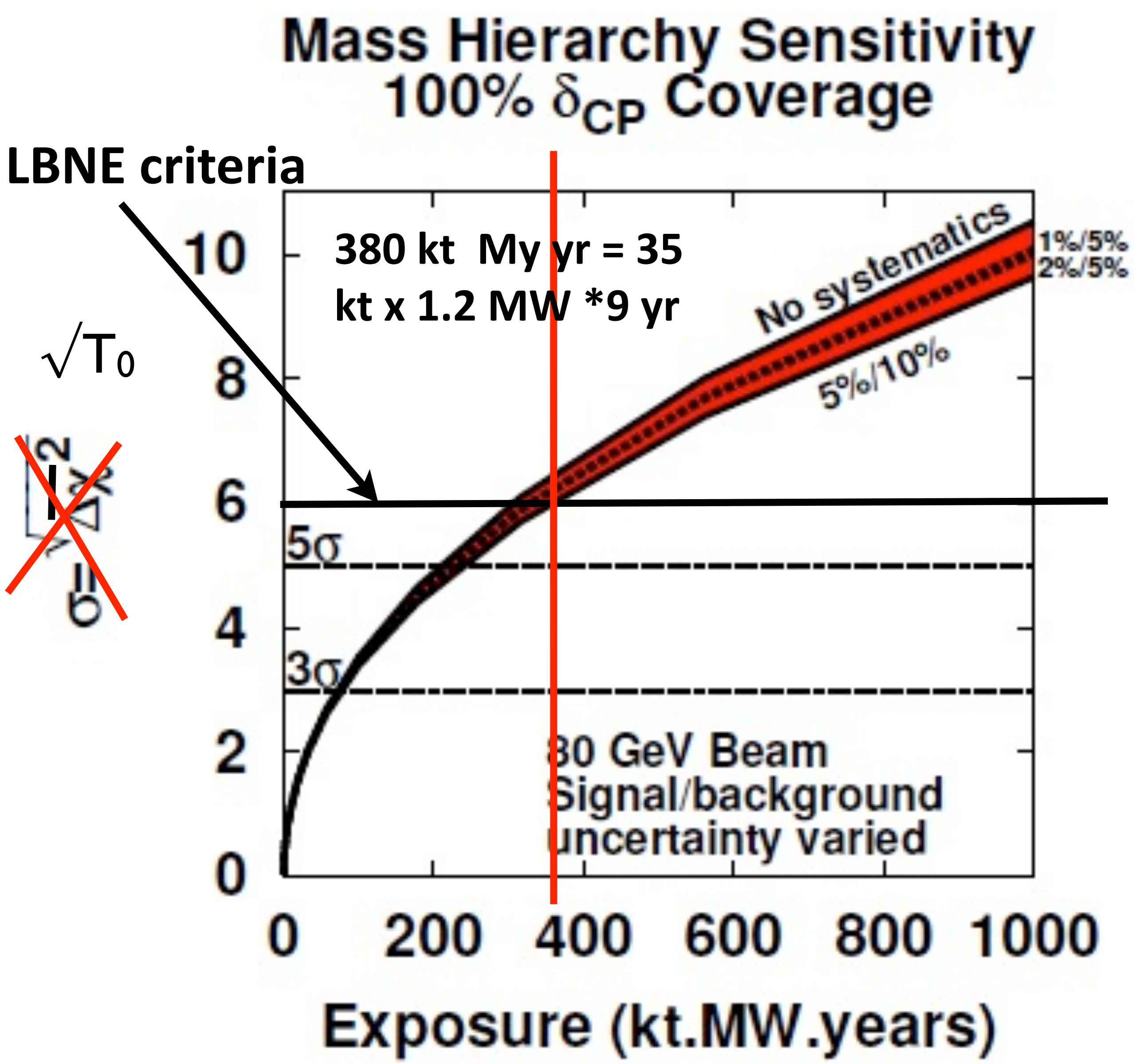

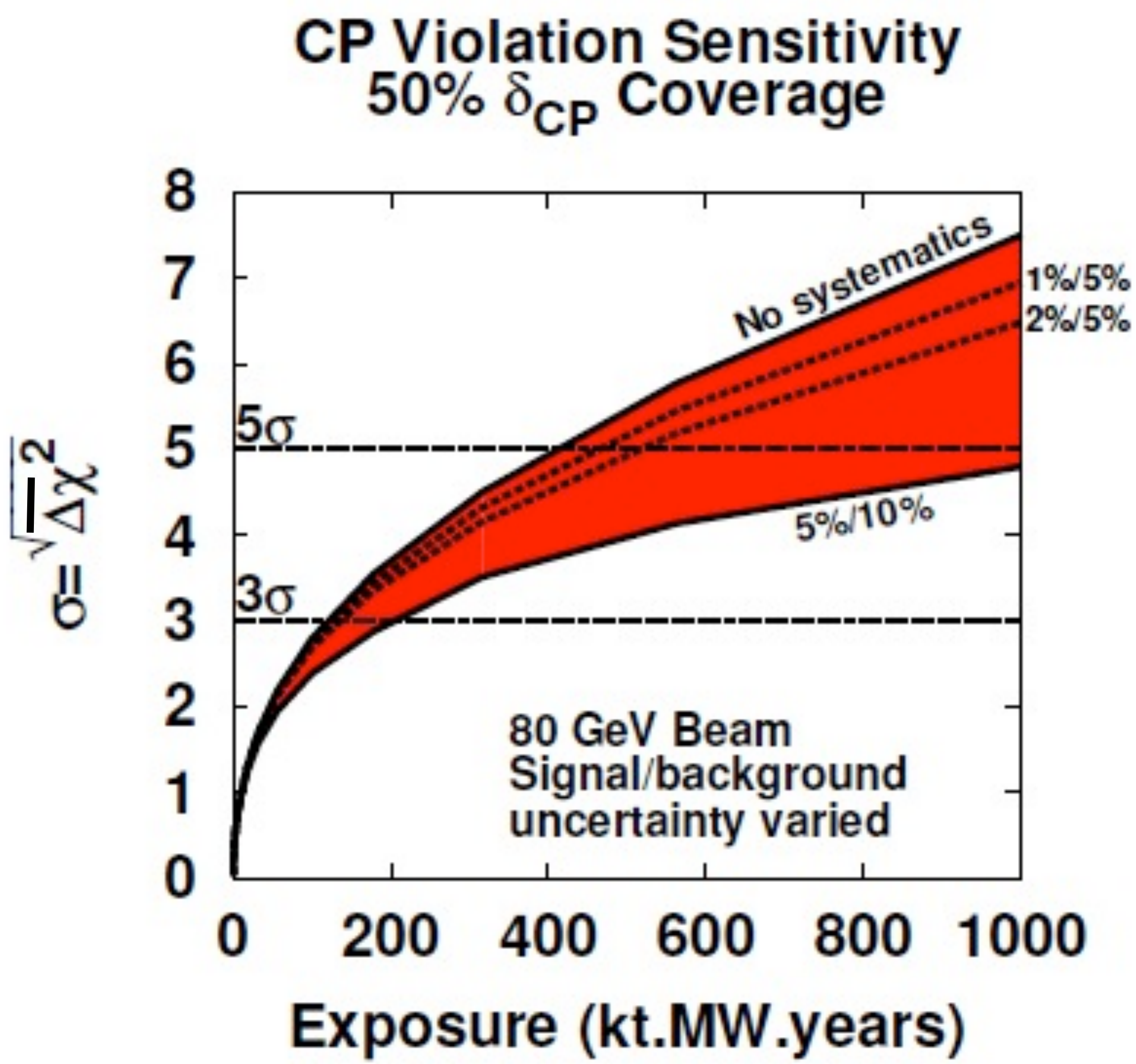

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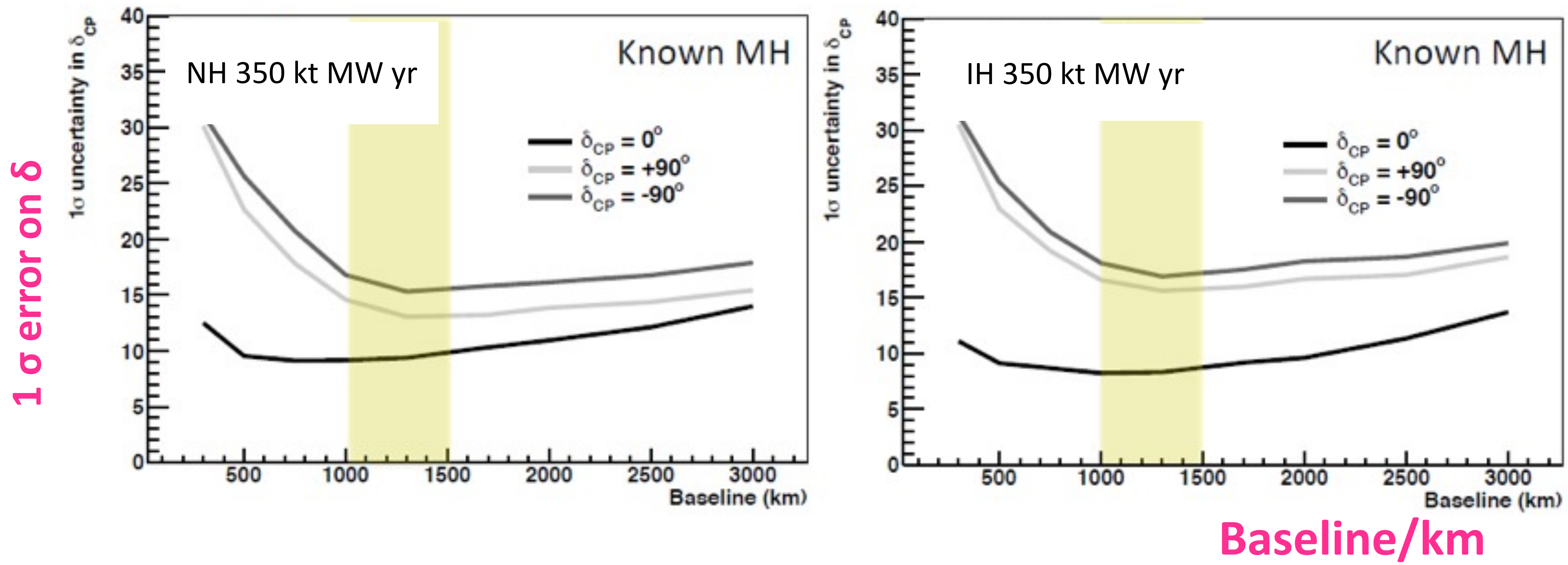
Baseline Optimization

