CPT violation in neutrinos

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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 talk I 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.

Striclty 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 work is a test of one of the predictions of CPT conservation, ie, the same mass and mixing parameters in neutrinos and anti-neutrinos. In order to do that we calculate the current CPT bound on all the neutrino mixing parameters.

After deriving the most updated bound on CPT from neutrino oscillation data, I will 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. Finally I show that, if CPT is violated in nature, combining neutrino with antineutrino data in oscillation analysis will produce imposter solutions.

INTRODUCTION

CPT invariance is surely one of the predictions of major importance of local, relativistic quantum field theory. One of the predictions of CPT invariance is that particles and antiparticles have the same masses and, if unstable, the same lifetimes. To prove the CPT theorem one needs only three ingredients [1]:

1. Lorentz invariance
2. Hermiticity of the Hamiltonian
3. Locality

If CPT turned out to be violated, the effect on modern fundamental particle physics would be gigantic. We would have to rethink our model-building strategies, since one of the three ingredients above would not hold anymore. Experimental bounds on CPT invariance can be derived using the neutral kaon system [2]:

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

This result, however, should be interpreted very carefully because of two reasons: first, we do not have a complete theory of CPT violation. Therefore, it is rather arbitrary to take the kaon-mass as a scale. Second, since kaons are bosons, the term entering the Lagrangian is the mass squared and not the mass itself. Having this in mind, we can rewrite the previous bound in this way

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

Here we will see that neutrinos can test the predictions of the CPT theorem to an unprecedented extent and could therefore provide stronger limits than the ones regarded as the most stringent ones by now, It should be noticed that 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.. In the absence of a solid model of flavor, not to mention one of CPT violation, the spectrum of neutrinos and antineutrinos can differ both in the mass eigenstates themselves as well as in the flavour composition of each of these states. It is important to notice then that neutrino oscillation experiments can only test CPT in the mass differences and mixing angles. An overall shift between the neutrino and antineutrino spectra will be missed by oscillation experiments. Nevertheless such a pattern can be bounded by cosmological data, see Ref. [3]. Unfortunately direct searches for neutrino mass (past, present and future) involve only antineutrinos and therefore cannot be used to draw any conclusion on CPT invariance on the absolute mass scale either. Therefore, using neutrino oscillation data, we will compare the mass splittings and mixing angles of neutrinos with those of antineutrinos. Differences in the neutrino and antineutrino spectrum, as schematically depicted in Fig. 1, would imply the violation of the CPT theorem. Let us stress, however, that without an explicit model for CPT violation [4] 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. Nevertheless, there are reasons to believe that neutrinos are an ideal candidate to test 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

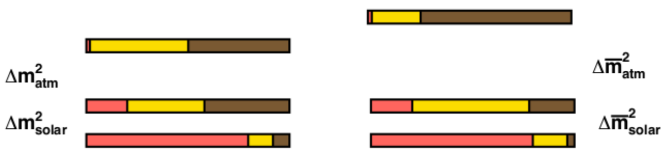

FIG. 1. Generic CPT violating spectrum. We have not included an overall shift between the neutrino and antineutrino sector as it cannot be tested by oscillation experiments

see them. Also, since neutrinos offer a unique mass generation mechanism, the see-saw, their masses should be sensitive to new physics and new scales. Scales where non-locality might show up.

In Ref. [6] the authors derived most up-to-date bounds on CPT invariance from the neutrino sector. The data used to derive these bounds are the same considered in the global fit to neutrino oscillations in Ref. [7]. Of course, experiments which cannot distinguish between neutrinos and antineutrinos, such as atmospheric data from Super-Kamiokande, IceCube-DeepCore and ANTARES were not included. The complete data set used, as well as the parameters they are sensitive to are the following:

- solar neutrino data: θ_{12}, Δm^2_{21}, θ_{13}
- neutrino mode in long–baseline experiments K2K, MINOS, T2K and NOνA: θ_{23}, Δm^2_{31}, θ_{13}
- KamLAND reactor antineutrino data: $\overline{\theta}_{12}$, $\Delta\overline{m}^2_{21}$, $\overline{\theta}_{13}$
- short–baseline reactor antineutrino experiments Daya Bay, RENO and Double Chooz: $\overline{\theta}_{13}$, $\Delta\overline{m}^2_{31}$
- antineutrino mode in long–baseline experiments (The K2K experiment took data only in neutrino mode, while the NOνA experiment has not published data in the antineutrino mode yet) MINOS and T2K: $\overline{\theta}_{23}$, $\Delta\overline{m}^2_{31}$ $\overline{\theta}_{13}$

From the analysis of all previous data samples, one can derive the most up-to-date bounds on CPT violation:

$$\begin{aligned}
|\Delta m^2_{21} - \Delta\overline{m}^2_{21}| &< 4.7\times10^{-5}\,\mathrm{eV}^2,\\
|\Delta m^2_{31} - \Delta\overline{m}^2_{31}| &< 3.7\times10^{-4}\,\mathrm{eV}^2,\\
|\sin^2\theta_{12} - \sin^2\overline{\theta}_{12}| &< 0.14,\\
|\sin^2\theta_{13} - \sin^2\overline{\theta}_{13}| &< 0.03,\\
|\sin^2\theta_{23} - \sin^2\overline{\theta}_{23}| &< 0.32.
\end{aligned} \tag{3}$$

At the moment it is not possible to set any bound on $|\delta-\overline{\delta}|$, since all possible values of δ or $\overline{\delta}$ are allowed by data. The preferred intervals of δ obtained in Ref. [7] can only be obtained after combining the neutrino and antineutrino data samples. The limits on $\Delta(\Delta m^2_{31})$ and $\Delta(\Delta m^2_{21})$ are already better than the one derived from the neutral kaon system and should be regarded as the best bounds on CPT violation on the mass squared so far.

