DUNE: Status and Prospects

Dr. Luke A. Corwin for the DUNE Collaboration

South Dakota School of Mines & Technology

15th Conference on Flavor Physics and CP Violation
June 5–9, 2017
Prague, Czech Republic

Outline

Conference Invitation

"The topics include CP violation, rare decays, CKM elements with heavy quark decays, flavor phenomena in charged leptons and neutrinos, and also interplay between flavor and LHC high Pt physics."

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1. Introduction
   - Physics
   - Experiment
2. Flavor Phenomena in Neutrinos
3. CP Violation
4. Status and Prospects

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3. CP Violation
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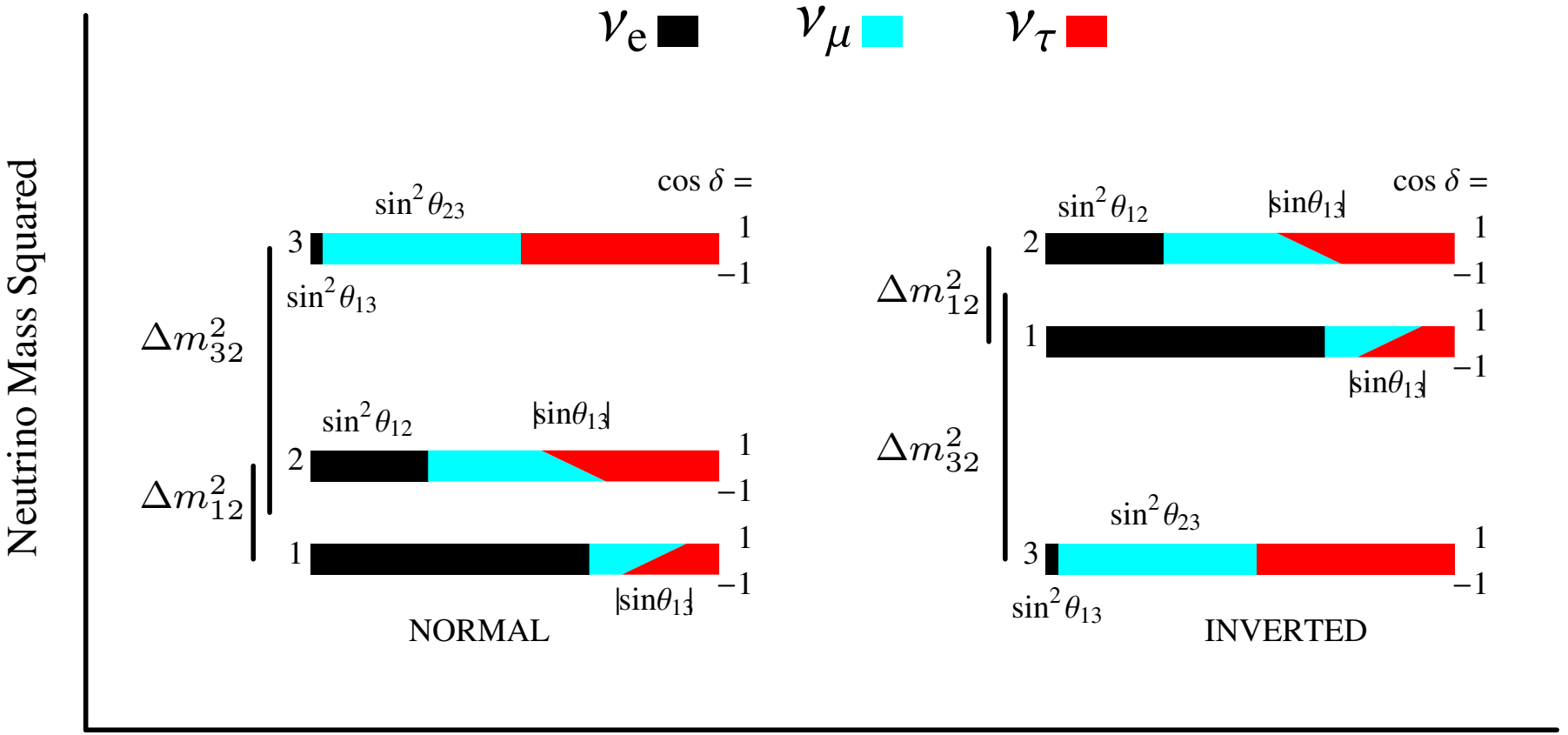
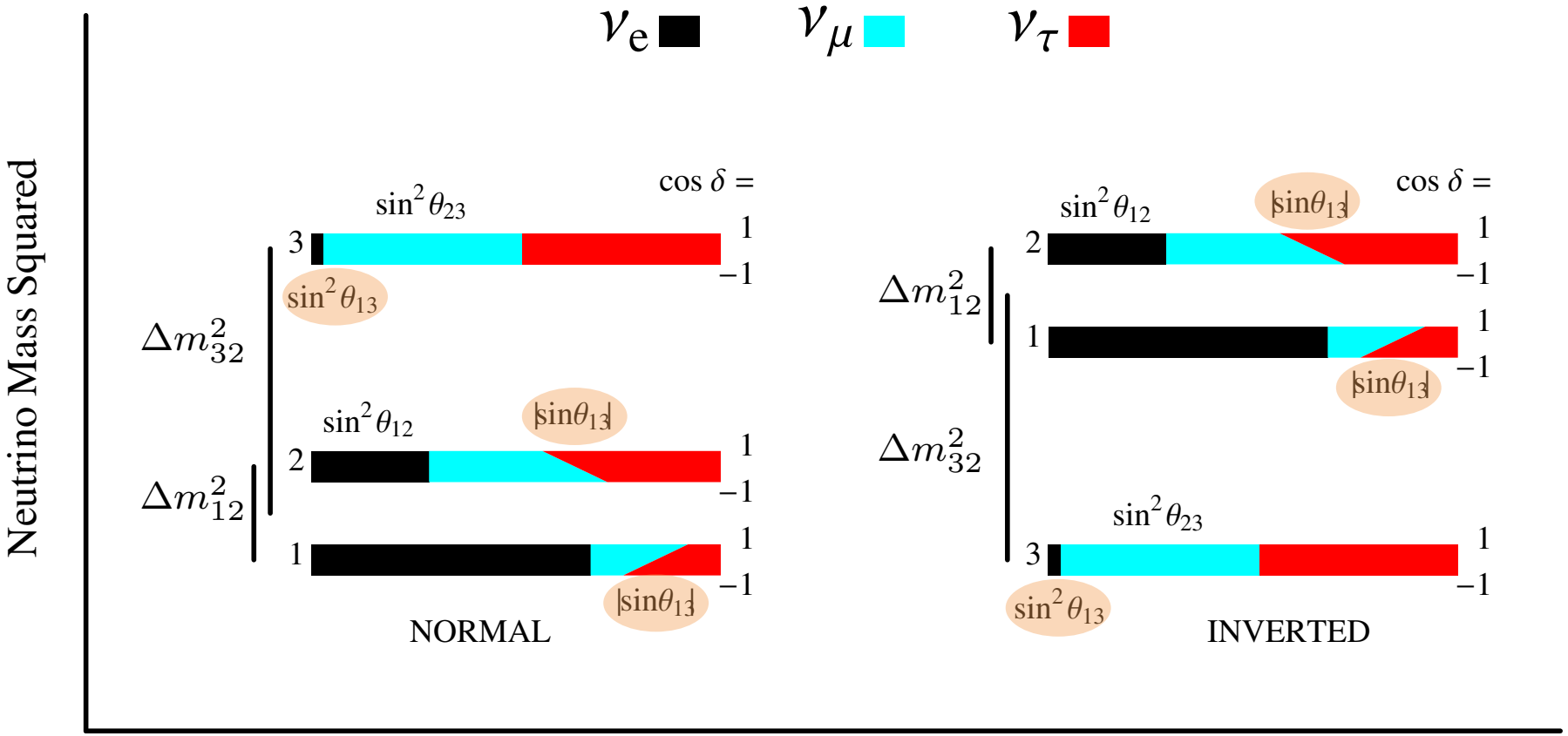
DUNE

A long-baseline neutrino experiment with a large liquid argon time projection chamber (LArTPC) as the far detector.



Graphic credit: `arXiv:hep-ph/0312131`

Fractional Flavor Content varying cos δ

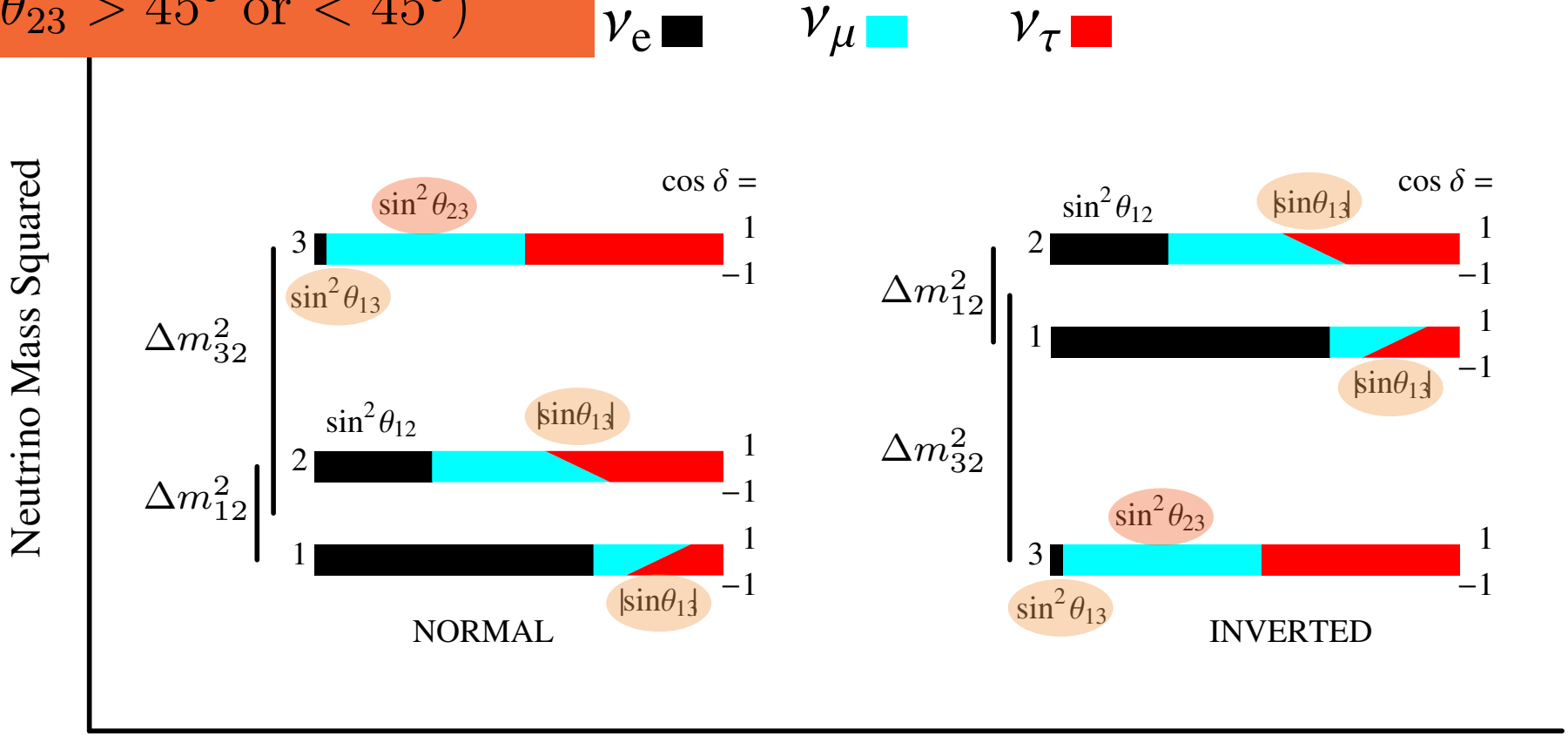


Graphic credit: `arXiv:hep-ph/0312131`

Fractional Flavor Content varying cos δ

DUNE resolution on θ_{13} will be comparable to reactor experiments

If $\theta_{23} \neq 45°$, we want to determine the octant ($\theta_{23} > 45°$ or $< 45°$)



Graphic credit: arXiv:hep-ph/0312131

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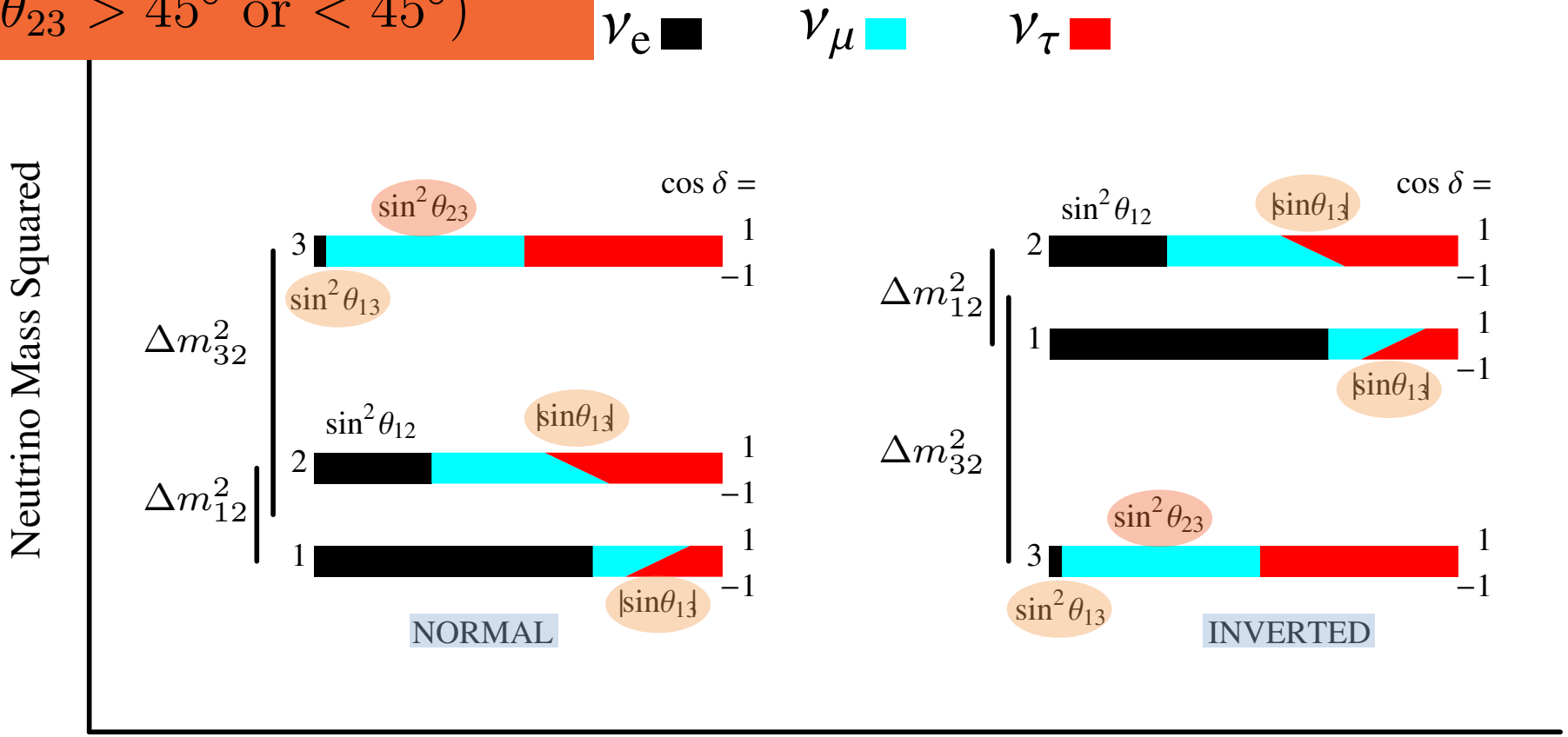
DUNE will measure ν mass ordering



