# Matter vs. vacuum oscillations at long-baseline accelerator neutrino experiments arXiv:2001.08676

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## Abstract

We search for evidence of modification of neutrino oscillation by matter effect in the data of T2K and NO$\nu$A. We find that vacuum oscillations provide as good a fit to the data as matter modified oscillations. Even an extended run of these experiments, with 5 years each in neutrino and anti-neutrino modes, can **not** make a 3 $\sigma$ distinction between vacuum and matter modified oscillations. A 5 $\sigma$ discrimination against vacuum oscillations requires the combination of $(5\nu + 5\bar{\nu})$ runs of T2K, NO$\nu$A and DUNE.

## Introduction

Due to the propagation of the neutrinos through earth matter, it is expected that the oscillation probabilities would be modified by matter effects. These matter effects are sensitive to the sign of $\Delta_{31}$ and their observation can lead to a determination of this sign. For baselines less than 1000 km, the matter effects lead to negligibly small changes in $\nu_\mu/\bar{\nu}_\mu$ survival probabilities [1]. In the case of atmospheric neutrinos, the survival probabilities $P_{\mu\mu}$ and $P_{\bar{\mu}\bar{\mu}}$ are expected to undergo significant changes due to matter effects. However, at present Super-Kamiokande is able to make only a small distinction between them [2]. In the long-baseline accelerator experiment, the $\nu_e/\bar{\nu}_e$ appearance data is sensitive to matter effects [3, 4]. But they are also sensitive to the unknown CP violating phase $\delta_{\rm CP}$. Given a set of data, three solutions are likely to occur [5, 6]:

- matter modified oscillations with NH and $\delta^1_{\rm CP}$,
- vacuum oscillations with $\delta^2_{\rm CP}$ and
- matter modified oscillations with IH and $\delta^3_{\rm CP}$.

Unless the question of vacuum vs matter modified oscillations is resolved, it may not be possible to measure $\delta_{\rm CP}$. Establishing CP violation in neutrino oscillations is one of the most important goals of both current and future long-baseline accelerator neutrino experiments. To achieve this goal, it becomes important to establish a distinction between vacuum oscillations and matter modified oscillations.

## Analysis procedure

We calculated the theoretical event spectra with three flavour oscillations using GLoBES [7, 8], for the appearance and disappearance channels in both neutrino and anti-neutrino modes for T2K and for NO$\nu$A. These rates are calculated with the matter potential parametrized as $q * A$, where $A$ is the standard Wolfenstein matter term [9] and $q$ is a multiplicative factor. In this analysis, we consider the possibility of non-standard matter term, as was done in ref. [2]. $\Delta_{21}$ and $\sin^2\theta_{12}$ were held fixed to their best-fit values [10]. Other oscillation parameters were varied in their 3 sigma ranges given in ref. [10]. $q$ has been varied in the range [0, 2]. For each data set of each experiment, the Poissonian $\chi^2$ is calculated with

$$\chi^2 = \sum_i 2[(N_i^{\rm th} - N_i^{\rm exp}) + N_i^{\rm exp} \times \ln(N_i^{\rm exp}/N_i^{\rm th})] + \sum_j [2 \times N_j^{\rm th}] + \chi^2({\rm sys}), \quad (1)$$

where $i$ stands for bins for which $N_i^{\rm exp} \neq 0$ and $j$ stands for bins for which $N_j^{\rm exp} = 0$. The term $\chi^2$(sys) arise due to systematic uncertainties. For each of the two experiments, we included systematic uncertainty of 10%, using the pull method. We varied the pull parameter in $3\sigma$ range and marginalized over it to determine $\chi^2$ as a function of test values of oscillation parameters, mass hierarchies and $q$. We calculated the total $\chi^2$ for both NH test and IH test by adding up $\chi^2_m$ from all experiments and all channels, but for same parameter values. We added priors on $\sin^2\theta_{13}$, $\sin^2\theta_{23}$ and $|\Delta_{31}|$ ($|\Delta_{32}|$) for NH (IH). We found the minimum of $\chi^2$(tot) and subtracted it from all other values of $\chi^2$(tot) to obtain $\Delta\chi^2$ and marginalised $\Delta\chi^2$ over all the oscillations parameters except hierarchy and $q$.

