Accelerator neutrino oscillations in the case of non-standard interactions

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The Plan

1. Introduction
2. Theoretical descriptions of production, oscillation and detection proces in density matrix formalism
3. Numerical results for OPERA and NOνA
4. Summary

Introduction

Why?

- Neutrino sector of Standard Model
- Neutrino Oscillation - Physics beyond SM
- Nature of neutrino mass - νSM
- Solar, atmosferic, reactor experiments
- Accelerator experiments

New Physics models:

- SUSY
- theories with light (electroweak scale) leptoquark
- models with extra Higgs bosons,
- models with strong TeV scale gravitational interactions.

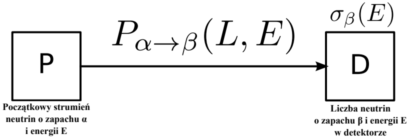
General Process

The general form of the process:

$$P_1 \xrightarrow{P} P_2 + \bar{l}_\alpha + (\nu_\alpha \xrightarrow{O} \nu_\beta) + D_1 \xrightarrow{D} D_2 + l_\beta$$

For SM factorization:

$$N_{\beta\alpha} = \text{flux}_\alpha \times P_{\beta\alpha} \times \sigma_\beta,$$



Effective CC lagrangian

$$\mathcal{L}_{CC}^{SM} = \frac{-\,e}{2\sqrt{2}\sin\theta_W} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_\alpha\, \gamma^\mu (1-\gamma_5)\varepsilon_L\, l^\alpha\, W_\mu^+ + \sum_{u,d} \bar{u}\, \gamma^\mu (1-\gamma_5)\varepsilon_L^q V_{ud}^*\, d\, W_\mu^+ + h.c.$$

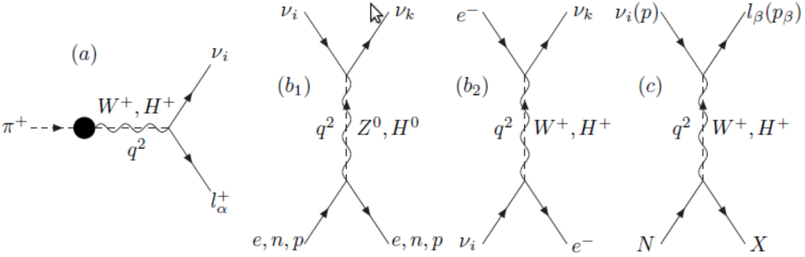
$$\begin{aligned}\mathcal{L}_{CC}^{NP} = \frac{-\,e}{2\sqrt{2}sin\theta_W} \Big\{ & \sum_{\alpha,i} \bar{\nu}_i \left[\gamma^\mu (1-\gamma_5)\varepsilon_L U_{\alpha i}^{L*} + \gamma^\mu (1+\gamma_5)\varepsilon_R U_{\alpha i}^{R*} \right] l_\alpha\, W_\mu^+ \\ & + \sum_{\alpha,i} \bar{\nu}_i \left[(1-\gamma_5)\eta_L V_{\alpha i}^{L*} + (1+\gamma_5)\eta_R V_{\alpha i}^{R*} \right] l_\alpha\, H^+ \\ & + \sum_{u,d} \bar{u} \left[\gamma^\mu (1-\gamma_5)\varepsilon_L^q V_{ud}^* + \gamma^\mu (1+\gamma_5)\varepsilon_R^q V_{ud}^* \right] d\, W_\mu^+ \\ & + \sum_{u,d} \bar{u} \left[(1-\gamma_5)\tau_L W_{ud}^{L*} + (1+\gamma_5)\tau_R W_{ud}^{R*} \right] d\, H^+ \Big\} + h.c.\end{aligned}$$

