Fermilab Neutrino Program

GINA RAMEIKA
FERMILAB

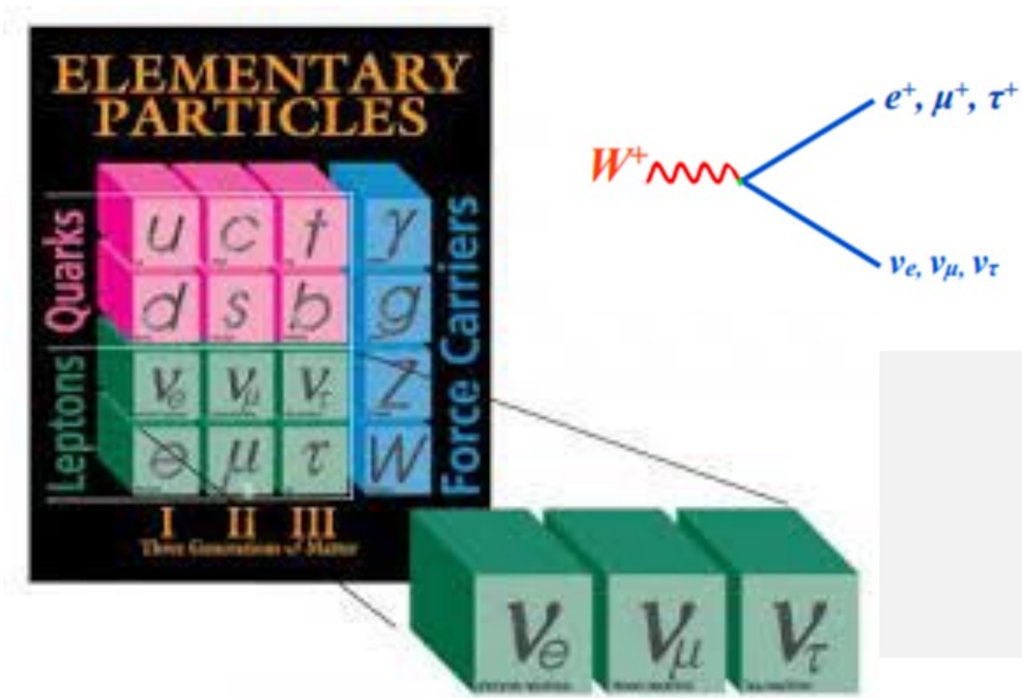
OUTLINE

- Who am I
- A Little History of Neutrinos
  - at Fermilab
- The On-going Neutrino Program
- What's next ?!
- Summary and Outlook

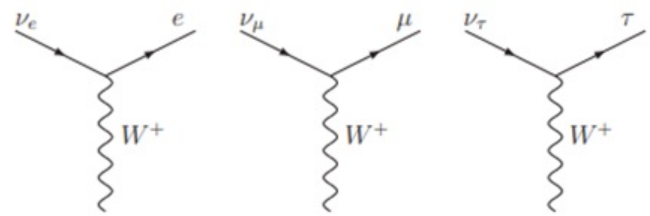
WHO AM I?

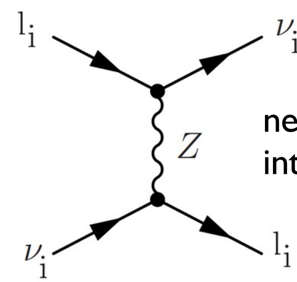
- I have worked at Fermilab for my entire career (1978 – present)
- I have been working on Neutrino Experiments since 1993
  - *Before that I studied Hyperon Polarization and Magnetic Moments*
- In the early '90's I worked on the development, operation and analysis of the Fermilab MINOS and DONUT Experiments
- I have also worked on NOvA, MicroBooNE
- I am currently the Co-spokesperson of DUNE (Deep Underground Neutrino Experiment)

NEUTRINOS IN THE STANDARD MODEL



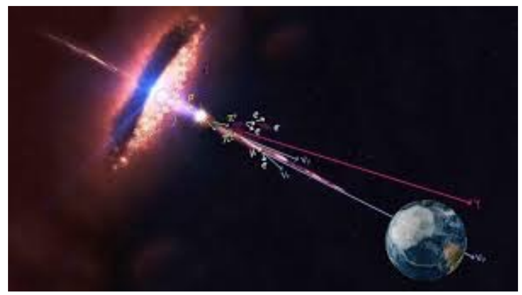
charged current interactions

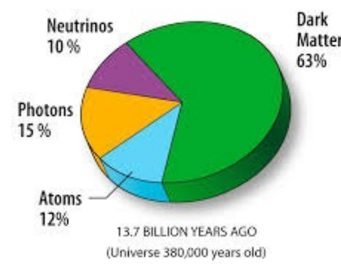


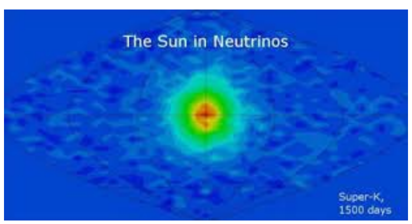


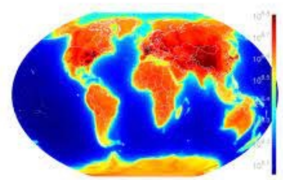
neutral current interactions

NEUTRINOS IN OUR UNIVERSE









A LITTLE HISTORY OF NEUTRINOS

- The existence of a neutrino was hypothesized in 1930 as a ZERO MASS elementary particle to concerve the concept of conservation of energy in the beta decay process
- The first detection of neutrinos occurred in 1956 in the landmark experiment of Reines and Cowen at the Savannah River nuclear power plant
- In 1957 Bruno Pontecorvo hypothesized that neutrinos may oscillate, or change from one *type* to another
- In 1962 a second *type* or *flavor* of neutrino was identified in a Brookhaven Laboratory experiment led by Lederman, Swartz and Steinberger; the charged current neutrino interaction produced a MUON (rather than electron)
- In 1968 neutrinos from the sun were detected in a huge tank of perchloroethylene (dry cleaning fluid) located in the Homestake Gold Mine in South Dakota; the team was led by Ray Davis, and the detected number of neutrinos was low compared to theoretical predictions!!
- In 1973 NEUTRAL CURRENT interactions were detected at CERN by the Gargamelle experiment
- In 1975 the first detection of TAU Leptons at SLAC lead to the prediction of a third flavor of neutrino : the TAU Neutrino
- In 1983 studies of atmospheric neutrinos in the Kamiokande (Japan) and IMB (Irvine, Michigan, Brookhaven) Collaborations measured an anomaly in the muon to electron neutrino interaction rates!!!

- In 1998 the Super-Kamiokande experiment determined that atmospheric muon neutrinos were "disappearing" as they traveled from their production to interaction point; as predicted by PONTECORVO more than 20 years earlier : flavor changing neutrinos have MASS!!!
  - *The hypothesis by now was that MUON neutrinos were oscillating into TAU neutrinos; HOWEVER, no one had yet detected a TAU neutrino interaction.*
- In 1998 the LSND collaboration at Los Alamos reported an excess of events in a nmu -> nue oscillation search, which could be interpreted as an oscillation to a high mass sterile neutrino.
- In 2000, scientists from the DONUT collaboration announced the recording of 4 TAU neutrino interactions (a total of 9 interactions were published in the final data analysis)
- In 2002, the SNO experiment (Canada) announced conclusive evidence that THREE flavors of solar neutrinos were accounted for.
- In 2007 the miniBooNE experiment at Fermilab, which was designed to confirm or refute the LSND results, first reported no evidence of oscillations, but subsequent analysis indicated a confirmation of a low energy excess.
- In 2010 the OPERA experiment, using the same detector technique in DONUT, searched for TAU neutrino appearance using a neutrino beam from CERN. In 2015 they announced the detection of 5 TAU neutrino interactions.

DETECTING NEUTRINOS

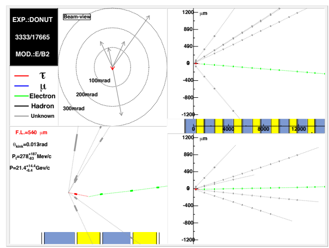
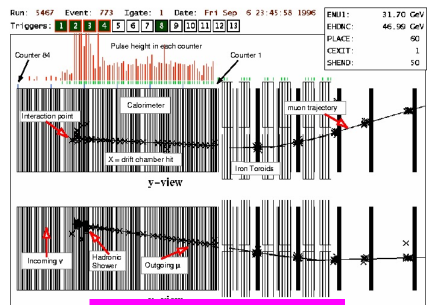
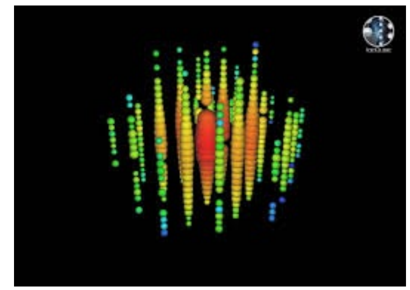


Fig. 15. Event 3333-17665: $\tau \rightarrow e + \nu_\tau + \nu_e$

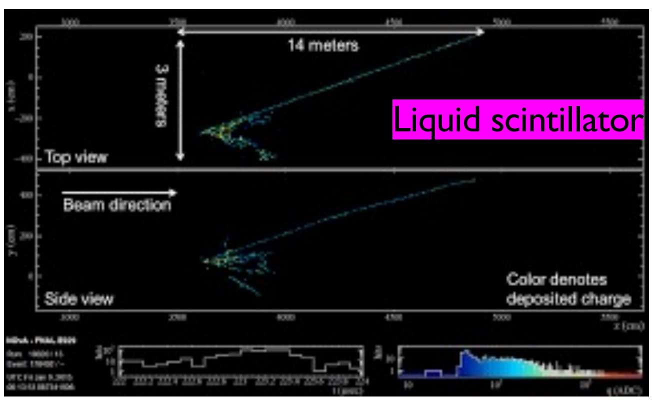
Emulsion

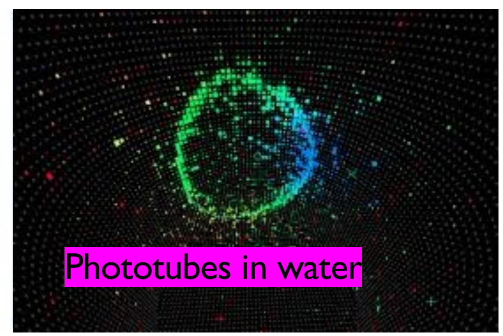


Iron & scintillator



Phototubes in ice

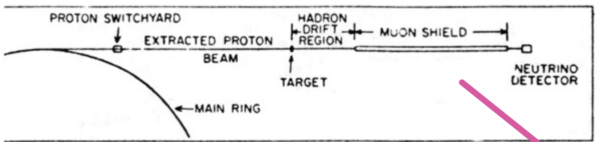




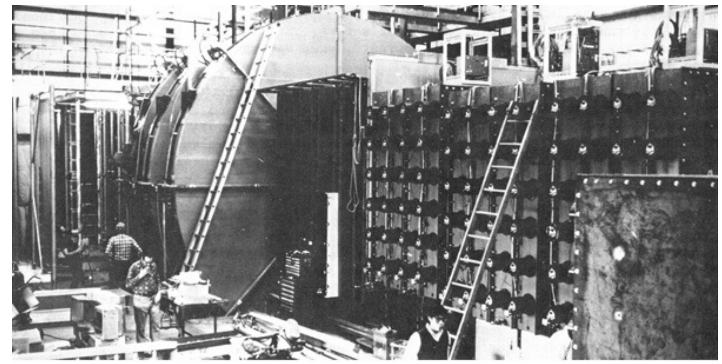
LET'S VISIT FERMILAB

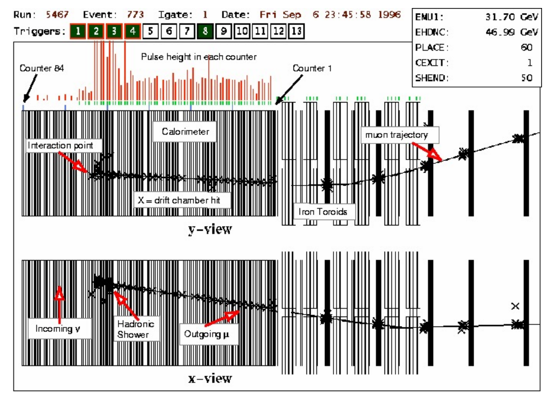
Wilson Hall

FERMILAB NEUTRINO EXPERIMENTS



First experiment approved
at Fermilab : E1A
1972





NuTeV :
~2000

Let's fast forward twenty years….

NEUTRINO OSCILLATIONS

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

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

Features : Mixing angles and CP phase

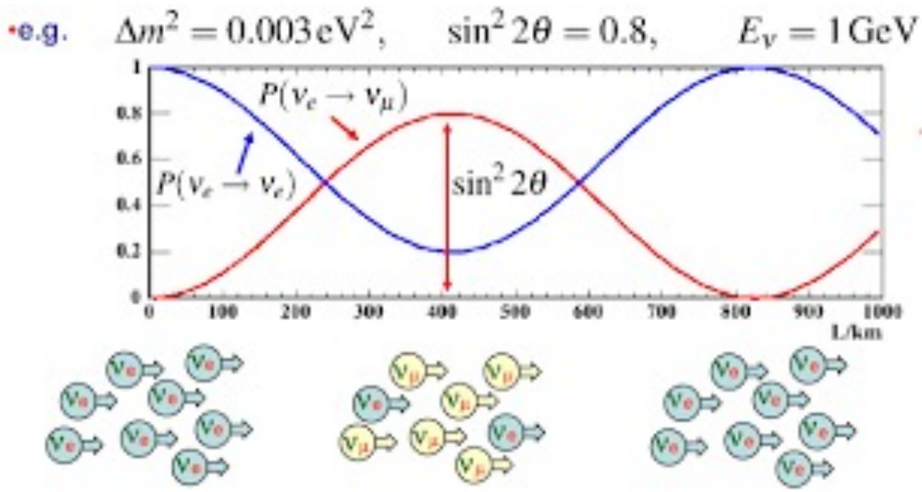
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \, |\nu_i\rangle \, ,$$
$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} \, |\nu_\alpha\rangle \, ,$$

where

- $|\nu_\alpha\rangle$ is a neutrino with definite flavor α = e (electron), μ (muon) or τ (tauon),
- $|\nu_i\rangle$ is a neutrino with definite mass m_i, $i = 1, 2, 3$,

HOW DO WE INTERPRET THE MATH?

