DUNE Sensitivity Study

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Summer Student Project 2018

Abstract

This report discusses the work that has been done in the context of the CERN Summer Student Project with the EP-NU group, from 2nd of July until the 14th of September of 2018. This internship was realised under the supervision of Davide Sgalaberna and Leigh Whitehead. The aim of this project was to study the sensitivity to the mass hierarchy and C.P violating phase of DUNE, a long-baseline neutrino experiment that is still in a prototype phase and is will start taking data in 2026.

1 Introduction

Neutrino oscillations have been observed in multiple experiments with different neutrino sources and different detection principles. These observations are well described by the three active flavour mixing framework. This framework is characterised by three flavour states (ν_e, ν_μ, ν_τ) that are unitary linear combinations of three mass states (ν_1, ν_2, ν_3). The probability of oscillating between two flavour states depends on many parameters such as the squared mass difference between the mass states and the mixing angles.

One of the unanswered questions of neutrino physics is the value of the C.P. violating phase, δ_{CP}, and the sign of Δm^2_{23}. δ_{CP} is responsible for charge parity violation, i.e. if $\sin(\delta_{CP}) \neq 0$ then $\mathrm{P}(\bar{\nu_a} \to \bar{\nu_b}) \neq \mathrm{P}(\nu_a \to \nu_b)$ and there is C.P. violation. The sign of Δm^2_{23} will define the hierarchy of the mass states (MH) ν_1, ν_2, ν_3, i.e. if nature has a "normal" hierarchy (NH) $\nu_1 < \nu_2 < \nu_3$ or "inverted" hierarchy (IH) $\nu_2 > \nu_1 > \nu_3$.

Experiments that are currently running, such as T2K and NOνA, show preference for C.P. violation and normal hierarchy. However, due to a small target mass and lower beam power they will are limited by statistics and will not be able to reach a 5σ significance needed to claim a discovery, neither on mass hierarchy nor on C.P. violation. Thus a new generation of experiments, such as DUNE and JUNO.

This report will mainly focus on DUNE and its sensitivity to the discovery of C.P. violation and the mass hierarchy.

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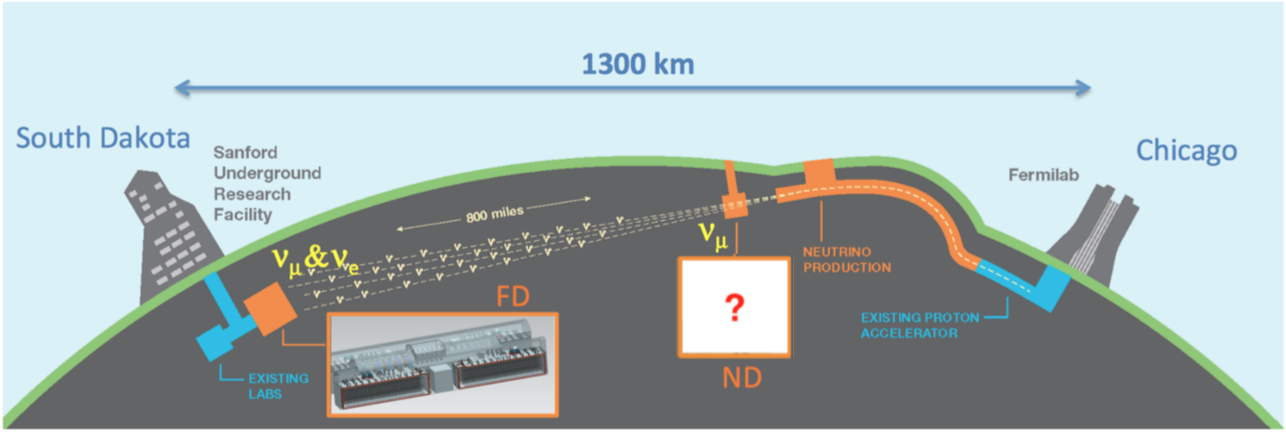


Figure 1: An overview of the DUNE experiment

1.1 DUNE

The Deep Underground Neutrino Experiment (DUNE) is long-baseline on-axis experiment, with a baseline of 1300 km. The neutrino beam is produced by an accelerated proton beam on a carbon target, which produces $K^{\pm}$ and mainly, $\pi^{\pm}$ which then predominantly decay to $\mu^{\pm}$ and $\overset{(-)}{\nu}_{\mu}$. The beam has two modes, ν and $\bar{\nu}$, that are selected by inverting the polarity of a magnet.

