Tau neutrino as a probe of nonstandard interactions via charged Higgs and W' contribution

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Neutrino oscillation

- In vacuum: The transition probability

\[ P_{\nu_\alpha \to \nu_\beta} (t) \equiv \left| \langle \nu_\beta | \nu_\alpha (t) \rangle \right|^2 = \left| \sum_k U_{\alpha k} U^*_{\beta k} e^{-i \frac{m_k^2 L}{2E}} \right|^2 \]

\[ i \frac{d}{dt} |\nu_k (t)\rangle = H |\nu_k (t)\rangle, \quad H = \frac{1}{2E} U \text{diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) U^+ \]

- In matter: Disregarding NC, the effective Hamiltonian

\[ \tilde{H}_{\alpha \beta} = H_{\alpha \beta} + a \delta_{\alpha e} \delta_{\beta e}, \quad a = \sqrt{2G_F} N_e \]
Non-standard neutrino interactions (NSI)

- At propagation:
  \[
  \tilde{H}_{\alpha\beta} = H_{\alpha\beta} + a\left(\delta_{\alpha e}\delta_{\beta e} + \varepsilon_{\alpha\beta}\right)
  \]
  \[
  \tilde{H} = \frac{1}{2E} \tilde{U} \text{diag}(\tilde{m}_1^2, \tilde{m}_2^2, \tilde{m}_3^2)\tilde{U}^+
  \]

- At source and detector
  \[
  \left|\nu_{\alpha}^s\rightangle = \left|\nu_{\alpha}\rightangle + \sum_{\beta=e,\mu,\tau} \varepsilon_{\alpha\beta}^s \left|\nu_{\beta}\rightangle
  \]
  \[
  \langle\nu_{\beta}^d\rangle = \langle\nu_{\beta}\rangle + \sum_{\alpha=e,\mu,\tau} \varepsilon_{\alpha\beta}^d \langle\nu_{\alpha}\rangle
  \]

- The transition probability
  \[
  P_{\nu_{\alpha} \rightarrow \nu_{\beta}} = \left|\sum_{\gamma,\delta,k} \left(1 + \varepsilon_{\alpha\beta}^d\right)_{\gamma\beta} \left(1 + \varepsilon_{\alpha\beta}^s\right)_{\alpha\delta} \tilde{U}_{\delta k} \tilde{U}_{\gamma k}^* e^{-i\tilde{m}_k^2 L / 2E} \right|^2
  \]
Partonic vs hadronic: NSI parameters

- Partonic level: constant $\epsilon_{\alpha\beta}$

$$\mathcal{L}_{\text{NSI}}^q = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{q q'} V_{qq'}^\dagger [\bar{q} \gamma^\mu P q'] [\bar{\ell} \gamma_\mu P L \ell \gamma_5] + \text{h.c.}$$

- Hadronic level: energy dependent $\epsilon_{\alpha\beta}$ charged hadronic current

\[
\begin{align*}
\langle p(p')|J_\mu^+|n(p)\rangle &= V_{ud} \langle p(p')|(V_\mu - A_\mu)|n(p)\rangle \\
\langle p(p')|V_\mu|n(p)\rangle &= \bar{u}_p(p') \left[ \gamma_\mu F_1^V + \frac{i}{2M} \sigma_{\mu\nu} q^\nu F_2^V + \frac{q_\mu}{M} F_S \right] u_n(p), \\
-\langle p(p')|A_\mu|n(p)\rangle &= \bar{u}_p(p') \left[ \gamma_\mu F_A + \frac{i}{2M} \sigma_{\mu\nu} q^\nu F_T + \frac{q_\mu}{M} F_P \right] \gamma_5 u_n(p).
\end{align*}
\]
Often in the analysis of NSI, hadronization effects of the quarks via form factors are not included.

The form factors play an important role in the energy dependence of the NP effects.

Reasons to consider NSI involving the ($\nu_\tau$, $\tau$) sector:
- Tau-neutrino nucleon cross-section is not well measured
- Mass dependence of NP non-universal couplings
- The constraints on NP involving the third generation leptons are weaker allowing for larger NP effects
Two examples:

1. Quasi-elastic: Threshold energy 3.5 GeV \( W = M \)
2. \( \Delta \)-Resonance: 4.35 GeV, \( M + m_{\pi} < W < W_{\text{cut}} \)
3. Deep Inelastic Scattering: Dominant above 10 GeV

\( W_{\text{cut}} < W < \sqrt{s} - m_{\tau} \)
Model independent analysis of NP

- The atmospheric and reactor angles:
  \[ N(\nu_\tau) = P(\nu_\mu \to \nu_\tau) \times \Phi(\nu_\mu) \times \sigma(\nu_\tau) \]
  \[ N(\bar{\nu}_\tau) = P(\bar{\nu}_e \to \bar{\nu}_\tau) \times \Phi(\bar{\nu}_e) \times \sigma(\bar{\nu}_\tau) \]

