Invariant Amplitudes, Unpolarized Cross Sections, Polarization Observables in Charged-Current Elastic Neutrino-Nucleon Scattering

PIKIMO-15, Indiana University

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arXiv:2311.XXXXX

University of Kentucky

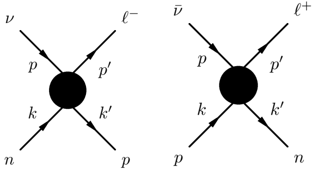
November 11, 2023

Goal of the talk

- We present a general decomposition of (anti)neutrino-nucleon charged-current elastic scattering amplitudes.
- We evaluate the expressions for the unpolarized cross section and single-spin asymmetries in terms of these invariant amplitudes.
- We plot the numerical results for all observables as a function of Q^2 at relevant fixed neutrino energies with tree-level nucleon form factors.
- We explore the impact of both unpolarized cross-section and polarized observables on constraining the amplitudes.

Outline

Amplitude decomposition for elastic (anti)neutrino-nucleon scattering



- In the $m_\ell = 0$ limit, the matrix element of the charged-current elastic process can be given by,

$$T^{m_\ell=0}_{\nu_\ell n\to\ell^- p} = \sqrt{2}\mathrm{G_F}\,V_{ud}\,\bar{\ell}^-\gamma^\mu\mathrm{P_L}\nu_\ell\,\bar{p}\left(\gamma_\mu\left(g_M + f_A\gamma_5\right) - \left(f_2 + f_A^3\gamma_5\right)\frac{K_\mu}{M}\right)n$$

$$T^{m_\ell=0}_{\bar{\nu}_\ell p\to\ell^+ n} = \sqrt{2}\mathrm{G_F}\,V^*_{ud}\,\bar{\nu}_\ell\gamma^\mu\mathrm{P_L}\ell^+\,\bar{n}\left(\gamma_\mu\left(\bar{g}_M + \bar{f}_A\gamma_5\right) - \left(\bar{f}_2 - \bar{f}_A^3\gamma_5\right)\frac{K_\mu}{M}\right)p$$

where, $K_\mu = (k_\mu + k'_\mu)/2$, the averaged nucleon momentum.

- For $m_\ell \neq 0$, the matrix element for charged currents contains four more invariant amplitudes,

$$T_{\nu_\ell n\to\ell^- p} = T^{m_\ell=0}_{\nu_\ell n\to\ell^- p} - \sqrt{2}\mathrm{G_F}\,V_{ud}\,\frac{m_\ell}{M}\,\bar{\ell}^-\mathrm{P_L}\nu_\ell\,\bar{p}\left(f_{P5} + f_P\gamma_5 - \frac{f_3}{4}\frac{\not{P}}{M}\gamma_5\right)n$$

$$+\sqrt{2}\mathrm{G_F}\,V_{ud}\,\frac{m_\ell}{M}\frac{f_T}{4}\,\bar{\ell}^-\sigma^{\mu\nu}\mathrm{P_L}\nu_\ell\,\bar{p}\sigma_{\mu\nu}n$$

$$T_{\bar{\nu}_\ell p\to\ell^+ n} = T^{m_\ell=0}_{\bar{\nu}_\ell p\to\ell^+ n} - \sqrt{2}\mathrm{G_F}\,V^*_{ud}\,\frac{m_\ell}{M}\,\bar{\nu}_\ell\mathrm{P_R}\ell^+\,\bar{n}\left(\bar{f}_{P5} + \bar{f}_P\gamma_5 - \frac{\bar{f}_3}{4}\frac{\not{P}}{M}\gamma_5\right)p$$

$$+\sqrt{2}\mathrm{G_F}\,V^\star_{ud}\,\frac{m_\ell}{M}\frac{\bar{f}_T}{4}\,\bar{\nu}_\ell\sigma^{\mu\nu}\mathrm{P_R}\ell^+\,\bar{n}\sigma_{\mu\nu}p$$

where, $P_\mu = (p_\mu + p'_\mu)/2$, the averaged lepton momentum.

Unpolarized Cross Section

- The charged-current elastic cross section, in the laboratory frame, is expressed in terms of invariant amplitudes as,

$$\frac{d\sigma}{dQ^2}(E_\nu, Q^2) = \frac{\mathrm{G}_\mathrm{F}^2|V_{ud}|^2}{2\pi}\frac{M^2}{E_\nu^2}\left[\left(\tau + r^2\right)A(\nu,\ Q^2) - \frac{\nu}{M^2}B(\nu,\ Q^2) + \frac{\nu^2}{M^4}\frac{C(\nu,\ Q^2)}{1+\tau}\right]$$

