The Neutrino Program at Fermilab

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INFN
Vulcano Workshop, 29/09/2022

Fermilab INFN DUNE

Looking for “unknown unknowns”

Needs a synergic use of:

- High-Energy colliders
- neutrino experiments (solar, atmospheric, cosmogenic, short/long baseline, reactors, $0\nu\beta\beta$ decays, masses)
- cosmic surveys (CMB, Supernovae, BAO, Dark E)
- gravitational waves
- dark matter direct and indirect detection
- precision measurements of rare decays and phenomena
- dedicated searches (WIMPS, axions, dark-sector particles)
- …..

Fermilab

From the P5 Report (USA) 2014

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

From the European Strategy Document (2013)

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.

From Japan HEP Community(2012)

The committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

……….

Should the neutrino mixing angle $\boldsymbol{\theta}_{13}$ be confirmed as large, **Japan should aim to realize a large-scale neutrino detector through international cooperation**, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.
This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

Standard Three Neutrino Paradigm

Unitary PNMS matrix described by 3 Euler angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and 1 complex phase ($\delta$). $\delta \neq \{0, \pi\}$ → **CP Violation**

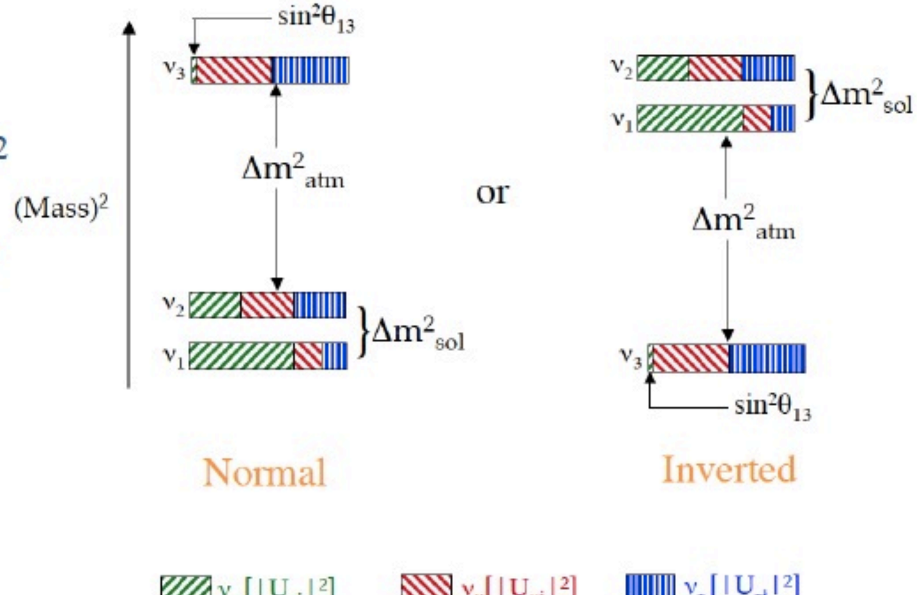
$\theta_{23} \sim 45^\circ$ $\theta_{13} \sim 9^\circ$ $\theta_{12} \sim 30^\circ$

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \; ; \; c_{ij} = \cos\theta_{ij}$$

$\Delta m^2_{atm} \sim 2.5\times10^{-3}$ eV^2

$\Delta m^2_{sol} \sim 7.5\times10^{-5}$ eV^2

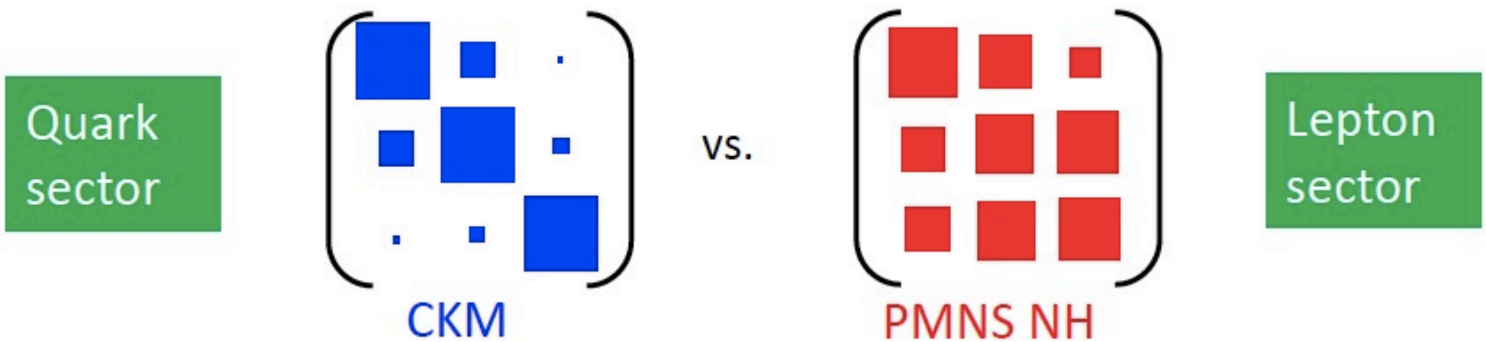


Key Questions in Neutrino Physics

- Do neutrinos violate CP symmetry?

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

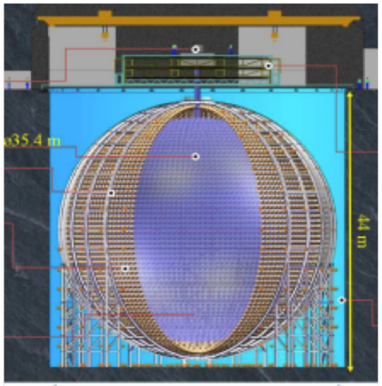
- What is the mass ordering?
- Why are the quark and neutrino mixing matrices so different?

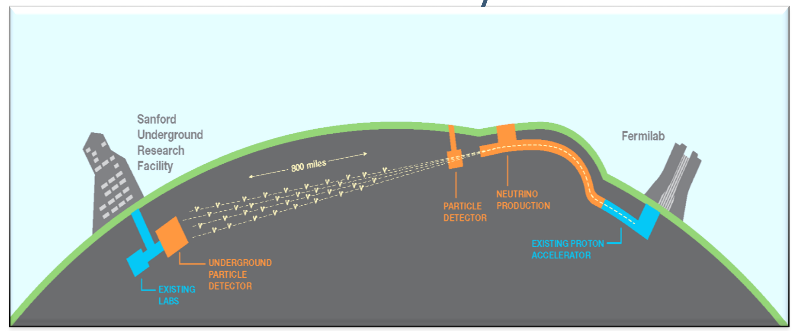


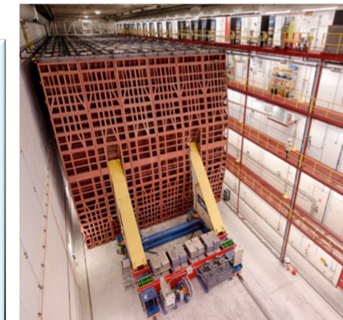
- Are there additional neutrino states?
- Are neutrinos their own antiparticles?
- What is the neutrino mass?

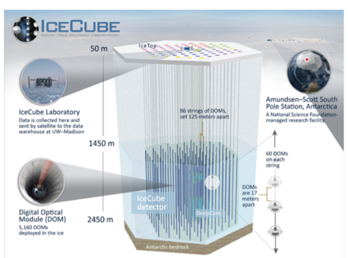
An Exciting Global Initiative to Understand the Most Abundant Known Matter Particle in the Universe

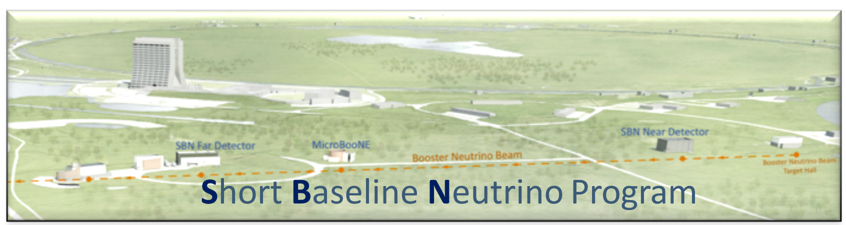
Deep **U**nderground **N**eutrino **E**xperiment
at the
Long **B**aseline **N**eutrino **F**acility

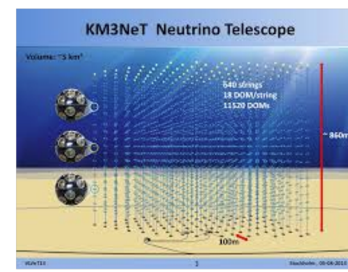


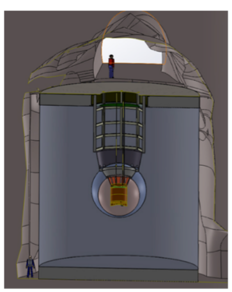


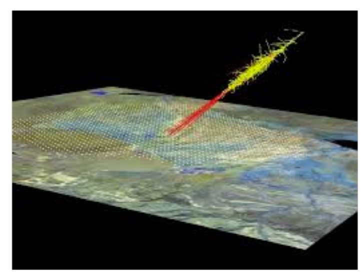


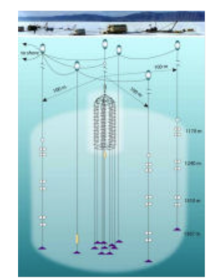












How to search for CP violation

- Compare oscillation oscillation rates for νs and $\bar{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

(in vacuum)

- As in quark sector, CP violating effects $\propto J \equiv c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta$, and require no degenerate masses

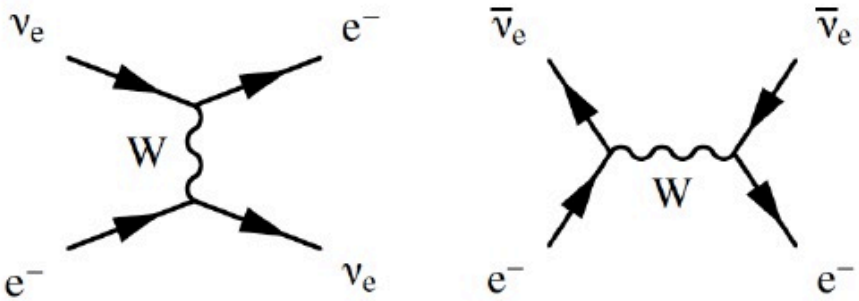
- We know mixing angles and mass differences, so we can measure $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and determine δ, but there is a complication...

Matter Effects

- In real experiments, even in the absence of CPV,

$$P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \neq 0$$

  Neutrinos travel through material that is not CP symmetric, i.e., matter not antimatter
- In vacuum, the mass eigenstates ν_1, ν_2, ν_3 correspond to the eigenstates of the Hamiltonian:
  - they propagate independently (with appropriate phases)
- In matter, there is an effective potential due to the forward weak scattering processes. **Effect depends on Mass Hierarchy**



$$V = \pm\sqrt{2}G_F n_e$$

Different sign for ν_e vs $\overline{\nu}_e$

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Possible Experimental Strategies

EITHER:

- Keep L small (~200 km): so that matter effects are insignificant
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1\,\mathrm{GeV}$$

  - Want high flux at oscillation maximum

➡ **Off-axis beam:** narrow range of neutrino energies

OR:

- Make L large (>1000 km): measure the matter effects (i.e., MH)
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu > 2\,\mathrm{GeV}$$

  - **Unfold CPV from Matter Effects through E dependence**

➡ **On-axis beam:** wide range of neutrino energies

Possible Experimental Strategies

EITHER:

- Keep L small (~200 km): so that matter effe are insignificant
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

  - Want hi tion maximum

➡ **Off- eam:** narrow range of neutrino energies

Hyper-Kamiokande

OR:

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  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

  - **Unfold CPV from Ma ts through E dependence**

➡ **On-axis beam:** wide range of neutrino energies

DUNE

It's not only statistics....

In the experiment we measure:

$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * D^{far}_{\nu_e}(E_\nu, E_{rec})\ dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * D^{near}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu}$$

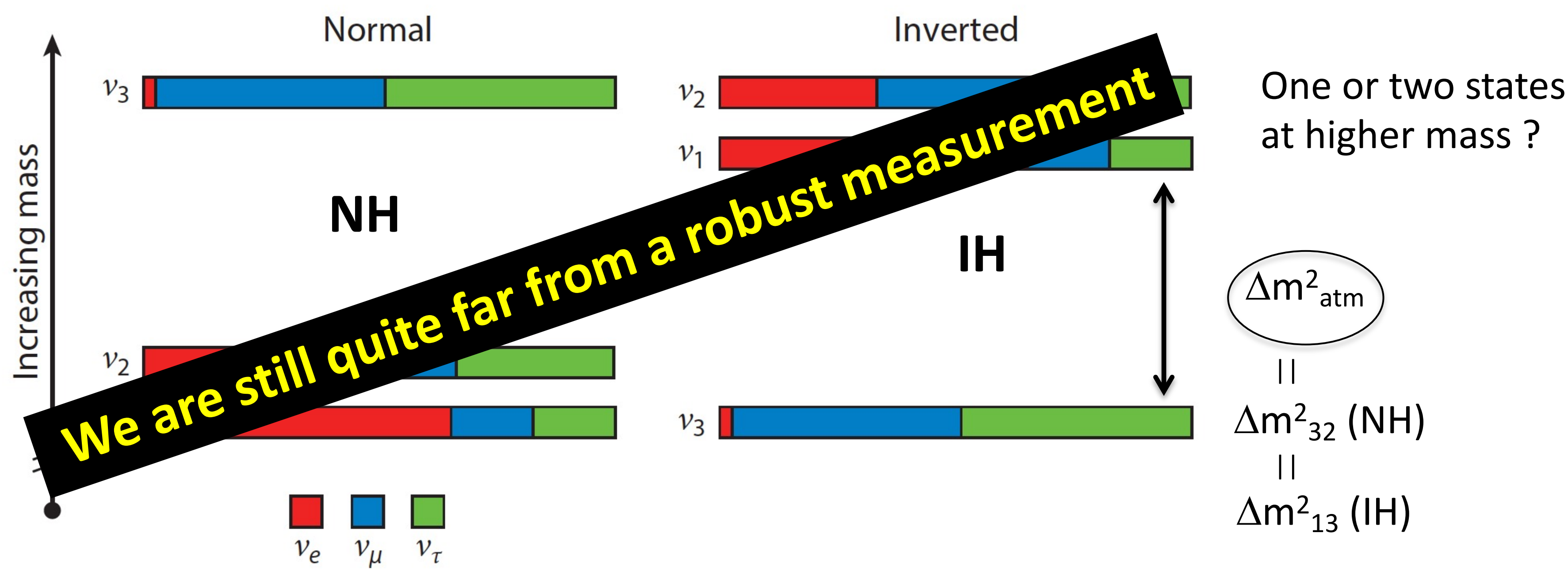
In order to get the physical quantities, we have to control flux, energy distribution/geometry of the beam, efficiencies, acceptances, etc..

