Tau Polarization in (anti-)neutrino-nucleon Interactions.

Mohammad Rafi Alam[†]

Luis Alvarez-Ruso[#] **Toru Sato**[††]

[†]Aligarh Muslim University, India

[#]IFIC-CSIC, U.V.,Valencia

[††]RCNP, Osaka University, Japan

Outline

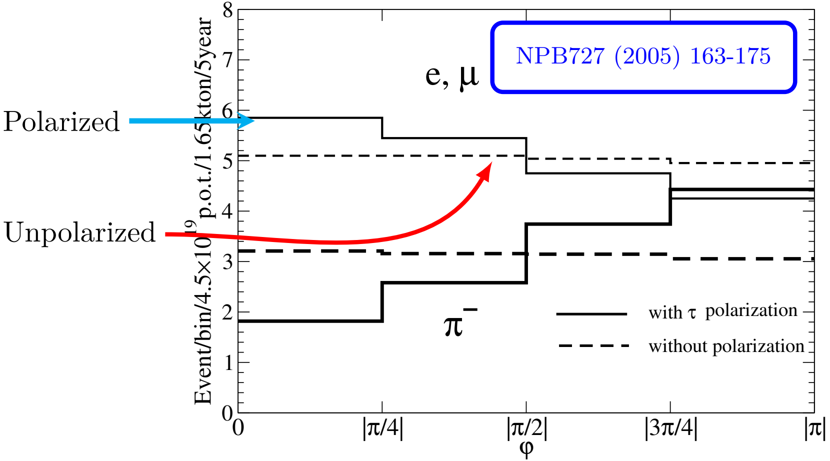
Motivation

- τ leptons were observed in experiments:
  - Atmospheric Experiments : SuperK, IceCUBE
  - Accelerator Experiments : DONOT, OPERA
- New Experiments : SHiP, DsTau, DUNE
- Neutrino Oscillation : appearance experiment $\nu_\mu \to \nu_\tau$
  - Observed by the ν_τ induced (CC)interaction

$$\overset{(-)}{\nu}_\tau(k,0) + N(p,M) \to \tau^\pm(k',m_l) + X(p')$$

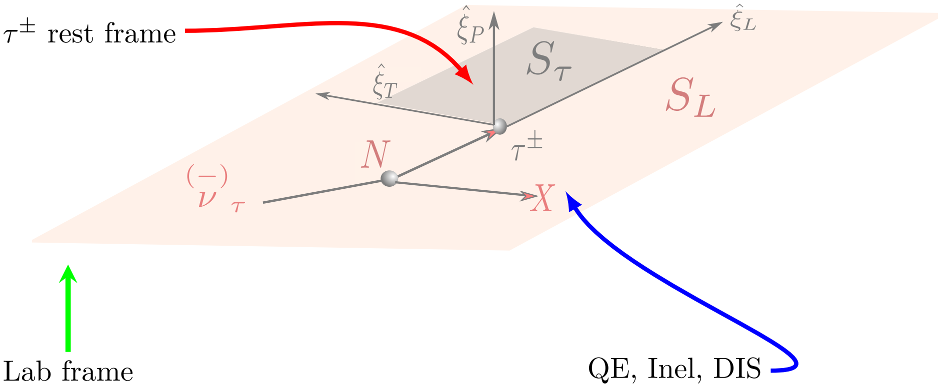
  - Challenges :
    - short lifetime of τ ($10^{-13} sec$): Practically impossible to detect!
  - Observe the decay channels
- Decay distribution has a strong dependence on τ spin polarization.

