Effects of new physics in neutrino oscillations in matter

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Abstract. A new flavor changing electron neutrino interaction with matter would always dominate the ν_e oscillation probability at sufficiently high neutrino energies. Being suppressed by θ_{13}, the energy scale at which the new effect starts to be relevant may be within the reach of realistic experiments, where the peculiar dependence of the signal with energy could give rise to a clear signature in the $\nu_e \to \nu_\tau$ channel. The latter could be observed by means of a coarse large magnetized detector exploiting $\tau \to \mu$ decays. We discuss the possibility of identifying or constraining such effects with a high energy neutrino factory. We also comment on the model independent limits on them.

1. Introduction

We consider, from a model independent point of view, the possibility of measurable effects in a high intensity controlled neutrino experiment. As in all other cases, NP can give rise to corrections to the production or detection interaction [1, 2, 3], as well as to the interaction with matter during propagation [4, 5, 3, 6]. Here we are interested in the latter possibility. Effects in the production and detection processes may also play a role. The features of the two types of effects are quite different, which should make them relatively easy to disentangle. In fact, due to the geometrical L^{-2} suppression, the latter are best studied at a smaller baseline L [2], whereas in the former case the L^{-2} suppression is compensated (up to a certain L) by the unfolding of the oscillation. Moreover, the former effect exhibits a peculiar growth with the energy which, as we will see, may give rise to a noticeable signature. For a more detailed study, see [7]

2. The mixing matrix

The neutrino potential induced by $\nu_\alpha f \to \nu_\beta f$ interactions ($\alpha, \beta = e, \mu, \tau$ and f represents an electron or a up or down quark) can be parameterized as $V_{\alpha\beta} = \sqrt{2} G_F \epsilon_{\alpha\beta} N_e = \epsilon_{\alpha\beta} V$, where $V = \sqrt{2} G_F N_e$, N_e is the electron number density and $\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}| e^{i\phi_{\alpha\beta}}$ are small parameters satisfying $\epsilon_{\beta\alpha} = \epsilon^*_{\alpha\beta}$

The effective neutrino squared mass matrix ${M_{eff}}^2$ is then

$$ {M_{eff}}^2 = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + 2EV \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{\tau e} & \epsilon_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix} , \qquad (1) $$

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where E is the neutrino energy, U is the MNS mixing matrix in the usual parameterization and $\Delta m^2_{21} > 0$ is the smaller squared mass difference. The resonant energy of the MSW effect will occur for $E_{\rm res} \simeq 10\,{\rm GeV}\left(\frac{\Delta m^2_{31}}{2.5\cdot 10^{-3}\,{\rm eV}^2}\right)\left(\frac{1.65\,{\rm g\,cm}^3}{\rho\, Y_e}\right)$ where Y_e is the number of electrons per baryon in matter n_e/n_B. The $E/E_{\rm res}$ enhancement of matter effects allows even small ϵ parameters to have a role at sufficiently high energy. This may happen at accessible energies especially in the case of the $\epsilon_{\tau e}$ parameter, which is most weekly constrained — values of $\epsilon_{\tau e}$ as values of $\epsilon_{\tau e}$ as large as 0.1 are not excluded. From the experimental point of view, a study of the effect in the $\nu_e \leftrightarrow \nu_\tau$ channel through direct τ detection is certainly challenging. However, it is possible to take advantage of τ decays into muons to look for the effect in the spectrum of "wrong sign" muon events by means of a coarse neutrino detector with only muon identification capabilities (see e.g. [8]). Whereas a sizable $\epsilon_{\tau\mu}$ might also give rise to some effects, we focus here on $\epsilon_{\tau e}$ and set all the other $\epsilon_{\alpha\beta}$ parameters to zero in our numerical calculations. To the leading contributions in the large $E/E_{\rm res}$ limit, oscillations have the following simple expression,

$$P(\nu_e \to \nu_\tau) \sim 4\left|\epsilon_{\tau e} + \frac{E_{\rm res}}{E} c_{23} s_{13}\right|^2 \sin^2\frac{LV}{2} \tag{2}$$

$$P(\nu_e \to \nu_\mu) \sim 4\left|\epsilon_{\mu e} + \frac{E_{\rm res}}{E} s_{23} s_{13}\right|^2 \sin^2\frac{LV}{2} \tag{3}$$

(4)

where we included the leading $E_{\rm res}/E$ correction to the energy-independent amplitudes. We explicitly see that the oscillation probability is no longer suppressed any more by two powers of the energy but reaches instead a constant value $4|\epsilon|^2\sin^2(LV/2)$ at high energies. In an experiment at a Neutrino Factory, the effect of such an energy independent probability is enhanced by the growth with energy of the neutrino flux and of the neutrino cross section. This gives rise to a striking (approximately cubic before approaching the energy cut off) growth of the signal with energy.

3. Observable effects at a Neutrino Factory

In a Neutrino Factory, the cleanest experimental observable to measure neutrino oscillations is the appearance of wrong-sign muons, i.e. muons observed in the detector with a charge opposite to those circulating in the storage ring. Also $\nu_e \to \nu_\tau$ oscillations will contribute to this channel, via $\tau \to \mu$ decays (B.R. $\approx 17\%$), that will produce muons of the same sign of those coming directly from $\nu_e \to \nu_\mu$ oscillations. We already saw in the previous section that the presence of new physics in matter propagation could lead to a noticeable change of the $\nu_e \to \nu_\tau$ oscillation probability for large neutrino energies, especially for small values of θ_{13}. This effect will then be visible in the wrong-sign muon spectrum due to $\tau \to \mu$ decays.