- The quantities A, B, and C are given by,

$$\begin{aligned}
A &= \tau|g_M|^2 - |g_E|^2 + (1+\tau)|f_A|^2 - r^2\left(|g_M|^2 + |f_A + 2f_P|^2 - 4(1+\tau)\left(|f_P|^2 + |f_{P5}|^2\right)\right) \\
&\quad - \tau(1+\tau)|f_A^3|^2 - 2r^2\mathfrak{Re}\left[\left(g_E + 2g_M + (1+\tau)f_A^3\right)f_T^\star\right] - \eta r^2\left(1+\tau+r^2\right)\mathfrak{Re}\left[f_A f_3^\star\right] \\
&\quad + \frac{r^2}{4}\left(\nu^2 + 1 + \tau - \left(1+\tau+r^2\right)^2\right)|f_3|^2 - 2\eta r^4\mathfrak{Re}\left[f_P f_3^\star\right] - r^2\left(1+2r^2\right)|f_T|^2, \\
B &= \mathfrak{Re}\left[4\eta\tau f_A^* g_M + 2\eta r^2\left(f_A - 2\tau f_P\right)^* f_A^3 + 4r^2 g_E f_{P5}^\star - 2\eta r^2\left(3f_A - 2\tau\left(f_P - \eta f_{P5}\right)\right)f_T^\star\right. \\
&\quad \left. + r^4\left(f_A^3 - f_T\right)f_3^\star\right], \\
C &= \tau|g_M|^2 + |g_E|^2 + (1+\tau)|f_A|^2 + \tau(1+\tau)|f_A^3|^2 + 2r^2(1+\tau)|f_T|^2 + \eta r^2(1+\tau)\mathfrak{Re}\left[f_A f_3^\star\right],
\end{aligned}$$

where, $\eta = \pm 1$ for neutrino/antineutrino scattering.

Single Spin Asymmetries

- The single-spin asymmetry is determined as the difference of the cross section $\sigma(S)$ with a definite spin four-vector S of one initial- or final-state particle and the cross section with an opposite spin direction $\sigma(-S)$ normalized to the unpolarized cross section as given by,

$$\mathrm{T}, \mathrm{R}, \mathrm{L} = \frac{d\sigma(S) - d\sigma(-S)}{d\sigma(S) + d\sigma(-S)},$$

  where we denote target, recoil, and lepton asymmetries as T, R, and L.

- We can express T, R, and L in terms of new structure-dependent functions as follows,

$$\mathrm{T}, \mathrm{R}, \mathrm{L} = \frac{\left(\tau + r^2\right) A^{\mathrm{T},\mathrm{R},\mathrm{L}}(\nu, Q^2) - \nu B^{\mathrm{T},\mathrm{R},\mathrm{L}}(\nu, Q^2) + \frac{\nu^2}{1+\tau} C^{\mathrm{T},\mathrm{R},\mathrm{L}}(\nu, Q^2)}{(\tau + r^2) A(\nu, Q^2) - \nu B(\nu, Q^2) + \frac{\nu^2}{1+\tau} C(\nu, Q^2)}$$

- We explore 3 special cases for each of T, R, and L.

- For example, in the case of T,
  - T_{t} : target polarization is transverse to the beam direction with the spin vector in the scattering plane
  - T_{l} : target polarization is along the beam direction
  - $\mathrm{T}_{\perp}$: target polarization is transverse to the scattering plane

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Single Spin Asymmetries

- For example, in the case of T,

$$A^{\mathrm{T}} = \mathfrak{Re}\Big[(f_A - \eta g_E)\, g_M^\star \left(p'\cdot S\right) - 2\eta g_M g_E^\star \left(k'\cdot S\right) + 2r^2 \left(\frac{\eta g_E - f_A + 2\tau f_P}{\tau + r^2} \left(\left(p'\cdot S\right) \right.\right.$$

$$\left.\left. + \left(k'\cdot S\right)\right) - f_P \left(p'\cdot S\right)\right) g_M^\star - 2\frac{1+\tau}{\tau+r^2}\left(\tau f_A^3 + 2r^2 f_{P5}\right) f_A^\star \left(\left(p'\cdot S\right) + \left(k'\cdot S\right)\right)$$

$$+ \left((1+\tau)\, f_A^3 + 2r^2 f_{P5}\right) f_A^\star \left(p'\cdot S\right) + \eta f_A^3 g_E^\star \left(p'\cdot S\right) + \eta r^2 \left(\frac{2\left(g_E - 2\eta f_A + r^2 f_T\right) - r^2 f_3}{\tau + r^2} \right.$$

$$\left. \left(\left(p'\cdot S\right) + \left(k'\cdot S\right)\right) + \left(f_A^3 - \frac{f_3}{2}\right)\left(p'\cdot S\right)\right) f_T^\star - \eta r^2 (1+\tau)\, f_{P5} f_3^\star \left(k'\cdot S\right)$$

$$- r^2 \left(\frac{\tau - r^2}{\tau + r^2}\left(p'\cdot S\right) + \frac{2\tau\left(k'\cdot S\right)}{\tau + r^2} \right) \left(\eta g_M + f_A - 2f_P\right) f_T^\star - \eta r^2 \left((1+\tau)\, f_{P5} + \frac{r^2 g_M}{\tau + r^2}\right)$$

$$f_3^\star \left(\left(p'\cdot S\right) + \left(k'\cdot S\right)\right)\Big] - \frac{\rho_\perp}{\tau + r^2}\mathfrak{Im}\Big[2r^2\left(g_M f_{P5}^\star - f_A f_P^\star\right) + \eta f_A g_E^\star - \tau f_A^3 g_M^\star$$

$$+ r^2 \left(\eta f_A + f_A^3 + g_M - 2f_{P5}\right) f_T^\star\Big] + \eta r^2 \mathfrak{Re}\left[\left(4\eta f_P + r^2 f_3\right) f_{P5}^\star - \frac{1}{2} g_M f_3^\star\right]\left(p'\cdot S\right)$$

$$- \rho_\perp \eta r^2 \mathfrak{Im}\left[\left(f_P - \frac{1}{2}\frac{f_A}{\tau + r^2}\right) f_3^\star\right],$$

where $\rho_\perp = \frac{\varepsilon^{\mu\nu\lambda\rho} k_\mu k'_\nu p_\lambda S_\rho}{M^3} = 2\sqrt{\tau\nu^2 - (1+\tau)(\tau + r^2)^2}\cos\phi_\perp$.

