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Long-baseline Oscillations and CP in the US: NOvA and DUNE

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Introduction

- Operating long-baseline accelerator neutrino oscillation experiments will transition into the next generation of experiments in the next decade
  - This generation: T2K (Japan) + NOvA (U.S.)
  - Next generation: T2HK (Japan) + DUNE (U.S.)
  - This talk will focus on the current and next generation experiments that are based in the U.S - NOvA and DUNE
    - Will make some references to the counterparts in Japan

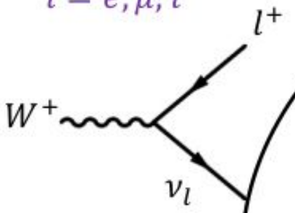
- Disclaimer: I am a DUNE and T2K collaborator, but I am speaking today as a member of the Neutrino community.

Neutrino Oscillations

produced in flavor eigenstates | *propagate in mass eigenstates* | *observed in flavor eigenstates*

flavor states

$l = e, \mu, \tau$



mass states

$i = 1, 2, 3$

$$|\alpha(0)\rangle = |\nu_l\rangle = \sum_i c_i |\nu_i\rangle$$

$$|\alpha(x)\rangle = \sum_i c_i |\nu_i\rangle e^{-ip_i \cdot x}$$

$$\Rightarrow |\langle \nu_{l'} | \alpha(x)\rangle|^2 \neq \delta_{ll'}$$

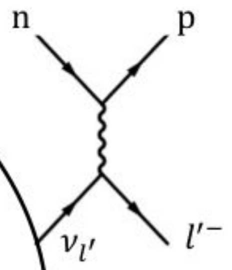
$s_{ij} \equiv \sin\theta_{ij}$

$c_{ij} \equiv \cos\theta_{ij}$

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

Majorana phases (no effect on oscillations)

U_{PMNS}



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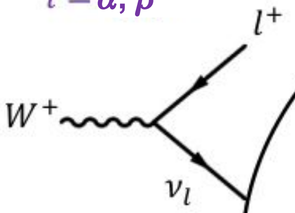
Neutrino Oscillations

produced in flavor eigenstates | *propagate in mass eigenstates* | *observed in flavor eigenstates*

flavor states

$l = \alpha, \beta$



mass states

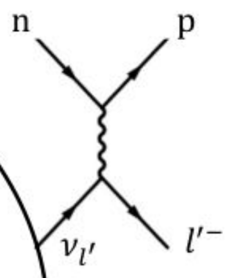
$i = 1, 2$

simplified 2-neutrino example

Nature dictates these

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 \cdot L}{4E}\right)$$

Experimentalists can have some control over these



ν_e Appearance Channel

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E} \qquad a[\mathrm{eV}^2/c^4] \equiv 7.56\times10^{-5}\rho\left[\mathrm{g/cm}^3\right]E[\mathrm{GeV}]$$

sensitive to octant of θ_{23}

sensitive to δ_{CP} and $\mathrm{sign}\left(\Delta m^2_{31}\right) \rightarrow$ mass hierarchy

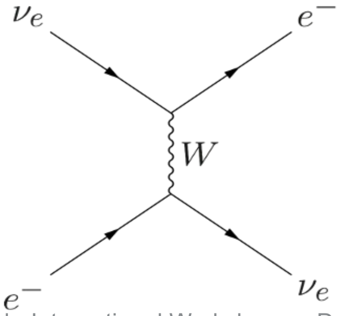
- Sub-leading → compare neutrino & antineutrino
- ∃ degeneracies

$$P\left(\overset{(-)}{\nu_\mu} \rightarrow \overset{(-)}{\nu_e}\right) = \sin^2 2\theta_{13}\, s^2_{23} \sin^2\phi_{31} \mp 8\, s_{13}c^2_{13}s_{12}c_{12}s_{23}c_{23}\sin\delta_{CP} \sin\phi_{32} \sin\phi_{31} \sin\phi_{21}$$

Jarlskog Invariant

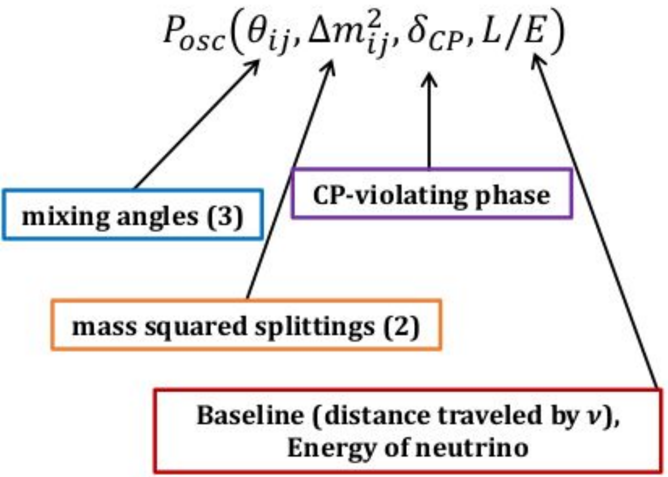
$$\mp 8c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})\frac{aL}{4E}\sin\phi_{31}\cos\phi_{32} + \cdots$$

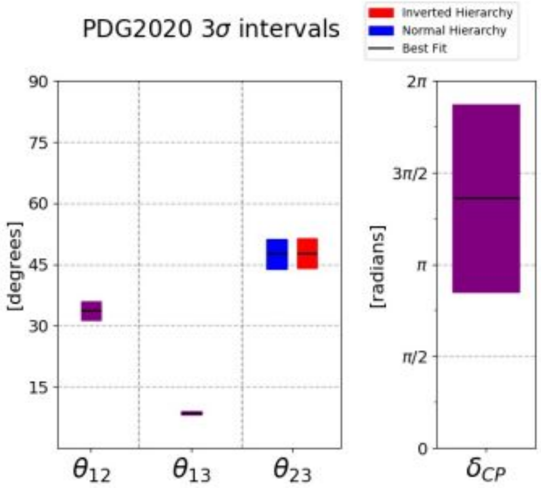
Matter effect: coherent forward elastic CC scattering only for ν_e



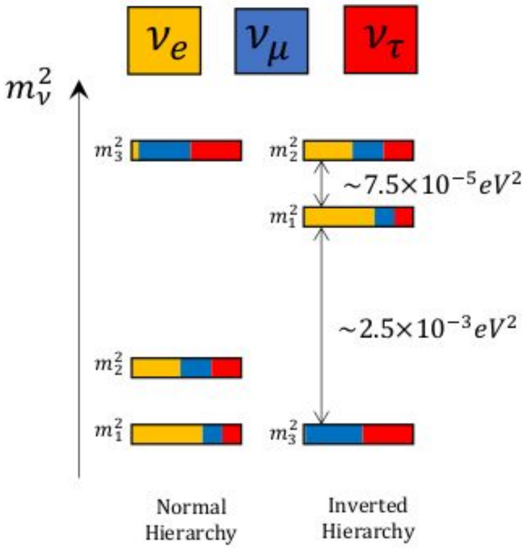
Long baselines can break degeneracies by exploiting the matter effect

What do we (not) know?





Δm^2's measured at few-% level



Neutrinos oscillate!

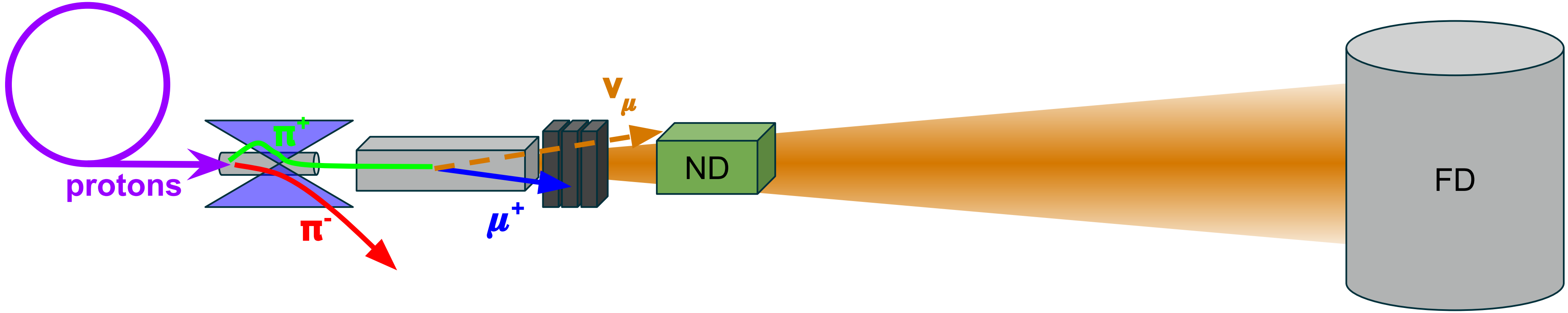
Octant of θ_{23}?

CP Violated?

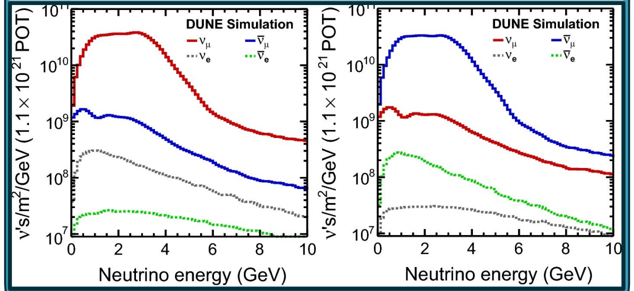
Mass hierarchy?

