QFT results for neutrino oscillations and New Physics

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The CP asymmetry in neutrino oscillations, assuming new physics at production and/or detection processes, is analyzed. We compute this CP asymmetry using the standard quantum field theory within a general new physics scenario that may generate new sources of CP and flavor violation. Well known results for the CP asymmetry are reproduced in the case of V-A operators, and additional contributions from new physics operators are derived. We apply this formalism to SUSY extensions of the Standard Model where the contributions from new operators could produce a CP asymmetry observable in the next generation of neutrino experiments.

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I. INTRODUCTION.

Since the experimental results implying that the neutrinos are massive [1], it is expected to have CP violation phases in the leptonic sector. However, the situation in the leptonic sector is very different from the quark sector where the CP violation is clearly established in $K$ and $B$ mesons physics. The only evidence for flavor violation in the leptonic sector comes from neutrino oscillations and there is, so far, no confirmation for CP violation in leptonic decays. Hence, measuring any CP asymmetry in neutrino oscillation will open a new window to study CP violation and related problems as leptogenesis or CP violation in $\tau$ decays. New physics beyond the Standard Model (SM), like low energy supersymmetry, may be probed at the LHC and consequently new sources of CP and flavor violation can be expected. These new sources of CP and lepton flavor violation, also classified as non-standard interactions (NSI), could give important contributions to the CP asymmetry in neutrino oscillation (see ref.[2, 3, 4, 5]).

In addition, a proper procedure to take into account these non-standard interactions is important as neutrino experiments are reaching a high level of accuracy. Even if neutrino masses and lepton mixing matrices solve the solar and atmospheric neutrino anomalies, it is clear that NSI could affect the oscillations parameters as determined by the next generation of neutrino experiments. Effects of NSI have been widely studied, considering their contributions to solar and atmospheric neutrino problems, in neutrinos factories, in conventional and upgraded neutrino beta beams, $e^+e^-$ colliders, neutrino-electron and neutrino-nucleus scattering and in many other aspects of neutrino physics [3, 6, 7, 8, 9, 10, 11, 12, 13].

The interpretation of a possible CP asymmetry in neutrino oscillation due to the SM or NSI is still an open question. The following two hypothesis are usually considered in the analysis of CP asymmetry in neutrino oscillations: (i) The probability of a process associated to neutrino oscillation can be factorized into three independent parts: the production process, the oscillation probability and the detection cross section. (ii) The CP asymmetry in this process is due to the CP violating phase in the lepton mixing matrix. In a pioneering work, the authors of Ref. [2] have studied CP violating effects due to contributions from new neutrino interactions in the production and/or detection processes in neutrino oscillation experiments. However, only corrections to the V-A SM charged current interactions were considered [2]. In Ref. [3], the (V-A)(V-A) and (V-A)(V+A) operators associated to muon decays, but not to the pion decay, have been considered. In muon decays, the interference between SM and New Physics of (V-A)(V+A) operators is suppressed by $m_e/m_\mu$ [30]. In Ref. [14], the quantum field theory formalism has been used to describe neutrino oscillations but New Flavour Interactions were not taken into account.

The goal of this paper is to go beyond this approximation and to propose a generic framework based on quantum field theory to get a simple expression for the CP asymmetry without imposing any assumptions on the operators generated by New Physics. We shall show that in such a case, new contributions to the CP asymme-
try appear and it could be important to take them into account once we want to constraint new physics using experimental data. We shall illustrate this in the case of the supersymmetric extension of the Standard Model but it is clear that our treatment is valid beyond that and it can be applied to NSI effects in all neutrino experiments.

II. GENERAL FORMALISM

Let us start by giving a sketch of the idea of the present work. Let us consider a virtual neutrino that is produced at the space-time location \((x,t)\), travels to \((x', t')\) and is detected there because it interacts with a target producing a charged lepton \(l\). For definiteness, we illustrate this process with the production of the neutrino in \(\pi^+\) decay and its later detection via its weak interaction with a target nucleon \(N\) (see Figure 1):

\[
\pi(p_1) \rightarrow \mu^+(p_2) + \nu_\mu(p) \quad \leftrightarrow \quad \nu_\mu^+(p) + N(p_N) \rightarrow N'(p_{N'}) + l(p_l).
\]

We shall call \(\nu_{\mu,\pi}^d\) state, respectively the neutrino which is produced at source in conjunction of a \(\mu^+\) and the neutrino which is detected through the detection of a charged lepton of flavour \(l\). These effective states are not necessary of \(\mu\) or \(l\) flavour once NSI are introduced.