- **Study of optimization of a long-baseline experiment by LBNE collaborators (arXiv: 1311.0212). For each baseline length, beam optimization was in a realistic way using simulations of a horn-produced beam with 120 GeV protons.**



- **The resolutions calculated as a function of exposure as well as baseline length. An optimum is obtained for phase resolution when there is sufficient shape information and statistics.**
- **The event rate at first and second maximum per unit exposure is largely independent of baseline due to kinematics.**

Further Scientific Issues

- **Since project start LBNE has addressed financial and schedule constraints. The CD1 conceptual design includes many compromises as well as opportunities.**
- **Phasing: Our intent remains to achieve the full LBNE configuration as soon as possible, but given the financial constraints we must examine intermediate steps for detector mass.**
- **Beam optimization: Possible enhancements by improvements to the decay pipe, horns, target, and lower energy running are under consideration.**
- **Possibility for Growth: The geotechnical studies at SURF will examine enough rock to accommodate >70 kt detector. The beam shielding will be designed to withstand >2.3 MW.**
- **FNAL is committed to increasing the beam power from the Main Injector in reasonable steps in parallel to LBNE.**

Detector Mass/Beam Power Scenario

- **Plausible timeline for a phased international program**

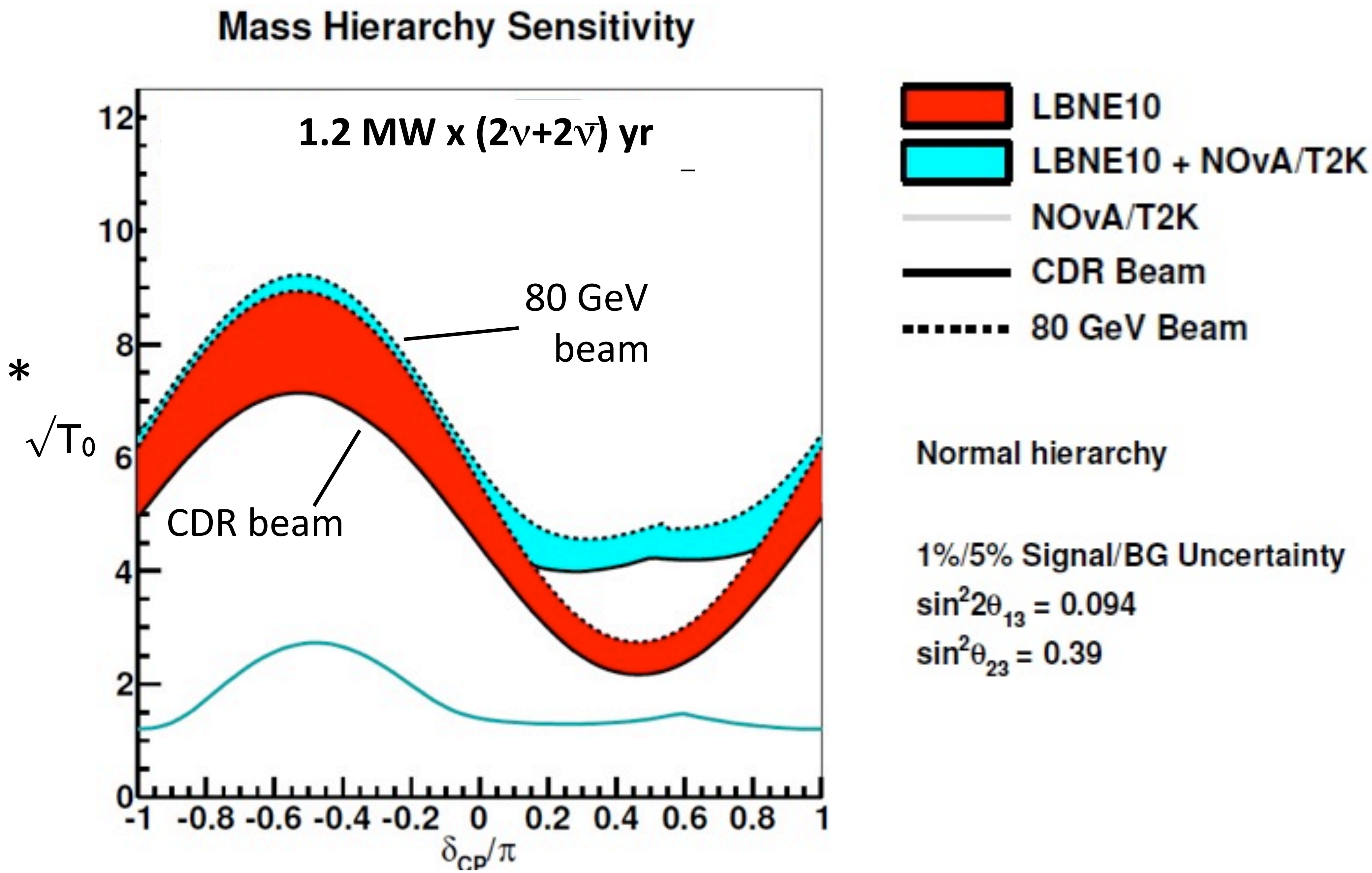
  - **2025-2030**
    Detector mass: 15 kt (fid.)
    Proton beam power: 1.2 MW
  - **Exposure: 90 kt.MW.yr**

- **2030-2035**
  Add 20 kt = 35 kt
  Proton beam power: 2.3 MW
- **Total Exposure: 490 kt.MW.yr**

Project Status and Schedule

- DOE has granted CD1 (critical decision on conceptual design with site decision) with $867M commitment with flexible scope in December of 2012.
- There is agreement that scope presented at CD1 (reduced surface FD, no ND) will be modified based on evolving partnerships.
- To get the full scope of LBNE (and money for operations), significant international partnerships and leadership are essential.
- The project schedule and funding profile from the DOE can be adjusted to produce the best global experiment. We intend to form an International Advisory Group of scientists to advise on collaborative and financial mechanisms with our respective funding agencies.
- The project will proceed according to the current DOE Critical Decision (CD) process modified to include multiple international partnerships. We have many examples to guide us including CMS, ATLAS, LHC, Daya Bay, etc.

MH Sensitivity – 15kt Far Detector



- **LBNE 15 kt has a significant probability to reject the wrong hierarchy. And in combination with T2K+NOvA we can cover all of δ_{CP} but not at T = 36**

The US DOE Critical Decision Process
We have assurance that this is flexible

- CD-0 (“Mission Need”) approves the need for the project.
- CD-1 (“Alternative Selection and Cost Range”) approves overall design, cost and schedule.
- CD-2 (“Performance Baseline”) approves the precise technical design, cost and schedule.
- CD-3A (“Approve Long-Lead Item Procurements”) approves early start of selected parts of the project.
- CD-3 (“Start of Construction”) approves the start of full construction of the rest of the project.
- CD-4 (“Project Completion”) approves transition to operations.

We are beyond CD1. CD2 will be a critical step that requires a complete Technical Design and essentially all R&D and prototyping to be completed.
We can modify this process to suit our collaborators.

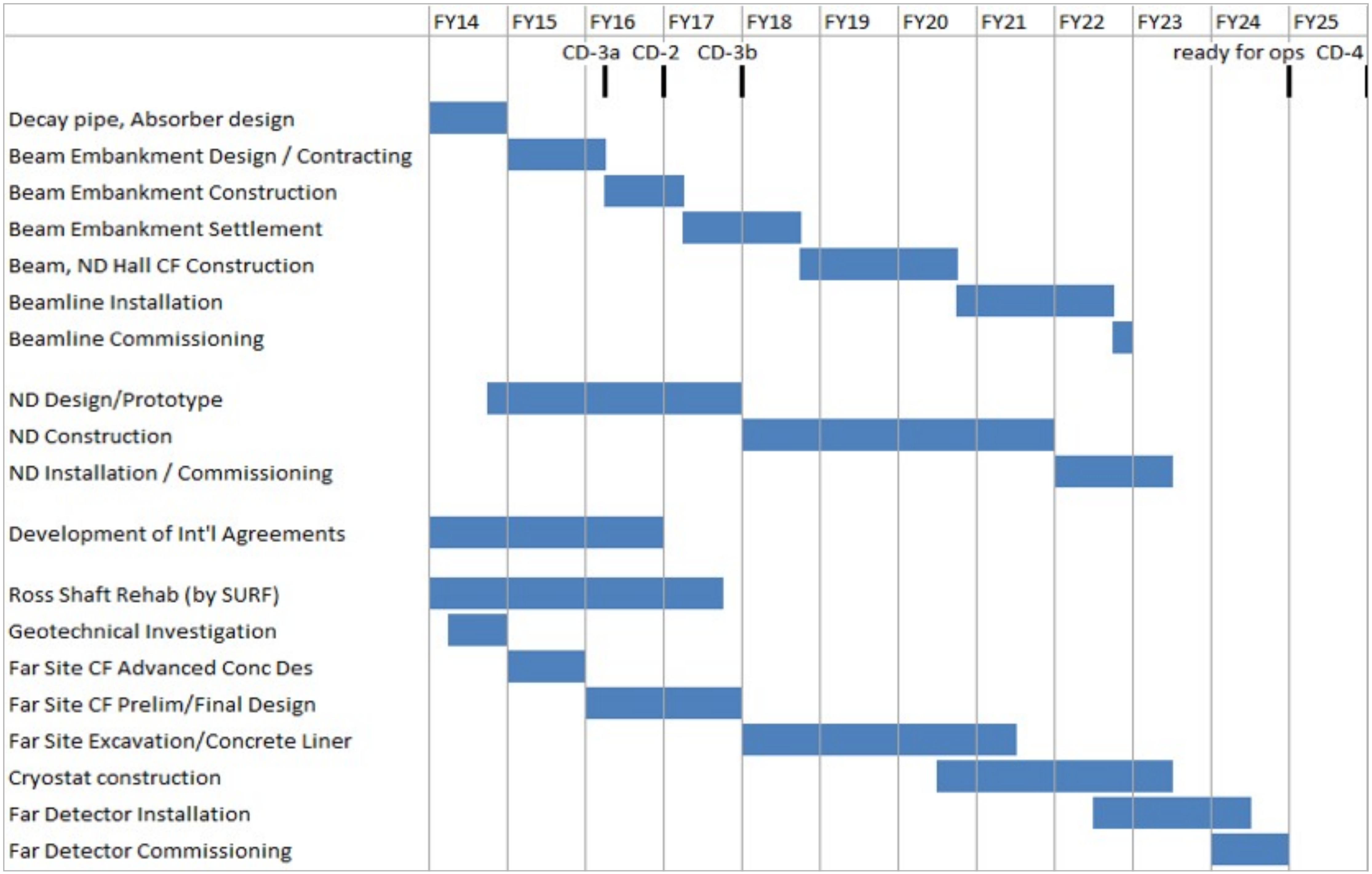
The US DOE Critical Decision Process
We have assurance that this is flexible

- 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. — *Mid 2016*
- CD-3 ("Start of Construction") approves the start of full construction of the rest of the project. — *Late 2017*
- CD-4 ("Project Completion") approves transition to operations. — *2024*

We are beyond CD1. CD2 will be a critical step that requires a complete Technical Design and essentially all R&D and prototyping to be completed.
We can modify this process to suit our collaborators.