Need a sophisticated Near Detector complex to control beam and systematics

The present scenario

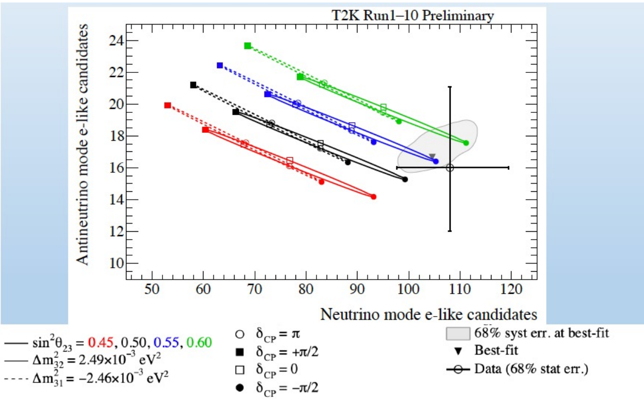
We are entering in the precision era, but there are still 4 results to be obtained, at least at first order :

1) Leptonic CP violation (phase δ_{CP})
2) Mass ordering (MO)
3) (θ_{23} octant)
4) Presence or not of more (sterile ?) neutrinos states

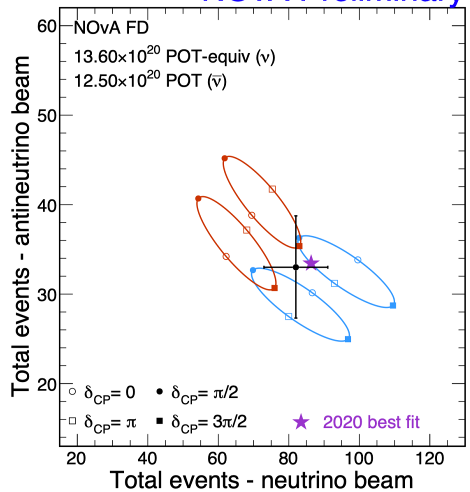


Comparing scenarios

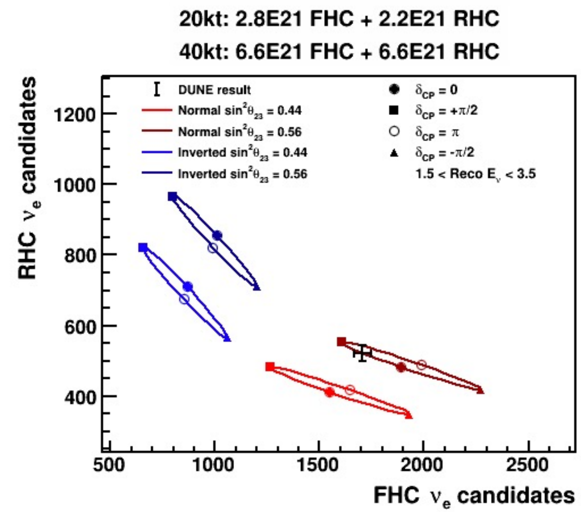
T2K



NOvA Preliminary



DUNE simulation



In Hyper-K only the error bars will shrink

With 2 or 4 dects, 100 kt-MW-y, shared between FHC and RHC, in 3 y ramp-up

T2K -> Hyper-K:

Same baseline
Same beam spectrum
Same detector technology

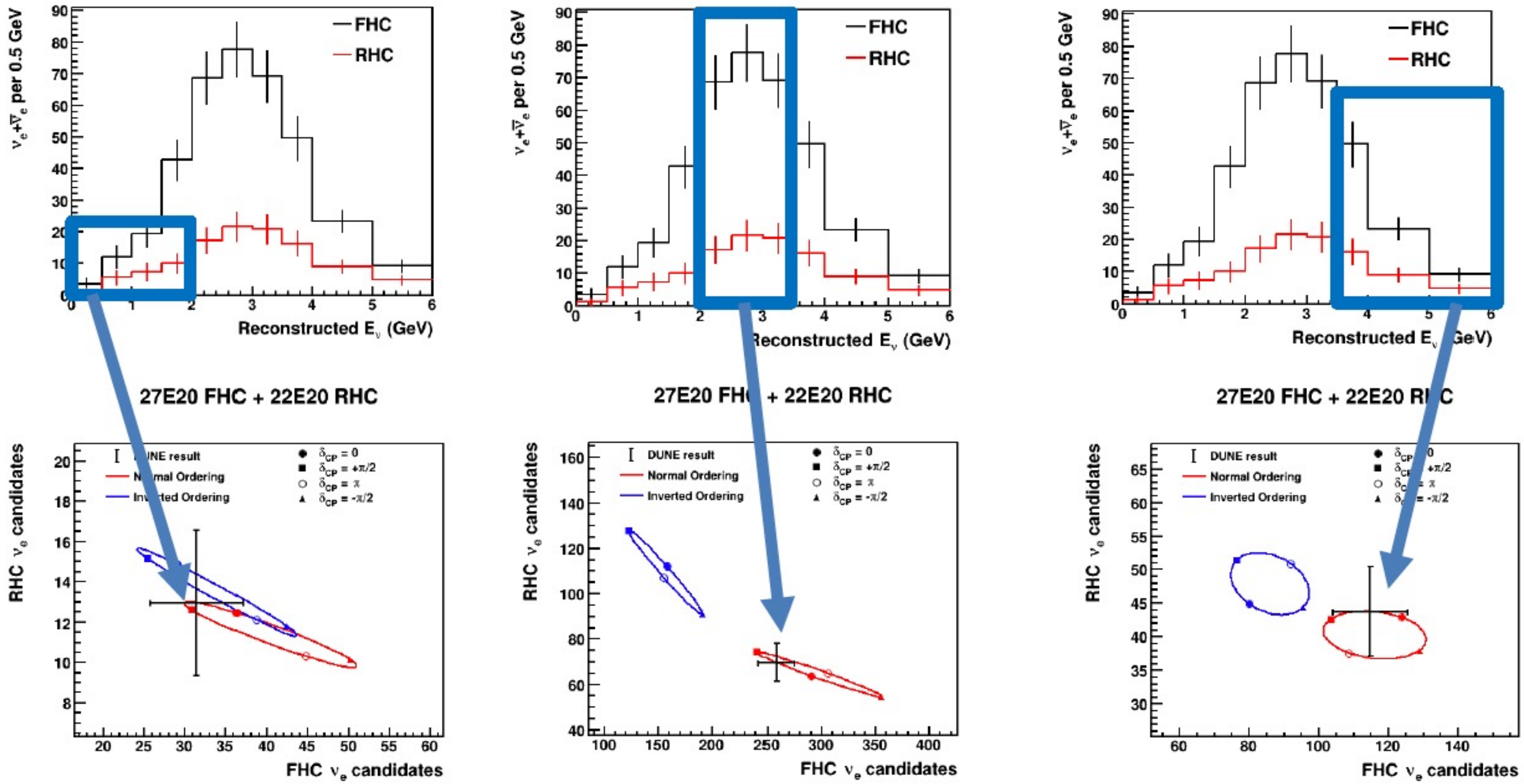
NoVA -> DUNE:

Longer baseline
Wideband beam
Better event reconstruction

FHC: Forward Horn Current
RHC: Reverse Horn Current

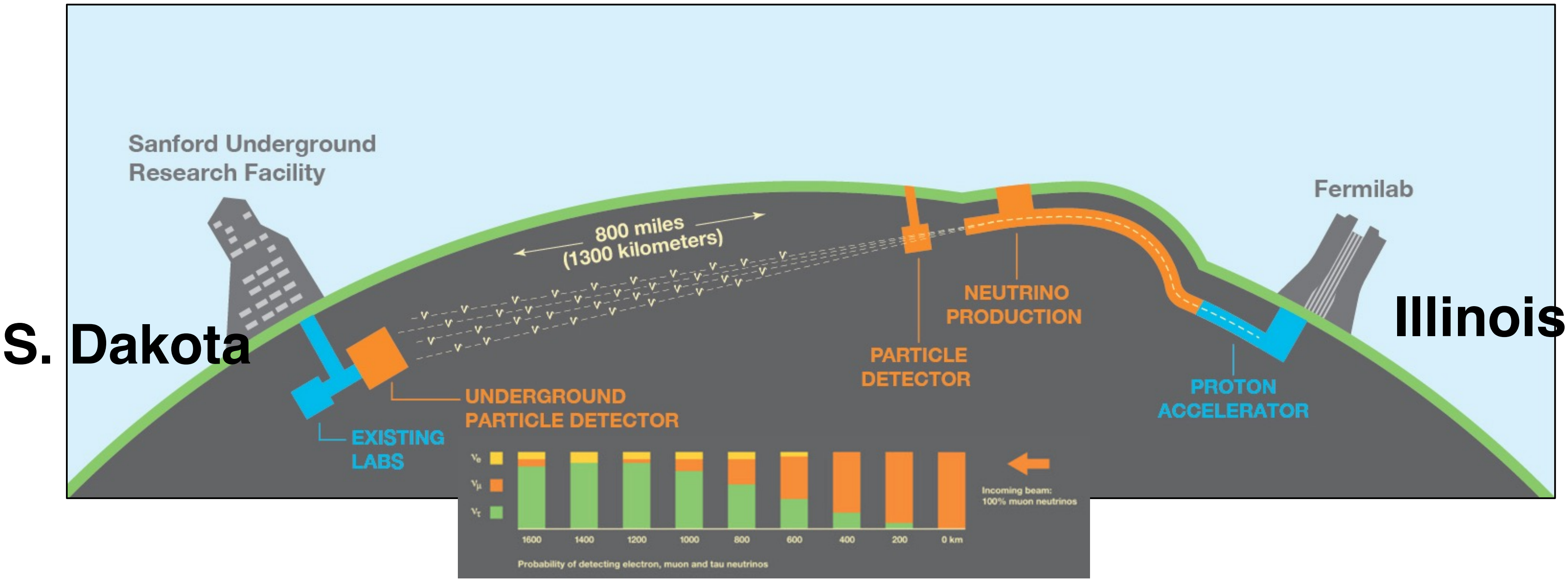
DUNE : enhanced by the wide-band beam

spectrum shape carries information (need proper energy reconstruction)



100 kt-MW-y,
shared between FHC and RHC,
in 3 y ramp-up

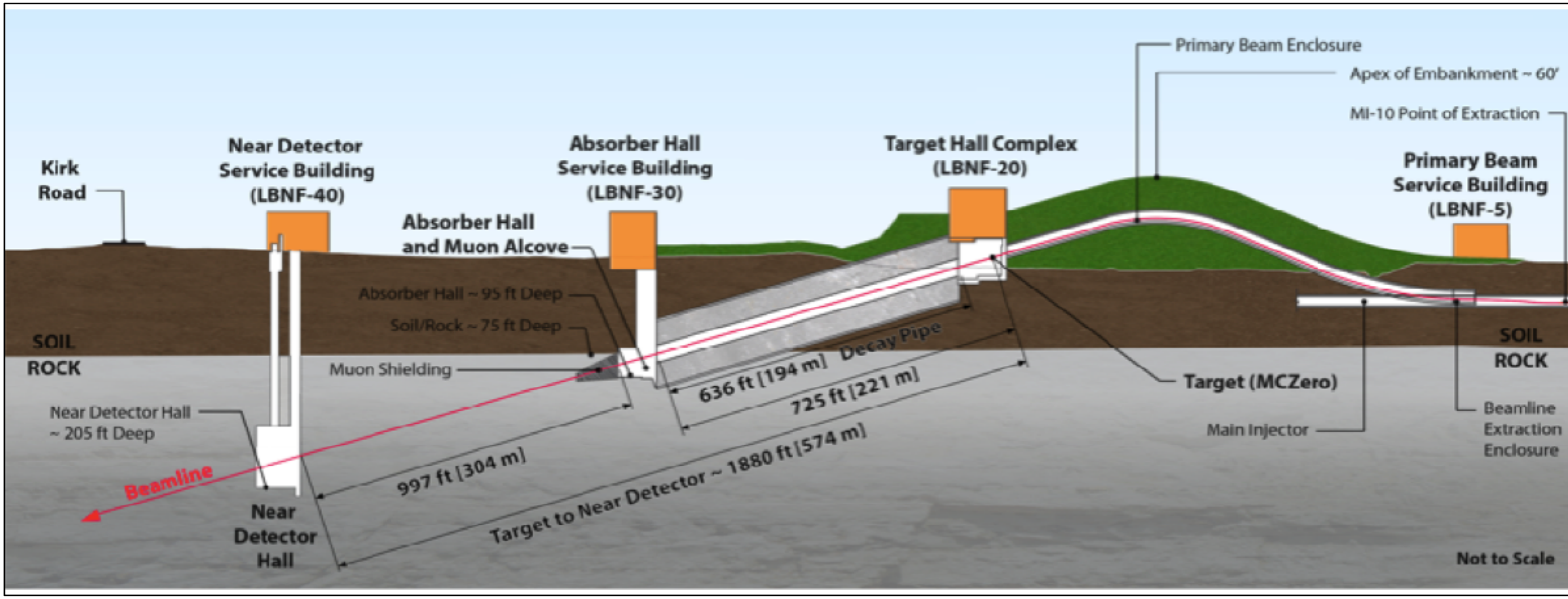
Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE)



The DUNE Experimental Design

- DUNE TDR (Vol I,III,IV https://iopscience.iop.org/journal/1748-0221/page/extraproc95, Vol II arxiv:2002.03005 for Physics)
- ND CDR (arXiv:2103.13910, Instrument 5 (2021) 4, 31)

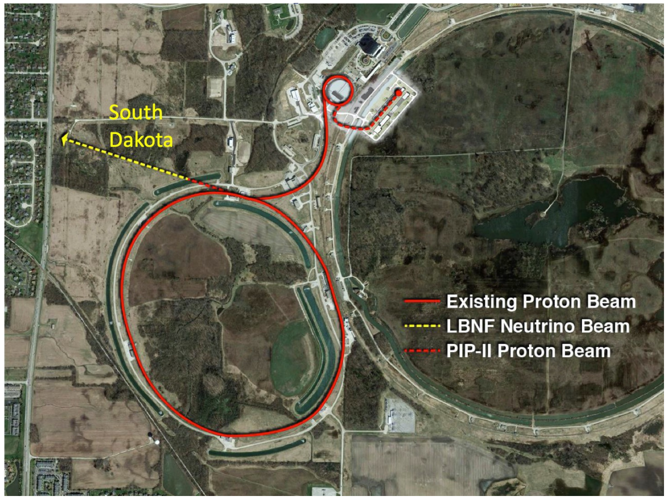
Long-Baseline Neutrino Facility (LBNF) Neutrino Beam

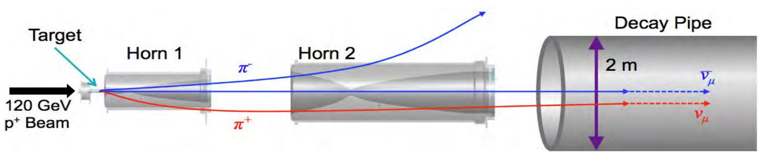


- ✓ LBNF will house and deliver beam to detectors built by DUNE Collaboration
- ✓ 60-120 GeV protons from Fermilab's Main Injector
- ✓ Initial power: 1.2 MW (@120 GeV); plan to upgrade to 2.4 MW
- ✓ 200 m decay pipe, angled at South Dakota (Sanford Underground Research Facility- SURF)
- ✓ Separate ν and ν-bar and running modes

LBNF wide-band beam

At FNAL, Fermi NAtional Lab



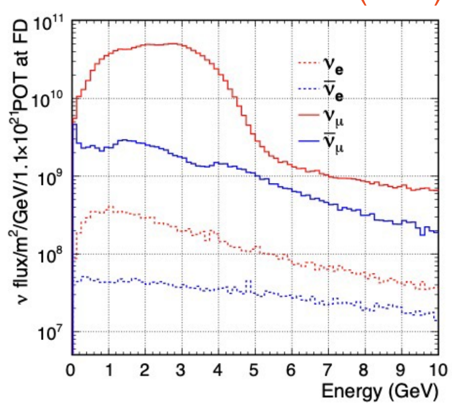


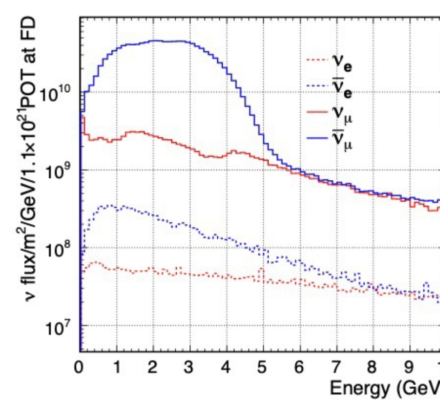
Horn-focused neutrino beam line optimized for CP violation sensitivity using genetic algorithm

1.2MW @ 100% efficiency=2x10^{21} pot/year
The 3-year ramp-up is equivalent to
one year of operation at 1.2MW from Day 1

The LBNF neutrino beam will provide neutrinos and antineutrinos with energies from 0 to 8 GeV

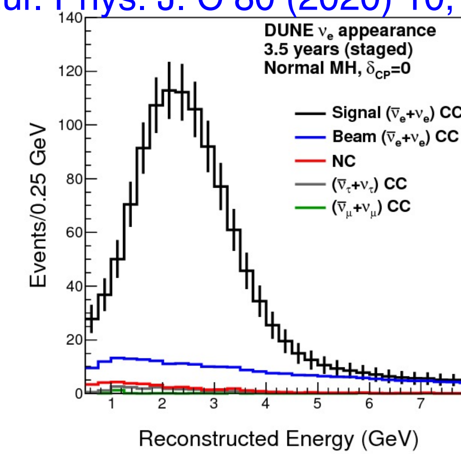
Neutrino Flux at SURF, 1300 km away





[Eur. Phys. J. C 80 (2020) 10, 978]

(DUNE CDR)