Motivation

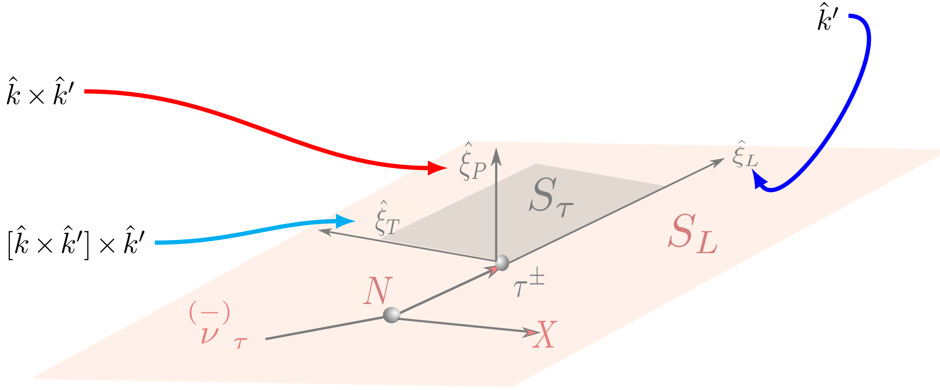


Polarized
Unpolarized
NPB727 (2005) 163-175
e, μ
π⁻
with τ polarization
without polarization
Event/bin/4.5×10^19 p.o.t./1.65kton/5year
φ
0
|π/4|
|π/2|
|3π/4|
|π|
0
1
2
3
4
5
6
7
8

$\overset{(-)}{\nu}_\tau(k,0) + N(p,M) \to \tau^\pm(k',m_l) + X(p')$



$\overset{(-)}{\nu}_\tau(k,0) + N(p,M) \to \tau^\pm(k',m_l) + X(p')$



Polarization Vector

$$\vec{\xi} = P_L\hat{\xi}_L + P_t\hat{\xi}_T + \cancel{P_{t'}\hat{\xi}_P}$$

- Quasi-elastic $\left[\tau^{\pm}N\right]$
- Inelastic $\left[\tau^{\pm}\pi N,\, \tau^{\pm}KN,\, \cdots\right] \longrightarrow$ (Dynamical Coupled Channel)
- Deep-Inelastic $\left[\tau^{\pm} + Jet\right]$

- Quasi-elastic $\left[\tau^{\pm} N\right]$
- Inelastic $\left[\tau^{\pm}\pi N,\, \tau^{\pm} K N,\, \cdots\right]$ $\longrightarrow$ (Dynamical Coupled Channel)
- Deep-Inelastic $\left[\tau^{\pm} + Jet\right]$

Hadronic Tensor

$$W_{\mu\nu}(p,q) = -g_{\mu\nu} W_1(p\cdot q, Q^2) + \frac{p_\mu p_\nu}{M^2} W_2(p\cdot q, Q^2) - i\epsilon_{\mu\nu\alpha\beta}\frac{p^\alpha q^\beta}{2M^2} W_3(p\cdot q, Q^2)$$
$$+ \frac{q_\mu q_\nu}{M^2} W_4(p\cdot q, Q^2) + \frac{p_\mu q_\nu + q_\mu p_\nu}{2M^2} W_5(p\cdot q, Q^2), +i\frac{p_\mu q_\nu - q_\mu p_\nu}{M^2} W_6(p\cdot q, Q^2)$$

$$FP_{t'} = -\frac{2m_l}{M} p_l W_6 \sin\theta$$

$$FP_t = -m_l \sin\theta \left[\pm \left(2W_1 - W2 - \frac{m_l^2}{M^2} W_4 + \frac{2E_l}{M} W_5 \right) - \frac{E_\nu}{M} W_3 \right]$$

$$FP_l = \mp \left[\left(2W_1 - \frac{m_l^2}{M^2} W_4 \right) (p_l - E_l \cos\theta) + W_2 (p_l + E_l \cos\theta) - \frac{2m_l^2}{M} \cos\theta W_5 \right]$$
$$- \frac{W_3}{M} \left(\cos\theta (E_\nu E_l + p_l^2) - p_l (E_\nu + E_l) \right)$$

$$F = \left(2W_1 + \frac{m_l^2}{M^2} W_4 \right) \left[E_l - p_l \cos\theta \right] + W_2 (E_l + p_l \cos\theta)$$
$$\pm \frac{W_3}{M} \left[(E_\nu + E_l)(E_l - p_l \cos\theta) - m_l^2 \right] - \frac{2m_l^2}{M} W_5$$

Quasi-elastic

$$
\begin{aligned}
\nu_\tau(k) + n(p) &\longrightarrow \tau^-(k') + p(p'), \\
\bar{\nu}_\tau(k) + p(p) &\longrightarrow \tau^+(k') + n(p'),
\end{aligned}
$$

