Towards the low energy frontier

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Abstract. Unanswered and interesting questions arise in the leptonic sector of the standard model of particle physics: Are there new sources of CP violation? Are the neutrinos Dirac or Majorana particles? Are there more than one Higgs doublet that modify the leptonic or semi-leptonic decays of mesons? All these questions may be answered by a detailed study of low energy experiments. In this talk we present a short review of some examples where using present or future data on D meson decays, neutrino scattering on electron or coherent scattering on nucleus and neutrinos produced in accelerators may help us to answer those questions.

1. Introduction
High energy physics experiments, such as LEP, HERA, TEVATRON, and more recently the LHC, have portrayed a very accurate picture of the Standard Model (SM) description of particle interactions up to energies above the electroweak scale. Future runs of the LHC will search for new physics (NP) and probably probe energy scales up to 13 TeV in center of mass energy. On the other hand, low energy scale experiments (below the electroweak scale) or the so-called intensity frontier (figure 1) may shed some light in the search for physics beyond the Standard Model due to their possibility of getting high statistics and hence indirect observables of NP (see for example [1]). A remarkable example of how low energy experiments have changed dramatically the SM is the discovery of neutrino oscillations thanks to the study of solar, atmospheric and reactor neutrinos whose energies range from a few GeV down to MeV [2]. Additional low energy tests include rare processes, forbidden or highly suppressed in the SM, such as electric dipole moments, lepton number violation, flavor changing neutral processes, etc. Other studies include particle decays, CP asymmetries and flavor transitions, allowed within the SM but with sufficient precision to test NP.

Many of the low energy processes mentioned above can be studied within a model-independent framework following an effective Lagrangian approach to parametrize the NP effects. Below the electroweak scale, after integrating out the W and Z bosons (high momentum modes), the dynamics are described by a set of effective operators, that include the SM high momentum modes plus the NP high momentum modes. The dominant effects will be generated by the lowest dimensional effective operators, an effective four Fermi interaction usually called Non Standard Interaction (NSI). The addition of those NSI may enhance the decay rate or the cross...
Low energy processes such as leptonic and semileptonic decay of mesons, neutrino scattering both in electrons and nucleus may reveal complementary or new constraints on models beyond the SM. It this conference paper we review several cases that show the usefulness of this approach in the low energy frontier, spanning energies ranges from GeV to eV. We also address other interesting phenomena beyond the standard model, such as novel sources of CP violation or the feasibility of distinguishing the Dirac or Majorana nature of the neutrino by studying low energy $\nu - e$ scattering. The article is organized as follows: In Sec. 2 we review a set of model independent constraints imposed on NSI by studying different processes. Firstly, we recall constraints on NSI for a $c \rightarrow s$ transition process using both leptonic and semileptonic D meson decays \cite{3}. It is found that those particular processes impose restrictive constraints over leptoquark models for the second generation of quarks. Secondly, at even lower energies, of order $\sim 10$ MeV $- 10^{-1}$ MeV, the $\nu - e$ elastic scattering in nuclear reactor, accelerator and solar $\nu$-detectors, are a useful probe. We recall a global analysis done considering non-universal and flavor changing NSI including all relevant experiments and future low energy solar neutrino detector prospects \cite{9, 10}. As a final example, for extremely low threshold energies, the coherent neutrino scatterings may be very sensitive to NSI of neutrinos with quarks, that is neutral quark and lepton operators products \cite{12}, due to the enhancement of the cross section and the fact that neutrinos can scatter coherently not only on the nucleons inside the nucleus but also on the atom itself. Final part of Sec. 2 revise its potential to make precision tests of NP.

The possibilities of finding new CP violating sources are explored in section 3. It is a study of the feasibility of generating new sources of CP and flavor violation (coming from NP) on neutrino oscillation experiments at low energies, of order $\sim 1$ GeV, using a standard S-matrix formalism with the relevant set of effective operators \cite{8}. We summarize the relevant results using a generic framework based on quantum field theory to get a simple expression for the CP asymmetry in neutrino oscillations without imposing any assumptions on the effective operators generated by NP.

