DUNE and the neutrino oscillation program at FermiLab, *future and near future*

Luca Stanco,

INFN – Padova, stanco@pd.infn.it

INFN Istituto Nazionale di Fisica Nucleare

NOW 2022
Neutrino Oscillation Workshop

On behalf of DUNE collaboration and SBN collaborations

Content

- Standard Neutrino Oscillation
- LBNF project
- The DUNE experiment - status of the project
- Near Detector
- Perspectives for
  - MH and δ_{CP} determinations
  - *astronomical neutrinos (SuperNovae)*
  - *solar neutrinos*
- SBN project at FNAL
  (MicroBooNE, ICARUS, SBND)

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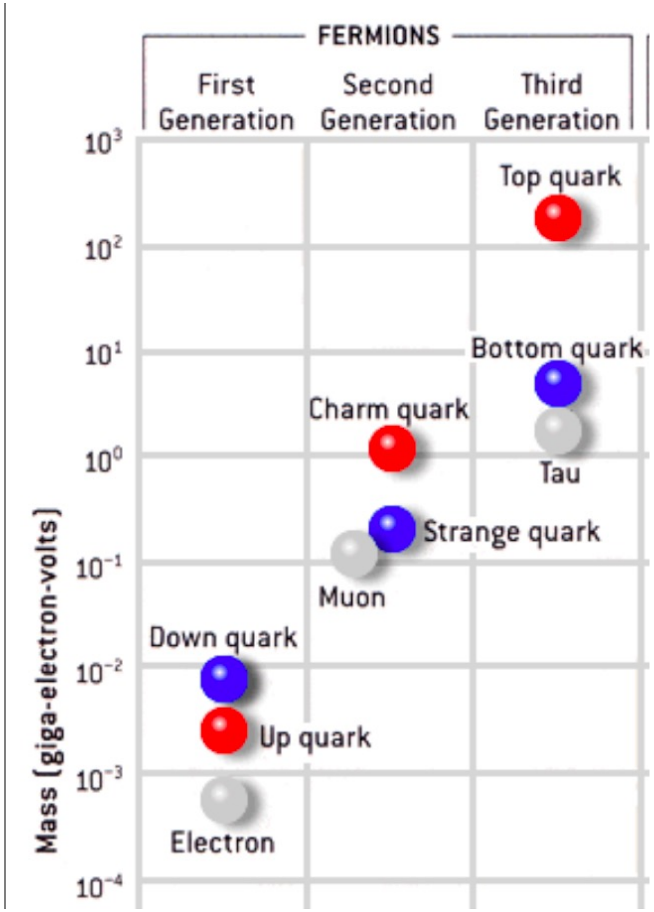
Preamble   Big Open Questions in Particle Physics

- What more than the Higgs particle and the "Standard Model"?
- Origin of the Dark Matter and Dark Energy
- The Flavour issue

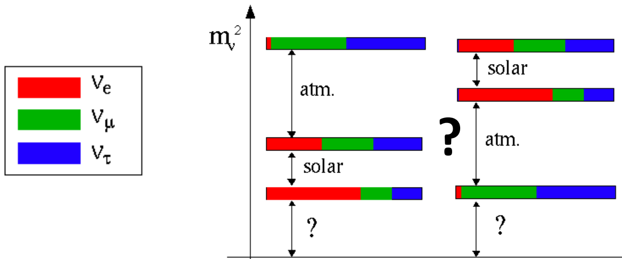


- Strong hierarchical pattern of quark and charged-lepton masses
- Almost diagonal CKM (quark-mixing) matrix

$$V_{CKM} \sim \begin{pmatrix} 0.9744 & 0.2250 & 0.0037 \\ 0.2248 & 0.9735 & 0.0418 \\ 0.0086 & 0.0411 & 0.99912 \end{pmatrix}$$

@PDG2022

- **LARGE** mixing angles in the neutrino sector
- Neutrino spectrum not fully known yet, but certainly not very hierarchical



Mass Ordering ?

$m_\nu < 0.8$ eV @90%

Neutrinos: What we do & do not know

- Neutral leptons with 3 active flavors
- Tiny small masses
  - Existing limits on sum of neutrino masses are order few hundred meV/c^2
- Flavor eigenstates (ν_e,ν_μ,ν_τ) ≠ mass eigenstates (ν_1,ν_2,ν_3)
  - Mixing described by PMNS matrix
  - All mixing angles and mass splittings have been measured
- Neutrinos detected via their interaction products
  - Neutrino interaction cross sections are small, $\mathcal{O}$(10^{-38} cm^2/nucleon) at 1 GeV
- May be Majorana or Dirac

- Other kind of ”Sterile” neutrinos?
- Direct measurement limits currently ≲ 1 eV/c^2
- *More precise measurements of mixing angles needed

- *CP violation in PMNS?
- *Unitarity?

**Very large detectors are needed*

- Neutrino-nucleus interaction model has large uncertainties

- Majorana phases?

A not so bright future (to me)

The (experimental) synthesis from the recent Neutrino 2022:

- Oscillations in a decade
- Neutrino masses in two decades
- Neutrino nature in three decades

A different perspective is much more desirable,
at least for people "differently young" like me…

- Some kind of sterile neutrinos need to be confirmed yet
- δ_{CP} and MO could be disentangled only through extended PMNS
- PMNS unitarity be broken
- tensions, tensions, tensions…

possibly based on physics and not on experiment discrepancies…

Panorama

flavour states **mass states**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Super-K, K2K, MINOS, OPERA, NOvA, T2K

DChooz, Daya Bay, RENO MINOS, NOvA, T2K

Super-K, SNO, KamLAND

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$
(PMNS Neglecting possible Majorana phases)

Long-baseline neutrino beams

Studies going-up

DUNE

DUNE: What, How, When?

What to measure?
How to measure it?
When be available?

→

DUNE/LBNF, a multi-B$ project, to measure missing parameters of the 3 ν picture, with high precision the others, and sensitivity to SNB and BSM

With artificial beam from 1.2 to 2.4 MW proton beam and multi-kton Liquid-Argon detectors

Starting data taking for oscillations in 8 years from now (or less)

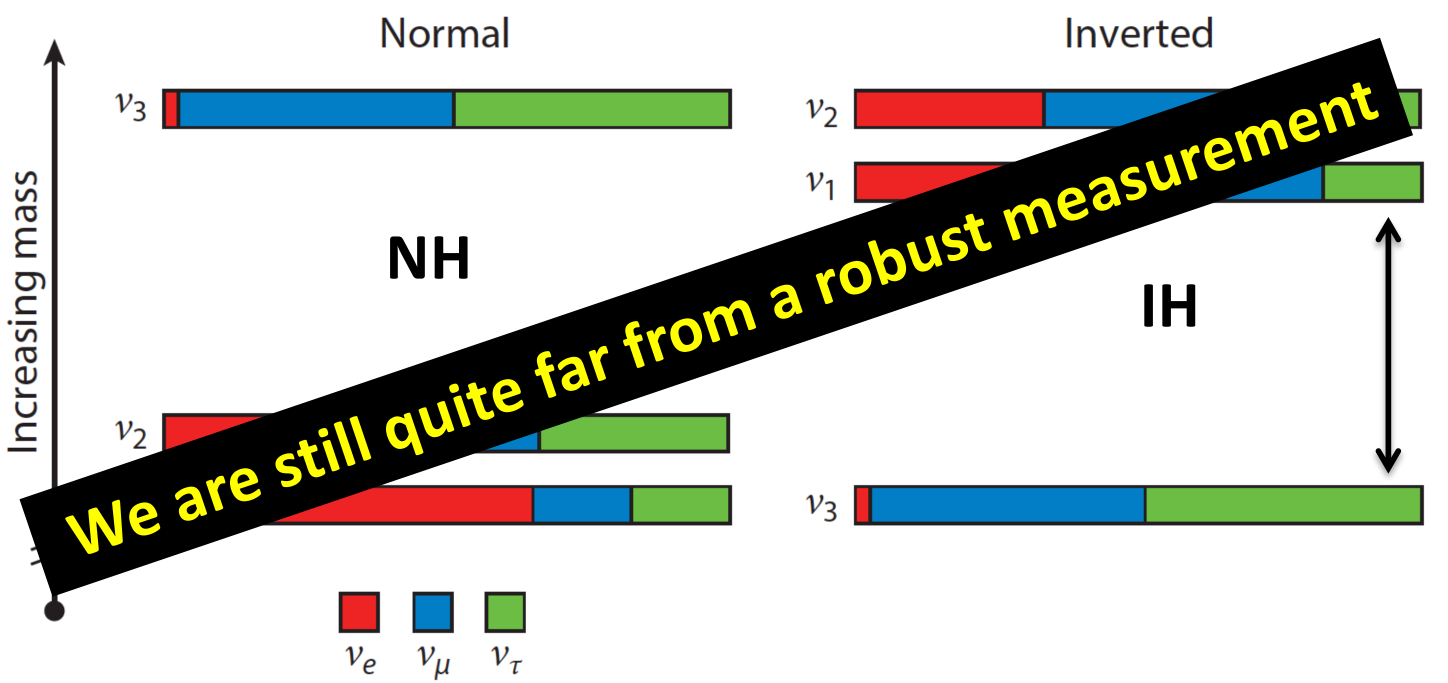
1

Neutrino Physics

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



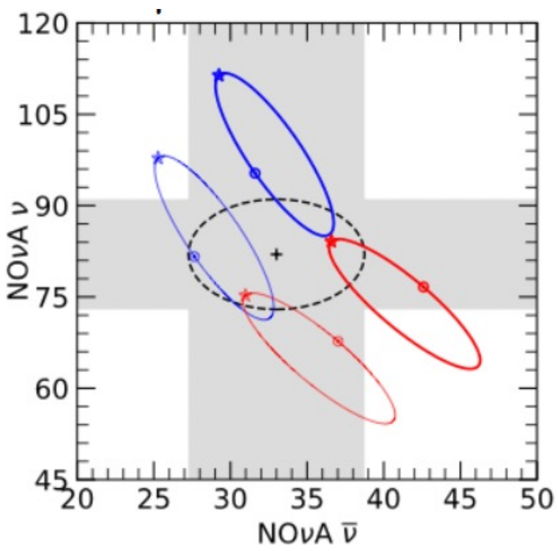
One or two states at higher mass ?

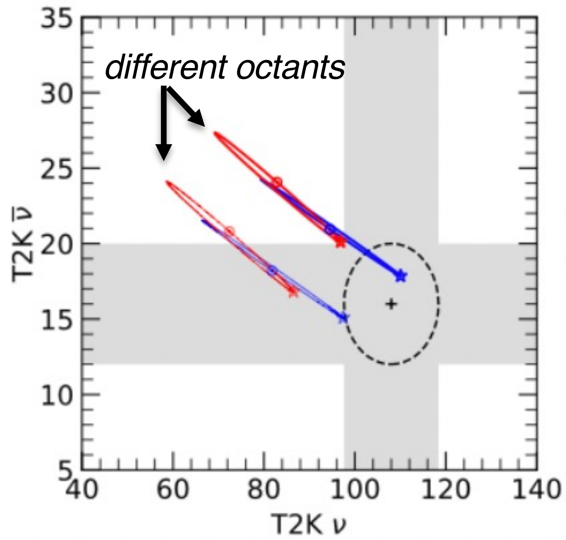
Δm^2_{atm}
||
Δm^2_{32} (NH)
||
Δm^2_{13} (IH)

Measuring MH AND δ_{CP}

- In the last couple of years oscillation analysis is showing up rather controversial effects, due to correlations and degeneracies

Current experiments: NOνA(US)   T2K (Japan)





ν_e prediction as function of δ_{CP}

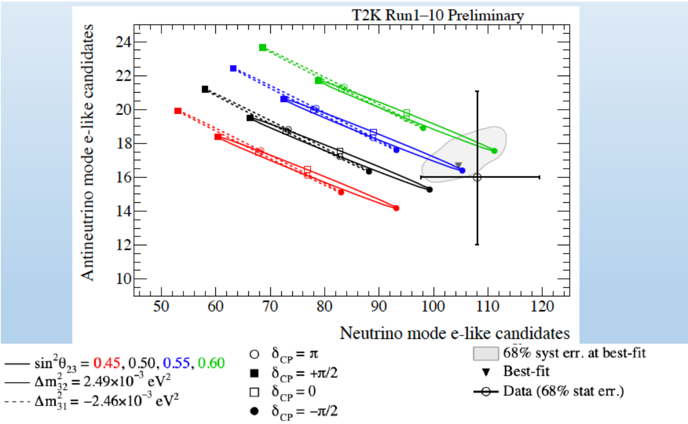
from A. Marrone, NeuTel, Feb. 2021

electron-ν appearance events,
in several years of data taking

- It seems mandatory to measure both MH and δ_{CP} in the same experiment

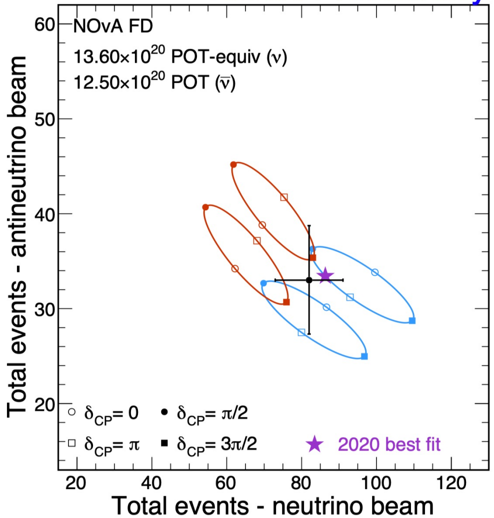
Comparing scenarios

T2K

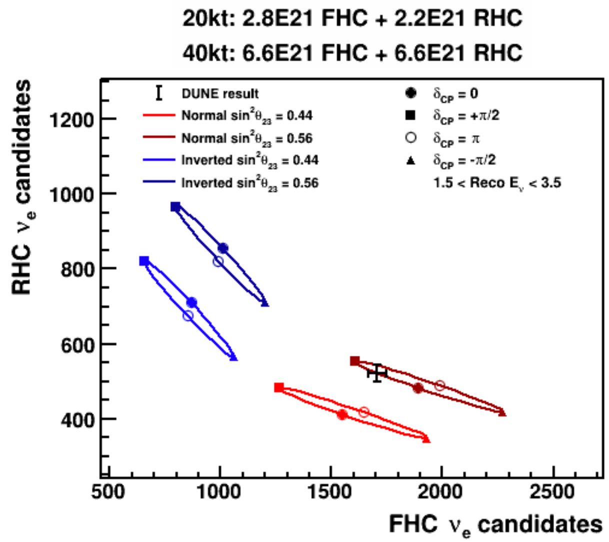


In Hyper-K only the error bars will shrink

NOvA Preliminary



DUNE simulation



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

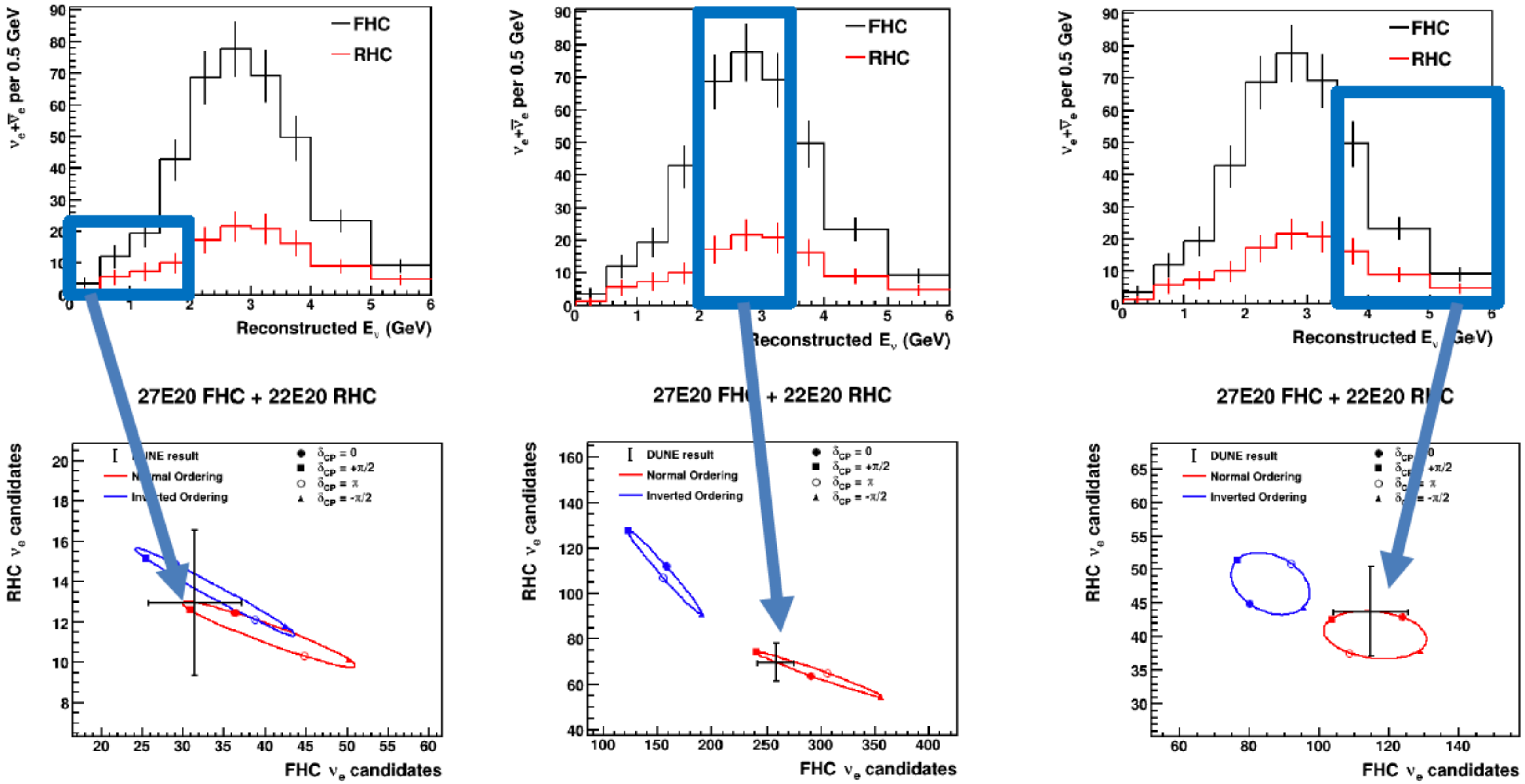
T2K -> Hyper-K:
Same baseline
Same beam spectrum
Same detector technology

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 FHCand RHC,
in 3 y ramp-up

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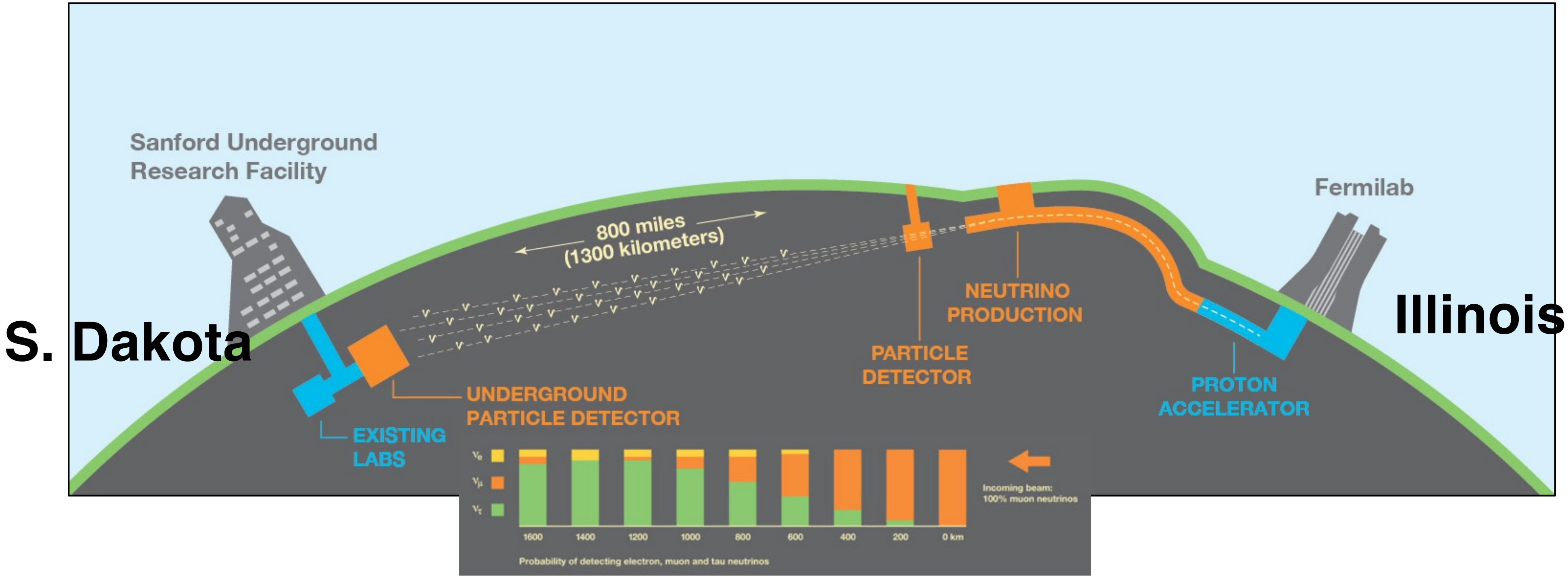
The LBNF/DUNE project

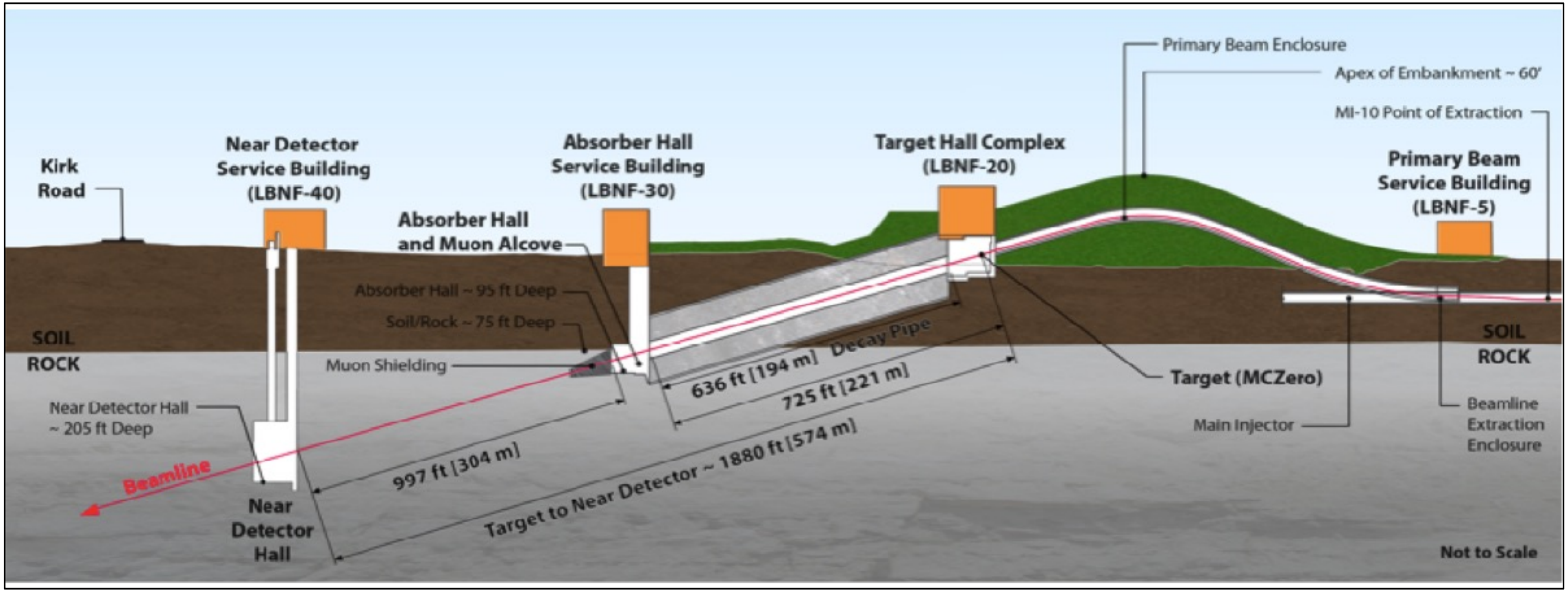
Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE)



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)

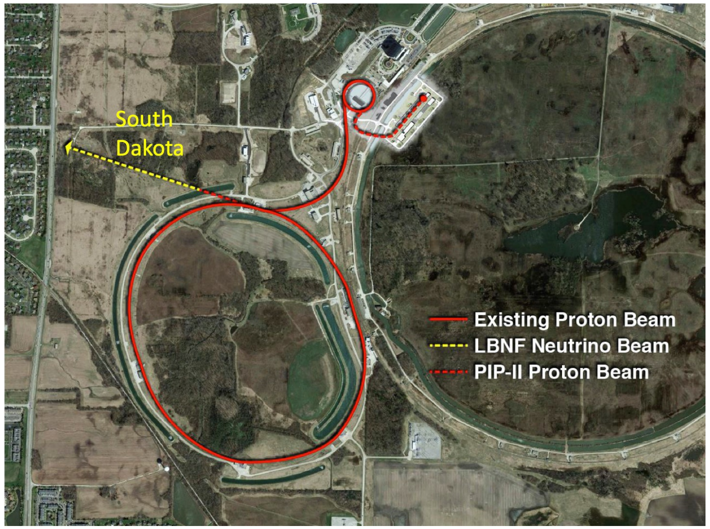
Long-Baseline Neutrino Facility (LBNF) Neutrino Beam



