Sensitivity of the DUNE Experiment to CP Violation

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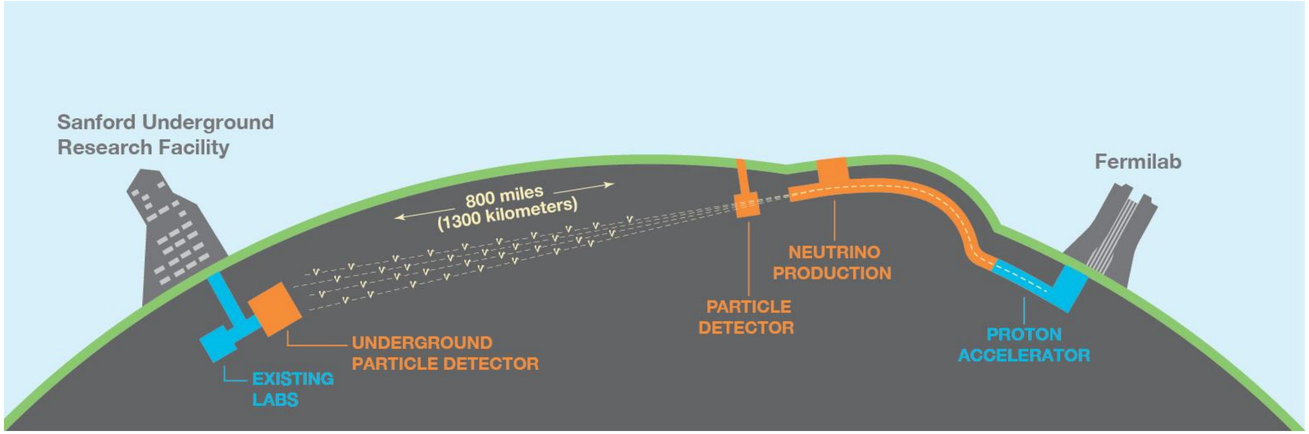

TAUP 2017
July 26, 2017

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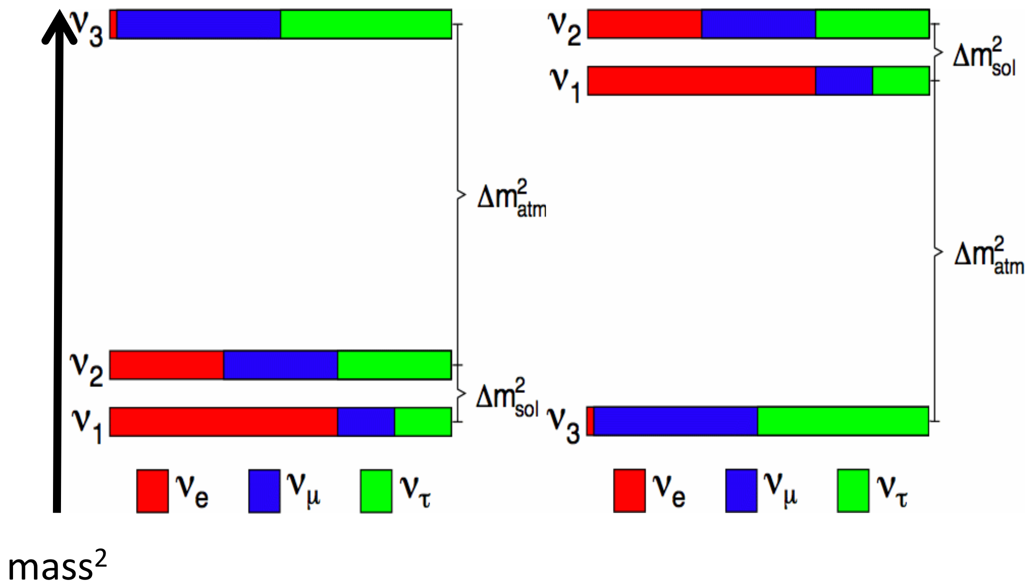
Neutrino Oscillations



Normal **Inverted**

- All mixing angles have been measured, allowing measurements of the CP-violating phase
- Some open questions:
  - Is CP violated in neutrino oscillations ($\delta \neq 0, \pi$)?
  - Is θ_{23} maximal? (=π/4?)
  - What is the neutrino mass ordering?

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

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\ e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

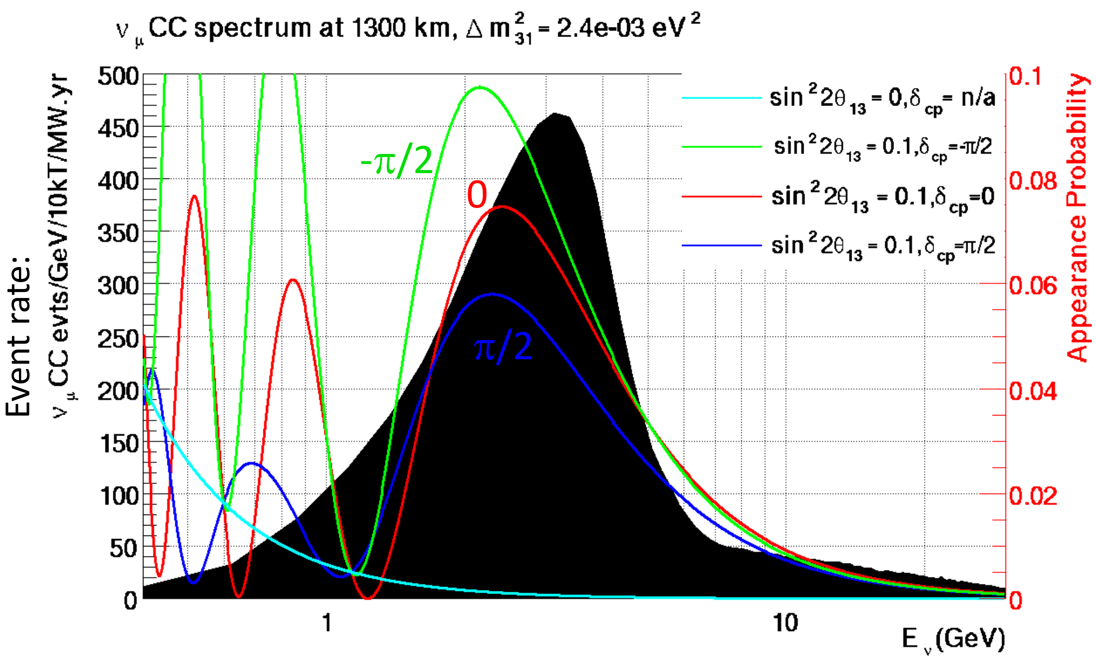
Electron Neutrino Appearance

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\Delta_{31}^2$$
$$+ \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31} + \delta_{CP})$$
$$+ \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

