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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.

Contents

1 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 [4–15].

Higher gamma options for the beta beams have also been studied in the literature [10, 16–24]. 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 (~ 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 $W^+ \to \ell^+ \nu_\ell$ decay by identifying the 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 $W^+ \to e^+ \nu_e$ decay and invisible Z width we set the bounds of [25]

$$-0.016 \leq \Delta'_e \leq 0.016 \tag{1.1}$$

$$|\Delta_e + \Delta_\mu + \Delta_\tau| \leq 0.009 \tag{1.2}$$

where the parameters $\Delta'_e, \Delta_e, \Delta_\mu$ and Δ_τ describe possible deviations from the SM coming from new physics. They modify the charged and neutral neutrino current as [26]

$$J_\mu^{CC} = \left[1 + \Delta'_e\right] \bar{\nu}_{eL} \gamma_\mu e_L \,, \qquad J_\mu^{NC} = \frac{1}{2} \sum_{i=e,\mu,\tau} [1 + \Delta_i] \bar{\nu}_{iL} \gamma_\mu \nu_{iL} \tag{1.3}$$

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 [27, 28]

$$|\Delta_\mu| \leq 0.037 \,, \qquad -0.167 \leq \ \Delta_e \leq 0.237. \tag{1.4}$$

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.

2 Effective Lagrangian for $Z\nu\nu$ and $W\ell\nu$ couplings

There is an extensive literature on non-standard interactions of neutrinos [29–36]. 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 $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ 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:

$$O_j = i \left(\phi^\dagger D_\mu \phi \right) \left(\bar{\psi}_j \gamma^\mu \psi_j \right) \tag{2.1}$$

$$O_j' = i \left(\phi^\dagger D_\mu \vec{\tau} \phi \right) \cdot \left(\bar{\psi}_j \gamma^\mu \vec{\tau} \psi_j \right) \tag{2.2}$$

where ψ_j is the left-handed lepton doublet for flavor $j = e, \mu$ or τ; ϕ is the scalar doublet; and D_μ is the covariant derivative, defined by

$$D_\mu = \partial_\mu + i \frac{g}{2} \vec{\tau} \cdot \vec{W}_\mu + i \frac{g'}{2} Y B_\mu. \tag{2.3}$$

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

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

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{j=e,\mu,\tau} \frac{1}{\Lambda^2} \left(\alpha_j O_j + \alpha_j' O_j' \right) \tag{2.4}$$

where $\mathcal{L}_{SM}$ is the SM Lagrangian, Λ is the energy scale of new physics and α_j, α_j' are the anomalous couplings. After symmetry breaking, Lagrangian in eq. (2.4) reduces to [37]

$$\mathcal{L}' = \frac{g}{\sqrt{2}} \left(J_\mu^{CC} W^{+\mu} + J_\mu^{CC\,\dagger} W^{-\mu} \right) + \frac{g}{\cos \theta_W} J_\mu^{NC} Z^\mu, \tag{2.5}$$

where J_μ^{CC} and J_μ^{NC} are charged and neutral currents. They are given by

$$J_\mu^{CC} = \left[1 + 2\alpha_j' \frac{v^2}{\Lambda^2} \right] \bar{\nu}_{jL} \gamma_\mu \ell_{jL} \tag{2.6}$$

$$J_\mu^{NC} = \left[\frac{1}{2} + \frac{v^2}{2\Lambda^2}(-\alpha_j + \alpha_j') \right] \bar{\nu}_{jL} \gamma_\mu \nu_{jL} + \left[-\frac{1}{2} + \sin^2\theta_W - \frac{v^2}{2\Lambda^2}(\alpha_j + \alpha_j') \right] \bar{\ell}_{jL} \gamma_\mu \ell_{jL} \tag{2.7}$$

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 $\Lambda = 1\,\mathrm{TeV}$ in the calculations presented in this paper).

As can be seen from the current in eq. (2.7), the operators of eq. (2.1) and (2.2) modify not only the neutrino currents, but also the left-handed charged lepton currents. On the other hand, right-handed charged lepton currents are not modified. α_j' couplings contribute both to the charged and neutral currents but α_j contribute only to the neutral

current. Therefore studying charged current processes one can isolate the couplings α'_j. The parameters Δ_j and Δ'_j introduced in the introduction section are then expressed as follows

$$\Delta_j = \frac{v^2}{\Lambda^2}(-\alpha_j + \alpha'_j), \qquad \Delta'_j = 2\alpha'_j \frac{v^2}{\Lambda^2}. \tag{2.8}$$