Mass nature/origins

Long-Baseline Accelerator Neutrino Oscillations

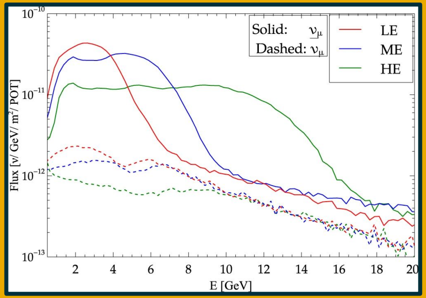


Operate in ν OR $\bar{\nu}$ mode



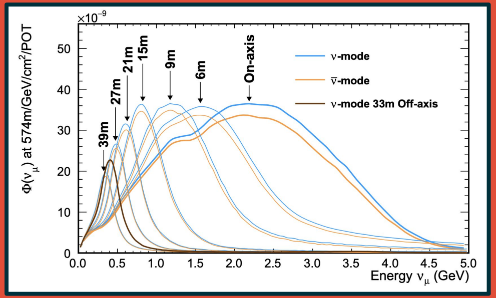
Abi, B., Acciarri, R., Acero, M.A. et al. Long-baseline neutrino oscillation physics potential of the DUNE experiment. Eur. Phys. J. C 80, 978 (2020)

Tunable neutrino source



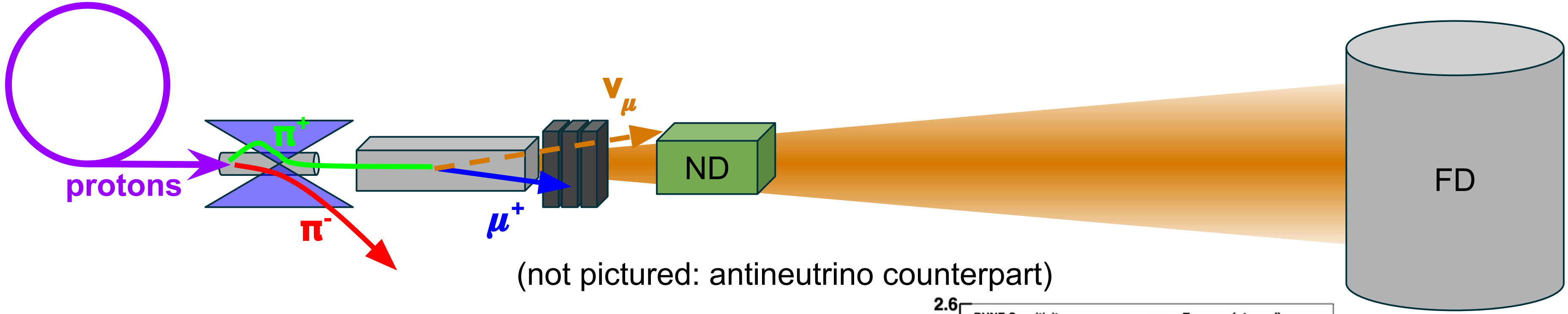
Masud, M., Bishai, M. & Mehta, P. Extricating New Physics Scenarios at DUNE with Higher Energy Beams. Sci Rep 9, 352 (2019)

The off-axis "trick"

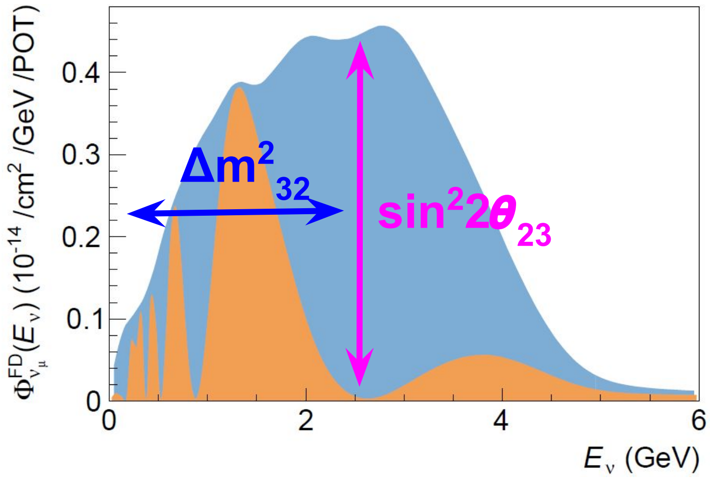


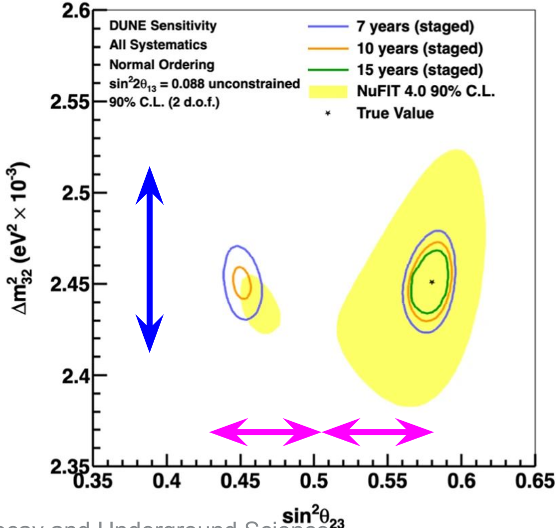
Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics. arXiv:2002.03005

Long-Baseline Accelerator Neutrino Oscillations



(not pictured: antineutrino counterpart)





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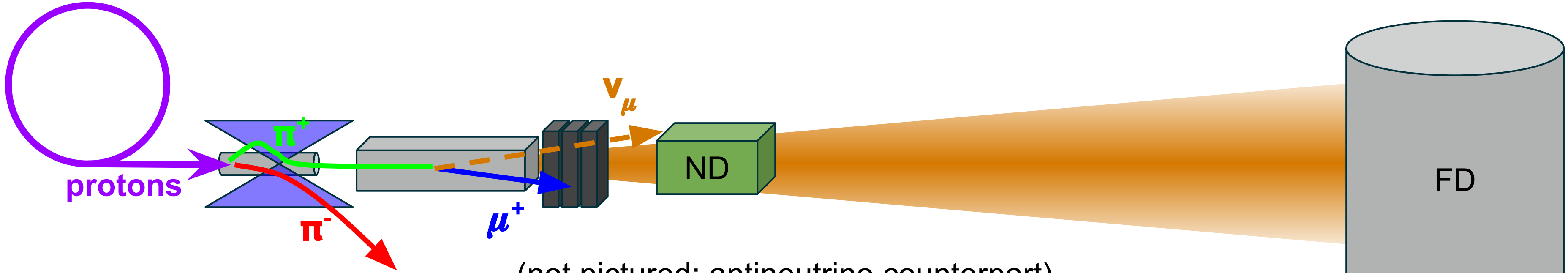
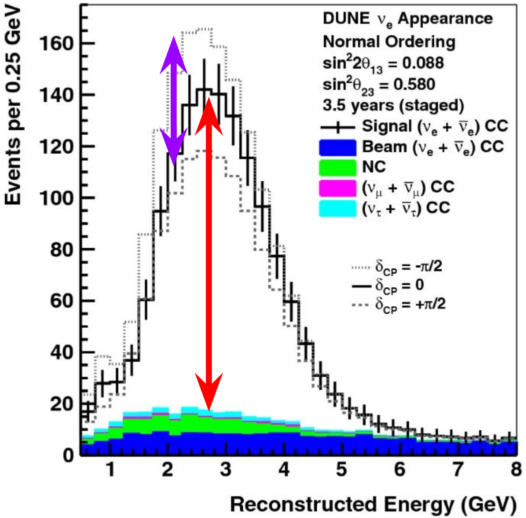
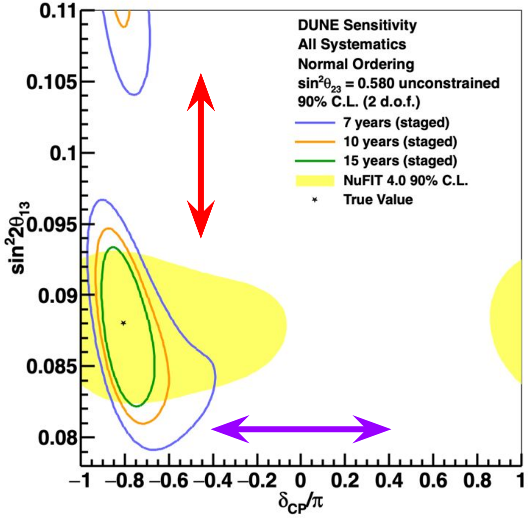


(not pictured: antineutrino counterpart)

