THE FERMILAB NEUTRINO PROGRAM

Antonio Ereditato – Yale University

Yale University

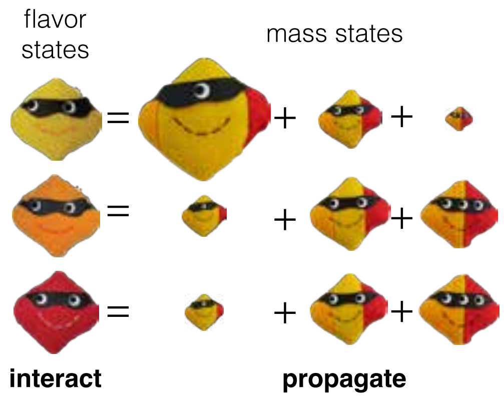
Neutrino oscillations

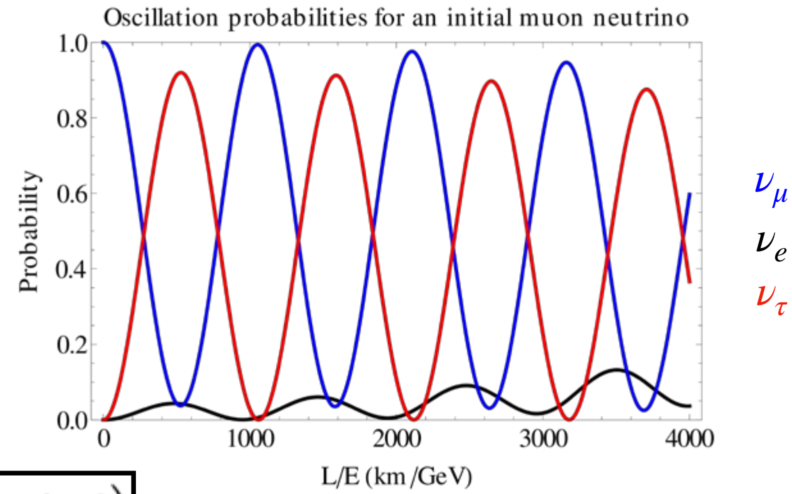
Mixing matrix

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

Flavor eigenstates participating in weak interactions

Mass eigenstates ν_1, ν_2, ν_3





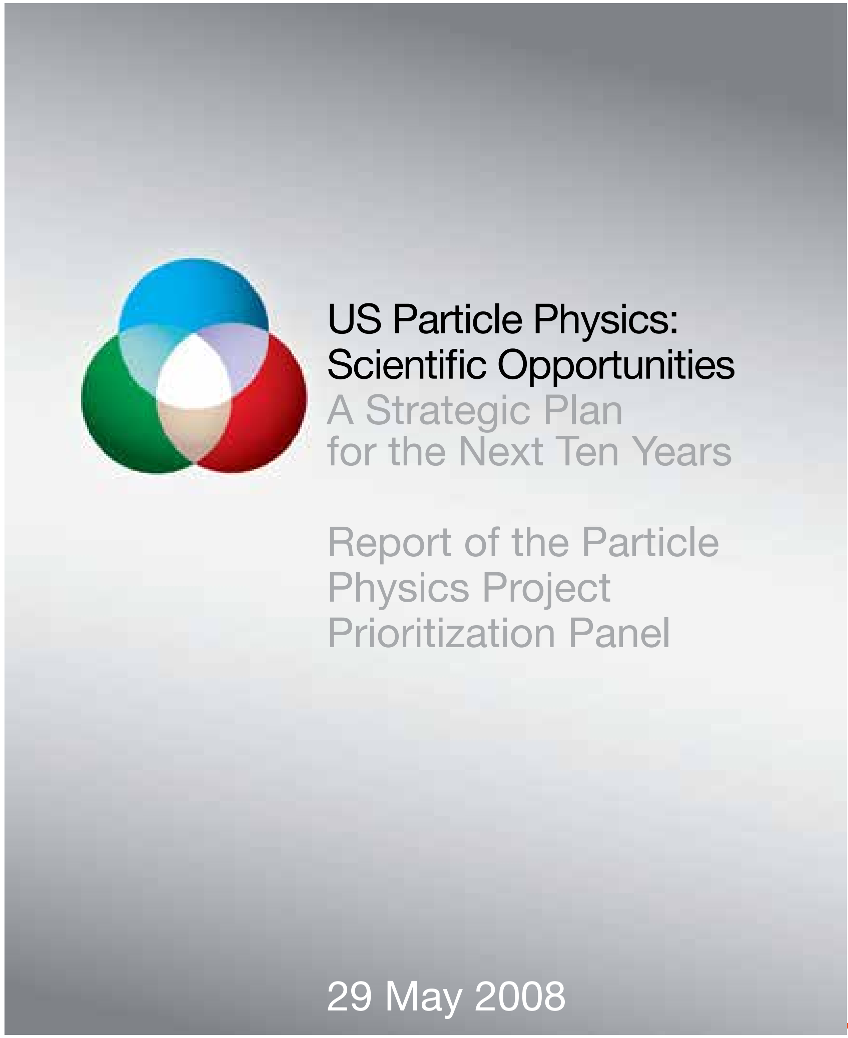
two-neutrino model

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2\ [\mathrm{eV}]^2 \cdot L\ [\mathrm{km}]}{E_\nu\ [\mathrm{GeV}]}\right)$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

A long story…

2008 P5



4 THE DEEP UNDERGROUND SCIENCE AND ENGINEERING LABORATORY—DUSEL

The Deep Underground Science and Engineering Laboratory would offer a major new facility for US particle physics. Located in the Homestake mine in Lead, South Dakota, DUSEL would be an underground laboratory housing a wide spectrum of experiments. When the first parts of the laboratory begin operation around 2013, DUSEL would be a key element in the US particle physics program. A large detector for long-baseline neutrino physics would be part of the initial suite of experiments, as would detectors for dark matter and double beta decay experiments.

Recommendation

The panel endorses the importance of a deep underground laboratory to particle physics, and it urges NSF to make this facility a reality as rapidly as possible. Furthermore, the panel recommends that DOE and NSF work together to realize the experimental particle physics program at DUSEL.

The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab.

The panel further recommends that in any funding scenario considered by the panel Fermilab proceed with the upgrade of the present proton source by about a factor of two, to 700 kilowatts to allow for an extended physics reach using the current beamline and a timely start for the neutrino program in the Homestake mine.

Next Steps

January 2010 -> Mission Need

Excerpt from
Mission Need Statement for a
Long Baseline Neutrino Experiment (LBNE)

Office of High Energy Physics
Office of Science

A. Statement of Mission Need

The mission of the High Energy Physics (HEP) program is to support exploration of the physical universe through the discovery and study of the elementary constituents of matter and energy and the nature of space and time. These areas of research are an integral component for the advancement of all science and technology and an expression of society's timeless intellectual quest to understand the universe. The Standard Model of particle physics represents an unprecedentedly successful description of the elementary particles and their interactions; however, we know this model is incomplete and our present understanding indicates the existence of a more fundamental underlying theory. Elucidating this deeper theory requires a broad research program at the complementary and interrelated Energy, Intensity, and Cosmic Frontiers of particle physics.

At the Intensity Frontier, intense particle beams are utilized to investigate the properties of neutrinos and rare processes, both probes of new physics. Results from the last decade conclusively demonstrate that the three known neutrinos have nonzero mass, mix with one another, and oscillate between generations-properties which represent tantalizing hints of physics beyond the Standard Model. Cosmology indicates that the neutrino mass is less than one-millionth that of the electron, yet oscillation studies from experiments find tiny, but nonzero, mass differences between neutrino generations and large values for two of the three mixing angles. Currently, the individual masses are unknown and only an upper limit exists for the third angle.

The recent progress in neutrino physics has laid the basis for new discovery opportunities. As a fundamental physical constant, measurement of the unknown third mixing angle is of great interest and will influence the direction and evolution of an international neutrino program. Determining the relative masses and mass ordering of the three known neutrinos will give guidance and constraints to theories beyond the Standard Model. The study and observation of the different behavior of neutrinos and antineutrinos traversing matter will offer insight into the dominance of matter over antimatter in our universe and, therefore, the very structure of our universe. The only other source of the matter-antimatter asymmetry, in the quark sector, is too small to account for the observed matter dominance. A popular hypothesis asserts that the asymmetry arises from neutrino interactions and is the subject of intense research.

The Office of High Energy Physics proposes construction of an experiment comprised of a large detector illuminated by a distant, intense neutrino source and a much smaller detector located close to the source. The far detector must be at a long distance from the neutrino source to increase sensitivity to neutrino oscillations and have sufficient sensitivity (through increased size and technological innovation or both) to improve neutrino detection. A new intense neutrino source, pointing towards the detector, is also needed along with a nearby detector to measure the initial composition of the neutrino beam. The increased research capabilities afforded by a long baseline (distance between the detector and the neutrino source) neutrino experiment will enable a world-class program in neutrino physics that can measure fundamental physical parameters, explore physics beyond the Standard Model, and better elucidate the nature of matter and antimatter.

Preliminary Critical Decisions

CD-0 Approve Mission Need	1st quarter FY 2010
CD-1 Approve Alternative and Cost Range	1st quarter FY 2011
CD-2 Approve Performance Baseline	3rd quarter FY 2012
CD-3 Approve Start of Construction	1st quarter FY 2014
CD-4 Approve Start of Operations	2nd quarter FY 2020

Even, not knowing the value of θ_{13}, the community and DOE were ready to explore the unknown

Spring 2012 Game Changer

The Daya Bay Reactor Neutrino Experiment has measured a non-zero value for the neutrino mixing angle θ_{13} with a significance of 5.2 standard deviations. Antineutrinos from six 2.9 $\mathrm{GW_{th}}$ reactors were detected in six antineutrino detectors deployed in two near (flux-weighted baseline 470 m and 576 m) and one far (1648 m) underground experimental halls. With a 43,000 ton-$\mathrm{GW_{th}}$-day livetime exposure in 55 days, 10416 (80376) electron antineutrino candidates were detected at the far hall (near halls). The ratio of the observed to expected number of antineutrinos at the far hall is $R = 0.940 \pm 0.011(\mathrm{stat}) \pm 0.004(\mathrm{syst})$. A rate-only analysis finds $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$ in a three-neutrino framework.

