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Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Experimental Program at the Long-Baseline Neutrino Facility

Jim Strait

Neutrino Telescopes 2015

5 March 2015

U.S. P5 Report

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S.

The minimum requirements to proceed are the identified capability to reach an exposure of at least **120 kt*MW*yr by the 2035 timeframe**, the far detector situated **underground** with cavern space for expansion **to at least 40 kt LAr fiducial mass**, and **1.2 MW beam power upgradable to multi-megawatt** power. The experiment should have the demonstrated capability to search for **supernova (SN) bursts** and for **proton decay**, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.

European Strategy Document

f) 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**.

ELBNF and LBNF

ELBNF: An Experimental Program in Neutrino Physics, Nucleon Decay, and Astroparticle Physics at the Fermilab Long Baseline Neutrino Facility (LBNF)

A merger of previous efforts and any other interested parties to build, operate, exploit

- a (staged) 40 kt LAr detector, at the Sanford Underground Research Facility (SURF), 1300 km from Fermilab
- a high granularity/high precision near detector
- exposed to a 1.2 MW, tunable, wide-band ν beam produced by the PIP-II upgrade at FNAL by 2024, evolving to a power of 2.4 MW by ~ 2030

A 25+ year physics program

With the beam:

- Perform a comprehensive investigation of neutrino oscillations to:
  - test CP violation in the lepton sector
  - determine the ordering of the neutrino masses
  - test the three-neutrino paradigm
- Perform a broad set of neutrino scattering measurements with the near detector

Exploit the large, high-resolution, underground far detector for non-accelerator physics topics:

- atmospheric neutrino measurements
- searches for nucleon decay
- measurement of astrophysical neutrinos (especially those from a core-collapse supernova).

Letter of Intent: Nucleation Point for New Collaboration

http://www.fnal.gov/directorate/program_planning/Jan2015Public/LOI-LBNF.pdf

An Experimental Program in Neutrino Physics, Nucleon Decay, and Astroparticle Physics Enabled by the Fermilab Long-Baseline Neutrino Facility

Letter of Intent Submitted to the Fermilab PAC
P-1062

January 5, 2015

Fermilab

An Experimental Program in Neutrino Physics, Nucleon Decay, and Astroparticle Physics Enabled by the Fermilab Long-Baseline Neutrino Facility

1. Executive Summary

This is a Letter of Intent (LOI) by a global neutrino community to pursue an accelerator-based long-baseline neutrino experiment, as well as neutrino astrophysics and nucleon decay, with an approximately 40-kt (fiducial mass) modular liquid argon TPC (LAr-TPC) detector located deep underground and a high-resolution near detector. Several independent worldwide efforts, developed through many years of detailed studies, have now converged around the opportunity provided by the megawatt neutrino beam facility planned at Fermilab and by the new significant expansion with improved access foreseen at the Sanford Underground Research Facility in South Dakota, 1,300 km from Fermilab.

The principle goals of this experiment are to carry out a comprehensive investigation of neutrino oscillations to test CP violation in the lepton sector, to determine the ordering of the neutrino masses, and to test the three-neutrino paradigm; to perform a broad set of neutrino scattering measurements with the near detector; and to exploit the large, high-resolution, underground far detector for non-accelerator physics topics, including atmospheric neutrino measurements, searches for nucleon decay, and measurement of astrophysical neutrinos (especially those from a core-collapse supernova).

The new international team has the necessary expertise, technical knowledge, and critical mass to design and implement this exciting discovery experiment in a relatively short timeframe. The goal is the deployment of the first 10-kt fiducial mass detector on the timescale of 2021, followed by future expansion to the full detector size as soon as possible. The PIP-II accelerator upgrade at Fermilab will provide 1.2 MW of power by 2024 to drive a new neutrino beam line at Fermilab. There also exists a plan that could further upgrade the Fermilab accelerator complex to enable it to provide up to 2.4 MW of beam power by 2030. With the availability of space for expansion and improved access at the Sanford laboratory, this international collaboration will develop the necessary framework to design, build and operate a world-class deep-underground neutrino and nucleon decay observatory. Fermilab will act as the host laboratory. This plan is aligned with the European Strategy Report and the US HEPAP Particle Physics Project Prioritization Panel (P5) report.

ELBNF LOI Signatures* from 142 Institutions

UFABC
Alabama
Alfenas
Aligarh Muslim
APC - Paris
Argonne
ASCR
Atlantico
Banaras
Bartoszek Engineering
Bern
Bhabha
Boston
Brookhaven
Brown
Budker
California (Berkeley)
California (Davis)
California (Irvine)
California (Los Angeles)
Caltech
Cambridge
Campinas
Catania
CBPF
CERN
Charles University
Chicago
Ciemat
Cincinnati
Cinvestav
Colima
Colorado
Colorado State
Columbia
COMSATS IIT
CTU
Dakota State
Delhi
DESY
Drexel
Duke
ETHZ
Feira de Santana
Fermilab
Goias
Gran Sasso
Guwahati
Hamburg
Harish-Chandra
Hawaii
Houston
Huddersfield
Hyderabad
Idaho State
IFAE
IFC
IIT
Indiana
Institute for Nuclear Search
Iowa State
IPM
IPNL Lyon
IPPP Durham
Jammu
JG Boissevain Design
Kansas State
KEK
Koneru Lakshmaiah
Lancaster
LAPP
Lawrence Berkeley National Lab
Liege
Liverpool
London UCL
Los Alamos National Laboratory
Louisiana State
Lucknow
Manchester
Maryland
Max Planck MPP
MIT
Michigan State
Milano
Milano & INFN Bicocca
Minnesota
Minnesota (Duluth)
Napoli
NCBJ
Nehru
New Mexico
NIKHEF
Northern Illinois
Northwestern
Notre Dame
Observatorio Nacional
Ohio State
Order of Engineers Genoa
Oregon State
Oxford
Ozark Integrated Circuits Co
Padova
Panjab
Pavia
Pennsylvania State
Pisa
Pittsburgh
Princeton
Punjab
Rochester
Saclay
SLAC
STFC Rutherford Appleton
Sheffield
Sofia
South Carolina
South Dakota
SD School of Mines & Technology
SURF
South Dakota State
Southern Methodist
Stanford
Stony Brook
Sussex
Syracuse
Tennessee
Texas (Arlington)
Texas (Austin)
Tubitak
Tufts
VECC
Virginia Tech
Warwick
Warsaw
Washington
Wichita State
William and Mary
Wisconsin
Wroclaw
Yale
Yerevan
York

*As of 11 Jan 2015

ELBNF Collaboration

As of 27 Feb 2015 there were 527 signatures to the LOI

- They form the basis of the new ELBNF collaboration
- Signers represent:
  - 147 Institutions
  - 68 US Institutions
  - 79 non-US Institutions
  - 24 Countries

Countries represented:

Armenia, Belgium, Brazil, Bulgaria, Canada, China, Colombia, Czech Republic, France, Germany, India, Iran, Italy, Japan, Mexico, Netherlands, Pakistan, Poland, Russia, Spain, Switzerland, Turkey, UK, USA

Beam-based Neutrino Oscillations

3.1.1. Phenomenology

To first order, the oscillation probability of $\nu_\mu \rightarrow \nu_e$ through matter in a constant density approximation is [1]:

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$

$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{aL}\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2 \qquad (1)$$

where, $\Delta_{ij} = \Delta m_{ij}^2 L/4E$, and $a = G_F N_e/\sqrt{2}$.

In the above, both δ_{CP} and a switch signs in going from the $\nu_\mu \rightarrow \nu_e$ to the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel; i.e., a neutrino-antineutrino asymmetry is introduced both by the CP-violating phase, δ_{CP}, and the matter effect, the origin of which is simply the presence of electrons and absence of positrons in the Earth.

Neutrino Spectra and Oscillation Probabilities

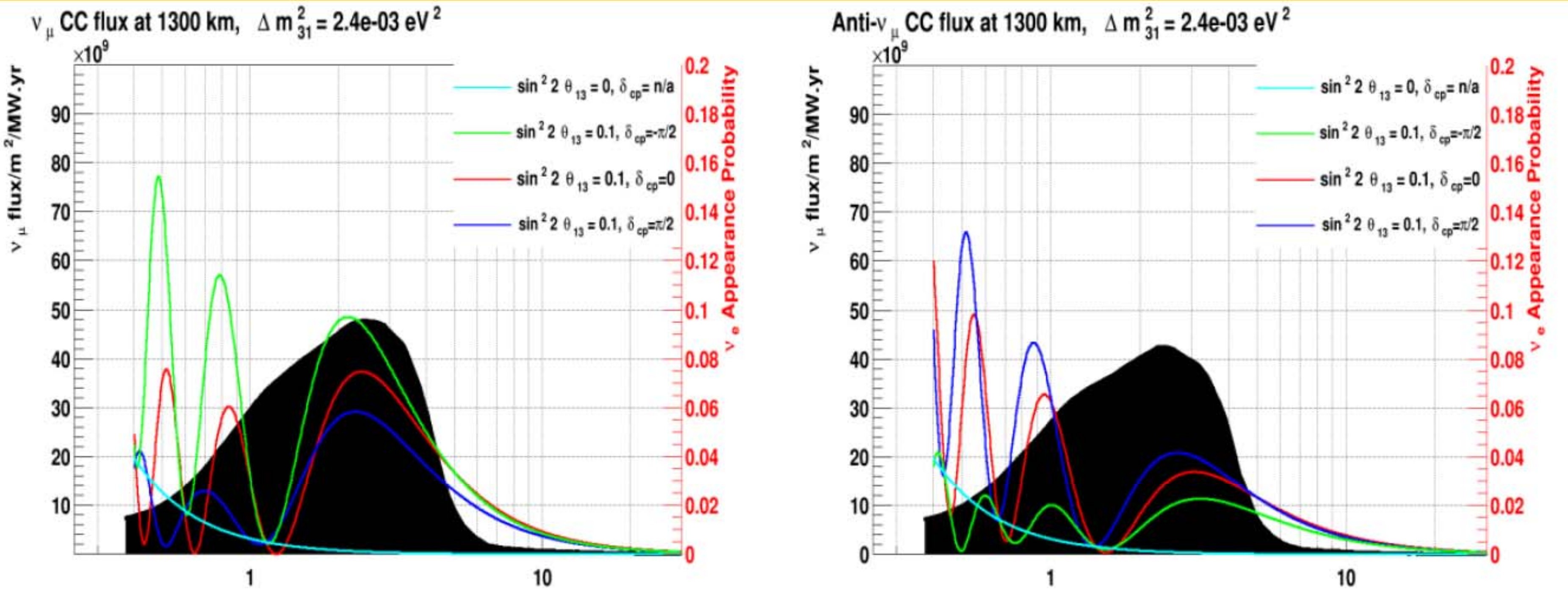


FIGURE 1: *The colored curves represent $P(\nu_\mu \rightarrow \nu_e)$ at a baseline of 1300 km, as a function of neutrino energy, for δ_{CP} = π/2 (blue), 0 (red), and -π/2 (green), for neutrinos (left) and antineutrinos (right), for normal hierarchy. The cyan curve indicates the oscillation probability if θ_{13} were equal to zero. The black solid histogram is the unoscillated ν_μ (left) and $\bar{\nu}_\mu$ (right) flux at 1300 km from an 80GeV MI beam using NuMI horns for focusing.*