$$a = G_F N_e / \sqrt{2}$$

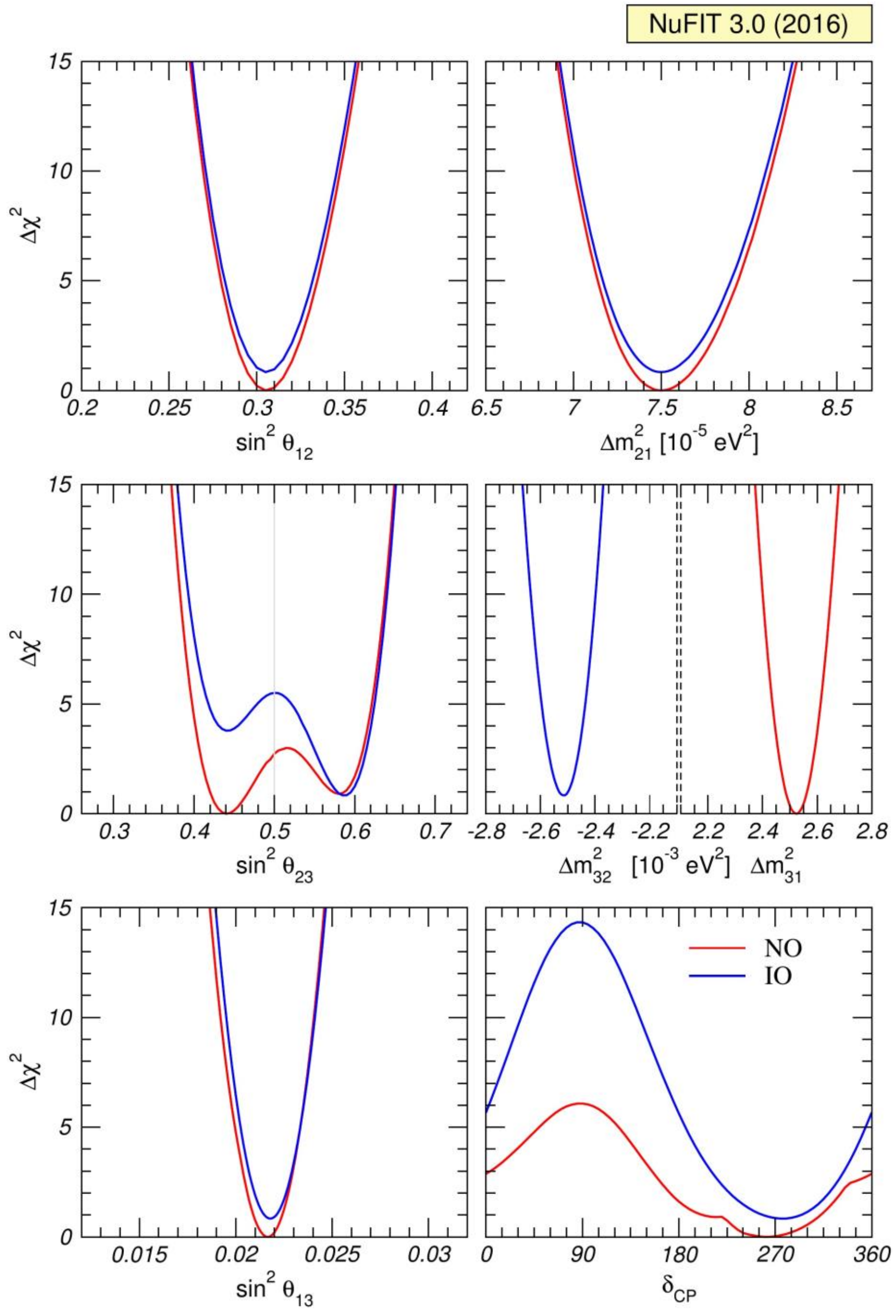
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

(For antineutrinos, $a \rightarrow -a$ and $\delta \rightarrow -\delta$)



- ν_e appearance probability depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects – measurements of all four possible in a single experiment
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample

2016 Global Oscillation Parameter Fit



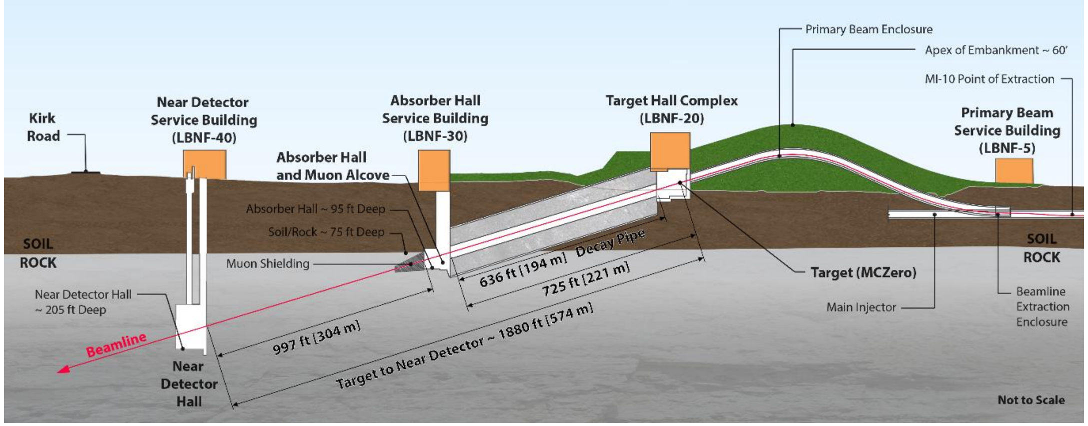
Best fit $\delta_{CP} = 261°^{+51°}_{-59°}$
$(\approx -\pi/2)$

