PROCEEDINGS OF SCIENCE

DUNE oscillation physics

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The Deep Underground Neutrino Experiment (DUNE) will make a beam of muon neutrinos or antineutrinos at Fermilab starting in 2026. This beam will pass through two detectors: the near detector will be 574 metres from the target and will consist of a liquid argon time projection chamber (LArTPC) and either a straw-tube tracker or a high-pressure argon gas TPC, while the far detector will be a suite of 4 LArTPCs located at a distance of 1300 km from Fermilab. These detectors will be on the axis of the beam, which will give neutrino flux over a broad range of energies including the first and second oscillation maxima. Sensitivity studies are presented that suggest that, in 7 years' running, DUNE will be able to resolve the neutrino mass hierarchy to at least $\sqrt{\Delta\chi^2} = 5$ for all true values of δ_{CP} using beam neutrinos. In 10 years' running, DUNE will be able to measure δ_{CP} to better than 10 degrees if its true value is 0 or better than 20 degrees if it is $-\frac{\pi}{2}$, resolve the θ_{23} octant with 5σ significance if the true value of $\sin^2\theta_{23}$ is ≤ 0.45 or ≥ 0.57, and make precise measurements of other neutrino oscillation parameters.

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1. Introduction

The Deep Underground Neutrino Experiment (DUNE) is a long-baseline neutrino experiment in the mid-western United States. From 2026, it will make a beam of muon neutrinos or antineutrinos at Fermilab, Illinois and send it through two detectors. The near detector will be 574 metres from the target and will consist of a 30 tonne liquid argon time projection chamber (LArTPC) with a downstream magnetised spectrometer that will be either a straw-tube tracker or a high-pressure argon gas time projection chamber. The far detector will be a suite of four 10 kt LArTPCs located 1500 metres underground at the Sanford Underground Research Facility, South Dakota, which is 1300 km from Fermilab. LArTPC technology gives excellent calorimetric and spatial resolution, and high-quality tracking of charged particles down to low momenta.

The DUNE neutrino beam will be made at Fermilab using a proton beam that will initially have a power of 1.2 MW but can be upgraded to 2.4 MW. The DUNE detectors will be on the neutrino beam axis, and this will give neutrino flux over a broad range of energies including the first and second oscillation maxima at ≈2.6 and ≈0.9 GeV respectively (figures 1 and 2).

