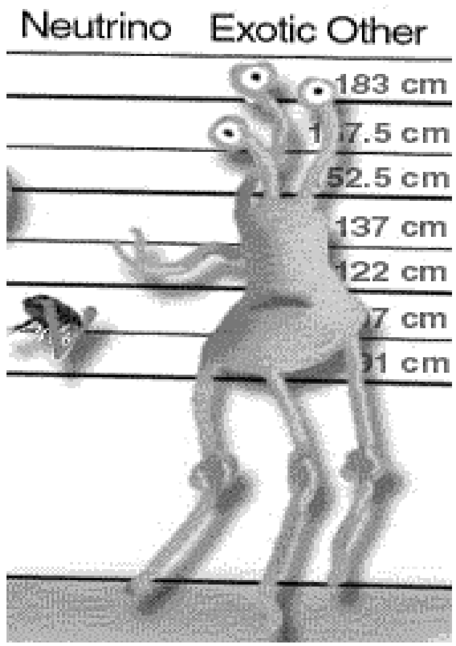
Effects of exotic interactions in Neutrino Oscillations in matter



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Introduction

As we know, the SM describes neutrino production and interaction, and the mixing with charged leptons and masses can be accounted for by non-renormalizable interactions

$h_{ij}(L_i H)(L_j H)/\Lambda$

No surprise if the ultra-violet completion of the SM (either SUSY or extra-dimension) would give observable low-energy effects.

Effects of new physics

New physics can arise in:

- Neutrino production
- Neutrino interactions
- Neutrino propagation in matter

I will describe in detail the latter case, since it is the most relevant to long-baseline neutrino experiments.

The first two cases are normally better studied in a short-baseline experiment, due to the higher flux; for the latter, the effect is of course more visible at longer distances, and the particular energy-dependent growth makes higher energies particularly appealing.

Theoretical background

Standard MSW effect gives rise to a diagonal contribution to the mixing matrix, proportional to neutrino energy.

The most natural way to express a flavor-changing interactions in matter propagation would be to consider non-diagonal terms in the effective matrix:

$$M_{eff}^2 = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^+ + 2EV \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix}$$

$$V = \sqrt{2} G_F N_e$$

$$\varepsilon_{\beta\alpha} = \varepsilon^*_{\alpha\beta(\alpha,\beta=e,\mu,\tau)}$$

Present limits on $\varepsilon_{\alpha\beta}$

A model-independent limit from atmospheric neutrinos yields $\varepsilon_{\mu\tau}<0.05$

Assuming that NP operators conserve $SU(2)_W$, stringent bounds can be extracted:

$$\varepsilon^{e}_{\mu e} < 10^{-6} \quad \varepsilon^{e}_{\tau\mu} < 3\cdot 10^{-3} \quad \varepsilon^{e}_{\tau e} < 4\cdot 10^{-3}$$
$$\varepsilon^{u,d}_{\mu e} < 10^{-5} \quad \varepsilon^{u,d}_{\tau\mu} < 10^{-2} \quad \varepsilon^{u,d}_{\tau e} < 10^{-2}$$

Since $SU(2)_W$ is broken (e.g. by a multiplet of bosons with $SU(2)_W$ breaking masses), the above limits can be relaxed up to a factor 7, and still be compatible with the EW data.

In a more general framework, non-diagonal terms can only be inferred from neutrino experiments, yielding weaker bounds, like

$$\varepsilon_{\mu e} < 0.05 \quad \varepsilon_{\tau e} < 0.1$$

Θ_{13} and new physics

To better understand the practical implications of the ε parameters on the oscillations, we write the effective mass matrix in the simplified form it takes when we assume

$\Delta m^2_{12}=0$, $\theta_{23}=\pi/4$, $\cos 2\theta_{13}=1$, $s_{13}\equiv\sin\theta_{13}e^{i\delta}$:

$$M^2_{eff}=\Delta m^2_{31}\begin{pmatrix} |s^2_{13}|^2+(E/E_{res})(1+\varepsilon_{ee}) & s^*_{13}/\sqrt{2}+(E/E_{res})\varepsilon^*_{\mu e} & s^*_{13}/\sqrt{2}+(E/E_{res})\varepsilon^*_{\tau e} \\ s_{13}/\sqrt{2}+(E/E_{res})\varepsilon_{\mu e} & 1/2+(E/E_{res})\varepsilon_{\mu e} & 1/2+(E/E_{res})\varepsilon^*_{\tau\mu} \\ s_{13}/\sqrt{2}+(E/E_{res})\varepsilon_{\tau e} & 1/2+(E/E_{res})\varepsilon_{\tau\mu} & 1/2+(E/E_{res})\varepsilon_{\tau\tau} \end{pmatrix}$$