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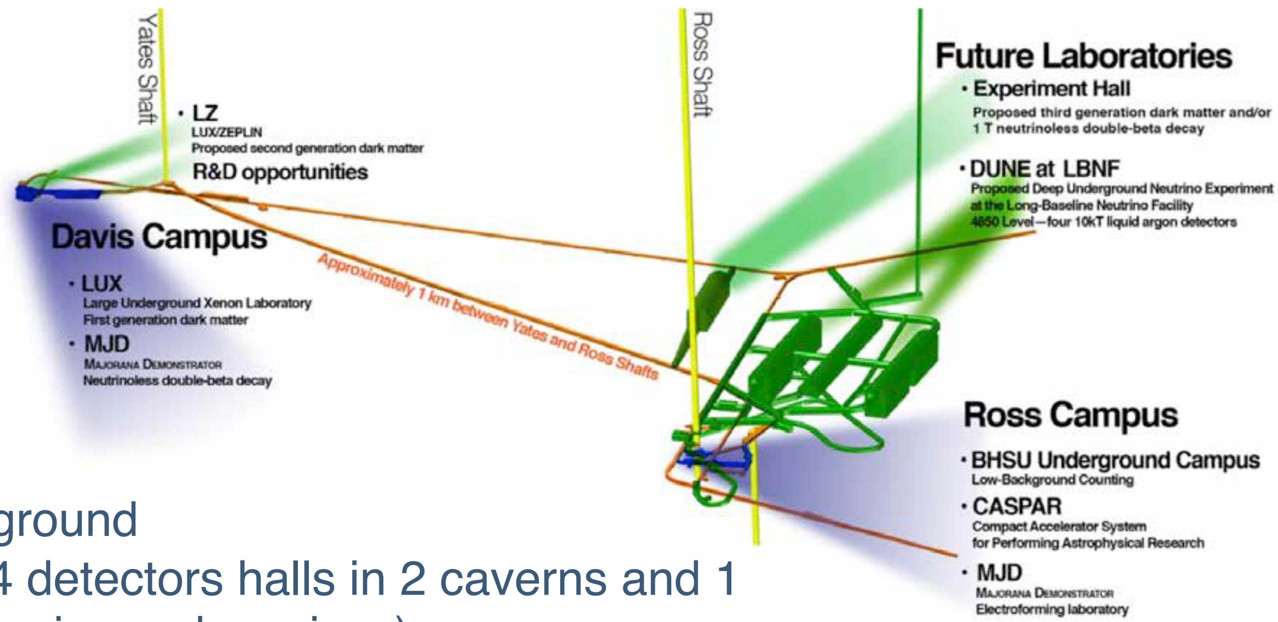
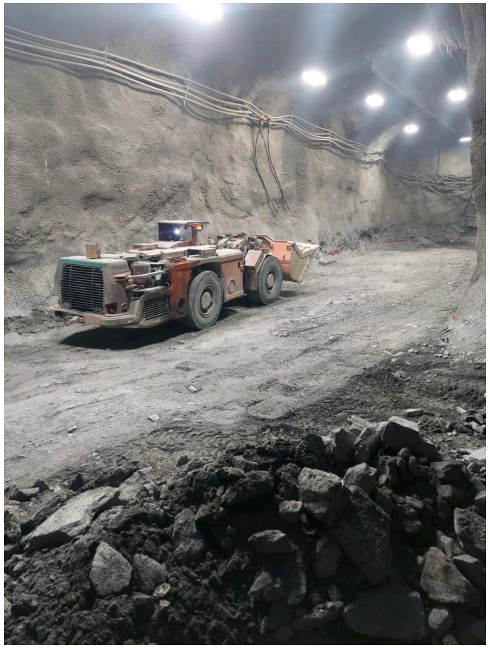
SURF

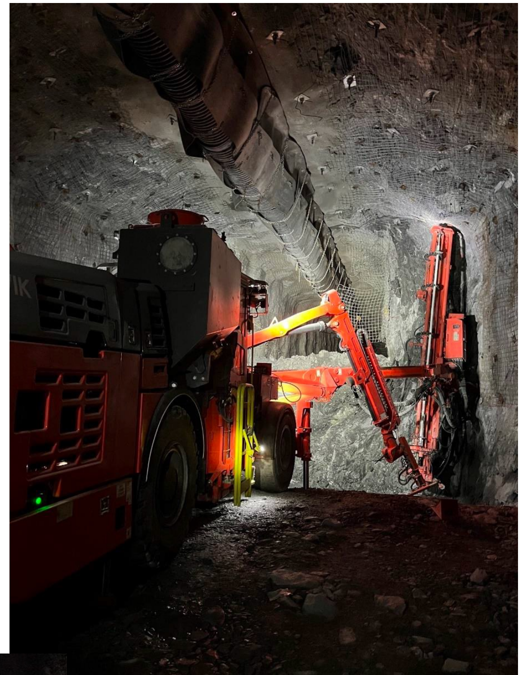


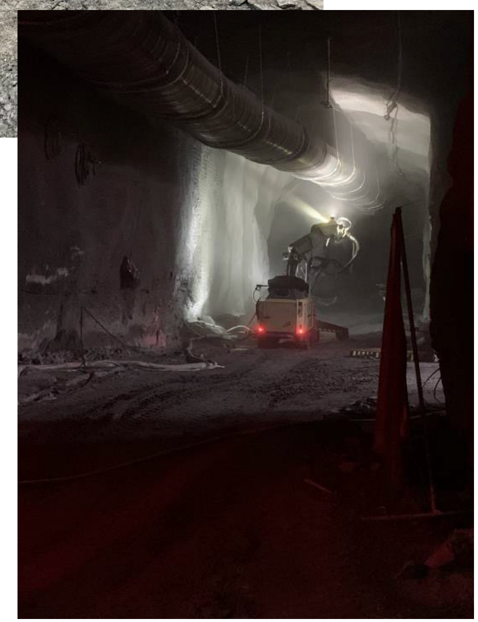
- Deepest laboratory in the US: 1.5 km underground
- Three main caverns: 4 detectors halls in 2 caverns and 1 support cavern (cryogenics and services)
- Excavation is ongoing *(875,000 tons of rock to be excavated)*
- FD first module installation second half of 2020's

Previously known as Homestake (gold) Mine close to Lead,
in the Black Hills (South Dakota),
50 miles from Mount Rushmore and Crazy Horse monuments

Excavation at SURF underway

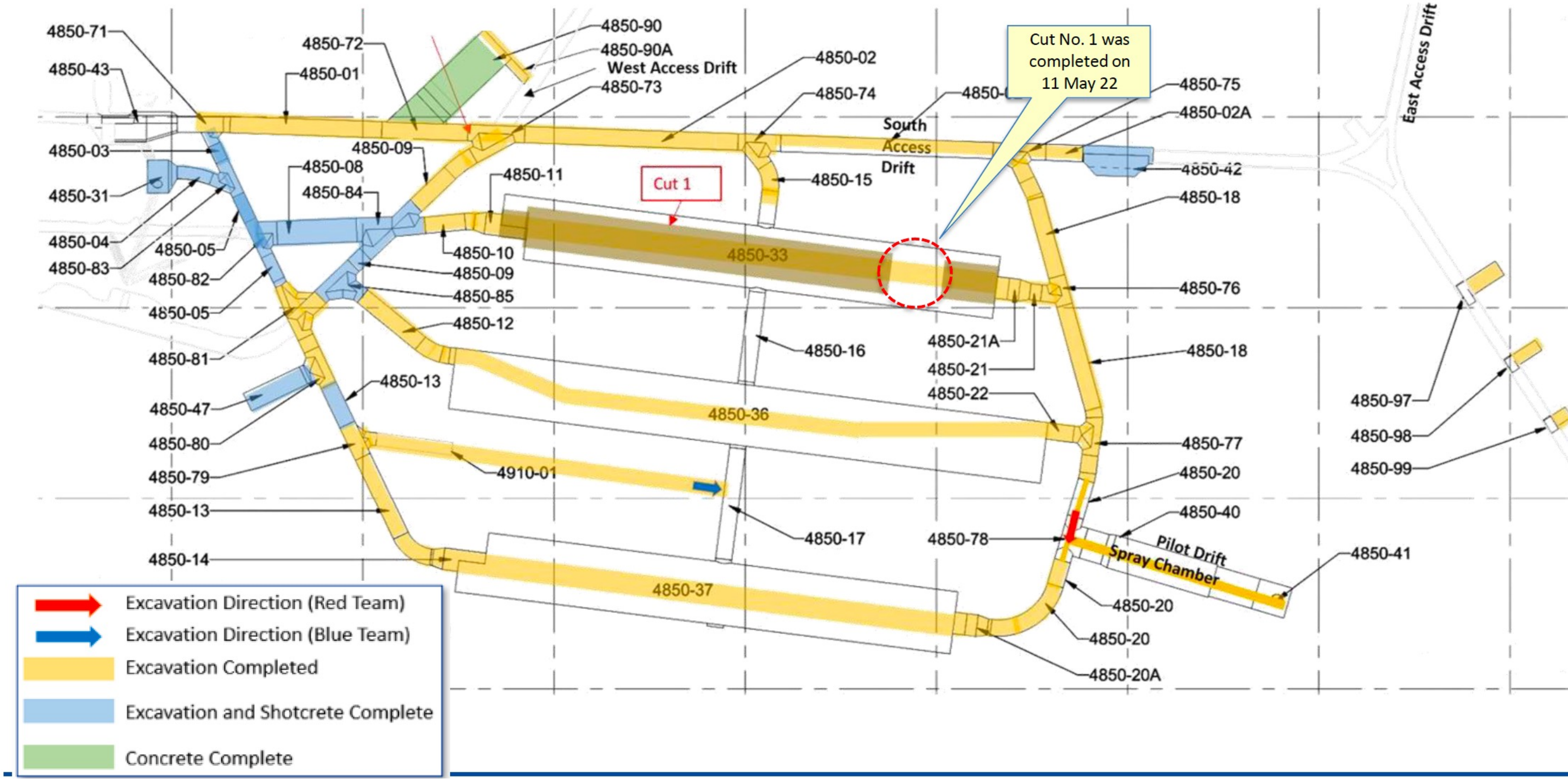






Sanford Underground Research Facility (SURF)

Excavation Update *(May 2022)*



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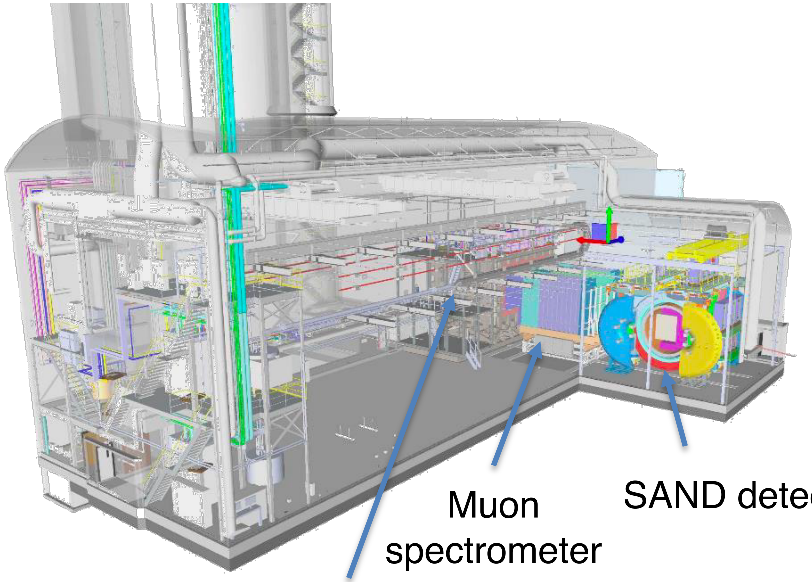
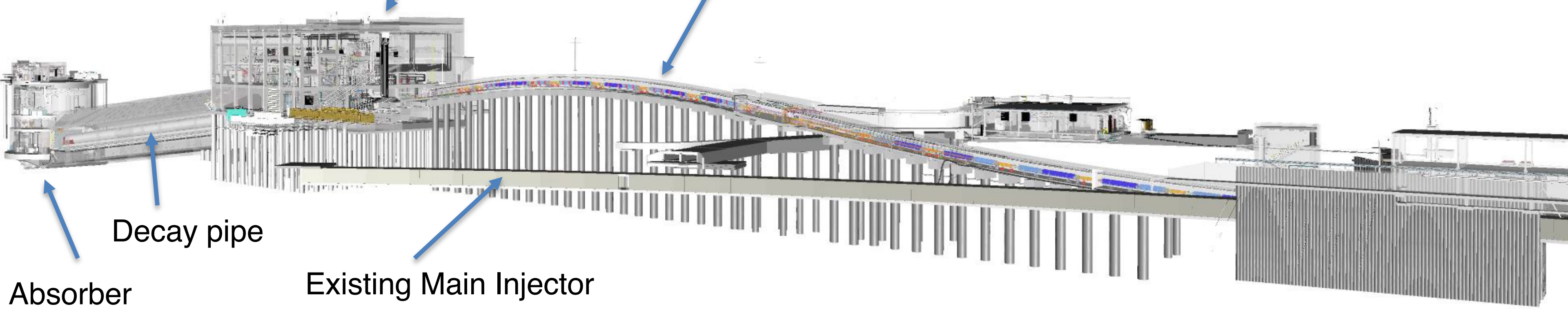
Near Site Conventional Facilities

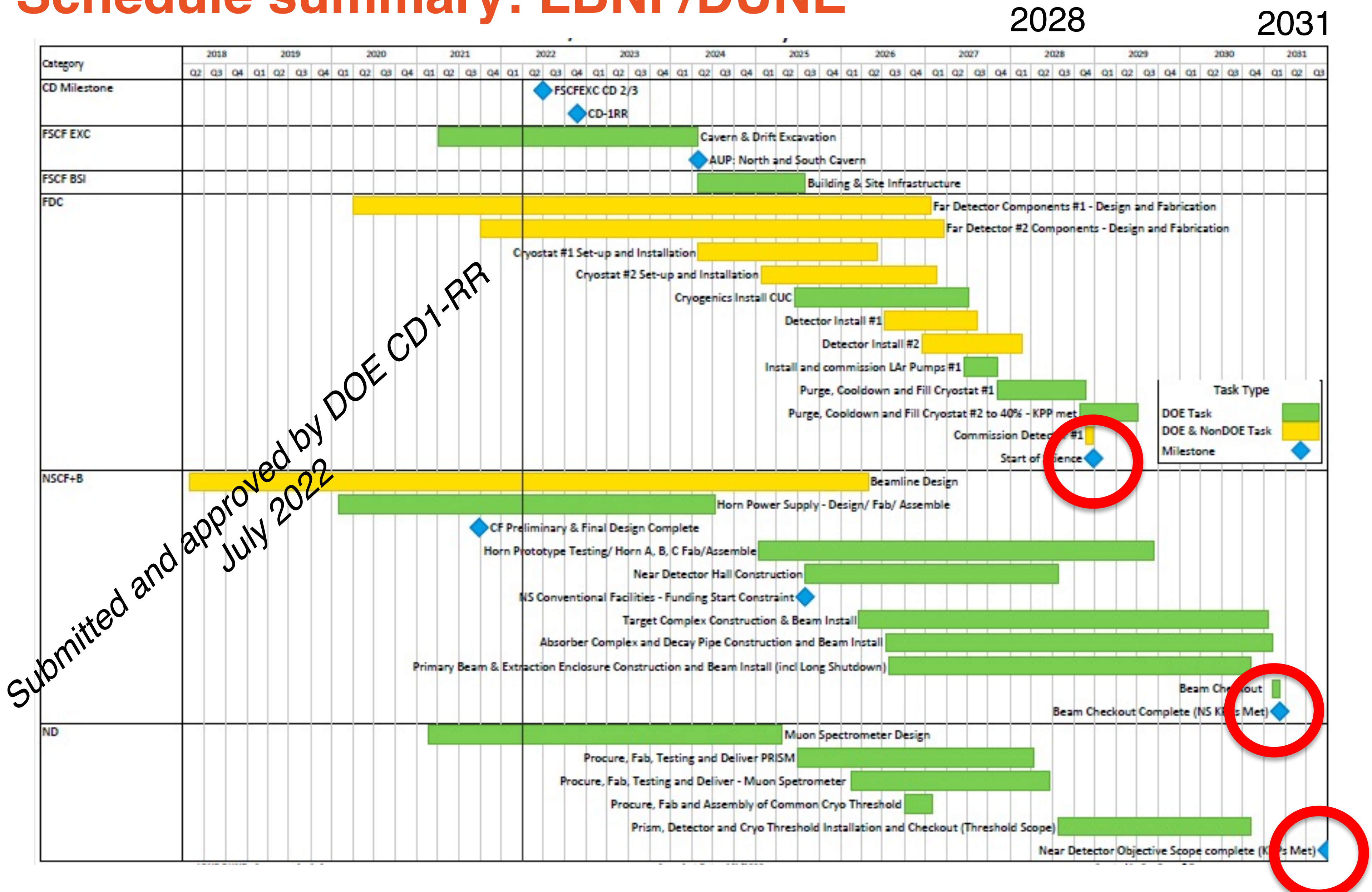
Status:

- 100% final *design* completed on 28 Sep 2021 for the Beamline Complex and Near Detector Complex
- NSCF will start construction upon funding availability *(possibly better sooner than later)*