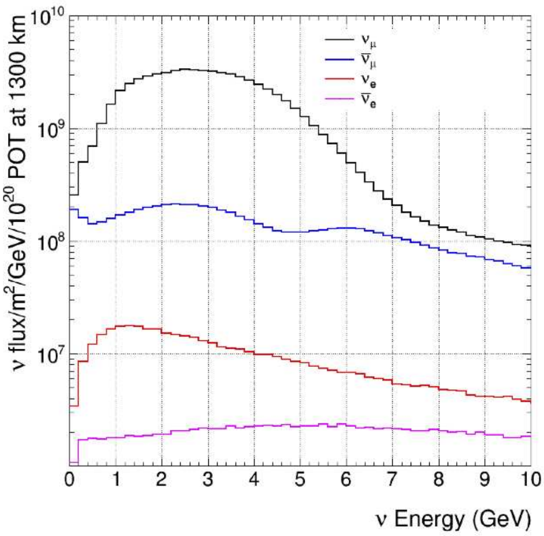


Figure 1: DUNE neutrino beam fluxes

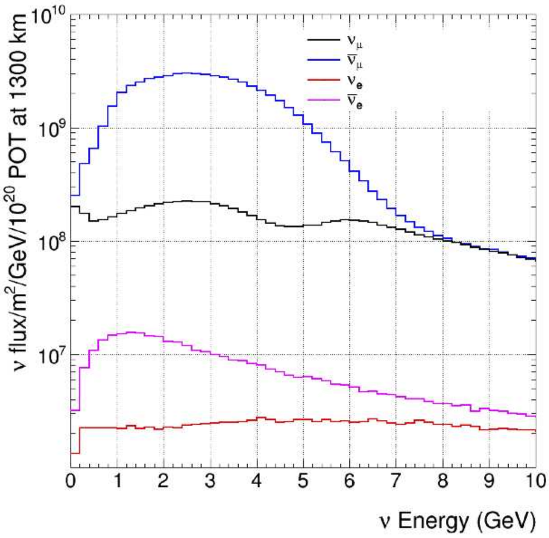


Figure 2: DUNE antineutrino beam fluxes

DUNE plans a rich physics programme including precise measurements of neutrino oscillation parameters and determination of the neutrino mass hierarchy and the octant of θ_{23}. It also plans to determine whether CP is violated in neutrinos and to make a measurement of δ_{CP}. Searches will be made for ν_τ appearance, nucleon decay and physics beyond the Standard Model, e.g. sterile neutrinos, heavy neutral leptons, non-standard interactions and large extra dimensions. Precise measurements of neutrino interactions will be made in the near detector, while the far detector will be ready to detect low-energy neutrinos from a core-collapse supernova if one occurs.

2. Sensitivities to neutrino oscillation parameters and mass hierarchy

Sensitivities to the neutrino oscillation parameters and mass hierarchy are obtained by using

GLoBES [1, 2] to simultaneously fit the $\nu_\mu \to \nu_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$, $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ reconstructed energy spectra (figures 3-6).

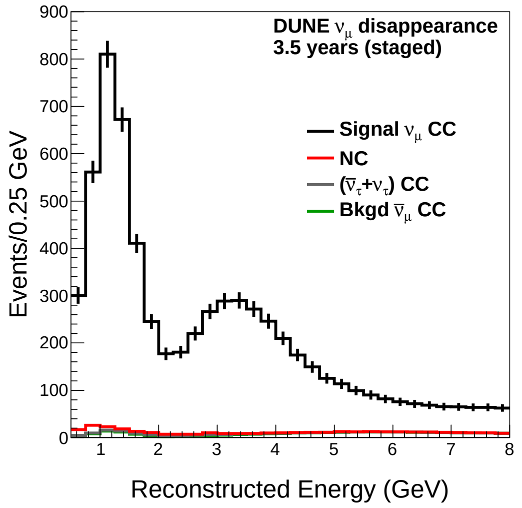


Figure 3: DUNE $\nu_\mu \to \nu_\mu$ reconstructed energy spectrum (the normal mass hierarchy is assumed)

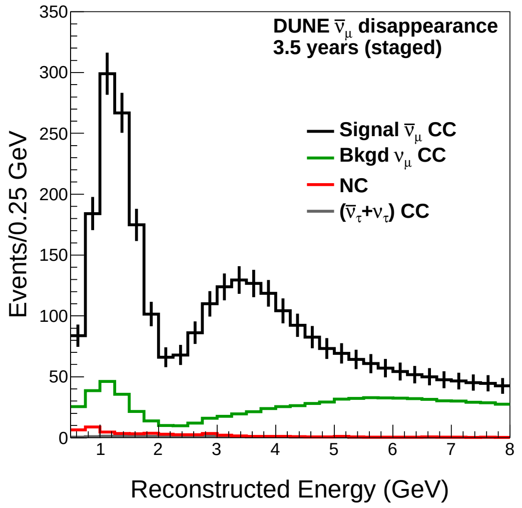


Figure 4: DUNE $\bar{\nu}_\mu \to \bar{\nu}_\mu$ reconstructed energy spectrum (the normal mass hierarchy is assumed)

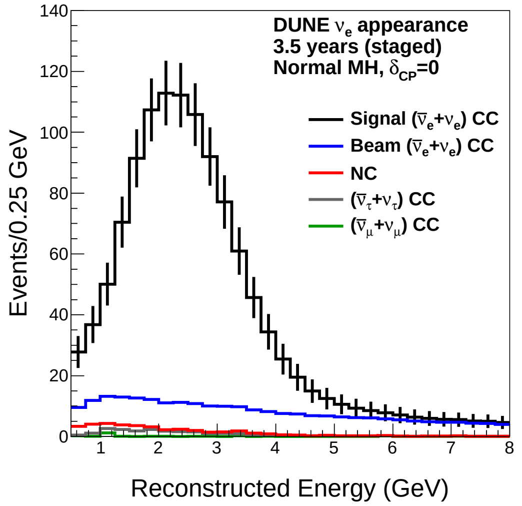


Figure 5: DUNE $\nu_\mu \to \nu_e$ reconstructed energy spectrum (the normal mass hierarchy is assumed)

