DUNE Oscillation Physics

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for the DUNE collaboration

NUFACT 2017

University of Uppsala
28th September 2017

DUNE physics aims

DUNE has a rich physics programme which includes:

1. Make precise measurements of the oscillation parameters θ_{23}, θ_{13} and Δm_{31}^2.

2. Resolve the neutrino mass hierarchy, i.e. whether $m_3^2 > m_2^2$ or $m_3^2 < m_2^2$.

3. Determine the octant of θ_{23}.

4. Determine whether CP is violated in neutrinos and make a measurement of δ_{CP}.

5. Search for τ appearance.

6. Check the unitarity of the PMNS matrix

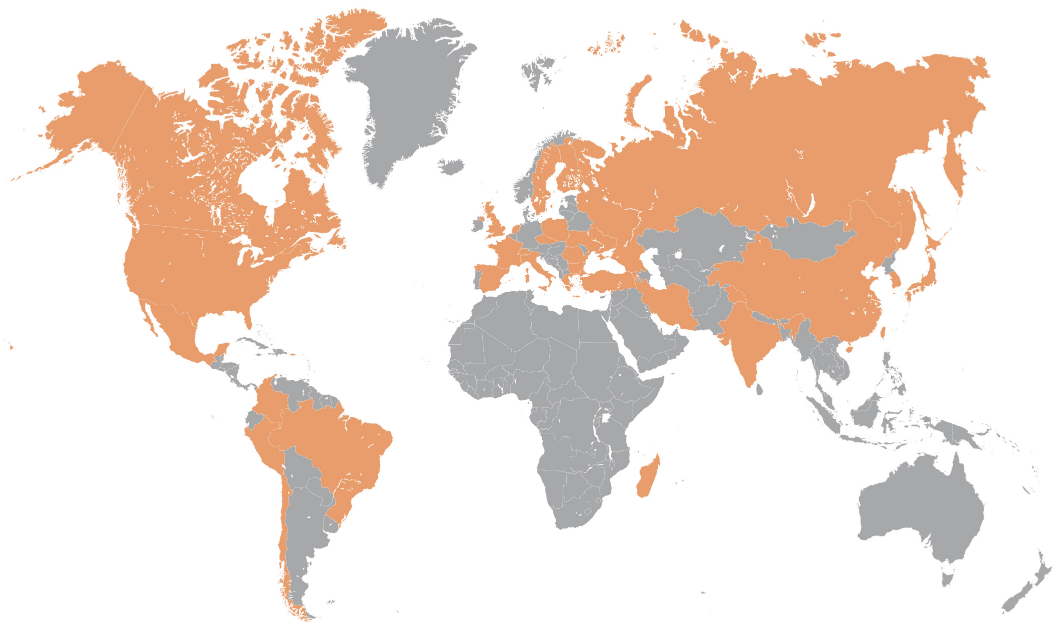
7. Search for nucleon decay, e.g. $p^+ \to K^+$ nubar.

8. Be ready to detect low-energy neutrinos from a core-collapse supernova.

9. Search for Beyond Standard Model physics, e.g. sterile neutrinos, heavy neutral leptons, large extra dimensions, non-standard interactions.

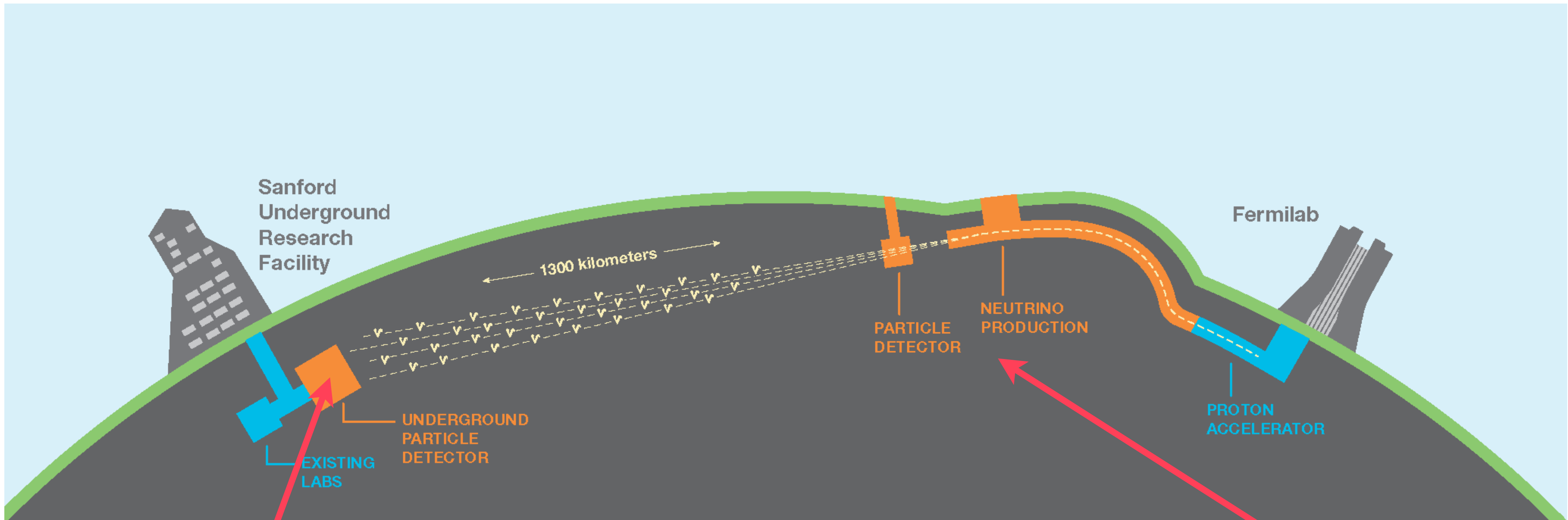
This talk will focus on neutrino oscillation physics (items 1-4) at DUNE.

DUNE



The Deep Underground Neutrino Experiment (DUNE) is a large international collaboration with >1000 collaborators from 164 institutions in 30 countries.

DUNE



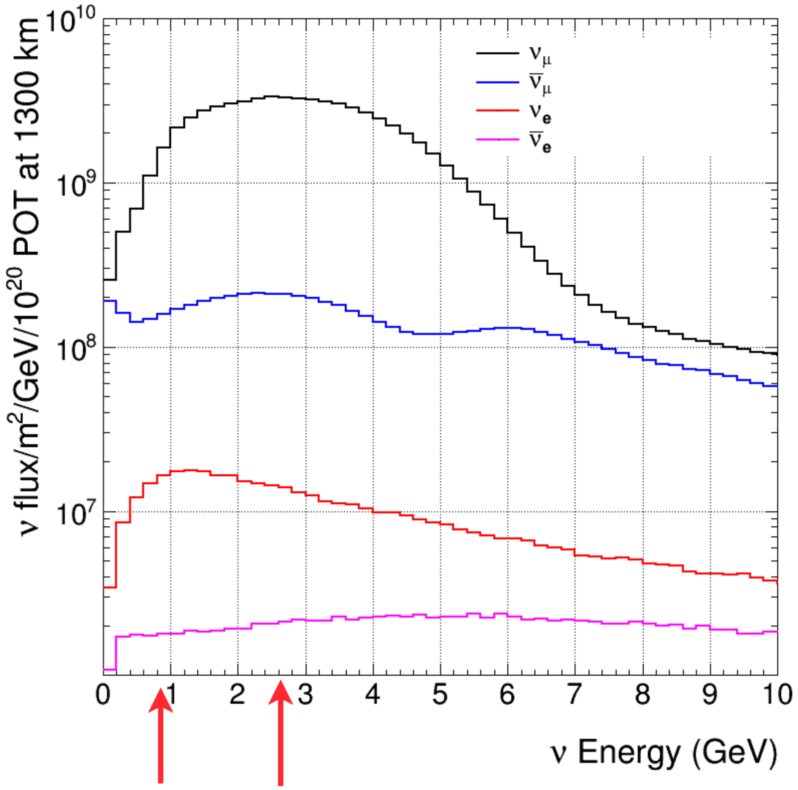
DUNE will make a beam of ν_μ or $\nu_\mu$bar at Fermilab. This beam will pass through the near detector (574 metres from target) and the far detector (1300 km distant).

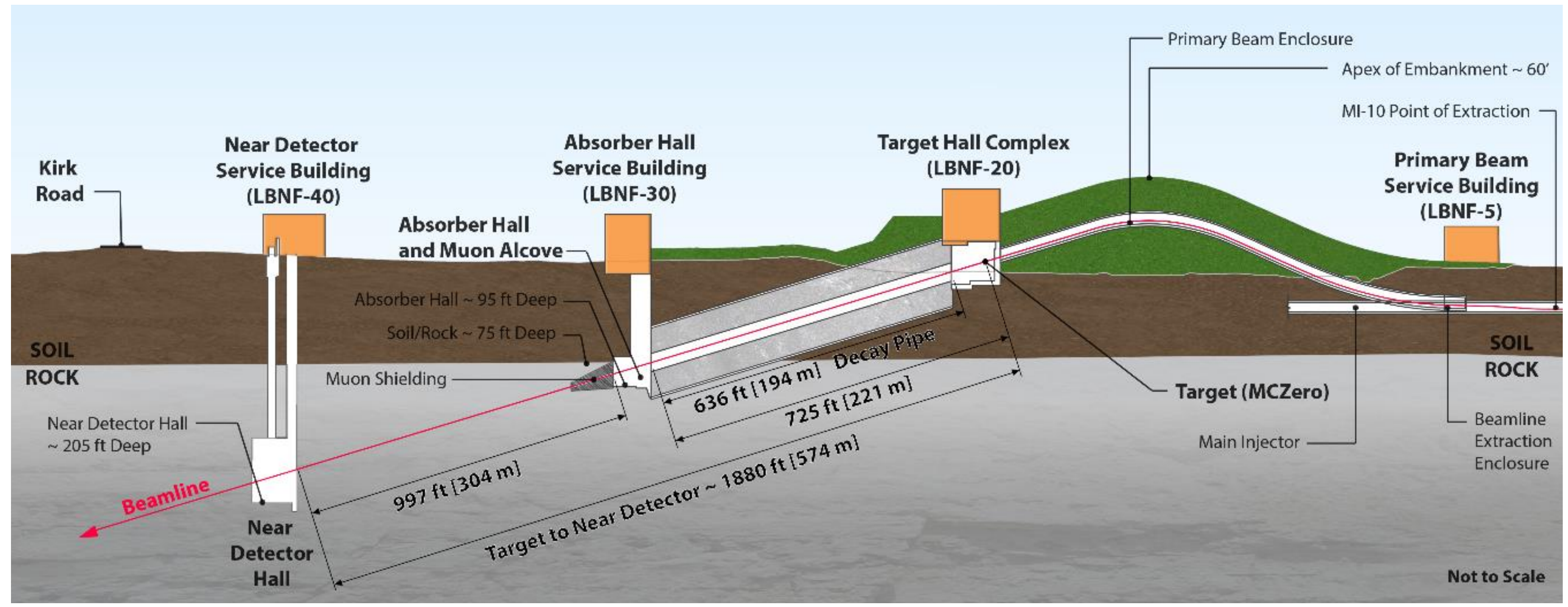
Far detector at Sanford Underground Research Facility (SURF)

Neutrino beam and near detector at Fermilab

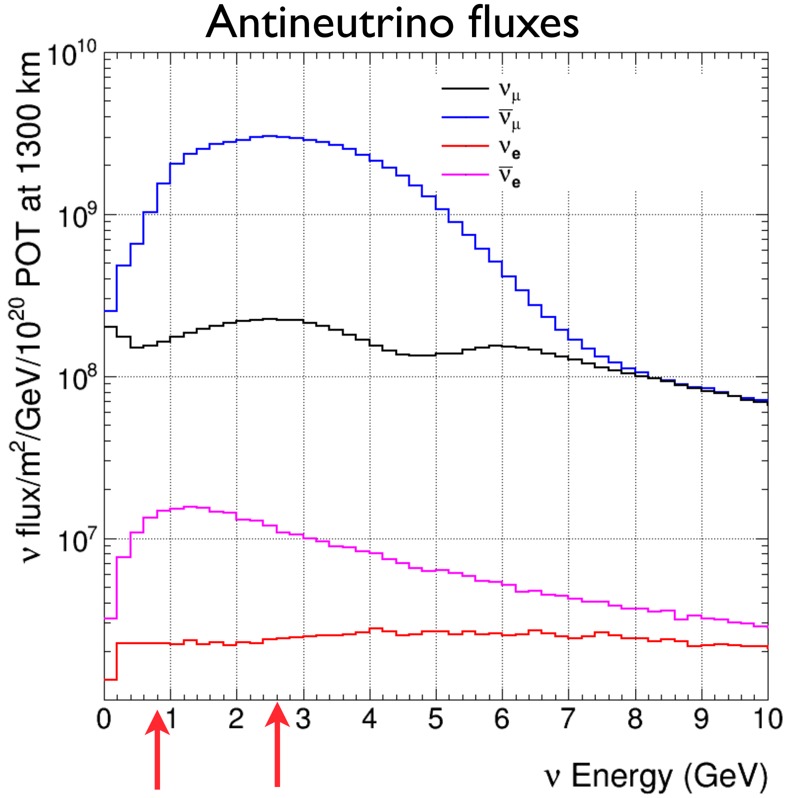
DUNE neutrino beam

Neutrino fluxes





Antineutrino fluxes

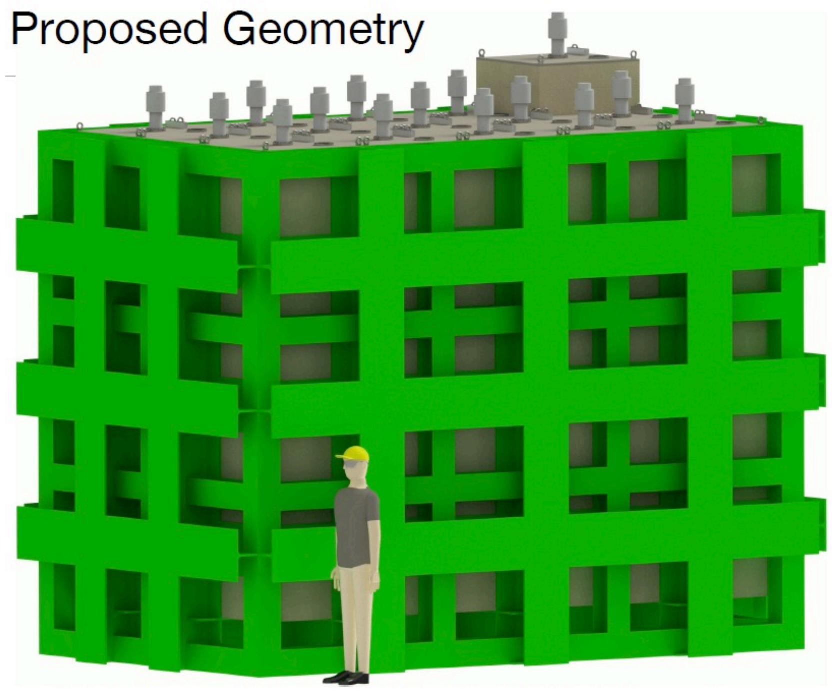


The DUNE neutrino beam will be made using a proton beam that is initially 1.2 MW and can be upgraded to 2.4 MW.

