$\nu_\tau - N$ DIS cross sections in the few GeV energy region

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In this paper, we have studied $\nu_\tau + N \rightarrow \tau^- + X$ deep inelastic scattering (DIS) process to which less theoretical attention has been paid. However, this process has been experimentally studied by OPERA, DONuT, Super-K, and are planned to be studied by the next generation oscillation experiments like DUNE, SHiP, etc. In all the atmospheric neutrino events tauon events arise due to the interactions of multiGeV ν_τ. Moreover, the present study is also important because IceCube, a cubic-kilometer-scale high-energy neutrino observatory, at the geographic South Pole is trying to elucidate the mechanisms for production of high-energy cosmic rays by detecting high-energy neutrinos from astrophysical sources [1], and for the Monte Carlo simulation of the events, a good control on the cross section estimate is required. It is important to point out that due to the large mass of the $\tau^\pm$ relative to the $e^\pm$ and $\mu^\pm$, the threshold for this process to occur is 3.5 GeV.

In this work the numerical calculations are performed by evaluating the parton densities at next-to-the leading order (NLO) in the four flavour scheme, treating light quarks like u, d and s to be massless while charm quark as a massive object. In the case of ν_τ induced DIS process two additional structure functions, i.e. $F_{4N}^{WI}(x,Q^2)$ and $F_{5N}^{WI}(x,Q^2)$ also contribute. These structure functions are generally omitted for $\nu_{e,\mu}$ interactions as they are suppressed by a factor of $\frac{m_l^2}{Q^2}$ in comparison to rest of the three structure functions ($F_{iN}^{WI}(x,Q^2)$; $(i = 1-3)$). In the present work, we have studied the effect of target mass correction following the works of Kretzer et al. [2, 3], effect of massive charm as well as the effect of $F_{4N}^{WI}(x,Q^2)$ and $F_{5N}^{WI}(x,Q^2)$ structure functions on the differential scattering cross section. The perturbative and the nonperturbative effects taken into consideration here are discussed in Ref.[4, 5].

Formalism

The general expression of differential scattering cross section with lepton mass is given by

$$\frac{d^2\sigma}{dx\,dy} = \kappa \left[\left(\frac{m_l^2\, y}{2\,M\,E} + x\,y^2 \right) F_{1N}(x,Q^2) + \left(1 - y - \frac{x\,y\,M}{2\,E} - \frac{m_l^2}{4\,E^2} \right) F_{2N}(x,Q^2) + \left(-\frac{m_l^2\, y}{4\,M\,E} + y\left(1 - \frac{y}{2}\right) \right) F_{3N}(x,Q^2) + \frac{m_l^2(m_l^2+Q^2)}{4E^2M^2x} F_{4N}(x,Q^2) - \frac{m_l^2}{ME} F_{5N}(x,Q^2) \right]$$

where the constant factor $\kappa = \frac{G_F^2 ME}{\pi}$ with Fermi coupling constant $G_F = 1.16 \times 10^{-5}$ GeV^{-2}. m_l is the mass of final state lepton, x, y are the scaling variables and M and E are respectively, the target nucleon mass and the energy of the incoming beam. $F_{iN}(x,Q^2)$; $(i = 1-5)$ are the free nucleon structure functions which are obtained as:

$$F_{iN}^{(n_f=4)}(x,Q^2) = \underbrace{F_{iN}^{(n_f=3)}(x,Q^2)}_{massless\ u,d,s} + \underbrace{F_{iN}^{(n_f=1)}(x,Q^2)}_{massive\ c}$$

where n_f is the number of quarks flavour. These nucleon structure functions are generally written in terms of parton distribution functions (PDFs), for example, the charm quark PDFs is expressed as

$$c(x) = \cos^2\theta_C\ s(x) + \sin^2\theta_C\ d(x), \qquad (1)$$

where θ_C is the Cabibbo angle and $\cos^2\theta_C$ and $\sin^2\theta_C$ are respectively the factors for Cabibbo- favoured and suppressed reactions.