Project Status and Schedule (cont.)

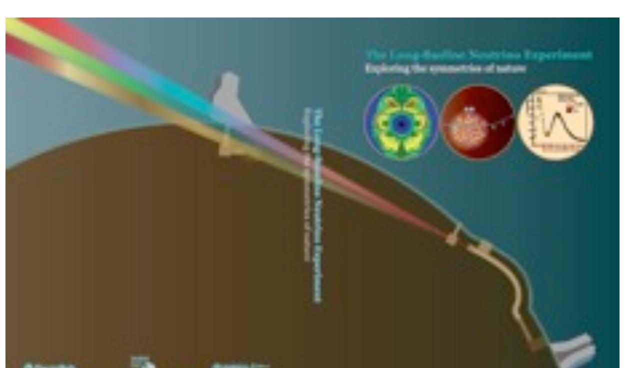
Plausible Schedule for international LBNE



We are attempting to accelerate this.

Conclusion

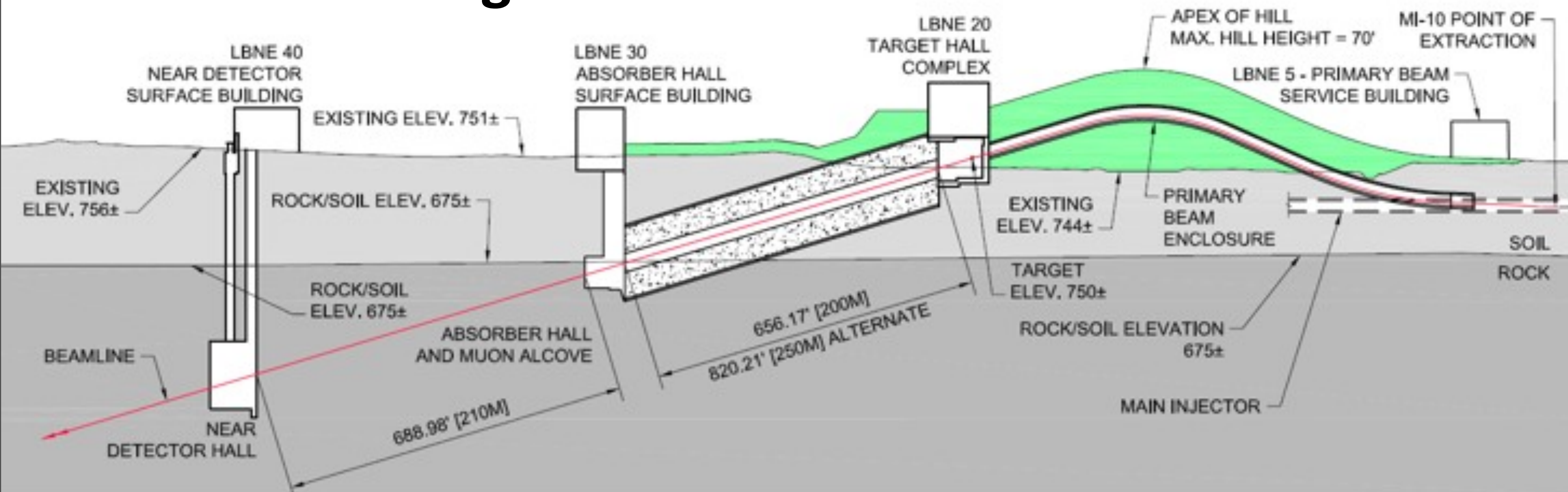
- **Scientific motivation and scale of the next generation long-baseline neutrino oscillation experiment is well-known. LBNE design in the US meets the requirements for a comprehensive experiment aimed towards CP violation in the neutrino sector.**
- **The US is in a unique position to execute this program given the availability of high intensity accelerator**
  - **700 kW upgrade in commissioning**
  - **1.2 MW by the time of LBNE start**
  - **Further upgrades to >2.3 MW**
- **An operating world-class Sanford Underground Research Facility (Dark Matter and Double Beta Decay experiments have started at 4850L)**
- **Optimal baseline for a comprehensive oscillation program.**

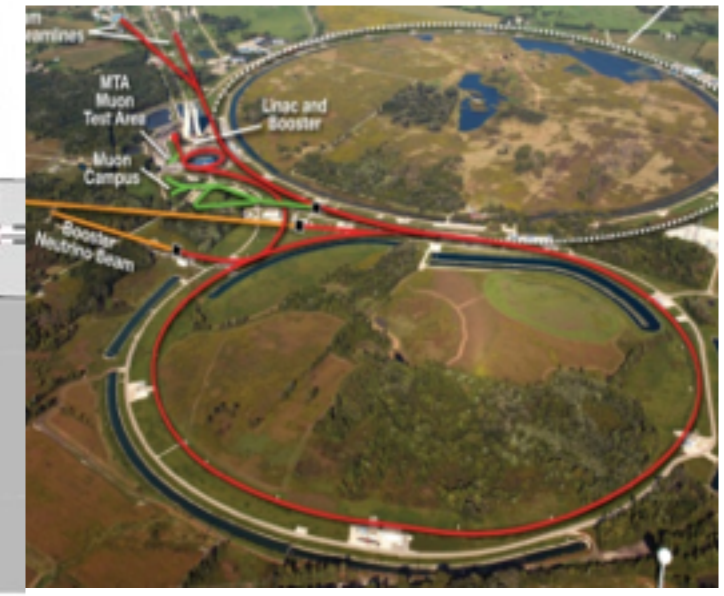


- Snowmass detailed-whitepaper arXiv:1307.7335
- To be updated annually and printed.