The neutrino beam will be on axis and have a broad range of energies covering both the first and second oscillation maxima - these are shown with red arrows ↑.

For further details, please see talk by Tristan Davenne on Monday at 15.30.

DUNE near detector



The near detector (ND) will be a ~30 tonne liquid argon time projection chamber with a downstream magnetised multi-purpose spectrometer at Fermilab. Design of spectrometer not yet finalised, it could be a straw-tube tracker or a high-pressure gas argon time projection chamber.

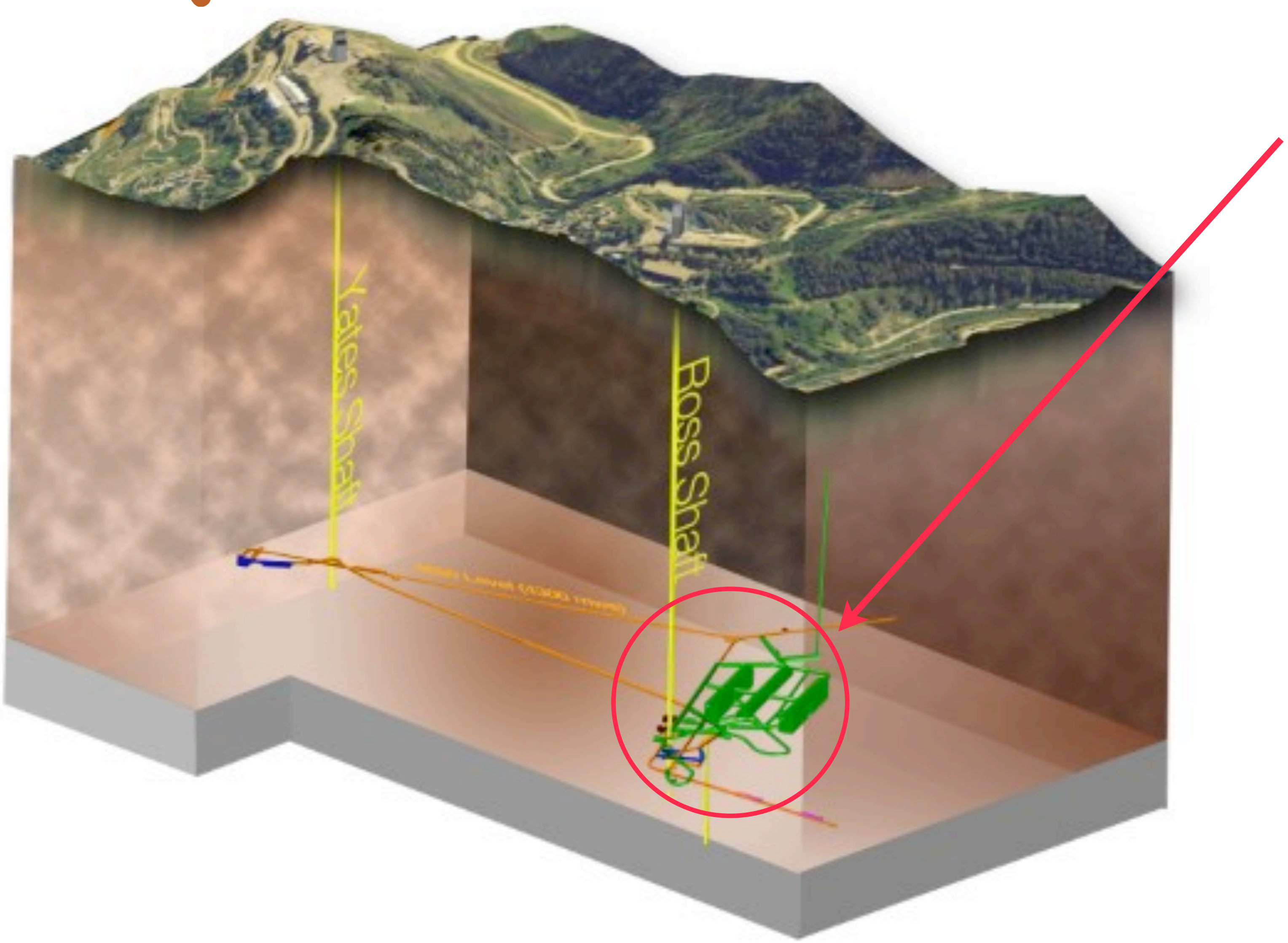
Its goals are

1. Constrain systematic uncertainties, e.g. flux and cross sections, in oscillation analyses.

2. Make precision measurements of neutrino interaction cross sections - for further details, please see talk by Hongyue Duyang on Friday at 12.00.

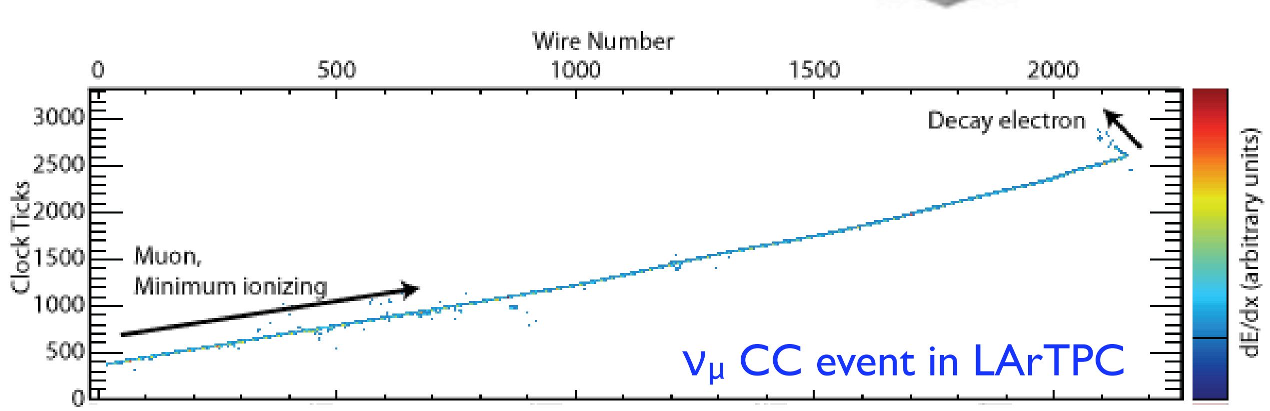
3. Search for new physics, e.g. sterile neutrinos.

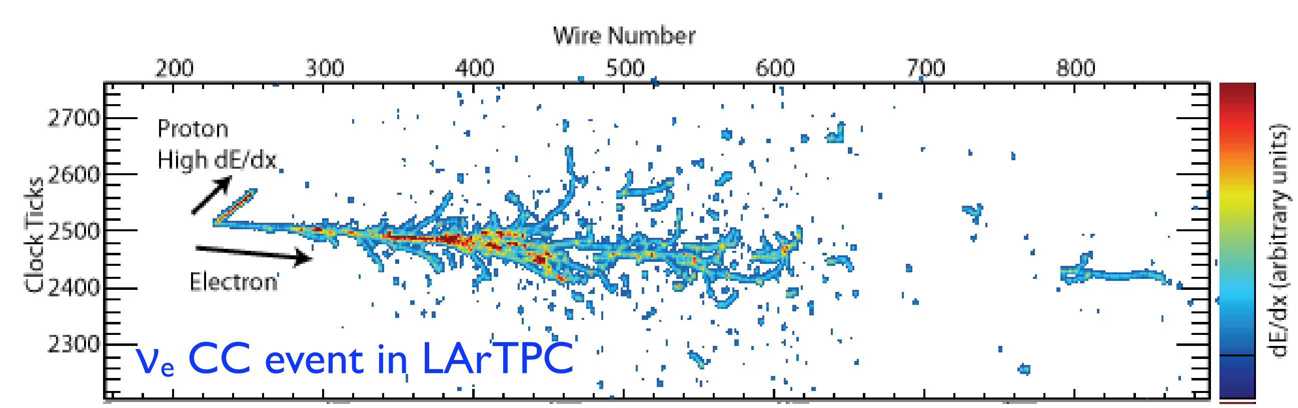
DUNE far detector



The far detector (FD) will be a suite of four 10 kt liquid argon time projection chambers (LArTPCs) at the 4850 feet underground level in SURF, South Dakota.

LArTPC technology gives excellent calorimetric and spatial resolution, and provides high-quality tracking of charged particles down to low momenta.



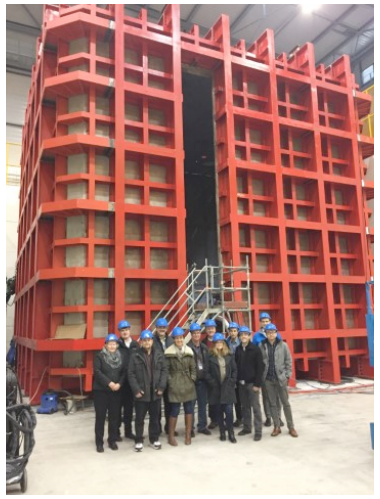


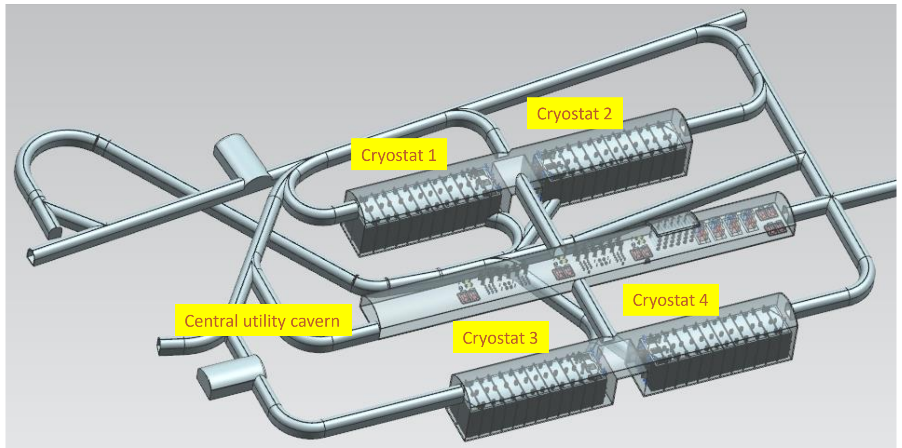
Ref: http://docs.dunescience.org/cgi-bin/ShowDocument?docid=183&asof=2016-1-30

