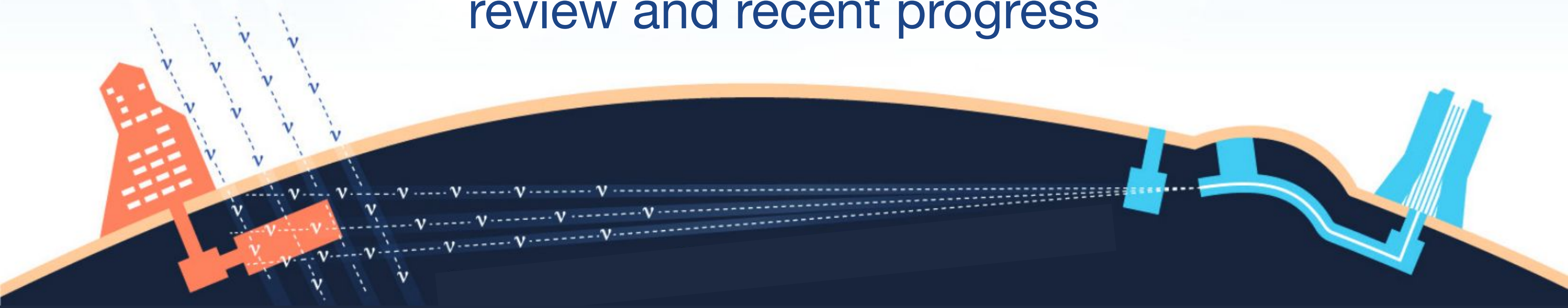
Deep Underground Neutrino Experiment

review and recent progress



Claire David
on behalf of the DUNE Collaboration

CAP Congress | 8 June 2021

YORK UNIVERSITÉ UNIVERSITY

Fermilab

This talk

Review

L B N F Long-Baseline Neutrino Facility

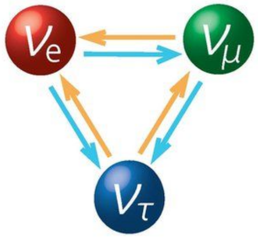
DUNE Deep Underground Neutrino Experiment

ProtoDUNE @ CERN Neutrino platform Prototyping efforts & first results

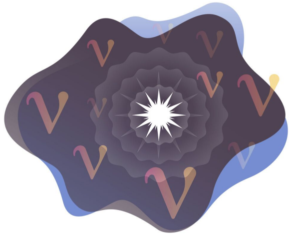
Prospects DUNE's sensitivity

DUNE-Canada and how you can contribute

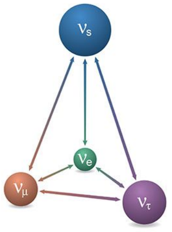
Primary physics program of DUNE



- **Oscillation physics**
  - Search for leptonic CP violation — *Do neutrinos oscillate the same way as antineutrinos?*
  - Determine the neutrino mass hierarchy — *Is ν_3 the lightest?*
  - Precision measurements on PMNS matrix parameters



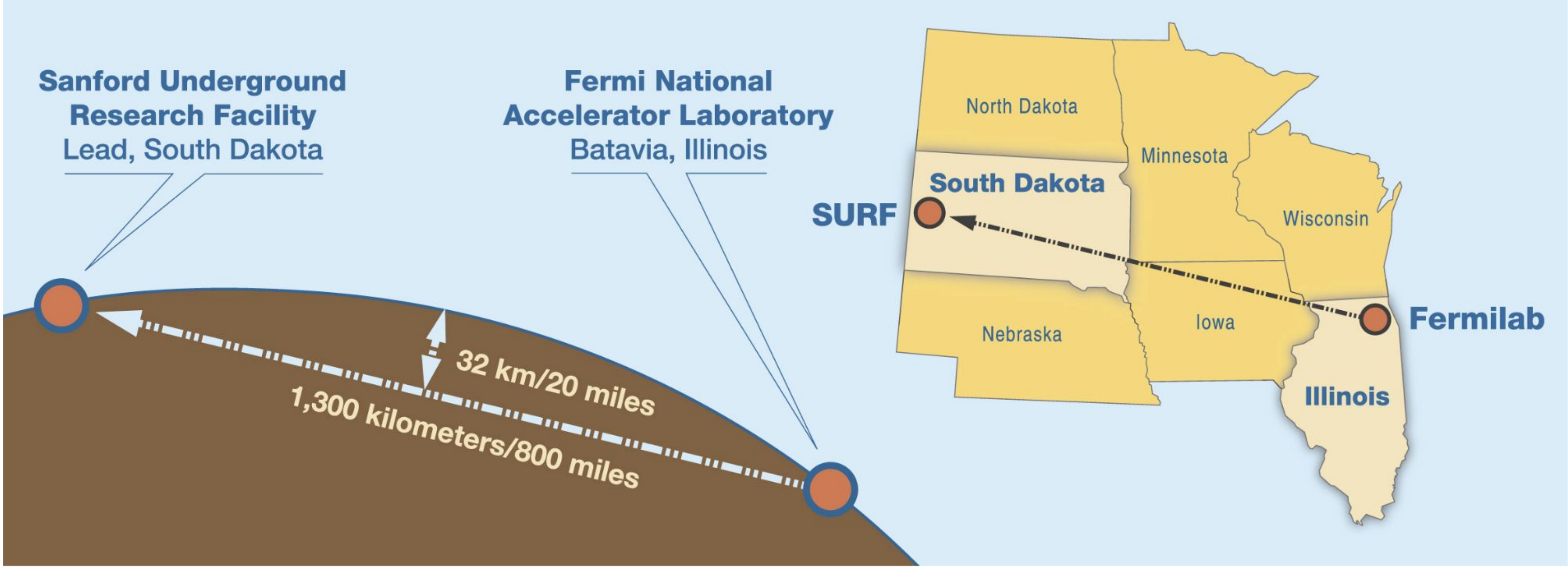
- **Supernova physics**
  - What is the astrophysics of core-collapse supernova?
  - What are the properties of neutrinos from a supernova burst
  - Possibility to estimate direction: warning telescopes (light comes hours after ν)



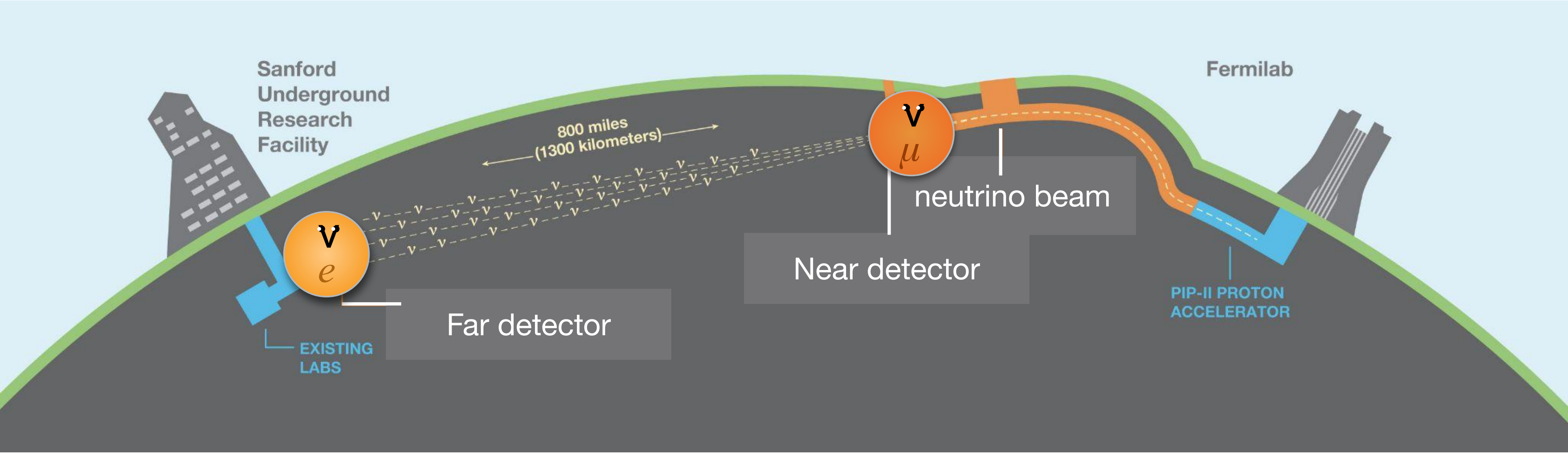
- **Beyond Standard Model (BSM)**
  - Probing numerous BSM models on baryon number violation
  - Non-standard Neutrino Interactions (NSI), sterile neutrinos, dark matter
  - Sensitivity to proton decay, predicted by GUT models (e.g. $p \rightarrow K^+ \overline{\nu}$ channel)

DUNE: Deep Underground Neutrino Experiment

Measuring ν_μ survival/disappearance + ν_e appearance probabilities → function of $\frac{L}{E}$ (L ← *distance*, E ← *ν energy*)



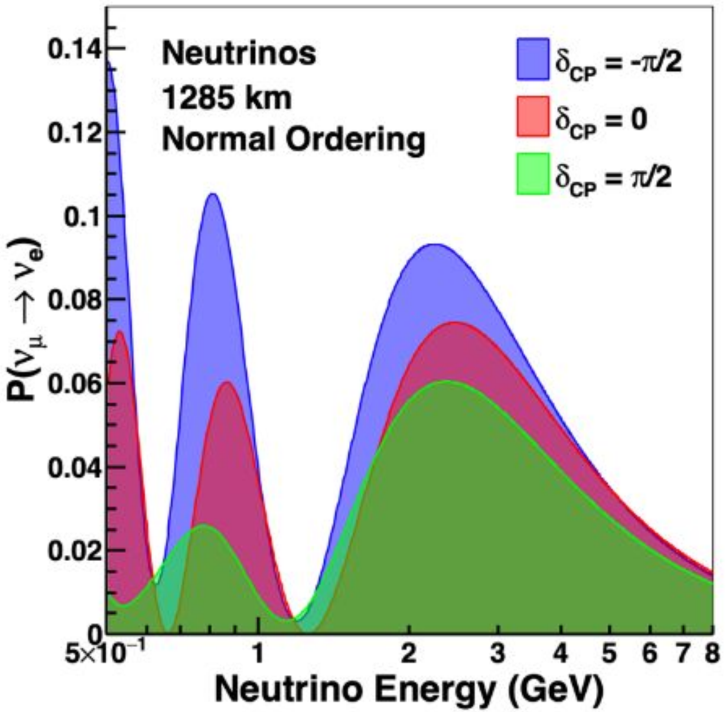
Long-baseline oscillation experiment

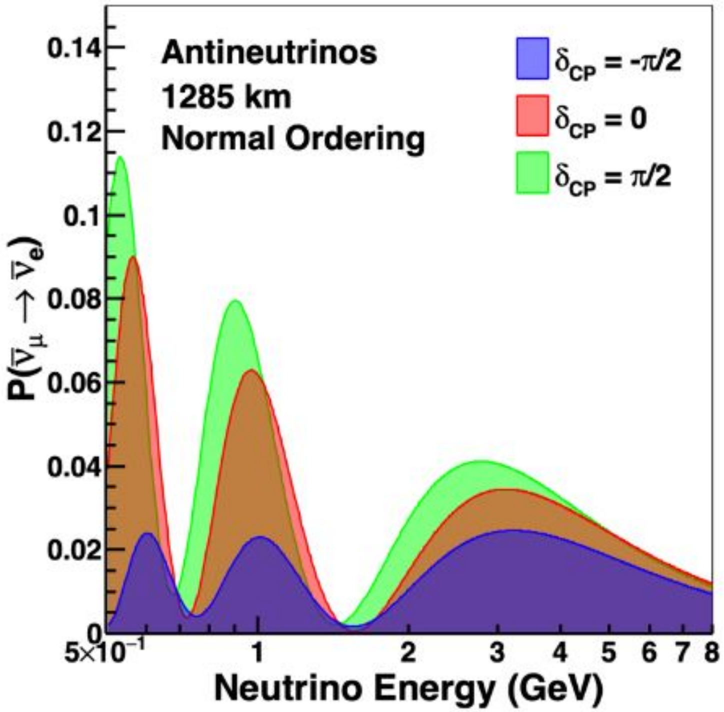


Need to model matter effects through Earth (full of electrons, no positrons)

Appearance probability at 1285 km

DUNE will be sensitive to the shape of neutrino oscillation spectrum   arXiv:2006.16043





Long-baseline Neutrino Facility (LBNF)