The hadronic current J_μ is expressed as:

$$J_\mu = \bar{u}(p')\left[V_\mu - A_\mu\right]u(p)$$

$$
\begin{aligned}
\langle N'(p')|V_\mu|N(p)\rangle &= \bar{u}(p')\left[\gamma_\mu f_1(Q^2) + i\sigma_{\mu\nu}\frac{q^\nu}{M_p+M_n}f_2(Q^2) + \cancel{\frac{2\ q_\mu}{M_p+M_n}}f_3(Q^2)\right]u(p), \\
\langle N'(p')|A_\mu|N(p)\rangle &= \bar{u}(p')\left[\gamma_\mu\gamma_5 g_1(Q^2) + \cancel{i\sigma_{\mu\nu}\frac{q^\nu}{M_p+M_n}\gamma_5 g_2(Q^2)} + \frac{2\ q_\mu}{M_p+M_n}g_3(Q^2)\gamma_5\right]u(p
\end{aligned}
$$

Dynamical Coupled Channel

- Extension of Sato-Lee model
  - Only πN state and works in $\Delta(1232)$ region.
- The building blocks of DCC
  - stable two-particle channels $(\pi N, \eta N, K\Lambda, K\Sigma)$
  - quasi-stable channels $(\rho N, \sigma N, \pi\Delta)$
- The T-matrix are constructed for the meson-baryon scattering has been obtained from the coupled-channel Lippmann-Schwinger equation:

$$\begin{aligned} \langle\alpha,\vec{p}'|T(W)|\beta,\vec{p}\rangle &= \langle\alpha,\vec{p}'|V(W)|\beta,\vec{p}\rangle \\ &+ \sum_{\gamma}\int d^3k\,\langle\alpha,\vec{p}'|V(W)|\gamma,\vec{k}\rangle G^0_{\gamma}(\vec{k},W)\langle\gamma,\vec{k}|T(W)|\beta,\vec{p}\rangle \end{aligned}$$

  where α,β and γ are the meson-baryon two-body states.
- Satisfies two- and three- body unitarity.

Structure Function

momentum fraction

Parton distribution fuction

Elements of CKM Matrix

$$W_{\mu\nu} = \sum_{q,q'=u,d,\ldots,\bar{u},\bar{d},\ldots} \int \frac{d\xi}{\xi} f_q(\xi, Q^2) K_{\mu\nu}(p_q, q) |V_{qq'}|^2$$

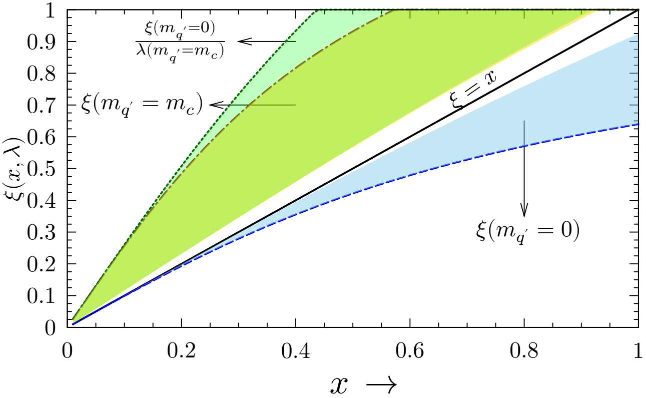
$$K^{\mu\nu} = \delta\left[(p_q + q)^2 - m_{q'}^2\right] \times 2\left\{ -g^{\mu\nu} p_q \cdot q + 2p_q^\mu p_q^\nu \mp i\varepsilon^{\mu\nu\alpha\beta} p_{q_\alpha} p_{q_\beta} + (p_q^\mu q^\nu + q^\mu p_q^\nu)\right\}.$$

parton mass

parton momentum $p_q = \xi p$, p is nucleon momentum

$$\xi_0 = \frac{2x/\lambda}{1+\sqrt{1+4M^2x^2/(\lambda Q^2)}}$$

$1 \leq Q^2 \leq 10\,GeV^2$



Structure Function

$$W_1 = \sum_j f_j(\xi)|V_{ij}|^2 = F_1(\xi)\,,$$

$$W_2 = \frac{M^2}{p\cdot q + \xi M^2}\sum_j 2\xi f_j(\xi)|V_{ij}|^2 = \frac{M^2}{p\cdot q + \xi M^2}F_2(\xi)\,,$$

$$W_3 = \frac{M^2}{p\cdot q + \xi M^2}\left[\sum_j 2 f_j(\xi)|V_{ij}|^2\right] = \frac{M^2}{p\cdot q + \xi M^2}F_3(\xi)\,,$$

$$W_4 = \frac{M^2}{p\cdot q + \xi M^2}\sum_j f_j(\xi)|V_{ij}|^2 = \frac{M^2}{p\cdot q + \xi M^2}F_4(\xi)\,,$$