DUNE timeline

DUNE groundbreaking at SURF !!!
21st July 2017

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



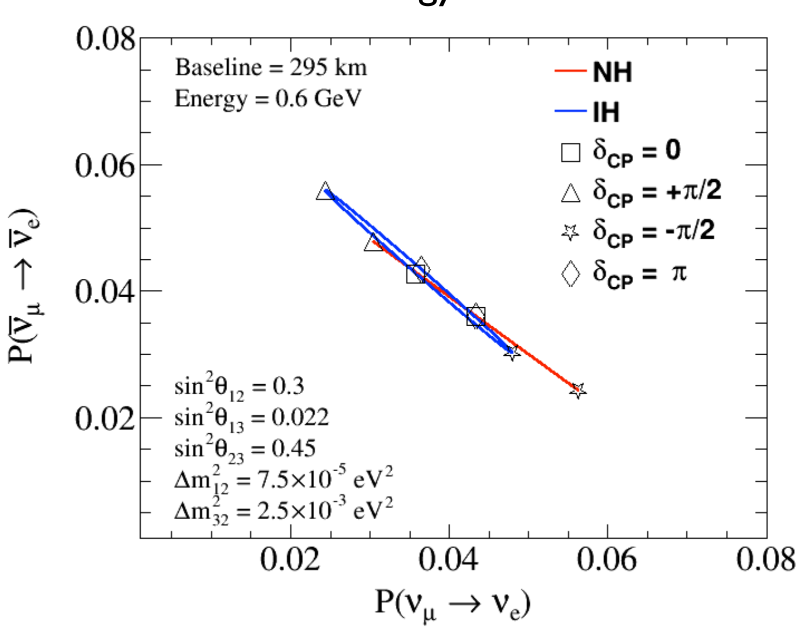


Neutrino mass hierarchy

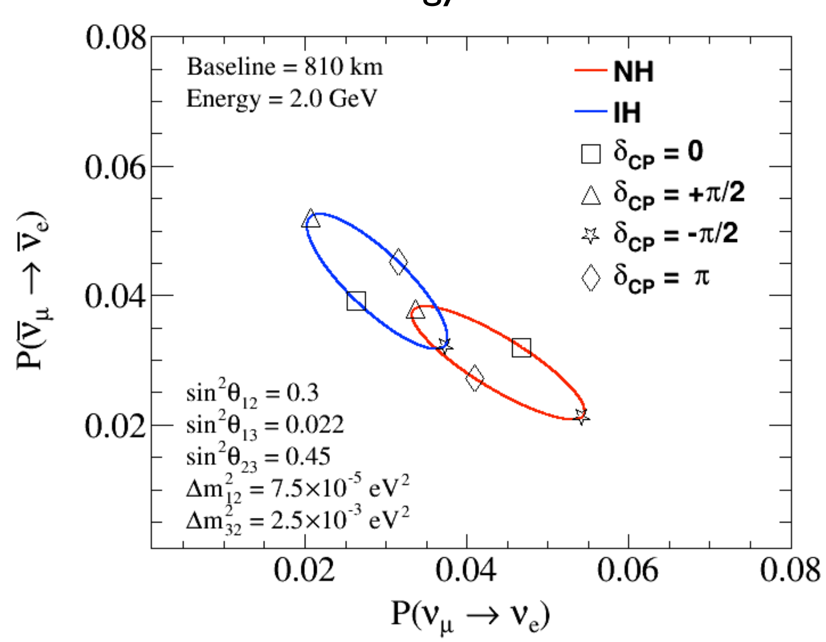
If $\delta_{CP} \neq 0$ or π, the oscillation probability $P(\nu_\mu \rightarrow \nu_e)$ is not the same as $P(\nu_\mu\text{bar} \rightarrow \nu_e\text{bar})$. There is also a significant difference between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\nu_\mu\text{bar} \rightarrow \nu_e\text{bar})$ due to matter effects.

Due to the 1300 km baseline, the asymmetry due to matter effects is ~40% in region of peak flux, which is greater than largest possible asymmetry from CP violation. The sign of this difference depends on the mass hierarchy. This means that the mass hierarchy can be resolved by DUNE irrespective of the value of δ_{CP}.

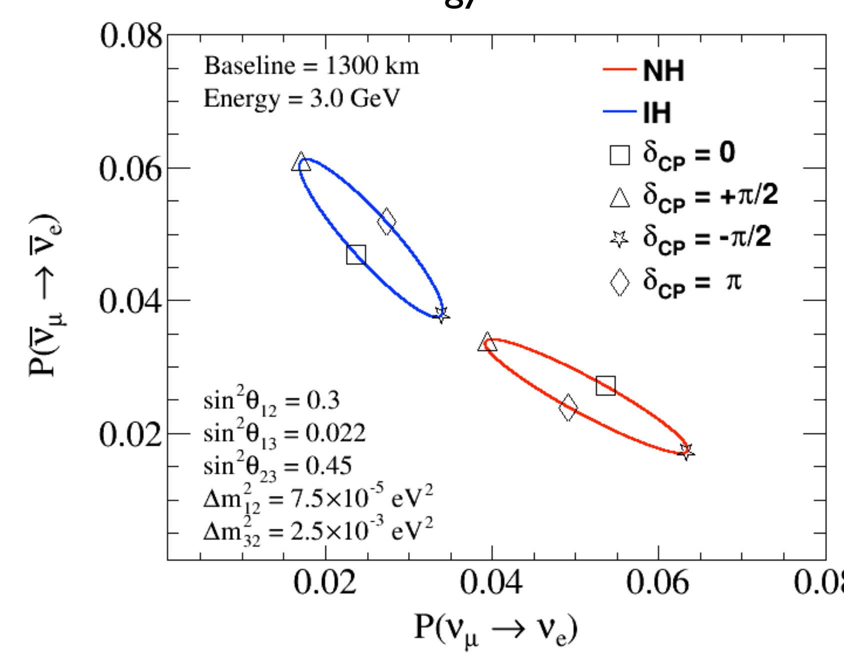
Baseline 295 km
Energy 0.6 GeV



Baseline 810 km
Energy 2.0 GeV



Baseline 1300 km
Energy 3.0 GeV



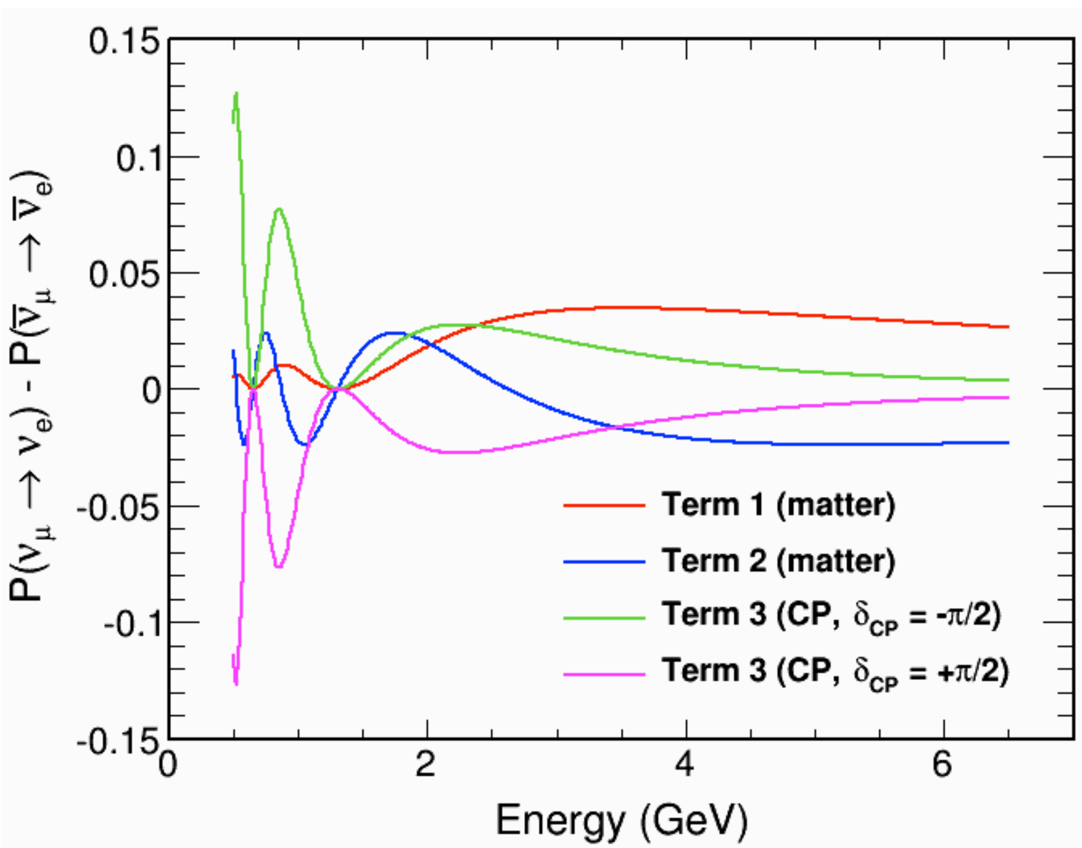
CP violation

To search for CP violation or to measure δ_{CP}, use difference between $\nu_\mu \to \nu_e$ and $\nu_\mu bar \to \nu_e bar$ reconstructed spectra; need to disentangle matter effects from those due to CP violation.

$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$ has 3 terms to good approximation (formulae in backup).

(ref: https://arxiv.org/pdf/hep-ph/9703351.pdf)

The three terms all oscillate but amplitudes have different energy dependence. Can separate CP violation from matter effects using broad range of energies. CP term more important at low energy.



Graphs for normal mass hierarchy

For inverted hierarchy, term 1 (red) changes sign.

Baseline = 1300 km

Reconstructed energy spectra

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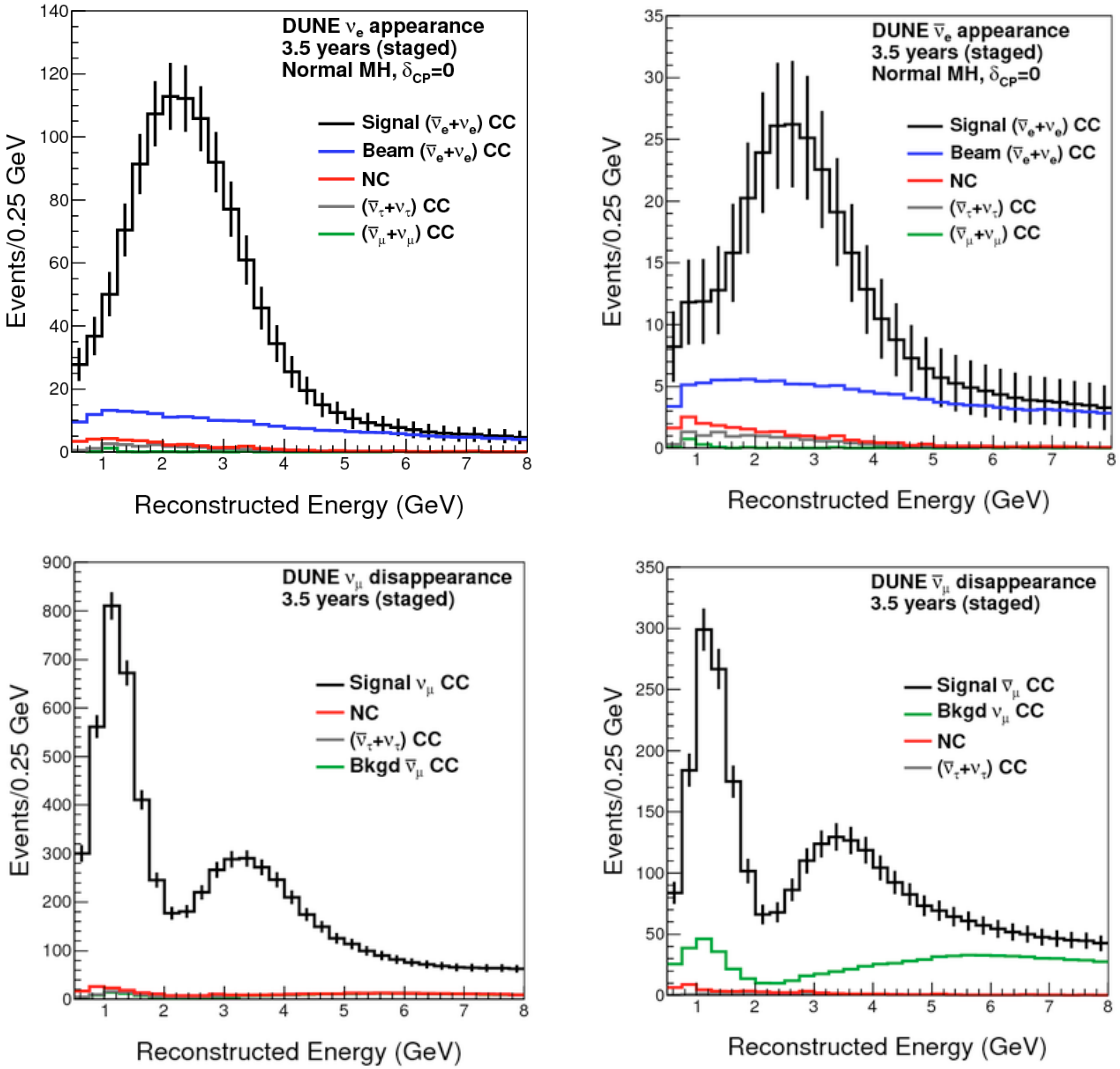


Sensitivities to the mass hierarchy and CP violation are obtained by using GLoBES to simultaneously fit the $\nu_\mu \to \nu_\mu$, $\nu_\mu$bar$\to\nu_\mu$bar, $\nu_\mu \to \nu_e$ and $\nu_\mu$bar$\to\nu_e$bar reconstructed spectra.

Assume 50% of running in neutrino mode, 50% in antineutrino mode.

2026 20 kt far detector with 1.2 MW beam

2027 30 kt far detector

2029 40 kt far detector

2032 Upgrade to 2.4 MW beam

Uncertainties

Neutrino oscillation parameters are allowed to vary in the fits with a Gaussian constraint using NuFit 2016 values.

Effect of systematic uncertainties is approximated using normalisation uncertainties in each constituent interaction mode that comprise signal and background in each event sample.

Signal normalisation uncertainty is $5 \oplus 2\%$ in both neutrino and antineutrino modes, where 5% is the normalisation uncertainty in the FD ν_μ sample and 2% is the effective uncorrelated uncertainty in the FD ν_e sample after fits to both ND and FD data and external constraints.

