T violating effects in $\nu_\tau(\bar{\nu}_\tau)$–nucleon quasielastic scattering

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Introduction

The future experiments like SHiP, DsTau and DUNE are proposed to study the properties and the production cross sections of the τ lepton and its corresponding neutrino (ν_τ) both theoretically as well as experimentally. Recently we have performed [1, 2, 3] a theoretical study of the production cross section as well as the polarization observables of the τ lepton and the final nucleon/hyperon produced in the quasielastic $\nu_\tau(\bar{\nu}_\tau) - N$ scattering in the few GeV energy region. The τ lepton produced in $\nu_\tau - N$ scattering decays to leptons and pions through the leptonic and hadronic decay modes. In this energy region, the production cross section of τ, its decay and the characteristics of the decay products depend significantly on the τ polarization. The production cross section and polarization of τ lepton are calculated using various weak nucleon form factors which are determined using various symmetry properties of the weak currents in the vector and the axial vector sectors, assuming G and T invariances. We have studied the effect of G and T violating terms in the transition matrix element on the cross sections and the τ polarization in quasielastic $\nu_\tau(\bar{\nu}_\tau) - N$ scattering induced by strangeness conserving $\Delta S = 0$ and strangeness changing $\Delta S = 1$ weak currents. In the case of $\Delta S = 1$ reactions, we have also studied SU(3) symmetry breaking effects.

Quasielastic production of nucleons and hyperons

The $\nu_\tau(\bar{\nu}_\tau)$ induced quasielastic production on the free nucleon target are given by the reactions

$$\nu_\tau(\bar{\nu}_\tau)(k) + N(p) \longrightarrow \tau^\mp(k') + N(p'), \quad N = n, p$$
$$\bar{\nu}_\tau(k) + N(p) \longrightarrow \tau^+(k') + Y(p'), \quad Y = \Lambda, \Sigma^0, \Sigma^-.$$

The transition matrix element is given by

$$\mathcal{M} = \frac{G_F}{\sqrt{2}}\, a\, l^\mu\, J_\mu,$$

where $a = \cos_c\ (\sin_c)$ for $\Delta S = 0\ (1)$ processes.
The leptonic (l^μ) and the hadronic (J_μ) currents are defined as

$$l^\mu = \bar{u}(k')\gamma^\mu(1 \mp \gamma_5)u(k), \qquad -(+) \text{ is for } \nu_\tau\ (\bar{\nu}_\tau)$$
$$J_\mu = \bar{u}(p')\Big[\gamma_\mu f_1(Q^2) + i\sigma_{\mu\nu}\frac{q^\nu}{M+M_Y}f_2(Q^2) + \frac{2q_\mu}{M+M_Y}f_3(Q^2) - \gamma_\mu\gamma_5 g_1(Q^2) - i\sigma_{\mu\nu}\gamma_5\frac{q^\nu}{M+M_Y}g_2(Q^2) - \frac{2q_\mu\gamma_5}{M+M_Y}g_3(Q^2)\Big]u(p).$$

$f_{1,2}(Q^2)$ are determined in terms of the electromagnetic form factors while $f_3(Q^2) = 0$ due to CVC and G invariance.
The axial vector and the weak electric form factors $g_{1,2}(Q^2)$ are determined in terms of $g_{A,2}(Q^2)$, which are parameterized in the dipole form as

$$g_i(Q^2) = g_i(0)\left[1 + \frac{Q^2}{M_i^2}\right]^{-2}; \quad i = A, 2$$

with $g_A(0) = 1.267$, $g_2(0) = g_2^I(0)$ ($g_2^R(0)$) shows the presence of second class currents with(without) T-invariance, and $M_A = M_2 = 1.026$ GeV. For $g_3(Q^2)$, the parameterization given by Nambu is used, i.e.

$$g_3(Q^2) = \frac{(M+M_Y)^2}{2(m_K^2 + Q^2)}g_1(Q^2).$$

The Q^2 distribution is written as

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2\, a^2}{8\pi M^2 E^2_{\nu_\tau(\bar{\nu}_\tau)}}N(Q^2),$$

where the expression of $N(Q^2)$ is given in Ref. [3].