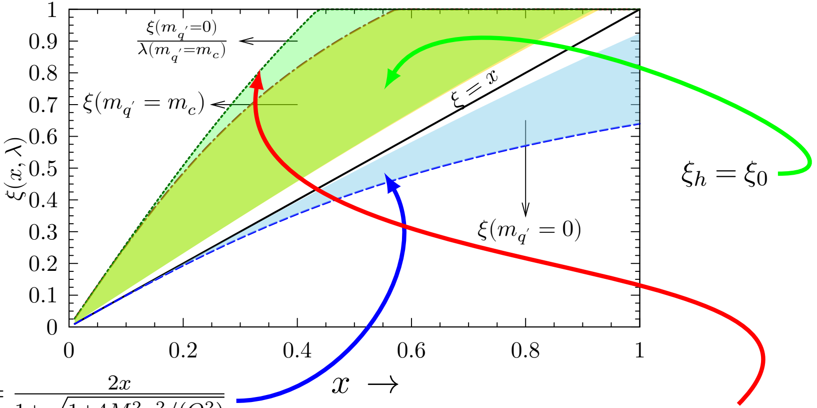
$$W_5 = \frac{M^2}{p\cdot q + \xi M^2}\left[\sum_j 2 f_j(\xi)|V_{ij}|^2\right] = \frac{M^2}{p\cdot q + \xi M^2}F_5(\xi)\,.$$

Structure Function

$$
\begin{aligned}
F_{1(l)}^{(N)} &= |V_{ud}|^2 f_d^{(N)}(\xi_l) + |V_{us}|^2 f_s^{(N)}(\xi_l) + (|V_{ud}|^2 + |V_{us}|^2) f_{\bar{u}}^{(N)}(\xi_l) \\
F_{1(h)}^{(N)} &= |V_{cd}|^2 f_d^{(N)}(\xi_h) + |V_{cs}|^2 f_s^{(N)}(\xi_h) \\
F_{2(l)}^{(N)} &= 2\xi_l \{|V_{ud}|^2 f_d^{(N)}(\xi_l) + |V_{us}|^2 f_s^{(N)}(\xi_l) + (|V_{ud}|^2 + |V_{us}|^2) f_{\bar{u}}^{(N)}(\xi_l)\} \\
F_{2(h)}^{(N)} &= 2\xi_h \{|V_{cd}|^2 f_d^{(N)}(\xi_h) + |V_{cs}|^2 f_s^{(N)}(\xi_h)\} \\
F_{3(l)}^{(N)} &= 2\{|V_{ud}|^2 f_d^{(N)}(\xi_l) + |V_{us}|^2 f_s^{(N)}(\xi_l) - (|V_{ud}|^2 + |V_{us}|^2) f_{\bar{u}}^{(N)}(\xi_l)\} \\
F_{3(h)}^{(N)} &= 2\{|V_{cd}|^2 f_d^{(N)}(\xi_h) + |V_{cs}|^2 f_s^{(N)}(\xi_h)\} \\
F_{4(l,h)}^{(N)} &= 0 \\
F_{5(l,h)}^{(N)} &= 2F_{1(l,h)}^{(N)}
\end{aligned}
$$

We use CTEQ6.6 for PDFs.