Energy-momentum conservation at the production and detection vertices requires \(p_1 = p_2 + p\) and \(p + p_N = p_{N'} + p_l\). Weak interactions in the SM acting at the production and detection vertices conserve lepton number and this process is interpreted as a flavor change: a \(\mu\)-neutrino is transformed into a \(l\)-neutrino due to oscillation. However, in the presence of new physics flavor violating weak interactions can occur, and the flavor identification of the neutrino at the production and/or decay locations via its associated charged lepton is not unique anymore.

This process is relevant for neutrino factories and long-baseline accelerator experiments such as superbeams. Particles are produced at the source when a high-energy proton beam (\(\sim 10^2\) GeV) hits a target (made of solid dense material e.g. Be, Al, Ca, etc...). Superbeam neutrino sources are mainly from pion decays while neutrino factories sources are mainly from mounds.

If we assume that light neutrinos are left-handed, Lepton Flavor (LF)-violating semi-leptonic interactions can be described by the following effective Hamiltonian:

\[
H = 2\sqrt{2} G_F V_{ud} \left\{ C_1^5 (\overline{\nu}_\mu P_L \nu_\mu) (\overline{\nu}_\gamma P_L d) + C_2^5 (\overline{\nu}_\mu P_L \nu_\mu) (\overline{\nu}_\gamma P_R d) + C_3^5 (\overline{\nu}_L P_L \nu_\mu) (\overline{\nu}_\gamma P_L d) + C_4^5 (\overline{\nu}_L P_L \nu_\mu) (\overline{\nu}_\gamma P_R d) + C_5^5 (\overline{\nu}_\gamma P_L \nu_\mu) (\overline{\nu}_\gamma P_L d) + C_6^5 (\overline{\nu}_\gamma P_L \nu_\mu) (\overline{\nu}_\gamma P_R d) \right\},
\]

where \(k\) runs over the three leptonic flavors and \(P_{R,L} = (1 \pm \gamma_5)/2\).

In the following and for simplicity, we consider the case where LF violation occurs only at the \(\pi^+\) decay vertex. It is straightforward to include the effects of such New Physics at the detection vertex using this formalism. Note that the tensor currents proportional to the \(C_{5L(R)}^5\) Wilson coefficients will not contribute to \(\pi^+\) decay because it is not possible to generate an antisymmetric tensor from the pion momentum alone. Thus, the only non-vanishing hadronic matrix elements at the production vertex are:

\[
\langle 0 | \overline{d} \gamma^\mu \gamma_5 u | \pi^+ \rangle = i f_\pi p_\mu^d,
\]

\[
\langle 0 | \overline{d} \gamma^\mu u | \pi^+ \rangle = -i f_\pi m_u^2 / (m_u + m_d),
\]

where \(f_\pi = 130\) MeV is the pion decay constant and \(m_{u,d}\) denote the light quark masses.

Using the relation \(\nu_k = \sum U_{ko} \nu_\alpha\) between flavor \(k\) and mass \(\alpha\) neutrino eigenstates, we get the following amplitude for \(\pi^+\) decay:

\[
\langle \mu^+ \nu_k | H | \pi^+ \rangle = \bar{u}(p) O^k v(p_2),
\]

where:

\[
O^k = \frac{G_F}{\sqrt{2}} V_{ud} (1 + \gamma_5) f_\pi \left( \frac{-im_u^2}{m_u + m_d} (C_3^5 - C_4^5) \right.
\]

\[
- i (C_1^5 - C_2^5) \hat{p}_\pi \left. \right) \]

with \(\hat{p}_\pi = \gamma_\mu p_\mu^d\).