Effective NC lagrangian

$$\mathcal{L}_{NC}^{SM} = \frac{-\,e}{4\sin\theta_W\cos\theta_W}\sum_{\alpha=e,\mu,\tau}\bar{\nu}_\alpha\,\gamma^\mu(1-\gamma_5)\varepsilon_L^{N\nu}\,\nu_\alpha\,Z_\mu + \\ + \sum_{f=e,u,d}\bar{f}\,[\,\gamma^\mu(1-\gamma_5)\varepsilon_L^{Nf} + \gamma^\mu(1+\gamma_5)\varepsilon_R^{Nf}]\,f\,Z_\mu,$$

$$\mathcal{L}_{NC} = -\frac{e}{4sin\theta_W cos\theta_W}\Big\{\sum_{i,j}\bar{\nu}_i\,[\,\gamma^\mu(1-\gamma_5)\varepsilon_L^{N\nu}\delta_{ij} + \gamma^\mu(1+\gamma_5)\varepsilon_R^{N\nu}\Omega_{ij}^R]\,\nu_j\,Z_\mu + \\ + \sum_{i,j}\bar{\nu}_i\,[\,(1-\gamma_5)\eta_L^{N\nu}\Omega_{ij}^{NL} + (1+\gamma_5)\eta_R^{N\nu}\Omega_{ij}^{NR}]\,\nu_j\,H^0 + \\ + \sum_{f=e,u,d}\bar{f}\,[\,\gamma^\mu(1-\gamma_5)\varepsilon_L^{Nf} + \gamma^\mu(1+\gamma_5)\varepsilon_R^{Nf}]\,f\,Z_\mu + \\ + \sum_{f=e,u,d}\bar{f}\,[\,(1-\gamma_5)\eta_L^{Nf} + (1+\gamma_5)\eta_R^{Nf}]\,f\,H^0\Big\}.$$

Feynman diagrams



Production process: Pion decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Neutrino states

$$\varrho_P^\mu(\mathbf{p}, L=0) = \sum_{\lambda,\lambda'=\pm 1} \sum_{i,i'=1}^{3} |\mathbf{p}, \lambda, i\rangle \; \varrho_P^\mu(\mathbf{p}; \lambda, i; \lambda', i') \; \langle \mathbf{p}, \lambda', i'|$$

$$\varrho_P^\mu(\mathbf{p}; \lambda, i; \lambda', i') = \frac{1}{N} \sum_{\lambda_{\mu^+}} A_i^\mu(\mathbf{p}; \lambda_{\mu^+}, \lambda) \; A_{i'}^{\mu\,*}(\mathbf{p}, \lambda_{\mu^+}, \lambda').$$

$$\varrho^{LAB}(\vec{p}_{LAB}) = \varrho^{CM}(\vec{p}_{CM})$$

M. Ochman, R. Szafron, and M. Zralek. Neutrino production states in oscillation phenomena - are they pure or mixed? J.Phys.G 35,065003, 2008

The normalization factor N_α gives properly normalized density matrix

$$Tr(\varrho_P^\alpha) \equiv \sum_{\lambda=\pm 1} \sum_{i=1}^{3} \varrho_P^\alpha(\lambda, i; \lambda, i) = 1\,.$$