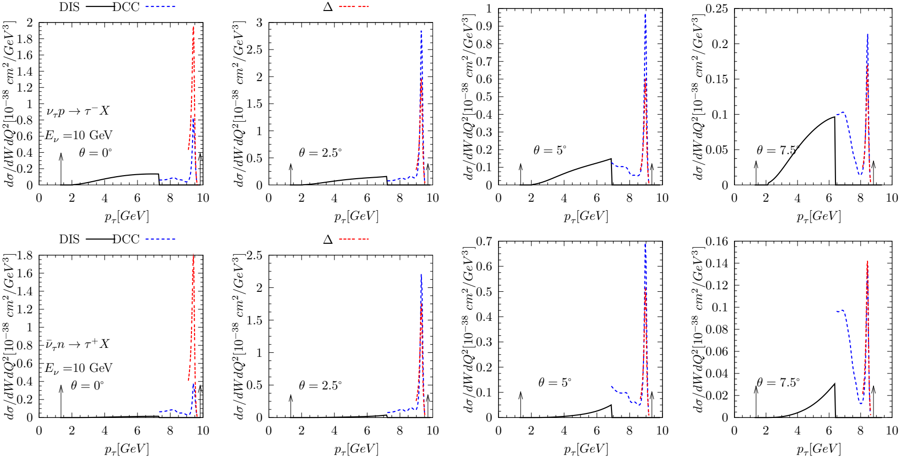
Structure Function



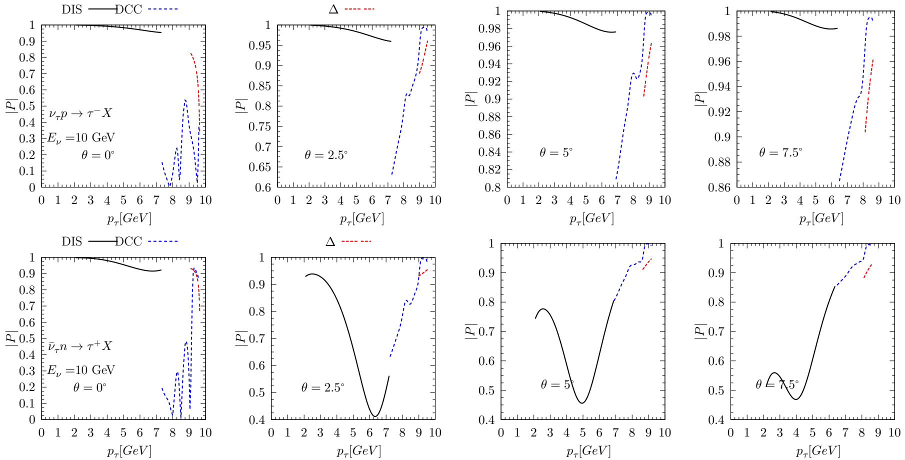
$$\xi_l = \frac{2x}{1+\sqrt{1+4M^2x^2/(Q^2)}}$$

$$\xi_N = \frac{2x/\lambda}{1+\sqrt{1+4M^2x^2/(Q^2)}}$$

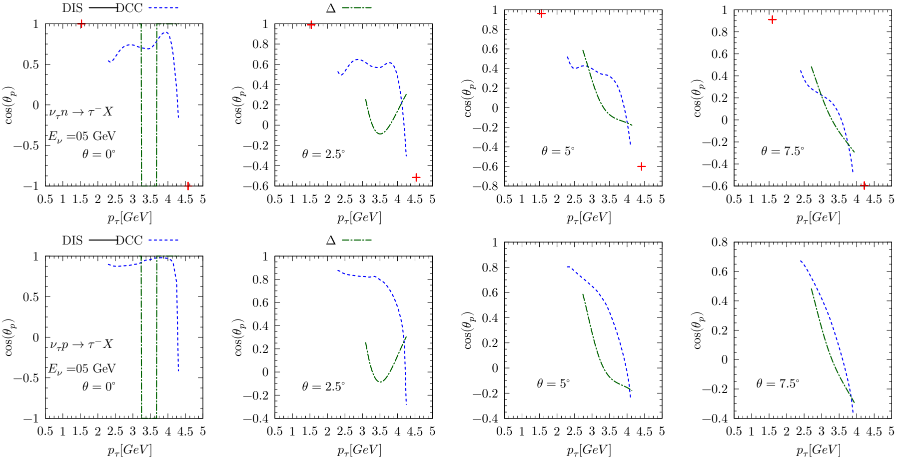
Differential cross-section at $E_\nu = 10$ GeV & $W_{cut} = 2.1 GeV$