The baseline, since longer than current experiments, makes DUNE more sensitive to matter effects. This leads to a larger asymmetry between P($\bar{\nu}_\mu \to \bar{\nu}_e$) and P($\nu_\mu \to \nu_e$). This asymmetry is larger than the possible effect from C.P. violating asymmetry and the asymmetry associated with the mass hierarchy, meaning it is large enough to distinguish both effects.

The near detector design is still under development and there are may proposals being studied. The main goal of this summer student project is to study the sensitivity to C.P. violation and mass ordering discovery, under different experiment configurations and understand the impact of the oscillation parameters.

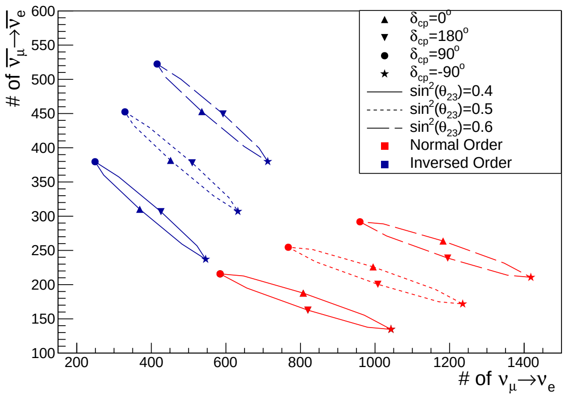


Figure 2: Number of $\nu_\mu \to \nu_e$ vs number of $\bar{\nu}_\mu \to \bar{\nu}_e$ plot, for different values of of the oscillation parameters

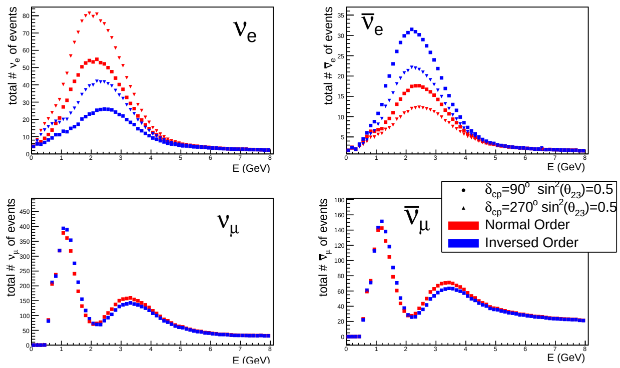


Figure 3: The reconstructed energy spectrum for the different neutrino beam modes and oscillation parameters

Figure 2 is a bi-events plot. It is possible to see that for higher values of the mixing angle θ_{23} there is better sensitivity to the determination of the mass hierarchy. However, even for lower values of θ_{23}, DUNE is capable of measuring the mass hierarchy and value of δ_{CP}.

The reconstructed energy spectra are shown in figure 3, i.e. the number of events as a function of reconstructed energy for different values of δ_{CP} and mass hierarchy. It is possible to see that the different values of δ_{CP} have a normalisation effect on the ν_e and $\bar{\nu}_e$ spectra, as well as shape effects.

2 Sensitivity Studies

2.1 Method

The sensitivity to the MH and δ_{CP} were made by fitting the Asimov data set, i.e. the highest probability data set that coincides with the Monte Carlo prediction for a given set of oscillation parameters.

The fit consists of the minimisation of eq. 1

$$\chi^2 = \sum \frac{(x-\mu)^2}{\sigma^2} + P \tag{1}$$

where

- x = observed events in the i-th energy bin;
- P penalty term;
- μ = expected events in the i-th energy bin;
- $\mu = \mu(f_{\text{systematics}}, f_{\text{osc. par.}})$

All the parameters of interest, not constrained by the penalty term, such as θ_{23} and $|\Delta m^2_{23}|$ are profiled.