Current Constraints on Various Amplitudes

- Best constraint for $\mathfrak{Re} f_{P5}$ comes from precise measurements of the beta decay rates. [J. C. Hardy and I. S. Towner, 2009]

$$\mathfrak{Re} f_{P5}(0)/f_1^V(0) = 0.0 \pm 1.8$$

- $\mathfrak{Im} f_{P5}$ is constrained by triple-correlation coefficient in the neutron decay. [A. Kozela et al., 2012]

$$\mathfrak{Im} f_{P5}(0) = -13 \pm 54$$

- f_T and $\mathfrak{Im} f_A$ are constrained from the fit to beta decay data. [M. González-Alonso et al., 2019, N. Severijns et al., 2006]

$$\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$$
$$\mathfrak{Im} f_T(0) = 1.4 \pm 11.9$$
$$\mathfrak{Im} f_A(0) = 0.00034 \pm 0.00058$$

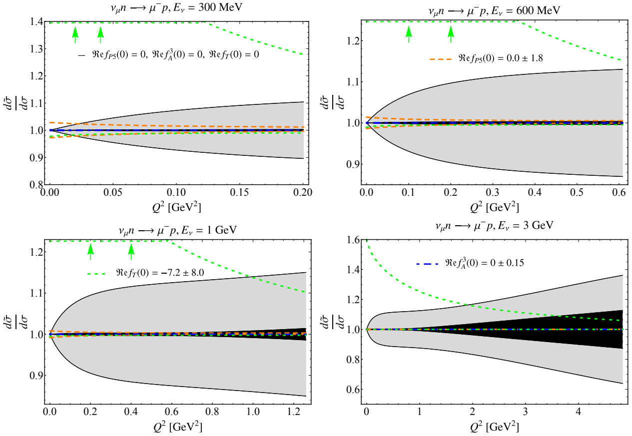
- For $\mathfrak{Re} f_A^3$, we have the following constraint. [M. Day and K. S. McFarland, 2012]

$$|\mathfrak{Re} f_A^3(0)| < 0.15$$

- For numerical estimates, we consider only either the real or the imaginary part of one additional amplitude at a time, assuming dipole form for Q^2 dependence with $\Lambda = 1$ GeV.

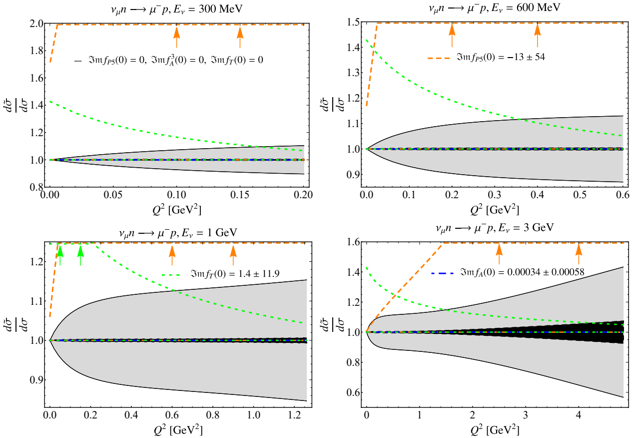
$$f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0) + i\mathfrak{Im} f_i^j(0)}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}$$

Unpolarized cross Section for Muon Neutrino



The ratio of the unpolarized cross section with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, to the tree-level result is shown as a function of the momentum transfer Q^2 at various fixed muon neutrino energies. The **dark black band** corresponds to the vector form-factor uncertainty and the **light gray band** represents the uncertainty that comes from the axial-vector form factor.

Unpolarized cross Section for Muon Neutrino



The ratio of the unpolarized cross section with one extra imaginary amplitude $f_i^j(\nu, Q^2) = \frac{i\Im\mathfrak{m} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\Im\mathfrak{m} f_{P5}(0)/f_1^V(0) = -13 \pm 54$, $\Im\mathfrak{m} f_T(0) = 1.4 \pm 11.9$, $\Im\mathfrak{m} f_A(0) = 0.00034 \pm 0.00058$, and $\Lambda = 1$ GeV, to the tree-level result is shown as a function of the momentum transfer Q^2 at various fixed muon neutrino energies.