Some pictures

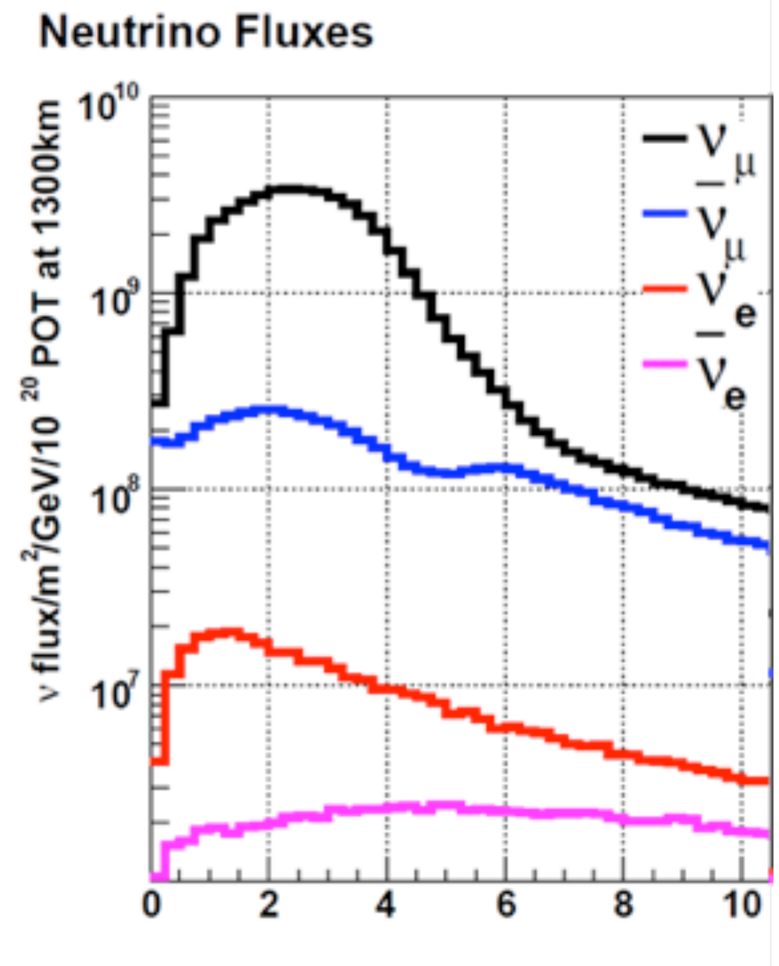
LBNE beam design





LUX @ Sanford

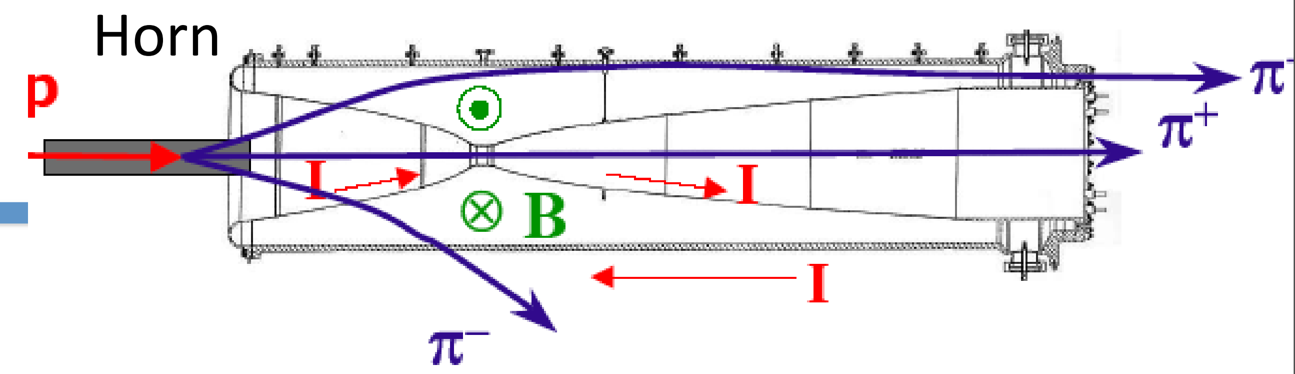
LBNE Beam

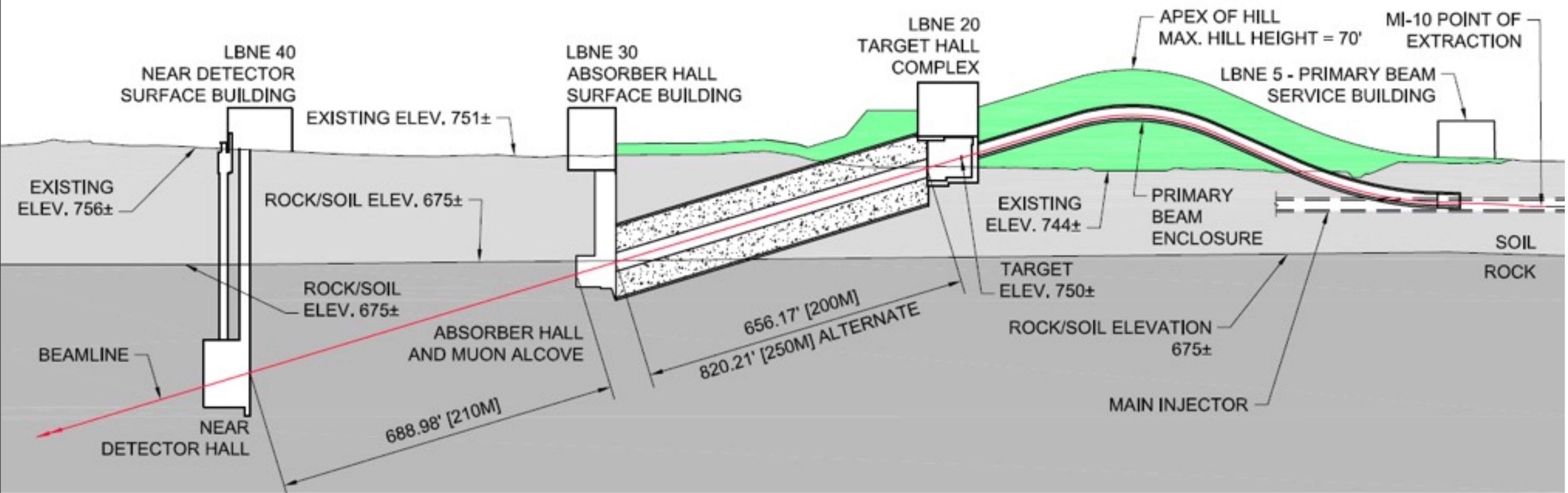


- Neutrino beam spectrum covers 1st and 2nd oscillation maxima
- Driven by high-intensity proton beam:
  - $60 \leq E_{beam} \leq 120$ GeV
  - 700 kW initially, upgradeable 2.3 MW
- Options under study to provide more flux
  - 204 m (reference design) vs. 250 m decay pipe
  - Air-filled (reference design) vs helium-filled decay pipe
  - Improved target/horn system design

LBNE is the key application for a high intensity superconducting proton accelerator.

LBNE Neutrino Beamline





- **Innovative design for safety and upgradeability.**
- **The geotechnical work has started and hill is scheduled to be built in 201**

Work Completed in FY 13

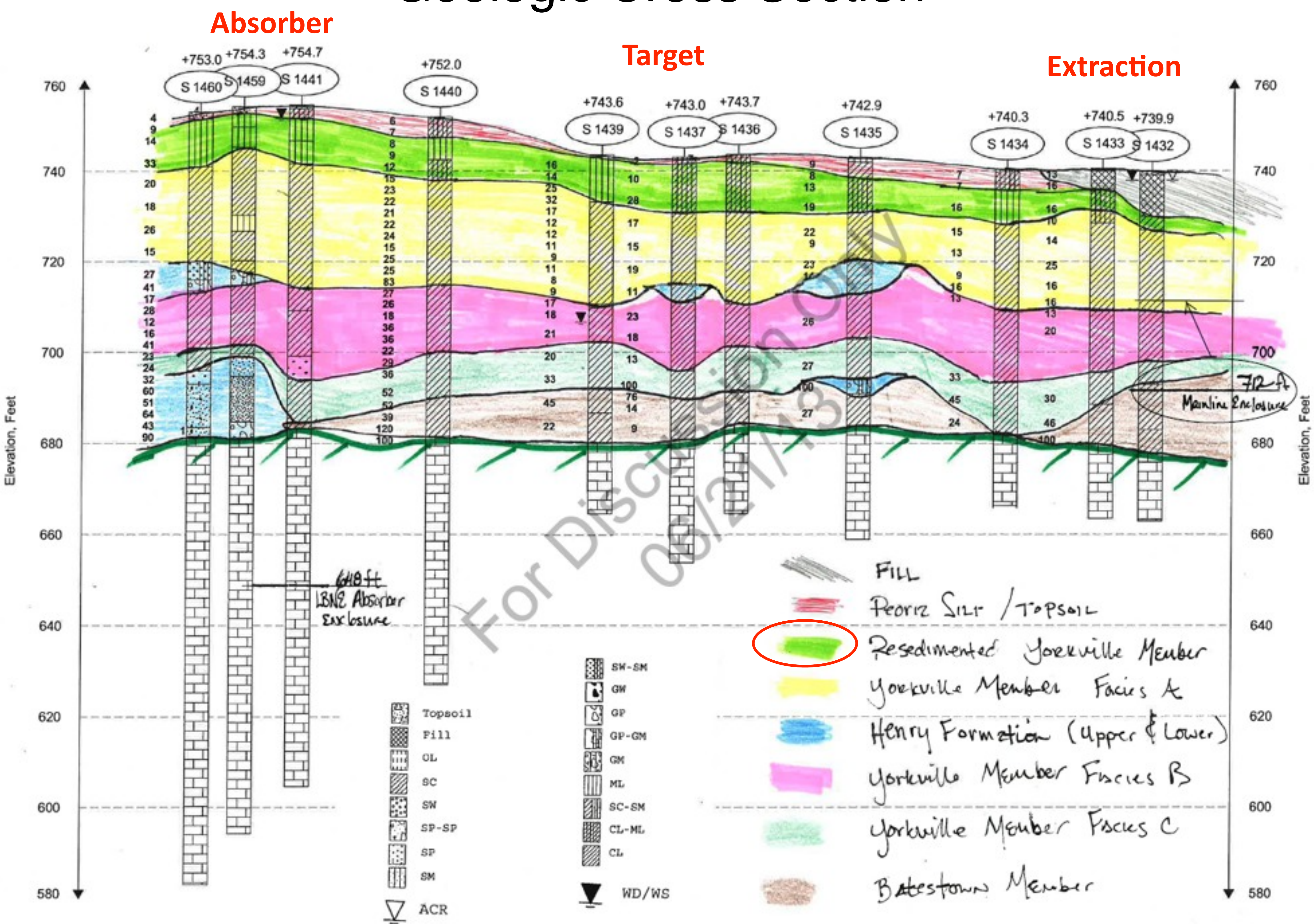
The geotechnical field investigation has been completed. This included borings to allow the Decay Pipe length to be expanded from 200m to 250m

