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Corrections to the tau neutrino mixing from charged Higgs and W' contribution to ν_τ-nucleon scattering

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Abstract

We study the quasielastic process in the tau-neutrino nucleon scattering $\nu_\tau + n \to \tau^- + p$ and $\bar{\nu}_\tau + p \to \tau^+ + n$ in the presence of a charged Higgs and a W' gauge boson. The extraction of the atmospheric and reactor mixing angles θ_{23} and θ_{13}, respectively, relies on the standard model cross section for the above processes. Consideration of the charged Higgs and W' contributions to those reactions modifies the measured mixing angles, assuming the standard model cross section. We include form factor effects in the new physics calculations and find the deviations of the mixing angles.

The existence of neutrino masses and mixing requires physics beyond the standard model (SM). Hence it is not unexpected that neutrinos could have non-standard interactions (NSI). The effects of NSI have been widely considered in neutrino phenomenology [1, 2, 3]. It has been established that NSI cannot be an explanation for the standard oscillation phenomena, but it may be present as a subleading effect. Many NSI involve flavor changing neutral current or charged current lepton flavor violating processes. Here we consider charged current interactions involving a charged Higgs and a W' gauge boson in the quasielastic scattering processes $\nu_\tau + n \to \tau^- + p$ and $\bar{\nu}_\tau + p \to \tau^+ + n$. In neutrino experiments, to measure the mixing angle the neutrino-nucleus interaction is assumed to be SM-like. If there is a charged Higgs or a W' contribution to this interaction, then there will be an error in the extracted mixing angle. We will calculate the error in the extracted mixing angle. Constraints on the new couplings come from the hadronic τ decays. We will consider constraints from the decays $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to \rho^- \nu_\tau$ [4, 5, 6].

There are several reasons to consider NSI involving the (ν_τ, τ) sector. First, the third generation may be more sensitive to new physics effects because of their larger masses. As an example, in certain versions of the two Higgs doublet models (2HDM) the couplings of the new Higgs bosons are proportional to the masses, and so new physics effects are more pronounced for the third generation. Second, the constraints on NP involving the third generation leptons are somewhat weaker, allowing for larger new physics effects. Interestingly,

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the branching ratio of B decays to τ final states shows some tension with the SM predictions [7, 8] and this could indicate NP, possibly in the scalar or gauge boson sector [9]. Some examples of work that deals with NSI at the detector, though not necessarily involving the third family leptons, can be found in Refs. [10, 11].

The process $\nu_\tau + n \to \tau^- + p$ will impact the measurement of the oscillation probability for the $\nu_\mu \to \nu_\tau$ transition and hence the extraction of the mixing angle θ_{23}. The measurement of the atmospheric mixing angle θ_{23} relies on the following relationship [12]:

$$N(\nu_\tau) = P(\nu_\mu \to \nu_\tau) \times \Phi(\nu_\mu) \times \sigma_{\rm SM}(\nu_\tau)\,, \quad (1)$$

where $N(\nu_\tau)$ is the number of observed events, $\Phi(\nu_\mu)$ is the flux of muon neutrinos at the detector, $\sigma^{\rm SM}(\nu_\tau)$ is the total cross section of tau neutrino interactions with nucleons in the SM at the detector, and $P(\nu_\mu \to \nu_\tau)$ is the probability for the flavor transition $\nu_\mu \to \nu_\tau$. This probability is a function of $(E,\ L,\ \Delta m^2_{ij},\ \theta_{ij})$ with $i,j = 1,2,3$, where Δm^2_{ij} is the squared-mass difference, θ_{ij} is the mixing angle, E is the energy of neutrinos, and L is the distance traveled by neutrinos. The dominant term of the probability is

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2 2\theta_{23} \cos^4\theta_{13} \sin^2(\Delta m^2_{23} L/4E). \quad (2)$$