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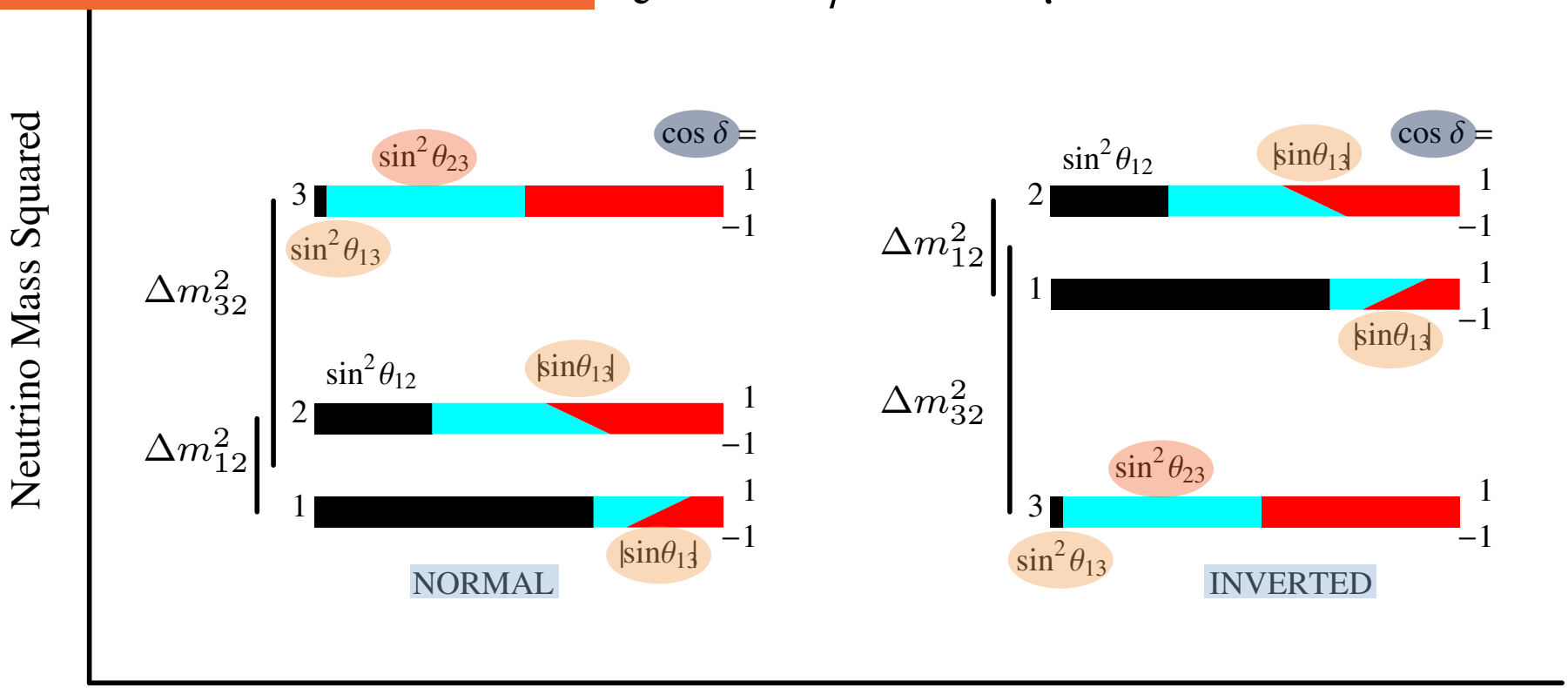


Graphic credit: arXiv:hep-ph/0312131 Fractional Flavor Content varying cos δ

DUNE resolution on θ_{13} will be comparable to reactor experiments

One of DUNE's primary goals is measuring δ_{CP}

The Math[1]

$$P(\nu_\mu \to \nu_e) = \left| \sum_j U_{\mu j} e^{-\frac{i m_j^2 t}{2E}} U_{je}^* \right|^2$$

$$\approx P_{\text{atm}} + P_{\text{sol}} + \sqrt{P_{\text{atm}} P_{\text{sol}}} \left(\cos\Delta_{32} \cos\delta \mp \sin\Delta_{32} \sin\delta \right)$$

$$P_{\text{atm}} = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$$

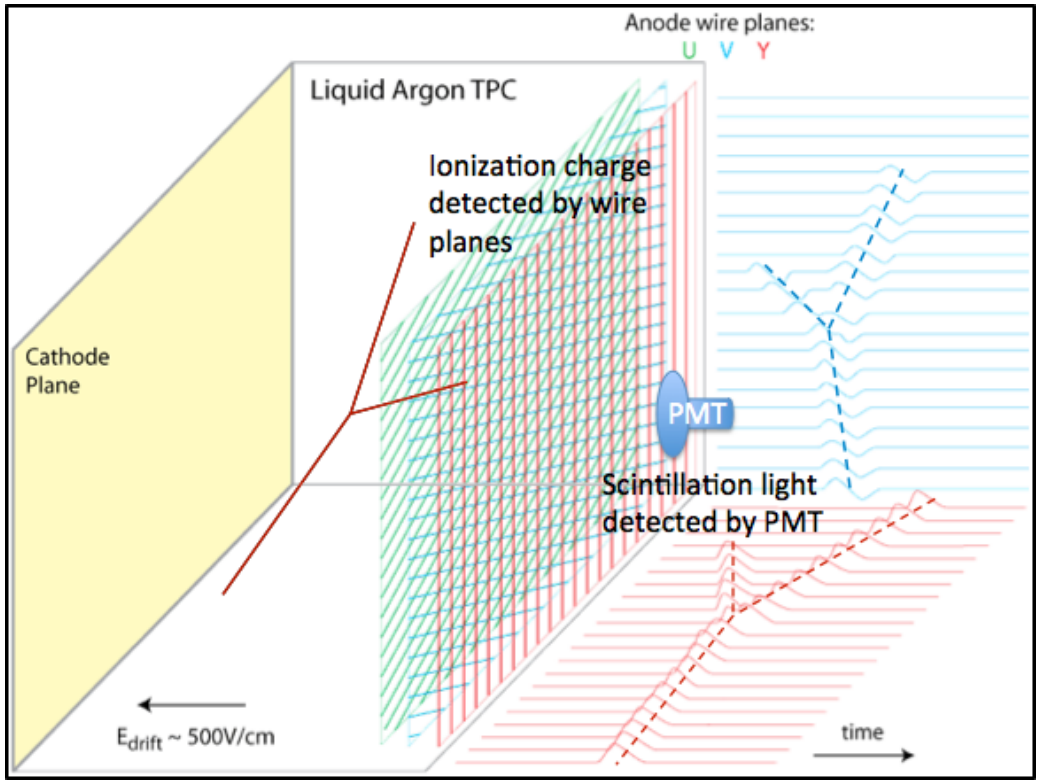
$$P_{\text{sol}} = \cos^2(\theta_{23}) \cos(2\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$

$$\Delta_{ij} = \frac{1.27(\Delta m_{ij}^2/\text{eV}^2)(L/\text{km})}{E/\text{GeV}}$$

$$P_{\text{matter}}(\nu_\mu \to \nu_e) \approx \left(1 + \frac{E \Delta m_{32}^2}{2\sqrt{2} G_F N_e} \right) P_{\text{vacuum}}$$

[1] V. Barger, *et al. Phys Rev. D* **22**:2718 (1980)
Nunokawa, Parke, and Valle, *Prog. Part. Nucl. Phys.* **60** (2008) 338-402

Liquid Argon Time Projection Chamber



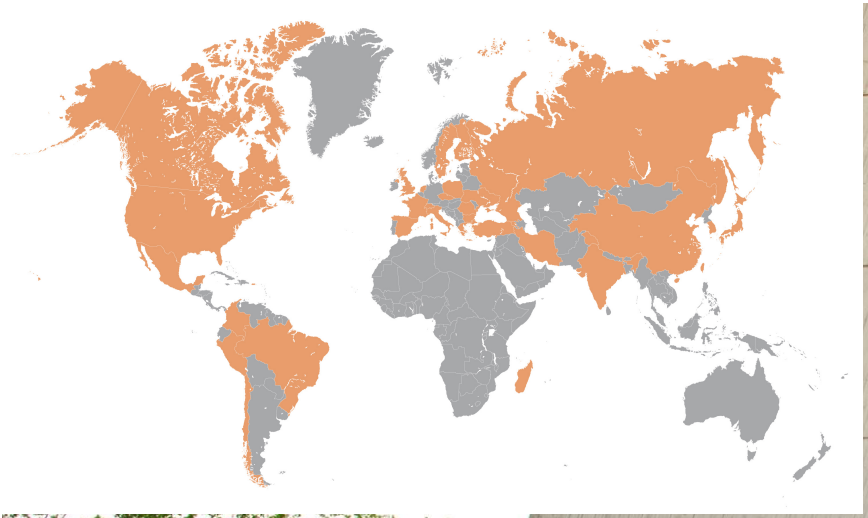
Graphic from T. Yang (FNAL) and Bo Yu (BNL)

- Neutrinos produce charged particles, which ionize the Ar
- Electrons drawn to wire planes by electric field and detected there.
- Liquid Ar also produces scintillation light when charged particles pass through it.
- The difference in arrival time between light and electrons provides timing and position information, which is especially helpful for non-beam events.

Plan for the Experiment

- Learn from Liquid Argon Time Projection Chamber Prototypes
  - 35 ton prototype
  - $3\,\mathrm{m}^3$ Dual Phase
  - protoDUNE Dual Phase
  - protoDUNE Single Phase
- Collect Data with Near and Far Detectors
  - We run in with ν_μ and $\bar{\nu}_\mu$ beams to measure $\nu/\overline{\nu}$ asymmetry and to break degeneracy between δ_{CP} and other oscillation parameter and systematic effects
  - Search for ν_e Appearance and ν_μ disappearance
  - We will take atmospheric neutrino data before and during beam running.

DUNE Collaboration (as of May 2017)