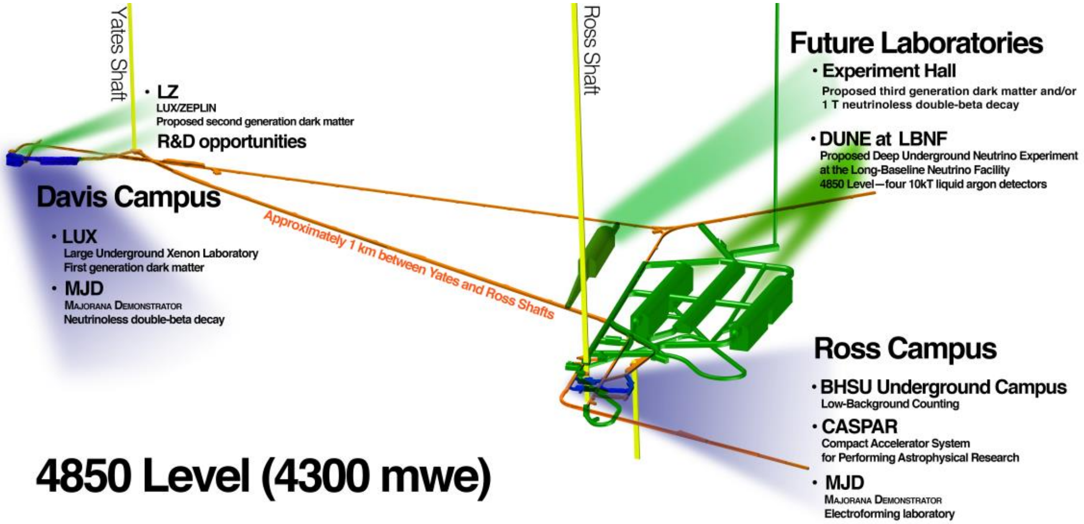
Some values of δ_{CP} excluded at 3σ for IH

http://www.nu-fit.org

Deep Underground Neutrino Experiment (DUNE)

- Muon neutrino beam from Fermilab (LBNF – Long-Baseline Neutrino Facility)
  - On-axis, conventional horn-focused beam
  - Beam intensity of 1.2 MW, upgradeable to 2.4 MW (for 120 GeV primary protons)
- Near detector (ND) at Fermilab
- Far detector (FD) at SURF (Sanford Underground Research Facility) in South Dakota, 1300 km baseline
  - 40 kt liquid argon (LAr) TPC (4 x 10 kt modules)





UNIVERSITY of HOUSTON DUNE

Status and Timeline

Collaboration meeting in May 2017

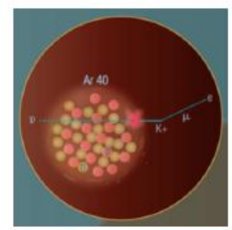
- DUNE Collaboration began in 2015
- Today: 964 collaborators, 164 institutions, 30 countries

DUNE Timeline

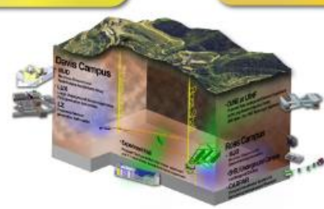
DEEP UNDERGROUND NEUTRINO EXPERIMENT

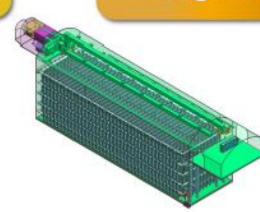
Far site ground breaking ceremony July 21!

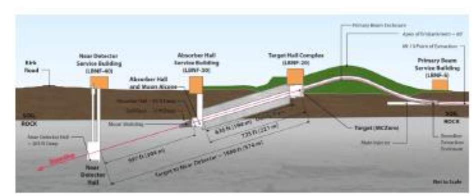
The CERN Neutrino Platform



2017: Far Site Construction Begins → 2018: protoDUNEs at CERN → 2021: Far Detector Installation Begins → 2024: Physics Data (20 kt) → 2026: Neutrino Beam Available