We have also updated all CF risks and requirements

1. Looking from Wilson Hall

1. View with Project

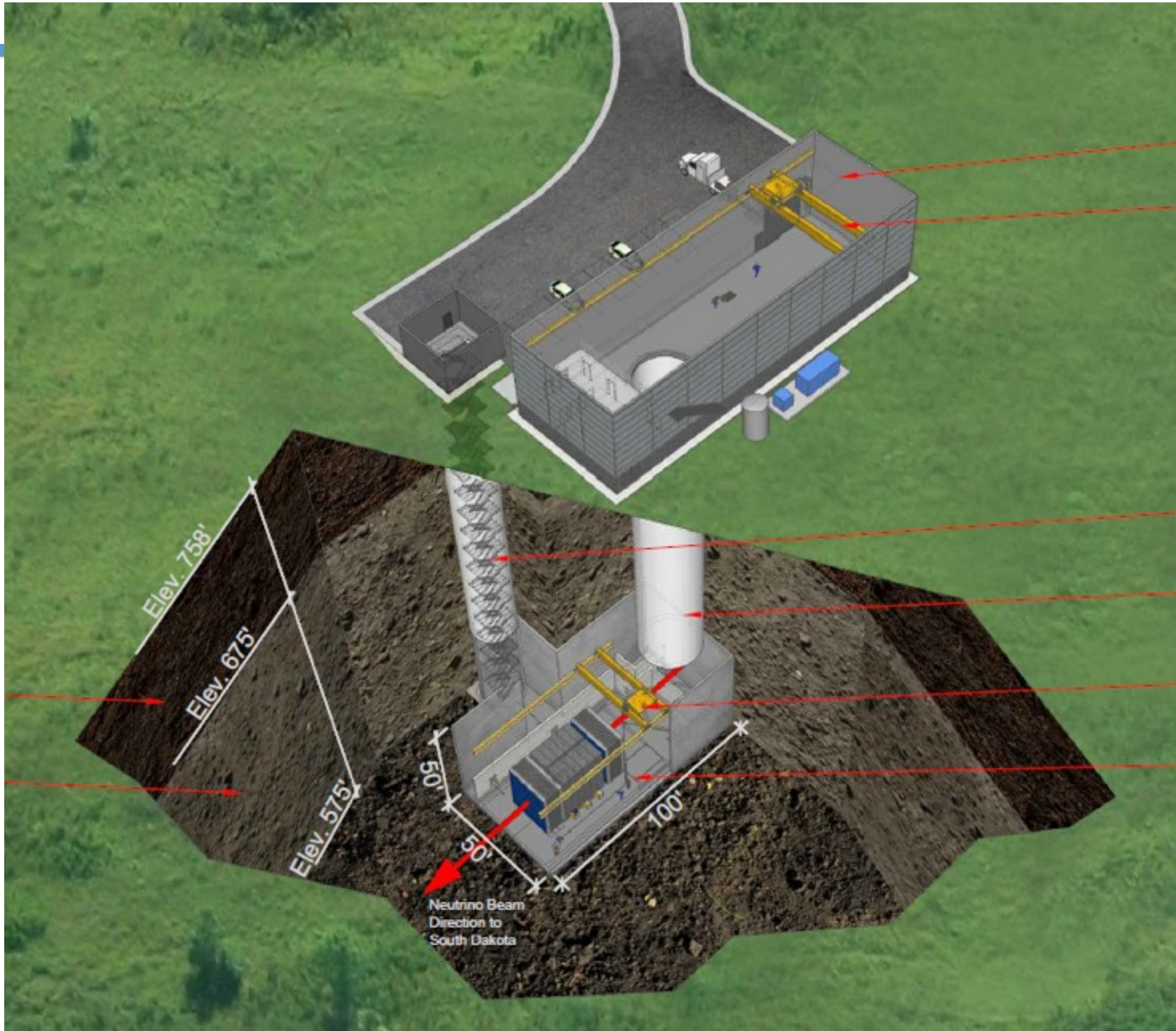
Geologic Cross Section



Near Neutrino Detector Civil Study

Permitting scope includes siting a Near Neutrino Detector near Kirk Road which is based on the March 2012 Directors review configuration

Near Neutrino Detector Update



ND Service Building with Crane

Egress and Equipment Shafts

ND Hall with Crane

Soil

Rock

Near Neutrino Detector Update

Considered design changes that increase the physics potential

Ratio of $\nu_\mu \rightarrow \nu_e$ CC appearance rates at the far detector

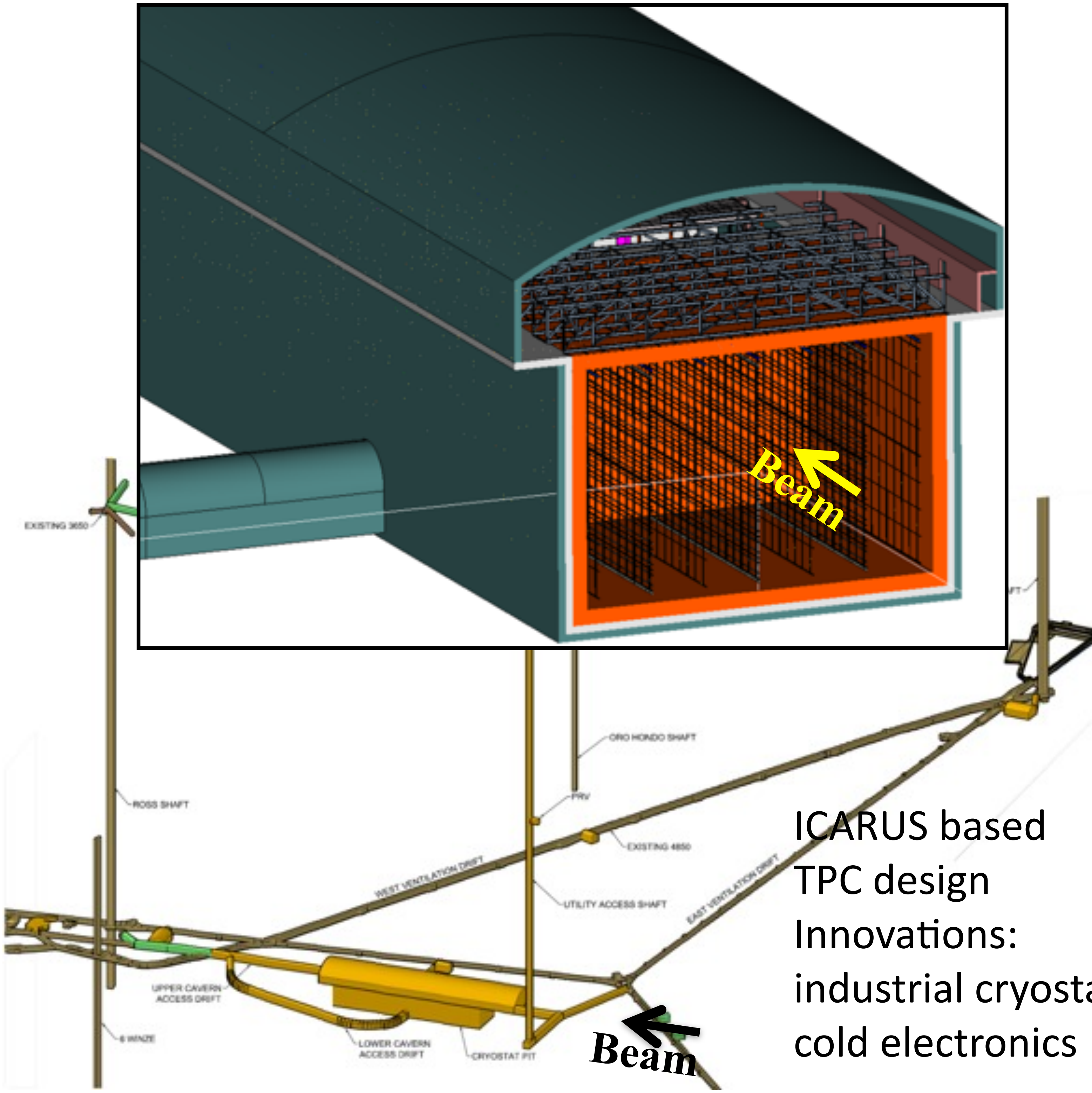
Change	0.5-2.0 GeV	2.0-5.0 GeV
DK pipe Air → He *	1.07	1.11
DK pipe length 200 m → 250 m (4m D)	1.04	1.12
DK pipe diameter 4 m → 6 m (200m L)	1.06	1.02
Horn current 200 kA → 230 kA	1.00	1.12
Proton beam 120 → 80 GeV, 700 kW	1.14	1.05
Target graphite fins → Be fins	1.03	1.02
Total	1.39	1.52

* Simplifies the handling of systematics as well

Items to be considered for collaboration.

- Magnets: dipoles and correctors
- Quadrupole magnet power supplies
- Primary Beamline instrumentation
- Target and Baffle support module
- Target R&D
- Horn R&D for improved neutrino flux and higher beam power
- Support modules for the two horns
- Upstream decay pipe window
- Hadron Monitor
- Remote handling
- Target chase shielding
- Hadron absorber
- Corrosion studies for target chase, decay pipe and absorber
- Radionuclide handling (Na^{22}, H^{3}, Ar^{41})
- Beam simulations
- . . .

Far Detector Design at depth: LAr TPC Detector at 4850 ft



ICARUS based TPC design Innovations: industrial cryostat, cold electronics

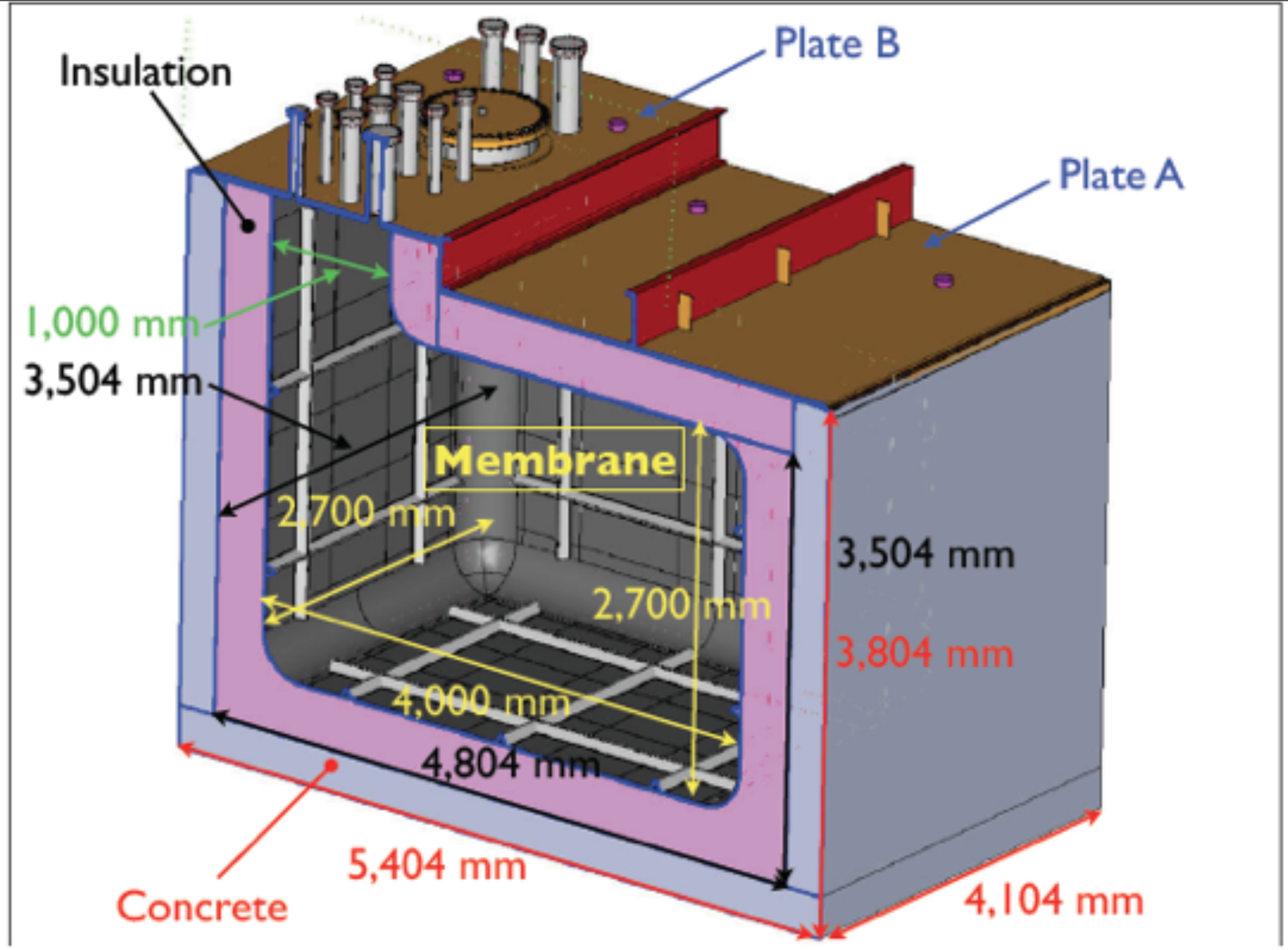
- Two detectors in a common cavern at 4850 ft. depth
- Active volume of each detector: 22.4 x 14 x 45.6 m^3
- 34 kt fiducial mass
- TPC design:
  - 3.7 m drift length
  - 5 mm wire spacing
  - three stereo views
  - 2X108 anode chambers
  - 2 X 275k channels
  - S/N ~ 10

