

## Search for exotic contributions to atmospheric neutrino oscillations

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The energy spectrum of neutrino-induced upward-going muons in MACRO was analysed in terms of relativity principles violating effects, keeping standard mass-induced atmospheric neutrino oscillations as the dominant source of  $\nu_\mu \rightarrow \nu_\tau$  transitions. The data disfavor these possibilities even at a sub-dominant level; stringent 90% C.L. limits are placed on the Lorentz invariance violation parameter  $|\Delta v| < 6 \times 10^{-24}$  at  $\sin 2\theta_v = 0$  and  $|\Delta v| < 2.5 \div 5 \times 10^{-26}$  at  $\sin 2\theta_v = \pm 1$ . The limits can be re-interpreted as bounds on the Equivalence Principle violation parameters.

### 1. Introduction

The phenomenon of neutrino flavor oscillations, induced by flavor-mass eigenstate mixing, is considered the favored solution for solar and atmospheric neutrino data [1]-[5] over a wide range of alternative solutions [6]-[14]. These latter mechanisms were considered under the hypothesis that each one of them solely accounts for the observed effects. Here we address the possibility of a mixed scenario: one mechanism, the mass-induced flavor oscillations, is dominant and a second mechanism is included as sub-dominant: it could be neutrino flavor transitions induced by violations of relativity principles, i.e. violation of the Lorentz invariance (VLI) or of the equivalence principle (VEP). In this mixed scenario, assuming that neutrinos can be described in terms of three distinct bases - flavor, mass and velocity eigenstates - the latter being characterized by different maximum attainable velocities (MAVs), and by considering that only two families contribute to the atmospheric  $\nu$  violation oscillations, the  $\nu_\mu$  survival probability can be expressed as [10]-[12]

$$P_{\nu_\mu \rightarrow \nu_\mu} = 1 - \sin^2 2\Theta \sin^2 \Omega \quad (1)$$

where the global mixing angle  $\Theta$  and the term  $\Omega$  are given by:

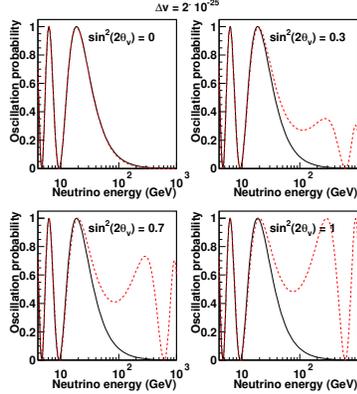
$$2\Theta = \arctan(a_1/a_2), \quad \Omega = \sqrt{(a_1^2 + a_2^2)}. \quad (2)$$

The terms  $a_1$  and  $a_2$  in Eq. (2) contain the relevant physical information

$$\begin{aligned} a_1 &= 1.27 |\Delta m^2 \sin 2\theta_m L/E + 2 \cdot 10^{18} \Delta v \sin 2\theta_v L E e^{i\eta}| \\ a_2 &= 1.27 (\Delta m^2 \cos 2\theta_m L/E + 2 \cdot 10^{18} \Delta v \cos 2\theta_v L E), \end{aligned} \quad (3)$$

where the muon neutrino pathlength  $L$  is expressed in km, the neutrino energy  $E$  in GeV and the oscillation parameters  $\Delta m^2 = m_{\nu_3}^2 - m_{\nu_2}^2$  and  $\Delta v = v_{\nu_3} - v_{\nu_2}$  are in  $\text{eV}^2$  and  $c$  units, respectively. The unconstrained phase  $\eta$  refers to the connection between mass and velocity eigenstates. The whole domain of variability of the parameters can be accessed with the requirements  $\Delta m^2 \geq 0$ ,  $0 \leq \theta_m \leq \pi/2$ ,  $\Delta v \geq 0$  and  $-\pi/4 \leq \theta_v \leq \pi/4$ .

The same formalism also applies to violation of the equivalence principle, after substituting  $\Delta v/2$  with the adimensional product  $|\phi|\Delta\gamma$ ;  $\Delta\gamma$  is the difference of the coupling constants for neutrinos of different types to the gravitational potential  $\phi$  [15].



**Figure 1.** Energy dependence of the  $\nu_\mu \rightarrow \nu_\tau$  oscillation probability for mass induced oscillations alone (continuous curves), and mass-induced + VLI oscillations for  $\Delta v = 2 \times 10^{-25}$  and different values of the  $\sin^2 2\theta_v$  parameter (dashed curves). The neutrino pathlength was fixed at  $L = 10^4$  km.