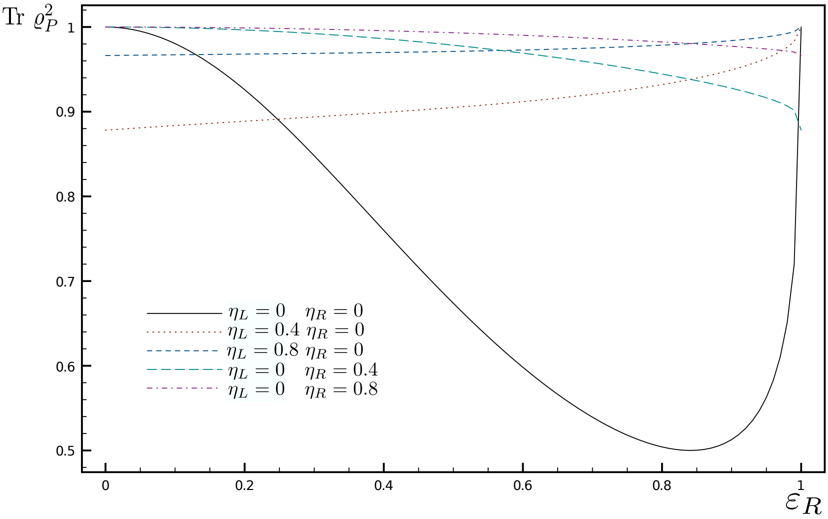
Neutrino states in the NP case

$$\begin{aligned}
\varrho_P^{\mu}(-1, i;\, -1, i') &= \frac{2}{N_\mu\, m_\pi^2}\, G_F^2\, \Big[\tilde{f}_\pi^2\, (W_{ud}^R)^2\, \eta_R^2\, V_{i\mu}^{R*}\, V_{i'\mu}^{R} + \\
&+ f_\pi^2\, m_\mu^2\, V_{ud}^2\, \varepsilon_L^2\, U_{i\mu}^{L*}\, U_{i'\mu}^{L} + \\
&+ f_\pi\, \tilde{f}_\pi\, V_{ud}\, W_{ud}^R\, \eta_R \varepsilon_L m_\mu\, (V_{i\mu}^{R*}\, U_{i'\mu}^{L} + U_{i\mu}^{L*}\, V_{i'\mu}^{R}) \Big]\, (m_\pi^2 - m_\mu^2),
\end{aligned}$$

$$\begin{aligned}
\varrho_P^{\mu}(+1, i;\, +1, i') &= \frac{2}{N_\mu\, m_\pi^2}\, G_F^2\, \Big[\tilde{f}_\pi^2\, (W_{ud}^L)^2\, \eta_L^2\, V_{i\mu}^{L*}\, V_{i'\mu}^{L} + \\
&+ f_\pi^2\, m_\mu^2\, V_{ud}^2\, \varepsilon_R^2\, U_{i\mu}^{R*}\, U_{i'\mu}^{R} + \\
&+ f_\pi\, \tilde{f}_\pi\, V_{ud}\, W_{ud}^L\, \eta_L \varepsilon_R m_\mu\, (V_{i\mu}^{L*}\, U_{i'\mu}^{R} + U_{i\mu}^{R*}\, V_{i'\mu}^{L}) \Big]\, (m_\pi^2 - m_\mu^2).
\end{aligned}$$

Scalar factors η_L, η_R bounds from R_{π^+}:

$$R_{e/\mu} \equiv \frac{\Gamma(\pi^+ \to e^+ \nu_e)}{\Gamma(\pi^+ \to \mu^+ \nu_\mu)}.$$


Tr ϱ_P^2
1
0.9
0.8
0.7
0.6
0.5
0
0.2
0.4
0.6
0.8
1
ε_R
$\eta_L = 0 \quad \eta_R = 0$
$\eta_L = 0.4 \ \eta_R = 0$
$\eta_L = 0.8 \ \eta_R = 0$
$\eta_L = 0 \quad \eta_R = 0.4$
$\eta_L = 0 \quad \eta_R = 0.8$

Oscilation - evolution

Requirement:

- non-dissipative homogeneous medium
- ultrarelativistic case $(L = T_L)$

the evolution rule for the statistical operator is as follows:

$$\rho_P^\alpha(L=0) \to \rho_P^\alpha(L \neq 0) =$$

$$= e^{-i\mathcal{H}\,L} \rho_P^\alpha(L=0)\; e^{i\mathcal{H}\,L}\,.$$

The effective Hamiltonian

The effective interaction Hamiltonian $\mathcal{H}_{eff}$ describes the coherent neutrino scattering inside matter.
The general structure of the effective low energy four-fermion interaction Hamiltonian is:

$$\mathcal{H}_{eff} = \sum_{f=e,p,n} \frac{G_F}{\sqrt{2}} \sum_{i,j} \sum_{a=V,A} (\bar{\nu}_i \Gamma^a \nu_j) \left[\bar{f}\, \Gamma_a \left(g^{ij}_{fa} + \bar{g}^{ij}_{fa} \gamma_5 \right) f \right]$$

where coefficients g^{ij}_{fa}, $\bar{g}^{ij}_{fa}$ we get from New Physics Lagrangians NC and CC (after Fierz rearragnement).