The plots shown are for 7 years of beam time - 3.5 years in ν mode and 3.5 years in $\bar{\nu}$ mode.

2.2 Oscillation Parameters

This section will compare two distinct sets of oscillation parameter, seen in table 1 and table 2. The "CDR Parameters" are the used parameters in previous DUNE publications (such as [1]). The "New Parameters" refer to the latest results from *NuFact 2018*, a neutrino conference which took place this summer [2]. The sensitivity results are obtained by considering that nature is consistent with either one of them.

Parameter	Central Value	Relative Uncertainty
θ_{12}	0.5843	2.3%
θ_{13}	0.148	2.5%
θ_{23} (NH)	0.738	5.9%
θ_{23} (IH)	0.864	4.9%
Δm^2_{12} (eV^2)	7.5×10^{-5}	2.4%
Δm^2_{23} (eV^2) (NH)	2.457×10^{-3}	2.0%
Δm^2_{23} (eV^2) (IH)	-2.449×10^{-3}	1.9%

Table 1: CDR oscillation parameters [1]

For the values of θ_{23} and Δm^2_{23} the latest results of the T2K experiment are used. However, the relative uncertainty of Δm^2_{23} is taken from the prediction of JUNO [4], that would be available after 7 years of DUNE.

Parameter	Central Value	Relative Uncertainty
$\sin^2(\theta_{12})$ [3]	0.307	2.3%
$\sin^2(\theta_{13})$ [3]	0.02206	0.17%
$\sin^2(\theta_{23})$ [2]	0.536	5.7%
Δm^2_{12} (eV^2) [3]	7.4×10^{-5}	2.8%
Δm^2_{23} (eV^2) (NH)	2.434×10^{-3} [2]	0.5% [4]
Δm^2_{23} (eV^2) (IH)	-2.410×10^{-3} [2]	0.5% [4]

Table 2: New oscillation parameters

2.2.1 Sensitivity to the Determination of the Mass Hierarchy

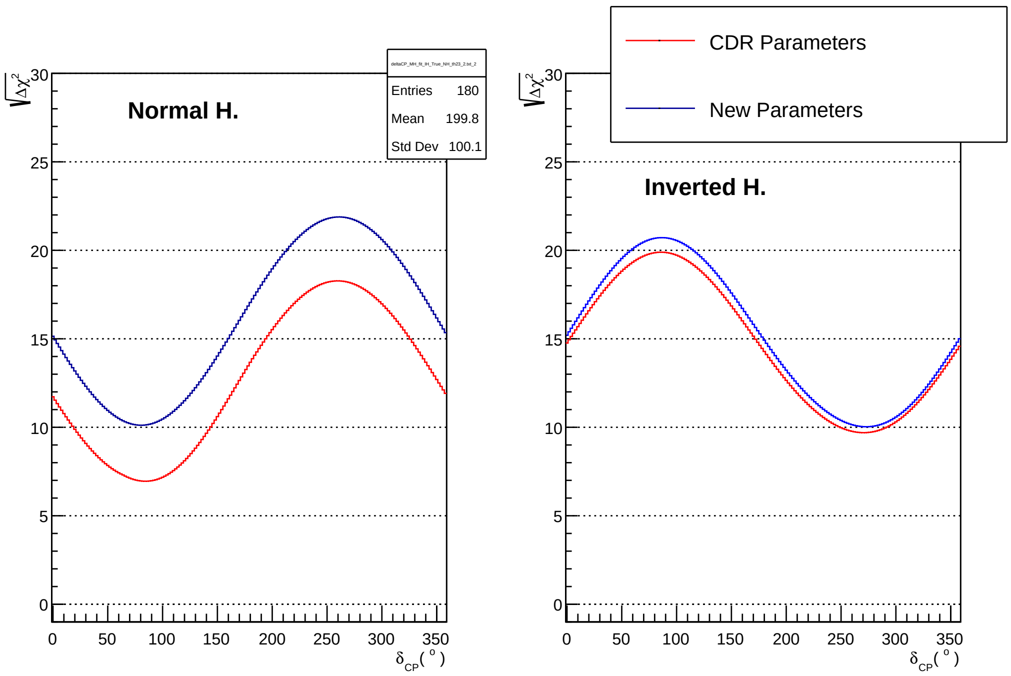


Figure 4: Mass hierarchy sensitivity. On the left the truth is defined as normal hierarchy and on the right it is defined as inverted hierarchy. On both plots there is a comparison between two sets of parameters. In blue the new parameters (table 2) and in red the CDR parameters (table 1)