Finally, once the neutrino polarization evolution is considered, the $\nu - e$ scattering process may shed some light into the neutrino nature: Dirac or Majorana. The change of polarization may be achieved in astrophysical environments with strong magnetic fields. Section 4 summarizes this interesting feature, examined in \cite{11}. 

Figure 1. Low energy processes such as leptonic and semileptonic decay of mesons, neutrino scattering both in electrons and nucleus may reveal complementary or new constraints on models beyond the SM.
2. Constraining NSI with low energy experiments

There have been significant improvements in the experimental measurements of the meson decays branching ratios, and we are now entering in the precision measurement of the neutrino properties (mixings and masses). This experimental data in combination with accurate theoretical calculations may be used to determine the accuracy of the SM and to search for NP. This allows us to constrain systematically a set of Wilson coefficients using some low energy data that parametrizes NP. Some examples are:

(i) D meson decays (GeV range): D meson physics gained special interest when it was first pointed out that the leptonic decay branching ratio measurement was in minor disagreement with the SM [20]. Recent measurements are now within agreement but there is however a consistent small deviation in each decay channel (semileptonic and leptonic) (CLEO [13], [14, 15, 16], Belle [17]). For the ∆C = ΔS leptonic and semileptonic D meson decays, the new particle state should couple to the leptons and the second generation of quarks, leaving an effective four Fermi interaction parametrized by the Wilson coefficients $C_{q_1q_2I}$ as

$$-\frac{\mathcal{L}_{\text{NSI}}}{G_F} = \sum_{c,s,l,\nu} \sum_{I=L,R} C_{q_1q_2I} \frac{1}{P_1P_2}(q_1\Gamma_{I}P_1q_2) \cdot (\bar{\nu}_I\Gamma_{I}P_2\ell).$$

Any kind of intermediate state, such as scalars, vectors or even tensors, are allowed. A model independent analysis is shown in [3], combining the total leptonic and semileptonic branching ratios of D meson decays (previous analysis were done for leptonic or semileptonic decays independently [20, 21, 22]). The latest results on the calculations for the relevant form factors were implemented, which have been improved significantly reaching a remarkable precision [18, 19]. The $q^2$ distributions for the $D^+ \to K^0e^+\nu_e$ and $D^0 \to K^-e^+\nu_e$ decays are also considered. This analysis is restricted to three fermion family models of physics BSM, as the CKM matrix element is deduced from unitarity constraints, $W \to cs$ decay and neutrino-nucleon scattering [23].

(ii) Constraining $\nu$-e NSI Neutrino-electron scatterings are described by pure neutral lepton operator products that induce non standard flavor changing interactions.

Now we will consider NSI in the leptonic sector for neutral currents. The general class of non-standard interactions is described via the effective four fermion Lagrangian,

$$-\mathcal{L}_{\text{eff}}^{\nu e} = \sum_{\alpha,\beta} e^{FP} \frac{1}{2} 2\sqrt{2}G_F (\bar{\nu}_\alpha\gamma_\mu L\nu_\beta)(\bar{f}\gamma^\mu P\ell),$$

where $e^{FP}$ parametrize the strength of the NSI. In this particular case we consider only electrons, hence $f = e$). The current sensitivity on NSI as inferred from a global analysis of processes involving (anti)-neutrinos and electrons combines the relevant experimental “neutrino counting” data from $e^+e^-\to\nu\bar{\nu}+\gamma$ obtained by the four LEP collaborations and with all the $\nu_e + e \to \nu_e + e$ data obtained by LSND, and the $\nu_e + e \to \nu_e + e$ scattering measured in reactor experiments (Irvine, MUNU and Rovno) together with $\nu_\mu + e \to \nu_\mu + e$ and $\bar{\nu}_\mu + e \to \bar{\nu}_\mu + e$ measured at CHARM II.

