Study of τ^+-lepton polarization in charged current deep inelastic $\bar{\nu}_\tau - N/A$ scattering

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The understanding of $\tau-$lepton physics is the topic of current interest in the particle physics community, as it is required for various important aspects such as testing the lepton flavor universality, the accurate measurement of the neutrino oscillation parameters, reducing the uncertainties in the ν_l-nucleus cross section measurements, etc. Since the direct detection of the τ-lepton is very difficult due to its short lifetime, it is identified by the observation of leptons and pions, whose decay rates and topologies depend upon the production cross section and polarization of the τ-leptons produced through the various reaction channels in the $\nu_\tau/\bar{\nu}_\tau$-nucleon interactions. Hence, it is important to investigate the effect of $\tau-$lepton polarization on the $\tau-$lepton production signal and for estimating the background events in $\nu_\mu \to \nu_e$ appearance channel, etc. Various experiments such as DsTau, FASERν, SND@LHC, DUNE, IceCube upgrade, etc., have been planned to study the $\tau-$lepton production with improved statistics. Most of the neutrino experiments are performed using nuclear targets, therefore, it is important to study the impact of the nuclear medium effects on the polarization observables of $\tau-$lepton produced in the final state. In this work, we have studied the τ^+-lepton polarization in the charged current $\bar{\nu}_\tau$ induced deep inelastic scattering (DIS) from the free nucleon as well as off the nuclear targets that are being used in ongoing and upcoming experiments such as IceCube, DUNE, etc. In the case of free nucleon target, the numerical results are obtained by incorporating the non-perturbative effect like target mass corrections (TMC) and the perturbative effect like the evolution of the parton densities at the next-to-leading order (NLO) in the four flavor $\overline{\text{MS}}-$scheme. For nucleons bound inside a nuclear target, we have taken into account the nuclear medium effects such as Fermi motion, binding energy, and nucleon correlations, through the use of the nucleon spectral function.

The expression of differential scattering cross section for the polarized $\tau-$lepton production via charged current (CC) $\nu_\tau - N/A$ DIS process is given by [1]:

$$\frac{d^2\sigma^{pol}_{N/A}}{dE_\tau\ d\cos\theta} = (1 - h s^\alpha \mathcal{P}^\alpha)\frac{d^2\sigma_{N/A}}{dE_\tau\ d\cos\theta},$$

where the unpolarized $\tau-$lepton production cross section $\frac{d^2\sigma_{N/A}}{dE_\tau\ d\cos\theta}$ is expressed as [1]:

$$\begin{aligned}\frac{d^2\sigma_{N/A}}{dE_\tau\ d\cos\theta} &= \frac{G_F^2|\vec{k}'|}{2\pi M_N(1+\frac{Q^2}{M_W^2})^2}\Big[2F_{1j}(x,Q^2)(E_\tau - |\vec{k}'|\cos\theta)\\ &+ F_{2j}(x,Q^2)\,\frac{M_N}{\nu}(E_\tau + |\vec{k}'|\cos\theta)\\ &- F_{3j}(x,Q^2)\,\frac{1}{\nu}(|\vec{k}'|^2 + E_\nu E_\tau - (E_\nu + E_\tau)|\vec{k}'|\ \cos\theta)\\ &+ F_{4j}(x,Q^2)\,\frac{m_\tau^2}{\nu M_N x}(E_\tau - |\vec{k}'|\cos\theta) - F_{5j}(x,Q^2)\,\frac{2m_\tau^2}{\nu}\Big],\end{aligned}$$

with $F_{ij}(x,Q^2);\ i = 1-5;\ j = N/A$ as the dimensionless nucleon/nuclear structure functions. In the above expression, $x = \frac{Q^2}{2M_N\nu}$ is the Bjorken variable, Q^2 is the four momentum transfer square, $\nu = (E_\nu - E_\tau)$ is the energy transfer, G_F is the Fermi coupling constant and M_W is the mass of intermediate vector W-boson. In Eq.1, $h = \pm 1$ is the helicity, $s^\alpha = (0, \hat{n})$ is the spin four-vector, $\mathcal{P}^\alpha$ is the polarization vector of the final state charged lepton that is decomposed into longitudinal (P_L), perpendicular (P_P), and transverse (P_T)

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components which are expressed as [1]:

$$
\begin{aligned}
P_L &= \frac{E_\nu}{L_{\mu\nu} W_N^{\mu\nu}} \Bigg[\Big(2F_{1j}(x,Q^2) - \frac{m_\tau^2}{M_N \nu x} F_{4j}(x,Q^2) \Big) (|\vec{k}'| - E_\tau \cos\theta) \\
&+ F_{2j}(x,Q^2) \frac{M_N}{\nu} (|\vec{k}'| + E_\tau \cos\theta) - \frac{2}{\nu} m_\tau^2 \cos\theta \, F_{5j}(x,Q^2) \\
&- \frac{F_{3j}(x,Q^2)}{\nu} (|\vec{k}'|(E_\nu + E_\tau) - (|\vec{k}'|^2 + E_\nu E_\tau) \cos\theta) \Bigg] \\
P_T &= \frac{m_\tau sin\theta E_\nu}{L_{\mu\nu} W_N^{\mu\nu}} \Bigg[2F_{1j}(x,Q^2) - F_{2j}(x,Q^2) \frac{M_N}{\nu} \\
&- \frac{E_\nu}{\nu} F_{3j}(x,Q^2) - \frac{m_\tau^2}{M_N \nu x} F_{4j}(x,Q^2) + \frac{2E_\tau}{\nu} F_{5j}(x,Q^2) \Bigg],
\end{aligned}
$$