The hypothesis test for mass hierarchy was based on the likely-hood ratio, where the test statistic was defined as $\Delta\chi^2 = \chi^2(\text{NH}) - \chi^2(\text{IH})$ and the number of standard deviation is $\sqrt{\Delta\chi^2}$. Figure 4 shows the sensitivity to reject the mass hierarchy. The sensitivity to reject the wrong MH is shown on the left, where the true MH is defined to be normal. This is done for both sets of oscillation parameters in table 1 and 2.

In both cases, the New Parameters show an improvement in the rejection of the wrong hierarchy. Nevertheless the CDR parameters still reject at more than 5σ significance.

2.2.2 Sensitivity to CP violation and measurement of δ_{CP}

The test statistic used is $\Delta\chi^2 = \chi^2(\sin(\delta_{cp}) = 0) - \chi^2(\text{Best-Fit})$.

Figure 5 shows as well, the comparison between the two set of parameters, for normal and inverted hierarchy, i.e. the significance to reject C.P. conservation ($\sin(\delta_{CP}) = 0$) for different true values of δ_{CP}.

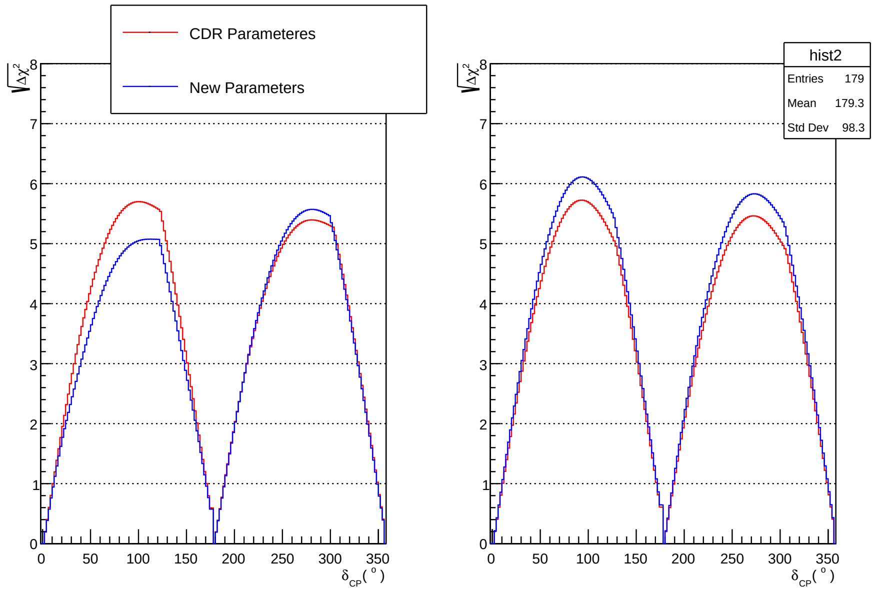
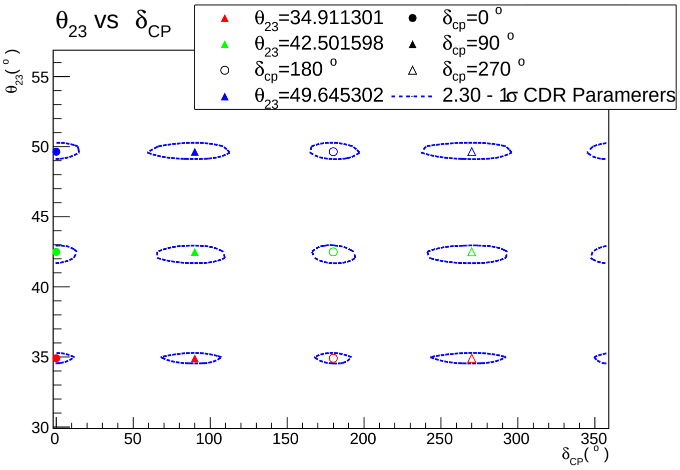