SU(3) symmetry breaking effects

The SU(3) symmetry breaking effects are incorporated following the works of Faessler *et al.* [4] and Schlumpf [5]. The main features of these models are summarized as:

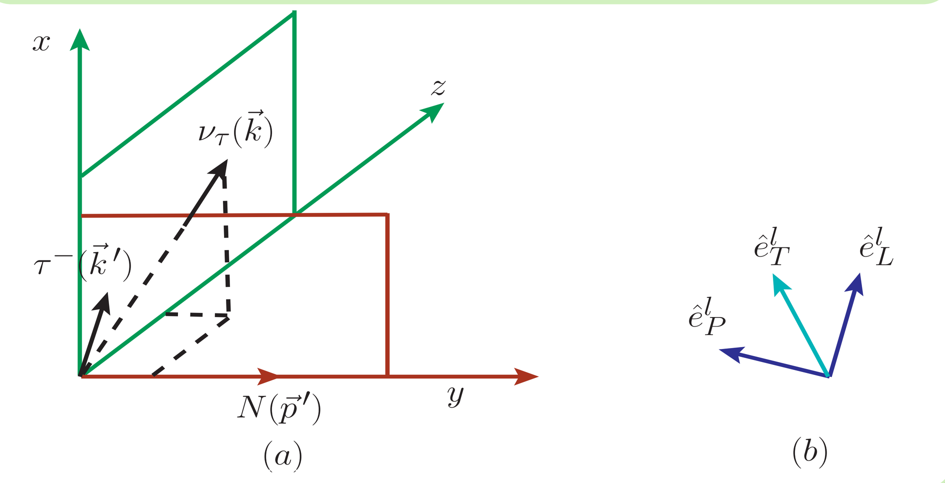
- Faessler *et al.* have studied the SU(3) symmetry breaking effects on $f_2(Q^2)$ and $g_1(Q^2)$ form factors. $f_1(Q^2)$ recieves no contribution at the leading order because of the Ademollo-Gatto theorem and $g_3(Q^2)$ recieves the SU(3) breaking effects via $g_1(Q^2)$:

$$\mathcal{F}^{p\Lambda}(0) = -\sqrt{\frac{3}{2}}\left(F + \frac{D}{3} + \frac{1}{9}(H_1 - 2H_2 - 3H_3 - 6H_4)\right),$$
$$\mathcal{F}^{n\Sigma^-}(0) = D - F - \frac{1}{3}(H_1 + H_3).$$

- Schlumpf [5] has studied SU(3) symmetry breaking in the hadronic current containing axial $f_1(Q^2)$ and axial vector $g_1(Q^2)$ form factors using relativistic quark model. The modified $f_1(Q^2)$ and $g_1(Q^2)$ form factors are given by

$$f_1'(Q^2) = \alpha f_1(Q^2), \qquad g_1'(Q^2) = \beta g_1(Q^2).$$

Polarization components of the final lepton



Polarization of the final lepton

If one assumes the final lepton to be polarized, then the polarization 4-vector (ζ^τ) is written as

$$\zeta^\tau = \frac{\mathrm{Tr}[\gamma^\tau\gamma_5\, \rho_f(k')]}{\mathrm{Tr}[\rho_f(k')]},$$

and the spin density matrix for the final lepton $\rho_f(k')$ is given by

$$\rho_f(k') = \mathcal{J}^{\alpha\beta}\,\mathrm{Tr}[\Lambda(k')\gamma_\alpha(1 \pm \gamma_5)\Lambda(k)\tilde{\gamma}_\beta(1 \pm \tilde{\gamma}_5)\Lambda(k')],$$

with $\tilde{\gamma}_\alpha = \gamma^0\gamma_\alpha^\dagger\gamma^0$ and $\tilde{\gamma}_5 = \gamma^0\gamma_5^\dagger\gamma^0$. The polarization vector $\vec{\zeta}$ can be rewritten as

$$\vec{\zeta} = \zeta_L\hat{e}_L^l + \zeta_P\hat{e}_P^l + \zeta_T\hat{e}_T^l,$$

where $\hat{e}_P^l$, $\hat{e}_L^l$ and $\hat{e}_T^l$ are the unit vectors corresponding to the perpendicular, longitudinal and transverse directions along the momentum of the final lepton and are given as

$$\hat{e}_L^l = \frac{\vec{k}'}{|\vec{k}'|}, \quad \hat{e}_P^l = \hat{e}_L^l \times \hat{e}_T^l, \quad \hat{e}_T^l = \frac{\vec{k}\times\vec{k}'}{|\vec{k}\times\vec{k}'|},$$