- In the presence of NP

  \[ r_{23} = \left[ \frac{\sin 2(\theta_{23})_{SM}}{\sin 2((\theta_{23})_{SM} + \delta_{23})} \right]^2 - 1 \]
  \[ r_{13} = \left[ \frac{\sin 2(\theta_{13})_{SM}}{\sin 2((\theta_{13})_{SM} + \delta_{13})} \right]^2 - 1 \]

  \[ \sigma_{tot} = \sigma_{SM} + \sigma_{NP} \]

  \[ r = \frac{\sigma_{NP}}{\sigma_{SM}} , \quad \delta = \theta_{ac} - \theta_{SM} \]
Constraint on the size of the operator \( O_{NP} = \bar{u} \Gamma_i d \bar{\tau} \Gamma_j \nu_\tau \) can be obtained from the branching ratio of the decay \( \tau^- \rightarrow \pi^- \nu_\tau \).

Constraint at 95\% CL, The colored region is allowed.
Constraints: W` model

- Constraint on the size of the operator $O_{NP} = \bar{u}\Gamma_i d\bar{\tau}\Gamma_j \nu_\tau$ can be obtained from the branching ratio of the decay $\tau^- \rightarrow \pi^- \nu_\tau$ and $\tau^- \rightarrow \rho^- \nu_\tau$ at 1σ with/without RH couplings.
We define the charged hadronic current for the process 
\[ \nu_l(k) + n(p) \rightarrow l(k') + p(p') \]
\[ \langle p(p')|J_\mu|n(p)\rangle = V_{ud}\langle p(p')|(V_\mu - A_\mu)|n(p)\rangle \]
\[ \langle p(p')|V_\mu|n(p)\rangle = \bar{u}_p(p')\left[\gamma_\mu F_1^V + \frac{i}{2M}\sigma_{\mu\nu}q^\nu F_2^V\right]u_n(p), \]
\[ -\langle p(p')|A_\mu|n(p)\rangle = \bar{u}_p(p')\left[\gamma_\mu F_A + \frac{q_\mu}{M}F_P\right]\gamma_5u_n(p). \]

The SM differential cross section for the reaction
\[ \frac{d\sigma_{SM}}{dt} = \frac{M^2G_F^2\cos^2\theta_W}{8\pi E^2_v} \left[ A_{SM} + B_{SM}\frac{(s-u)}{M^2} + C_{SM}\frac{(s-u)^2}{M^4} \right] \]
The most general coupling of the charged Higgs

\[ \mathcal{L} = \frac{g}{2\sqrt{2}} \left[ V_{u_i d_j} \bar{u}_i (g_S^u d_j + g_P^u d_j \gamma^5) d_j + \bar{\nu}_i (g_S^{\nu} l_j + g_P^{\nu} \gamma^5) l_j \right] H^+ \]

\[ g_{S}^{u_d} = \left( \frac{m_d \tan \beta + m_u \cot \beta}{m_W} \right), \quad g_{S}^{\nu l} = \left( \frac{m_l \tan \beta - m_u \cot \beta}{m_W} \right), \quad g_{P}^{\nu l} = \frac{m_l \tan \beta}{m_W}. \]

The modified differential cross section

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

\[ A_H = A_{SM} + 2x_H Re(A_H^I) + x_H^2 A_H^P, \text{ and } B_H = B_{SM} + 2x_H Re(B_H^I) \]

\[ x_H = \frac{m_W^2}{M_H^2} \]
Results

- **Atm:** $M_H = 200\text{GeV}$, $E_\nu = 5\text{GeV}$, $\tan\beta = 40, 50, 60$

- **Reactor:** $M_H = 200\text{GeV}$, $E_\nu = 8\text{GeV}$, $\tan\beta = 80, 90, 100$
Quasi-elastic - W' model

- The lowest dimension effective Lagrangian for W' interactions to the SM fermions

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

- The modified differential cross section

\[ \frac{d\sigma_{SM+W'}}{dt} = \frac{M^2 G_F^2 \cos^2 \theta_c}{8 \pi E^2_\nu} \left[ A' + B' \frac{(s - u)}{M^2} + C' \frac{(s - u)^2}{M^4} \right] \]

\[ f' = f_{SM} + 2x_{W'} Re(f_{W'}^I) + x_{W'}^2 f_{W'}^P, \quad x_{W'} = \frac{M_W^2}{M_{W'}^2}, \quad f = A, B, C \]
Results