Sensitivities

Sensitivities are calculated using test statistic $\Delta\chi^2$ comparing reconstructed spectra for different hypotheses:

$$\begin{aligned}\Delta\chi^2_{MH} &= \chi^2_{IH} - \chi^2_{NH} \text{ (true normal hierarchy)},\\ \Delta\chi^2_{MH} &= \chi^2_{NH} - \chi^2_{IH} \text{ (true inverted hierarchy)}\end{aligned}$$

$$\Delta\chi^2_{CPV} = Min[\Delta\chi^2_{CP}(\delta^{test}_{\mathrm{CP}} = 0), \Delta\chi^2_{CP}(\delta^{test}_{\mathrm{CP}} = \pi)], \text{ where } \Delta\chi^2_{CP} = \chi^2_{\delta^{test}_{\mathrm{CP}}} - \chi^2_{\delta^{true}_{\mathrm{CP}}}$$

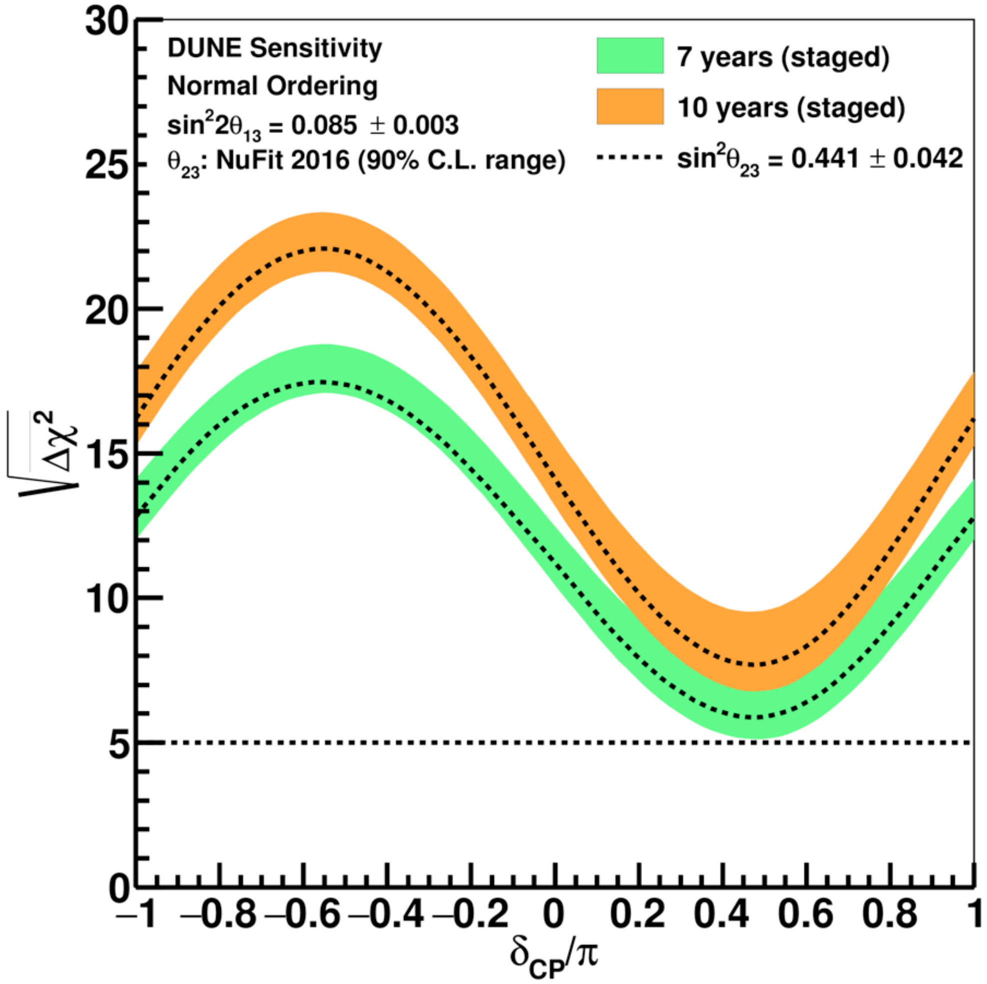
Scan over all values of true δ_{CP} and use lowest value of $\Delta\chi^2$. Assume mass hierarchy and θ_{23} octant unknown, vary them in fits and use lowest value of $\Delta\chi^2$.

More details of the GLoBES configuration are given in https://arxiv.org/pdf/1606.09550.pdf

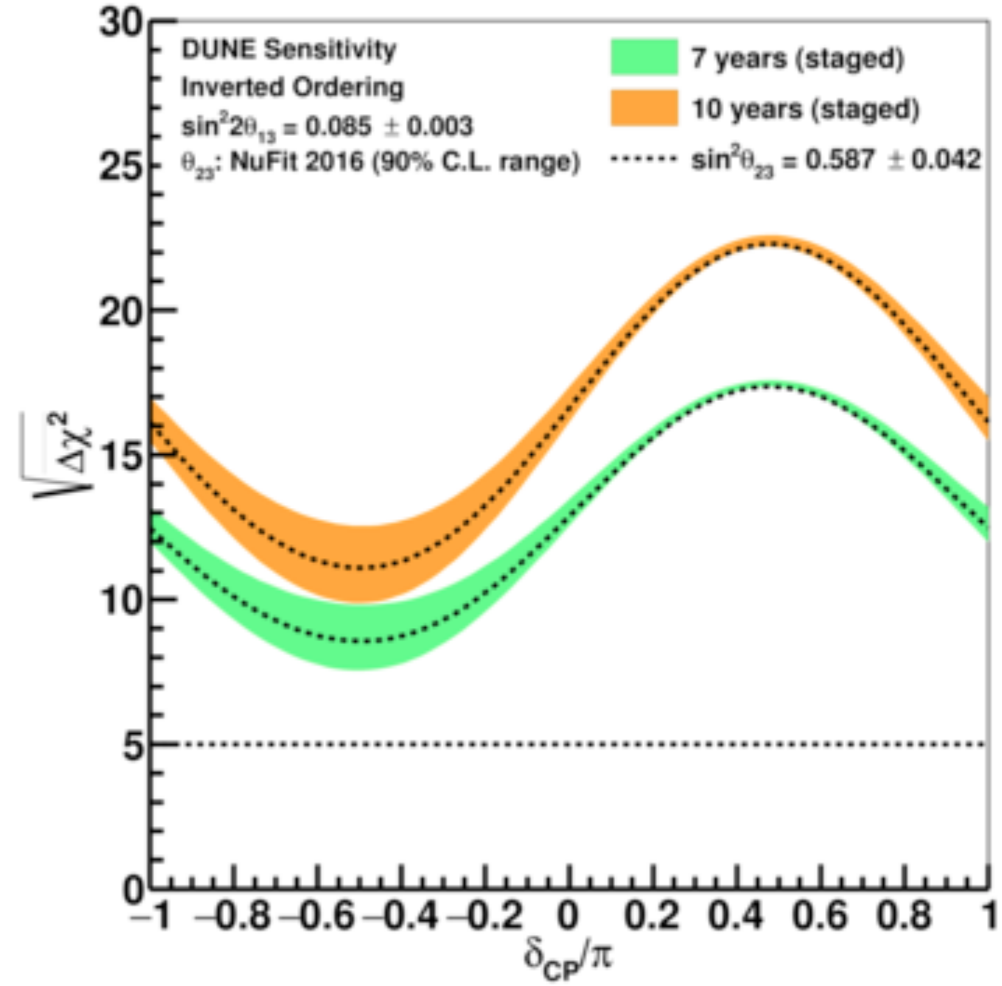
Mass hierarchy sensitivity

Sensitivity to determination of mass hierarchy as a function of true value of δ_{CP}.
Bands represent range of sensitivity for different values of θ_{23} (NuFit 2016 90% C.L. range).
Significance increases with increasing θ_{23}.
θ_{13} and $\Delta m_{31}{}^2$ have smaller effect on significance than θ_{23}.

Normal ordering



Inverted ordering

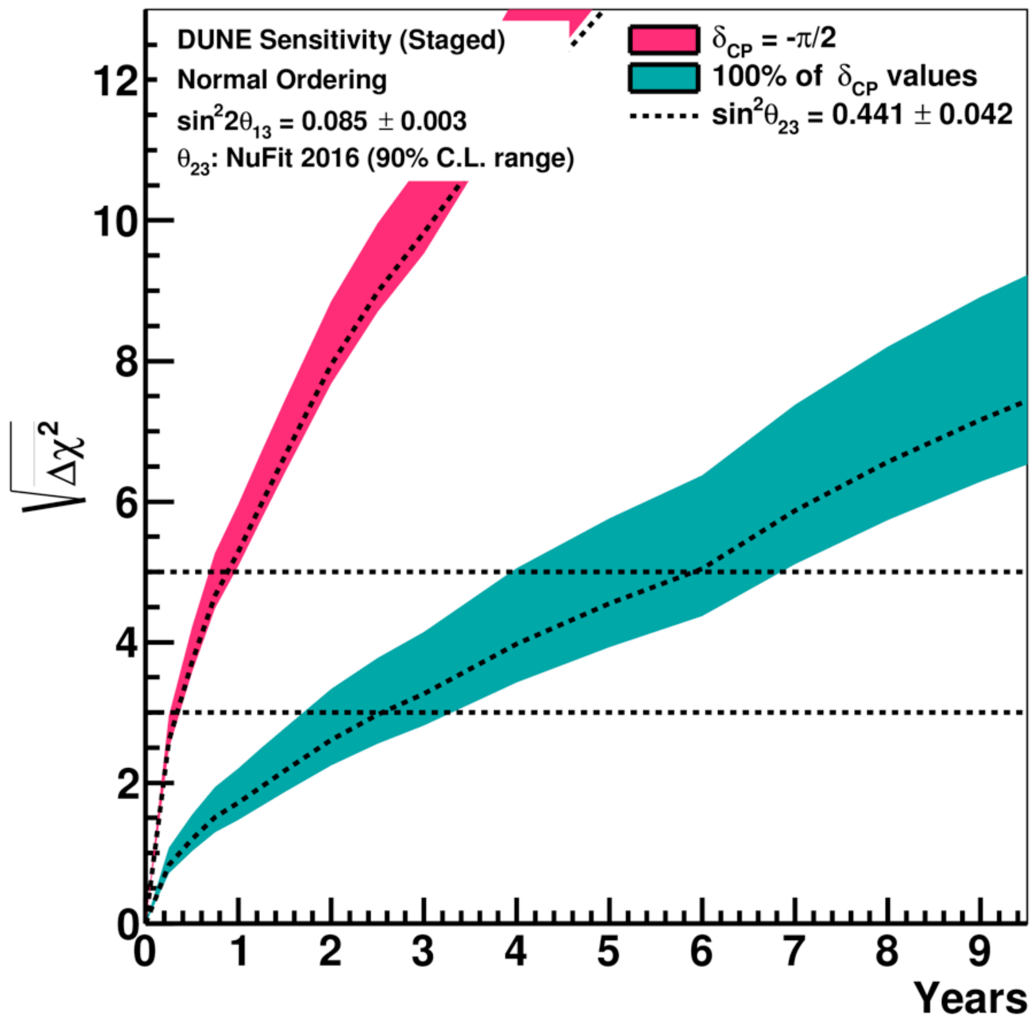


Mass hierarchy sensitivity

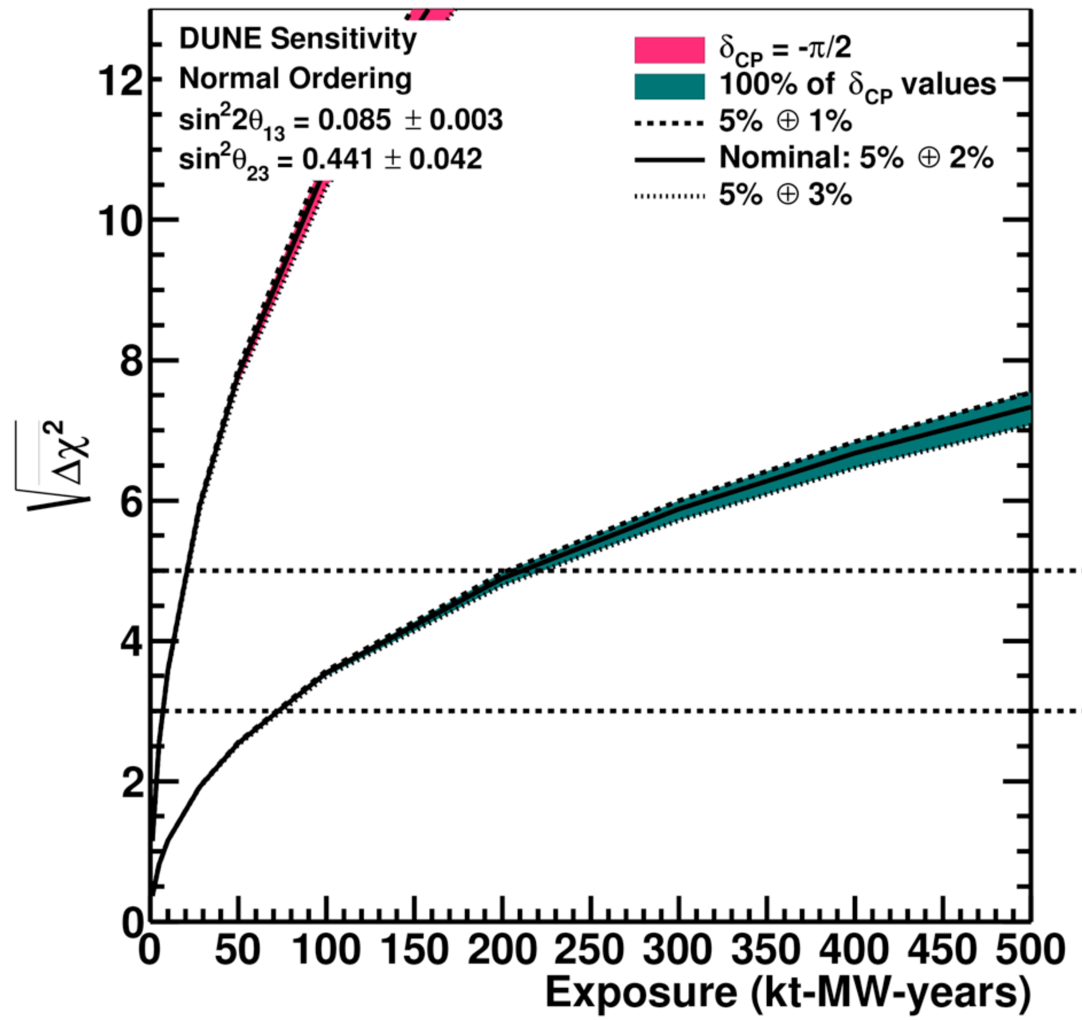
Sensitivity to determination of mass hierarchy as a function of time

Normal mass ordering is assumed.

