τ polarization in the charged current $\nu_\tau - N$ and $\nu_\tau - A$ DIS processes

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Outline

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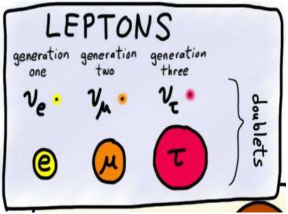
1. *Introduction*
2. *$\nu_\tau - N$ DIS*
   - Lepton polarization
   - Allowed kinematic regions
3. *$\nu_\tau - A$ DIS*
4. *Results*
5. *Summary & Conclusions*

Introduction

- Among the three generations of the standard model leptons, we know least about the neutral partner (ν_τ) of the third generation weak isospin doublet.



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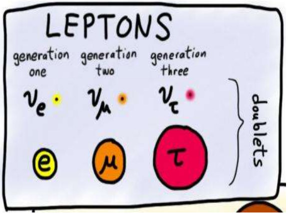
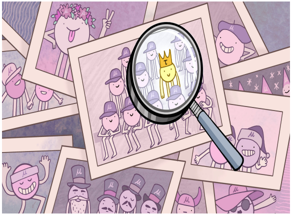


- Experimenters aim to determine some of the oscillation parameters with greater precision, CP violating phase in the leptonic sector and to fix neutrino mass hierarchy.

- The $\tau-$lepton production via the charged current $\nu_\tau - N/A$ interactions is of great topical interest in the study of neutrino oscillations.



- DONuT, OPERA, SuperK and IceCube have observed tau (anti)neutrino events but with very limited statistics.

ν_τ events & cross sections

J.Phys.G 49 (2022) 11, 110501

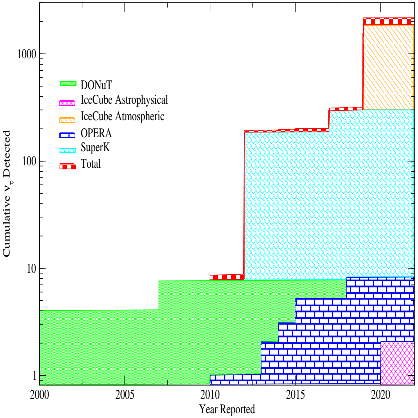


Figure: A cumulative number of detected tauon type neutrinos vs the year of report.

Phys. Rev. D 102 (2020) 11, 113007

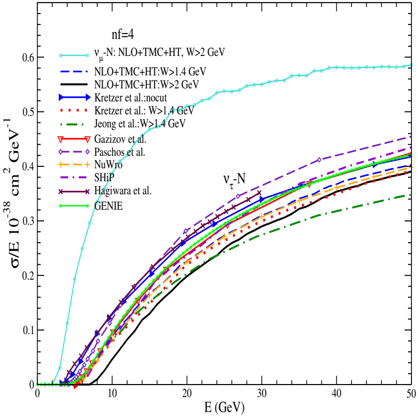
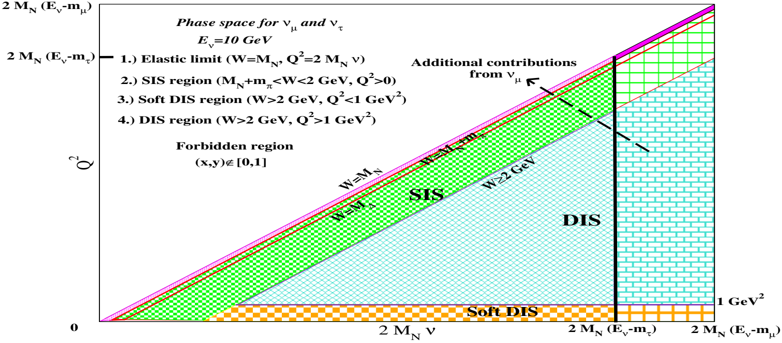


Figure: Cross section for $\nu_\tau - N$ DIS process.