3 Neutrino fluxes and cross sections

Accelerating β-unstable heavy ions to a given γ 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

$$\frac{dN}{d\cos\theta dE_\nu} \sim E_\nu^2(E_0 - E_\nu)\sqrt{(E_\nu - E_0)^2 - m_e^2} \tag{3.1}$$

where E_0 is the electron end-point energy, m_e is the electron mass. E_ν and θ 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 [16]

$$\left(\frac{d\phi^{Lab}}{dSdy}\right)_{\theta\simeq0} \simeq \frac{N_\beta}{\pi L^2}\frac{\gamma^2}{g(y_e)}y^2(1-y)\sqrt{(1-y)^2 - y_e^2}, \tag{3.2}$$

where $0 \le y \le 1 - y_e$, $y = \frac{E_\nu}{2\gamma E_0}$, $y_e = \frac{m_e}{E_0}$ and

$$g(y_e) = \frac{1}{60}\left(\sqrt{1-y_e^2}(2 - 9y_e^2 - 8y_e^4) + 15y_e^4 Log\left[\frac{y_e}{1 - \sqrt{1-y_e^2}}\right]\right). \tag{3.3}$$

^{18}Ne and ^6He 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 $^{18}_{10}Ne \to^{18}_9 Fe^+\nu_e$ and $^6_2He^{++} \to^6_3 Li^{+++}e^-\bar{\nu}_e$. We assume that total number of ion decays per year is $N_\beta = 1.1 \times 10^{18}$ for ^{18}Ne and $N_\beta = 2.9 \times 10^{18}$ for ^6He.

In figure 1 we plot neutrino and anti-neutrino fluxes as a function of (anti-)neutrino energy at a detector of L = 732 km distance. γ parameters for ions are taken to be $\gamma = 350$ for ^6He and $\gamma = 580$ for ^{18}Ne. The foregoing detector distance and γ 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 figure 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 β-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.
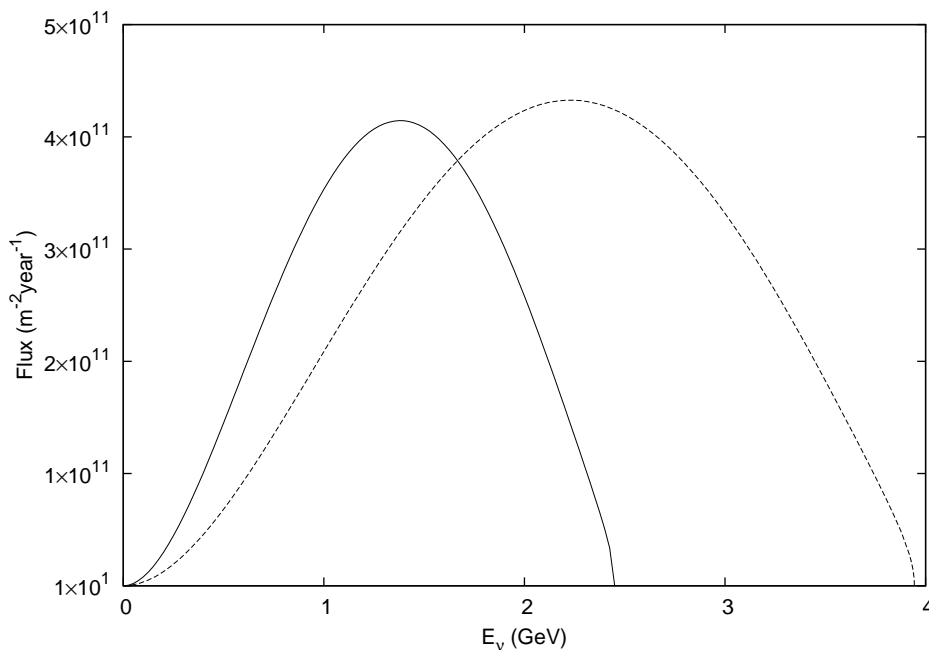
Figure 1. Beta-beam fluxes as a function of neutrino energy for $\bar{\nu}_e$ (solid line) and ν_e (dotted line). γ parameter is taken to be 350 for $\bar{\nu}_e$ and 580 for ν_e.

3.1 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

$$\sigma(\nu_e e^- \to \nu_e e^-) = \frac{G_F^2 E_\nu^2 m_e}{\pi(2E_\nu + m_e)^3} \left[\frac{16}{3} \left(g_A''^2 + g_V''^2 + g_A'' g_V'' \right) E_\nu^2 + 4m_e \left(2g_A''^2 + g_V''^2 \right. \right.$$
$$\left. \left. + g_A'' g_V'' \right) E_\nu + m_e^2 \left(3g_A''^2 + g_V''^2 \right) \right] \tag{3.4}$$

where E_ν 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

$$g_{A(V)}'' = \left(1 + \frac{v^2}{\Lambda^2}(-\alpha_e + \alpha_e') \right) g_{A(V)}' + \left(1 + \frac{2v^2}{\Lambda^2}\alpha_e' \right)^2,$$
$$g_{A(V)}' = g_{A(V)} - \frac{v^2}{2\Lambda^2}(\alpha_e + \alpha_e'),$$
$$g_A = -\frac{1}{2}, \quad g_V = -\frac{1}{2} + 2\sin^2\theta_W, \tag{3.5}$$

where Λ 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 (3.4) by making the substitution $g_A'' \to -g_A''$.