(iii) Constraining NSI with coherent neutrino-Nucleus ($\nu$-N) scatterings (eV range): It is one of the few processes predicted by the SM that has not been experimentally detected. This process takes place when the momentum transfer, $q$, is small compared with the inverse nucleus or atom size. The typical inverse sizes of most nuclei are in the range from 25 to 150 MeV. Therefore the condition for full coherence in the neutrino-nuclei scattering is well satisfied for reactor neutrinos and also for solar, supernovae neutrinos and artificial neutrino sources. The effective Lagrangian at low energies is:
where the NSI parameters have been added to the SM effective coupling constants:
\[ f^{\mu L}_{\alpha\beta} = \rho_{\nu N}^{NC} \left( \frac{1}{2} - \frac{2}{3} \kappa_{\nu N} s_2 \right) Z_{2} \right) + \lambda \alpha^L + \varepsilon_{uL}^{\nu L} \right]_{\alpha \beta} + f^{qL}_{\alpha\beta} \left[ \bar{q} \gamma_{\mu} (1 - \gamma^5) q \right] + f^{qR}_{\alpha\beta} \left[ \bar{q} \gamma_{\mu} (1 + \gamma^5) q \right], \]
where \[ \kappa \] is an estimation on the leptoquark mass of a leptoquark with charge 1.

For masses normalized to 100 GeV we can constrain the parameter \( \epsilon \) on \( Z \). In particular, we have estimated the sensitivity for a detector’s mass of 1Kg and a time of 1 year of data taking, i.e. a facility such as the Texono detector proposal. The sensitivity for the mass of an extra gauge boson \( Z' \) in the particular chi-model arising from our constraint on \( \epsilon \) corresponds to \( M_{Z'} < 792\text{GeV} \) at 90\%C.L. Another interesting where we can apply our bounds is the leptoquark model. By fixing the coupling of the leptoquark \( \lambda = 4\pi/137 \) we got an estimation on the leptoquark mass of \( m_q > 894 \text{ GeV} \) at 90\% C.L. which is slightly above the current Tevatron limit. Similarly, the case of SUSY with R-parity breaking terms, with s-quark masses normalized to 100 GeV we can constrain the parameter \( \frac{\alpha^{\mu L}_{\alpha\beta}}{m^{\mu L}} \). Under some simplifying assumptions, the model independent constraints can be mapped to some particular models, exemplifying the usefulness of this kind of analysis.

### Table 1. Constrains on the Wilson coefficients that parameterize non standard interactions obtained with different low energy experiments

| D meson bounds | Neutrino NSI | Coherent bounds |
|----------------|--------------|-----------------|
| 0.072 < \( C^{\nu L}_{\alpha\beta} \) < 0.14 | -0.03 < \( \epsilon_{\nu L}^{\alpha\beta} \) < 0.08 | | \( |\epsilon_{\nu L}^{\alpha\beta}| < 0.003 \) |
| 0.057 < \( C^{\nu R}_{\alpha\beta} \) < 0.13 | 0.004 < \( \epsilon_{\nu R}^{\alpha\beta} \) < 0.151 | | \( |\epsilon_{\nu R}^{\alpha\beta}| < 0.032 \) |
| 0.00 < \( C_{\alpha\beta}^{\mu\nu} \) < 0.13 | \( |\epsilon_{\mu\nu}^{\alpha\beta}| < 0.03 \) | | \( |\epsilon_{\mu\nu}^{\alpha\beta}| < 0.032 \) |
| -0.12 < \( C_{\alpha\beta}^{\mu\nu} \) < 0.00 | \( |\epsilon_{\mu\nu}^{\alpha\beta}| < 0.03 \) | | \( |\epsilon_{\mu\nu}^{\alpha\beta}| < 0.036 \) |

Under some simplifying assumptions, the model independent constraints can be mapped to some particular models, exemplifying the usefulness of this kind of analysis.

