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Neutrinos, DUNE and the world best bound on CPT invariance

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ABSTRACT

CPT symmetry, the combination of Charge Conjugation, Parity and Time reversal, is a cornerstone of our model building strategy and therefore the repercussions of its potential violation will severely threaten the most extended tool we currently use to describe physics, *i.e.* local relativistic quantum fields. However, limits on its conservation from the Kaon system look indeed imposing. In this work we will show that neutrino oscillation experiments can improve this limit by several orders of magnitude and therefore are an ideal tool to explore the foundations of our approach to Nature.

Strictly speaking testing CPT violation would require an explicit model for how CPT is broken and its effects on physics. Instead, what is presented in this paper is a test of one of the predictions of CPT conservation, i.e., the same mass and mixing parameters in neutrinos and antineutrinos. In order to do that we calculate the current CPT bound on all the neutrino mixing parameters and study the sensitivity of the DUNE experiment to such an observable. After deriving the most updated bound on CPT from neutrino oscillation data, we show that, if the recent T2K results turn out to be the true values of neutrino and antineutrino oscillations, DUNE would measure the fallout of CPT conservation at more than 3σ. Then, we study the sensitivity of the experiment to measure CPT invariance in general, finding that DUNE will be able to improve the current bounds on $\Delta(\Delta m^2_{31})$ by at least one order of magnitude. We also study the sensitivity to the other oscillation parameters. Finally we show that, if CPT is violated in nature, combining neutrino with antineutrino data in oscillation analysis will produce imposter solutions.

1. Introduction

CPT invariance is arguably one of the few sacred cows of particle physics. Its position as such arises from the fact that CPT conservation is a natural consequence of only three assumptions: Lorentz invariance, locality and hermiticity of the Hamiltonian, all of which have plenty of reasons to be included in our theory, besides CPT itself. In short, the CPT theorem states that particle and antiparticle have the same mass and, if unstable, also the same lifetime (for a nice proof of the CPT theorem see Ref. [1]). Therefore, the consequences of finding evidence of CPT non-conservation would be gigantic [2]. At least one of the three ingredients above must be false and our model building strategy would need to be revisited.

It should be noted however that testing the predictions of CPT conservation is not strictly equivalent to constraining CPT violation. Tests of CPT conservation might be performed by comparing the masses of particles and antiparticles. Indeed, these mass differences might be regarded as CPT violating observables. Nevertheless, the interpretation and comparison of bounds from different observables would only be possible with the consideration of a particular model of CPT violation.

Having said that, it is also clear that tests of CPT invariance have been historically associated with the neutral kaon system and therefore although in the absence of an explicit model any connection is meaningless, the comparison between kaons and neutrinos seems unavoidable. A superficial face value extrapolation leaves no room to be optimistic: the current limits on CPT violation arising from the neutral Kaon system seem to be quite solid

$$\frac{|m(K^0)-m(\overline{K}^0)|}{m_K} < 0.6\times 10^{-18}\,. \tag{1}$$

However, the strength of this limit is indeed artificial. Its robustness derives from the choice of the scale in the denominator, which is arbitrary at any rate and has nothing to do with a

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Fig. 1. Generic CPT violating spectrum. We have not included an overall shift between the neutrino and antineutrino sector as it cannot be tested by oscillation experiments.

concrete model of CPT violation. Besides the Kaon is not an elementary particle and therefore this test has more to do with testing QCD rather than a fundamental symmetry of (elementary) fermions. Additionally, the parameter present in the Lagrangian is not the mass but the mass squared and therefore this limit should be re-written as

$$|m^2(K^0) - m^2(\overline{K}^0)| < 0.25\ \text{eV}^2\,. \tag{2}$$

Now it becomes obvious that neutrino experiments can test CPT to an unprecedented extent and therefore can provide stronger limits than the ones regarded as the most stringent now.[1] Let us stress again, however, that without an explicit model for CPT violation it is not straightforward or even meaningful to compare the neutrino-antineutrino mass squared differences and the kaon ones. CPT violation may show up only in one of the sectors and therefore the strong bounds in one of them might not be directly applicable to the other.

On the other hand, there are reasons to believe neutrinos are an ideal probe for CPT violation: quantum gravity is assumed to be non-local, opening the door to a potential CPT violation. Its effects however are expected to be Planck suppressed, *i.e.* $\langle v\rangle^2/M_{\rm P}$, exactly in the right ballpark for neutrino experiments to see them.

Furthermore, as it is well known, neutrinos offer a unique mass generation mechanism, the see-saw, and therefore their masses are sensitive to new physics and new scales. Scales where non-locality can be expected to show up. Of course, in lack of a concrete theory of flavor, let alone one of CPT violation, the difference in the spectra of neutrinos and antineutrinos can appear not only in the mass eigenstates but also in the mixing between flavor and mass eigenstates. Neutrino oscillation experiments can test only CPT in the mass differences and mixing angles. An overall shift on the spectrum of neutrinos relative to that of antineutrinos cannot be detected in oscillation experiments and can be bound only by cosmological data, see Ref. [3]. It is important to notice that future kinematical direct searches for neutrino mass use only antineutrinos and thus cannot be used as a CPT test on the absolute mass scale either. (See Fig. 1.)