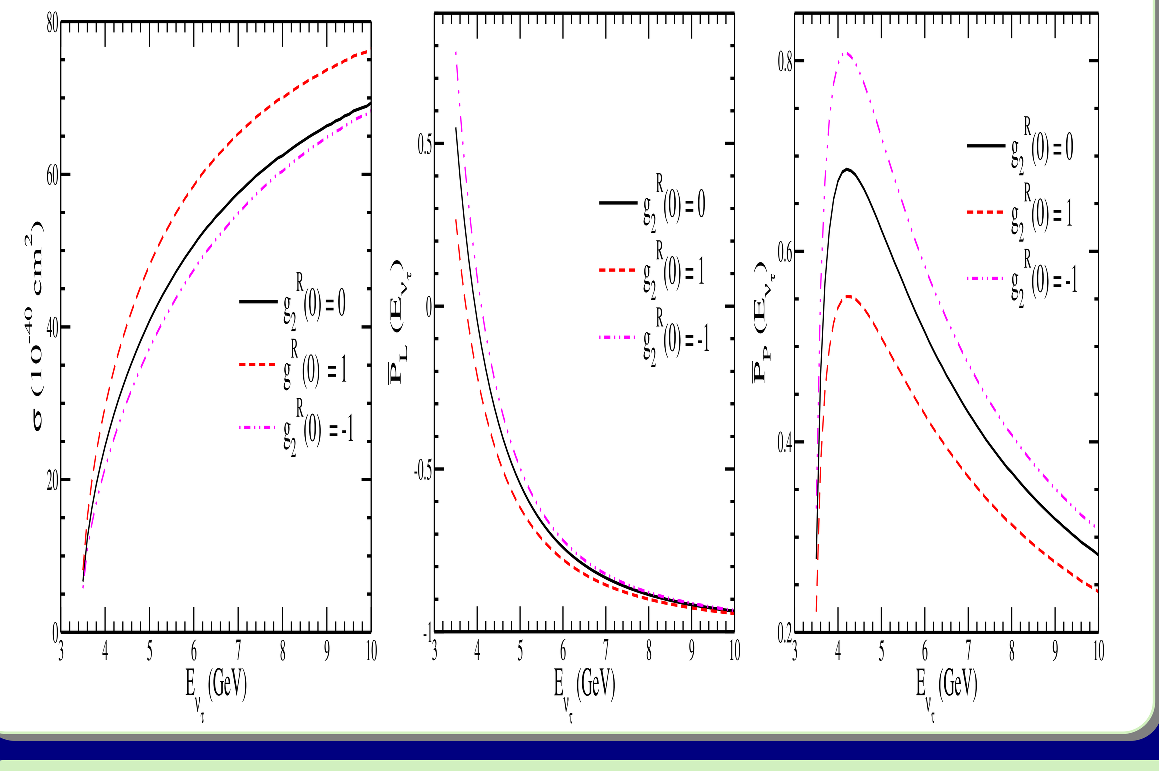
with $\zeta_{L,P,T}(Q^2) = \vec{\zeta}\cdot\hat{e}_{L,P,T}^l$.
The longitudinal $P_L^l(Q^2)$, perpendicular $P_P^l(Q^2)$ and transverse $P_T^l(Q^2)$ components of the polarization vector are obtained as:

$$P_L^l(Q^2) = \frac{m_\tau}{E_{k'}}\frac{A^l(Q^2)\vec{k}.\vec{k}' + B^l(Q^2)|\vec{k}'|^2}{N(Q^2)\,|\vec{k}'|},$$
$$P_P^l(Q^2) = \frac{A^l(Q^2)[|\vec{k}|^2|\vec{k}'|^2 - (\vec{k}.\vec{k}')^2]}{N(Q^2)\,|\vec{k}'|\,|\vec{k}\times\vec{k}'|},$$
$$P_T^l(Q^2) = \frac{C^l(Q^2)M[(\vec{k}.\vec{k}')^2 - |\vec{k}|^2|\vec{k}'|^2]}{N(Q^2)\,|\vec{k}\times\vec{k}'|}.$$