Bands represent range of sensitivity for different values of θ_{23} (NuFit 2016 90% C.L. range)



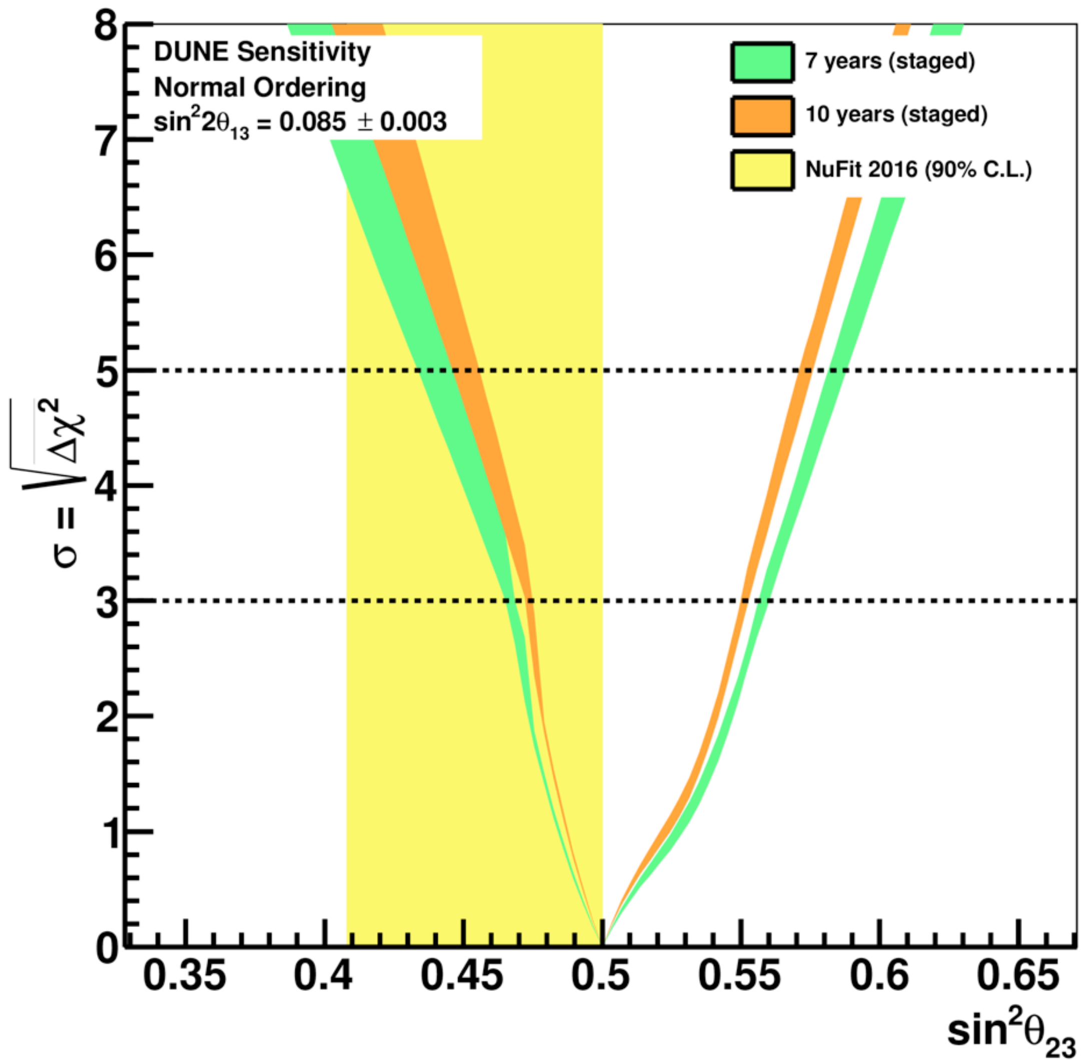
Bands represent difference between 1% and 3% uncertainty in ν_e signal normalisation



(300 kt MW years ≈ 7 years running)

Sensitivity to θ_{23} octant

Significance with which θ_{23} octant can be determined as a function of true value of $\sin^2\theta_{23}$.
Normal mass ordering is assumed.
Bands represent range of significance for different values of δ_{CP}; band covers least extreme 80% of values, i.e. best and worst 10% of significances are not shown.
Yellow shaded band represents 90% C.L. allowed region for value of $\sin^2\theta_{23}$ from NuFit 2016.



Sensitivity to CP violation

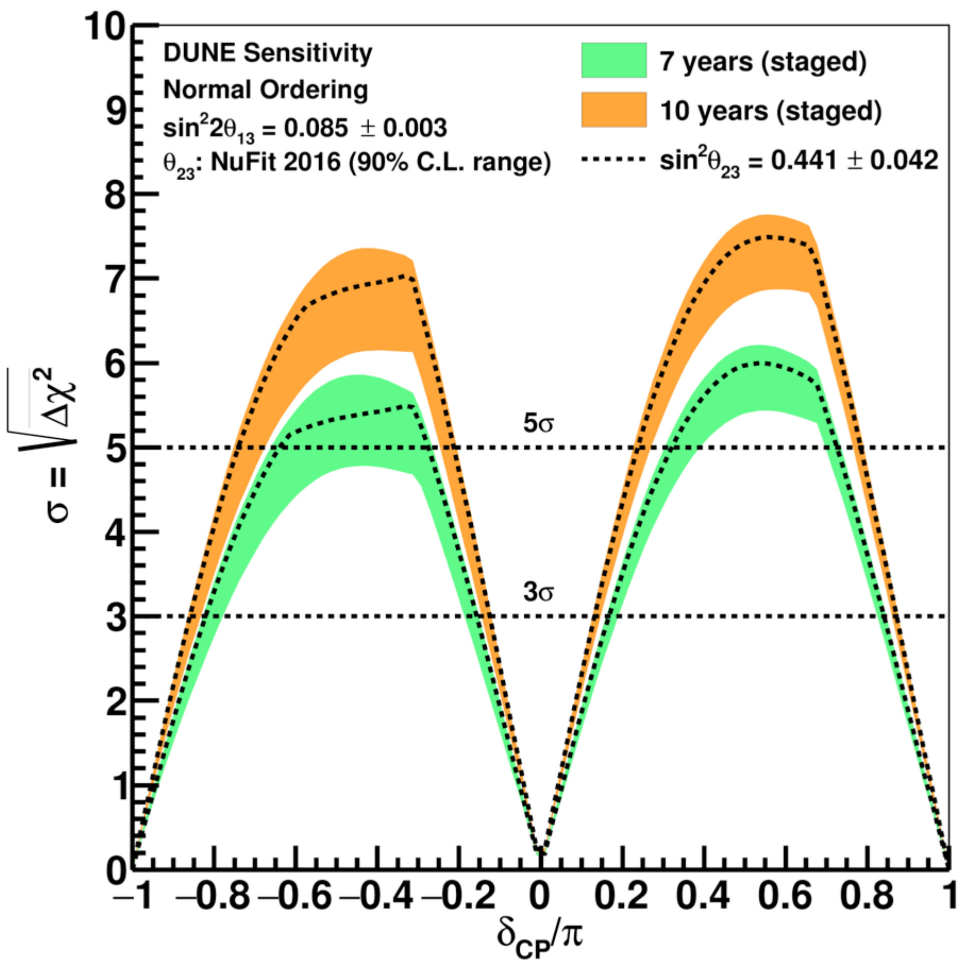
Significance with which CP violation ($\delta_{CP} \neq 0$ or π) can be determined as a function of true value of δ_{CP}.

Bands represent range of significance for different values of θ_{23} (NuFit 2016 90% C.L. range).

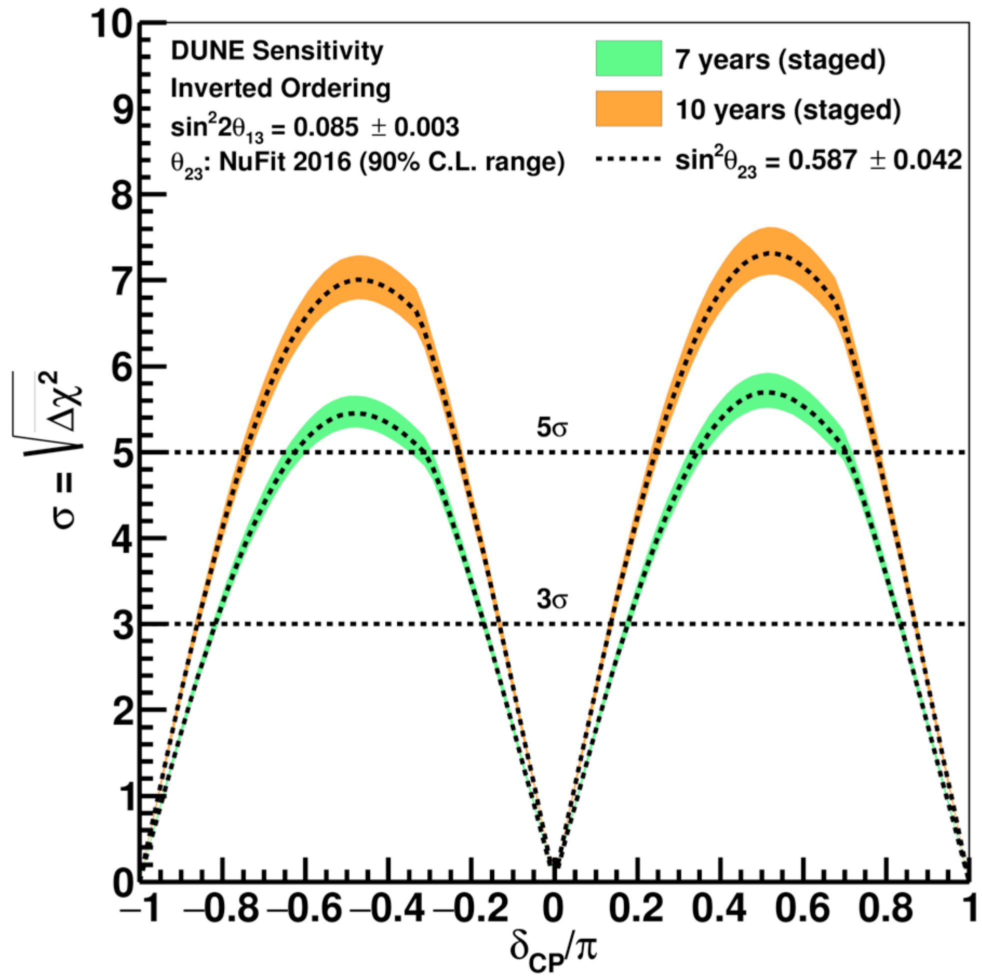
Significance decreases with increasing θ_{23}.

θ_{13} and Δm_{31}^2 have smaller effect on significance than θ_{23}.