Now consider a neutrino of flavor \(k\) that is produced in \(\pi^+\) decay via LF-violating interactions and is detected with flavor \(l\) at a later time via (LF-conserving) charged current scattering off the nucleon \(N\) (Figure 1). In Quantum Field Formalism, the S-matrix amplitude for the evolution of the system from initial state is given by:

\[
T_{\nu_{\mu}^d - \nu_l} = \int d^4 x' d^4 x \sum_k e^{i(p_l - p_N + p_{N'})} x' G_F V_{ud} (J_{N N'})_{\mu} \bar{\nu}_l(p_l) \gamma^\mu (1 - \gamma_5) \Delta^0_{\mu} (x' - x) O^k v(p_2) e^{i(p_2 - p_l) \cdot x}
\]
where $\Delta^{\nu k}(x' - x)$ basically describes oscillation of neutrinos during its propagation. It is important to stress that we never introduce Energy-momentum eigenstates to describe the neutrinos as in our formalism the neutrinos appear as virtual particles. In terms of massive neutrino propagators we can write

$$\Delta^{\nu k}(x' - x) = \sum_i U_{li} U_{ki}^* \int \frac{d^3p}{(2\pi)^3} e^{-ip(x' - x)} \frac{i}{\not{p} - m_{\nu_i} + i\epsilon}$$

where $U_{li}$ are the usual elements of the $U_{\text{MNS}}$ mixing matrix. We write this propagator in a more convenient form by integrating upon the time component of the four-momentum [12]:

$$\Delta^{\nu k}(x' - x) = \sum_i U_{li} U_{ki}^* \int \frac{d^3p}{(2\pi)^3}$$

$$\times \left( \frac{e^{-iE(t' - t)} e^{i\vec{p}(x' - x)}}{2E_{\nu_i}} (E_{\nu_i} \gamma^0 - \not{p} \cdot \gamma + m_{\nu_i}) \theta(t' - t) + e^{iE(t' - t)} e^{i\vec{p}(x' - x)} (E_{\nu_i} \gamma^0 - \not{p} \cdot \gamma + m_{\nu_i}) \theta(t' - t) \right)$$

where $E_{\nu_i} = \sqrt{p^2 + m_{\nu_i}^2}$. As usual, we interpret the first term as neutrinos propagating forwards in time and the second as anti-neutrinos propagating backwards in time.

Thus, by keeping only the first term of the propagator in Eq. (6) we get the amplitude

$$T_{\nu^c \nu} = i \int \frac{d\tau}{2E_{\nu}} e^{ip_{\nu}^c \gamma} (2\pi)^4 \delta^4(P_F + p_2 - p_1)$$

$$\times \frac{G_F V_{ud}}{\sqrt{2}} (J_{N'N})_{\mu} \sum_{i,k} U_{li} U_{ki}^* \bar{u}_i(p_1) \gamma^\mu (1 - \gamma_5)$$

$$\times e^{-i(E_{\nu_i})_{\nu}^\nu} (p_1 + m_{\nu_i}) C^k_{\nu} v(p_2)$$

with $\tau = (t' - t) > 0$ is the time elapsed from the production to the detection space-time locations of neutrinos and $P_F \equiv p_1 + p_{N'} + p_{N''}$. Equivalently, the time-dependent amplitude from initial to final states is the integrand of eq.(7):

$$T_{\nu^c \nu} = (2\pi)^4 \delta^4(P_F + p_2 - p_1) (G_F V_{ud})^2 (J_{N'N})_{\mu}$$

$$\times f_{\tau} \sum_{k} \bar{u}_i(p_1) \gamma^\mu (1 - \gamma_5) (\not{p}_1 + m_{\nu_i} + \not{p}_{N'+})$$

$$\times (m_{\nu_i} A_k^* + B_k^* \not{p}_\tau)v(p_2) e^{ip_{\nu}^c \gamma}$$

$$\times \sum_i U_{li} U_{ki}^* \frac{e^{-i(E_{\nu_i})_{\nu}^\nu}}{2E_{\nu_i}}$$

The time evolution amplitude for the corresponding CP-conjugate process which correspond to the observation at source of a $\mu^-$ and detection of a $l^+$ is given by:

$$T_{\mu^c \tau} = (2\pi)^4 \delta^4(P_F + p_2 - p_1) (G_F V_{ud})^2 (J_{N'N})_{\mu}$$

$$\times f_{\tau} \sum_{k} \bar{u}_i(p_1) \gamma^\mu (1 - \gamma_5) (\not{p}_1 + m_{\nu_i} + \not{p}_{N'+})$$

$$\times (m_{\nu_i} A_k^* + B_k^* \not{p}_\tau) v(p_2) e^{ip_{\nu}^c \gamma}$$

$$\times \sum_i U_{li} U_{ki}^* \frac{e^{-i(E_{\nu_i})_{\nu}^\nu}}{2E_{\nu_i}}$$

In order to get the CP asymmetry in the general case, let us choose the following form of the nucleon weak vertex:

$$(J_{N'N})_{\mu} = \bar{u}_N(p_{N'}) \gamma_{\mu} (g_V + g_A \gamma_5) u_N(p_N)$$

with $g_V = g_V(q^2 = 0) = 1$ and $g_A = g_A(q^2 = 0) \approx -1.27$ [10]. Under these approximations, one has:

$$|T_{\nu^c \nu}(t)|^2 \equiv \sum_{q,k} (B_q^* m_{\mu} - m_{\pi} A_q^*) (B_k m_{\mu} - m_{\pi} A_k)$$

$$U_{li} U_{ki}^* e^{-i(E_{\nu_i})_{\nu}^\nu} F(P, M)$$

where $F(P, M)$ is a kinematical function that depends on masses and momenta of external particles but not on neutrino flavour and will drop in the $a_{CP}(\tau)$ asymmetry defined as:

$$a_{CP}(\tau) = \frac{|T_{\nu^c \nu}(\tau)|^2 - |T_{\mu^c \tau}(\tau)|^2}{|T_{\nu^c \nu}(\tau)|^2 + |T_{\mu^c \tau}(\tau)|^2}$$

$$N(\tau) = \frac{|T_{\nu^c \nu}(\tau)|^2}{|T_{\mu^c \tau}(\tau)|^2}$$

III. CP ASYMMETRY FROM $C_1$ WILSON COEFFICIENT ((V-A)(V-A) OPERATOR)

In the usual formalism developed by refs. [2][3] one considers only New Physics corrections due to $C_1^k = C_{SM}(\delta_{k\mu} + \epsilon_{k\mu})$. In this approximation, one gets for the amplitude:

$$T_{\nu^c \nu}(\tau) = (2\pi)^4 e^{ip_{\nu}^c \gamma} (P_F + p_2 - p_1) (G_F V_{ud})^2 (J_{N'N})_{\mu}$$

$$\times f_{\tau} C_{SM} \bar{u}_i(p_1) \gamma^\mu (1 - \gamma_5) (\not{p}_1 + m_{\nu_i} + \not{p}_{N'+}) \not{p}_{\tau} v(p_2)$$

$$\times \sum_i U_{li} U_{ki}^* \frac{e^{-i(E_{\nu_i})_{\nu}^\nu}}{2E_{\nu_i}}$$

Once taking the $|T_{\nu^c \nu}(\tau)|^2$, the first two lines of the previous equation will give us the kinematical part of the process which is common to all neutrino flavor and the last line will give, at first order in neutrino masses, the usual neutrino oscillation results including Non Standard Interactions. It is interesting to note the equivalence of
our expression with the approach done in ref.2 where they defined:

\[ |\nu^a_\mu| = \sum_i (U^a_{ei} \epsilon_{\mu e} + U^a_{\mu i}(1 + \epsilon_{\mu \mu}) + U^a_{\tau i} \epsilon_{\mu \tau}) |\nu_i| > (17) \]

where |\nu_i| > are the neutrino mass eigenstates and |\nu^a_\mu| is the initial flavour state produced at neutrino source. Computing \(|\langle \nu_i | \nu^a_\mu(\tau) \rangle|^2\), one obtains the neutrino oscillation part of \(|T_{\nu_i^a - \nu_l}(t)|^2\) once assuming that 1/2E_\nu = (1/2E_\nu) + \(O(m^2_\nu)\) and keeping the first term of the expansion in \(m^2_\nu\).

IV. CP ASYMMETRY FROM \(C_{3,4}\) WILSON COEFFICIENTS

The interesting results of this formalism is that naturally all NSI can be taken into account without making any a priori assumptions. In particular, one can easily include the effects of new CP violating phases and flavour-violating interactions from \(C_{3,4}\) Wilson coefficients which involve scalar and pseudoscalar density operators. As an example, let us assume that the only sources of CP violating phases are coming from the scalar operators \(A_k\) and \(B_k\), different from \(n\pi\), so the numerator of the CP asymmetry will be proportional to

\[ N(\tau) \propto Re \left( \sum_{i,j,k,q} A_k B_q U_{li} U^{*}_{kj} e^{-i\tau(E_{li} - E_{kj})} \right) - Re \left( \sum_{i,j,k,q} A^*_k B^*_q U_{li} U^{*}_{kj} e^{-i\tau(E_{li} - E_{kj})} \right) \]

The Standard model contributes only to \(C^S_{1,4} = C_{SM}\delta_{i\mu} + \) corrections from New Physics (in our convention, \(C_{SM} = 1\) and \(C_{3,4}\) are produced by New Physics. At first order in new physics, one has to replace \(B_q\) by \(\delta_{i\mu}\) in the CP asymmetry as previously defined.