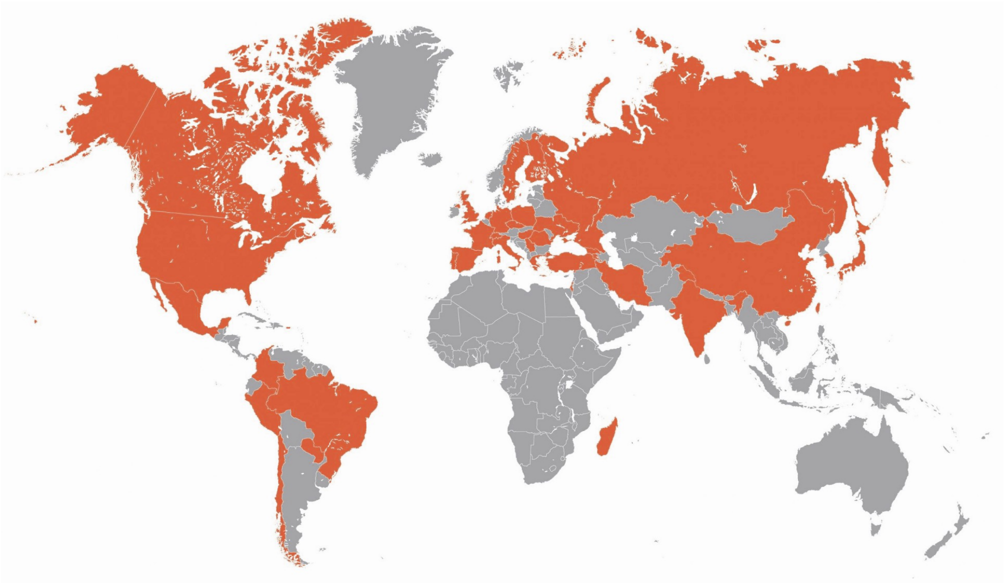


Schedule summary: LBNF/DUNE



Fermilab INFN DUNE

DUNE collaboration

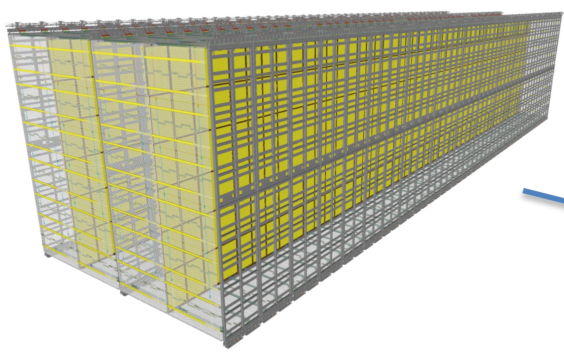


Over 1,300 scientists, from more than 200 Institutions, $\geq$ 37 countries plus CERN

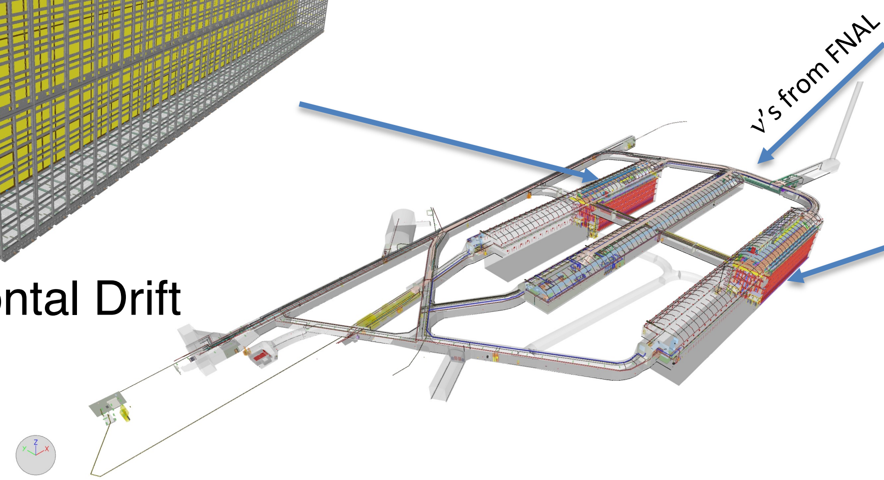
Back in presence, DUNE coll. Meet at FNAL, May. 2022

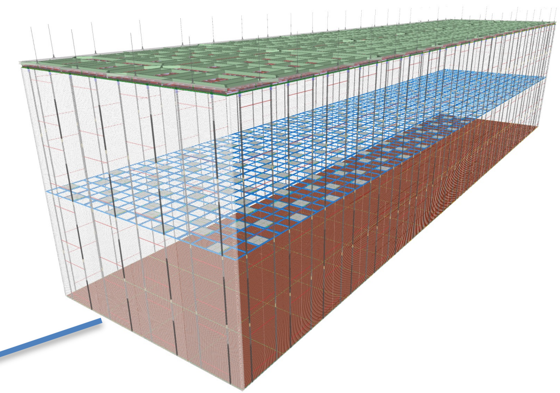
DUNE – Phase I

- 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)



APA* Horizontal Drift





CRP** Vertical Drift

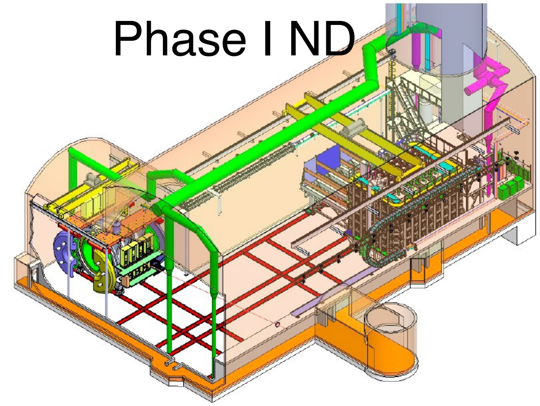
Note : DUNE Science begins when FD1 is filled and turned on and recording tracks

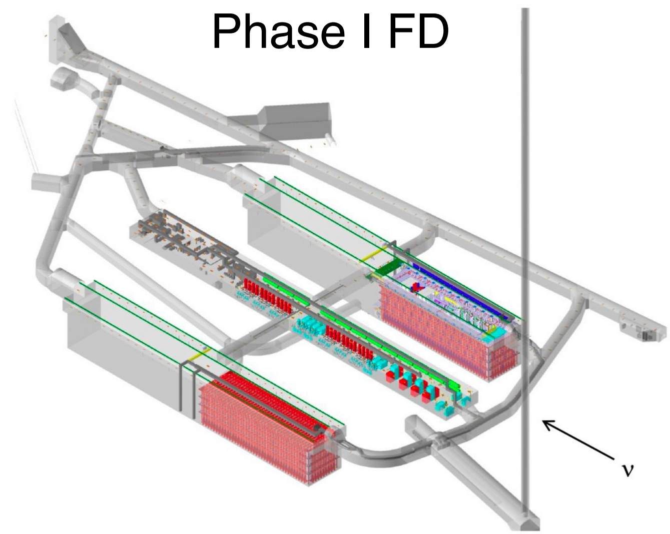
*Anode Plane Assemblies
**Charge Readout Planes

DUNE– Phase I (cont.)

DUNE Phase I:

- Neutrino beam with 1.2 MW intensity
- Two 17kt LAr TPC FD modules
- Underground facilities and cryogenic infrastructure to support four modules
- Near detector: ND-LAr + TMS (movable) + SAND
- The US DOE scope of Phase I was approved in July 2022 (CD1-RR)



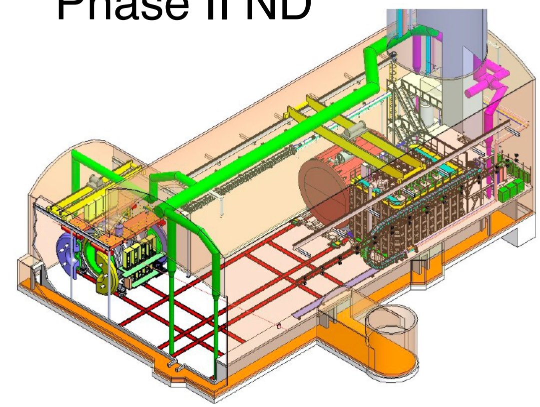


DUNE – Phase II

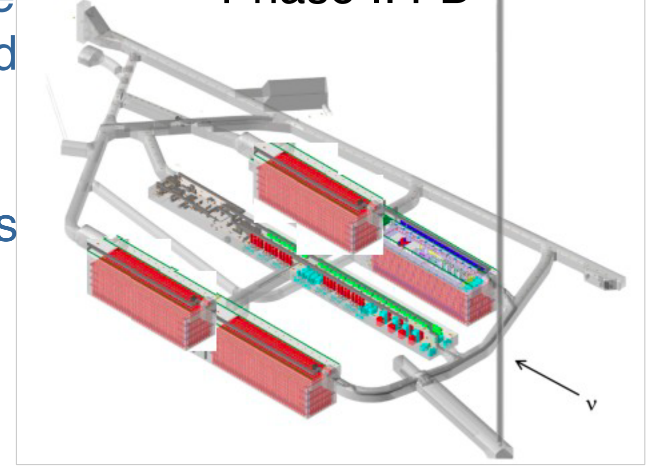
DUNE Phase II:

- Two additional 17kt FD modules
- Near detector: ND-LAr + MCND (movable) + SAND
- Fermilab proton beam upgrade to 2.4 MW

Phase II ND



Phase II FD



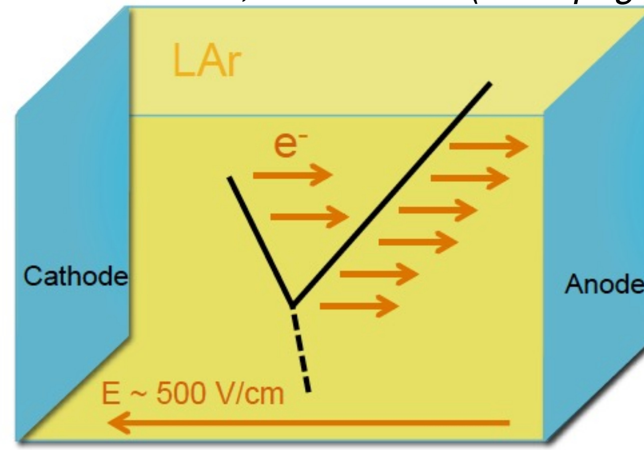
ND upgrade is driven by improved performance at reducing systematics, not driven by increased beam intensity

DUNE Phase II will collect 4x as many neutrinos

DUNE Far Detector (FD)

DUNE Far Detector Technical Design Reports in arXiv:2002.02967, 2002.03005, 2002.03008, 2002.03010 (1483 pages)

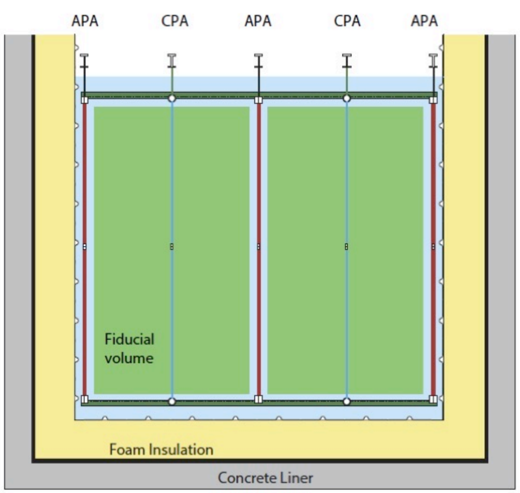
Four 17-kt liquid argon TPC modules
- **Horizontal** and **Vertical**-drift detector for the first 2 modules
- Integrated photon detection
- Modules will not be identical

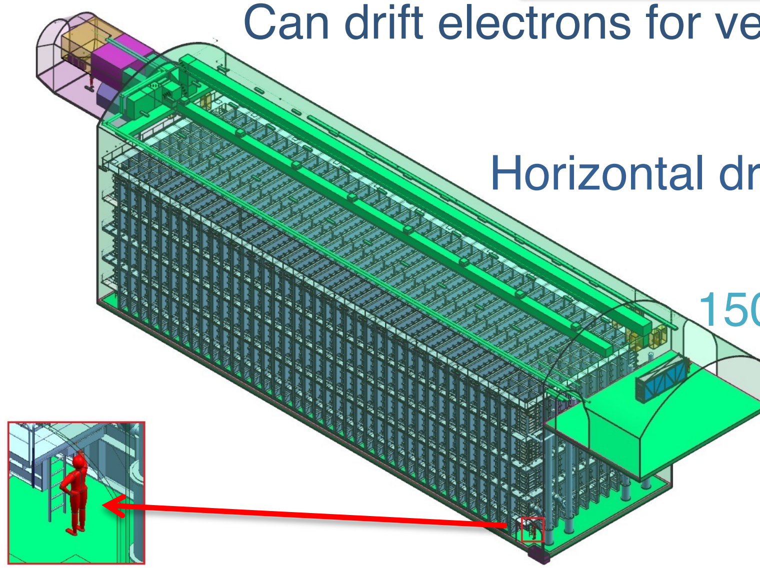


TPC Critical features:
- LAr ultra-high purity
- E Field: *uniformity* and *stability*

Can drift electrons for very large distances

Horizontal drift: modular wire-plane readout





Horizontal drift: 17 kt module

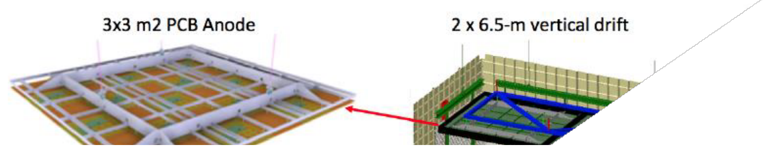
384,000 readout wires

150 “APAs” (2.3 m x 6 m)

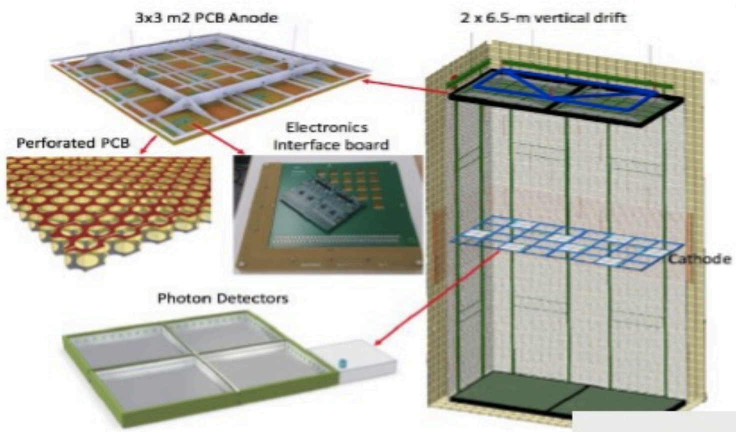
12 m high

15.5 m wide

58 m long



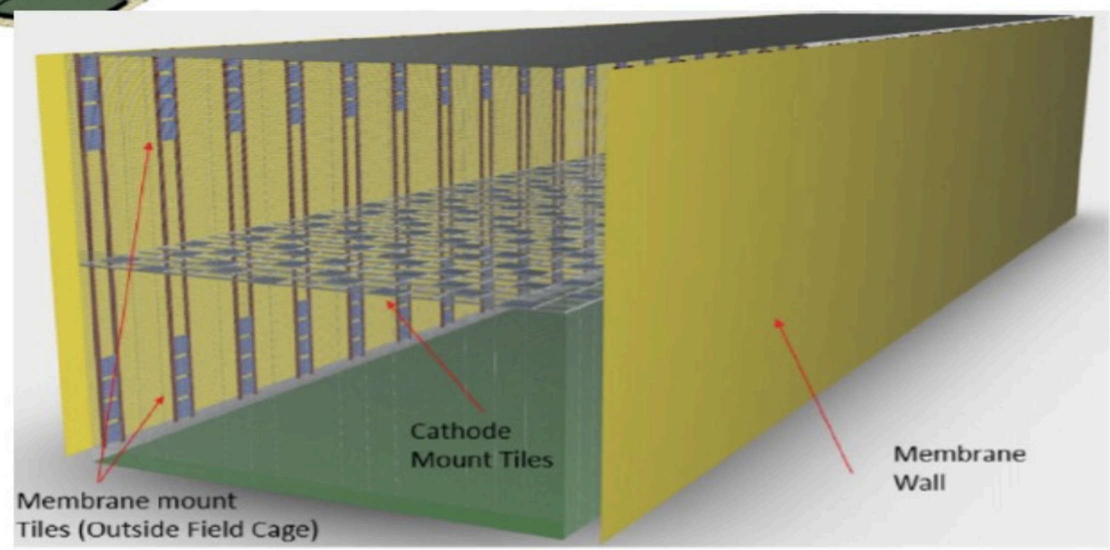
FD 2 : Vertical Drift



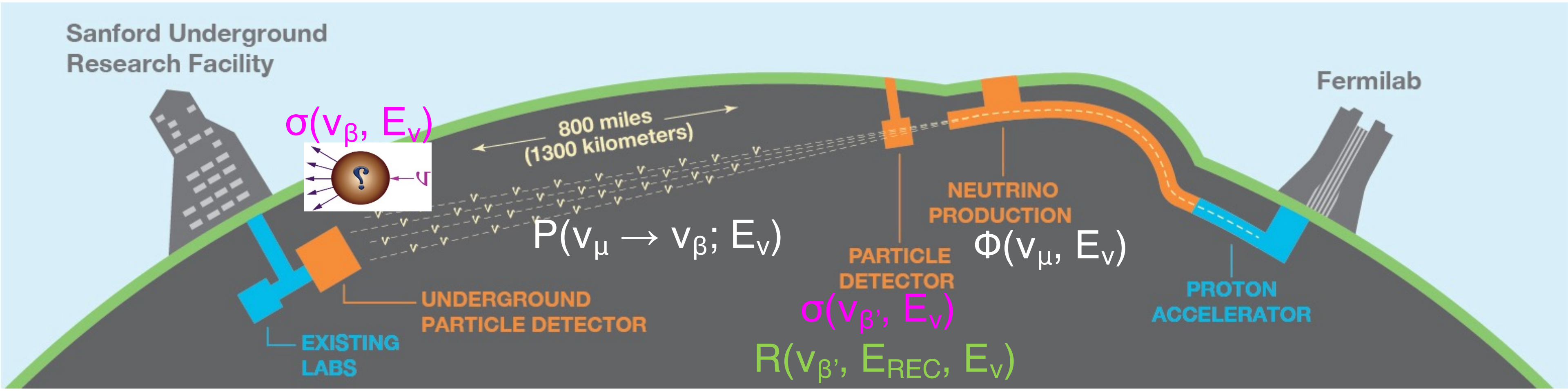
- Drift is vertical and the drift length is twice the first module: less electronic channels and, hence, less costs
- Cathode in the middle of the TPC
- Cold electronics in the top, accessible during data taking
- No wires, replaced by PCB strips (less costs)