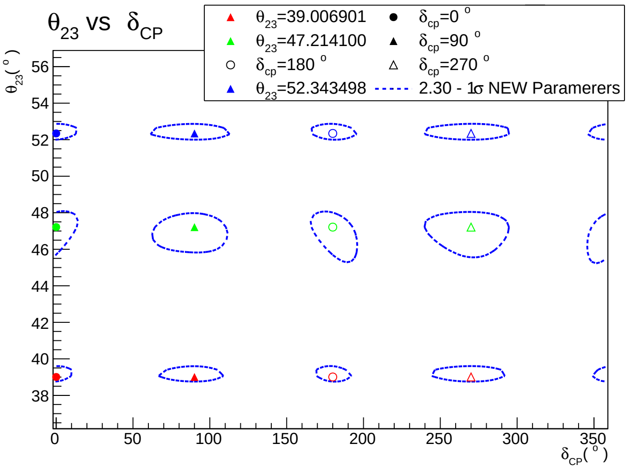
Figure 5: C.P Violation Sensitivity. On the right the truth is defined as normal hierarchy and on the left it is defined as inverted hierarchy. On both plots there is a comparison between two sets of parameters. In blue the new parameters 2 and in red the CDR parameters 1

The new set of parameters improve the rejection of C.P. conservation. For normal hierarchy the New parameters give an overall decrease in the rejection of the hypothesis.

The degeneracy between δ_{CP} and the mass hierarchy is completely resolved for $\delta_{CP} = 0^o$ and $\delta_{CP} = 180^o$.



(a) CDR parameters



(b) New parameters

Figure 6: Sensitivity to θ_{23} and δ_{CP}. Each plot shows this with a different set os parameters, fig. 6a with the parameters found in table 1 and fig. 6b with the ones in table 2

In figure 6a and 6a it is shown that the new parameters there is less sensitivity to the value δ_{CP} and θ_{23}. However, there is only a significant variation around the central value, closer to 45^o. This is due to the octant degeneracy.

For the following sections, the new parameters (table 2) are considered as well as normal hierarchy to be the "truth".

2.3 Systematic Uncertainties

In this section two hypotheses for the systematic uncertainties of the signal are made. In hypothesis 1 it is assumed that for ν_e and $\bar{\nu}_e$ the only systematic error comes from the far detector (2%) and in hypothesis 2 a contribution from the near detector is taken into account, giving an additional 5% uncertainty.

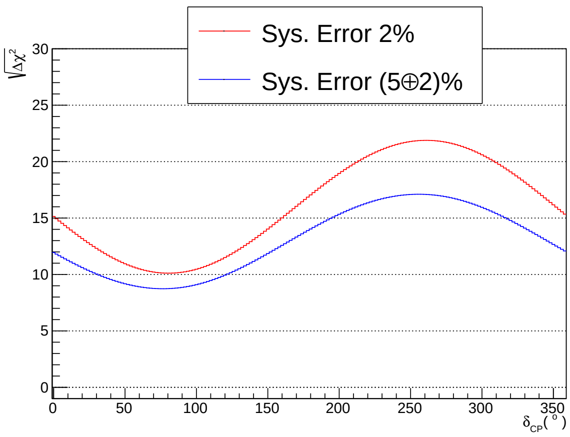
Parameter	hypothesis 1	hypothesis 2
ν_e	2%	(5⊕2)%
$\bar{\nu}_e$	2%	(5⊕2)%
ν_μ	5%	5%
$\bar{\nu_\mu}$	5%	5%