30 Nations
166 Institutions
974 Collaborators

www.facebook.com/DUNEscience/ @DUNEScience

nationalatlas.gov ™
Where We Are
GENERAL REFERENCE
CANADA
MEXICO
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO
CUBA
THE BAHAMAS
WASHINGTON
OREGON
CALIFORNIA
NEVADA
IDAHO
MONTANA
WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
NORTH DAKOTA
SOUTH DAKOTA
NEBRASKA
KANSAS
OKLAHOMA
TEXAS
MINNESOTA
IOWA
MISSOURI
ARKANSAS
LOUISIANA
WISCONSIN
ILLINOIS
MICHIGAN
INDIANA
OHIO
KENTUCKY
TENNESSEE
MISSISSIPPI
ALABAMA
GEORGIA
FLORIDA
SOUTH CAROLINA
NORTH CAROLINA
VIRGINIA
WEST VIRGINIA
PENNSYLVANIA
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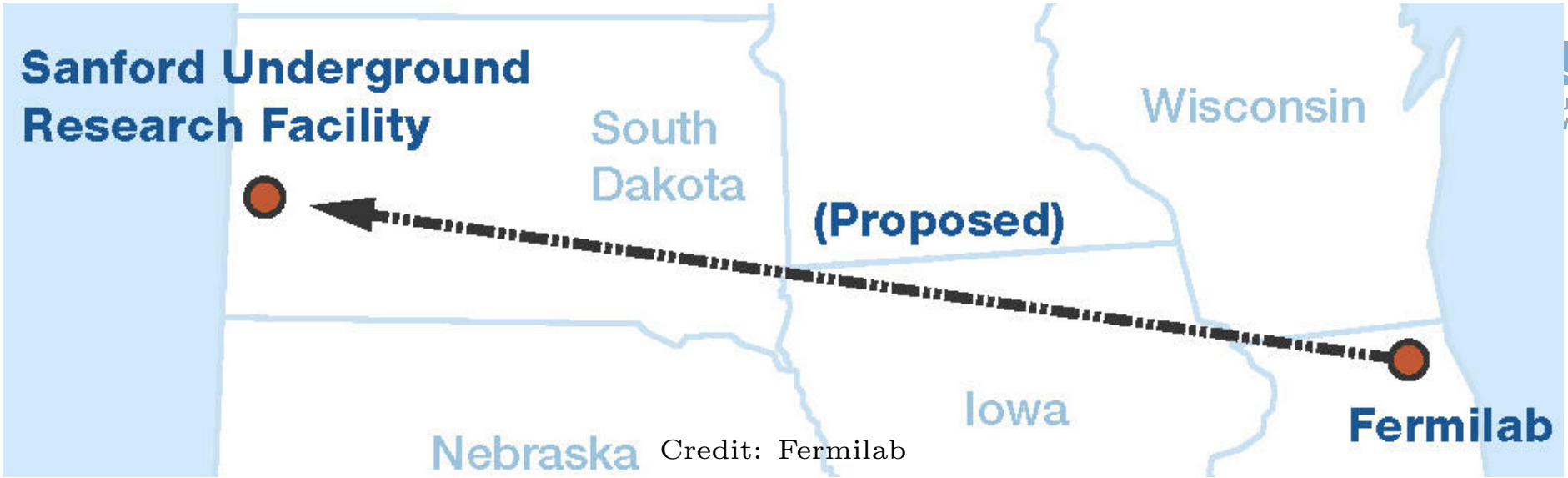
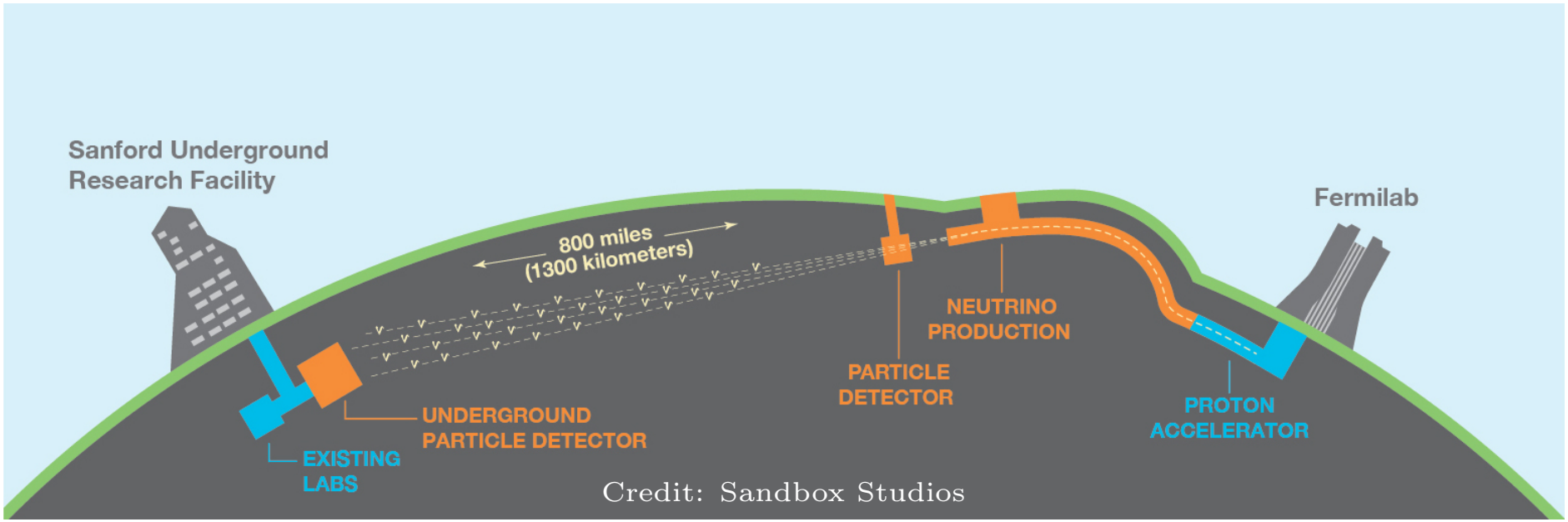
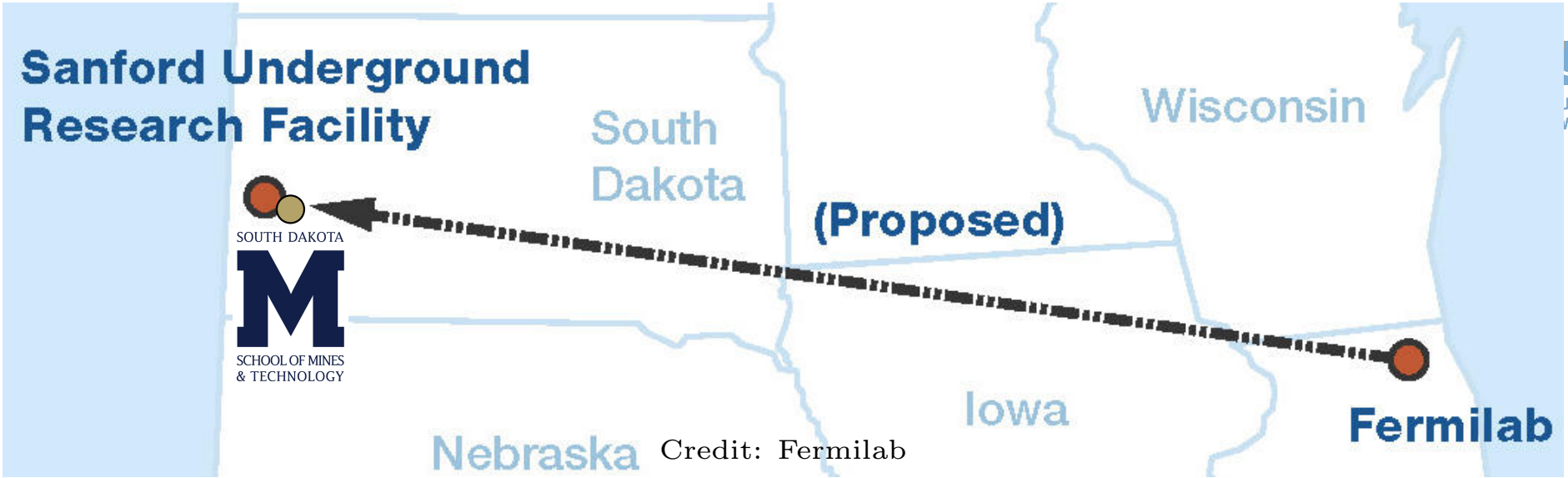


Credit: Fermilab



Credit: Sandbox Studios



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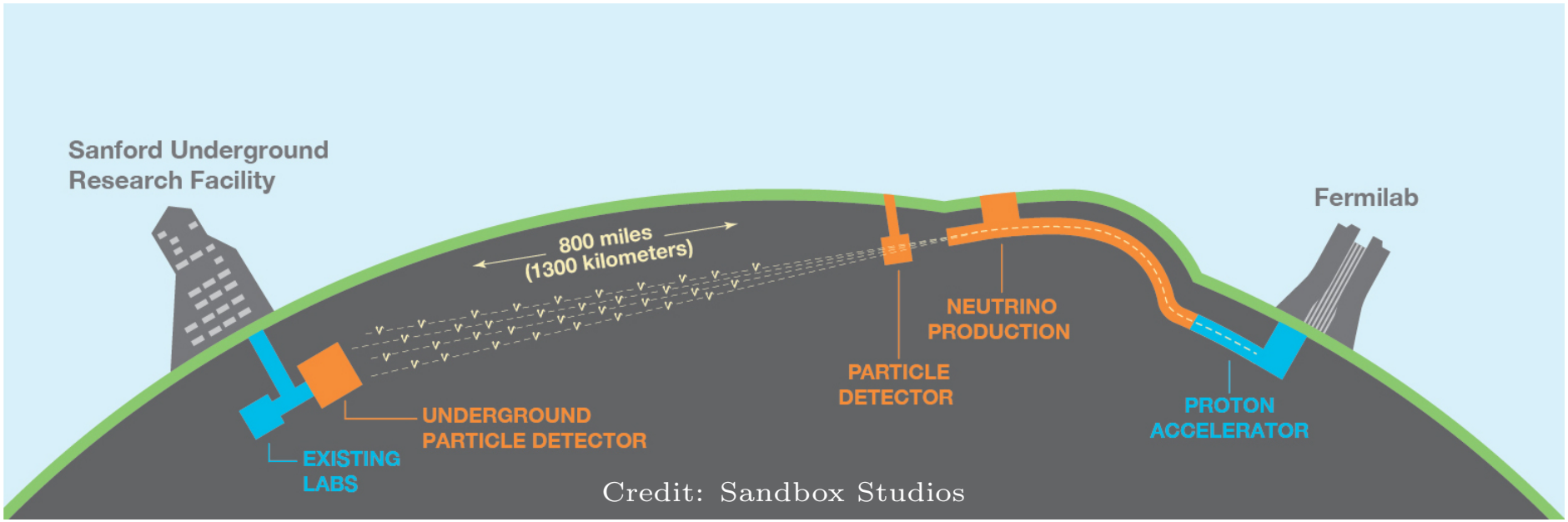
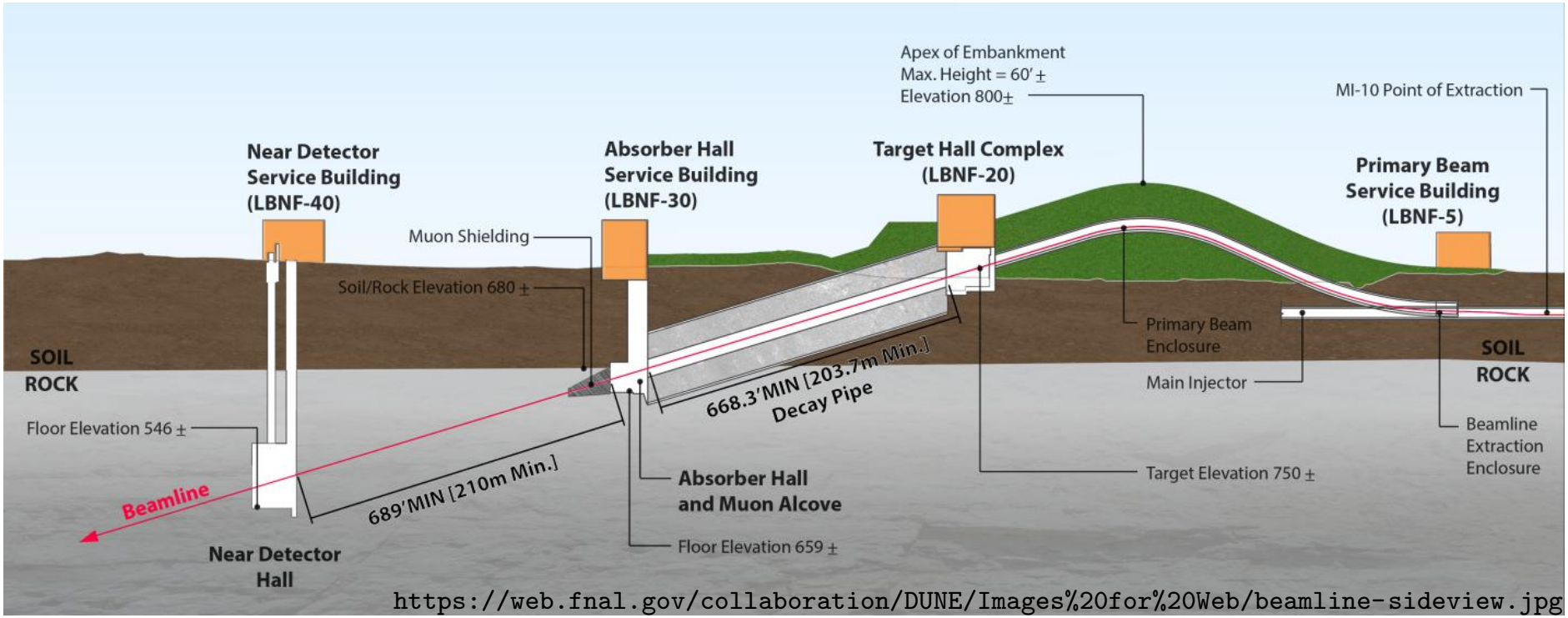


Credit: Sandbox Studios

Beamline



- New beamline to be constructed at Fermilab at MI-10 on the Main Injector
- Broadband, tunable energy ν_μ and $\overline{\nu}_\mu$ beam
  - 1.03 MW at 60 GeV
  - 1.07 MW at 80 GeV (used for sensitivity calculations)
  - 1.2 MW at 120 GeV

Three Horns

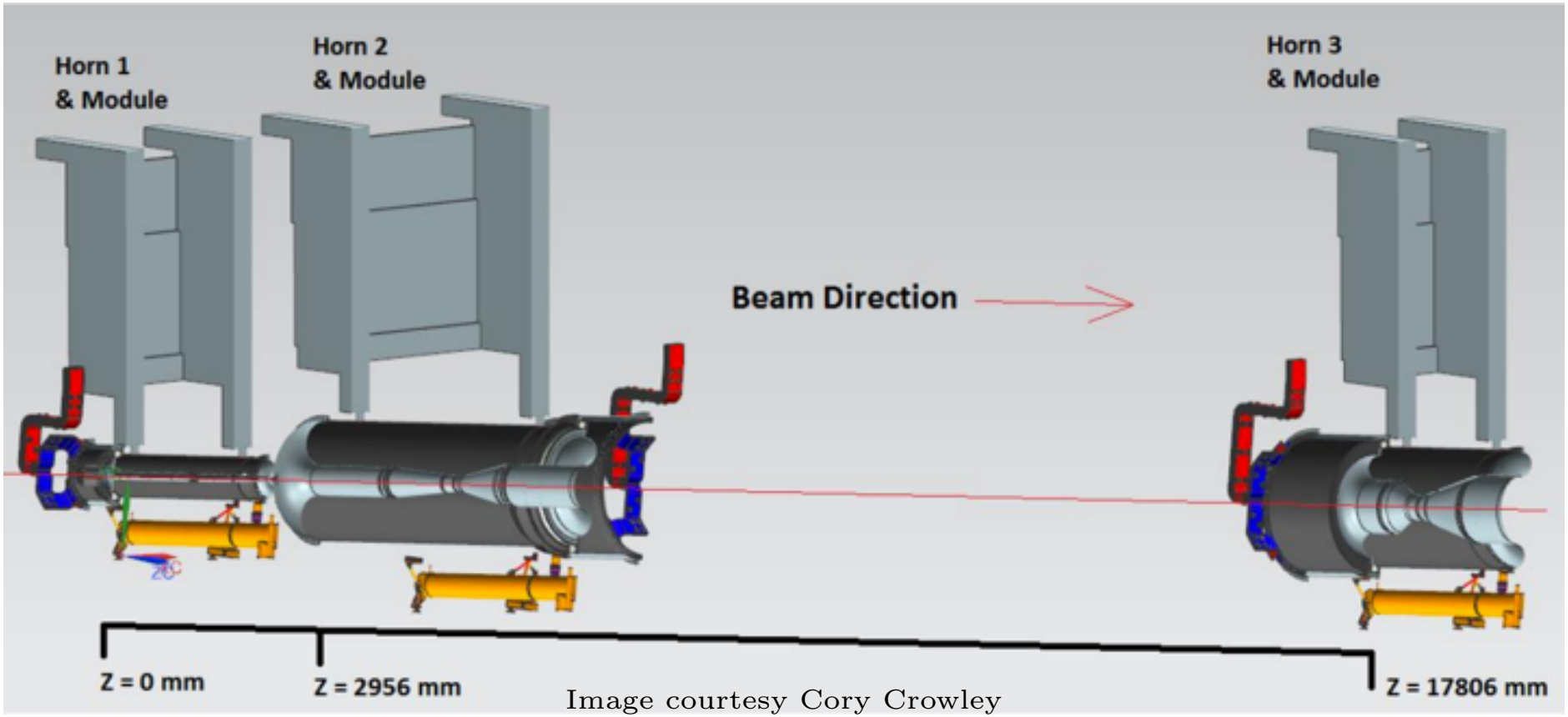
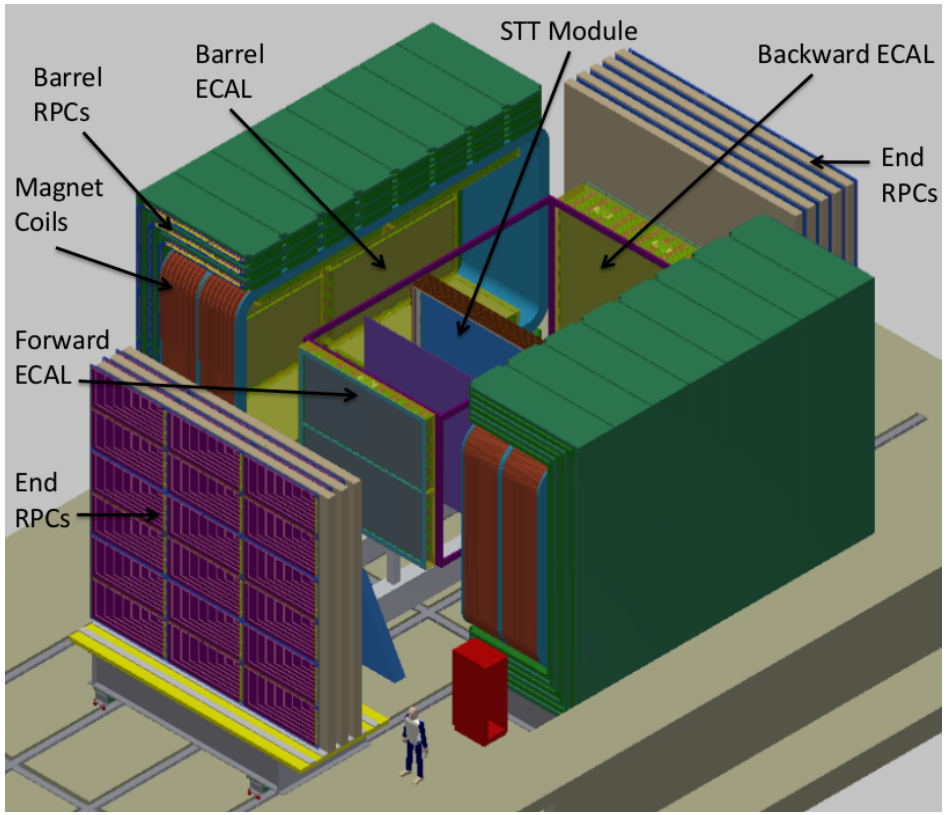


Image courtesy Cory Crowley

- Horns will focus $\pi^{\pm}$ to produce a ν_μ or $\overline{\nu}_\mu$ beam.