Salient features: ν_τ vs ν_μ

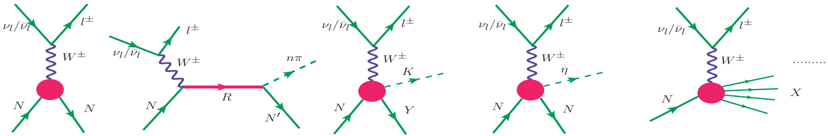
- $\tau-$lepton is ≈ 17 times heavier than muon.
- So, threshold energy for τ production is ≈ 3.5 GeV while for μ production it is 110 MeV.
- $\tau-$lepton lifetime is very short ($\approx 10^{-13}$ sec) as compared to muon ($\approx 10^{-6}$ sec).
- Structure functions $F_{4N}(x)$ and $F_{5N}(x)$ contribute to $\nu_\tau - N$ DIS process but negligible in the case of $\nu_\mu - N$.



Phys. Rev. D.105 (2022) 3, 033010

Future experiments

- SHiP, DUNE, HyperK, FASERν and DsTau are among the experiments which plan to observe $\nu_\tau/\bar{\nu}_\tau$ interactions on the different nuclear targets.
- $\tau-$lepton is reconstructed from its decay products. For example, $D_s \to \tau\nu_\tau$ and $\tau \to \nu_\tau X$.
- $\tau-$leptons are identified by the observation of leptons and pions whose decay rates and the topologies depend upon the production cross section and polarization of the $\tau-$leptons produced through the various reaction processes such as quasielastic, inelastic and deep inelastic scattering.



- The upcoming experiments are sensitive to the few GeV energy region such as DUNE experiment have (anti)neutrino peak energy at around 2.5 GeV.
- At DUNE it is expected that ν_τ events in the appearance mode would be between 100 to 1000.
- The large mass ($m_\tau \simeq 1.77GeV$) of the $\tau-$lepton implies that it may not be fully polarized.
- Understanding of $\tau-$lepton polarization in the few GeV energy region is very important.

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$\nu_\tau - N$ DIS: Unpolarized

The differential scattering cross section for

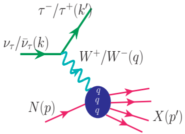
$$\nu_\tau(k) + N(p) \to \tau^-(k') + X(p')$$

is given by

$$\frac{d^2\sigma_N}{dE_l d\cos\theta} = \frac{G_F^2|\vec{k}'|}{2\pi M_N E_\nu}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 L_{\mu\nu}W_N^{\mu\nu},$$

Leptonic tensor is written as

$$L_{\mu\nu} = 8(k_\mu k'_\nu + k_\nu k'_\mu - k\cdot k' g_{\mu\nu} - i\epsilon_{\mu\nu\rho\sigma}k^\rho k'^\sigma)$$



The kinematic variables are defined as follows

$$k = (E_\nu, 0, 0, E_\nu)\ ;\ k' = (E_l, \vec{k}'\sin\theta, 0, \vec{k}'\cos\theta)$$
$$q^2 = -Q^2 = (k-k')^2 = m_l^2 - 2E_\nu(E_l - |\vec{k}'|cos\theta)$$
$$W = \sqrt{(p+q)^2} = \sqrt{(M_N^2 - Q^2 + 2M_N\nu)}$$

Hadronic tensor is defined as

$$W_N^{\mu\nu} = \left(\frac{q^\mu q^\nu}{q^2} - g^{\mu\nu}\right) W_{1N}(\nu,Q^2) + \frac{W_{2N}(\nu,Q^2)}{M_N^2}\left(p_N^\mu - \frac{p_N.q}{q^2}\,q^\mu\right)$$
$$\times \left(p_N^\nu - \frac{p_N.q}{q^2}\,q^\nu\right) - \frac{i}{M_N^2}\epsilon^{\mu\nu\rho\sigma}p_{N\rho}q_\sigma W_{3N}(\nu,Q^2) + \frac{W_{4N}(\nu,Q^2)}{M_N^2}q^\mu q^\nu$$
$$+ \frac{W_{5N}(\nu,Q^2)}{M_N^2}(p_N^\mu q^\nu + q^\mu p_N^\nu) + \frac{i}{M_N^2}(p_N^\mu q^\nu - q^\mu p_N^\nu)W_{6N}(\nu,Q^2),$$