DUNE Spectra

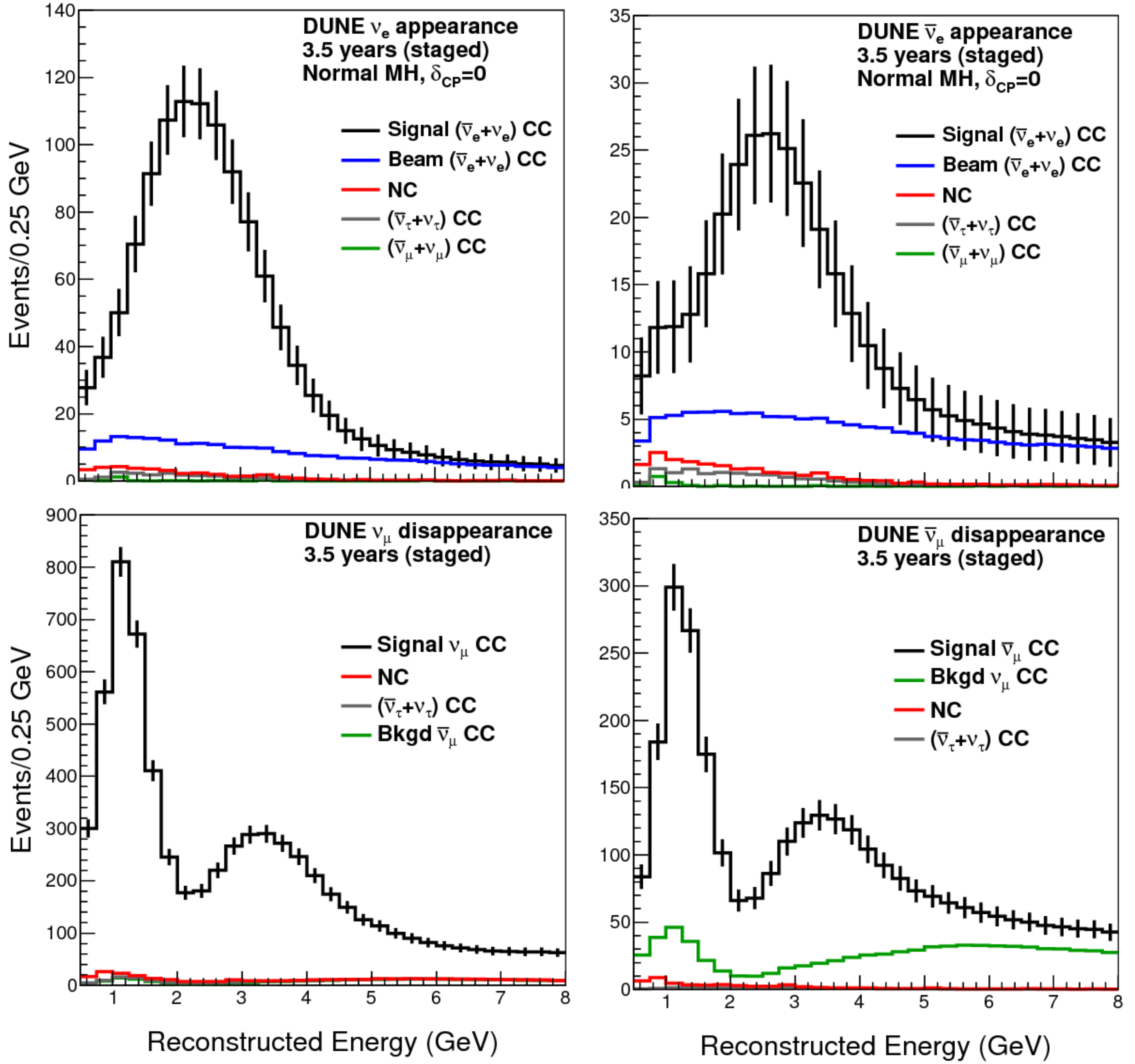
~1000 appearance events in ~7 years

GLoBES inputs described in arXiv:1606.09550

Neutrino beam flux simulated using GEANT4

GENIE event generator

Reconstructed spectra predicted using detector response parameterized at the single particle level



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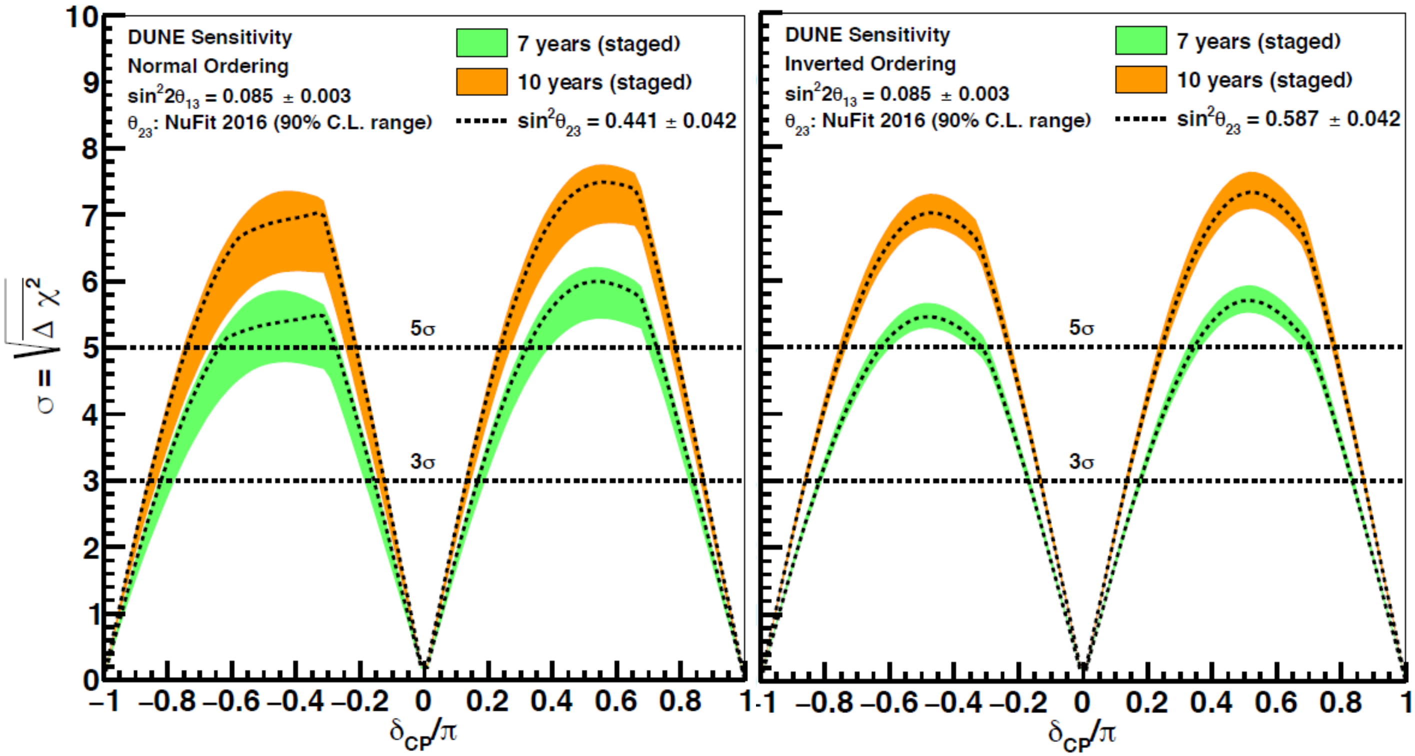
CP Violation Sensitivity

