Chiral Effective Fields Theory for Coherent Neutrino-Nucleus Scattering

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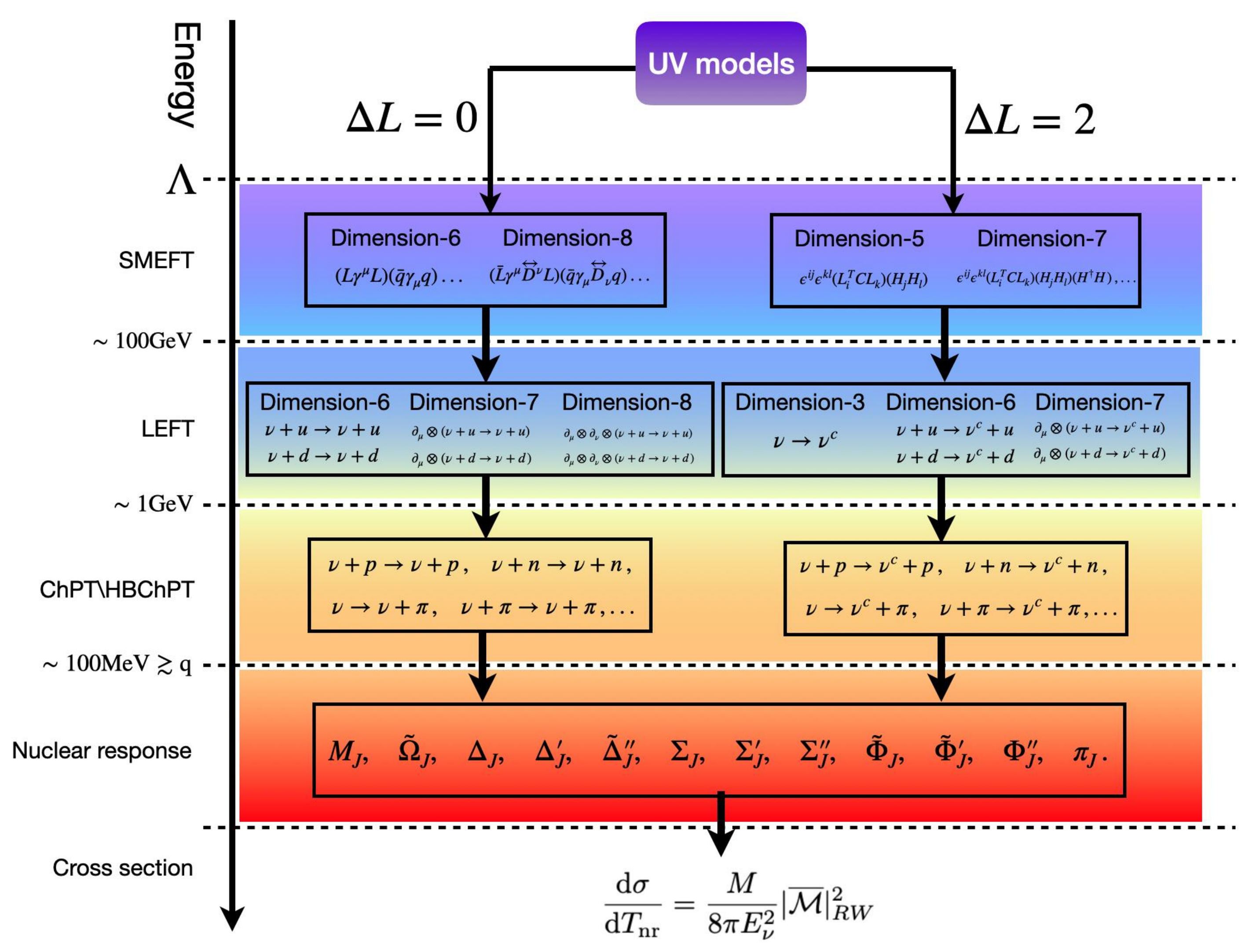
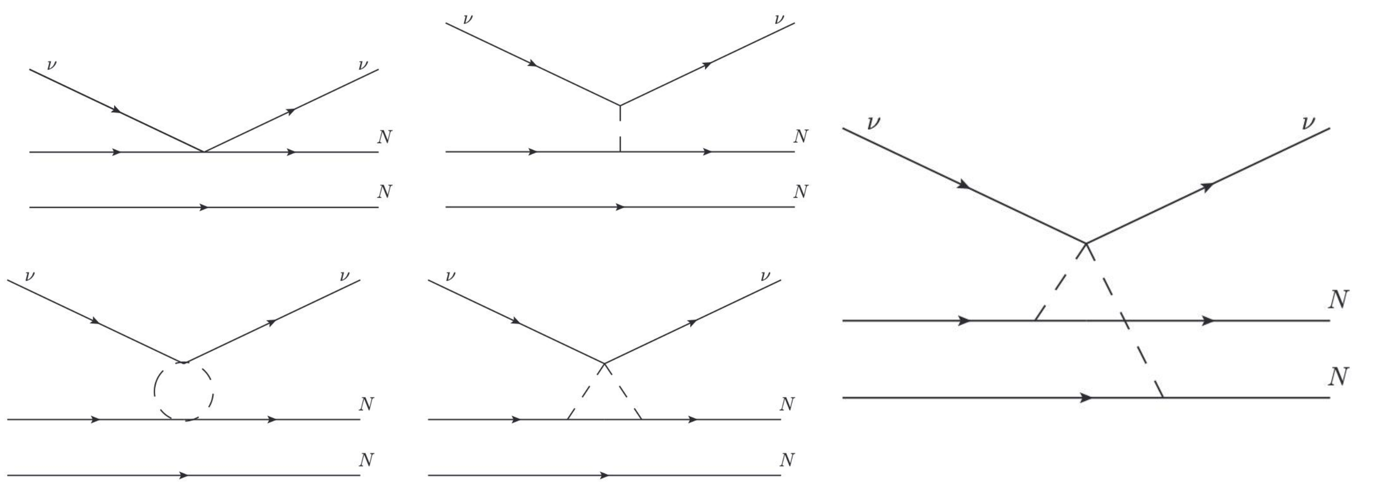
10th Workshop on Chiral Effective Field Theory, NanJing