$$E_{res}\cong 10GeV\left(\frac{\Delta m^2_{31}}{2.5\cdot 10^{-3}eV^2}\right)\left(\frac{1.65gcm^3}{\rho Y_e}\right)$$

Θ_{13} and new physics

The term (E/E_{res}) enhances the effect of the ε at high energy. For $\varepsilon_{\tau e}$ =0.1 (not excluded), at E=50 GeV the NP term corresponds to maximal Θ_{13}.

$\varepsilon_{\tau e}$ corresponds to $\sin\theta_{13} \cong 7\varepsilon(E/50\ \mathrm{GeV})$

In other words, NP terms overtake oscillations for

$$|\varepsilon| \geq \frac{|s_{13}|}{\sqrt{2}} \frac{E_{res}}{E_\mu}$$

For example, at E_μ=50 GeV, it becomes $|\varepsilon|>0.14|s_{13}|$

($|s_{13}|=0.05$ corresponds to $\sin^2 2\theta_{13}=10^{-2}$)

High-energy behavior

Oscillation probabilities in matter in the limit $E \gg E_{res}$:

Standard MSW: $\Delta m^2_{31} \propto 2\,EV$; $\sin^2 2\theta_{13} \propto (E_{res}/E)^2$

$$P(\nu_e \to \nu_\tau) \propto \left(\frac{E_{res}}{E}\right)^2 \cos^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{LV}{2}$$

$$P(\nu_e \to \nu_\mu) \propto \left(\frac{E_{res}}{E}\right)^2 \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{LV}{2}$$

New Physics: $s_{13} \to (E/E_{res})\, s_{13} + c_{23}\varepsilon_{\tau e} + s_{23}\,\varepsilon_{\mu e}$

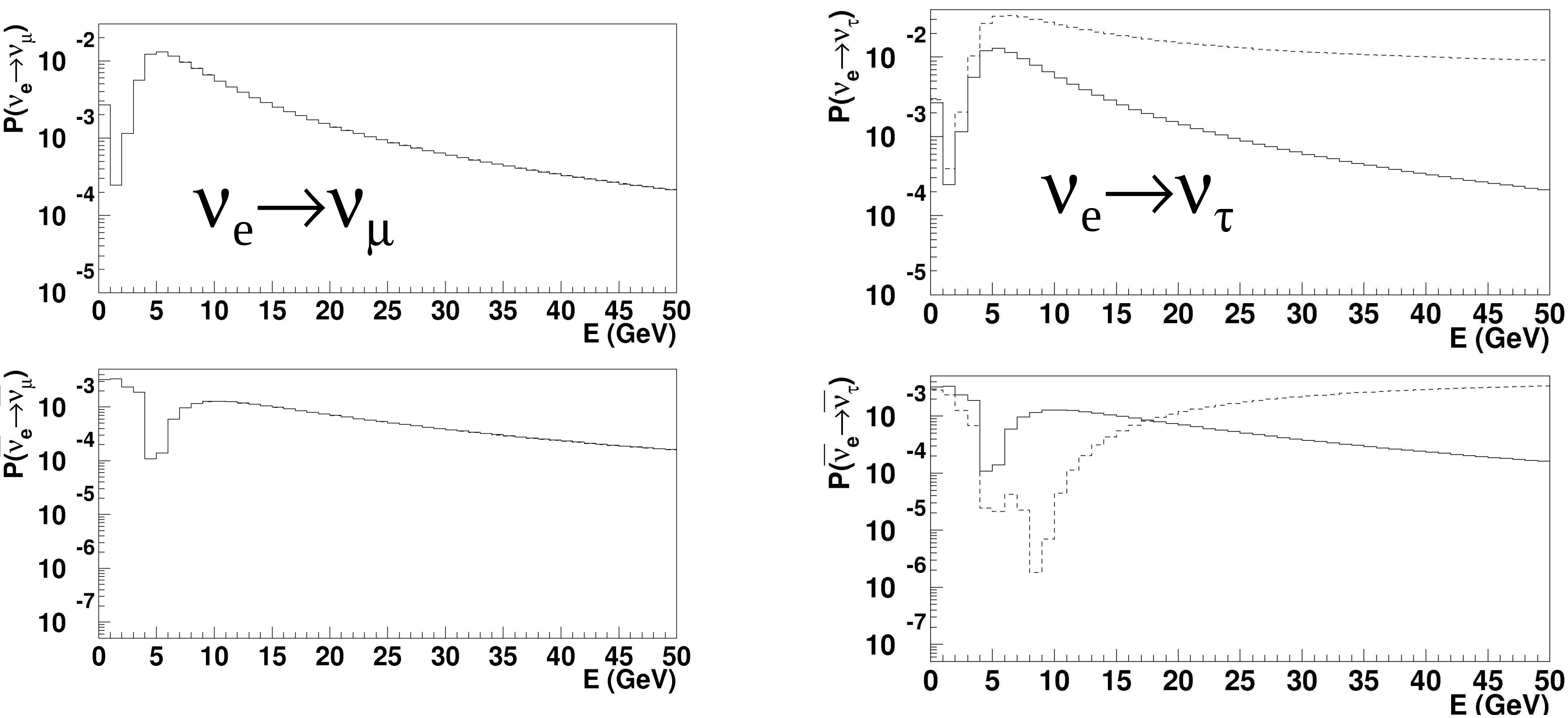
$$P(\nu_e \to \nu_\tau) \propto 4\left|\varepsilon_{\tau e} + \frac{E_{res}}{E} c_{23} s_{13}\right|^2 \sin^2 \frac{LV}{2}$$