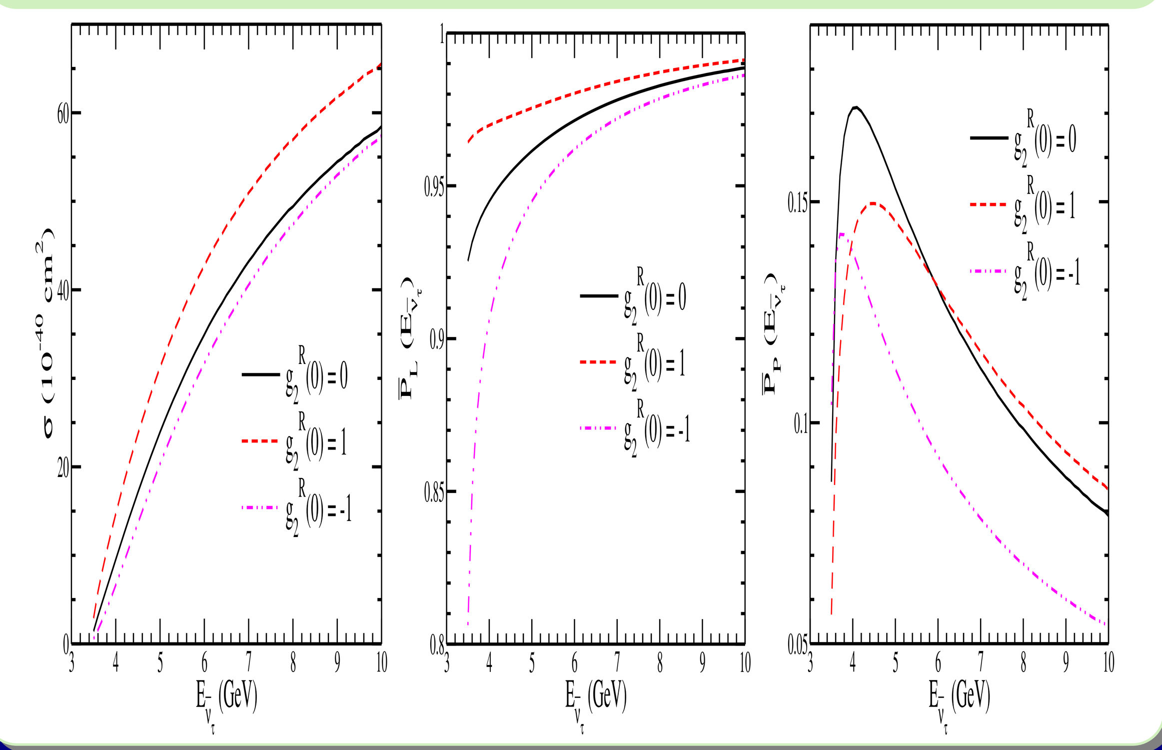
The expressions of $A^l(Q^2)$, $B^l(Q^2)$, $C^l(Q^2)$ are given in Refs. [3].

The real value of $g_2(0)$ gives G violation keeping T conserved. The transverse component of polarization, which arises due to the interference terms of the first and the second class current, vanishes when $g_2(0)$ is taken to be purely real. The imaginary value of $g_2(0)$ gives G violation as well as T violation.