Expected Sensitivities to MH and CPV

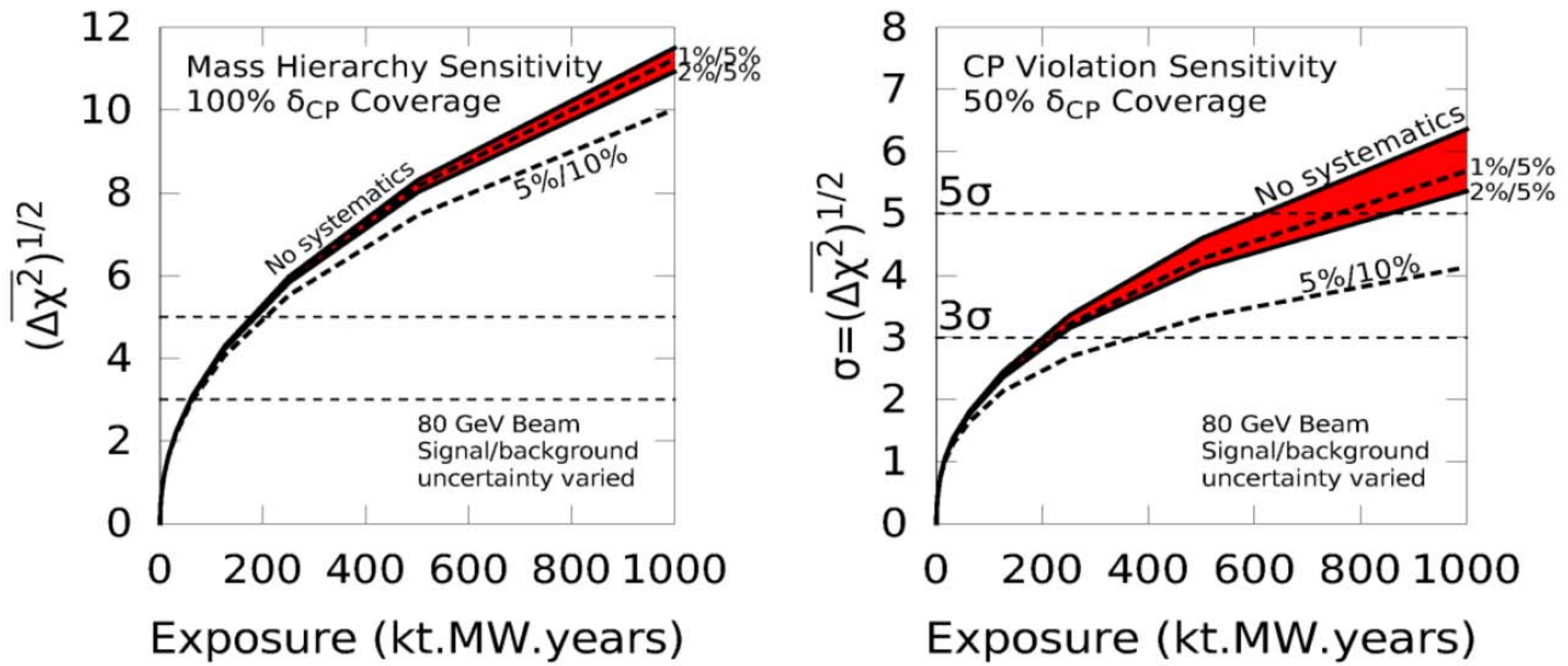


FIGURE 8: *Expected sensitivity of ELBNF to determination of the neutrino mass hierarchy (left) and discovery of CP violation, i.e. $\delta_{CP} \neq 0$ or π, (right) as a function of exposure in kt-MW-years, assuming equal running in neutrino and antineutrino mode, for a range of values for the residual ν_e and $\bar{\nu}_e$ signal and background normalization uncertainties. The sensitivities quoted are the minimum sensitivity for 100% of δ_{CP} values in the case of mass hierarchy and 50% of δ_{CP} values in the case of CP violation. Sensitivities are for true normal hierarchy; neutrino mass hierarchy is assumed to be unknown in the CPV fits.*

Proton Decay: $p \to K^+ \bar{\nu}$

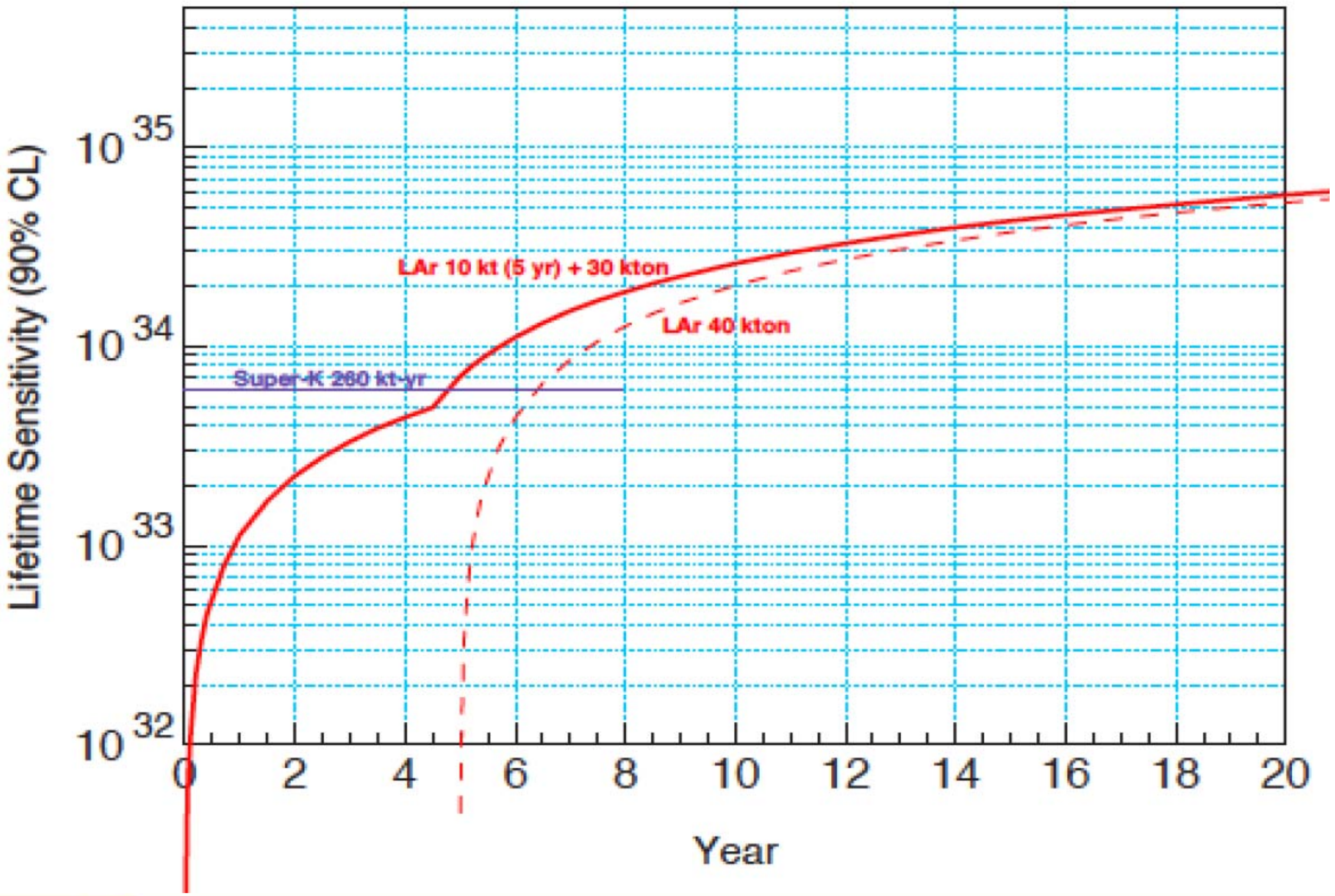


FIGURE 10: *The 90% CL lifetime limit for p - nu K+ as a function of time for a LArTPC. The solid curve considers an initial exposure of 5 years by a 10-kton detector followed by an additional 30-kton after the 5th year. For comparison a dashed line shows the 90% CL lifetime limit assuming all 40 ktons commences in year 5.*