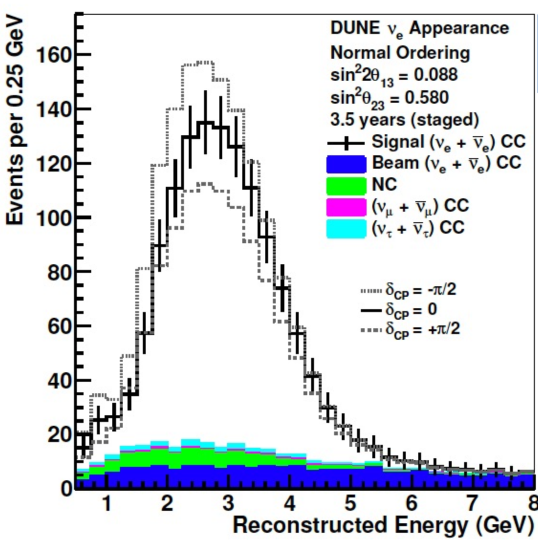
Rationale:

A detector that has the same performance as the first module but a reduced cost. It arises from the R&D done in ProtoDUNE-DP



Dune at work





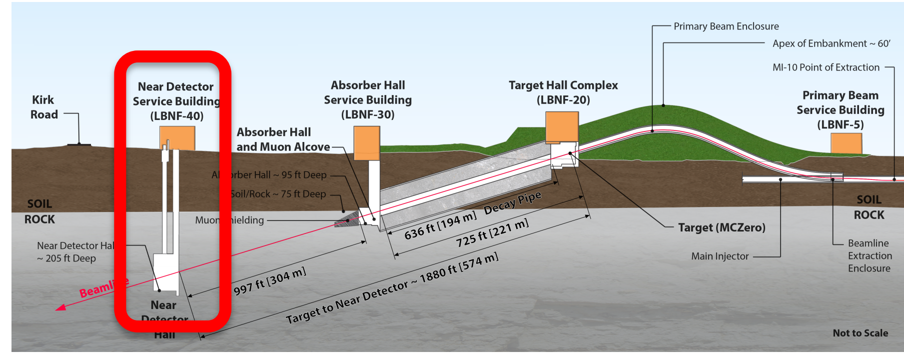
ν_e appearance from ν_μ beam after 3.5 years (staged)

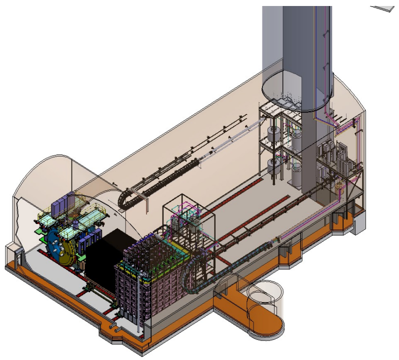
Need maximal control of prediction under PMNS parameters:
fluxes, cross-sections, detector responses

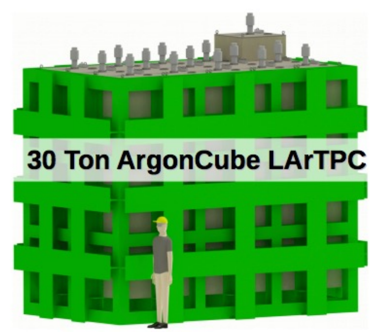
To maximize deconvolution of intrinsic degeneracies perform single measurements for as many as possible sources of systematics effects ☞ Near Detector complex

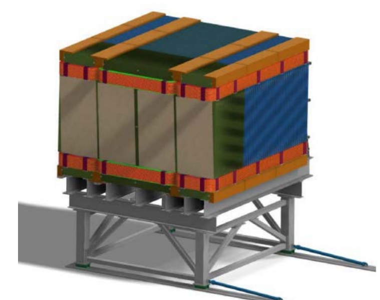
Near Detector (ND) – Phase I

- Role: constrain systematic uncertainties needed to oscillation analyses
  - Measure unoscillated beam flux
  - Measure multiple interaction cross-section channels
- Hall location
  - 574 m from LBNF target
  - ~60 m underground
- Multi-component Near detector
  - Highly segmented LArTPC
  - Magnetized tracker
  - Electromagnetic calorimeter
- Move (part of) ND detectors for off-axis measurements (PRISM concept)



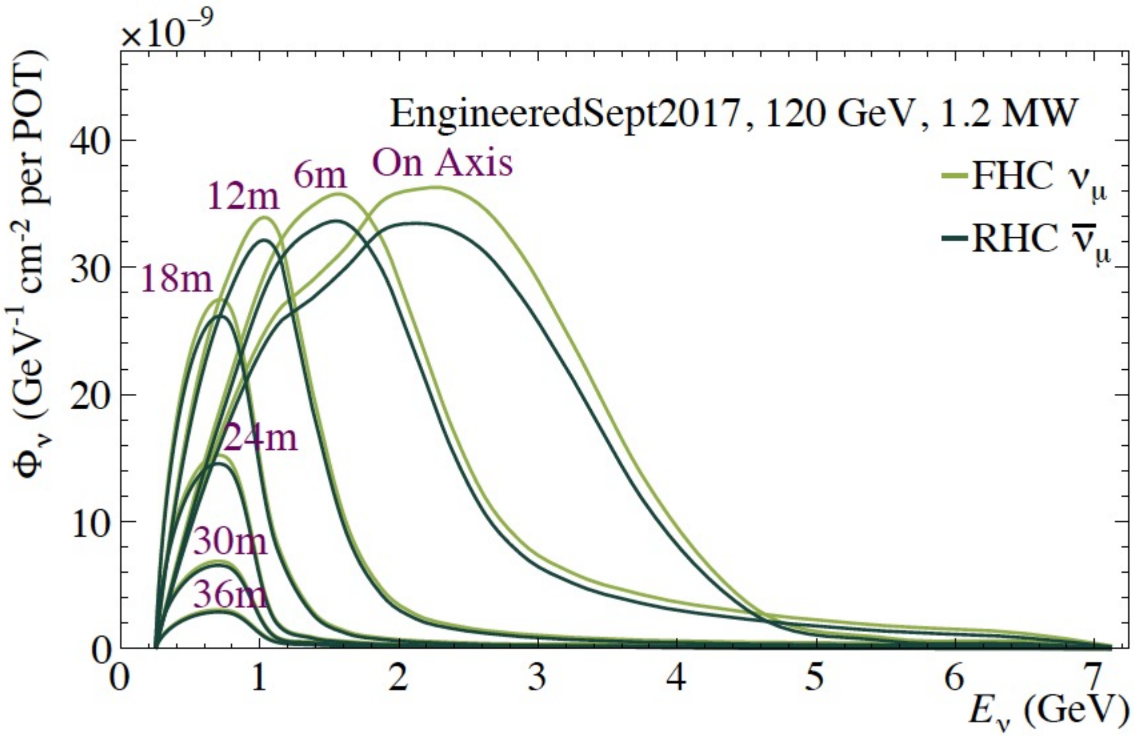






DUNE ND capabilities

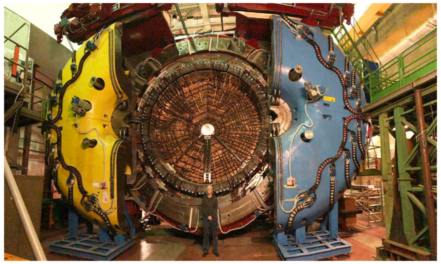
>100 million interactions will enable a rich non-oscillation physics program



Capability to move ND (LAr+TMS) for off-axis measurements (DUNE-Prism)

SAND

System on Axis for Neutrino Detection



1. It **should** monitor the (relevant) beam changes on a **weekly basis** with sufficient sensitivity
2. It **should** contribute to remove **degeneracies** when the other components are off-axis (50% of the time)
3. It **should** provide an independent measurement of the **flux** and measure the **flavor** content of the neutrino beam on event-by-event basis.
4. It **would** add robustness to the ND complex to keep **systematics** and **background** under control
5. While delivering all of the above, it **would** contribute to **oscillation analysis** and enjoy the high statistics to perform a plethora of **other physics** measurements.

As a matter of fact SAND will be a multipurpose detector

(with innovative compromises between mass, ID and tracking)

Proto-DUNE detectors R&D and goals

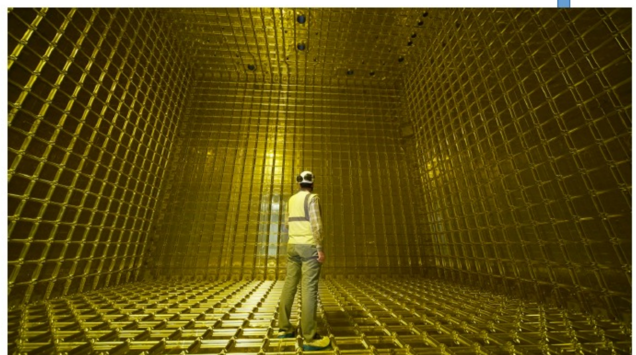
- Prototyping production and installation procedures for DUNE Far Detector Design

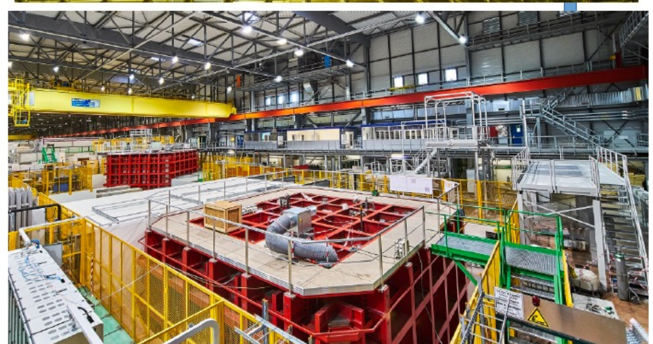
  many of the components for the far detector prototyping at 1:1 scale
- Validating design from perspective of basic detector performance
- **Accumulating test-beam data to understand/calibrate response of detector to different particle species**
- Demonstrating long term operational stability of the detector

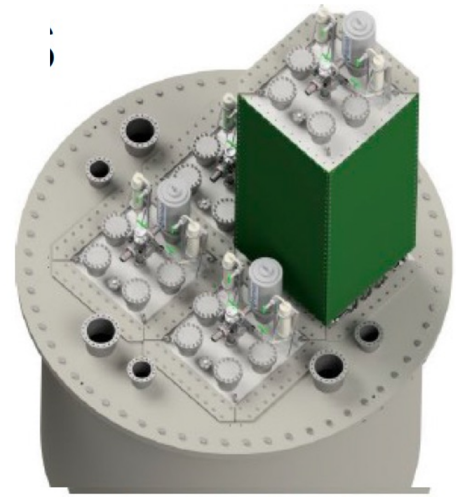
1 kton massive Liquid Argon detectors

DUNE prototypes

- ProtoDUNEs at CERN with charged particle beam
- 2x1kton cryostats used to validate FD components at full scale.
- Successful run from 2018-2020
- Next phase starting in spring 2023







ArgonCube 2x2 ND-LAr Demonstrator.

4 independent modules, test In NuMI beam scheduled in 2022

First R&D and physics results published
[JINST 15 (2020) 12, P12004]
(see backup for full list)

DUNE Physics Program—Neutrino Oscillation

Three-neutrino oscillations: ν_μ / $\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance

- Charge-Parity symmetry violation (CPV): δ_{CP}
- Neutrino mass ordering: normal or inverted
- Neutrino mixing parameters

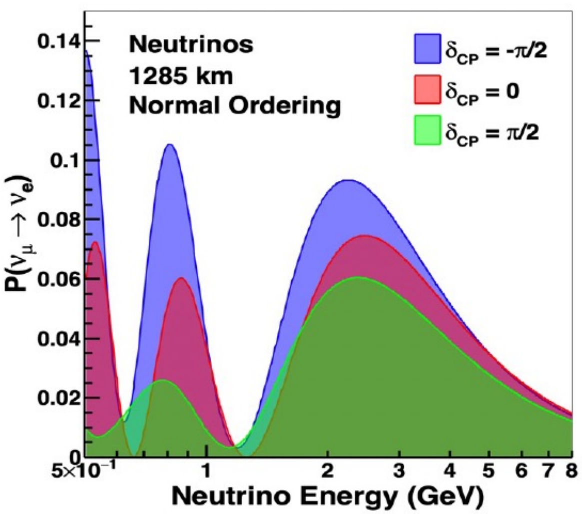
[Eur. Phys. J. C 80 (2020) 10, 978]

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Phi_{31}-aL)}{(\Phi_{31}-aL)^2}\Phi_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Phi_{31}-aL)}{(\Phi_{31}-aL)}\Phi_{31}\frac{\sin(aL)}{(aL)}\Phi_{21}\cos(\Phi_{31}\pm\delta_{CP}) + \ldots$$

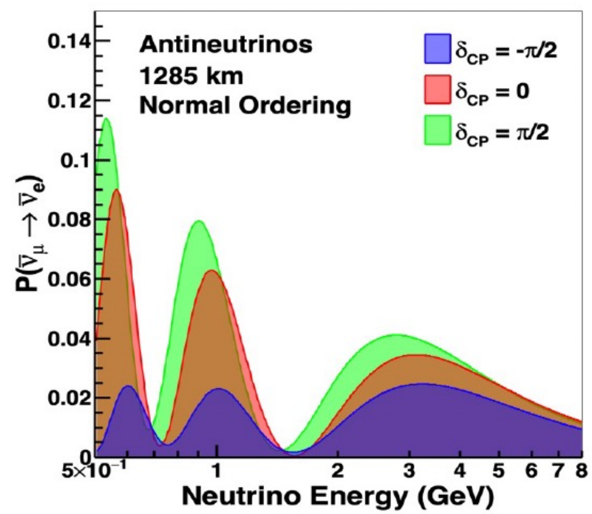
$$\Phi_{ji} = \frac{1.27\Delta m_{ji}^2 L}{E_\nu} \qquad a = \pm\frac{G_F N_e}{\sqrt{2}}$$