Regarding the future, the Deep Underground Neutrino Experiment (DUNE) will consist of two detectors exposed to a megawatt-scale muon neutrino beam that will be produced at Fermilab. DUNE will be using 1.47×10^{21} protons on target (POT) per year, which amounts basically in one single year to the same amount T2K has used in all of its lifetime until now (runs 1–7c). Performing the CPT violating analysis with DUNE setup we obtain very interesting results for $\Delta(\Delta m^2_{31})$ and $\Delta(\sin^2\theta_{23})$. We find that DUNE should be able to set bounds on $\Delta(\Delta m^2_{31})$ tighter than 8.1×10^{-5} at 3σ confidence level. This would imply an improvement of one order of magnitude with respect to the old bound and four orders of magnitude with respect to the neutral Kaon bound, once it is viewed as a bound on the mass squared. Concerning the atmospheric mixing angle, we obtain different results depending on the true value assumed to simulate DUNE data. In the case of true maximal mixing, the sensitivity increases with $\Delta(\sin^2\theta_{23})$, as one might expect. However, if we assume the true values to be in the first or second octant, a degenerate solution appears in the complementary octant.

In different types of neutrino oscillation experiments, as for example accelerators, neutrino and antineutrino data are obtained in separate experimental runs. However, the usual procedure followed by the experimental collaborations, as well as the global oscillation fits as for example Ref. [7], assumes CPT invariance and analyzes the full data sample in a joint way. Such a path is not risk-free. Indeed, the opportunity to test CPT invariance in the neutrino sector is lost. Even more important, if CPT is violated in nature, the outcome of the joint data analysis might give rise to what we call an imposter solution. A solution which results from the combined analysis but does not correspond to the true solution of any channel.

Under the assumption of CPT conservation, the χ^2–functions are computed according to

$$\chi^2_{\mathrm{total}} = \chi^2(\nu) + \chi^2(\overline{\nu})\,, \tag{4}$$

and assuming that the same parameters describe neutrino and antineutrino flavor oscillations. In contrast, in our analysis we first marginalized over the parameters in neutrino and antineutrino mode separately and then added the marginalized profiles. Here, we shall assume CPT to be violated in nature, but perform our analysis as if it was conserved. As an example, we assume

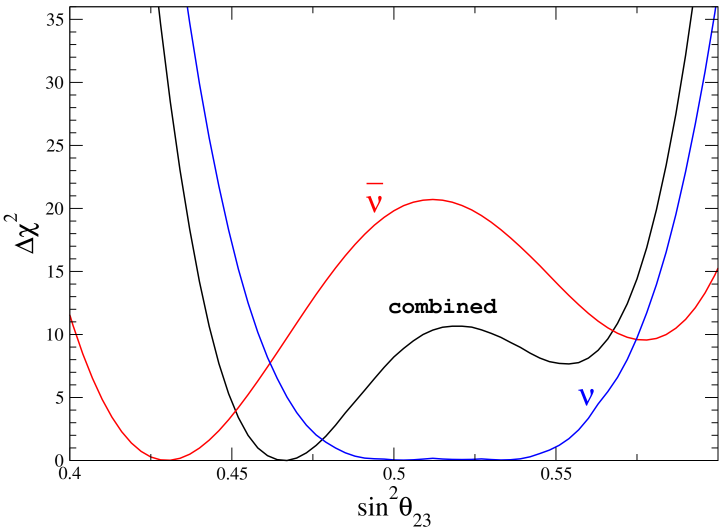

FIG. 2. DUNE sensitivity to the atmospheric angle for neutrinos (blue), antineutrinos (red) and to the combination of both under the assumption of CPT conservation (black).

that the true value for the atmospheric neutrino mixing is $\sin^2\theta_{23} = 0.5$, while the antineutrino mixing angle is given by $\sin^2\overline{\theta}_{23} = 0.43$. The rest of the oscillation parameters are set to their best fit values. Performing the statistical analysis in the CPT conserving way, as indicated in Eq. (4), we obtain the profile of the atmospheric mixing angle presented in Fig. 2. The profiles for the individual reconstructed results (neutrino and antineutrino) are also shown in the figure for comparison. As can be seen, we obtain a new best fit value at $\sin^2\theta_{23}^{\rm comb} = 0.467$, disfavoring the true values for neutrino and antineutrino parameters at approximately 3σ and more than 5σ, respectively.

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