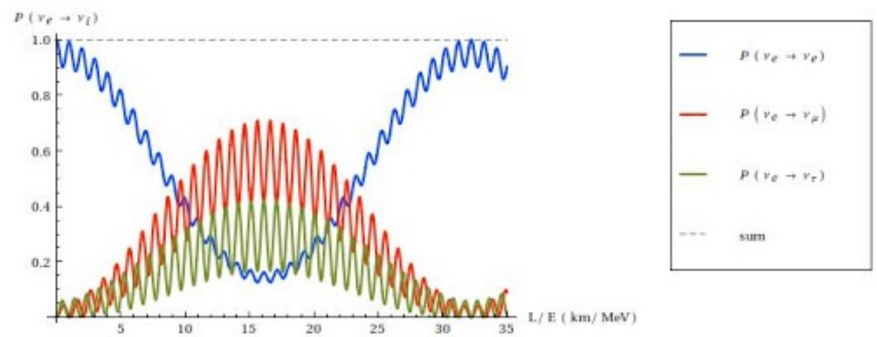
Two flavor approximation

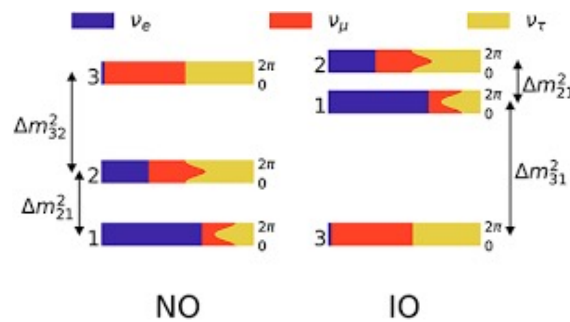


$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

Mass difference

Three flavors





Two distinct mass differences

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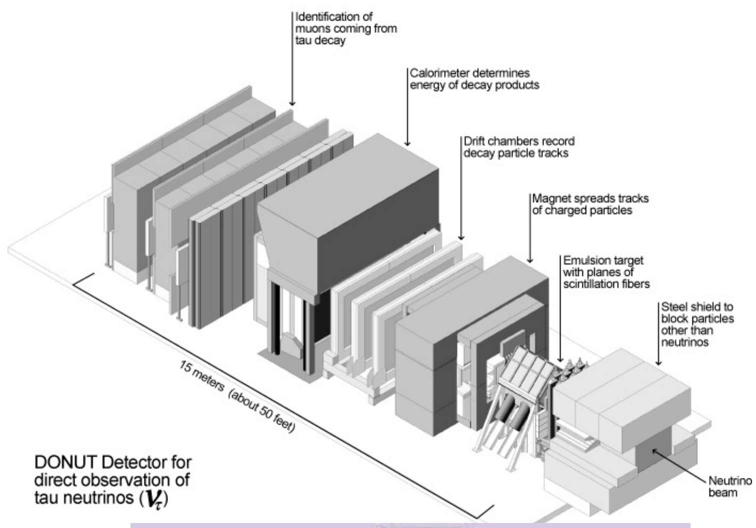
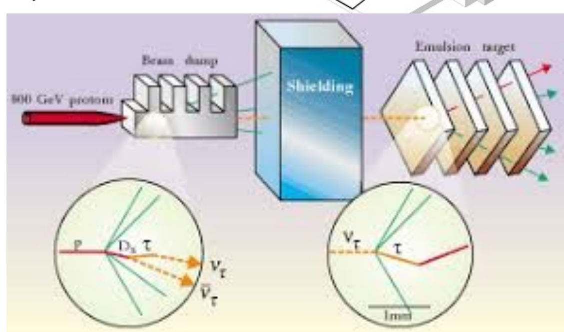
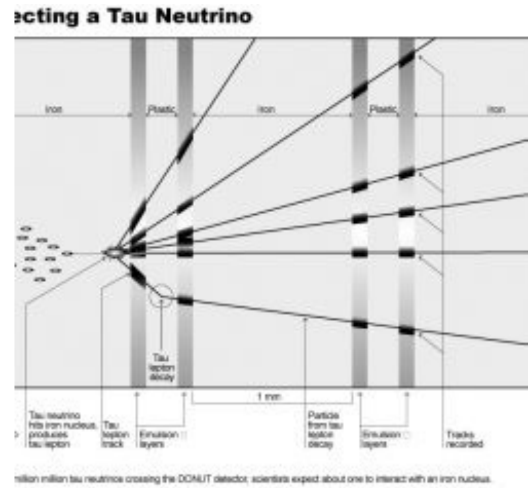
WHERE IS THE TAU NEUTRINO (1997-2000)

St. Charles, Illinois

DONUT Detector







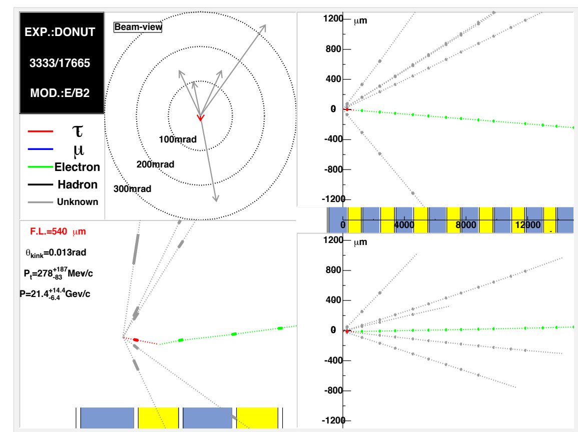
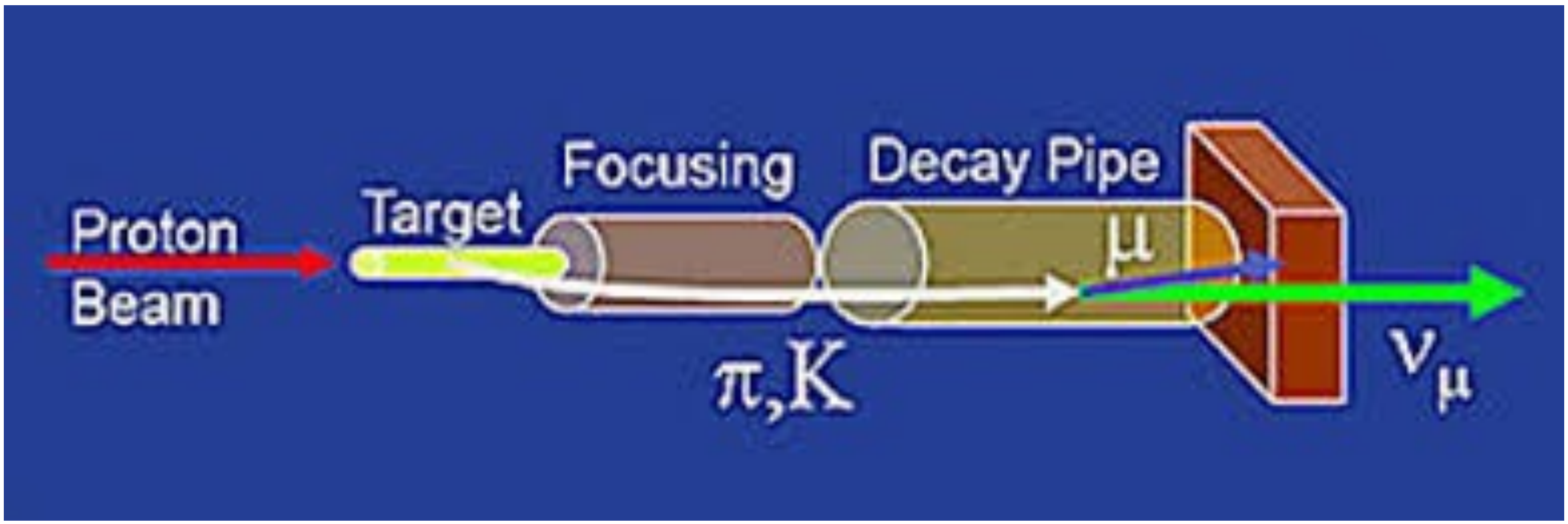


Fig. 15. Event 3333-17665: $\tau \to e + \nu_\tau + \nu_e$

HOW DO WE STUDY OSCILLATIONS IN THE LABORATORY?



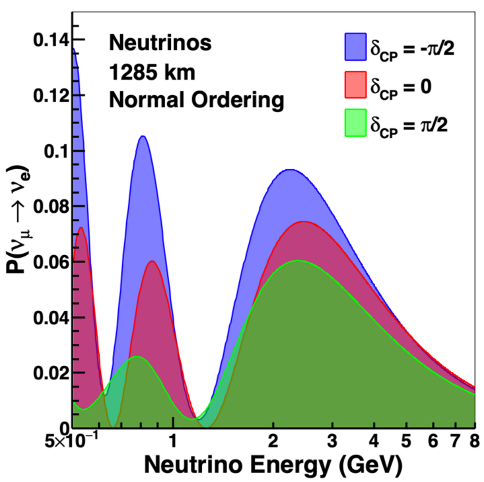
ONE IMPORTANT COMPLICATION AND IMPORTANT FEATURE

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

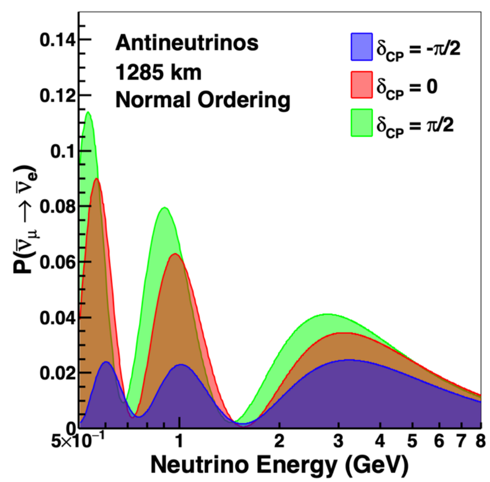
$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

Neutrinos



Antineutrinos



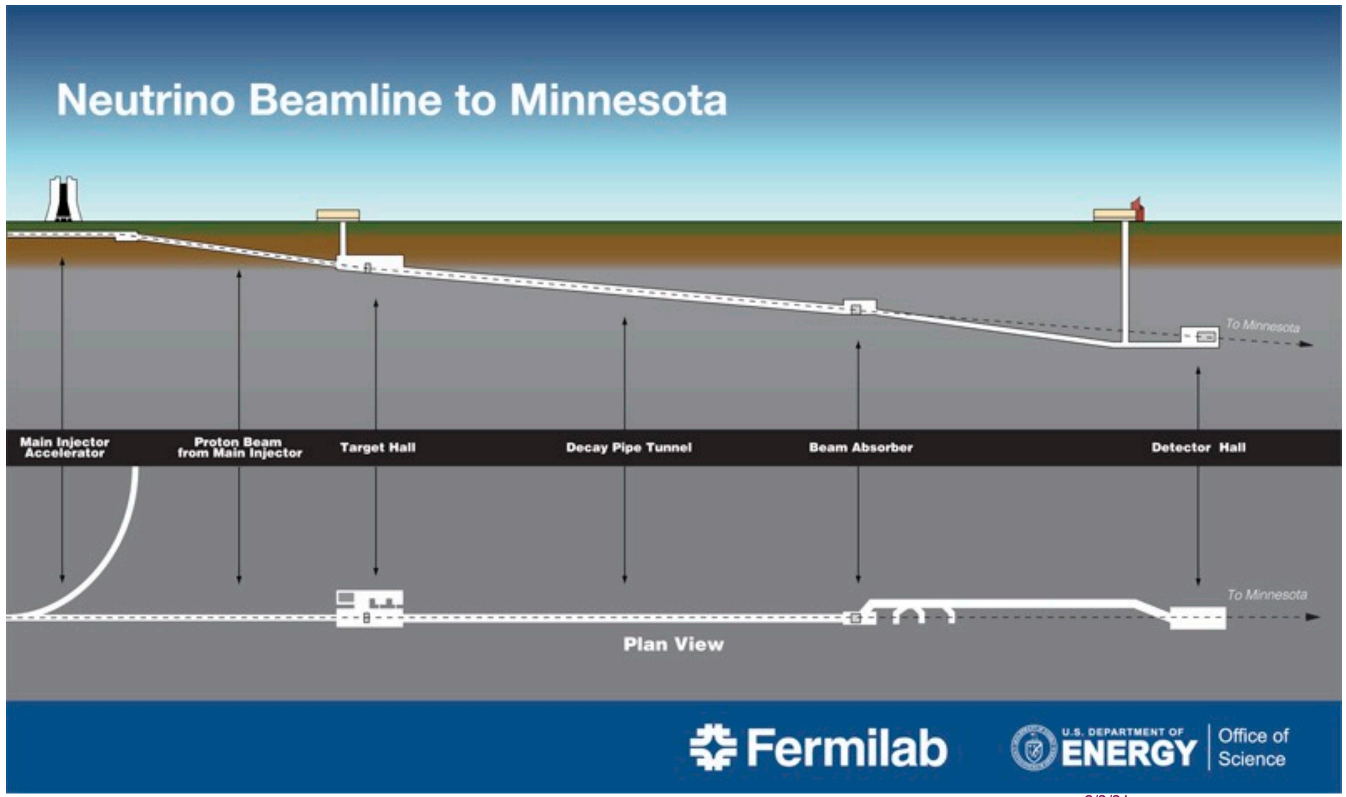
Neutrino and anti-neutrino oscillation probabilities are moderated by the matter through which they pass