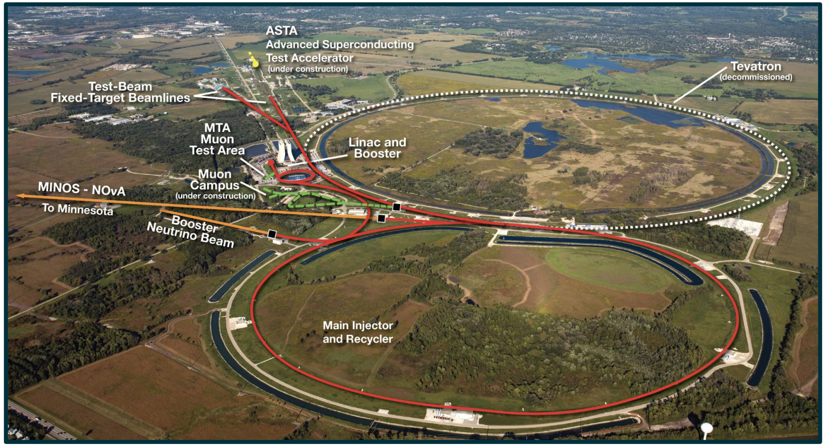
δ_{CP}



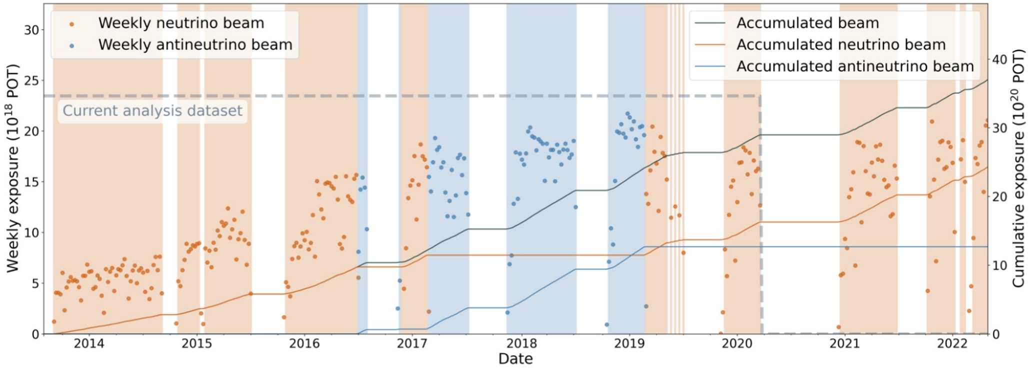


$\sin^2\theta_{23}$ & $\sin^2\theta_{13}$

NOvA in the NuMI beamline



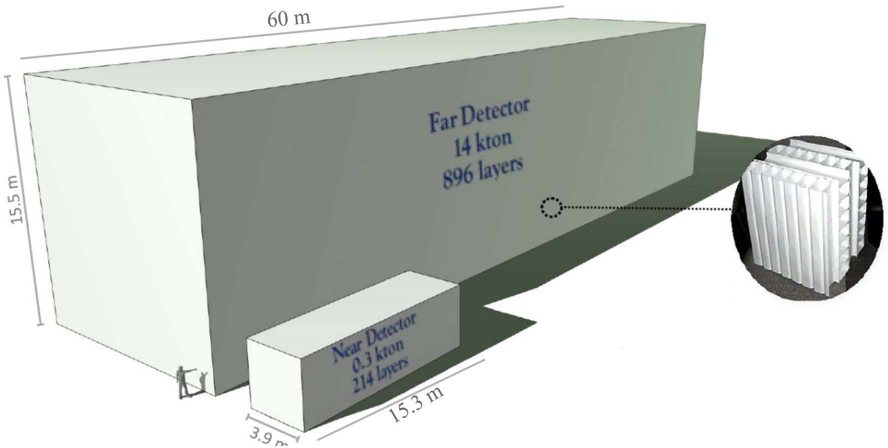
J. Hartnell, Neutrino 2022

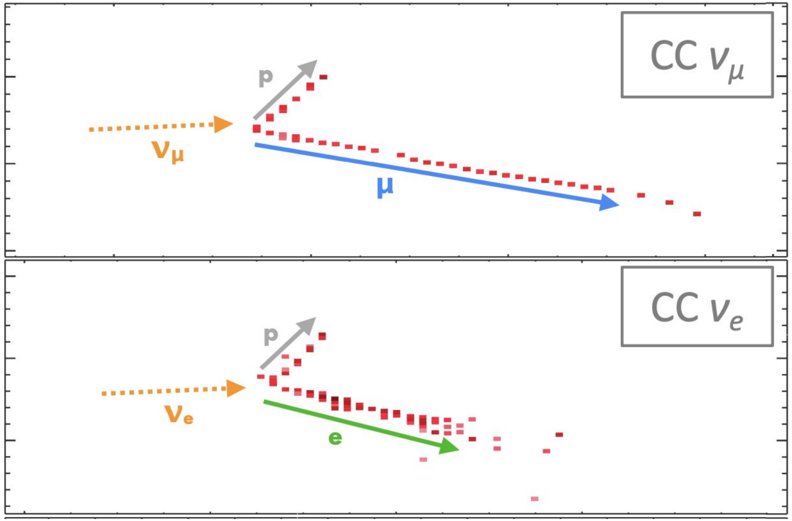


- NOvA samples the NuMI beamline from Fermilab
- 120 GeV protons from Main Injector
- Incident on cylindrical graphite target
- Products focused with series of magnetic horns and directed towards Minnesota
- Pion decay in flight produces neutrinos

- Data included in most recent analysis:
  - 13.6×10^{20} POT in neutrino mode
  - 12.5×10^{20} POT in antineutrino mode
- Anticipating more antineutrino data in 2024

NOvA Detectors

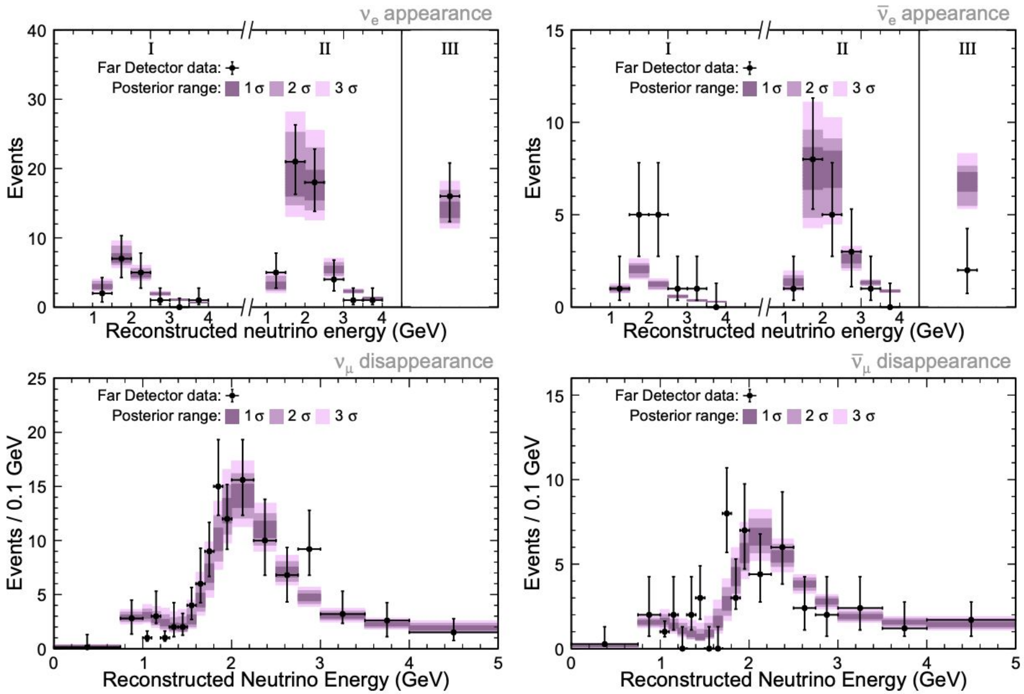




- Functionally identical near (300 ton) and far (14,000 ton) detectors
- 14 mrad off axis, ND 100m underground and FD on surface
- Extruded plastic rods filled with liquid scintillator arranged into alternating planes
- Fast readout via wavelength shifting fibers and APD's to reject cosmic background

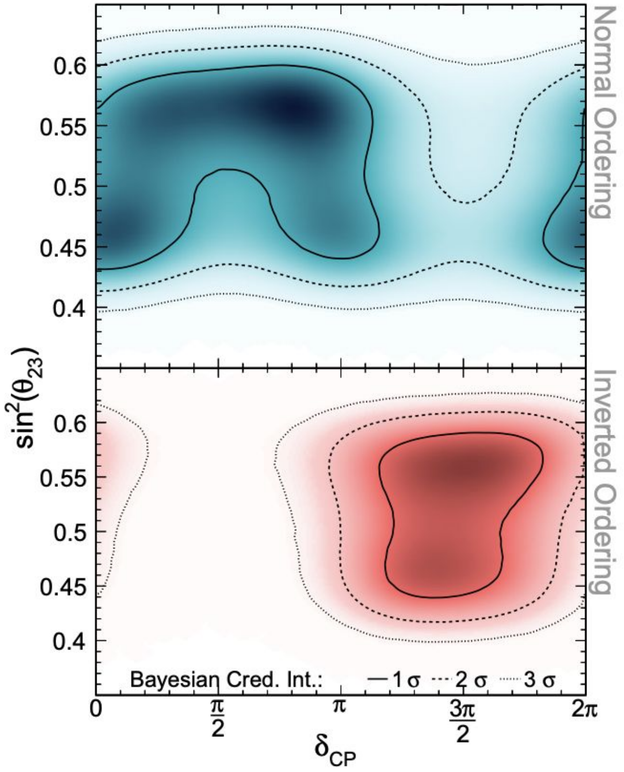
NOvA Samples

- CNN used to classify event topologies and select ν_e-CC and ν_μ-CC samples
  - BDT for rejecting cosmic background at the FD
- ν_e-CC is further subdivided based on CNN score in the fit to allow for better signal / background discrimination
  - peripheral sample for a candidate events that fails cuts with high PID
- ν_μ-CC subdivided into p_t bins into aid ND extrapolation technique



NOvA Results

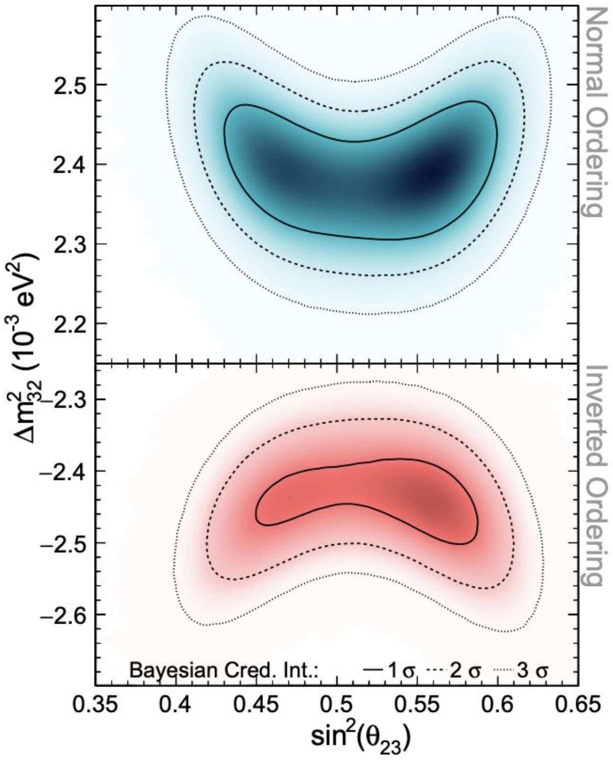
arXiv:2311.07835



- External $\sin^2(2\theta_{13})$ applied
  - Consistent with NOvA's meas.

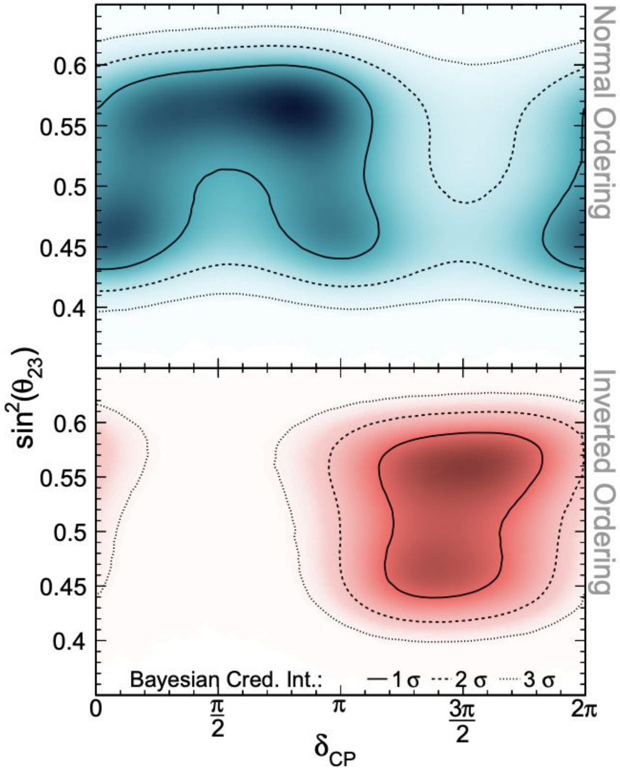
	MO	HPD	$1\,\sigma$
δ_{CP}	Both	0.91π	$[0.02\pi, 0.31\pi] \cup [0.68\pi, 1.67\pi]$
	Normal	0.89π	$[0.54\pi, 1.07\pi] \cup [1.99\pi, 0.48\pi]$
	Inverted	1.44π	$[1.26\pi, 1.65\pi]$
$\sin^2\theta_{23}$	Both	0.56	$[0.45, 0.49] \cup [0.52, 0.59]$
	Normal	0.56	$[0.44, 0.59]$
	Inverted	0.56	$[0.55, 0.57]$
Δm^2_{32}	Normal	2.39	$[2.32, 2.46]$
$(\times 10^{-3})$	Inverted	-2.44	$[-2.47, -2.41]$

- CPV and θ_{23}-octant still rather unclear. *Very* slight preference for CPV.