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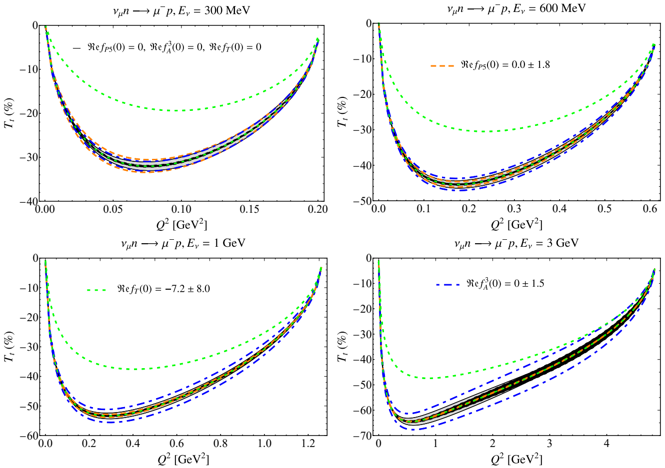
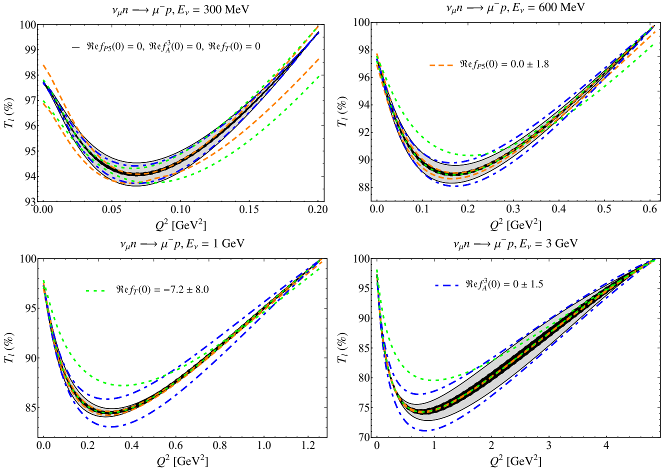
Polarization Observable for Muon Neutrino, T_t



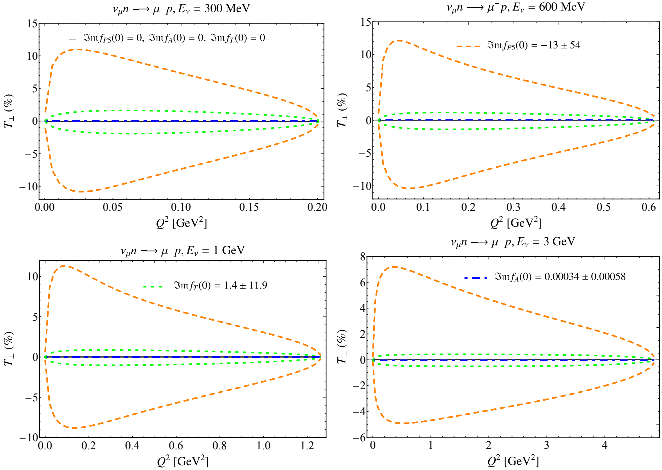
The transverse polarization observable T_t, target nucleon single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\Re e f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\Re e f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\Re e f_T(0) = -7.2 \pm 8.0$, $\Re e f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Neutrino, T_l



The longitudinal polarization observable T_l, target nucleon single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Neutrino, $T_\perp$



The transverse polarization observable $T_\perp$, target nucleon single-spin asymmetry with zero spin projection in the scattering plane, with one extra imaginary amplitude

$f_i^j(\nu, Q^2) = \frac{i\Im\mathfrak{m} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\Im\mathfrak{m} f_{P5}(0)/f_1^V(0) = -13 \pm 54$, $\Im\mathfrak{m} f_T(0) = 1.4 \pm 11.9$, $\Im\mathfrak{m} f_A(0) = 0.00034 \pm 0.00058$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Conclusion

- Expressions for the unpolarized cross section and single-spin asymmetries in terms of (anti)neutrino-nucleon charged-current elastic scattering amplitudes are calculated under a general framework.
- Numerical results for all observables are plotted as a function of Q^2 at relevant fixed neutrino energies with tree-level nucleon form factors.
- QED contributions to unpolarized muon (anti)neutrino-nucleon charged-current elastic scattering cross sections are of the order of the theoretical uncertainty, and negligible for single-spin asymmetries.
- Assuming only dipole form for Q^2 dependence, for possible new physics contributions to the invariant amplitudes, the influence of beta decay constraints on unpolarized cross sections and polarization observables is estimated.
- The available constraints on both real and imaginary parts of the tensor amplitude as well as constraints on the imaginary part of the scalar amplitude can be significantly improved with current data on the unpolarized antineutrino-hydrogen and neutrino-deuterium cross sections.

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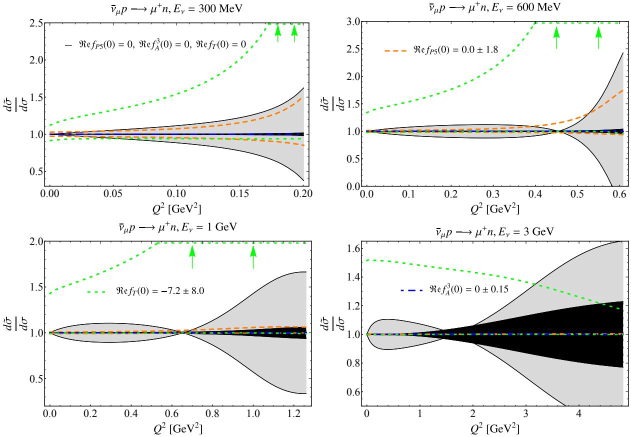
Backup Slides