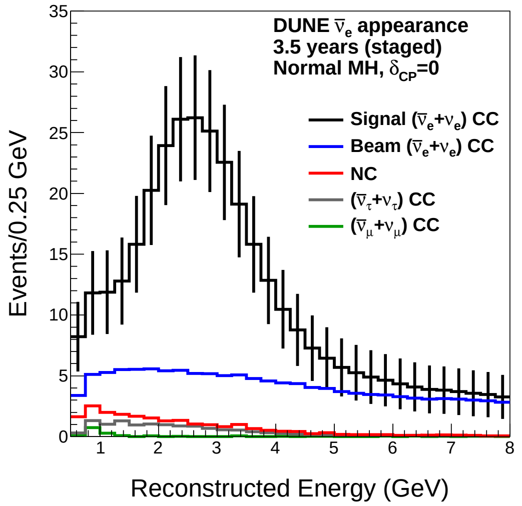


Figure 6: DUNE $\bar{\nu}_\mu \to \bar{\nu}_e$ reconstructed energy spectrum (the normal mass hierarchy is assumed)

It is assumed that the running time will be split 50/50 between neutrino and antineutrino modes. Another assumption is that the far detector will be constructed in stages: it will be 20 kt at the start of beam running in 2026, 30 kt by 2027, and 40 kt by 2029. It is further assumed that the beam power will be increased to 2.4 MW in 2032.

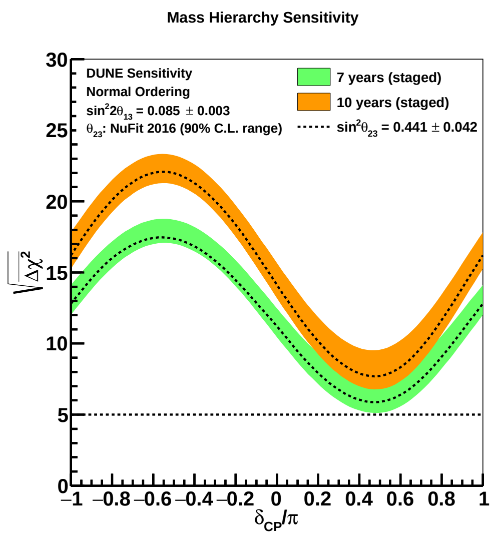
The neutrino oscillation parameters are allowed to vary in the fits with a Gaussian constraint using NuFIT 2016 values [3]. The effect of systematic uncertainties is approximated using normalisation uncertainties in each constituent interaction mode that comprise signal and background in each event sample. The signal normalisation uncertainty is 5$\bigoplus$2% in both neutrino and antineutrino modes, where 5% is the normalisation uncertainty in the far-detector ν_μ or $\overline{\nu}_\mu$ sample and 2% is the effective correlated uncertainty in the far-detector ν_e or $\overline{\nu}_e$ sample after fits of both near- and far-detector data and external constraints.

The sensitivities are calculated using a $\Delta\chi^2$ test statistic that compares the predicted energy spectra for different hypotheses. For the neutrino mass hierarchy, $\Delta\chi^2_{MH}$ = χ^2_{IH} - χ^2_{NH} (true normal hierarchy) or χ^2_{NH} - χ^2_{IH} (true inverted hierarchy), while for CP violation $\Delta\chi^2_{CPV}$ = Min[$\Delta\chi^2_{CP}$ ($\delta_{CP}^{\mathrm{test}}$ = 0), $\Delta\chi^2_{CP}$ ($\delta_{CP}^{\mathrm{test}}$ = π)], where $\Delta\chi^2_{CP}$ = $\chi^2_{\delta_{CP}^{\mathrm{test}}}$ - $\chi^2_{\delta_{CP}^{\mathrm{true}}}$ and a scan is made over all possible values of $\delta_{CP}^{\mathrm{true}}$. The neutrino mass hierarchy and θ_{23} octant are varied in the fits, and the lowest value of $\Delta\chi^2$ is used to estimate the sensitivities. For each set of input parameters, the predicted spectrum is calculated without applying statistical fluctuations, meaning that χ^2 is zero for $\delta_{CP}^{\mathrm{true}}$ and the true mass hierarchy.