- ✓ 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



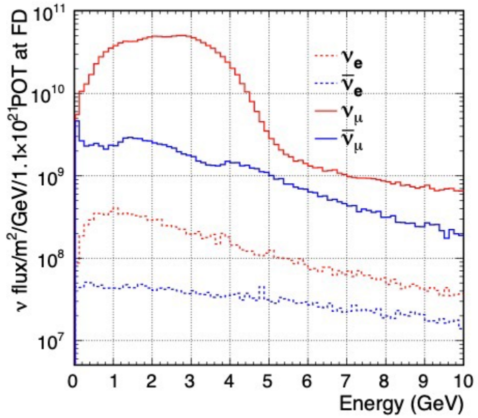
Horn-focused neutrino beam line optimized for CP violation sensitivity using genetic algorithm

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

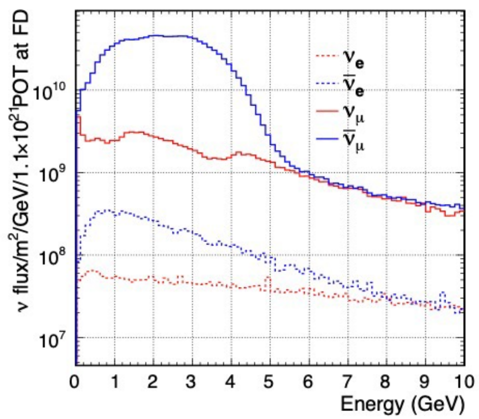
The LBNF neutrino beam will provide neutrinos and antineutrinos with energies from 0 to 8 GeV

Neutrino Flux at SURF, 1300 km away

Forward Horn Current (FHC)

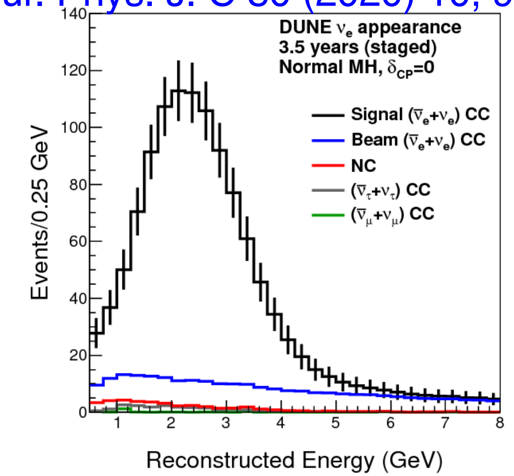


Reverse Horn Current (RHC)

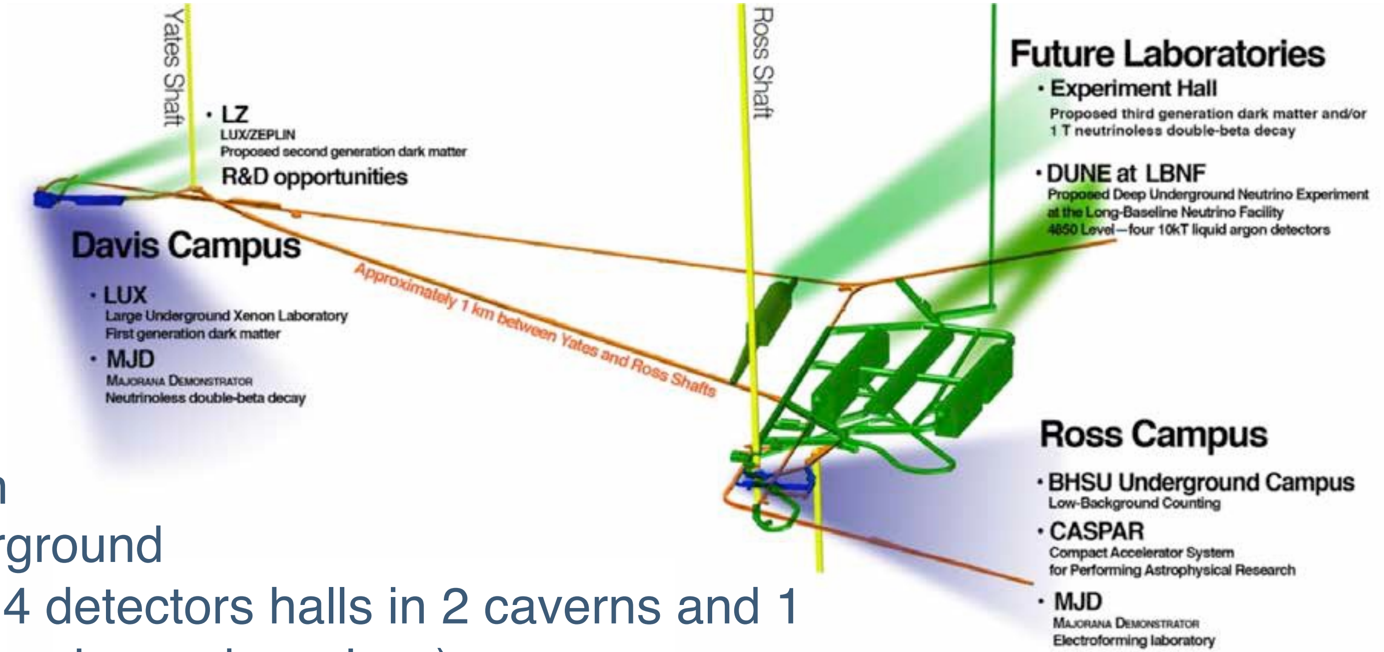


[Eur. Phys. J. C 80 (2020) 10, 978]

(DUNE CDR)

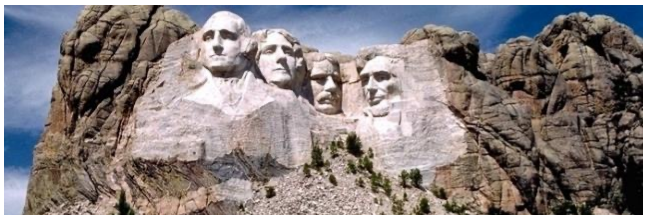


SURF

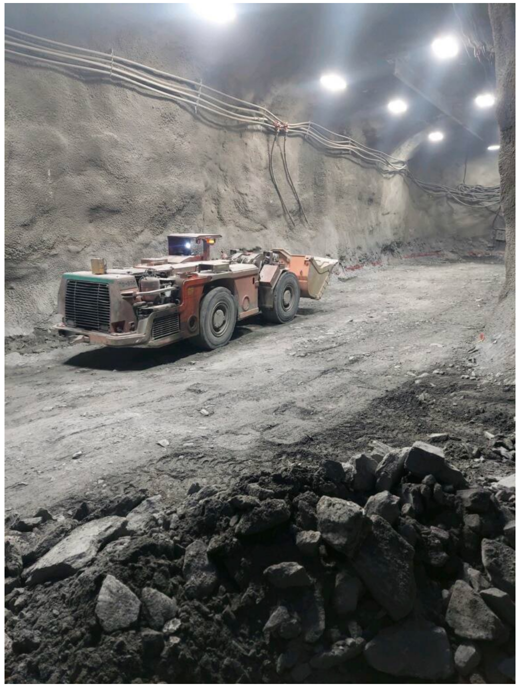


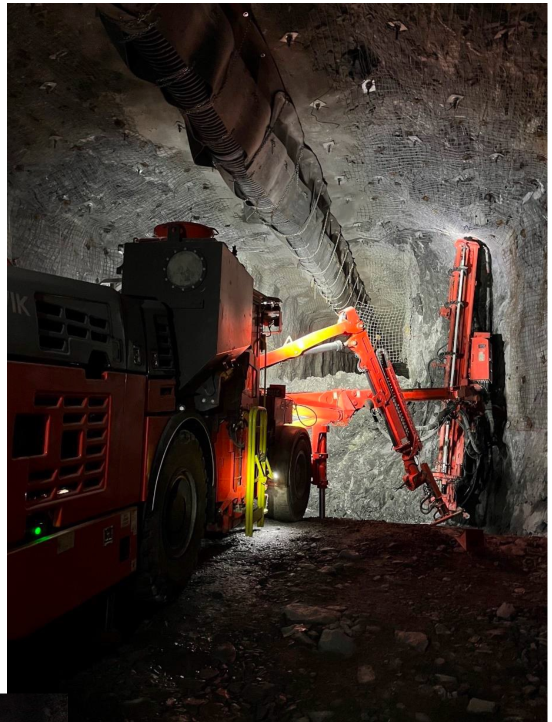
- Deepest laboratory in the US: 1.5 km underground
- Three main caverns: 4 detectors halls in 2 caverns and 1 support cavern (cryogenics and services)
- Excavation is ongoing *(875,000 tons of rock to be excavated)*
- FD first module installation second half of 2020's

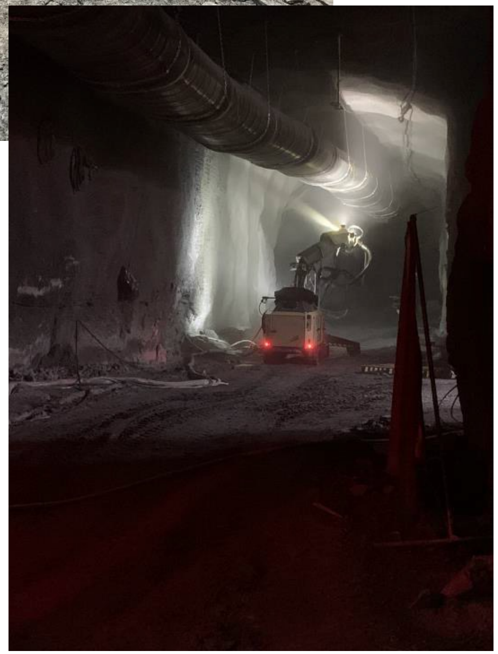
Previously known as Homestake (gold) Mine close to Lead,
in the Black Hills (South Dakota),
50 miles from Mount Rushmore and Crazy Horse statues

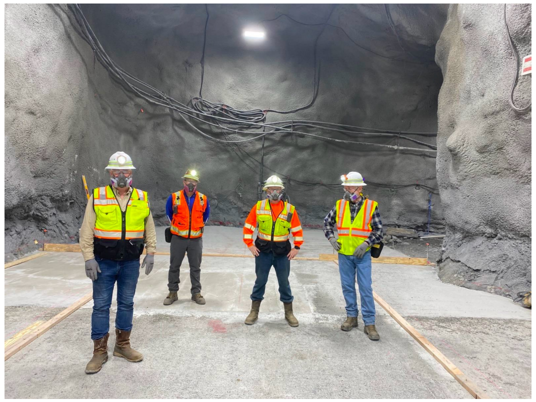


Excavation at SURF is ongoing



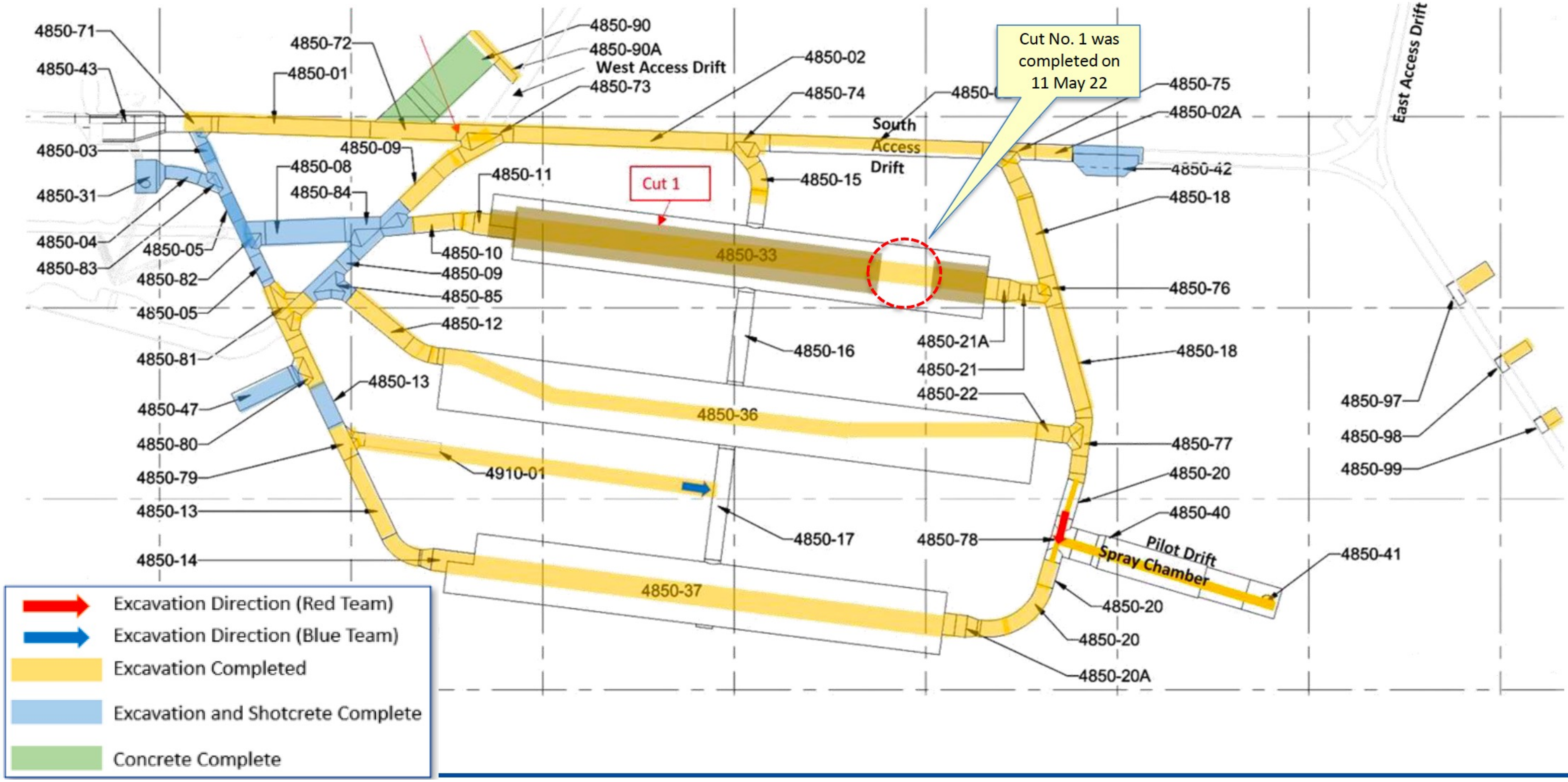






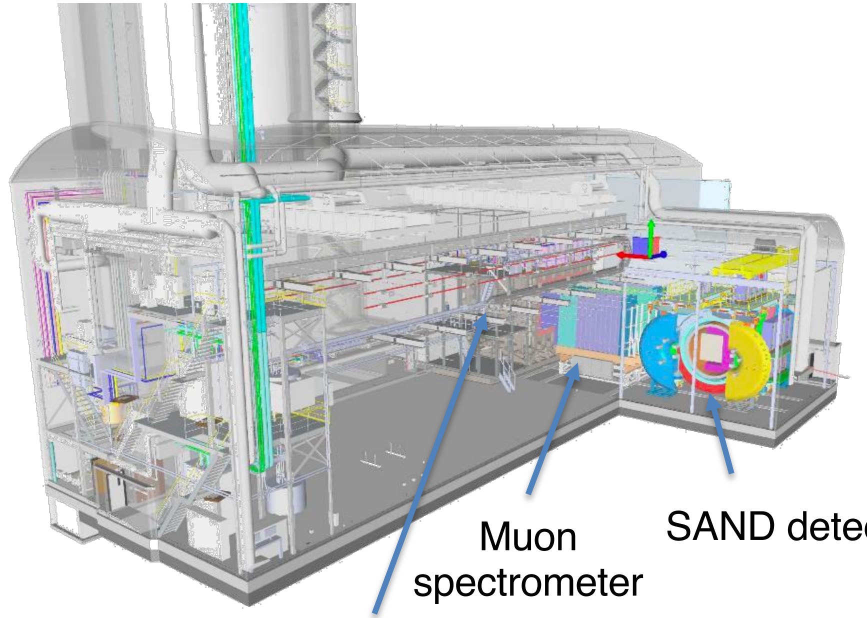
Sanford Underground Research Facility (SURF)

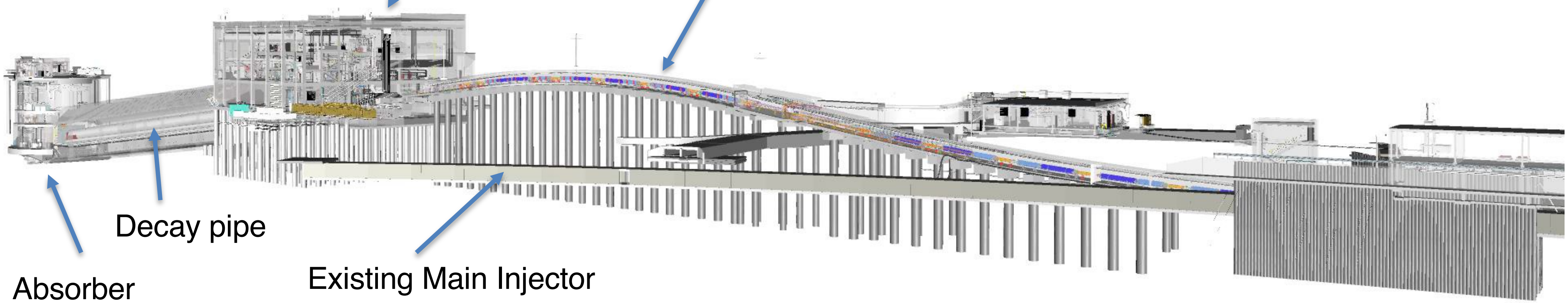
Excavation Update *(May 2022)*



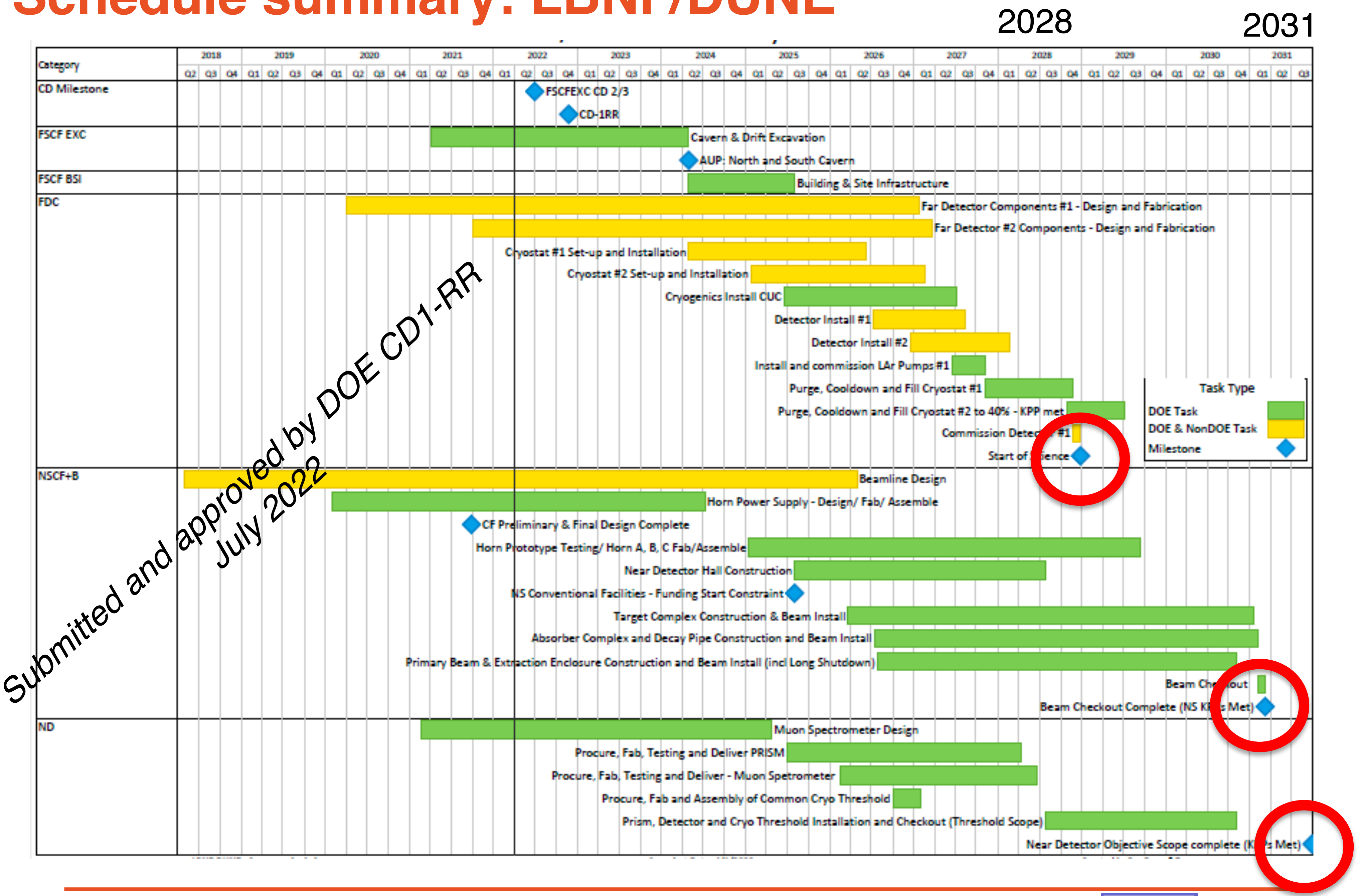
Near Site Conventional Facilities

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)*

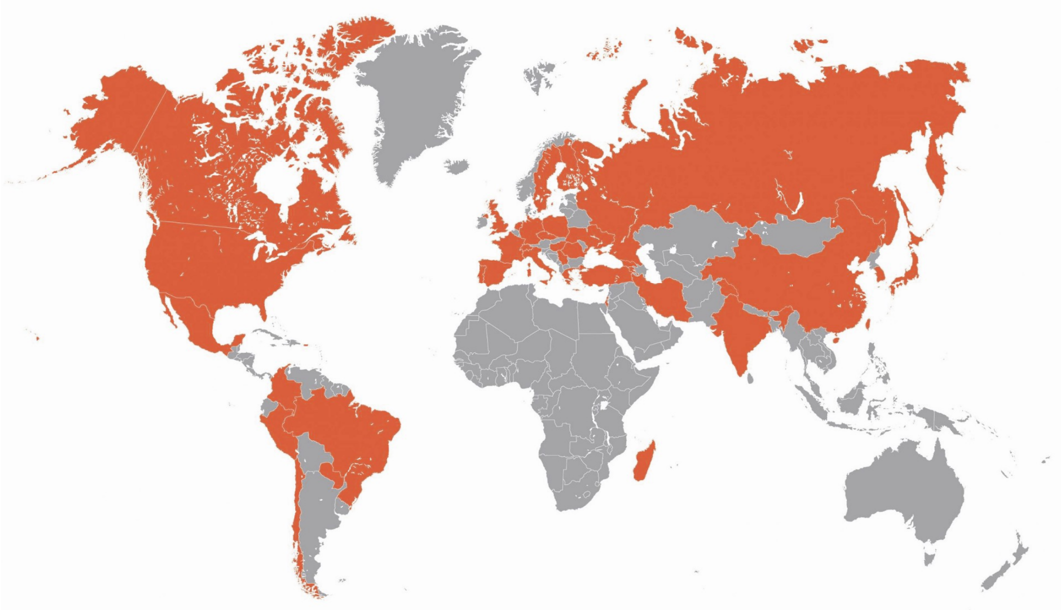




Schedule summary: LBNF/DUNE



DUNE collaboration

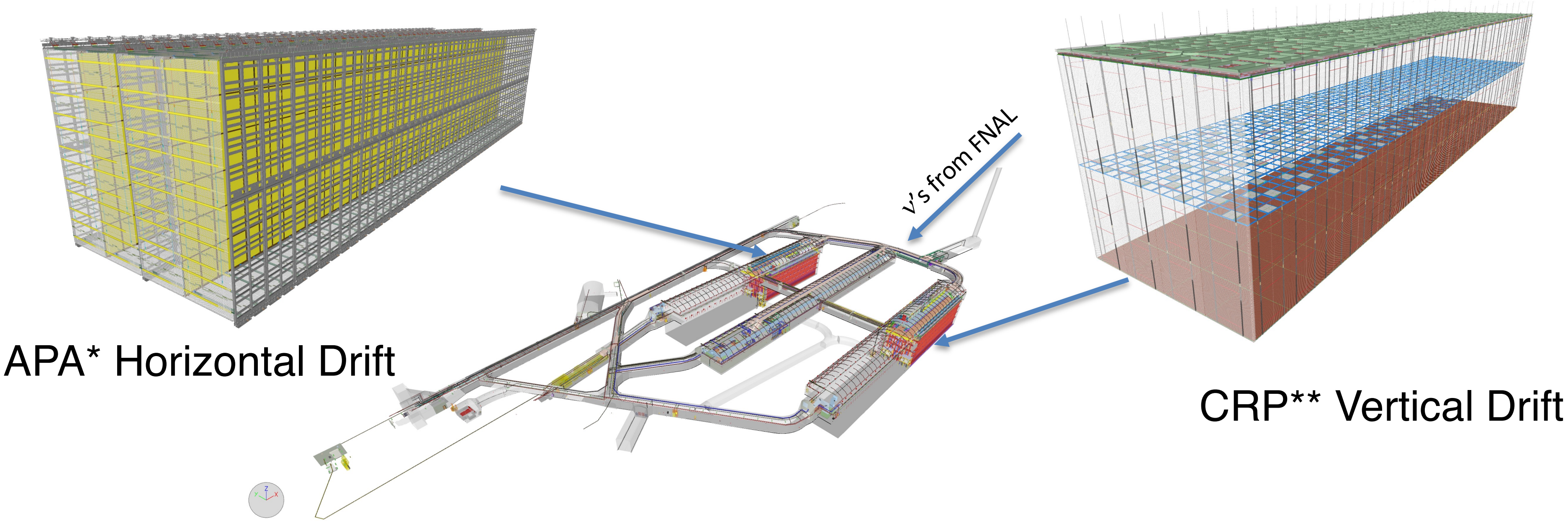


Over 1,300 scientists, from more than 200 Institutions, $\geq$ 37 countries plus CERN