For a normal mass hierarchy, neutrinos are enhanced and anti-neutrinos are suppressed

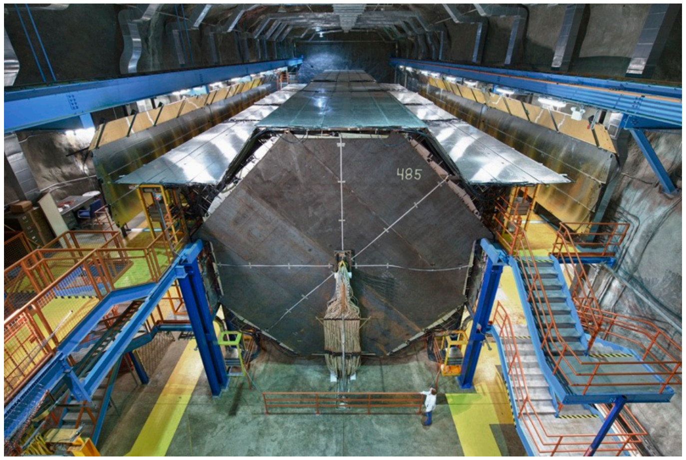
In an inverted hierarch, the effect is reversed

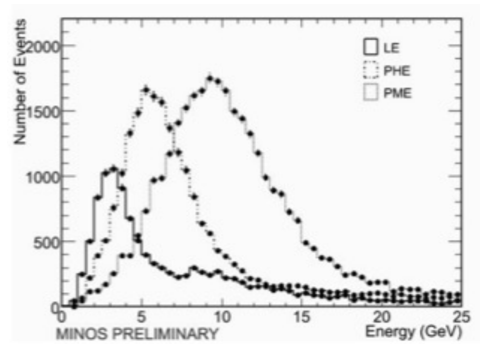
THE MINOS EXPERIMENT IN THE NUMI BEAM (2005 – 2016)

The NuMI Beam

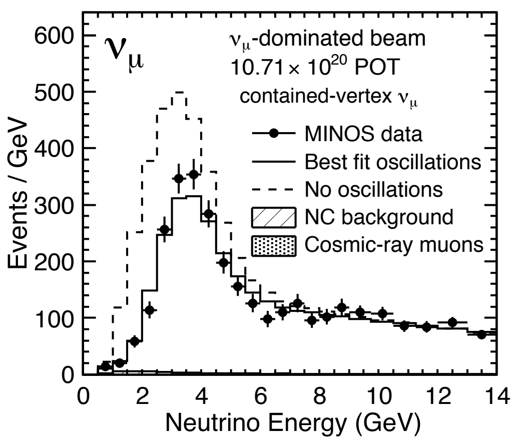


THE MINOS EXPERIMENT (2005 – 2016)



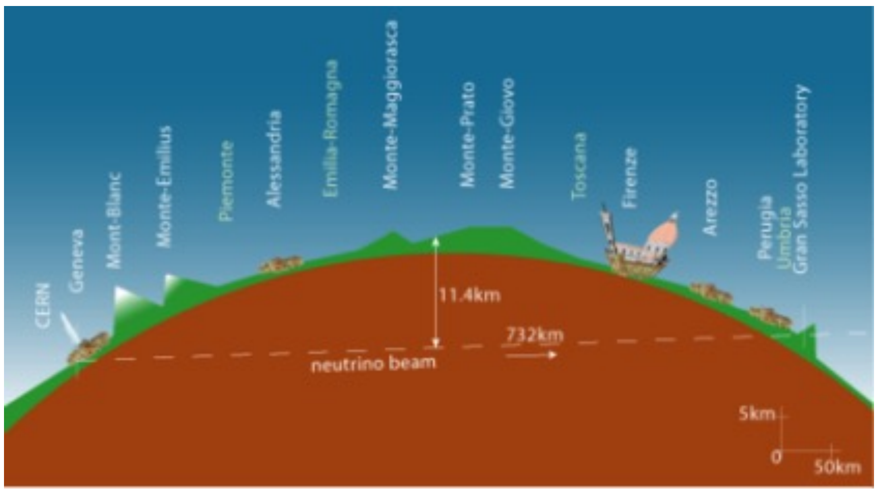


Nuclear Physics B (Proc. Suppl.) 159 (2006) 63–68

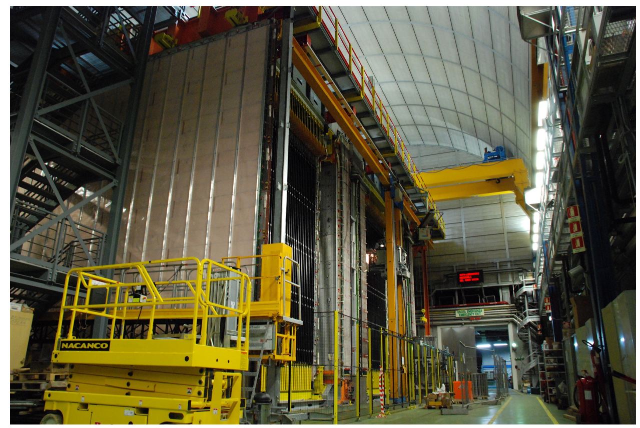


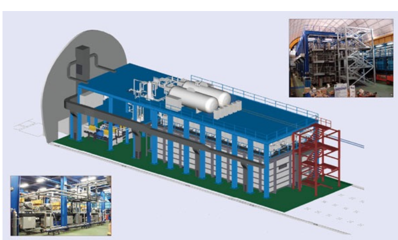
arXiv:hep-ex/1304.6335

CERN BEAM TO GRAN SASSO

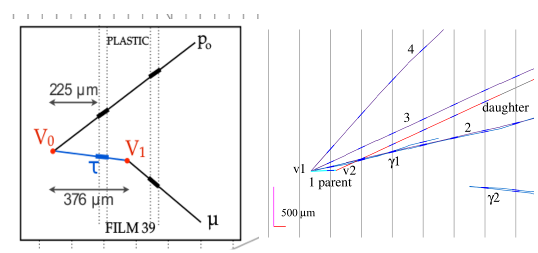


OPERA Detector





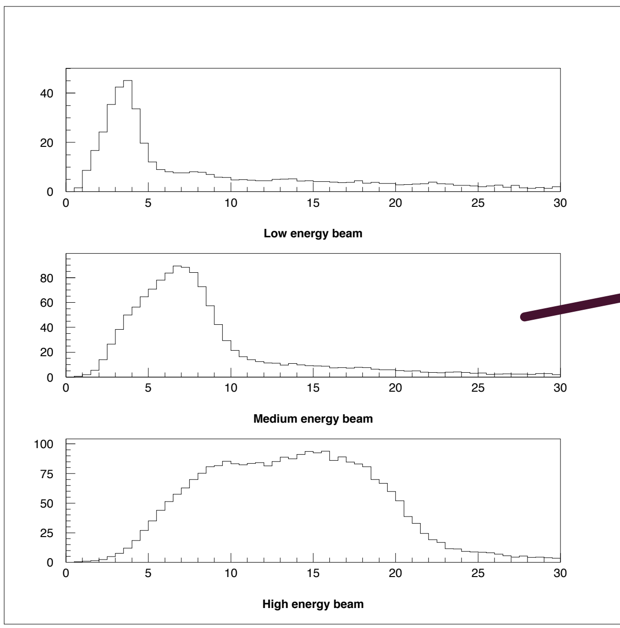
ICARUS Liquid Argon Detector (now at FNAL for short baseline experiment)

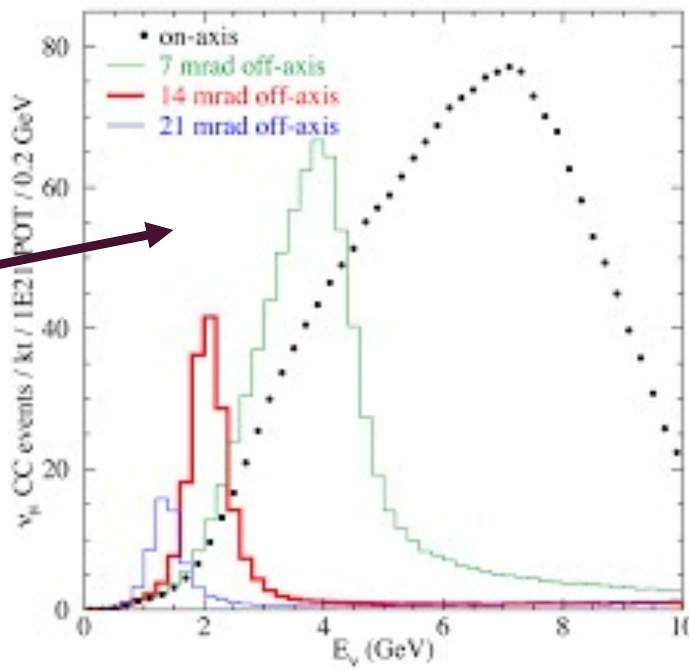


Tau neutrino events in OPERA

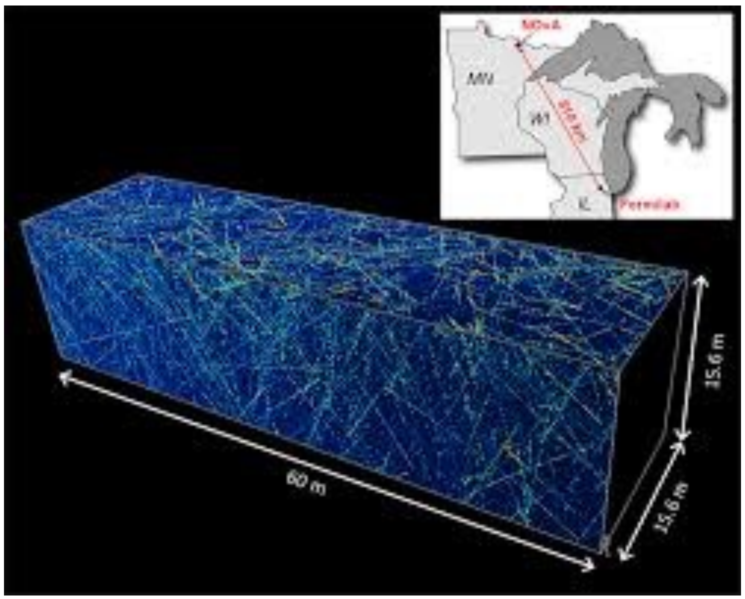
HOW BIG IS THE BEAM – AND WHAT HAPPENS IF YOU PUT A DETECTOR OFF-AXIS?

NuMI Beam spectra can be tuned by varying the horn currents

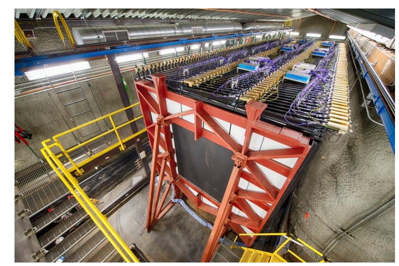




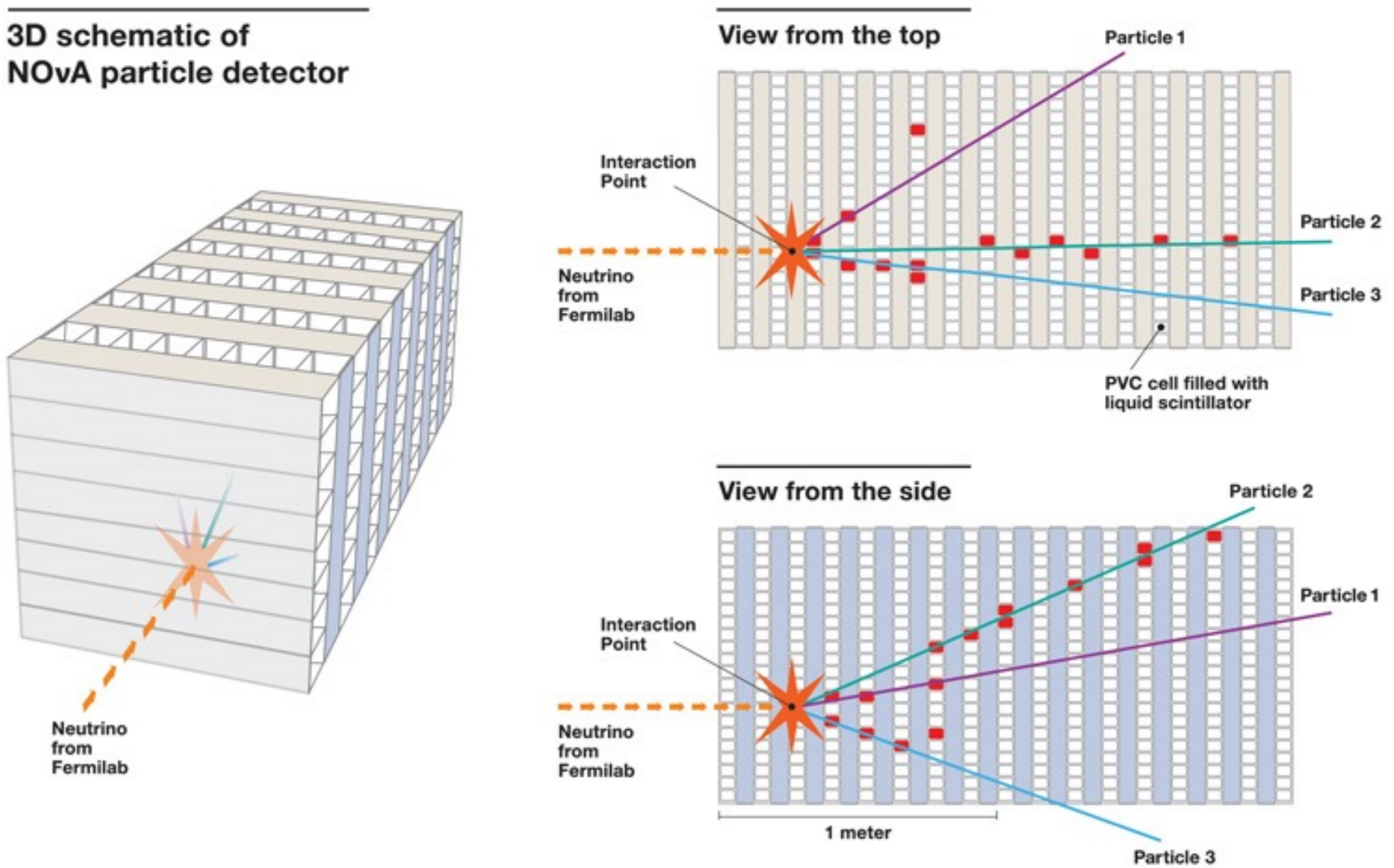
NOVA (NUMI OFF-AXIS NEUTRINO APPARATUS)