Introduction



Nuclear Reponse



$$\mathcal{M}_{1,\mathrm{NR}} = \bar{\nu}_L l_0 \bar{\nu}_L \cdot 1_N + \bar{\nu}_L l_{0,A} \bar{\nu}_L \cdot \left(\frac{\mathbf{K}\cdot\mathbf{S}_N}{m_N}\right) + \bar{\nu}_L \mathbf{l}_5 \bar{\nu}_L \cdot (2\mathbf{S}_N) + \bar{\nu}_L \mathbf{l}_M \bar{\nu}_L \cdot \left(\frac{\mathbf{K}}{2m_N}\right) + \bar{\nu}_L \mathbf{l}_E \bar{\nu}_L \cdot \left(-i\ \frac{\mathbf{K}\times\mathbf{S}_N}{m_N}\right).$$

$$\mathcal{M}_{2,\mathrm{NR}} = -\left(\frac{g_A}{2F_\pi}\right)^2 f_\pi M_\pi \frac{(\tau_1\cdot\tau_2)(\sigma_1\cdot\mathbf{q}_1)(\sigma_2\cdot\mathbf{q}_2)}{(q_1^2+M_\pi^2)(q_2^2+M_\pi^2)}$$

$$M_J,\ \Delta_J,\ \Sigma'_J,\ \Sigma''_J,\ \tilde{\Phi}'_J,\ \Phi''_J,\ \pi_J$$

LEFT Operators

$\Delta L = 0$

$$\mathcal{O}_1^{6p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma_\mu \tau^{p/n} q)\,, \qquad \mathcal{O}_2^{6p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\gamma_\mu \tau^{p/n} q)\,,$$
$$\mathcal{O}_1^{7p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\overleftrightarrow{\partial}_\mu \tau^{p/n} q)\,, \qquad \mathcal{O}_2^{7p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\overleftrightarrow{\partial}_\mu \tau^{p/n} q)\,,$$
$$\mathcal{O}_1^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})\partial^2(\bar{q}\gamma_\mu \tau^{p/n} q)\,, \qquad \mathcal{O}_2^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})\partial^2(\bar{q}\gamma^5\gamma_\mu \tau^{p/n} q)\,.$$
$$\mathcal{O}_3^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \overleftrightarrow{\partial}^\nu \nu_{L\beta})(\bar{q}\gamma_\mu \overleftrightarrow{\partial}_\nu \tau^{p/n} q)\,, \qquad \mathcal{O}_4^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \overleftrightarrow{\partial}^\nu \nu_{L\beta})(\bar{q}\gamma^5\gamma_\mu \overleftrightarrow{\partial}_\nu \tau^{p/n} q)$$
$$\mathcal{O}_5^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^\nu T^A \tau^{p/n} q)G^A_{\mu\nu}\,, \qquad \mathcal{O}_6^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\gamma^\nu T^A \tau^{p/n} q)G^A_{\mu\nu}$$