It is interesting to note that we could get this result by assuming from the beginning that

\[ a_{CP}(\tau) = \frac{\langle |\nu_i| |\nu^a_\mu(\tau)\rangle |^2 - \langle |\nu_i| \nu^a_\mu(\tau)\rangle |^2}{\langle |\nu_i| \nu^a_\mu(\tau)\rangle |^2 + \langle |\nu_i| |\nu^a_\mu(\tau)\rangle |^2} (18) \]

where one defines the

\[ |\nu^a_\mu| = \sum_i (U^a_{ei} \epsilon_{\mu e} + U^a_{\mu i}(1 + \epsilon_{\mu \mu}) + U^a_{\tau i} \epsilon_{\mu \tau}) |\nu_i| > (19) \]

with \(\epsilon_{\mu\mu} = \frac{A_k}{C_{SM}}\). It is worth mentioning that using the QFT formalism, all \(\epsilon^{s,d}_{i\mu}\) are expressed in terms of the Wilson coefficients and once the \(\epsilon^{s,d}_{i\mu}\) are defined, the analysis considered in Ref.2,3 can be easily implemented. As one can see from eq.(11), the New Physics is enhanced by a factor \(m_{\tau}/(m_u + m_d) \approx 15\) which multiplies the Wilson coefficients \(C^S_{3,4}\) as mentioned previously in refs.17,18.

It is clear that the limit on helicity of the muon in pion decays 19,10 will constraint the contribution of \(C_{3,4}\) not to be bigger than a few percent. It is important to note that most of the constraints on \(\epsilon_{ij}\) come from four lepton Fermi Operators (see ref.3) as in \(\mu \rightarrow eee\) or rare muon decays as \(\mu \rightarrow e\gamma\); also some lepton flavour violating tau decays impose very strong constraints on \(\epsilon_{i\mu}\) with \(i = e\) or \(\tau\). In the case of operators which contribute to pion decays, one should note that these operators can be written as the product of a leptonic current and a hadronic current. Thus, the Wilson coefficients in both cases can not be related to each other unless they can be factorized into the product of a leptonic current and a hadronic current. This procedure is model-dependent and should be verified in each specific model of New Flavour Interactions.

V. APPLICATION TO SUSY MODELS

Let us apply this formalism to the usual Minimal Supersymmetric extension of the SM. Hence, as an application, we calculate the supersymmetric (SUSY) contributions to the dominant pion decay mode \(\pi^- \rightarrow \mu^- \nu_\mu\) (or its charge conjugate) 27,28,29 through the Wilson coefficients and focus our attention on the SUSY contributions to scalars and pseudoscalars Wilson coefficients \((C_3\) and \(C_4)\).

The effective lagrangian contributing to the \(\nu_\mu \rightarrow \nu_k\) flavor change at the neutrino source, is given by

\[ \mathcal{L}_{eff} = 2\sqrt{2}G_{Feff}V_{ud} \sum_j C^k_j \mathcal{O}^k_j, \]

where \(C^k_j\) are the dimensionless Wilson coefficients and \(\mathcal{O}^k_j\) are the relevant local operators at low energy scale as defined in Eq.(2). The leading order contributions to \(C_3\) and \(C_4\) under the experimental constraints for the Wilson coefficients induced by SUSY are explicitly shown in the expressions below. These describe box type diagrams of chargino-neutralino exchanges. Other SUSY contributions (vertex corrections) are suppressed by the Yukawa couplings of light leptons. In fig.2, the Feynman diagrams of dominant SUSY contribution to the pion decay, \(\pi^- \rightarrow \mu^- \nu_\mu\), are represented.