As shown in [11, 12, 16], the most sensitive tests of VLI can be made by analysing the high energy tail of atmospheric neutrinos at large pathlengths values. Fig. 1 shows the energy dependence of the  $\nu_\mu \rightarrow \nu_\tau$  oscillation probability as a function of the neutrino energy, for neutrino mass-induced oscillations alone and for both mass and VLI-induced oscillations.

## 2. Exotic contributions to mass-induced oscillations

In order to analyze the MACRO data in terms of VLI, we used the subsample of 300 upward-throughgoing muons whose energies were estimated via Multiple Coulomb Scattering [17]-[18]. Two independent and complementary analyzes have been carried out: one based on the  $\chi^2$  criterion and the Feldman and Cousins prescription [19], and a second one based on the maximum likelihood technique [20].

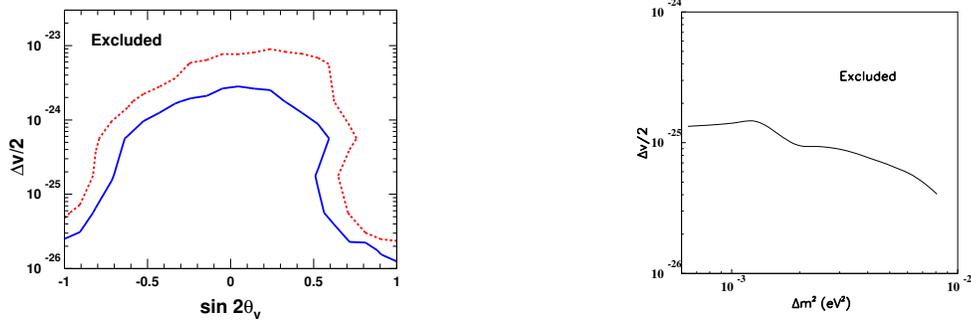
### 2.1 $\chi^2$ Analysis

Following the analysis in [18], we selected a low and a high energy sample by requiring that the reconstructed neutrino energy  $E_\nu^{rec}$  should be  $E_\nu^{rec} < 30$  GeV and  $E_\nu^{rec} > 130$  GeV. The number of events surviving these cuts is  $N_{low} = 49$  and  $N_{high} = 58$ ; their median energies, estimated via Monte Carlo, are 13 GeV and 204 GeV (assuming mass-induced oscillations). We then keep the neutrino mass oscillation parameters fixed at the values of [3]. The factor  $e^{i\eta}$  is assumed to be real ( $\eta = 0$  or  $\pi$ ). Then, we scanned the plane of the 2 free parameters ( $\Delta v, \theta_v$ ) minimizing the  $\chi^2$  function comprehensive of statistical and systematic uncertainties [20]. For the Monte Carlo simulation described in [18] the neutrino fluxes in input is given by [21]. The largest relative difference of the extreme values of the MC expected ratio  $N_{low}/N_{high}$  is 13%. However, in the evaluation of the systematic error, the main sources of uncertainties for this ratio (namely the primary cosmic ray spectral index and neutrino cross sections) have been separately estimated and their effects added in quadrature (see [18] for details): in this work, we use a conservative 16% theoretical systematic error on the ratio  $N_{low}/N_{high}$ . The experimental systematic error on the ratio was estimated to be 6%. The inclusion of the VLI effect does not improve the  $\chi^2$  in any point of the ( $\Delta v, \theta_v$ ) plane, compared to mass-induced oscillations stand-alone, and limits on VLI parameters were obtained. The 90% C.L. limits on  $\Delta v$  and  $\theta_v$ , computed with the Feldman

and Cousins prescription [19], are shown by the dashed line in Fig. 2-left. The energy cuts described above were optimized for mass-induced neutrino oscillations. In order to maximize the sensitivity of the analysis for VLI induced oscillations, we performed a blind analysis, based only on Monte Carlo events, to determine the energy cuts which yield the best performances. The results of this study suggest the cuts  $E_\nu^{rec} < 28$  GeV and  $E_\nu^{rec} > 142$  GeV; with these cuts the number of events in the real data are  $N_{low}^l = 44$  events and  $N_{high}^l = 35$  events. The limits obtained with this selection are shown in Fig. 2-left by the continuous line. As expected, the limits are now more stringent than for the previous choice. In order to understand the dependence of this result with respect to the choice of the  $\overline{\Delta m^2}$  parameter, we varied them around the best-fit point. We found that a variation of  $\overline{\Delta m^2}$  of  $\pm 30\%$  moves up/down the upper limit of VLI parameters by at most a factor 2. Finally, we computed the limit on  $\Delta v$  marginalized with respect to all the other parameters left free to change inside the intervals:  $\Delta m^2 = \overline{\Delta m^2} \pm 30\%$ ,  $\theta_m = \overline{\theta}_m \pm 20\%$ ,  $-\pi/4 \leq \theta_v \leq \pi/4$  and any value of the phase  $\eta$ . We obtained the 90% C.L. upper limit  $|\Delta v| < 3 \times 10^{-25}$ .