NOvA Results

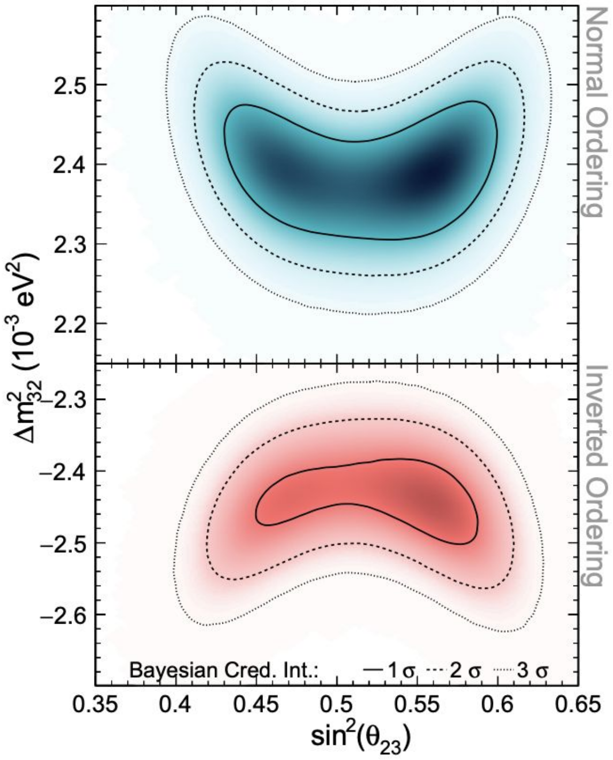
arXiv:2311.07835



- External $\sin^2(2\theta_{13})$ applied
  - Consistent with NOvA's meas.
- Bayes factor (posterior probability) table:

	Normal Ordering	Inverted Ordering	Total
Upper Octant	0.71 (0.42)	0.26 (0.21)	1.67 (0.63)
Lower Octant	0.35 (0.26)	0.13 (0.12)	0.60 (0.38)
Total	2.08 (0.68)	0.48 (0.33)	(1.0)

- Very weak preference for normal ordering and upper θ_{23}-octant



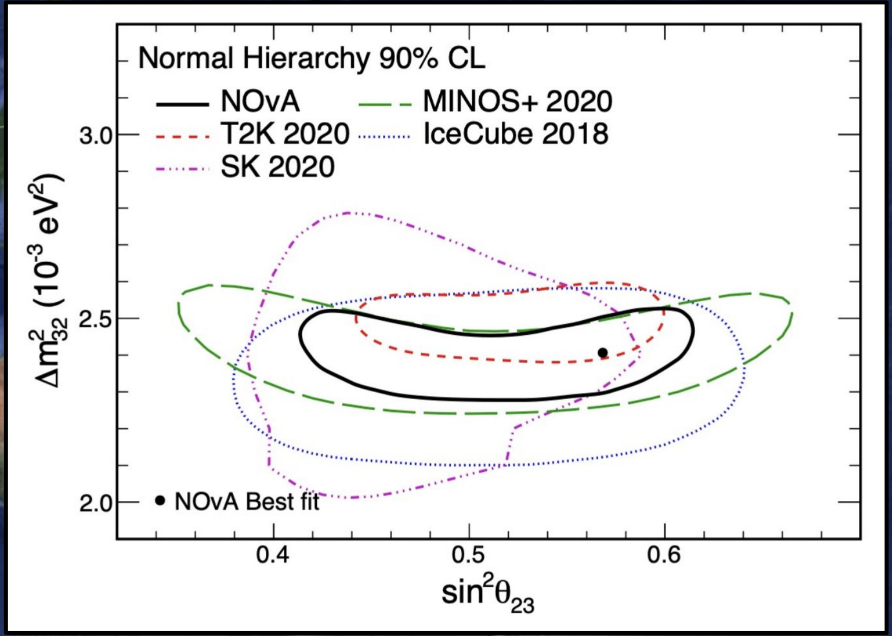
Current Generation Experiments

T2K	NOvA
Flux peak ~600 MeV	Flux peak ~2 GeV
295 km baseline	810 km baseline
CCQE dominant interaction mode	Broad mix of interaction modes
Reconstruct energy from lepton kinematics	Calorimetric energy reconstruction
FD 2.5° off axis	FD 1.5° off axis
Different ND and FD technologies	Functionally identical ND and FD
ND constrains systematics in the model (*fit*)	ND *tunes* FD pred. without fitting

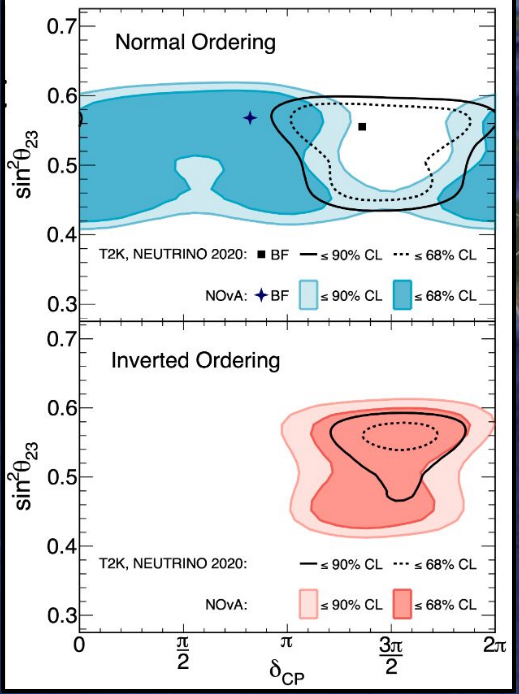
Current Generation Experiments

T2K far site
T2K near site
Japan

NOvA far site
NOvA near site
USA



NOvA Neutrino 2022

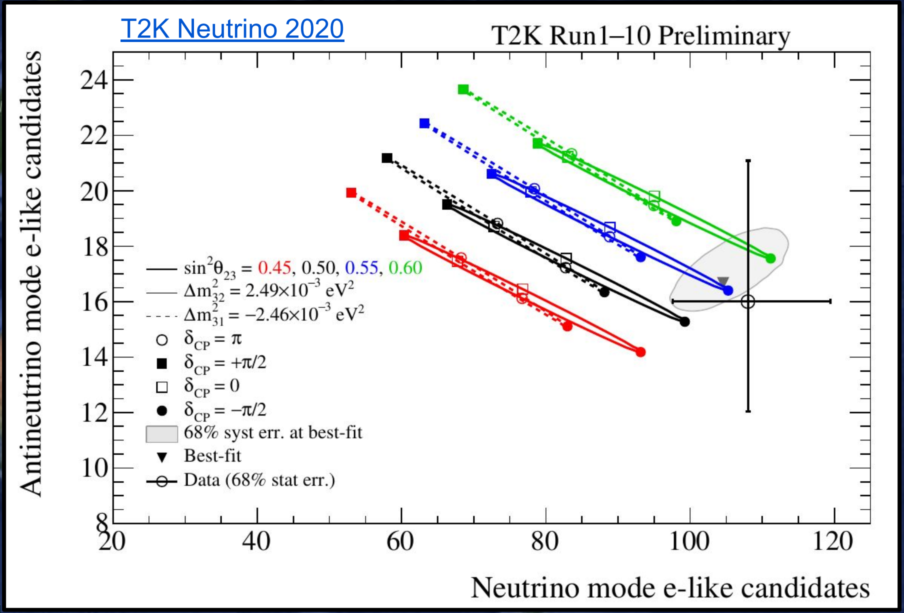


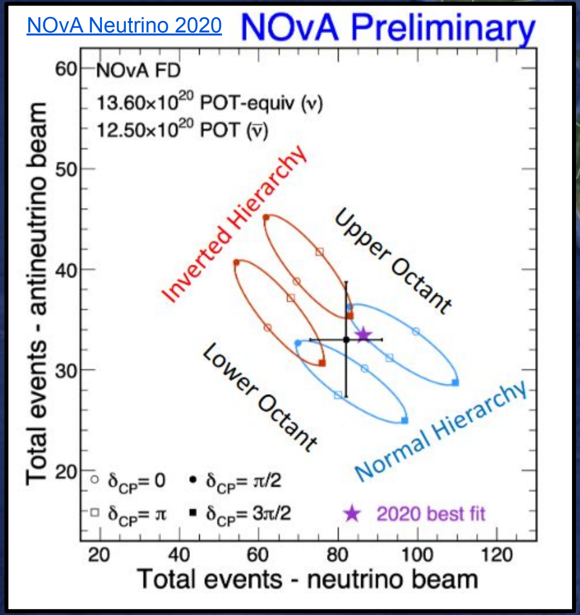
Current Generation Experiments

T2K far site
T2K near site
Japan

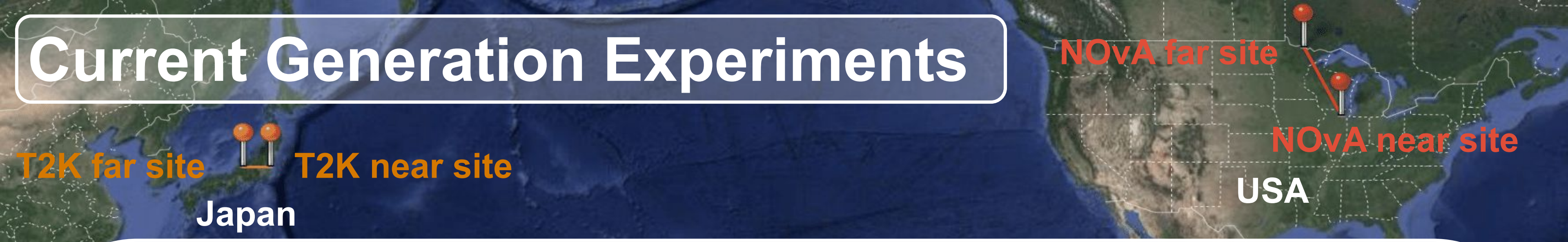
NOvA far site
NOvA near site
USA

Complementarity that breaks degeneracies otherwise present in standalone experiments.





