Probe of anomalous neutrino couplings to W and Z in medium energy setup of a beta-beam facility

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Abstract

Capability of medium energy setup of a beta beam experiment to probe new physics contributions to neutrino-W and neutrino-Z couplings are investigated. We employ the effective lagrangian approach of Buchmuller and Wyler and obtain 95% confidence level limits on neutrino couplings to these gauge bosons without assuming the flavor universality of the coupling of neutrinos. We show that a beta beam facility with a systematic error of 2% can place 10 times more restrictive limit than present one on the deviations from the electron neutrino-Z couplings in the Standard Model.
I. INTRODUCTION

Beta beams are electron neutrino and antineutrino beams produced via the beta decay of boosted radioactive ions [1]. Such decays produce pure, intense and collimated neutrino or antineutrino beams. In the original scenario ion beams are accelerated in the proton synchrotron (PS) or super proton synchrotron (SPS) at CERN up to a Lorentz gamma factor of $\gamma \sim 100$, and then they are allowed to decay in the straight section of a storage ring. Feasibility of this design has been demonstrated in Ref. [2]. After the original proposal, different options for beta beams were investigated. A low gamma ($\gamma = 5 - 14$) option was first proposed by Volpe [3]. Physics potential of low-energy beta beams was discussed in detail. It was shown that such beams could have an important impact on nuclear physics, particle physics and astrophysics [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15].

Higher gamma options for the beta beams have also been studied in the literature [10, 16, 17, 18, 19, 20, 21, 22, 23, 24]. A higher gamma factor provides several advantages. Firstly, neutrino fluxes increase quadratically with the gamma factor. Secondly, neutrino scattering cross sections grow with the energy and hence considerable enhancement is expected in the statistics. An additional advantage of a higher gamma option is that it provides us the opportunity to study deep-inelastic neutrino scattering from the nucleus. Very high gamma ($\sim 2000$) options would require modifications in the original plan such as using LHC and therefore extensive feasibility study is needed. In this context medium energy setup is more appealing and less speculative. We investigate the physics potential of a medium energy setup ($\gamma = 350 - 580$) proposed in Ref. [16] to probe non-standard neutrino-$Z$ and neutrino-$W$ interactions. We do not make the a priori assumption of the flavor universality of the coupling of neutrinos to these gauge bosons.

Neutrino-$W$ and neutrino-$Z$ couplings have been precisely tested at CERN $e^+e^-$ collider LEP. Non-standard $W\ell\nu$ couplings are constrained via $W$ boson decay to leptons. It is possible to discern neutrino flavor in $W^+ \rightarrow \ell^+\nu_\ell$ decay by identifying charged lepton flavor. Therefore individual limits on neutrino-$W$ couplings for different neutrino flavors can be obtained from the LEP data. On the other hand neutrino-$Z$ couplings are primarily constrained by the invisible $Z$ width, which receives contributions from all neutrino flavors. Hence it is impossible to discern possible universality violating neutrino-$Z$ couplings from the LEP data alone. It is however possible to constrain new physics contributions to $Z\nu\nu$
that respect universality. From the data on $W^+ \rightarrow e^+ \nu_e$ decay and invisible $Z$ width we set the bounds of

\begin{align}
-0.016 & \leq \Delta_e' \leq 0.016 \\
|\Delta_e + \Delta_\mu + \Delta_\tau| & \leq 0.009
\end{align}

where the parameters $\Delta_e'$, $\Delta_e$, $\Delta_\mu$ and $\Delta_\tau$ describe possible deviations from the SM coming from new physics. They modify the charged and neutral neutrino current as

\begin{align}
J_{CC}^\mu &= [1 + \Delta_e'] \bar{\nu}_e \gamma_\mu e_L, \\
J_{NC}^\mu &= \frac{1}{2} \sum_{i=e,\mu,\tau} [1 + \Delta_i] \bar{\nu}_i \gamma_\mu \nu_i
\end{align}

These new physics contributions respect universality of the coupling of neutrinos to $Z$ if the equality $\Delta_e = \Delta_\mu = \Delta_\tau$ holds. If we assume the universality of the coupling of neutrinos to $Z$, LEP data give a stringent limit of $-0.003 < \Delta_e < 0.003$.