$$\mathcal{O}_7^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^\nu T^A \tau^{p/n} q)\tilde{G}^A_{\mu\nu}\,, \qquad \mathcal{O}_8^{8p/n} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\gamma^\nu T^A \tau^{p/n} q)\tilde{G}^A_{\mu\nu}\,,$$
$$\mathcal{O}_9^{8} = (\bar{\nu}_{L\alpha}\gamma^\mu \overleftrightarrow{\partial}^\nu \nu_{L\beta})G^A_{\mu\rho}G^{A\rho}_\nu\,,$$

$\Delta L = 2$

$$\mathcal{O}_1^{5} = (\nu^T_{L\alpha} C\sigma^{\mu\nu}\nu_{L\beta})F_{\mu\nu}\,, \qquad \mathcal{O}_3^{6p/n} = (\nu^T_{L\alpha} C\sigma^{\mu\nu}\nu_{L\beta})(\bar{q}\sigma_{\mu\nu}\tau^{p/n} q)\,,$$
$$\mathcal{O}_4^{6p/n} = (\nu^T_{L\alpha} C\nu_{L\beta})(\bar{q}\tau^{p/n} q)\,, \qquad \mathcal{O}_5^{6p/n} = (\nu^T_{L\alpha} C\nu_{L\beta})(\bar{q}\gamma^5\tau^{p/n} q)\,,$$

Cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{dT}} = \frac{1}{32\pi m_A E_\nu^2}\left(|\overline{\mathcal{M}}_{1C} + \overline{\mathcal{M}}_{2C}|^2\right)$$

$$|\overline{\mathcal{M}}_{1C}|^2 = \frac{4\pi}{2J_A+1}\sum_{\tau,\tau'}\Bigg\{\left[R^{\tau\tau'}_{MM}W^{\tau\tau'}_{MM}(y) + R^{\tau\tau'}_{\Sigma''\Sigma''}W^{\tau\tau'}_{\Sigma''\Sigma''}(y) + R^{\tau\tau'}_{\Sigma'\Sigma'}W^{\tau\tau'}_{\Sigma'\Sigma'}(y)\right] + \frac{|\mathbf{q}|^2}{m_N^2}\left[R^{\tau\tau'}_{\Phi''\Phi''}W^{\tau\tau'}_{\Phi''\Phi''}(y) + R^{\tau\tau'}_{\tilde{\Phi}'\tilde{\Phi}'}W^{\tau\tau'}_{\tilde{\Phi}'\tilde{\Phi}'}(y) + R^{\tau\tau'}_{\Delta\Delta}W^{\tau\tau'}_{\Delta\Delta}(y)\right] - \frac{2|\mathbf{q}|}{m_N}\left[R^{\tau\tau'}_{\Phi''M}W^{\tau\tau'}_{\Phi''M}(y) + R^{\tau\tau'}_{\Delta\Sigma'}W^{\tau\tau'}_{\Delta\Sigma'}(y)\right]\Bigg\},$$

$$|\overline{\mathcal{M}}_{2C}|^2 = \frac{4\pi}{2J_A+1}\sum_{\tau,\tau'}\left[R^{\tau\tau'}_{\pi\pi}W^{\tau\tau'}_{\pi\pi}(y)\right]$$

$$|\overline{\mathcal{M}}_{1C}\overline{\mathcal{M}}_{2C}| = \frac{4\pi}{2J_A+1}\sum_{\tau,\tau'}\left[R^{\tau\tau'}_{\pi M}W^{\tau\tau'}_{\pi M}(y)\right]$$