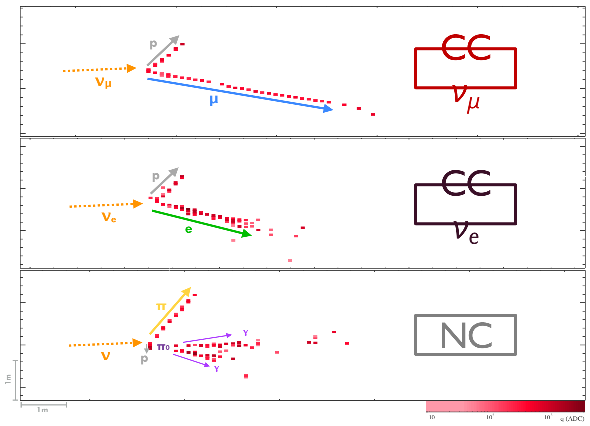


Very large detector – located on the surface

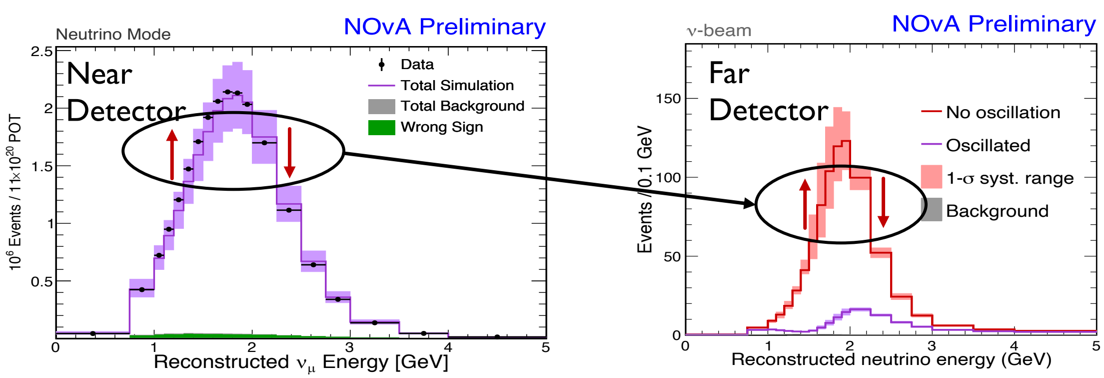


Near Detector at FNAL


3D schematic of
NOvA particle detector
Neutrino
from
Fermilab
View from the top
Particle 1
Interaction
Point
Particle 2
Particle 3
Neutrino
from
Fermilab
PVC cell filled with
liquid scintillator
View from the side
Particle 2
Particle 1
Interaction
Point
Neutrino
from
Fermilab
1 meter
Particle 3



- Measure charged particles produced in neutrino scattering.
- Identify flavor based on the outgoing lepton using a computer vision technique called a Convolutional Neural network
  - The first physics experiment to use a CNN for a result.
- Measure energy of muons based on range, and all other energies calorimetrically.
- Use the ND to measure the neutrino beam before oscillations to control systematics via extrapolation.



LONG-BASELINE NEUTRINO EXPERIMENTS TO DATE

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–

Written August 2019 by M.C. Gonzalez-Garcia (YITP, Stony Brook; ICREA, Barcelona; ICC, U. of Barcelona) and M. Yokoyama (Tokyo U.; Kavli IPMU (WPI), U. Tokyo).

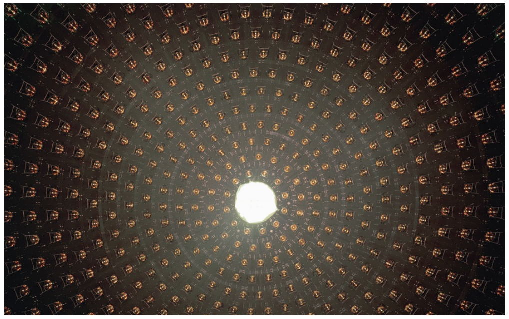
In addition to LBL experiments a program of measurements using reactor neutrinos has contributed to the global knowledge of neutrino mass and mixing parameters ….

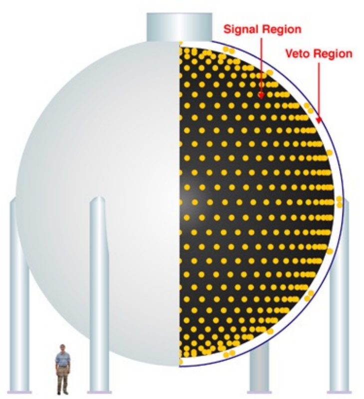
From PDG 2020

- In general, the data show consistent results for the better known parameters : θ_{12}, θ_{13} , Δm^2_{21}, and $|\Delta m^2_{32}|$
- The issues which still require clarification are : the mass ordering discrimination, the determination of θ_{23} and the leptonic CP phase δ_{CP} .
  - In all analyses the best fit is for the NORMAL mass ordering
  - All analyses find some preference for the second octant of θ_{23} but with statistical significance still well below 3σ.
  - The best fit for in NORMAL ordering is at δ_{CP} ~120° but CP conservation (for δ_{CP} = 180°) is still allowed at a 1-2σ confidence level
  - The significance of CP violation in the global analysis is reduced with respect to that reported by T2K because NOvA data does not show a significant indication of CP violation

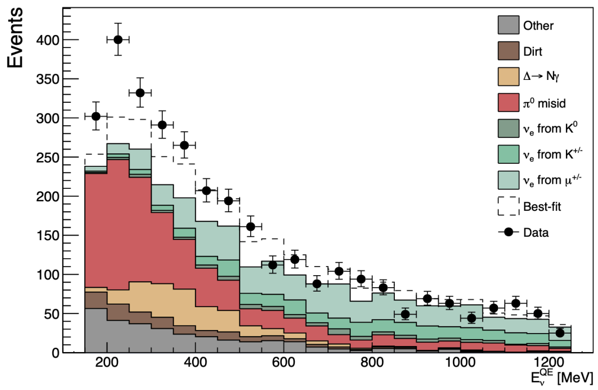
- So what's next?

REMEMBER LSND AND MINIBOONE



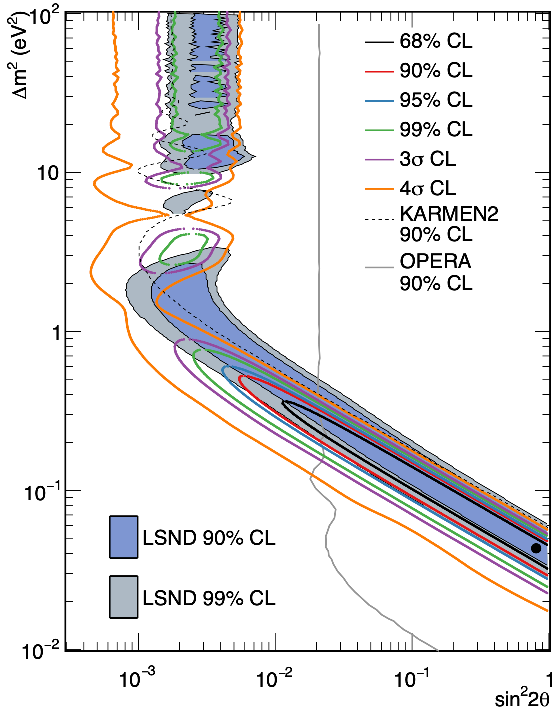


Phys. Rev. D 103, 052002 (2021)



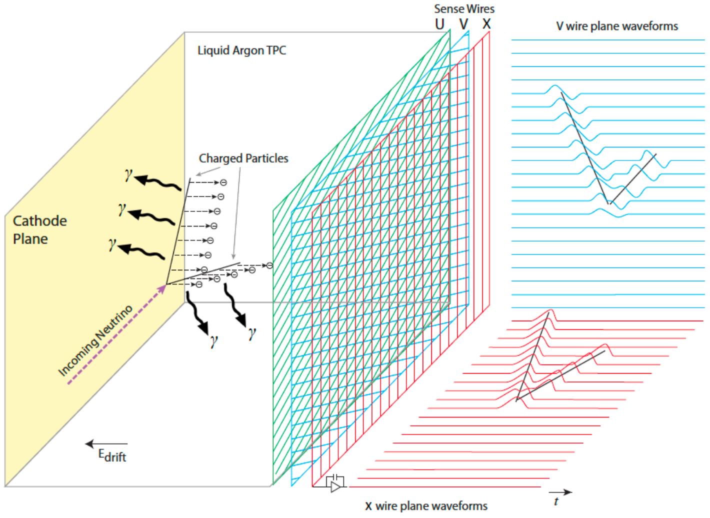
MiniBooNE's neutrino mode energy distribution. Best fit to neutrino mode data assuming 2-neutrino oscillations

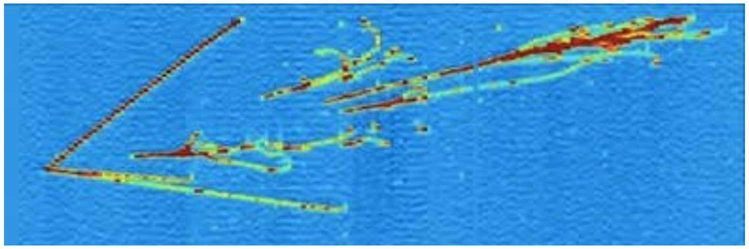
Is it really and electron excess, or a background?



MiniBooNE's allowed regions for combined neutrino and antineutrino mode data assuming 2-neutrino oscillations.

BUILD A BETTER DETECTOR : LIQUID ARGON DETECTORS





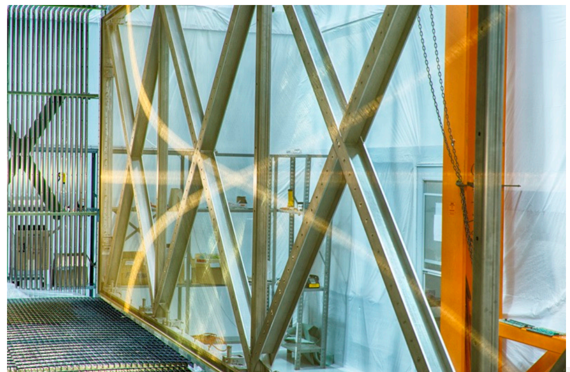
Pioneered by the ICARUS collaboration

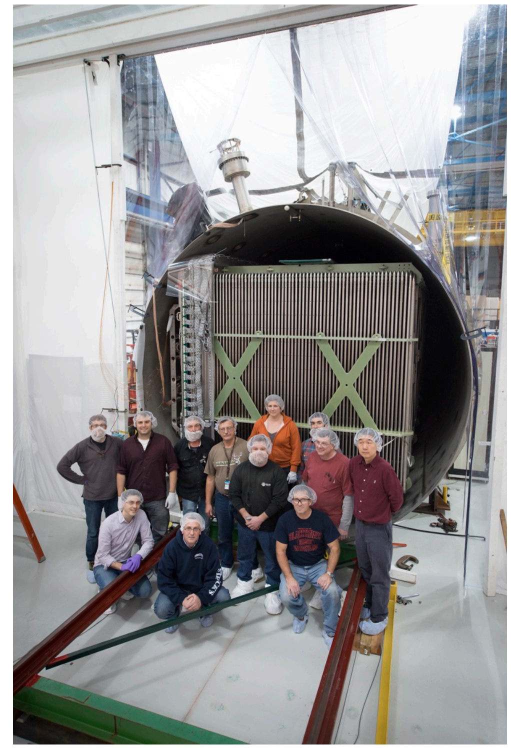
- Drift ionization charge : High Voltage
  - HV power supply and feed-through
  - Cathode Plane
  - Field Cages
    - Resistive dividers
- Collect ionization charge : Sense wires, electronics
  - Anode Planes
  - Front-end amplification, digitization, readout
- Collect scintillation light : wavelength shifters, light guides, light collection electronics