Normal ordering



Inverted ordering

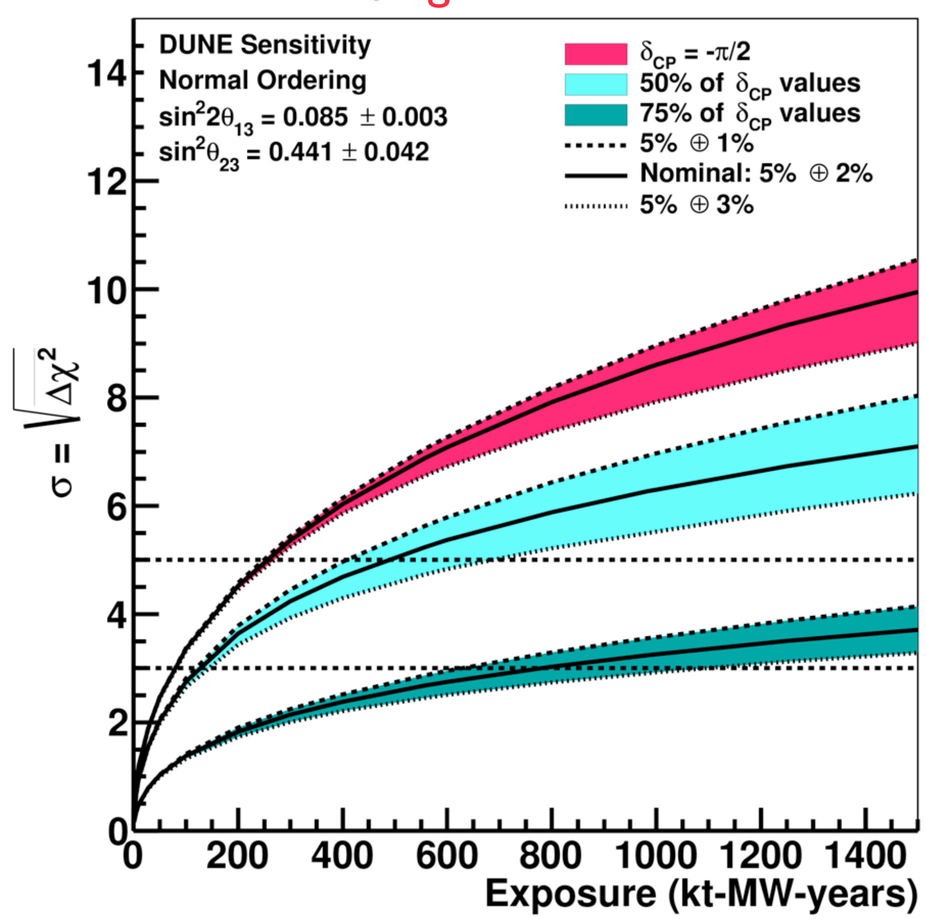


Sensitivity to CP violation

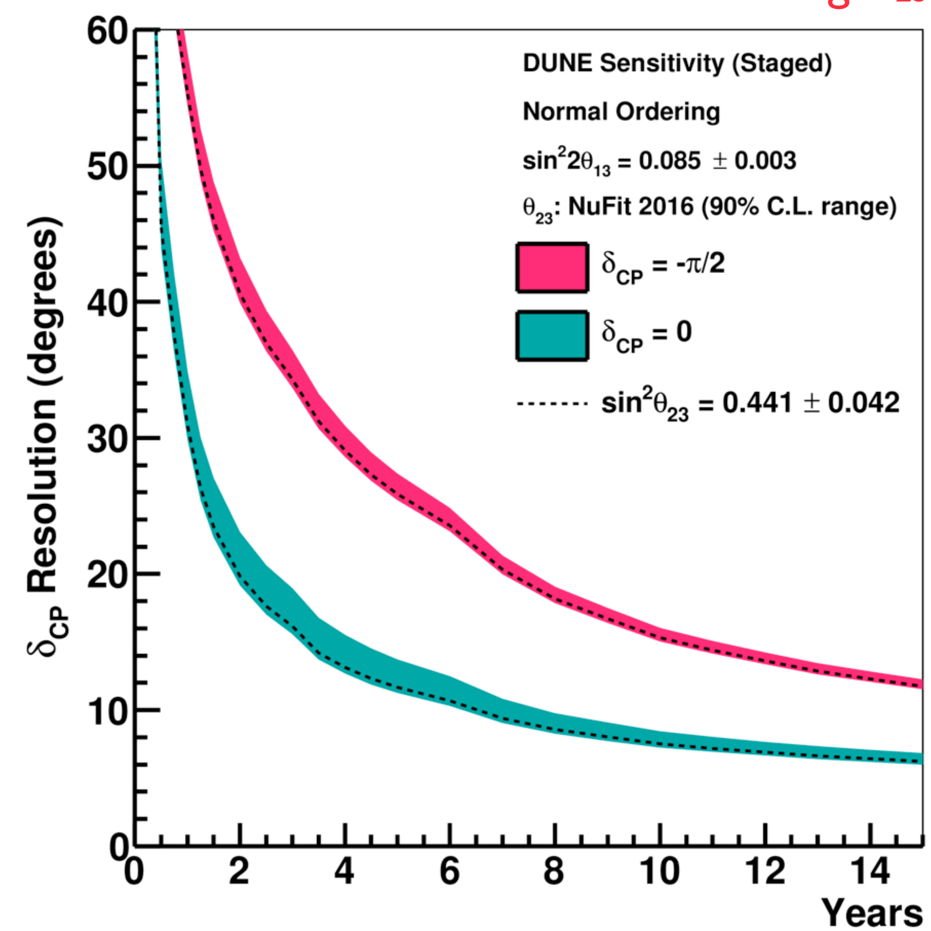
Significance with which CP violation ($\delta_{CP} \neq 0$ or π) can be determined (left) and δ_{CP} resolution (right) as a function of time.

Normal mass ordering is assumed.

Bands represent difference between 1% and 3% uncertainty in ν_e signal normalisation



Bands represent resolution for different values of θ_{23} (NuFit 2016 90% C.L. range). Resolution worsens with increasing θ_{23}

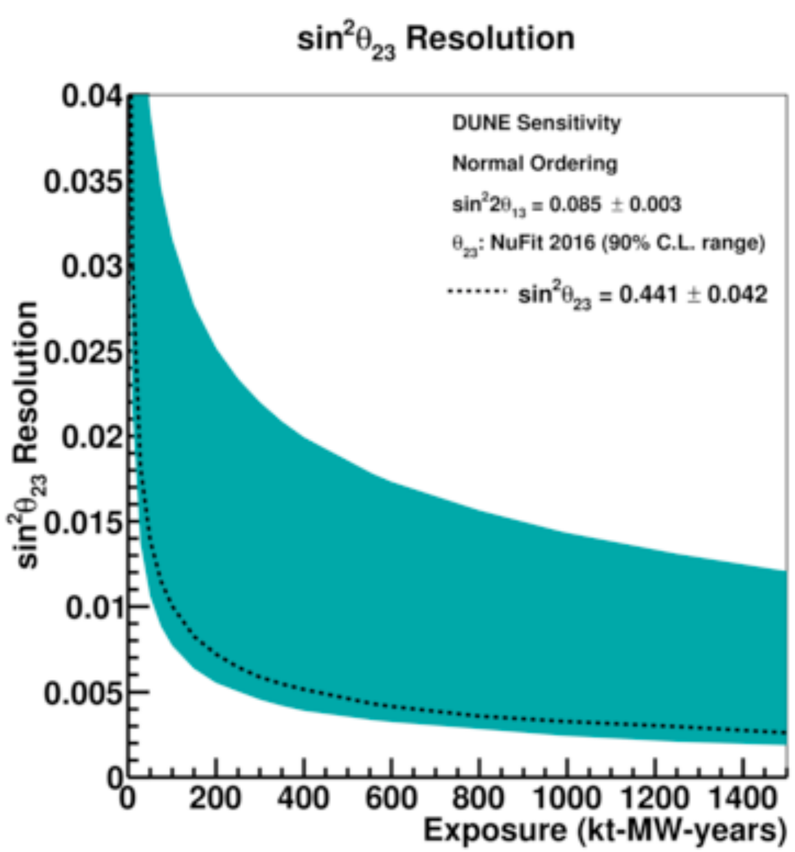


Oscillation parameter resolution

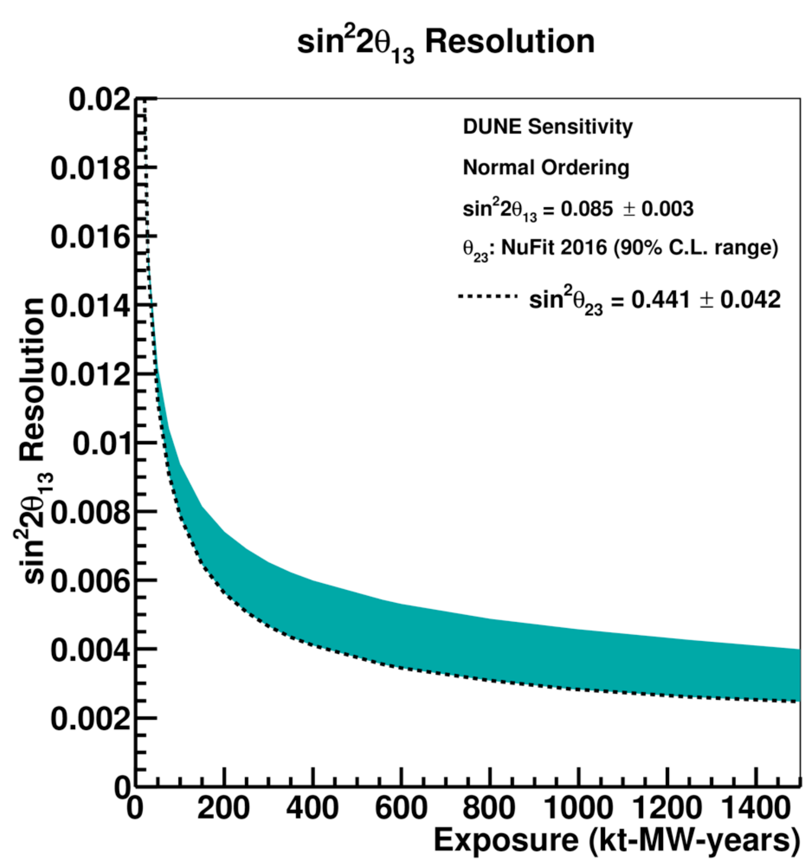
Resolutions of measurements of $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ and Δm_{31}^2

Normal mass ordering

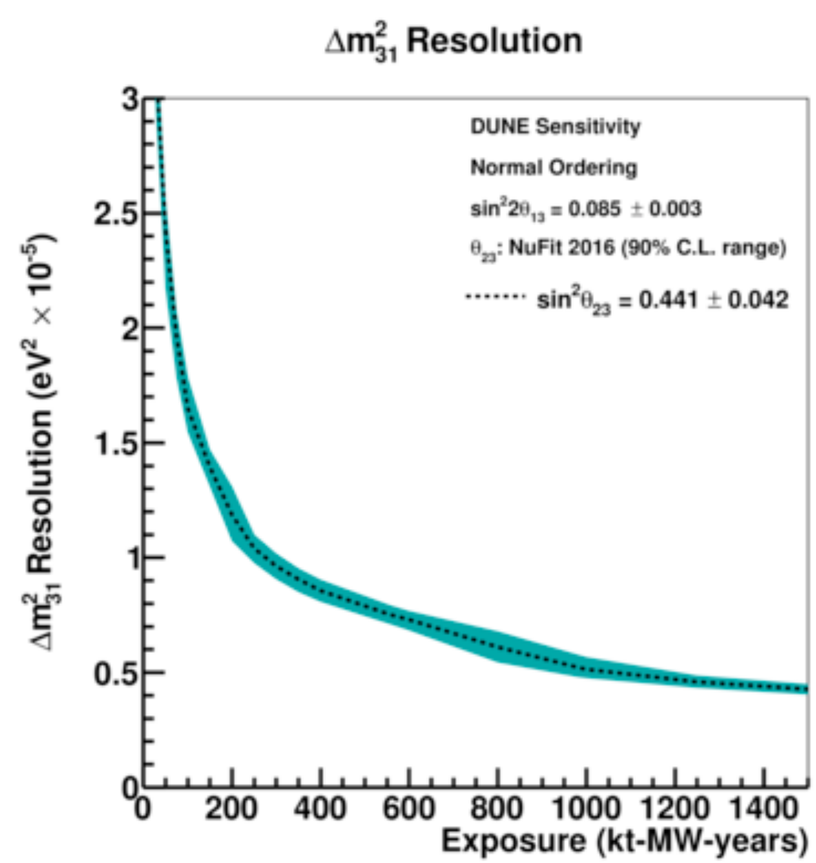
Bands represent range of resolution for different values of θ_{23} (NuFit 2016 90% C.L. range).



Resolution worsens with increasing θ_{23}.



Resolution best at nominal value of θ_{23}, worst at highest value of θ_{23}.



Resolution improves with increasing θ_{23}.

Summary

DUNE will use an on-axis ν_μ and $\nu_\mu$bar beam with a broad range of energies including the first and second oscillation maxima.

Due to its long baseline of 1300 km, neutrino oscillations between the DUNE near and far detectors will be significantly altered by matter effects.

These features will enable DUNE to resolve the neutrino mass hierarchy and the octant of θ_{23}, search for CP violation in neutrinos and measure δ_{CP} in a single experiment. DUNE will also make measurements of θ_{23}, θ_{13} and Δm_{31}^2, search for τ appearance and test the unitarity of the PMNS matrix.

We expect to update the sensitivities presented here with an analysis based on full MC simulation, full reconstruction and a more complete systematics treatment by 2019.

BACKUP SLIDES

GLoBES inputs

Reference beam flux

80 GeV protons
204 m x 4 m helium-filled decay pipe
1.07 MW
Two-horn system with 1 m target inserted 2/3 of way into horn 1

Optimised beam flux

3 horns, 2 m target entirely in horn 1; this increases flux in oscillation region (including second maximum), decreases flux in high-energy tail, increases sensitivity to CP violation.
For more details, please see talk by Tristan Davenne at 15.30 on Monday.

Expected detector performance

Based on previous experience, e.g. ICARUS, ArgoNEUT

Cross sections

GENIE

Systematic uncertainties

Anticipated systematic uncertainties based on experience from MINOS and T2K. Supported by preliminary studies with DUNE fast Monte Carlo.

Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e
Beam Flux after N/F extrapolation	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	$\sim 2\%$
Energy scale (ν_μ)	3.5%	included above	(2%)
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial volume	2.4%	1%	1%
Total	5.7%	6.8%	3.6 %
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$

DUNE goal for total uncertainty in ν_e sample is <4%. Cancellation of correlated portion of uncertainty is expected in four-sample fit, meaning that residual uncorrelated uncertainty in ν_e sample is reduced to 1-2%. For sensitivities used $5 \oplus 2\%$, uncorrelated between neutrinos and antineutrinos.

