Charged current reactions in the NuSOnG and a test of neutrino-W couplings

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Abstract

We explore the physics potential of NuSOnG experiment to probe new physics contributions to $W_{\mu\nu\mu}$ couplings in inverse muon decay and charged current deep inelastic scattering processes. We show that NuSOnG provides two order of magnitude improvement in $W_{\mu\nu\mu}$ compared to LEP bound at 95% C.L.. Combining the results presented here with our earlier results, we obtain a significant improvement in the limits on neutrino flavor universality violation in neutrino-W and neutrino-Z couplings.
I. INTRODUCTION

The physics potential of the recently proposed NuSOnG (Neutrino Scattering on Glass) experiment \cite{1} is under intensive study. It is suggested that NuSOnG can look beyond the standard model at terascale energies by making precision electroweak and QCD measurements. NuSOnG can place stringent constraints on possible non-standard neutrino interactions. Potential of the NuSOnG experiment to probe new physics contributions to $Z\nu\nu$ couplings in muon-neutrino electron elastic and neutral-current deep-inelastic scattering processes have been studied in Ref. \cite{2}. It was shown that NuSOnG experiment has significant potential to probe neutrino-Z couplings. In the current paper we investigate NuSOnG sensitivity limits on non-standard neutrino-W couplings via inverse muon decay and charged current deep inelastic scattering.

Non-standard $W\ell\nu$ couplings are constrained approximately by up to an order of $10^{-2}$ from the LEP data via $W$ boson decay to leptons \cite{3}. Precision measurement of muon decay also constrains the coupling with about the same order \cite{4}. There is an extensive literature on non-standard interactions of neutrinos \cite{5,6,7,8,9,10}. Our formalism is based on an effective lagrangian approach presented in Ref. \cite{11}. We do not a priori assume the universality of the coupling of neutrinos to $W$. Combining our results with the results obtained in Ref. \cite{2} we discuss the potential of NuSOnG experiment to probe possible universality violation at neutrino-Z and neutrino-W couplings.

In the effective lagrangian approach of Ref.\cite{11}, possible deviations from the standard model that may violate flavor universality of the neutrino-V ($V=Z,W$) couplings are described by the following $SU(2)_L \otimes U(1)_Y$ invariant dimension-6 effective operators:

\[ O_j = i(\phi^\dagger D_\mu \phi)(\bar{\psi}_j \gamma^\mu \psi_j) \] (1)
\[ O'_j = i(\phi^\dagger D_\mu \tau \phi) \cdot (\bar{\psi}_j \gamma^\mu \tau \psi_j) \] (2)

where $\psi_j$ is the left-handed lepton doublet for flavor $j = e, \mu$ or $\tau$; $\phi$ is the scalar doublet; and $D_\mu$ is the covariant derivative, defined by

\[ D_\mu = \partial_\mu + i \frac{g}{2} \mathbf{\tau} \cdot \mathbf{W}_\mu + i \frac{g'}{2} Y B_\mu. \] (3)

Here $g$ and $g'$ are the $SU(2)_L$ and $U(1)_Y$ gauge couplings, $Y$ is the hypercharge and the gauge fields $W_\mu^{(\ell)}$ and $B_\mu$ sit in the $SU(2)_L$ triplet and $U(1)_Y$ singlet representations, respectively.
After symmetry breaking operators (1) and (2) modify the charged and neutral currents as

\[ J_{CC}^\mu = \left[ 1 + 2\alpha'_j \frac{v^2}{\Lambda^2} \right] \bar{\nu}_{jL} \gamma_\mu \ell_{jL} \] (4)

\[ J_{NC}^\mu = \left[ \frac{1}{2} + \frac{v^2}{2\Lambda^2} (-\alpha_j + \alpha'_j) \right] \bar{\nu}_{jL} \gamma_\mu \nu_{jL} + \left[ -\frac{1}{2} + \sin^2 \theta_W - \frac{v^2}{2\Lambda^2} (\alpha_j + \alpha'_j) \right] \bar{\ell}_{jL} \gamma_\mu \ell_{jL} \] (5)

In this effective current subscript "L" represents the left-handed leptons and \( v \) represents the vacuum expectation value of the scalar field and \( \Lambda \) represents new physics energy scale. (For definiteness, we take \( v = 246 \text{ GeV} \) and \( \Lambda = 1 \text{ TeV} \) in the calculations presented in this paper). \( \alpha_j \) and \( \alpha'_j \) are the coupling constants for the operators (1) and (2) respectively.

One can see from (4) and (5) that the coupling \( \alpha'_j \) contribute both charged and neutral currents. But the charged current isolates it. Therefore a combine analysis of charged and neutral currents provides us the opportunity to discern the couplings \( \alpha'_j \) and \( \alpha_j \).