$$g_{fV}^{ij} = (g_{fV}^{L})_{ij} + (g_{fV}^{R})_{ij}, \qquad \bar{g}_{fV}^{ij} = (\bar{g}_{fV}^{L})_{ij} + (\bar{g}_{fV}^{R})_{ij},$$
$$g_{fA}^{ij} = (g_{fA}^{L})_{ij} + (g_{fA}^{R})_{ij}, \qquad \bar{g}_{fA}^{ij} = (\bar{g}_{fA}^{L})_{ij} + (\bar{g}_{fA}^{R})_{ij},$$

where

$$g_{fV}^{L} = g_f^{WL} + g_f^{HL} + g_f^{NL}, \qquad g_{fV}^{R} = g_f^{WR} + g_f^{HR} + g_f^{NR},$$
$$\bar{g}_{fV}^{L} = -g_f^{WL} - g_f^{HL} + \bar{g}_f^{NL}, \qquad \bar{g}_{fV}^{R} = g_f^{WR} + g_f^{HR} + \bar{g}_f^{NR},$$
$$g_{fA}^{L} = g_f^{WL} - g_f^{HL} - \bar{g}_f^{NL}, \qquad g_{fA}^{R} = g_f^{WR} - g_f^{HR} + \bar{g}_f^{NR},$$
$$\bar{g}_{fA}^{L} = -g_f^{WL} + g_f^{HL} - g_f^{NL}, \qquad \bar{g}_{fA}^{R} = g_f^{WR} - g_f^{HR} + g_f^{NR}.$$

g_f^{mn}	$n = L$	$n = R$
$m = W$	$\left\|\varepsilon_L^c\right\|^2 U_{ie}^{L*}\ U_{je}^{L}\ \delta^{fe}$	$\left\|\varepsilon_R^c\right\|^2 U_{ie}^{R*}\ U_{je}^{R}\ \delta^{fe}$
$m = H$	$\frac{1}{2}\eta_L\eta_R^* \frac{M_W^2}{M_H^2} V_{ie}^{L*} V_{je}^{R} \delta_{fe}$	$\frac{1}{2}\eta_R\eta_L^* \frac{M_W^2}{M_H^2} V_{ie}^{R*} V_{je}^{L} \delta_{fe}$
$m = N$	$\frac{\rho}{2}\varepsilon_L^{N\nu}\varepsilon_L^{Nf}\delta_{ij} + \frac{\rho}{2}\varepsilon_L^{N\nu}\varepsilon_R^{Nf}\delta_{ij}$	$\frac{\rho}{2}\varepsilon_R^{N\nu}\varepsilon_L^{Nf}\Omega_{ij}^R + \frac{\rho}{2}\varepsilon_R^{N\nu}\varepsilon_R^{Nf}\Omega_{ij}^R$
$\bar{g}_f^{Nn}$	$-\frac{\rho}{2}\varepsilon_L^{N\nu}\varepsilon_L^{Nf}\delta_{ij} + \frac{\rho}{2}\varepsilon_L^{N\nu}\varepsilon_R^{Nf}\delta_{ij}$	$-\frac{\rho}{2}\varepsilon_R^{N\nu}\varepsilon_L^{Nf}\Omega_{ij}^R + \frac{\rho}{2}\varepsilon_R^{N\nu}\varepsilon_R^{Nf}\Omega_{ij}^R$

$\varepsilon_R^{N\nu}$ from new Z' physics.