The bounds on the Wilson coefficients coming from current neutrino experiments are loose. Nevertheless, the bounds obtained from the coherent neutrino-nuclei scattering are promising. In particular, we have estimated the sensitivity for a detector’s mass of 1Kg and a time of 1 year of data taking, i.e. a facility such as the Texono detector proposal. The sensitivity for the mass of an extra gauge boson \( Z' \) in the particular chi-model arising from our constraint on \( \epsilon \) corresponds to \( M_{Z'} < 792\text{GeV} \) at 90\%C.L. Another interesting where we can apply our bounds is the leptoquark model. By fixing the coupling of the leptoquark \( \lambda = 4\pi/137 \) we got an estimation on the leptoquark mass of \( m_q > 894 \text{ GeV} \) at 90\% C.L. which is slightly above the current Tevatron limit. Similarly, the case of SUSY with R-parity breaking terms, with s-quark masses normalized to 100 GeV we can constrain the parameter \( \frac{|\lambda^{\nu L}_{\alpha\beta}|}{m^{\nu L}} \). Under some simplifying assumptions, the model independent constraints can be mapped to some particular models, exemplifying the usefulness of this kind of analysis.

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Now, if we see the model independent bounds from the D meson decays, they can be mapped to constraints on the parameters of Two Higgs Doublet Model. It is found that the allowed region at 68\% C.L. is: \(-1.8 \times 10^{-3} \text{ GeV}^{-1} < (m_\nu - m_s \tan^2 \beta)/M_{Z'}^2 < 0.023 \text{ GeV}^{-1}\). Similarly, the D meson decays constrain Leptoquark couplings. If one considers leptoquark states that only couple to the second generation of left handed quarks (chiral generation leptoquarks) and the first generation of left handed leptons stringent constraints are found. The allowed region at 95\% C.L. from the semileptonic decays of the D mesons is given by: \( 0.05 \left( \frac{m_{S_0}}{M_{Higgs}} \right)^2 < |\kappa_1^{e}\alpha\beta|^2 < 0.11 \left( \frac{m_{S_0}}{M_{Higgs}} \right)^2 \) while previous bounds are reported to be \( \kappa^2 < 5 \times (M_{LQ}/300\text{GeV})^2 \) [23], where \( S_0 \) is a scalar leptoquark with charge 1/3 and (3,1,2/3) gauge numbers.
3. Constraining NSI in neutrino oscillations

Neutrino interactions on the other hand, either at the source or at the detector site, in oscillation experiments are described by effective Lagrangians that include both quark and lepton operators products, that in general induce new sources of flavor and CP violation. Hence, NSI may modify the oscillation pattern and enhancing the CP asymmetry (see for example [4, 5, 6, 7]), even if neutrino masses and lepton mixing matrices solve the solar and atmospheric neutrinos anomalies. There is an extraordinary effort and a large number of experiments planned to increase the precision measurement of the oscillation parameters and hence allowing us to test NP effects in different oscillation channels (or flavor transitions). Going beyond the usual plane-wave propagation approximation, a generic framework based on quantum field theory is proposed in [8], to get a simple expression for the CP asymmetry without imposing any assumptions on the operators generated by NP. Indeed: 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, let us illustrate this process with the production of the neutrino in a \(\pi^+\) decay and its later detection via its weak interaction with a target nucleon \(N\) in an accelerator experiment. If we assume that light neutrinos are left-handed, lepton flavor (LF)-violating semileptonic interactions can be described by the Lagrangian in eq. (1) for the quarks \(u\) and \(d\) and adding an index for the neutrino flavor \(k\).