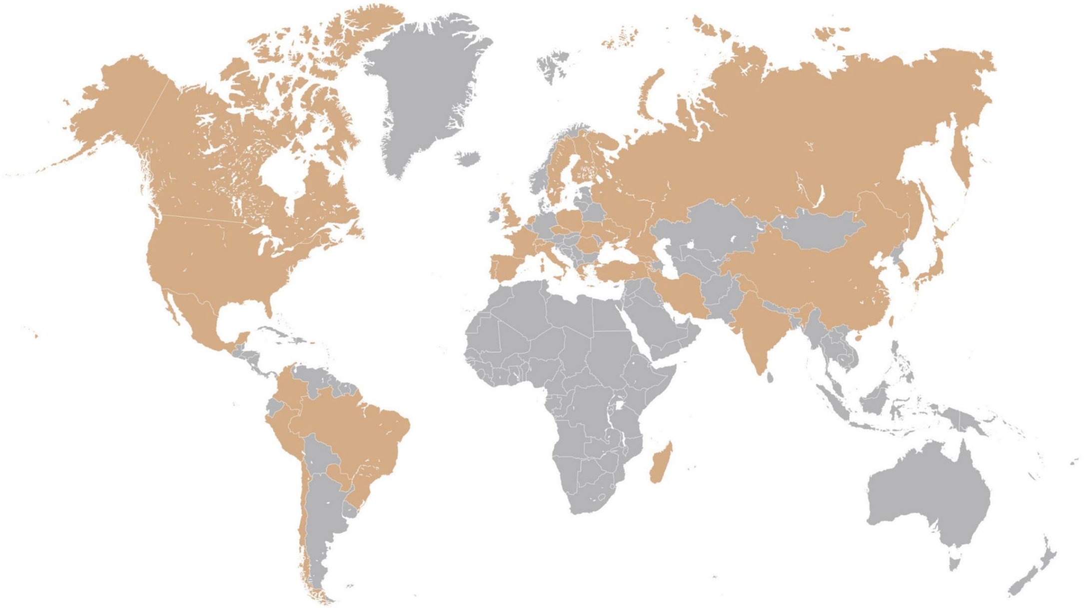
LBNF DOE/Fermilab-hosted facilities project, with international participation

DUNE The international scientific collaboration

1347 collaborators

204 institutions

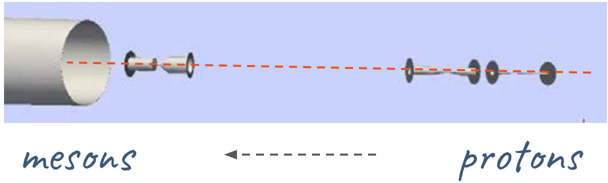
33 countries + CERN

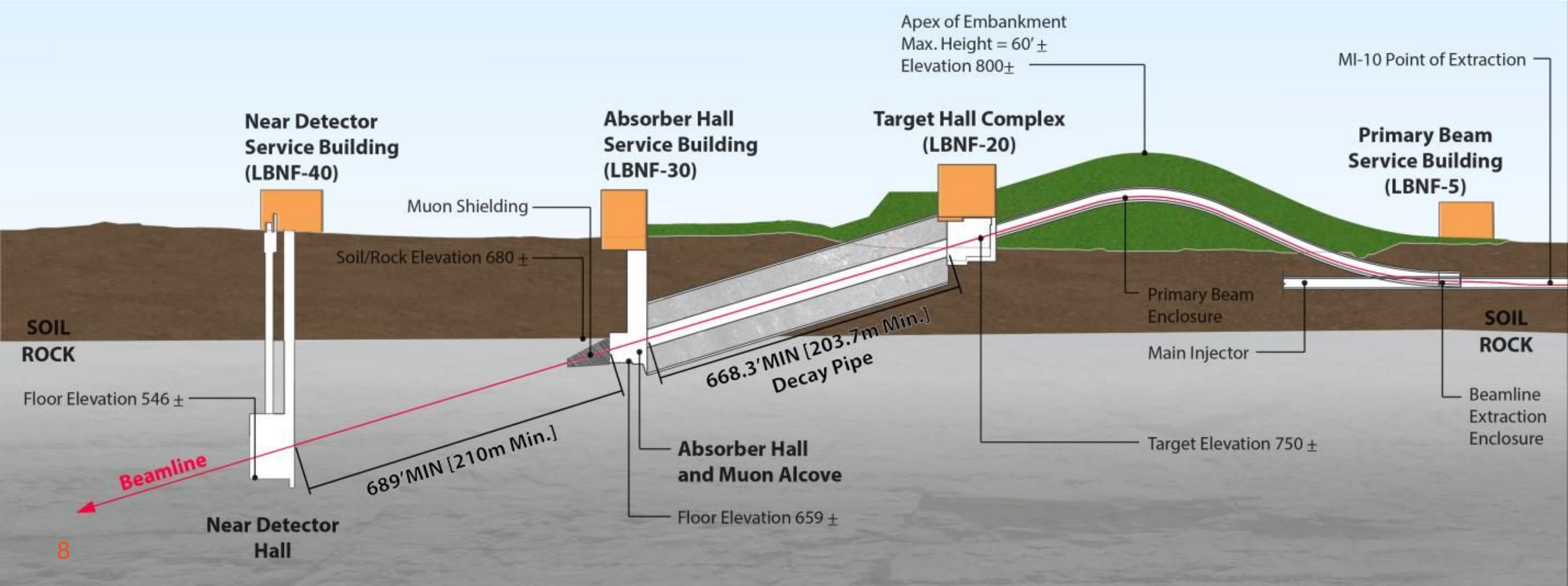


Beamline

Horn-focused beamline

- 60 –120 GeV protons from Fermilab's Main Injector
- 200 m decay pipe at -5.8° pitch, angled at South Dakota (SURF)
- Initial power 1.1 MW, upgradable to 2.4 MW



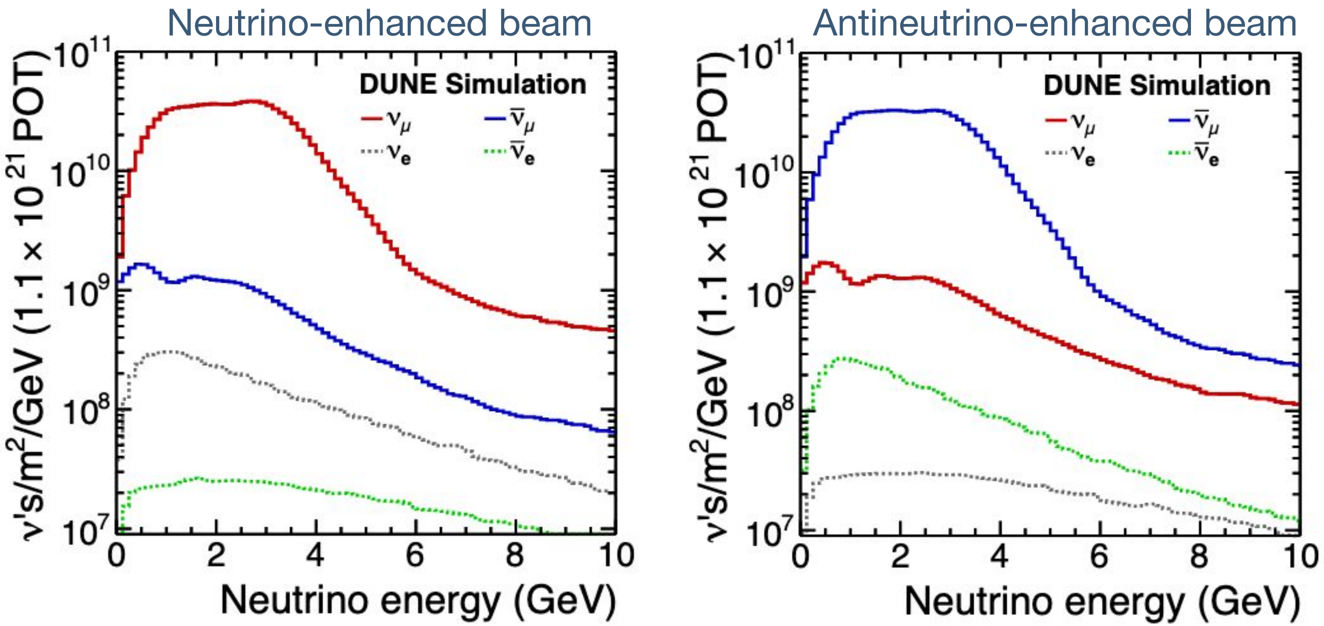


Beamline

Horn-focused beamline

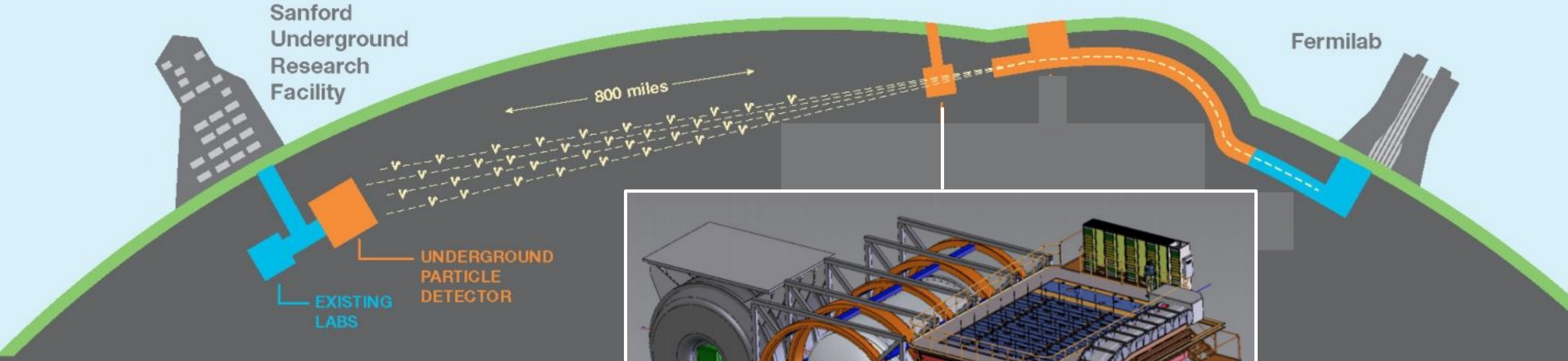
- 60 –120 GeV protons from Fermilab's Main Injector
- 200 m decay pipe at -5.8° pitch, angled at South Dakota (SURF)
- Initial power 1.1 MW, upgradable to 2.4 MW

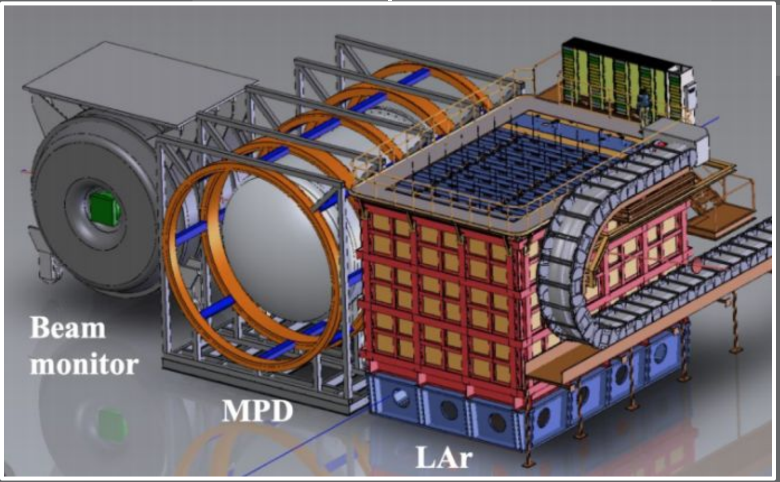
Broadband energy spread



DUNE Near Detector complex

- Measures the neutrino beam rate and spectrum
- Constrains systematic uncertainties in neutrino flux, neutrino scattering cross sections





DUNE ND has also its own physics program:

- neutrino-nucleus scattering measurements
- search for non-standard neutrinos

Challenge

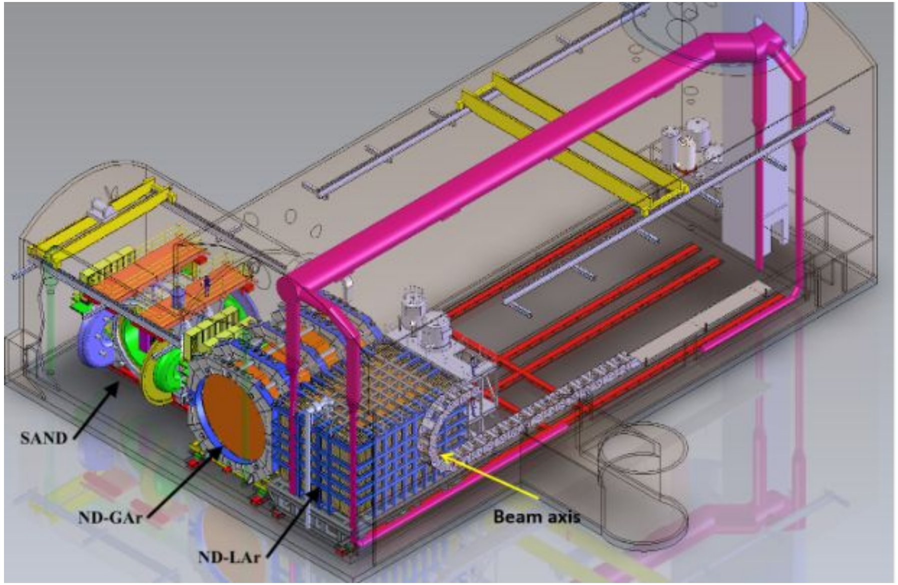
50 interactions / 10 μs

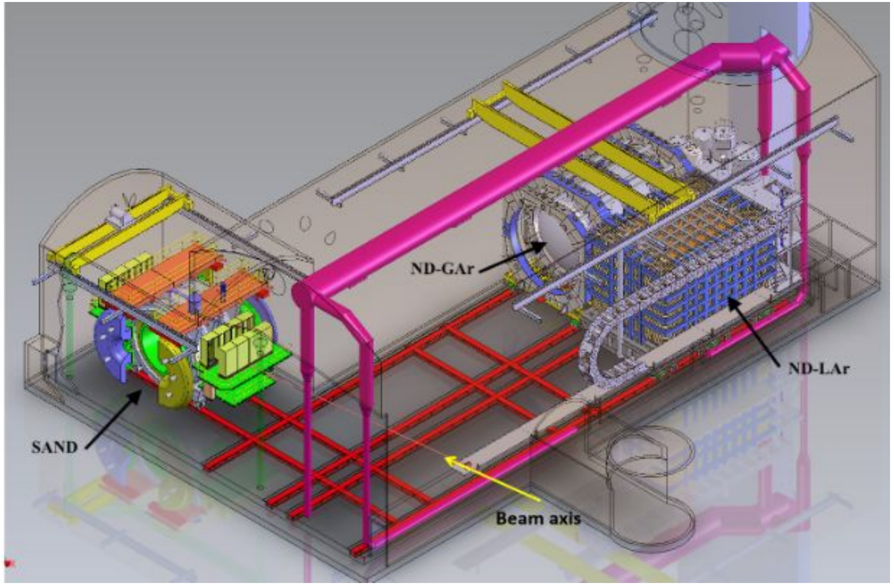
⇒ need new design

DUNE Near Detector CDR Reference

arXiv:2103.13910

Conceptual Design Report (March 2021), now transitioning to TDR (2022)





SAND System for on-Axis Neutrino Detection = tracker + ECAL ⇒ beam monitor

ND-LAr **L**iquid **Ar**gon detector (similar technology as Far Detector)

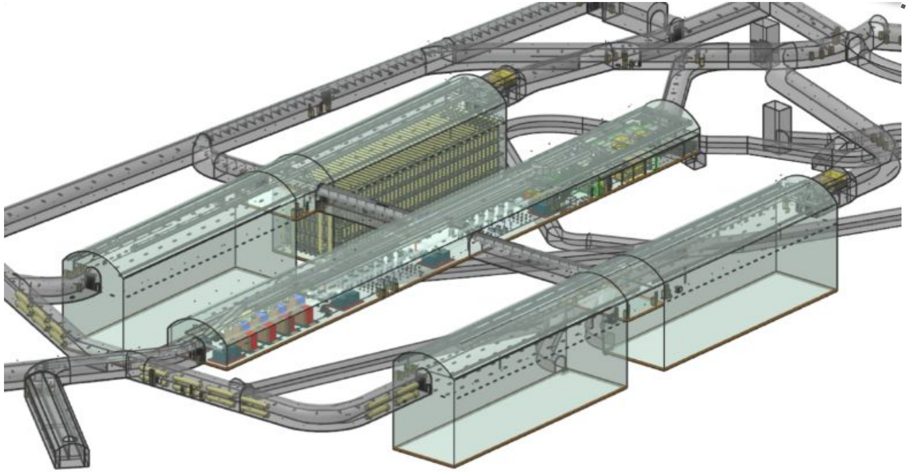
ND-GAr **G**aseous **Ar**gon TPC and downstream muon tracker

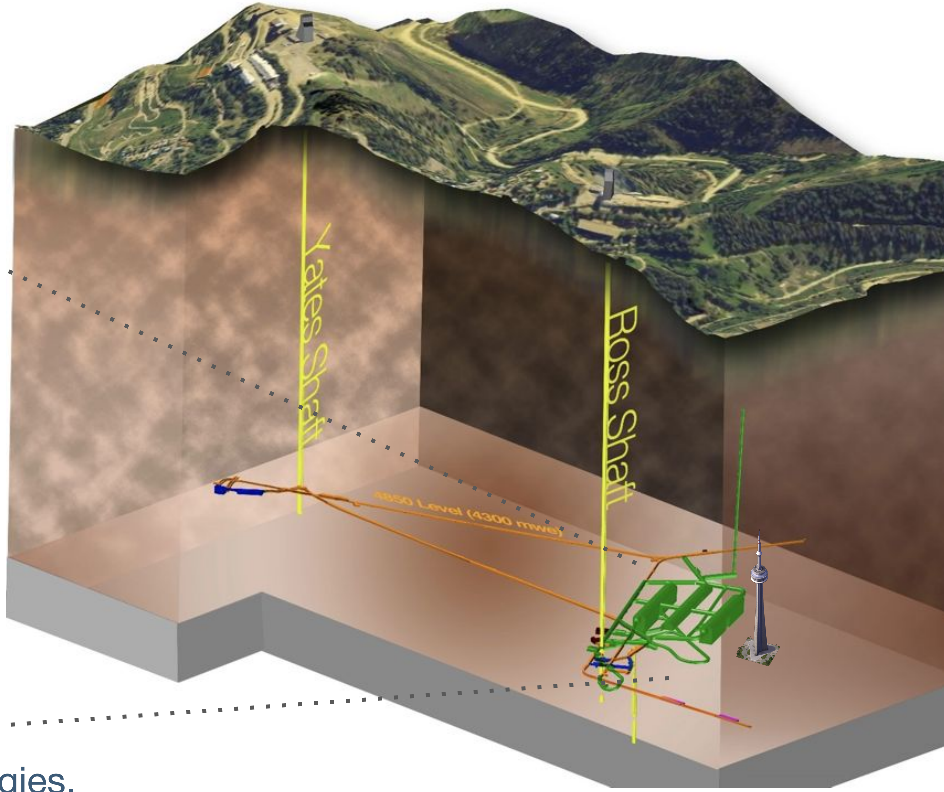
} can move over ≠ angles off-axis ⇒ sample diff. E_ν distributions

1285 km later...

DUNE’s Far Detector

- Largest cryogenic instrument ever (89 kT) with 4 modules of 10 kt (fiducial) liquid argon each





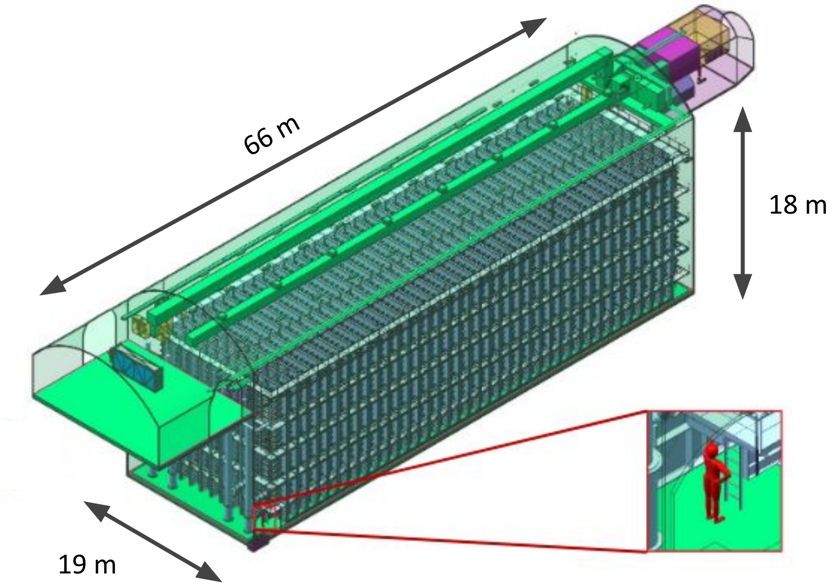
Modules installed in stages & different detection technologies.

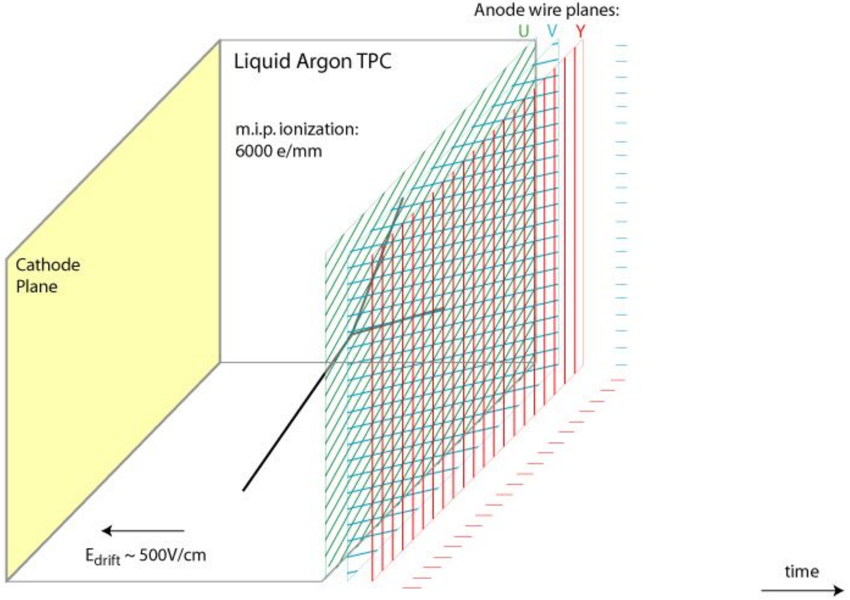
First module: single phase **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber ← **LArTPC**

Second module: single phase Vertical Drift (R&D ongoing)

DUNE Far Detector Single Phase design

- Ionization readout: Anode Plane Assemblies (APA)
- 3 wire planes (2 induction +1 collection views)
- Photo-detections done by ARAPUCA (trap + SiPMs)