Unpolarized cross Section for Muon Antineutrino



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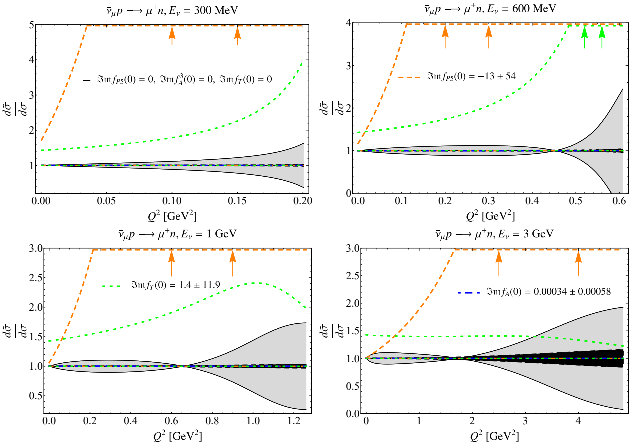
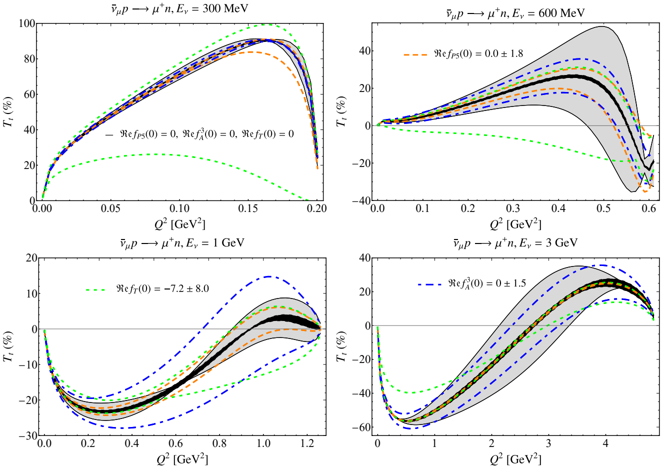
Unpolarized cross Section for Muon Antineutrino



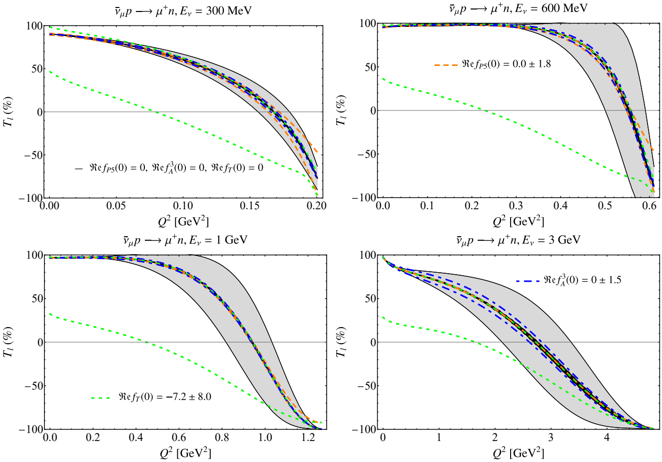
The ratio of the unpolarized cross section with one extra imaginary amplitude $f_i^j(\nu, Q^2) = \frac{i\mathfrak{Im} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Im} f_{P5}(0)/f_1^V(0) = -13 \pm 54$, $\mathfrak{Im} f_T(0) = 1.4 \pm 11.9$, $\mathfrak{Im} f_A(0) = 0.00034 \pm 0.00058$, and $\Lambda = 1$ GeV, to the tree-level result is shown as a function of the momentum transfer Q^2 at various fixed muon neutrino energies. The dark black band corresponds to the vector form-factor uncertainty and the light gray band represents the uncertainty that comes from the axial-vector form factor.

Polarization Observable for Muon Antineutrino, T_t



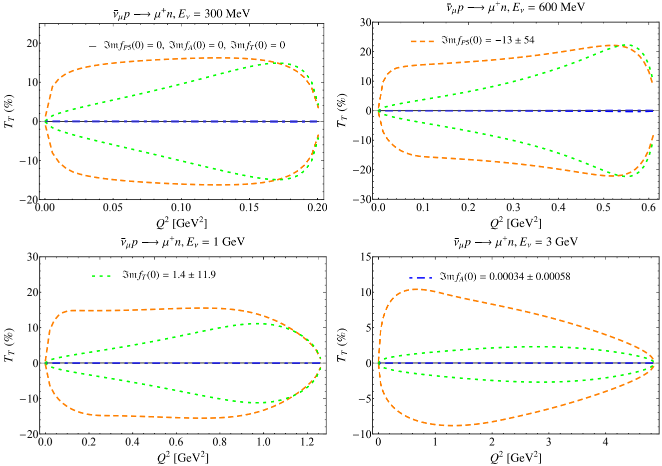
The transverse polarization observable T_t, target nucleon single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Antineutrino, T_l



The longitudinal polarization observable T_t, target nucleon single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Antineutrino, $T_\perp$



The transverse polarization observable $T_\perp$, target nucleon single-spin asymmetry with zero spin projection in the scattering plane, with one extra imaginary amplitude

$f_i^j(\nu, Q^2) = \frac{i\mathfrak{Im} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Im} f_{P5}(0)/f_1^V(0) = -13 \pm 54$, $\mathfrak{Im} f_T(0) = 1.4 \pm 11.9$,