Oscillation in matter

For earth matter:

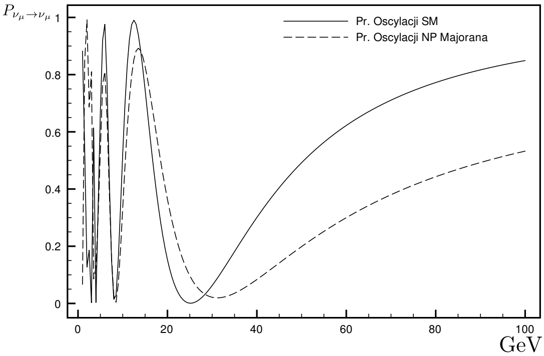
- not polarized, $\left\langle \frac{s^f_\mu}{E_f} \right\rangle = 0$,
- isotrophy $\langle \mathbf{k}_f \rangle = 0$, $\left\langle \frac{k^f_\mu}{E_f} \right\rangle n^\mu = 1$,
- neutral $N_p = N_e \neq N_n$

We obtain:

$$\mathcal{H}^D_{ij}\ (\lambda = -1) = \sqrt{2}\, G_F \sum_{f=e,n,p} N_f((g_f^{WL})_{ij} + (g_f^{NL})_{ij} + (g_f^{HR})_{ij}),$$

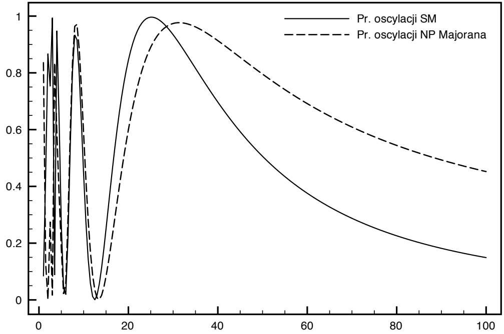
$$\mathcal{H}^M_{ij}(\lambda = -1) = \sqrt{2}\, G_F \sum_{f=e,n,p} N_f \Big((g_f^{WL})_{ij} + (g_f^{NL})_{ij} + (g_f^{HR})_{ij} + \\ -(g_f^{WR})^*_{ij} - (g_f^{NR})^*_{ij} - (g_f^{HL})^*_{ij}\Big)\,.$$

Numerical results



Probability distributions $\nu_\mu \to \nu_\mu$ - Majorana case $L = 13000$, $\varepsilon_R^{N\nu} = 0.1$

Numerical results



Probability distributions $\nu_\mu \rightarrow \nu_\tau$ - Majorana case $L = 13000$, $\varepsilon_R^{N\nu} = 0.1$

Detection process

The Detection process is:

$$\nu_i + N \longrightarrow l_\beta + X.$$

Assumptions:

- N is not polarized
- polarizations of the final particles are not measured
- For the ultrarelativistic neutrino, when $m_n \ll E_\nu < 150$ GeV in the LAB frame of the detection D, the form-factors of the nuclei could be neglected and nucleons = free particles.
- scattering on a particular nucleon via the CC interactions is mainly of the inclusive deep inelastic (DIS) kind.

Neglect the NP corrections to the CC interaction for the hadron part of the detection proces D: $\epsilon_R^q = \tau_L = \tau_R = 0$, $\sigma_{\beta\,\alpha}$ takes the form:

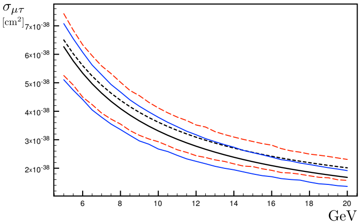
$$\frac{d\sigma_{\beta\;\alpha}}{d\Omega_\beta} = f_D \sum_{\substack{\lambda, i;\, \lambda', i' \\ \lambda_{D_1}, \lambda_{D_2}, \lambda_\beta}} A_{i\;\lambda_\beta,\lambda_{D_2}}^{\beta\;\lambda,\lambda_{D_1}}(\mathbf{p}_\beta)\;\varrho^{\alpha}(\lambda, i; \lambda', i'; L \neq 0)\,(A_{i'\,\lambda_\beta,\lambda_{D_2}}^{\beta\;\lambda',\lambda_{D_1}}(\mathbf{p}_\beta)\,)^*,$$