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 $\nu_e n \to p\, e^-$ is given by

$$\frac{d\sigma}{d|q^2|} = \frac{G_F^2 \cos^2 \theta_C}{4\pi} \left(1 + \frac{2v^2}{\Lambda^2} \alpha_e'\right)^2$$

$$\times \Bigg\{ (F_V + F_W + F_A)^2 + (F_V + F_W - F_A)^2 \left(1 + \frac{q^2}{2E_\nu m_N}\right)^2$$

$$+ \left[F_A^2 - (F_V + F_W)^2\right] \frac{(-q^2)}{2E_\nu^2} + \left[F_W^2 \frac{(-q^2 + 4m_N^2)}{4m_N^2} - 2(F_V + F_W)F_W\right]$$

$$\times \left[2 + \frac{q^2(m_N + 2E_\nu)}{2E_\nu^2 m_N}\right] \Bigg\} \tag{3.6}$$

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 (3.6) 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]:

$$F_V(q^2) = \left(1 - \frac{q^2}{(0.84\,GeV)^2}\right)^{-2}$$

$$F_W(q^2) = \left(\frac{\mu_p - \mu_n}{2m_N}\right) F_V(q^2) \tag{3.7}$$

$$F_A(q^2) = 1.262 \left(1 - \frac{q^2}{(1.032\,GeV)^2}\right)^{-2}$$

Here $\mu_p - \mu_n = 3.706$ is the difference in the anomalous magnetic moments of the nucleons. We see from (3.6) that quasi elastic scattering isolates the coupling α_e' and new physics contribution can be factorized in the cross section. Differential cross section for reaction $\bar{\nu}_e p \to n\, e^+$ can be obtained from (3.6) by making the substitution $F_A \to -F_A$.

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

$$\chi^2 = \left(\frac{N_{SM} - N_{AN}}{N_{SM}\, \delta_{\exp}}\right)^2 \tag{3.8}$$

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 $\delta_{\exp} = \sqrt{\delta_{\mathrm{stat}}^2 + \delta_{\mathrm{syst}}^2}$ where δ_{stat} and δ_{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
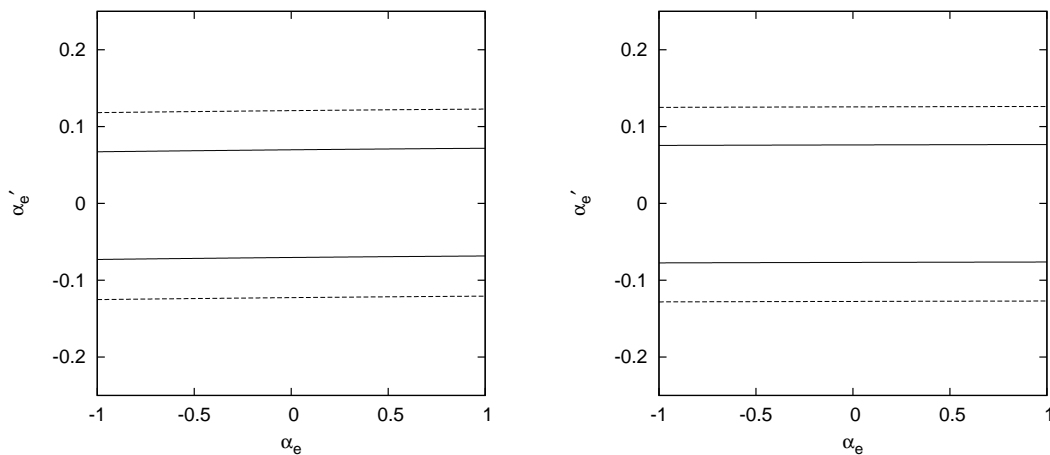
Figure 2. 95% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for ν_e (on the left) and $\bar{\nu}_e$ (on the right) scatterings. The areas restricted by the solid lines show the sensitivity bounds without a systematic error and dotted lines show the sensitivity bounds with a systematic 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 $\Lambda = 1\,\mathrm{TeV}$.