## Analysis and expectations of NO$\nu$A and T2K

present T2K and NO$\nu$A data for the POTs mentioned in the caption of fig. 1 have been analysed. The data set, with 152 data points, was fit to the hypothesis of three flavour oscillations with variable matter term. The minimum $\chi^2 = 173.2$ occurs for $\Delta_{31}$ positive and $q = 0.6$. Vacuum oscillations ($q = 0$) provide **as good a fit** to the data as matter modified oscillations with NH (with $\chi^2 = 173.7$).

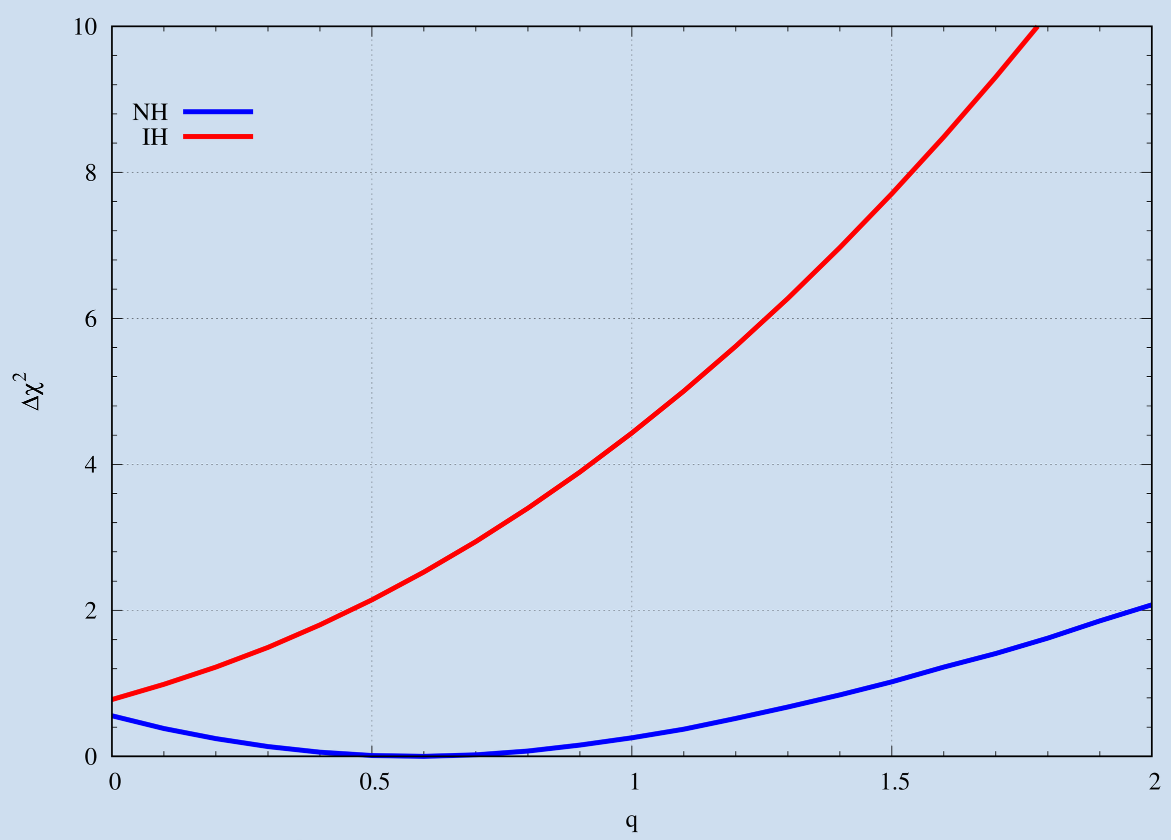


**Figure 1.** $\Delta\chi^2$ vs $q$ for the present data of T2K and NO$\nu$A. The data of NO$\nu$A consists of $8.85 \times 10^{20}$ POT in $\nu$ mode and $12.33 \times 10^{20}$ POT in $\bar{\nu}$ mode. The appearance data of T2K consists of $14.9 \times 10^{20}$ POT in $\nu$ mode and $16.4 \times 10^{20}$ POT in $\bar{\nu}$ mode. The disappearance data of T2K consists of $14.7 \times 10^{20}$ POT in $\nu$ mode and $7.6 \times 10^{20}$ POT in $\bar{\nu}$ mode.