Sign change for ν_e and $\bar{\nu}_e$

Interplay between mass ordering



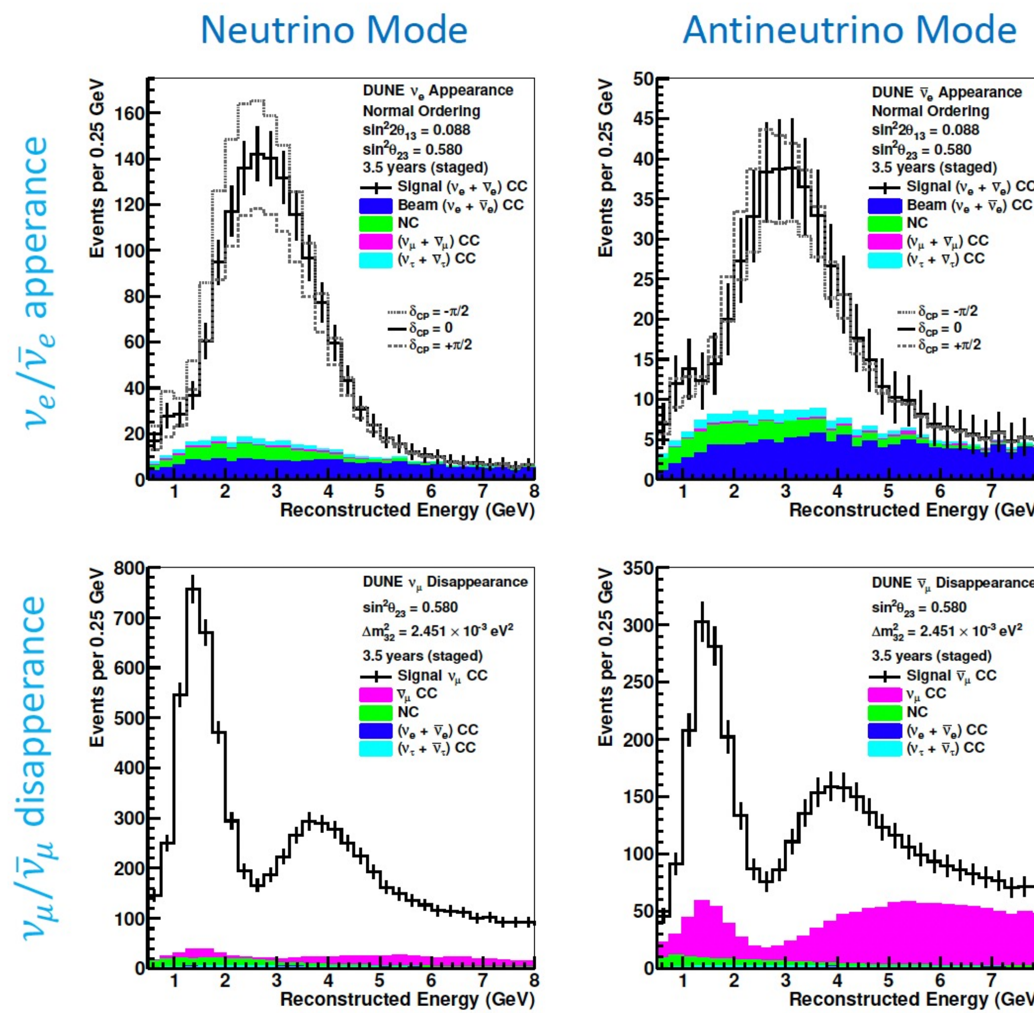
$$\nu_\mu \to \nu_e \overset{?}{\Leftrightarrow} \bar{\nu}_\mu \to \bar{\nu}_e$$



Oscillation Sensitivity for DUNE

[Eur. Phys. J. C 80 (2020) 10, 978]

- Reconstructed spectra of selected CC-like events
- Sensitivity assessment includes full FD systematics treatment
- 3.5 years neutrino beam mode
- 3.5 years anti-neutrino beam mode
- ~1000 ν_e/ν_e–bar events in 7years
- ~10,000 ν_μ/ν_μ-bar events in 7years

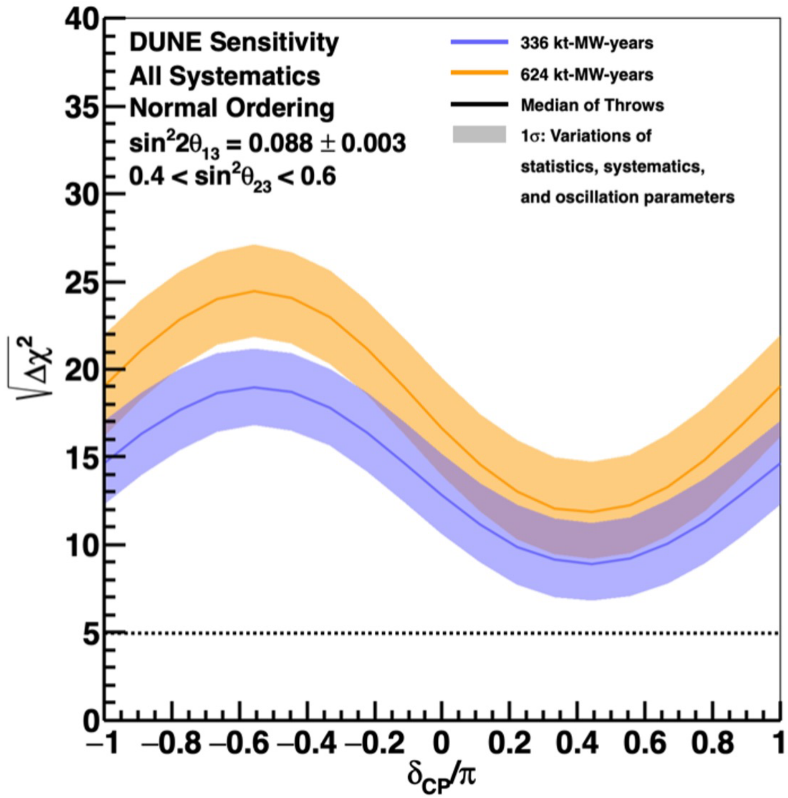


Simultaneous fit to four spectra to extract oscillation parameters

MH and θ_{23} Oscillation Physics

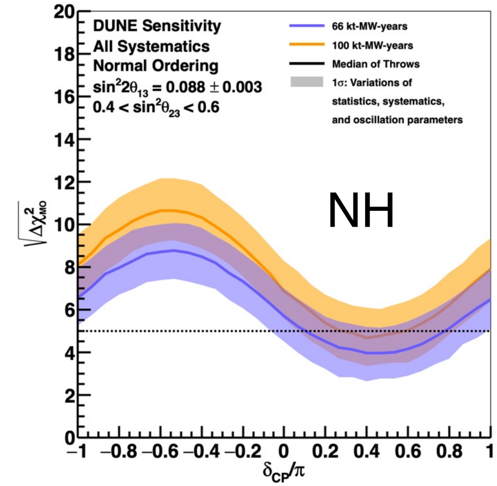
Mass Ordering

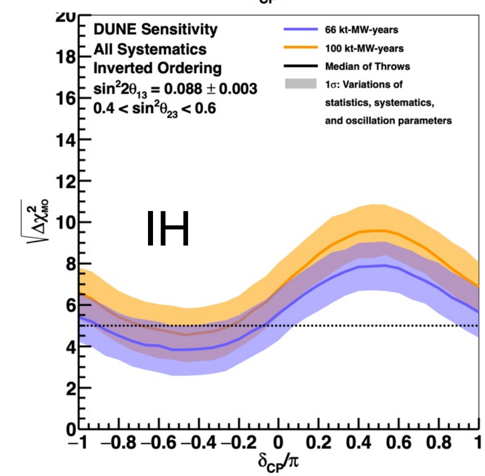
DUNE low exposure, PRD (2022) 105, 7, 072006
arXiv:2109.01304



EPJC 80 (2020) 978

100 kt
66 kt



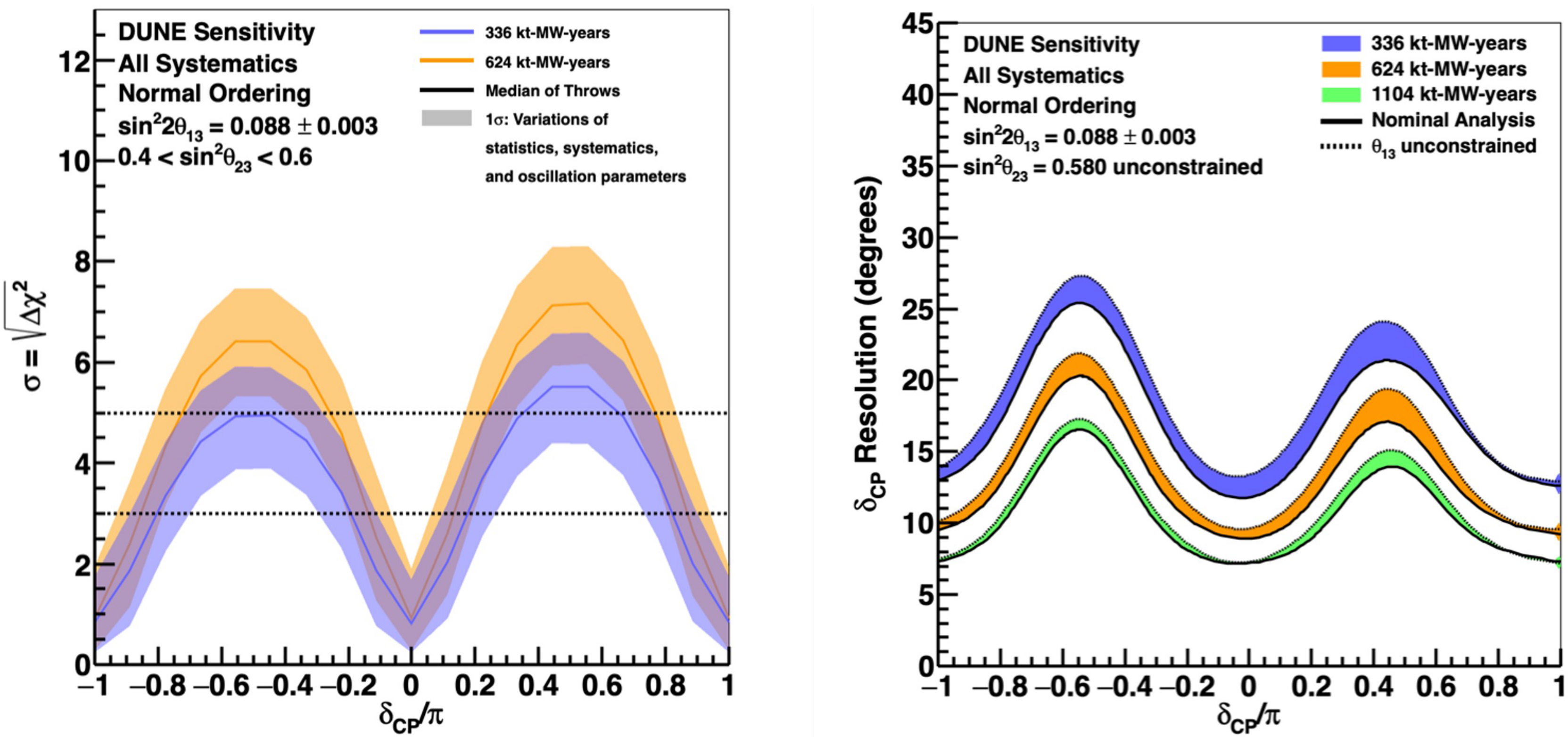


- Width of band indicates variation in possible central values of θ_{23}
- Width of band indicates variation in possible true value of δ_{CP}

By exposure of 66 kt-MW-yr, probability to extract wrong ordering < 0.01

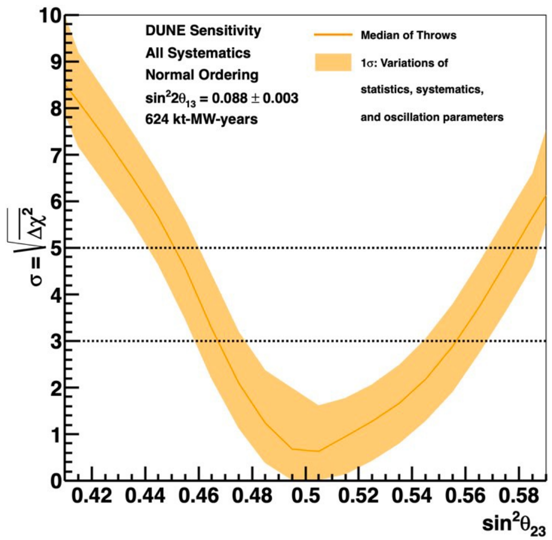
Sensitivity to CPV for DUNE

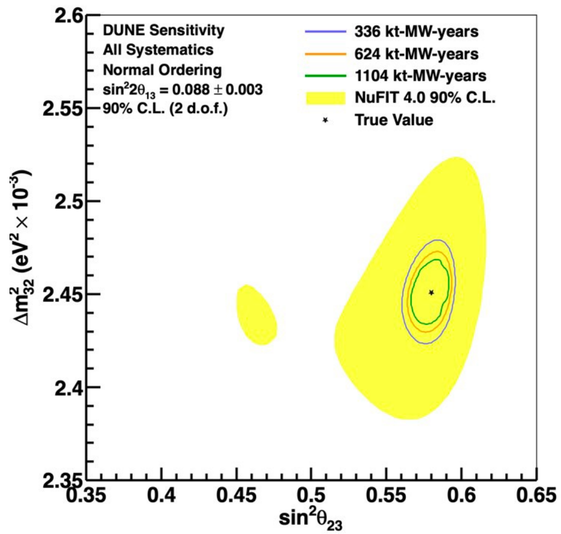
- 5σ discovery potential for CP violation over >50% of δ_{CP} values
- 7-16° resolution to δ_{CP}, with external input for only solar parameters.

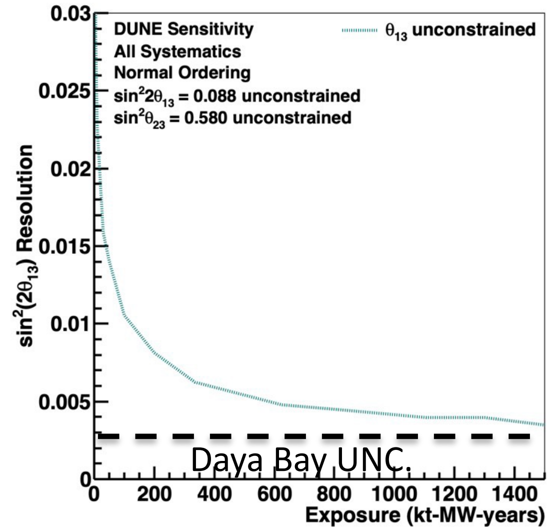


- Simultaneous measurement of neutrino mixing angles and δ_{CP}
- Width of band indicates variation in possible central values of θ_{23}

Oscillation Parameter Sensitivity





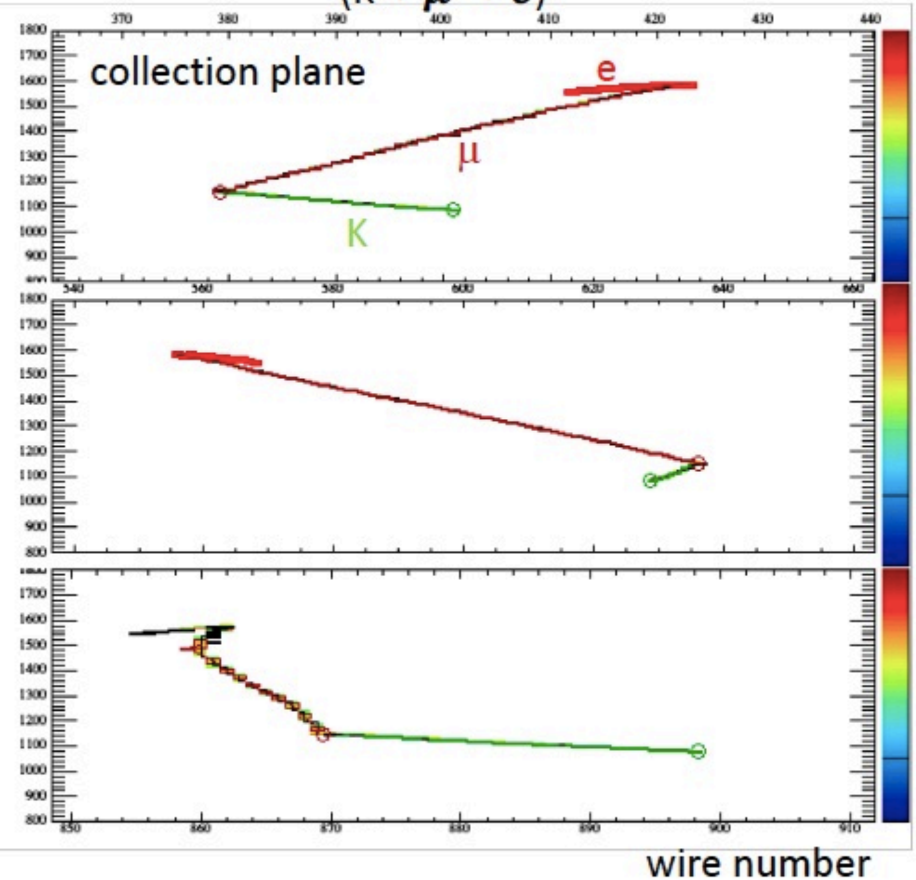


- Excellent on Δm^2_{32} and θ_{23}, including octant, and unique PRISM measurement technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