If $\delta_{CP} \neq 0$ or π, the oscillation probability P($\nu_\mu \rightarrow \nu_e$) is not the same as P($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$). There is also a significant asymmetry between P($\nu_\mu \rightarrow \nu_e$) and P($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$) due to matter effects, with the sign of the asymmetry depending on the mass hierarchy. The DUNE baseline is relatively long at 1300 km, and the asymmetry from matter effects is ≈40% in the region of the peak flux, which is greater than the largest possible asymmetry from CP violation. This means that the mass hierarchy can be resolved by DUNE irrespective of the value of δ_{CP}. The DUNE sensitivities to determination of the mass hierarchy are shown as a function of the true value of δ_{CP} for exposures of 7 and 10 years for the normal hierarchy in figure 7 and for the inverted hierarchy in figure 8. For the normal hierarchy, the sensitivity is best at δ_{CP} = -$\frac{\pi}{2}$ since the asymmetry due to CP violation adds to that due to matter effects, and it is worst at δ_{CP} = +$\frac{\pi}{2}$ as the asymmetries are in opposite directions. This is reversed for the inverted hierarchy for which the sensitivity is best at δ_{CP} = +$\frac{\pi}{2}$ and worst at δ_{CP} = -$\frac{\pi}{2}$. DUNE aims to determine the mass hierarchy to at least $\sqrt{\Delta\chi^2}$ = 5 for all true values of δ_{CP} using beam neutrinos; figures 7 and 8 suggest it will be able to do this in 7 years' running.

DUNE will use the full range of its broad energy spectrum in searching for CP violation and making measurements of δ_{CP}. This broad spectrum will help to separate the asymmetry due to δ_{CP} from that due to matter effects since the latter predominates at high energies around the first oscillation maximum, whereas the former is most prominent at low energies and particularly at the second oscillation maximum at ≈0.9 GeV. The significances with which DUNE can determine CP violation, i.e. $\delta_{CP} \neq 0$ or π, are shown as a function of the true value of δ_{CP} for exposures of 7 and 10 years for the normal hierarchy in figure 9 and for the inverted hierarchy in figure 10. Other than the true value of δ_{CP} itself, the most important factor in these significances is the value of θ_{23} which has a larger effect than θ_{13} or Δm^2_{31}; the significances are highest for the lowest allowed value of $\sin^2\theta_{23}$. The resolution of the measurement of δ_{CP} is shown as a function of running time for true δ_{CP} = -$\frac{\pi}{2}$ and 0 in figure 11; this shows that the resolution is better when CP is conserved than when it is maximally violated, and suggests that DUNE can measure δ_{CP} in 10 years' running to better than 10 degrees if it is 0 or to better than 20 degrees if it is -$\frac{\pi}{2}$.

The sensitivity to the θ_{23} octant is shown as a function of the true value of $\sin^2\theta_{23}$ for exposures of 7 and 10 years in figure 12. As expected, the significance increases steeply as true $\sin^2\theta_{23}$ increases or decreases away from maximal mixing, and the results suggest that DUNE can resolve the octant at 5σ significance in 10 years' running if true $\sin^2\theta_{23}$ is $\leq$ 0.45 or $\geq$ 0.57.



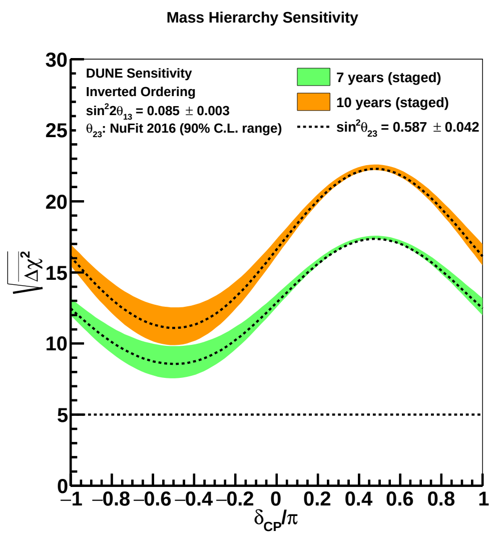
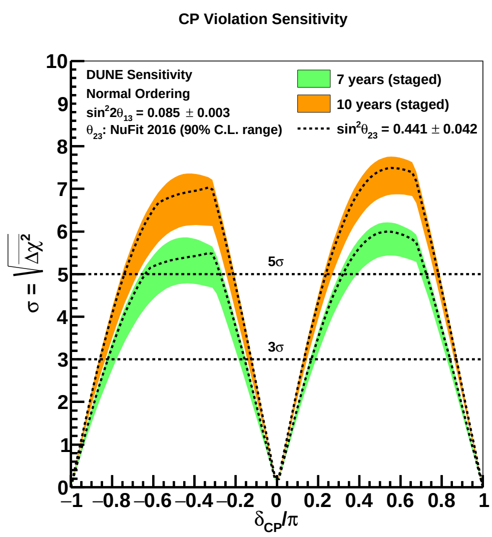


Figure 7: Sensitivity to the neutrino mass hierarchy as a function of the true value of δ_{CP} (true normal hierarchy). The dashed lines are the sensitivities for the central value of θ_{23} and the widths of the bands show the range of sensitivities for the 90% C.L. range in θ_{23} values; sensitivity increases with increasing θ_{23}.