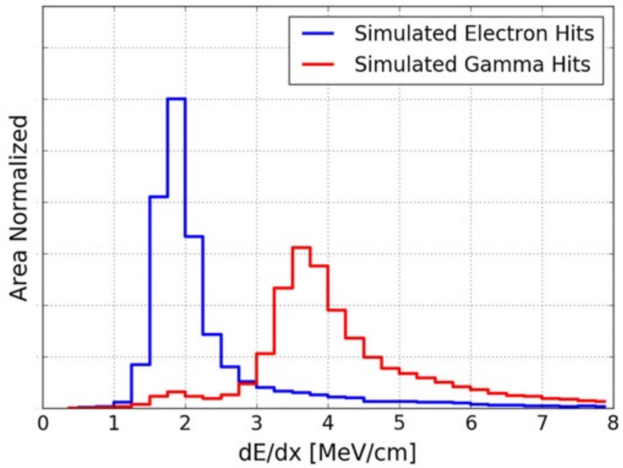
INSIDE ICARUS

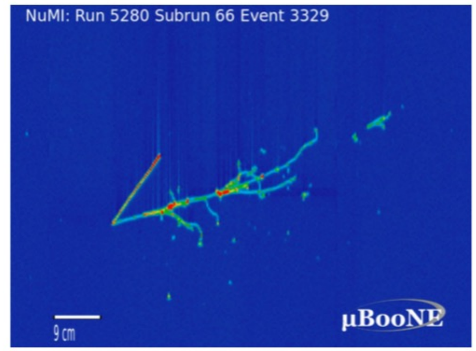
S. Amerio et al. / Nuclear Instruments and Methods in Physics Research A 527 (2004) 329–410

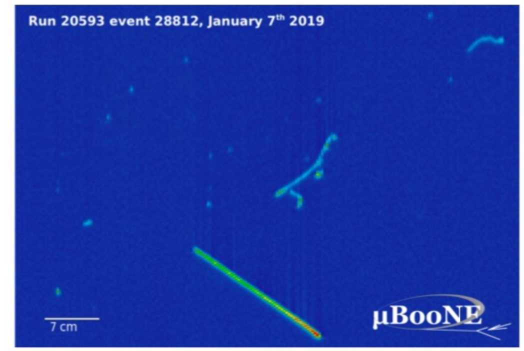
ENTER : THE MICROBOONE DETECTOR



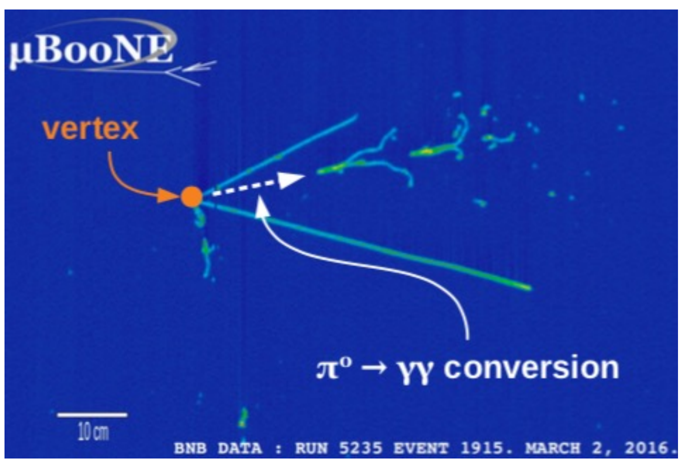


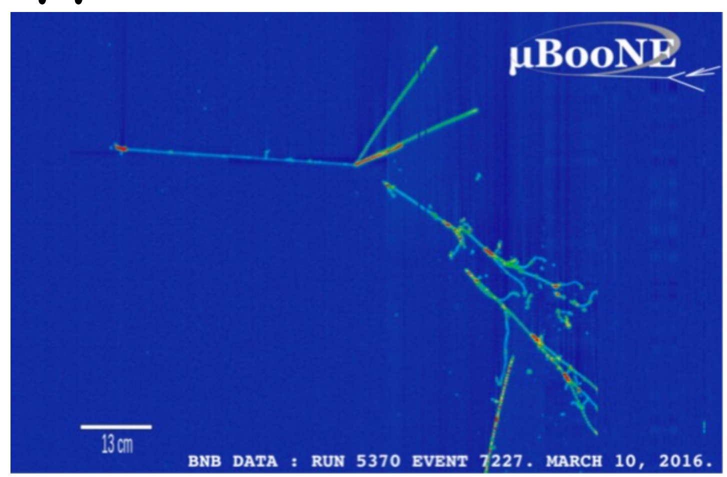






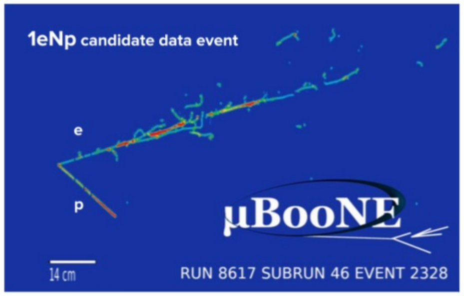
$\pi^0 \rightarrow \gamma\gamma$

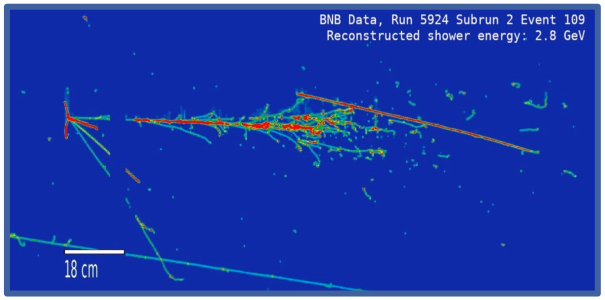


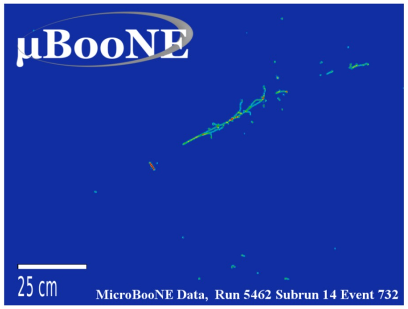


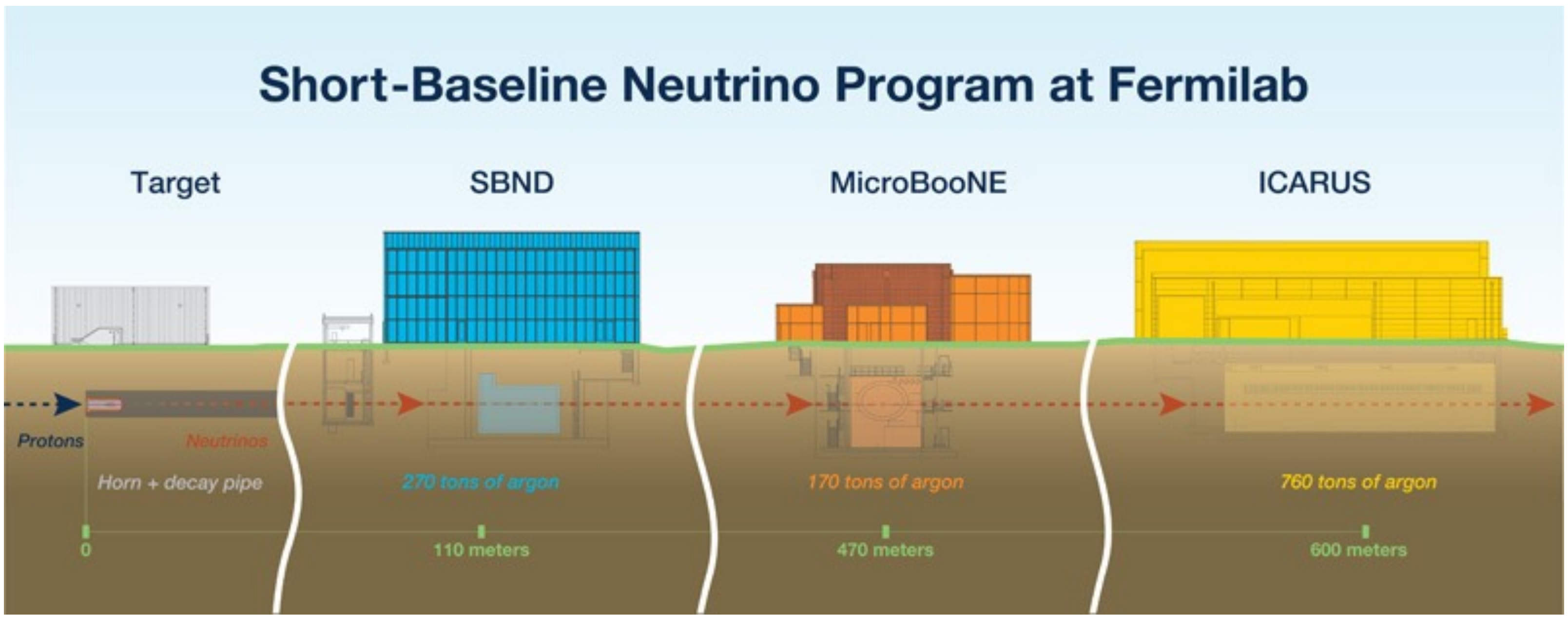
MICROBOONE STATUS

- Currently the world's longest running liquid argon TPC
  - Physics runs complete, R&D program underway now
- Analysis of high statistics data and long-term operational experience is informing the future LAr neutrino program
- Publishing papers on neutrino cross sections, BSM physics, algorithm developments, and detector R&D.
- MicroBooNE has been developing pioneering new tools, techniques, and physics analysis methods in liquid argon and sharing this with the community along the way
- A series of first results on the MiniBooNE low energy excess observations are around the corner. The short-baseline anomaly landscape has evolved. MicroBooNE is poised to explore this landscape using the full capabilities of LAr TPCs.

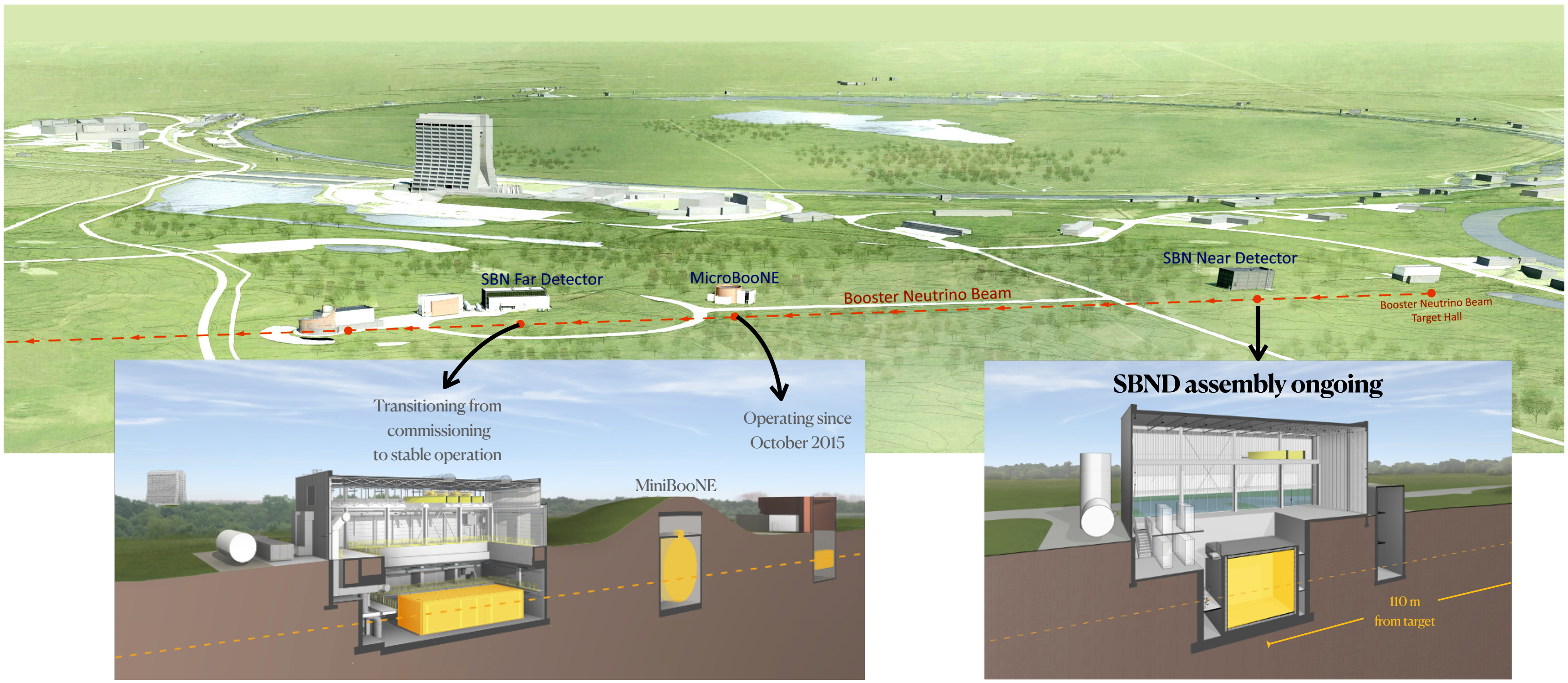




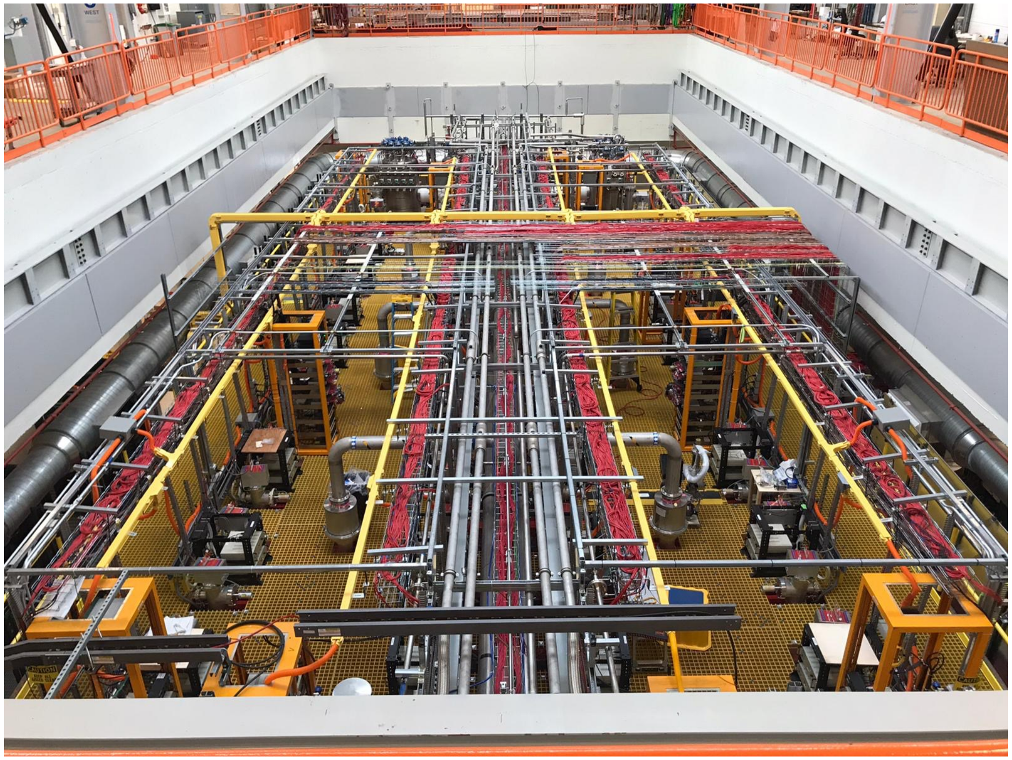



Short-Baseline Neutrino Program at Fermilab
Target
SBND
MicroBooNE
ICARUS
Protons
Neutrinos
Horn + decay pipe
270 tons of argon
170 tons of argon
760 tons of argon
0
110 meters
470 meters
600 meters