Baryon Number Violation

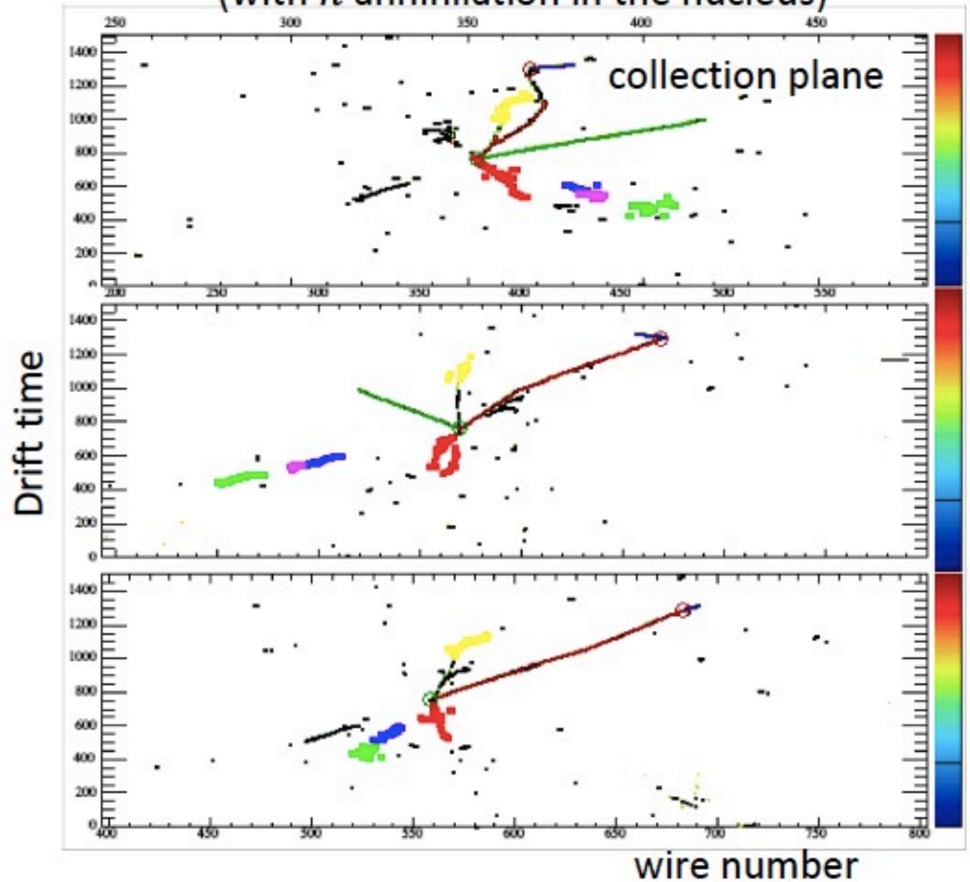
$p \rightarrow \bar{\nu} K$

(K→ $\mu \rightarrow e$)



$n - \bar{n}$ **oscillation**

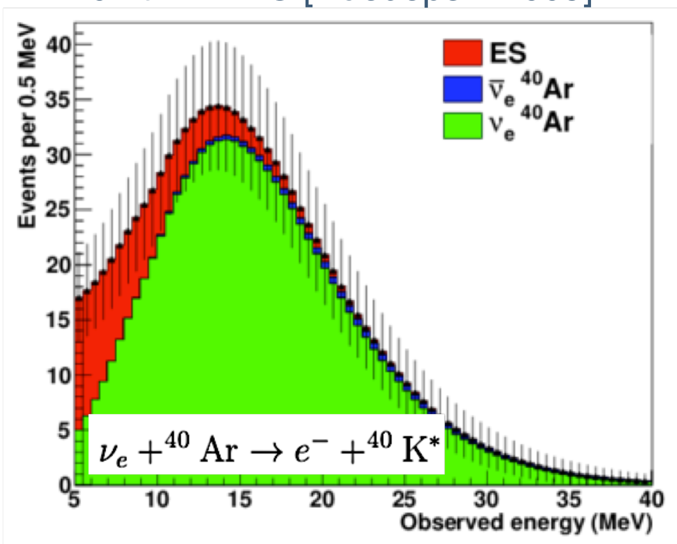
(with $\bar{n}$ annihilation in the nucleus)



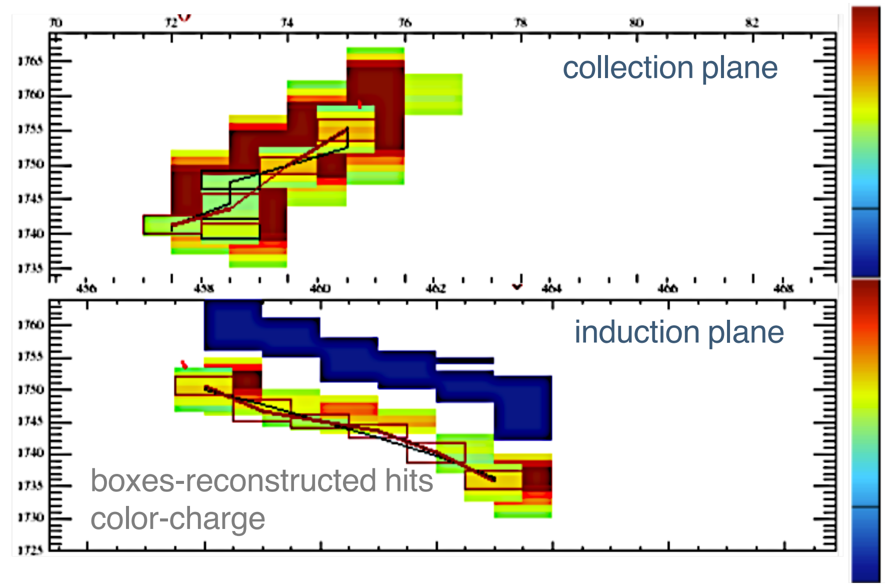
- Full simulation and reconstruction

Supernova Burst/Low Energy Neutrinos

Electron-capture SN at 10 kpc in
40-kt LArTPC [Huedepohl 2009]



10.25 MeV electron

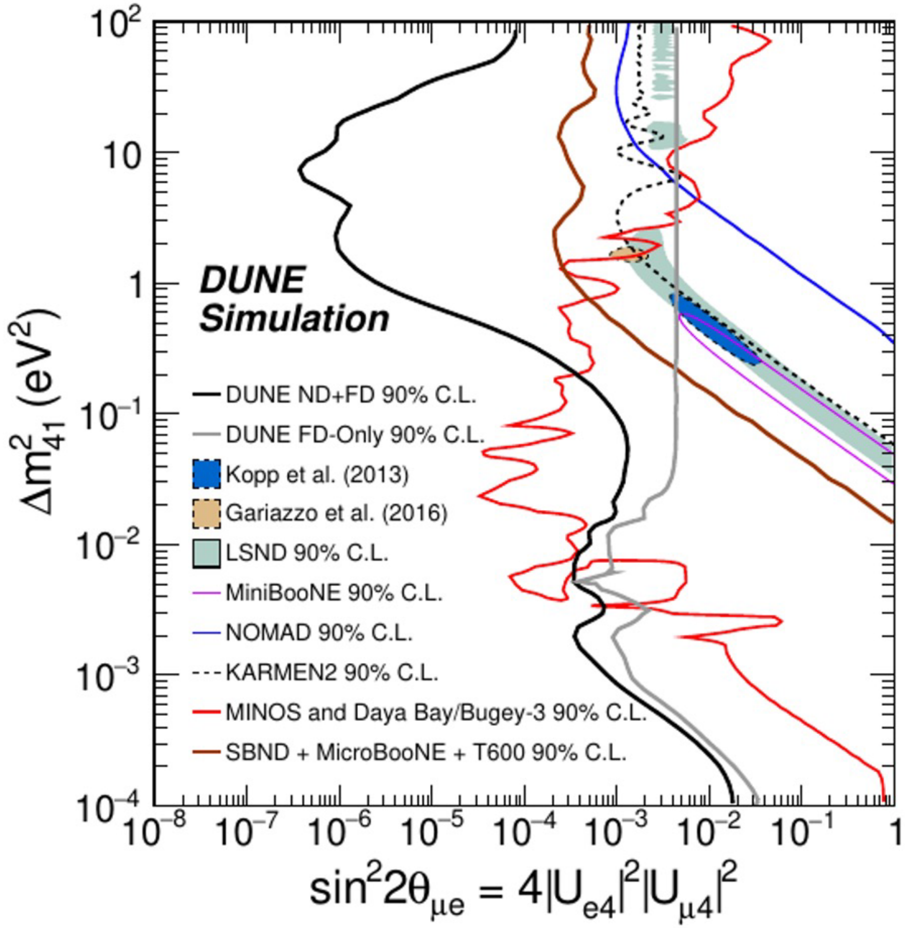


- Sensitive to ν_e; complementary to water Cherenkov detectors
- Tracks only a few centimeters long but event-by-event energy reconstruction is possible in LAr
- Pointing may be possible using elastic scattering (ES) from electrons
- Triggering understood for SNB (100 sec readout buffer) but a challenge for solar neutrinos

BSM searches

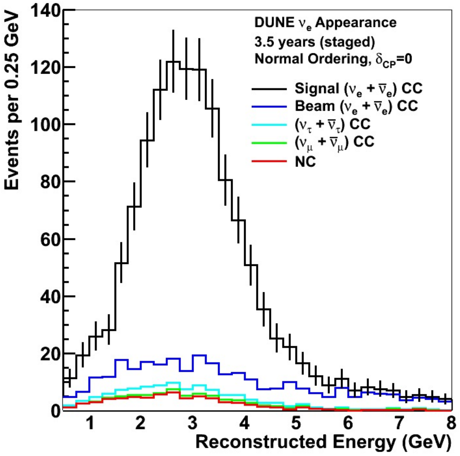
- DUNE sensitive to many BSM particles and processes
  - *Light dark matter*
  - *Boosted dark matter*
  - *Sterile neutrinos*
  - *Non-standard interactions, non-unitary mixing, CPT violation*
  - *Neutrino trident searches*
  - *Large extra dimensions*
  - *Neutrinos from dark matter annihilation in sun*
- Active area of research within phenomenology community as well as the DUNE collaboration
- GLoBES configurations arXiv:1606.09550

Sterile Neutrino Sensitivity (ν_e CC appearance at ND)

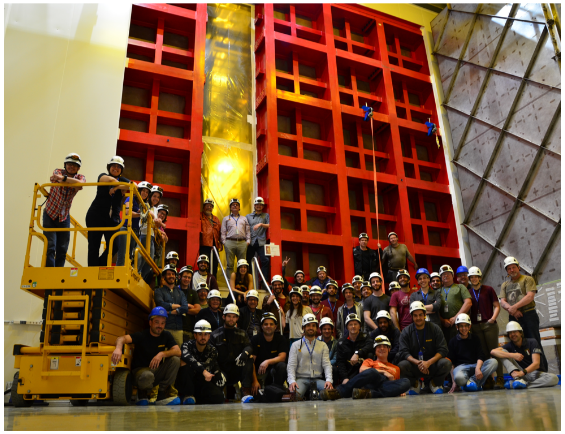


Summary for DUNE

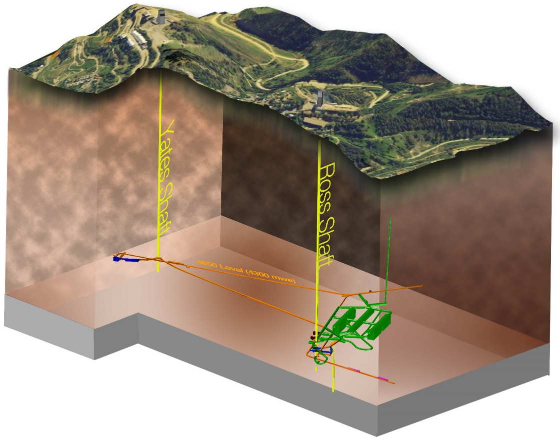
Foreseen Analysis



protoDUNE

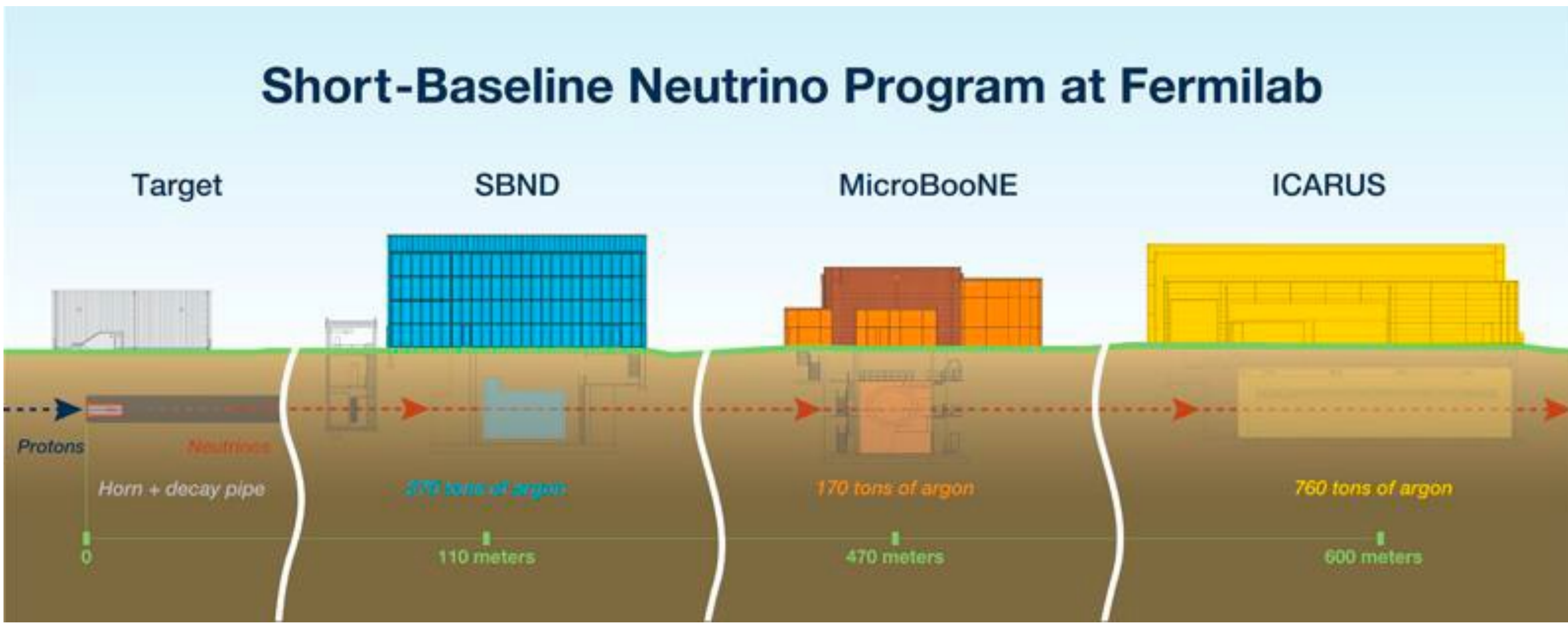


Coming …



- LBNF/DUNE: the ultimate neutrino facility/observatory
- DUNE will enable very rich physics program in the next decades (LifeCycle 20 years):
  - Neutrino oscillations
  - Studies of MeV-scale neutrinos
  - Many BSM searches
- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis
- Expect first DUNE FD data in 2028, oscillation physics starts end of this decade

SBN project(s) at FNAL (MicroBooNE, ICARUS, SBND)



