Eur. Phys. J. C (2017) 77:766
https://doi.org/10.1140/epjc/s10052-017-5347-y

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Cosmology and CPT violating neutrinos

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Received: 20 August 2017 / Accepted: 1 November 2017 / Published online: 15 November 2017

Abstract The combination charge conjugation–parity–time reversal (CPT) is a fundamental symmetry in our current understanding of nature. As such, testing CPT violation is a strongly motivated path to explore new physics. In this paper we study CPT violation in the neutrino sector, giving for the first time a bound, for a fundamental particle, in the CPT violating particle-antiparticle gravitational mass difference. We argue that cosmology is nowadays the only data sensitive to CPT violation for the neutrino–antineutrino mass splitting and we use the latest data release from Planck combined with the current baryonic-acoustic-oscillation measurement to perform a full cosmological analysis. To show the potential of the future experiments we also show the results for Euclid, a next generation large scale structure experiment.

1 Introduction

On general grounds, local, relativistic quantum field theory makes only a couple of predictions. CPT invariance [1] is one of them, and undoubtedly the cornerstone of our model building strategy. The CPT theorem, in short, states that every particle does have the same mass as its antiparticle and, if unstable, also the same lifetime. Its position as one of the celebrated results of particle physics is based on the fact that in order to prove it only three ingredients are needed, all of which are "natural" and have other reasons to be in our theory, way beyond the CPT theorem itself. They are

- Lorentz invariance,
- hermiticity of the Hamiltonian,
- locality.

Precisely because of this, if CPT is found not to be conserved, the impact of such an observation to fundamental physics would be gigantic. It would necessarily mean that at least one of the three assumptions above must be violated [2,3]. Therefore it will automatically imply that our description of nature in terms of local, Lorentz invariant field theory would be dramatically challenged and our model building strategy would need to be seriously revisited.

Largely because of its huge potential implications, the experimental signature of CPT violation was searched in the past and according to the PDG [22], the most stringent limit comes from the neutral kaon system [21]. Due to the mixing between K^0 and $\overline{K}^0$, the limit on the possible mass difference between them is

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

However, it is important to notice that the robustness of the CPT limit from the neutral kaon system is somewhat misleading. Although it is nice to have a limit in a dimensionless way, we do not have a concrete theory of CPT violation and therefore the scale with which we are comparing the mass difference, the kaon mass in this case, is by all means arbitrary. A much more stringent limit could have been obtained by using the Planck mass instead, making exactly the same sense as the one we currently use.[1]

Until we have a full theory on CPT violation, the limit in Eq. (1) should be looked upon as

$$|m(K^0) - m(\overline{K}^0)| < 0.6 \times 10^{-18} m_K \simeq 10^{-9}\text{eV}. \quad (2)$$

Moreover, as for bosons, the parameter entering the Lagrangian is the mass squared, rather than the mass, the bound can alternatively be written as $|m^2(K^0) - m^2(\overline{K}^0)| < 0.25\ \text{eV}^2$, which does not look nearly as strong as before.

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[1] Some authors argue that the appropriate quantity to compare with $|m(K^0) - m(\overline{K}^0)|$ in the analysis is $\Delta m^2/E$ [4], although it is not evident why the merit of the bound should depend on the energy.

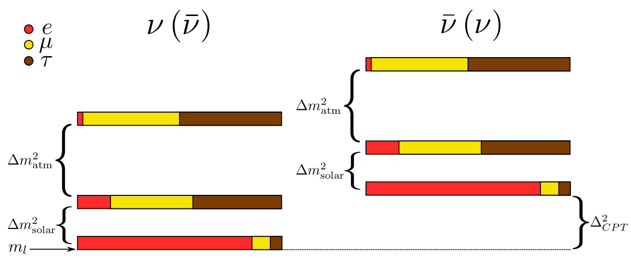

Fig. 1 Scheme for normal ordering mass spectrum with neutrinos and antineutrinos where we illustrate the extended parameters Δ_{CPT} and m_l

Besides, given that the mass of the kaons is largely due to QCD, this test cannot tell directly whether elementary particles indeed respect the CPT symmetry. For such a test, a search for CPT violation in the leptonic sector is mandatory. Using charged leptons the most stringent bound comes from electron–positron $g-2$ experiments [23,24] and hydrogen–antiantihydrogen spectroscopy [25]. These measurements, however, involve some combination of mass and charge as the testing parameter. On the other hand, in the neutral sector, the discovery of neutrino oscillations established that neutrinos are massive particles and in the so-called see-saw models the light masses are naturally related with the grand unified scale, making neutrinos distinctively sensitive to new physics/new scales. This exclusive mass generation mechanism along with the fact that there is no charge contamination comprised in the test makes neutrinos specially appealing to study CPT violation.