Atmospheric Neutrinos

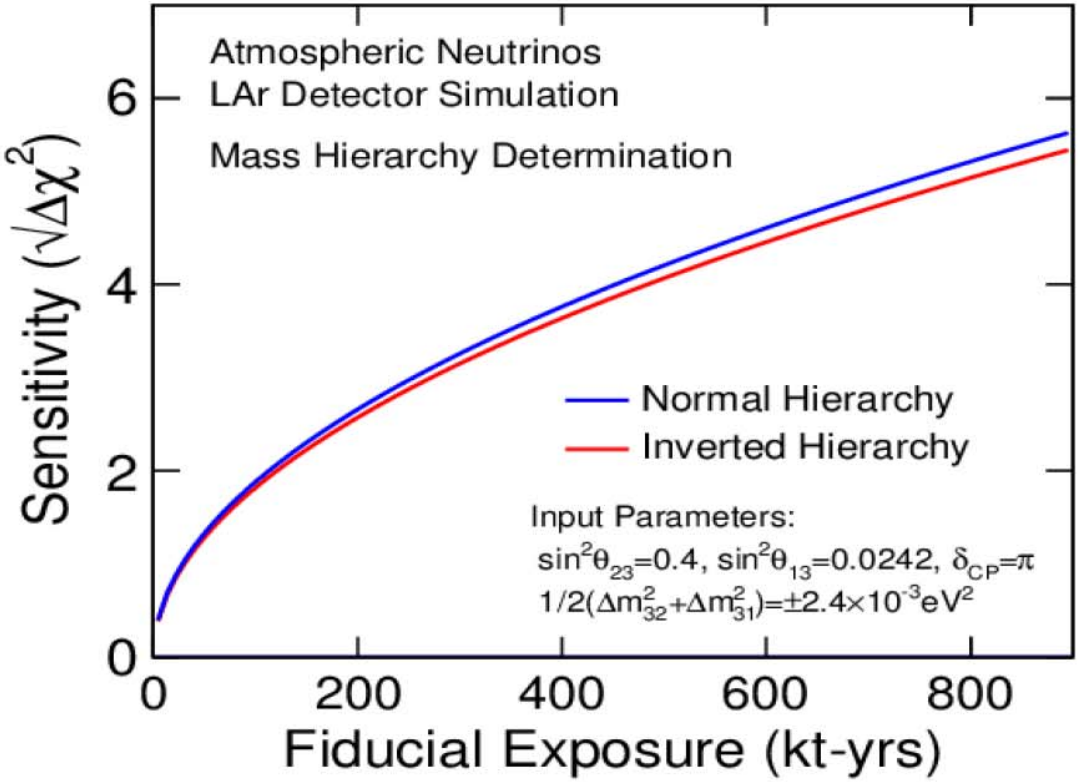


FIGURE 11: *Sensitivity to mass hierarchy using atmospheric neutrinos as a function of the fiducial exposure in kt*years.*

Supernova Neutrinos

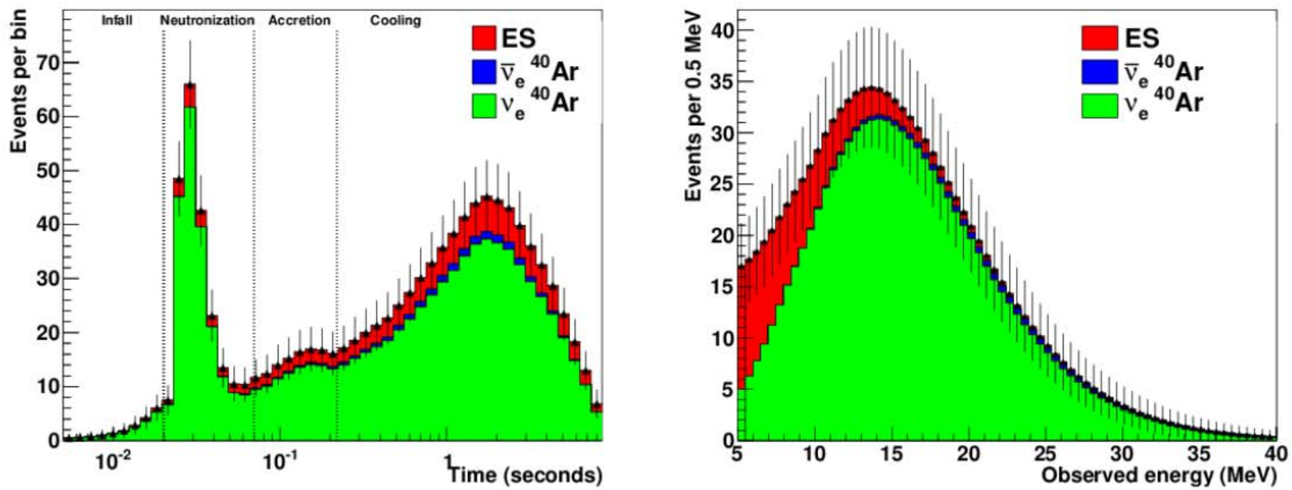


FIGURE 13: Left: *Expected time-dependent signal in 40 kt of liquid argon for a specific flux model for an electron-capture supernova [19] at 10 kpc, calculated using SNoWGLoBES [20]. Note the logarithmic binning in time; the plot shows the number of events expected in the given bin for three detection channels and the error bars are statistical. The vertical dashed line at 0.02 seconds indicates the time of core bounce, and the vertical lines indicate different eras in the supernova evolution. The leftmost time interval indicates the infall period. The next interval, from core bounce to 50 ms, is the neutronization burst era, in which the flux is composed primarily of ν_e. The next period, from 50 to 200 ms, is the accretion period. The final era, from 0.2 to 9 seconds, is the proto-neutron-star cooling period.* Right: *Expected measured event spectrum for the same model, integrated over time.*

Far Detector: Single- or Dual-Phase LAr TPC

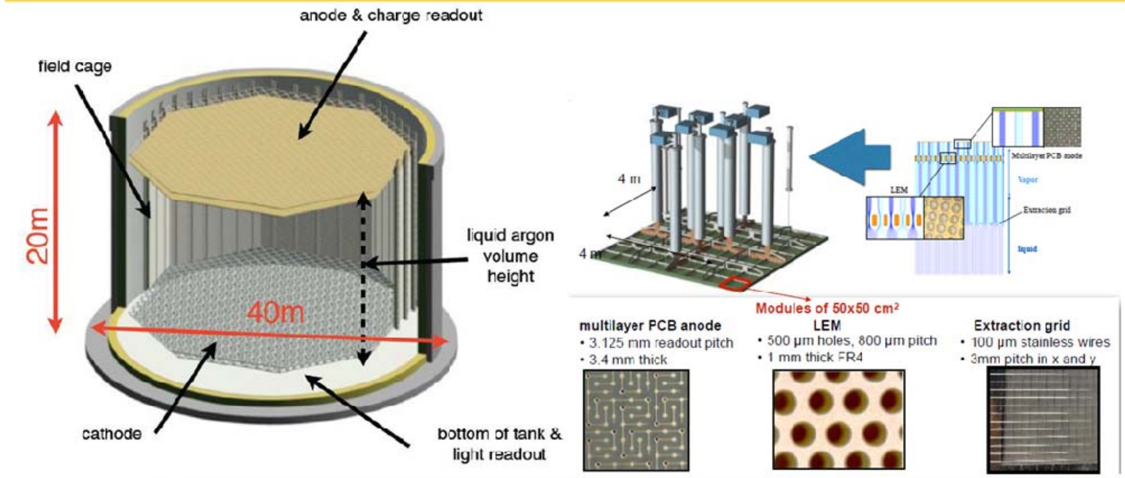
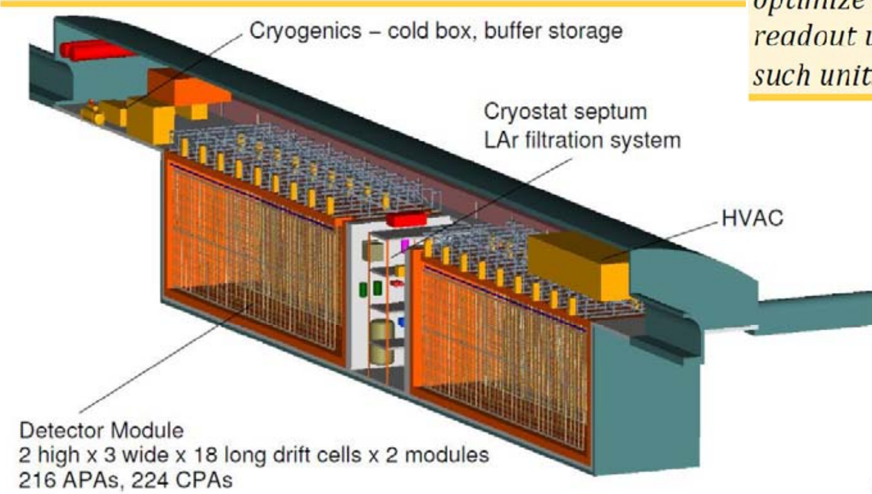


FIGURE 15. *Schematic view (left) of the 20-kt double-phase LAr detector optimized for the Pyhäsalmi mine location. Engineering work is presently being performed to optimize the geometry to a SURF location (right) the basic 4x4 m² double-phase readout unit with their extraction, LEM amplifying stage, and anode layer. In total 65 such units of 4x4 m² will be needed for the 23.3-kt detector.*



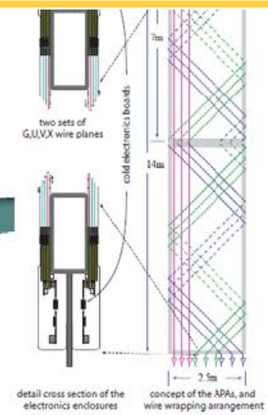


FIGURE 16. *Schematic of a 34-kt fiducial mass LArTPC design (left). The detector comprises two 17-kt fiducial mass LArTPC detectors. The design of a pair of Anode Plane Assemblies is shown at* right.