In the presence of NP, Eq. 1 is modified as

$$N(\nu_\tau) = P(\nu_\mu \to \nu_\tau) \times \Phi(\nu_\mu) \times \sigma_{\rm tot}(\nu_\tau), \quad (3)$$

with $\sigma_{\rm tot}(\nu_\tau) = \sigma_{\rm SM}(\nu_\tau) + \sigma_{\rm NP}(\nu_\tau)$, where $\sigma_{\rm NP}(\nu_\tau)$ refers to the additional terms of the SM contribution towards the total cross section. Hence, $\sigma_{\rm NP}(\nu_\tau)$ includes contributions from both the SM and NP interference amplitudes, and the pure NP amplitude. From Eqs. (1, 3), assuming θ_{13} to be small,[2]

$$\sin^2 2(\theta_{23}) \;=\; \sin^2 2(\theta_{23})_{SM} \frac{1}{1+r_{23}}\,, \quad (4)$$

where $\theta_{23} = (\theta_{23})_{SM} + \delta_{23}$ is the actual atmospheric mixing angle, whereas $(\theta_{23})_{SM}$ is the extracted mixing angle assuming the SM ν_τ scattering cross section. Assuming negligible new physics effects in the $\mu - N$ interaction, the actual mixing angle θ_{23} is the same as the mixing angle extracted from the survival probability $P(\nu_\mu \to \nu_\mu)$ measurement. We will take the best-fit value for the mixing angle to be given by $\theta_{23} = 42.8^\circ$ [13]. In other words, the presence of new physics in a ν_τ-nucleon scattering will result in the mixing angle, extracted from a ν_τ appearance experiment, being different than the mixing angle from ν_μ survival probability measurements. The relationship between the ratio of the NP contribution to the SM cross section $r_{23} = \sigma_{NP}(\nu_\tau)/\sigma_{SM}(\nu_\tau)$ and δ_{23} can be expressed in a model-independent form as

$$r_{23} \;=\; \Big[\frac{\sin 2(\theta_{23})_{SM}}{\sin 2((\theta_{23})_{SM} + \delta_{23})}\Big]^2 - 1\,. \quad (5)$$

[2]The presence of NP impacts the extraction of the combination $\sin^2 2\theta_{23}\cos^4\theta_{13}$. The NP changes the extracted value of θ_{23} as well as θ_{13}. But we fix the value of θ_{13} as an input at this point.

The reactor neutrino experiments can determine the mixing angle θ_{13} from the oscillation probability, $\mathrm{P}(\bar{\nu}_e \to \bar{\nu}_e)$. The probability of the tau antineutrino appearance $\bar{\nu}_e \to \bar{\nu}_\tau$ can be used to extract θ_{13}. In this case the effect of NP contributions to the process $\bar{\nu}_\tau + p \to \tau^+ + n$ is pertinent. The best-fit value for the mixing angle to be given by $\theta_{13} = 9.1^\circ$ [14]. Many neutrino mixing models have expected non-zero value for θ_{13} [15]. The relationship used in measuring θ_{13} will be given as

$$N(\bar{\nu}_\tau) = P(\bar{\nu}_e \to \bar{\nu}_\tau) \times \Phi(\bar{\nu}_e) \times \sigma_{\rm tot}(\bar{\nu}_\tau)\,, \tag{6}$$

where [16, 17, 18]

$$P(\bar{\nu}_e \to \bar{\nu}_\tau) \approx \sin^2 2\theta_{13} \cos^2\theta_{23} \sin^2(\Delta m^2_{13} L/4E). \tag{7}$$

Thus the relationship between the ratio of the NP contribution to the SM cross section $r_{13} = \sigma_{NP}(\bar{\nu}_\tau)/\sigma_{SM}(\bar{\nu}_\tau)$ and δ_{13} can be obtained in a model-independent form as

$$r_{13} \;=\; \Big[\frac{\sin 2(\theta_{13})_{SM}}{\sin 2((\theta_{13})_{SM} + \delta_{13})}\Big]^2 - 1\,. \tag{8}$$

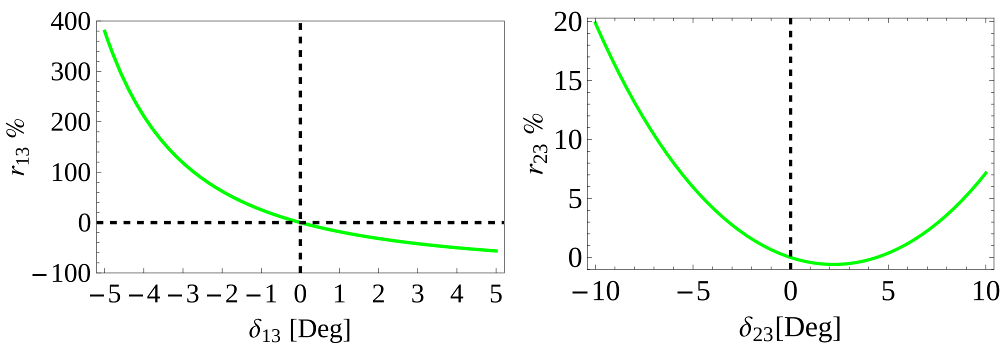

Figure 1: Correlation plot for $r_{23} = \sigma_{NP}(\nu_\tau)/\sigma_{SM}(\nu_\tau)\%$ versus $\delta_{23}[Deg]$, and $r_{13} = \sigma_{NP}(\bar{\nu}_\tau)/\sigma_{SM}(\bar{\nu}_\tau)\%$ versus $\delta_{13}[Deg]$.