On the other hand our purpose is to carry out a general treatment and we do not a priori assume universality of the couplings of neutrinos to gauge bosons. The processes isolating a single neutrino flavor do not imply neutrino flavor universality and therefore provide more information about new physics probes on $Z\nu\nu$ couplings as compared to the invisible decay width experiments of $Z$ boson. There are experimental results from CHARM Collaboration obtained from muon-neutrino and electron-neutrino scattering reactions. We have the following limits from CHARM and CHARM II data

\begin{align}
|\Delta_\mu| & \leq 0.037, \\
-0.167 & \leq \Delta_e \leq 0.237.
\end{align}

The plan of this paper is as follows: In the next section we outline the effective Lagrangian approach. In section III we summarize the neutrino fluxes and the cross sections for elastic, inelastic and deep-inelastic scattering and present our main results. Finally Section IV includes concluding remarks.

II. EFFECTIVE LAGRANGIAN FOR Z\nu\nu AND W\ell\nu COUPLINGS

There is an extensive literature on non-standard interactions of neutrinos. New physics contributions to neutrino-$Z$ and neutrino-$W$ couplings can be investigated in a model independent way by means of the effective Lagrangian approach. The theoretical basis of such an approach rely on the assumption that at higher energies
beyond where the Standard Model (SM) is tested, there is a more fundamental theory which reduces to the SM at lower energies: The SM is assumed to be an effective low-energy theory in which heavy fields have been integrated out. Such a procedure is quite general and independent of the new interactions at the new physics energy scale.

We consider the $SU(2)_L \otimes U(1)_Y$ invariant effective Lagrangian introduced in Ref. [37]. Possible deviations from the SM that may violate flavor universality of the neutrino-V ($V=Z,W$) couplings are described by the following dimension-6 effective operators:

\[ O_j = i(\phi^\dagger D_\mu \phi)(\bar{\psi}_j \gamma^\mu \psi_j) \] (5)
\[ O'_j = i(\phi^\dagger D_\mu \tau \phi)(\bar{\psi}_j \gamma^\mu \tau \psi_j) \] (6)

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

\[ D_\mu = \partial_\mu + ig \frac{2}{\sqrt{2}} \vec{\tau} \cdot \vec{W}_\mu + ig' Y B_\mu. \] (7)

Here $g$ and $g'$ are the $SU(2)_L$ and $U(1)_Y$ gauge couplings, $Y$ is the hypercharge and the gauge fields $W^{(i)}_\mu$ and $B_\mu$ sit in the $SU(2)_L$ triplet and $U(1)_Y$ singlet representations, respectively.

The most general $SU(2)_L \otimes U(1)_Y$ invariant Lagrangian up to dimension-6 operators, containing new physics contributions that may violate universality of the neutrino-V couplings, is then given by

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum_{j=e,\mu,\tau} \frac{1}{\Lambda^2}(\alpha_j O_j + \alpha'_j O'_j) \] (8)

where $\mathcal{L}_{SM}$ is the SM Lagrangian, $\Lambda$ is the energy scale of new physics and $\alpha_j, \alpha'_j$ are the anomalous couplings. After symmetry breaking, Lagrangian in Eq. (8) reduces to

\[ \mathcal{L}' = \frac{g}{\sqrt{2}} \left( J^{CC}_\mu W^{+\mu} + J^{CC^\dagger}_\mu W^{-\mu} \right) + \frac{g}{\cos \theta_W} J^{NC}_\mu Z_\mu, \] (9)

where $J^{CC}_\mu$ and $J^{NC}_\mu$ are charged and neutral currents. They are given by

\[ J^{CC}_\mu = \left[ 1 + 2\alpha'_j \frac{v^2}{\Lambda^2} \right] \bar{\nu}_j L \gamma^\mu \ell_j L \] (10)
\[ J^{NC}_\mu = \left[ \frac{1}{2} + \frac{v^2}{2\Lambda^2}(-\alpha_j + \alpha'_j) \right] \bar{\nu}_j L \gamma^\mu \nu_j L + \left[ -\frac{1}{2} + \sin^2 \theta_W - \frac{v^2}{2\Lambda^2}(\alpha_j + \alpha'_j) \right] \bar{\ell}_j L \gamma^\mu \ell_j L \] (11)
In this effective current subscript "L" represents the left-handed leptons and \( v \) represents the vacuum expectation value of the scalar field. (For definiteness, we take \( v = 246 \) GeV and \( \Lambda = 1 \) TeV in the calculations presented in this paper).