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)



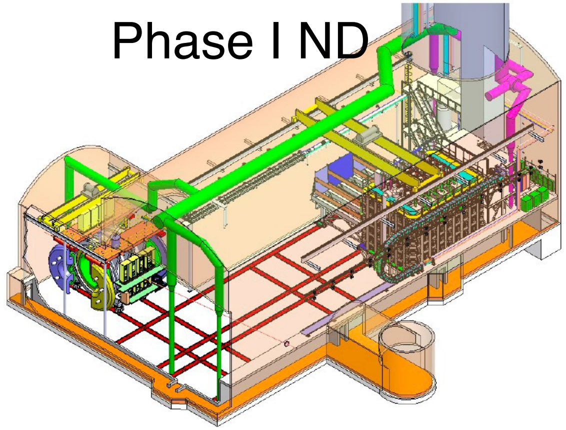
Note : DUNE Science begins when FD1 is filled and turned on and recording tracks

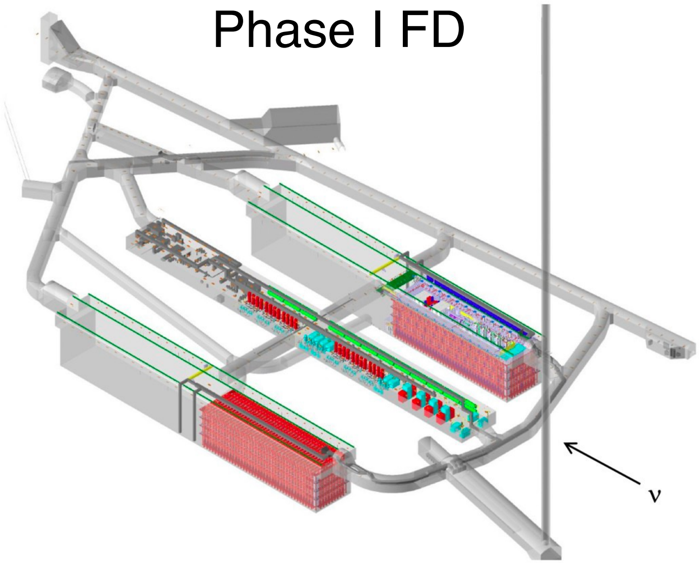
*Anode Plane Assemblies
**Charge Readout Planes

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)



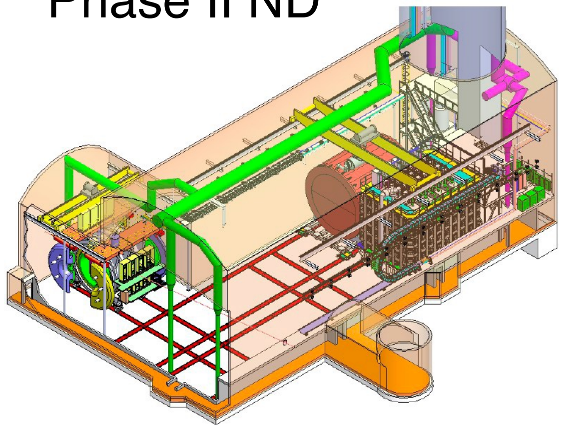


DUNE – Phase II

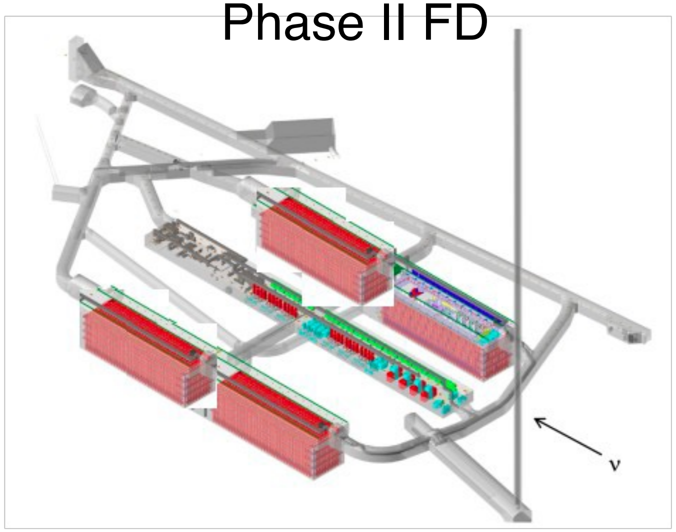
DUNE Phase II:

- Fermilab proton beam upgrade to 2.4 MW
- Two additional 17kt FD modules
- Near detector: ND-LAr + MCND (movable) + SAND
- ND upgrade is driven by improved performance at reducing systematics, not driven by increased beam intensity
- DUNE Phase II will collect twice as many neutrinos

Phase II ND



Phase II FD

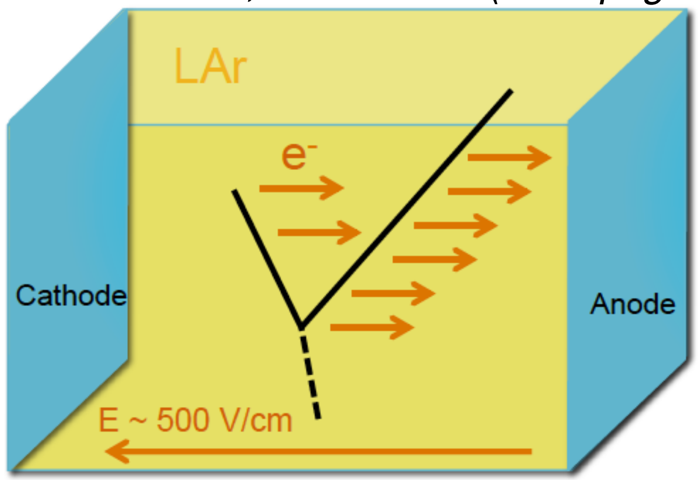


DUNE Far Detector (FD)

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

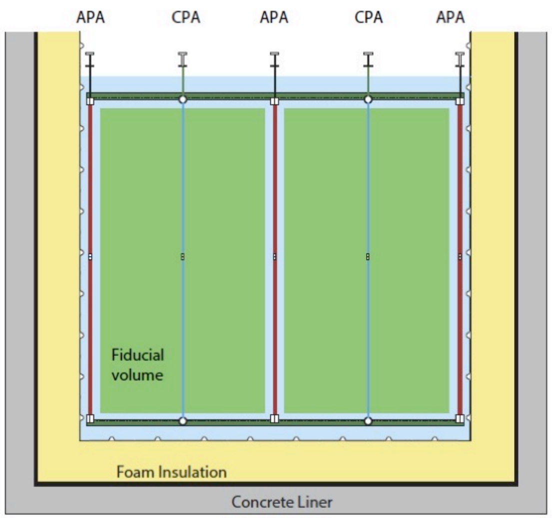
Four 17-kt liquid argon TPC modules
- **Horizontal** and **Vertical**-drift detector for the first 2 modules
- Integrated photon detection
- Modules will not be identical

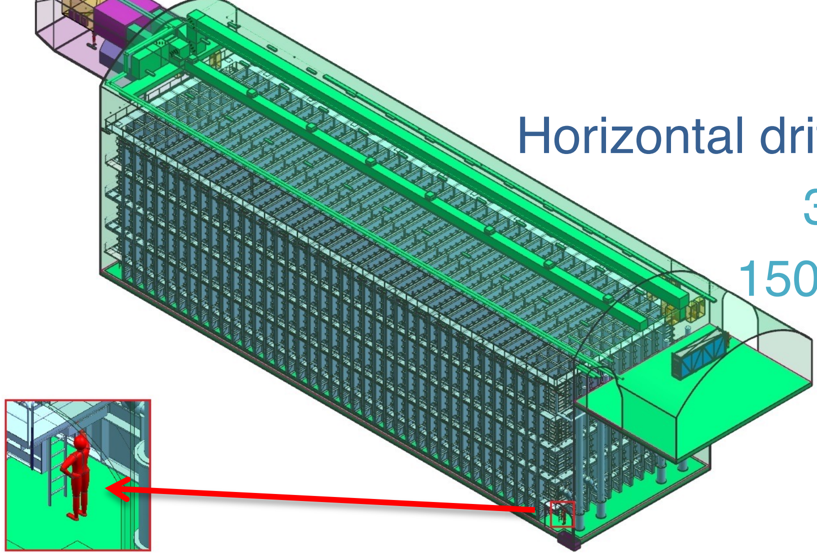
TPC Critical features:
- LAr ultra-high purity
- E Field: *uniformity* and *stability*



Can drift electrons for very large distances

Horizontal drift: modular wire-plane readout





Horizontal drift: 17 kt module

384,000 readout wires

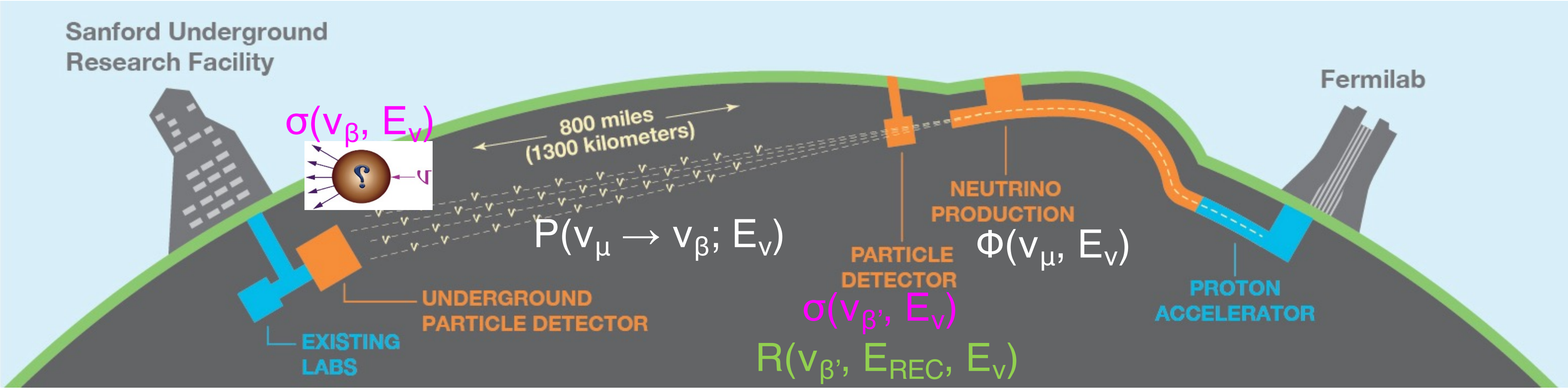
150 “APAs” (2.3 m x 6 m)

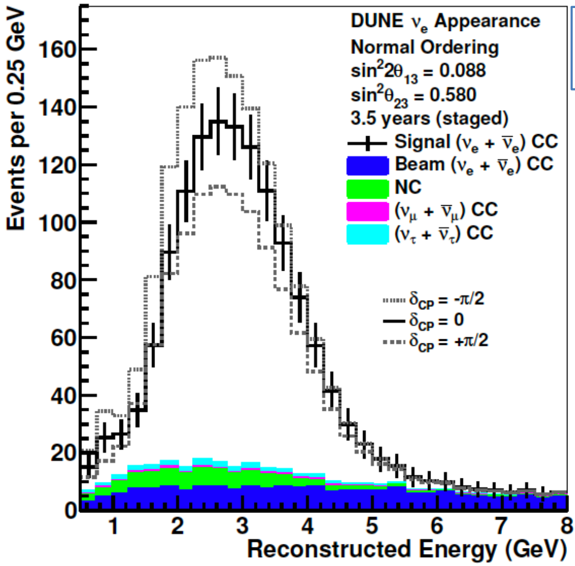
12 m high

15.5 m wide

58 m long

Dune at work





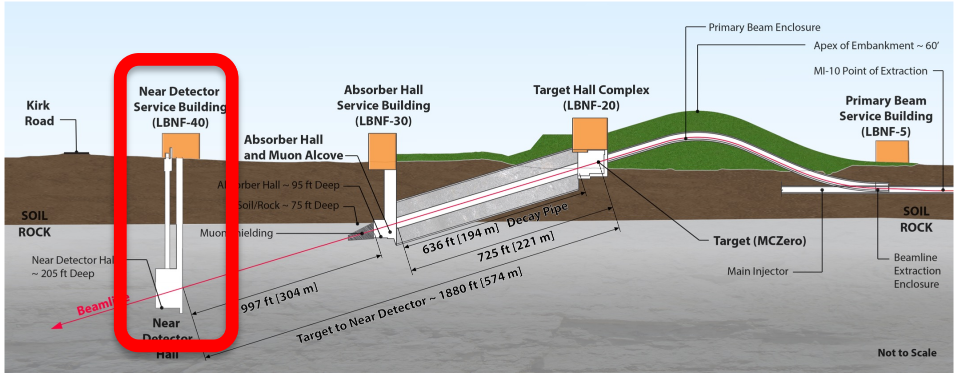
ν_e appearance from ν_μ beam after 3.5 years (staged)

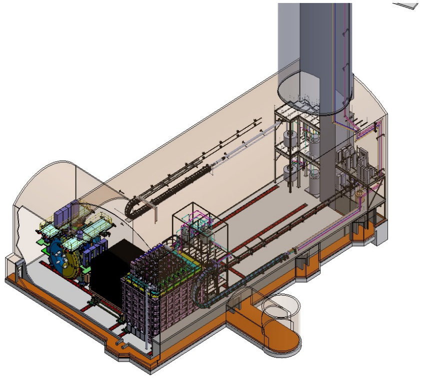
Need maximal control of prediction under PMNS parameters:
fluxes, cross-sections, detector responses

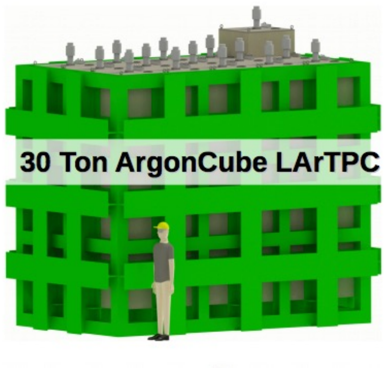
To maximize deconvolution of intrinsic degeneracies perform single measurements for as many as possible sources of systematics effects ☞ Near Detector complex

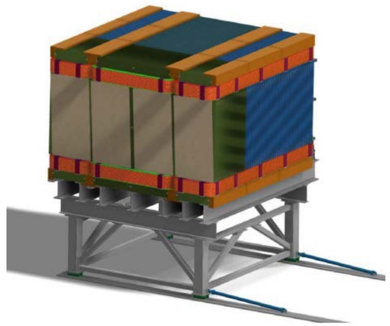
Near Detector (ND) – Phase I

- 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)



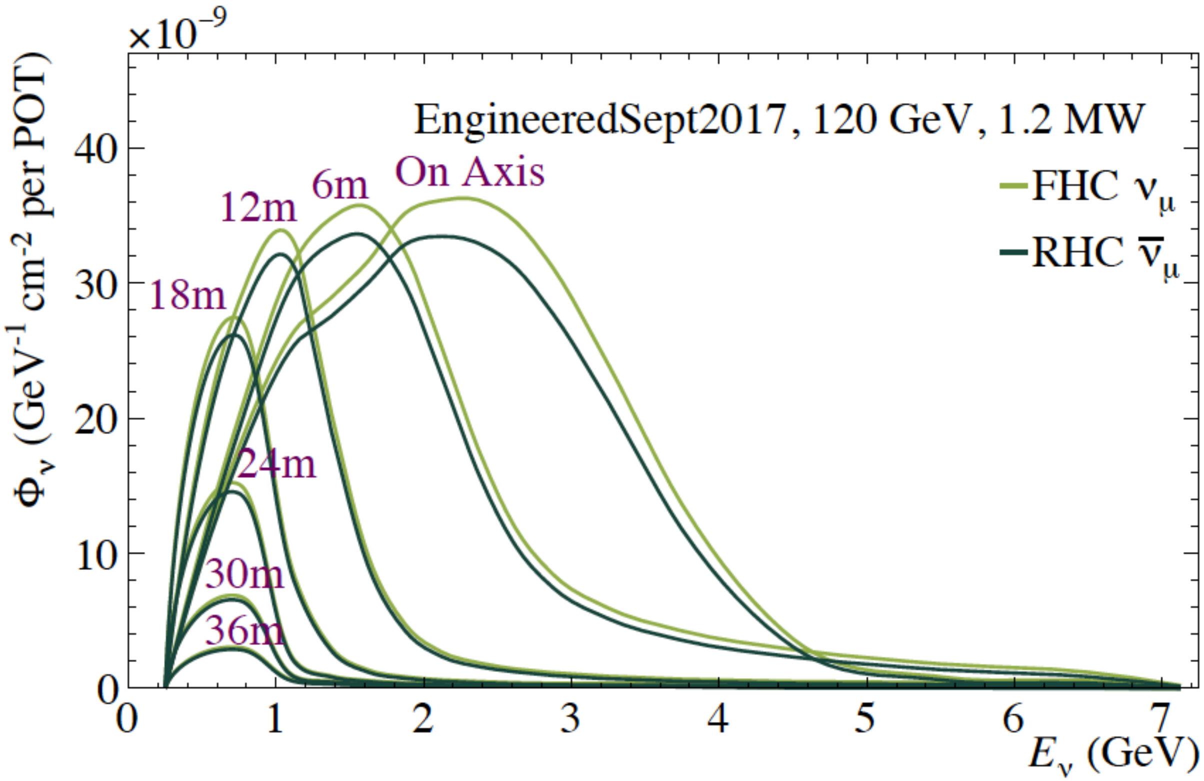






DUNE ND capabilities

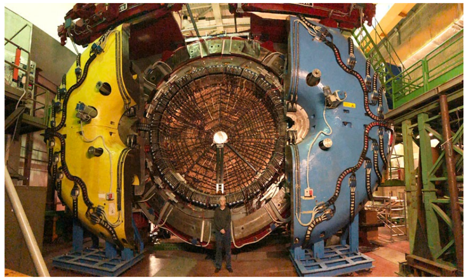
>100 million interactions will enable a rich non-oscillation physics program



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

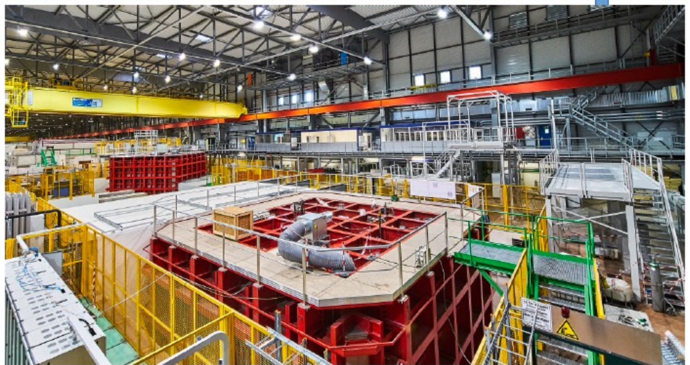
- Prototyping production and installation procedures for DUNE Far Detector Design

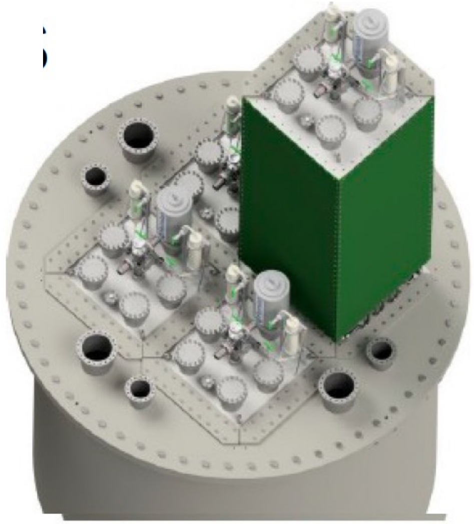
  many of the components for the far detector prototyping at 1:1 scale
- Validating design from perspective of basic detector performance
- **Accumulating test-beam data to understand/calibrate response of detector to different particle species**
- Demonstrating long term operational stability of the detector

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)

3

Perspectives

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

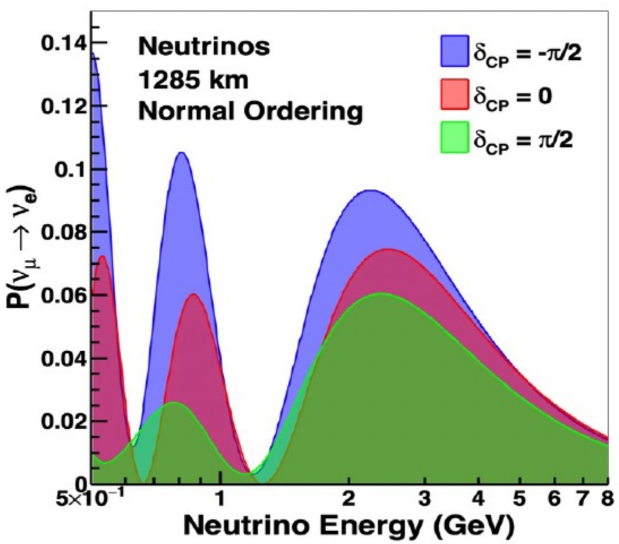
[Eur. Phys. J. C 80 (2020) 10, 978]

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

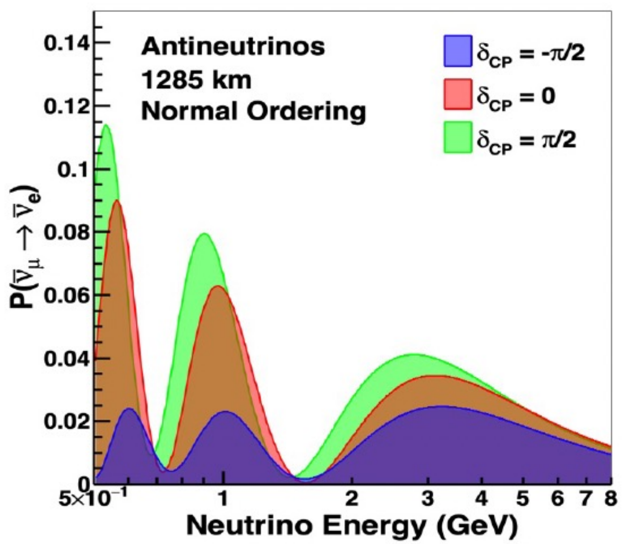
$$\Phi_{ji} = \frac{1.27\Delta m^2_{ji}L}{E_\nu} \qquad a = \pm\frac{G_F N_e}{\sqrt{2}}$$