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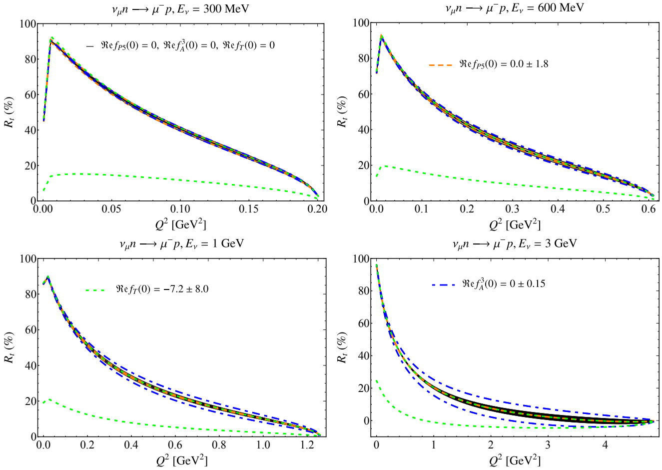
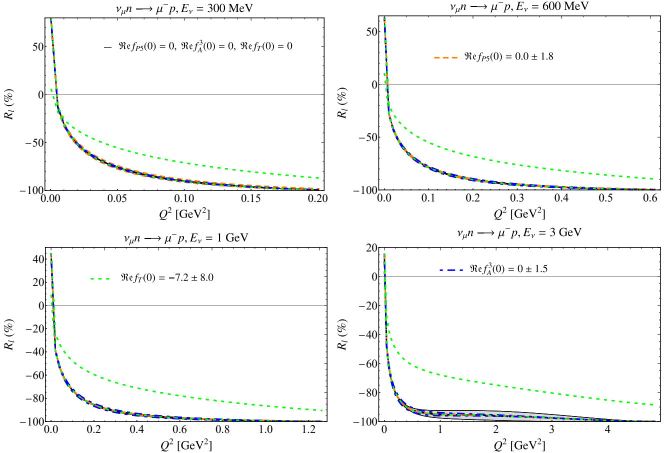
Polarization Observable for Muon Neutrino, R_t



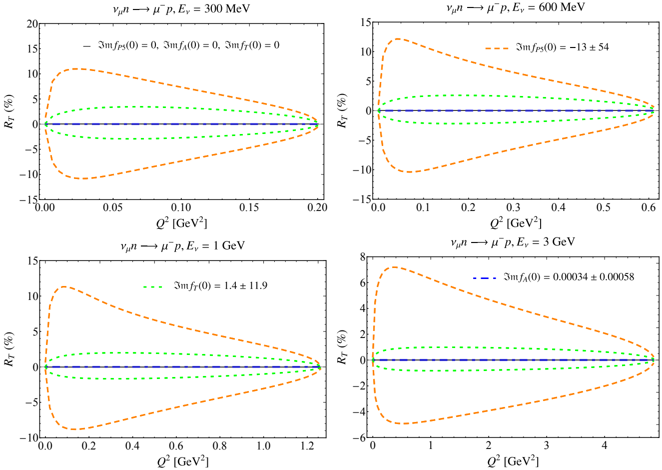
The transverse polarization observable R_t, recoil nucleon single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Neutrino, R_l



The longitudinal polarization observable R_t, recoil nucleon single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Neutrino, $R_\perp$



The transverse polarization observable $R_\perp$, recoil nucleon single-spin asymmetry with zero spin projection in the scattering plane, with one extra imaginary amplitude

$f_i^j(\nu, Q^2) = \frac{i\mathfrak{Im} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Im} f_{P5}(0)/f_1^V(0) = -13 \pm 54$, $\mathfrak{Im} f_T(0) = 1.4 \pm 11.9$,

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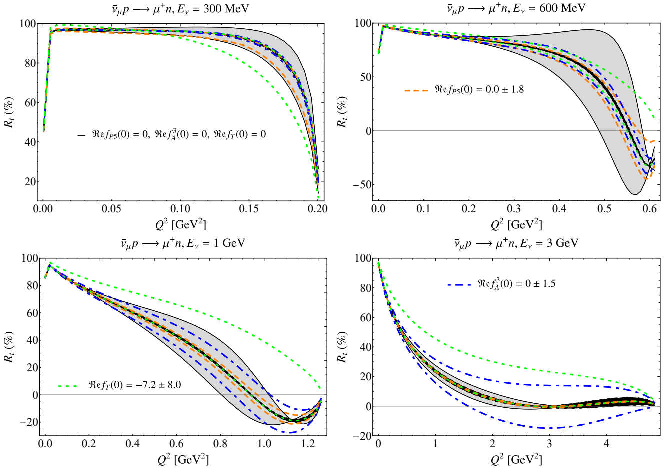
Polarization Observable for Muon Antineutrino, R_t