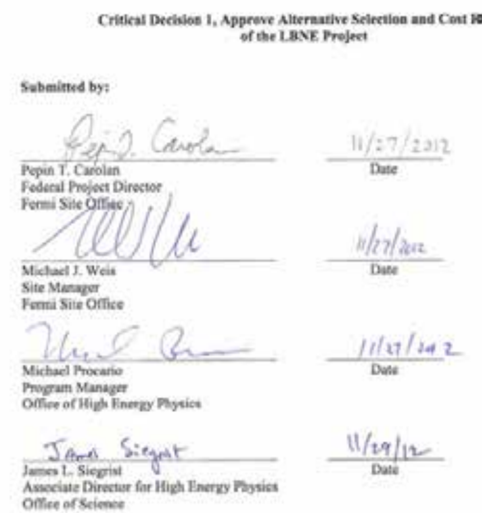
arXiv:1203.1669v2 [hep-ex] 2 Apr 2012

θ_{13} is large and we PROCEED

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

Description of Scope	Threshold Key Performance Parameter (KPP)	Objective KPP
Primary Beam Power to produce neutrinos directed to the far detector site	Capable of delivering 700 kiloWatts , with beamline hardware commissioning complete.	
Long-Baseline Distance between neutrino source and far detector	1,000-1,500 kilometers	
Liquid Argon Far Detector	Operational capability installed for a 10 kiloton detector and demonstration of threshold performance by observation of cosmic ray interactions.	Additional detector mass and/or underground siting, facilitated by non-DOE in-kind contributions
Near Detector	Tertiary Muon Detector components tested in NUMI beam.	Near Detector facilitated by non-DOE in-kind contributions

Critical Decision Milestone	Schedule
CD-0 Approve Mission Need	1/8/2010 (Actual)
CD-1 Approve Alternative Selection and Cost Range	1st Quarter, FY2013
CD-3a Approve Long Lead Procurement	3rd Quarter, FY2015
CD-2 Approve Performance Baseline	3rd Quarter, FY2016
CD-3b Approve Start of Construction	3rd Quarter, FY2017
CD-4 Approve Project Completion	3rd Quarter FY2025


Critical Decision 1, Approve Alternative Selection and Cost R
of the LBNE Project

Submitted by:

Pepin T. Carolan, Federal Project Director, Fermi Site Office — Date: 11/27/2012
Michael J. Weis, Site Manager, Fermi Site Office — Date: 11/27/2012
Michael Procario, Program Manager, Office of High Energy Physics — Date: 11/27/2012
James L. Siegrist, Associate Director for High Energy Physics, Office of Science — Date: 11/29/12

CD-1 for LBNE

European Strategy for Particle Physics – 2013 update

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*.

Fermilab interim International Executive Board (iIEB) for the Long Baseline Neutrino Facility (LBNF), 2014

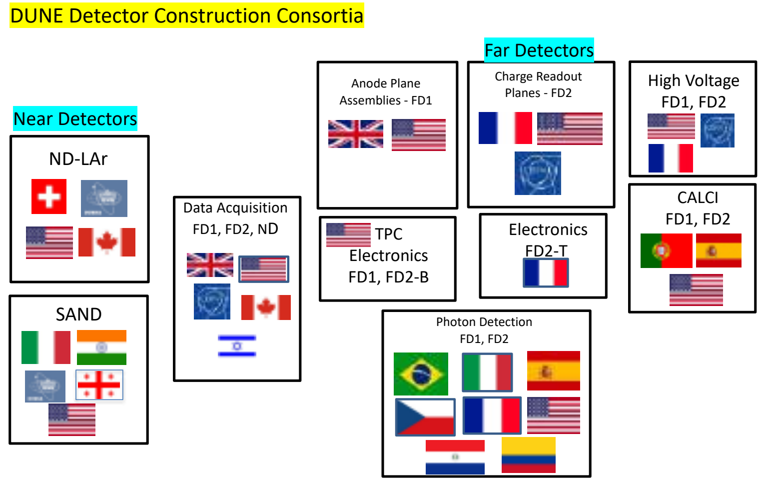
2014 P5 Report : 4 recommendations

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation[2] of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}. By current estimates, this goal corresponds to an exposure of 600 kt*MW*yr assuming systematic uncertainties of 1% and 5% for the signal and background, respectively. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this exposure implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector. **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 volume, 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.**

These minimum requirements are not met by the current LBNE project's CD-1 minimum scope. The long-baseline neutrino program plan has undergone multiple significant transformations since the 2008 P5 report. Formulated as a primarily domestic experiment, the minimal CD-1 configuration with a small, far detector on the surface has very limited capabilities. A more ambitious long-baseline neutrino facility has also been urged by the Snowmass community study and in expressions of interest from physicists in other regions. To address even the minimum requirements specified above, the expertise and resources of the international neutrino community are needed. **A change in approach is therefore required.** The activity should be reformulated under the auspices of a new international collaboration, as an internationally coordinated and internationally funded program, with Fermilab as host. There should be international participation in defining the program's scope and capabilities. The experiment should be designed, constructed, and operated by the international collaboration. The goal should be to achieve, and even exceed if physics eventually demands, the target requirements through the broadest possible international participation.

√ **Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.**



√ **Recommendation 14: 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.**

√ **Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.**

The ICARUS detector was installed in its Fermilab research hall in 2018.

This image shows the particle tracks resulting from the interaction of a neutrino with liquid argon inside the MicroBooNE detector.

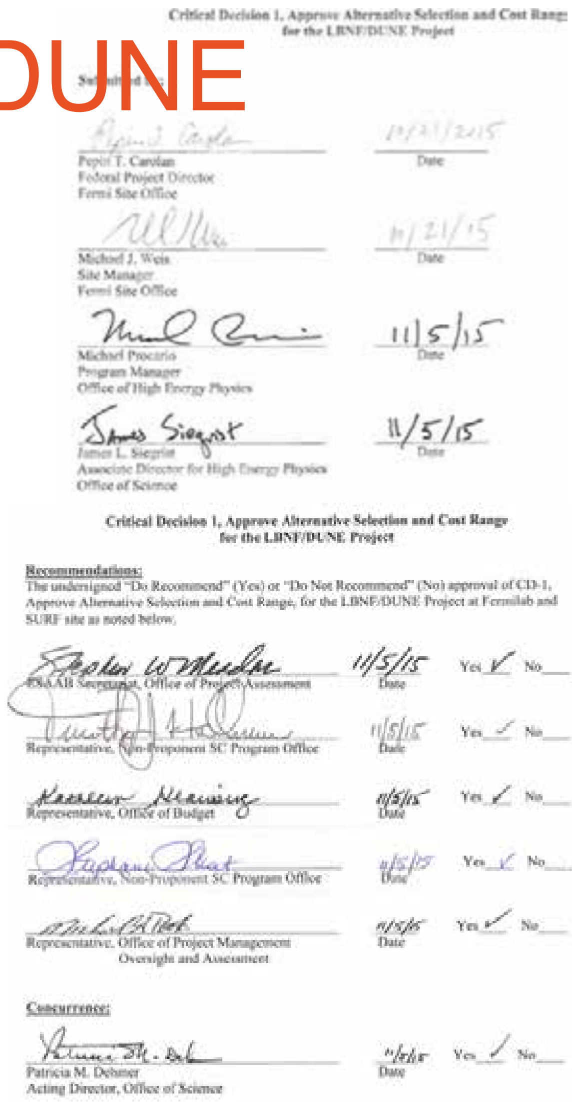
2015 CD-1R for LBNF/DUNE

Critical Decision 1, Approve Alternative Selection and Cost Range
for the
Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment
at
Fermi National Accelerator Laboratory and
Sanford Underground Research Facility

Office of High Energy Physics
Office of Science

Table 2 -LBNF/DUNE Preliminary DOE Schedule

Critical Decision Milestone	Schedule
CD-0, Approve Mission Need	1/8/2010 (Actual)
CD-1, Approve Alternative Selection and Cost Range	12/10/2012 (Actual)
CD-1, Approve Alternative Selection and Cost Range (Update)	1st Quarter, FY2016
CD-3a (1), Approve Initial Far Site Construction	2nd Quarter, FY2016
CD-3b (2), Approve Near Site Preparation/Far Site Long Lead Procurement	2nd Quarter FY2019
CD-2, Approve Performance Baseline	1st Quarter, FY2020
CD-3(3), Approve Start of Construction	1st Quarter, FY2020
CD-4 , Approve Project Completion	4th Quarter FY2030


Critical Decision 1, Approve Alternative Selection and Cost Range
for the LBNF/DUNE Project

Submitted by:

Pepin T. Carolan, Federal Project Director, Fermi Site Office — Date: 10/21/2015

Michael J. Weis, Site Manager, Fermi Site Office — Date: 10/21/15

Michael Procario, Program Manager, Office of High Energy Physics — Date: 11/5/15

James L. Siegrist, Associate Director for High Energy Physics, Office of Science — Date: 11/5/15

Critical Decision 1, Approve Alternative Selection and Cost Range
for the LBNF/DUNE Project

Recommendations:
The undersigned "Do Recommend" (Yes) or "Do Not Recommend" (No) approval of CD-1, Approve Alternative Selection and Cost Range, for the LBNF/DUNE Project at Fermilab and SURF site as noted below.