Challenges for scale up are under control : Purity, installation, safety

Far Detector Prototyping

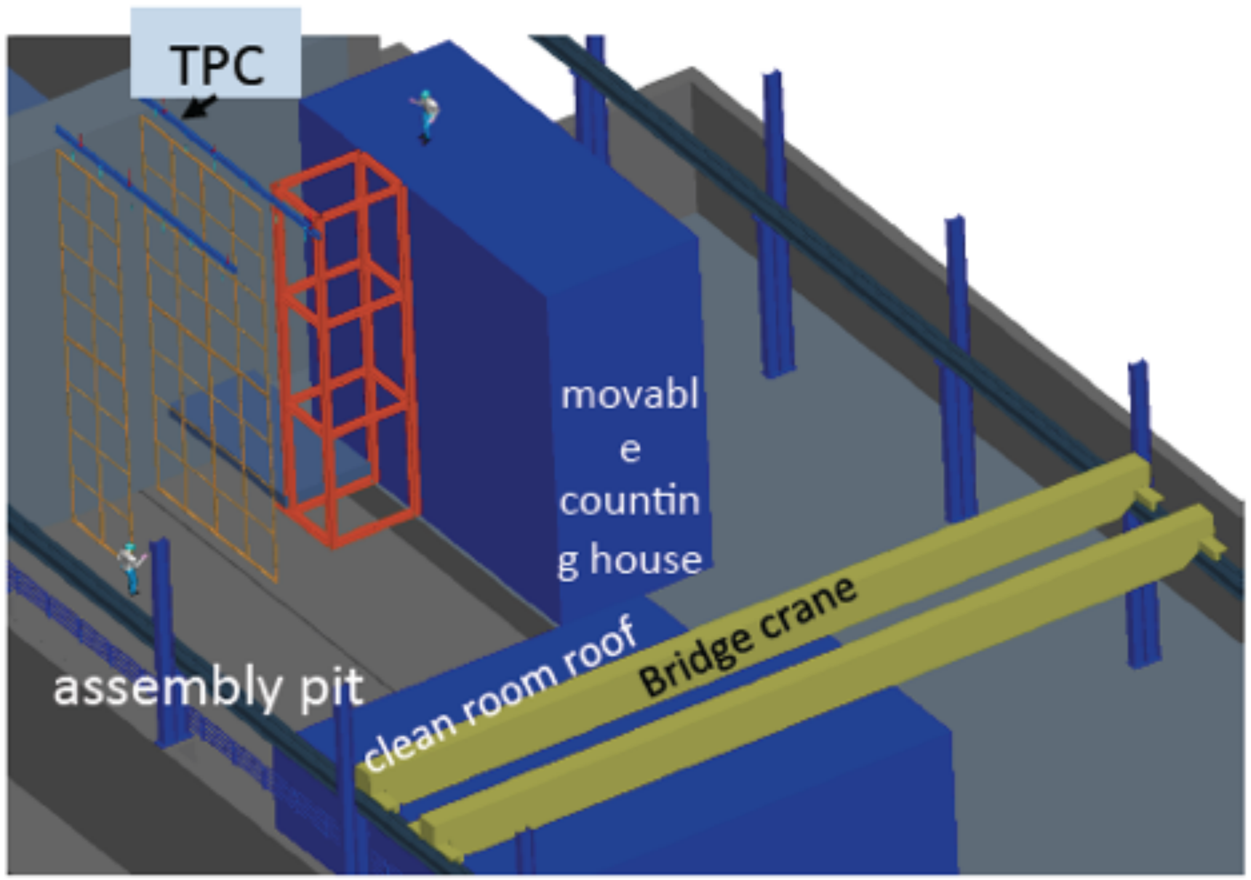
35t scale prototype

- Test membrane technology
- Cryo-system design
- Cryogenic commissioning now!
- Istaall prottoype TPC next summer.
- Take cosmic data in ~1 year.

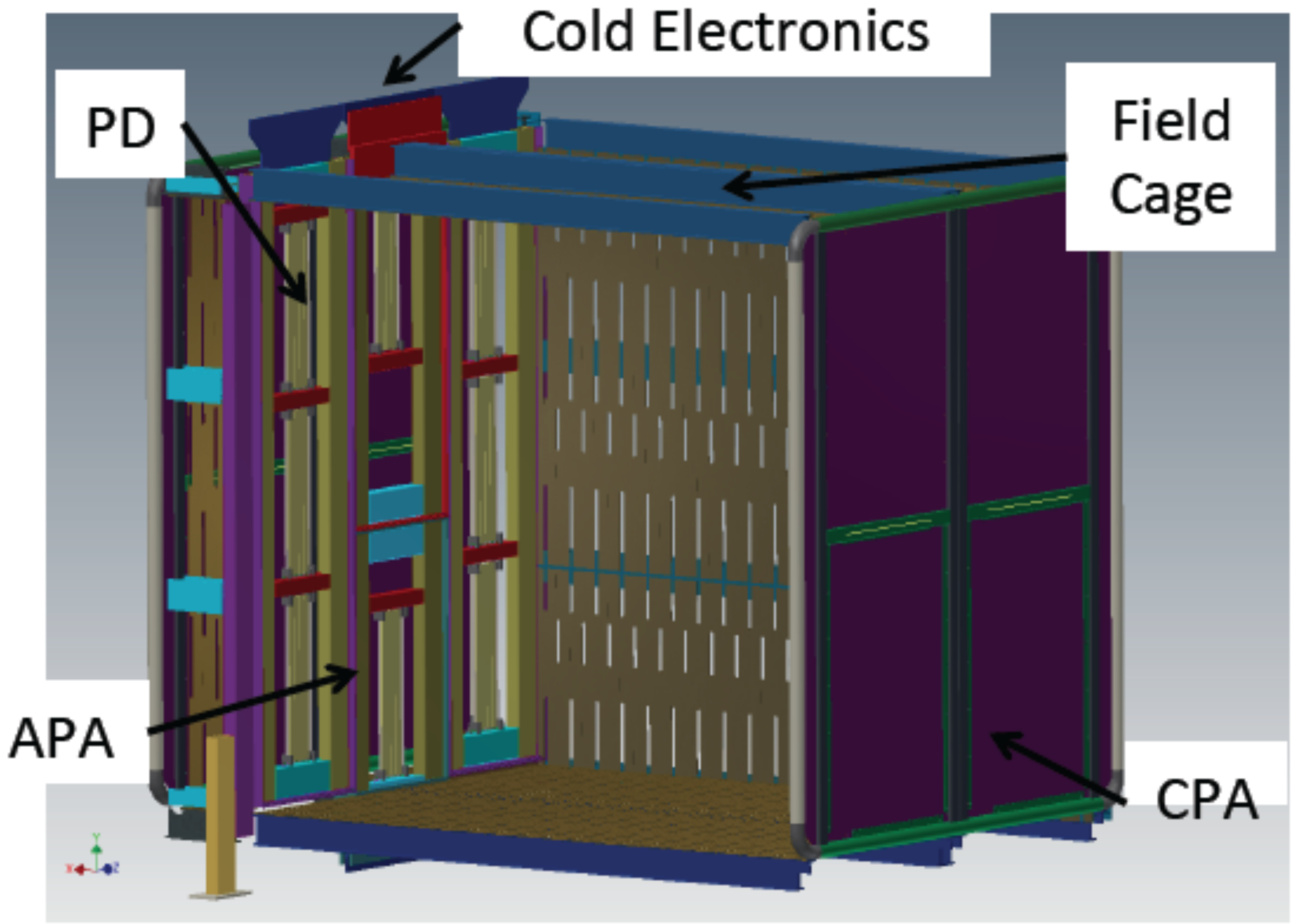


Full scale warm prototype

- Start construction in 1 year
- Full scale TPC module constructed.
- Installed at FNAL