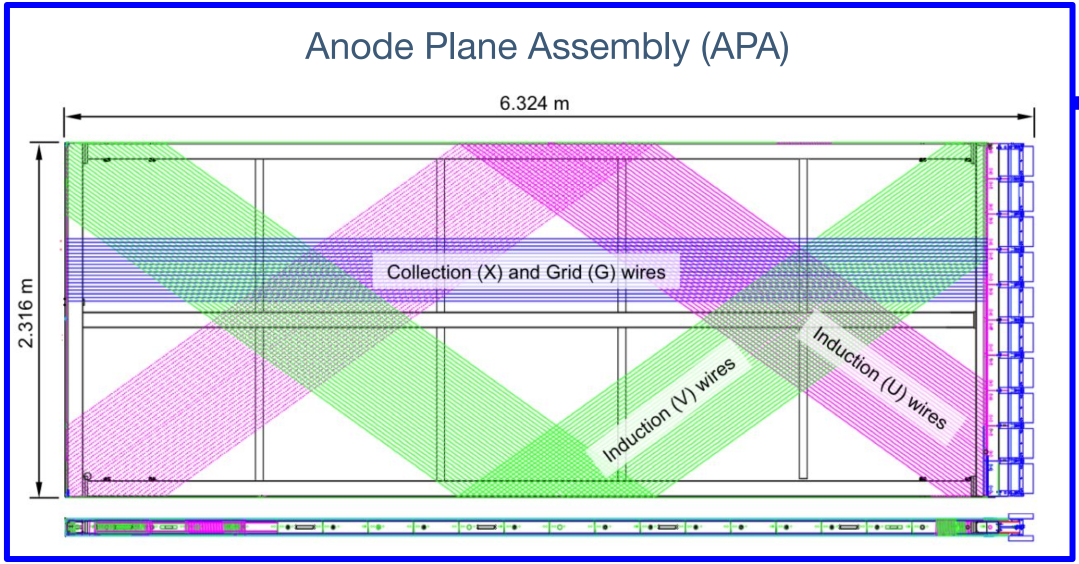
LArTPC technology

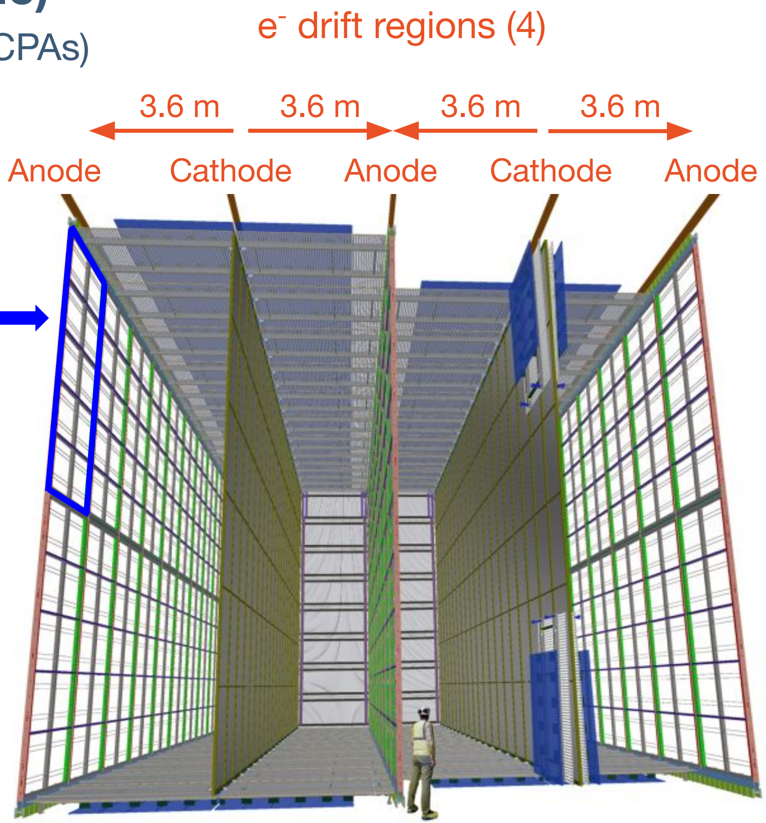
- 3D image of neutrino interactions with mm resolution
- LAr is good scintillator ⇒ provide t_0 (non-beam trigger)

DUNE Far Detector Anode & Cathode Planes

Single phase FD uses modular drift cells (scalable)

- Suspended Anode and Cathode Plane Assemblies (APAs and CPAs)
- Wrapped wire to reduce # of readout channels and cabling complexity



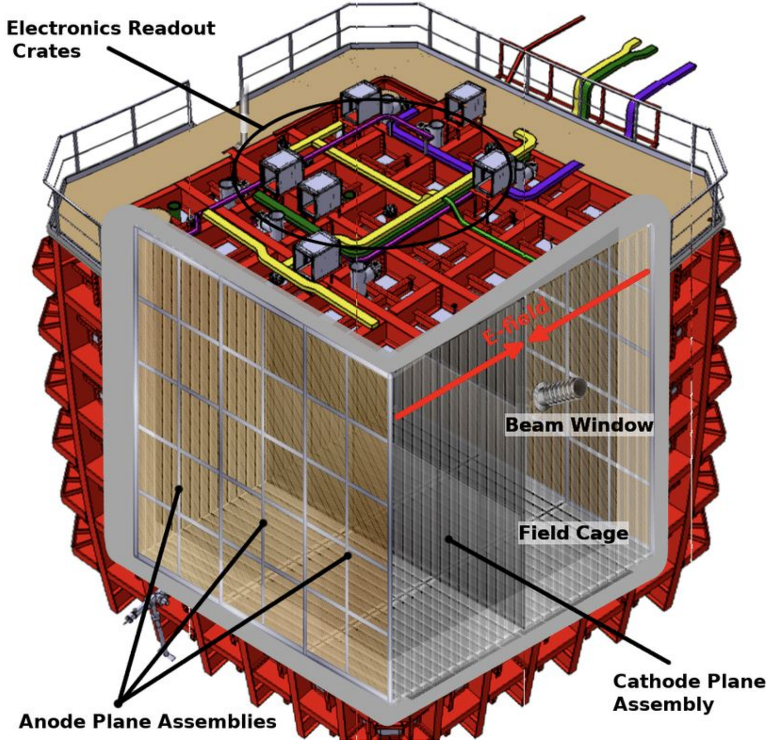


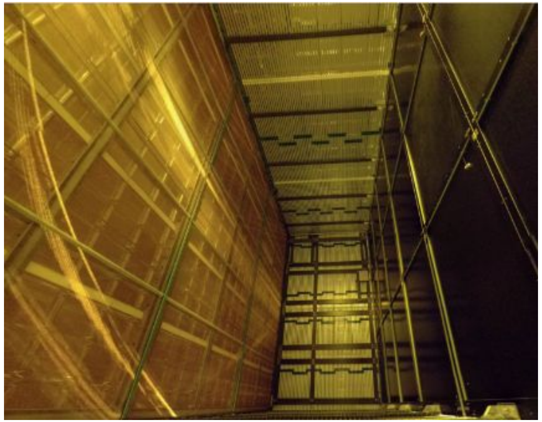
Meanwhile at CERN...

ProtoDUNE

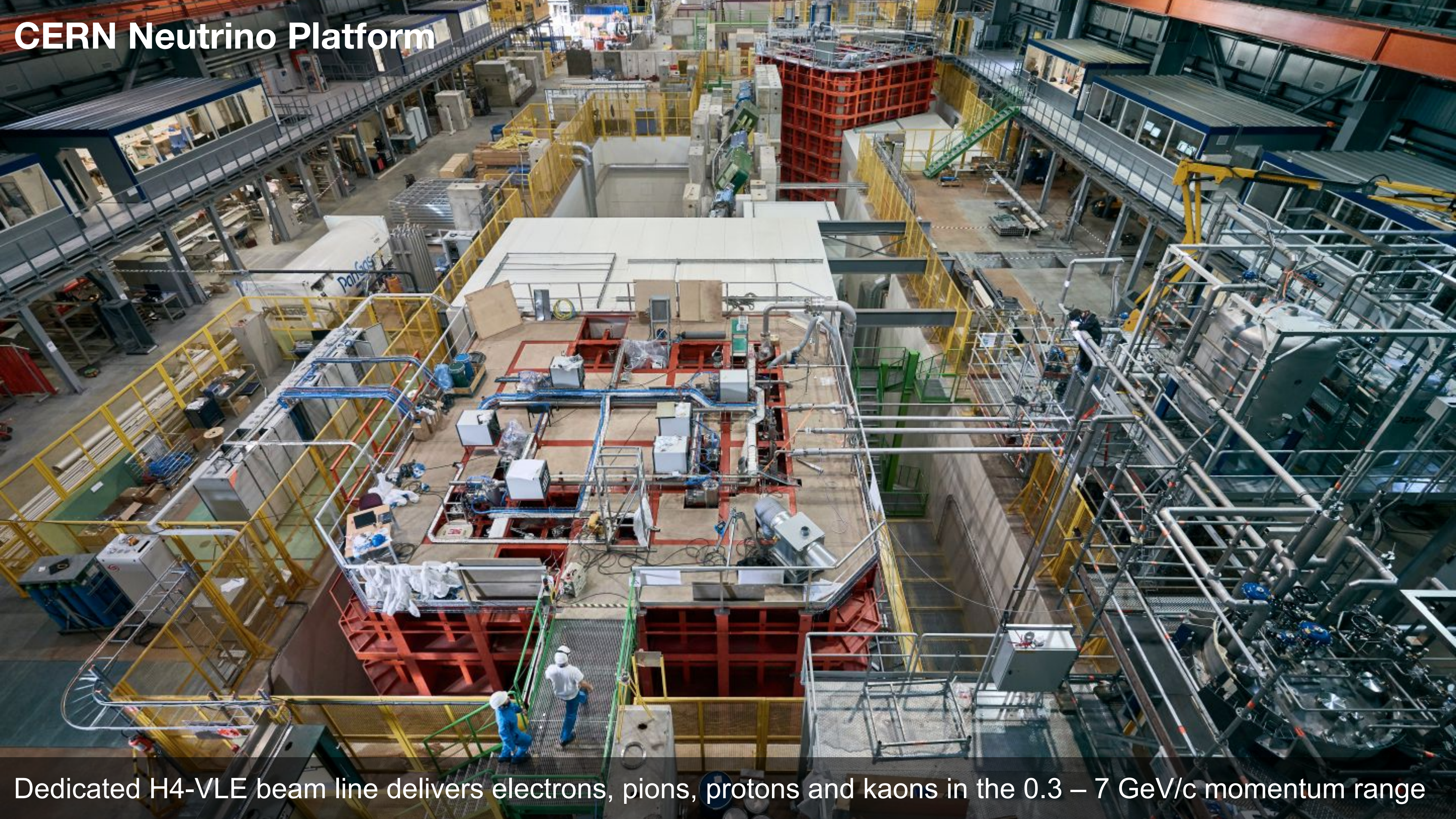
ProtoDUNE: prototyping effort

CERN neutrino platform: 2 prototypes 1/20th the size of DUNE | 770 t total LAr mass





CERN Neutrino Platform



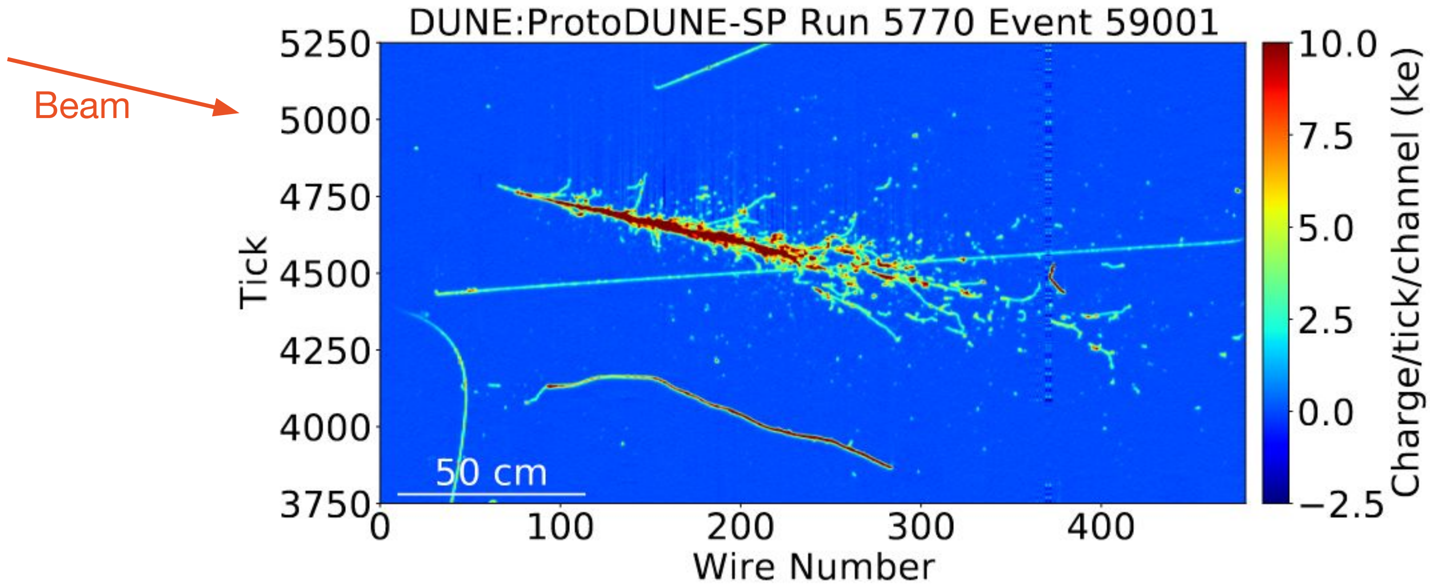
Dedicated H4-VLE beam line delivers electrons, pions, protons and kaons in the 0.3 – 7 GeV/c momentum range

First ProtoDUNE Single Phase results

Collected hadron data (beam) and cosmic rays from Fall 2018

Low noise levels | S/N ratio > 10 [> 40 for collection plane]

Example of an 6 GeV electron candidate event in the collection plane:

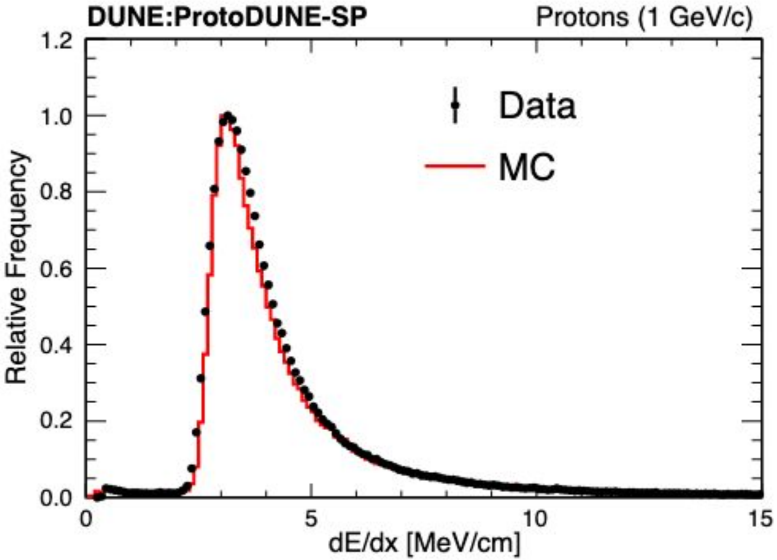


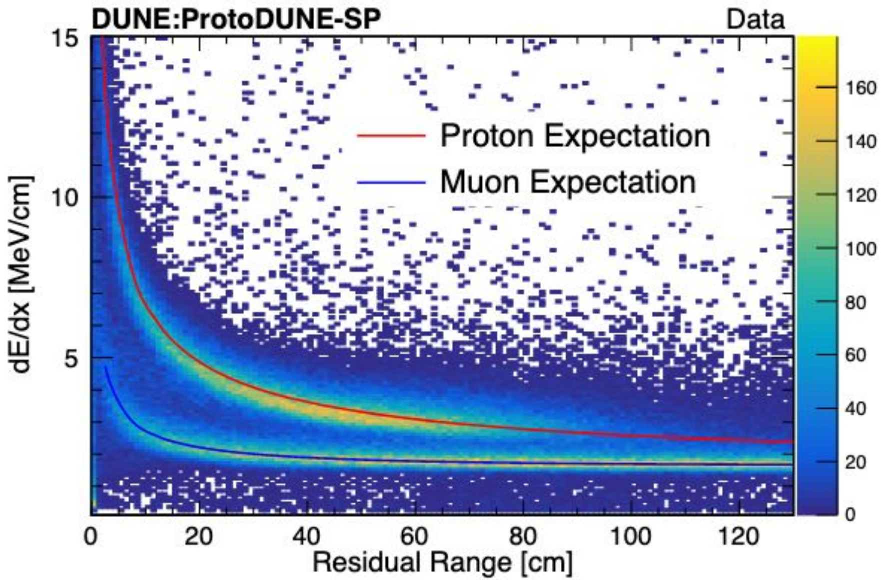
First results on ProtoDUNE SP

JINST **15**, P12004 (2020)
arXiv:2007.06722

Performance meets or exceeds the DUNE specifications

⇒ success of Single-Phase detector design + informing calibrations & reconstruction for single-phase DUNE Far Detector





Detector response calibration based on cosmic muons
→ good results for test beam protons and muons

Excellent proton-muon separation

Far Detector neutrino event reconstruction

Event reconstruction and classification

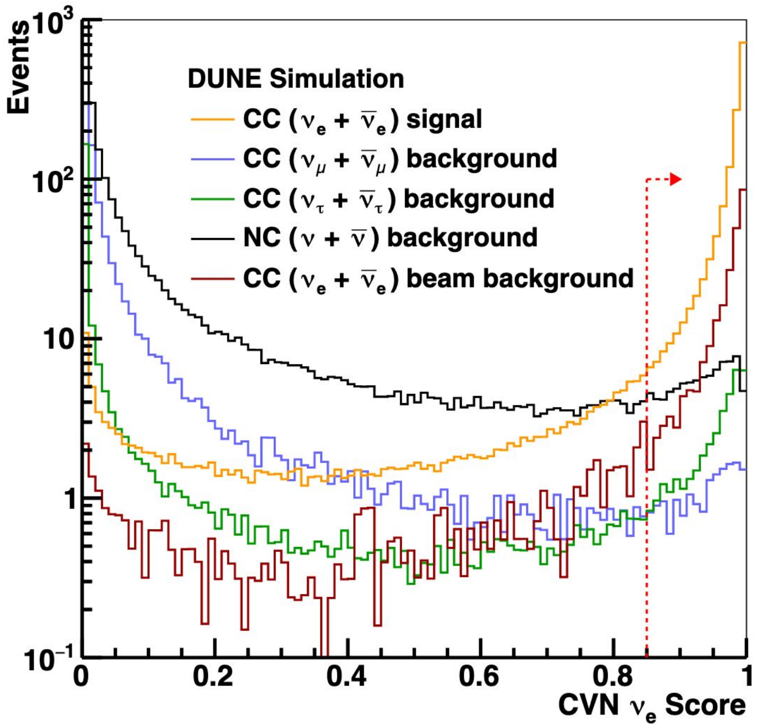
arXiv:2006.15052

Pattern recognition to reconstruct neutrino event in 3D

Neutrino flavour classification done using Convolutional Neural Network (CVN)

- outperforms CDR estimates
- reach 90% efficiencies for ν_e (95% ν_μ)

Work in progress to evaluate DUNE CVN for ProtoDUNE-SP data



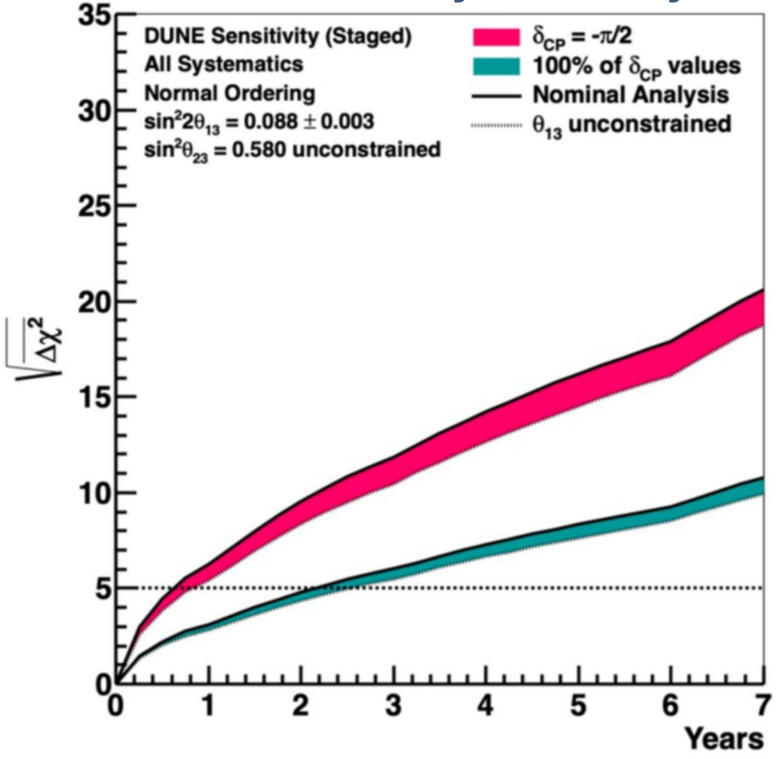
CVN ν_e score for beam neutrino mode (red arrow → TDR benchmark)

