基础物理与数学科学学院
School of Fundamental Physics and Mathematical Sciences

國科大杭州高等研究院
Hangzhou Institute for Advanced Study,UCAS

Chiral Operators Construction and Spurion Matching for New Physics Applications

Chuan-Qiang Song (HIAS)
2026.8.15

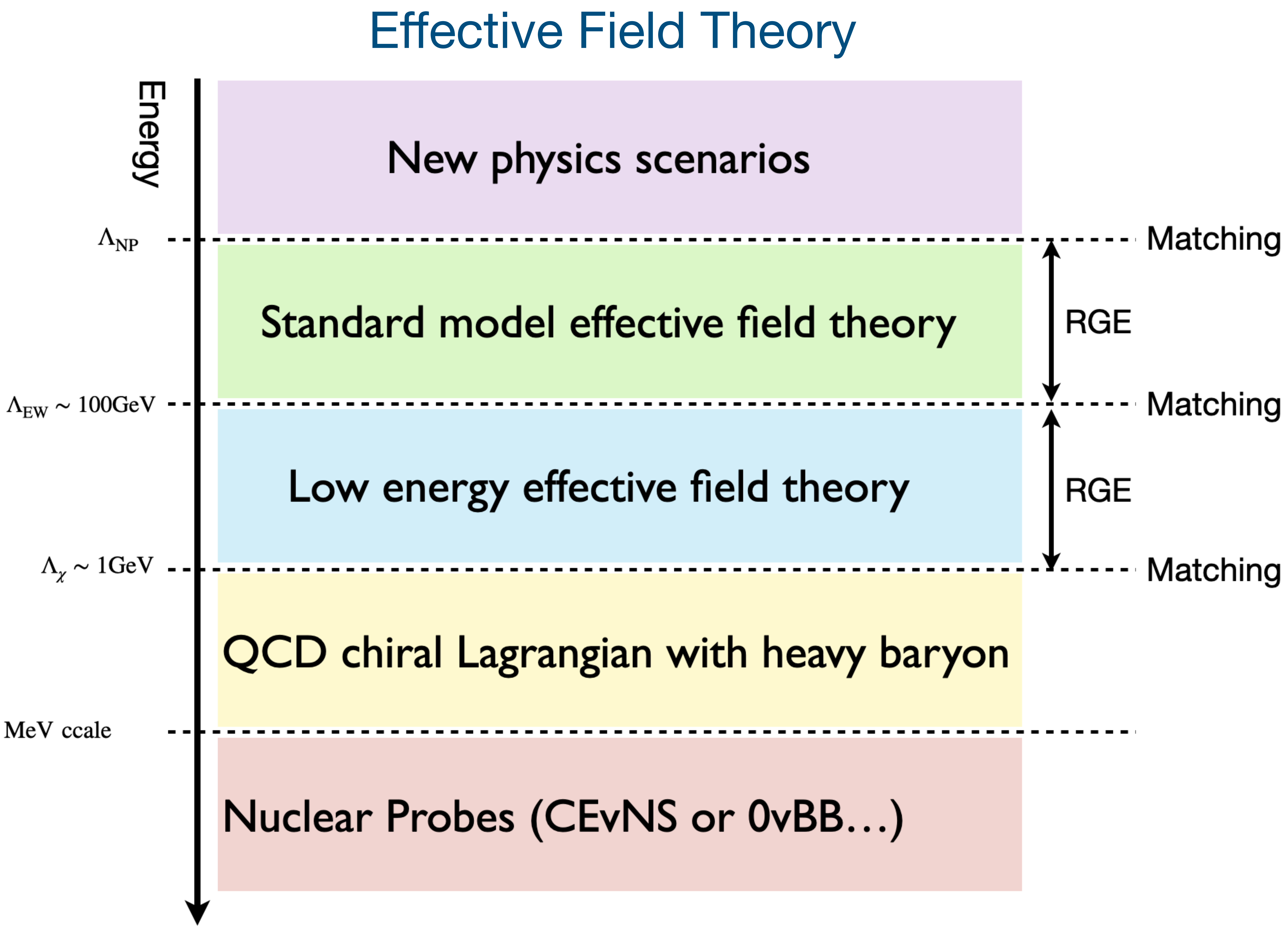
11th ChEFT (Lan Zhou)

Collaborators: Gang Li, Hao Sun, Feng-Jie Tang, Jiang-Hao Yu

Contents

- Introduction
- Construction Of Chiral Operators
- Systematic Spurion Matching
- New Physics Applications
- Summary

Introduction



Introduction

SMEFT and LEFT

The degrees of freedom for SMEFT are the same as those for the SM, and they share the same symmetries

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \sum_{d>4} \left(\frac{1}{\Lambda}\right)^{d-4} \sum_i C_i^{(d)} \mathcal{O}_i^{(d)},$$

The LEFT contains five types of light quarks, as well as leptons, photons, and gluons, and its symmetry is SU(3)✖U(1)

$$\mathcal{L}_{\mathrm{LEFT}} = \mathcal{L}_{\mathrm{QCD+QED}} + \sum_{d>4} \left(\frac{1}{\Lambda_{\mathrm{EW}}}\right)^{d-4} \sum_i \mathcal{C}_i^{(d)} \mathcal{O}_i^{(d)},$$