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

Goes to $4|\varepsilon|^2 \sin^2 LV/2$ at high energy!

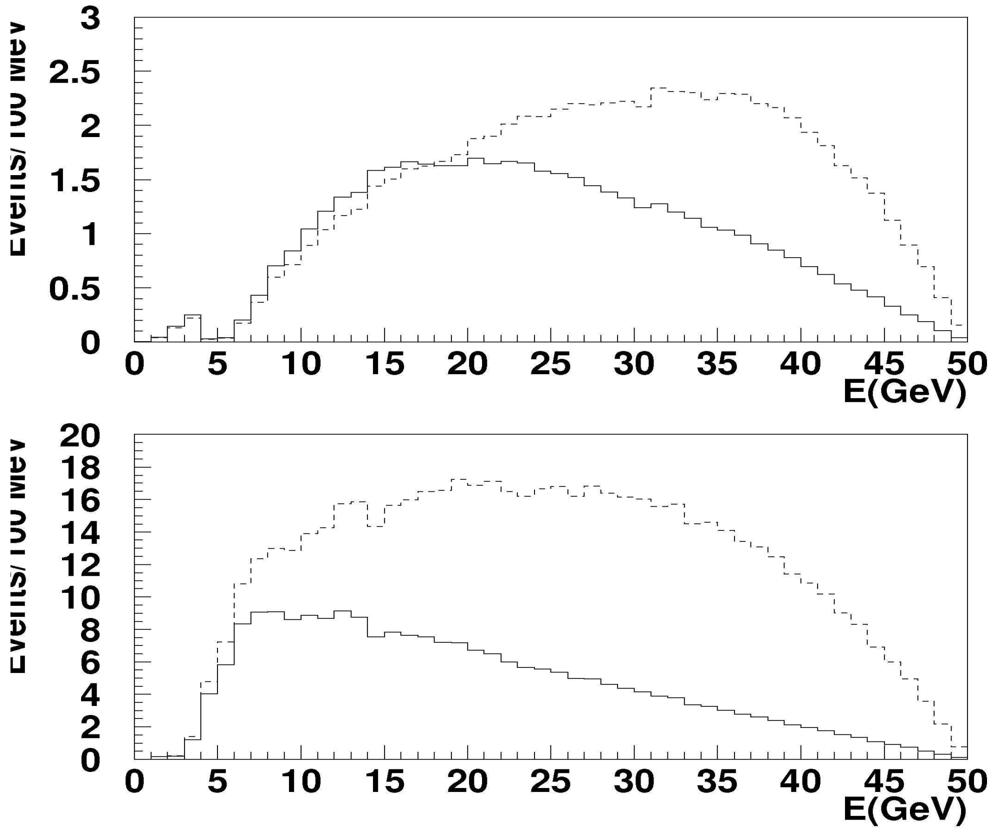
Oscillation probabilities

The very stringent bounds on $|\varepsilon_{e\mu}|$ make new physics effects very hard to detect in direct $\nu_e \rightarrow \nu_\mu$ oscillations. On the other hand, taking $|\varepsilon_{e\tau}|$ close to the boundaries produces dramatic effects:



Neutrino Factory

The peculiar increase of the oscillation with energy well matches the growth of the Neutrino Factory flux. From the experimental point of view a direct τ search is certainly challenging; however, it is possible to highlight the presence of new physics from $\tau \to \mu$ decays (18% of BR).



Muon energy spectrum shows clear variation and shift towards larger momenta

L=3000 km

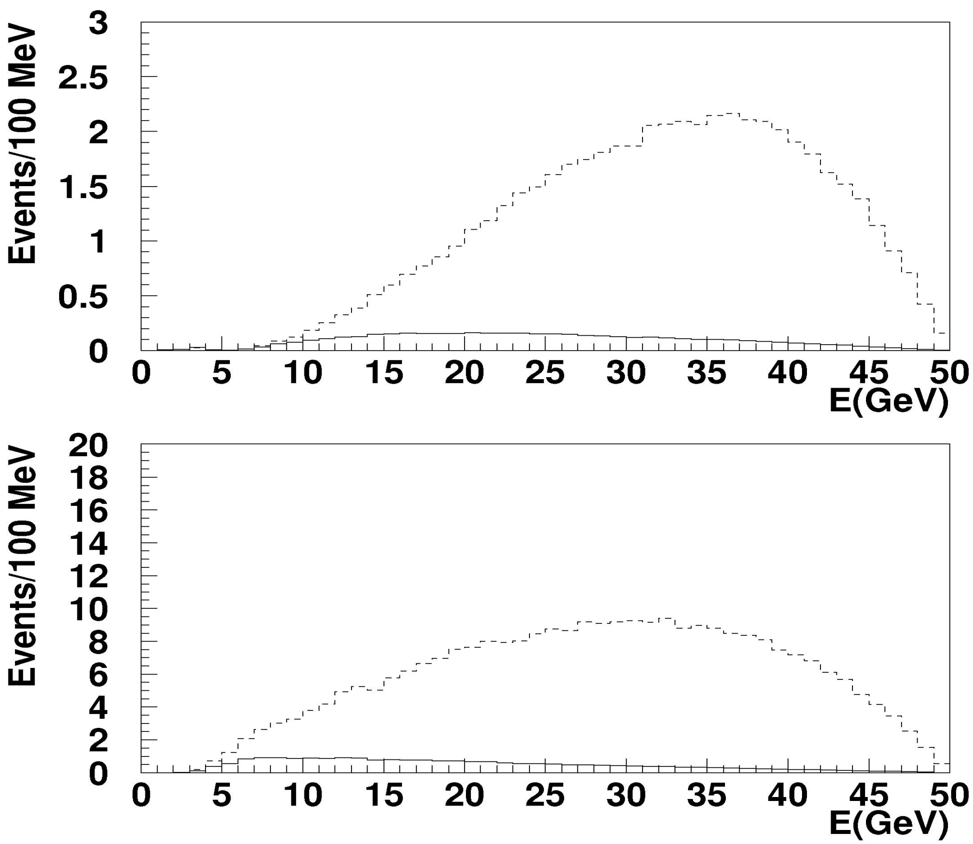
M=40 kt

$\sin^2 2\theta_{13} = 0.01$

$\varepsilon_{e\mu} = 7\ 10^{-2}$

Dependence on θ_{13}

A very interesting property is that new physics effects are much more visible for small values of θ_{13} , since oscillation probability stays constant, while it drops for standard MSW.