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 figure 2 we plot 95% C.L. bounds on the $\alpha_e - \alpha'_e$ parameter space for ν_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 $0.5 - 1.5\,\mathrm{GeV}$ for quasi elastic scattering and $0.5 - 4(2.5)\,\mathrm{GeV}$ for ν_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 figure 2 that although the cross sections for $\bar{\nu}_e$ scatterings are smaller than ν_e scatterings, limits on $\alpha_e - \alpha'_e$ are almost the same. This is reasonable since the $\bar{\nu}_e$ flux peaks at about $1.4\,\mathrm{GeV}$ and it is larger than ν_e flux everywhere in the interval $0.5 - 1.5\,\mathrm{GeV}$ (figure 1).

3.2 Neutral- and charged-current deep inelastic scatterings

When neutrino energy exceeds $1.5\,\mathrm{GeV}$, deep inelastic scattering starts to dominate the cross section. Since neutrino spectra extend up to $4\,\mathrm{GeV}$ and the deep inelastic cross sections for ν_e scattering at this energy range are large, medium energy setup β-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 ν_e cross sections. Moreover $\bar{\nu}_e$ spectra extend only up to $2.5\,\mathrm{GeV}$ and it decreases rapidly after $1.5\,\mathrm{GeV}$ (figure 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 (2.1), (2.2) hadron tensor does not receive any contribution. It is defined in the standard form [39, 40]

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x, Q^2) + \frac{\hat{p}_\mu \hat{p}_\nu}{p \cdot q} F_2(x, Q^2) - i\epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha p^\beta}{2p \cdot q} F_3(x, Q^2) \quad (3.9)$$

where p_μ is the nucleon momentum, q_μ 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]

$$\begin{aligned} F_2^{NC} &= x\left[(u_L^2 + u_R^2 + d_L^2 + d_R^2)(q_{\text{val}} + 2\bar{q}) - 2(u_L^2 + u_R^2 - d_L^2 - d_R^2)(s - c)\right] \\ F_3^{NC} &= (u_L^2 - u_R^2 + d_L^2 - d_R^2)q_{\text{val}} \end{aligned} \quad (3.10)$$

$$\begin{aligned} F_2^{CC} &= x(q_{val} + 2\bar{q}) + x(s - c) \\ F_3^{CC} &= q_{\text{val}} \end{aligned} \quad (3.11)$$

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

$$\begin{aligned} u_L &= \frac{1}{2} - \frac{2}{3}\sin^2\theta_W, & u_R &= -\frac{2}{3}\sin^2\theta_W \\ d_L &= -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W, & d_R &= \frac{1}{3}\sin^2\theta_W \end{aligned}$$

The form factors F_1's can be obtained from (3.10) and (3.11) 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. 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 (2.1) and (2.2) only modify the lepton tensors:

$$L_{\mu\nu}^{NC} = 4\left(1 + \frac{v^2}{\Lambda^2}(-\alpha_e + \alpha_e')\right)^2 \left(k_\mu k_\nu' + k_\mu' k_\nu - k \cdot k' g_{\mu\nu} + i\epsilon_{\mu\nu\alpha\beta}k^\alpha k'^\beta\right) \quad (3.12)$$

$$L_{\mu\nu}^{CC} = 8\left(1 + \frac{2v^2}{\Lambda^2}\alpha_e'\right)^2 \left(k_\mu k_\nu' + k_\mu' k_\nu - k \cdot k' g_{\mu\nu} + i\epsilon_{\mu\nu\alpha\beta}k^\alpha k'^\beta\right) \quad (3.13)$$

where k_μ and k_μ' are the momenta of initial ν_e and final ν_e or e^-, respectively.
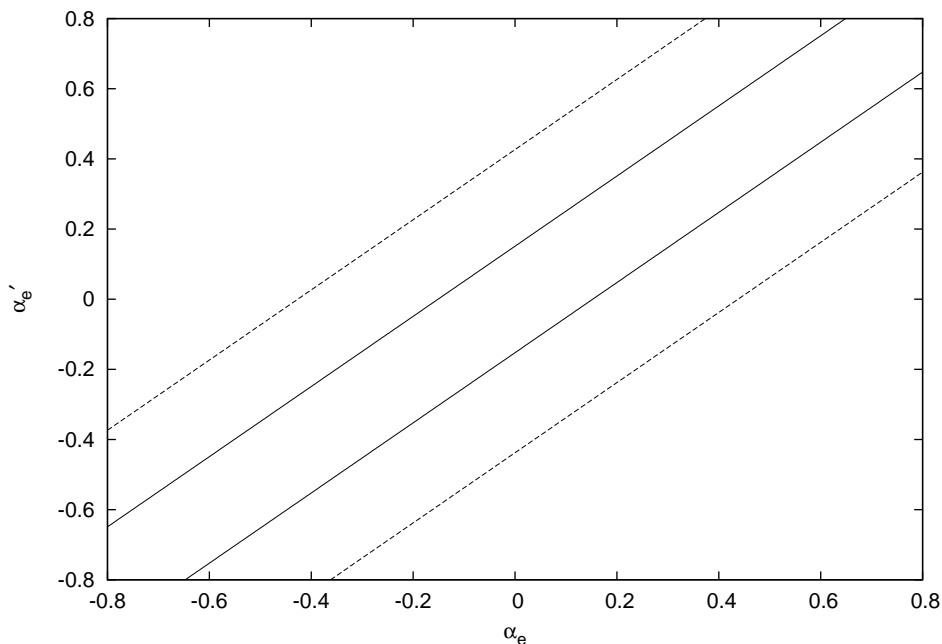
Figure 3. 95% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for neutral-current deep inelastic scattering of ν_e. The area restricted by the solid lines shows the sensitivity bound without a systematic error and dotted lines shows the sensitivity bound with a systematic error of 2%. The energy scale of new physics is taken to be $\Lambda = 1 \, \text{TeV}$.