$\nu_\tau - N$ DIS: Unpolarized

We define

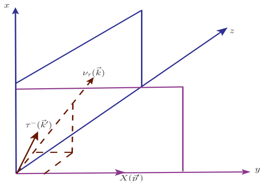
$$\begin{aligned} W_{1N}(\nu,Q^2) &= F_{1N}(x)\,;\;\; W_{2N}(\nu,Q^2) = \frac{M_N}{\nu}\,F_{2N}(x)\,; \\ W_{3N}(\nu,Q^2) &= \frac{M_N}{2\nu}\,F_{3N}(x)\,;\;\; W_{4N}(\nu,Q^2) = \frac{M_N}{x\nu}F_{4N}(x)\,;\; W_{5N}(\nu,Q^2) = \frac{M_N}{\nu}\,F_{5N}(x). \end{aligned}$$

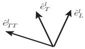
Then we obtain

$$\begin{aligned} L_{\mu\nu}\,W_N^{\mu\nu} &= E_\nu\,\Bigg(\left[2F_{1N}(x,Q^2)+\frac{m_l^2}{M_N\nu x}F_{4N}(x,Q^2)\right](E_l-|\vec{k}'|\,\cos\theta)-\frac{2m_l^2}{\nu}F_{5N}(x,Q^2) \\ &+ \frac{M_N}{\nu}(E_l+|\vec{k}'|\cos\theta)F_{2N}(x,Q^2)+\frac{1}{\nu}(|\vec{k}'|^2+E_\nu\,E_l-(E_\nu+E_l)|\vec{k}'|\cos\theta)F_{3N}(x,Q^2)\Bigg) \end{aligned}$$

$$\begin{aligned} \Rightarrow \frac{d^2\sigma}{dE_l d\cos\theta} &= \frac{G_F^2|\vec{k}'|\kappa^2}{2\pi M_N}\Bigg(\left[2F_{1N}(x,Q^2)+\frac{m_l^2}{M_N\nu x}F_{4N}(x,Q^2)\right](E_l-|\vec{k}'|\,\cos\theta)-\frac{2m_l^2}{\nu}F_{5N}(x,Q^2) \\ &+ \frac{M_N}{\nu}(E_l+|\vec{k}'|\cos\theta)F_{2N}(x,Q^2)+\frac{1}{\nu}(|\vec{k}'|^2+E_\nu\,E_l-(E_\nu+E_l)|\vec{k}'|\cos\theta)F_{3N}(x,Q^2)\Bigg) \end{aligned}$$

Polarized charged lepton





- For a polarized outgoing lepton the DCX is expressed as

$$\frac{d^2\sigma_N}{dE_l d\cos\theta} = \frac{G_F^2|\vec{k}'|}{2\pi M_N E_\nu}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 L_{\mu\nu}(s;h)W_N^{\mu\nu},$$

  - The polarized leptonic tensor is given by

$$L_{\mu\nu}(s;h) = \frac{L_{\mu\nu}}{2} - \frac{1}{2}\eta h m_l s^\alpha (k_\mu g_{\nu\alpha} + k_\nu g_{\mu\alpha} - k_\alpha g_{\mu\nu} + i\eta\epsilon_{\mu\nu\alpha\beta}k^\beta),$$

where spin 4-vector $s^\mu = \left(\frac{\vec{k}'\cdot\hat{n}}{m_l}, \hat{n} + \frac{\vec{k}'(\vec{k}'\cdot\hat{n})}{m_l(E_l+m_l)}\right)$ such that $s^2 = -1$ and $s\cdot k' = 0$, and $\hat{n} = \pm\frac{\vec{k}'}{|\vec{k}'|}$.