As can be seen from the current in Eq. (11), the operators of Eq. (5) and (6) modify not only the neutrino currents, but also the left-handed charge lepton currents. On the other hand, right-handed charged lepton currents are not modified. \( \alpha'_{j} \) couplings contribute both to the charged and neutral currents but \( \alpha_{j} \) contribute only to the neutral current. Therefore studying charged current processes one can isolate the couplings \( \alpha'_{j} \). The parameters \( \Delta_{j} \) and \( \Delta'_{j} \) introduced in the introduction section are then expressed as follows

\[
\Delta_{j} = \frac{v^2}{\Lambda^2}(-\alpha_{j} + \alpha'_{j}), \quad \Delta'_{j} = 2\alpha'_{j}\frac{v^2}{\Lambda^2}.
\] (12)

III. NEUTRINO FLUXES AND CROSS SECTIONS

Accelerating \( \beta \)-unstable heavy ions to a given \( \gamma \) factor and allowing them to decay in the straight section of a storage ring, very intense neutrino or anti-neutrino beams can be produced. In the ion rest frame the neutrino spectrum is given by

\[
\frac{dN}{d\cos\theta dE_{\nu}} \sim E_{\nu}^2(E_{0} - E_{\nu})\sqrt{(E_{\nu} - E_{0})^2 - m_{e}^2}
\] (13)

where \( E_{0} \) is the electron end-point energy, \( m_{e} \) is the electron mass. \( E_{\nu} \) and \( \theta \) are the energy and polar angle of the neutrino. The neutrino flux from accelerated ions can be obtained by performing a boost. The neutrino flux per solid angle in a detector located at a distance \( L \) is then

\[
\left( \frac{d\phi^{Lab}}{dS dy} \right)_{\theta=0} \simeq \frac{N_{\beta}}{\pi L^2} \frac{\gamma^2}{g(y_{e})} y^2(1 - y)\sqrt{(1 - y)^2 - y_{e}^2},
\] (14)

where \( 0 \leq y \leq 1 - y_{e}, \ y = \frac{E_{\nu}}{2\gamma E_{0}}, \ y_{e} = \frac{m_{e}}{E_{0}} \) and

\[
g(y_{e}) = \frac{1}{60} \left[ \sqrt{1 - y_{e}^2} (2 - 9y_{e}^2 - 8y_{e}^4) + 15y_{e}^4 \log \left( \frac{y_{e}}{1 - \sqrt{1 - y_{e}^2}} \right) \right].
\] (15)

\( ^{18}\text{Ne} \) and \( ^{6}\text{He} \) have been proposed as ideal candidates for a neutrino and an anti-neutrino source, respectively \[1, 16\]. They produce pure (anti-)neutrino beams via the reactions

\( ^{18}\text{Ne} \rightarrow ^{18}\text{F} e^{+}\nu_{e} \) and \( ^{6}\text{He}^{++} \rightarrow ^{3}\text{Li}^{++} e^{-}\bar{\nu}_{e} \). We assume that total number of ion decays per year is \( N_{\beta} = 1.1 \times 10^{18} \) for \( ^{18}\text{Ne} \) and \( N_{\beta} = 2.9 \times 10^{18} \) for \( ^{6}\text{He} \).
In Fig. 1 we plot neutrino and anti-neutrino fluxes as a function of (anti-)neutrino energy at a detector of \( L = 732 \) km distance. \( \gamma \) parameters for ions are taken to be \( \gamma = 350 \) for \( ^6\)He and \( \gamma = 580 \) for \( ^{18}\)Ne. The foregoing detector distance and \( \gamma \) values have been proposed in Ref. [16] as a medium energy setup. In Ref. [16] authors have considered a Megaton-class water Cerenkov detector with a fiducial mass of 400 kiloton. They show that a cut demanding the reconstructed energy to be larger than 500 MeV suppresses most of the residual backgrounds. We assumed a water Cerenkov detector with the same mass and a cut of 500 MeV for the calculations presented here.