Sensitivities

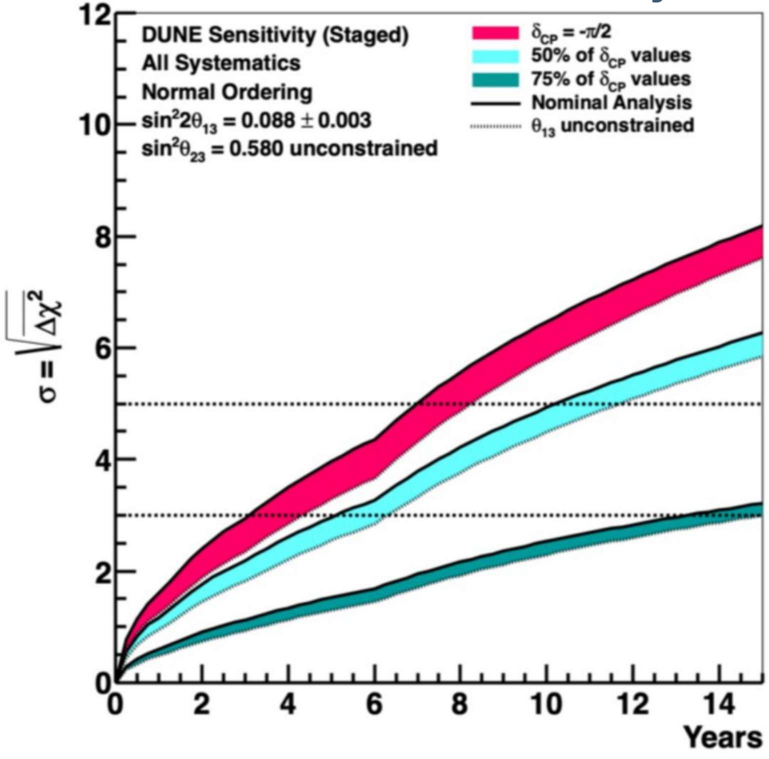
Sensitivity vs time

arXiv:2006.16043

Mass Hierarchy sensitivity



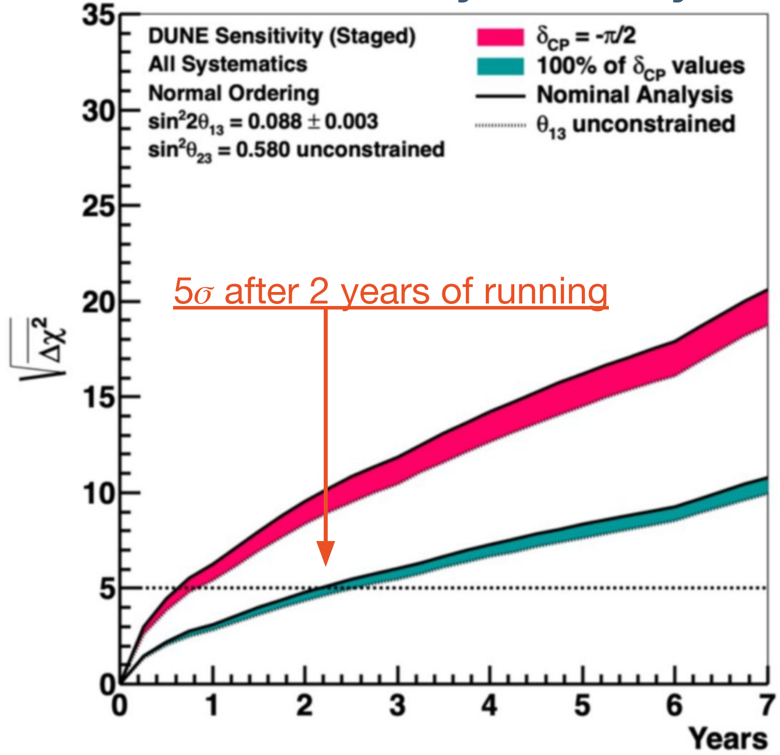
CP Violation Sensitivity



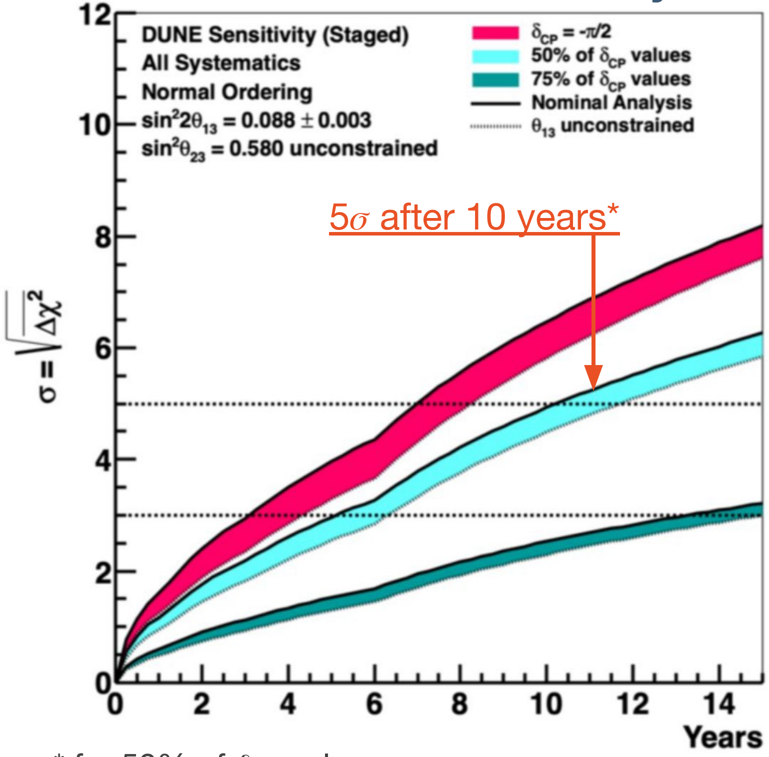
Sensitivity vs time

arXiv:2006.16043

Mass Hierarchy sensitivity



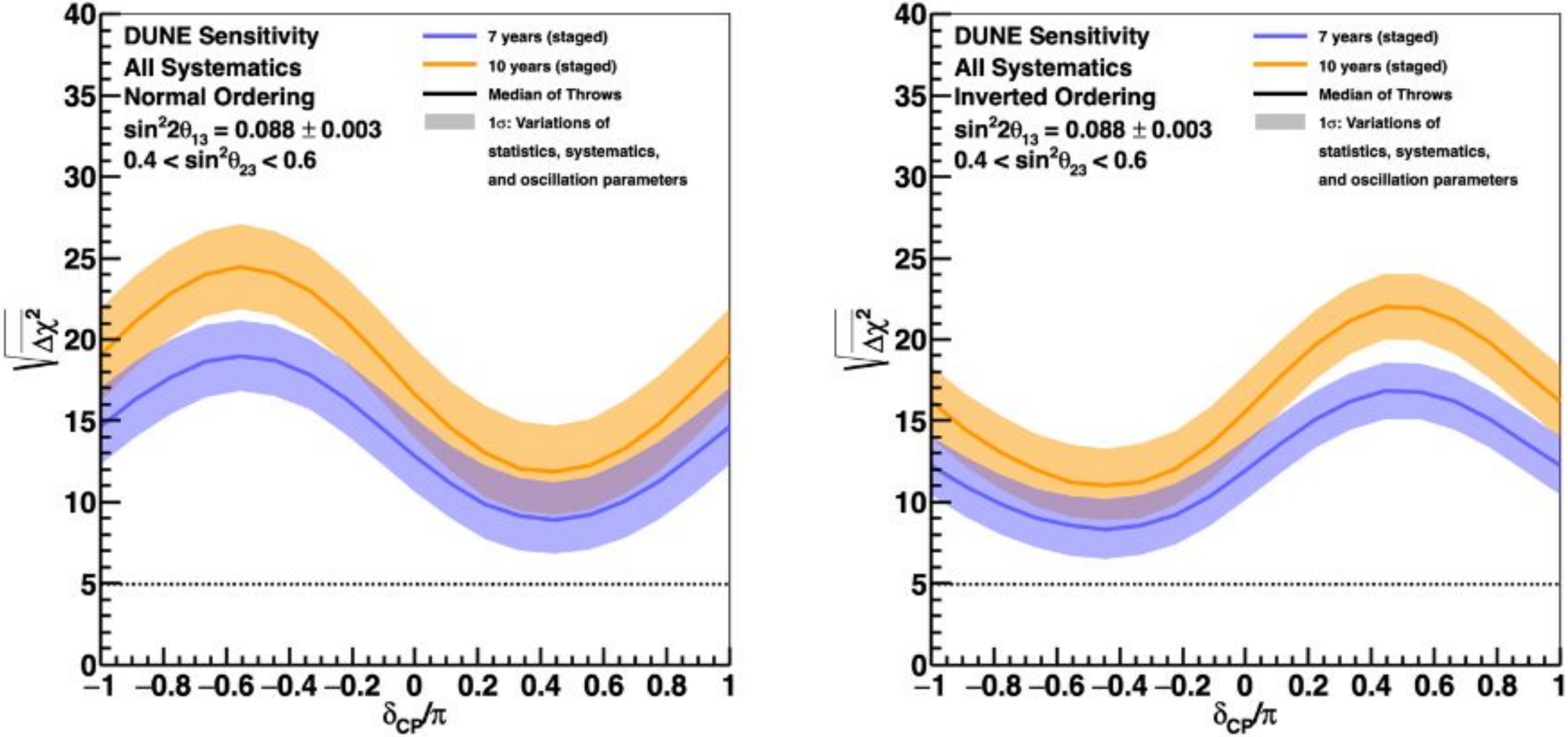
CP Violation Sensitivity



* for 50% of δ_{CP} values

Mass hierarchy sensitivity

arXiv:2006.16043



Supernova Neutrino Bursts

arXiv:2008.06647

DUNE Far Detector will be sensitive to core-collapse supernova in Milky Way neighborhood

- Estimated to occur every 30-200 years
- 99% of energy is carried away by neutrinos, giving unique information on:
  - **cosmology**: core-collapse mechanism, black hole formation…
  - **particle physics**: flavour transformations in core, mass hierarchy, extra dimensions…

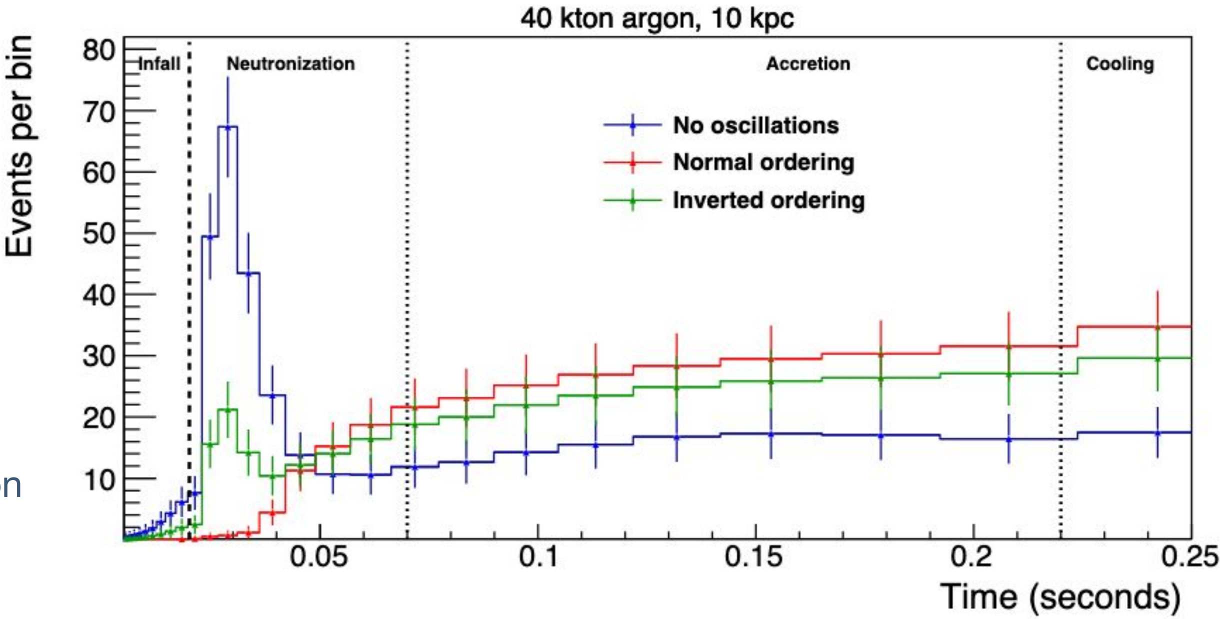
Primary interaction in argon:

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

(unique among neutrino detectors)

- Excellent energy resolution with both TPC and photodetectors
- Sensitivity to ν_e elastic scattering, which can provide directionality

⇒ can achieve 4.5° pointing resolution



More on the DUNE Physics Program

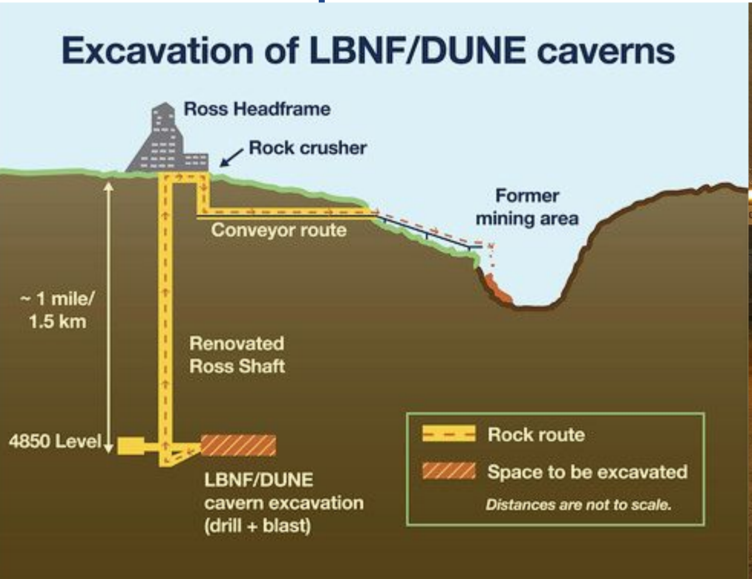
- Atmospheric and solar neutrinos
  - Can use atmospheric neutrinos to extract neutrino properties
  - Low-energy neutrino sensitivity for ^{8}B and hep solar neutrinos under investigation
- Baryon number violation and proton decay search
  - DUNE will have large exposure (40 kton, 20+ y) and low background rates (1.5 km underground)
  - Precision tracking of LArTPC technology ⇒ clear signature in channel $p \rightarrow K^{+}\overline{\nu}$
- Large catalog of Beyond Standard Model (BSM) searches at DUNE
  - Light sterile neutrinos
  - Non-standard interactions
  - Dark matter
  - Lorentz violation
  - Effective CPTv
  - Large extra dimensions
  - Neutrino tridents (Z' and muon g - 2)

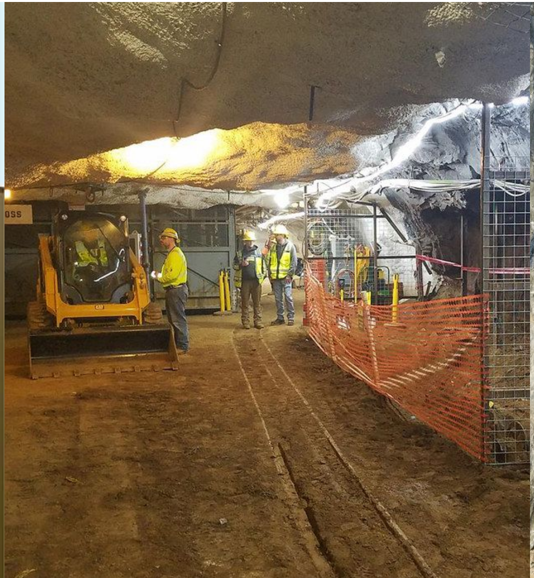
Detailed review by Nikolina Ilic at CAP Congress 2020 [link]

DUNE Timeline

2021 — **2029** — **2036**

R&D | DUNE construction | DUNE operations | Continued physics exploitation beyond operations





C A N A D A

DUNE-Canada

NSERC Discovery Grant (April 2020) and approved as Institute of Particle Physics (IPP) project (Sept. 2020)

Nikolina Ilić
PI UofT / IPP

Deborah Harris
PI YorkU / Fermilab

Claire David
PI YorkU / Fermilab

Nico Giangiacomi
Postdoc

Matthew Man
Graduate Student

Fady Shaker
Postdoc

Rowan Zaki
Student

Minoo Kabirnezhad
Postdoc

Tejin Cai
Postdoc

DUNE-Canada

NSERC Discovery Grant (April 2020) and approved as Institute of Particle Physics (IPP) project (Sept. 2020)

DAQ system

FELIX readout cards

Nikolina Ilić
PI UofT / IPP

Nico Giangiacomi
Postdoc

Matthew Man
Graduate Student

Near Detector Reco-algorithms

Deborah Harris
PI YorkU / Fermilab

Fady Shaker
Postdoc

Rowan Zaki
Student

Computing Documentation & Training

Analysis Facility

Claire David

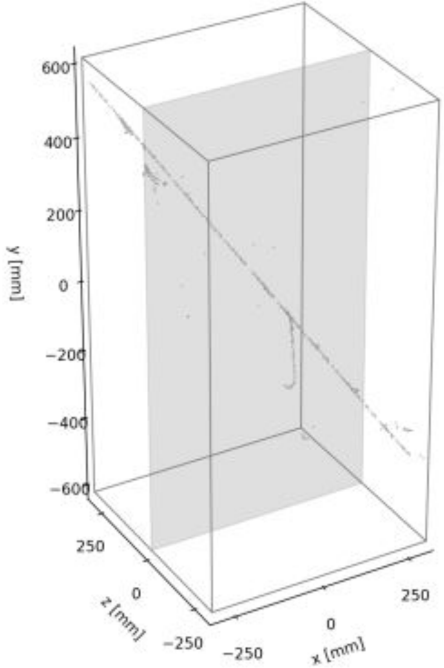
Neutrino Interaction Model Development

Minoo Kabirnezhad
Postdoc

Tejin Cai
Postdoc

DUNE-Canada activities in the past year

Nov 2020	**DUNE Expertise Sharing Workshop | 2-day event** Discussing areas of common interest: photon detection, DAQ, high intensity neutrino beams, liquid argon
Jan 2021	**DUNE Computing Training** Remotely | 60 participants | Positive feedback
Feb 2021	**GPU Hackathon (SFU)** Improved the speed near detector Liquid Argon simulations by factor 10
Apr 2021	**Compute-Canada Resource Allocation** DUNE gets VCPU and cloud storage for an "Interactive Analysis Facility" project
	ND Prototype Test Runs →
May 2021	**DUNE Computing Training, augmented edition** New website based on Software Carpentry format + quizzes, live Q&A and asynchronous lectures | 112 registrants | very positive feedback



Cosmic ray interactions within the prototype module, imaged in full 3D using a LArPix system with approximately 80,000 pixels.
Credit: Dan Dwyer, Berkeley Lab

Summary & Outlook

- DUNE is a unique broadband energy neutrino experiment designed for discoveries
- Very ambitious physics program, from ν oscillation to supernova to proton decay
- Unprecedented sensitivity to mass hierarchy, CP violation & numerous BSM searches
- protoDUNE is running smoothly and exceeding expectations
- DUNE-Canada is growing: good timing to get involved!