Systematic uncertainties

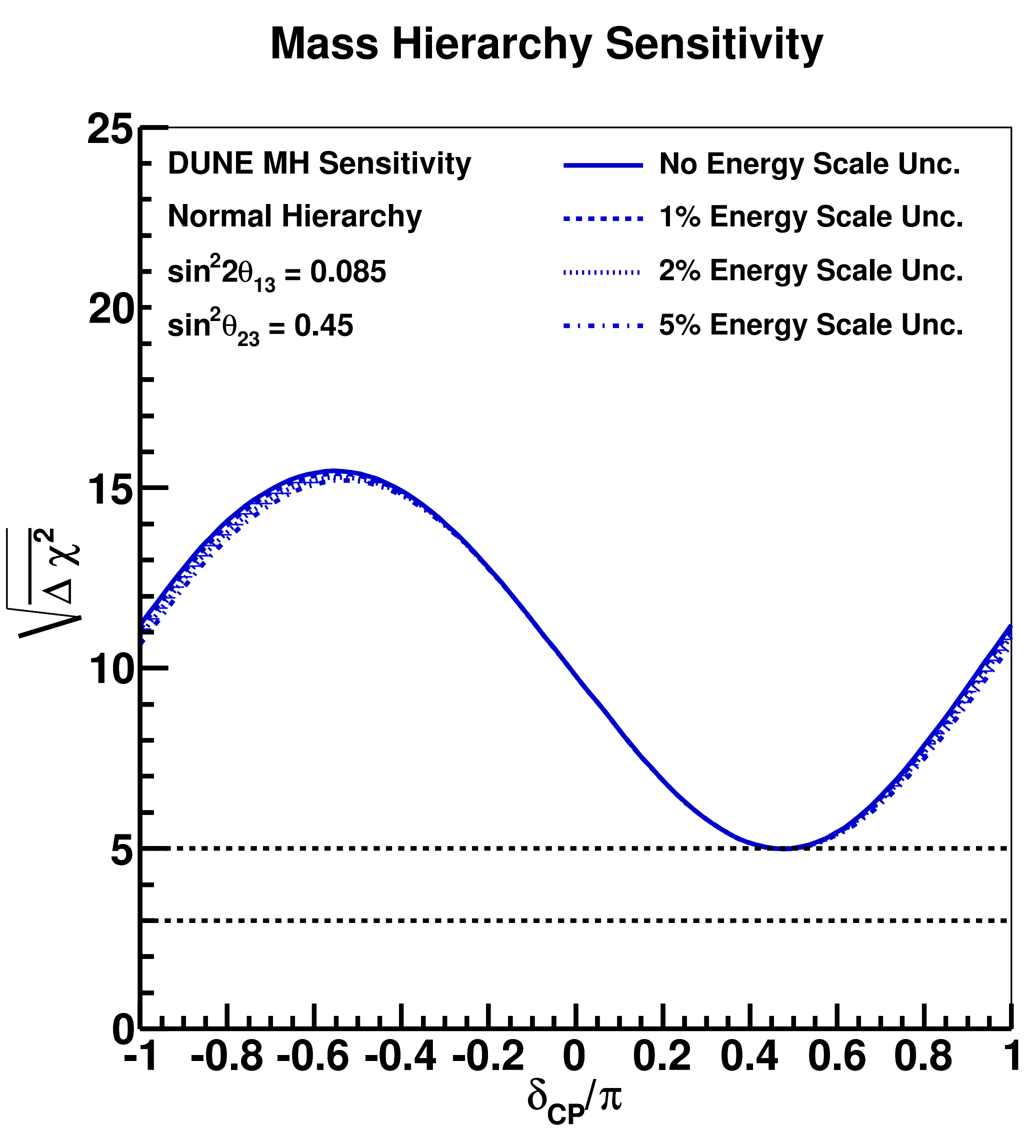
Absolute normalisation of ν_μ sample must be known to ~5% and normalisation of ν_e sample, relative to ν_μ, $\nu_\mu$bar and $\nu_e$bar samples and after applying all constraints from external, near and far detector data, must be determined to the few percent level.

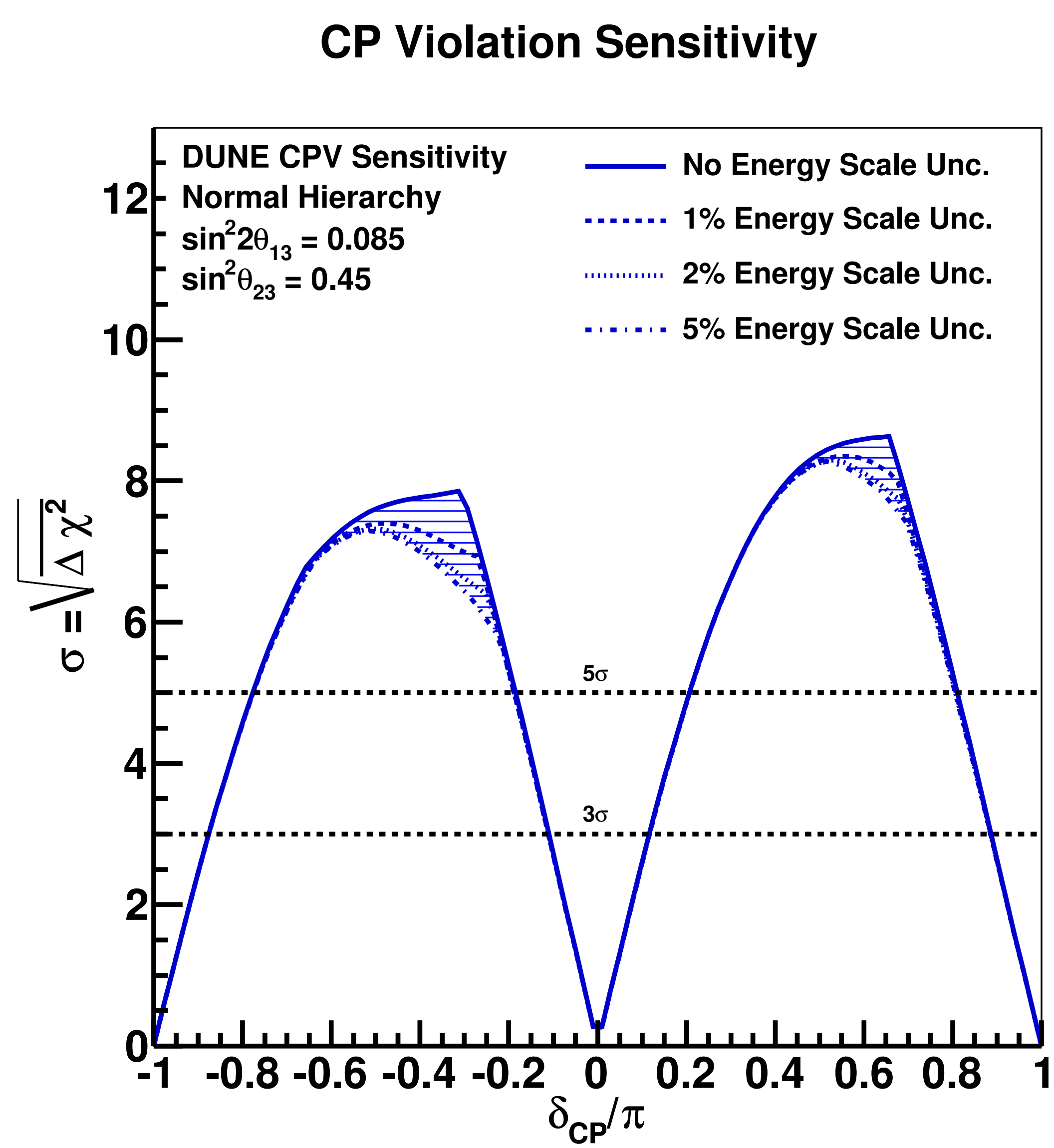
Background uncertainties

Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

Uncertainty in energy scale

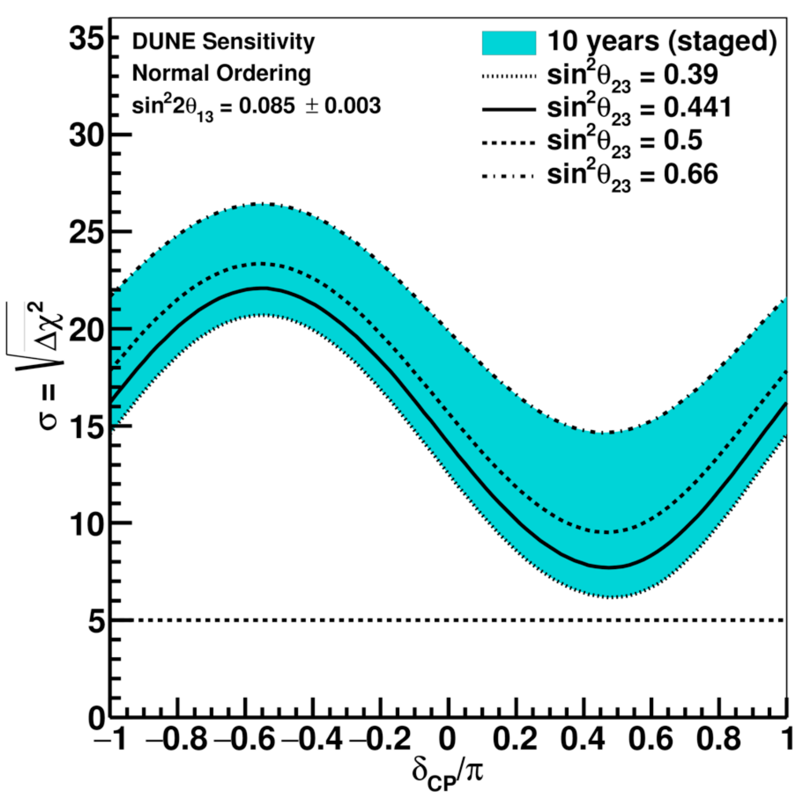
Adjust energy bins from n(E) to n[(1+a)E].



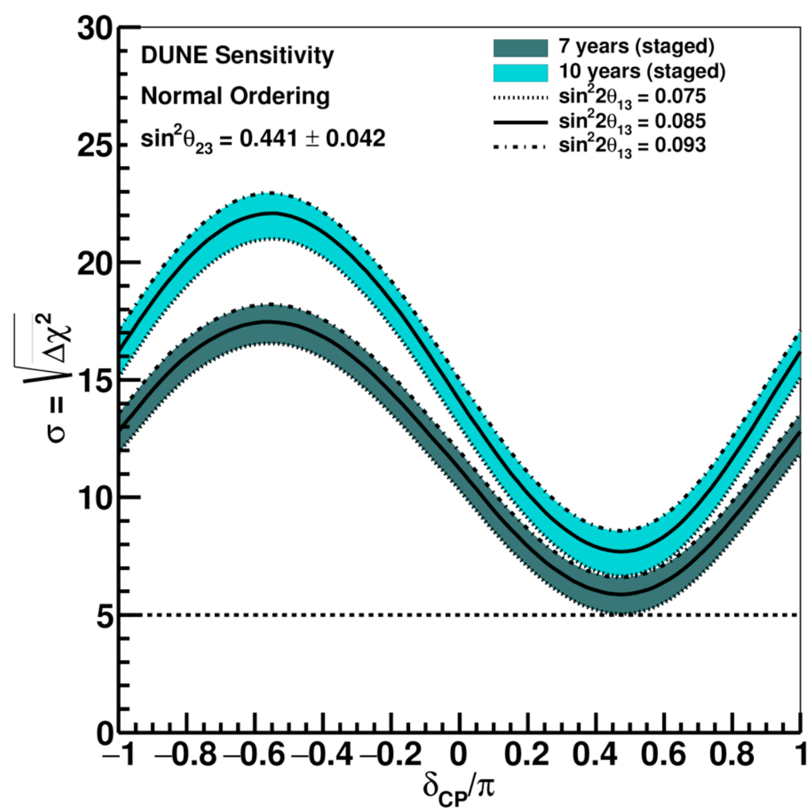


Uncertainties in oscillation parameters

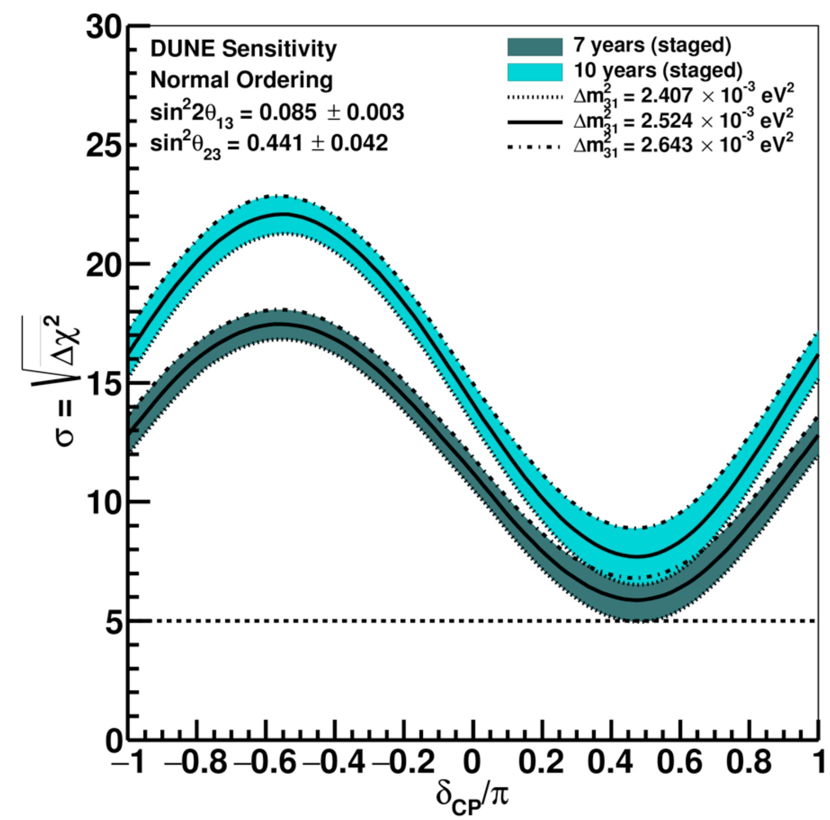
Effect of uncertainty in $\sin^2\theta_{23}$ on mass hierarchy sensitivity