  - $h = \pm 1$ corresponds to positive and negative helicity states and $\eta = +1$ for neutrino and -1 for antineutrino.
  - The polarization vector of the final state charged lepton is given by

$$\mathscr{P}_\alpha^{(l^-,l^+)} = \frac{\pm m_l(k_\mu g_{\nu\alpha} + k_\nu g_{\mu\alpha} - k_\alpha g_{\mu\nu} \pm i\epsilon_{\mu\nu\alpha\beta}k^\beta)\, W_N^{\mu\nu}}{2(L_{\mu\nu}W_N^{\mu\nu})_{(l^-,l^+)}}$$

Polarized charged lepton

- $\mathscr{P}_\alpha^{(l^-,l^+)}$ can be decomposed as follows

$$\mathscr{P}_\alpha^{(l^-,l^+)} = -(P_L\, n_L^\alpha + P_T\, n_T^\alpha + P_{TT}\, n_{TT}^\alpha)_{(l^-,l^+)},$$

- The 4-vectors are given by

$$n_l^\alpha \quad = \quad \left(\frac{|\vec{k}'|}{m_l}, \frac{E_l}{m_l}\frac{\vec{k}'}{|\vec{k}'|}\right),\; n_t^\alpha = \left(0, \frac{(\vec{k}\times\vec{k}')\times\vec{k}'}{|(\vec{k}\times\vec{k}')\times\vec{k}'|}\right),\; n_{tt}^\alpha = \left(0, \frac{\vec{k}\times\vec{k}'}{|\vec{k}\times\vec{k}'|}\right)$$

- The polarizations vectors are evaluated as follows

$$P_L = (\mathscr{P}_\alpha \cdot n_L^\alpha)\,;\;\; P_T = (\mathscr{P}_\alpha \cdot n_T^\alpha)\,;\;\; P_{TT} = (\mathscr{P}_\alpha \cdot n_{TT}^\alpha)$$

- For the perpendicular component

$$\mathscr{P}_\alpha^{(l^-,l^+)} \cdot n_{TT} = 0 \Rightarrow P_{TT} = 0.$$

- The degree of polarization is given by

$$\mathscr{P} = 2\sqrt{(P_L^2 + P_T^2)} \Rightarrow |\mathscr{P}| \leq 1.$$

- Spin polarization vector in the $\tau-$lepton's rest frame:

$$\vec{s} = (s_x, s_y, s_z) = \frac{\mathscr{P}}{2}\left(\sin\theta_P\ \cos\psi_P, \sin\theta_P\ \sin\psi_P, \cos\theta_P\right)$$

- $z-$axis is taken along it's momentum direction.
- Azimuthal angle ψ_P takes 0 or π
- Polar angle of spin-vector:

$$\theta_P = \cos^{-1}\left(\frac{P_L}{\mathscr{P}/2}\right)$$

- We follow Hagiwara et al., Nucl.Phys.B 668 (2003) 364 and Hernandez et al., Phys.Lett.B 829 (2022) 137046.

Polarized charged lepton

Following expressions are obtained:

- longitudinal component

$$P_L = \pm\frac{E_\nu}{2(L_{\mu\nu}W^{\mu\nu})_{(l^-,l^+)}}\left[\left(2F_{1N}-\frac{m_l^2}{M_N^2\,\nu\,x}F_{4N}\right)(|\vec{k}'|-E_l\,\cos\theta)+F_{2N}\frac{M_N}{\nu}(|\vec{k}'|+E_l\,\cos\theta)\right.$$
$$\left.\pm\frac{F_{3N}}{\nu}(|\vec{k}'|(E_\nu+E_l)-(|\vec{k}'|^2+E_\nu\,E_l)\cos\theta)-\frac{2m_l^2\cos\theta}{\nu}F_{5N}\right]$$