Chiral Lagrangian

$$\begin{aligned}
\mathcal{L}_\pi =\ & \frac{\Lambda_\chi^2}{\Lambda_{\mathrm{EW}}^2}\mathcal{C}^{6p/n}_{1,2}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\langle Q_\mp u_\mu\rangle + \frac{\Lambda_\chi^2}{\Lambda_{\mathrm{EW}}^2}2B_0\mathcal{C}^{6p/n}_{4,5}(\nu^T_{L\alpha}C\nu_{L\beta})\langle\Sigma_\pm\rangle \\
& + \frac{\Lambda_\chi}{\Lambda_{\mathrm{EW}}^2}\mathcal{C}^{6p/n}_{3}(\nu^T_{L\alpha}C\sigma^{\mu\nu}\nu_{L\beta})\Big\{\Lambda_1\langle\Sigma_+[u_\mu,u_\nu]\rangle + \Lambda_2\langle\Sigma_-[u_\mu,u_\nu]\rangle\Big\} \\
& + \frac{\Lambda_\chi}{\Lambda_{\mathrm{EW}}^3}\mathcal{C}^{7p/n}_{1,2}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\Big\{g_1^\pi\langle\Sigma_\pm[\nabla^\nu u_\mu,u_\nu]\rangle + g_2^\pi\langle\nabla^\nu\Sigma_\pm[u_\mu,u_\nu]\rangle \\
& \qquad + g_3^\pi\langle\Sigma_\pm[u_\mu,\chi_-]\rangle + g_4^\pi\langle\Sigma_\mp[u_\mu,\chi_+]\rangle + \varepsilon_{\mu\nu\rho\lambda}\langle u^\nu u^\rho\nabla^\lambda\Sigma_\mp\rangle\Big\} \\
& + \frac{\Lambda_\chi^4}{\Lambda_{\mathrm{EW}}^4}\mathcal{C}^{8p/n}_{5,6}g_5^\pi(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\langle Q_\mp u_\mu\rangle \\
& + \frac{\Lambda_\chi^2}{\Lambda_{\mathrm{EW}}^4}\mathcal{C}^{8p/n}_{7,8}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\Big\{g_6^\pi\langle u^\nu u_\nu[u_\mu,Q_\pm]\rangle + g_7^\pi\langle\chi_+[u_\mu,Q_\pm]\rangle\Big\} \\
& + \frac{\Lambda_\chi^2}{\Lambda_{\mathrm{EW}}^4}\mathcal{C}^{8p/n}_{9}g_8^\pi(\bar{\nu}_L\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_L)\langle u^\rho u_\rho\rangle\langle u_\mu u_\nu\rangle + \ldots.
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\pi N} =\ & \frac{(4\pi)^2}{\Lambda_{\mathrm{EW}}^2}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\left\{\mathcal{C}^{6p/n}_{1,2}\left[(\bar{N}_v v_\mu Q_\pm N_v) + g_A(\bar{N}_v S_\mu Q_\mp N_v)\right]\right\} \\
& \frac{(4\pi)^2\Lambda_\chi^2}{\Lambda_{\mathrm{EW}}^4}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\left\{\mathcal{C}^{8p/n}_{5,6}[(\bar{N}_v v_\mu Q_\pm N_v) + g_A^1(\bar{N}_v S_\mu Q_\mp N_v)]\right\} \\
& \frac{(4\pi)^2\Lambda_\chi^2}{\Lambda_{\mathrm{EW}}^4}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\left\{\mathcal{C}^{8p/n}_{7}(\bar{N}_v[u_\mu,Q_+]N_v) + \mathcal{C}^{8p/n}_{8}(\bar{N}_v[u_\mu,Q_-]N_v)\right\} \\
& + \frac{(4\pi)^2}{\Lambda_{\mathrm{EW}}^2}(\nu^T_{L\alpha}C\nu_{L\beta})\left\{\mathcal{C}^{6p/n}_{4,5}\left[(\bar{N}_v\Sigma_\pm N_v) + (\bar{N}_v N_v)\langle\Sigma_\pm\rangle\right]\right\} \\
& + \frac{(4\pi)^2}{\Lambda_{\mathrm{EW}}^2}(\nu^T_{L\alpha}C\sigma^{\mu\nu}\nu_{L\beta})\left\{\mathcal{C}^{6p/n}_{3}\left[\varepsilon_{\mu\nu\rho\lambda}(\bar{N}_v v^\rho S^\lambda\Sigma_+N_v) + (\bar{N}_v[v_\mu,S_\nu]\Sigma_-N)\right]\right\} \\
& + \frac{(4\pi)^2\Lambda_\chi}{\Lambda_{\mathrm{EW}}^3}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\left\{\mathcal{C}^{7p/n}_{1,2}\left[(\bar{N}_v v^\mu\Sigma_\pm N_v) + (\bar{N}_v v^\mu N_v)\langle\Sigma_\pm\rangle\right]\right\} \\
& + \frac{\Lambda_\chi(4\pi)^2}{\Lambda_{\mathrm{EW}}^4}(\bar{\nu}_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})\left\{\mathcal{C}^{8p/n}_{3,4}\left[(\bar{N}_v Q_\pm v_\mu v_\nu N_v) + (\bar{N}_v Q_\mp S_\mu v_\nu N_v)\right]\right\} + \ldots,
\end{aligned}$$

