MACRO constraints on violation of Lorentz invariance

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The energy spectrum of neutrino-induced upward-going muons in MACRO has been 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 exotic possibilities even at a sub-dominant level, and 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 $\sin 2\theta_v = \pm 1$. These limits can also be re-interpreted as upper bounds on the parameters describing violation of the Equivalence Principle.

1. Introduction

Neutrino mass-induced oscillations are the best explanation of the atmospheric neutrino problem [1234]. Two flavor $\nu_\mu \rightarrow \nu_\tau$ oscillations are strongly favored over a wide range of alternative solutions [567891011]. These alternative mechanisms have been considered under the hypothesis that each one of them solely accounts for the observed effects. We address the possibility of a mixed scenario: one mechanism, the mass-induced flavor oscillations, is considered dominant and a second mechanism is included in competition with the former. We studied, as sub-dominant mechanism, 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, we assume that neutrinos can be described in terms of three distinct bases: flavor eigenstates, mass eigenstates and velocity eigenstates, the latter being characterized by different maximum attainable velocities (MAVs), and consider that only two families contribute to the atmospheric neutrino oscillations. When both mass-induced and VLI-induced neutrino oscillations are considered simultaneously, the $\nu_\mu$ survival probability can be expressed as [910]

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

(1)

where $\Theta$ and $\Omega$ are given by:

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

The terms $a_1$ and $a_2$ contain the relevant physical information and 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 functional form of the oscillation probabilities for mass induced (VLI induced) oscillations exhibits an $L/E_\nu$ ($L/E_\nu$) dependence on the neutrino energies and pathlengths respectively. 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 $\phi$ [12].

As shown in [10], the most sensitive tests of VLI can be made by analysing the high energy tail of atmospheric neutrinos at large pathlength values. As an example, Fig. 1 shows the energy dependence of the $\nu_\mu \rightarrow \nu_\mu$ survival probability as a function of the neutrino energy, for neutrino mass-induced oscillations alone and for both mass and VLI-induced oscillations for $\Delta v = 2 \times 10^{-25}$ and $\sin^2 2\theta_v = \pm 1$. Notice that for $m_\nu \leq 1$ eV, neutrinos with energies larger than 100 GeV are extremely relativistic, with Lorentz $\gamma$ factors larger than $10^{11}$.

2. Experimental data and analysis

In order to analyse the MACRO data in terms of VLI, we used a subsample of 300 upward-throughgoing muons whose energies were estimated via multiple Coulomb scattering in the 7
living these cuts is proceeds by fixing the neutrino mass oscillation mass-induced oscillations). The analysis then Monte Carlo, are 13 GeV and 204 GeV (assum-

\( E_{\nu} < E_{\nu}^{\text{rec}} \) and \( E_{\nu}^{\text{rec}} > 130 \) GeV. The number of events surviving these cuts is \( N_{\text{low}} = 49 \) and \( N_{\text{high}} = 58 \), respectively; their median energies, estimated via Monte Carlo, are 13 GeV and 204 GeV (assuming mass-induced oscillations). The analysis then proceeds by fixing the neutrino mass oscillation parameters at the values of [2]. Then, we scanned the plane of the two free parameters \((\Delta \nu, \theta_v)\) minimizing the \( \chi^2 \) function comprehensive of statistical and systematic uncertainties [15]. For the Monte Carlo simulation described in [14] the neutrino fluxes in input is given by [16]. The largest relative difference of the extreme values of the MC expected ratio \( N_{\text{low}}/N_{\text{high}} \) 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 [14] for details): in this work, we use a conservative 16% theoretical systematic error on the ratio \( N_{\text{low}}/N_{\text{high}} \). 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 \((\Delta \nu, \theta_v)\) plane, compared to mass-induced oscillations stand-alone, and proper upper limits on VLI parameters were obtained. The 90% C.L. limits on \( \Delta \nu \) and \( \theta_v \), computed with the Feldman and Cousins prescription [17], are shown by the dashed line in Fig. 2. The energy cuts described above (the same used in Ref. [14]) 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 \( E_{\nu}^{\text{rec}} < 28 \) GeV and \( E_{\nu}^{\text{rec}} > 142 \) GeV; with these cuts the number of events in the real data are \( N'_{\text{low}} = 44 \) events and \( N'_{\text{high}} = 35 \) events. The limits obtained with this selection are shown in Fig. 2 by the continuous line. As expected, the limits are now more stringent than for the previous choice.

An independent and complementary analysis was performed on a sample of events with a re-

constructed neutrino energy 25 GeV < \( E_{\nu}^{\text{rec}} < 75 \) GeV. The number of events satisfying this condition is 106. A negative log-likelihood function was built event by event and then fitted to the data. We allowed mass-induced oscillation parameters to vary inside the MACRO 90% C.L. region and we left VLI parameters free in the whole \((\Delta \nu, \theta_v)\) plane. The upper limit on the \( \Delta \nu \) parameter re-
sulting from this analysis is slowly varying with $\Delta m^2$ and is of the order of $\approx 10^{-25}$.

3. Conclusions

We have searched for “exotic” contributions to standard mass-induced atmospheric neutrino oscillations arising from a possible violation of Lorentz invariance. Two different and complementary analyses were performed on the data, both of them yielding compatible upper limits for the VLI contribution. We used a subsample of MACRO muon events for which an energy measurement was made via multiple Coulomb scattering. The inclusion of VLI effects does not improve the fit to the data, and we conclude that these effects are disfavored even at the sub-dominant level [15]. The VLI parameter bound is (at 90% C.L.) $|\Delta \nu| < 3 \times 10^{-25}$. This result may be reinterpreted in terms of 90% C.L. limits of parameters connected with violation of the equivalence principle, giving the limit $|\delta \Delta \gamma| < 1.5 \times 10^{-25}$. The second approach exploits the information contained in a data sub-set characterized by intermediate muon energies. It is based on the maximum likelihood technique, and considers the mass neutrino oscillation parameters inside the 90% border of the global result [2]. The obtained 90% CL upper limit on the $\Delta \nu$ VLI parameter versus the assumed $\Delta m^2$ values is also around $10^{-25}$. The limits reported in this paper are comparable to those estimated using Super-Kamiokande and K2K data [9].

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