II. CROSS SECTIONS AND NUMERICAL ANALYSIS

The charged current process \( \nu_\mu e^- \rightarrow \nu_e \mu^- \), called "inverse muon decay" is described by a t-channel W exchange diagram. As can be seen from current (4) that in case of neutrino flavor universality violation \( W_{\mu\nu} \) and \( W_{e\nu} \) vertices are modified by different operators. The cross section is then given by the simple formula

\[ \frac{d\sigma}{dy}(\nu_\mu e^- \rightarrow \nu_e \mu^-) = \frac{G_F^2}{\pi} \left( 1 + \frac{2v^2}{\Lambda^2} \alpha'_j \right)^2 \left( 1 + \frac{2v^2}{\Lambda^2} \alpha'_{e} \right)^2 \left( 2m_e E_\nu - (m_{\mu}^2 - m_{e}^2) \right) \] (6)

where \( E_\nu \) is the initial neutrino energy, \( m_e \) and \( m_{\mu} \) are the mass of the electron and muon, \( G_F \) is the Fermi constant and

\[ y = \frac{E_{\mu} - \frac{m_{\mu}^2 + m_{e}^2}{2m_e}}{E_\nu} \] (7)

with \( E_{\mu} \) being the final muon energy. The range of \( y \) is

\[ 0 \leq y \leq 1 - \frac{m_{\mu}^2}{2m_e E_\nu + m_{e}^2} \] (8)

We studied 95% C.L. bounds using two-parameter \( \chi^2 \) analysis with and without a systematic error. The \( \chi^2 \) function is given by,

\[ \chi^2 = \left( \frac{\sigma_{SM} - \sigma_{AN}}{\sigma_{SM} \delta_{exp}} \right)^2 \] (9)
where $\sigma_{AN}$ is the cross section containing new physics effects and $\delta_{\text{exp}} = \sqrt{\delta_{\text{stat}}^2 + \delta_{\text{syst}}^2}$. $
abla^\frac{\sigma}{\sigma}$ is the statistical error and $\delta_{\text{syst}}$ is the systematic error. The number of events for inverse muon decay is proposed to be $N = 7 \times 10^5$ in the NuSOnG proposal [1]. Therefore we assume this event number.

In Fig.1 we plot 95% C.L. bounds on the parameter space $\alpha_{\mu} - \alpha'_{e}$ for inverse muon decay. We consider two cases; bounds without a systematic error and with a systematic error of the same order as the statistical one. We see from the figure that our limit with a statistical error is about an order of magnitude better than the limit obtained from muon decay [4].

NuSOnG experiment would provide unprecedented statistics for charged current deep inelastic scattering from the nuclei in glass. The expected number of events for $\nu_\mu$ charged current deep inelastic scattering is $600 \times 10^6$ [1]. In contrast, NuTeV had $1.62 \times 10^6$ deep inelastic scattering (NC+CC) events in neutrino mode [12]. Therefore NuSOnG could provide two orders of magnitude more events. In the effective lagrangian approach of Ref. [11], operators (1) and (2) do not modify the quark couplings to W and Z. Therefore the hadron tensor remains in the standard form [13, 14]

$$W_{\mu\nu} = \left( -g_{\mu\nu} + \frac{q_{\mu}q_{\nu}}{Q^2} \right) F_1(x, Q^2) + \hat{p}_{\mu} \hat{p}_{\nu} F_2(x, Q^2) - i\epsilon_{\mu\alpha\beta} \frac{g^\alpha p^\beta}{2p \cdot q} F_3(x, Q^2)$$

where $p_{\mu}$ is the nucleon momentum, $q_{\mu}$ is the momentum of the gauge boson propagator, $Q^2 = -q^2$, $x = \frac{Q^2}{2p \cdot q}$ and

$$\hat{p}_{\mu} \equiv p_{\mu} - \frac{p \cdot q}{Q^2} q_{\mu}$$

The charged current structure functions for an isoscalar target are defined as follows [15]

$$F_2 = x(q_{\text{val}} + 2\bar{q}) + x(s - c)$$

$$F_3 = q_{\text{val}}$$

where, $q_{\text{val}}$’s are valence quark and $q$’s are sea quark distributions. The form factors $F_1$’s can be obtained from (11) by using Callan-Gross relation $2xF_1 = F_2$ [16]. In our calculations parton distribution functions of Martin, Roberts, Stirling and Thorne (MRST2004) [17] have been used. We assume an isoscalar nucleus $N = (p + n)/2$. This is a good assumption for a glass target as was discussed in Ref. [2].

New physics contributions coming from the operators in (1) and (2) only modify the
lepton tensor:

\[ L_{\mu\nu} = 8 \left( 1 + \frac{2\nu^2}{\Lambda^2} \alpha'_{\mu} \right)^2 \left( k_{\mu}k'_{\nu} + k'_{\mu}k_{\nu} - k \cdot k' g_{\mu\nu} + i\epsilon_{\mu\nu\alpha\beta} k^\alpha k'^\beta \right) \]  \hspace{1cm} (12)

where, \( k_{\mu} \) and \( k'_{\mu} \) are the momenta of initial \( \nu_{\mu} \) and final \( \mu^- \) respectively. We see from (12) that charged current deep inelastic scattering isolates the coupling \( \alpha'_{\mu} \). It does not receive any contribution from \( \alpha'_{\epsilon} \). As we have seen this is not the case in inverse muon decay.