CP (NH) **CP (IH)**



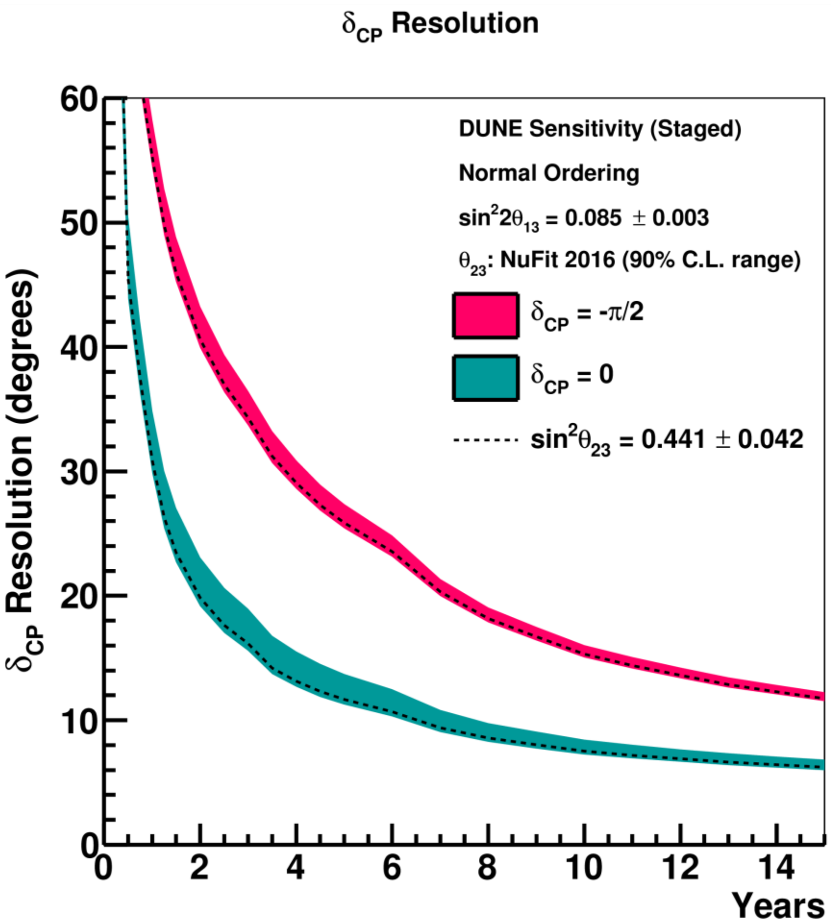
GLoBES-based fit of four event samples

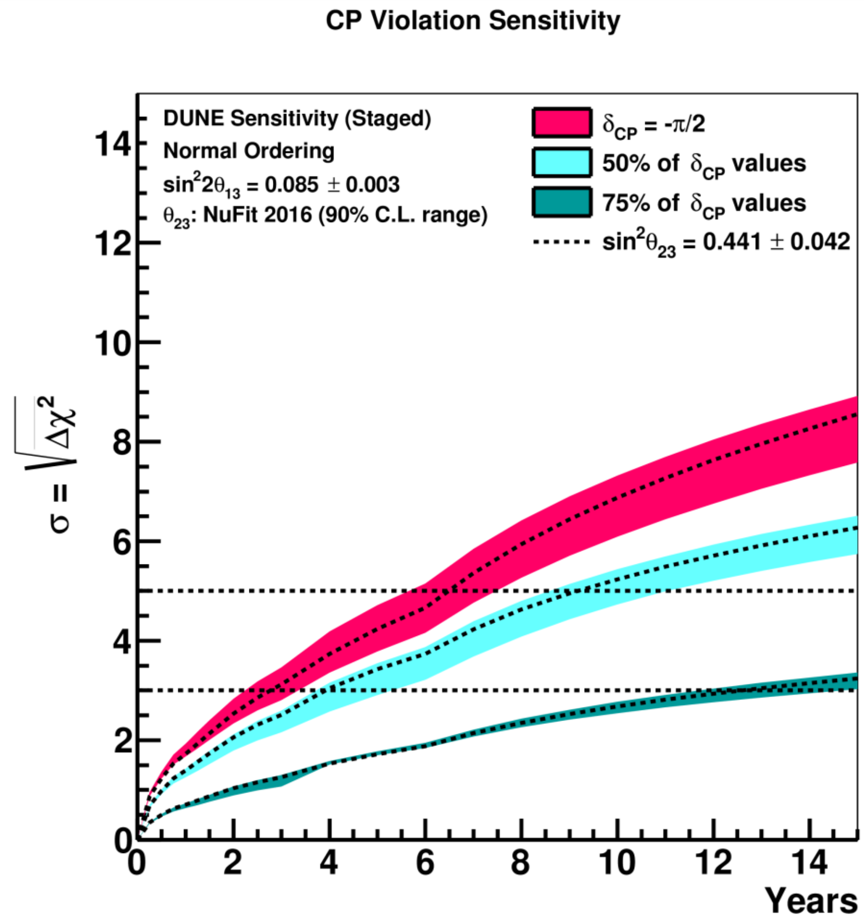
Beam and detector staging assumptions are included:

- Start with 20 kt, increasing to 40 kt
- 80 GeV primary protons @ 1.07 MW, increasing to 2.14 MW

- Width of band indicates variation in sensitivity for θ_{23} values in the NuFit 2016 90% C.L. range
- Assumes equal running in neutrino and antineutrino mode
- Includes simple normalization systematics and oscillation parameter variations

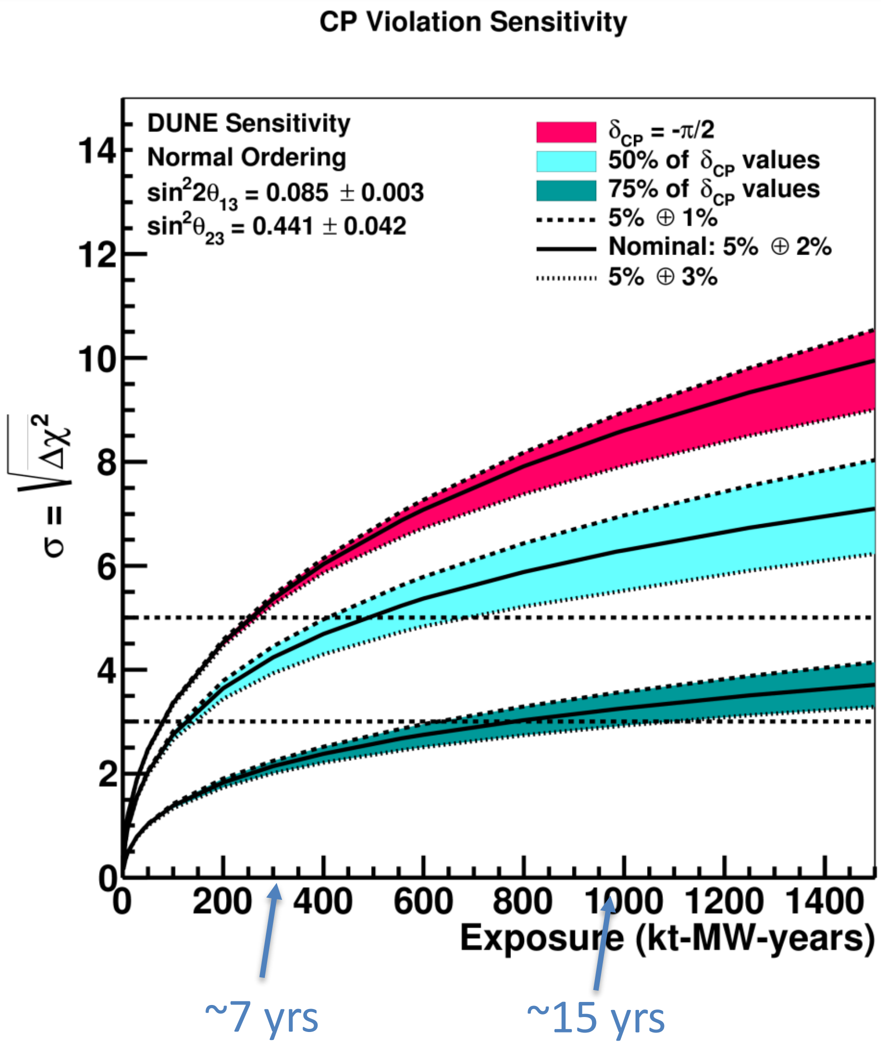
Sensitivity Over Time





- Width of band indicates variation in sensitivity for θ_{23} values in the NuFit 2016 90% C.L. range