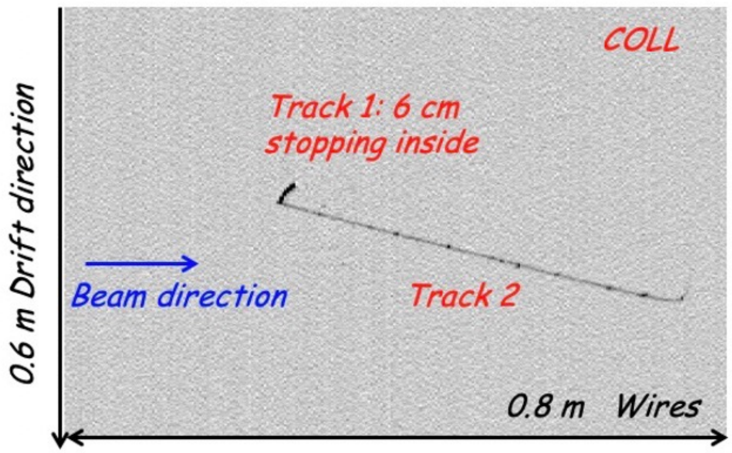
The Short Baseline Neutrino Program

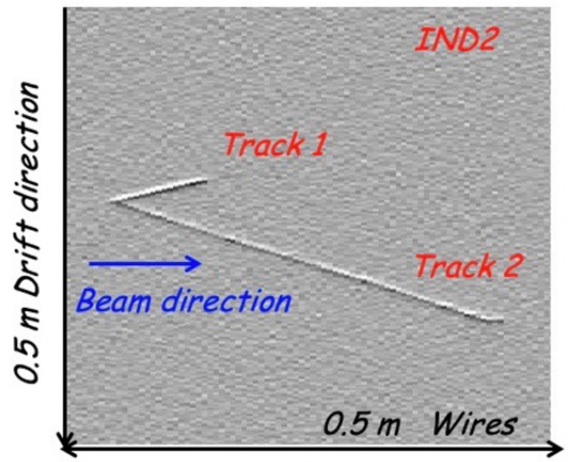


ICARUS MOVES TO FERMILAB



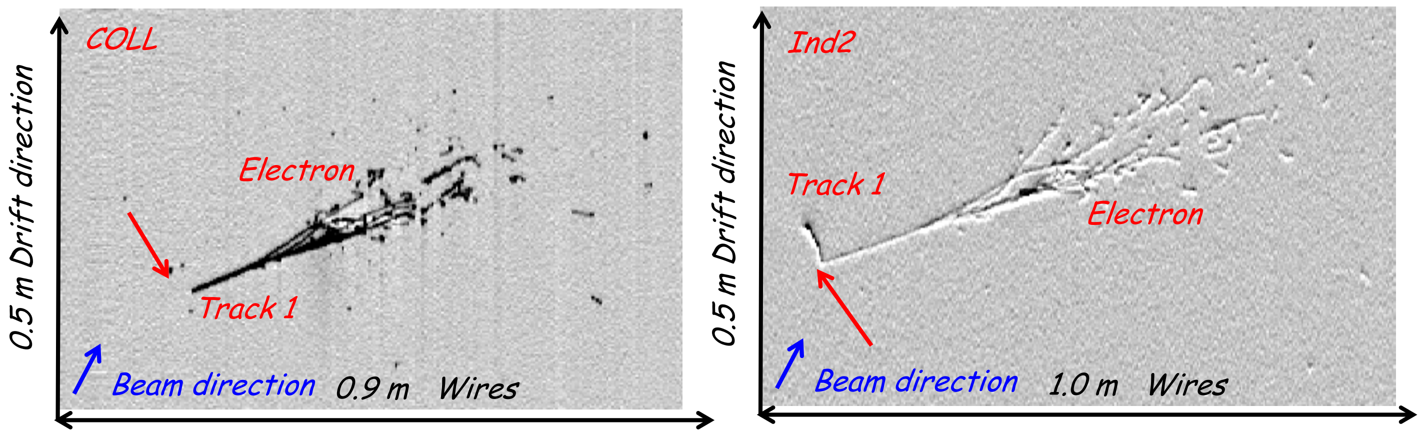
First Events : Example of BNB ν_μCC candidate in ICARUS





- QE ν_μCC candidate (run #4626, ev #227) in COLL and IND2 views.
- Vertex at 29 cm from the bottom wall. Two tracks produced, E_{DEP} ~ 170 MeV
  - Track 1 is the proton candidate with E_K ~ 70 MeV, stopping after L = 6 cm
  - Track 2 is likely the μ exiting on bottom wall after L = 51 cm.

First events : Example of NuMI ν_eCC candidate

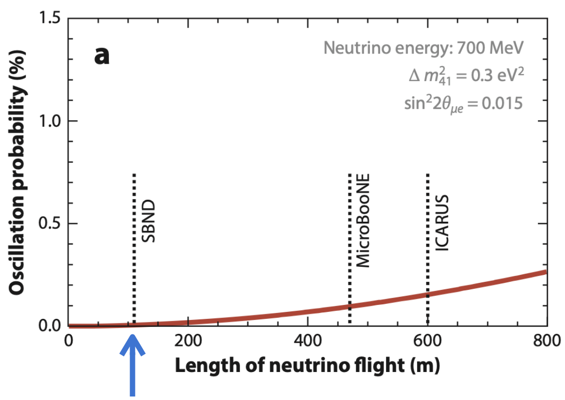


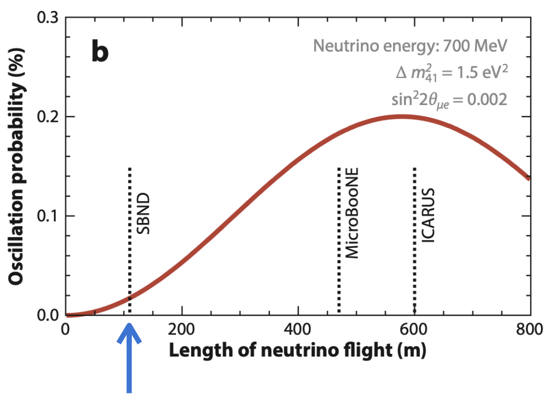
○QE electron neutrino candidate with two particles at the primary vertex (indicated by red arrows):

- Track 1 is the upward going proton candidate stopping inside L= 13 cm
- The electron shower is downward going: the beginning of the shower is clearly visible in particular in Induction 2 view (in Collection the e^- and track 1 are overlapped).

THE NEAR DETECTOR : SBND

Sterile neutrino oscillations

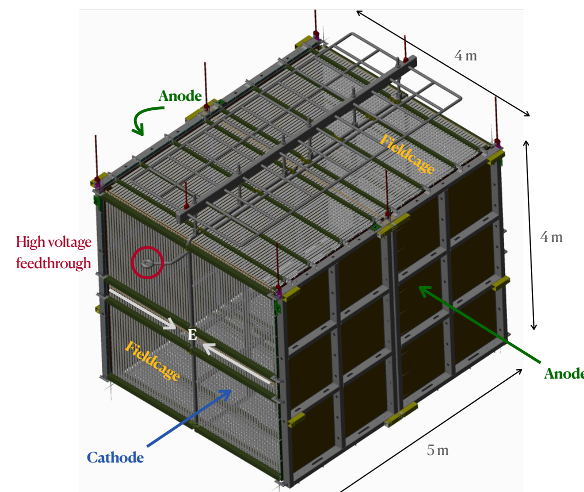




Detector design

Time Projection Chamber

- Single phase LArTPC
- 112 tons active mass
- 5m x 4m x 4m active volume
- One central cathode plane assembly (CPA)
  - Divides detector in two drift windows
- Two anode plane assemblies (APAs)
  - 3 wire planes (vertical, +- 60 to the vertical)
  - Wire pitch and plane spacing = 3mm
- Field cage to maintain 500 V/cm drift field

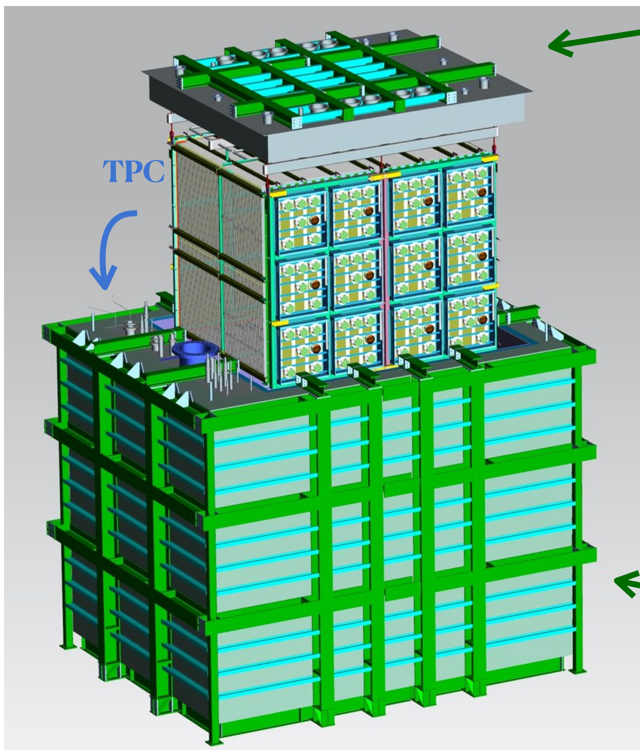


ASSEMBLY UNDERWAY AT DAB

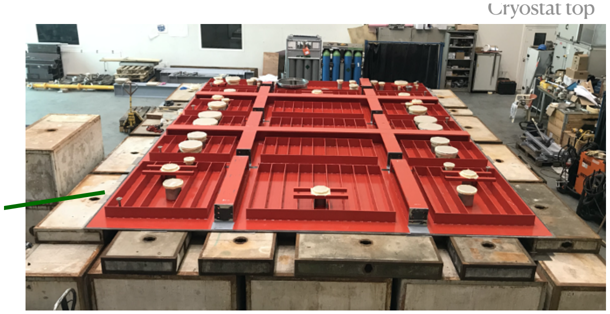
Assembly transport frame

Clean tent

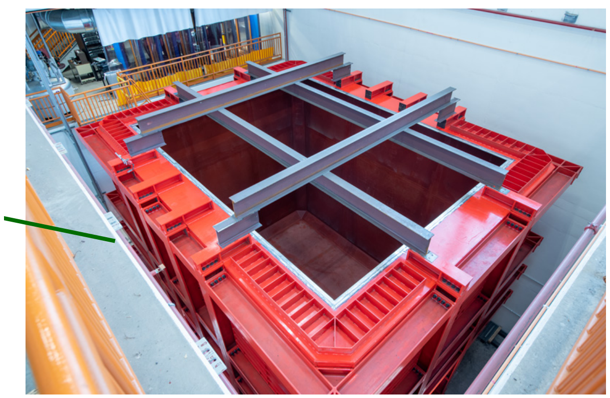
WHEN ASSEMBLED WILL MOVE TO NEW HOME ON BNB