We see from Fig. 1 that neutrino spectra extend up to 4 GeV and anti-neutrino spectra extend up to 2.5 GeV. Between 0.5 - 1.5 GeV quasi elastic nucleon scattering dominates the cross section. In this energy range, protons scattered via inverse \( \beta \)-decay are generally below Cerenkov threshold and thus it is very difficult to discern quasi elastic scattering from neutrino-electron scattering. Therefore we will add number of events provided by these reactions during statistical analysis. As the energy increases, deep inelastic scattering starts dominating the cross section. The turn-over region is about 1.5 GeV.

A. Neutrino electron scattering and neutrino nucleon quasi elastic scattering

Electron-neutrino electron scattering in SM is described by two tree-level diagrams containing \( W \) and \( Z \) exchange. As we have discussed in the previous section, not only the \( \nu_e \nu_e Z \) and \( \nu_e eW \) vertices but also the \( e^- e^- Z \) vertex is modified by the effective Lagrangian. The total cross section is given by

\[
\sigma(\nu_e e^- \rightarrow \nu_e e^-) = \frac{G_F^2 E_\nu^2 m_e}{\pi(2E_\nu + m_e)^3} \left[ \frac{16}{3} (g''_A + g''_V + g''_A g''_V) E_\nu^2 + 4m_e(2g'^2 + g''_V) + g''_A g''_V - m_e^2 (3g'^2 + g''_V) \right]
\]

(16)

where \( E_\nu \) is the initial neutrino energy, \( m_e \) is the mass of the electron and \( G_F \) is the Fermi constant. The couplings \( g''_A \) and \( g''_V \) are defined as follows

\[
g''_A(V) = \left( 1 + \frac{v^2}{\Lambda^2} \right) g'A(V) + \left( 1 + \frac{2v^2}{\Lambda^2} \right),
\]

\[
g'_A(V) = g_A(V) - \frac{v^2}{2\Lambda^2} (\alpha_e + \alpha'_e),
\]

\[
g_A = -\frac{1}{2}, \quad g_V = -\frac{1}{2} + 2 \sin^2 \theta_W,
\]

(17)
where \( \Lambda \) is the energy scale of new physics and \( v \) is the vacuum expectation value of the scalar field. Anti-neutrino cross section can be obtained from (16) by making the substitution \( g''_A \rightarrow -g''_A \).

As we have discussed it is very difficult to discern neutrino electron scattering from quasi elastic scattering with a Cerenkov detector. The differential cross section for \( \nu_e n \rightarrow p e^- \) is given by

\[
\frac{d\sigma}{dq^2} = \frac{G_F^2 \cos^2 \theta_C}{4\pi} \left( 1 + \frac{2v^2}{\Lambda^2 a'_e} \right)^2 \left\{ (F_V + F_W + F_A)^2 + (F_V + F_W - F_A)^2 \left( 1 + \frac{q^2}{2E_{\nu}m_N} \right)^2 \right. \\
+ \left[ F_A^2 - (F_V + F_W)^2 \right] \frac{(-q^2)}{2E_{\nu}^2} + \left[ F_W^2 \left( -q^2 + 4m_N^2 \right) \right. \\
\left. \left. - 2(F_V + F_W)F_W \right] \times \left[ 2 + \frac{q^2(m_N + 2E_{\nu})}{2E_{\nu}^2 m_N} \right] \right\} 
\]

(18)

where \( \cos \theta_C = 0.974 \) is the Cabibbo angle, and \( F \)'s are invariant form factors that depend on the transferred momentum \( q^2 \equiv (p_p - p_n)^2 \). In (18) we ignore the terms proportional to electron mass squared which give only a minor contribution. The \( F \)'s are known as vector \( F_V \), axial-vector \( F_A \) and tensor \( F_W \) (or weak magnetism) form factors. They are all G-parity invariant. We adopt the same parameterization of the momentum dependence as in Ref. [9]:

\[
F_V(q^2) = \left( 1 - \frac{q^2}{(0.84 \text{GeV})^2} \right)^{-2} \\
F_W(q^2) = \left( \frac{\mu_p - \mu_n}{2m_N} \right) F_V(q^2) \\
F_A(q^2) = 1.262 \left( 1 - \frac{q^2}{(1.032 \text{GeV})^2} \right)^{-2} 
\]

(19)

Here \( \mu_p - \mu_n = 3.706 \) is the difference in the anomalous magnetic moments of the nucleons. We see from (18) that quasi elastic scattering isolates the coupling \( a'_e \) and new physics contribution can be factorized in the cross section. Differential cross section for reaction \( \bar{\nu}_e p \rightarrow n e^+ \) can be obtained from (18) by making the substitution \( F_A \rightarrow -F_A \).