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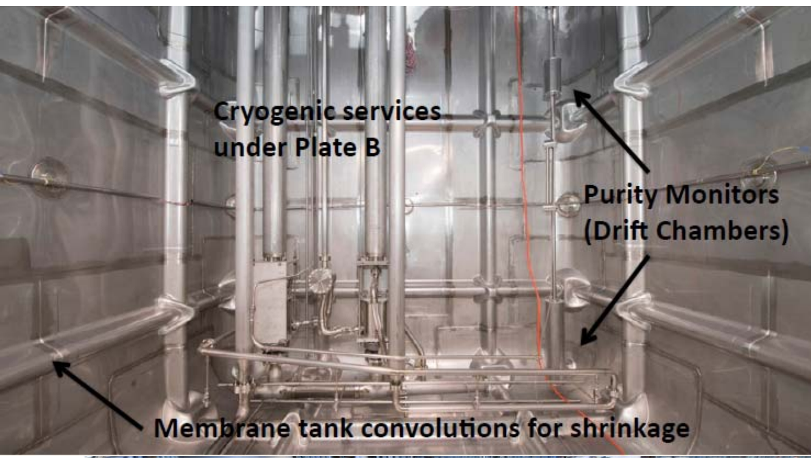
Cryostat Development

35 t membrane cryostat prototype operational at FNAL

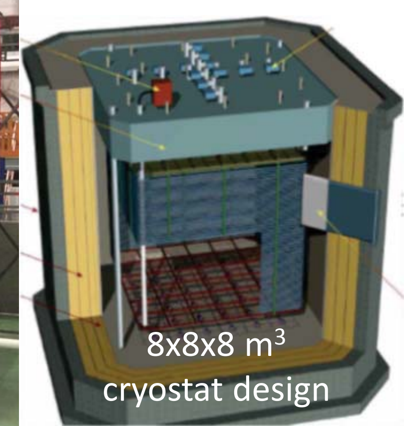
- Learn construction methods
- Purity tests
- Vessel for detector prototyping

17 m^3 membrane cryostat prototype under construction at CERN

- Learn construction methods
- Purity tests
- Vessel for detector prototyping

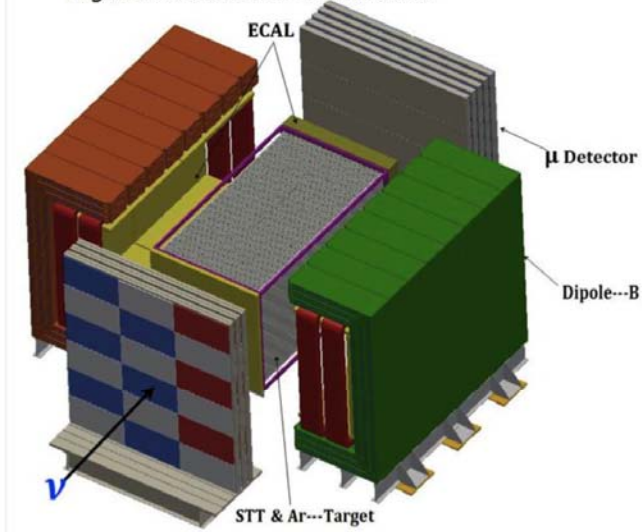


See M.Nessi's talk yesterday



Proposed Near Detector Designs

Fine-Grained Tracker



- ~3.5m x 3.5m x 7m STT ($\rho \simeq 0.1 gm/cm^3$)
- 4π---ECAL in a Dipole---B---Field (0.4T)
- 4π---μ---Detector (RPC) in Dipole and Downstream
- Pressurized Ar---target (≃x5 FD---Stat) ⇛ *LAr-FD*

Transition Radiation → $e^{+/---}$ ID ⇒ γ
dE/dx → Proton, $\pi^{+/---}$, $K^{+/---}$
Magnet/Muon Detector → $\mu^{+/-}$ $e^{+/-}$
(⇒ ***Absolute Flux measurement***)

FIGURE 17: *Schematic of the Fine-Grained Tracker Near Detector, with straw-tube tracker (STT), electromagnetic calorimeter (ECAL), large-aperture dipole magnet, and resistive plate chamber (RPC) muon detectors.*

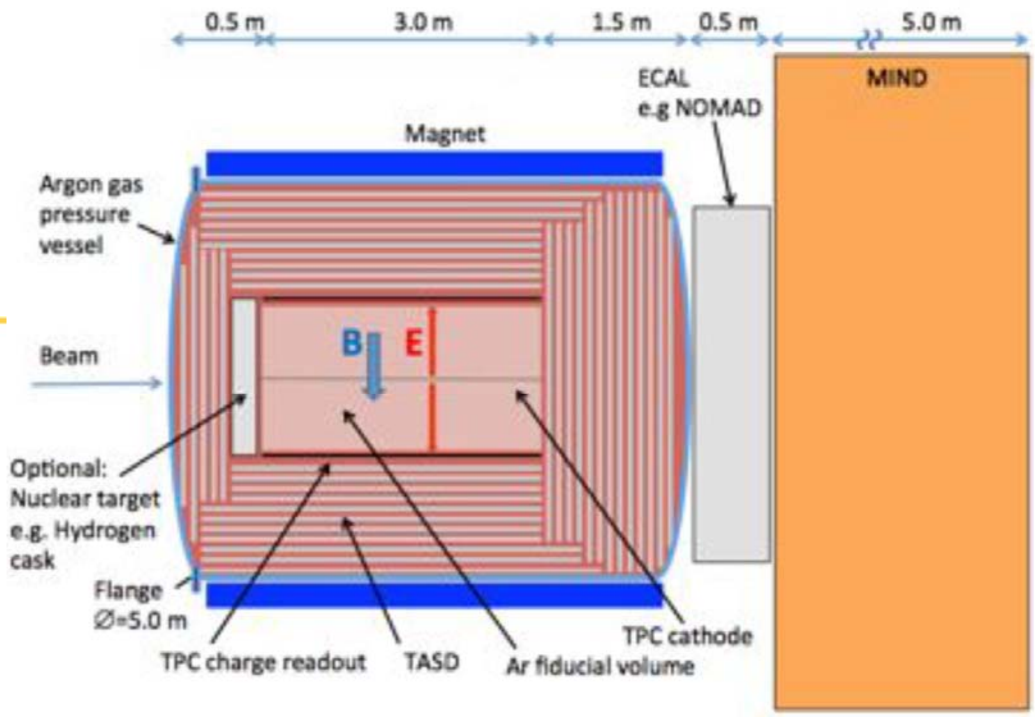
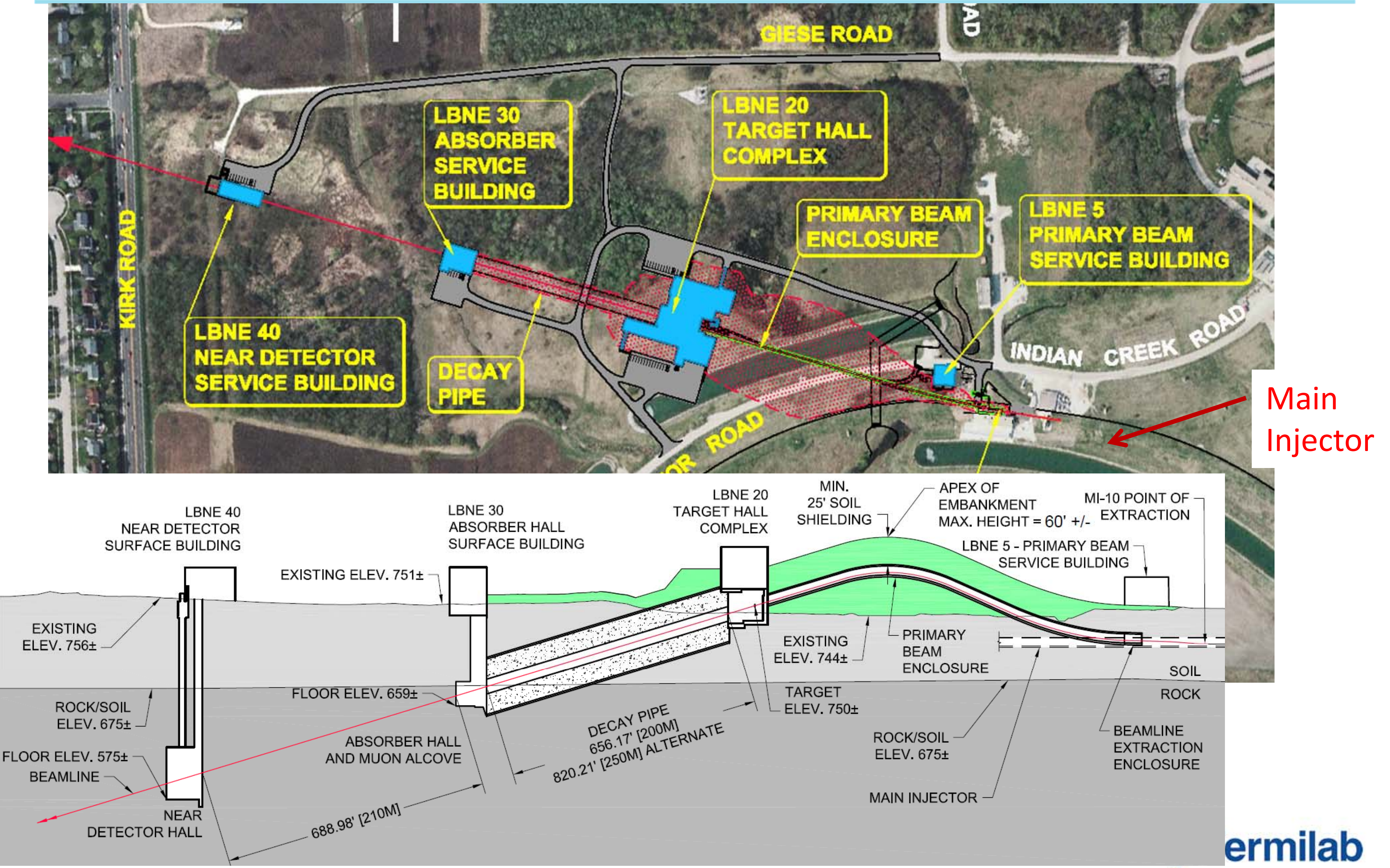