Near Detector

- DUNE will have a Near Detector
- The primary purpose of of the ND is constraining systematic uncertainties in the oscillation analyses
- The ND design is currently being developed with several detector technologies under consideration
- At right is one of many possible designs.

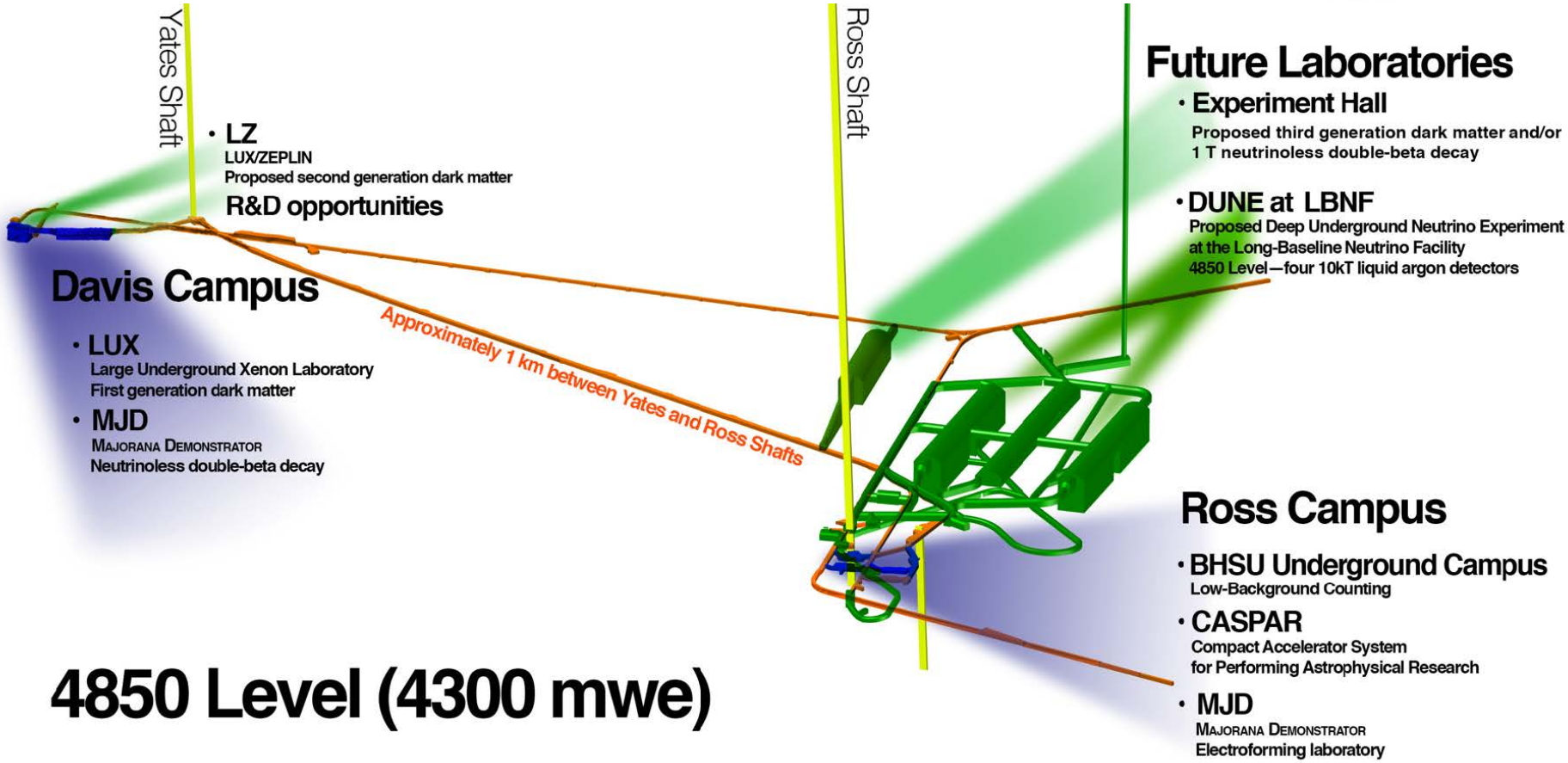


https://web.fnal.gov/collaboration/DUNE/Images%20for%20Web/FGT_Overview.png

Sanford Underground Research Facility

Credit: Matthew Kapust, Sanford Underground Research Facility ©South Dakota Science and Technology Authority

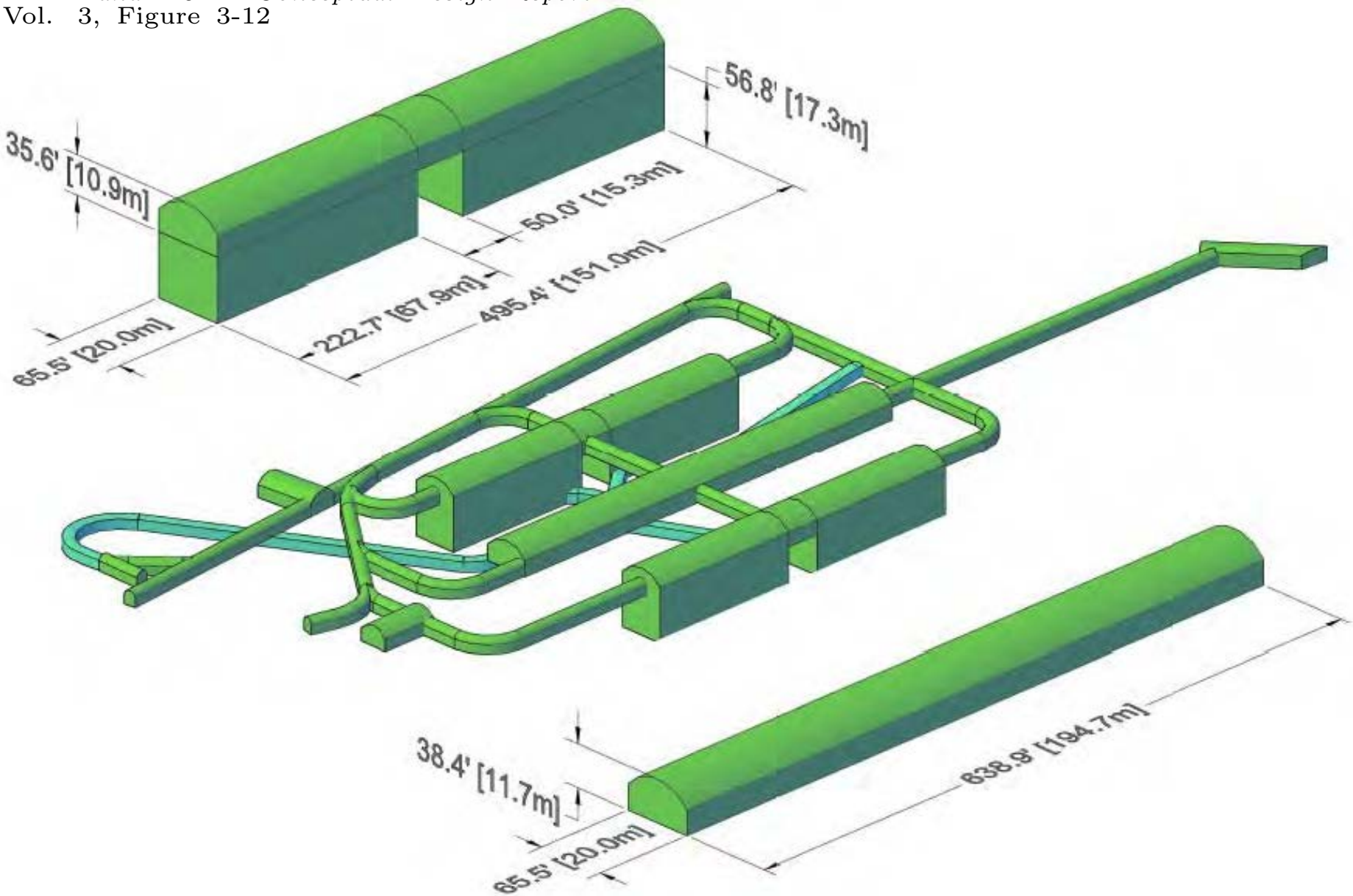
Sanford Underground Research Facility



J. Phys. Conf. Ser. **606** 012015 (2015) also arXiv:1503.01112
Phys Procedia **61** 542 (2015)
Green = future, Blue = existing

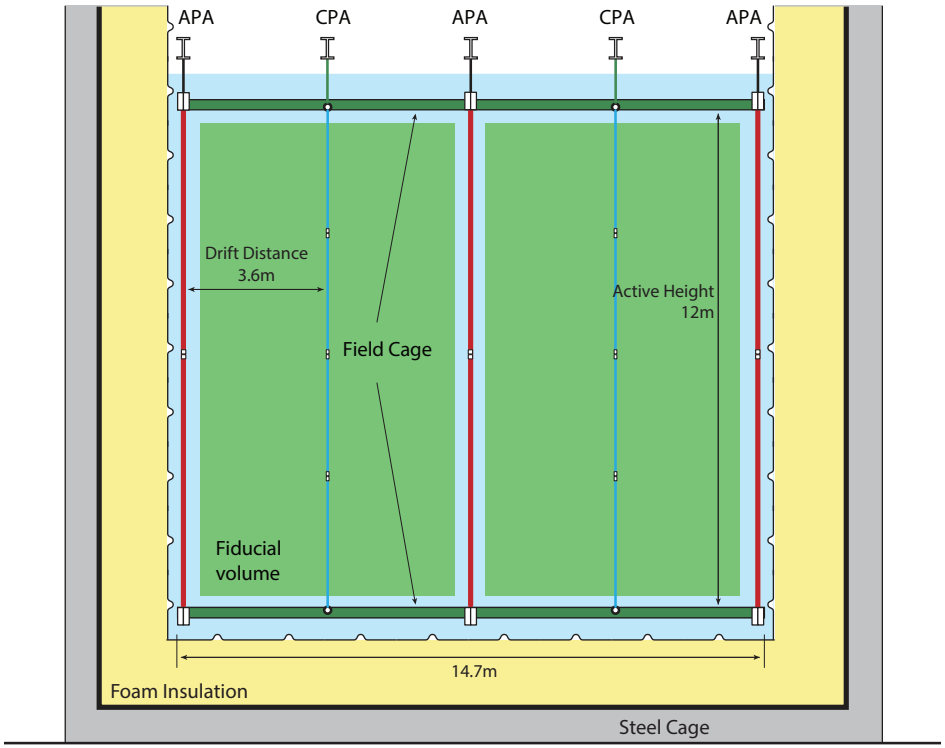
Far Detector Caverns

LBNF and DUNE Conceptual Design Report
Vol. 3, Figure 3-12



Far Detector: Single Phase

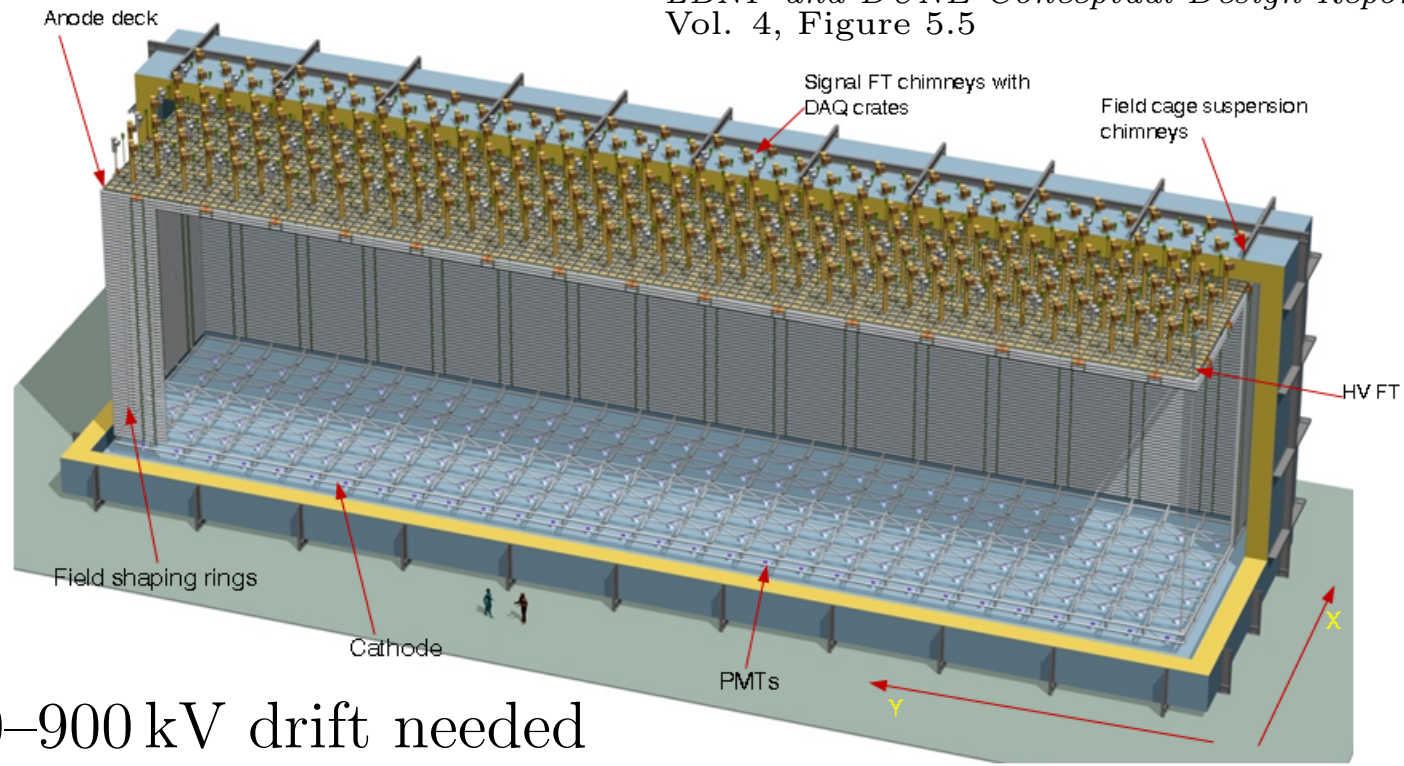
- All argon is in liquid phase
- APA = Anode Plane Assembly, includes wires for electron capture and light guides for photon capture
- CPA = Cathode Plane Assembly
- 180 kV potential difference (500 V/m)
- All detector electronics are cryogenic