Write us! dune-canada@fnal.gov

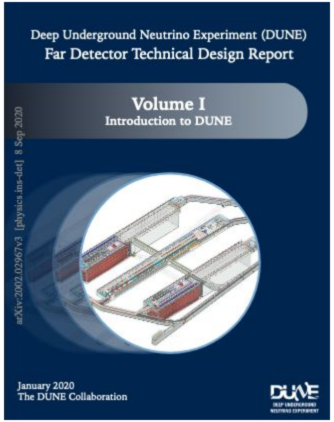
Liquid Argon
Accelerators
Cosmology
Dark Matter searches
Non-standard interactions
Dielectric materials
Large scale computing
Photodetection
Beamline
Neutrino interaction model

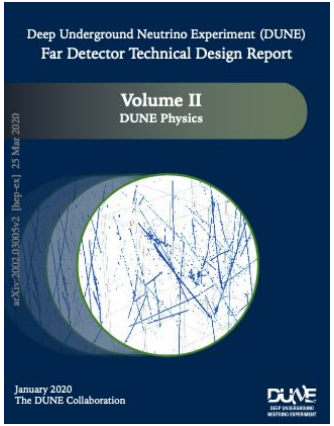
References

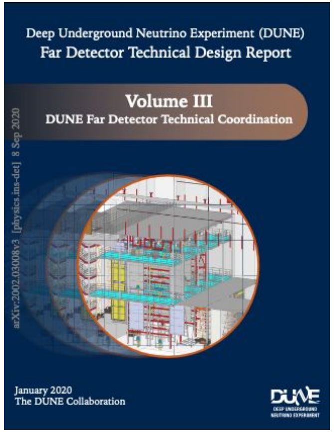
February 2020

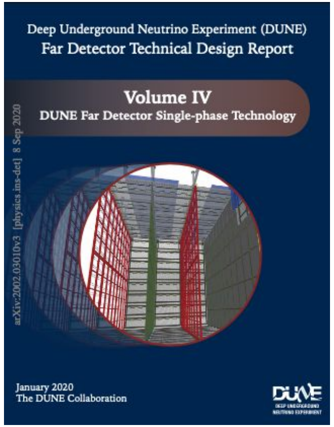
DUNE TDR

Click on the images









June 2020
Long-baseline neutrino oscillation physics potential of the DUNE experiment | arXiv:2006.16043

August 2020
Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment | arXiv:2008.06647

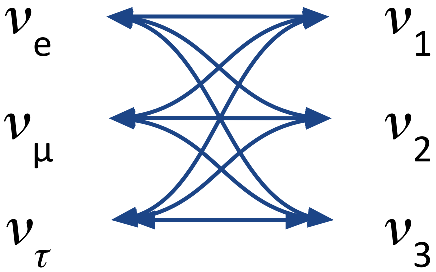
March 2021
Deep Underground Neutrino Experiment Near Detector Conceptual Design Report | arXiv:2103.13910

extra neutrinos?

Neutrinos

- There are 2 basis that are ‘rotated’ , with superposition of states:

Flavour eigenstates
neutrino in detection
weak interaction



Mass eigenstates
neutrino in propagation
free flight

- The Pontecorvo–Maki–Nakagawa–Sakata (PMNS) unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

See extra slides for details

What we know

- Parametrization:
- 3 rotations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

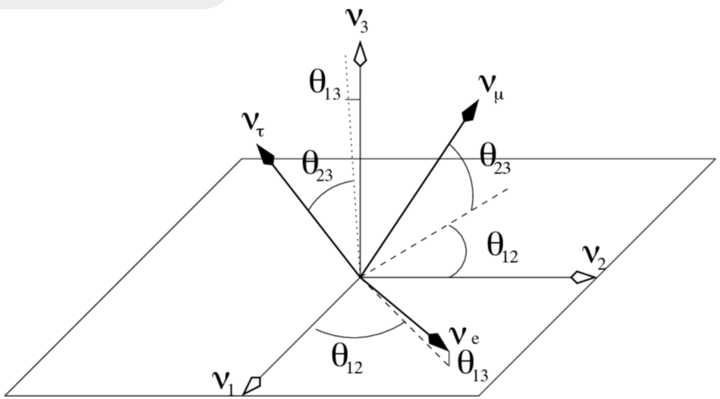
Complex phases for Majorana neutrinos

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij}$$

Only 4 parameters:

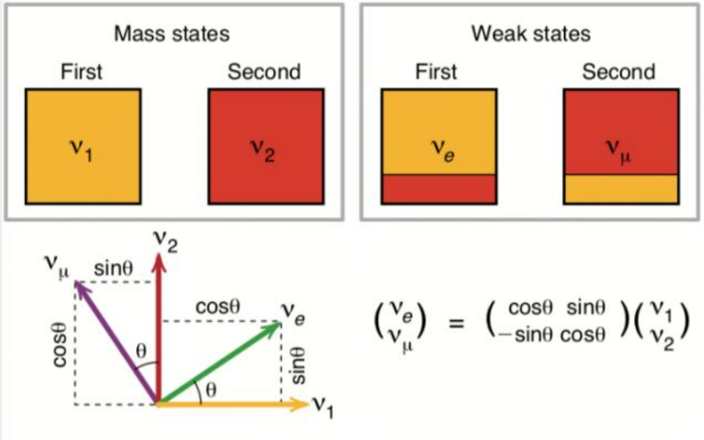
- 3 angles : θ_{12} , θ_{13} , θ_{23}
- 1 phase δCP



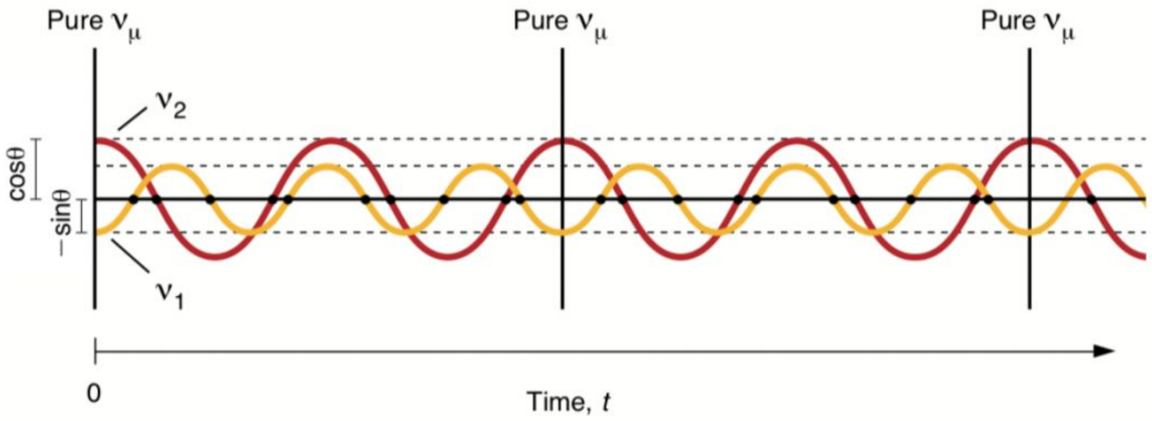
Number freak?
Check www.nu-fit.org

Neutrino oscillations

Simplified 2 neutrino model.



Superposition of mass eigenstates with different 'phases'



Time evolution ⇒ periodic **'appearance'** and **'disappearance'** of a weak/flavour state.

Neutrinos have mass

But why so light?

See-saw mechanism?

= heavy (possibly GUT-scale) right handed (RH) neutrinos alongside light left-handed (LH) neutrinos

Implications

⇒ the physics of neutrino mass is connected to extremely high energy scales

Potential new physics signatures in oscillation experiments

non-unitarity, non-standard interactions, > 3 neutrinos, large extra dimensions, effective CPTv, decoherence, neutrino decay, …

See-saw mechanism:
P. Minkowski (1977);M. Gell-Mann, P. Ramond and R. Slansky (1979); and T. Yanagida (1979)

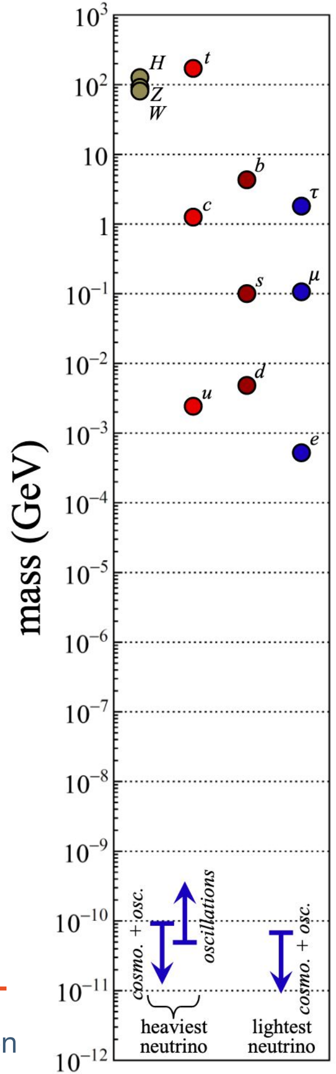


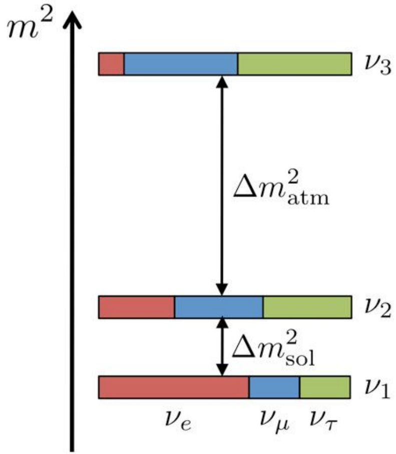
Image: Ryan Patterson

Neutrino mixing

Experimental question:

$\sin^2 \theta_{23} \neq 0.5$?

Non-maximal mixing?
If so, which way does it break?



← $|U_{e3}| \neq 0$? recent discovery
← $|U_{\mu3}| \neq |U_{\tau3}|$ maximal mixing

← approx 1:1:1 ratio

The "?"

Why massive? Why so light?

Mixings and mass hierarchy

CP violation

Are neutrinos oscillating the same way as antineutrinos?

New source of CP violation required to explain baryon asymmetry of universe

Neutrino CP violation allowed in νSM, but not yet observed → experimental challenge

$\sin\delta \neq 0$?

The "?"

Why massive? Why so light?