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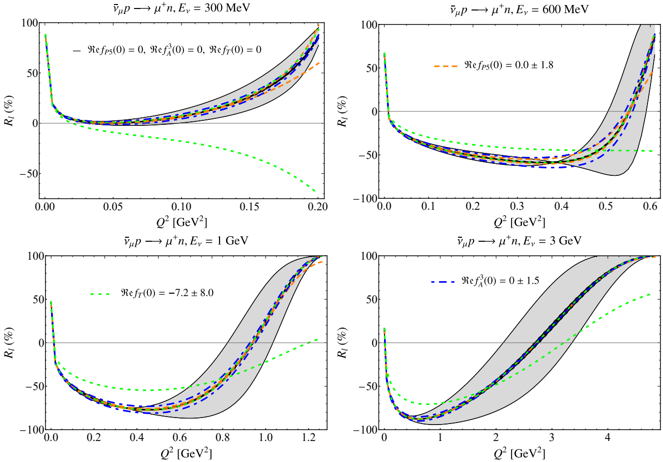
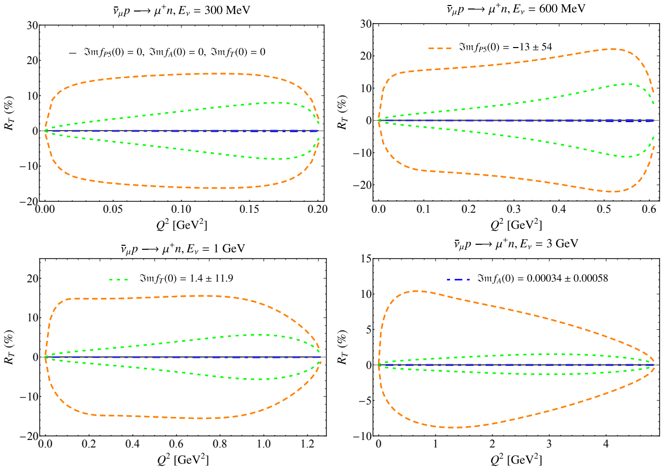
Polarization Observable for Muon Antineutrino, R_l



The longitudinal polarization observable R_t, recoil nucleon single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\Re\mathfrak{e} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\Re\mathfrak{e} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\Re\mathfrak{e} f_T(0) = -7.2 \pm 8.0$, $\Re\mathfrak{e} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Antineutrino, $R_\perp$

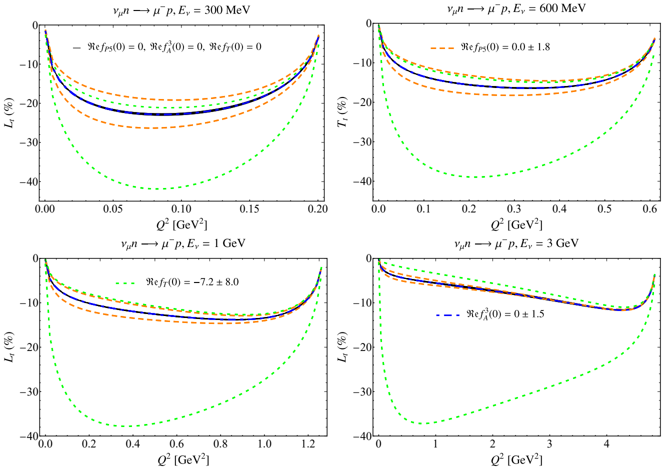


The transverse polarization observable $R_\perp$, recoil nucleon single-spin asymmetry with zero spin projection in the scattering plane, with one extra imaginary amplitude

$f_i^j(\nu, Q^2) = \frac{i\mathfrak{Im} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Im} f_{P5}(0)/f_1^V(0) = -13 \pm 54$, $\mathfrak{Im} f_T(0) = 1.4 \pm 11.9$,

$\mathfrak{Im} f_A(0) = 0.00034 \pm 0.00058$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Neutrino, L_t



The transverse polarization observable L_t, recoil lepton single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

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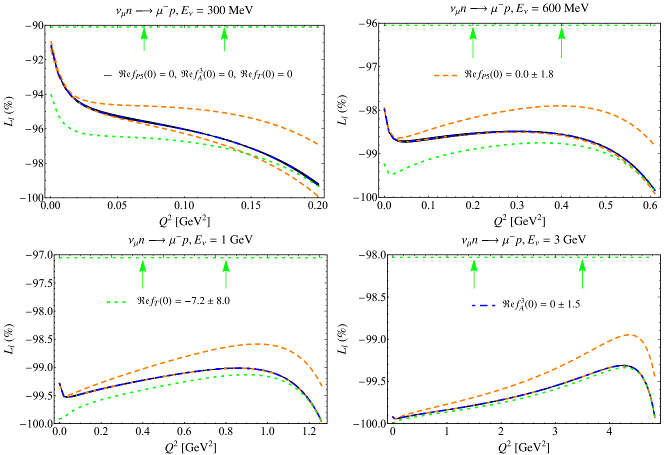
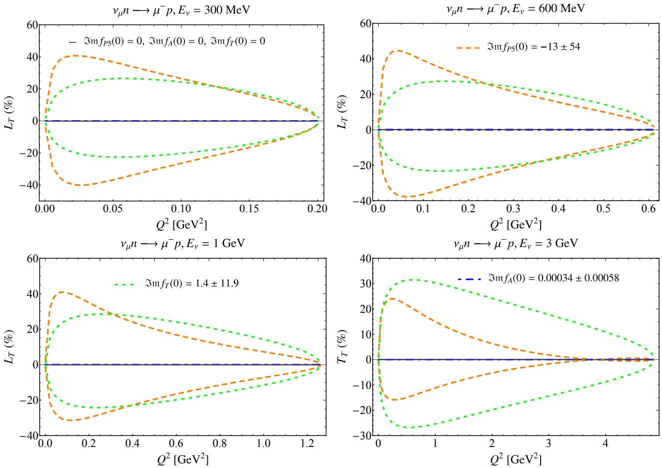
Polarization Observable for Muon Neutrino, L_l