LBNF and DUNE Conceptual Design Report Vol. 4, Figure 4.3

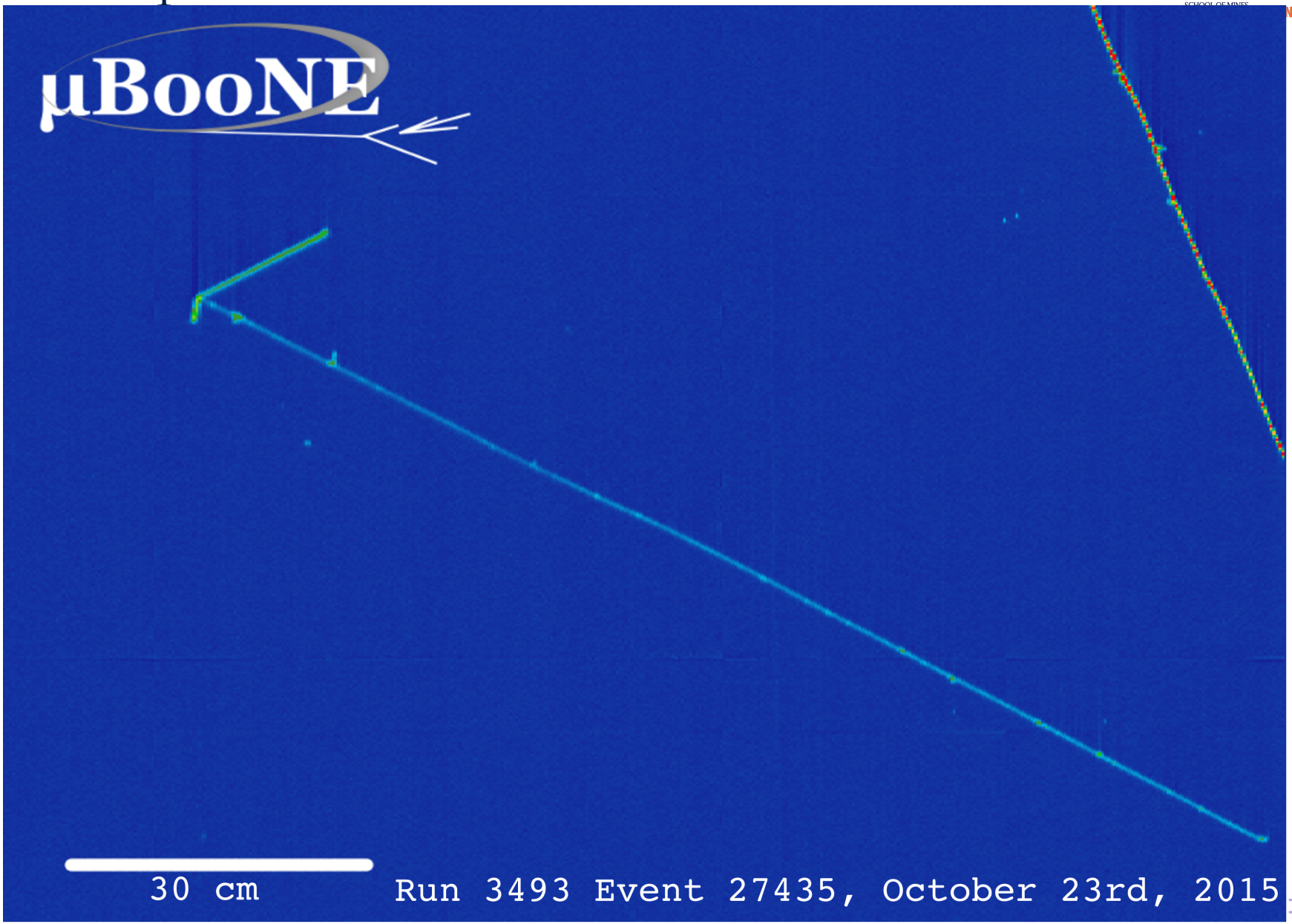
Far Detector: Dual Phase

LBNF and DUNE Conceptual Design Report
Vol. 4, Figure 5.5

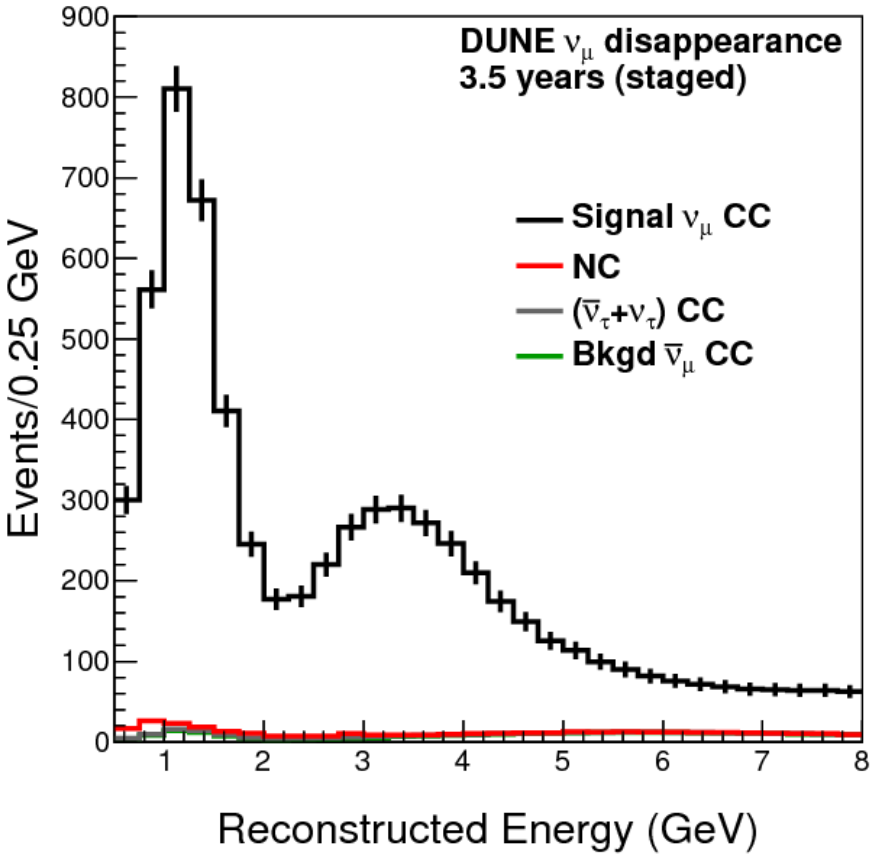


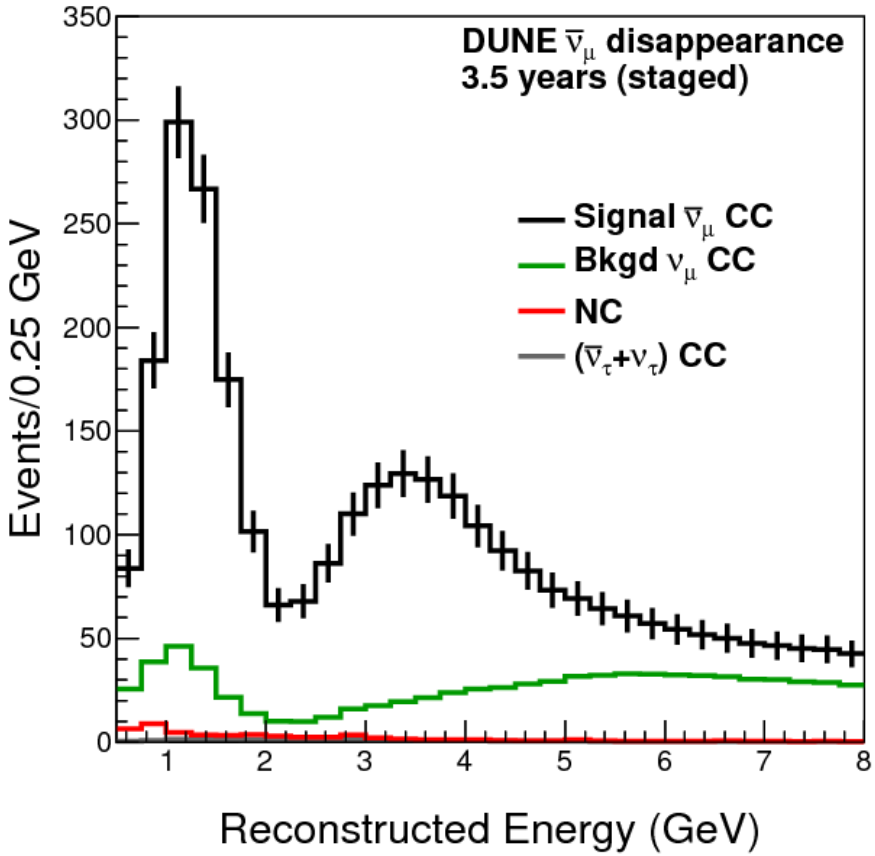
- 600–900 kV drift needed
- Gas phase on top of liquid phase
- Electronics in gaseous phase → easier maintenance
- The gas phase amplification of the signal → higher S/N ratio
- Fewer readout channels (153,600 vs 384,000)
- No dead (potentially radioactive) material in liquid Ar

Example LAr TPC Event



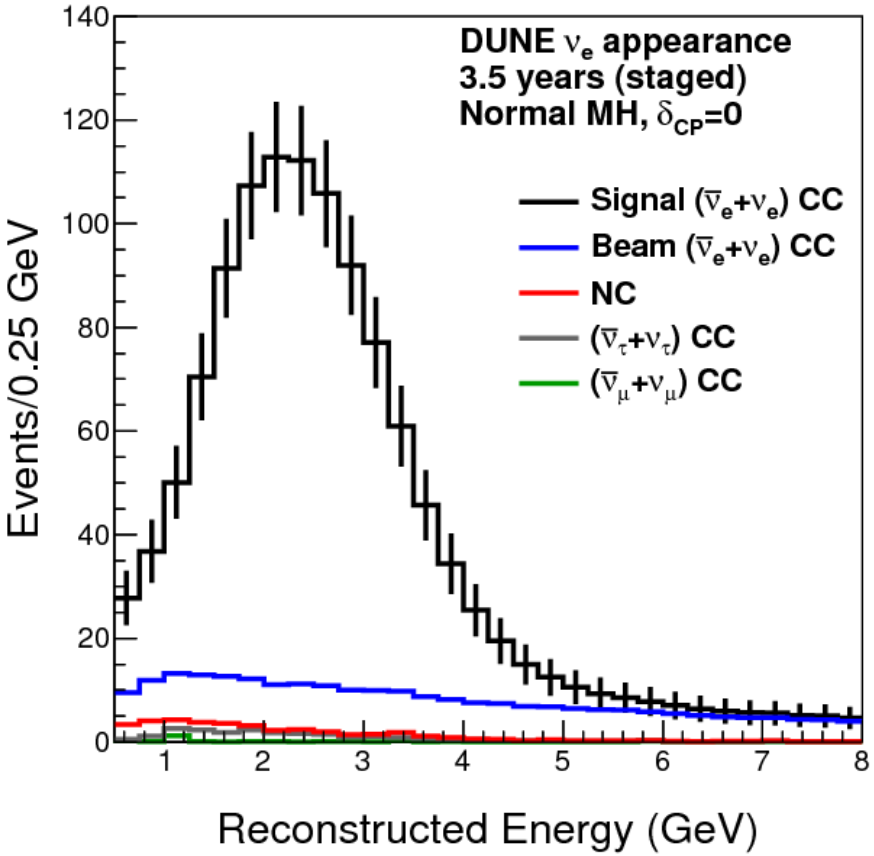
Expected Data ν_μ

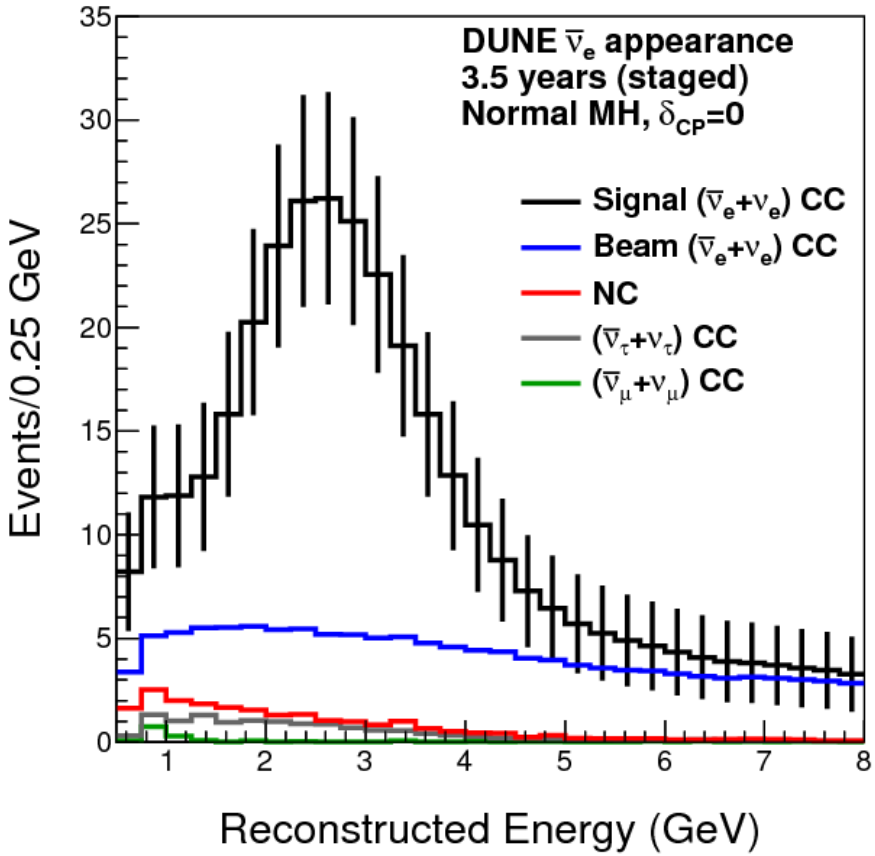




Reconstructed energy distribution of selected ν_μ (left) and $\bar{\nu}_\mu$ (right) CC-like events assuming true normal ordering. Oscillation parameters are based on NuFit 2016.