Sign change for ν_e and $\bar{\nu}_e$

Interplay between mass ordering



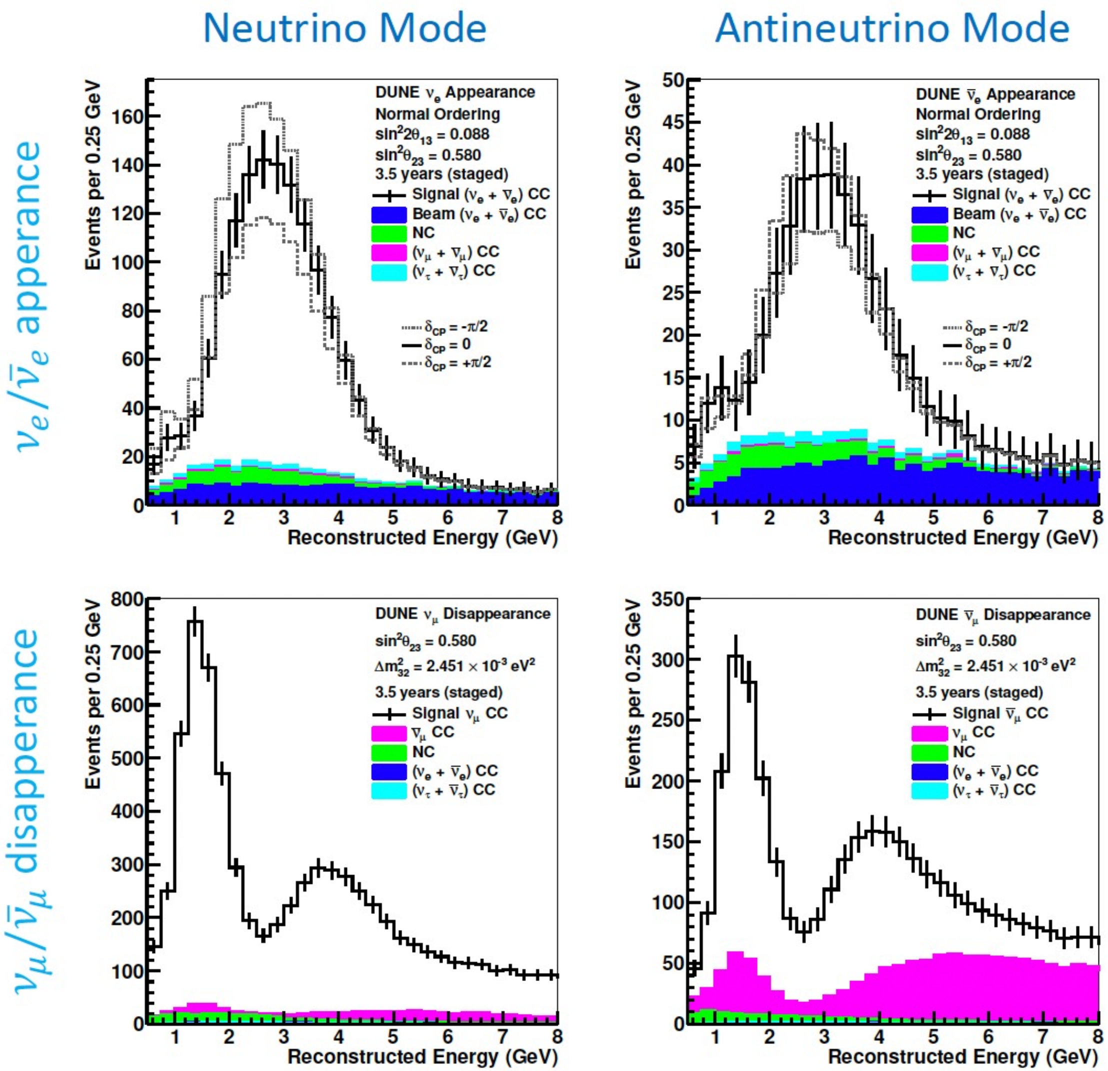
$\nu_\mu \to \nu_e \overset{?}{\Leftrightarrow} \bar{\nu}_\mu \to \bar{\nu}_e$



Oscillation Sensitivity for DUNE

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

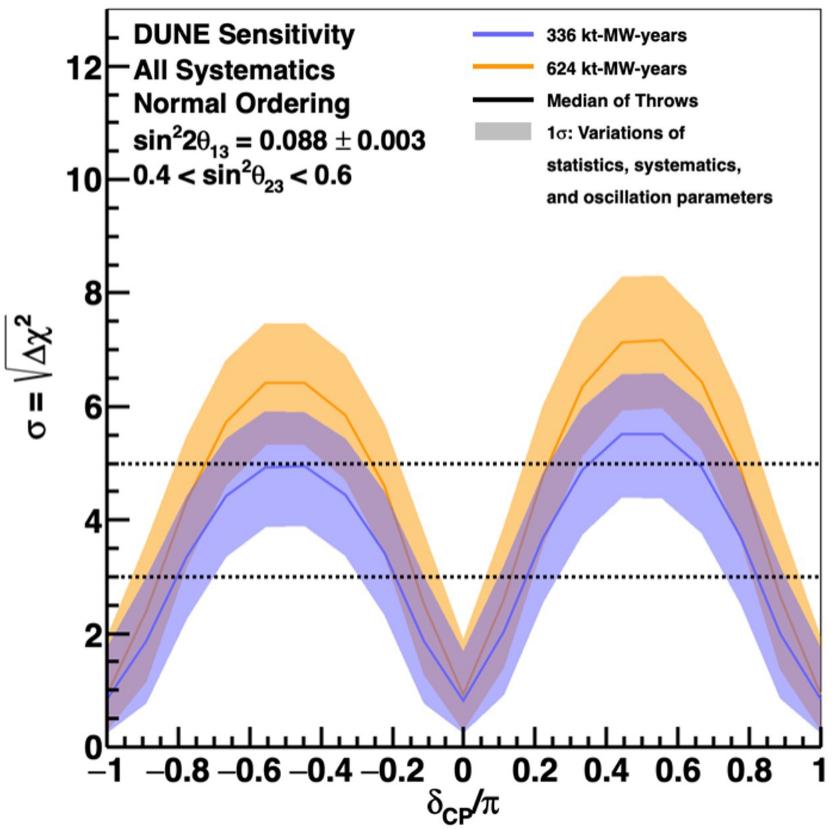
- Reconstructed spectra of selected CC-like events
- Sensitivity assessment includes full FD systematics treatment
- 3.5 years neutrino beam mode
- 3.5 years anti-neutrino beam mode
- ~1000 ν_e/ν_e–bar events in 7years
- ~10,000 ν_μ/ν_μ-bar events in 7years

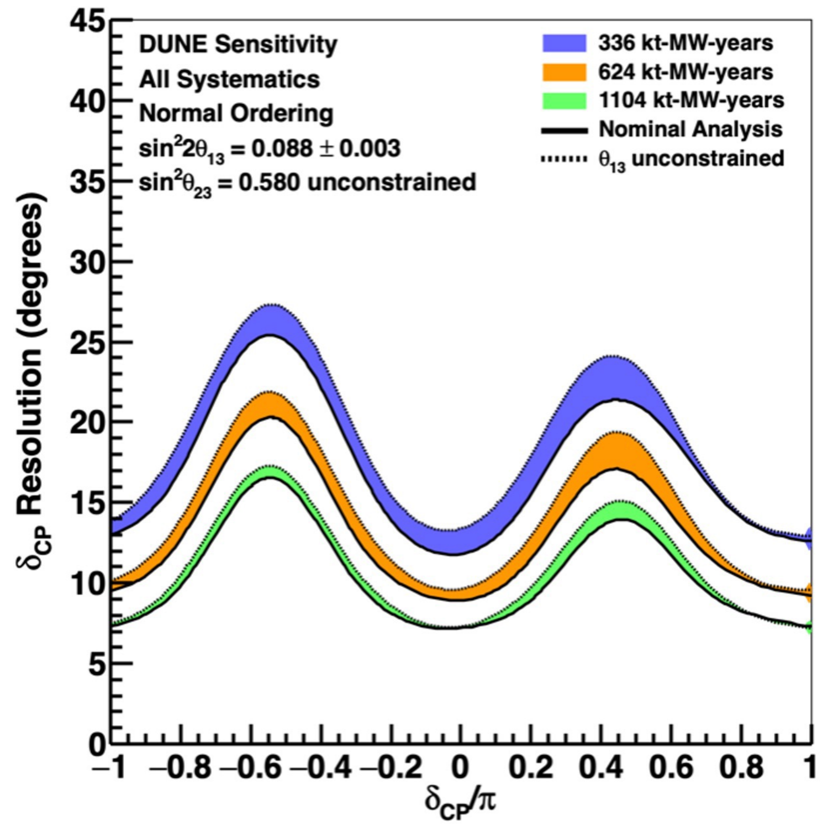


Simultaneous fit to four spectra to extract oscillation parameters

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}

Perspectives for MH

Many different ways to define "sensitivity"

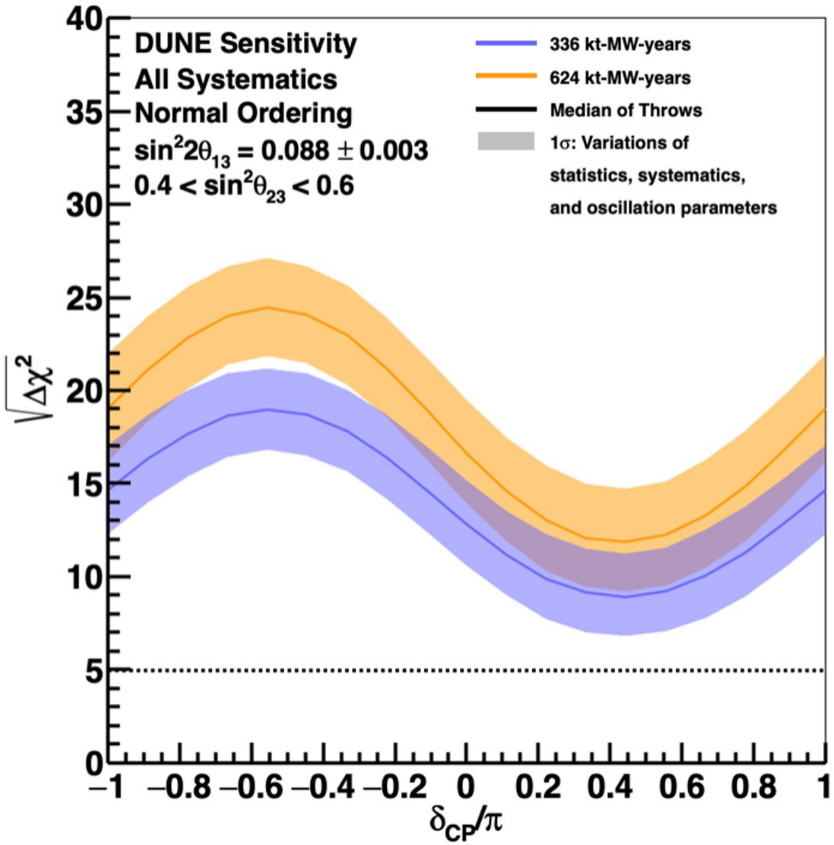
Only above 5 σ
we are "unsensitive"
to methodology

- NOvA: Degeneracy with δ_{CP} ?
- PINGU/ORCA: funded ? systematics ?
  Degeneracy with δ_{CP} and θ_{23} ?
- INO: really ?
- JUNO: technical challenge on energy resolution ?
  Degeneracy with Δm^2_{atm} ?

DUNE: ok, it will get it

MH and θ_{23} Oscillation Physics

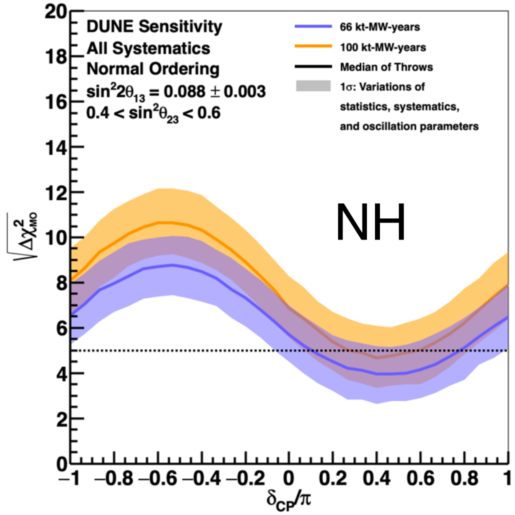
Mass Ordering

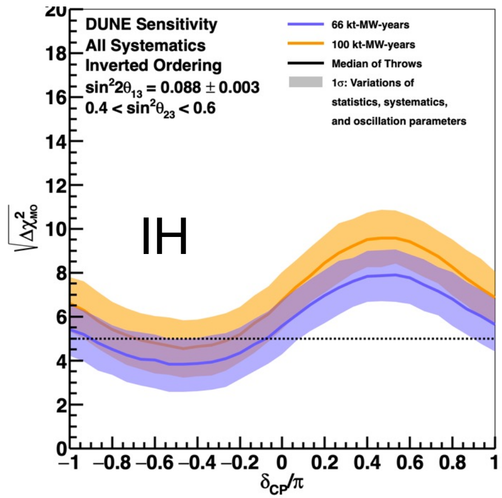


EPJC 80 (2020) 978

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

100 kt
66 kt

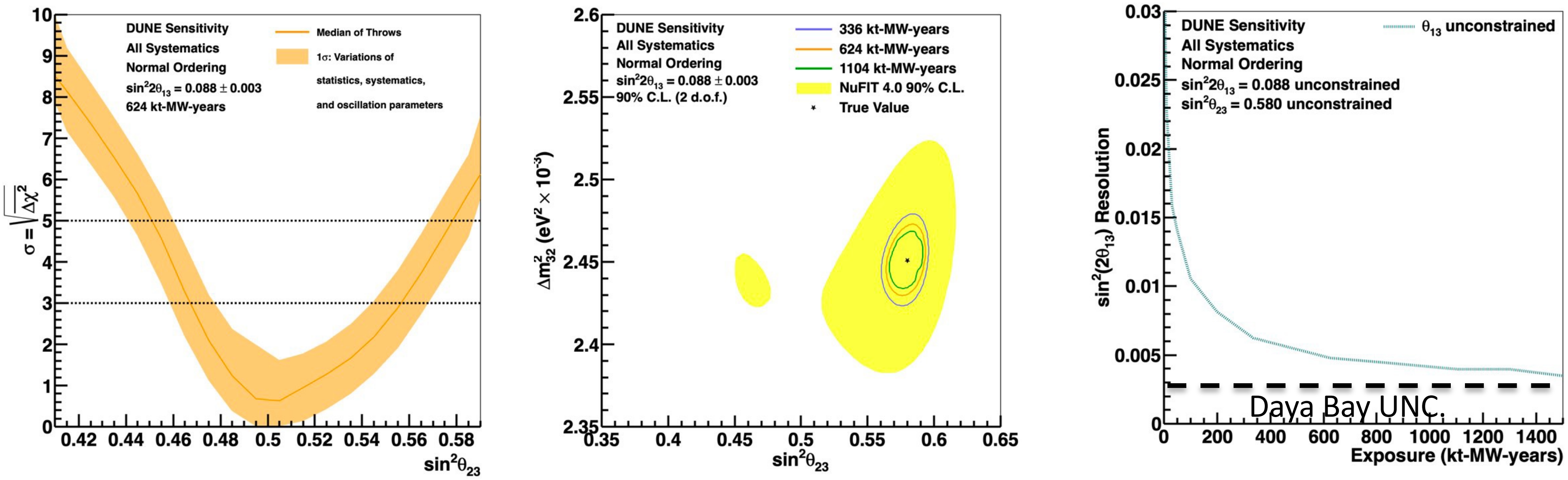




- Width of band indicates variation in possible central values of θ_{23}
- Width of band indicates variation in possible true value of δ_{CP}

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

Oscillation Parameter Sensitivity

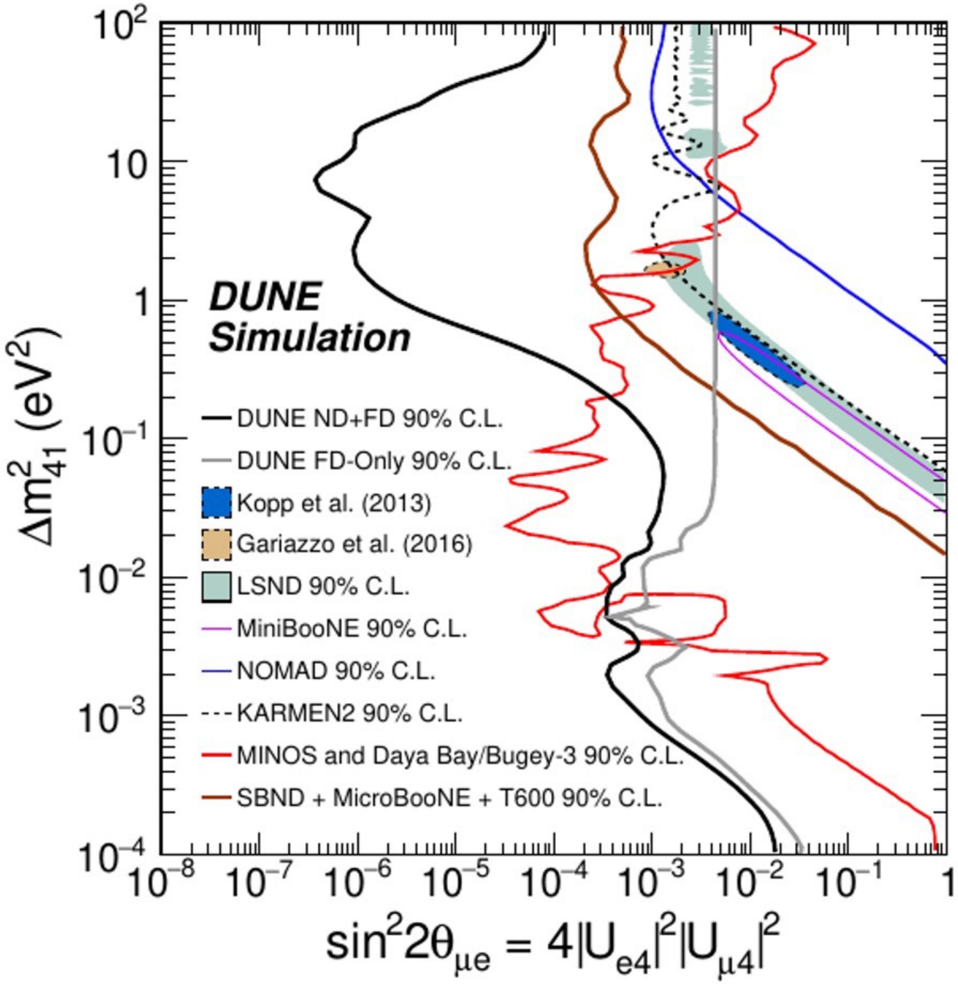


- Excellent on Δm^2_{32} and θ_{23}, including octant, and unique PRISM measurement technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

BSM searches

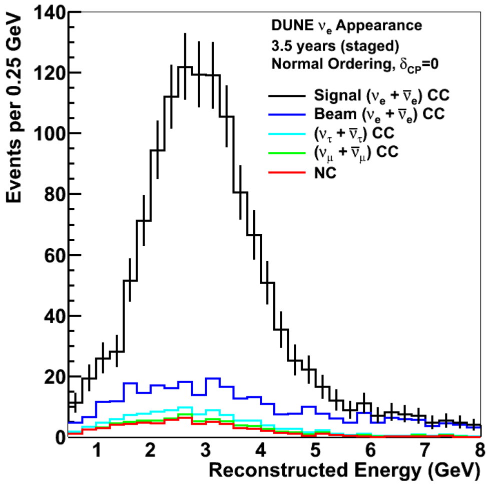
- DUNE sensitive to many BSM particles and processes
  - *Light dark matter*
  - *Boosted dark matter*
  - *Sterile neutrinos*
  - *Non-standard interactions, non-unitary mixing, CPT violation*
  - *Neutrino trident searches*
  - *Large extra dimensions*
  - *Neutrinos from dark matter annihilation in 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)

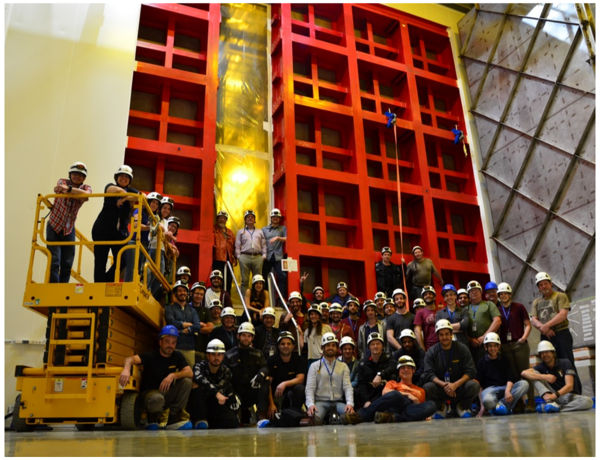


Summary for DUNE

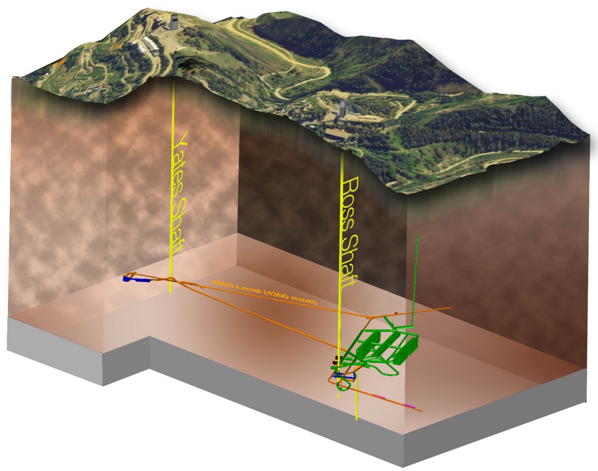
Foreseen Analysis



protoDUNE



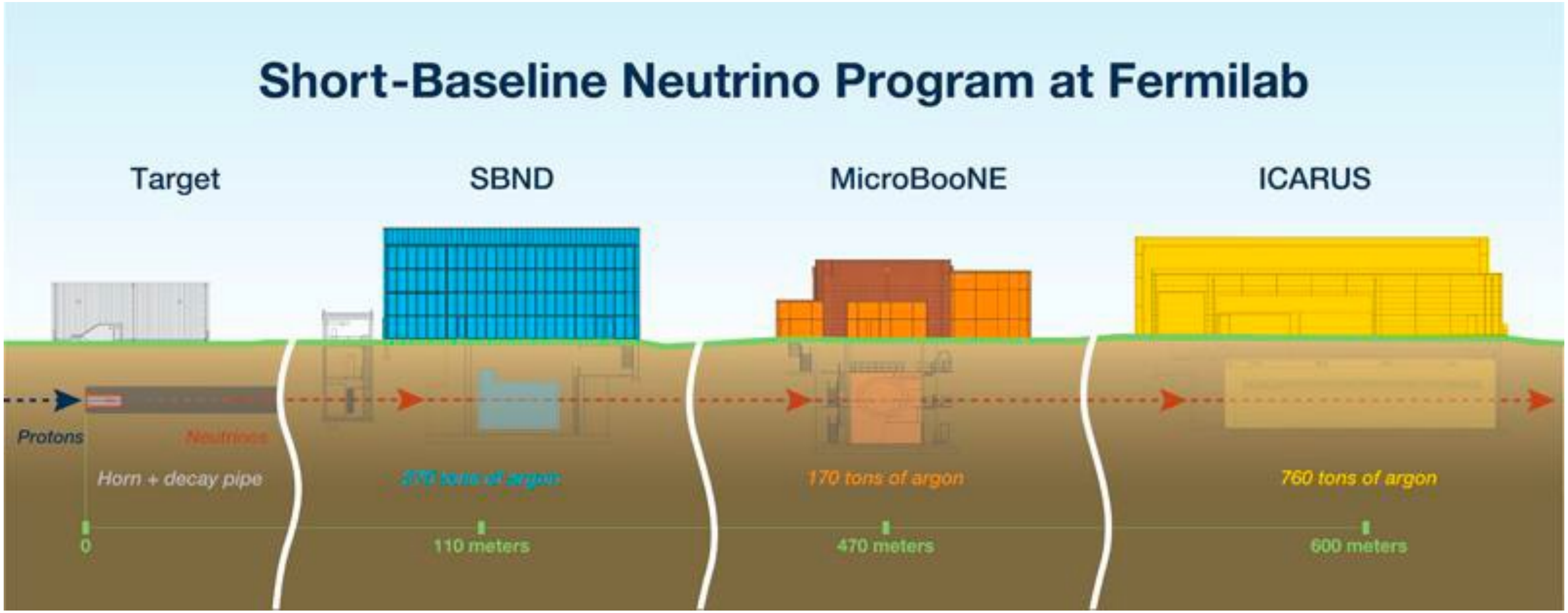
Coming …



- 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

4

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



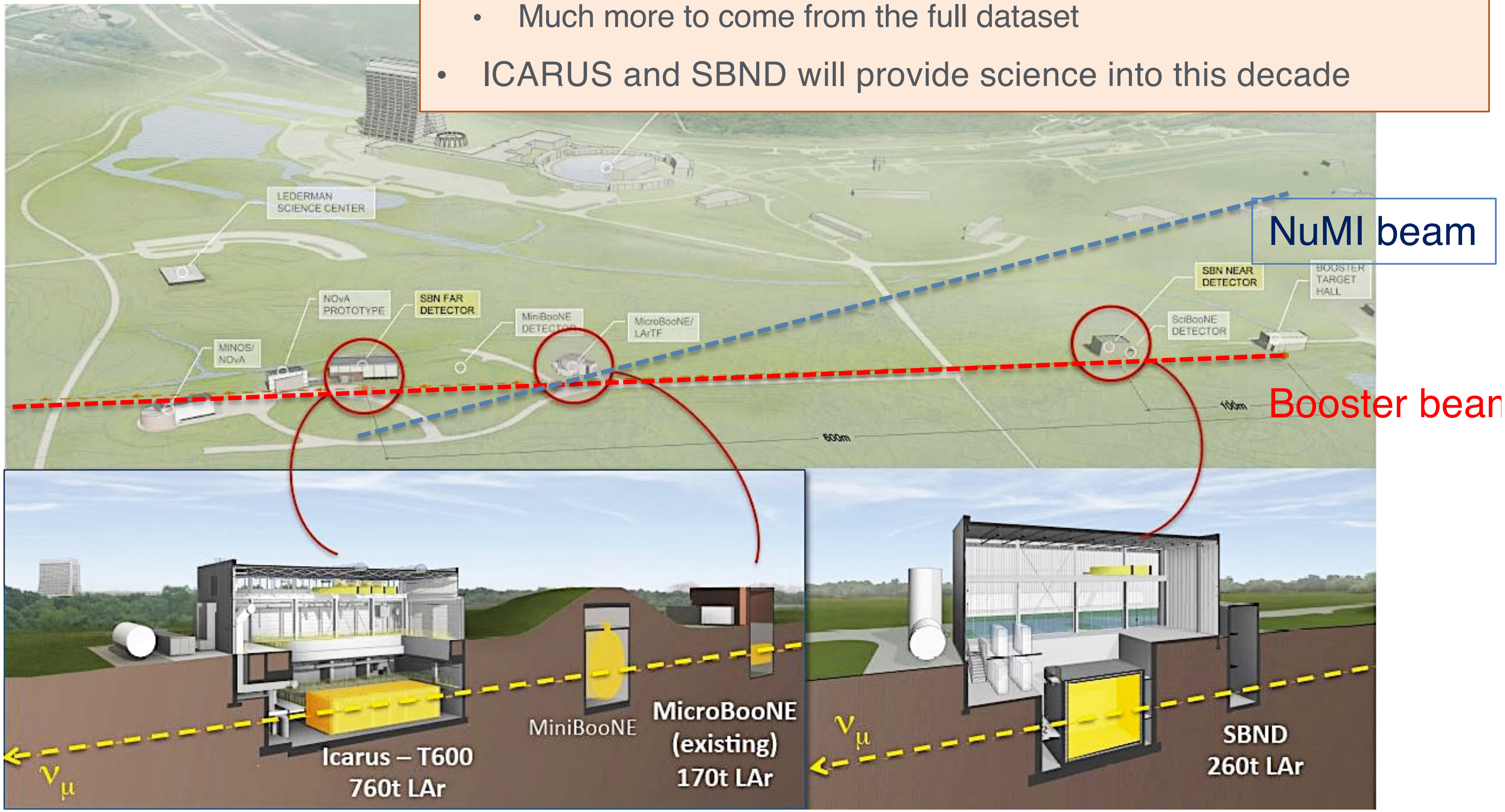
https://sbn.fnal.gov/

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.