Using GLoBES, we simulated event spectra of T2K and NO$\nu$A for 5 years each of $\nu$ and $\bar{\nu}$ runs. We used the best fit values for the neutrino oscillation parameters for both NH and IH being true hierarchy. IH (NH) is ruled out at 3 $\sigma$ (2 $\sigma$) if NH (IH) is the true hierarchy. The vacuum oscillations have a very small $\Delta\chi^2 \simeq 2$.

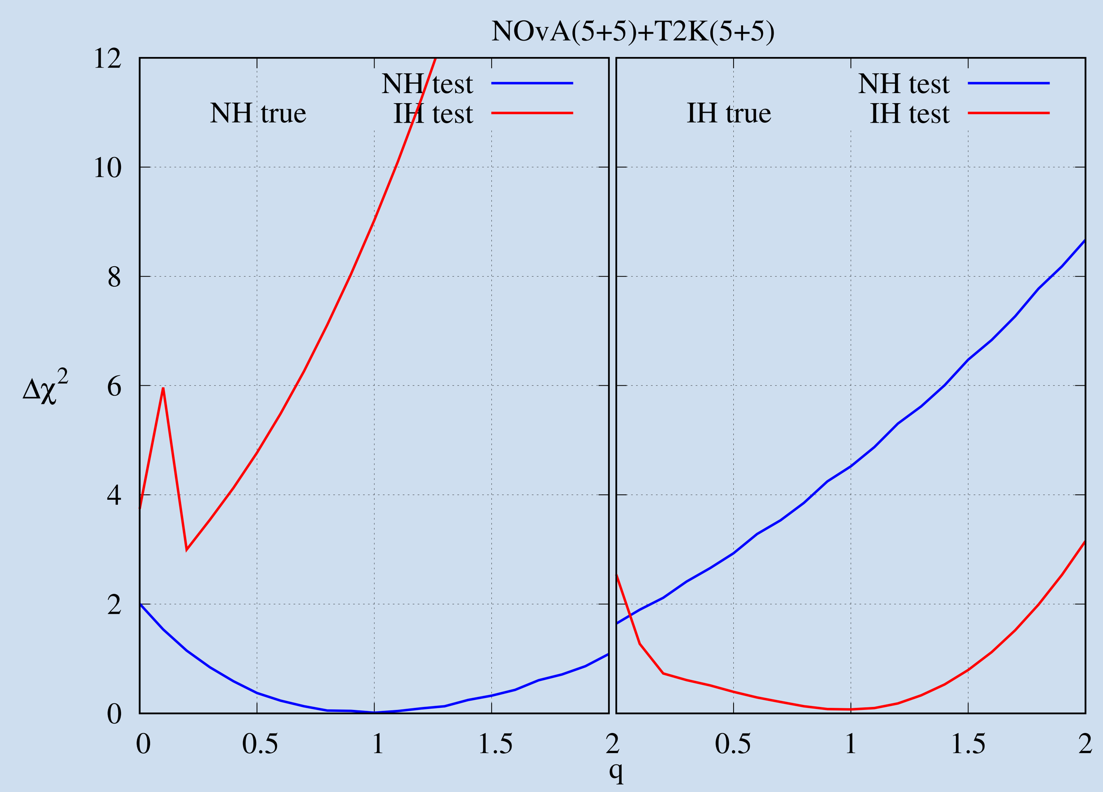


**Figure 2.** $\Delta\chi^2$ vs $q$ for an expected T2K run with $37.4 \times 10^{20}$ POT each in both $\nu$ and $\bar{\nu}$ mode and a NO$\nu$A run with $30.25 \times 10^{20}$ POT each in both $\nu$ and $\bar{\nu}$ mode. The left (right) panel assumes the true hierarchy to be normal (inverted). The blue (red) curves assume the test hierarchy to be normal (inverted).