The quantum interference phenomena observed in neutrino oscillation is very sensitive to new physics, and it has been proposed to constrain CPT and Lorentz violation [30] in solar [4], short and long base line [6–8] atmospheric neutrino [26,27] oscillations experiments. A constraint in the full decoherent oscillation regime using the recent discovered ultra high energy neutrinos by IceCube [31] has also been proposed [28,29]. In general neutrino oscillation physics has shown a strong potential to constrain CPT, being comparable with or even stronger than that in the kaon system [9].

Unfortunately, all the experiments mentioned above always measure Δm^2, and they cannot measure the value of the masses themselves; therefore, only CPT violation in the mass differences, i.e. $\Delta m^2_\nu - \Delta m^2_{\bar{\nu}}$ can be tested. Moreover, if the possible violation of CPT has its origin in quantum gravity, we would naturally expect it to appear in the masses themselves and not in the mass differences [10].

Here we focus on the study of the yet unconstrained CPT violating mass difference between neutrinos and antineutrinos, $\Delta_{\mathrm{CPT}} = |m_l^\nu - m_l^{\bar{\nu}}|$. It is worth noting, nevertheless, that the direct (kinematical) searches for neutrino masses, carried out in tritium β-decay experiments [5] involve only anti(electron) neutrinos and therefore strictly speaking only bound the masses in the antineutrino sector, not probing anything about the neutrino one. An overall shift on the spectrum, as the one shown in Fig. 1, which potentially is much larger than the mass differences themselves, cannot be detected in neutrino oscillation experiments or bounded by future direct kinematical searches. This leaves as the only option using cosmological data, for such a purpose.

In this article we give the first bound on CPT violation for the neutrino–antineutrino absolute mass difference Δ_{CPT} using current cosmological data. We also perform a forecast analysis for the future next generation European Space Agency Cosmic Vision mission, Euclid [32].[2]

2 Cosmological bounds

Currently cosmology gives the strongest bound on the neutrino mass scale. In the standard cosmological scenario neutrinos are produced thermally; therefore, since neutrinos decouple when they are relativistic, the number densities for ν and $\bar{\nu}$ in the cosmic neutrino background are the same. This implies that cosmology is giving a bound on neutrinos and antineutrinos separately and therefore is currently the only physical observable to both neutrino and antineutrino mass scales. Note that since gravitational interactions cannot distinguish particles from antiparticles, cosmology can only constrain the absolute value of the mass difference and have nothing to say on which spectrum is the heaviest/lightest.

In this section we perform a Bayesian analysis for different sets of cosmological observables. The cosmological model is given by ΛCDM+$m_l + \Delta_{\mathrm{cpt}}$ where ΛCDM stands for the six standard cosmological parameters, m_l for the value of the lightest neutrino mass and $\Delta_{\mathrm{CPT}} = |m_l^\nu - m_l^{\bar{\nu}}|$ is the absolute mass difference between neutrinos and antineutrinos. The list of the cosmological parameters and the assumed ranges in the analysis are given in Table 1. An extra 94 fast sampling nuisance parameters are included to account for systematic and calibration errors for Planck data [11]. In the case of the Euclid forecast we neglect any theoretical error and include an extra nuisance parameter to take into account the parametrization uncertainty in the shot noise error [32].

The effect of the neutrino masses in cosmology comes mainly via the free streaming of the neutrinos in the cosmic neutrinos background during the growth of the large scale structure. In Fig. 2 we show the effect in the temperature-temperature (TT) CMB power spectrum and in the total matter power spectrum for different values of the CPT violating mass splitting Δ_{CPT} and $m_l = 0$; the rest of the cosmological parameters are set to the Planck2015 ΛCDM best fit [11].

To perform the cosmological analysis, we modify the publicly available Boltzmann code CLASS [18] by adding the new above-mentioned parameters. More precisely this

[2] http://www.euclid-ec.org/.