In Fig. 1 we show the correlation between $r_{23(13)}\%$ and $\delta_{23(13)}$ [Deg]. One can see that $\delta_{23} \sim -5^\circ$ requires $r_{23} \sim 5\%$. But $\delta_{13} \sim -1^\circ$ requires $r_{13} \sim 25\%$. In the following sections, we consider specific models of NP to calculate r_{23} and r_{13}. We will consider a model with a charged Higgs and a W' model with both left- and right-handed couplings.

One can obtain the SM differential cross section for the reaction $\nu_l(k) + n(p) \to l^-(k') + p(p')$ [19],

$$\frac{d\sigma_{SM}(\nu_l/\bar{\nu}_l)}{dt} \;=\; \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\Big[A_{SM} \pm B_{SM}\frac{(s-u)}{M^2} + C_{SM}\frac{(s-u)^2}{M^4}\Big]\,, \tag{9}$$

where $G_F = 1.116637 \times 10^{-5}$ GeV^{-2} is the Fermi coupling constant, $\cos\theta_c = 0.9746$ is the cosine of the Cabibbo angle, M_W is the W boson mass, and E_ν is the incident neutrino energy. $M = (M_p + M_n)/2 \approx 938.9$ MeV is the nucleon mass, and we neglect the proton-neutron mass difference. The Mandelstam variables are defined by $s = (k+p)^2$, $t = q^2 = (k-k')^2$, and $u = (k-p')^2$. The expressions for the coefficients f_{SM} ($f = A, B, C$) are

$$\begin{aligned}
A_{SM} &= 4(x_t - x_l)\Big[(F_1^V)^2(1+x_l+x_t) + (F_A)^2(-1+x_l+x_t) + (F_2^V)^2(x_l + x_t^2 + x_t) \\
&\quad +4F_P^2 x_l x_t + 2F_1^V F_2^V(x_l + 2x_t) + 4F_A F_P x_l\Big]\,, \\
B_{SM} &= 4x_t F_A(F_1^V + F_2^V)\,, \\
C_{SM} &= \frac{(F_1^V)^2 + F_A^2 - x_t(F_2^V)^2}{4}\,. \qquad (10)
\end{aligned}$$

where $x_l = m_l^2/4M^2$ and $x_t = t/4M^2$. The form factors are given in [4, 5, 6].

The coupling of charged Higgs boson ($H^\pm$) interactions to a SM fermion in the 2HDM II is [20]

$$\mathcal{L} = \frac{g}{\sqrt{2}M_W}\sum_{ij}\Big[m_{u_i}\cot\beta\,\bar{u}_i V_{ij} P_{L,R} d_j + m_{d_j}\tan\beta\,\bar{u}_i V_{ij} P_{R,L} d_j + m_{l_j}\tan\beta\,\bar{\nu}_i P_{R,L} l_j\Big] H^\pm, \quad (11)$$

where $P_{L,R} = (1 \mp \gamma^5)/2$, and $\tan\beta$ is the ratio between the two vacuum expectation values (vev's) of the two Higgs doublets, and

$$\begin{aligned}
g_S^{u_i d_j} &= \left(\frac{m_{d_j}\tan\beta + m_{u_i}\cot\beta}{M_W}\right), \\
g_P^{u_i d_j} &= \left(\frac{m_{d_j}\tan\beta - m_{u_i}\cot\beta}{M_W}\right), \\
g_S^{\nu_i l_j} &= g_P^{\nu_i l_j} = \frac{m_{l_j}\tan\beta}{M_W}. \qquad (12)
\end{aligned}$$