- transverse component

$$P_T = \pm\frac{m_l E_\nu\sin\theta}{2(L_{\mu\nu}W^{\mu\nu})_{(l^-,l^+)}}\left[2F_{1N}-\frac{M_N}{\nu}F_{2N}\pm\frac{E_\nu}{\nu}F_{3N}-\frac{m_l^2}{M_N\,\nu\,x}F_{4N}+\frac{2E_l}{\nu}F_{5N}\right]$$

- The dimensionless nucleon structure functions are generally expressed in terms of parton distribution functions at the leading order of perturbative QCD, for example,

$$F_{2N}(x) = x[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)+2s(x)+2\bar{c}(x)],$$

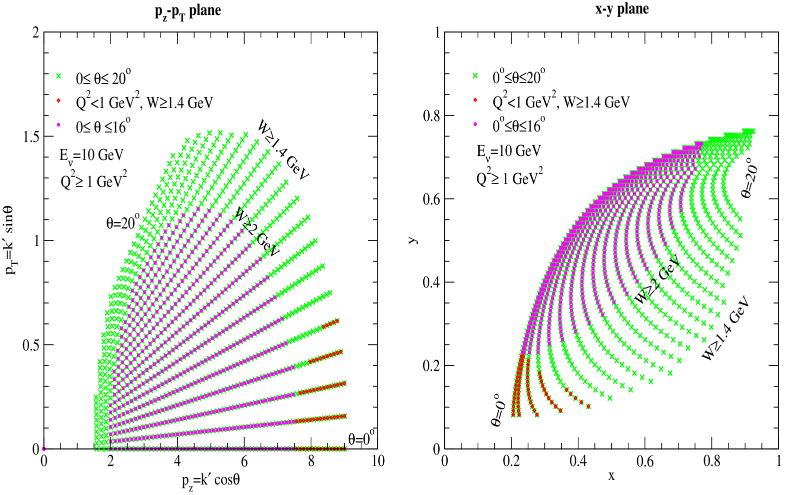
$$xF_{3N}(x) = x[u(x)-\bar{u}(x)+d(x)-\bar{d}(x)+2s(x)-2\bar{c}(x)],$$

- We use Callan-Gross and Albright-Jarlskog relations at LO

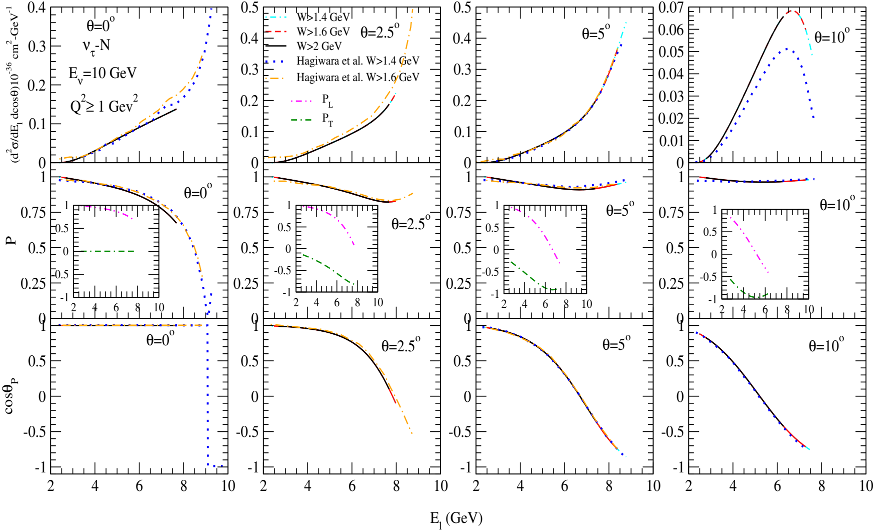
$$F_{1N}(x)=\frac{F_{2N}(x)}{2x}\;;\quad F_{4N}(x)=0\,;\; F_{5N}(x)=\frac{F_{5N}(x)}{2x}$$

- We have also evolved $F_{iN}(x)$ at NLO and incorporate the TMC effect (Phys. Rev. D 101, (2020) 033001).