## Expectations from DUNE

The future long-baseline accelerator neutrino experiment DUNE [11, 12, 13] has a baseline ($L \simeq 1300$ km) which is much longer than that of T2K or NO$\nu$A. Its peak energy is correspondingly higher and matter effects larger. The figure below shows that after one year neutrino run of DUNE, vacuum oscillations are ruled out at 3 $\sigma$ (2 $\sigma$) if the true hierarchy is NH (IH).

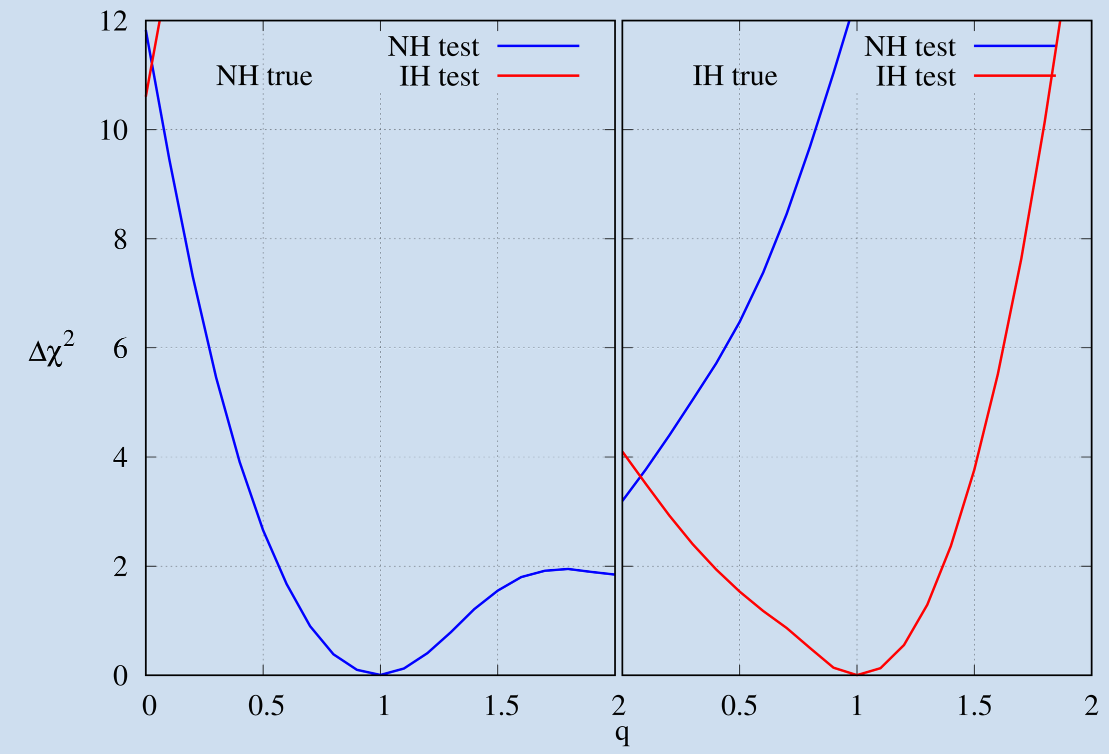


**Figure 3.** $\Delta\chi^2$ vs $q$ for an expected one year neutrino run of DUNE ($14.7 \times 10^{20}$ POT). The left (right) panel assumes the true hierarchy to be normal (inverted). The blue (red) curves assume the test hierarchy to be normal (inverted).

Addition of T2K $(5\nu + 5\bar{\nu})$ and NO$\nu$A $(5\nu + 5\bar{\nu})$ runs leads only to a marginal improvement but not 3 $\sigma$ discrimination. A 5 $\sigma$ discrimination is possible for both hierarchies if the data of DUNE $(5\nu + 5\bar{\nu})$ run is considered in conjunction with T2K $(5\nu + 5\bar{\nu})$ and NO$\nu$A $(5\nu + 5\bar{\nu})$ runs, as illustrated in the figure below. We also note from this figure that values of $q$ out side the range $(1 \pm 0.4)$ are ruled out at 3 $\sigma$ or better.