Figure 8: Sensitivity to the neutrino mass hierarchy as a function of the true value of δ_{CP} (true inverted hierarchy). The dashed lines are the sensitivities for the central value of θ_{23} and the widths of the bands show the range of sensitivities for the 90% C.L. range in θ_{23} values; sensitivity increases with increasing θ_{23}.



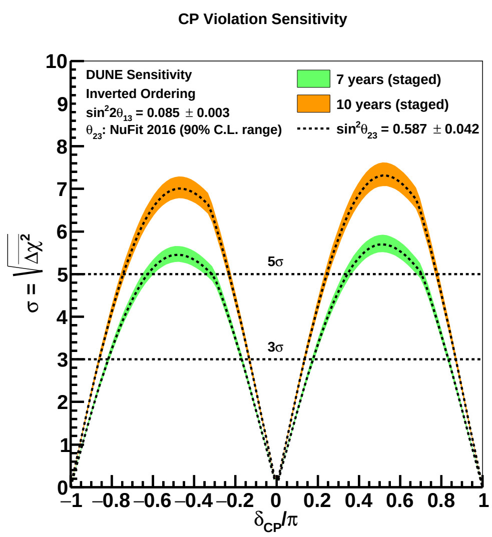


Figure 9: Sensitivity to CP violation, defined as $\delta_{CP} \neq 0$ or π, as a function of the true value of δ_{CP} (the normal mass hierarchy is assumed). The dashed lines are the significances for the central value of θ_{23} and the widths of the bands show the range of significances for the 90% C.L. range in θ_{23} values; significance decreases with increasing θ_{23}.

Figure 10: Sensitivity to CP violation, defined as $\delta_{CP} \neq 0$ or π, as a function of the true value of δ_{CP} (the inverted mass hierarchy is assumed). The dashed lines are the significances for the central value of θ_{23} and the widths of the bands show the range of significances for the 90% C.L. range in θ_{23} values; significance decreases with increasing θ_{23}.

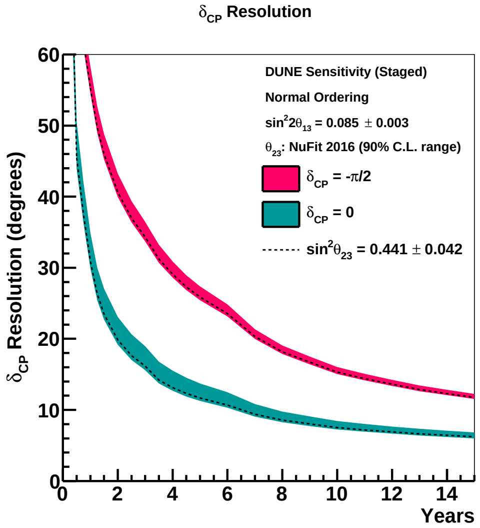


Figure 11: δ_{CP} resolution as a function of running time (the normal mass hierarchy is assumed). The dashed lines are the resolutions for the central value of θ_{23} and the bands represent the ranges of resolutions for the 90% C.L. range of values of θ_{23}; resolution worsens with increasing θ_{23}.

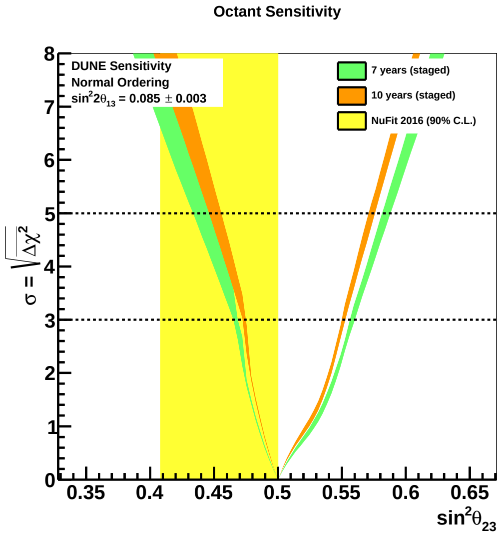


Figure 12: Sensitivity to θ_{23} octant as a function of the true value of $\sin^2\theta_{23}$ (the normal mass hierarchy is assumed); the green and orange bands represent the range of significances due to uncertainty in δ_{CP} excluding the best and worst 10% of significances. The yellow band shows the 90% C.L. range of allowed values of $\sin^2\theta_{23}$ from NuFIT 2016 [3].