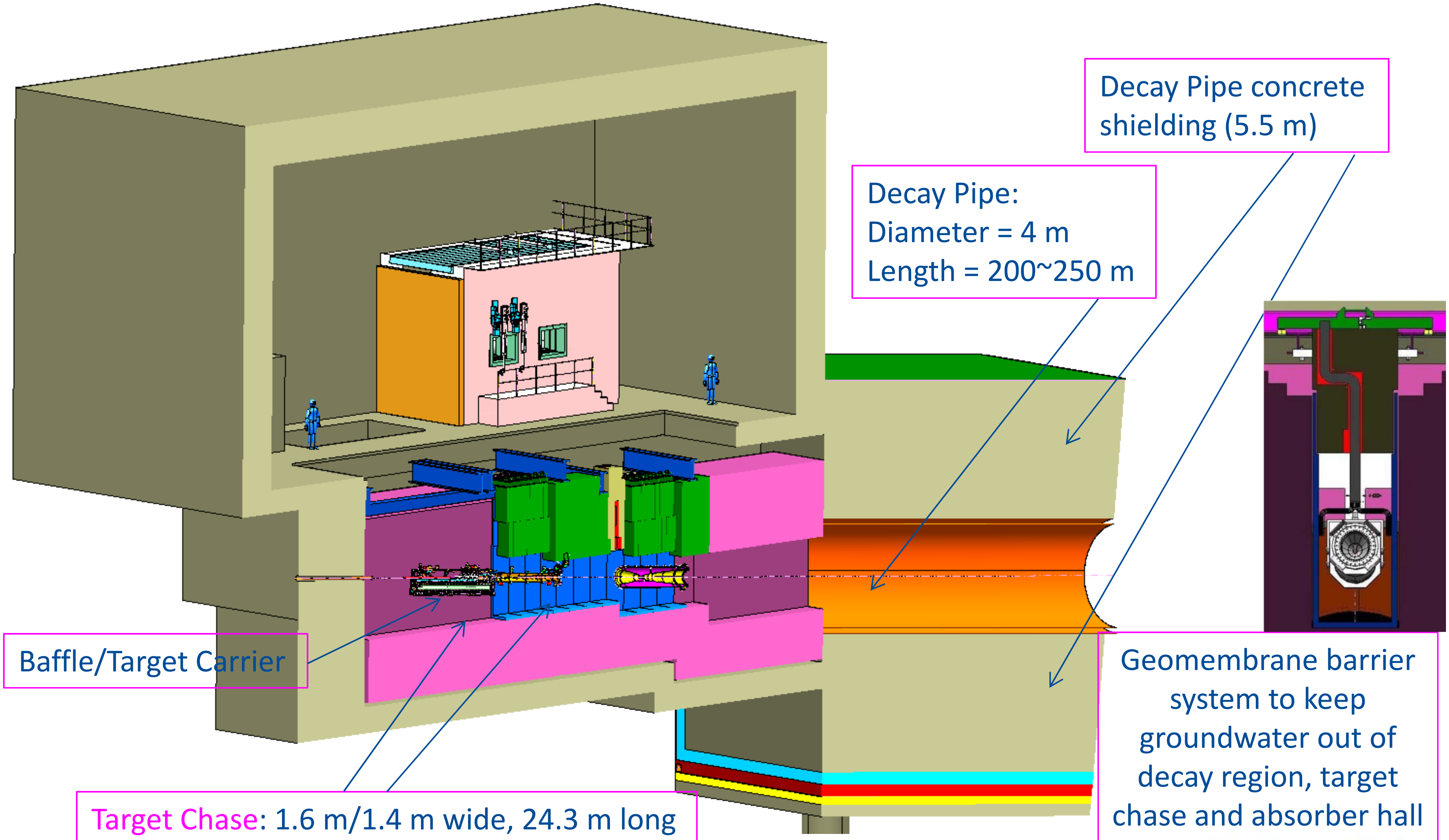
Figure 8.4: *Schematic layout of the LBNO ND.*

High-pressure GAr TPC

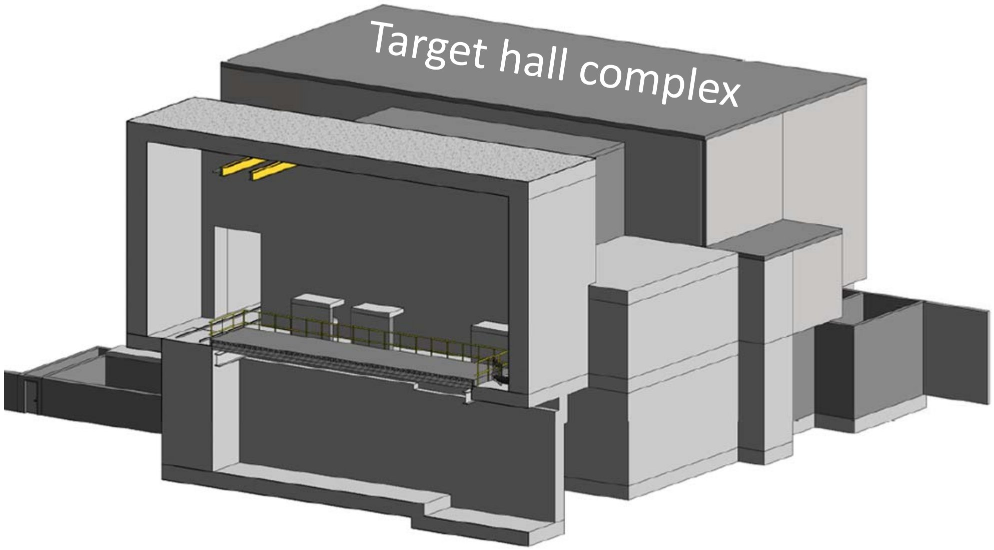
Beamline for a new Long-Baseline Neutrino Facility

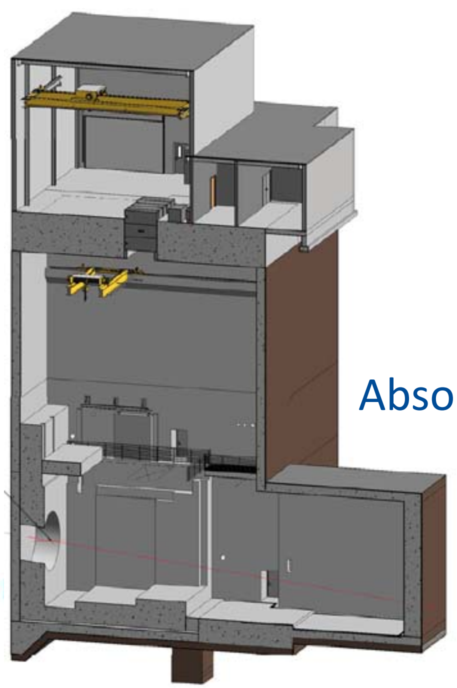


Target Hall and Decay Pipe Layout



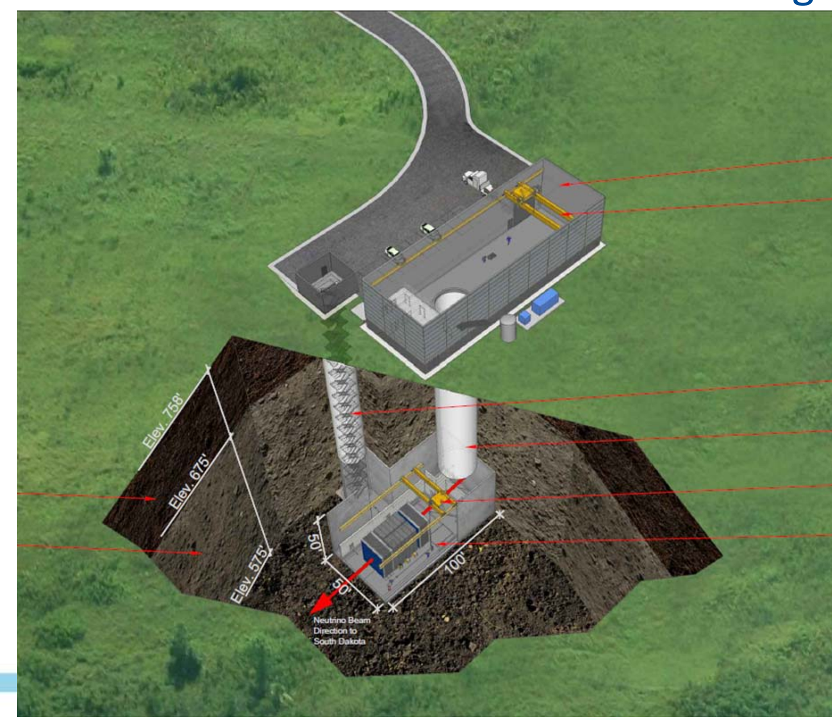
Conventional Facilities Designs





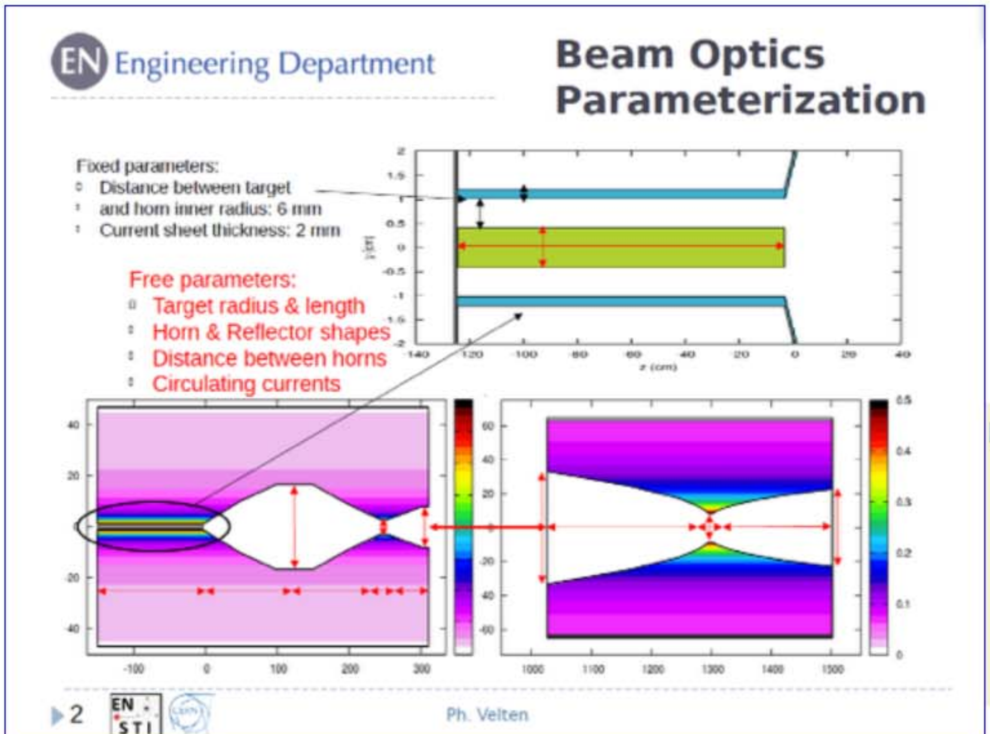
Absorber hall

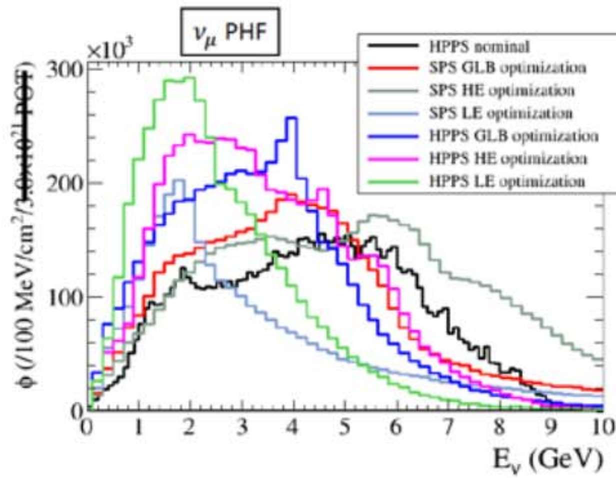
Near Detector Hall and Surface Building



CN2PY ν-beam optimisation

- Beam target and focusing system optimization using Genetic Algorithm
  - Multi-variable analysis of horn/reflector parameters
  - Optimization:
    - **use GLOBES** to maximize the δ_{CP} sensitivity at the FD
    - **HE-optimization**: maximum yield of ν-s in the range [1-10]GeV
    - **LE-optimization**: maximum yield of ν-s in the range [1-2] GeV