ESAAB Secretariat, Office of Project Assessment — Date: 11/5/15 — Yes ✓ No___

Representative, Non-Proponent SC Program Office — Date: 11/5/15 — Yes ✓ No___

Representative, Office of Budget — Date: 11/5/15 — Yes ✓ No___

Representative, Non-Proponent SC Program Office — Date: 11/5/15 — Yes ✓ No___

Representative, Office of Project Management Oversight and Assessment — Date: 11/5/15 — Yes ✓ No___

Concurrence:

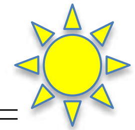
Patricia M. Dehmer, Acting Director, Office of Science — Date: 11/5/15 — Yes ✓ No___

Evolution of accelerator neutrino experiments

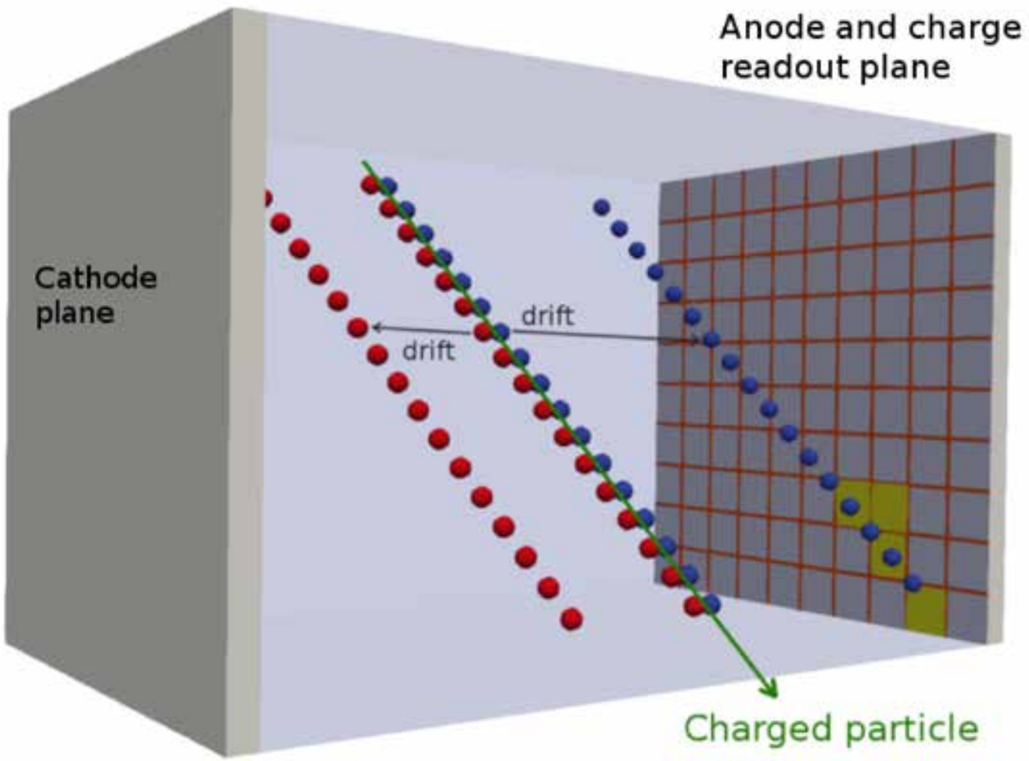
- Since the late 1990's accelerator based neutrino beams have been constructed and operated to explore and measure the parameters of neutrino mass and mixing;

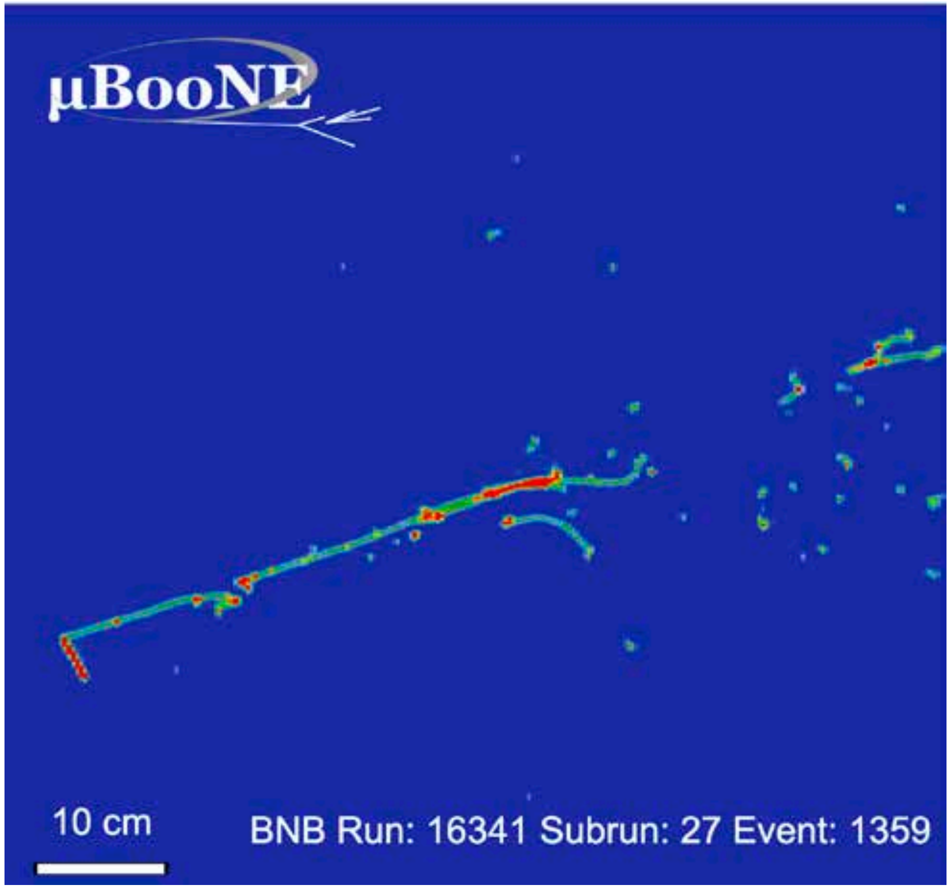
Table 14.3: List of long-baseline neutrino oscillation experiments

Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6	2010–
NOvA	NuMI	Liquid scint. tracking calorimeter	810	2	2014–



The detector choice: liquid argon TPC



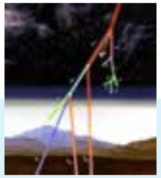
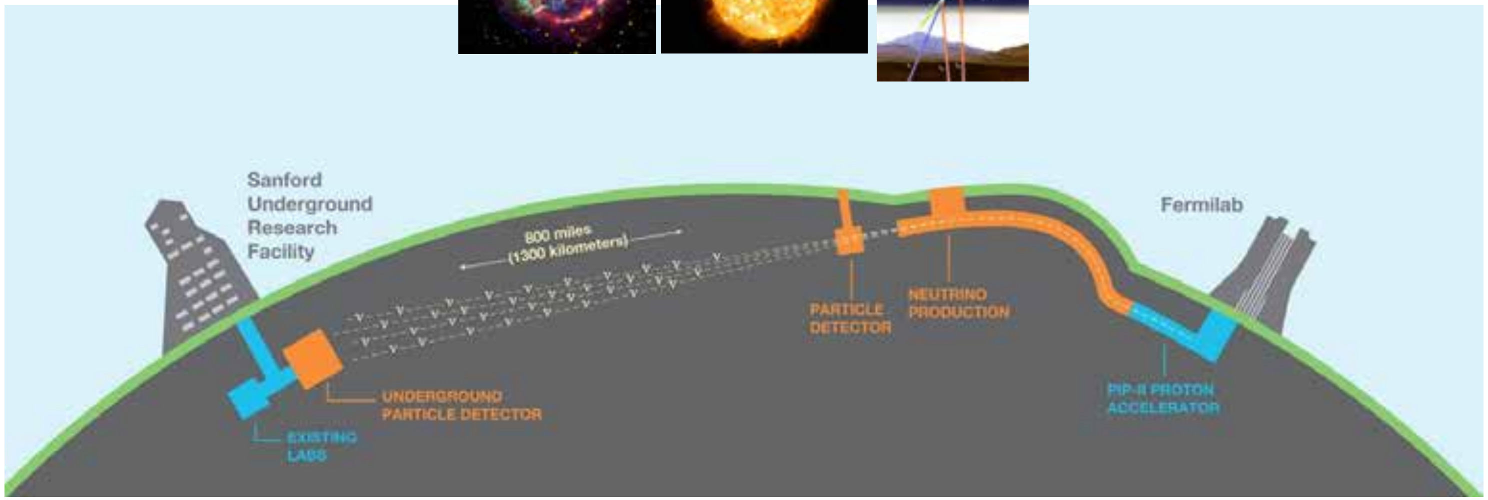