The behavior of the charged current deep inelastic scattering cross section as a function of initial neutrino energy is plotted for various values of the anomalous coupling \( \alpha'_{\mu} \) in the left panel of Fig.2. We see from this figure that deviation of the anomalous cross sections from the SM increase as the energy increases. Therefore high energy neutrino experiments are expected to reach a high sensitivity to probe this anomalous coupling. In the right panel of Fig.2 \( \chi^2 \) function versus anomalous coupling \( \alpha'_{\mu} \) is plotted for charged current deep inelastic scattering. 95\% C.L. sensitivity bound on \( \alpha'_{\mu} \) with a systematic error of the same order as the statistical one is \( |\alpha'_{\mu}| \leq 5 \times 10^{-4} \). This bound is two order of magnitude better than the LEP bound obtained from \( W^+ \rightarrow \mu^+\nu_{\mu} \) decay [3].

Neutral current deep inelastic scattering was analyzed in Ref.[2] in detail. We see from (5) that it receives contributions both from couplings \( \alpha'_{\mu} \) and \( \alpha_{\mu} \). Therefore it is impossible to set a limit on \( \alpha_{\mu} \) independent from \( \alpha'_{\mu} \) with neutral current deep inelastic scattering alone. It is rather possible to set a limit on \( \alpha'_{\mu} - \alpha_{\mu} \) plane. On the other hand charged current deep inelastic scattering isolates the coupling \( \alpha'_{\mu} \) and therefore combining charged and neutral current scattering we can extract the limit on \( \alpha_{\mu} \). In Fig.3 we plot neutral current deep inelastic scattering limits (solid lines) of Ref.[2] and charged current deep inelastic scattering limits (dotted lines) on \( \alpha'_{\mu} \). Intersection of these two bounds gives us the limit \( |\alpha_{\mu}| \leq 2.6 \times 10^{-3} \) at 95\% C.L..

Universality assumption of the standard model that states \( \nu_e, \nu_{\mu} \) and \( \nu_\tau \) couple with the same strength to W and Z at the tree level has been discussed in Ref.2 and the NuSONG bounds on universality violation have been obtained from neutral current reactions. Authors obtained the limits \( |\alpha'_{e} - \alpha_{\mu}| \leq 0.074 (\alpha_{\mu} = 0) \) and \( |\alpha_e - \alpha_{\mu}| \leq 0.071 (\alpha'_{\mu} = 0) \) under the assumption that only one type of operator \( O_{\mu} \) or \( O'_{\mu} \) contributes to the effective lagrangian. This assumption is necessary since neutral current receives contributions both from \( O_{\mu} \) and \( O'_{\mu} \). On the other hand we see that the couplings \( \alpha'_{\mu} \) and \( \alpha_{\mu} \) can be constrained separately by studying neutral and charged current reactions together. By combining charged current deep
inelastic scattering limit with the results of Ref. \[2\] we obtain \( |\alpha_e - \alpha_\mu| \leq 0.071 \). Similarly combining the limit \( |\alpha'_\mu| \leq 5 \times 10^{-4} \) with the bound in Fig.\[1\] we obtain \( |\alpha'_e - \alpha'_\mu| \leq 0.019 \). These limits are at 95\% C.L. with a systematic error of the same order as the statistical one. We consider both of the operators (1) and (2) and do not assume that only one of them contribute to the effective lagrangian at once.

III. CONCLUSIONS

In this paper we investigated signatures for deviation from standard model predictions in neutrino-W boson couplings via charged current reactions in the NuSOnG. We showed that charged current deep inelastic scattering can explore new physics signatures with a sensitivity of order \( 10^{-4} \). Therefore NuSOnG provides exceptional prospect to probe neutrino-W couplings. We also explored the NuSOnG potential to probe neutrino flavor universality violation in neutrino-W and neutrino-Z couplings. Combining the results for charged current reactions with the results for neutral current reactions of Ref.\[2\] we achieved a complete analysis. We deduce that NuSOnG has a great potential to probe possible universality violation in neutrino-W and neutrino-Z couplings.

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FIG. 1: 95% C.L. sensitivity bounds on the parameter space $\alpha'_\mu - \alpha'_e$. The area restricted by the solid lines shows the sensitivity bound without a systematic error and dotted lines shows the sensitivity bound with a systematic error of the same order as the statistical one.
FIG. 2: Figure on the left shows charged current deep inelastic scattering cross section of $\nu_\mu$ from an isoscalar nucleus as a function of neutrino energy for the standard model (SM-solid line) and two values of the anomalous coupling $\alpha'_\mu$. Figure on the right shows $\chi^2$ function versus $\alpha'_\mu$ with (dotted line) and without (solid line) a systematic error. Systematic error is taken to be of the same order as the statistical one.
FIG. 3: Neutral current deep inelastic scattering limits (solid lines) of Ref. [2] and charged current deep inelastic scattering limits (dotted lines) on $\alpha'_\mu$. Limits are at 95% C.L. with a systematic error of the same order as the statistical one.