In figure 3 we show 95% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for neutral current deep inelastic ν_e scattering reaction. When we compare these bounds with the bounds shown in figure 2 we observe that limit on α'_e shown in figure 3 is not as restrictive as the limit in figure 2. For example when $\alpha_e = 0$ the limit on α'_e without a systematic error is $-0.07 \leq \alpha'_e \leq 0.07$ in figure 2 (left panel). But same limit observed from figure 3 is $-0.15 \leq \alpha'_e \leq 0.15$. On the other hand limits on α_e are very weak in figure 2 as compared with figure 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 α_e.
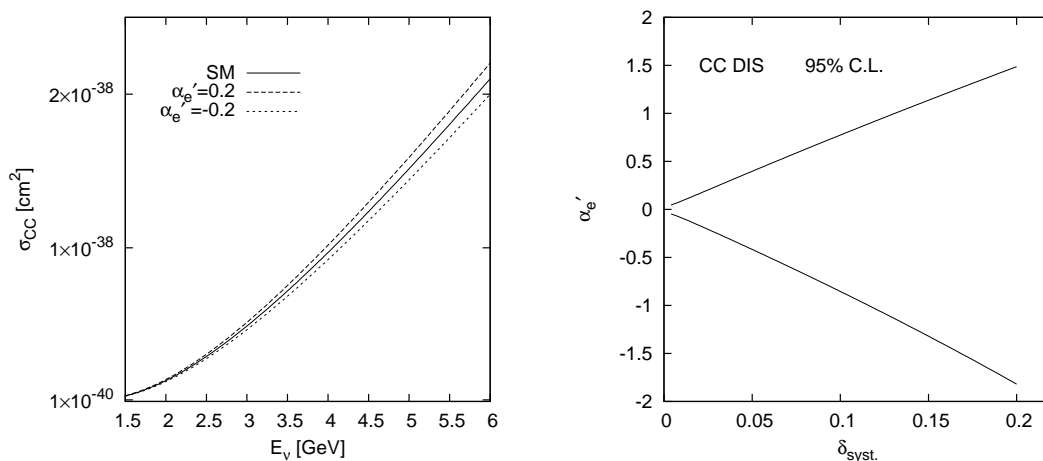
The behavior of the neutral (charged) current deep inelastic scattering cross section as a function of initial neutrino energy is plotted for various values of the anomalous coupling Δ_e (α'_e) in the left panel of figure 4 (figure 5). We see from these figures that deviation of the anomalous cross sections 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 Δ_e and α'_e
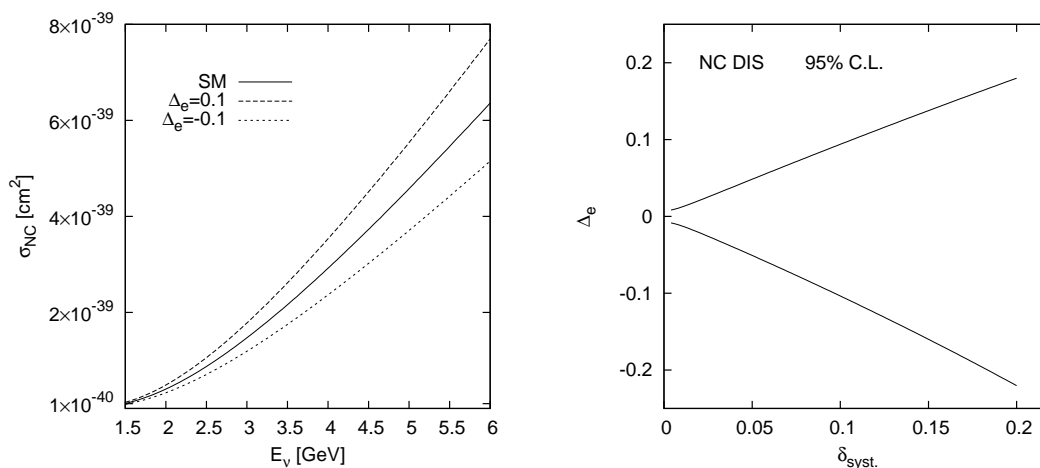
Figure 4. figure on the left shows neutral current deep inelastic scattering cross section of ν_e from an isoscalar nucleus as a function of neutrino energy. The legends are for standard model (SM) and various values of the anomalous coupling $\Delta_e = \frac{v^2}{\Lambda^2}(-\alpha_e + \alpha'_e)$. figure on the right shows 95% C.L. limits on Δ_e as a function of systematic error. The energy scale of new physics is taken to be $\Lambda = 1\,\mathrm{TeV}$.