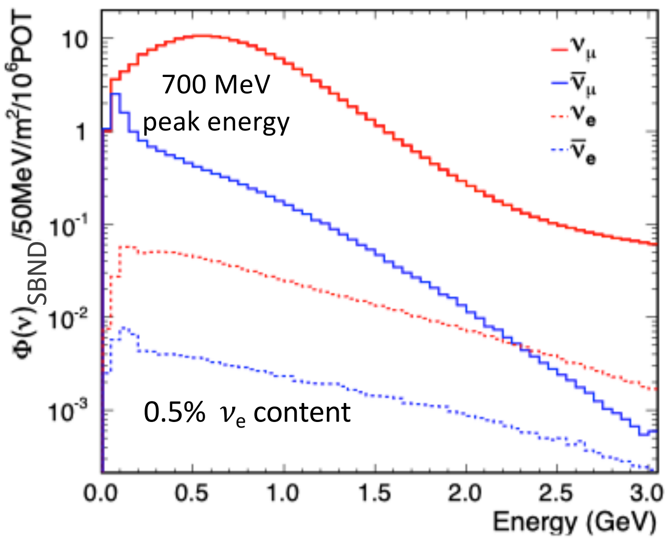
SBN Complex at Fermilab

- 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)

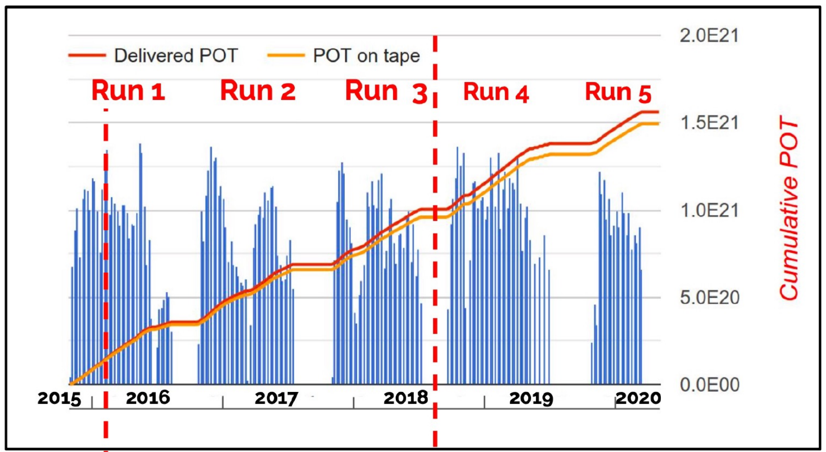
From 8 GeV Booster



- 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



BNB data ~7x10^{20} POT analyzed

MicroBooNE collection

(see Giorgia Karagiorgi on Wednesday afternoon)

ICARUS-T600 at FNAL

Aug. 2020: start of TPC/PMT operation

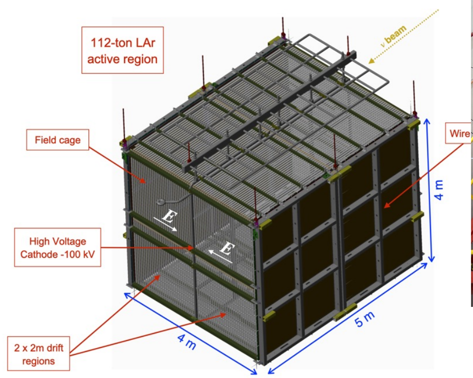
Dec. 2021: CRT installation complete

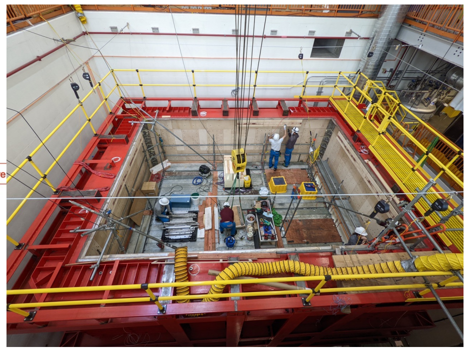
June 2022: overburden complete

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



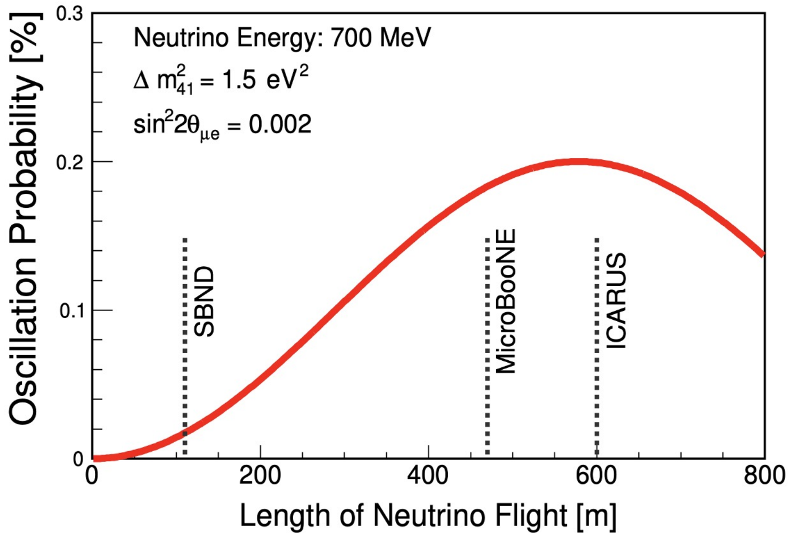


- Ground-up new detector – 4 m x 4m x 5m, 112 t active mass LAr
- Incorporating technology important for DUNE (cryostat, 2-m drift TPC, X-Arapuca photon detectors)

Installation complete and ready to fill in June 2023

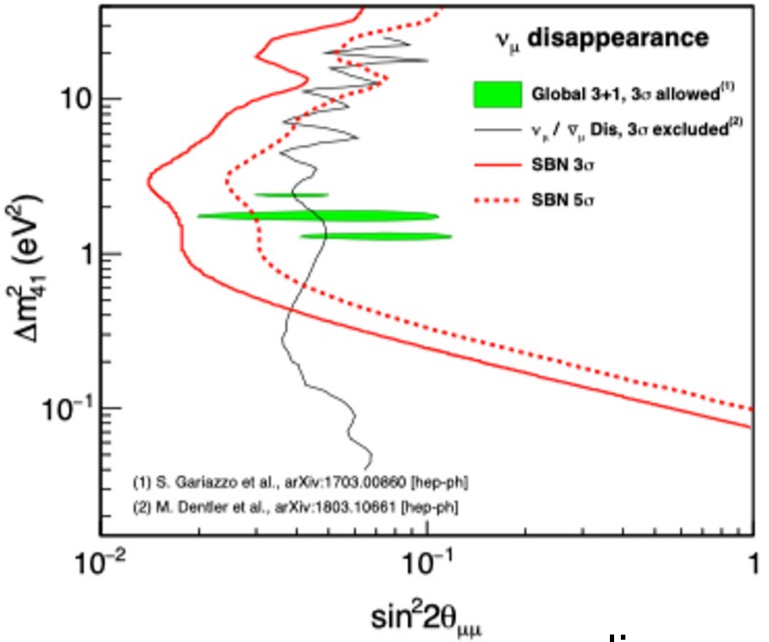
SBN Oscillation Sensitivity

Example oscillation at BNB peak energy



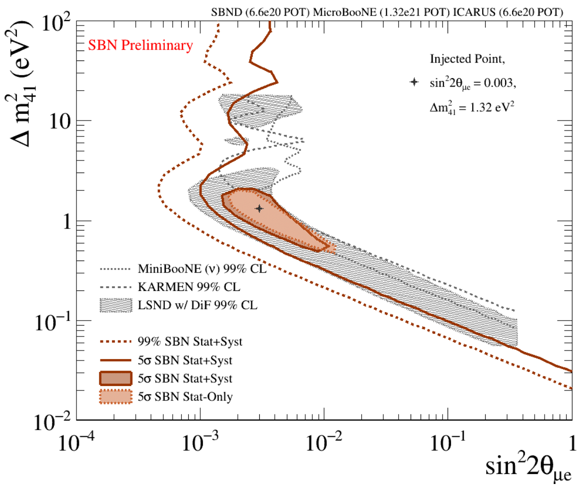
P. Machado et al., arXiv:1903.04608V11

SBN proposal

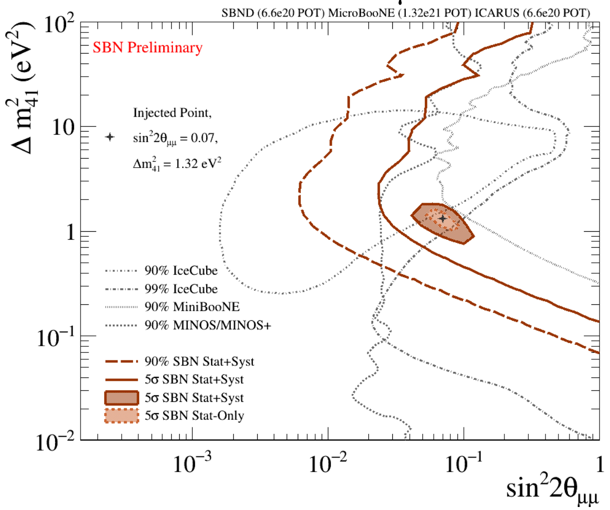


SBN update *(work in progress)*: SBN sensitivities for 6.6 x 10^{20} protons on the BNB target; to be updated to the larger dataset

ν_e appearance



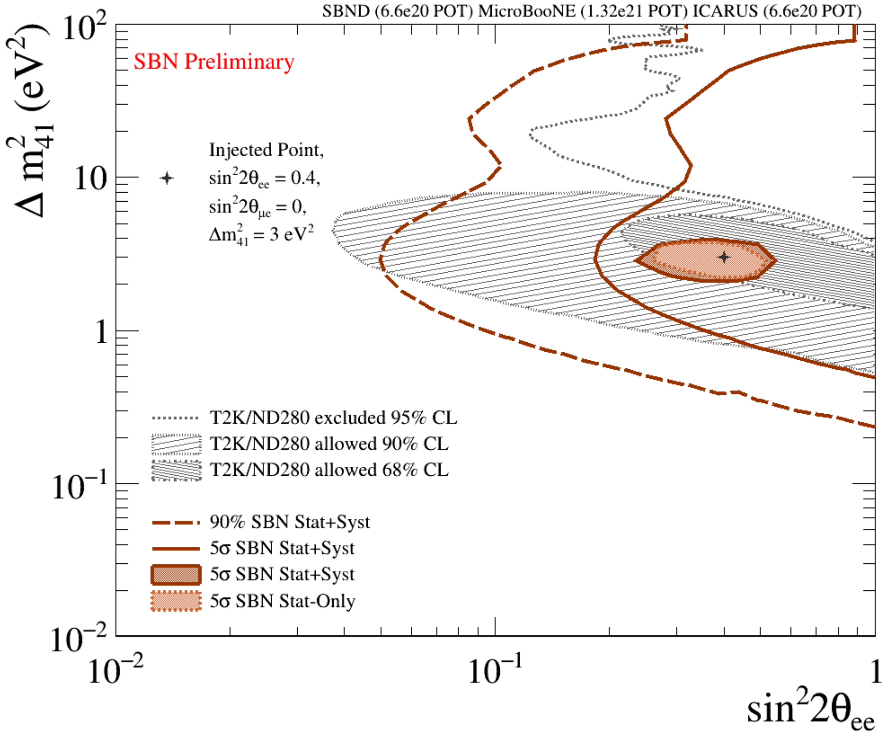
ν_μ disappearance



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

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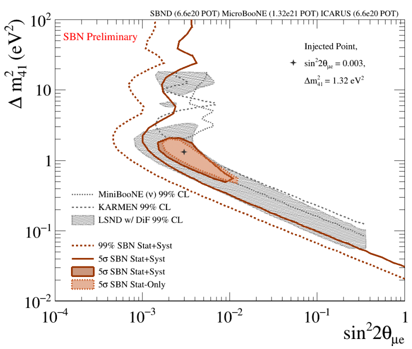
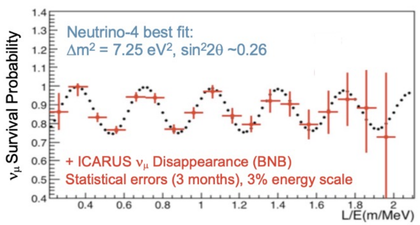
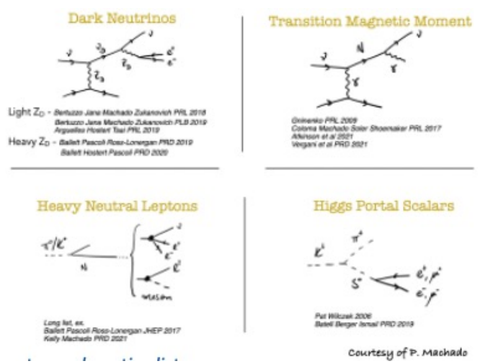
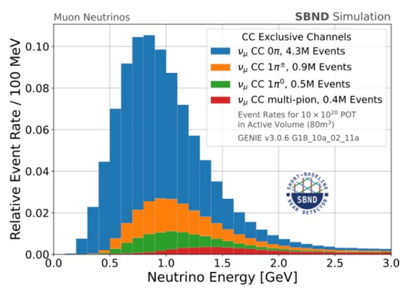
ICARUS/SBN Outlook

- 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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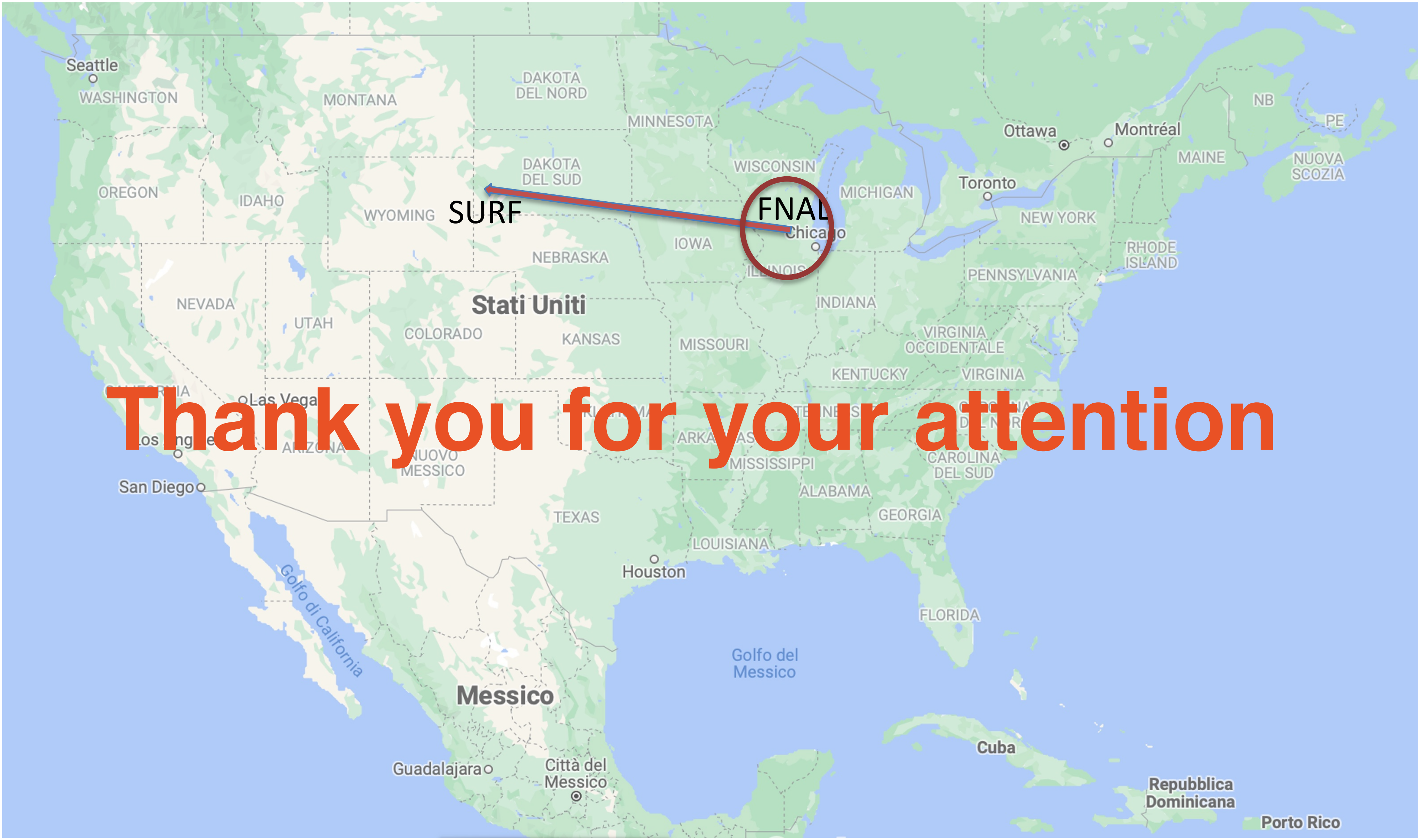
Thank you for your attention



Backup slides

The wonderful frame pinpointed for the 3 standard neutrinos, beautifully adjusted by the θ_{13} measurement, left out some relevant questions:

- Mass ordering: **MH**
- Leptonic Charge-Parity violation: δ_{CP}
- Anomalies and discrepancies in some measurements,
- Mass values
- **…**
- Dark Matter
- …

The importance of measuring δ_{CP}

- *Matter/antimatter asymmetry in the Universe requires CP violation*

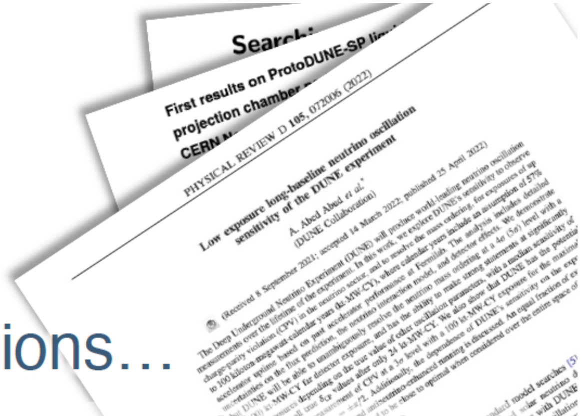
- CP violation in the quark sector has been measured the first time 58 years ago, but this violation does not help very much in understanding what happened soon after the Big Bang ($J_{CKM} \approx 3 \times 10^{-5}$)

- *Through leptogenesis, theory links the ν–mass generation to the generation of baryon asymmetry of the Universe (Fukugita and Yanagida, 1986).*

- *The Dirac phase δ_{CP} can be one of the ingredients of these mechanisms (and $J_{PMNS} \approx 0.033 \sin\delta_{CP}$)*

- It is mandatory to measure its value… also because it is one of the few unknowns of the Standard Model (together with neutrino masses)

DUNE Publications



- DUNE collaborators have produced 29 publications…

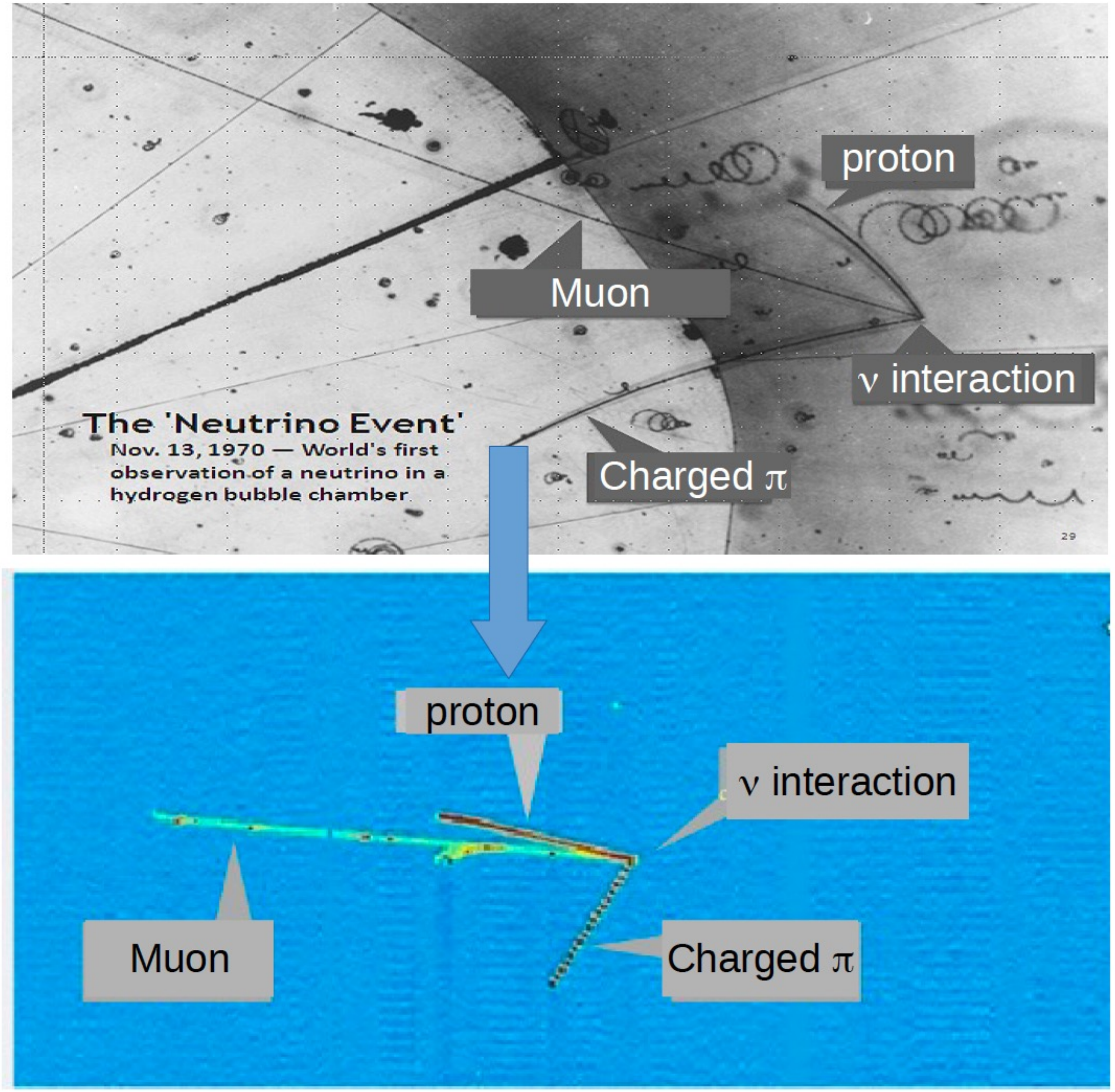
Title (Most Recent Full Collaborations Publications)	arXiv	Journal
Experiment Simulation Configurations Approximating DUNE TDR	2103.04797	none
Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC	2108.01902	JINST
Probing KDAR in the Sun with DUNE	2107.09109	JCAP
Prospects for Beyond the Standard Model Physics Searches at the Deep Underground Neutrino Experiment	2008.12769	EPJC
First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform	2007.06722	JINST
Long-baseline neutrino oscillation physics potential of the DUNE experiment	2006.16043	EPJC
Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment	2008.06647	EPJC
Neutrino interaction classification with a convolutional neural network in the DUNE far detector	2006.15052	PRD
Low exposure long-baseline neutrino oscillation sensitivity of the DUNE experiment	2109.01304	PRD

- …with many others in progress

Title (Nearing Publication)	arXiv
Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora	
Separation of track- and shower-like energy deposits in ProtoDUNE-SP using a Convolutional Neural Network	2203.17053
Scintillation light detection in the 6-m drift-length ProtoDUNE Dual Phase liquid argon TPC	2203.16134
Identification and reconstruction of low-energy electrons in the ProtoDUNE-SP detector	
Deep-Learning-Based Kinematic Reconstruction for DUNE	

Why Liquid Argon?