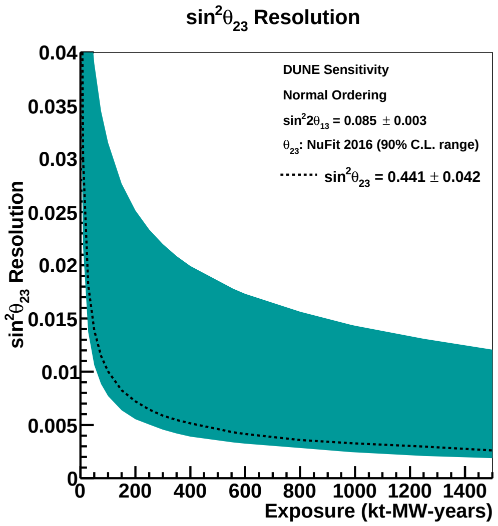


Figure 13: $\sin^2\theta_{23}$ resolution as a function of exposure (the normal mass hierarchy is assumed). The dashed line is the resolution for the central value of θ_{23} and the band represents the range of resolution for the 90% C.L. range of values of θ_{23}; resolution worsens with increasing θ_{23}.

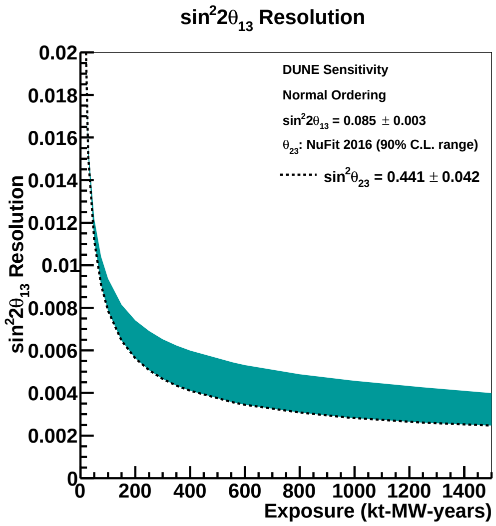


Figure 14: $\sin^2 2\theta_{13}$ resolution as a function of exposure (the normal mass hierarchy is assumed). The dashed line is the resolution for the central value of θ_{23} which gives the best resolution; the highest value of θ_{23} is at the top of the band and the lowest value in the middle of the band.

The resolutions of measurements of oscillation parameters are shown for $\sin^2\theta_{23}$ in figure 13 and for $\sin^2 2\theta_{13}$ in figure 14. These resolutions are expected to improve quickly in the early stages of the experiment but to flatten as it continues. The results suggest that DUNE will be able to measure $\sin^2\theta_{23}$ to 0.004 - 0.018 and $\sin^2 2\theta_{13}$ to 0.004 - 0.006 in 10 years' running.

3. Conclusion

DUNE will produce an on-axis ν_μ and $\bar{\nu}_\mu$ 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 near and far detectors will be significantly altered by matter effects. These features will enable DUNE to search for CP violation in neutrinos, measure δ_{CP}, and resolve the neutrino mass hierarchy and the θ_{23} octant in a single experiment. Matter effects will enable DUNE to resolve the neutrino mass hierarchy for any true value of δ_{CP}, and the broad range of energies will facilitate the measurement of δ_{CP} since its effects on reconstructed energy spectra are most apparent at the second oscillation maximum.

References

[1] P. Huber et al., *Simulation of long-baseline neutrino oscillation experiments with GLoBES*, https://arxiv.org/abs/hep-ph/0407333

[2] P. Huber et al., *New features in the simulation of neutrino oscillation experiments with GLoBES 3.0*, https://arxiv.org/abs/hep-ph/0701187

[3] *NuFIT 3.0* (2016), http://www.nu-fit.org/