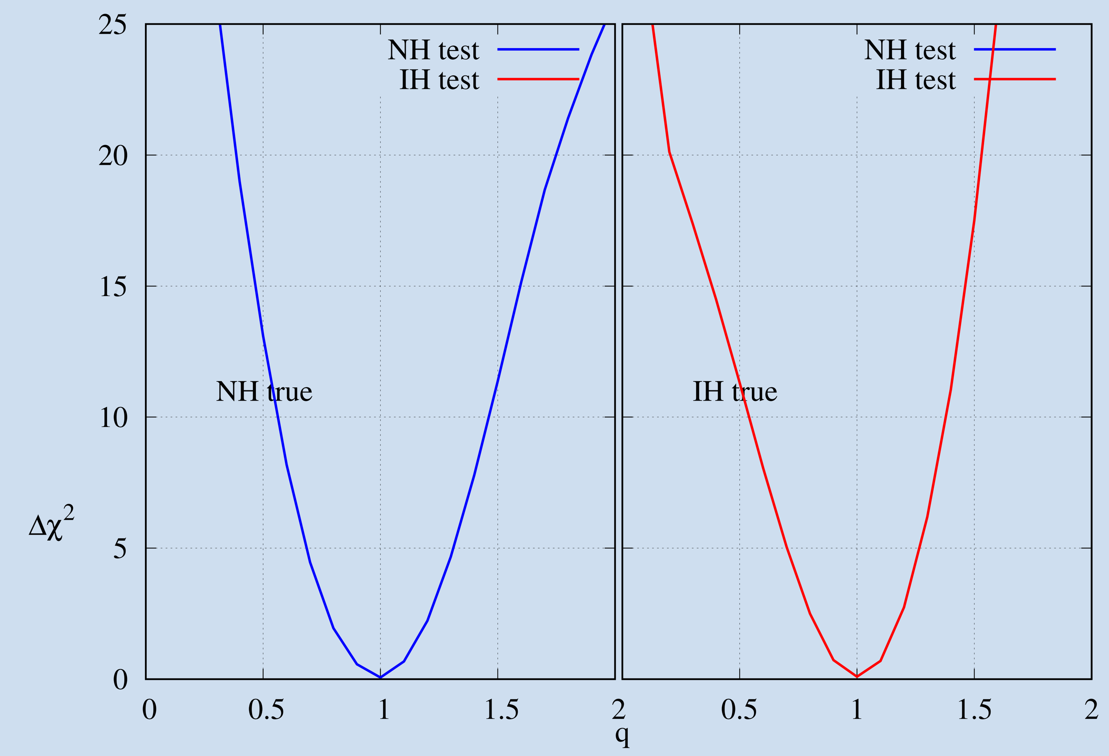


**Figure 4.** $\Delta\chi^2$ vs $q$ for an expected $(5\nu+5\bar{\nu})$ run of DUNE plus equal $\nu$ and $\bar{\nu}$ runs of T2K with $37.4 \times 10^{20}$ POT and of NO$\nu$A with $30.25 \times 10^{20}$ POT. The left (right) panel assumes the true hierarchy to be normal (inverted). The blue (red) curves assume the test hierarchy to be normal (inverted).

## Conclusion

The existence of matter effects at the scale of $\Delta_{21}$ is well established [14]. However, at the scale of $\Delta_{31}$, vacuum oscillations fit the data nearly as well as matter modified oscillations. This is true for both atmospheric neutrino data [2] and for present long-baseline accelerator data, as demonstrated in this work. We also show that extended runs of T2K and NO$\nu$A can not rule out vacuum oscillations at 3 $\sigma$. Such a result can be achieved with one year neutrino run of DUNE, if NH is the true hierarchy but not if IH is the true hierarchy. Ruling out vacuum oscillations at 5 $\sigma$ requires the combined data of $(5\nu + 5\bar{\nu})$ runs of T2K, NO$\nu$A and DUNE. Such a data can also establish the strength of matter effects with good precision.

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