SMEFT UV Models

Dimension-6		Dimension-5	
$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_5$	$\epsilon^{ik}\epsilon^{jl}(\ell_i^T C\ell_j)H_k H_l$
$\mathcal{O}_{HW}$	$H^\dagger H W^I_{\mu\nu}W^{I\mu\nu}$	Dimension-7	
$\mathcal{O}_{HB}$	$H^\dagger H B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{QuLLH}$	$\epsilon^{ij}(\overline{Q}^k u_R)(\ell_k^T C\ell_i)H_j$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dLQLH1}$	$\epsilon^{ij}\epsilon^{kl}(\overline{d}_R\ell_i)(Q_j^T C\ell_k)H_l$
$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^*(H^\dagger D^\mu H)$	$\mathcal{O}_{dLQLH2}$	$\epsilon^{ik}\epsilon^{jl}(\overline{d}_R\ell_i)(Q_j^T C\ell_k)H_l$
$\mathcal{O}^{(1)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu\ell)$	Dimension-8	
$\mathcal{O}^{(3)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{\ell}\tau^I\gamma^\mu\ell)$	$\mathcal{O}_{l^2G^2D}$	$(\bar{\ell}\gamma^\mu i\overleftrightarrow{D}^\nu\ell)G^A_{\mu\rho}G^{A\rho}_\nu$
$\mathcal{O}^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}^{(1)}_{l^2q^2G}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{Q}\gamma^\nu T^A Q)G^A_{\mu\nu}$
$\mathcal{O}^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$	$\mathcal{O}^{(2)}_{l^2q^2G}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{Q}\gamma^\nu T^A Q)\widetilde{G}^A_{\mu\nu}$
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}^{(3)}_{l^2q^2G}$	$(\bar{\ell}\gamma^\mu\tau^I\ell)(\bar{Q}\gamma^\nu T^A\tau^I Q)G^A_{\mu\nu}$
$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}^{(4)}_{l^2q^2G}$	$(\bar{\ell}\gamma^\mu\tau^I\ell)(\bar{Q}\gamma^\nu T^A\tau^I Q)\widetilde{G}^A_{\mu\nu}$
$\mathcal{O}_{uB}$	$(\bar{Q}\sigma^{\mu\nu}u_R)\tilde{H}B_{\mu\nu}$	$\mathcal{O}^{(1)}_{l^2u^2G}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{u}_R\gamma^\nu T^A u_R)G^A_{\mu\nu}$
$\mathcal{O}_{uW}$	$(\bar{Q}\sigma^{\mu\nu}u_R)\tau^I\tilde{H}W^I_{\mu\nu}$	$\mathcal{O}^{(2)}_{l^2u^2G}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{u}_R\gamma^\nu T^A u_R)\widetilde{G}^A_{\mu\nu}$
$\mathcal{O}_{dB}$	$(\bar{Q}\sigma^{\mu\nu}d_R)HB_{\mu\nu}$	$\mathcal{O}^{(1)}_{l^2d^2G}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{d}_R\gamma^\nu T^A d_R)G^A_{\mu\nu}$
$\mathcal{O}_{dW}$	$(\bar{Q}\sigma^{\mu\nu}d_R)\tau^I HW^I_{\mu\nu}$	$\mathcal{O}^{(2)}_{l^2d^2G}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{d}_R\gamma^\nu T^A d_R)\widetilde{G}^A_{\mu\nu}$
$\mathcal{O}^{(1)}_{\ell q}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{Q}\gamma_\mu Q)$	$\mathcal{O}^{(2)}_{l^2q^2D^2}$	$(\bar{\ell}\gamma^\mu\overleftrightarrow{D}^\nu\ell)(\bar{Q}\gamma_\mu\overleftrightarrow{D}_\nu Q)$
$\mathcal{O}^{(3)}_{\ell q}$	$(\bar{\ell}\gamma^\mu\tau^I\ell)(\bar{Q}\gamma_\mu\tau^I Q)$	$\mathcal{O}^{(4)}_{l^2q^2D^2}$	$(\bar{\ell}\gamma^\mu\overleftrightarrow{D}^{I\nu}\ell)(\bar{Q}\gamma_\mu\overleftrightarrow{D}^I_\nu Q)$
$\mathcal{O}_{\ell u}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{u}_R\gamma_\mu u_R)$	$\mathcal{O}^{(2)}_{l^2u^2D^2}$	$(\bar{\ell}\gamma^\mu\overleftrightarrow{D}^\nu\ell)(\bar{u}_R\gamma_\mu\overleftrightarrow{D}_\nu u_R)$
$\mathcal{O}_{\ell d}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{d}_R\gamma_\mu d_R)$	$\mathcal{O}^{(2)}_{l^2d^2D^2}$	$(\bar{\ell}\gamma^\mu\overleftrightarrow{D}^\nu\ell)(\bar{d}_R\gamma_\mu\overleftrightarrow{D}_\nu d_R)$