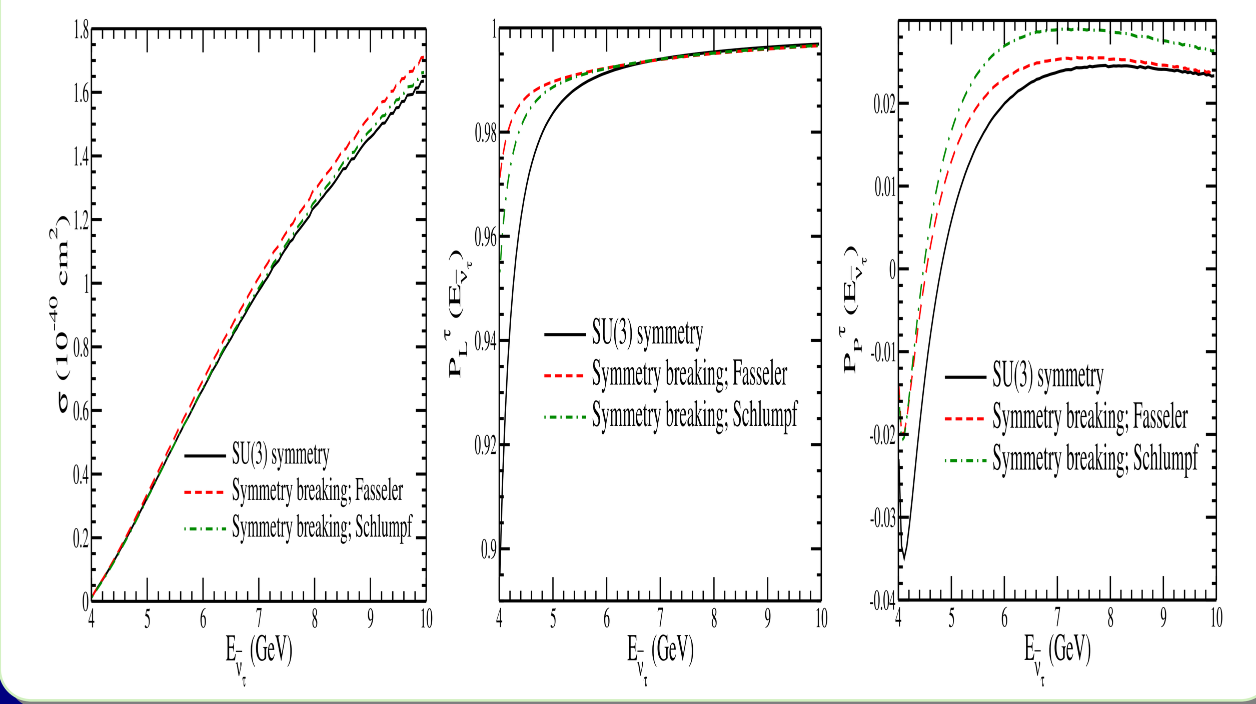
σ, $\overline{P}_L(E_{\nu_\tau})$ and $\overline{P}_P(E_{\nu_\tau})$ versus E_{ν_τ} for the process $\nu_\tau + n \longrightarrow \tau^- + p$ when τ^- is polarized. The results are shown for the different values of $g_2^R(0) = 0, \pm 1$.