Weinberg, Phys.Rev.Lett. 43 (1979) 1566-1570
Buchmulle, Wyler, Nucl.Phys.B 268 (1986) 621-653
Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884 (JHEP)
Lehman, 1410.4193 (PRD)
Liao, Ma, 1607.07309 (JHEP)
Murphy, 2005.00059 (JHEP)
Li, Ren, Shu, Xiao, Yu, Zheng, 2005.00008 (PRD)
Li, Ren, Xiao, Yu, Zheng, 2007.07899 (PRD)

The matching between SMEFT and LEFT

$$L = \frac{O_d}{\Lambda_{\mathrm{EW}}^{d-4}} \left(\frac{\Lambda_{\mathrm{EW}}}{\Lambda}\right)^{\sum_i (D_i - 4)}.$$

Jenkins, Manohar, Stoffer, 1709.04486 (JHEP)
Liao, Ma, Wang, 2005.08013 (JHEP)
Li, Ren, Xiao, Yu, Zheng, 2012.09188 (JHEP)

Construction Of Chiral Operators

Young tensor technique

Lorentz structure

$$\text{Scalar field: } \phi \in (0,0) \sim 1$$

$$\text{Left-handed spinor field: } \psi \in (\frac{1}{2},0) \sim \lambda_\alpha$$

$$\text{Right-handed spinor field: } \psi^\dagger \in (0,\frac{1}{2}) \sim \tilde{\lambda}_{\dot\alpha}$$

$$\text{Left-handed field strength tensor: } F_L = \frac{F - i\tilde{F}}{2} \in (1,0) \sim \lambda_\alpha \lambda_\beta$$

$$\text{Right-handed field strength tensor: } F_R = \frac{F + i\tilde{F}}{2} \in (0,1) \sim \tilde{\lambda}_{\dot\alpha} \tilde{\lambda}_{\dot\beta}$$

$$\text{Derivative: } D \in (1,1) \sim \lambda_\alpha \tilde{\lambda}_{\dot\alpha}\,,$$

$$\epsilon^{\alpha\beta}\lambda^i_\beta \lambda^j_\alpha = \langle ij\rangle\,, \quad \tilde{\lambda}^i_{\dot\alpha}\tilde{\lambda}^j_{\dot\beta}\epsilon^{\dot\beta\dot\alpha} = [ij]\,,$$

$$\mathcal{B} = \prod^{n}\langle ij\rangle \prod^{\tilde{n}}[kl]\,,$$

Gauge structure

$$SU(2) \sim \ydiagram{2,2}\cdots\ydiagram{1,1}\,, \qquad SU(3) \sim \ydiagram{2,2,2}\cdots\ydiagram{1,1,1}\,.$$

$SU(2)$	$\mathbf{1}$	$\mathbf{2}$	$\bar{\mathbf{2}}$	$\mathbf{3}$	$SU(3)$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{8}$
	$\ydiagram{1,1}$	$\ydiagram{1}$	$\ydiagram{1}$	$\ydiagram{2}$		$\ydiagram{1,1,1}$	$\ydiagram{1}$	$\ydiagram{1,1}$	$\ydiagram{2,1}$

Li, Ren, Xiao, Yu, Zheng, 2007.07899
Li, Ren, Xiao, Yu, Zheng, 2201.04639
Li, Ren, Shu, Xiao, Yu, Zheng, 2005.00008

SMEFT, LEFT, …..

Construction Of Chiral Operators

The building block of the chiral operators can be defined by CCWZ

Coleman, Wess, Zumino, Phys.Rev. 177 (1969) 2239-2247
Callan, Coleman, Wess, Zumino, Phys.Rev. 177 (1969) 2247-2250

$$u(x) = \exp\left(\frac{i\phi(x)^a\lambda^a}{2f}\right) \qquad u \to RuV^\dagger = VuL^\dagger, \quad u^\dagger \to Lu^\dagger V^\dagger = Vu^\dagger R^\dagger\,,$$

$$L \in SU(3)_L \quad R \in SU(3)_R \quad V \in SU(3)_V$$

All of the building blocks are dressed through u

$$u_\mu = i(u^\dagger(\partial_\mu - ir_\mu)u - u(\partial_\mu - il_\mu)u^\dagger)\,,$$

$$\chi_\pm = u^\dagger\chi u^\dagger \pm u\chi^\dagger u\,,$$

$$f_{\pm\mu\nu} = u^\dagger f^R_{\mu\nu}u \pm u f^L_{\mu\nu}u^\dagger\,,$$

where $\chi = 2B(s+ip)\,,$

$$f^R_{\mu\nu} = \partial_\mu r_\nu - \partial_\nu r_\mu - i[r_\mu, r_\nu]\,, \quad r_\mu = v_\mu + a_\mu\,,$$

$$f^L_{\mu\nu} = \partial_\mu l_\nu - \partial_\nu l_\mu - i[l_\mu, l_\nu]\,, \quad l_\mu = v_\mu - a_\mu\,,$$

$$\nabla_\mu X = \partial_\mu X + [\Gamma_\mu, X]\,, \quad \Gamma_\mu \equiv \frac{1}{2}\left[u^\dagger(\partial_\mu - ir_\mu)u + u(\partial_\mu - i\ell_\mu)u^\dagger\right].$$