Table 1 ΛCDM+νCPT parameters and the given ranges in where we take flat priors

Parameter	Prior
$\Omega_b h^2$	[0.001, 0.1]
$\Omega_c h^2$	[0.01, 0.99]
$100\Theta_s$	[0.01, 10]
n_s	[0.5, 1.5]
$\log(10^{10} A_s)$	[1, 5]
m_l (eV)	[0, 10]
$\Delta_{\rm CPT}$ (eV)	[0, 10]

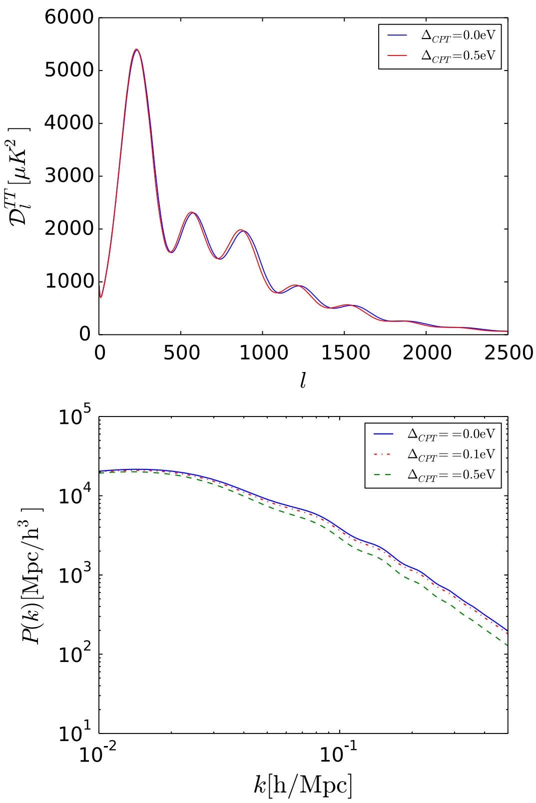

Fig. 2 Effect of changing $\Delta_{\rm CPT}$ in the TT CMB power spectrum (top) and total matter power spectrum (bottom)

is implemented by adding six mass states where we set the entries in the degeneracy parameter array, `deg_ncdm`, to 0.5. We split them in two sets of three where the splittings are fixed and only m_l and $\Delta_{\rm CPT}$ are implemented as standard input parameters. We use the MontePython wrapper [17] to perform a Bayesian data analysis on the full set of eight cosmological parameters.

For both neutrinos and antineutrinos we fix the atmospheric and solar mass splitting to the value of the global neutrino oscillation results given by the ν-fit collaboration[3] [19] and we introduce the proper modifications to use m_l and $\Delta_{\rm CPT}$ to parametrize the massive neutrinos.

From the current cosmological data we use the combined (TTEEE, low-l, lensing) data from Planck2015 [11] and the measurement of the Baryonic Acoustic Oscillation (BAO) scale from SDSS-DR10 SDSS-DR11 and 6dF [12–14]. We do not include the less conservative local measurements of the local expansion rate nor the full matter power spectrum, since this does not give a significant improvement in the determination of the neutrino masses [20] – and a proper precise study of the approximate non-linear correction in $\Delta_{\rm CPT}$ parameter is beyond the scope of the paper. In the following we designate by (CMB) the full set of Planck2015 data and by (BAO) the combination of the Baryonic Acoustic Oscillation scale mentioned before.

The mean value and 95% intervals for the two data sets CMB and CMB+BAO and for the two cases of normal and inverted ordering are summarized in Table 2.

In Figs. 3 and 4 we show the results of the posterior probability distribution for the new parameters m_l and $\Delta_{\rm CPT}$. For the sake of clarity and to make the comparison easier all the one dimensional probability distributions are normalized so that they get the same arbitrary value at the maximum.

In Fig. 5 we show the two dimensional 68 and 95% probability contours for the following cases: normal ordering using CMB only (red solid line), inverted ordering using CMB only (blue dashed line), normal ordering with CMB+BAO (red filled contours) and inverted ordering with CMB+BAO (blue filled regions). These constraints constitute the world's best bound on CPT violation in elementary particle masses so far.

In order to illustrate the potential of the near future data we perform an analysis using a simulated power spectrum for Euclid. We use the version of the Euclid likelihood implemented in the MontePyton wrapper [17] with parameters specified in Table 3. More details can be found in the Euclid Red Book [32].

For the forecast analysis we produce a simulated matter power spectrum data setting the cosmological parameters to the ΛCDM best fit and $\Delta_{\rm CPT} = m_l = 0$. We do the forecast fit only for normal ordering.