Allowed Kinematic Region



$\nu_\tau - N$ cross sections & polarization at NLO

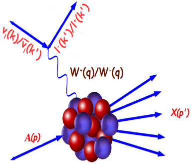


- Hagiwara et al., Nucl.Phys.B 668 (2003) 364.
- Hagiwara et al., Nuclear Physics B (Proc. Suppl.) 139 (2005) 140.

Outline

$\nu_\tau - A$ DIS & Nuclear effects

$$\nu_l(k) + A(p) \rightarrow l^-(k') + X(p')$$



The differential scattering cross section for neutrino induced DIS process off nuclear target is given by:

$$\begin{aligned}
\frac{d^2\sigma_A}{dE_l d\cos\theta} &= \frac{G_F^2|\vec{k}'|\kappa^2}{2\pi M_N}\Bigg(\Bigg[2F_{1A}(x,Q^2) \\
&+ \frac{m_l^2}{M_N \nu x}F_{4A}(x,Q^2)\Bigg](E_l - |\vec{k}'|\,\cos\theta) \\
&+ \frac{M_N}{\nu}(E_l + |\vec{k}'|\cos\theta)F_{2A}(x,Q^2) \\
&+ \frac{1}{\nu}(|\vec{k}'|^2 + E_\nu\, E_l - (E_\nu + E_l)|\vec{k}'|\cos\theta) \\
&\times F_{3A}(x,Q^2) - \frac{2m_l^2}{\nu}F_{5A}(x,Q^2)\Bigg),
\end{aligned}$$

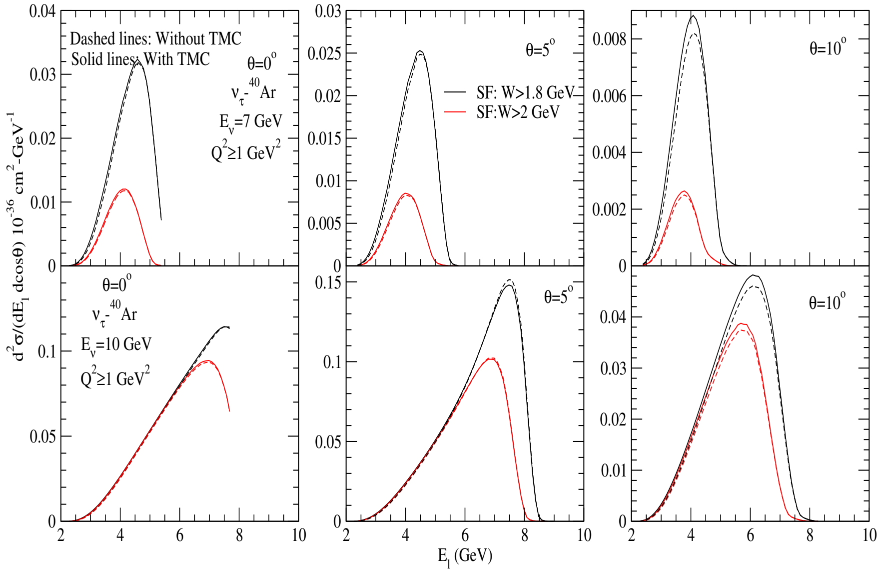
where $F_{iA}(x,Q^2);\ i = 1-5$ are the nuclear structure functions.

We incorporate following effects in the evaluation of $F_{iA}(x,Q^2);\ i = 1-5$:

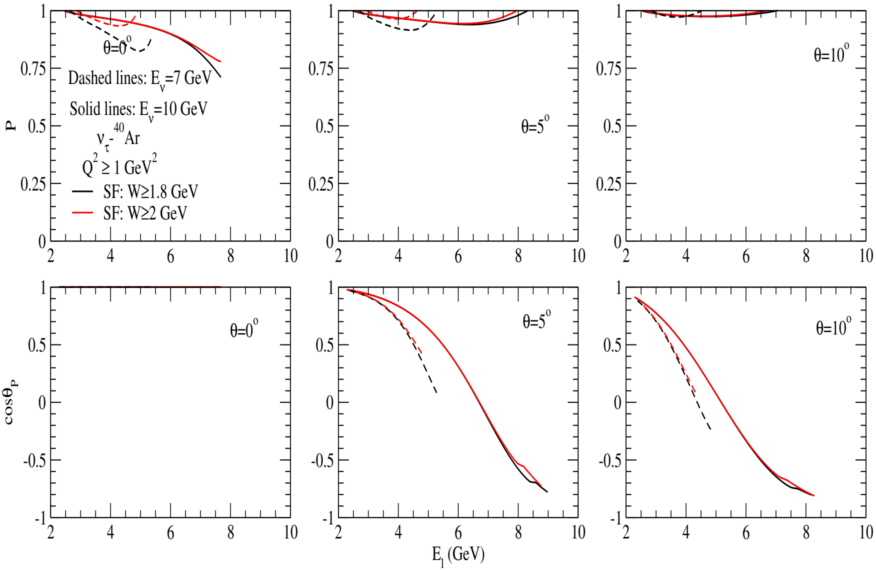
- Fermi motion, binding energy and nucleon correlations through spectral function.
- The spectral functions has been calculated using Lehmann's representation for the relativistic nucleon propagator.
- Nuclear many body theory is used to calculate it for an interacting Fermi sea in nuclear matter (Phys.Rev.D 105 (2022), 033010; Phys.Rev.D 101 (2020), 033001).

Outline

$\nu_\tau - ^{40}Ar$ cross sections & polarization at NLO



$\nu_\tau -^{40}Ar$ cross sections & polarization at NLO



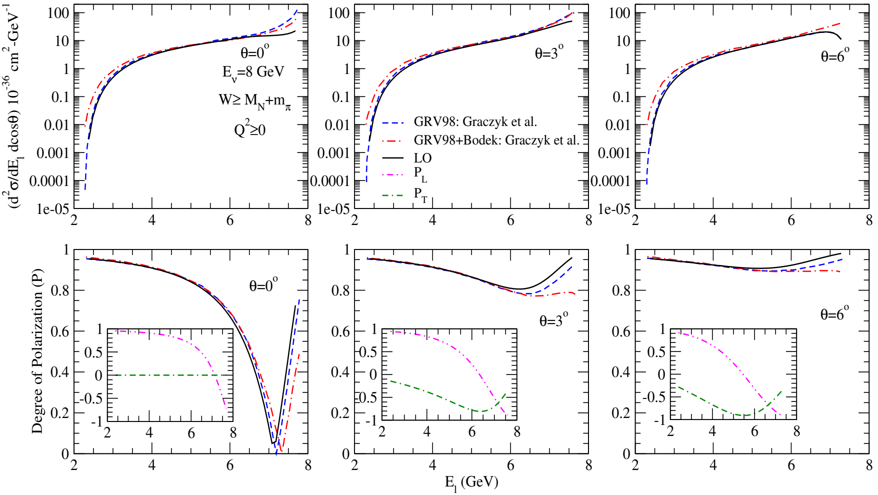
Outline

Summary & Conclusions

- The understanding of $\tau-$lepton polarization produced via $\nu_\tau - N/A$ deep inelastic scattering is required to identify the $\tau-$lepton production signal since the decay particle distributions depend crucially on the $\tau-$lepton spin.
- $\tau-$lepton degree of polarization is significant at forward scattering angles and in the region of low and intermediate energies of $\tau-$lepton.
- Effect of lepton mass is found to be important.
- We find that the target mass correction effect is not significant.
- Our work on $\tau-$lepton polarization observable is under progress and we will soon communicate it in the journal of international repute.

“Thank You”

$\nu_\tau - N$ cross sections & polarization at LO



- K. M. Graczyk, Nucl.Phys.B Proc.Suppl. 139 (2005) 150.

$\nu_l - {}^{40}Ar$ cross sections & polarization at NLO