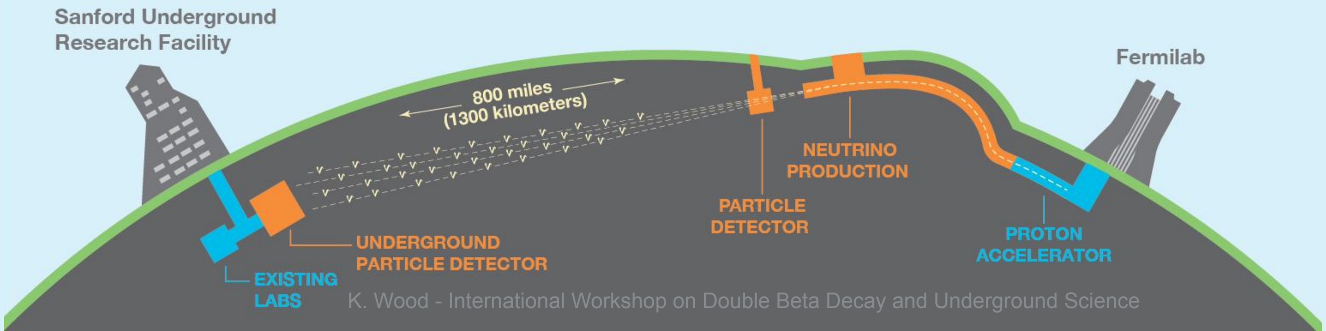
Current Generation Experiments



- NOvA and T2K collaborations pursuing joint analysis
- Exploit the complementarity and leverage all of the sophisticated analysis tools/considerations from each standalone experiment
- Targeting a release in the coming months - stay tuned!

Deep Underground Neutrino Experiment

- Next generation long-baseline accelerator neutrino oscillation experiment in U.S.
- Very long baseline → matter effect enhance mass ordering sensitivity
- Requires moving beam to higher energies → complicated interaction modes
  - LArTPC technology for detailed detection abilities
- Very intense beam and very large far detectors → systematics must be understood better than current gen. experiments



DUNE's Phased Construction

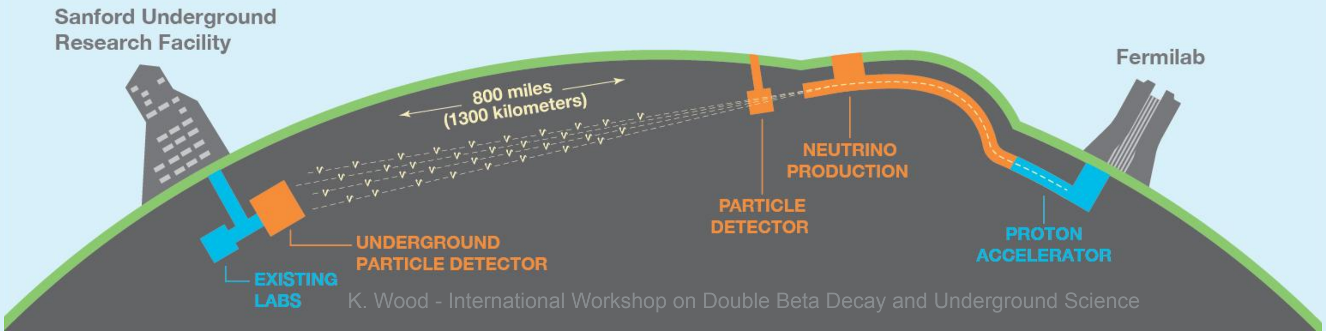
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Phased approach to realize full scope of DUNE's physics program:

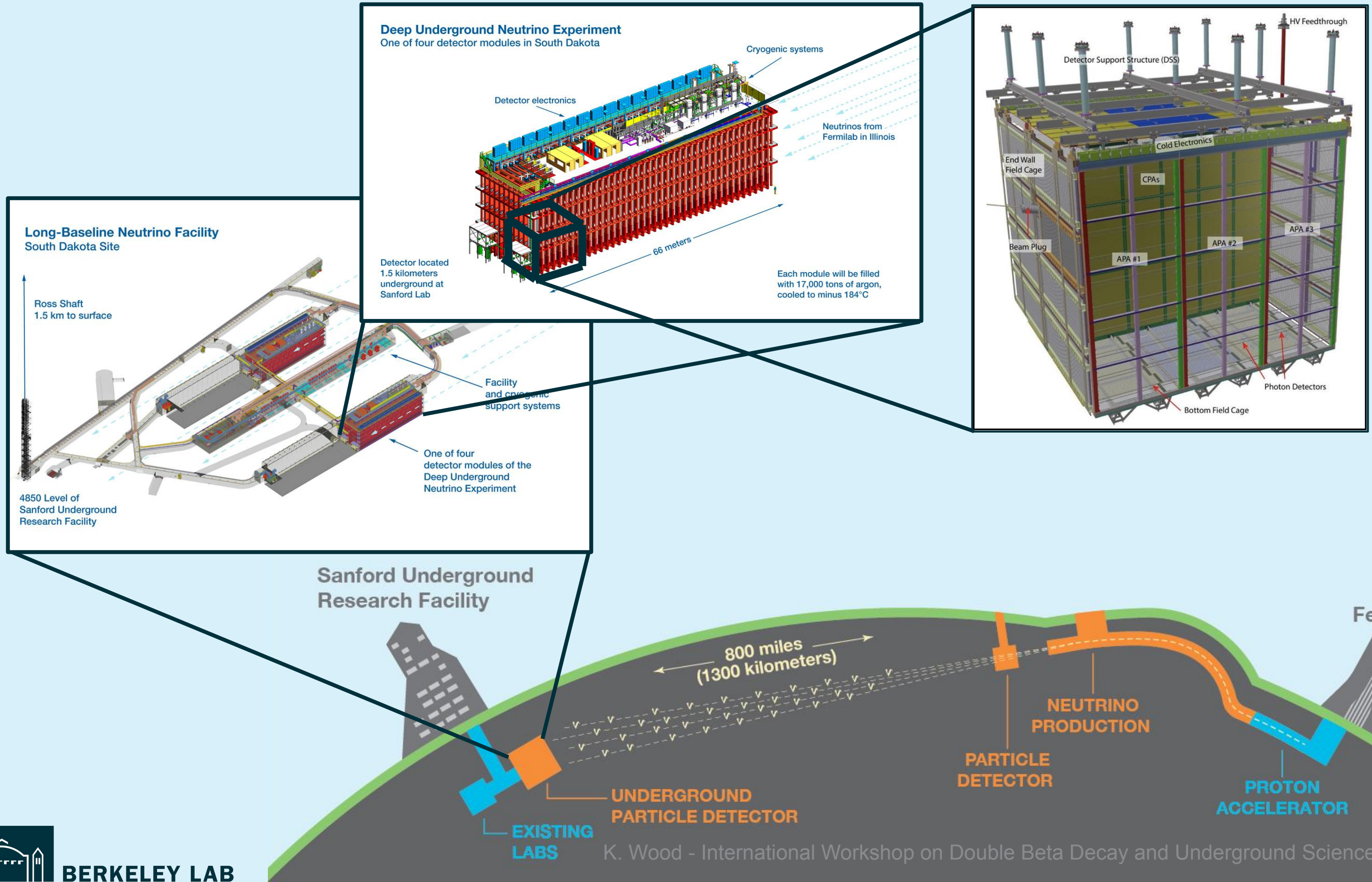
- **Phase 1:**
  - 1.2 MW neutrino beam
  - 2x17 kton far detector LArTPC
  - Near detector complex: ND-LAr + TMS (moveable) & SAND

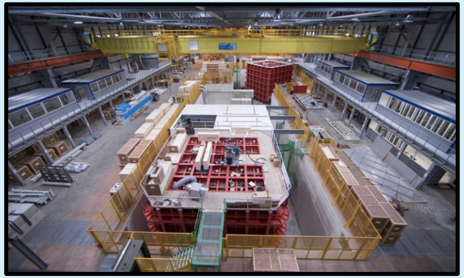
Phase 1 has passed CD1(-RR). Current schedule has 2 FDs taking data in 2029 and beam online in 2031.

- **Phase 2:**
  - 2.4 MW neutrino beam
  - 2 additional 17 kton far detectors
  - Upgrade TMS (muon spectrometer) to more capable detector to further constrain systematics