Bubble chamber quality of data with added full calorimetry



Liquid Argon Time Projection Chamber (LArTPC)

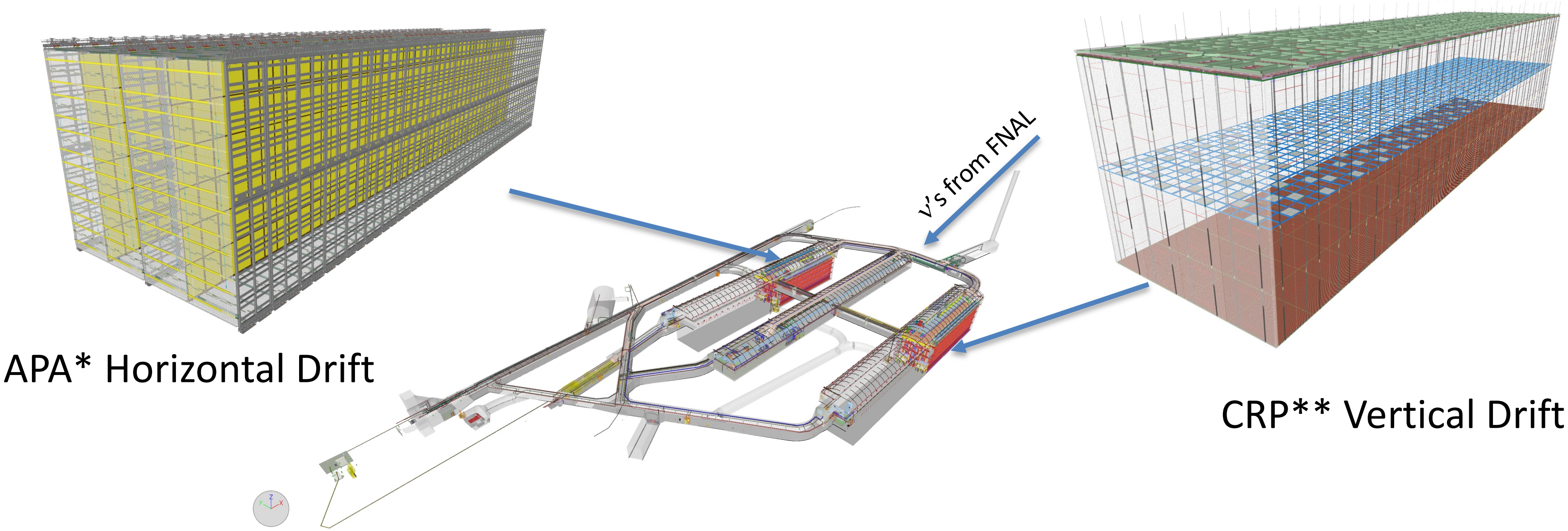
	Water	He	Ne	Ar	Kr	Xe
Boiling Point [K] @ 1atm	373	4.2	27.1	87.3	120.0	165.0
Density [g/cm^3]	1	0.125	1.2	1.4	2.4	3.0
Radiation Length [cm]	36.1	755.2	24.0	14.0	4.9	2.8
Scintillation [γ /MeV]	-	19,000	30,000	40,000	25,000	42,000
dE/dx [MeV/cm]	1.9		1.4	2.1	3.0	3.8
Scintillation λ [nm]		80	78	128	150	175
		~10$/L	~500$/L	~0.5$/L	~700$/L	~3000$/L

Liquid argon: an excellent choice for neutrino detectors

- Dense: 40% more dense than water
- Easily ionizable: 55,000 electrons/cm
- Highly scintillating: possible for photon detector system
- Very good dielectric properties: allow high-voltages in detector
- Long drift distance for ionization electrons (under high purity)
- Abundant & cheap: 1% of the atmosphere

DUNE – Phase 1

- 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)



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

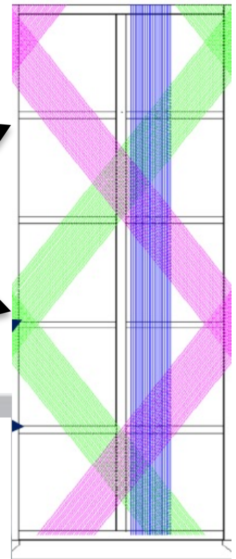
*Anode Plane Assemblies
**Charge Readout Planes

FD design: Horizontal drift LAr TPC

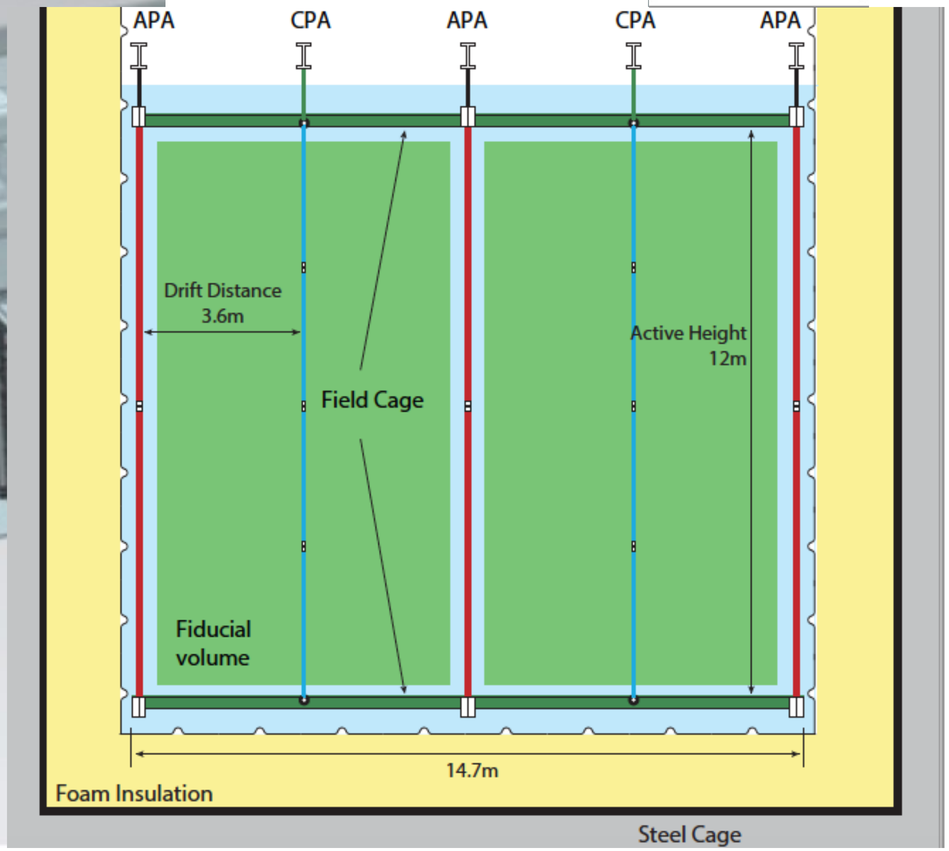
- Design *fixed* for the first 17 kton total (10 kton fiducial) module ➔ based on LBNE modular drift cell design
- APA (anode) and CPA (cathode) suspended from ceiling like curtains
- APA with “wrapped” induction and collection planes
- Photon detectors detect Ar scintillation with light guides and SiPMs at the end

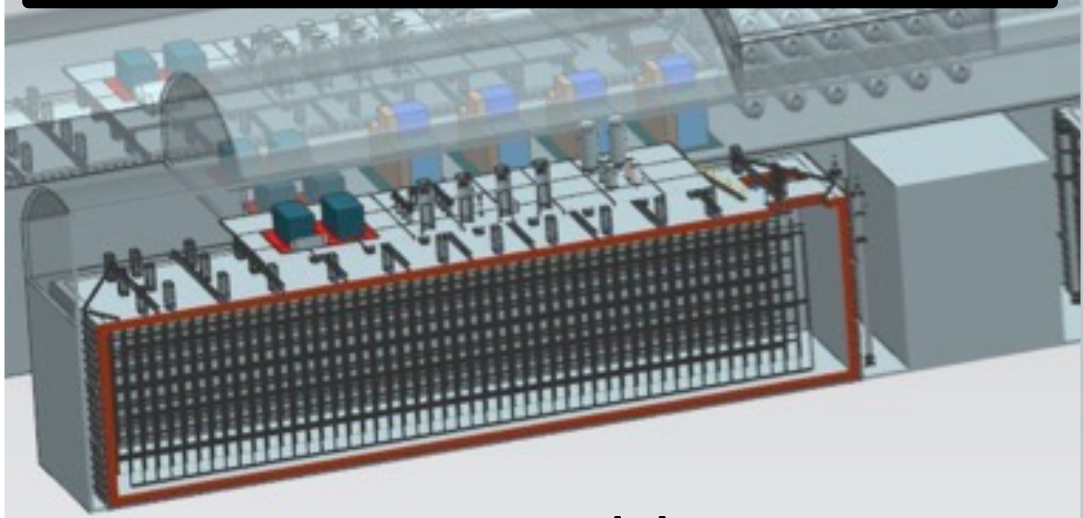
APA “wrapped”

Photon detectors
APA planes



APA: 2 x 6 x 2.3 m
Paired top to bottom

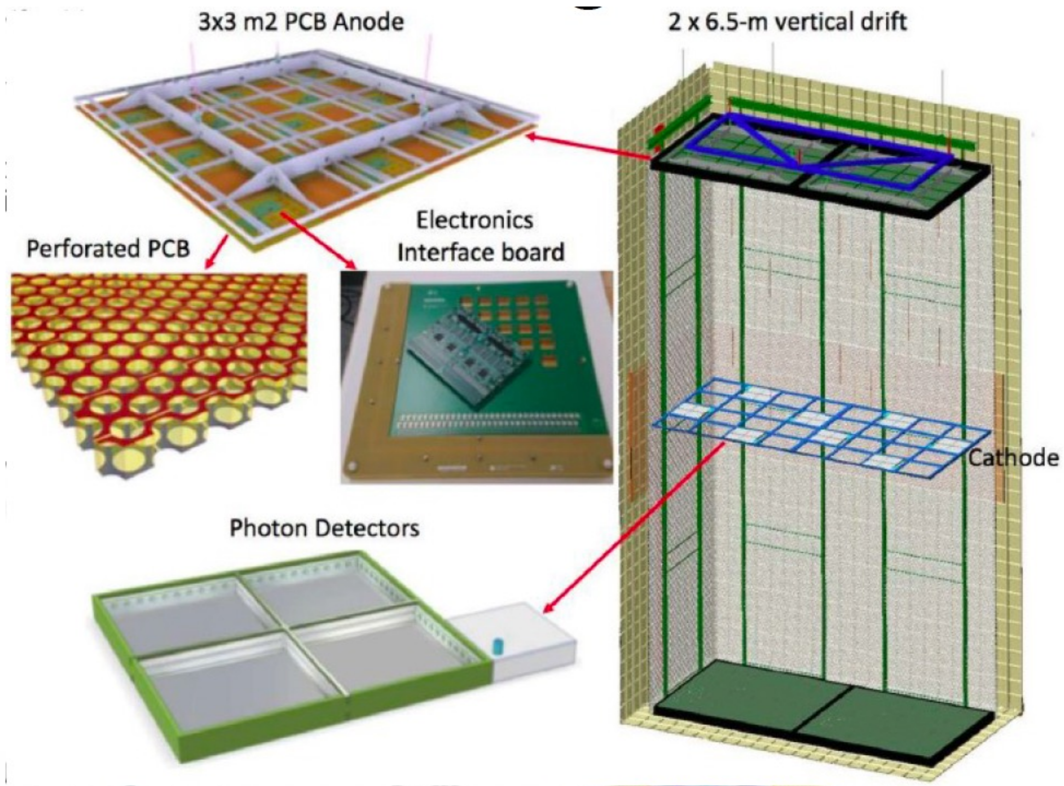


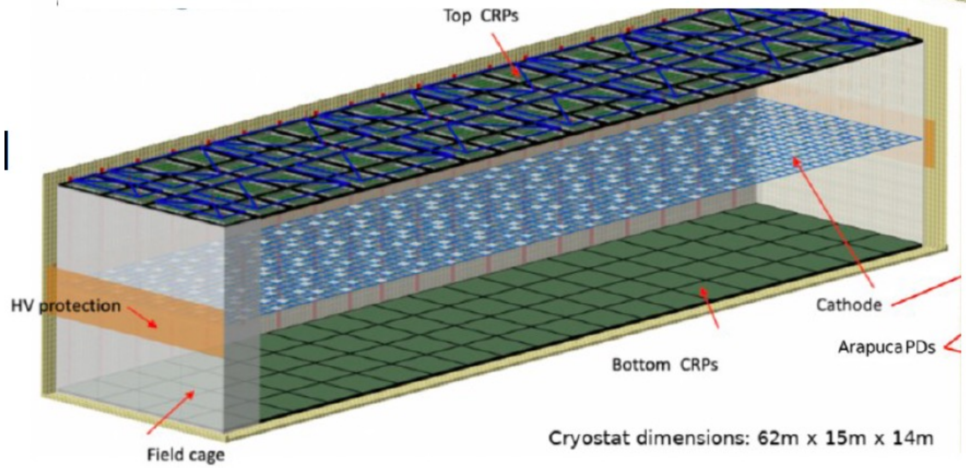


FD module

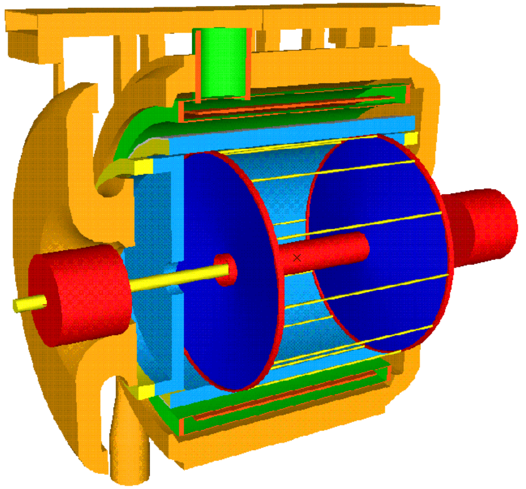
FD design: Vertical drift LAr TPC

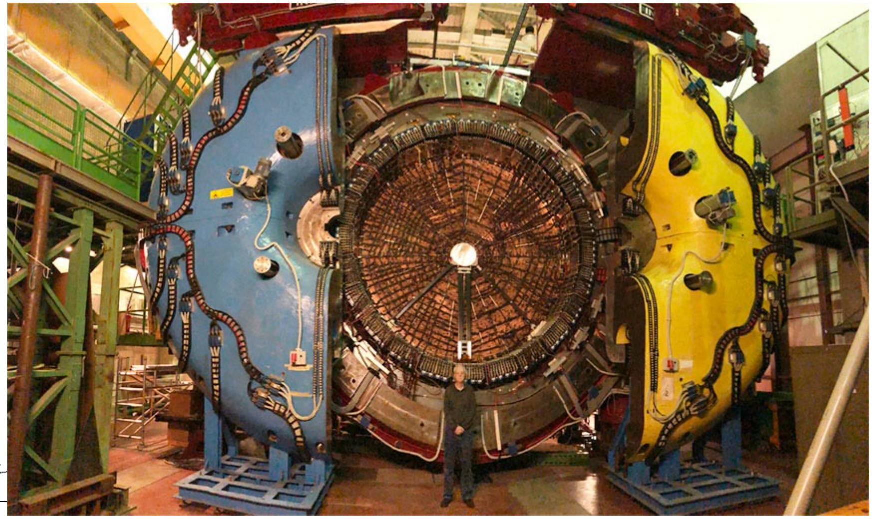
- Second module built will be Vertical Drift
- Evolution of the double phase concept
- Charge drifted vertically (6.5m), cathode in the middle
- Requires HV= -300kV
- Anode built out of strips etched on PCBs
- Large X-ARAPUCA detectors on cathode and walls.



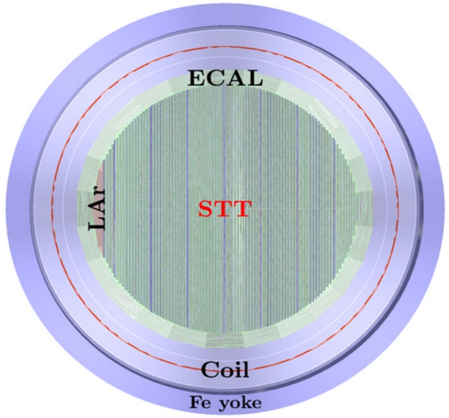


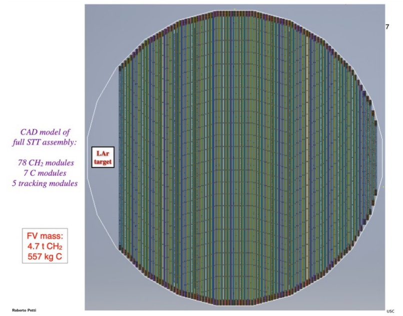
KLOE → SAND





ν–beam





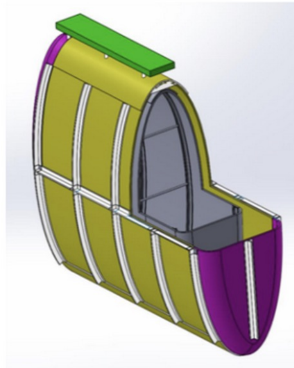
~200K Straw Tubes

KLOE experiment run at Laboratori Nazionali di Frascati(Rome) Italy from 1999 until 2018, at DAΦNE e^+e^- collider, for physics of K and Φ mesons.

Electromagnetic calorimeter
- Lead/scintillating fibers
- 4880 PMT's

Superconducting coil (5 m bore)
B = 0.6 T ($\int$ B dl = 2.2 T.m)

- Energy resolution
  $\sigma/E=5.7\%/\sqrt{E(\mathrm{GeV})}$
- Time resolution
  $\sigma=54\ \mathrm{ps}/\sqrt{E(\mathrm{GeV})} \oplus 50\mathrm{ps}$

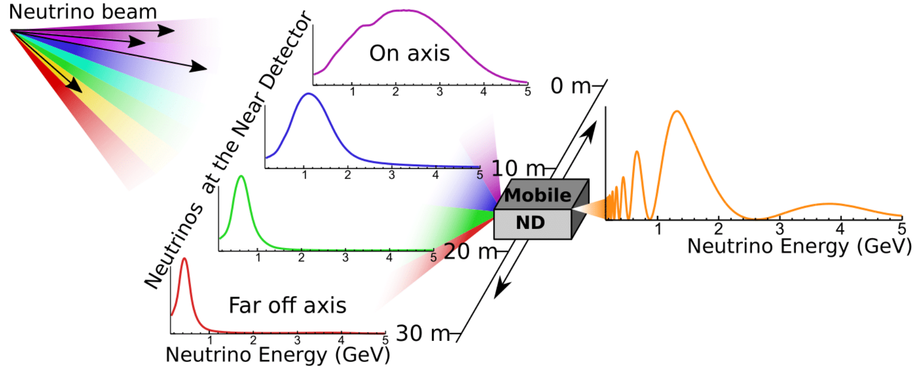


Liquid Argon target

New technique in Long-Baseline data taking and analysis

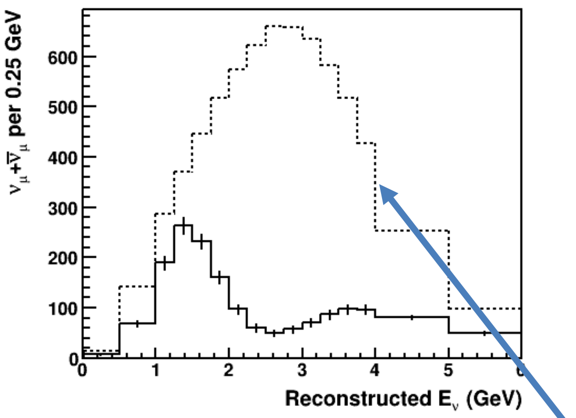
DUNE PRISM

Traditionally : use on-axis near detector to PREDICT an un-oscillated spectrum at the Far Site



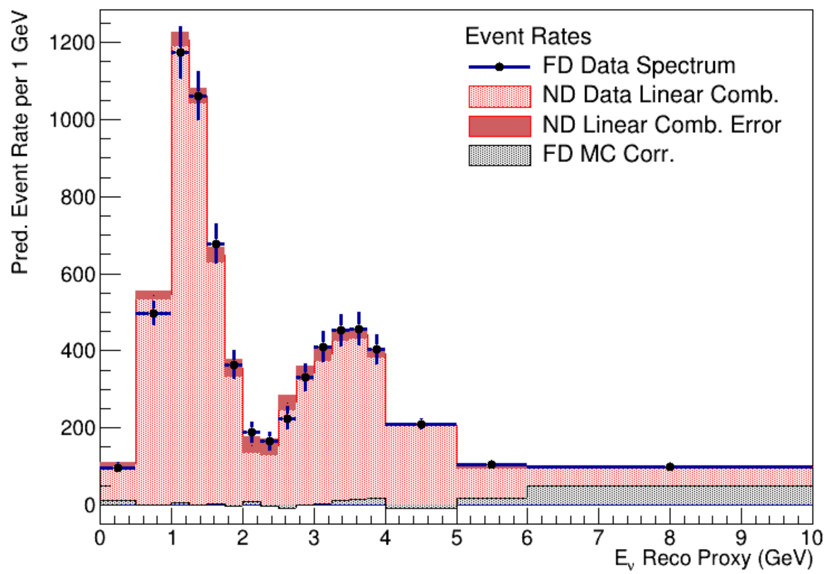
FD DATA

27E20 POT FHC

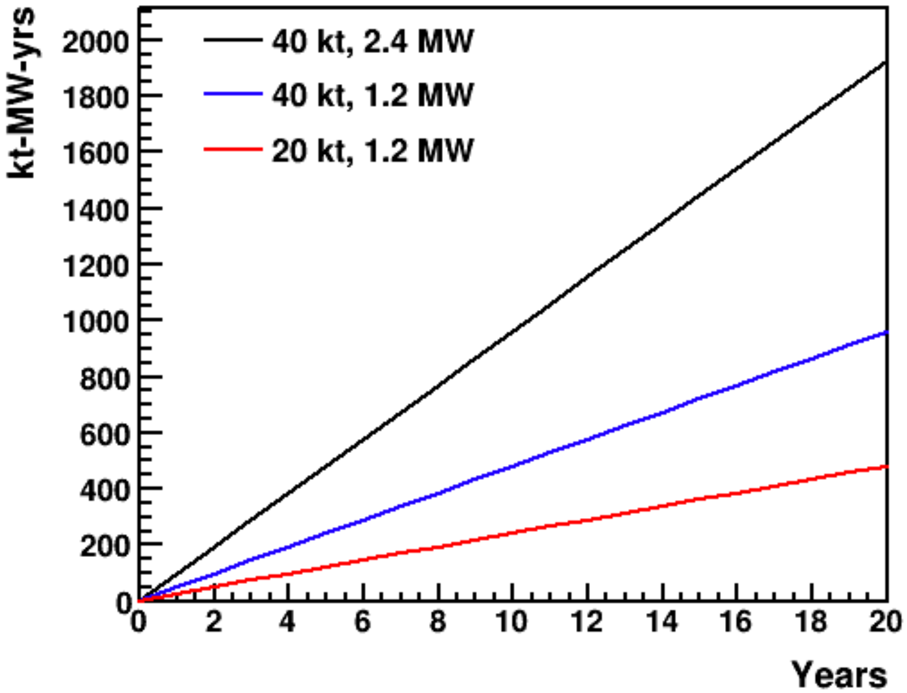


Un-oscillated MC prediction ~ on-axis near detector spectrum

PRISM FD Prediction



Why DUNE needs 2.4 MW



Precision physics of DUNE requires O(1000) kt-MW-yr beam exposure

- We want to achieve this in ~1 decade
  - 46 years in Phase I
  - 23 years with 40 kt but still 1.2 MW
  - 11.5 years with 40 kt and 2.4 MW