Far Detector Prototyping

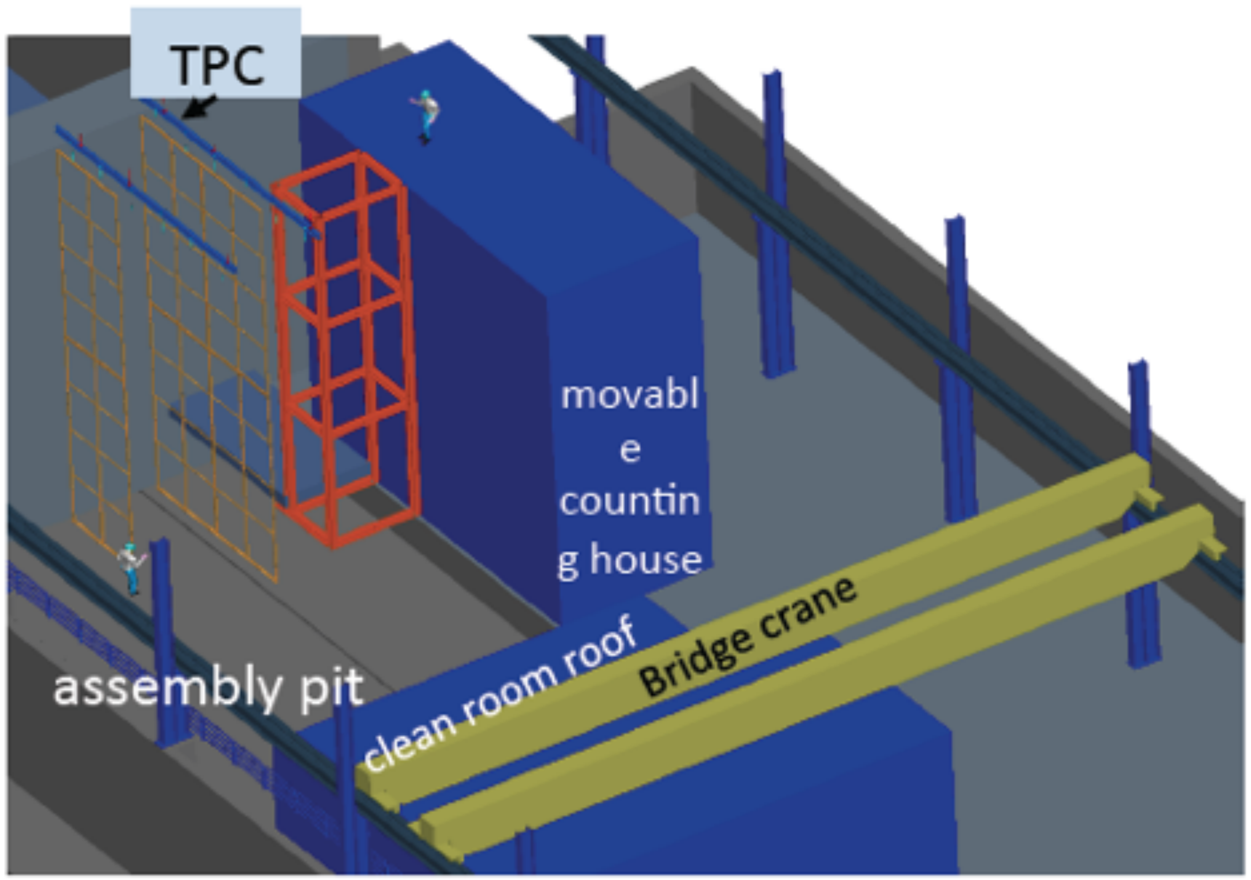


35t scale prototype

- Test membrane technology
- Cryo-system design
- Cryogenic commissioning now!
- Istaall prottoype TPC next summer.
- Take cosmic data in ~1 year.

Full scale warm prototype

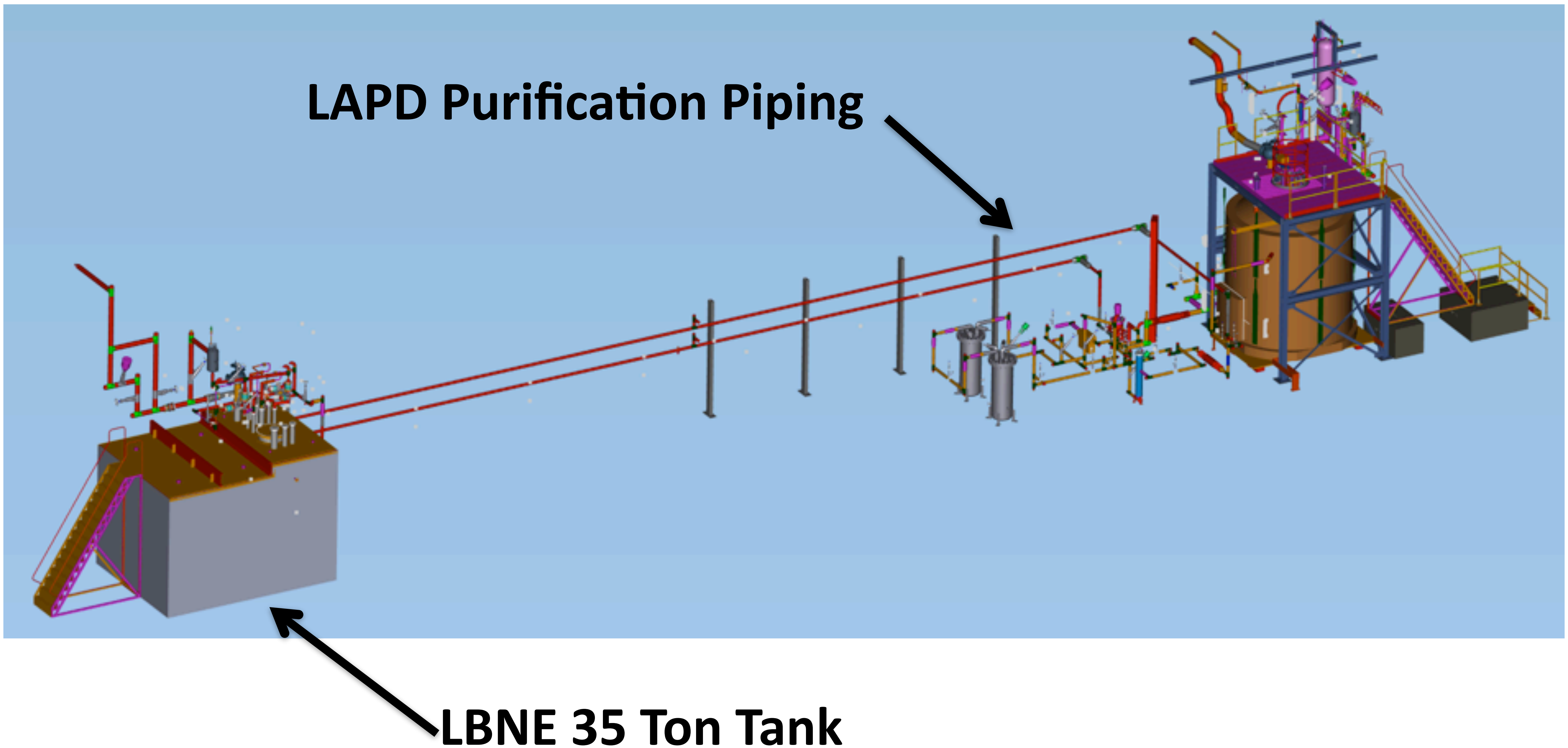
- Start construction in 1 year
- Full scale TPC module constructed.
- Installed at FNAL



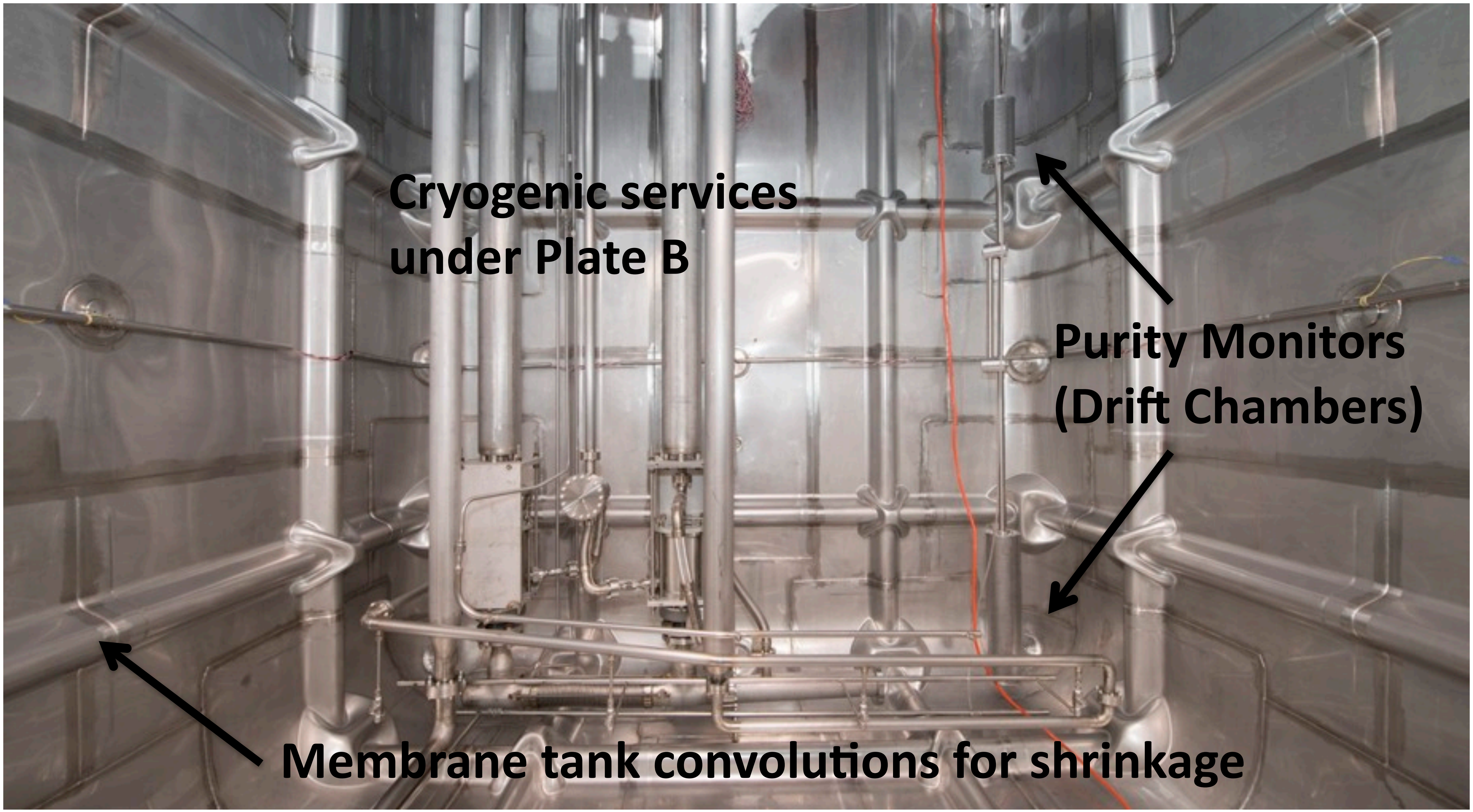
LBNE 35 Ton Liquid Argon Tank

- LBNE 35 Ton is a prototype membrane tank at Fermilab for liquid argon built by the Japanese company IHI using LNG industry technology
- Liquid volume of 27.7 m^3 which is equivalent to 38.7 tonnes of liquid argon
- Connected to the existing LAPD cryogenic purification system
- Commissioning started in November 2013