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,

\[
\chi^2 = \left( \frac{N_{SM} - N_{AN}}{N_{SM} \delta_{exp}} \right)^2 
\]

(20)

where \( N_{SM} \) is the number of events expected in the SM and \( N_{AN} \) is the number of events containing new physics effects. The experimental error is \( \delta_{exp} = \sqrt{\delta_{stat}^2 + \delta_{syst}^2} \) where \( \delta_{stat} \) and \( \delta_{syst} \) are the statistical and systematic errors, respectively.
In the quasi elastic scattering the main source of uncertainties comes from the $q^2$-dependence of the form factors. The slope of the electromagnetic form factors at $q^2 = 0$ is conventionally expressed in terms of a nucleon radius. The uncertainty for these radii is calculated to be 1% [38]. From this uncertainty we have calculated the uncertainties in the number of events. Uncertainties in the number of events for neutrino-nucleon and antineutrino-nucleon quasi elastic scatterings are 1.1% and 0.25% respectively.

In Fig. 2 we plot 95% C.L. bounds on the $\alpha_e - \alpha'_e$ parameter space for $\nu_e$ and $\bar{\nu}_e$ scatterings. Number of events has been obtained by integrating cross section over the (anti-)neutrino energy spectrum and multiplying by the appropriate factor that accounts for the number of corresponding particles (electrons, protons or neutrons) in a 400 kiloton fiducial mass of the detector. Integration ranges are $0.5 - 1.5$ GeV for quasi elastic scattering and $0.5 - 4(2.5)$ GeV for $\nu_e$ ($\bar{\nu}_e$) electron scattering. Number of events provided by (anti-)neutrino electron and (anti-)neutrino nucleon quasi elastic scatterings have been combined. We see from Fig. 2 that although the cross sections for $\bar{\nu}_e$ scatterings are smaller than $\nu_e$ scatterings, limits on $\alpha_e - \alpha'_e$ are almost the same. This is reasonable since the $\bar{\nu}_e$ flux peaks at about 1.4 GeV and it is larger than $\nu_e$ flux everywhere in the interval $0.5 - 1.5$ GeV (Fig. 1).

B. Neutral- and charged-current deep inelastic scatterings

When neutrino energy exceeds 1.5 GeV, deep inelastic scattering starts to dominate the cross section. Since neutrino spectra extend up to 4 GeV and the deep inelastic cross sections for $\nu_e$ scattering at this energy range are large, medium energy setup $\beta$-beam experiment will provide high statistics deep inelastic scattering from the nuclei. On the other hand, $\bar{\nu}_e$ deep inelastic cross sections are smaller than the $\nu_e$ cross sections. Moreover $\bar{\nu}_e$ spectra extend only up to 2.5 GeV and it decreases rapidly after 1.5 GeV (Fig. 1). Therefore number of deep inelastic events for anti-neutrinos is low and its statistics is poor. So we do not perform a statistical analysis for anti-neutrinos.

Neutral- and charged-current deep inelastic scatterings of electron-neutrinos from the nuclei are described by t-channel $Z$ and $W$ exchange diagrams respectively. Since quark couplings to $W$ and $Z$ boson are not modified by operators (5,6) hadron tensor does not
receive any contribution. It is defined in the standard form \[39, 40\]

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

(21)

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 structure functions for an isoscalar target are defined as follows \[41\]

\[ F_{2NC} = \quad x \left[ (u_L^2 + u_R^2 + d_L^2 + d_R^2)(q_{val} + 2\bar{q}) - 2(u_L^2 + u_R^2 - d_L^2 - d_R^2)(s - c) \right] \]

\[ F_{3NC} = \quad (u_L^2 - u_R^2 + d_L^2 - d_R^2)q_{val} \]

\[ F_{2CC} = \quad x(q_{val} + 2\bar{q}) + x(s - c) \]

\[ F_{3CC} = \quad q_{val} \]  

(22)