Systematic Uncertainty

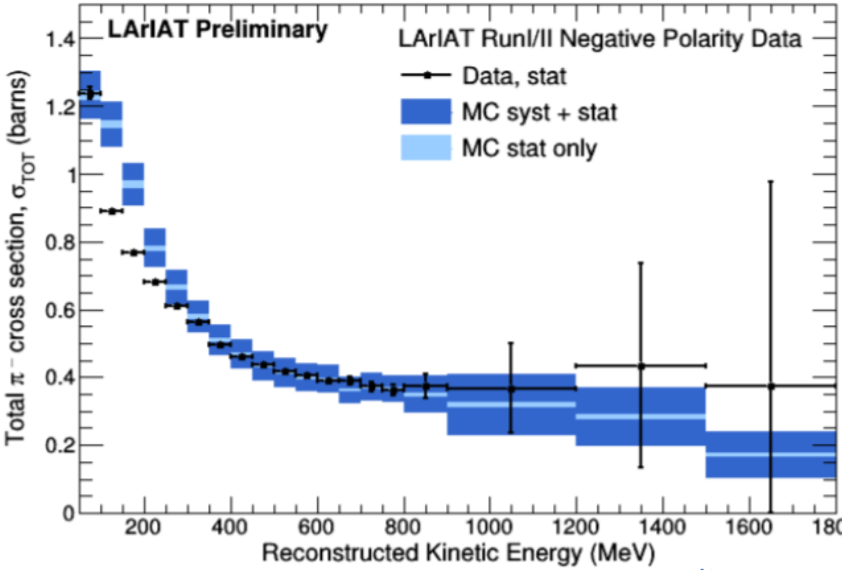


- CPV measurement statistically limited for ~100 kt-MW-years
- Sensitivities in DUNE CDR are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using uncorrelated signal normalization uncertainties.
  - $\nu_\mu = \bar{\nu}_\mu$ = 5% (Flux uncertainty after ND constraint)
  - $\nu_e = \bar{\nu}_e$ = 2% (Residual uncertainty after constraints from other samples)

Strategy for Controlling Systematic Uncertainties

- Flux uncertainties (see the next talk!):
  - ND measurements of fully leptonic neutrino interactions, low-ν method, hadron production measurements (NA61/SHINE)
- Interaction model uncertainties:
  - ND constraints (argon target)
  - Improved models in neutrino interaction generators
  - Neutrino interaction data (ArgoNeuT, MINERvA, NOvA ND, T2K ND280, MicroBooNE, SBND, ICARUS, …)
- Detector effects:
  - Prototypes and calibration measurements (LArIAT, Mini-CAPTAIN, DUNE 35t, ProtoDUNE, …)