For instance, this is how the muon spectrum becomes for $\sin^2 2\,\theta_{13}=10^{-3}$. A comparison with the previous case (done for $\sin^2 2\,\theta_{13}=10^{-2}$) clearly shows that standard oscillations are suppressed, while non-standard interactions change very little

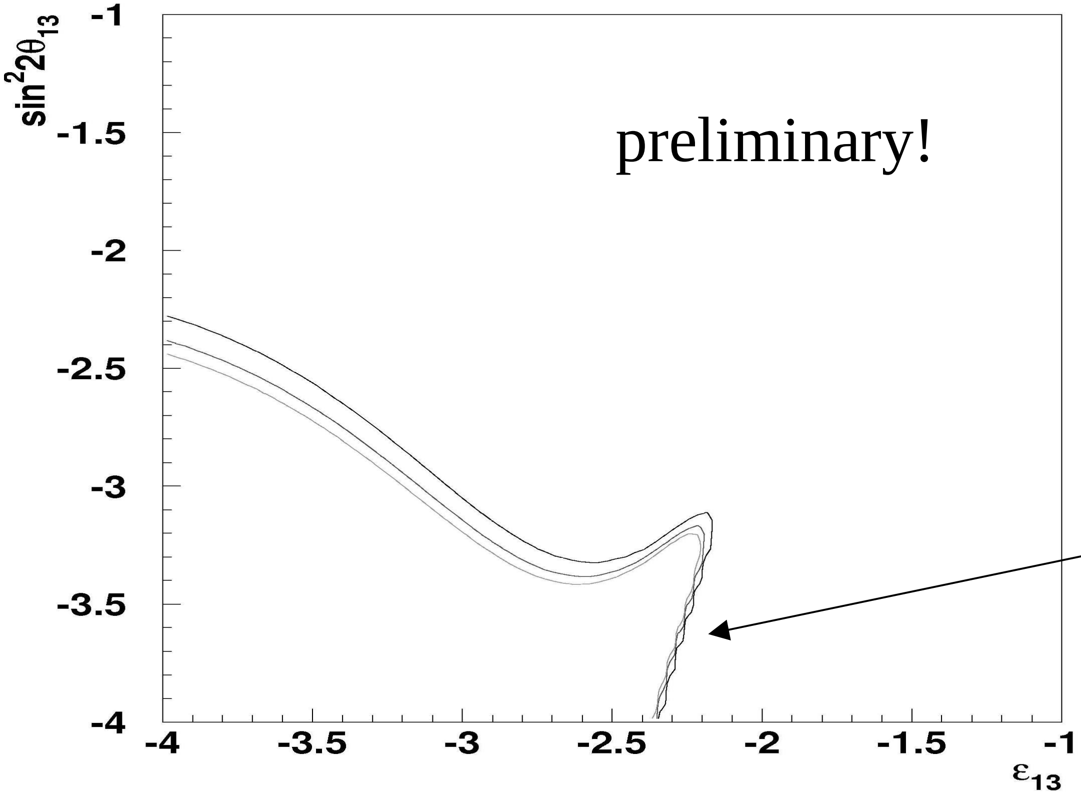
Discriminating new physics and standard oscillations

A very important point is: if new physics show up, will we be able to recognize it, or will we just measure a wrong value of $\sin^2 2\,\theta_{13}$?

Traditionally, new physics effects are considered as possible source of confusion for the measurement of the standard oscillation parameters (for instance, Huber et al. in hep-ph/0111224 and hep-ph/022048)

Distcriminating new physics and standard oscillations

We believe that a detector with muon momentum resolutions similar to those assumed for the neutrino factory could be able to disentangle the two effects using the energy spectrum of wrong-sign muons from $\tau \rightarrow \mu$ decays.



Use of a likelihood based on Poisson probabilities between the two wrong-sign muon spectra

Can go to very low values of θ_{13} , since we would still see "oscillations", but with a completely wrong spectrum

Conclusions (preliminary)

Neutrino oscillations are an obvious place for new interactions to show up at low energy.

Short-baseline experiments already have stringent limits on flavor-changing neutrino production and interactions, and the front-end of a neutrino factory will push much further these limits

Flavor-changing in matter interactions are not so much constrained since they require intense long-baseline beams, and would be mistaken as oscillations

However, the energy dependence of minimal non-standard interactions would be very different to that of neutrino oscillations, in particular we would not observe the classical probability drop with energy, therefore it would exploit the energy rise of the neutrino factory spectrum

Even an experiment looking at only wrong-sign muons would be able to distinguish them from standard oscillations comparing the spectral shape.