Expected Data ν_e





Reconstructed energy distribution of selected ν_e (left) and $\bar{\nu}_e$ (right) CC-like events assuming true normal mass ordering. Oscillation parameters are based on NuFit 2016.

Sensitivity

In this and following plots . . .

- Equal running in ν_μ and $\overline{\nu}_\mu$ beam
- Oscillation parameters from NuFit 2016.
- Exposure Assumptions
  - Year 1 (2026): 20-kt FD with 1.07 MW (80 GeV) beam
  - Year 2 (2027): 30 kt FD
  - Year 4 (2029): 40 kt FD
  - Year 7 (2032): upgrade to 2.14 MW (80 GeV) beam

Sensitivity to θ_{13}

In this and following plots ...

- Equal running in ν_μ and $\overline{\nu}_\mu$ beam
- Oscillation parameters from NuFit 2016.
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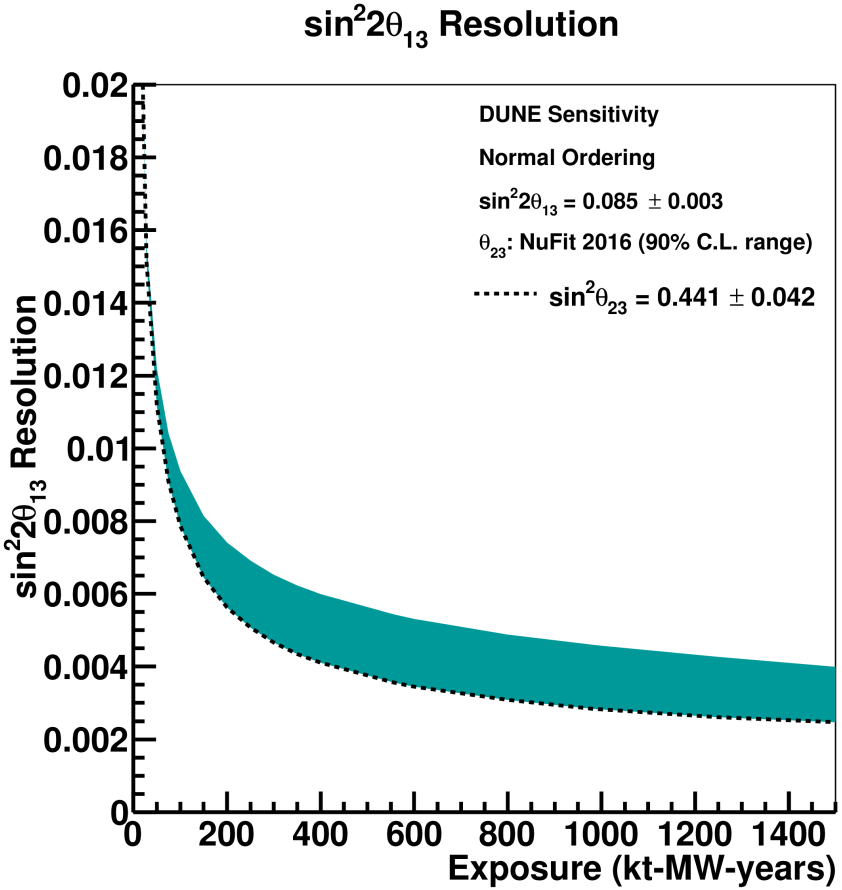
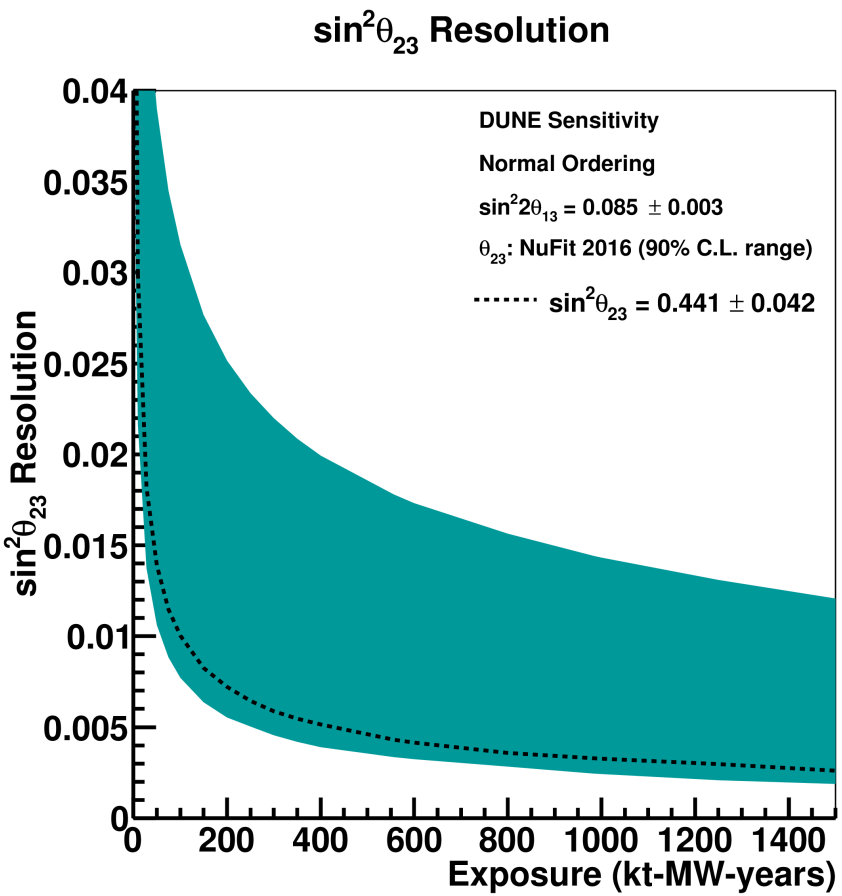
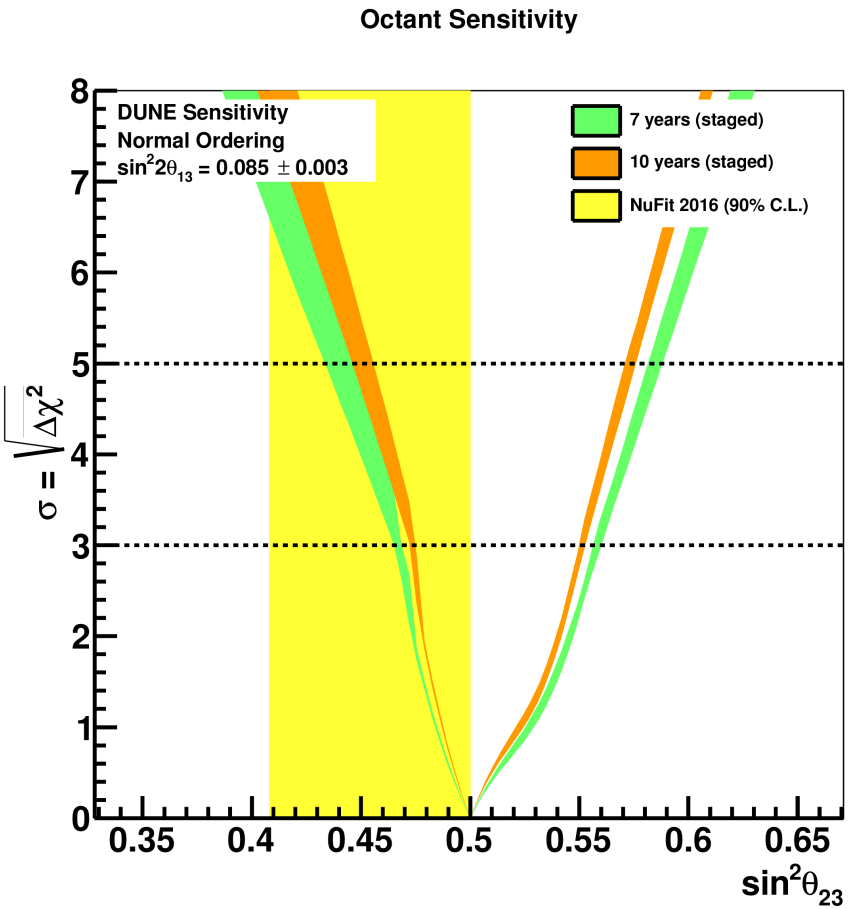


- Best resolution at central value of θ_{23} from NuFit; top of band is highest θ_{23} value

θ_{23} Octant



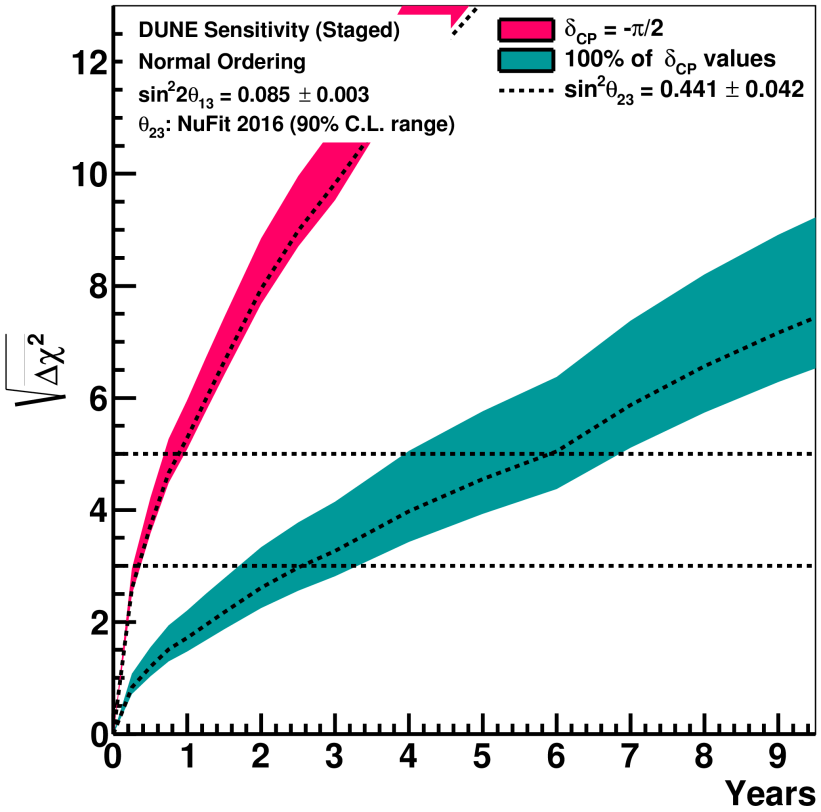
Smaller $\theta_{23} \rightarrow$ better res.



Band covers 80% of δ_{CP} values where sensitivity is least extreme

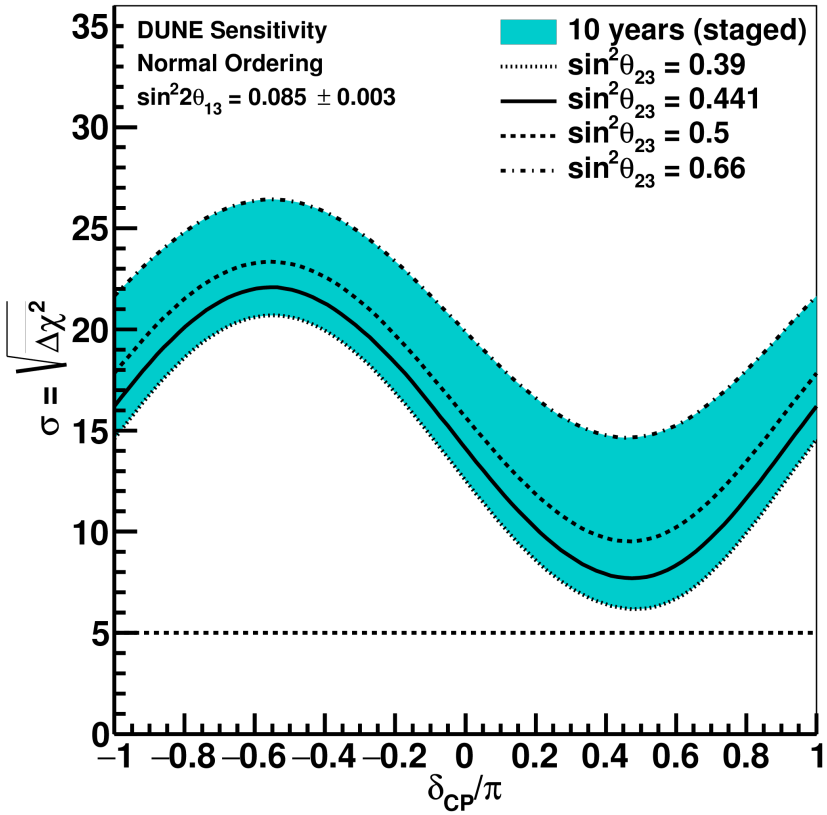
Mass Ordering

MH Sensitivity



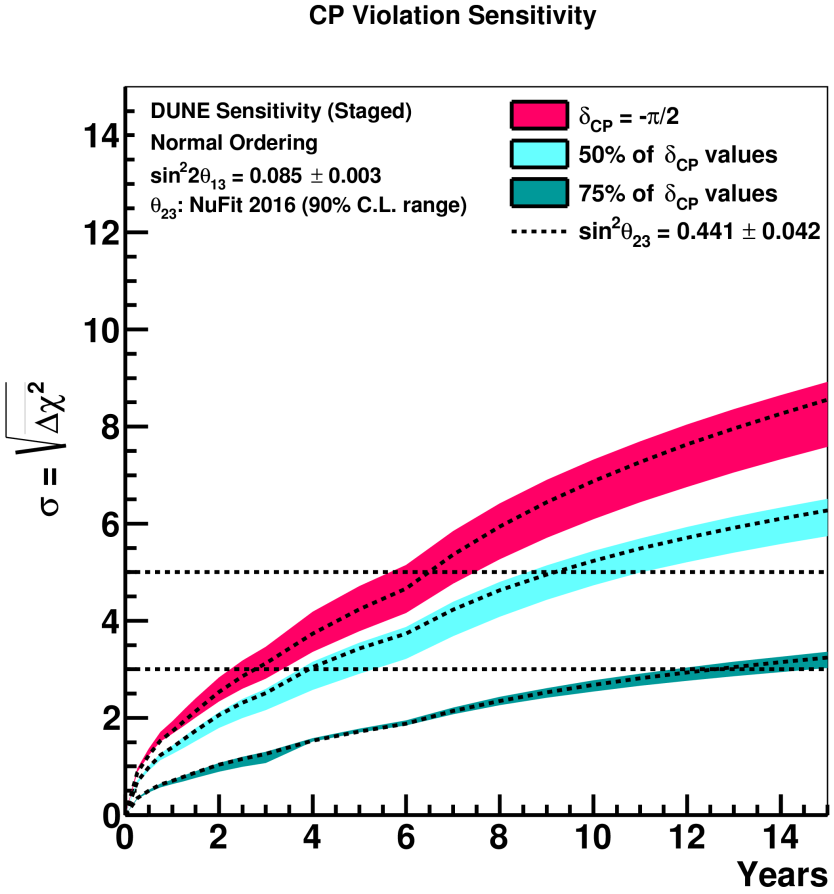
- Largest θ_{23} at top of bands
- $\delta_{\mathrm{CP}} = -\frac{\pi}{2}$ is near best case
- Green is for worst δ_{CP} case