Studies separating neutrinos and antineutrinos were done in the past [4–7] under several assumptions. In Ref. [8] the authors obtained the following model-independent bounds on CPT invariance for the different parameters [2]:

$$\begin{aligned}
|\Delta m^2_{21} - \Delta\overline{m}^2_{21}| &< 5.9\times 10^{-5}\ \text{eV}^2,\\
|\Delta m^2_{31} - \Delta\overline{m}^2_{31}| &< 1.1\times 10^{-3}\ \text{eV}^2,\\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.25,\\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.03,\\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.44,
\end{aligned} \tag{3}$$

at 3σ. MINOS has also bounded the difference in the atmospheric mass-splitting to be

$$|\Delta m^2_{31} - \Delta\overline{m}^2_{31}| < 0.8\times 10^{-3}\ \text{eV}^2 \tag{4}$$

at 3σ, see Ref. [5]. Although this latter bound is stronger than the one in Eq. (3), it is not indicated whether it has been obtained after marginalizing over the atmospheric mixing angle or not. In any case, it seems clear that the previous bounds in Eqs. (3) and (4) have been derived assuming the same mass ordering for neutrinos and antineutrinos. Note that different mass orderings for neutrinos and antineutrinos would automatically imply CPT violation, even if the same value for the mass difference is obtained. At this point it is worth noting that, in this work, we are not considering any particular model of CPT violation and therefore all the results obtained can be regarded as model-independent.

In the light of the new experimental data, mainly from reactor and long–baseline accelerator experiments, here we are going to update the bounds on CPT from neutrino oscillation data. We will use basically the same data considered in the global fit to neutrino oscillations in Ref. [9]. Note, however, that in this work we will analyze neutrino and antineutrino data separately. Given that current atmospheric experiments, such as Super-Kamiokande [10], IceCube-DeepCore [11,12] and ANTARES [13], can not distinguish neutrinos from antineutrinos event by event, we will not include them in this study. Here we summarize the neutrino samples considered, indicating in each case the neutrino or antineutrino parameters they are sensitive to

- solar neutrino data [14–23]: θ_{12}, Δm^2_{21}, θ_{13}
- neutrino mode in long–baseline experiments K2K [24], MINOS [5,25], T2K [26,6] and NOνA [27,28]: θ_{23}, Δm^2_{31}, θ_{13}
- KamLAND reactor antineutrino data [29]: $\overline{\theta}_{12}$, $\Delta\overline{m}^2_{21}$, $\overline{\theta}_{13}$
- short–baseline reactor antineutrino experiments Daya Bay [30], RENO [31] and Double Chooz [32]: $\overline{\theta}_{13}$, $\Delta\overline{m}^2_{31}$
- antineutrino mode in long–baseline experiments[3] MINOS [5, 25] and T2K [26,6]: $\overline{\theta}_{23}$, $\Delta\overline{m}^2_{31}$ $\overline{\theta}_{13}$

There is no reason to put bounds on $|\delta - \overline{\delta}|$ at the moment, since all possible values of δ or $\overline{\delta}$ are allowed. The exclusion of certain values of δ in Ref. [9] can only be obtained after combining neutrino and antineutrino data. Hence, performing such an exercise, the most up-to-date bounds on CPT violation are:

$$\begin{aligned}
|\Delta m^2_{21} - \Delta\overline{m}^2_{21}| &< 4.7\times 10^{-5}\text{eV}^2,\\
|\Delta m^2_{31} - \Delta\overline{m}^2_{31}| &< 3.7\times 10^{-4}\text{eV}^2,\\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.14,\\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.03,\\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.32,
\end{aligned} \tag{5}$$

improving the older bounds in Eqs. (3) and (4), except for $\sin^2\theta_{13}$, that remains unchanged. Note that the limit on $\Delta(\Delta m^2_{31})$ is already better than the one of the neutral Kaon system and should be regarded as the best bound on CPT violation on the mass squared so far. It should be noted as well that, to obtain these bounds we assume that neutrinos and antineutrinos have the same definition of Δm^2, *i.e.* the mass difference has the same sign. In principle, of course the mass difference in neutrinos and antineutrinos may have a different sign, but in this case one may argue that the sign difference is already a sign of CPT violation in itself.

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[1] CPT was tested also using charged leptons. However, these measurements involve a combination of mass and charge and are not a direct CPT test. Only neutrinos can provide CPT tests on an elementary mass not contaminated by charge.

[2] Here we follow the standard convention of denoting neutrino parameters as Δm^2_{ij}, θ_{ij}, and antineutrino parameters as $\Delta\overline{m}^2_{ij}$, $\overline{\theta}_{ij}$.

[3] The K2K experiment took only data in neutrino mode. The NOνA experiment has not yet published data in antineutrino mode.

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