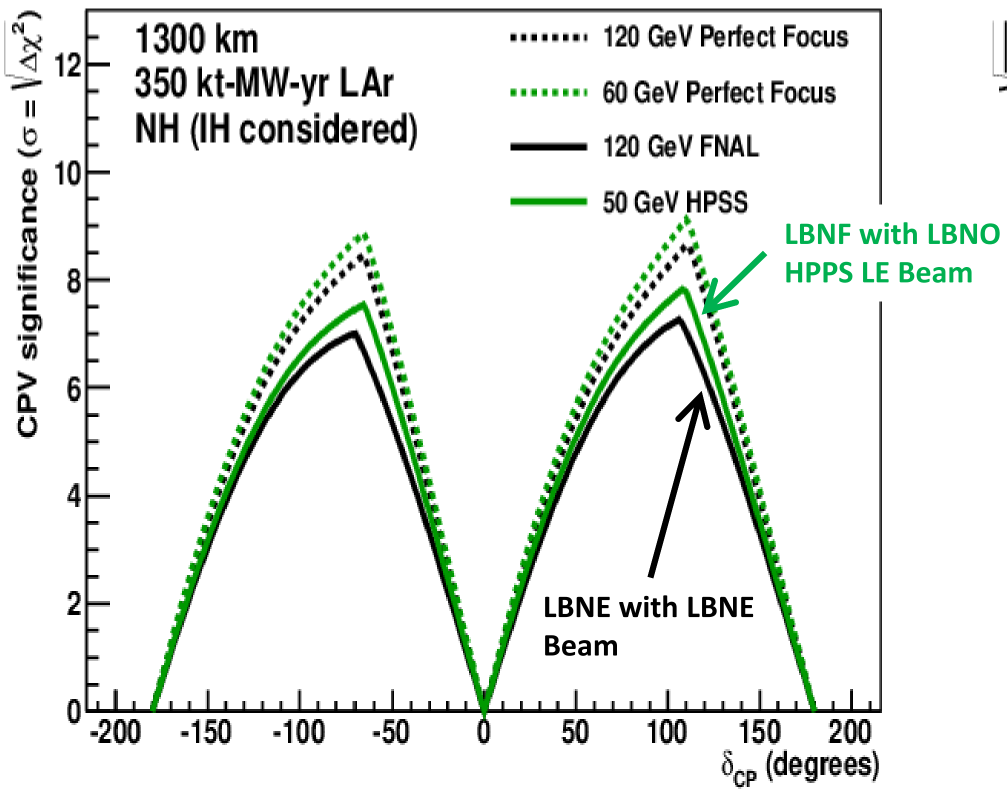


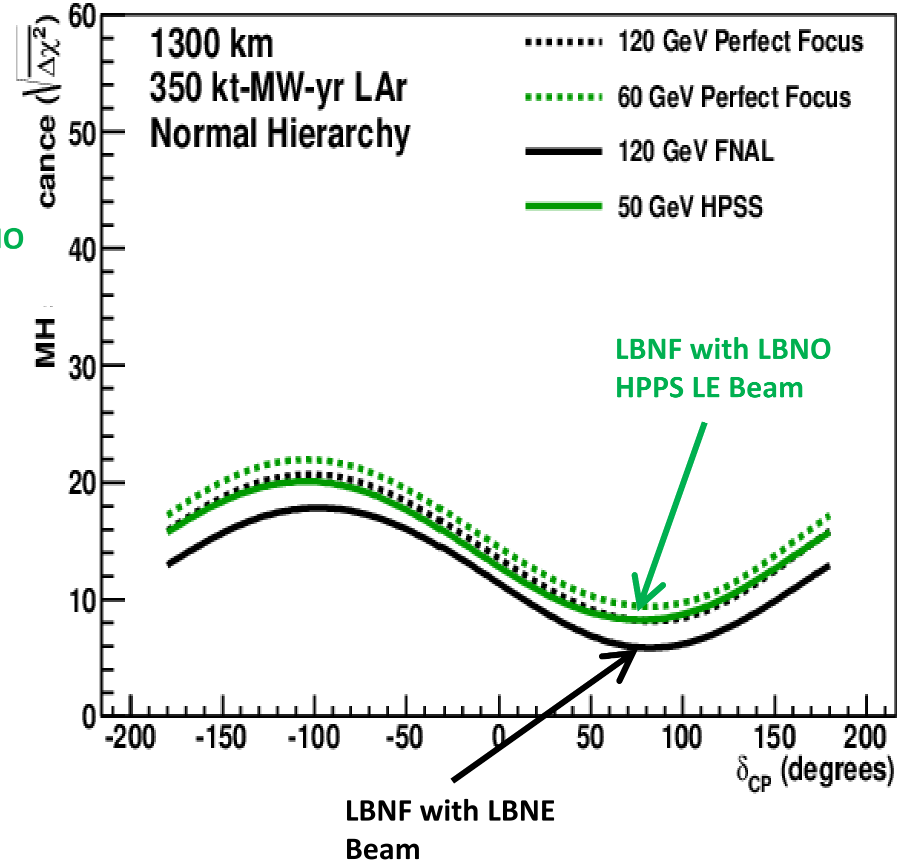


POT normalization for SPS: 3.75E+20
POT normalization for HPPS: 3.0E+21

- New optimization for CDR, using additional engineering constraints:
  - R_{min} horn ~27mm
  - Same relative position horn/reflector for 400/50 GeV beams
  - Target length <1.3 m

Apply LBNO-design low-energy beam (HPPS LE) to LBNF

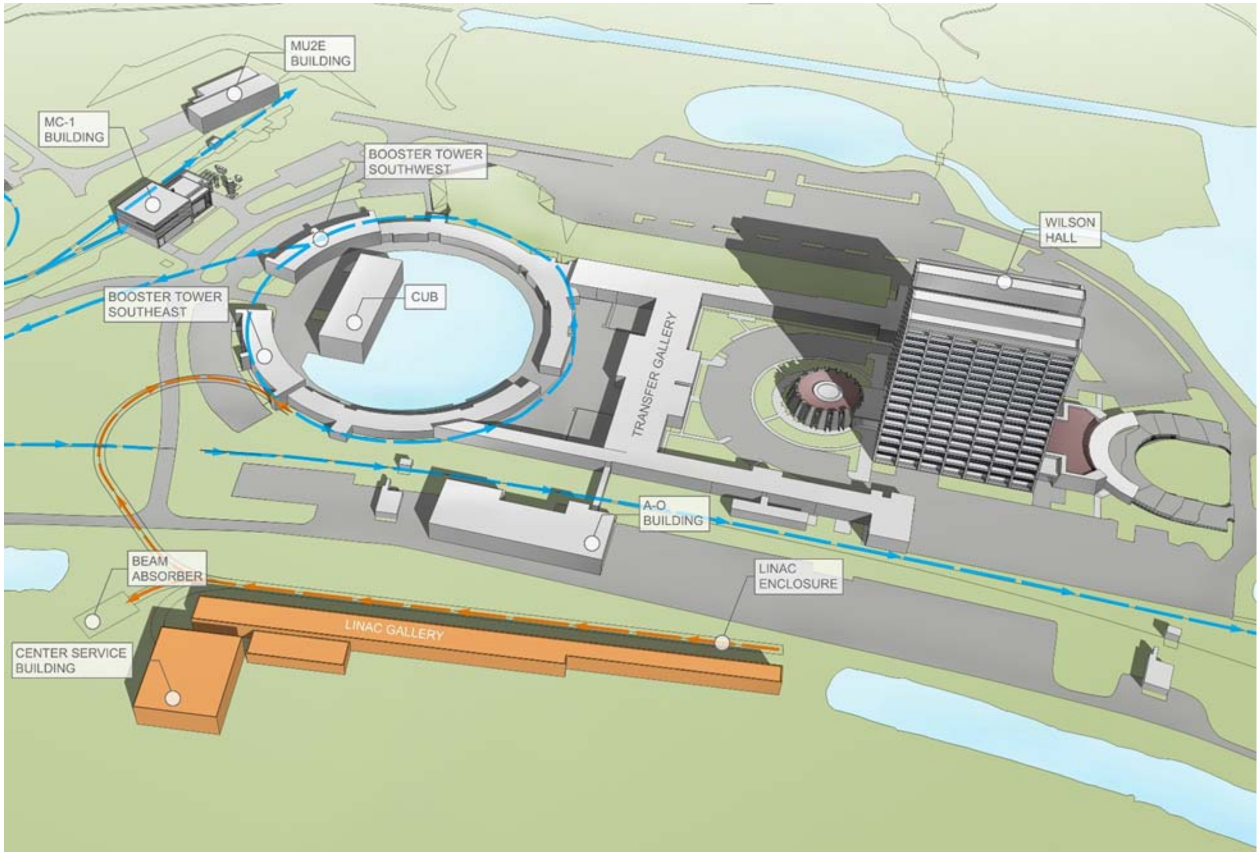




- Application of HPPS LE beam spectrum to LBNF baseline
  - modestly improves CP violation reach
  - improves minimum $\Delta\chi^2$ by ~x2 for MH