C.Marshall@Snowmass2022

Perspectives…

“Experiments” in running:

- NOvA
- T2K
- Cosmology
- SuperNovae

Future:

- JUNO ➔ *Reactor neutrinos*

- ORCA (KM3Net)
- PINGU (IceCube)
- INO
- HK

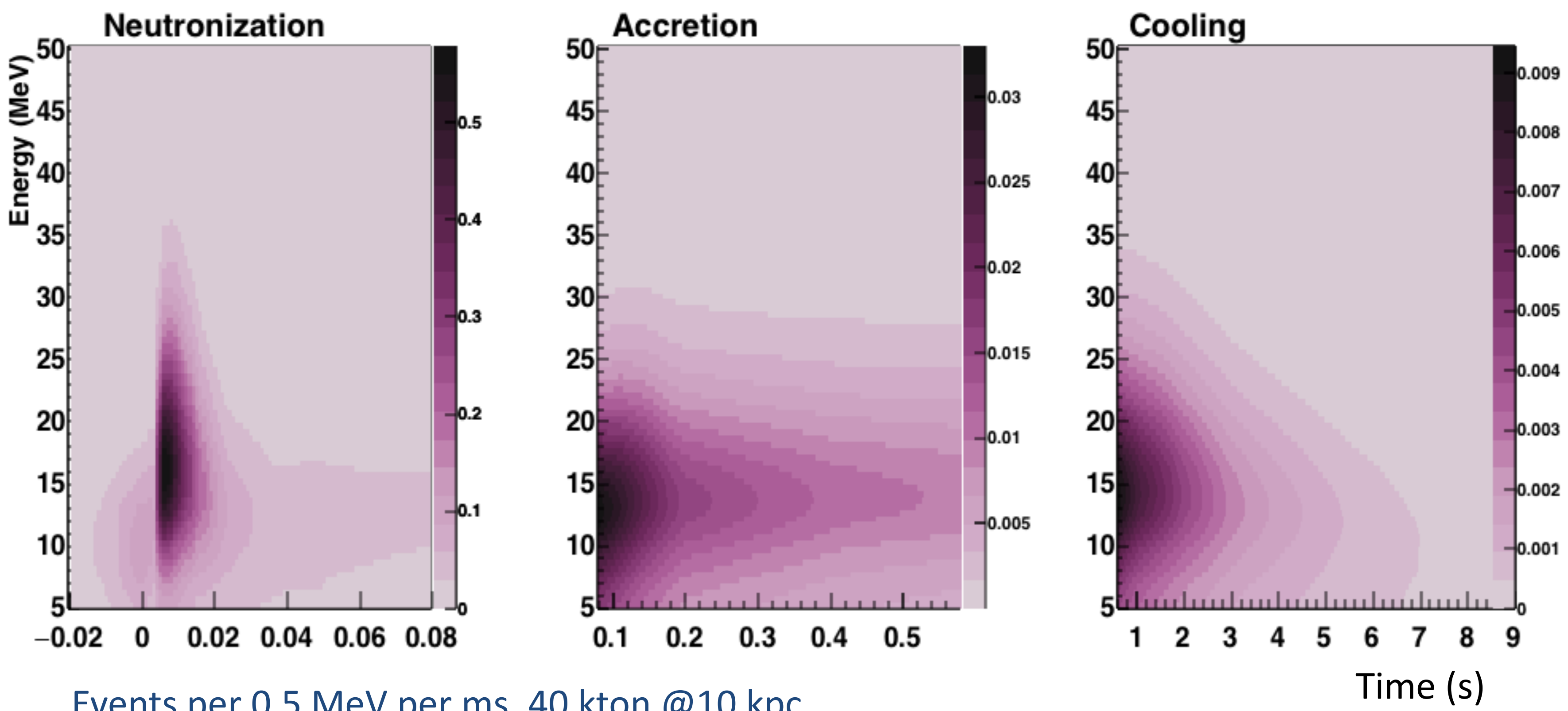
➔ *Atmospheric neutrinos*

- NOvA+T2KII
- **DUNE**
- HK (T2KK)

➔ *Long baseline*

SNB neutrinos

In LArTPC, SNB signal dominated by electron neutrinos: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

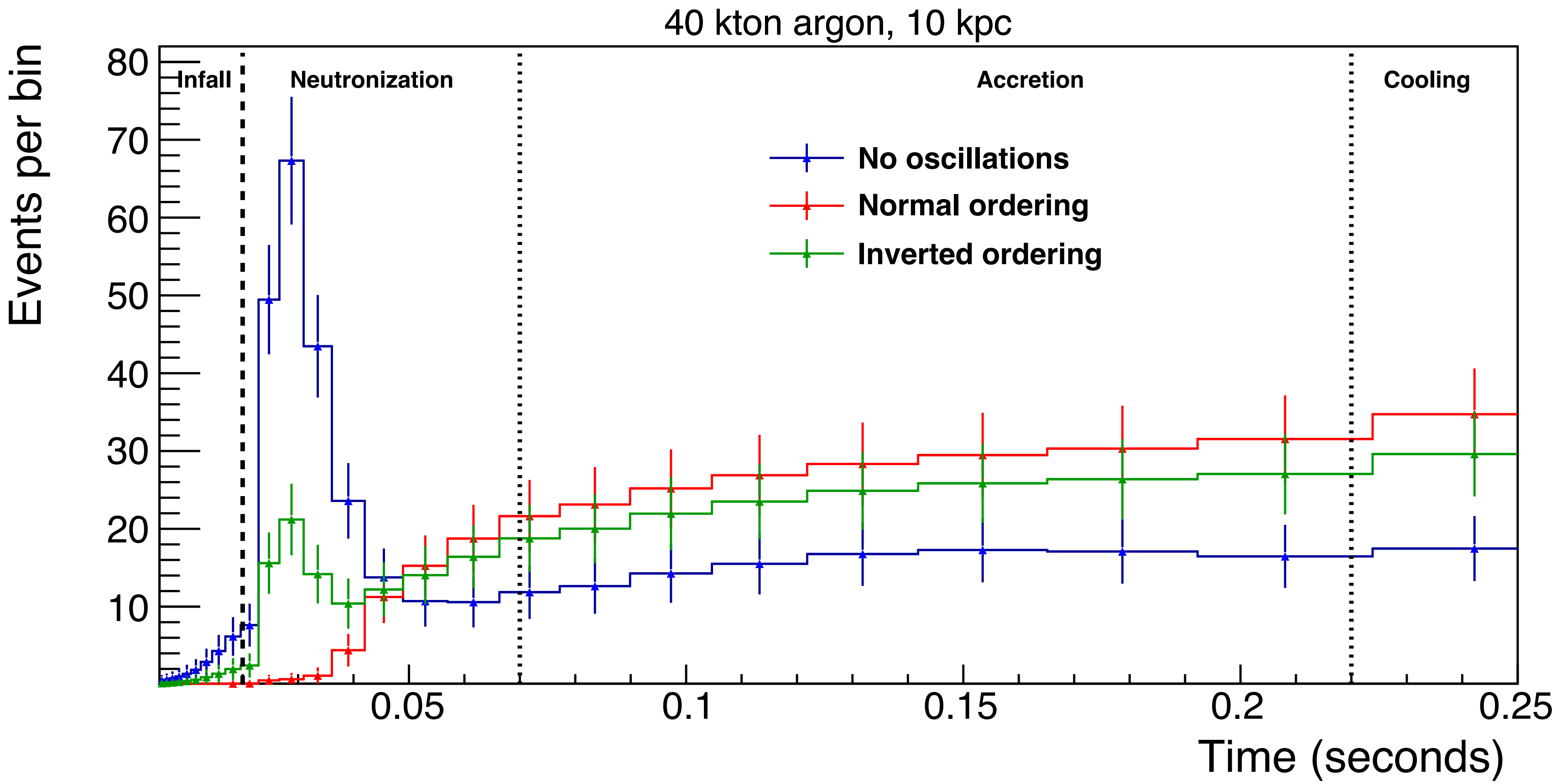


Events per 0.5 MeV per ms, 40 kton @10 kpc

SNB neutrinos

Eur.Phys.J. C81 (2021) 5, 423

In LArTPC, SNB signal dominated by electron neutrinos: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

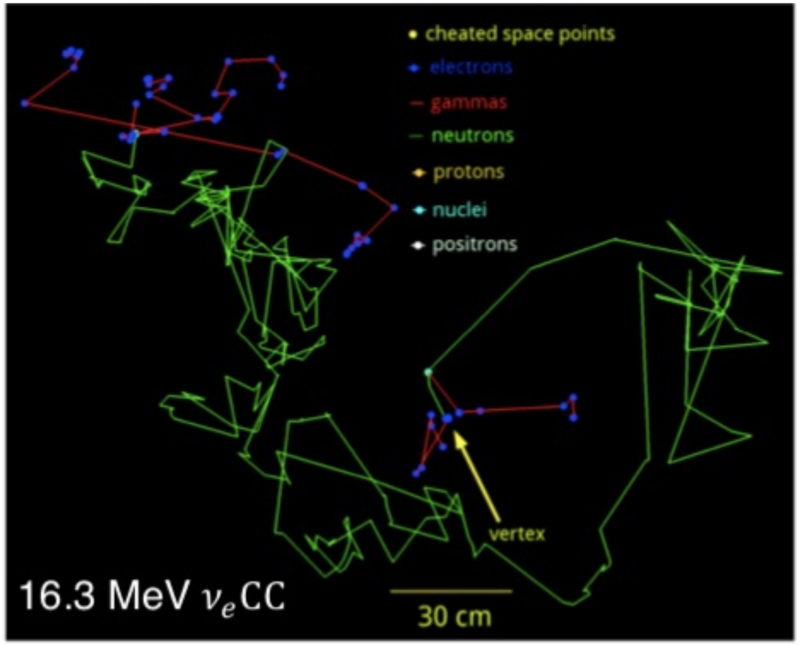


Observation of early time development yields sensitivity to neutrino mass ordering and details of SNB model.

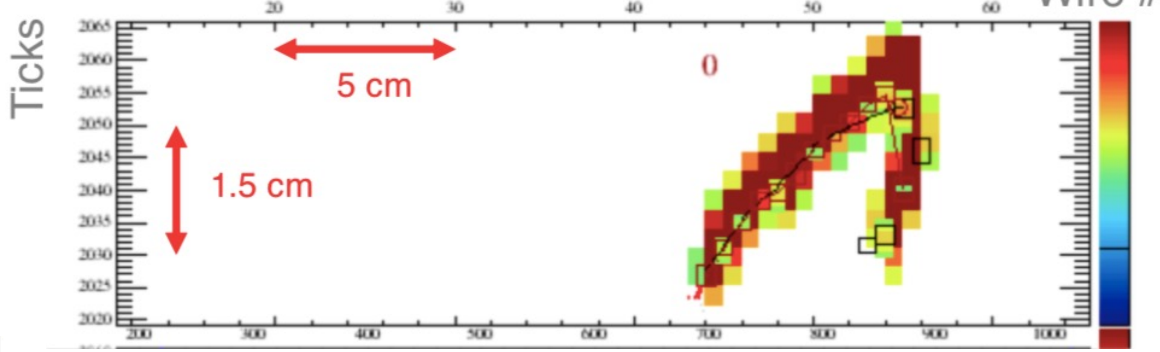
SNB ν Simulation & Reconstruction

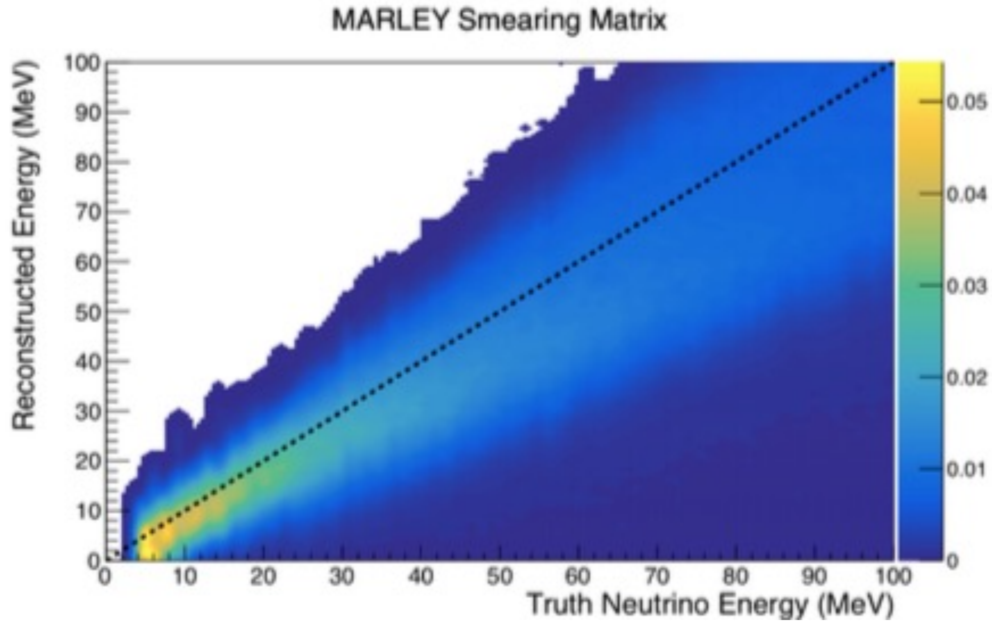
Work underway on improved event reconstruction and tagging of 5-100 MeV events+ DAQ/triggering

MARLEY event generator: marleygen.org



DUNE Simulation 30.25-MeV ν

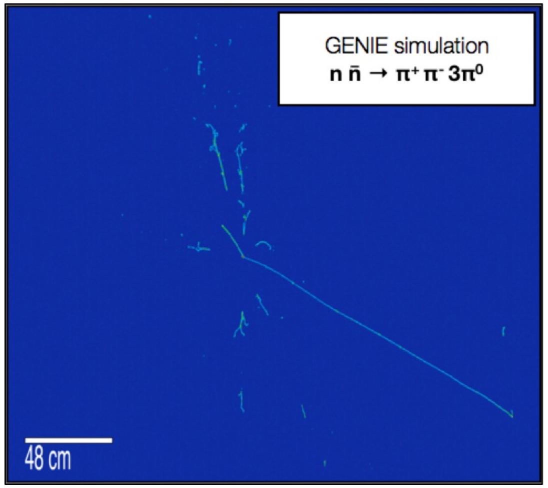




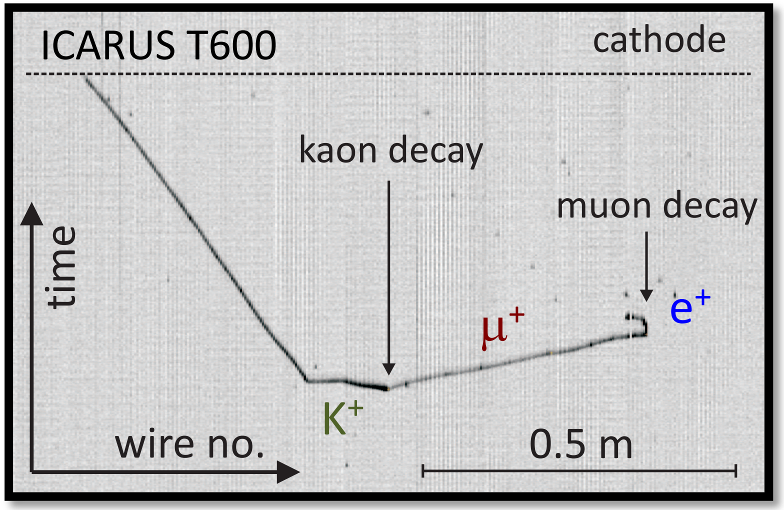
Baryon Number Violation

- Deep underground location and precise particle tracking facilitate DUNE sensitivity to many baryon number violating processes including:
  - Neutron-antineutron oscillation
  - $p \to \nu K^+$, $n \to K^+ e^-$
  - $p \to \pi^0 e^+$

$n\bar{n}$ MC:

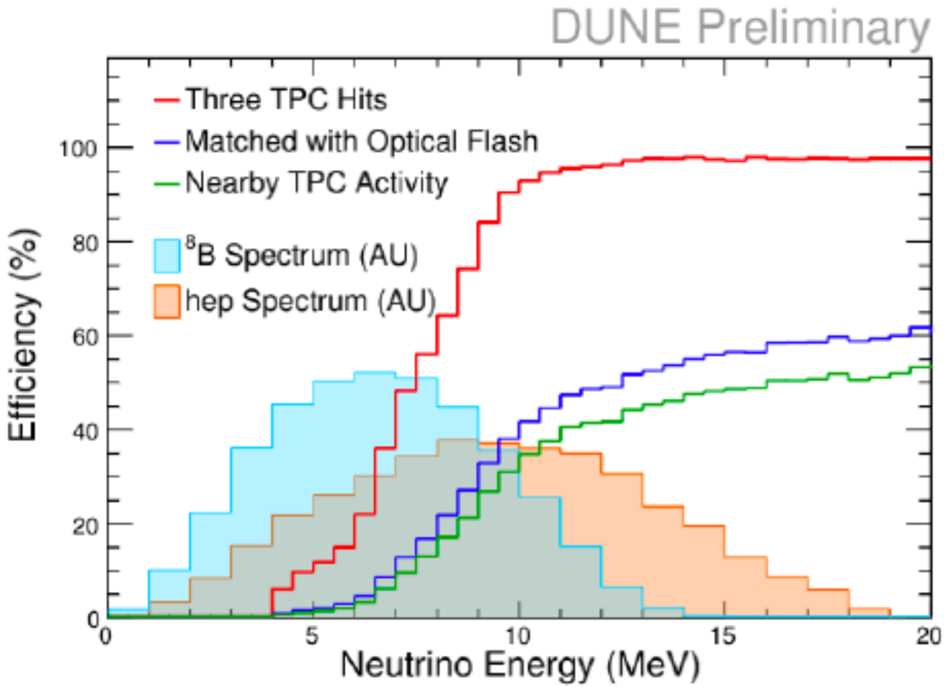


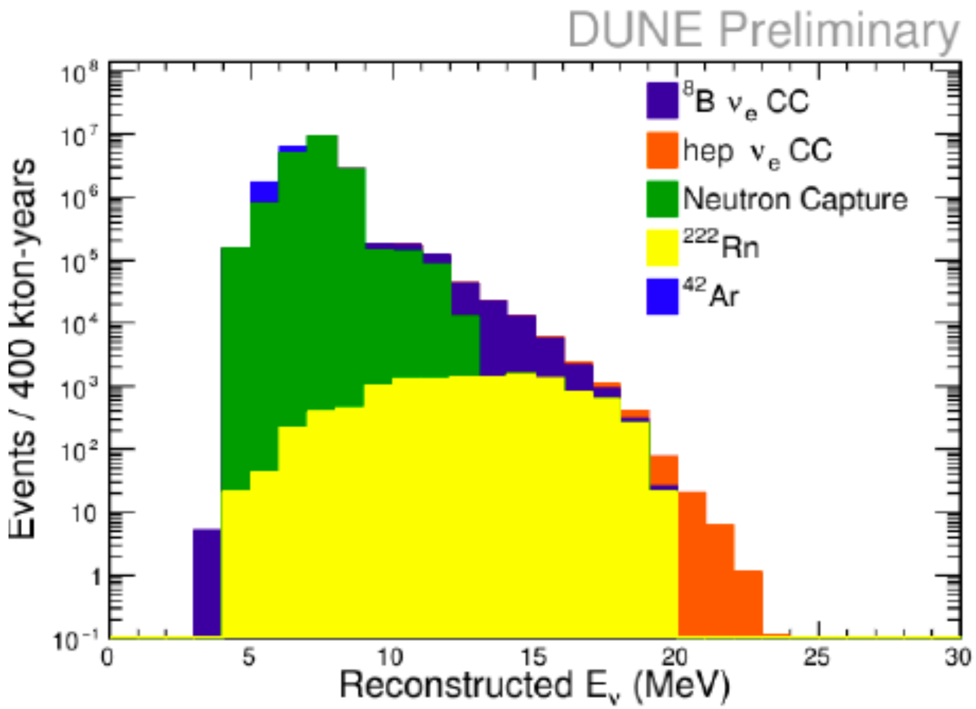
Cosmogenically induced K^+ event:



- Sensitivity based on full MC and automated reconstruction and event selection
- Challenges include atmospheric neutrino background and final state interactions within the argon nucleus

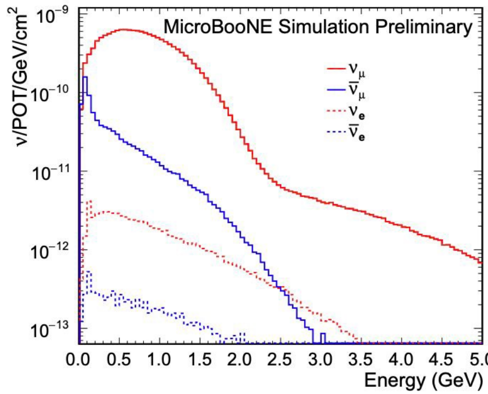
Solar neutrinos

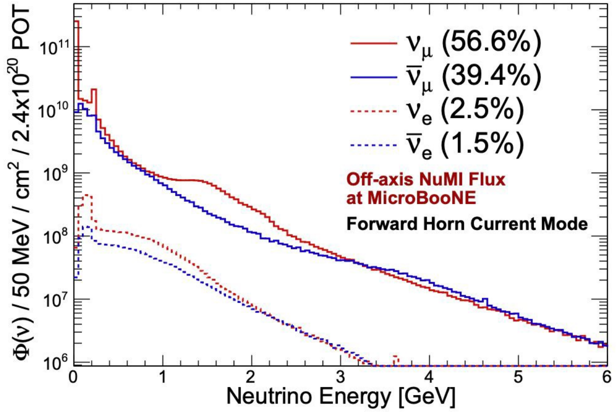


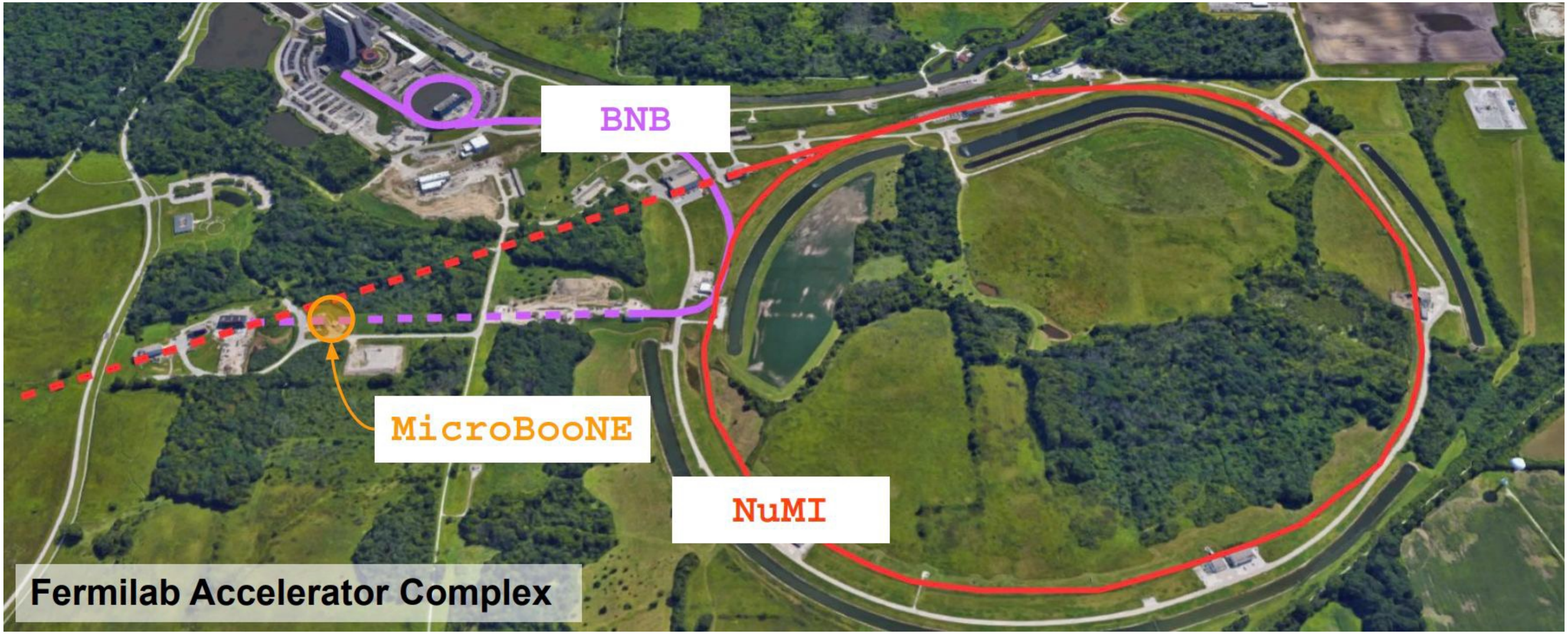


- Solar neutrino sensitivity to ^{8}B and discovery potential of hep flux, with capability to measure solar mixing parameters θ_{12} and Δm^2_{12}
- ve flux → measure neutronization burst
- Main backgrounds: neutrons and Rn-induced alpha-gamma interactions

FNAL neutrino beams

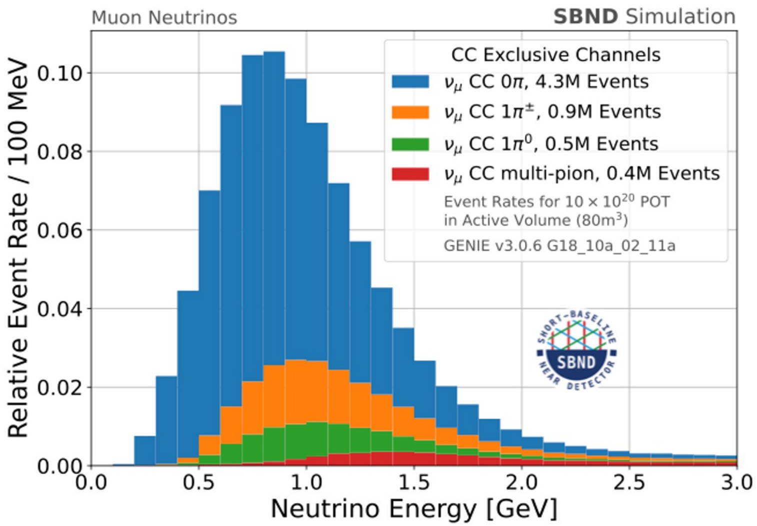




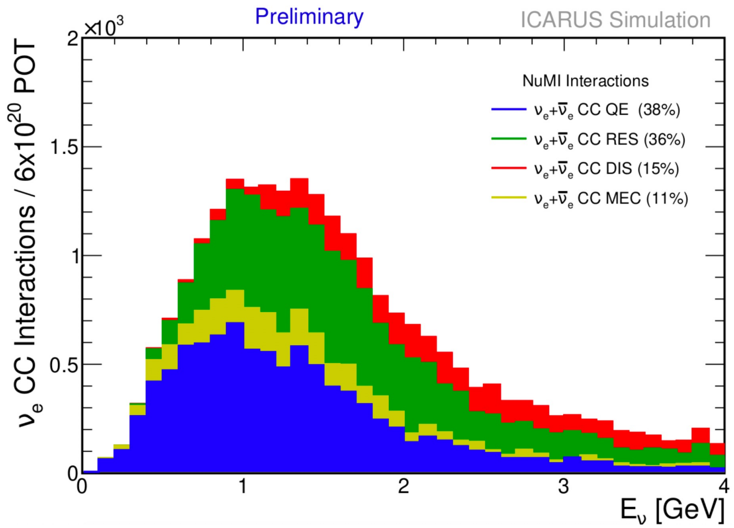


SBN cross sections measurements

SBND High-statistics measurements of many signatures and can observe rare channels such as heavy baryons (Λ^0, Σ^+), NC coherent single photon production, etc.