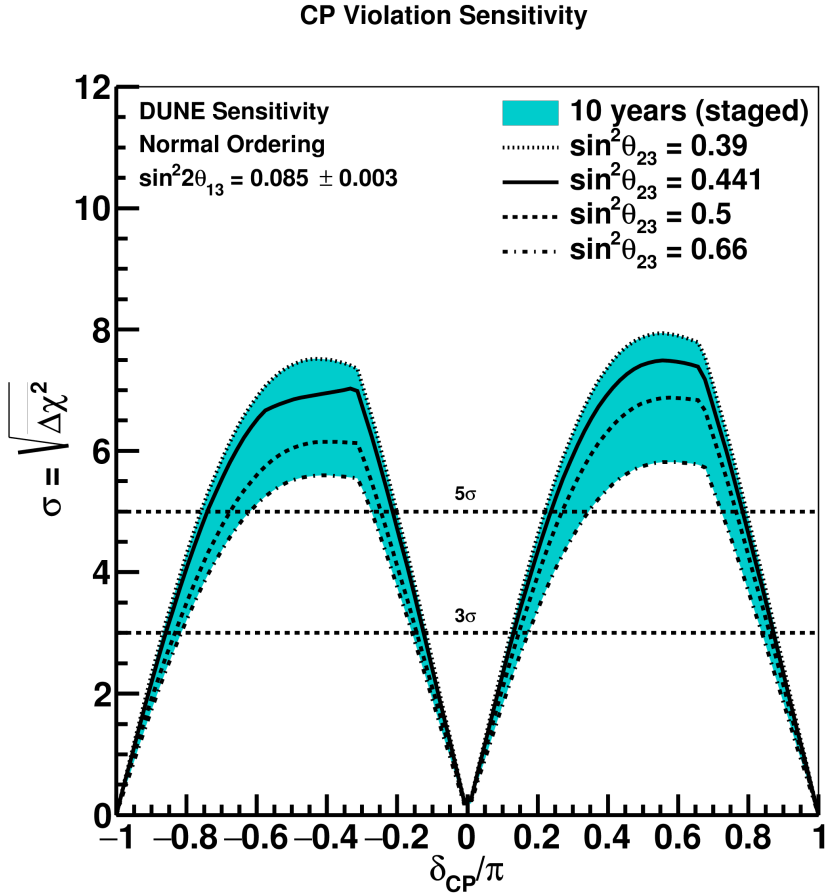
Mass Hierarchy Sensitivity



- We expect to achieve 5σ within 10 years for all values of δ_{CP}.

Expected Sensitivity to δ_{CP}

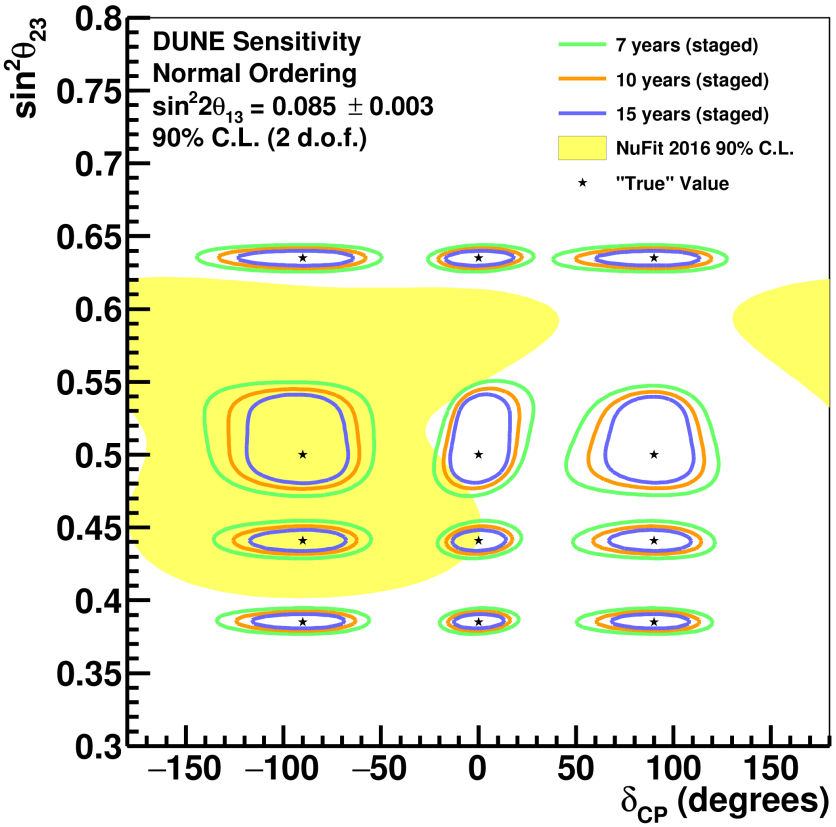


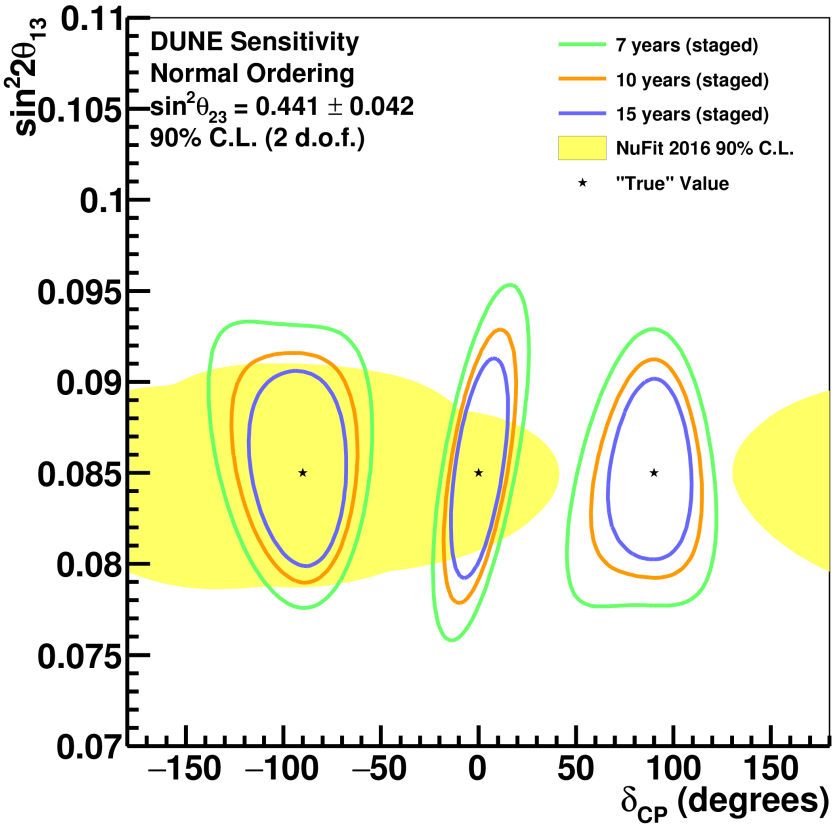


- Smallest θ_{23} at top of bands
- Green band is minimum sig. for 75% of δ_{CP} values

- CP violation is defined as $\delta_{CP} \neq 0$ or π

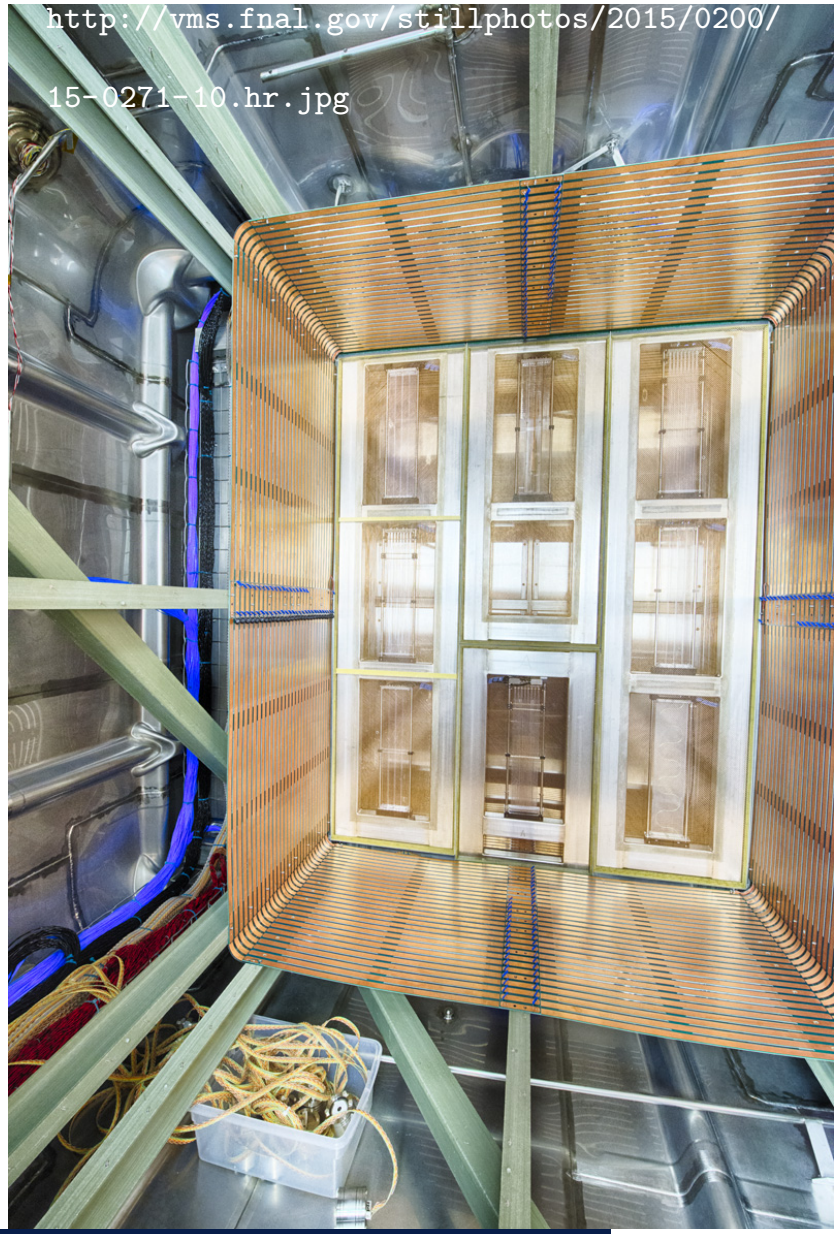
Combined Plots





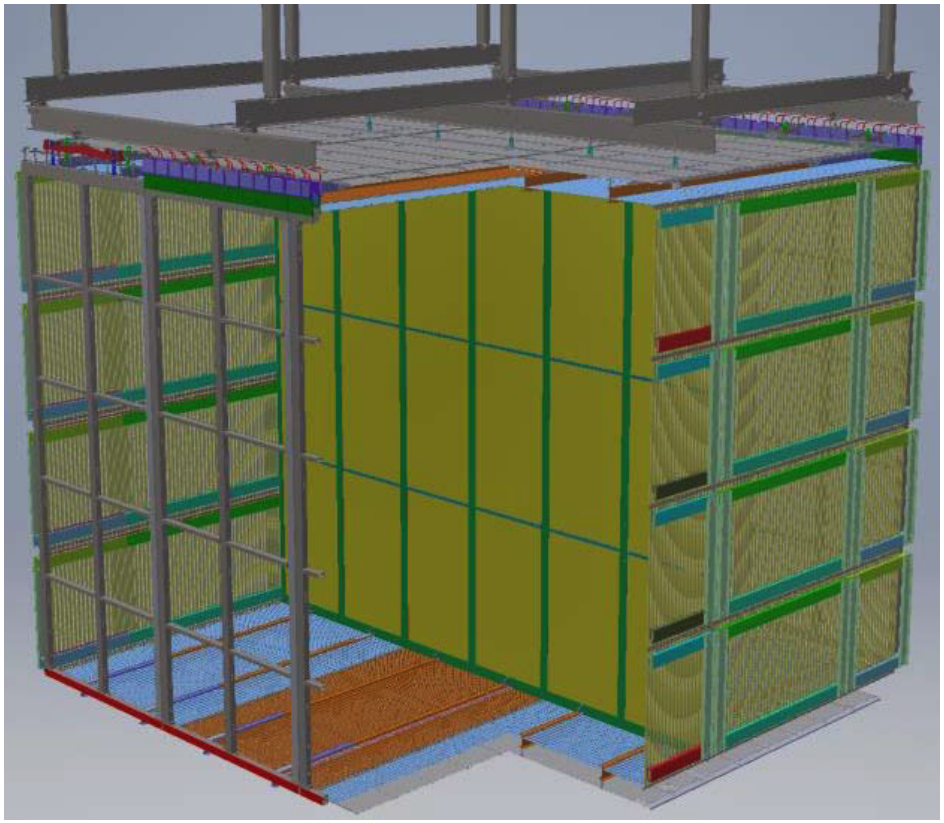
- Relationships between expected sensitivities for various true values of the oscillation and CP parameters