The fact that the neutrino factory flux increases for large energies allows a precise exploration of the high-energy oscillation probability. In figure 3 we show spectra for wrong-sign muon events in a neutrino factory with 10^{21} muon decays and a 40 kt far detector. The large difference observable between normal matter propagation and FCI at high energy is almost only due to τ decays, since the very strong bound existing on $|\epsilon_{e\mu}|$ prevents any measurable effect from this parameter.

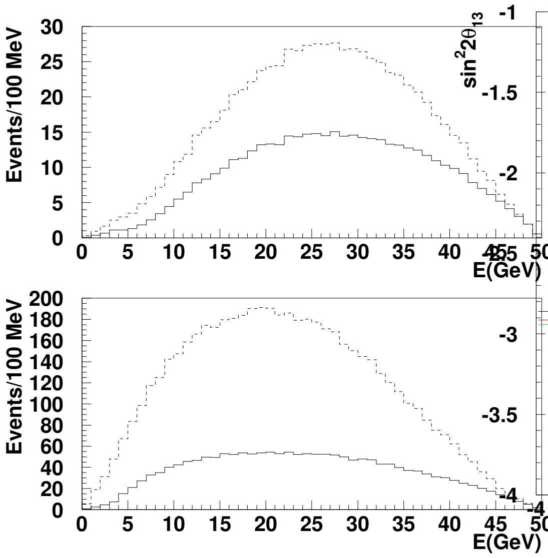

Figure 1. Observed visible energy spectrum for wrong-sign muon events in the case of μ^- (upper plot) and μ^+ (lower plot) circulating in the storage ring. The full histogram is the standard MSW case, the dashed histogram is in the presence of new interactions.

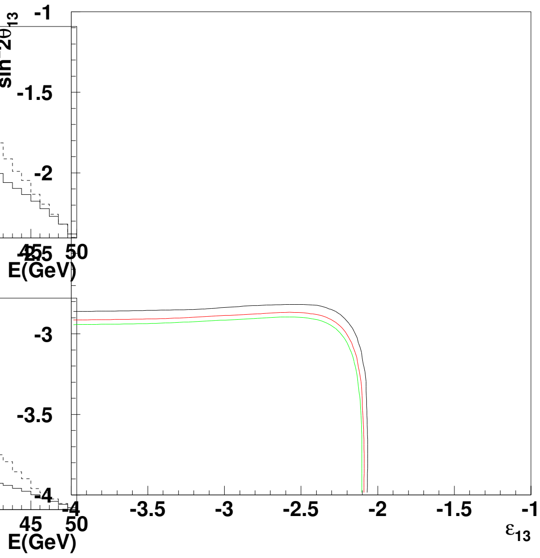

Figure 2. 99, 95 and 90% C.L contour in the plane $\sin^2 2\theta_{13}$, $\epsilon_{e\tau}$ of the possibility of distinguishing new physics from standard oscillations, extracting the oscillation parameter θ_{13} from the counting of the number of events and performing a χ^2 test on the spectral shape.

In presence of new effects, one wonders whether it is possible to measure both the new physics parameters, in our case $\epsilon_{\tau e}$, and the oscillation parameters, in particular s_{13}. The spectral information is essential for this purpose. Only counting the number of wrong-sign muons will lead to the impossibility of correctly interpreting the observed neutrino transitions in the case of new physics. The role of $\tau \to \mu$ decays is crucial here. If they were neglected and only direct $\nu_e \to \nu_\mu$ transitions were considered, a confusion would arise between $\epsilon_{\tau e}$ and θ_{13} even if the spectral information were taken into account [5, 6].

To be more general, figure 2 shows 90% C.L. contours for observing FCI effects for values of $|\epsilon_{e\tau}|$ in the range $10^{-4} - 10^{-2}$, and $\sin^2 2\theta_{13}$ between $5 \times 10^{-5} - 10^{-2}$.

4. Conclusions

We have considered the effects of a possible new flavor-changing interaction affecting the propagation of electron neutrinos in matter. We studied the problem in a quantitative way, assuming a coarse magnetized iron detector, and observed that, for new physics close to the present experimental bounds, a noticeable signal could be observed in $\nu_e \to \nu_\tau$ transitions, exploiting the wrong-sign muons produced in $\tau \to \mu$ decays.

[1] A. Bueno et al., JHEP 06 (2001) 032, hep-ph/0010308.
I.I.Y. Bigi et al., (2001), hep-ph/0106177.
NuTeV, J.A. Formaggio et al., Phys. Rev. Lett. 87 (2001) 071803, hep-ex/0104029.
A. Datta et al., Phys. Rev. D64 (2001) 015011, hep-ph/0011375.
[2] M.C. Gonzalez-Garcia et al., Phys. Rev. D64 (2001) 096006, hep-ph/0105159.
[3] T. Ota, J. Sato and N.a. Yamashita, (2001), hep-ph/0112329.
[4] A.M. Gago et al., Phys. Rev. D64 (2001) 073003, hep-ph/0105196.
P. Huber and J.W.F. Valle, Phys. Lett. B523 (2001) 151, hep-ph/0108193.
[5] P. Huber, T. Schwetz and J.W.F. Valle, (2001), hep-ph/0111224.
[6] P. Huber, T. Schwetz and J.W.F. Valle, (2002), hep-ph/0202048.
[7] M.Campanelli and A.Romanino, hep-ph/0207350, to be published on Phys. Rev. D
[8] A. Cervera et al., Nucl. Phys. B579 (2000) 17, hep-ph/0002108.