ATMOSPHERIC NEUTRINOS AS PROBES OF CPT VIOLATION

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We show that atmospheric neutrinos can provide a sensitive and robust probe of CPT violation (CPTV). We perform realistic event-rate calculations and study the variations of the ratio of total muon to antimuon survival rates with L/E and L ($L \equiv$ baseline length, $E \equiv$ neutrino energy) in a detector capable of identifying the muon charge. We demonstrate that measurements of these ratios when coupled with the significant L and E range which characterizes the atmospheric neutrino spectrum provides a method of both detecting the presence of such violations and putting bounds on them which compare very favourably with those possible from a future neutrino factory.

1 Introduction

The CPT invariance of quantum field theories is a consequence of basic principles such as Lorentz invariance, the spin-statistics theorem, and the local and hermitian nature of the Lagrangian [1]. Tests of CPT invariance thus assume great importance because any violation of CPT would signal radical new physics. In particular, Greenberg [2] has shown that CPT violation necesssarily implies violation of Lorentz invariance.

One of the exciting results to emerge in particle physics during the past decade is that the neutrino sector is the most likely place for the detection of physics beyond the SM [3]. The role of neutrinos as probes of CPT invariance was discussed in a general framework by Colladay and Kostelecky [4]. As proposed in [5,6] significant bounds on CPTV parameters can be set in neutrino factory experiments due to their expected high luminosities and low backgrounds [7]. However, with all their advantages, neutrino factories are unlikely to be available for at least twenty years or more.

In contrast to this, large mass magnetized iron calorimeter neutrino detectors, which employ well understood technology, were considered in [8] to study atmospheric neutrino interactions in great detail. Such detector is being currently actively planned to begin data-taking five years from now [9]. We show that such detecttors can form an ideal tool to detect CPTV in the neutrino sector. We study on the survival probabilities for ν_μ and $\bar{\nu}_\mu$. A difference in these quantities is a signal for CPTV. By calculating the ratio of their event-rates, we show that comprehensive tests of CPTV are possible in the atmospheric neutrino sector, with sensitivities which compare very favourably with those projected for neutrino factory experiments.

2 CPT Violation in ν Interactions

We consider the effective **C and CPT-odd interaction** terms $\bar{\nu}_L^\alpha b^\mu_{\alpha\beta}\gamma_\mu \nu_L^\beta$, where α and β are flavour indices [5]. In presence of this CPTV term, the neutrino energy acquires an additional term which comes from the matrix $b^0_{\alpha\beta}$. For anti-neutrinos, this term has the opposite sign. The energy eigenvalues of neutrinos (in ultra-relativistic limit) are obtained by diagonalizing the Hermitian matrix given by $A = m^2/2p + b$, where $m^2 \equiv m\,m^\dagger$ is the Hermitian mass squared matrix and we have dropped the superscript 0 from b^0.

We assume equal masses for neutrinos and anti-neutrinos. For simplicity we consider two flavour $\nu_\mu \to \nu_\tau$ oscillations only. This is equivalent to setting θ_{13} to be zero [10]. We further assume that the two mixing angles that diagonalize the matrices m^2 and b are equal (i.e. $\theta_m = \theta_b = \theta$). The expression for survival probability for the case of CPTV 2-flavour oscillations is

$$P_{\alpha\alpha}(L) = 1 - \sin^2 2\theta \sin^2\left[\left(\frac{\delta m^2}{4E} + \frac{\delta b}{2}\right) L\right]$$

where δm^2 and δb are the differences between the eigenvalues of the matrices m^2 and b, respectively and α corresponds to μ or τ flavours. Note that δb has units of energy (GeV). For $\bar{\nu}$, the sign of δb is reversed. The difference between $P_{\alpha\alpha}$ and $P_{\bar{\alpha}\bar{\alpha}}$ is given by,

$$\Delta P^{CPT}_{\alpha\alpha} = -\sin^2 2\theta\, \sin\left(\frac{\delta m^2 L}{2E}\right)\, \sin(\delta b L)$$

Note that, in order to see any observable effect of CPTV, one must have both CPT-even and CPT-odd terms to be non-zero.

