Effects of Non-Standard Interactions in Neutral Current Form Factors

Ilma[1], M. Rafi Alam[1],[*] M. Benitez Galan[2], I.
Ruiz Simo[2], L. Alvarez-Ruso[3], and S. K. Singh[1]
[1]*Department of Physics, Aligarh Muslim University, Aligarh - 202002, India*
[2]*Departamento de Física Atómica, Molecular y Nuclear, E-18071 Granada, Spain and*
[3]*Instituto de Física Corpuscular(IFIC), E-46980, Valencia, Spain*

Introduction

In the past few decades, electromagnetic form factors (EM FFs) have been extensively studied and are relatively well understood. Most form factor models remain phenomenological, but advancements have been made through lattice QCD studies [1]. On the other hand, both the vector and axial-vector FFs contribute to the weak processes. Thanks to the Conserved Vector Current(CVC), the EM FFs are used to describe the vector part of the weak current, while for axial FFs, we rely mainly on partial conservation of axial current(PCAC) and Goldberger Treiman relation.

Despite these improvements, challenges remain, particularly in the weak sector, where FFs are less well-constrained. These issues are often examined in the context of non-standard interactions (NSIs). Non-standard interactions are also categorized into Charged Current (CC) NSI and Neutral Current (NC) NSI, similar to the standard weak interactions. In this work, we specifically analyzed the impact of NC-NSIs on nucleon form factors, aiming to provide a deeper understanding of their structure and behavior. In this work, we specifically analyzed the impact of NC-NSIs on nucleon form factors.

Formalism and Discussion

The FFs for (anti-)neutrino induced Neutral current elastic (NCE) scattering is given by

$$\begin{aligned} V^\mu &\equiv \tilde{F}_1^{(N)}(Q^2)\gamma^\mu + i\frac{\tilde{F}_2^{(N)}(Q^2)}{2M}\sigma^{\mu\nu}q_\nu\,, \\ A^\mu &\equiv \tilde{F}_A^{(N)}(Q^2)\gamma^\mu\gamma_5\,, \end{aligned} \tag{1}$$

these FFs can be written in terms of the EM FF of protons and neutrons $F_{1,2}^{(p,n)}$ within SM as,

$$\begin{aligned} \tilde{F}_{1,2}^{(p,n)} &= \left(\frac{1}{2} - 2s_w^2\right)F_{1,2}^{(p,n)} - \frac{1}{2}F_{1,2}^{(n,p)} - \frac{1}{2}F_{1,2}^s\,, \\ \tilde{F}_A^{(p,n)} &= \pm\frac{1}{2}F_A^{iv} - \frac{1}{2}F_A^s\,; \quad s_w \equiv \sin\theta_w \end{aligned} \tag{2}$$

The weak NC interaction can be modified by adding an extra term in the lagrangian:

$$\mathcal{L}_{\text{NSI}}^{\text{NC}} = -2\sqrt{2}G_F\epsilon_{ij}^{fX}(\bar{\nu}^i\gamma_\mu P_L\nu^j)(\bar{f}\gamma^\mu P_X f)\,, \tag{3}$$

where G_F is the fermi constant, and ϵ_{ij}^{fX} denotes the strength of the NSI related to the quark fields f with suffix ij being the neutrino flavor indices. In general, the NC NSI can be flavor changing($i \neq j$) or flavor diagonal($i = j$); however, the present study is limited to the flavor diagonal only. The inclusion of Eq. 3, modifies the FFs in Eq. 4 as:

$$\begin{aligned} \tilde{F}_{1,2}^{(p,n)} &= \left[\frac{1}{2} - 2s_w^2 + 2\epsilon_{ij}^{uV} + \epsilon_{ij}^{dV}\right]F_{1,2}^{(p,n)} \\ &\quad + \left(-\frac{1}{2} + 2\epsilon_{ij}^{dV} + \epsilon_{ij}^{uV}\right)F_{1,2}^{(n,p)} - \frac{1}{2}F_{1,2}^s\,, \\ \tilde{F}_A^{(p,n)} &= \pm\frac{1}{2}\left(1 + \epsilon_{ij}^{uA} - \epsilon_{ij}^{dA}\right)F_A^{iv} \\ &\quad + \frac{1}{2}\left(\epsilon_{ij}^{uA} + \epsilon_{ij}^{dA}\right)F_A^{is} - \frac{1}{2}F_A^s\,. \end{aligned} \tag{4}$$