Table 3: Signal systematic errors

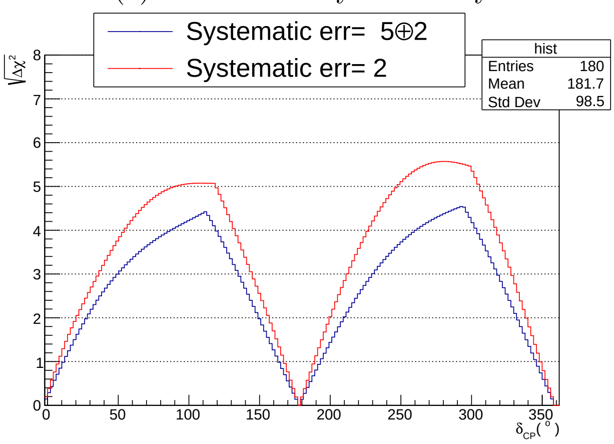
Parameter	Sys. Error
ν_μ	5%
ν_e	5%
ν_τ	20%
$\bar{\nu}_e$	5%
NC	10%

Table 4: Background systematic errors

2.3.1 Comparison Between Different Systematic Uncertainties



(a) Mass hierarchy sensitivity



(b) C.P Violation Sensitivity

Figure 7: Sensitivity to mass hierarchy (7a) and C.P. violation (7b) assuming normal hierarchy to be the truth. In red assuming hypothesis 1 and in blue for hypothesis 2 (see table 3)

As expected the sensitivity to C.P. violation and mass hierarchy worsen with hypothesis 2. For the mass hierarchy sensitivity, even with hypothesis 2, there is still a rejection with a significance of more than 5σ. Regarding the C.P. violation sensitivity, more time is needed to reach the 5σ exclusion.

A shape effect can also be observed in both figure 7b and 7a. This is thought to be due to matter effects.

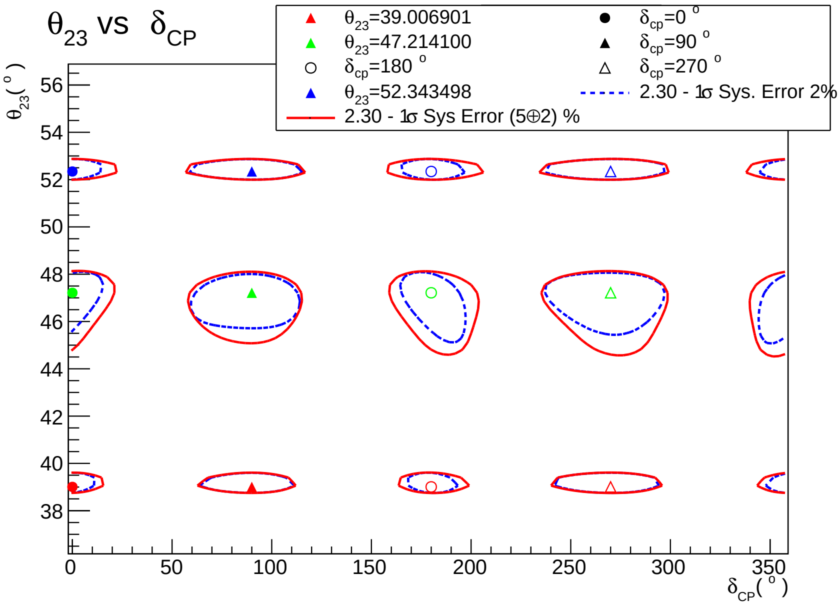


Figure 8: Sensitivity to the values of θ_{23} and δ_{CP} for different parameter values and different systematic uncertainties. In blue hypothesis 1 and in red hypothesis 2.

As for the sensitivity to the values of δ_{CP} and θ_{23}, they decrease with larger systematic error.

For the following sections, hypothesis 2 from table 3 is considered, on account of it being the more conservative scenario.

2.4 Impact of Improved Efficiencies

In this section different signal efficiencies are studied, to see how much the sensitivity to C.P. violation and to the values of δ_{CP} and θ_{23} would improve in a hypothetical scenario of 100% efficiency.