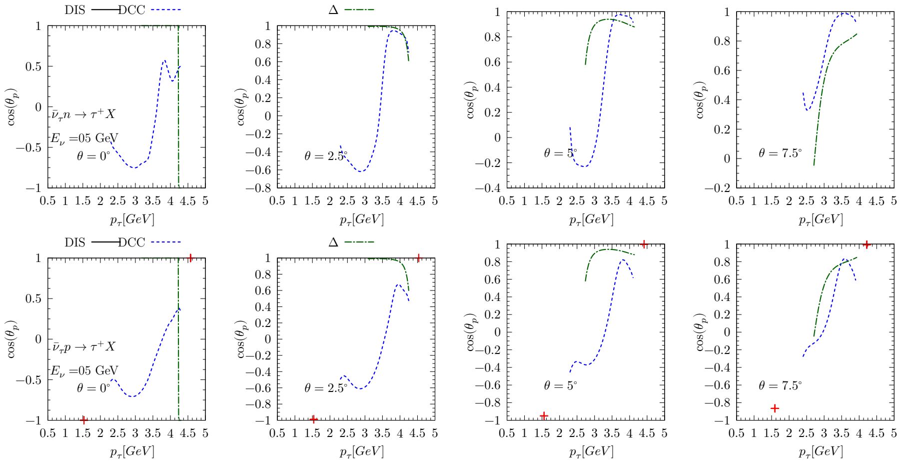


Degree of polarization

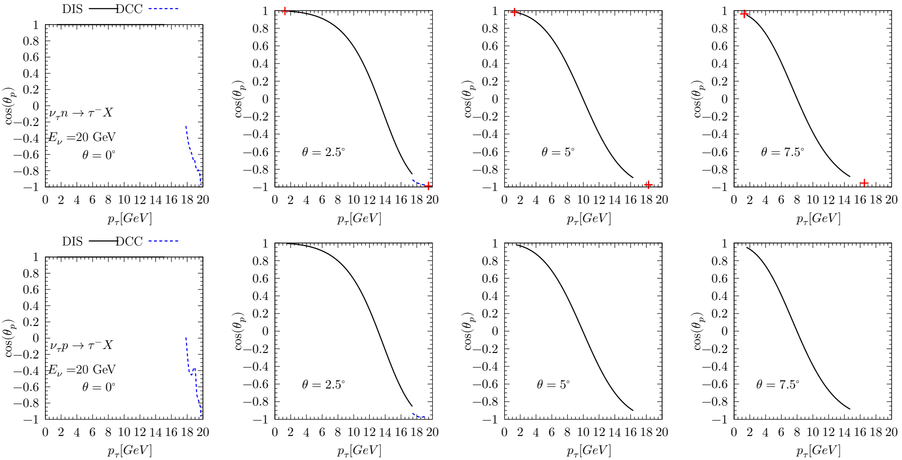


Polarization angle $\theta_P = \cos^{-1}\left[\frac{P_L}{P_T}\right] \quad E_\nu = 5GeV$