are plotted as a function of systematic error for neutral and charged current deep inelastic scattering processes in the right panels of figure 4 and figure 5. 95% C.L. sensitivity bounds on Δ_e and α'_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 (1.4) and (1.1). We see that medium energy setup of the β-beam experiment with 1 year of running and a systematic error of 2% provides approximately 10 times more restricted limit for Δ_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 α'_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: $G_F = 1.16637(1)10^{-5}GeV^{-2}$, $\sin^2\theta_W = 0.23122(15)$, $\sin\theta_C = 0.227(1)$ [25]. Here numbers in parentheses after the values give 1-standard-deviation uncertainties in the last digits. Uncertainty on the limit of Δ_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 α'_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

Figure 5. Figure on the left shows charged current deep inelastic scattering cross section of ν_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 α'_e. Figure on the right shows 95% C.L. limits on α'_e as a function of systematic error. The energy scale of new physics is taken to be $\Lambda = 1\,\mathrm{TeV}$.

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 γ factor of the accelerated ions can be varied. We see from (3.12) and (3.13) that new physics contributions are factorized in the cross sections. Therefore, the ratio of deep inelastic cross sections measured in two different γ 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.

3.3   Different γ options

It is important to investigate the variation of the sensitivity limits when the γ parameter of the ion beams are changed. Different from the proposed γ 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 γ values at a detector of 732 km distance are plotted in figure 6. We see from this figure that ν_e fluxes in the energy interval 0 - 1.5 GeV change very slightly with γ. 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 γ. Combined limits of anti-neutrino electron and anti-neutrino nucleon quasi elastic scatterings for γ=400 and γ=300 are given in figure 7. The number of deep inelastic events increase with γ due to two reasons: First, energy spectra of the neutrinos extend to higher energy values. Second, average fluxes grow with γ. Therefore one can expect a sizable improvement in the limits as the γ increases. In order to compare limits for different
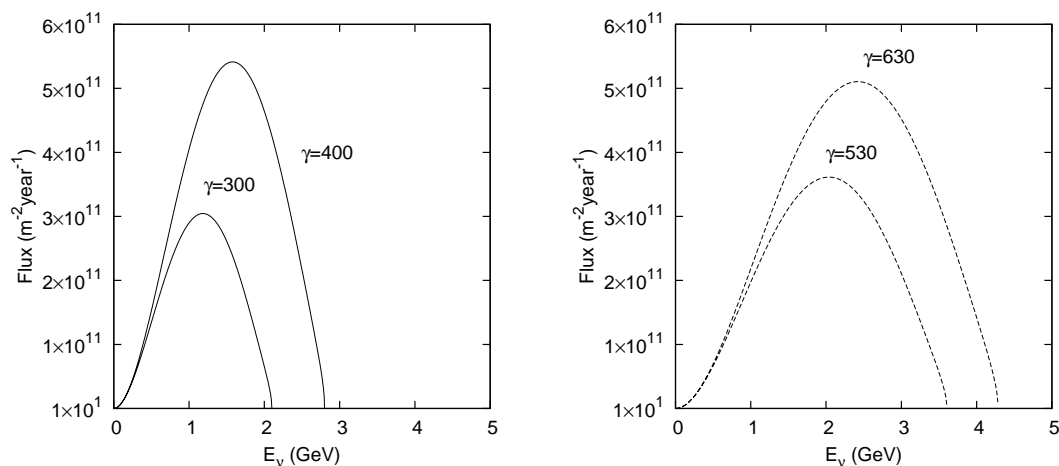
Figure 6. Fluxes as a function of neutrino energy for different values of the parameter γ stated on the figures. Figure on the left (right) shows fluxes for $\bar{\nu}_e$ (ν_e).
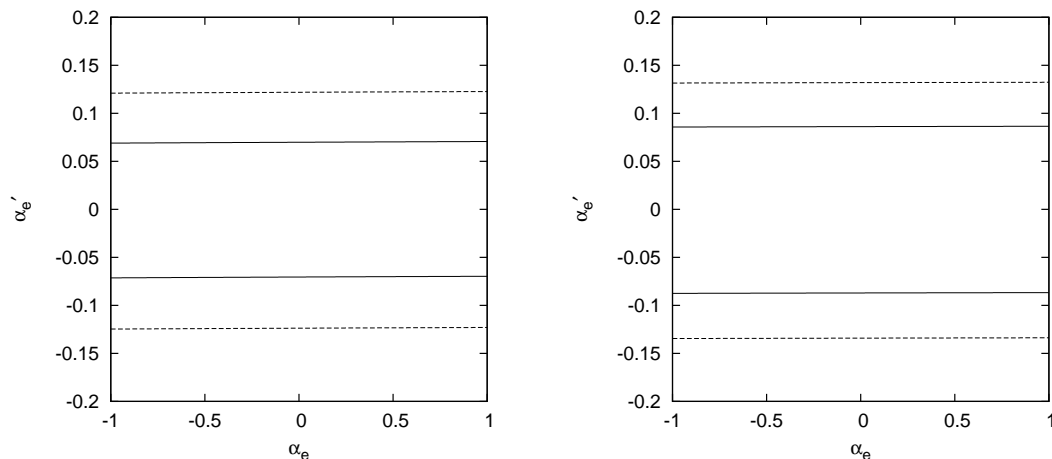