(23)

where superscripts ”NC” and ”CC” represents neutral current and charged current form factors, \( q_{val} \)’s are valence quark and \( q \)’s are sea quark distributions. We assumed that sea quark and antiquark distributions are the same, i.e. \( q = \bar{q} \). \( u \)’s and \( d \)'s are defined by

\[ u_L = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W, \quad u_R = -\frac{2}{3} \sin^2 \theta_W \]

\[ d_L = -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W, \quad d_R = \frac{1}{3} \sin^2 \theta_W \]

The form factors \( F_1 \)'s can be obtained from (22) and (23) by using Callan-Gross relation \[2xF_1 = F_2 \] \[42\]. In our calculations parton distribution functions of Martin, Roberts, Stirling and Thorne (MRST2004) \[43\] have been used. In our calculations we assumed an isoscalar oxygen nucleus \( N = (p + n)/2 \) and two free protons for each \( H_2O \) molecule. Naturally occurring oxygen is 99.8% \( ^{16}O \) which is isoscalar \[44\]. Hence the error incurred by assuming an isoscalar oxygen target would be not more than a fraction of one percent.

Possible new physics contributions coming from the operators in (5) and (6) only modify the lepton tensors:

\[ L_{\mu\nu}^{NC} = 4 \left(1 + \frac{\nu^2}{\Lambda^2} (-\alpha_e + \alpha'_e)^2 \right) \left(k_\mu k'_\nu + k'_\mu k_\nu - k\cdot k' g_{\mu\nu} + i\epsilon_{\mu\nu\alpha\beta} k^\alpha k'^\beta \right) \]  

(24)

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

(25)
where $k_\mu$ and $k'_\mu$ are the momenta of initial $\nu_e$ and final $\nu_e$ or $e^-$, respectively.

In Fig. 3 we show 95% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for neutral current deep inelastic $\nu_e$ scattering reaction. When we compare these bounds with the bounds shown in Fig. 2 we observe that limit on $\alpha'_e$ shown in Fig. 3 is not as restrictive as the limit in Fig. 2. For example when $\alpha_e = 0$ the limit on $\alpha'_e$ without a systematic error is $-0.07 \leq \alpha'_e \leq 0.07$ in Fig. 2 (left panel). But same limit observed from Fig. 3 is $-0.15 \leq \alpha'_e \leq 0.15$. On the other hand limits on $\alpha_e$ are very weak in Fig. 2 as compared with Fig. 3. This originates from the fact that, unlike the neutral current deep inelastic scattering, quasi elastic scattering, which dominates the cross section in the energy interval 0.5 - 1.5 GeV, does not contain any new physics contribution proportional to the coupling $\alpha_e$.

The behavior of the neutral (charged) current deep inelastic scattering cross section as a function of initial neutrino energy is plotted for various values of the anomalous coupling $\Delta_e (\alpha'_e)$ in the left panel of Fig. 4 (Fig. 5). We see from these figures that deviation of the anomalous cross sections from their SM values increases in magnitude as the energy increases. On the other hand, the percentage change in the cross section is energy independent. This is clear from the energy independence of new physics contributions. However the cross sections and therefore the statistics increase with the energy. We see from the figures that the increment in the cross sections is linear approximately after 3.5 GeV. Therefore high energy neutrino experiments are expected to reach a high sensitivity to probe these anomalous couplings. 95% C.L. limits on anomalous couplings $\Delta_e$ and $\alpha'_e$ are plotted as a function of systematic error for neutral and charged current deep inelastic scattering processes in the right panels of Fig. 4 and Fig. 5. 95% C.L. sensitivity bounds on $\Delta_e$ and $\alpha'_e$ are $-0.02 \leq \Delta_e \leq 0.02$ and $-0.167 \leq \alpha'_e \leq 0.164$ with a systematic error of 2%. These bounds can be compared with CHARM and LEP limits (4) and (1). We see that medium energy setup of the $\beta$-beam experiment with 1 year of running and a systematic error of 2% provides approximately 10 times more restricted limit for $\Delta_e$ as compared with the CHARM limit. This limit is 4 times more restricted even systematic error is 5%. On the other hand, limit on $\alpha'_e$ with a systematic error of 2% is approximately 1.3 times worse than the LEP limit.