---

[*] Electronic address: rafi.alam.amu@gmail.com

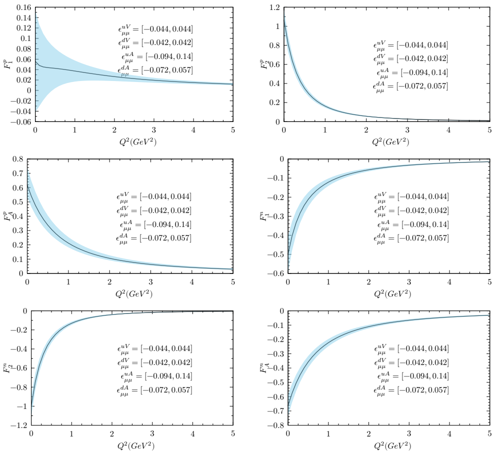

FIG. 1: The vector and axial NC FFs are plotted as a function of Q^2. Solid line correspond to the SM while the shaded bands show the deviations by NSI within the 90% CL intervals.

Interestingly, the nucleon NC matrix element in the presence of NSI depends not only on the standard axial isovector FF, F_A^{iv}, but also on the axial vector isoscalar FF, F_A^{is}, which is not probed by SM electroweak interactions. Further, we also consider the strangeness contribution in vector ($F_{1,2}^s$) and axial (F_A^s) FFs as:

$$F_1^s(Q^2) = -\frac{1}{6}\langle r_s^2\rangle Q^2 F(Q^2)$$
$$F_2^s(Q^2) = \mu_s F(Q^2) \qquad (5)$$

where $\langle r_s^2\rangle$ is the mean-squared strange radius of the nucleon and μ_s is the strange magnetic moment. The $\langle r_s^2\rangle$ can further be expressed with the help of square of strange charge radius, $\langle r_E^2\rangle^s$, as

$$\langle r_s^2\rangle = \langle r_E^2\rangle^s - \frac{3}{2}\frac{\mu_s}{m_N^2}; \qquad (6)$$

A modified dipole form factor, $F(Q^2) = \left(1 + Q^2/4M^2\right)^{-1}\left(1 + Q^2/m_v^2\right)^{-2}$ is taken for the Q^2 dependence with the dipole mass m_v, The dipole mass can then be related to the strange electric and magnetic mean squared radii $\langle r_E^2\rangle^s$ and $\langle r_m^2\rangle^s$, respectively as

$$m_v^2 = 12\mu_s(\langle r_m^2\rangle^s - \langle r_E^2\rangle^s)^{-1}\,. \qquad (7)$$

We adopt the numerical values of these parameters obtained in Ref [2] by the Extended Twisted Mass (ETM) Collaboration. The flavour decomposition of axial current is also performed by ETM collaboration. It provides dipole parametrizations as

$$F_A^q(Q^2) = g_A^q\left(1 + \frac{Q^2}{m_{A\,q}^2}\right)^{-2}. \qquad (8)$$

with $q = u, d, s$. It is then straightforward to find

$$F_A^{iv}(Q^2) = F_A^u(Q^2) - F_A^d(Q^2)$$
$$F_A^{is}(Q^2) = F_A^u(Q^2) + F_A^d(Q^2)\,. \qquad (9)$$

Couplings g_A^q and axial masses $m_{A\,q}^2$ are taken from Ref [3]. The NSI couplings in Eq. 4 are highly model dependent and are assumed to be flavour diagonal taken from Ref [4]. In the Q^2 distribution for weak NC vector $\tilde{F}_{1,2}^{p,n}$ and axial $\tilde{F}_A^{p,n}$ FFs shown in Fig 1, we observe that the impact of NSI band is enormous because $\tilde{F}_1^p$ is small in the SM and the possible NSI contribution is relatively large.

Acknowledgment

One of the authors (Ilma) would like to thank University Grants Commission(UGC), India for providing Senior Research Fellowship F.No. 16-9(June 2019)/2019(NET/CSIR).

References

[1] C. F. Perdrisat, V. Punjabi, and M. Vanderhaeghen, Prog. Part. Nucl. Phys. **59**, 694 (2007), hep-ph/0612014.

[2] C. Alexandrou, S. Bacchio, M. Constantinou, J. Finkenrath, K. Hadjiyiannakou, K. Jansen, and G. Koutsou, Phys. Rev. D **101**, 031501 (2020), 1909.10744.

[3] C. Alexandrou, S. Bacchio, M. Constantinou, K. Hadjiyiannakou, K. Jansen, and G. Koutsou, Phys. Rev. D **104**, 074503 (2021), 2106.13468.

[4] F. J. Escrihuela, M. Tortola, J. W. F. Valle, and O. G. Miranda, Phys. Rev. D **83**, 093002 (2011), 1103.1366.