DUNE Collaboration

Today: >1000 people from over 200 institutions from 30 countries

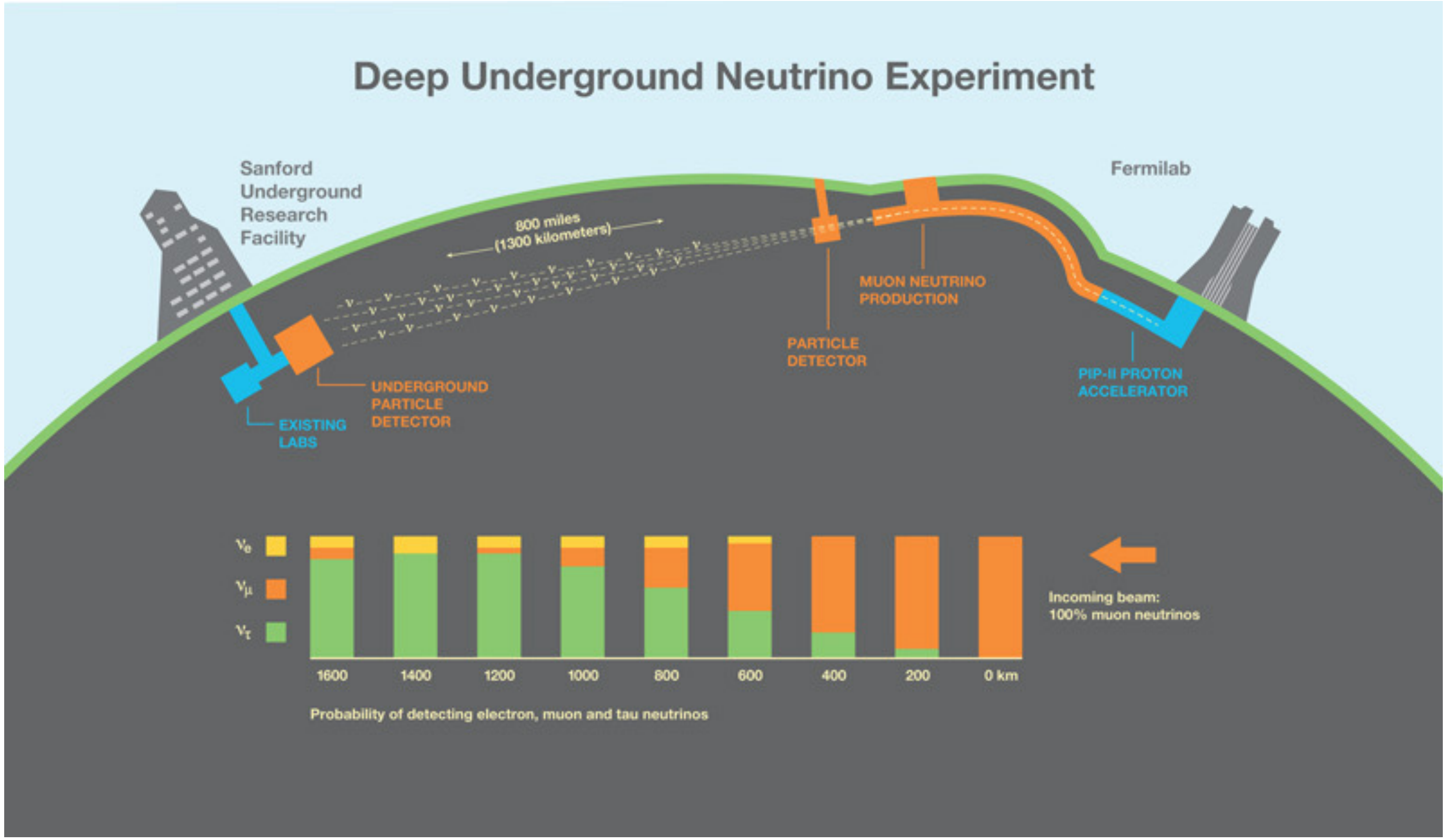
DUNE Physics Goals



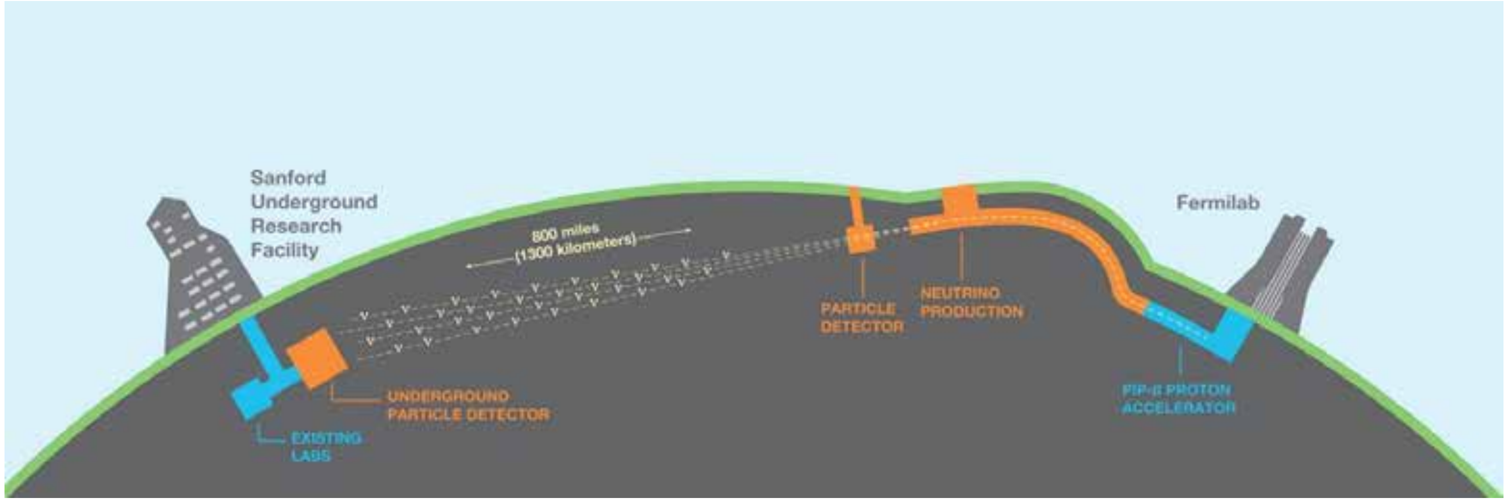
- Unambiguous, high precision measurements of Δm^2_{32}, δ_{CP}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ in a single experiment
- Discovery sensitivity to CP violation, mass ordering, θ_{23} octant over a wide range of parameter values
- Sensitivity to MeV-scale neutrinos, such as from a galactic supernova burst
- Low backgrounds for sensitivity to BSM physics including baryon number violation

Neutrino oscillations in DUNE



At the far detector we measure ν_μ ($\overline{\nu}_\mu$) disappearance and ν_e ($\overline{\nu}_e$) appearance

Neutrino oscillations in DUNE

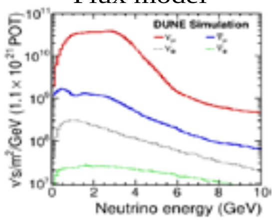


- The DUNE neutrino oscillation program is **exceptional** due to several key features of the experiment and facility design :
  - The **1300 km baseline** between Fermilab and SURF location for the far detectors enables an unambiguous measurement of the neutrino mass ordering (mass hierarchy)
  - The detector's on-axis location provides for a **wide-band energy spectrum of neutrinos** to be seen in the near and far locations enabling detailed fitting of the oscillation parameters
  - The **liquid argon detector technology** enables precise reconstruction of the neutrino interactions
  - The Near Detector complex at Fermilab will support near detectors that will provide **unprecedented control of systematic uncertainties** in the prediction of the un-oscillated neutrino flux

Key components of the long-baseline oscillation analysis

Use simulations to predict
Spectrum at far detector

Flux model



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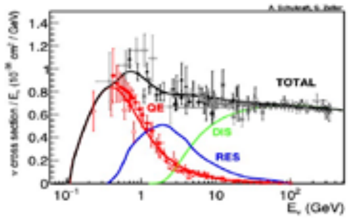

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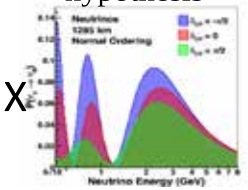
Oscillation hypothesis



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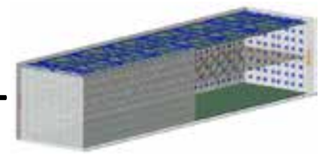
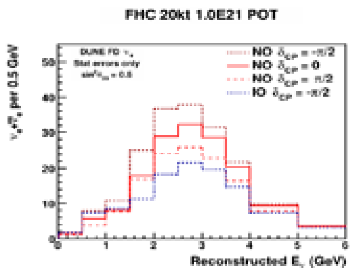
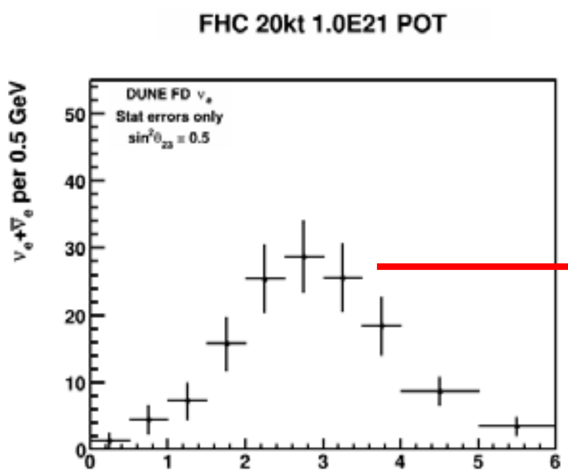
Detector Model