The results of the forecast analysis compared with the most stringent result using BAO measurements are shown in Fig. 6, for the $\Delta_{\rm CPT}$ parameter. The results for the 95% bound are $\Delta_{\rm CPT} < 0.0088$ eV and $m_l < 0.02$ eV. We checked

[3] http://www.nu-fit.org.

Table 2 Mean values and the 95% regions for the parameters for normal and inverted ordering and for the different sets of cosmological data CMB and CMB+BAO

Parameter	Planck2015 (95%)		Planck2015 + BAO (95%)	
	Normal	Inverted	Normal	Inverted
$10^{-2}\Omega_b h^2$	$2.210^{+0.036}_{-0.034}$	$2.206^{+0.032}_{-0.033}$	$2.238^{+0.031}_{-0.034}$	$2.240^{+0.028}_{-0.025}$
$\Omega_{cdm} h^2$	$0.1205^{+0.0031}_{-0.0030}$	$0.1209^{+0.0030}_{-0.0027}$	$0.1173^{+0.0022}_{-0.0025}$	$0.1166^{+0.0021}_{-0.0021}$
$H0$	$63.7^{+2.6}_{-3.2}$	$62.7^{+2.4}_{-3.0}$	$1.04203^{+0.00061}_{-0.00064}$	$65.97^{+0.99}_{-0.95}$
n_s	$0.9607^{+0.0095}_{-0.0094}$	$0.959^{+0.010}_{-0.010}$	$0.9690^{+0.0092}_{-0.011}$	$0.9716^{+0.0081}_{-0.0076}$
$\log(10^{10} A_s)$	$3.108^{+0.053}_{-0.053}$	$3.117^{+0.055}_{-0.054}$	$3.112^{+0.050}_{-0.052}$	$3.141^{+0.039}_{-0.038}$
τ_{reio}	$0.086^{+0.028}_{-0.029}$	$0.091^{+0.029}_{-0.029}$	$0.092^{+0.026}_{-0.027}$	$0.107^{+0.021}_{-0.023}$
Extended parameters				
m_l (eV)	< 0.133	< 0.149	< 0.0491	< 0.0423
$\Delta_{\rm CPT}$ (eV)	< 0.255	< 0.215	< 0.0588	< 0.0428

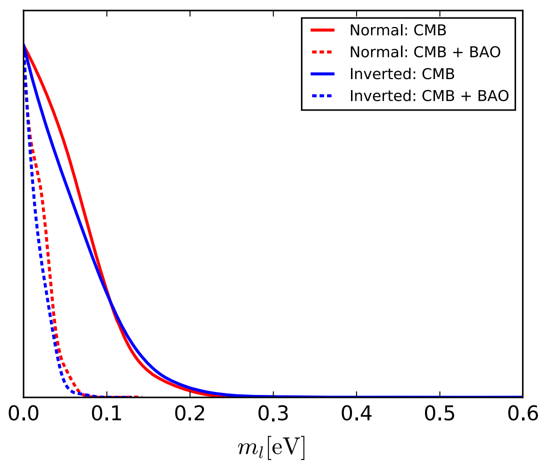

Fig. 3 1D posterior probability distribution for the parameters m_l using two different data sets, CMB (solid) and CMB+BAO (dashed); normal ordering and inverted ordering are designated by the blue and red curves, respectively

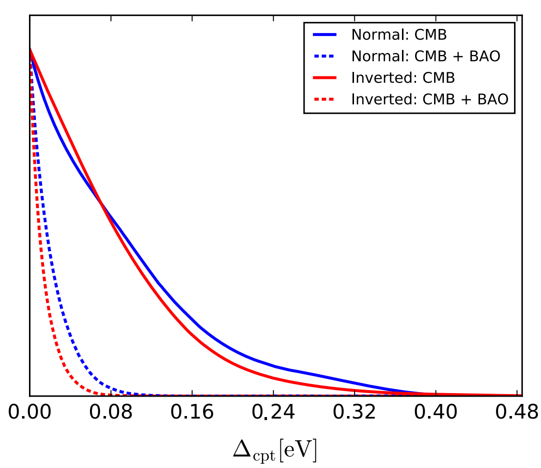

Fig. 4 1D posterior probability distribution for the parameters $\Delta_{\rm CPT}$ using two different data sets, CMB (solid) and CMB + BAO (dashed); normal ordering and inverted ordering are designated by the blue and red curves, respectively