Mixings and mass hierarchy

CP violation

Beyond Standard Model

Baryon number violation, Non-Standard Neutrino Interactions (NSI), dark matter, sterile neutrino mixing ...
Also proton decay predicted by GUT models decay $p \rightarrow K^+ \overline{\nu}$

Neutrino oscillation in matter

Oscillation probability of $\nu_\mu \rightarrow \nu_e$ through matter in the standard three-flavor model:

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$

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

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

Fermi constant

number density of electrons in Earth's crust

$$a = \pm\frac{G_F N_e}{\sqrt{2}} \approx \pm\frac{1}{3500\ \text{km}}\left(\frac{\rho}{3.0\ \text{g/cm}^3}\right)$$

$$\Delta_{ij} = 1.267\Delta m_{ij}^2 L/E_\nu$$

Asymmetry:

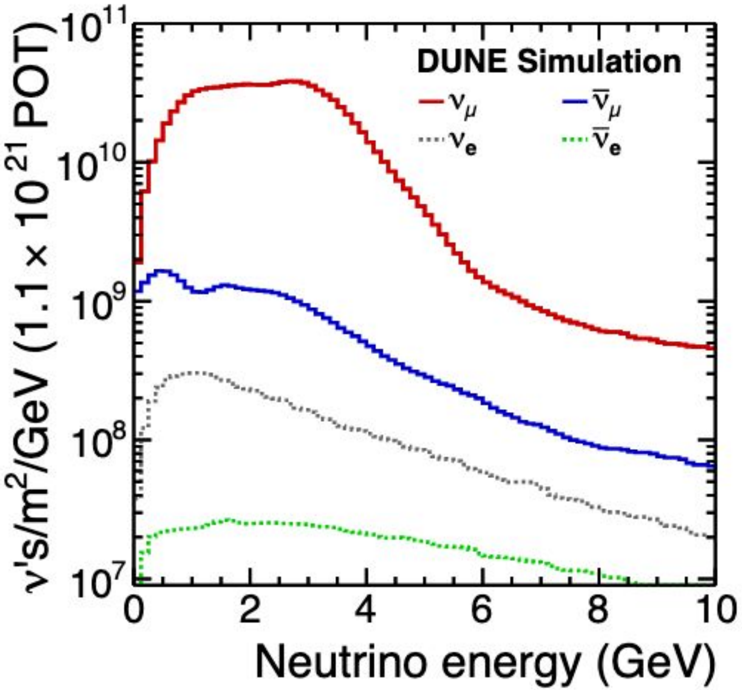
$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

$$\sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right) + \text{matter effects}$$

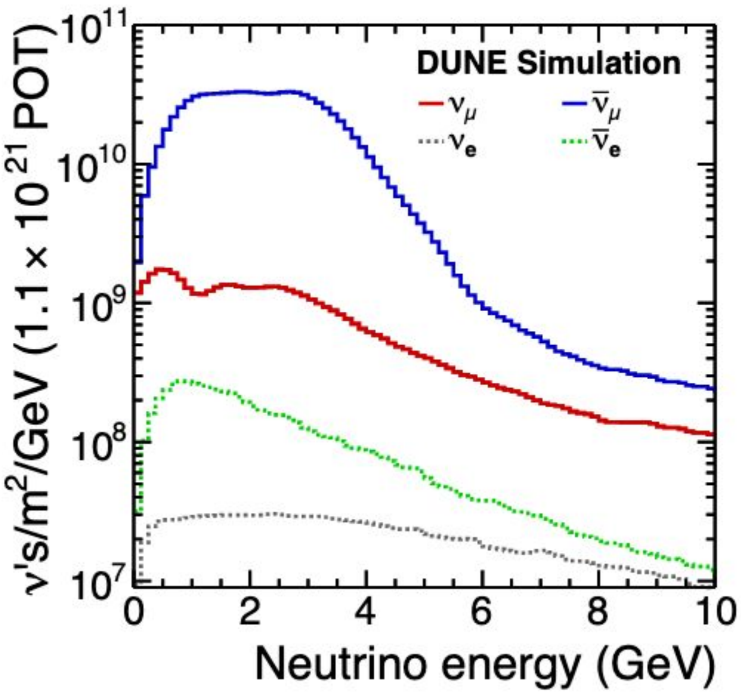
In the GeV range of E_ν, the degeneracy between the asymmetries from matter effect and C_{PV} effect is resolved for baselines > 1200 km.

Energy spread: fluxes at the Far Detector

NEUTRINO FLUXES



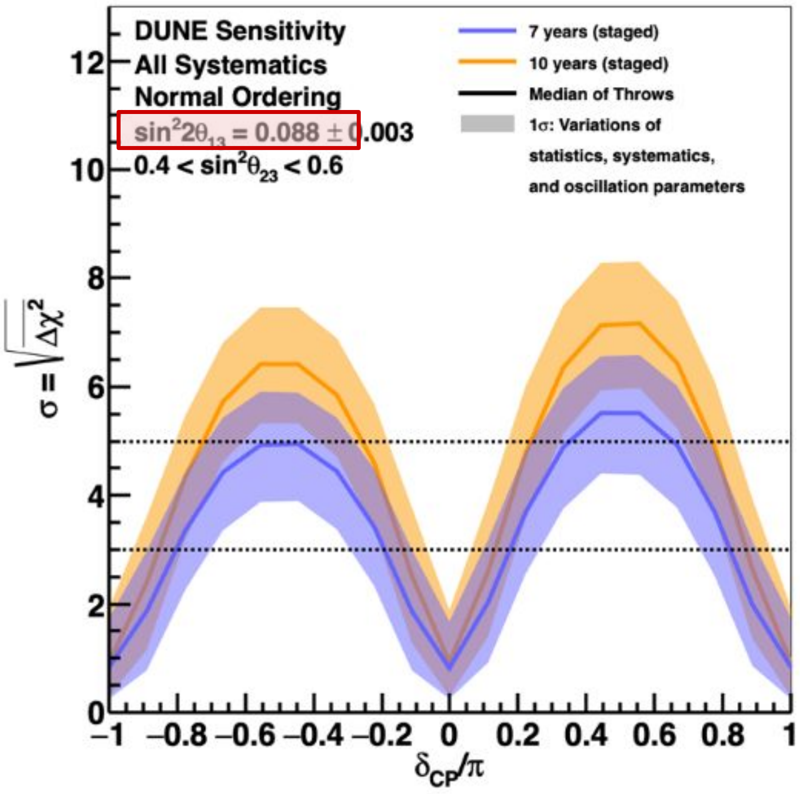
ANTINEUTRINO FLUXES

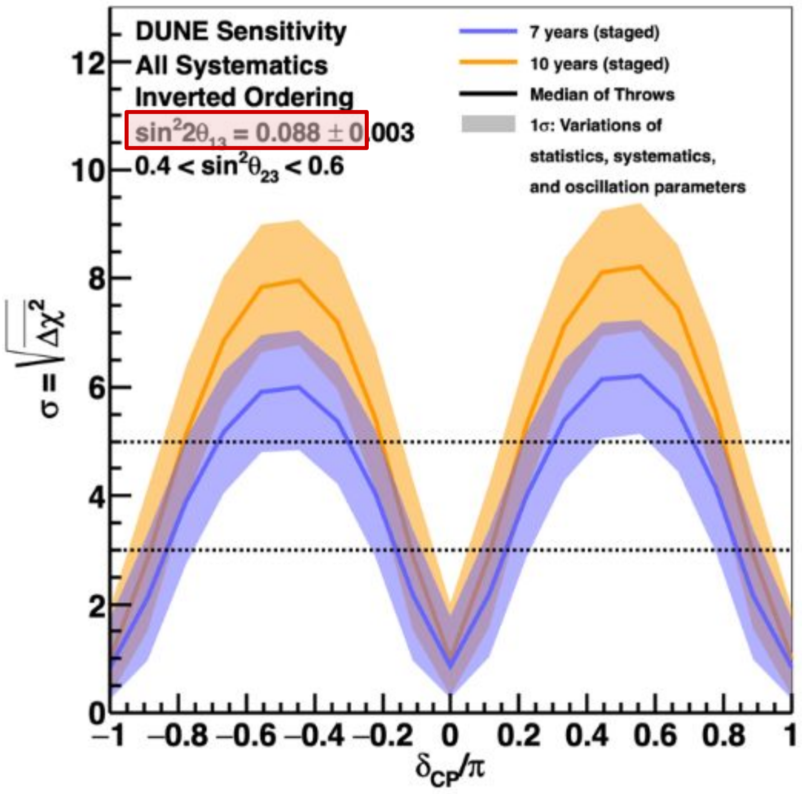


arXiv:2006.16043

CP-violation significance vs true δ_{CP}

arXiv:2006.16043





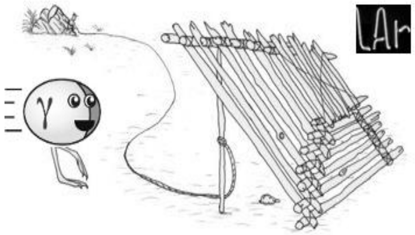
Significant CP violation discovery potential over wide range of true δCP values in 7-10 years (staged)

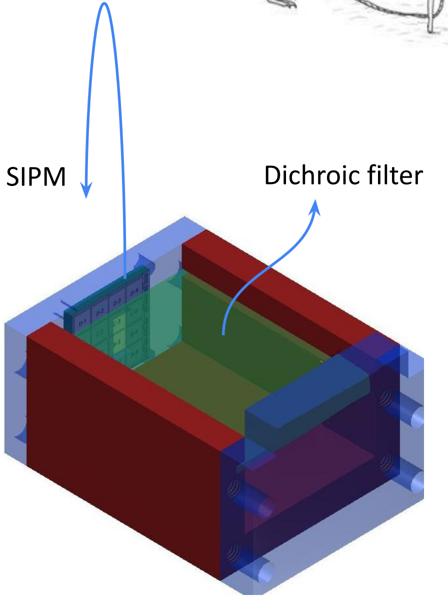
ARAPUCA

Goal

Develop an efficient photon collector system which allows to increase the effective area of the active devices (SiPMs).

ARAPUCA = trap for birds in native Brazilian





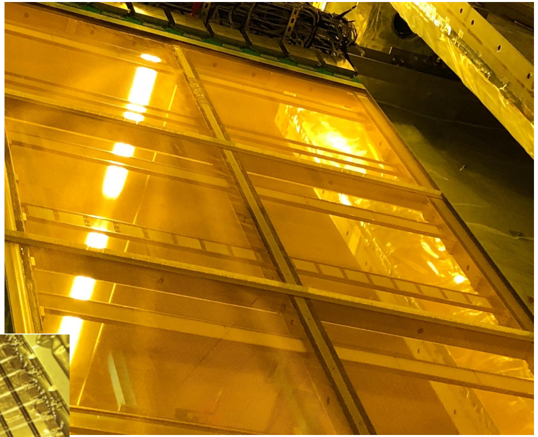
Basic Idea:

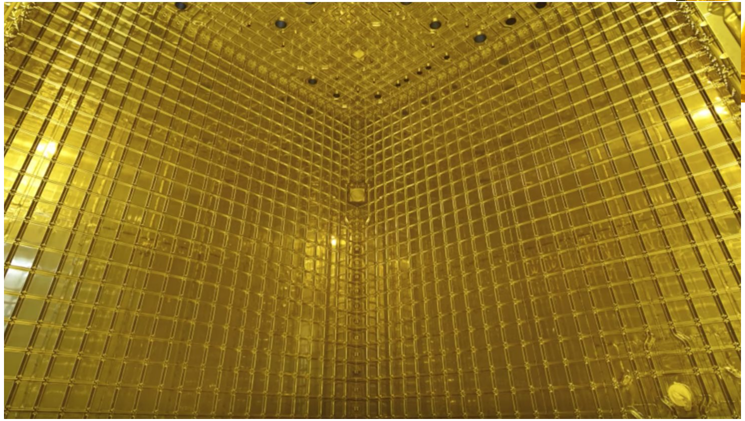
1. Trap photons inside a box with a high reflective internal surface

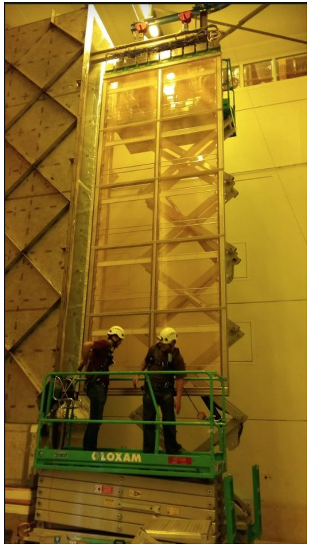
   After some reflections

2. Photons will be detected by a photo-sensor.

ARAPUCA







APA+PD
Entering in a cold box

T2HK and DUNE Comparison

Slide courtesy of Ryan Patterson

(10 yrs, staged deployment)		**T2HK**	**DUNE**	
CP violation	δ resolution	7° – 21°	7° – 15°	similar
	3σ coverage	78%	74%	
	5σ coverage	62%	54%	
νMH	sens. range	$5\sigma - 7\sigma$	$8\sigma - 20\sigma$+	DUNE superior
octant	sens. @ 0.45	5.8σ	5.1σ	similar
	5σ outside of…	[0.46, 0.56]	[0.45, 0.57]	
p decay (90% C.L.)	$p \rightarrow \bar{\nu} K^+$	>2.8e34 yrs	>3.6e34 yrs	mode dependent
	$p \rightarrow e^+ \pi^0$	>1.2e35 yrs	>1.6e34 yrs	
supernova ν (10 kpc or relic)	SNB $\bar{\nu}_e$	130k evts		complementary channels (ν_e vs. $\bar{\nu}_e$, though Hyper-K has more SN events total)
	SNB ν_e		3k evts	
	relic $\bar{\nu}_e$	100 evts, 5σ		
	relic ν_e		30 evts, 6σ	
NSI (90% C.L.)	$\lvert\varepsilon_{\mu e}\rvert$	<0.34	<0.05	DUNE superior
	$\lvert\varepsilon_{\mu\tau}\rvert$	<0.27	<0.08	
	$\lvert\varepsilon_{\tau e}\rvert$	<0.98	<0.25	

DUNE Collaboration

1347 collaborators

204 institutions

33 countries + CERN