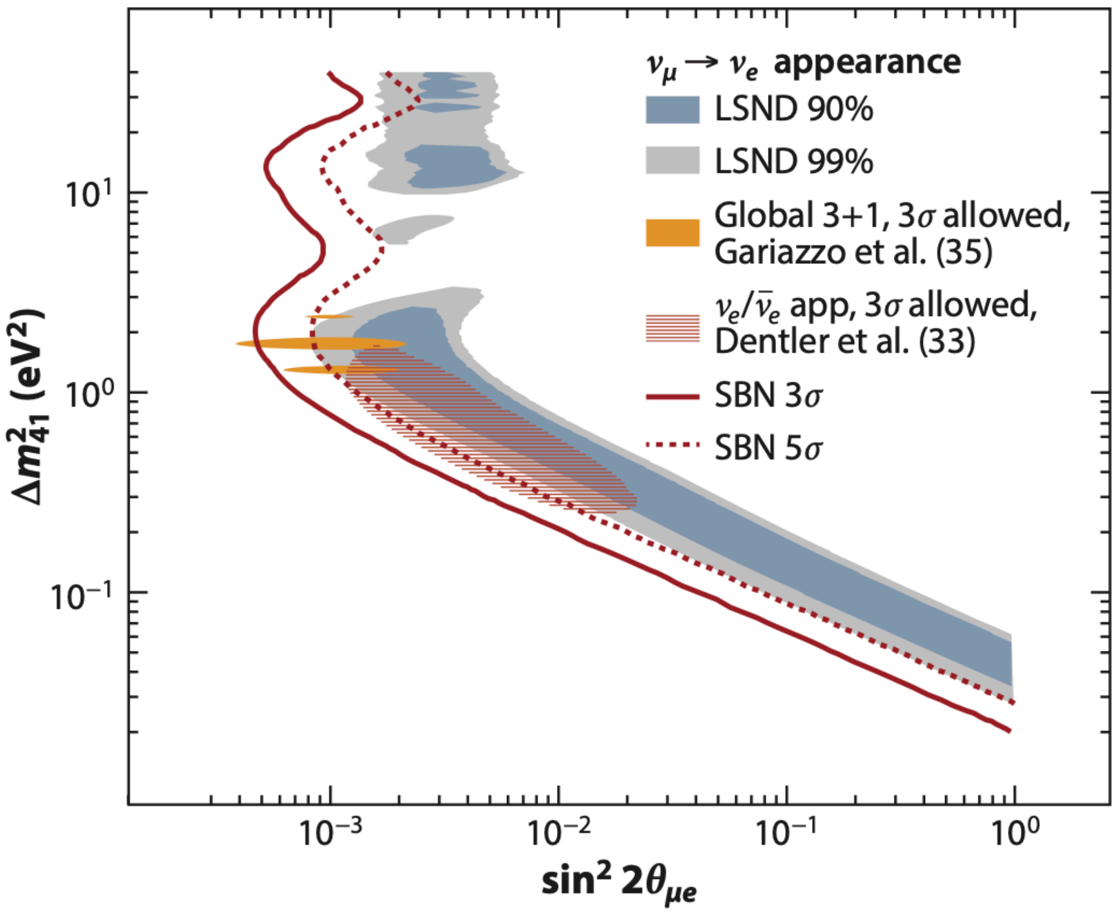
Cryostat top



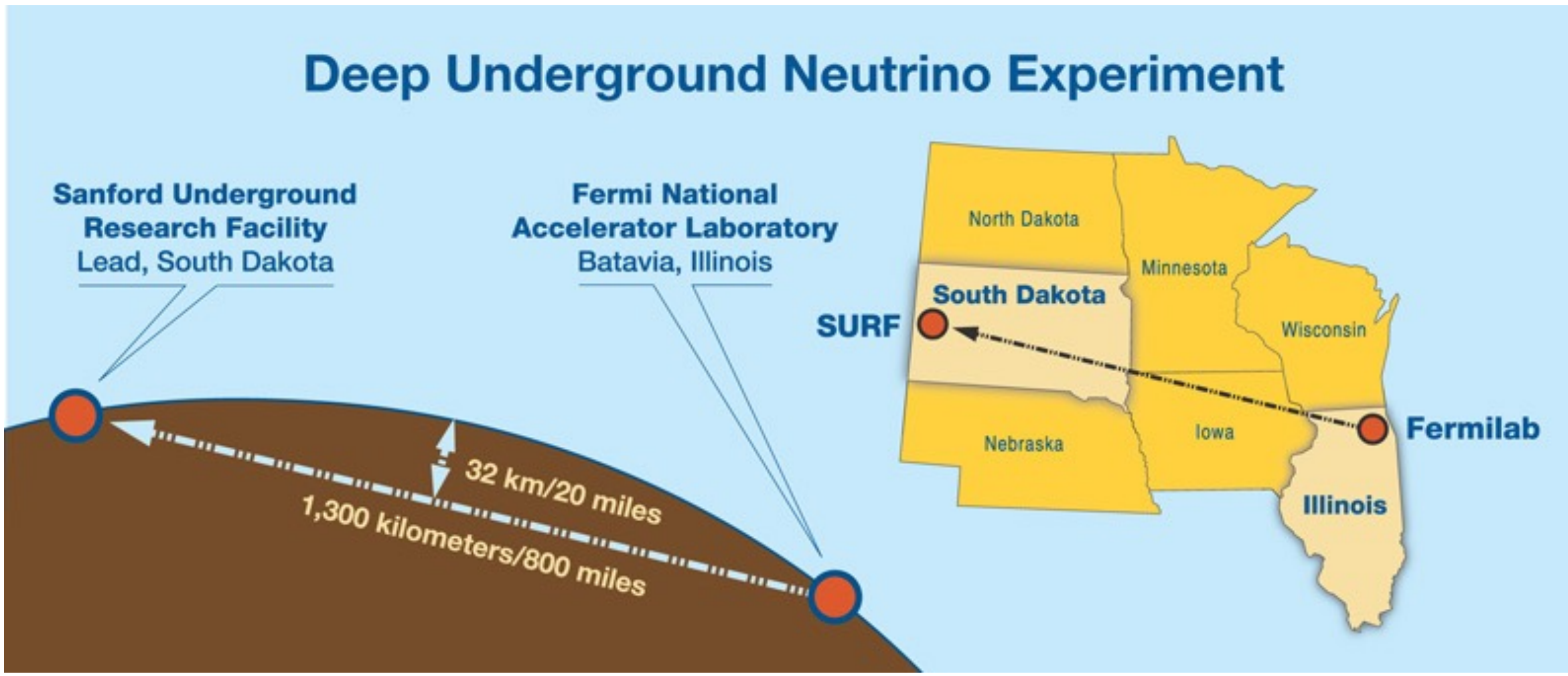
Warm vessel



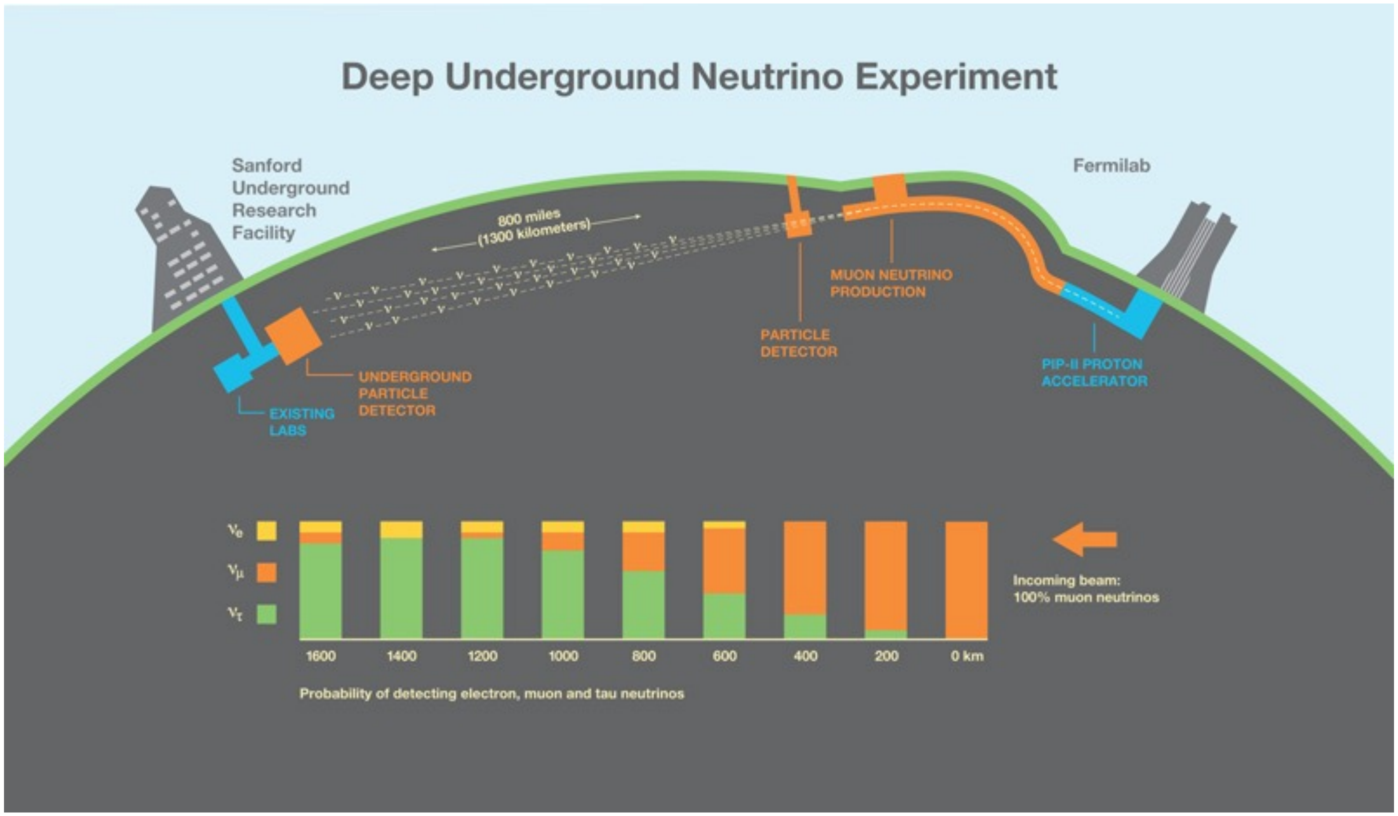
Goal of SBN Program



BACK TO LONG(ER) BASELINE



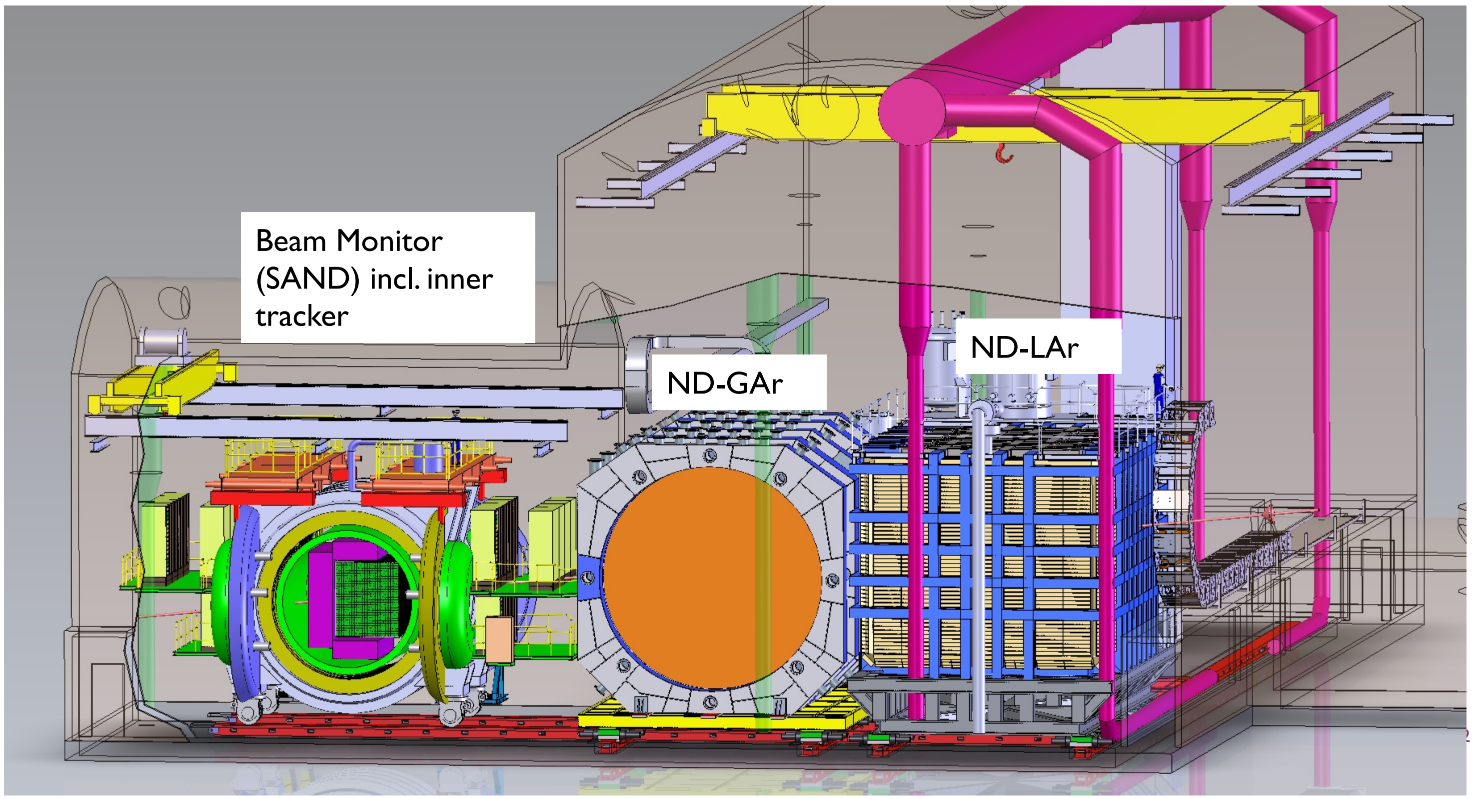
BACK TO HOMESTAKE (NOW KNOWN AS SURF)