Prototyping DUNE's Far Detectors

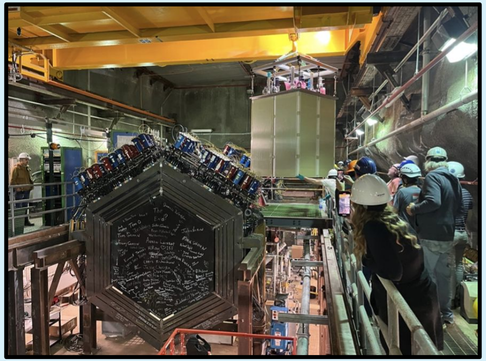




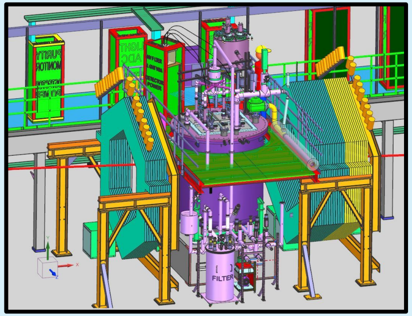
ProtoDUNEs @ CERN Neutrino Platform

Prototyping DUNE’s LAr Near Detector

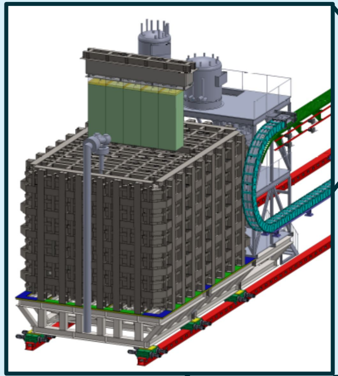
@ Fermilab’s MINOS underground hall



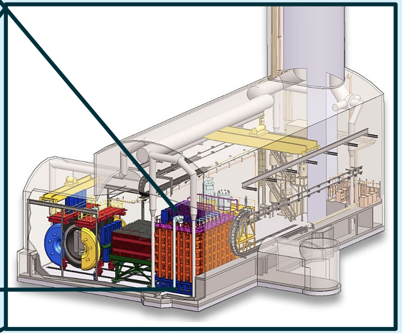
2x2 Demonstrator

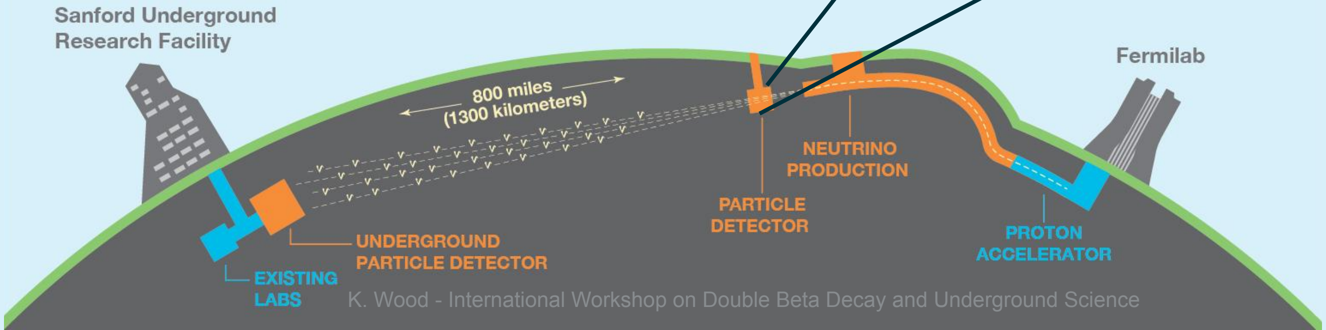


ND-LAr



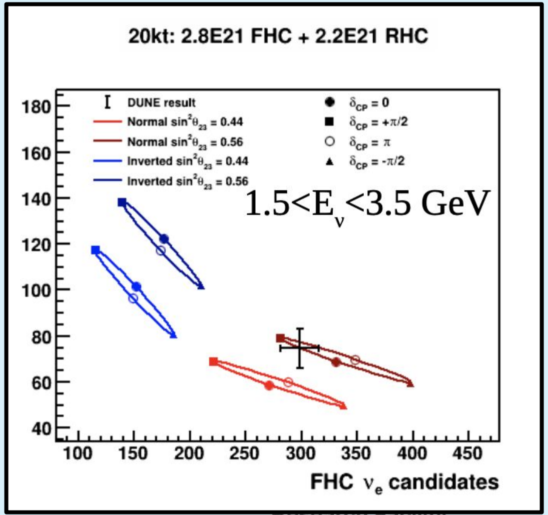
DUNE Near Detector Complex

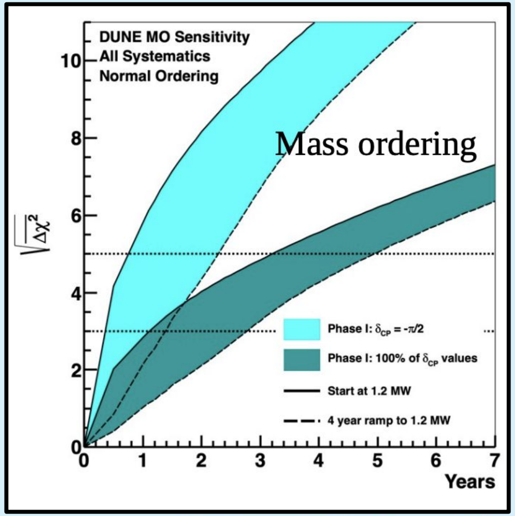


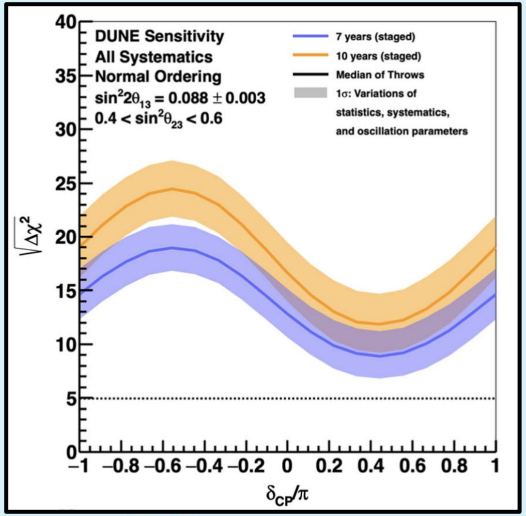


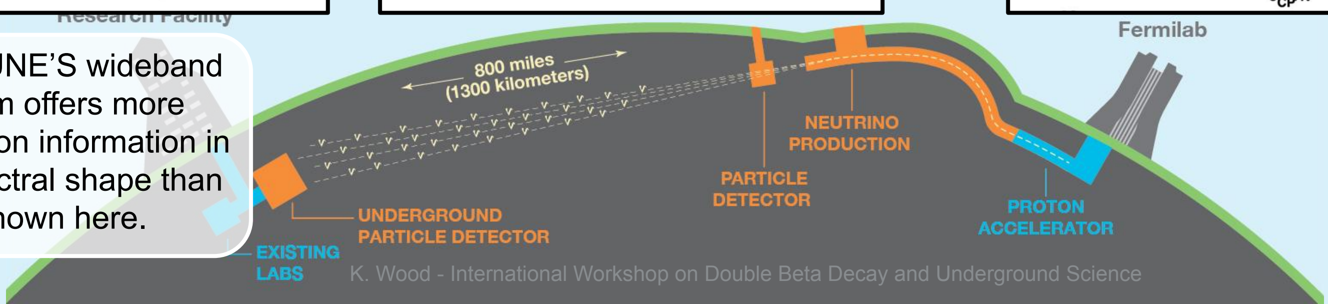
DUNE's Oscillation Physics Potential

- DUNE has an unrivaled ability to resolve neutrino mass ordering







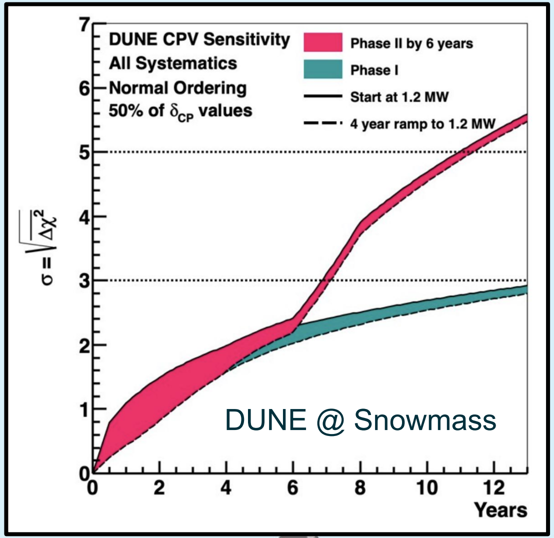


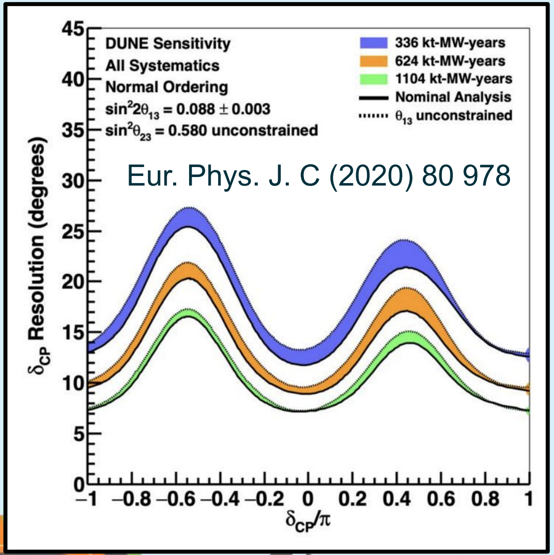
NB: DUNE'S wideband beam offers more oscillation information in it's spectral shape than shown here.

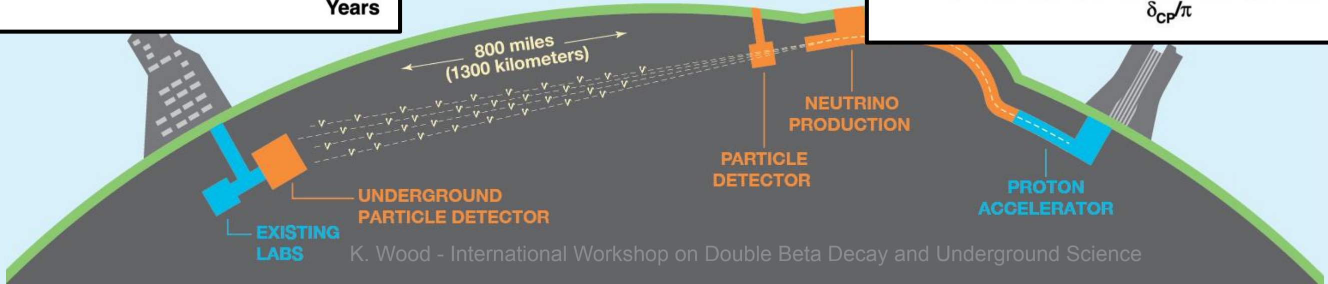
DUNE's Oscillation Physics Potential

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- DUNE will explore CP properties of neutrino oscillations