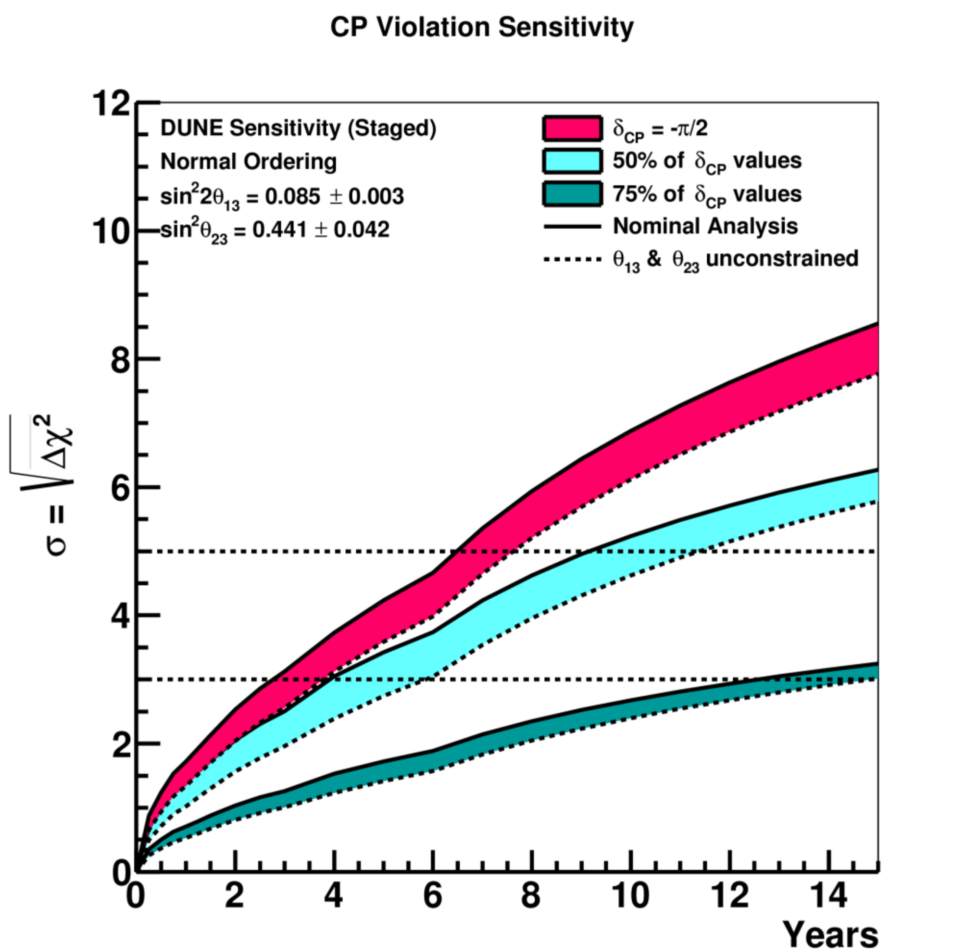
ProtoDUNE-SP at CERN

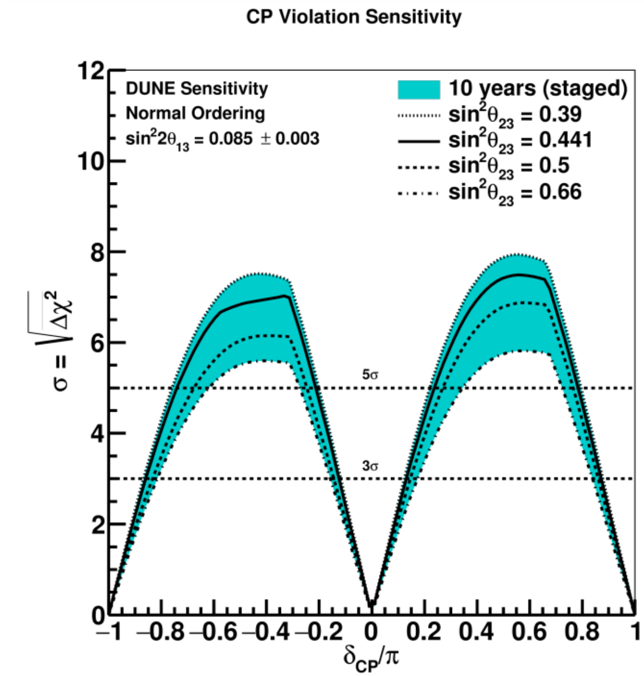


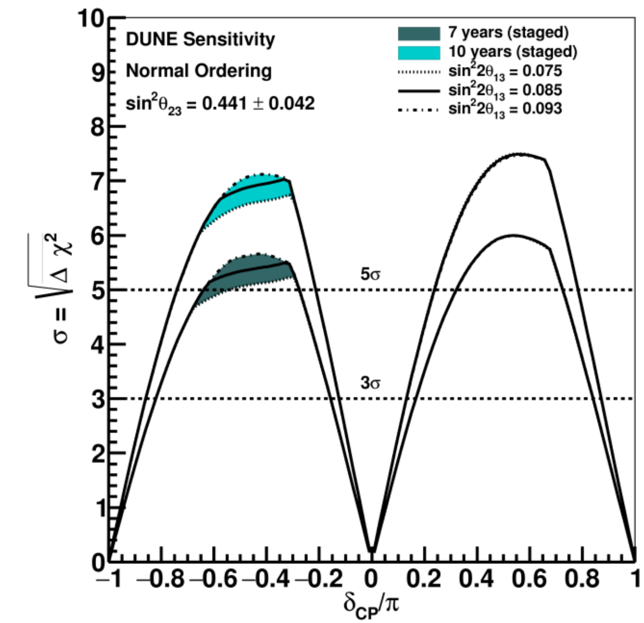
J. Asaadi, NuInt2017

- DUNE
  - Collaboration formed ~2 years ago; far site construction has begun
  - Long-baseline neutrino oscillation program is expected to begin in 2026 when the LBNF neutrino beam becomes available
- Experiment is optimized to answer remaining questions about 3-neutrino mixing, including sensitivity to CP violation for much of the parameter space
- DUNE experiment strategy to control systematic uncertainty includes:
  - High performance near and far detectors providing ability to constrain systematics using DUNE data
  - External measurements and calibration data
  - Improved modeling of neutrino interactions

Effect of θ_{23} & θ_{13}







Effect on CP sensitivity of using no external constraints on θ_{23} or θ_{13}

DUNE Staging Assumptions

Staging Assumptions:

- Year 1 (2026): 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints
- Year 2 (2027): 30-kt FD
- Year 4 (2029): 40-kt FD and improved ND constraints
- Year 7 (2032): upgrade to 2.14 MW (80-GeV) beam (technically limited schedule)