It is important to discuss uncertainties on these couplings due to uncertainties from structure functions and SM electroweak parameters. During calculations we used the following values for some SM parameters: $G_F = 1.16637(1) \times 10^{-5} \text{GeV}^{-2}$, $\sin^2 \theta_W = 0.23122(15)$,
\[ \sin \theta_C = 0.227(1) \] [25]. Here numbers in parentheses after the values give 1-standard-deviation uncertainties in the last digits. Uncertainty on the limit of \( \Delta_e \) in neutral current deep inelastic scattering due to uncertainties from the above SM parameters is order of \( 10^{-5} \). Uncertainty on the limit of \( \alpha'_e \) is order of \( 10^{-6} \) in charged current deep inelastic scattering and order of \( 10^{-5} \) in the combined analysis of (anti-)neutrino electron and (anti-)neutrino nucleon quasi elastic scatterings. Uncertainties in the structure functions may lead to a considerable uncertainty in the cross sections. Nucleon structure functions were precisely measured in neutrino-iron and anti-neutrino-iron scattering reactions at the Fermilab Tevatron by the CCFR collaboration. The systematic error of 2.1\% was reported in the cross sections [45]. In the near future, the precision on the structure functions is expected to increase dramatically [46]. In this context beta beam facility itself can be used to reduce uncertainties in the structure functions. Beta beams present an ideal venue to measure neutrino cross sections. For beta beams neutrino fluxes are precisely known and therefore uncertainties associated with the neutrino (anti-neutrino) fluxes are negligible. The Lorentz factor of the accelerated ions can be varied. We see from (24) and (25) that new physics contributions are factorized in the cross sections. Therefore, the ratio of deep inelastic cross sections measured in two different \( \gamma \) factors is independent from the new physics contributions that we considered. Theoretical predictions can be fitted to the measured ratio in order to eliminate uncertainties. This procedure can also be done for the ratio of neutrino and anti-neutrino deep inelastic cross sections. The ratio of neutrino and anti-neutrino deep inelastic cross sections is again independent from the new physics contributions and can be especially used to reduce the uncertainty in the structure function \( F_3 \).

\section*{C. Different \( \gamma \) options}

It is important to investigate the variation of the sensitivity limits when the \( \gamma \) parameter of the ion beams are changed. Different from the proposed \( \gamma \) values for a medium energy setup in Ref. [16] we consider \( \gamma = 300 \) and 400 for \( ^6He \) and \( \gamma = 530 \) and 630 for \( ^{18}Ne \). The fluxes for these \( \gamma \) values at a detector of 732 km distance are plotted in Fig. 6. We see from this figure that \( \nu_e \) fluxes in the energy interval 0 - 1.5 GeV change very slightly with \( \gamma \). Therefore the combined statistics of neutrino quasi elastic and neutrino electron scatterings do not change significantly. On the other hand, \( \bar{\nu}_e \) fluxes rapidly change after 1 GeV with \( \gamma \).
Combined limits of anti-neutrino electron and anti-neutrino nucleon quasi elastic scatterings for $\gamma=400$ and $\gamma=300$ are given in Fig. 7.

The number of deep inelastic events increase with $\gamma$ due to two reasons: First, energy spectra of the neutrinos extend to higher energy values. Second, average fluxes grow with $\gamma$. Therefore one can expect a sizable improvement in the limits as the $\gamma$ increases. In order to compare limits for different $\gamma$ options we present Figs. 8-10. We see from Fig. 8 that limits on $\alpha_e - \alpha'_e$ without a systematic error improves by more than a factor of 1.5 as the $\gamma$ increases from 530 to 630. In Fig. 9 and Fig. 10 we show the behavior of 95% C.L. sensitivity bounds as a function of Lorentz $\gamma$ factor. We see from Fig. 9 that 95% C.L. sensitivity bounds on $\Delta_e$ with a systematic error of 2% are $-0.021 \leq \Delta_e \leq 0.020$ for $\gamma=630$ and $-0.022 \leq \Delta_e \leq 0.022$ for $\gamma=530$. The influence of $\gamma$ on the limits of the coupling $\alpha'_e$ obtained from charged current deep inelastic scattering can be observed from Fig. 10. From Fig. 10 we have 95% C.L. limits of $-0.166 \leq \alpha'_e \leq 0.163$ for $\gamma=630$ and $-0.170 \leq \alpha'_e \leq 0.166$ for $\gamma=530$ with a systematic error of 2%.