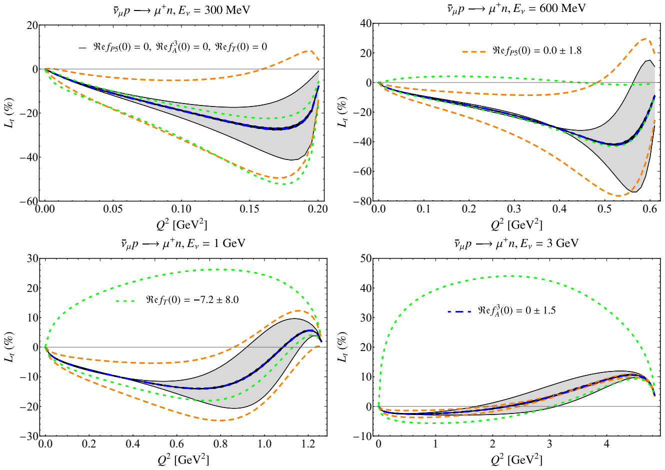
The longitudinal polarization observable L_t, recoil lepton single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Neutrino, $L_\perp$



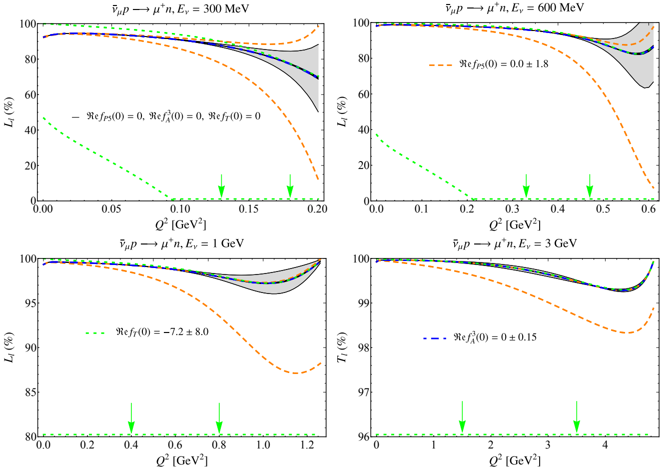
The transverse polarization observable $L_\perp$, recoil lepton single-spin asymmetry with zero spin projection in the scattering plane, with one extra imaginary amplitude $f_i^j(\nu, Q^2) = \frac{i\mathfrak{Im} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Im} f_{P5}(0)/f_1^V(0) = -13 \pm 54$, $\mathfrak{Im} f_T(0) = 1.4 \pm 11.9$, $\mathfrak{Im} f_A(0) = 0.00034 \pm 0.00058$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Antineutrino, L_t



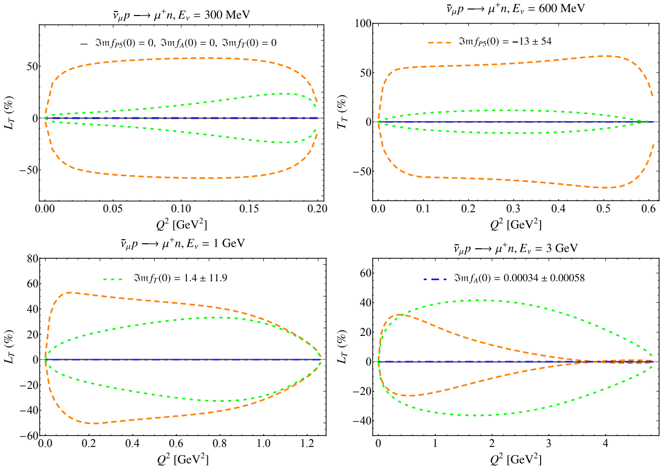
The transverse polarization observable L_t, recoil lepton single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re}\, f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re}\, f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re}\, f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re}\, f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Antineutrino, L_l



The longitudinal polarization observable L_t, recoil lepton single-spin asymmetry, with one extra real-valued amplitude $f_i^j(\nu, Q^2) = \frac{\mathfrak{Re} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$, where $\mathfrak{Re} f_{P5}(0)/f_1^V(0) = -0.0 \pm 1.8$, $\mathfrak{Re} f_T(0) = -7.2 \pm 8.0$, $\mathfrak{Re} f_A^3(0) = 0 \pm 0.15$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.

Polarization Observable for Muon Antineutrino, $L_\perp$



The transverse polarization observable $L_\perp$, recoil lepton single-spin asymmetry with zero spin projection in the scattering plane, with one extra imaginary amplitude $f_i^j(\nu, Q^2) = \frac{i\Im\mathfrak{m} f_i^j(0)}{\left(1+\frac{Q^2}{\Lambda^2}\right)^2}$,

where $\Im\mathfrak{m} f_{P5}(0)/f_1^V(0) = -13 \pm 54$, $\Im\mathfrak{m} f_T(0) = 1.4 \pm 11.9$, $\Im\mathfrak{m} f_A(0) = 0.00034 \pm 0.00058$, and $\Lambda = 1$ GeV, is compared to the tree-level result at various fixed muon neutrino energies.