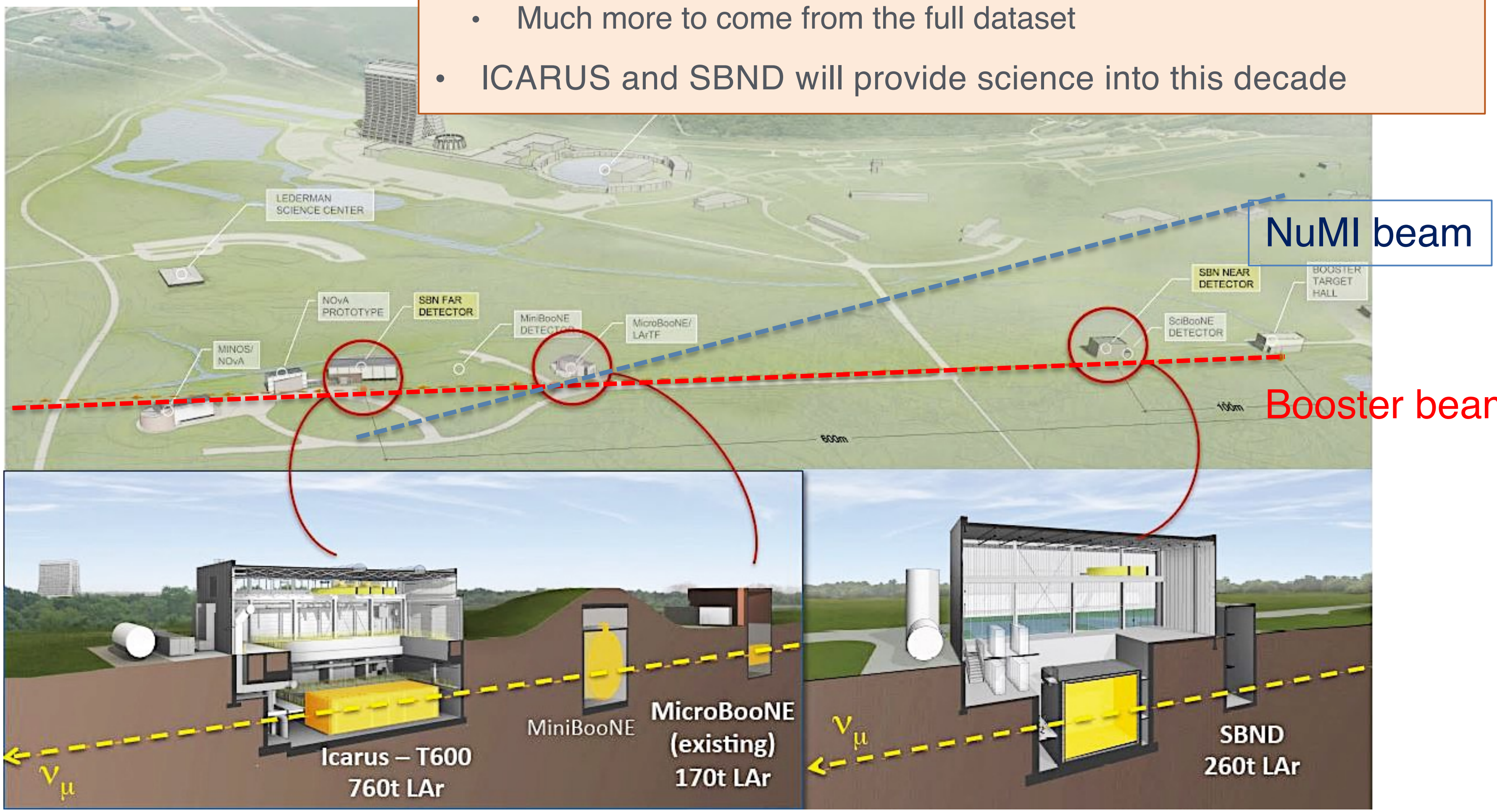
https://sbn.fnal.gov/

Motivations

- Anomalous MiniBooNE Events
  - Investigate source(s) of low-energy excess (LEE) events observed by MiniBooNE using LArTPCs → MicroBooNE
- Search for Sterile Neutrinos
  - Discovery or definitive exclusion of 1 eV–scale sterile neutrino mass region motivated by LSND and MiniBooNE results
  - Provide verification or refutation of the Neutrino-4 experiment's* evidence for a 7.3 eV^2, large mixing angle, sterile neutrino
- Neutrino Interactions in Argon
  - Millions of ν_μ and tens of thousands of ν_e from two neutrino beams (Booster and NuMI)
- Search for Beyond Standard Model Physics
  - Higgs portal dark scalar, large extra dimension models, Lorentz/CPT symmetry violation, non-standard interactions, dark neutrino sectors, etc.

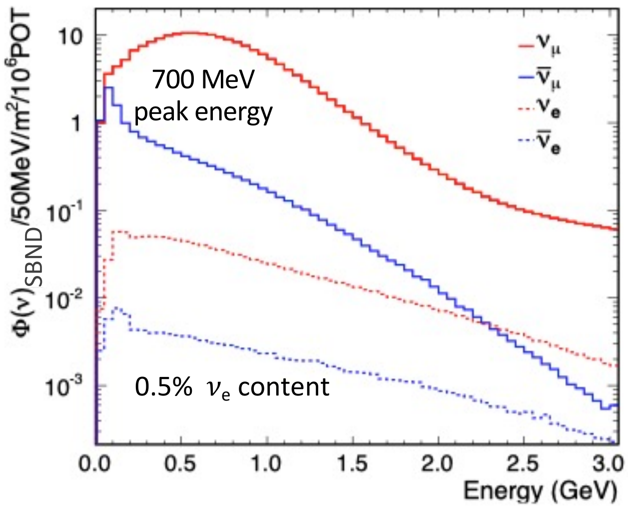
SBN Complex at Fermilab

- MicroBooNE completed its physics run in early 2020
  - Has published interesting results on LEE from 2016-18 data
  - Much more to come from the full dataset
- ICARUS and SBND will provide science into this decade



Neutrino beam(s)

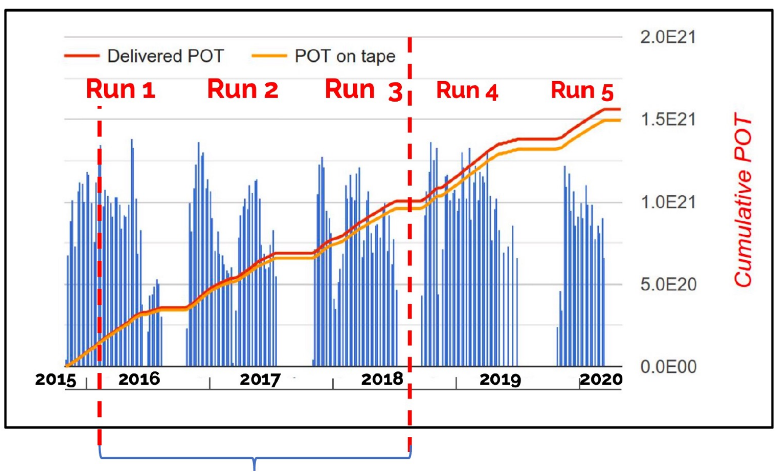
From 8 GeV Booster



- SBND: 0.25 Hz ν, 0.03 Hz cosmic
- ICARUS: 0.03 Hz ν, 0.14 Hz cosmic

(+ NuMI: 0.014 Hz ν, 0.08 Hz cosmic)

- SBN Proposal: 6.6 x 10^{20} POT
- BNB will operate until LBNF long-shutdown ~Jan. 2027 ⇒ with design POT delivery
  - ICARUS > 3X original SBN proposal
  - ICARUS+SBND > 2X original SBN proposal



MicroBooNE collection

BNB data ~7x10^{20} POT analyzed

Fermilab INFN DUNE

ICARUS-T600 at FNAL

Aug. 2020: start of TPC/PMT operation

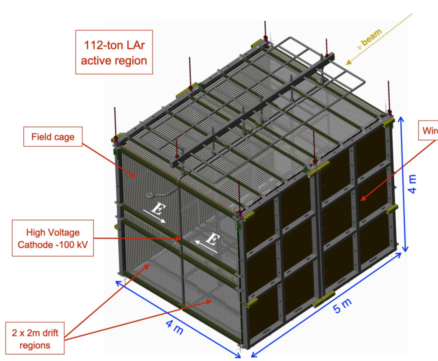
Dec. 2021: CRT installation complete

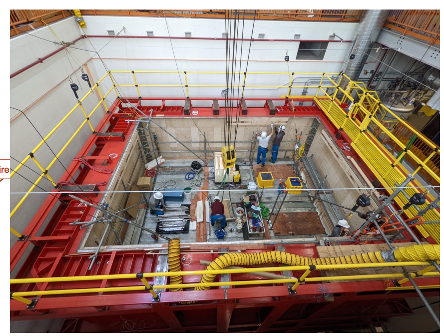
June 2022: overburden complete

Steady data taking with BNB, NuMI beams since March 2021, in parallel with commissioning activities.
Cosmics, ν_μ, and ν_e samples collected for trigger/calibration/reconstruction studies.

Data taking for Physics with BNB and NuMI beams 9 June 2022

SBND



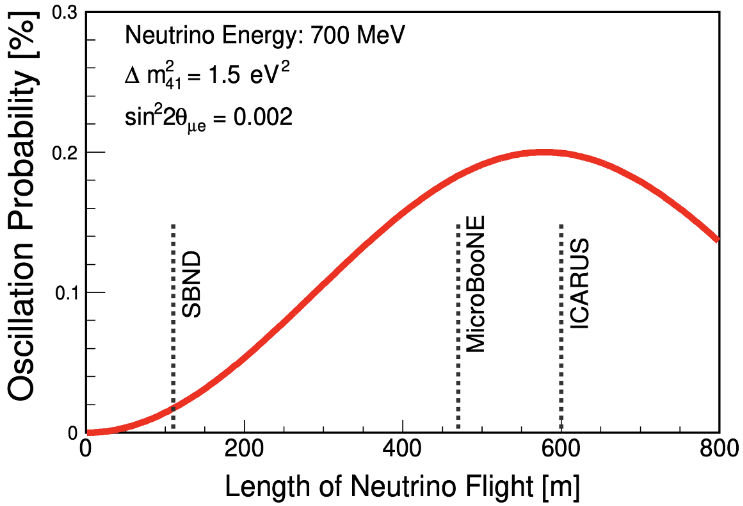


- Ground-up new detector – 4 m x 4m x 5m, 112 t active mass LAr
- Incorporating technology important for DUNE (cryostat, 2-m drift TPC, X-Arapuca photon detectors)

Installation complete and ready to fill in June 2023

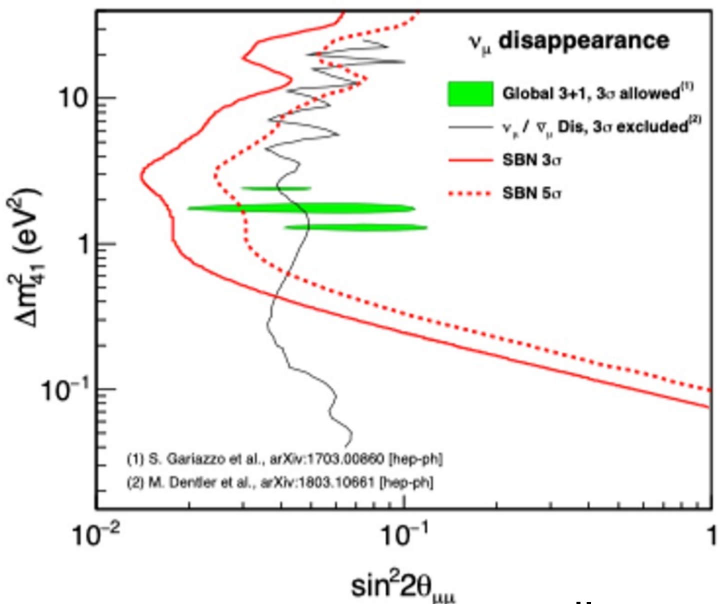
SBN Oscillation Sensitivity

Example oscillation at BNB peak energy



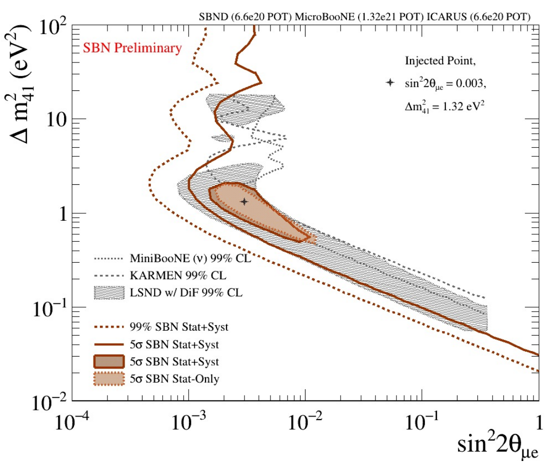
P. Machado et al., arXiv:1903.04608V11

SBN proposal

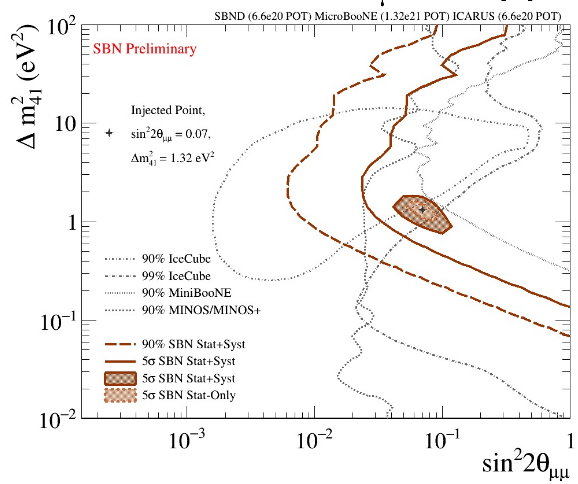


SBN update *(work in progress)*: SBN sensitivities for 6.6 x 10^{20} protons on the BNB target; to be updated to the larger dataset

ν_e appearance



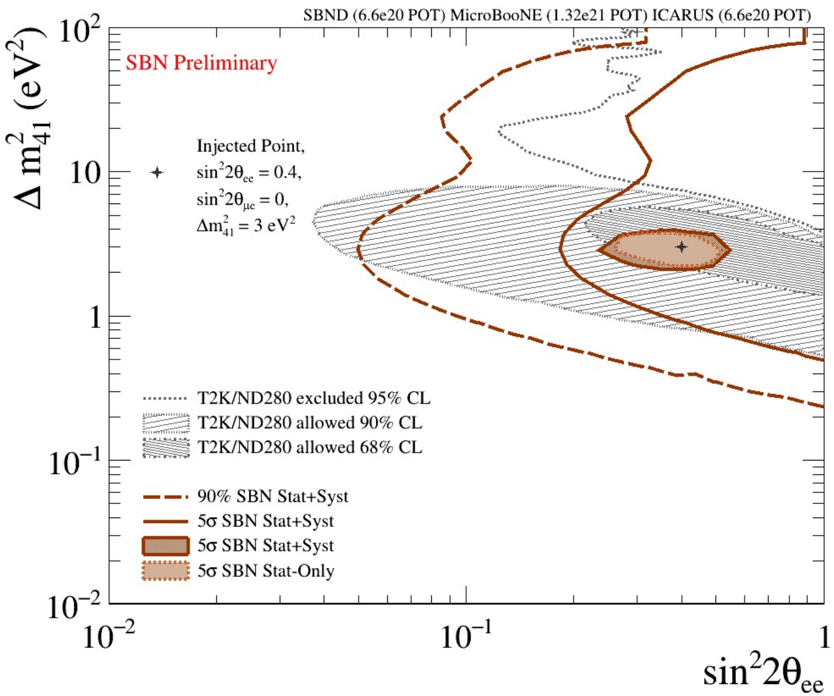
ν_μ disappearance



SBN new analysis

Direct probe of $\sin^2 2\theta_{ee}$ using a neutrino beam rather than lower energy (MeV) reactor antineutrinos

SBN ν_e disappearance



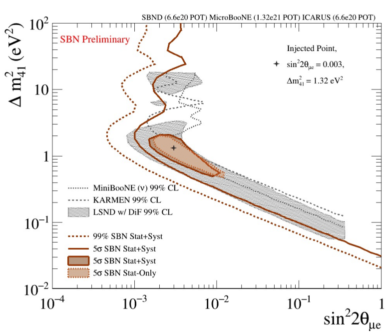
- ~35,000 intrinsic ν_e at SBND for 6.6 x 10^{20} BNB POT
- ICARUS will use ν_e disappearance from NuMI as part of Neutrino-4 signal investigation

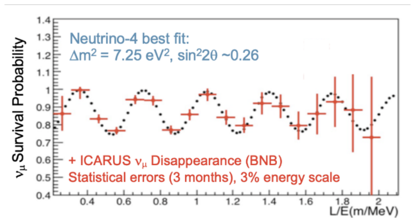
R.Wilson@Snowmass2022

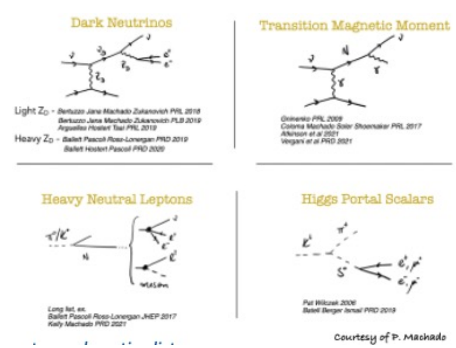
Fermilab INFN DUNE

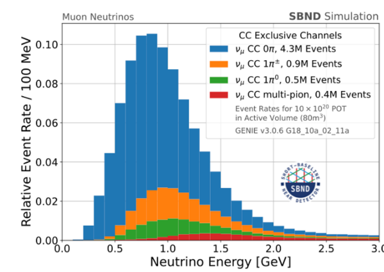
ICARUS/SBN Outlook

- ICARUS operated well in commissioning mode and has begun first physics run
- SBND is on track for operation in late 2023
- ICARUS will reach nominal dataset by mid-2024 and ICARUS+SBND by late 2025
  - 2-3X higher statistics by 2027
- The SBN program will provide a broad spectrum of neutrino and BSM physics and in-depth experience with LArTPC technology and analysis through to the start of DUNE program









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In Summary

- DUNE/LBNF is committed to be the best-in-class experiment for:
  - Neutrino oscillations
  - Studies of MeV-scale neutrinos
  - Many BSM searches
- LBNF and DUNE are making rapid progress on facility construction, detector design, and physics analysis
- First DUNE FD data expected in 2028, oscillation physics starts end of this decade.
- The SBN program will provide a broad spectrum of neutrino and BSM physics and in-depth experience with LArTPC technology and analysis through to the start of DUNE program

Thank You