Chiral transformation of the building blocks $X \to VXV^\dagger$

Chiral dimension and CP properties

X	u_μ	χ_+	χ_-	f_+	f_-	∇_μ
d_χ	1	2	2	2	2	1
C: $(-1)^X$	+	+	+	−	+	+
P: η_X	−	+	−	+	−	+

Γ	1	γ^5	γ^μ	$\gamma^5\gamma^\mu$	$\sigma^{\mu\nu}$	$\varepsilon_{\mu\nu\rho\lambda}$	$\overleftrightarrow{\nabla}^\mu$
d_χ	0	1	0	0	0	0	0
C: $(-1)^\Gamma$	+	+	−	+	−	+	−
P: η_Γ	+	−	+	−	+	−	+

Construction Of Chiral Operators

Young tensor technique for chiral operators

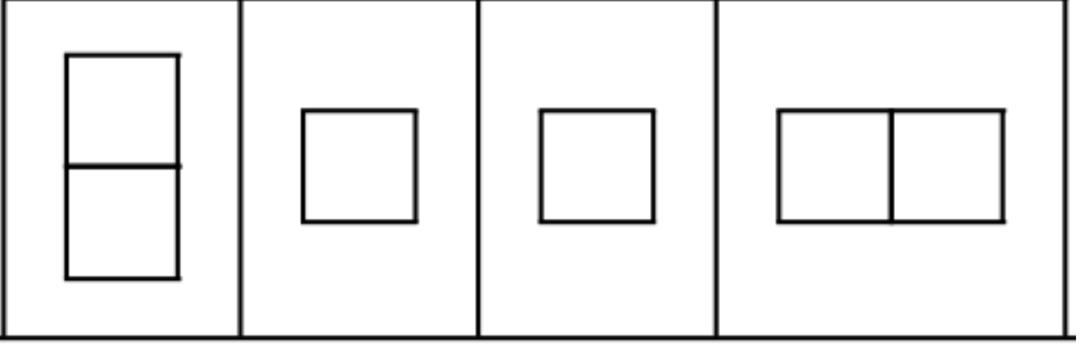
Lorentz structure

Fields	$SO(1,3)$
u_μ	(1/2,1/2)
$f_{\pm\mu\nu}$	(1,0)⊕(0,1)
$\tilde{f}_{\pm\mu\nu}$	(1,0)⊕(0,1)
$\Sigma_\pm$	(0,0)
$\langle\Sigma_\pm\rangle$	(0,0)
N_L	(1/2,0)
N_R	(0,1/2)

$$\text{Lorentz}: \ \sigma^{\mu\nu}_{\alpha\beta}, \bar{\sigma}^{\mu\nu}_{\dot{\alpha}\dot{\beta}}, \sigma^{\mu}_{\alpha\dot{\alpha}}, \bar{\sigma}^{\mu\dot{\alpha}\alpha}, \epsilon^{\alpha\beta}, \tilde{\epsilon}^{\dot{\alpha}\dot{\beta}}$$

Internal structure

$SU(2)$	**1**	**2**	$\overline{\mathbf{2}}$	**3**



$$SU(2): \quad \epsilon^{IJK}, \delta^{IJ}, (\tau^I)^j_i, \epsilon_{ij}, \epsilon^{ij},$$

Chiral operators

$$N = \begin{pmatrix} N_L \\ N_R \end{pmatrix} \qquad \gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix}$$

$$\mathcal{B}_1 = \delta^{IJ}(N_L^\dagger \bar{\sigma}^\mu \tau^I N_L) u_\mu^J \langle\Sigma_+\rangle\,, \quad \mathcal{B}_2 = \delta^{IJ}(N_R^\dagger \sigma^\mu \tau^I N_R) u_\mu^J \langle\Sigma_+\rangle\,.$$

$$\mathcal{B}_1 + \mathcal{B}_2 = (\overline{N}\gamma^\mu u_\mu N)\langle\Sigma_+\rangle\,, \quad -\mathcal{B}_1 + \mathcal{B}_2 = (\overline{N}\gamma^5\gamma^\mu u_\mu N)\langle\Sigma_+\rangle\,,$$

Construction Of Chiral Operators

Complete CP eigen state

Song, Sun, Yu, 2404.15047 (JHEP)

	order	$C+P+$	$C+P-$	$C-P+$	$C-P-$
$SU(2)$	$\mathcal{O}(p^2)$	6	4	1	2
	$\mathcal{O}(p^3)$	21	14	9	17
	$\mathcal{O}(p^4)$	95	85	67	73
	$\mathcal{O}(p^5)$	435	387	352	420
$SU(3)$	$\mathcal{O}(p^2)$	16	8	3	7
	$\mathcal{O}(p^3)$	78	66	48	70
	$\mathcal{O}(p^4)$	528	475	413	450