Keeping in mind the constraints in Ref. [4, 5, 6], we calculate the charged Higgs contribution to $\nu_\tau + n \to \tau^- + p$ and $\bar{\nu}_\tau + p \to \tau^+ + n$. The modified differential cross section for the reactions is

$$\frac{d\sigma_{SM+H}}{dt} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\Big[A_H + B_H\frac{(s-u)}{M^2} + C_{SM}\frac{(s-u)^2}{M^4}\Big], \quad (13)$$

where $x_H = m_W^2/M_H^2$, $A_H = A_{SM} + 2x_H Re(A_H^I) + x_H^2 A_H^P$, and $B_H = B_{SM} + 2x_H Re(B_H^I)$. Superscripts I and P denote the SM-Higgs interference and pure Higgs contributions, respectively. The expressions for the quantities $A_H^{I,P}$ and B_H^I are given as

$$\begin{aligned}
A_H^I &= 2\sqrt{x_l}(x_t - x_l) g_P^{ud}(g_S^{l\nu_l} - g_P^{l\nu_l}) G_P(F_A + 2F_P x_t)\,, \\
B_H^I &= \frac{1}{2}\sqrt{x_l} g_S^{ud}(g_S^{l\nu_l} - g_P^{l\nu_l}) G_S(F_1^V + F_2^V x_t)\,, \\
A_H^P &= 2(x_t - x_l)(|g_S^{l\nu_l}|^2 + |g_P^{l\nu_l}|^2)(|g_P^{ud}|^2 G_P^2 x_t + |g_S^{ud}|^2 G_S^2(x_t - 1))\,. \qquad (14)
\end{aligned}$$

The terms A_H^I and B_H^I are proportional to the tiny neutrino mass, and we will ignore them in our calculation. Note that this happens because we have chosen the couplings to be given by the 2HDM II. With general couplings of the charged Higgs, these interference terms will be present. The charged Higgs contribution relative to the SM $r_H^{23} = \frac{\sigma_H(\nu_\tau)}{\sigma_{SM}(\nu_\tau)}$ is proportional to t because of the dominant term $x_t G_P^2$. Consequently, r_H^{23} is proportional to the incident neutrino energy (see Fig. (2)). The deviation δ_{23} is negative, as there is no interference with the SM; hence, the cross section for $\nu_\tau + n \to \tau^- + p$ is always larger than the SM cross section. This means that, if the actual θ_{23} is close to maximal, then experiments should measure θ_{23} larger than the maximal value in the presence of a charged Higgs contribution.

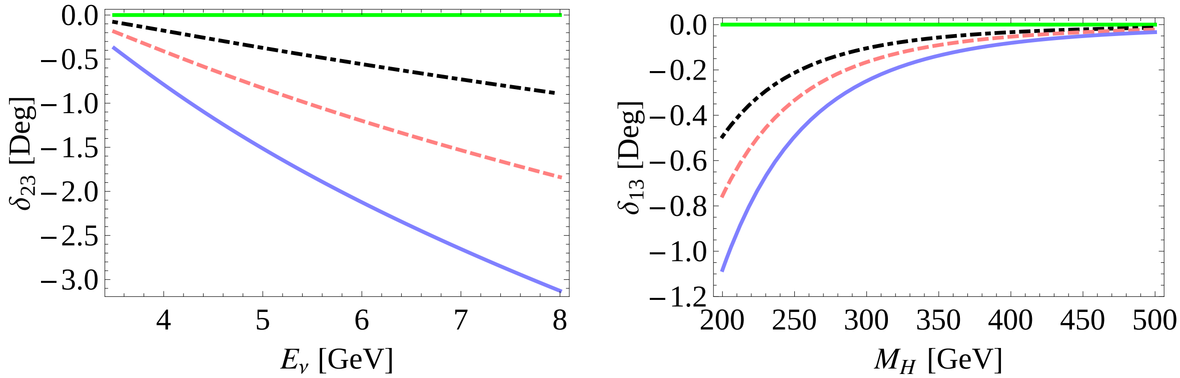

Figure 2: Left panel: Variation of δ_{23} with E_ν. The green line corresponds to the SM prediction. The black (dotdashed), pink (dashed), and blue (solid) lines correspond to $\tan\beta = 40, 50, 60$ at $M_H = 200$ GeV. Here, we use the best-fit value $\theta_{23} = 42.8°$ [13]. Right panel: Variation of δ_{13} with M_H. The green line corresponds to the SM prediction. The black (dotdashed), pink (dashed), and blue (solid) lines correspond to $\tan\beta = 80, 90, 100$ at $E_\nu = 5$ GeV. Here, we use the best-fit value $\theta_{13} = 9.1°$ [14].