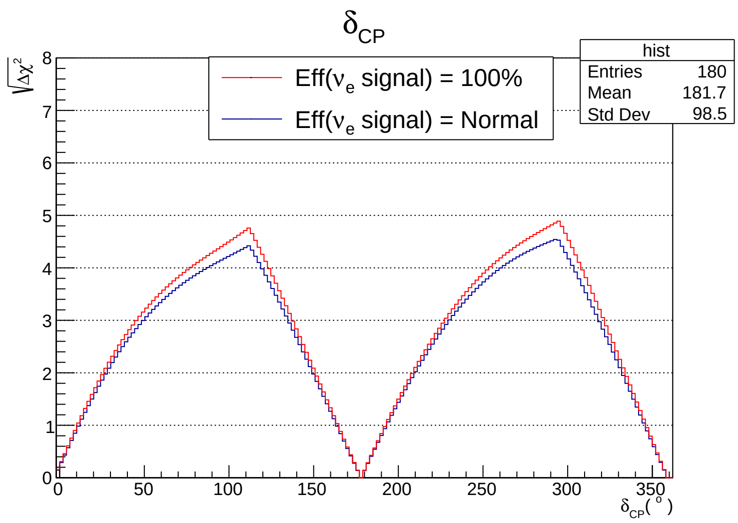


Figure 9: C.P Violation Sensitivity for different values of signal efficiency. In blue efficiency = 100% and in red "normal" efficiency

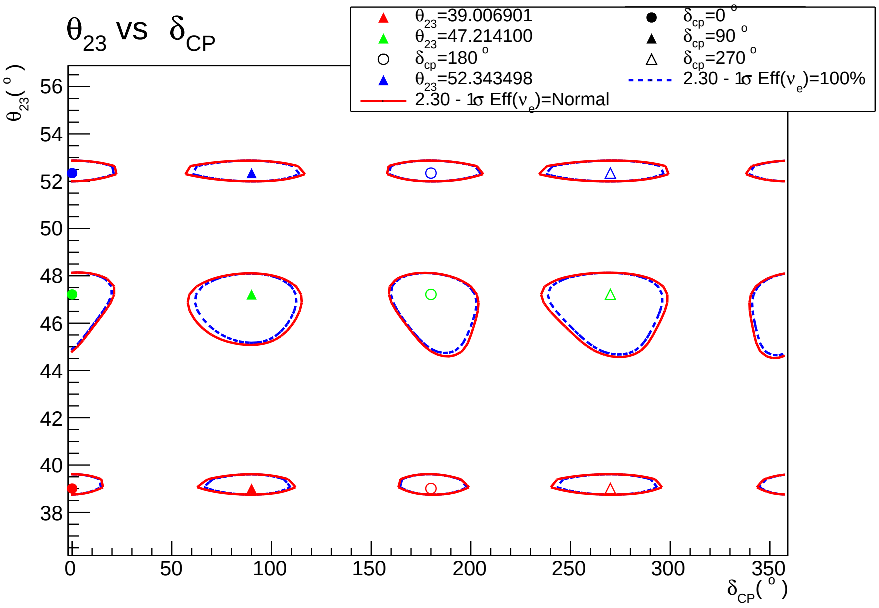


Figure 10: Sensitivity to the values of θ_{23} and δ_{CP} for different parameter values and different values of signal efficiency. In blue efficiency = 100% and in red "normal" efficiency

As we can see in both figure 9 and 10 with 100% efficiency there is a very small improvement, due to the fact that the "normal" efficiency is already fairly high, being approximately 80% over all the energy range.

References

[1] R. Acciarri, M. A. Acero, M. Adamowski, C. Adams, P. Adamson, S. Adhikari, Z. Ahmad, C. H. Albright, T. Alion, E. Amador, and et al. Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 1: The LBNF and DUNE Projects. *ArXiv e-prints*, January 2016.

[2] Dennis S. Results and prospects from t2k, August 2018.

[3] NuFit. Three-neutrino fit based on data available in january 2018.

[4] T. Adam, F. An, G. An, Q. An, N. Anfimov, V. Antonelli, G. Baccolo, M. Baldoncini, E. Baussan, M. Bellato, and et al. JUNO Conceptual Design Report. *ArXiv e-prints*, August 2015.