To simplify the expression, we shall assume that the squark and slepton masses are degenerated \((m_f \simeq \)
To conclude, we proposed a formalism based on Quantum Field Theory where it is possible to include all sources of Non Standard Interactions including new CP- and flavour-violating interactions. We show that using this method, it is straightforward to include the effects of the scalar and pseudoscalar operators densities which

non-vanishing imaginary part of $C_3$ or $C_4$. The complex phase of $C_{3,4}$ can be due to the matrices that diagonalize the squark mass matrix or the chargino mass matrix. If we assume that the squark matrices are diagonal, i.e. the diagonalizing matrices are identity, we do not have any source of CP violation from squark matrices. Then the only remaining source is the phase of $\mu$ which induces a complex phase in chargino mass matrix and hence $U$ and $V$ unitary matrices. This phase is strongly constrained by the neutron electric dipole moment (EDM) [21, 22, 23, 24, 25, 26] but it is possible to avoid this constraint if the first generation of squarks are heavy enough and decouple from the two other squark generations. Another way to avoid the neutron EDM constraint is to assume flavor violating structure in the squarks and sleptons mass matrices. This allows to have new sources of CP violation which could contribute to any CP violating observables and/or could relax the constraint on the $\mu$ term coming from neutron EDM limit [24].

Assuming that the CP violating sources comes from the $\mu$ term in the chargino sector, $\epsilon_{\mu e}$ is given by $C_{3,4}$ times the enhancement factor $m_\pi^3/(m_u + m_d)$. For typical chargino and neutralino masses of order 150 GeV and sfermion masses around 100 GeV, it is possible to obtain $\epsilon_{\mu e}$ as large as $10^{-3}$. In order to maximize the absolute values of $\epsilon$’s, one assumes that charginos and neutralinos have quasi-degenerated masses. In figure (3), we present our numerical results for $|\epsilon_{\mu e}|$ (solid line) and $|\epsilon_{\mu \tau}|$ (dashed and dotted lines) as function of the chargino mass, for $\tan \beta = 50$ and $\tan \beta = 10$. As expected from the expressions of $C_{3,4}$, $\epsilon_{\mu e}$ is not sensitive to $\tan \beta$ if $\theta_{13}^{MNS} \approx 0$. One should emphasize that the SUSY model presented in this section is the simplest one and we could expect enhancement in flavour violation effects once a non-universal structure is assumed in the soft-SUSY breaking terms. In this case, the values of $\epsilon_{\mu \tau}$ or/and $\epsilon_{\mu \tau}$ may be significantly enhanced. A detailed analysis for the CP asymmetry in neutrino oscillation in SUSY model with non-minimal flavor will be considered elsewhere.

As one can see from Fig. (3), $\epsilon_{\mu \mu}$ is typically of order $10^{-3}$. These values lead to CP asymmetry in neutrino oscillation of order $10^{-1} \sim 10^{-2}$, depending of the parameters of the neutrino beam and the size of the experiment baseline [2]. Such asymmetries are reachable at next generation of reactor and beam neutrino oscillation experiments [3, 4, 5, 6, 7].

VI. CONCLUSIONS

To conclude, we proposed a formalism based on Quantum Field Theory where it is possible to include all sources of Non Standard Interactions including new CP- and flavour-violating interactions. We show that using this method, it is straightforward to include the effects of the scalar and pseudoscalar operators densities which
FIG. 3: Absolute value of $\epsilon_{\mu e}$ (solid line) and $\epsilon_{\mu\tau}$ (dashed and dotted lines) for different choice of $\tan \beta$, respectively $\tan \beta = 50$ and $10$. The other parameters are given by $m_f = 100$ GeV and $m_{\chi^0} = 110$ GeV.

appears in any New Physics Models. In the limit where we consider only (V-A)(V-A) operator, we reproduce the usual results reported in Ref.[2]. It is important to emphasize that most of the studies on NSI in neutrino physics have been done assuming that New Physics contributions to neutrino interactions is mainly due to corrections to (V-A)(V-A) Wilson coefficients. This approach was well justified when neutrino experiments were not so accurate and other sources of New Physics could be easily neglected. But now neutrino experiments enter in the field of high precision experiments where the effects of NSI coming from (S-P)(S+P) and (S-P)(S-P) operators could have an impact on the determination of lepton mixing parameters including the CP violating phases. To illustrate our results, we applied it to SUSY models where we assume that the only CP-violating phases appear in $C_{3,4}$ Wilson coefficients which correspond respectively to (S-P)(S-P) and (S-P)(S+P) operators. In such a case, we show that with reasonable values for the SUSY parameters, it is possible to generate a CP asymmetry as large as $10^{-1} \sim 10^{-2}$.

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