The lowest dimension effective Lagrangian of W' interactions to the SM fermions has the form

$$\mathcal{L} = \frac{g}{\sqrt{2}} V_{f'f} \bar{f}' \gamma^\mu (g_L^{f'f} P_L + g_R^{f'f} P_R) f W'_\mu + \ h.c., \tag{15}$$

where f' and f refer to the fermions and $g_{L,R}^{f'f}$ are the left- and the right-handed couplings of the W'. For a SM-like W' boson, $g_L^{f'f} = 1$ and $g_R^{f'f} = 0$. We will assume $g_{L,R}^{f'f}$ to be real.

In the presence of the W' gauge boson, we can obtain the modified differential cross section for the reaction $\nu_\tau + n \to \tau^- + p$ and $\bar{\nu}_\tau + p \to \tau^+ + n$ as

$$\frac{d\sigma_{SM+W'}(\nu_\tau/\bar{\nu}_\tau)}{dt} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2} \Big[A' \pm B' \frac{(s-u)}{M^2} + C' \frac{(s-u)^2}{M^4} \Big], \tag{16}$$

where the coefficients A', B', C' include both the SM and W' contributions

$$\begin{aligned} A' &= 4(x_t - x_l) \Big[(1 + r_{W'}^\rho)^2 \Big((F_1^V)^2 (1 + x_l + x_t) + 2F_1^V F_2^V (x_l + 2x_t) + (F_2^V)^2 (x_l + x_t^2 + x_t) \Big) \\ &\quad + (1 + r_{W'}^\pi)^2 \Big((F_A)^2 (-1 + x_l + x_t) + 4F_A F_P x_l + 4F_P^2 x_l x_t \Big) \Big] , \\ B' &= 4Re[(1 + r_{W'}^\rho)(1 + r_{W'}^{\pi *})] x_t F_A (F_1^V + F_2^V) , \\ C' &= \frac{1}{4} \Big[(1 + r_{W'}^\rho)^2 ((F_1^V)^2 - x_t (F_2^V)^2) + (1 + r_{W'}^\pi)^2 F_A^2 \Big] . \end{aligned} \tag{17}$$

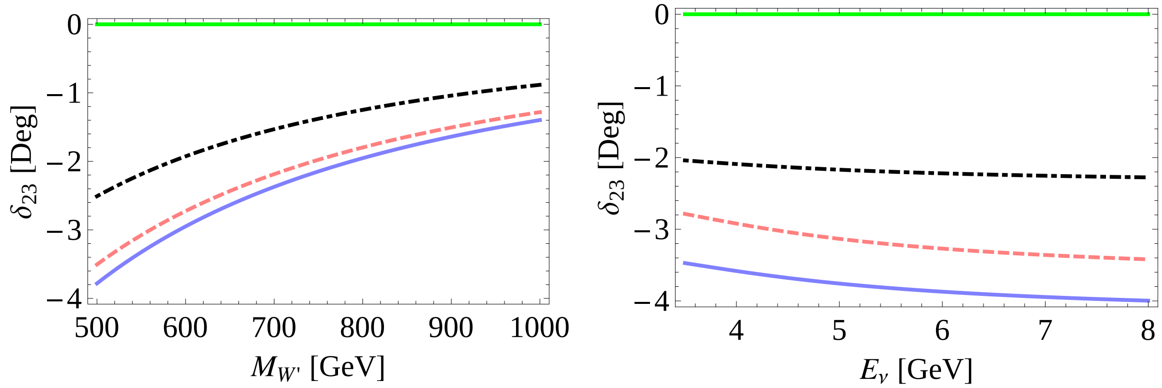

Figure 3: The left (right) panel illustrates the deviation δ_{23} with the W' mass (E_ν) when both the left- and right-handed W' couplings are present. The lines show predictions for some representative values of the W' couplings $(g_L^{\tau\nu_\tau}, g_L^{ud}, g_R^{ud})$. The green line corresponds to the SM prediction. The blue (solid, lower) line in the left figure corresponds to (-0.94 , -1.13 , -0.85) at $E_\nu = 5$ GeV, and the blue (solid, lower) line in the right figure corresponds to (1.23 , 0.84 , 0.61) at $M_{W'} = 500$ GeV. Here, we use the best-fit value $\theta_{23} = 42.8°$ [13].

The variation of δ_{23} with $M_{W'}$ and E_ν is shown in Fig. (3). The δ_{23} values are mostly negative. We find that δ_{23} depends slightly on the neutrino energy.

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