Eventually do the experiment
and collect data

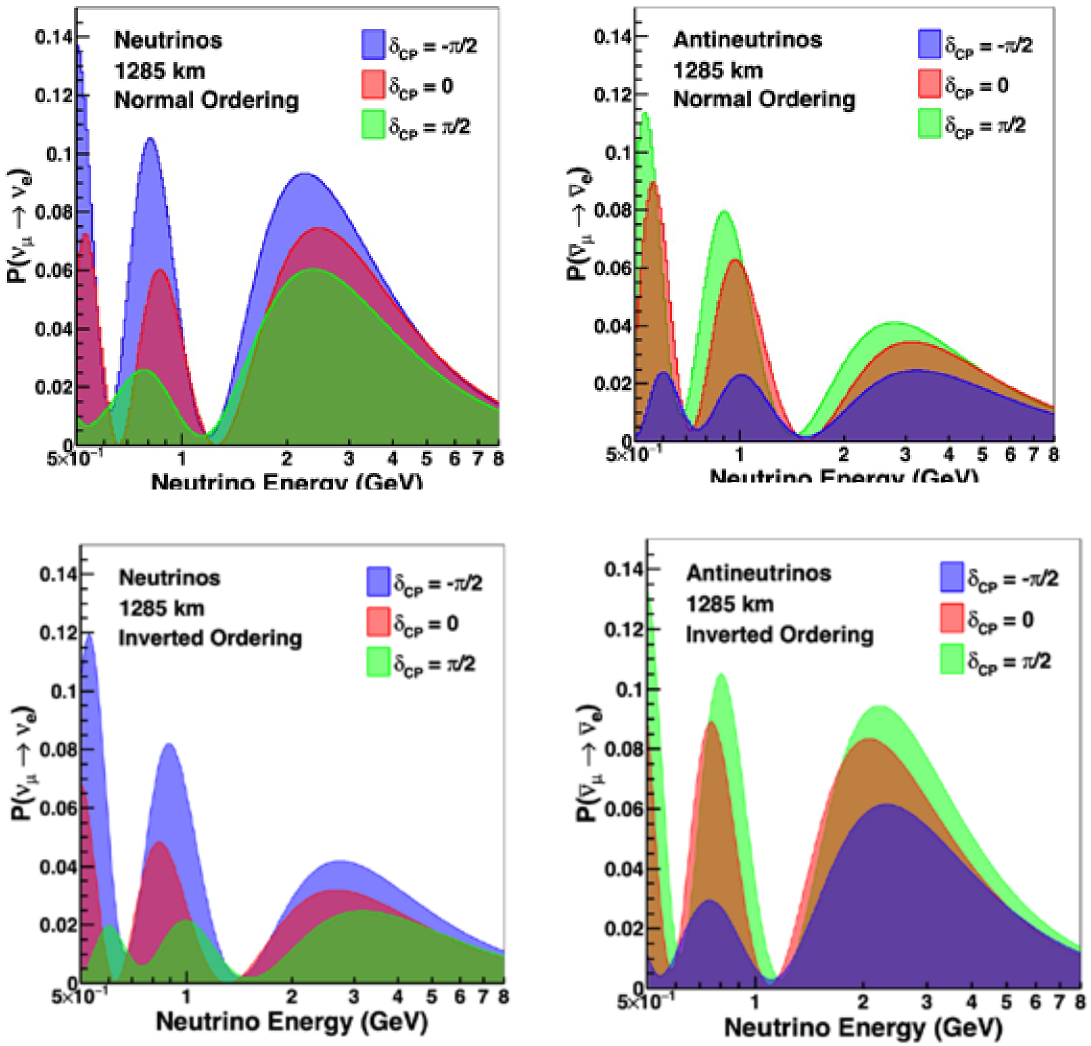
Fit the data to the prediction to extract an unknown parameter

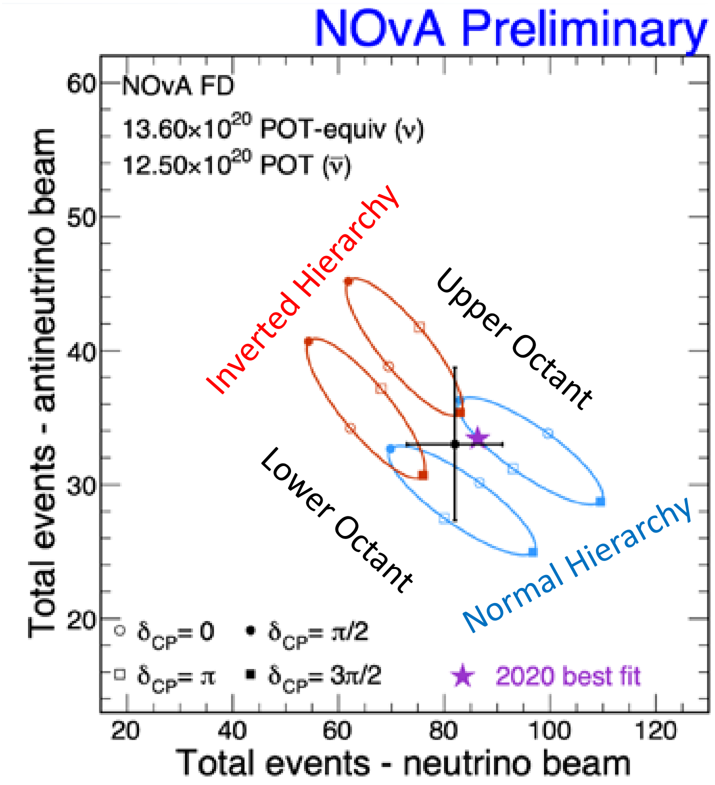


Reconstructed ν energy

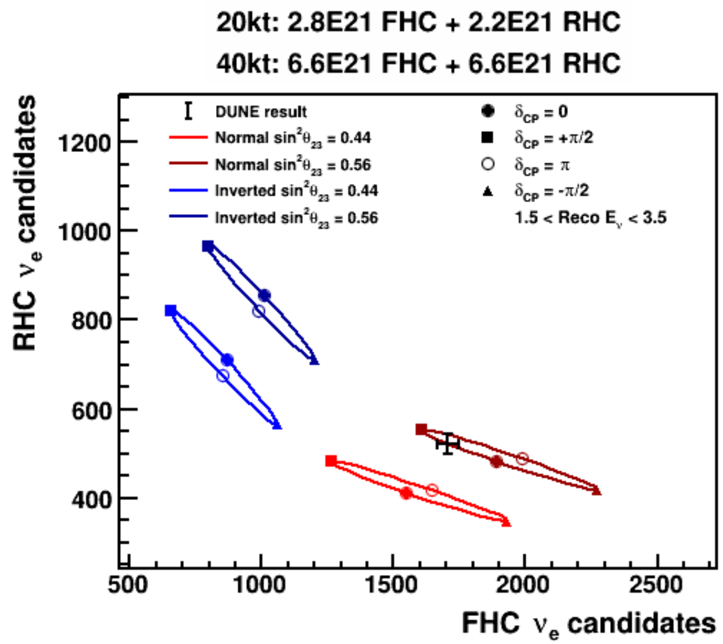
$$(\delta_{CP}) = 2\sum_{i}^{N_{bins}}\left[N_i^{pred}(\delta_{CP}) - N_i^{obs} + N_i^{obs}\ln\left(\frac{N_i^{obs}}{N_i^{pred}(\delta_{CP})}\right)\right]$$

ν_e appearance





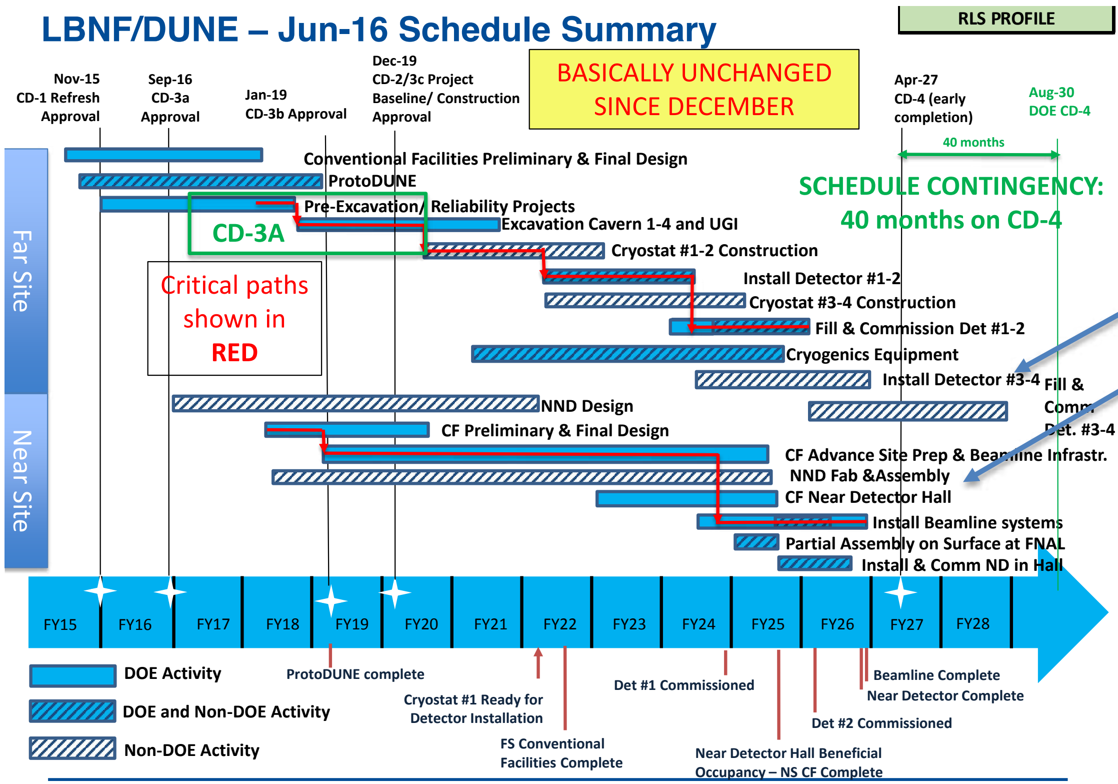
DUNE simulation



In DUNE we have unique Separation of the mass ordering …..