Systematic Spurion Matching

External source

$$\mathcal{L}_{\text{ext}} = \bar{q}\gamma^{\mu}\left(v_{\mu} + \gamma^{5}a_{\mu}\right)q - \bar{q}\left(s - i\gamma^{5}p\right)q + \bar{q}\sigma_{\mu\nu}\bar{t}^{\mu\nu}q\ ,$$

where

$$\begin{aligned} u_{\mu} &= i\{u^{\dagger}(\partial_{\mu} - ir_{\mu})u - u(\partial_{\mu} - i\ell_{\mu})u^{\dagger}\}\ , \\ \chi_{\pm} &= u^{\dagger}\chi u^{\dagger} \pm u\chi^{\dagger}u\ , \\ F^{\pm}_{\mu\nu} &= u^{\dagger}F^{R}_{\mu\nu}u \pm uF^{L}_{\mu\nu}u^{\dagger}\ , \end{aligned}$$

$$\begin{aligned} \chi &= 2B(s + ip)\ , \\ F^{\mu\nu}_{R} &= \partial^{\mu}r^{\nu} - \partial^{\nu}r^{\mu} - i[r^{\mu}, r^{\nu}]\ , \quad r_{\mu} = v_{\mu} + a_{\mu}\ , \\ F^{\mu\nu}_{L} &= \partial^{\mu}\ell^{\nu} - \partial^{\nu}\ell^{\mu} - i[\ell^{\mu}, \ell^{\nu}]\ , \quad \ell_{\mu} = v_{\mu} - a_{\mu}\ , \end{aligned}$$

$$\mathcal{L}_2' = \frac{F_0^2}{4}\langle u^{\mu}u_{\mu} + \chi_{+}\rangle$$

$$\begin{aligned} \mathcal{L}_4' = &L_1\langle u_{\mu}u^{\mu}\rangle\langle u_{\nu}u^{\nu}\rangle + L_2\langle u_{\mu}u_{\nu}\rangle\langle u^{\mu}u^{\nu}\rangle + L_3\langle\chi_{+}\rangle\langle u^{\mu}u_{\mu}\rangle \\ &+ L_4\langle f_{+}^{\mu\nu}u_{\mu}u_{\nu}\rangle + L_5\langle f_{+}^{\mu\nu}f_{+\mu\nu}\rangle + L_6\langle f_{+}^{\mu\nu}f_{+\mu\nu}\rangle \\ &+ L_7\langle\chi_{+}\chi_{+}\rangle + L_8\langle\chi_{-}\chi_{-}\rangle + L_9\langle\chi_{+}\rangle\langle\chi_{+}\rangle + L_{10}\langle\chi_{-}\rangle\langle\chi_{-}\rangle \end{aligned}$$

The external source method is limited by the interactions (V/A, S/P, T).

Systematic Spurion Matching

Spurion matching

$$(\bar{q}_L \Gamma \Sigma_L q_L), \quad (\bar{q}_R \Gamma \Sigma_R q_R), \quad (\bar{q}_R \Gamma \Sigma q_L), \quad (\bar{q}_L \Gamma \Sigma^\dagger q_R)\,,$$

$$\begin{pmatrix} q_L \\ q_R \\ \bar{q}_L \\ \bar{q}_R \\ \hat{\chi} \\ \hat{\chi}^\dagger \\ \Sigma \\ \Sigma^\dagger \\ \Sigma_L \\ \Sigma_R \\ e_L \\ e_R \\ \nu_L \\ \bar{e}_L \\ \bar{e}_R \\ \bar{\nu}_L \end{pmatrix} \to \begin{pmatrix} L q_L \\ R q_R \\ \bar{q}_L L^\dagger \\ \bar{q}_R R^\dagger \\ R\hat{\chi} L^\dagger \\ L\hat{\chi}^\dagger R^\dagger \\ R\Sigma L^\dagger \\ L\Sigma^\dagger R^\dagger \\ L\Sigma_L L^\dagger \\ R\Sigma_R R^\dagger \\ e_L \\ e_R \\ \nu_L \\ \bar{e}_L \\ \bar{e}_R \\ \bar{\nu}_L \end{pmatrix}, \quad L \in SU(2)_L\,,\ R \in SU(2)_R$$

$$\begin{aligned} \hat{\chi}_\pm &= u\,\hat{\chi}^\dagger\,u \pm u^\dagger\,\hat{\chi}\,u^\dagger\,, \\ \Sigma_\pm &= u\,\Sigma^\dagger\,u \pm u^\dagger\,\Sigma\,u^\dagger\,, \\ Q_\pm &= u^\dagger\,\Sigma_R\,u \pm u\,\Sigma_L\,u^\dagger\,. \\ \hat{u}_\mu &\equiv u_\mu|_{r_\mu=0\,,\ell_\mu=0} \end{aligned}$$

$$\begin{pmatrix} \hat{u}_\mu \\ \Sigma_\pm \\ \chi_\pm \\ Q_\pm \\ N \\ e_L \\ e_R \\ \nu_L \\ \bar{e}_L \\ \bar{e}_R \\ \bar{\nu}_L \end{pmatrix} \to \begin{pmatrix} V\hat{u}_\mu V^\dagger \\ V\Sigma_\pm V^\dagger \\ V\chi_\pm V^\dagger \\ VQ_\pm V^\dagger \\ VN \\ e_L \\ e_R \\ \nu_L \\ \bar{e}_L \\ \bar{e}_R \\ \bar{\nu}_L \end{pmatrix}, \quad V \in SU(2)_V\,.$$