Effect of uncertainty in $\sin^2 2\theta_{13}$ on mass hierarchy sensitivity

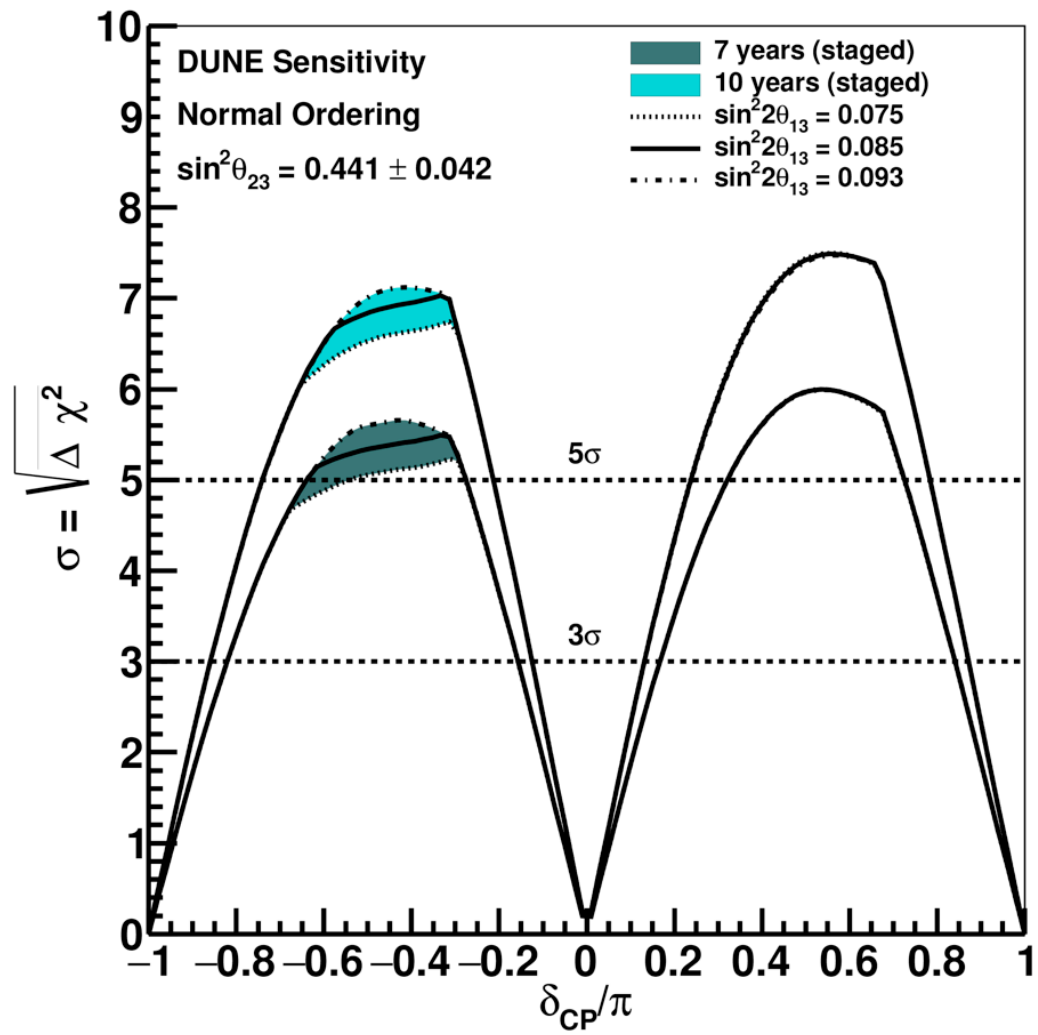


Effect of uncertainty in Δm_{31}^2 on mass hierarchy sensitivity

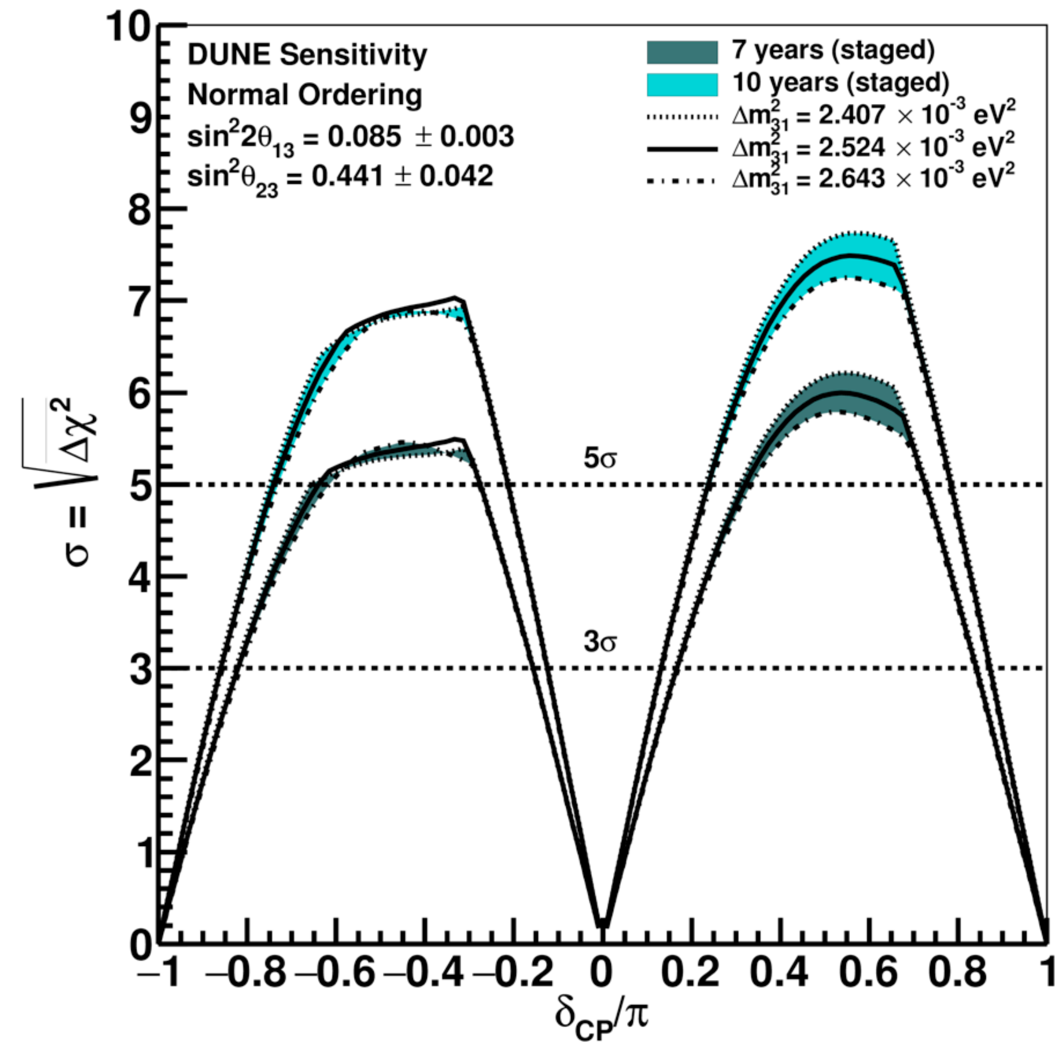


Uncertainties in oscillation parameters

Effect of uncertainty in $\sin^2 2\theta_{13}$ on CP violation sensitivity



Effect of uncertainty in Δm_{31}^2 on CP violation sensitivity



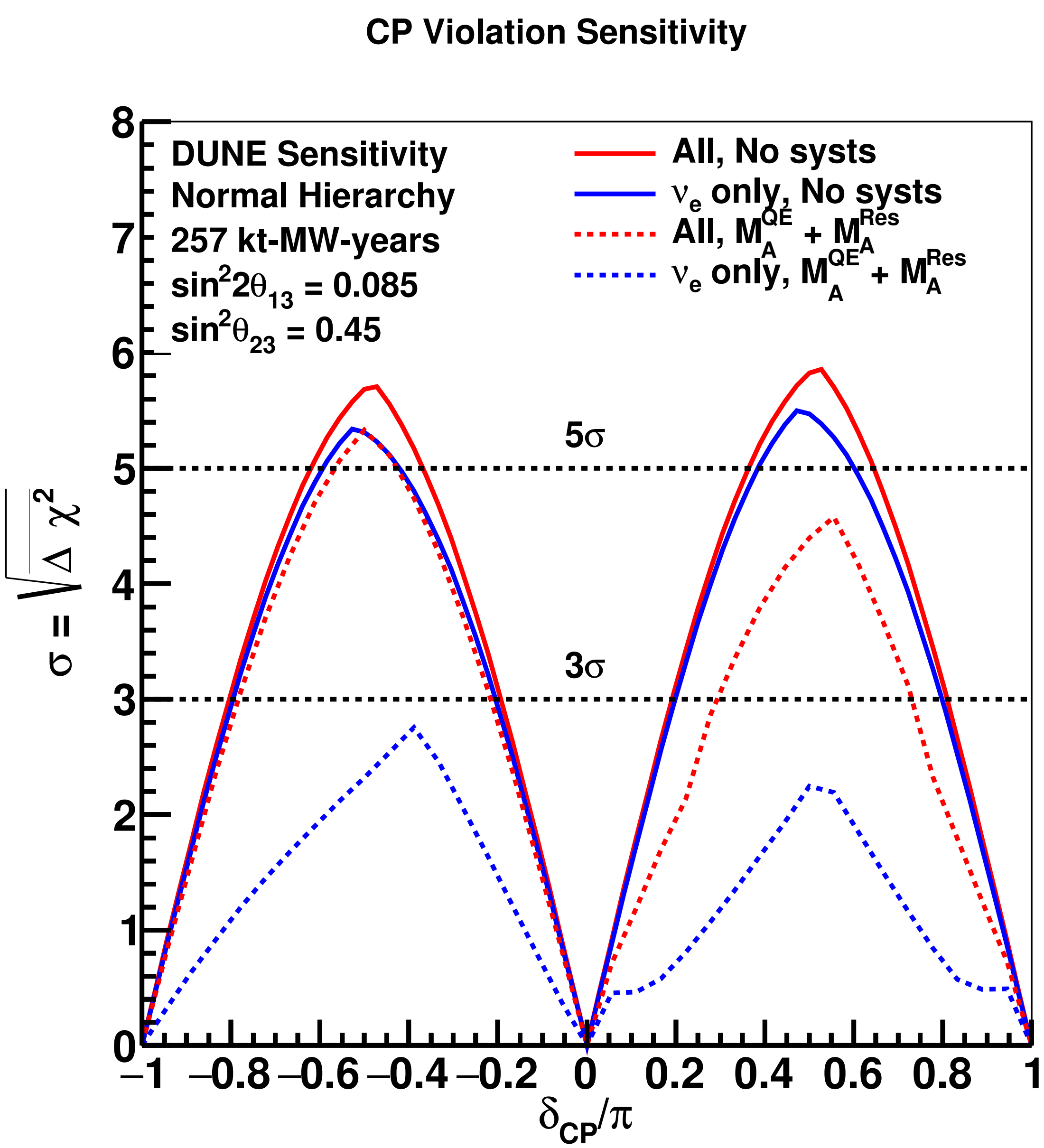
Particle response and thresholds

Parametrised detector response for individual final-state particles

Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^\pm$	30 MeV	Contained: from track length Exiting: 30 %	1^o
$\pi^\pm$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1^o
$e^\pm/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{(E/GeV)}$	1^o
p	50 MeV	$p < 400$ MeV: 10 % $p > 400$ MeV: $5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^o
n	50 MeV	$440\%/\sqrt{(E/GeV)}$	5^o
other	50 MeV	$5\% \oplus 30\%/\sqrt{(E/GeV)}$	5^o

Uncertainty in M_A

Uncertainties in M_AQE and M_ARes reduce sensitivity to CP violation if only ν_e sample considered (blue dotted line). However this reduction is much less if all four samples fitted together (red dotted line).



CP violation

To search for CP violation or to measure δ_{CP}, use difference between $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu$bar$\rightarrow \nu_e$bar reconstructed spectra; need to disentangle matter effects from those due to CP violation.

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx$$

$$\frac{16A}{\Delta m^2_{31}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \; c^2_{13} s^2_{13} s^2_{23} (1 - 2 s^2_{13})$$ (matter effect) α A ⇒ α E

$$- \frac{2AL}{E} \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) \; c^2_{13} s^2_{13} s^2_{23} (1 - 2 s^2_{13})$$ (matter effect) α AL/E ⇒ α L

$$- 8 \frac{\Delta m^2_{21} L}{2E} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \sin\delta \;\; s_{13} c^2_{13} c_{23} s_{23} c_{12} s_{12}$$ (CP effect) α L/E

where $A = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$ (ref: https://arxiv.org/pdf/hep-ph/9703351.pdf)

The three terms all oscillate but amplitudes have different energy dependence. Can separate CP violation from matter effects using broad range of energies. CP term more important at low energy.