International DUNE Experiment

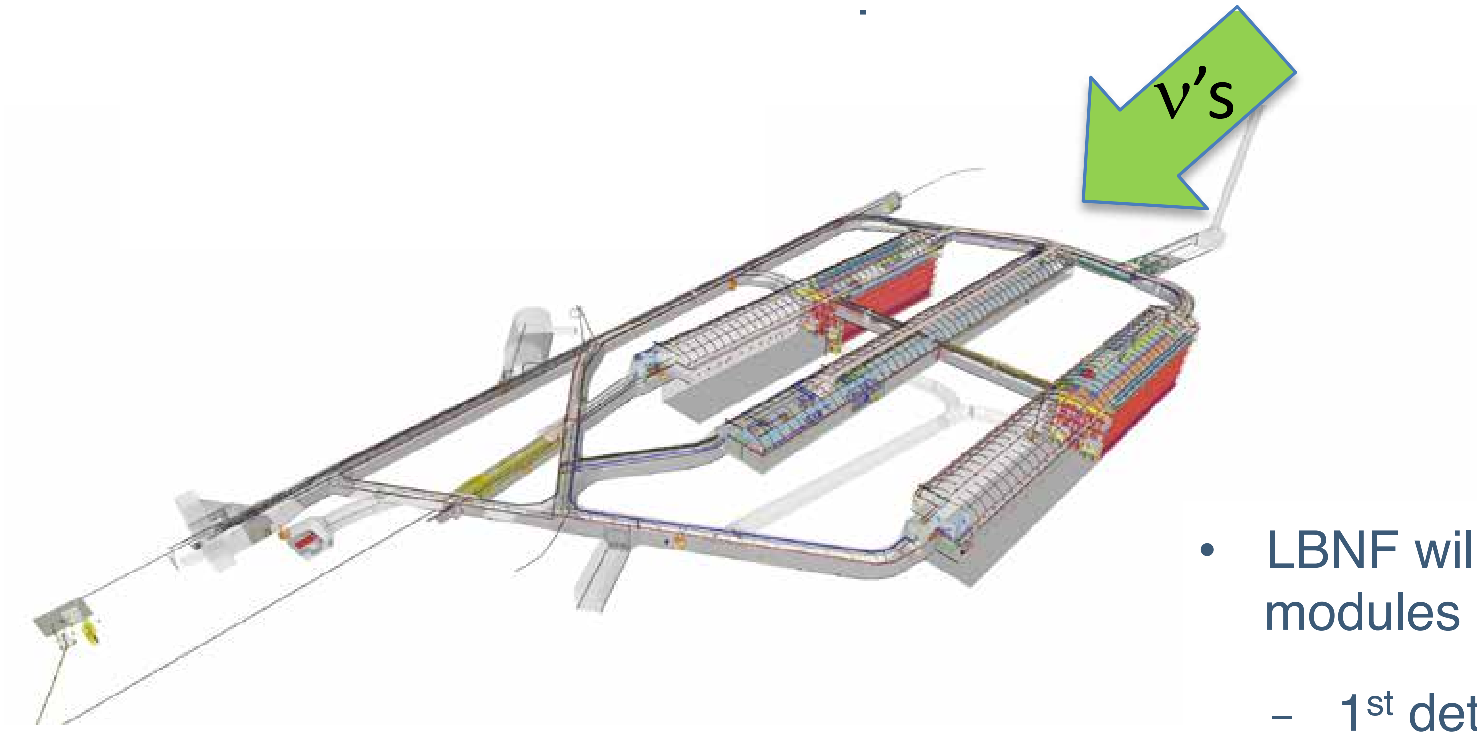
- Proposed post-P5 (2015)
  - 40 kT fiducial mass of LAr in 4 detector modules
  - “capable” Near Detector
  - 1.2 MW proton beam power



Aug 2016 IPR

- DOE Activity
- DOE and Non-DOE Activity
- Non-DOE Activity

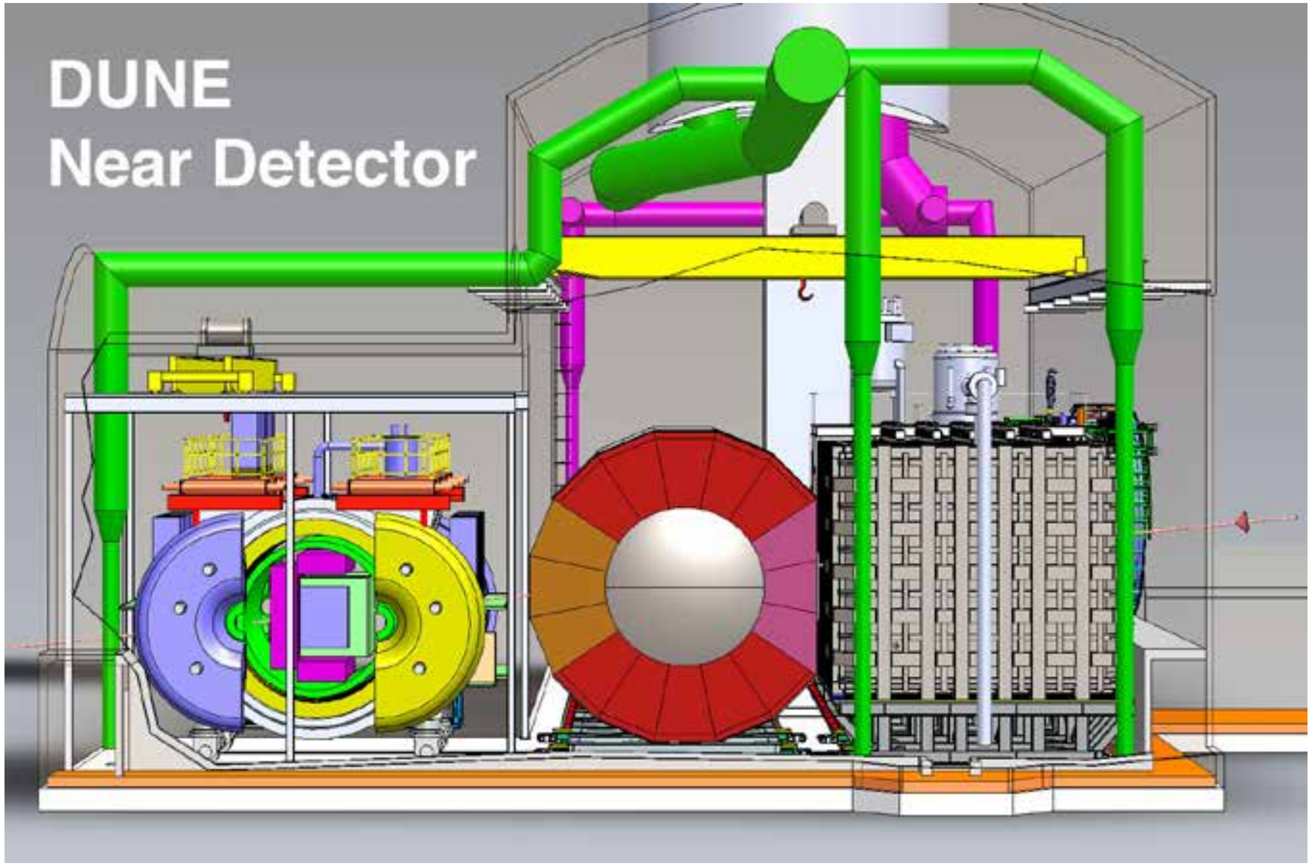
Detector’s 3&4 were always envisioned as not part of initial DOE scope;
Near Detector not initially in DOE scope



- LBNF will provide caverns for 4 detector modules at SURF
  - 1st detector to be installed in NE cavern has horizontal drift (like ICARUS and MicroBooNE)
  - 2nd detector will go into SE cavern and has vertical drift (capitalizing on elements of the dual phase development)

Excavation progressing @SURF

ProtoDune @CERN



- Near Detector Complex houses a set of detectors that work in concert with each other to predict the far detector spectrum and monitor the beam stability.
- These include
  - A liquid argon TPC (ND-LAr) plus a Muon Spectrometer (TMS) ; these can move off-axis
  - An on-axis beam monitor (SAND) ; SAND will also make precision measurements of multiple channels of neutrino interactions, leading to more control of systematics