External sources can be regarded as spurions

$$\begin{aligned} (v_\mu - a_\mu)' &= L(v_\mu - a_\mu + i\partial_\mu)L^\dagger \\ (v_\mu + a_\mu)' &= R(v_\mu + a_\mu + i\partial_\mu)R^\dagger \\ (s - ip)' &= L(s - ip)R^\dagger \end{aligned}$$

J. Gasser, H. Leutwyler, Annals Phys. 158 (1984) 142

External source and systematic spurion method

Matching rules

The information used in the matching is the spurions, the CP properties, and the non-quark fields.

- The spurions in the LEFT operators remains unchanged in the matching.
- The CP transformation properties of the LEFT and chiral operators are the same.
- The leptons parts are identical in the LEFT operators and chiral operators.

	Σ_+	Σ_-	Q_+	Q_-	$\hat{\chi}_+$	$\hat{\chi}_-$	$\hat{u}_\mu$
P	$+$	$-$	$+$	$-$	$+$	$-$	$-$
C	$+$	$+$	$+$	$-$	$+$	$+$	$+$

The matching for neutrino interaction

Dimension-7 operators

$$\mathcal{O}_1^{(7)} = (\bar{\nu}_L \gamma^\mu \nu_L)[\bar{q} i \overleftrightarrow{D}_\mu (\Sigma^\dagger P_R + \Sigma P_L) q]$$

$\text{Type } \Sigma u \nu^2 :$ $(\bar{\nu}_L \gamma^\mu \nu_L)\langle \hat{u}_\mu \Sigma_\pm \rangle$ Wrong CP properties

$\text{Type } \Sigma u \chi \nu^2 :$ $(\bar{\nu}_L \gamma^\mu \nu_L)\langle \hat{u}_\mu [\chi_\pm, \Sigma_\pm] \rangle$ $\xrightarrow{\text{CP properties}}$

$$(\bar{\nu}_L \gamma^\mu \nu_L)\langle \hat{u}_\mu [\chi_+, \Sigma_-] \rangle$$
$$(\bar{\nu}_L \gamma^\mu \nu_L)\langle \hat{u}_\mu [\chi_-, \Sigma_+] \rangle$$

$\text{Type } D \Sigma u^2 \nu^2 :$

$$(\bar{\nu}_L \gamma^\mu \nu_L)\langle \nabla^\nu \Sigma_\pm [u^\mu, u_\nu] \rangle$$
$$(\bar{\nu}_L \gamma^\mu \nu_L)\langle \Sigma_\pm [\nabla^\nu u_\mu, u_\nu] \rangle$$
$$(\bar{\nu}_L \gamma^\mu \nu_L)\langle \nabla^\nu \Sigma_\pm [u^\rho, u^\lambda] \rangle \epsilon_{\mu\nu\rho\lambda}$$

$\xrightarrow{\text{CP properties}}$

$$(\bar{\nu}_L \gamma^\mu \nu_L)\langle \nabla^\nu \Sigma_+ [u^\mu, u_\nu] \rangle$$
$$(\bar{\nu}_L \gamma^\mu \nu_L)\langle \Sigma_+ [\nabla^\nu u_\mu, u_\nu] \rangle$$
$$(\bar{\nu}_L \gamma^\mu \nu_L)\langle \nabla^\nu \Sigma_- [u^\rho, u^\lambda] \rangle \epsilon_{\mu\nu\rho\lambda}$$

The matching for neutrino interaction

Four quark part

$$(\bar{q}_L \Gamma\, \Sigma_L q_L)(\bar{q}_L \Gamma\, \Sigma_L q_L)\,, \qquad (\bar{q}_R \Gamma\, \Sigma_R q_R)(\bar{q}_R \Gamma\, \Sigma_R q_R)\,,$$
$$(\bar{q}_L \Gamma\, \Sigma_L q_L)(\bar{q}_R \Gamma\, \Sigma_R q_R)\,, \qquad (\bar{q}_L \Gamma\, \Sigma^\dagger q_R)(\bar{q}_L \Gamma\, \Sigma q_R)\,,$$
$$(\bar{q}_L \Gamma\, \Sigma^\dagger q_R)(\bar{q}_R \Gamma\, \Sigma^\dagger q_L)\,, \qquad (\bar{q}_R \Gamma\, \Sigma q_L)(\bar{q}_R \Gamma\, \Sigma q_L)\,,$$
$$(\bar{q}_L \Gamma\, \Sigma_L q_L)(\bar{q}_R \Gamma\, \Sigma q_L)\,, \qquad (\bar{q}_L \Gamma\, \Sigma_L q_L)(\bar{q}_L \Gamma\, \Sigma^\dagger q_R)\,,$$
$$(\bar{q}_R \Gamma \Sigma_R q_R)(\bar{q}_R \Gamma\, \Sigma q_L)\,, \qquad (\bar{q}_R \Gamma \Sigma_R q_R)(\bar{q}_L \Gamma\, \Sigma^\dagger q_R)\,.$$