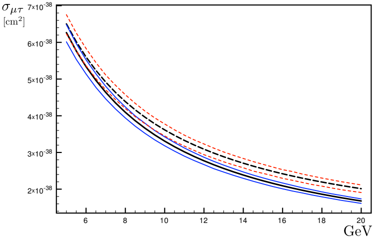
$$\sigma_{\beta\,\alpha}(L) = \sum_{i;\,i'}\Big(\sigma^{CC\;exp}_{\nu_\beta+N\to X+l_\beta}\,|\varepsilon_L|^2\,U^{L*}_{\beta i}\,U^{L}_{\beta i'}\,\varrho^{\alpha}_{P}(-1, i;\,-1, i'; L) +$$

$$+\sigma^{CC\;exp}_{\bar{\nu}_\beta+N\to X+l^+_\beta}\,|\varepsilon_R|^2\,U^{R*}_{\beta i}\,U^{R}_{\beta i'}\,\varrho^{\alpha}_{P}(1, i; 1, i'; L)\Big)$$

Numerical results - OPERA

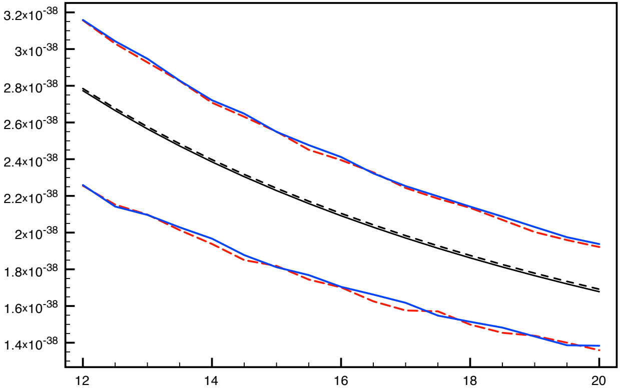
OPERA





L=730 km, $\rho = 3\frac{g}{cm^3}$, $\varepsilon_R = 0.04$, $\varepsilon_R^{N\nu} = 0.1$

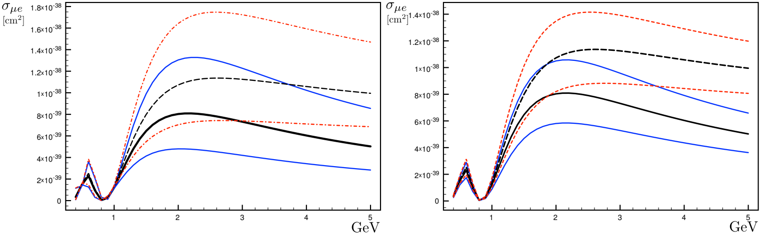
Numerical results - OPERA



L=730 km, $\rho = 3\frac{g}{cm^3}$, $\varepsilon_R = 0.04$, $\varepsilon_R^{N\nu} = 0.01$

Numerical results - NOνA

NOνA



L=810 km, $\rho = 3\frac{g}{cm^3}$, $\varepsilon_R = 0.04$, $\varepsilon_R^{N\nu} = 0.1$

summary

1. The amplitude $A_{i\ \lambda_{P_1},\lambda_{\wp_1}}^{\alpha\ \lambda;\lambda_{P_2}}(\vec{p})$ for the neutrino in the Production P.
2. The density matrix $\varrho_P^\alpha(\lambda, i; \lambda', i')$ is calculated.
3. This result is used as the initial $(t = 0, \vec{x} = 0)$ condition for the evolution equation during the O subprocess, from which $\varrho_P^\alpha(\lambda, i; \lambda', i'; T_L = L \neq 0)$ follows.
4. For the D subprocess the amplitude $A_{i\ \lambda_\beta \lambda_{D_2}}^{\beta\ \lambda,\lambda_{D_1}}(\vec{p}_\beta)$ is calculated.
5. This result gives the value of the transition rate $\sigma_{\beta\,\alpha}$ for the joint P, O, D process.