PIP-II: Beam power upgrade to 1.2 MW

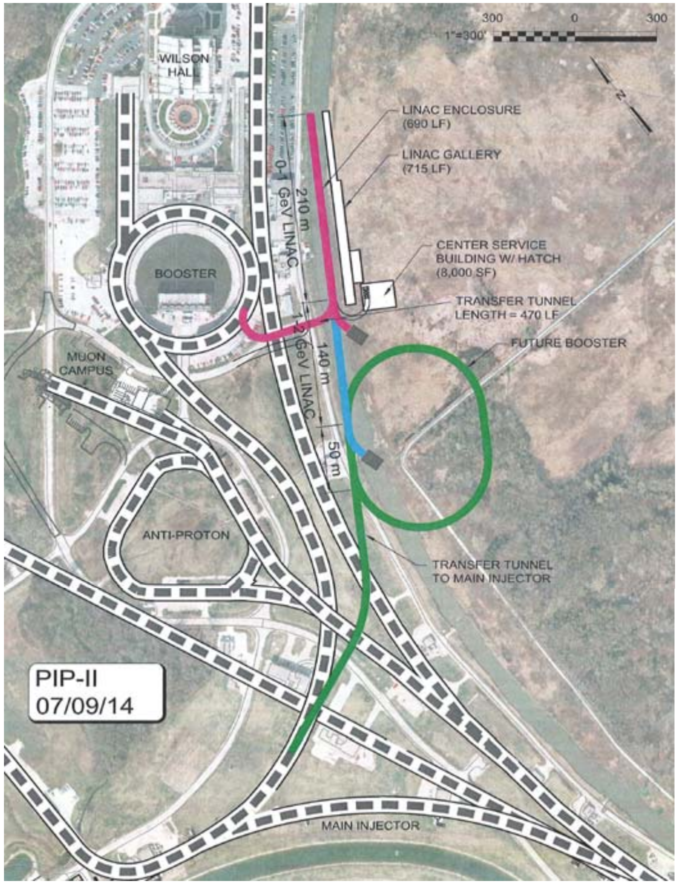
- Development phase
  - R&D program supports 2018-2019 construction start
  - Collaboration with India
- Strong support from P5, U.S. DOE, and the Fermilab Director
- Five year construction period would support operations startup in 2023

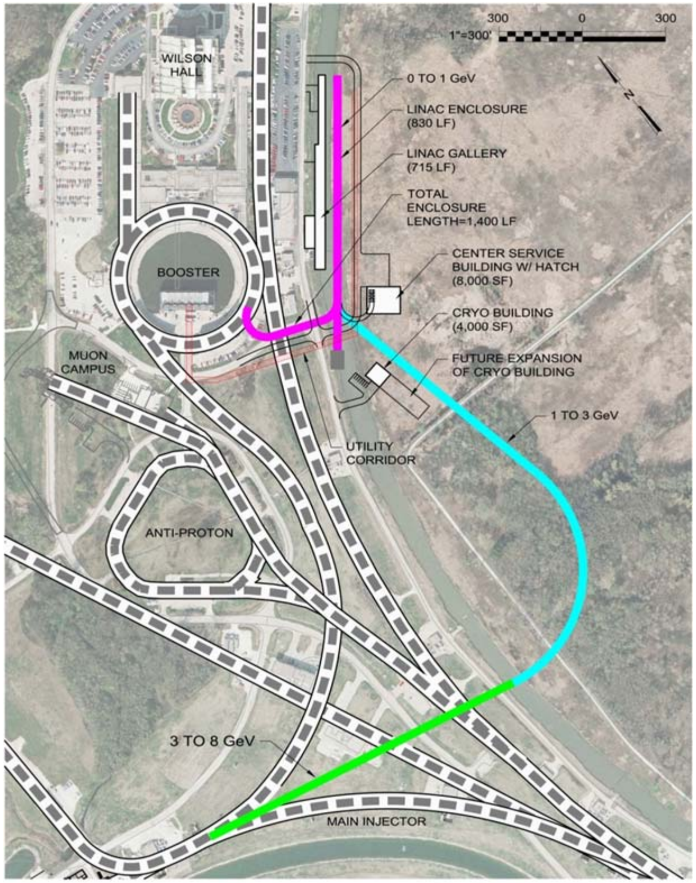


P5 R14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

Flexible Platform for the Future

- Opportunities for Booster replacement include full energy (8 GeV) linac or RCS => Beam power from Main Injector > 2 MW



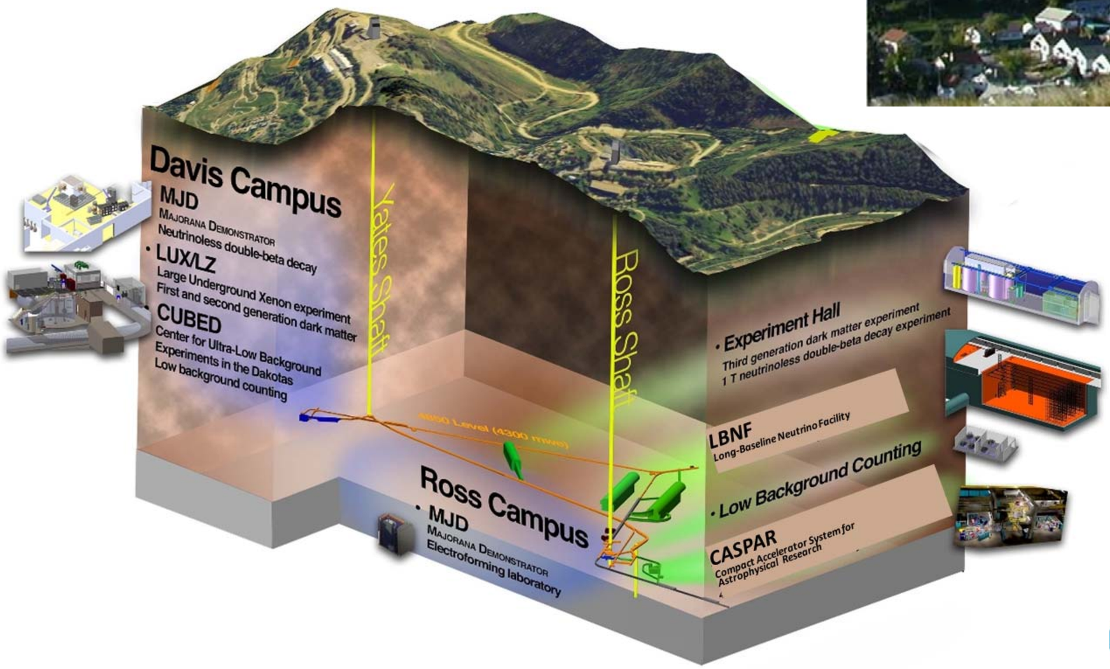


Sanford Underground Research Facility

Experimental facility operated by the State of South Dakota.

Current experiments:

- LUX (dark matter)
- Majorana ($0\nu\beta\beta$)
- Several smaller experiments



Future home of:

- LZ (G2 dark matter experiment)
- CASPAR (Compact Accelerator System for Astrophysical Research)
- LBNF

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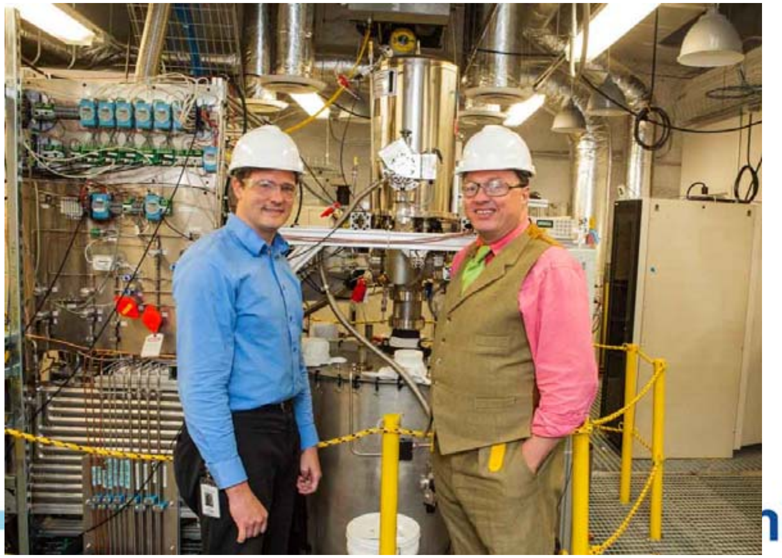
Sanford Underground Research Facility

Entrance to Davis Campus

Majorana Demonstrator (0νββ)

- Experimental Facilities at 4300 mwe
- Two vertical access shafts for safety
- Shaft refurbishment in process and has reached the 2000 foot level
- Total investment in underground infrastructure is >$100M
- Facility donated to the State of South Dakota for science in perpetuity