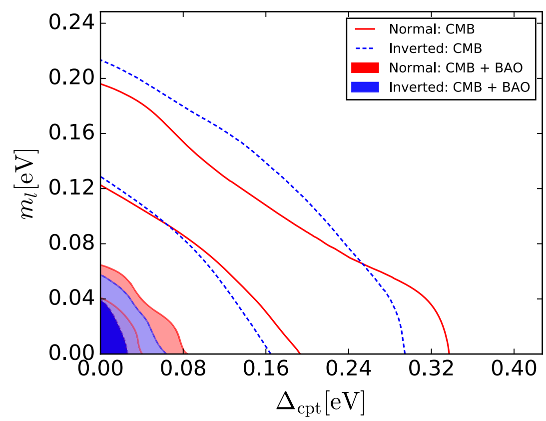

Fig. 5 68 and 95% probability contours for the light neutrino masses m_l and $\Delta_{\rm CPT}$, where (blue, red) and (solid, dashed) designate (normal, inverted) and (CMB, CMB+BAO), respectively

Table 3 Setup specification for the Euclid forecast

Forecast Spec.	Value
Num. Bins.	14
$[z_{\rm min}, z_{\rm max}]$	[0.07, 2.0]
Sky coverage	0.3636
$[k_{\rm min}, k_{\rm max}][h/{\rm Mpc}]$	[0.001, 0.2]

the forecast results for the other cosmological parameters are consistent with previous work [33] and with the injected values for the simulated spectrum.

3 Conclusions

We give, for the first time, a bound on CPT violation in the absolute value of the neutrino–antineutrino mass splitting. Since the kinematical laboratory experiments use only

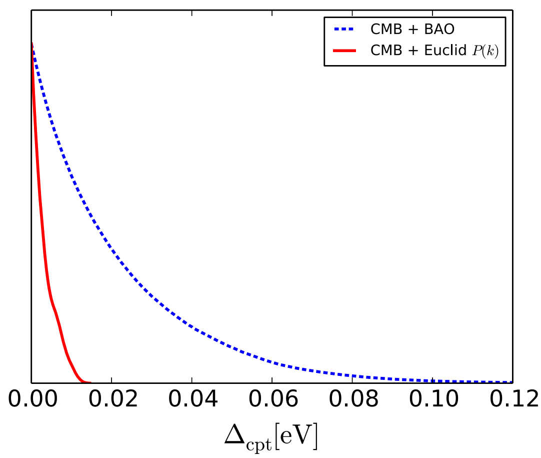

Fig. 6 1D posterior probability distribution for the parameters $\Delta_{\rm CPT}$, the blue(dashed) is the most stringent bound with current data shown in Fig. 4 and the red (solid) the bound using generated Euclid power spectrum data with $\Delta_{\rm CPT} = 0$ and $m_l = 0$

antineutrinos, they are not able to give any bound on CPT; hence, for now, the only possibility to bound $\Delta_{\rm CPT}$ is to use cosmological data.

In order to do that we perform a full cosmological analysis using the current CMB, and BAO data. Using only CMB the 95% bounds are $\Delta_{\rm CPT} < 0.26$ eV and $\Delta_{\rm CPT} < 0.21$ eV for normal and inverted ordering, respectively. Adding the BAO data we get a more stringent bound, $\Delta_{\rm CPT} < 0.059$ eV and $\Delta_{\rm CPT} < 0.043$ eV again for normal and inverted ordering, respectively.

To illustrate the potential of the future data by the Euclid satellite we perform a forecast analysis where we generate a power spectrum for the values $\Delta_{\rm CPT} = 0$ and $m_l = 0$. Performing the fit together with the Planck2015 data we see that the next generation of large scale structure experiments may give a 95% bound to the CPT violation and light neutrino masses of $\Delta_{\rm CPT} < 0.0088$ eV and $m_l < 0.02$ eV, respectively.

Acknowledgements GB acknowledges support from the MEC and FEDER (EC) Grants SEV-2014-0398, FIS2015-72245-EXP and FPA2014-54459 and the Generalitat Valenciana under grant PROMETEOII/2013/017. JS acknowledges support from FPA2014-57816-P and PROMETEOII/2014/050. This project has received funding from the European Union Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant H2020-MSCA-ITN-2015//674896-ELUSIVES and InvisiblesPlus H2020-MSCA-RISE-2015, agreement No 690575.

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