The CP asymmetry is defined as \(a_{\text{CP}}(\tau) = \frac{|T_{\mu\nu}^{\pi^+}(\tau)|^2 - |T_{\mu\nu}^{\pi^-}(\tau)|^2}{|T_{\mu\nu}^{\pi^+}(\tau)|^2 + |T_{\mu\nu}^{\pi^-}(\tau)|^2}\). Where \(T_{\mu\nu}^{(\pm)}(\tau)\) is the time dependent S-matrix amplitude for the evolution of the system from initial state (at the source) to the final state (at the detector). In the case where we consider only the \((V-A)/(V-A)\) operator, we reproduce the usual results [4], once assuming that \(1/2E_{\nu}\) \(= (1/2E_{\nu})(1 + O(m_{\nu}^2))\) and keeping the first term of the expansion in \(m_{\nu}^2\). However 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. In the case where the only sources of CP violating phases come from the scalar operators \(C^{k}_{k}^{LR(RR)}\), we find that we can equivalently define a flavour neutrino eigenstate \(|\nu^\mu_k\rangle = \sum_i \left(U_{\nu_i}^e \epsilon_{i\mu} + U_{\nu_i}^\tau (1 + \epsilon_{\mu\mu}) + U_{\nu_i}^\tau \epsilon_{i\mu}\right) |\nu_i\rangle\) and follow the usual plane-wave description of the propagation of neutrinos. The NSI parameters in this case are defined as \(\epsilon_{\mu\mu} = \frac{1}{\epsilon_{\mu\mu}} \sum_{k} \sum_{i} m_{\nu_i} (C^{k}_{k}^{LR(RR)} - C^{k}_{k}^{LR(RR)})\), and hence enhanced by a factor of \(\sim 15\).

Hence, it is shown that without imposing any assumptions on the operators generated by NP, new contributions to the CP asymmetry appear and it could be important to take them into account once we want to constrain NP using experimental data.

4. Probing Majorana or Dirac neutrinos with neutrino scatterings (KeV range)

If the neutrino polarization evolution is considered, the \(\nu - e\) scattering process may shed some light into the Dirac or Majorana nature of the neutrino. Indeed, for the Majorana and the Dirac cases the neutrino scattering amplitudes off electrons or nucleons are not the same [25] because if the neutrino is a Majorana particle, then the neutrino is identical to its own antiparticle. The equivalence in the cross sections arise because the neutrino mass is extremely small \((m_{\nu} < 2\ eV [23])\), thus these are almost completely chiral states, that is, almost fully polarized particles due to the left-handed nature of the charged weak interaction. For this reason, an extra state preparation factor \((1 - \gamma_3)/2\) is usually added such that the amplitudes become identical. Even if the initial neutrino polarization is considered, since all neutrinos from terrestrial experiments are produced via charged currents, it is extremely difficult to observe significant differences between Dirac and Majorana neutrinos [11]. Indeed, for detectable neutrino energies, the difference is negligible. It becomes significant only for unreasonable (of the order of eV) energies of the neutrino. However, a change of the neutrino polarization may be achieved in astrophysical
environments with strong magnetic fields. Indeed, any particle possessing a magnetic moment, as the neutrino does, interacts with external electromagnetic fields and consequently, its spin may rotate around the direction imposed by this external field. Actually, neutrinos can have a non-negligible magnetic moment $\mu_\nu$ (current constraints give $\mu_\nu < 5 \times 10^{-12} \mu_B$). Significant difference between Dirac and Majorana scattering cross section appears in the cross section as function of $s_{||}$, i.e. the longitudinal polarization of the neutrino. In particular, a 25% deviation from the original neutrinos helicity is required for a 10% difference between Dirac and Majorana scattering for any value of the neutrino energy, while a more precise experiment able to detect astrophysical neutrinos with a 2% accuracy will need only a 5% deviation in the neutrinos original helicity. The change of polarization can be achieved in very hot ($T \sim 20$ MeV) and large (such as AGN or SNR) astrophysical environments with strong magnetic fields if the neutrino magnetic moment is bigger than the expected SM prediction but smaller than the current experimental limit. More details can be found in [11].

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