Exposure (kt-MW-years)	Exposure (Years)
171	5
300	7
556	10
984	15

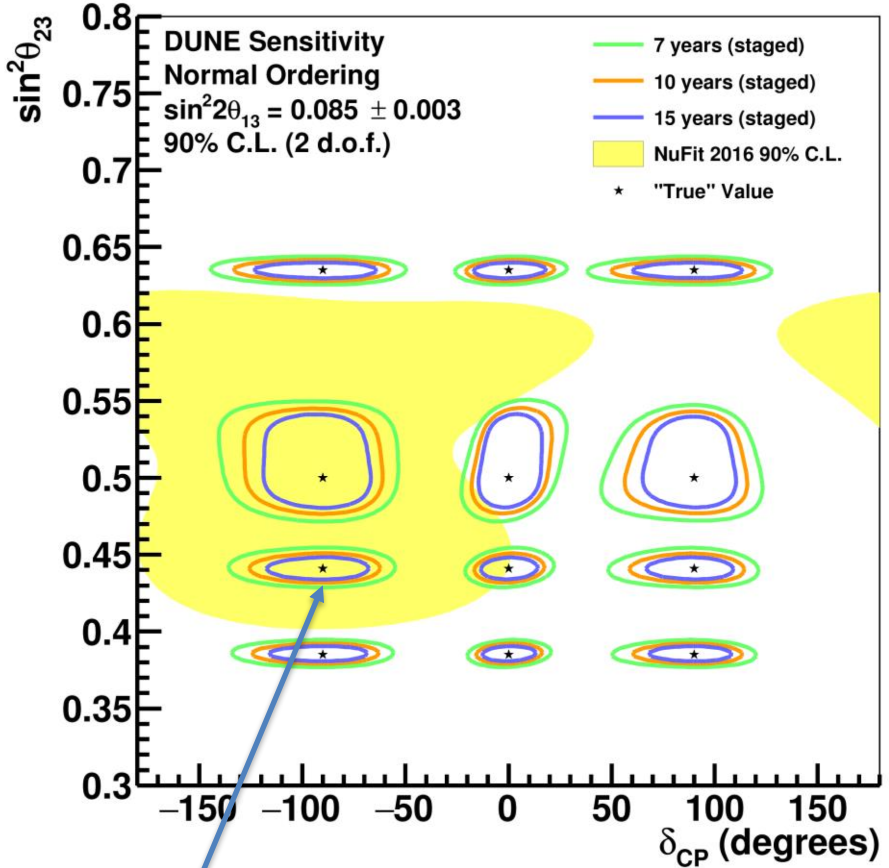
NuFIT 2016

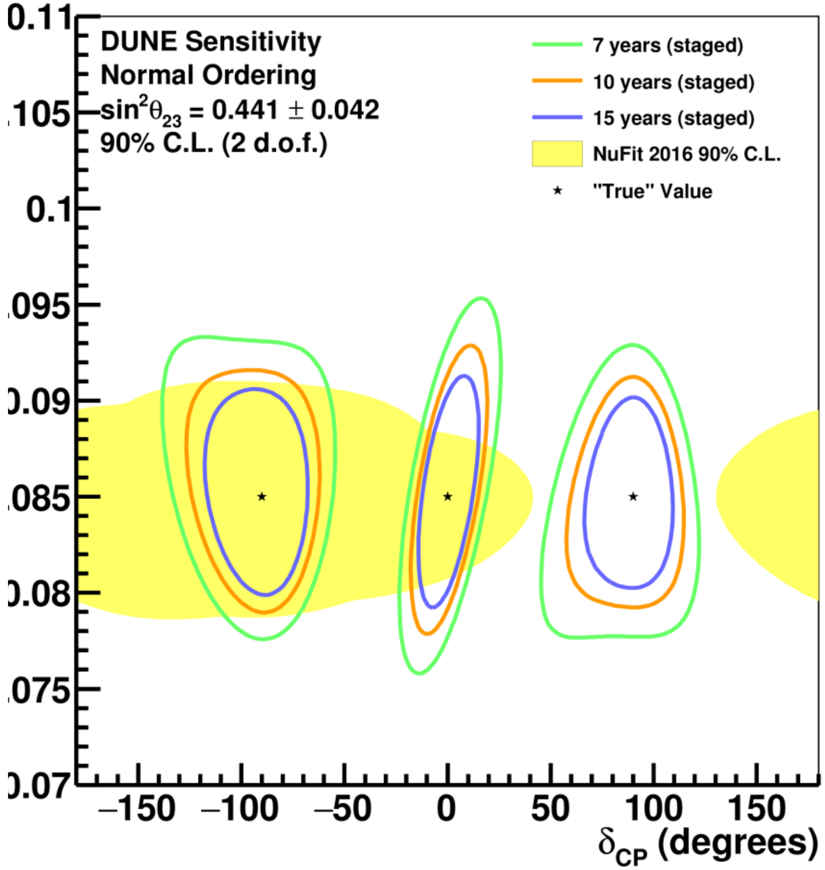
NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

For 1σ uncertainty in DUNE sensitivity calculations, we take 1/6 of the ±3σ range, to account for non-Gaussian PDFs in NuFit.

Comparison to 2016 Global Fit





Near NuFit 2016
best fit point

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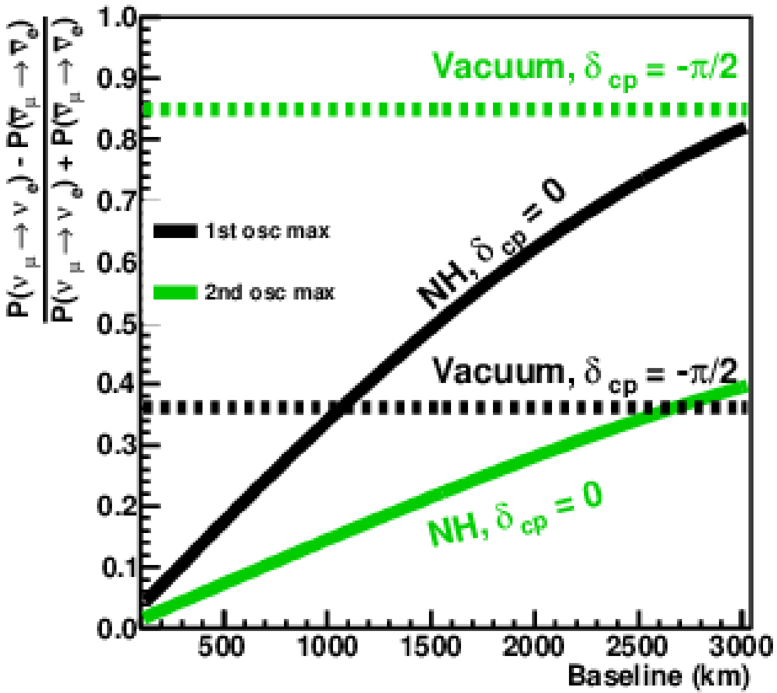
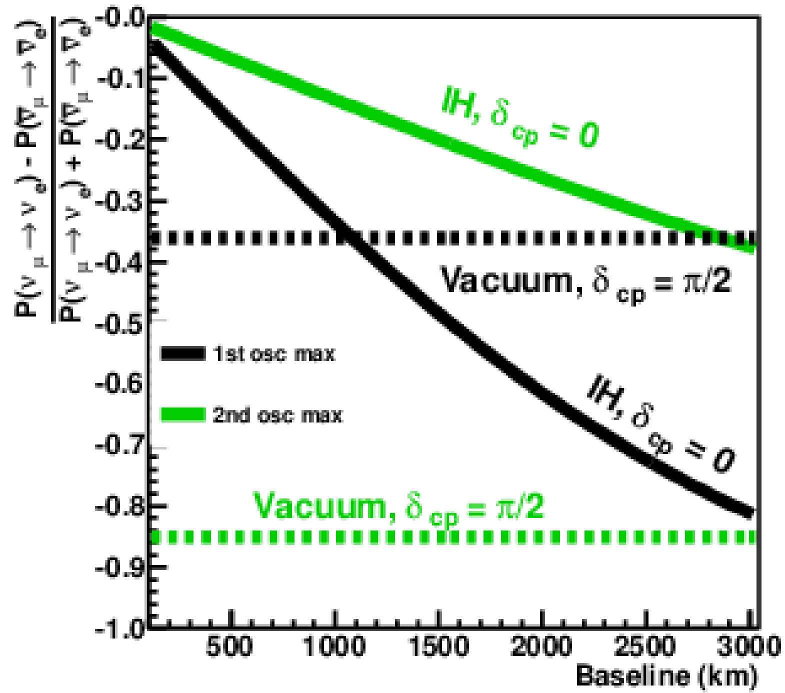
Neutrino-Antineutrino Asymmetry





$$\mathcal{A}_{cp}(E_\nu) = \left[\frac{\mathrm{P}(\nu_\mu \to \nu_e) - \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}{\mathrm{P}(\nu_\mu \to \nu_e) + \mathrm{P}(\bar{\nu}_\mu \to \bar{\nu}_e)}\right]$$

$$\mathcal{A}_{cp}(E_\nu) \approx \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{ matter effects.}$$

W. Marciano and Z. Parsa, Nucl. Phys. Proc. Suppl. 221, 166 (2011), arXiv:hep-ph/0610258[hep-ph].