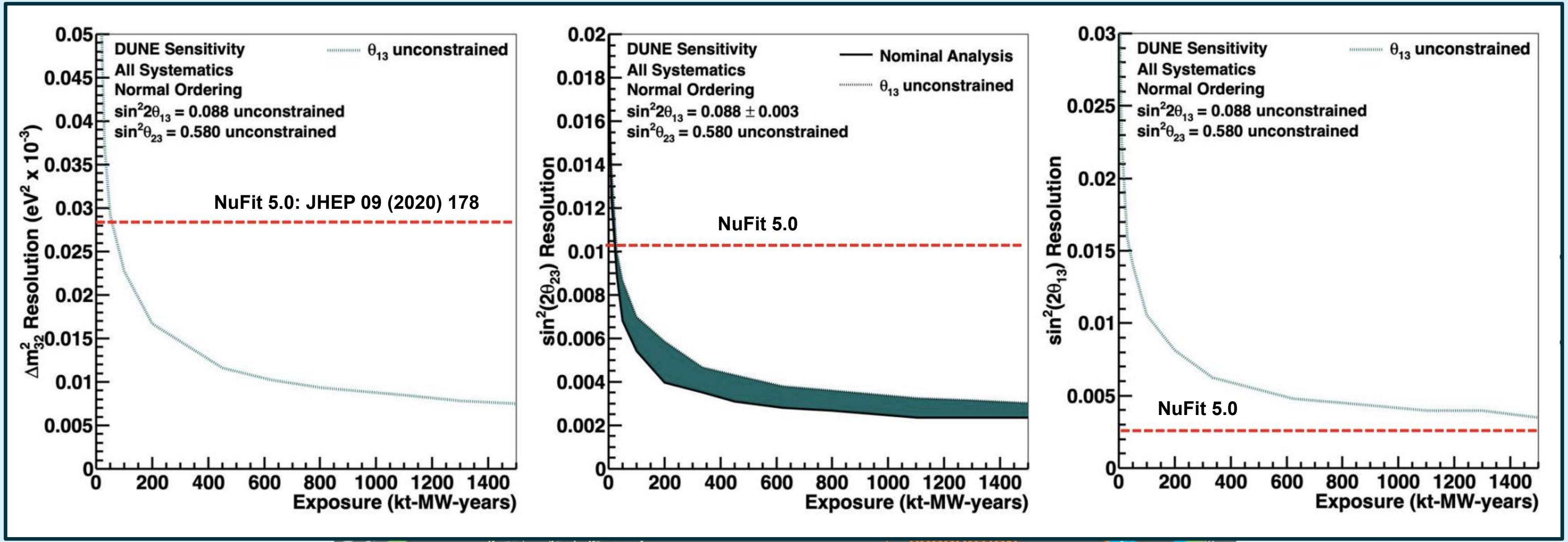






DUNE's Oscillation Physics Potential

- DUNE will enable precision measurements of oscillation parameters



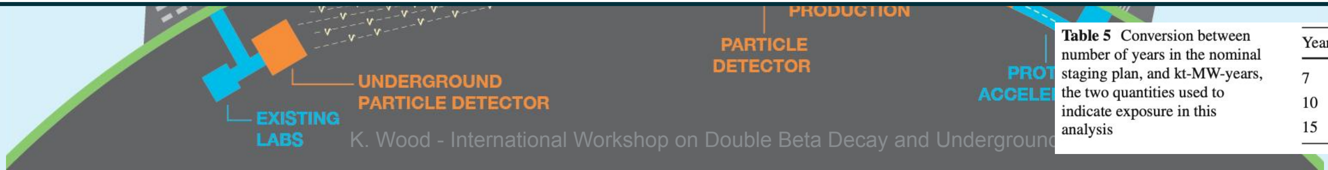


Table 5 Conversion between number of years in the nominal staging plan, and kt-MW-years, the two quantities used to indicate exposure in this analysis

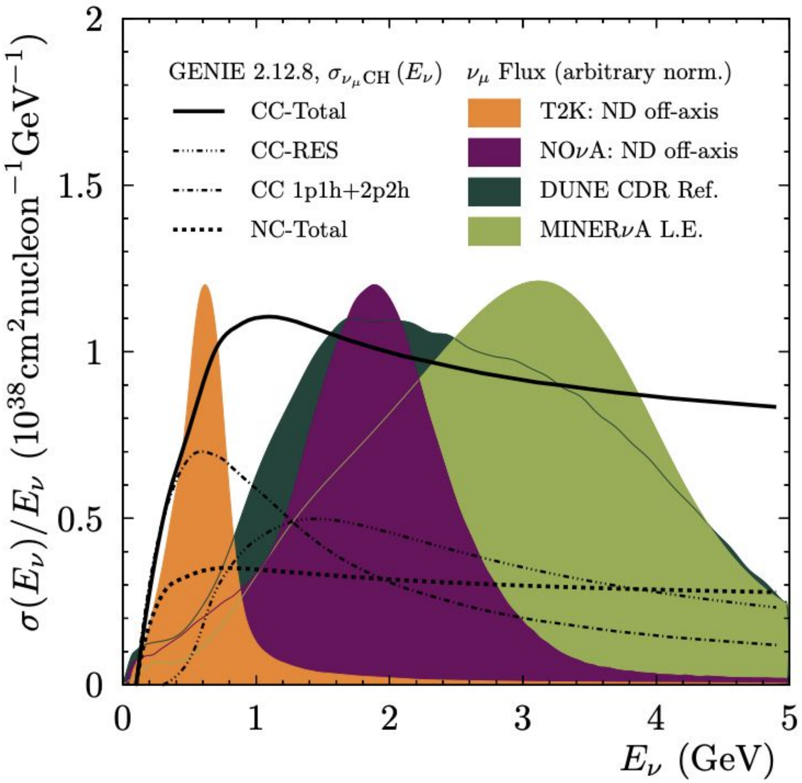
Years	kt-MW-years
7	336
10	624
15	1104

Closing

- Exciting times ahead for long-baseline accelerator neutrinos
- As the current generation of experiments finish up data collection in the coming years, analysis efforts ongoing to ensure robust legacy results
- Gearing up to realize the construction of next generation experiments, focused on DUNE here. Anticipating phase I first data in 2031.
- P5 report to be released to the HEP community in the next few weeks. How will the community endorse phase II DUNE???

Backup

Accelerator Neutrino Fluxes



K. Mahn, C. Marshall, & C. Wilkinson, Progress in Measurements of 0.1–10 GeV Neutrino–Nucleus Scattering and Anticipated Results from Future Experiments. Annual Review of Nuclear and Particle Science 68:1, 105-129 (2018).

NOvA $\sin^2(2\theta_{13})$ Measurement

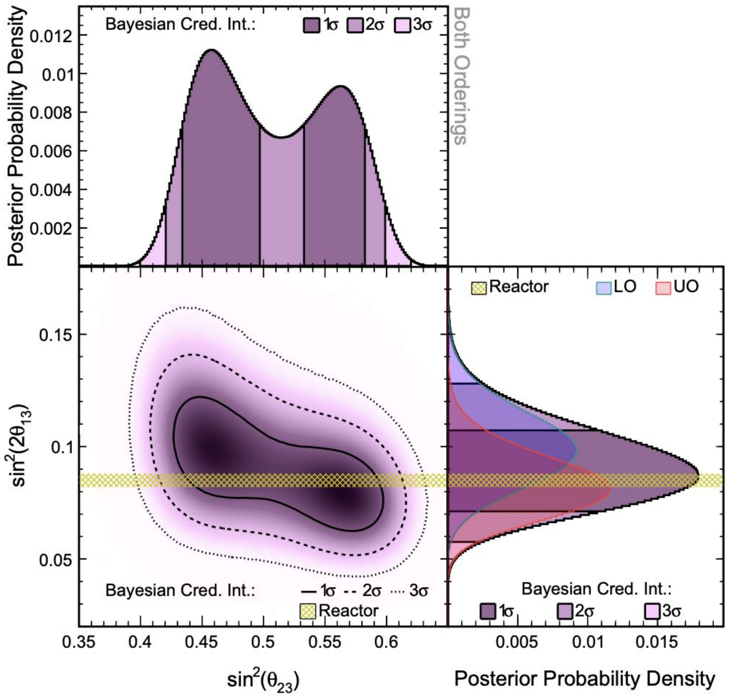
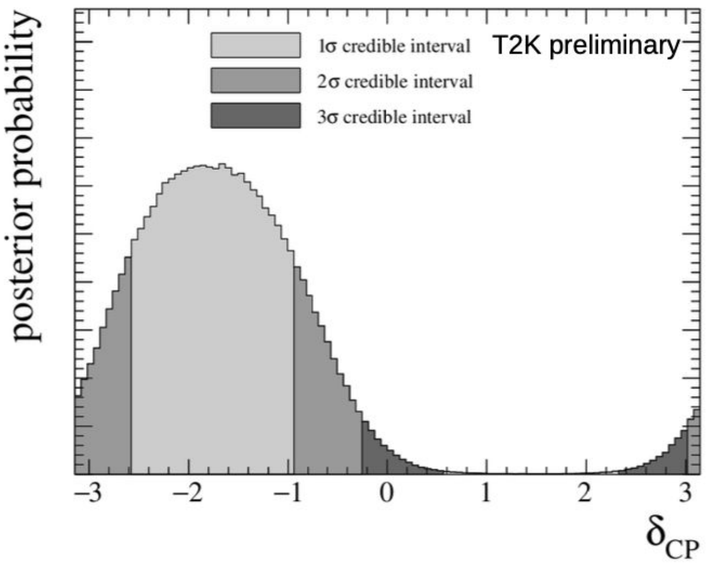
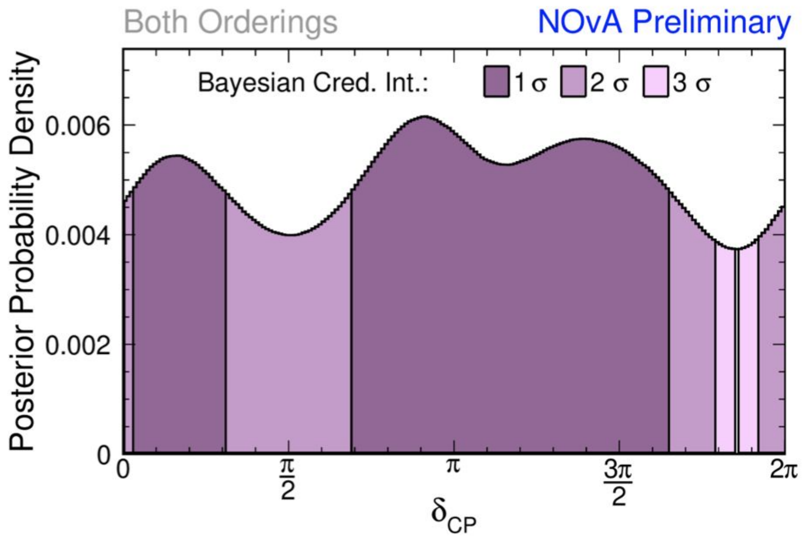


FIG. 13: $\sin^2\theta_{23}$–$\sin^2 2\theta_{13}$ posterior probability densities with 1, 2, and $3\,\sigma$ credible intervals, marginalized over both mass orderings. The posterior density was extracted from a fit with a prior uniform in $\sin^2 2\theta_{13}$. The reactor experiments' $1\,\sigma$ interval in $\sin^2 2\theta_{13}$ from the PDG 2019 [78] is shown in the yellow hatched bar. The right panel shows the posterior probability for $\sin^2 2\theta_{13}$, with its contributions from the upper octant (UO, transparent, red outline) and lower octant (LO, transparent, blue outline) of θ_{23}.