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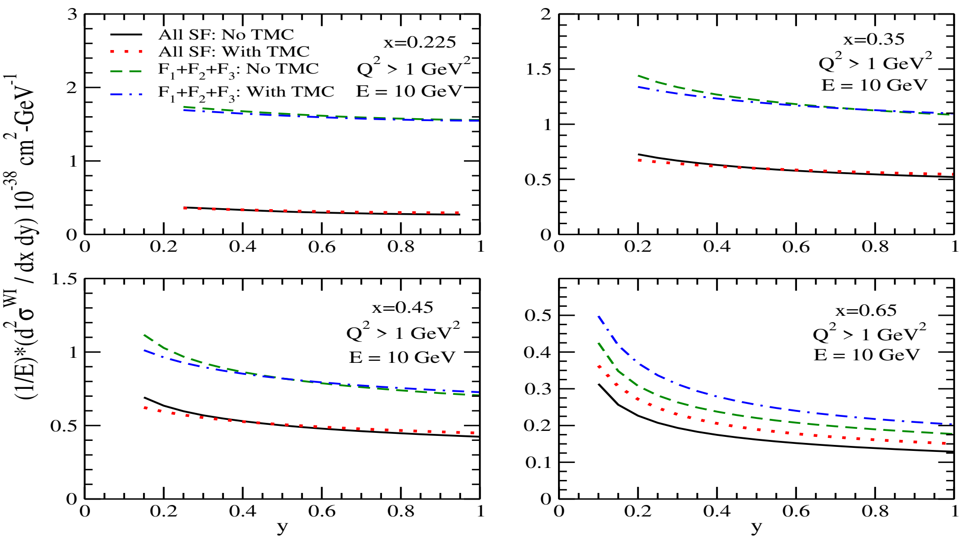

FIG. 1: Results are shown for $\frac{1}{E}\frac{d^2\sigma}{dx\ dy}$ vs y at $E_{\nu_\tau} = 10$ GeV with $Q^2 > 1GeV^2$, for ν_τ induced DIS process off free nucleon target. Numerical calculations are performed at NLO without and with the TMC effect [2, 3]. These results are presented at the different Bjorken scaling variable x. All SF stands for the results when the cross section is evaluated by taking the contributions from all the five structure functions i.e. $F_{iN}^{WI}(x, Q^2)$; $(i = 1-5)$. No TMC stands for the results when TMC effect is switched off.

For the numerical calculations, we have used the MMHT nucleonic PDFs parameterization [6] as well as incorporated the TMC effect which is important at high x and low Q^2. It is important to point out that for the massless quarks, TMC effect corrects the Bjorken variable x for the effects of hadronic mass and x modifies to the Nachtmann variable $\xi \left(= \frac{2x}{1+\sqrt{\frac{4M^2x^2}{Q^2}}}\right)$. While for the massive quarks ξ will be generalized to the slow rescaling variable $\bar{\xi} \left(= \xi \left[1 + \frac{m_q^2}{Q^2}\right]; m_q \equiv \text{quark mass}\right)$ due to the partonic effects.

Results and Discussion

In Fig. 1, we have shown the results for the differential scattering cross section $\frac{1}{E}\frac{d^2\sigma}{dx\ dy}$ vs y at E=10 GeV for the $\nu_\tau - N$ DIS process. The results are presented with all the five structure functions and with $F_{iN}^{WI}(x, Q^2)$; $(i = 1-3)$ only in order to observe the effect of $F_{4N}^{WI}(x, Q^2)$ and $F_{5N}^{WI}(x, Q^2)$ on the differential scattering cross section. We find the effect of these structure functions on the cross section to be small in the kinematic region of present interest. We find that the TMC effect is significant for $x > 0.45$. We have also observed that at E=10 GeV the contribution of massive charm is negligible while it becomes important at higher energies (not shown here). We will present and discuss these results in the forthcoming symposium.

References

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