Due to the time reversal invariance in the standard model P_P vanishes, therefore, the degree of polarization is given by $P = \sqrt{P_L^2 + P_T^2}$, lying in the range of $0 \le P \le 1$, and the direction of polarization vector is determined by $\cos\theta_P = \frac{P_L}{P}$. We obtain the nuclear structure functions in terms of the free nucleon structure function convoluted over the hole spectral function (S_h) [1]:

$$
F_{iA}(x,Q^2) = 4\int d^3r \int \frac{d^3p_N}{(2\pi)^3} \frac{M_N}{E_N(\vec{p}_N)} \times \int_{-\infty}^{\mu} dp^0 S_h(p_N^0, \vec{p}_N, \rho(r)) f_{iN}(x,Q^2),
$$

where $f_{iN}(x,Q^2)$; $(i = 1-5)$ is the factor containing the nucleon structure functions $F_{iN}(x,Q^2)$, μ is the chemical potential and $\rho(r)$ is the nucleon charge density inside the nucleus. For detailed formalism, please see Ref. [1] and references therein. In Fig. 1, the results are presented for $\bar{\nu}_\tau - ^{40}Ar$ DIS process at $E_\nu = 10$ GeV with different cuts on the center of mass energy (W). We observe that due to the nuclear medium effects the differential cross section for the τ^+-lepton production are reduced by about 47% at $\theta = 2.5^o$ and 55% at $\theta = 5^o$ as compared to the case of free nucleon at $E_\tau = 5$ GeV. With the increase in E_ν, the nuclear medium effects get reduced, quantitatively, there is a reduction of about 30% at $\theta = 0^o$ and 41% at $\theta = 5^o$ as compared to the case of $E_\nu = 8$ GeV (not shown here explicitly) when E_τ is fixed at 5 GeV. It may also be noticed that the τ^+-lepton has a comparatively lower degree of polarization at the moderate values of E_τ, however, at the extreme ends, it has a good strength of P except at $\theta = 0^o$. Furthermore, in the low and intermediate energy region of τ^+-lepton, the degree of polarization increases due to the nuclear medium effects, while in the higher region of E_τ it decreases for $\theta \neq 0^o$. We find that the value of $\cos\theta_P$ for the τ^+-lepton decreases due to the nuclear medium effects except at $\theta = 0^o$. For example, on comparing the results obtained with a cut of $W \ge 2$ GeV at $\theta = 0^o$, we observe that the value of $\cos\theta_P$ remains -1 in the entire range of E_τ when $\bar{\nu}_\tau$ interacts with a nucleon bound inside the argon nuclear target, however, in the case of free nucleon target $\cos\theta_P$ is -1 up to a certain value of E_τ after which the direction of polarization vector gets flipped and it becomes +1. It is also noticeable that at $\theta = 0^o$, the results obtained for ^{40}Ar with a lower cut on W, i.e., 1.6 GeV also shows the similar behavior as observed in the case of free nucleon target. We have observed that the nuclear medium effects on $\cos\theta_P$ for τ^+-lepton production are found to be larger than observed in the case of τ^-lepton production (not shown here). Comparative results of τ^+ and τ^- polarization would be presented in the symposium.

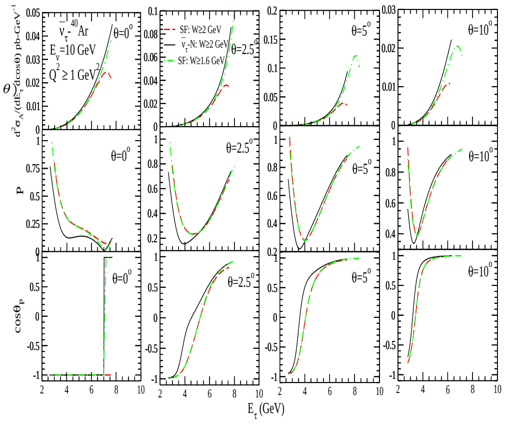

FIG. 1: Results for scattering cross sections and polarization observables in CC $\bar{\nu}_\tau - ^{40}Ar$ DIS.

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References

[1] F. Zaidi, M. Sajjad Athar and S. K. Singh, Phys. Rev. D (2023) in press,[arXiv:2307.12632 [hep-ph]].