δ_{CP} results marginalized over hierarchy

@ Neutrino 2022

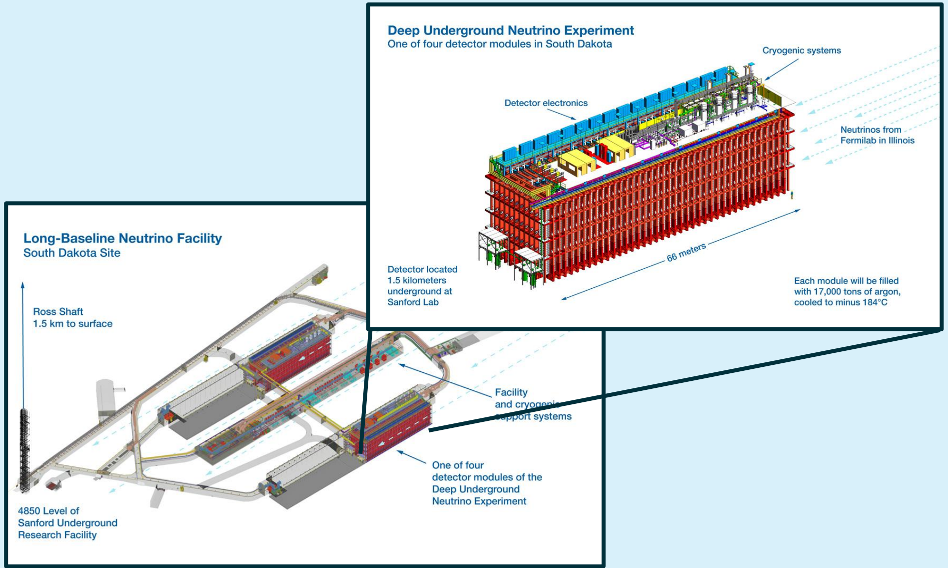


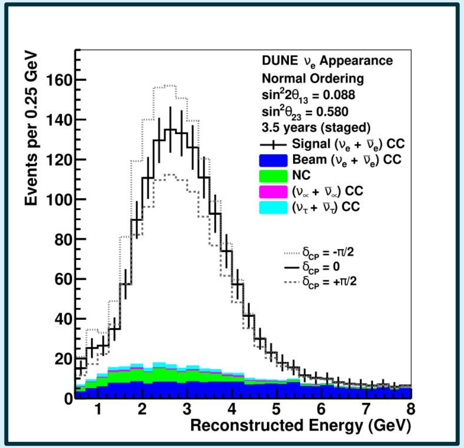


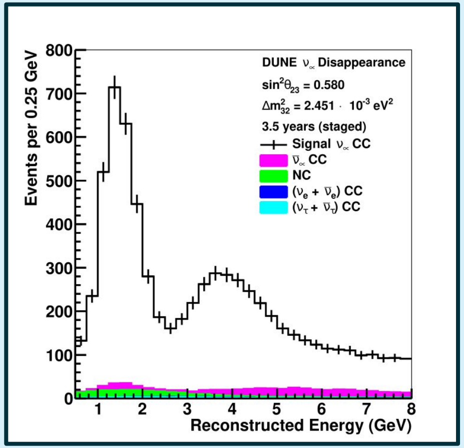
NOTE: Different convention for δ_{CP} range (which is 2π periodic)

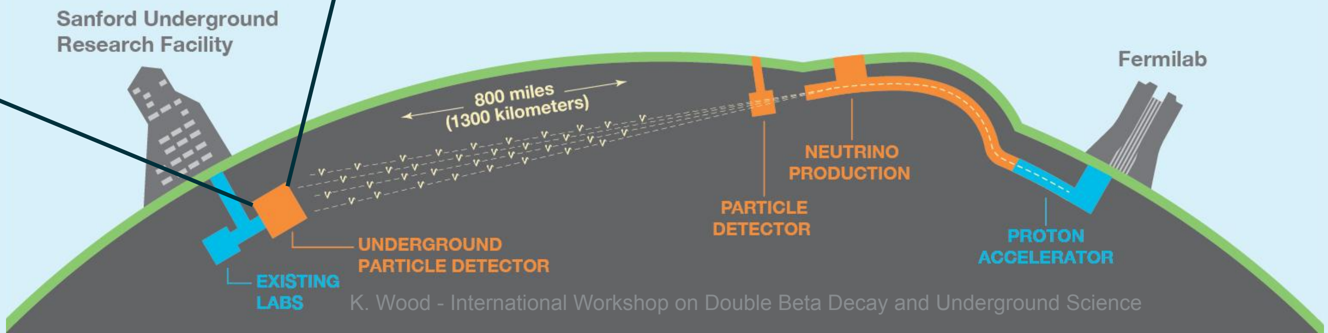
Neutrino Oscillations with DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT









Next Generation Experiments

T2HK	DUNE
Flux peak ~600 MeV, narrow band	Broadband beam up to ~5 GeV
295 km baseline	1300 km baseline
CCQE dominant interaction mode	Broad mix of interaction modes
FD 2.5° off axis	FD on axis
Water Cherenkov FD (258 kton total H_2O)	LArTPC FD (1st two modules)
1.3 MW beam	1.2 MW → 2.4 MW beam
ND280 upgrade, IWCD + PRISM concept	Performant ND complex + PRISM concept

Next Generation Experiments

DUNE far site

DUNE near site

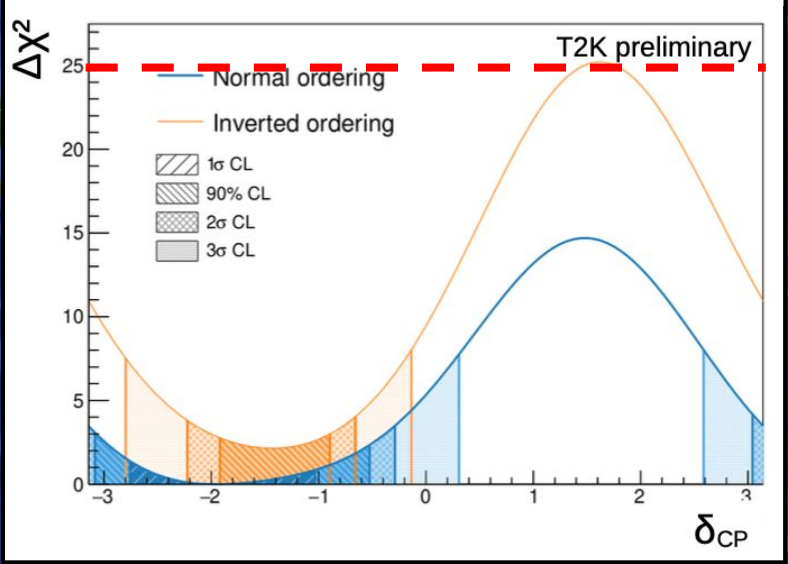
USA

T2HK far site

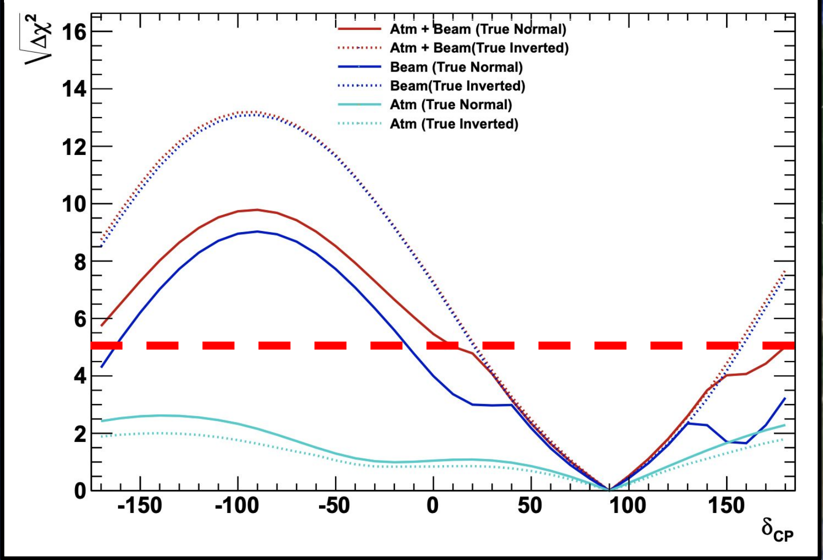
T2HK near site

Japan

T2K Neutrino 2022 (data)



T2HK Asimov (true dcp = 90°, NH assumed)



Next Generation Experiments

DUNE far site

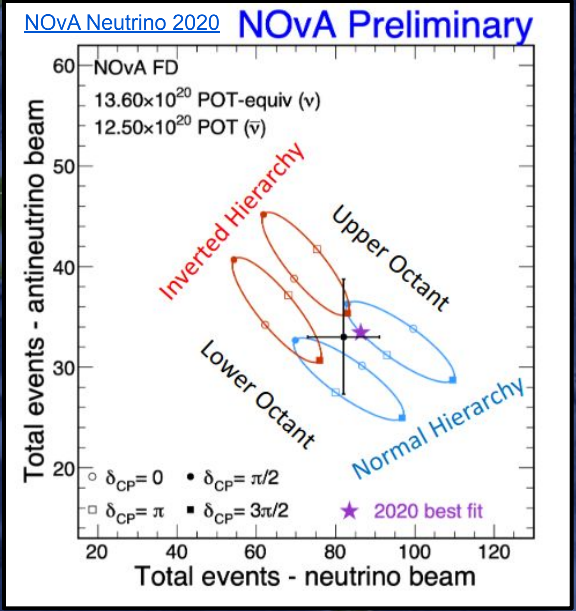
DUNE near site

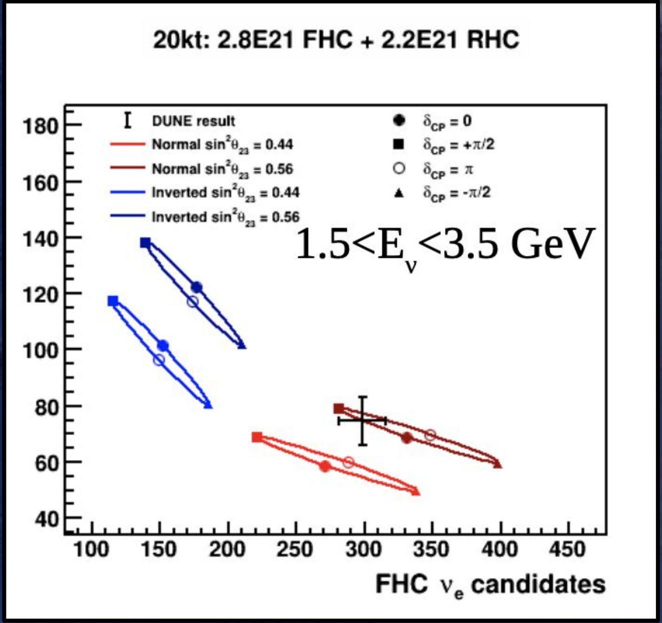
USA

T2HK far site

T2HK near site

Japan





NB: DUNE'S wideband beam offers more oscillation information in it's spectral shape than shown here.