Chiral representation

$$(\bar{\mathbf{2}}_L \otimes \mathbf{2}_L, \bar{\mathbf{2}}_R \otimes \mathbf{2}_R)\,,$$
$$(\bar{\mathbf{2}}_L \otimes \bar{\mathbf{2}}_L, \mathbf{2}_R \otimes \mathbf{2}_R)\,,$$
$$(\mathbf{2}_L \otimes \mathbf{2}_L, \bar{\mathbf{2}}_R \otimes \bar{\mathbf{2}}_R)\,,$$
$$(\mathbf{2}_L \otimes \mathbf{2}_L \otimes \bar{\mathbf{2}}_L, \bar{\mathbf{2}}_R)\,,$$
$$(\mathbf{2}_L \otimes \bar{\mathbf{2}}_L \otimes \bar{\mathbf{2}}_L, \mathbf{2}_R)\,,$$
$$(\bar{\mathbf{2}}_L, \mathbf{2}_R \otimes \mathbf{2}_R \otimes \bar{\mathbf{2}}_R)\,,$$
$$(\mathbf{2}_L, \mathbf{2}_R \otimes \bar{\mathbf{2}}_R \otimes \bar{\mathbf{2}}_R)\,,$$
$$(\bar{\mathbf{2}}_L \otimes \mathbf{2}_L \otimes \bar{\mathbf{2}}_L \otimes \mathbf{2}_L, \mathbf{1})\,,$$
$$(\mathbf{1}, \bar{\mathbf{2}}_R \otimes \mathbf{2}_R \otimes \bar{\mathbf{2}}_R \otimes \mathbf{2}_R)\,.$$

The combination of the spurions

$$\Sigma_L \sim (\mathbf{3}_L, \mathbf{1}_R)\,, \quad \Sigma_R \sim (\mathbf{1}_L, \mathbf{3}_R)\,, \quad \Sigma \sim (\bar{\mathbf{2}}_L, \mathbf{2}_R)\,, \quad \Sigma^\dagger \sim (\mathbf{2}_L, \bar{\mathbf{2}}_R)\,.$$

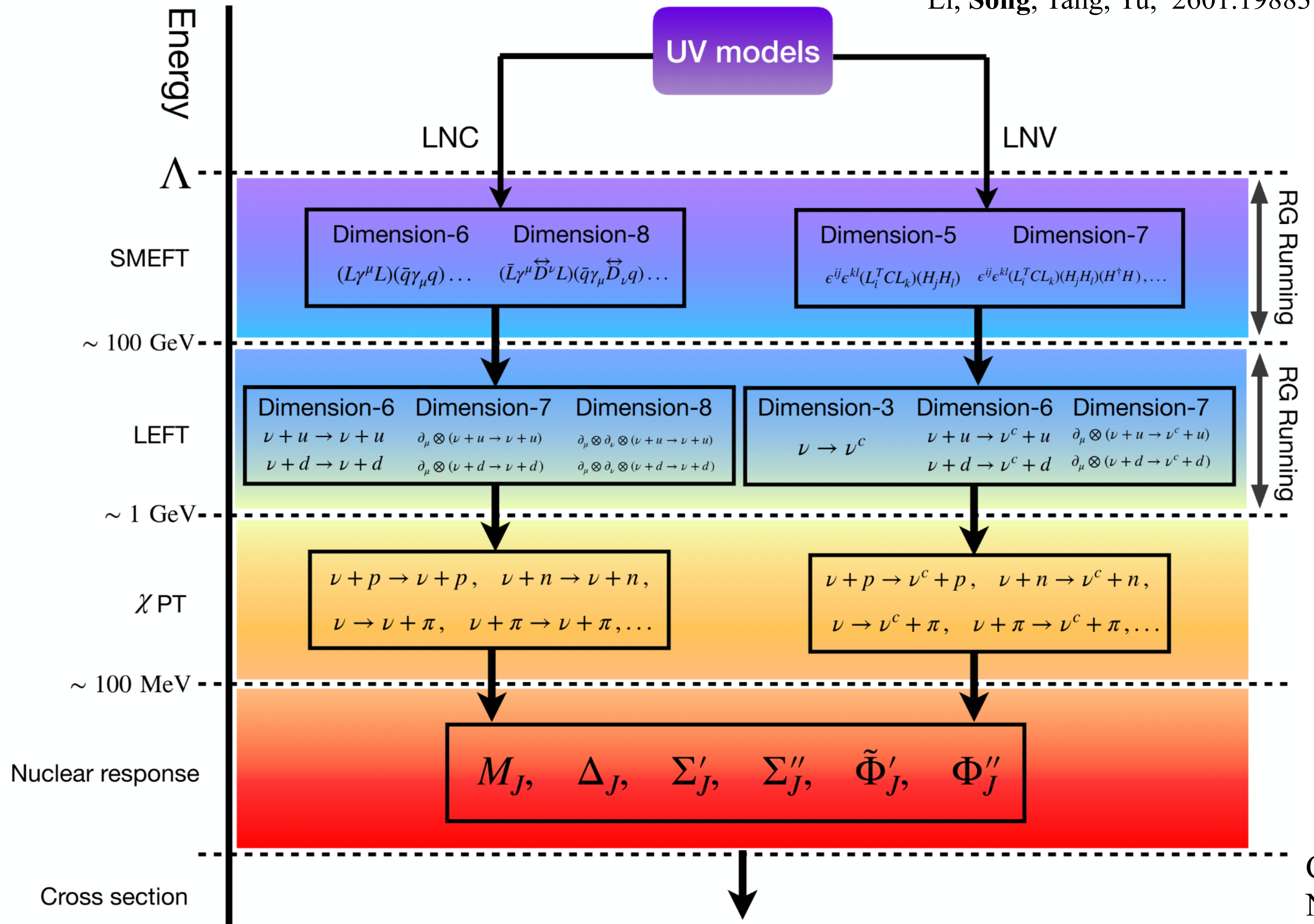
$$\Sigma_L \otimes \Sigma_L\,, \quad \Sigma_R \otimes \Sigma_R\,, \quad \Sigma_L \otimes \Sigma_R\,,$$
$$\Sigma \otimes \Sigma\,, \quad \Sigma^\dagger \otimes \Sigma^\dagger\,, \quad \Sigma \otimes \Sigma^\dagger\,,$$
$$\Sigma_L \otimes \Sigma\,, \quad \Sigma_L \otimes \Sigma^\dagger\,, \quad \Sigma_R \otimes \Sigma\,, \quad \Sigma_R \otimes \Sigma^\dagger\,.$$