The 2x2 ArgonCube detector

2020 Update of the European Strategy for Particle Physics

European Strategy Update

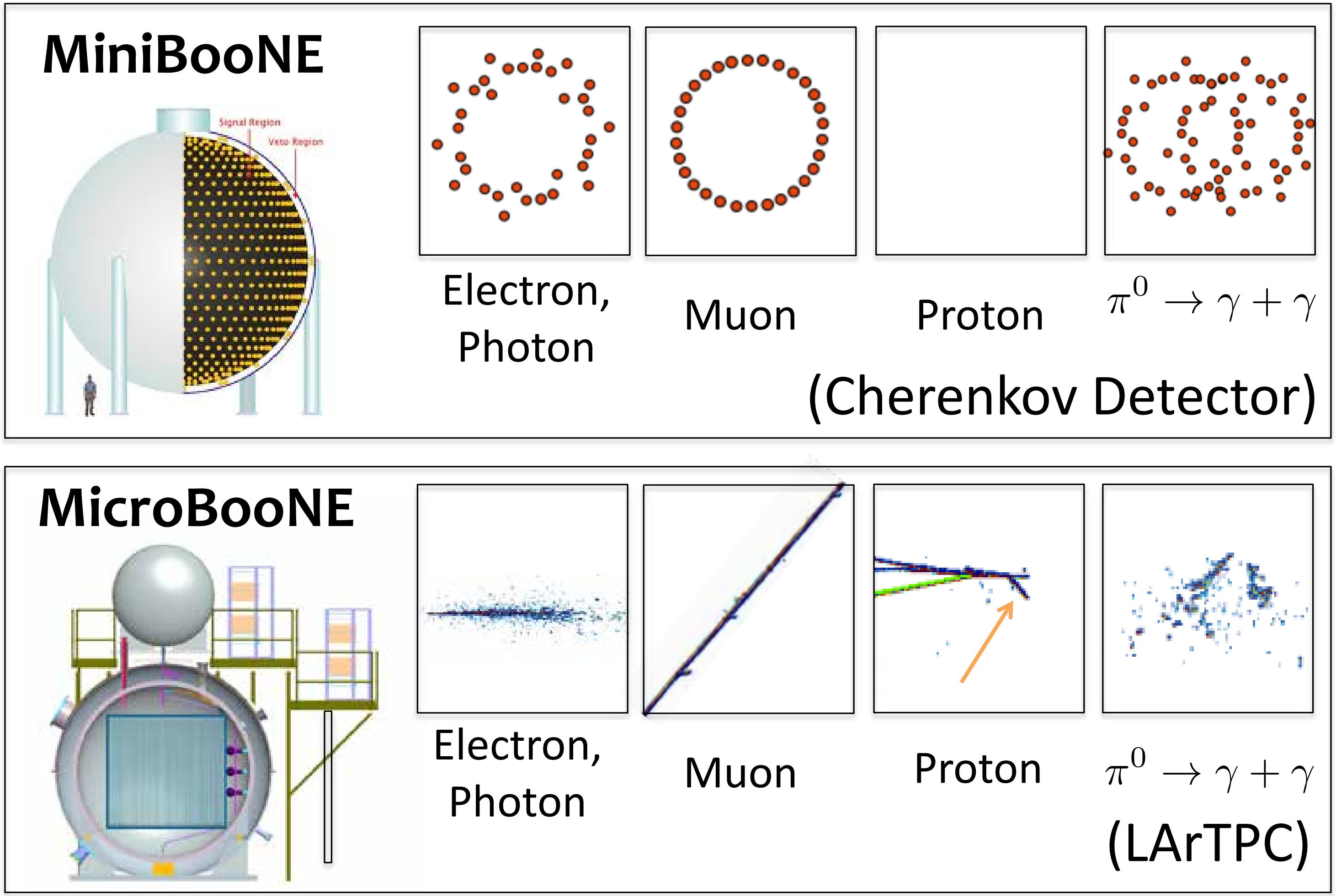
Major developments from the 2013 Strategy

B. The existence of non-zero neutrino masses is a compelling sign of new physics. The worldwide neutrino physics programme explores the full scope of the rich neutrino sector and commands strong support in Europe. Within that programme, the Neutrino Platform was established by CERN in response to the recommendation in the 2013 Strategy and has successfully acted as a hub for European neutrino research at accelerator-based projects outside Europe. ***Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).***

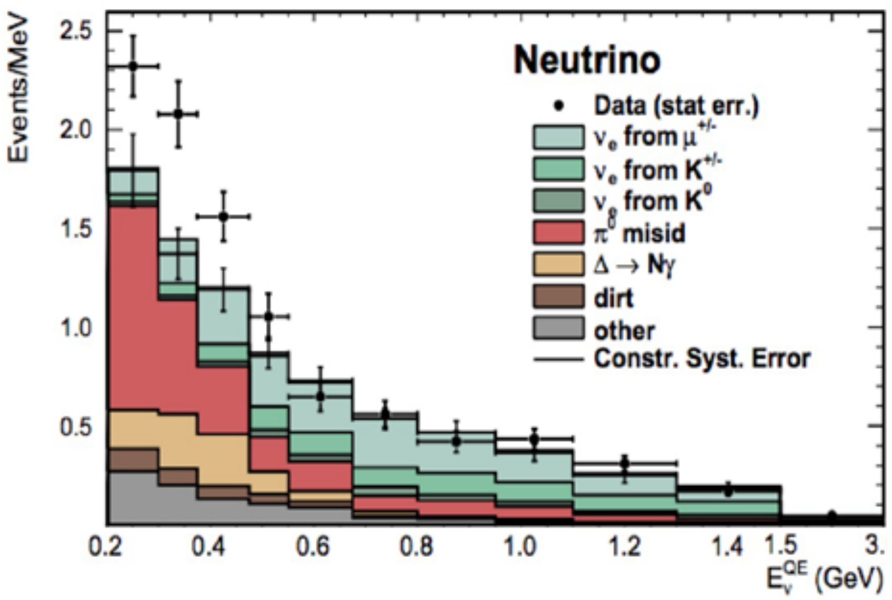
Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

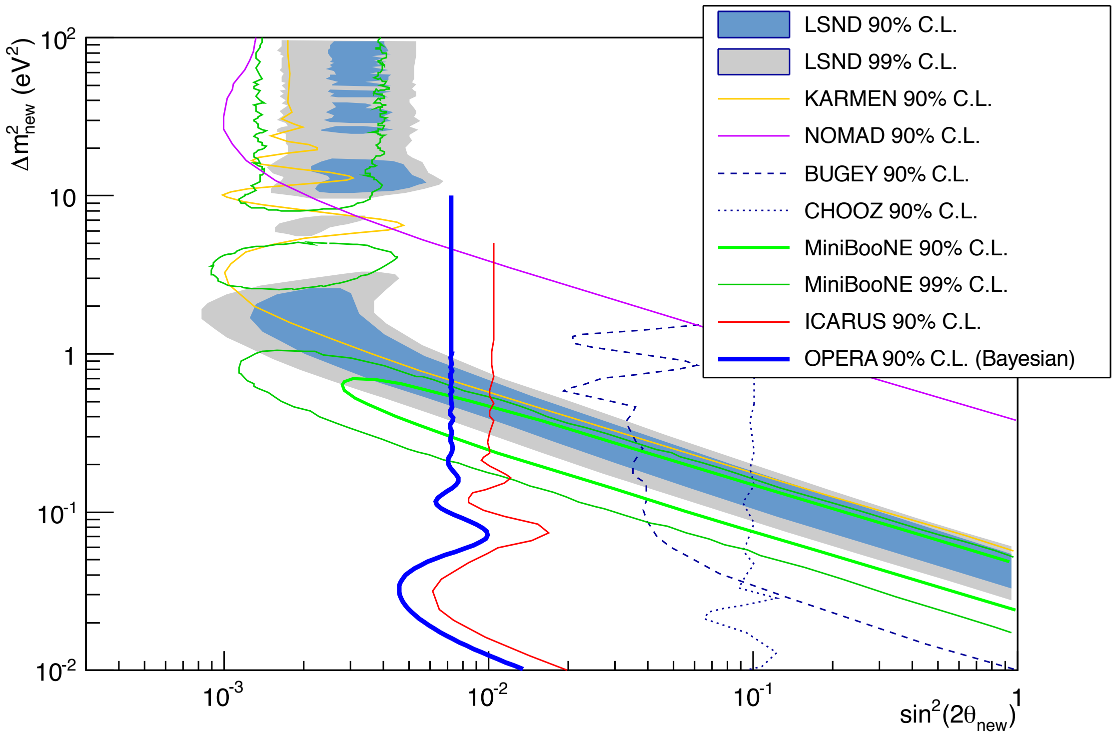
The Fermilab SBN program

Address the LSND/MiniBooNE signal with LAr TPCs

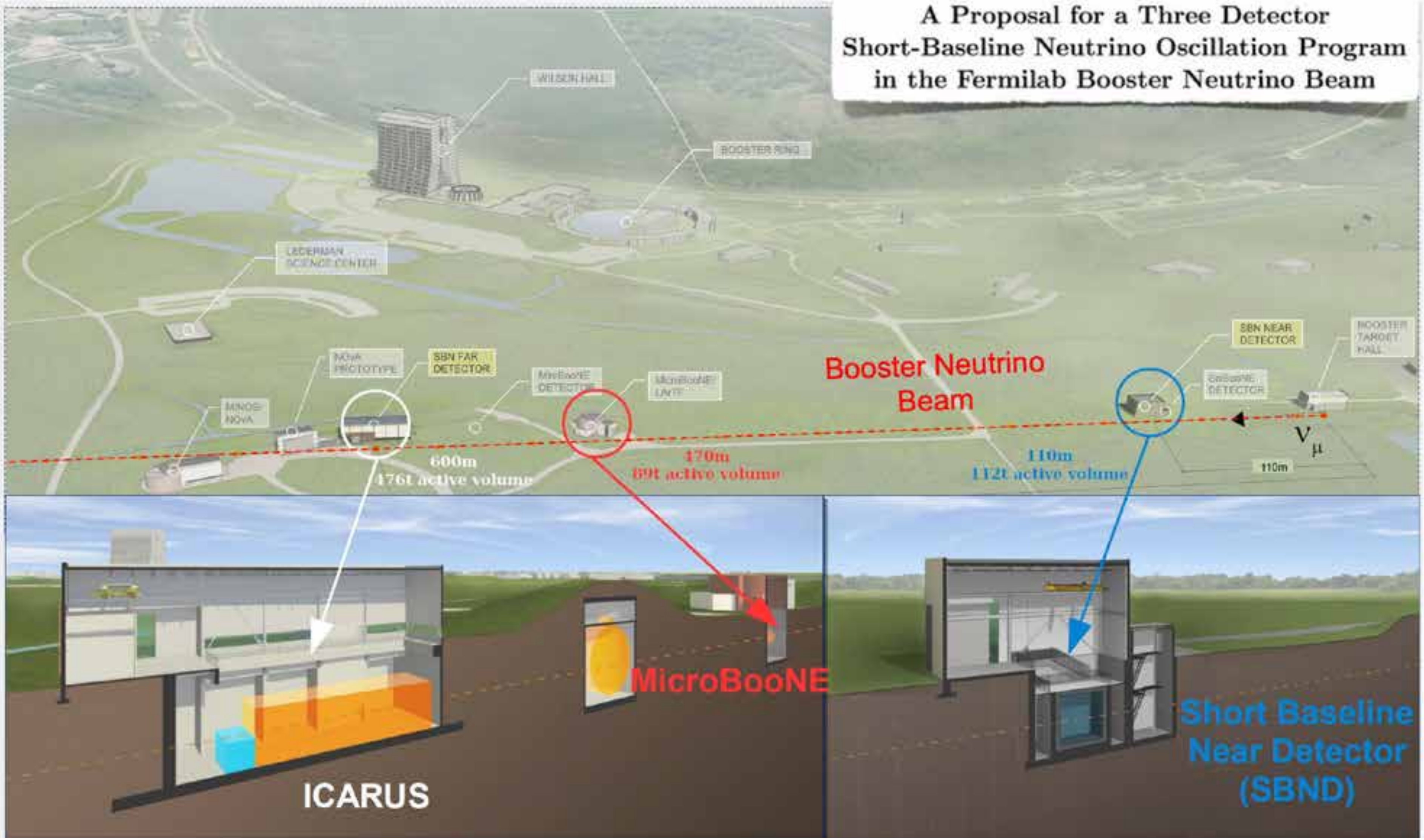


LSND/MiniBooNE "anomaly"