dimension-6 $S_{12}(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$ and $V_7(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$

$$\mathcal{L}_{\mathrm{UV}} = -2\mathcal{D}_{d^\dagger LS_{12}}\epsilon^{ij}[(\bar{d})^a(L)_i](S_{12})_{aj} + 2\mathcal{D}_{d^\dagger L^\dagger V_7}[(\bar{d})^a\gamma^\mu C\bar{L}_i](V_7)^i_{a\mu}$$

$$\mathcal{C}^{6n}_{1,2} = \frac{\Lambda_{\mathrm{EW}}^2}{\Lambda^2}C^{\alpha\beta}_{ld} = \Lambda_{\mathrm{EW}}^2\left(\frac{4\mathcal{D}_{d^\dagger L^\dagger V_7}\mathcal{D}_{d^\dagger L^\dagger V_7}}{M_{V_7}^2} - \frac{2\mathcal{D}_{d^\dagger LS_{12}}\mathcal{D}_{d^\dagger LS_{12}}}{M_{S_{12}}^2}\right)$$

dimension-7 $F_{12}(\mathbf{3},\mathbf{2})_{\frac{7}{6}}$ and $V_9(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$

$$\mathcal{L}^7_{\mathrm{UV}} = \mathcal{D}_{F_{12L}H^\dagger u^\dagger}(\bar{u}^a F_{12i})H^{\dagger i} + \mathcal{D}_{LQ^\dagger V_9}(\tau^I)^j_i(\bar{q}^{ai}\gamma_\mu\ell_j)V^{I\mu}_{9a} + \mathcal{D}_{LF_{12}V_9}\epsilon_{kj}(\tau^I)^k_i(\bar{\ell}^j\gamma_\mu F^{ai}_{12})V^{I\mu}_{9a} + \mathrm{h.c.}$$

$$\mathcal{C}^{6p}_{4,5} = \frac{\Lambda_{\mathrm{EW}}^3}{\Lambda^3}C_{QuLLH} = \Lambda_{\mathrm{EW}}^3\frac{16\mathcal{D}_{F_{12L}H^\dagger u^\dagger}\mathcal{D}_{LQ^\dagger V_9}\mathcal{D}_{LF_{12}V_9}}{M_{F_{12}}M_{V_9}^2}$$

Summary

We give the formalism of caculating the cross section of coherent neutrino-nucleus scattering from the new physics scale through the EFT framework. The SMEFT and LEFT operators are considered up to dimension-8, and we also include the chiral EFT up to NLO, both of the loop order and two body case are considered in this work.

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