Equivalence

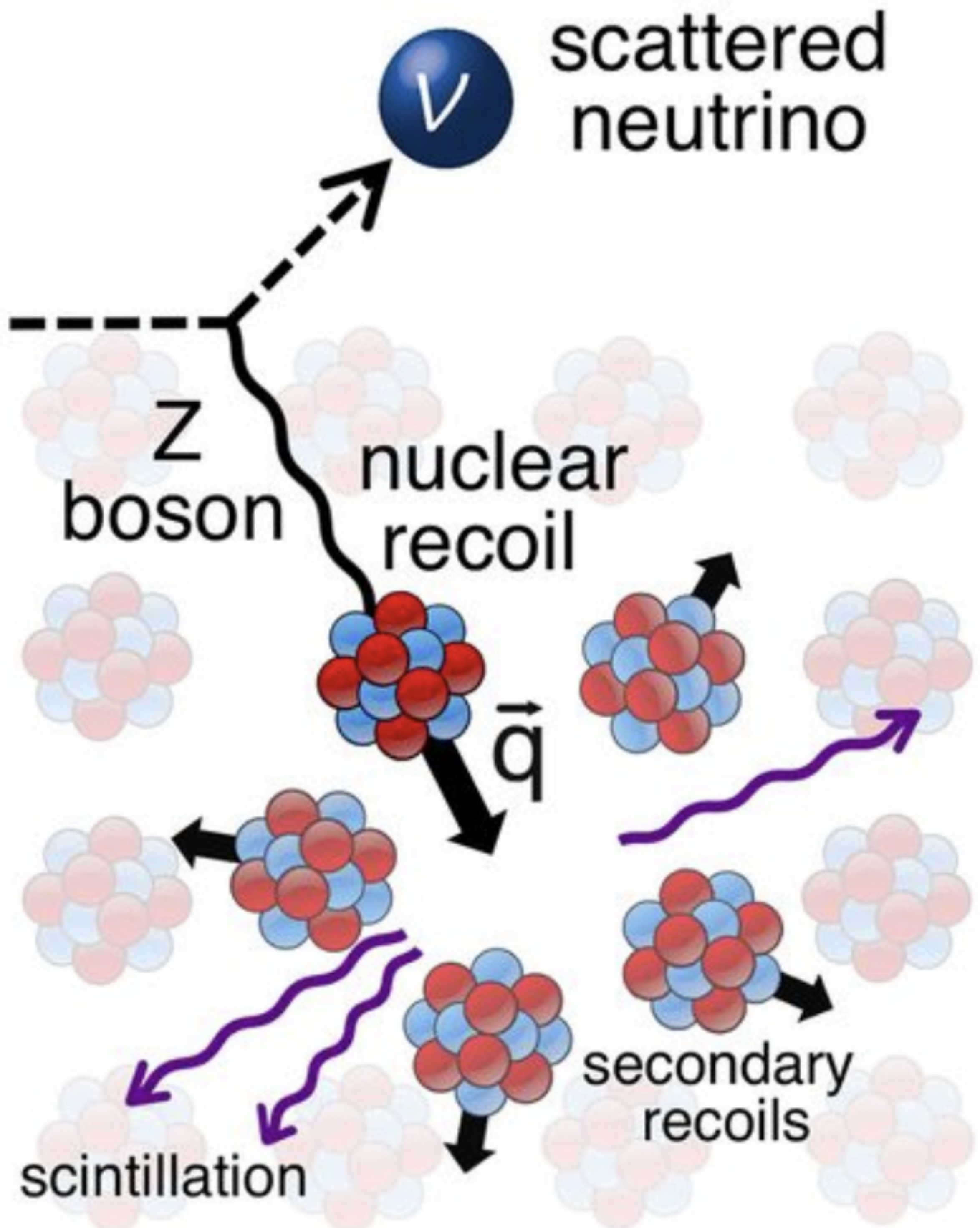
Li, **Song**, Yu, 2507.02538 (JHEP)