35 Ton Tank and Purification Piping



View Inside of 35 Ton Tank



View On Top of 35 Ton Tank

Argon Piston Purge

- Argon piston purge began 11.19.13
  - Piston purge is a cost effective alternative to evacuation to remove air and water from tank
  - Room temperature argon gas injected into the tank bottom to push air out the top at 0.2 m^3/hr resulting in 2.5 hours per volume change
  - Continued for 11.3 volume exchanges
- Contamination reduction
  - Oxygen 21% to 6.3 ppm
  - Nitrogen 78% to 10.6 ppm
  - Water 550 ppm to 1.2 ppm

Gas Recirculation

- Room temperature gas recirculation began 11.21.13
- Room temperature argon gas pumped from the tank to water and oxygen filters and then returned to tank
- Very important debugging phase before starting cool down for both cryogenics and purity monitor drift chambers
- Contamination reduction
  - Oxygen 6.3 ppm to 0.07 ppm
  - Nitrogen 47 ppm (not filtered and debugging introduced some N_2)
  - Water 1.2 ppm to 0.4 ppm
- Note that 1 ppm of contamination in the gas phase results in only ~1 ppb of contamination in the equivalent volume liquid phase due to mass difference between liquid and gaseous argon

Cool Down, Initial Fill, LAr Purification

- Cool down began 12.17.13
  - Followed tank mfg guidelines of 10 K/hr
  - Tank cooled by atomizing sprayers that create a fine liquid argon mist that is vaporized by heat input from the warm tank
- Filled with 26 tonnes of liquid argon from the LAPD tank on 12.18.13
- Resulted in a 70% full tank
  - Tougher from a purity perspective due to warmer surfaces
- Started in tank submerged pumps on 12.20.13
  - Liquid argon pumped thru water and oxygen filters and returned to tank
  - 2 m^3/hr filtration rate
  - Volume exchange every 9 hours
  - Refrigeration very stable at +/- 0.35 millibar over a 24 hour period

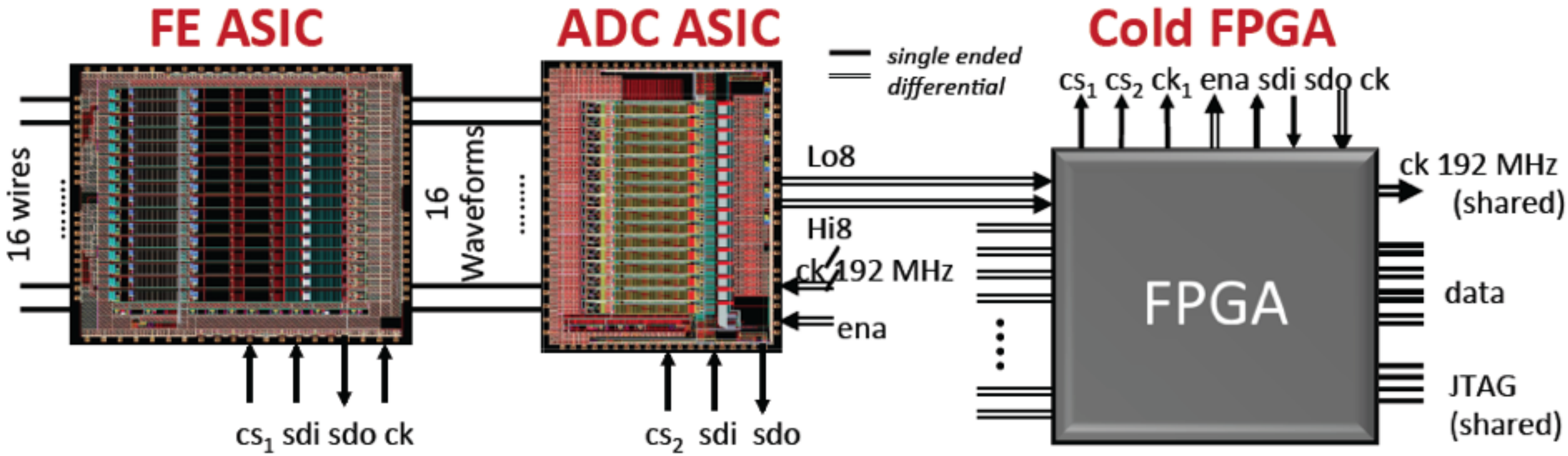
Initial Purity Results

- Purification quickly achieved "zero" on the commercial oxygen analyzers
- First purity monitor anode signals on 12.22.13
- First 1+ millisecond electron lifetime measured on 12.26.13
  - Equivalent to 300 parts per trillion oxygen
- Holiday period was spent working to improve the purity monitor signals with respect to electrical noise
- Lifetimes in excess of 2 milliseconds were measured
- Liquid purification ran smoothly until 1.6.13 at which time the tank was being filled with recycled DZERO Calorimeter LAr from 70% to 100% full (38 tonnes)

Far Detector Status

Cryogenics:	Cryostat design starts in 1 year and is 80% complete in 2yrs. Cryo-plant is being designed. Model exists and working on part lists and specifications.
TPC:	Design/Construction of full scale TPC module will start in 1 year.
DAQ:	Fully functional DAQ will be operational for the 35t test this year.
Photon System:	Baseline PD hardware tested last month at FNAL. Alternate photon detection devices will be tested in the 35t setup. Will select baseline device in 1-2yrs.
Installation:	Detailed installation planning will start in FY15. Now focused on 35t and grounding-shielding.
Cold Electronics	Pre-amp chip is final and used in MicroBooNE. ADC is at revision 4 and will be used in the 35t test. Cold digital control ASIC developemt has started. Configuraiton will be selected after 35t test.

Cold CMOS Electronics



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

Production ready

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

Prototype V4 in 1 mo

- **Digital Control Development**
- **Result for 35t defines baseline configuraiton**

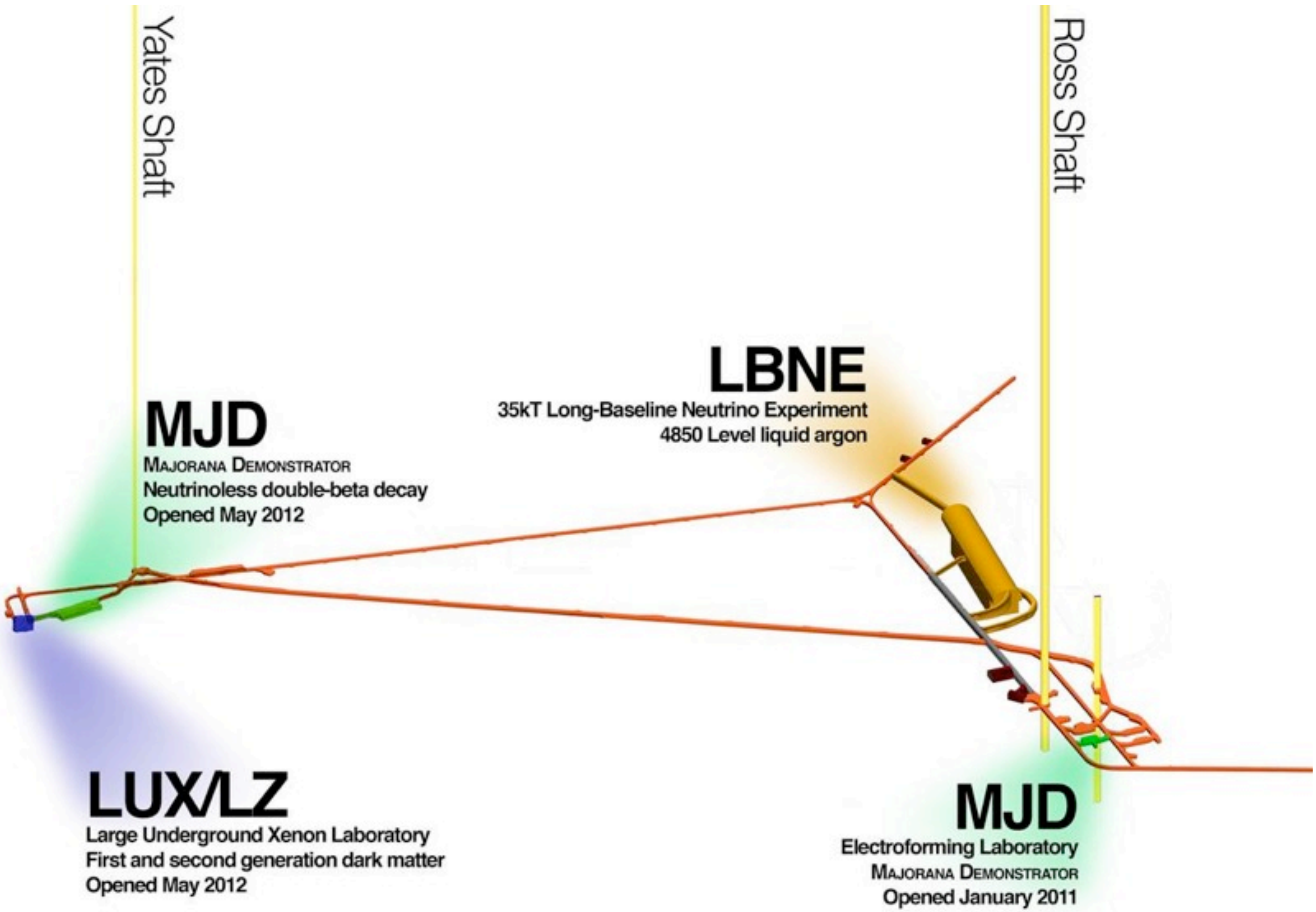
Cold Digital Control Development

Decide Cold commercial FPGA or Custom ASIC in FY15

Functionality defied in 35t test

Prototyping design rules for cold digital process now.

Rigorous full chain testing is a must.


Yates Shaft
Ross Shaft
LBNE
35kT Long-Baseline Neutrino Experiment
4850 Level liquid argon
MJD
Majorana Demonstrator
Neutrinoless double-beta decay
Opened May 2012
LUX/LZ
Large Underground Xenon Laboratory
First and second generation dark matter
Opened May 2012
MJD
Electroforming Laboratory
Majorana Demonstrator
Opened January 2011

CF Far Site Geotech Program

- General area where detector(s) could be placed is being explored.
- Planning to do drilling in early 2014.
- The scope of this drilling program was recently decided.