## 2.2 Maximum Likelihood Analysis (MLT)

A different and complementary analysis of VLI contributions to the atmospheric neutrino oscillations was made on the MACRO muon data corresponding to parent neutrino energies in the range  $25 \text{ GeV} \leq E \leq 75 \text{ GeV}$ . This energy region is characterized by the best energy reconstruction, and the number of muons satisfying this selection is 106. These events are outside the energy ranges used in the analysis discussed in Section 2.1, and thus the expected sensitivity to VLI (or VEP) contributions to the atmospheric neutrino oscillations should be lower; on the other hand, the maximum likelihood technique (MLT) has the advantage to exploit the information event-by-event (it is a bin-free approach). Given a specific hypothesis, MLT allows to determine the set of parameters  $\mathbf{a} = (\Delta m^2, \theta_m, \Delta v, \theta_v)$  that maximizes the probability of the realization of the actual measurements  $\mathbf{x} = (E, L)$ ; it was accomplished by minimizing negative a log-likelihood function  $\mathcal{L}$  [22]. We have chosen different fixed values of the  $\Delta m^2$  and  $\sin^2 2\theta_m$  mass-oscillation parameters in [3] and found the relative  $\Delta v$  and  $\sin^2 2\theta_v$  that maximize the  $f(\mathbf{x}_i; \mathbf{a})$  function proportional to the probability of realization of a given event. Fig. 2 shows the 90% CL upper of the VLI parameter  $\Delta v/2$  versus the assumed  $\Delta m^2$  values.



**Figure 2.** -left: 90% C.L. upper limits on the Lorentz invariance violation parameter  $\Delta v$  versus  $\sin 2\theta_v$ . Mass induced oscillations are assumed in the two-flavor  $\nu_\mu \rightarrow \nu_\tau$  approximation, with  $\Delta m^2 = 0.0023 \text{ eV}^2$  and  $\theta_m = \pi/4$ . The dashed line shows the limit obtained with the same selection criteria of Ref. [18] to define the low and high energy samples; the continuous line is the result obtained with the selection criteria optimized for the present analysis (see text). -right: 90% CL upper limits on the  $\Delta v/2$  parameter versus  $\Delta m^2$  varying inside the 90% CL MACRO global result [3].

### 3. Conclusions

We have searched for “exotic” contributions to standard mass-induced atmospheric neutrino oscillations arising from a possible violation of Lorentz invariance using two different and complementary analyses. The first approach uses two sub-sets of events referred to as the low energy and the high energy samples. The mass neutrino oscillation parameters have the values of [3], and we mapped the evolution of the  $\chi^2$  estimator in the plane of the VLI parameters,  $\Delta v$  and  $\sin^2 2\theta_v$ . No  $\chi^2$  improvement was found, so we applied the Feldman Cousins method to determine 90% CL limits on the VLI parameters:  $|\Delta v| < 6 \times 10^{-24}$  at  $\sin 2\theta_v = 0$  and  $|\Delta v| < 2.5 \div 5 \times 10^{-26}$  at  $\sin 2\theta_v = \pm 1$ . In terms of the parameter  $\Delta v$  alone (marginalization with respect to all the other parameters), the VLI parameter bound is (at 90% C.L.)  $|\Delta v| < 3 \times 10^{-25}$ . These results may be reinterpreted in terms of 90% C.L. limits of parameters connected with violation of the equivalence principle, giving the limit  $|\phi\Delta\gamma| < 1.5 \times 10^{-25}$ . The second approach exploits the information contained in a data sub-set characterized by intermediate muon energies. It is based on the MLT, and considers the mass neutrino oscillation parameters inside the 90% border of the global result [3]. The obtained 90% CL limit on the  $\Delta v$  VLI parameter is also around  $10^{-25}$ .

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