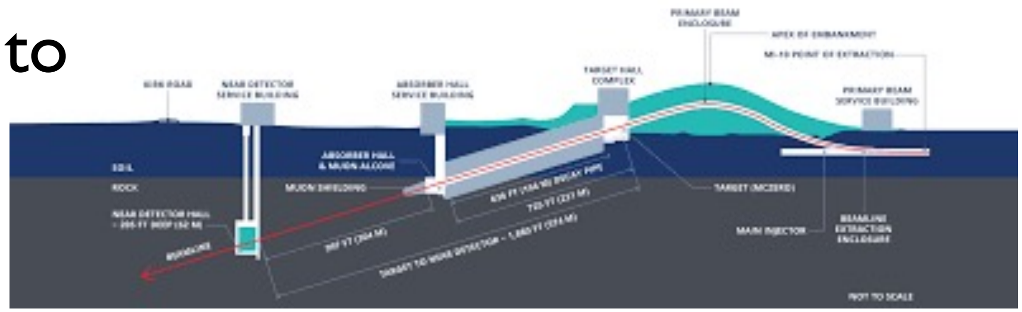
1300 kilometer baseline

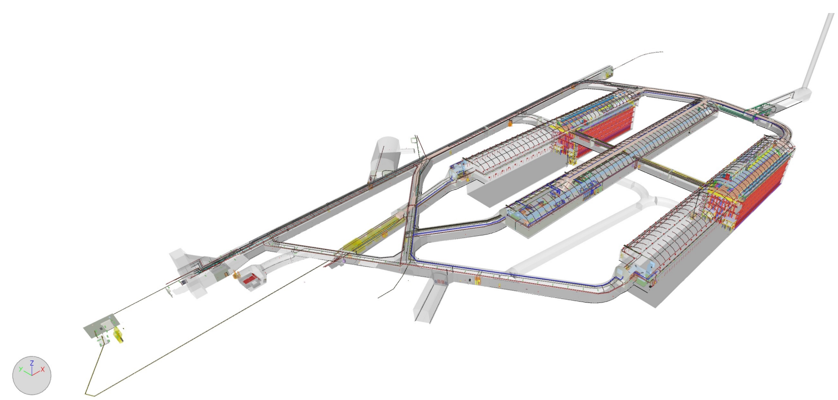
Sanford Underground Research Facility is located at the old Homestake Mine in Lead, South Dakota

THE DUNE NEAR DETECTOR



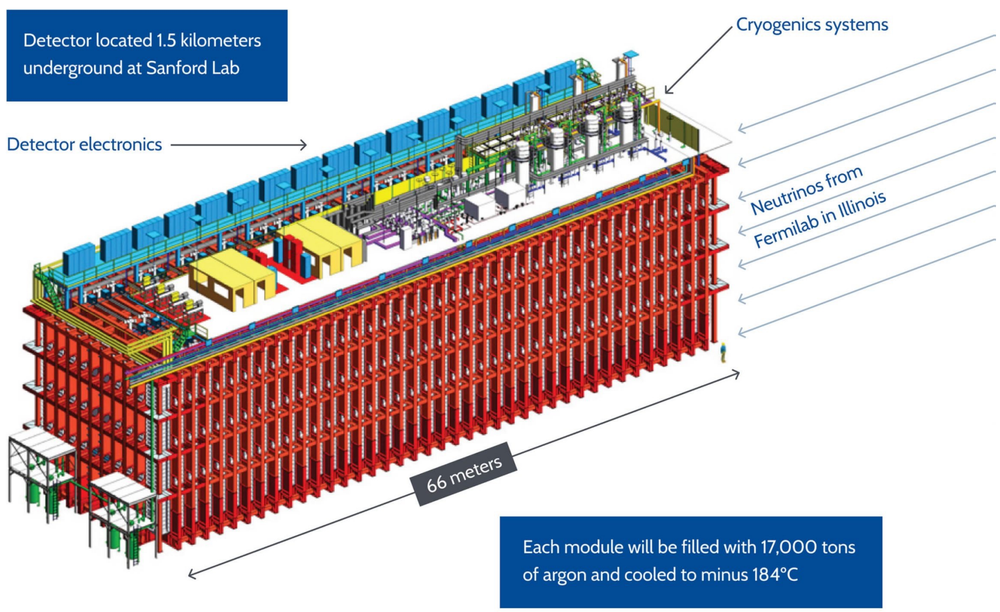
Lot's of new construction to build this experiment



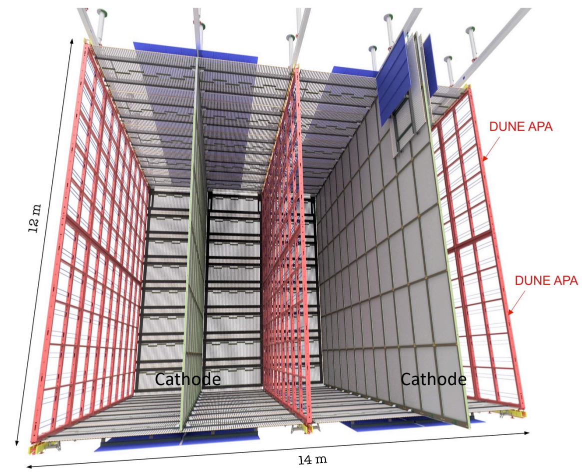


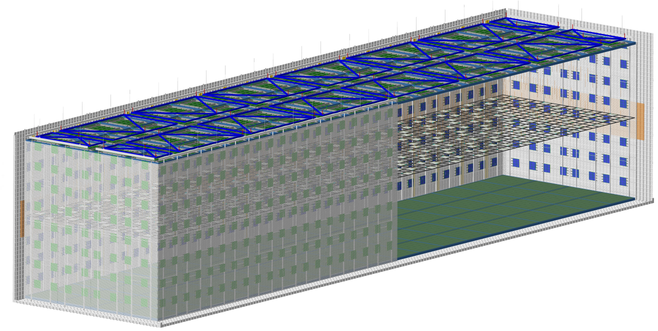
Underground cavern space for 4 detector modules

Horizontal and Vertical Drift TPCs for 1^{st} and 2^{nd} modules

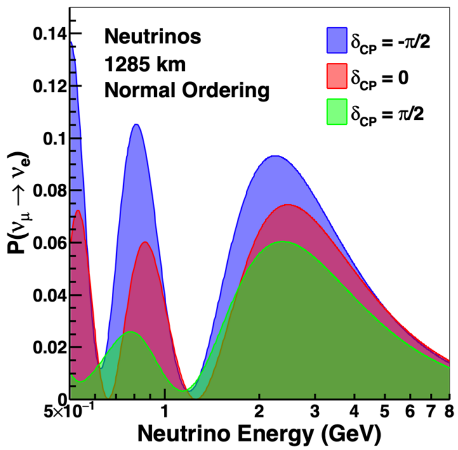


Liquid argon cryostat

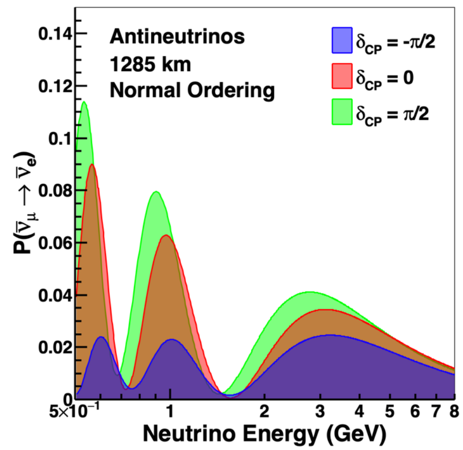


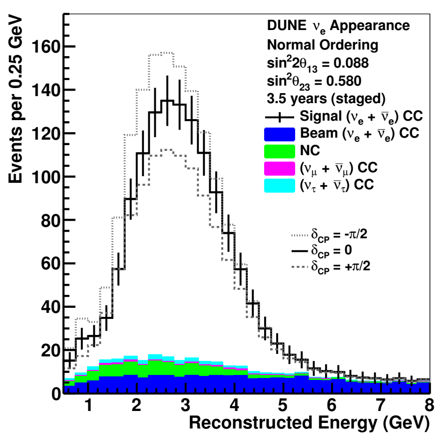


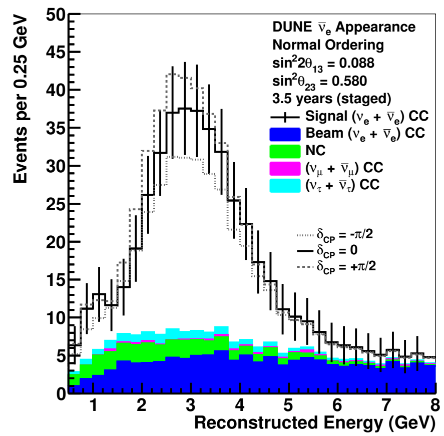
Neutrinos



Antineutrinos



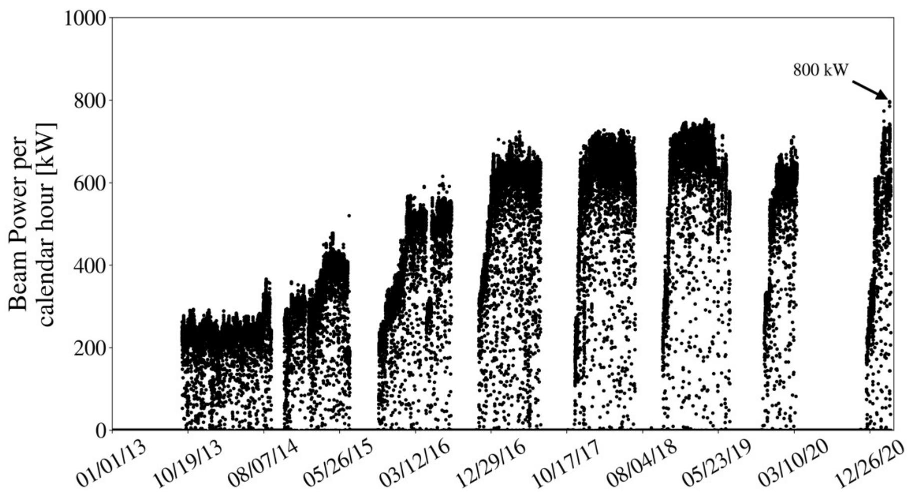




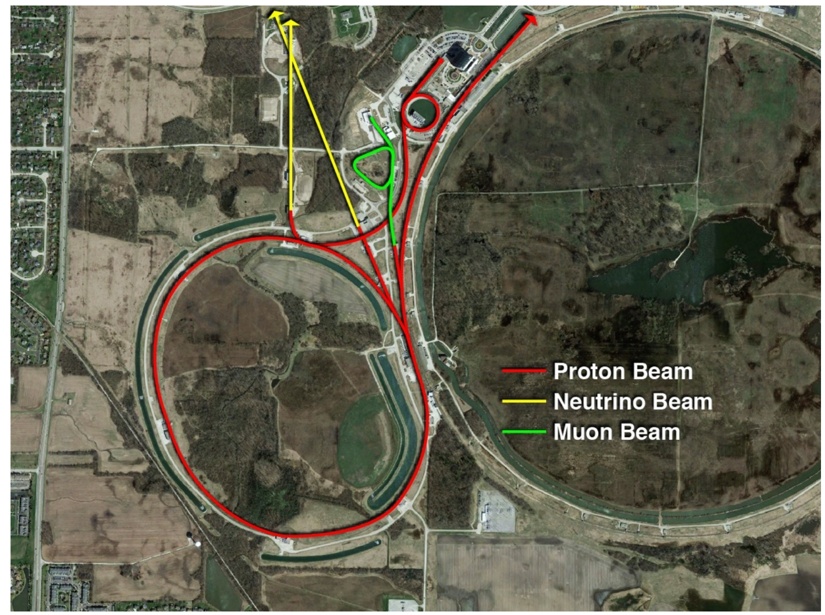
Event rates can be shown as a function
Of the product of kiloton-MW-years

With 1 MegaWatt of Beam Power
the DUNE detector should collect
~7nue events/kiloton/year (dcp = 0)

FINAL CHALLENGE : BEAM POWER



Proton Improvement Plan – I
MINOS -> NOvA

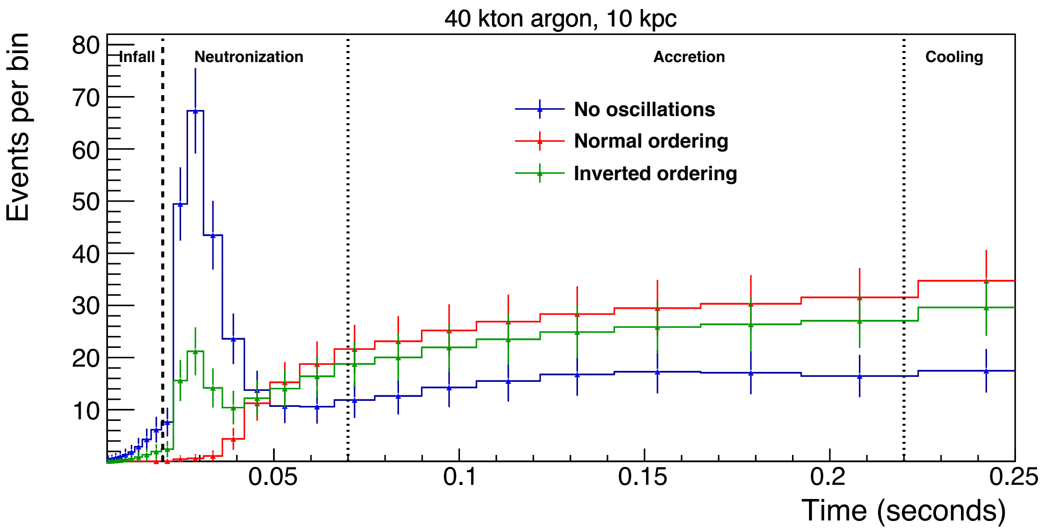


For LBNF/DUNE

Fermilab PIP-II under construction

Beam power to 1200kW, upgradable to 2400kW

BEYOND LONG BASELINE NEUTRINOS



DUNE wants to be up and running before the next supernova is detectable on earth!!

SUMMARY AND OUTLOOK

- For the next several years the NOvA and T2K experiments will continue to make world class measurements to confirm our understanding of the neutrino mass and mixing parameters
- The DUNE and Hyper-K experiments are beginning construction and once operating will offer unprecedented data sets to refine the parameters
- The long baseline of the DUNE experiment will enable a definitive measurement of the Mass Ordering within just a couple of years of operation
- The DUNE and Hyper-K experiments offer complimentary approaches to measuring the challenging parameter, δ_{CP}
- Both experiments will also provide laboratories which are sensitive to supernova, solar neutrinos and nucleon decay
- **The future is bright for neutrino enthusiasts**