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Tau-neutrino as a probe of nonstandard interaction

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Abstract

We study the Δ-resonance and deep inelastic scattering contributions in the tau-neutrino–nucleon scattering $\nu_\tau + N \to \tau^- + X$ and $\bar{\nu}_\tau + N \to \tau^+ + X$ in the presence of a charged Higgs and a W' gauge boson. The new physics effects to the quasielastic process have been discussed in a previous work. The extractions of the atmospheric mixing angle θ_{23} rely on the standard model cross sections for $\nu_\tau + N \to \tau^- + X$ in ν_τ appearance experiments. Corrections to the cross sections from the charged Higgs and W' contributions modify the measured mixing angle. We include form factor effects in the new physics calculations and find the deviations of the mixing angle. If high-energy Long Base Line experiments are designed to measure θ_{13} through tau-neutrino appearance, the new physics effects to $\nu_\tau + N \to \tau^- + X$ and $\bar{\nu}_\tau + N \to \tau^+ + X$ can impact the extraction of this mixing angle. Finally, we investigate the new physics effects on the polarization of the $\tau^\mp$ leptons produced in $\nu_\tau(\bar{\nu}_\tau)$–nucleon scattering.

1. Introduction

Neutrino oscillation results have confirmed that neutrinos are massive and lepton flavors are mixed. This opens a window for searching physics beyond the standard model (SM). Beside the standard matter effects, the possibility of having nonstandard neutrino interactions (NSIs) is opened up. Nonstandard neutrino interactions with matter have been extensively discussed [1–38]. General bounds on NSI are summarized in Refs. [39–41]. The NSI impact have been studied on solar neutrinos [42–44], atmospheric neutrinos [45–48], reactor neutrinos [49,50], and neutrino–nucleus scattering [51,52].

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At low energy, the most general effective NSI Lagrangian reads [25], if we consider only lepton number conserving operators,

$$\mathcal{L}_{\text{NSI}} = \mathcal{L}_{V\pm A} + \mathcal{L}_{S\pm P} + \mathcal{L}_{T}, \tag{1}$$

where the different terms are classified according to their Lorentz structure in the following way:

$$\begin{aligned}
\mathcal{L}_{V\pm A} &= \frac{G_F}{\sqrt{2}} \sum_{f,f'} \varepsilon_{\alpha\beta}^{f,f',V\pm A} \big[\bar{\nu}_\beta \gamma^\rho \big(1-\gamma^5\big)\ell_\alpha\big]\big[\bar{f}'\gamma_\rho\big(1\pm\gamma^5\big)f\big] \\
&\quad + \frac{G_F}{\sqrt{2}} \sum_{f} \varepsilon_{\alpha\beta}^{f,V\pm A} \big[\bar{\nu}_\alpha \gamma^\rho \big(1-\gamma^5\big)\nu_\beta\big]\big[\bar{f}\gamma_\rho\big(1\pm\gamma^5\big)f\big] + \text{h.c.}, \\
\mathcal{L}_{S\pm P} &= \frac{G_F}{\sqrt{2}} \sum_{f,f'} \varepsilon_{\alpha\beta}^{f,f',S\pm P} \big[\bar{\nu}_\beta \big(1+\gamma^5\big)\ell_\alpha\big]\big[\bar{f}'\big(1\pm\gamma^5\big)f\big] + \text{h.c.}, \\
\mathcal{L}_{T} &= \frac{G_F}{\sqrt{2}} \sum_{f,f'} \varepsilon_{\alpha\beta}^{f,f',T} \big[\bar{\nu}_\beta \sigma^{\rho\tau}\ell_\alpha\big]\big[\bar{f}'\sigma_{\rho\tau} f\big] + \text{h.c.},
\end{aligned} \tag{2}$$

where G_F is the Fermi constant, ν_α is the neutrino field of flavor α, ℓ_α is the corresponding charged lepton field, and f, f' are the components of an arbitrary weak doublet. The dimensionless NSI parameters ε's represent the strength of the nonstandard interactions relative to G_F and we consider only left-handed neutrinos. This constraint on the neutrino chirality forbids $\nu\nu ff$ terms in $\mathcal{L}_{S\pm P}$ and $\mathcal{L}_T$. If the nonstandard interactions are supposed to be mediated by a new state with a mass of order M_{NSI}, the effective vertices in Eq. (2) will be suppressed by $1/M_{\text{NSI}}^2$ in the same way as the standard weak interactions are suppressed by $1/M_{\text{W}}^2$. Therefore we expect that

$$|\varepsilon| \sim \frac{M_{\text{W}}^2}{M_{\text{NSI}}^2}. \tag{3}$$

In this work we consider the charged Higgs and W' gauge boson contributions to neutrino–nucleon scattering. Such new states arise in many extensions of the standard model and the phenomenology of these states have been widely studied [53]. In this paper we will focus on the Δ-resonance production (Δ-RES) and deep inelastic scattering (DIS) in the interactions $\nu_\tau + N \to \tau^- + X$ and $\bar{\nu}_\tau + N \to \tau^+ + X$ where $N = p, n$ is a nucleon and X is a possible final state. In the Δ-RES production we discuss the processes with $N = n$, p and $X = \Delta^+$, Δ^0, respectively. In the neutrino oscillation experiments, the neutrino–nucleus interaction in the detection process is assumed to be SM-like. Therefore, the extracted neutrino mixing angles, using the SM cross section, will have errors if there are new physics (NP) effects in the neutrino–nucleus amplitude. The NP effects modify the standard model cross section for $\nu_\tau + N \to \tau^- + X$ and thus impact the extraction of the atmospheric neutrino mixing angle θ_{23} in ν_τ appearance experiments. If high-energy Long Base Line (LBL) experiments (or atmospheric neutrino experiments scanning in the multi-GeV neutrino energy range) could measure θ_{13} via ν_τ appearance then the NP effects in $\nu_\tau + N \to \tau^- + X$ and $\bar{\nu}_\tau + N \to \tau^+ + X$ would impact the θ_{13} measurement and a mismatch between this measurement and that performed at the reactors could be a hint of a NSI in the former. The deviation of the actual mixing angle from the measured one, assuming the standard model cross section, will be studied including form factor effects in the Δ-RES case.

In this paper, we make the important assumption that NP effects only arise in the coupling between the new particles and the third generation leptons, neglecting possible (subleasing) NSI