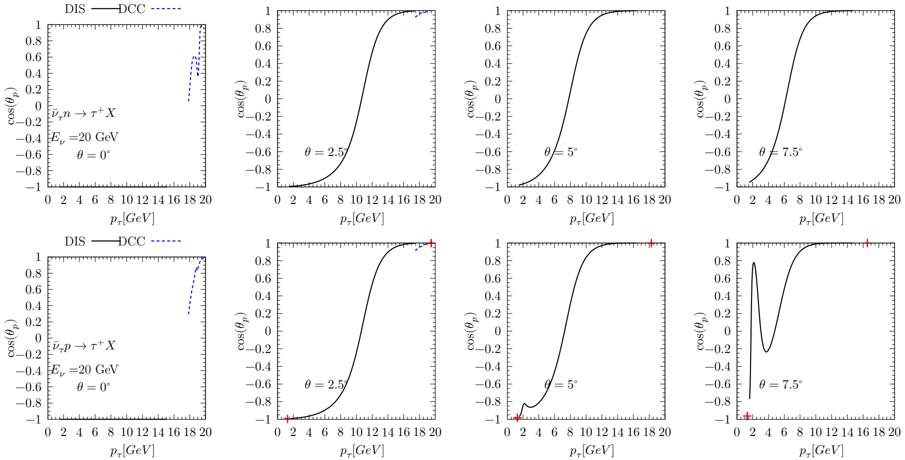


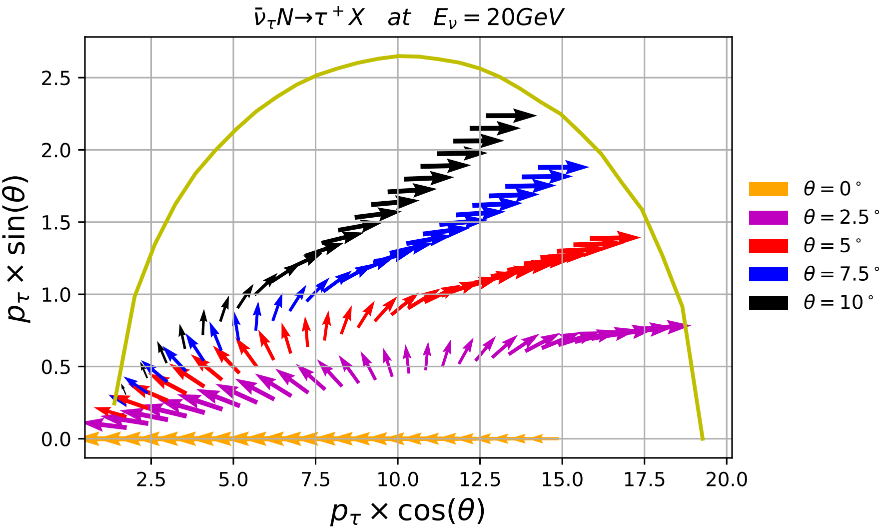


DIS
DCC
Δ
$\cos(\theta_p)$
$p_\tau[GeV]$
$\bar{\nu}_\tau n \to \tau^+ X$
$\bar{\nu}_\tau p \to \tau^+ X$
E_ν =05 GeV
$\theta = 0^\circ$
$\theta = 2.5^\circ$
$\theta = 5^\circ$
$\theta = 7.5^\circ$



DIS
DCC
$\cos(\theta_p)$
$p_\tau[GeV]$
$\nu_\tau n \to \tau^- X$
E_ν =20 GeV
$\theta = 0^\circ$
$\theta = 2.5^\circ$
$\theta = 5^\circ$
$\theta = 7.5^\circ$
$\nu_\tau p \to \tau^- X$
E_ν =20 GeV
$\theta = 0^\circ$
$\theta = 2.5^\circ$
$\theta = 5^\circ$
$\theta = 7.5^\circ$


DIS
DCC
$\cos(\theta_p)$
$p_\tau[GeV]$
$\bar{\nu}_\tau n \to \tau^+ X$
E_ν =20 GeV
$\theta = 0^\circ$
$\theta = 2.5^\circ$
$\theta = 5^\circ$
$\theta = 7.5^\circ$
DIS
DCC
$\bar{\nu}_\tau p \to \tau^+ X$
E_ν =20 GeV
$\theta = 0^\circ$
$\theta = 2.5^\circ$
$\theta = 5^\circ$
$\theta = 7.5^\circ$



$\bar{\nu}_\tau N \rightarrow \tau^+ X \quad at \quad E_\nu = 20GeV$
$p_\tau \times \sin(\theta)$
$p_\tau \times \cos(\theta)$
0.0
0.5
1.0
1.5
2.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
$\theta = 0^\circ$
$\theta = 2.5^\circ$
$\theta = 5^\circ$
$\theta = 7.5^\circ$
$\theta = 10^\circ$

Summary

- τ spin polarization is important for τ lepton detection
- The use of Dynamical Couple Channel model helps us to push the invariant mass up to 2.1GeV. In this region, DCC gave an accurate description of the inelastic process.
- In the DIS region, we improve the kinematic treatment (especially for low Q^2) and write the structure functions in a more consistent way.
- Around low invariant mass, the DIS results may need to improve for reasonable matching.

Summary

- τ spin polarization is important for τ lepton detection
- The use of Dynamical Couple Channel model helps us to push the invariant mass up to 2.1GeV. In this region, DCC gave an accurate description of the inelastic process.
- In the DIS region, we improve the kinematic treatment (especially for low Q^2) and write the structure functions in a more consistent way.
- Around low invariant mass, the DIS results may need to improve for reasonable matching.

Thanks