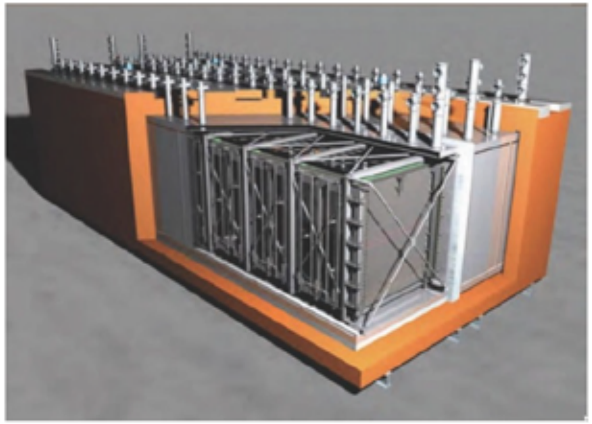




- Three liquid argon time projection chamber (LArTPC) detectors in the Booster Neutrino Beam (BNB) at Fermilab.

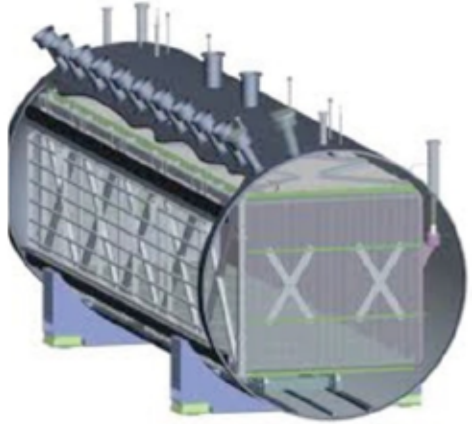


ICARUS



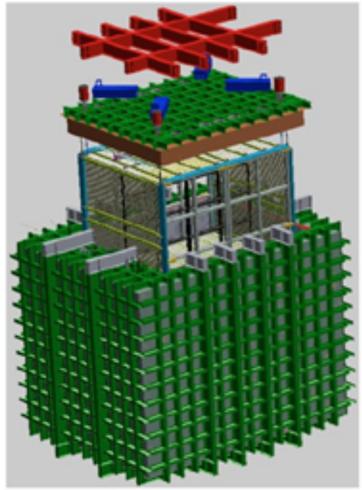
- LArTPC
- 600 m from ν production
- 476 ton active volume
- 4x1.5 m drift length
- 75kV high voltage
- 0.95 ms drift time at 500V/cm
- 3 wire planes: horizontal, ∓30 deg, 3mm wire pitch, 53246 wires
- Warm analog and digital electronics
- 360 8" PMTs

MicroBooNE



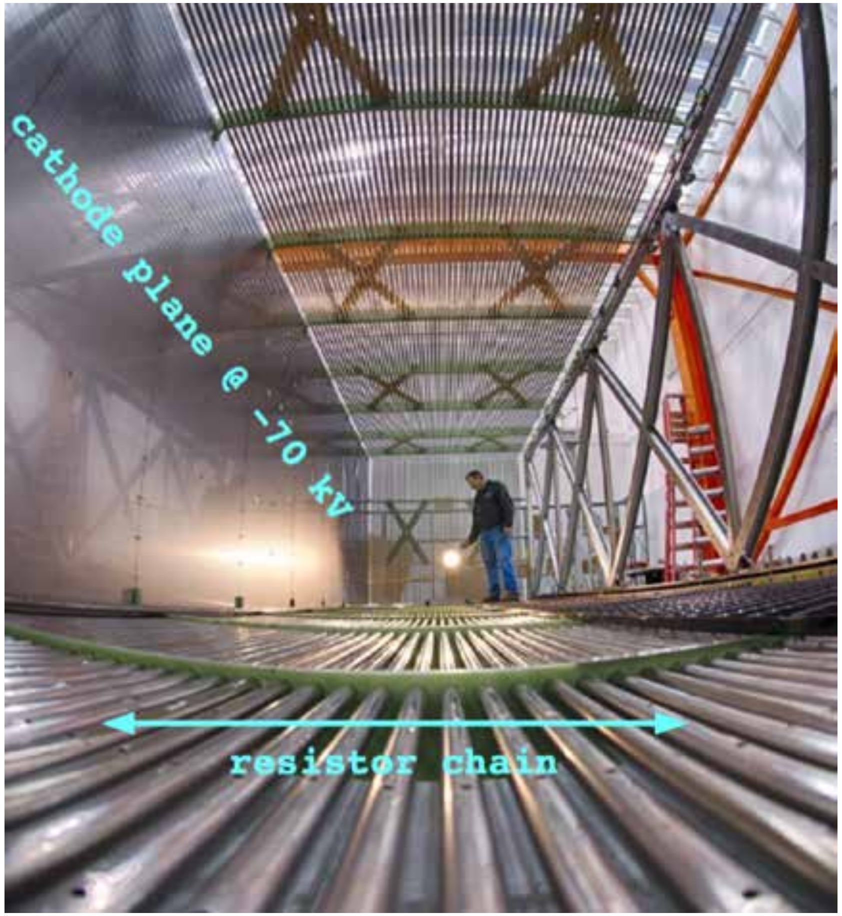
- LArTPC
- 470 m from ν production
- 85 ton active volume
- 2.56 m drift length
- 128 kV high voltage
- 1.6 ms drift time at 500V/cm
- 3 wire planes: 0, ∓60 deg, 3mm wire pitch, 8256 wires
- Cold analog/warm digital electronics
- 32 8" PMTs

SBND

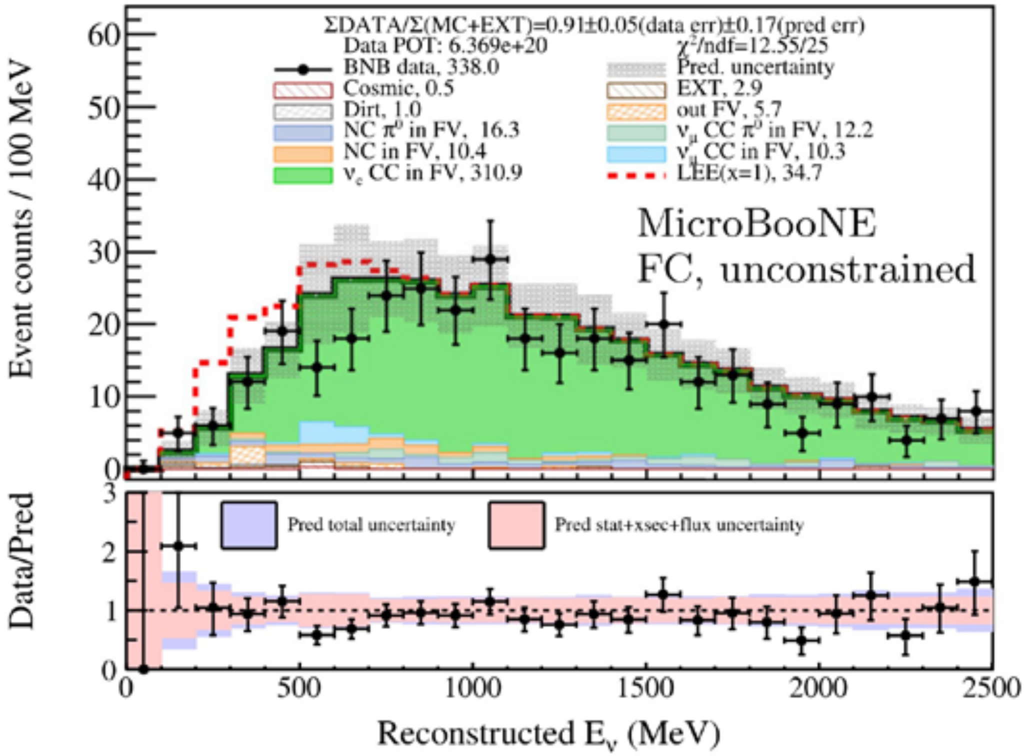


- LArTPC
- 110 m from ν production
- 112 ton active volume
- 2x2.0 m drift length
- 100 kV high voltage
- 1.28 ms drift time at 500V/cm
- 3 wire planes: 0, ∓60 deg, 3mm wire pitch, 11264 wires
- Cold analog and digital electronics
- 120 8" PMTs && scin. bars

The first in the line: MicroBooNE



Recent results from MicroBooNE:
the MiniBooNE excess is likely not due to sterile neutrinos!



MicroBooNE ruled out the most likely source of photons as the cause of MiniBooNE's excess events with 95% CL and ruled out electrons as the sole source with greater than 99% CL, with half of its data and more ways yet to analyze the data.

SBN will tell us what the origin of the effect is

Conclusions

- A rich and potentially groundbreaking neutrino program underway at Fermilab

- Several applications of the liquid argon TPC technology:
  «The» neutrino detector

- A lot of opportunities (and fun) for undergrad and grad students, as well as for PostDocs

- Enjoy your summer studentship!