- Atm: $M_{W'} = 500 \text{GeV}$, $E_{\nu} = 5 \text{GeV}$, $(g^{\tau\nu\tau}_L, g^{ud}_L, g^{ud}_R)$
\[ \Delta \text{ Resonance - Results} \]

- **Charged Higgs**: \( M_H = 200 \text{GeV}, \ \tan \beta = 40, 50, 60 \)

- **W' model**: \( M_{W'} = 200 \text{GeV} \)
  \[ (g_{L \nu \tau}^{ud}, g_L^{ud}, g_R^{ud}) = (1.23, 0.84, 0.61) \]
Deep Inelastic Scattering - Results

- Charged Higgs: The deviations of the mixing angles are negligibly within the kinematical interval.

- $W'$ model: $E_{\nu} = 17\,\text{GeV}$, \( (g_{L}^{\tau\nu\tau}, g_{L}^{ud}, g_{R}^{ud}) = (-0.94, -1.13, -0.85) \)
Flux effect

\[
\frac{N^{SM+NSI}_\tau}{N^{SM}_\tau}(E_\nu) \sim \frac{\int \Phi^{SM}_{\nu_\mu,\nu_e} \times \sin^2(2\tilde{\theta}^{SM+NSI}_{ij}) \times \frac{d\sigma^{SM+NSI}_{\nu_\tau N}}{dE_\nu}}{\int \Phi^{SM}_{\nu_\mu,\nu_e}(E_\nu) \times \sin^2(2\tilde{\theta}^{SM}_{ij}) \times \frac{d\sigma^{SM}_{\nu_\tau N}}{dE_\nu}} dE_\nu
\]

- Resonance - Charged Higgs & W` model
Number of events

- Super-K estimated 180.1 ± 44.3 (stat) +17.8 −15.2 (syst) produced in the 22.5 kton fiducial volume of the detector by tau neutrinos during the 2806 day.

- The $\nu_\tau$ cross section can be parametrized as

$$\sigma_{\nu_\tau}^{SM} = \sigma_{\nu_\tau}^{\text{const}} E K(E).$$
Number of events (Cont.)

- From the SM universality: \( \sigma_{\nu_T}^{\text{const}} = \sigma_{\nu_\mu}^{\text{const}} \)
- Within neutrino energy 30-100 GeV
  - Using Honda model for the atmospheric neutrino flux
  - Using vertically upward going neutrinos (\( \cos \theta = -1 \))

SM results: \( N_{SM} = 30.7 \pm 3.37 \)

NP results: \( N_{NSI} = 30.08 @ \) zero \( W' \) couplings
\( N_{NSI} = 41.49 @ M_{W'} = 200 \text{GeV} \)

NSI is potentially detectable
Conclusion

- We calculated the effect of a charged Higgs and a $W'$ contribution to the neutrino-nucleon scattering.

- Both models can produce significant corrections to the measured mixing angle $\theta_{23}$ and $\theta_{13}$.

- The deviation in the charged Higgs model is more sensitive to energy variation than in the $W'$ model.
Conclusion

- We calculated the effect of a charged Higgs and a $W'$ contribution to the neutrino-nucleon scattering.

- Both models can produce significant corrections to the measured mixing angle $\theta_{23}$ and $\theta_{13}$.

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Thank you
Backup Slides
Constraints: Charged Higgs

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\[
\Gamma_{SM}^{\tau^- \rightarrow \pi^- \nu_{\tau}} = \frac{G_F^2}{16\pi} |V_{ud}|^2 f_\pi^2 m_\tau^3 \left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2 \delta_{\tau/\pi} = 10.82 \pm .02\%
\]

- Constraint at 95%CL,
  The colored region is allowed.
Quasi-elastic neutrino scattering

- Quasi-elastic scattering makes up the largest single component of the total $\nu$–N interaction rate in the threshold regime $E_\nu \leq 2$ GeV.

- Llewellyn-Smith formalism for differential cross section

\[
\frac{d\sigma}{dQ^2} \left( \nu_l + n \rightarrow l^- + p \right) = \frac{M^2 G_F^2 \cos^2 \theta_c}{8\pi E_\nu^2} \left\{ A(Q^2) \pm B(Q^2) \frac{(s - u)}{M^2} + C(Q^2) \frac{(s - u)^2}{M^4} \right\}
\]
Q.E. form factors

\[ \{f_1, f_2\} = \frac{1 - (1 + \xi) t/4M^2, \xi}{(1 - t/4M^2)(1 - t/M_V^2)^2}, \quad g_1 = \frac{g_1(0)}{(1 - t/M_A^2)^2}, \quad g_2 = \frac{2M^2 g_1}{m_{\pi}^2 - t} \]
Thank you