IV. CONCLUSIONS

Experiments that isolate only a single neutrino flavor such as $\beta$-beam proposals or NuSOnG [47] proposal do not require neutrino flavor universality assumption and therefore provide more information about new physics probes on neutrino-gauge boson couplings. In this paper, we explored signatures for deviation from the SM predictions in neutrino-Z boson and neutrino-W boson couplings. We do not a priori assume universality of the couplings of neutrinos to these gauge bosons. We deduce that medium energy setup of the $\beta$-beam experiment has a great potential to probe possible new physics contributions to $Z_\nu_e \nu_e$ coupling. Beta beam experiment with a systematic error of 2% improves the limit on $Z_\nu_e \nu_e$ approximately a factor of 10 compared with CHARM limit. It also probes $W e_\nu_e$ coupling with a good sensitivity. The limit obtained for the coupling $W e_\nu_e$ is in the same order of the LEP limit. Coupled with possible complementary measurements of muon-neutrino or/and tau-neutrino scattering cross sections for example at NuSOnG experiment [35, 36], beta beam experiment can be a powerful probe of new neutrino physics.
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FIG. 1: Beta-beam fluxes as a function of neutrino energy for $\bar{\nu}_e$ (solid line) and $\nu_e$ (dotted line). $\gamma$ parameter is taken to be 350 for $\bar{\nu}_e$ and 580 for $\nu_e$. 
FIG. 2: 95% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for $\nu_e$ (on the left) and $\bar{\nu}_e$ (on the right) scatterings. The areas restricted by the solid lines show the sensitivity bounds without a systematic error and dotted lines show the sensitivity bounds with a systematic error of 1%. Number of events provided by (anti-)neutrino electron and (anti-)neutrino nucleon quasi elastic scatterings have been combined. The energy scale of new physics is taken to be $\Lambda = 1$ TeV.
FIG. 3: 95% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for neutral-current deep inelastic scattering of $\nu_e$. 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 2%. The energy scale of new physics is taken to be $\Lambda = 1$ TeV.
FIG. 4: Figure on the left shows neutral current deep inelastic scattering cross section of $\nu_e$ from an isoscalar nucleus as a function of neutrino energy. The legends are for standard model (SM) and various values of the anomalous coupling $\Delta_e = \frac{v^2}{\Lambda^2}(-\alpha_e + \alpha'_e)$. Figure on the right shows 95% C.L. limits on $\Delta_e$ as a function of systematic error. The energy scale of new physics is taken to be $\Lambda = 1$ TeV.
FIG. 5: Figure on the left shows charged current deep inelastic scattering cross section of $\nu_e$ from an isoscalar nucleus as a function of neutrino energy. The legends are for standard model (SM) and various values of the anomalous coupling $\alpha'_e$. Figure on the right shows 95% C.L. limits on $\alpha'_e$ as a function of systematic error. The energy scale of new physics is taken to be $\Lambda = 1$ TeV.

FIG. 6: Fluxes as a function of neutrino energy for different values of the parameter $\gamma$ stated on the figures. Figure on the left (right) shows fluxes for $\bar{\nu}_e$ ($\nu_e$).
FIG. 7: 95\% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for $\bar{\nu}_e$ scattering. Left panel is for $\gamma=400$ and right panel is for $\gamma=300$. The areas restricted by the solid lines show the sensitivity bounds without a systematic error and dotted lines show the sensitivity bounds with a systematic error of 1\%. Number of events provided by anti-neutrino electron and anti-neutrino nucleon quasi elastic scatterings have been combined. The energy scale of new physics is taken to be $\Lambda = 1$ TeV.
FIG. 8: 95% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for neutral current deep inelastic scattering of $\nu_e$. Left panel is for $\gamma=630$ and right panel is for $\gamma=530$. 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 2%. The energy scale of new physics is taken to be $\Lambda = 1$ TeV.
FIG. 9: 95% C.L. bounds on $\Delta_e$ as a function of Lorentz $\gamma$ factor with various systematic errors stated on the figure. Bounds obtained from neutral current deep inelastic $\nu_e$ scattering. The energy scale of new physics is taken to be $\Lambda = 1 \text{ TeV}$.
FIG. 10: 95% C.L. bounds on $\alpha'_e$ as a function of Lorentz $\gamma$ factor with various systematic errors stated on the figure. Bounds obtained from charged current deep inelastic $\nu_e$ scattering. The energy scale of new physics is taken to be $\Lambda = 1$ TeV.