3 Calculations

In order to quantitatively demonstrate the feasibility of using atmospheric neutrinos as a source of detecting and putting bounds on CPT violation, we focus on a typical detector which can detect muon energy and direction and also identify its charge. The simplest choice of a suitable prototype is an iron calorimeter with a magnetic field. Such a detector was proposed for Gran Sasso (MONOLITH) [8] and is also currently being planned for a location in India (INO) [9], with initial data-taking by 2009. It is contemplated as both a detector for atmospheric neutrinos and as a future end detector for a neutrino factory beam. Our prototype is a 50 kT Iron detector, with detection and charge discrimination capability for muons, provided by a B field of about 1.2 Tesla. We have assumed a (modest) 50% efficiency of the detector for muon detection and a muon energy resolution of within 5%.

In the calculations presented here, we have assumed that the atmospheric neutrino problem is resolved by $\nu_\mu \to \nu_\tau$ oscillations. Specifically, we use the following input parameters : $\delta m^2_{32} = 0.002$ eV^2, $\sin^2 2\theta_{23} = 1$, which are consistent with best fit values determined by the most recent analyses of atmospheric data combined with CHOOZ bounds [11]. In addition we have used the Bartol atmospheric flux [12] and set a muon detection threshold of 1 GeV. For neutrino energies below 1.8 GeV the quasi-elastic ν-nucleon crosssection has been used, while above this energy we have put in the DIS value of the crosssection. The number of muon events have been calculated using

$$N = N_n \times M_d \int \sigma^{CC}_{\nu_\mu - N}\, P(\nu_\mu \to \nu_\mu)\, \frac{dN_\nu}{dE_\nu}\, dE_\nu$$

where $N_n = 6.023 \times 10^{32}$ is the number of (isoscalar) nucleons in 1kT of target material and M_d is the detector mass. Our results are obtained from a simple parton level monte-carlo event generator. We have used CTEQ4LQ [13] parametrisations for the parton distribution functions to estimate the DIS crosssection.

Finally, we comment on the exposure

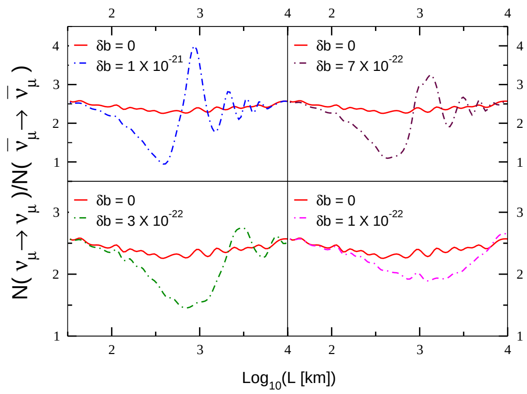

Figure 1. The ratio of total muon to anti-muon events plotted against $Log_{10}(L)$ for different values of δb (in GeV). The oscillation parameters used in all the plots are : $\delta m^2 = 2\times 10^{-3}$ eV^2 and $\sin^2 2\theta_{13} = 1$.

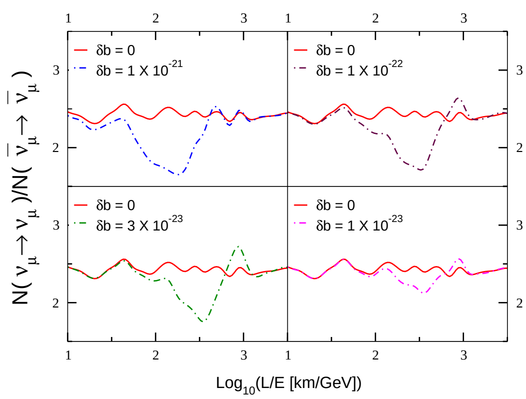

Figure 2. The ratio of total muon to anti-muon events plotted against $Log_{10}(L/E)$ for different values of δb (in GeV).

time necessary to see a dependable signal. Since the number of $\bar{\nu}$ atmospheric events will be significantly smaller than the number of ν events, reducing the statistical error in the ratio will require an exposure time that enables observations of a sufficient number of $\bar{\nu}$ events. Our calculations indicate that an exposure of 400 kT-yr would be sufficient for statistically significant signals to emerge.

4 Results and Discussions

Figure 1 shows the variation of the ratio of total (up + down) muon survival events to those of anti-muons, plotted vs L for various values of δb. The solid line in each of the plots is the (CPT conserving) $\delta b = 0$ case, shown for comparison. The overall shape and position of this (solid) curve is representative of the ratio of the two crosssections (ν vs $\bar{\nu}$) at the relatively low (few GeV) energies which dominate the event-rates. The small wiggles and variations are a result of the various energies and lengths involved and angular differences in fluxes which characterize the overall atmospheric neutrino spectrum.