35 ton Prototype



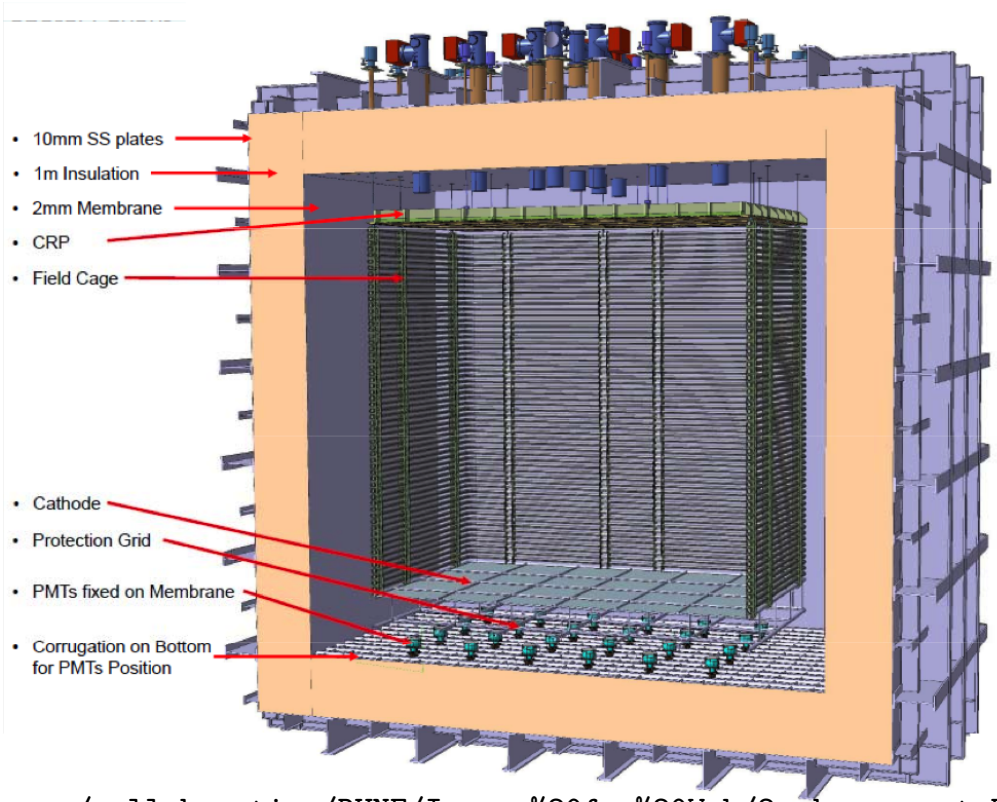
- First prototype of many novel LAr TPC elements required for DUNE
- Phase I (Dec. 2013 – Feb. 2014)
  - Tested cryostat & purification
  - Achieved e^- lifetime of 3 ms
- Phase II (Jan – Mar. 2016)
  - Successful operation of prototype detector in spite of some technical difficulties
  - Provided valuable insight into detector design, operations, and data analysis
  - Analysis of cosmic data ongoing
- Currently being used for high voltage tests

protoDUNE Single Phase



- Small scale version of single phase far detector with full size APAs
- $6\,\mathrm{m} \times 6\,\mathrm{m} \times 6\,\mathrm{m}$
- Under construction at CERN
- Will test many technologies and construction techniques for the far detector, including light guides.
- Plan to take cosmic ray and test beam data starting Aug. 2018

Dual Phase Prototypes



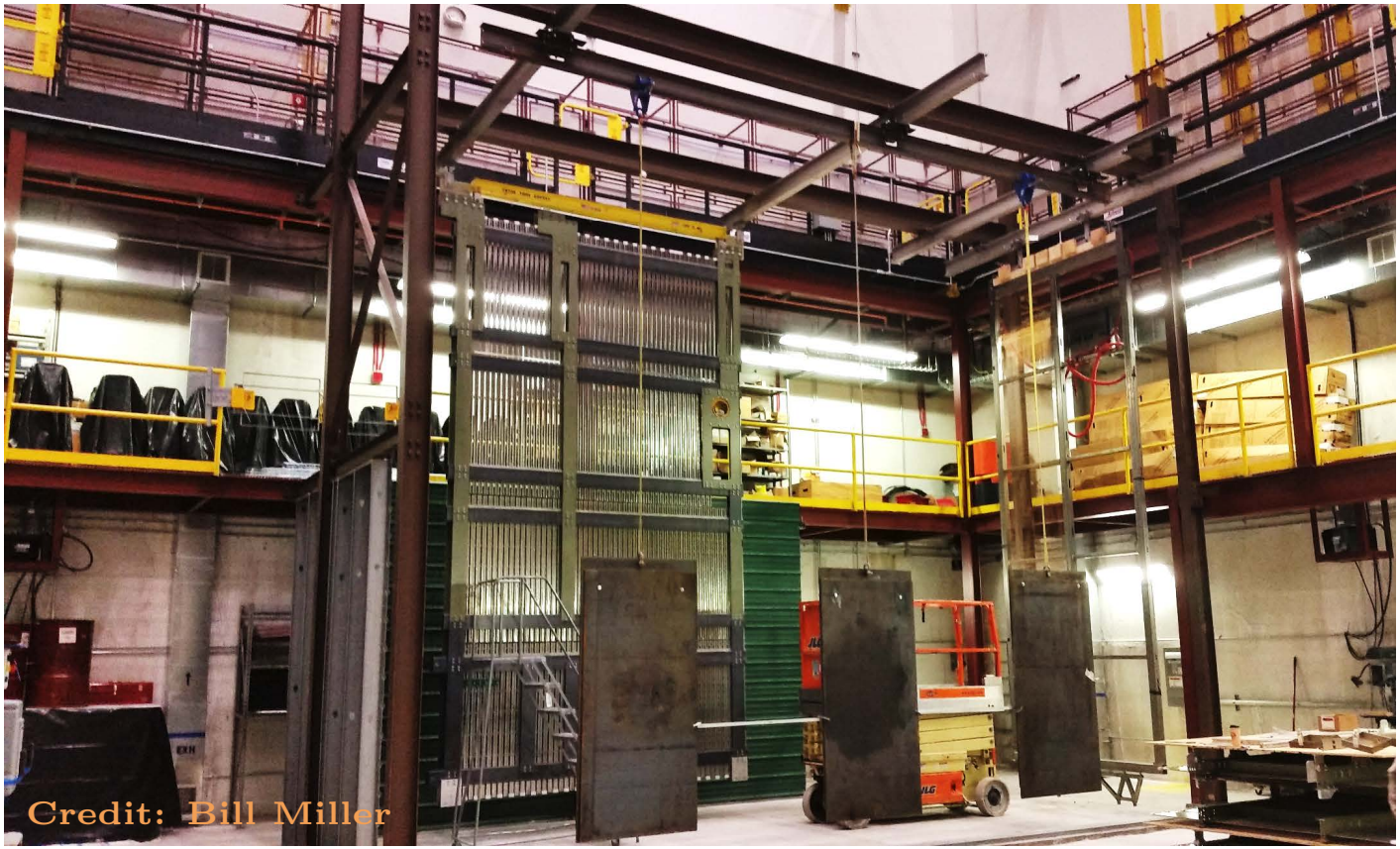
https://web.fnal.gov/collaboration/DUNE/Images%20for%20Web/2-phase-protoDUNE-interior.png

- Two dual phase prototypes
- $3\,\mathrm{m}^3$ ($3\,\mathrm{m} \times 1\,\mathrm{m} \times 1\,\mathrm{m}$) constructed, being filled at CERN
- protoDUNE DP ($6\,\mathrm{m} \times 6\,\mathrm{m} \times 6\,\mathrm{m}$) under construction at CERN. Will also take data starting Aug. 2018

Prototypes Live!

- Construction in EHN1 streamed live via web cam
- Left: NP02 (Dual Phase). Right: NP04 (Single Phase)
- Images updated every 30 minutes at `http://cenf-ehn1-np.web.cern.ch/multimedia/images`

Far Detector Construction Tests



- Black rectangles are pieces of the MINOS Far Detector
- This is in the NOvA Far Detector Hall, where the MINOS FD pieces are being used to test a trolley for moving pieces of the DUNE Far Detector.

Timeline

- Beamline, caverns and cryostat are responsibility of the Long-Baseline Neutrino Facility (LBNF)
- Detectors are the responsibility of DUNE
- 2017: Groundbreaking for surface construction at Sanford Lab
- 2018: Start excavation of far detector caverns at SURF
- 2018: Two prototypes (ProtoDUNEs) operational at CERN
- 2021: Start of 1st FD module installation
- 2023: Start of 2nd FD module installation
- 2024: 20 kt operational
- 2026: Beam operations at begin

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DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Thank you!
Any Questions?

Backup

Single Phase FD Performance

Parameter	Reference Performance	Achieved Elsewhere	Expected Performance
Signal/Noise Ratio[1]	9:1	10:1 [6, 7][2]	9:1
Electron Lifetime	3 ms	>15 ms [7]	>3 ms
Uncertainty on Charge Loss due to Lifetime	$<1\%$	$<1\%$ [7]	$<1\%$
Dynamic Range of Hit Charge Measurement	15 MIP		15 MIP
Vertex Position Resolution[3]	(2.5,2.5,2.5) cm		(1.1,1.4,1.7) cm [8, 9]
$e-\gamma$ separation ϵ_e	0.9		0.9
$e-\gamma$ separation γ rejection	0.99		0.99
Multiple Scattering Resolution on muon momentum[4]	$\sim$18%	$\sim$18% [10, 11]	$\sim$18%
Electron Energy Scale Uncertainty	5%	2.2%[12]	From LArIAT and CERN Prototype
Electron Energy Resolution	$0.15/\sqrt{E(\mathrm{MeV})}$ $\oplus 1\%$	$0.33/\sqrt{E(\mathrm{MeV})}$ [12] $+1\%$	From LArIAT and CERN Prototype
Energy Resolution for Stopping Hadrons	1–5%		From LArIAT and CERN Prototype
Stub-Finding Efficiency[5]	90%		$>90\%$

Dual Phase FD Performance

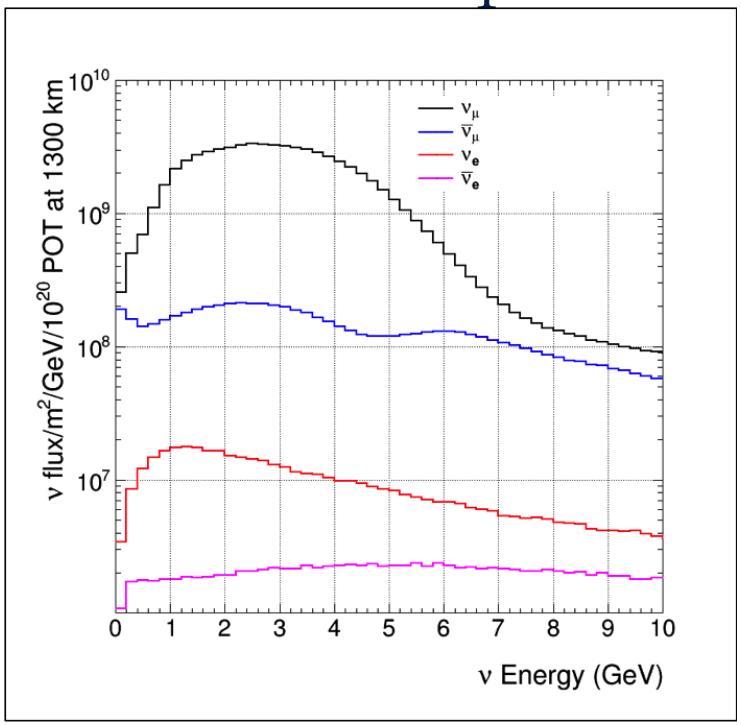
Table 5.1: Performance parameters specific to the dual-phase far detector design

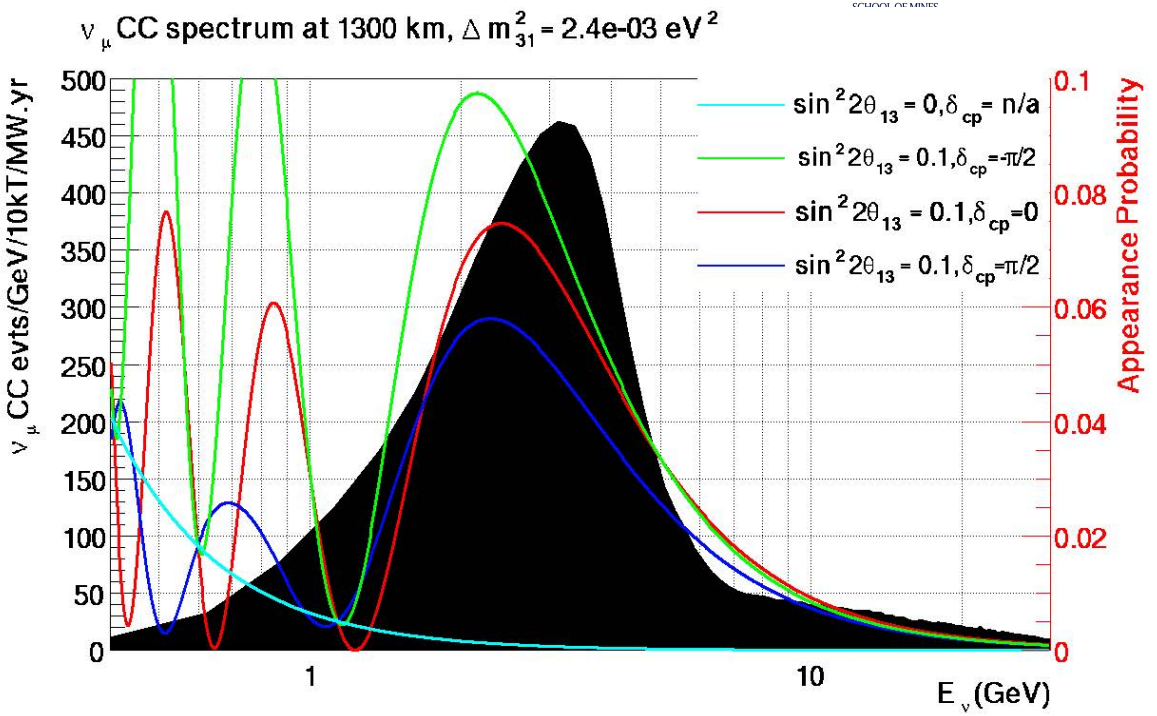
Parameter	Requirement	Achieved Elsewhere	Expected Performance
Gas phase gain	20	200	20-100
Electron Lifetime	3 ms	> 3 ms 35-t prototype	> 5 ms
Minimal S/N after 12 m drift	9:1	> 100:1	12:1-60:1

Table 5.2: Sizes and Dimensions for the 12-kt (15-kt) dual-phase LArTPC

Item	Value(s)	
Active volume width and length	W = 12 m	L = 60 m
Active volume height	H = 12 m (H = 15 m)	
Active volume/LAr mass	8,640 (10,800) m^3	12,096 (15,120) metric ton
Field ring vertical spacing	200 mm	
Field ring tube diameter	140 mm	
Anode plane size	W = 12 m	L = 60 m
CRP unit size	W = 3 m	L = 3 m
HV for vertical drift	600–900 kV	
Resistor value	100 MΩ	

Illustrative Spectra





- Left: An unoscillated spectrum at the far detector for a broadband beam similar to DUNE
- Right: Oscillation probabilities for several values of δ_{CP}
- DUNE will be able to measure the shape of the oscillation and some of the second oscillation node because of the broadband beam.