ICARUS can leverage its off-axis position in the NuMI beam and observe a ν_e enriched flux for ν_e-Ar measurements



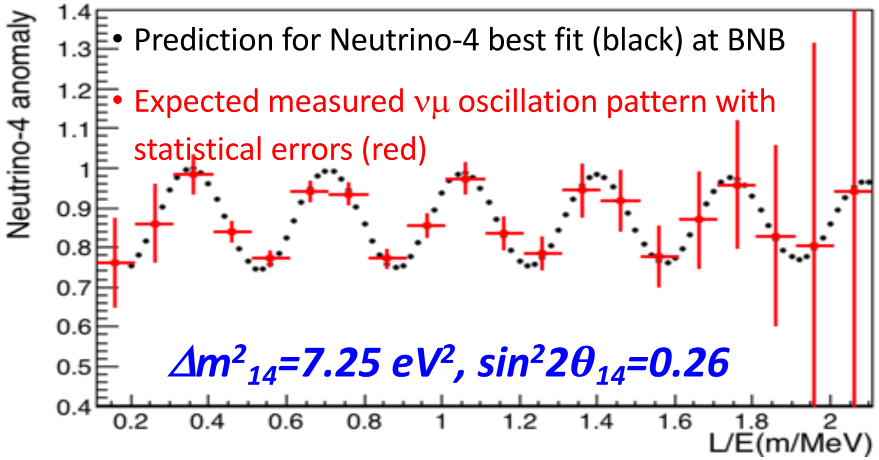
SBN cross section measurements will inform cross section theory & generator work, and lay groundwork to lower the systematic uncertainties for current and future high-precision experiments such as DUNE.

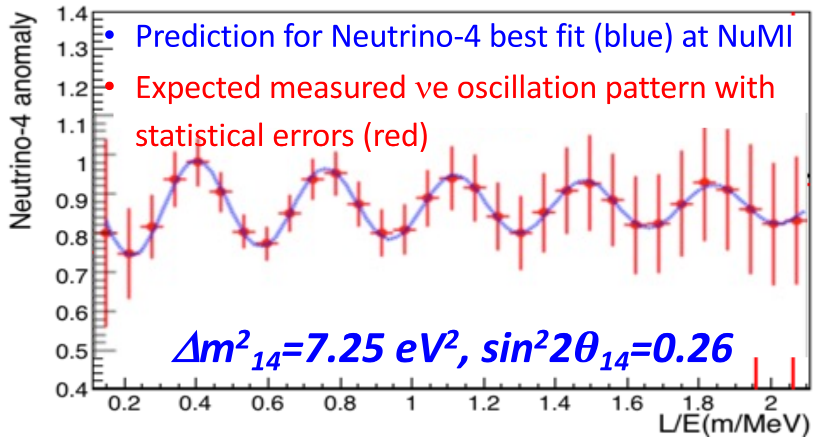
R.Wilson@Snowmass2022

Neutrino-4 oscillation check *(ICARUS)*

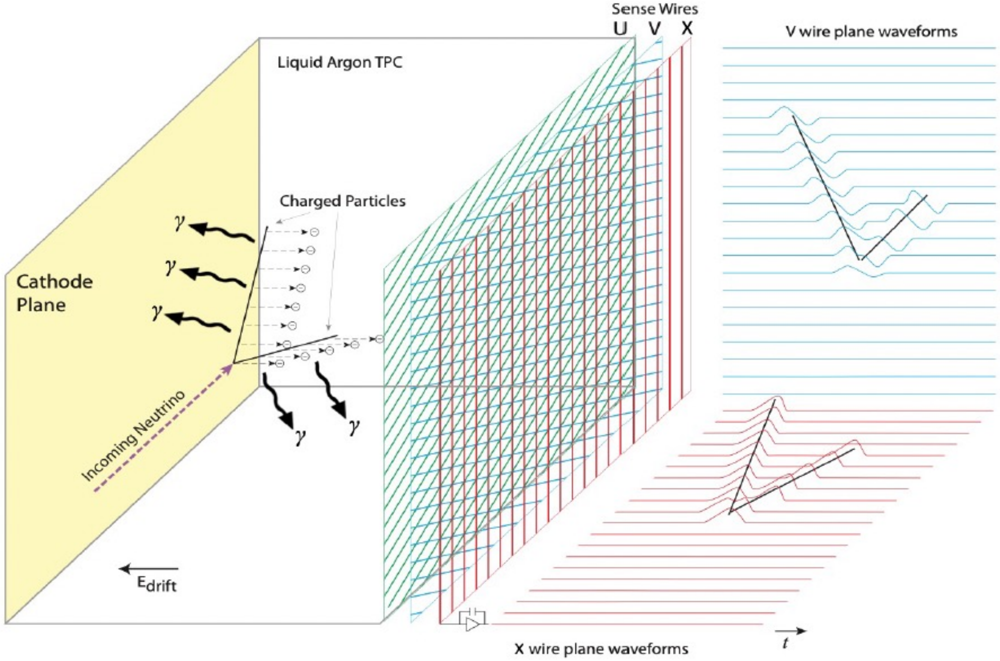
Given the ICARUS at FNAL similarities to NEUTRINO-4, the initial ICARUS data (~1 year) should allow to settle the two NEUTRINO-4 (~7 eV^2) sterile-ν claims:

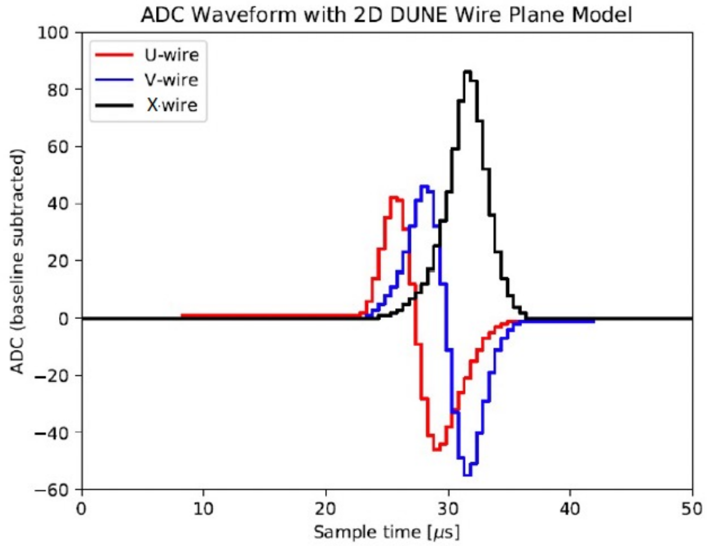
- Oscillations produce disappearance pattern of ν_μ in BNB and of ν_e in NuMI, in same L/E ~ 1-3 m/MeV of Neutrino-4 (at ~100 times higher energy), focusing on contained quasi-elastic CC interactions;
- L/Eν effect mostly related to variation of E_ν with a large and almost constant L: despite the 725 m NuMI decay tunnel ν_e mostly produced by kaons decaying close to target.





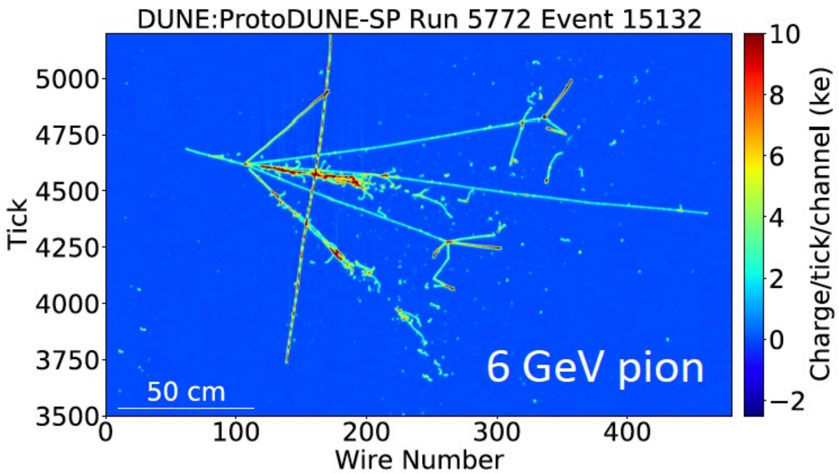
Liquid Argon Time Projection Chamber (LArTPC)



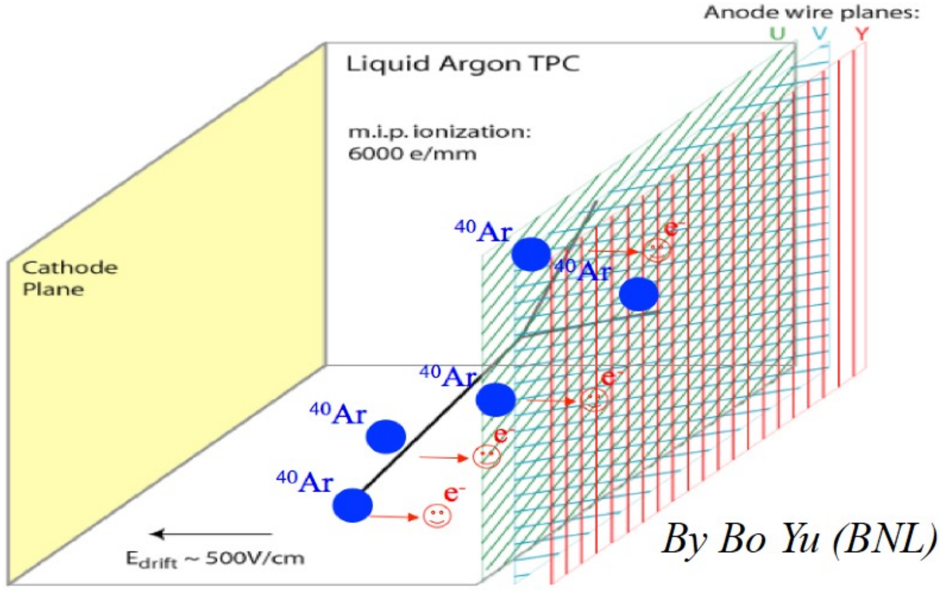


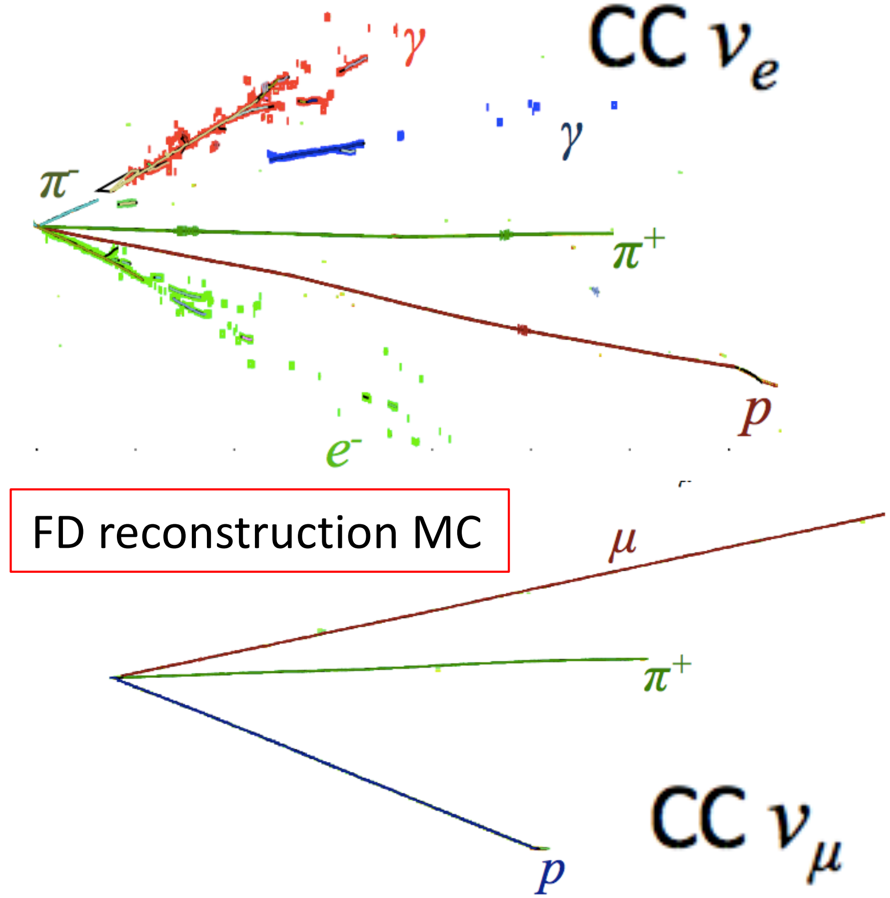
Primary detector technology for DUNE

- Detailed images of events
- Excellent spatial and calorimetric resolutions



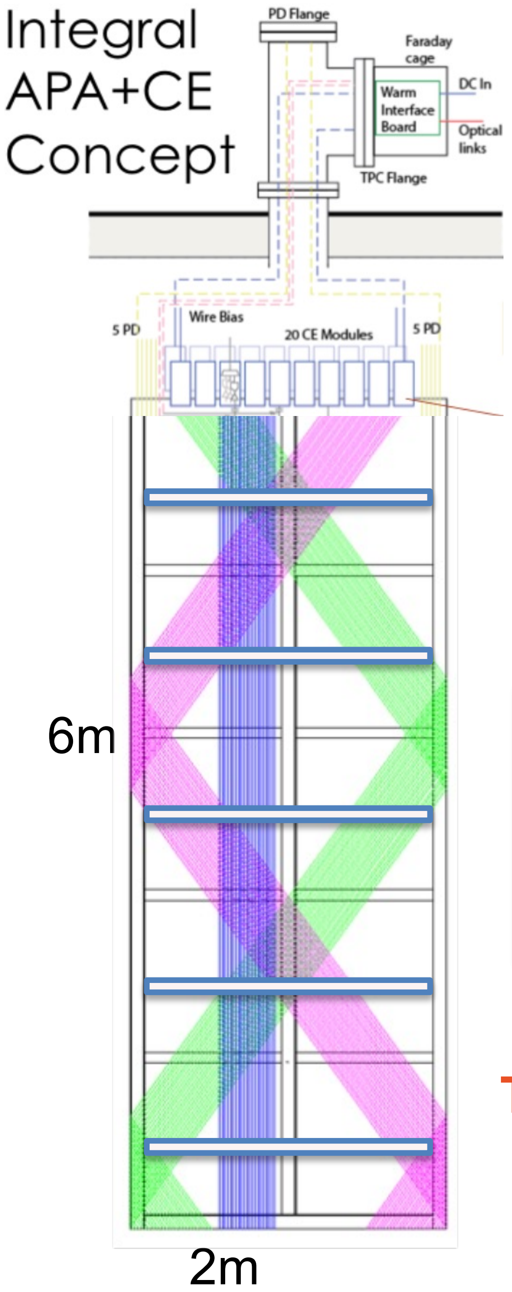
Far Detector Single Phase Technology – Liquid Argon Time Projection Chamber





- LAr TPC: excellent tracking and calorimetry
- Suitable for very large detectors – high signal eff. and bkg. discrimination
- High resolution 3D reconstruction – charged particles ionize Ar; electrons drift to anode wires (~ms) for xy coordinate; drift time – z coordinate
- Ar scintillation light (~ns) detected by photon detectors – provides t0

APA concept



Core detector element: Anode Plane Assemblies (APA) with integrated Cold Electronics Boards and Ph.Detector modules

Each APA : 960 X, 800 V, 800 U, 960 G (un-instrumented) wires

10 Photon Detectors are installed into each APA frame

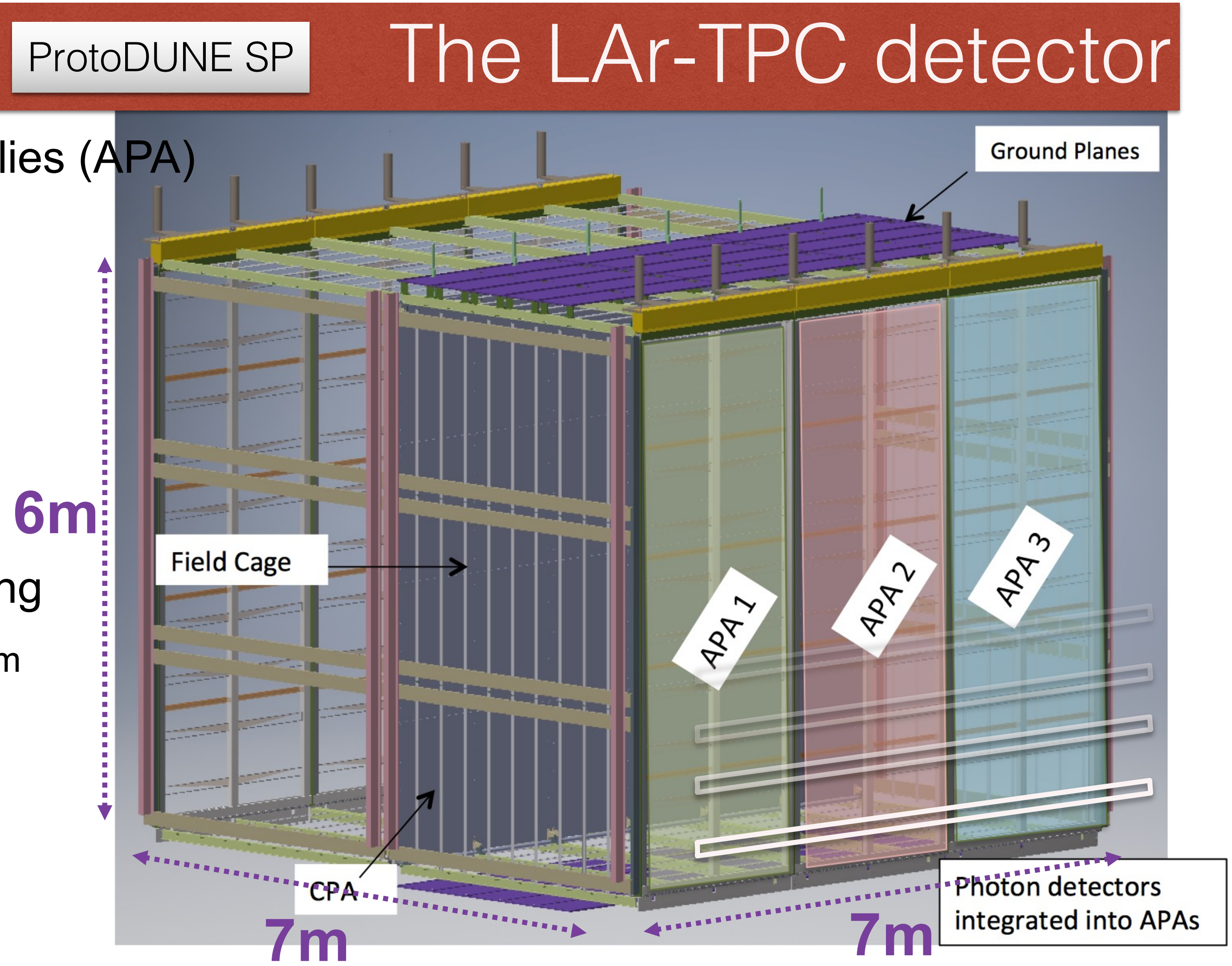
20 ColdElectronics Boxes mounted onto the APA frame and connected to the wires - 2560 Channels-Wire

- The modular approach to detector construction enables the construction of detector elements to take place in parallel and at multiple sites.

This will be an essential approach for the DUNE Far Detector

The ProtoDUNE SP Detector

- Six Anode Plane Assemblies (APA)
  - 3 APAs on each side
- Central cathode plane
  - -180 kV nominal
- Field Cage for field shaping
  - shaped profiles / G-10 I-Beam
  - Constructed in panels
- Ground Planes



DUNE Systematics: TDR

- Systematics analysis building on expertise developed in MINERvA, T2K, and NOvA
  - “DUNEResponse” ← “T2KReweight”
- CAFAna fitting framework facilitates more sophisticated treatment of systematic uncertainty than was possible for CDR
  - Systematic uncertainties in TDR will be based on detailed evaluation of flux, neutrino interaction, and detector uncertainties
  - Sensitivity calculations will be based on fits combining information from near and far detectors
- Flux and interaction systematics evaluated using reweighting technique (including GENIE and non-GENIE reweights)
  - Impact of systematic variations propagated through full analysis chain
  - Ability to consider systematics impacting kinematic distributions as well as normalization
- Detector systematics evaluated within the fit
  - Detector calibration task force evaluating magnitude and sources of detector uncertainty

YUKAWA HALL KYOTO

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Baryogenesis without Grand Unification

M. Fukugita

Research Institute for Fundamental Physics, Kyoto University

Kyoto 606, Japan

and

T. Yanagida

Institute of Physics, College of General Education, Tohoku University

Sendai 980, Japan

Abstract

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories. The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon-number violation of electroweak processes at high temperatures.

Classifying the free parameters of the Standard Model

The free parameters in the electroweak Standard Model for one generation are

- the two gauge couplings g, g' for the $SU(2)_L$ and $U(1)_Y$ gauge groups;
- the two parameters μ and λ in the potential $V(\Phi)$;
- the Yukawa couplings Y_u, Y_d, Y_e and Y_ν.

Adding the QCD sector and two more generations of quarks and leptons, the Standard Model contains at least 26 free parameters:

- 3 gauge couplings
- 6 quark masses
- 6 lepton masses
- 3+3 mixing angles
- 1+1 CP-violating phases
- 1 W or Z mass
- 1 Higgs mass
- 1 CP-violating angle

Physics beyond the Standard Model?

- The problem of mass:

  What is the origin of particle masses? Is it the SM Higgs field?
  What stabilizes the Higgs mass?
  What sets the scale of fermion masses?

- The problem of unification:

  Is there a simple framework for unifying all particle interactions?

- The problem of flavour:

  Why are there so many types of quarks and leptons?
  What is the origin of CP-violation?

- Cosmological problems:

  What is the origin of the baryon-antibaryon asymmetry?
  What is the nature of dark matter and dark energy?