From the expression for $\Delta P_{\alpha\alpha}$, we see that the CPTV difference in probabilities will become zero whenever $\delta b L = n\pi$ (n=integer), resulting in a node (*i.e.* an intersection with the $\delta b = 0$ curve). The positions and the number of nodes for the various curves nicely correspond to these expected "zeros" of CPTV and also provide a way of distinguishing between them. Clearly, parameter values of the order of $\delta b = 3 \times 10^{-22}$ GeV should be discernible in these observations.

In Figure 2, we plot the same ratio of event-rates vs L/E. The nodal position is now dictated by the term $\sin(\delta m^2 L/2E)$, resulting in a common node for the various δb values at $\delta m^2 L/2E = n\pi$. The plots also show a significant dip near $L/E \simeq 310$ km/GeV. This is explained by the fact that $\delta m^2 L/4E = \pi/4$ for this value. In the the expression for $P_{\alpha\alpha}$, the sine function has its maximum slope at this value of its argument, and hence the survival probabilities for ν and $\bar{\nu}$ differ maximally here due to the sign difference of the δb terms, providing highest sensitivity to the presence of CPTV parameters. We note that in the vicinity of the dip the antineutrino event-rate increases and the neutrino rate decreases, which consequently tends to reduce the statistical error in the ratio, aiding detection. This set of curves provides heightened sensitivity to the *presence* of CPTV, without the same discriminating sensitivity (between various δb values) of the plots in Figure 1. For instance, CPTV induced by parameter values as low as $\delta b = 3 \times 10^{-23}$ GeV can be detected.

5 Conclusions

Atmospheric neutrinos in a detector capable of measuring muon energy and direction and identifying its charge can allow us to set significant bounds on all types of CPTV in the neutrino sector. These bounds compare very favourably with those possible from future neutrino factories [5]. Specifically, the charge discrimination capability of such a detector when coupled with the significant L and E ranges which characterize the atmospheric neutrino spectrum provides a potent and sensitive probe of such violations. By calculating the ratios of muon and anti-muon events and studying their variation with L and L/E we have shown that the presence of CPTV can be detected provided $\delta b > 3 \times 10^{-23}$ GeV. For somewhat higher values of δb, it is also possible to obtain a measure of their magnitudes by studying their minima and zeros as discussed in the text.

Acknowledgements: S. Uma Sankar would like to thank the organizers of ICHEP-04 for the oppurtunity to give this talk. He also thanks I.I.T. Bombay for financial support which made his trip possible.

References

1. J. Bjorken and Sidney D. Drell, *Relativistic Quantum fields*(McGraw Hill, 1965), p. 143; Steven Weinberg, *The quantum theory of fields* (Cambridge University Press, 1995), p. 244 and references therein.
2. O. W. Greenberg, Phys. Rev. Lett. **89**, 231602 (2002) [arXiv:hep-ph/0201258];
3. For a recent review, *see* V. Barger, D. Marfatia and K. Whisnant, Int. J. Mod. Phys. E **12**, 569 (2003) [arXiv:hep-ph/0308123].
4. D. Colladay and V. A. Kostelecky, Phys. Rev. D **55**, 6760 (1997) [arXiv:hep-ph/9703464].
5. V. D. Barger *et al.*, Phys. Rev. Lett. **85**, 5055 (2000) [arXiv:hep-ph/0005197].
6. S. Pakvasa, [arXiv:hep-ph/0110175];
7. C. Albright *et al.*, [arXiv:hep-ex/0008064]; S. Geer, Comments Nucl. Part. Phys. A **2**, 284 (2002) [arXiv:hep-ph/0008155].
8. N. Y. Agafonova *et al.* [MONOLITH Collaboration], see http://castore.mi.infn.it/~monolith/
9. See http://www.imsc.res.in/~ino; and working reports and talks therein.
10. M. Apollonio *et al.* [CHOOZ Collaboration], Phys. Lett. B **466**, 415 (1999) [arXiv:hep-ex/9907037].
11. G. L. Fogli *et al.*, [arXiv:hep-ph/0308055].
12. V. Agrawal, T. K. Gaisser, P. Lipari and T. Stanev, Phys. Rev. D **53**, 1314 (1996) [arXiv:hep-ph/9509423].
13. H. L. Lai *et al.*, Phys. Rev. D **55**, 1280 (1997) [arXiv:hep-ph/9606399].