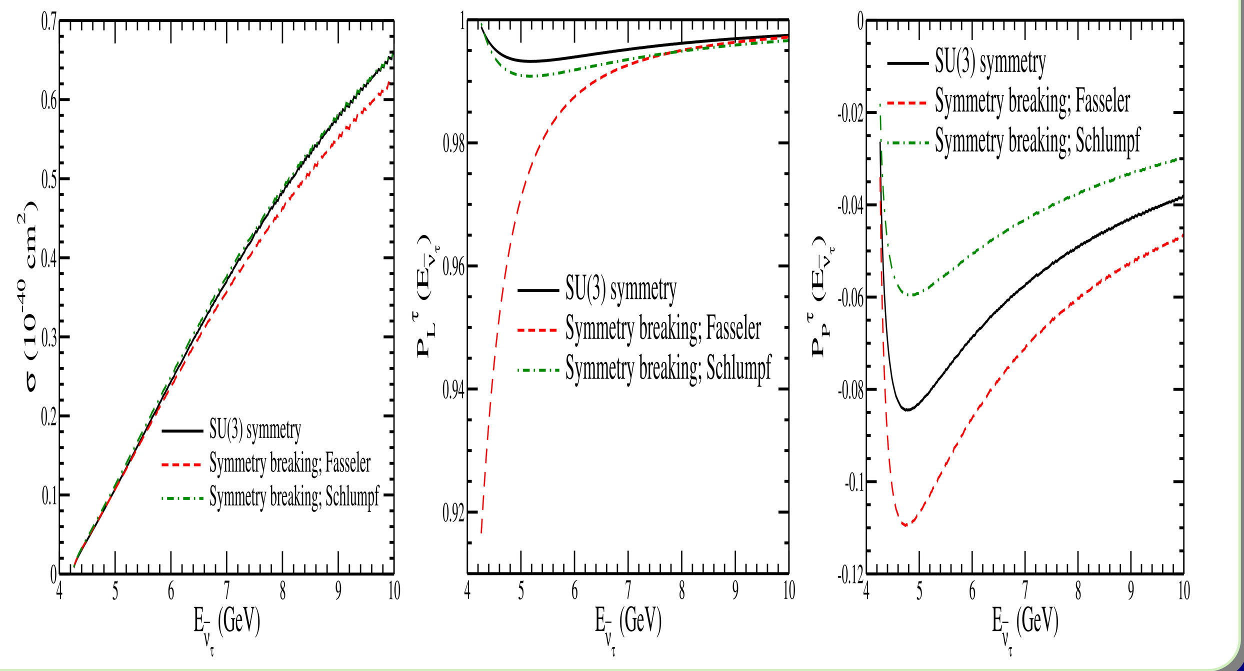
σ, $\overline{P}_L(E_{\bar{\nu}_\tau})$ and $\overline{P}_P(E_{\bar{\nu}_\tau})$ versus $E_{\bar{\nu}_\tau}$ for the process $\bar{\nu}_\tau + p \longrightarrow \tau^+ + n$ when τ^+ is polarized. The results are shown for the different values of $g_2^R(0) = 0, \pm 1$.



σ, $\overline{P}_L(E_{\bar{\nu}_\tau})$ and $\overline{P}_P(E_{\bar{\nu}_\tau})$ versus $E_{\bar{\nu}_\tau}$ for the process $\bar{\nu}_\tau + p \longrightarrow \tau^+ + \Lambda$. The calculations have been performed with SU(3) symmetry, and its breaking effects parameterized by Faessler *et al.* [4] and Schlumpf [5].



σ, $\overline{P}_L(E_{\bar{\nu}_\tau})$ and $\overline{P}_P(E_{\bar{\nu}_\tau})$ versus $E_{\bar{\nu}_\tau}$ for the process $\bar{\nu}_\tau + n \longrightarrow \tau^+ + \Sigma^-$. The calculations have been performed with SU(3) symmetry, and its breaking effects parameterized by Faessler *et al.* [4] and Schlumpf [5].



Conclusions

In the case of $\Delta S = 0$ processes, there is a strong dependence of M_A on $\sigma(E_{\nu_\tau(\bar{\nu}_\tau)})$ for both neutrino as well as antineutrino induced reactions. The polarization observables show mild dependence on M_A.

The effect of the second class current is appreciable for $g_2^R(0) = +1$ in the case of $\sigma(E_{\nu_\tau(\bar{\nu}_\tau)})$ both for the neutrino as well as antineutrino induced processes.

In the case of antineutrino induced reactions, there is an appreciable dependence of the polarization observables on $g_2^R(0)$, while in the case of neutrino induced reactions, the polarization observables show mild dependence on $g_2^R(0)$.

In the case of $\Delta S = 1$ processes, the total, differential cross section and the polarization observables are quite sensitive to: (i) the different parameterizations of the vector form factors and the pseudoscalar form factor, (ii) the choice of M_A and (iii) non-zero value of $g_2^R(0)$.

There is a significant variation in P_L and P_P, on the different parameterizations of the SU(3) symmetry breaking, while the effect of SU(3) symmetry breaking is not much in the case of total and differential cross sections.

These results are more prominent in the case of $\Delta S = 1$ processes.

References

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