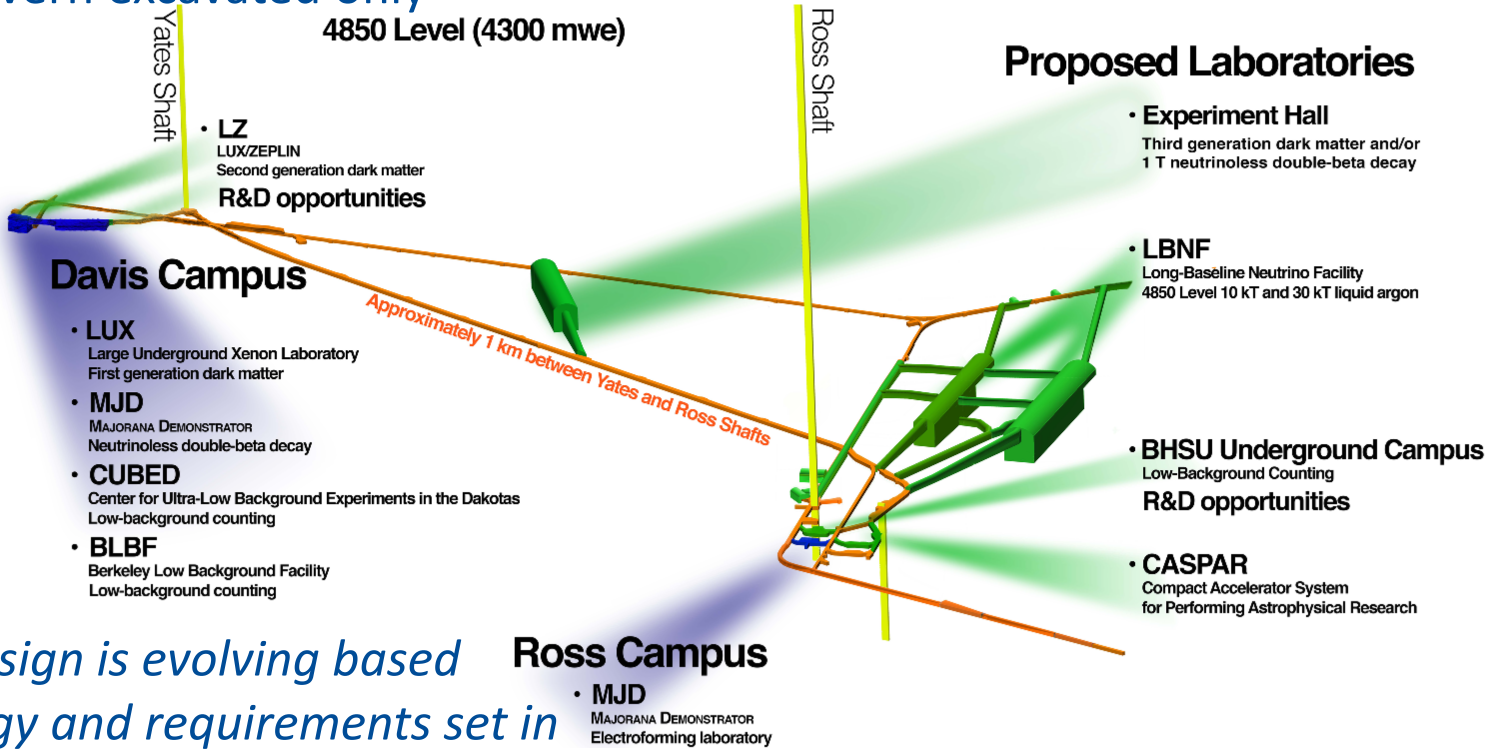
LUX (dark matter)



Planned Location of LBNF Cavern(s)

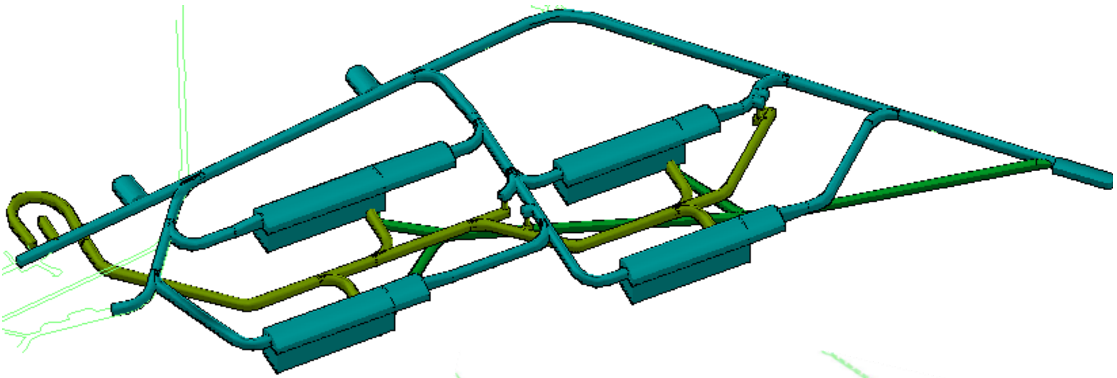
(Previous) reference* design:

- Rectangular caverns
- 2 caverns: 10 kt + 30 kt fiducial mass sizes
- 10 kt cavern fully outfitted and detector-ready
- 30 kt cavern excavated only

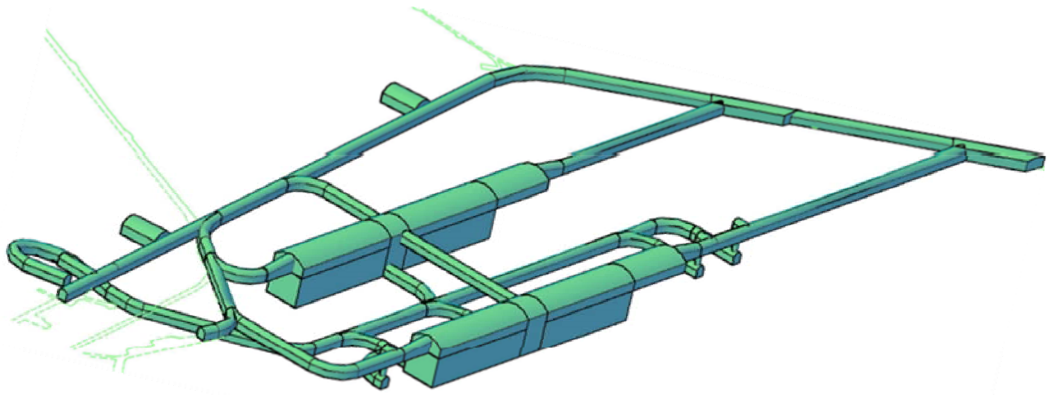


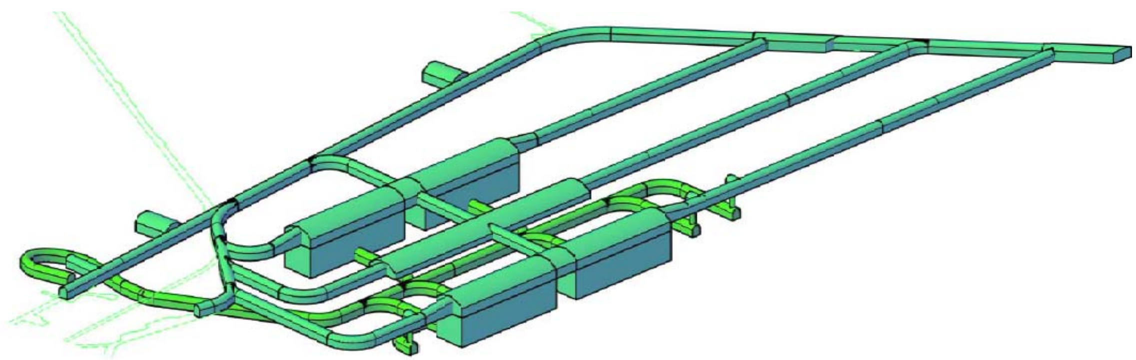
** Actual design is evolving based on strategy and requirements set in discussion with ELBNF Collaboration*

Cavern Layout Options Under Study



Based on use of four identical cryostats, designed to accommodate either single- or dual-phase LAr TPC detectors.





Schedule

<u>Schedule Goals set in the LOI</u>

> The new international team has the necessary expertise, technical knowledge, and critical mass to design and implement this exciting discovery experiment in a relatively short timeframe. The goal is the deployment of the first 10-kt fiducial mass detector on the timescale of 2021, followed by future expansion to the full detector size as soon as possible. The PIP-II accelerator upgrade at Fermilab will provide 1.2 MW of power by 2024 to drive a new neutrino beam line at Fermilab. There also exists a plan that could further upgrade the Fermilab accelerator complex to enable it to provide up to 2.4 MW of beam power by 2030.

- A project plan is being developed to try to meet them as closely as possible, subject to both on technical limitations and funding.
- Break the project into pieces which can be implemented in a sequence determined by the scientific strategy:
  - Far detector in 10 kt fiducial mass modules
  - Neutrino Beam
  - Near Detector

International Governance of ELBNF and LBNF

- ELBNF will follow a model derived from the CERN LHC, which clearly separates the ownership of the experiment (International Collaboration -- ELBNF) from the ownership of the facility (Host Lab with international partners -- LBNF)
- Collaboration and Host Lab rights and obligation are regulated by MOUs
- A strong Experiment - Facility Interface Group (EFIG) is key.
- Interim EFIG has been formed with representatives of the experiment appointed by the proto-Institutional Board and representatives of the facility project.
- DOE is engaged with other funding agencies interested in participating in and supporting this program to fully develop the governance model.

Organizing the Collaboration

- First collaboration meeting 22-23 January
  - First IB meeting held
  - Agreed on Memorandum of Collaboration which specifies procedures by which the collaboration starts to organize
- Committee to draft by-laws is at work
- Spokesperson election is under way – results on 7 March
- Collaboration naming “contest” under way – ballot closed yesterday.
- Weekly collaboration meetings by phone; monthly IB meetings.
- Next full collaboration meeting 16-18 April at Fermilab.

DOE Reviews

DOE is very supportive of the aggressive schedule goals

- Excavation of the caverns for the far detector starting in 2017
- Initial 10 kt detector operating as soon as possible.

To support the funding required, DOE has called for a “CD-1 Refresh” review in July for the whole LBNF + ELBNF enterprise...

- New / updated CDR and other technical documents incorporating designs and alternatives from all (E)LBNF partners.
- New / updated cost and schedule estimates.
- New / updated management plans and related documents

... and a CD-2a/3a review in November for the far site facilities.

- CD-2a: Project baseline (TDR-level) for this part of the project.
- CD-3a: Authorization to begin construction at the far site when funds become available.

Summary

- A new global collaboration has formed to perform an experimental program in neutrino physics, nucleon decay, and astroparticle physics at the Fermilab Long Baseline Neutrino Facility (LBNF).
- The collaboration organization is taking shape rapidly.
- The experiment and facility designs are being developed, incorporating ideas and designs developed by all collaborators.
- The goal is to enable the operation of an initial 10 kt far detector in ~2021 and provide a clear path to the full ELBNF experiment soon thereafter.
- DOE is fully supportive of this goal and is working with other funding agencies to gather the necessary resources.
- The next months will be crucial
  - Forming the ELBNF collaboration and LBNF project
  - Defining the international governance
  - Preparing for and passing the DOE “CD-1 refresh” and CD-2a/3a reviews.