Figure 7. 95% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for $\bar{\nu}_e$ scattering. Left panel is for γ=400 and right panel is for γ=300. The areas restricted by the solid lines show the sensitivity bounds without a systematic error and dotted lines show the sensitivity 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 $\Lambda = 1\,\mathrm{TeV}$.

γ options we present figures 8, 10. We see from figure 8 that limits on $\alpha_e - \alpha'_e$ without a systematic error improves by more than a factor of 1.5 as the γ increases from 530 to 630. In figure 9 and figure 10 we show the behavior of 95% C.L. sensitivity bounds as a function of Lorentz γ factor. We see from figure 9 that 95% C.L. sensitivity bounds on Δ_e with a systematic error of 2% are $-0.021 \leq \Delta_e \leq 0.020$ for γ=630 and $-0.022 \leq \Delta_e \leq 0.022$ for γ=530. The influence of γ on the limits of the coupling α'_e obtained from charged current deep inelastic scattering can be observed from figure 10. From figure 10 we have 95% C.L.
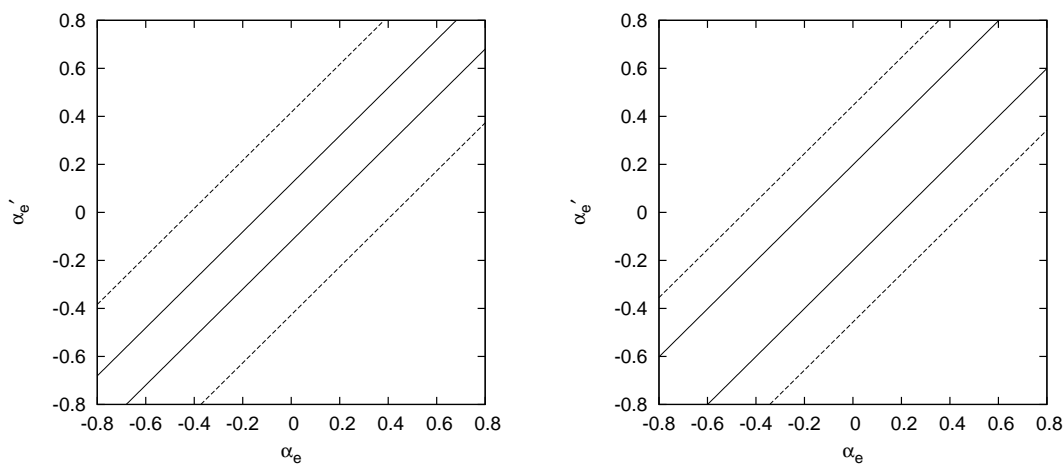
Figure 8. 95% C.L. sensitivity bounds on the parameter space $\alpha_e - \alpha'_e$ for neutral current deep inelastic scattering of ν_e. Left panel is for γ=630 and right panel is for γ=530. The area restricted by the solid lines shows the sensitivity bound without a systematic error and dotted lines shows the sensitivity bound with a systematic error of 2%. The energy scale of new physics is taken to be $\Lambda = 1\,\mathrm{TeV}$.
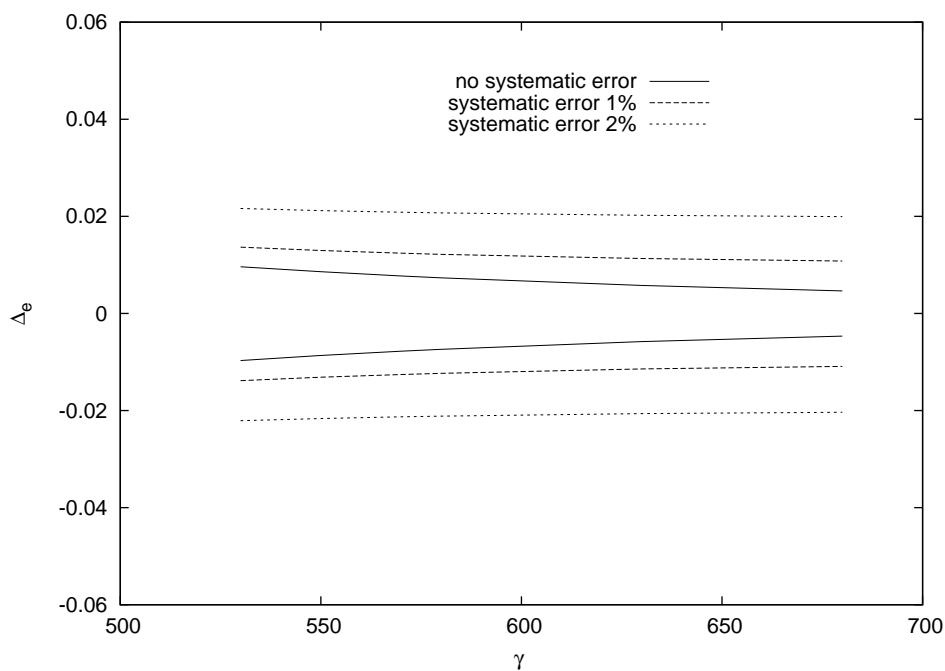
Figure 9. 95% C.L. bounds on Δ_e as a function of Lorentz γ factor with various systematic errors stated on the figure. Bounds obtained from neutral current deep inelastic ν_e scattering. The energy scale of new physics is taken to be $\Lambda = 1\,\mathrm{TeV}$.

limits of $-0.166 \leq \alpha'_e \leq 0.163$ for γ=630 and $-0.170 \leq \alpha'_e \leq 0.166$ for γ=530 with a systematic error of 2%.
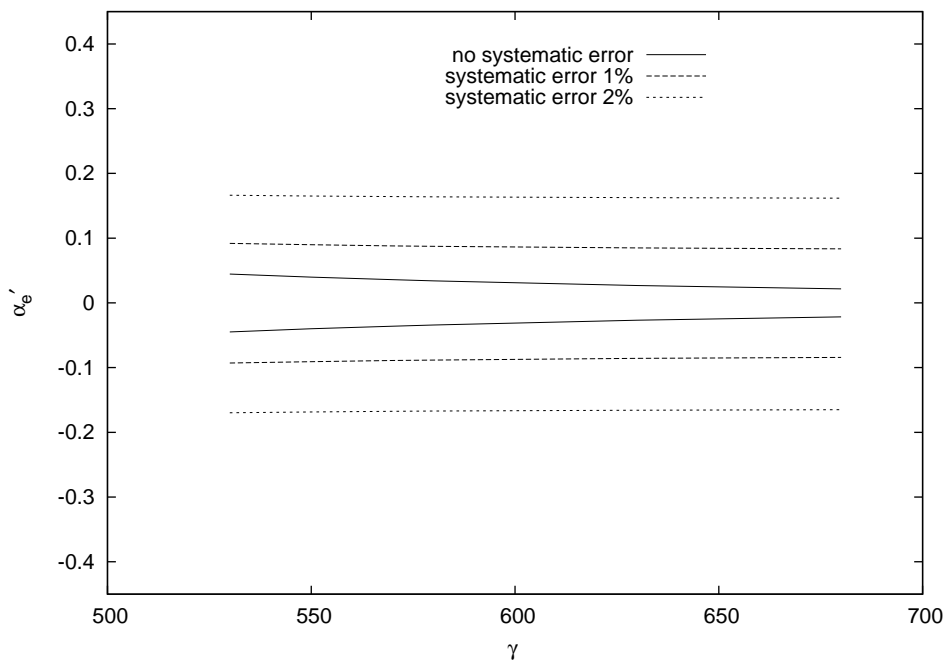
Figure 10. 95% C.L. bounds on α'_e as a function of Lorentz γ factor with various systematic errors stated on the figure. Bounds obtained from charged current deep inelastic ν_e scattering. The energy scale of new physics is taken to be $\Lambda = 1\,\mathrm{TeV}$.

4 Conclusions

Experiments that isolate only a single neutrino flavor such as β-beam proposals or Nu-SOnG [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 β-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 $We\nu_e$ coupling with a good sensitivity. The limit obtained for the coupling $We\nu_e$ 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.

Acknowledgments

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