New Physics Applications

Li, **Song**, Tang, Yu, 2601.19883 (PRD accepted)



$$\frac{d\sigma}{dT_{\rm nr}} = \frac{m_A}{8\pi E_\nu^2}\left|\overline{\mathcal{M}}\right|^2$$



D.Z Freedman, "Coherent Neutrino Nucleus Scattering as a Probe of the Weak Neutral Current", Phys.Rev.D 9(1974) 1389-1392

COHERENT Collaboration, "Observation of Coherent Elastic Neutrino-Nuclues Scattering", Science 357 (2017) 6356, 1123-1126

New Physics Applications

Coherent elastic neutrino-nucleus scattering

$\Delta L = 0$:

$$
\begin{aligned}
O_1^{6u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma_\mu \tau^{u/d} q)\,, & O_2^{6u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\gamma_\mu \tau^{u/d} q)\,,\\
O_1^{7u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\overleftrightarrow{D}_\mu \tau^{u/d} q)\,, & O_2^{7u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\overleftrightarrow{D}_\mu \tau^{u/d} q)\,,\\
O_1^{8u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \overleftrightarrow{D}^\nu \nu_{L\beta})(\bar{q}\gamma_\mu \overleftrightarrow{D}_\nu \tau^{u/d} q)\,, & O_2^{8u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \overleftrightarrow{D}^\nu \nu_{L\beta})(\bar{q}\gamma^5\gamma_\mu \overleftrightarrow{D}_\nu \tau^{u/d} q)\,,\\
O_3^{8u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^\nu T^A \tau^{u/d} q)G^A_{\mu\nu}\,, & O_4^{8u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\gamma^\nu T^A \tau^{u/d} q)G^A_{\mu\nu}\,,\\
O_5^{8u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})D^2(\bar{q}\gamma_\mu \tau^{u/d} q)\,, & O_6^{8u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})D^2(\bar{q}\gamma^5\gamma_\mu \tau^{u/d} q)\,,\\
O_7^{8u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^\nu T^A \tau^{u/d} q)\tilde{G}^A_{\mu\nu}\,, & O_8^{8u/d} &= (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{q}\gamma^5\gamma^\nu T^A \tau^{u/d} q)\tilde{G}^A_{\mu\nu}\,,\\
O_9^{8} &= (\bar{\nu}_{L\alpha}\gamma^\mu \overleftrightarrow{D}^\nu \nu_{L\beta})G^A_{\mu\rho}G^{A\rho}_{\nu}\,.
\end{aligned}
$$

$\Delta L = 2$:

$$
\begin{aligned}
O_1^5 &= \frac{e}{8\pi^2}(\nu^T_{L\alpha} C\sigma^{\mu\nu}\nu_{L\beta})F_{\mu\nu}\,, & O_3^{7u/d} &= m_q(\nu^T_{L\alpha} C\sigma^{\mu\nu}\nu_{L\beta})(\bar{q}\sigma_{\mu\nu}\tau^{u/d} q)\,,\\
O_4^{7u/d} &= m_q(\nu^T_{L\alpha} C\nu_{L\beta})(\bar{q}\tau^{u/d} q)\,, & O_5^{7u/d} &= m_q(\nu^T_{L\alpha} C\nu_{L\beta})(\bar{q}\gamma^5\tau^{u/d} q)\,,\\
O_6^7 &= \frac{\alpha_s}{\pi}(\nu^T_{L\alpha} C\nu_{L\beta})G^A_{\mu\nu}G^{A\mu\nu}\,, & O_7^7 &= \frac{\alpha_s}{\pi}(\nu^T_{L\alpha} C\nu_{L\beta})\tilde{G}^A_{\mu\nu}G^{A\mu\nu}\,,
\end{aligned}
$$

where spurious are defined

$$\Sigma_L = \Sigma_R = \Sigma = \Sigma^\dagger = \tau^{u/d}\ .$$

QCD RGE

$$
\begin{aligned}
\frac{d}{d\ln\mu}\hat{C}_3^{7u/d} &= 2C_F\frac{\alpha_s}{4\pi}\hat{C}_3^{7u/d}\,,\\
\frac{d}{d\ln\mu}\hat{C}_{4,5}^{7u/d} &= -6C_F\frac{\alpha_s}{4\pi}\hat{C}_{4,5}^{7u/d}\,,\\
\frac{d}{d\ln\mu}\hat{C}_{1,2}^{7u/d} &= 2C_F\frac{\alpha_s}{4\pi}\hat{C}_{1,2}^{7u/d}\,,
\end{aligned}
$$

$$\frac{d}{d\ln\mu}\begin{pmatrix}\hat{C}_{1,2}^{8u/d}\\ \hat{C}_{5,6}^{8u/d}\end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix}-\frac{8}{3}C_F & 0\\ \frac{4}{3}C_F & 0\end{pmatrix}\begin{pmatrix}\hat{C}_{1,2}^{8u/d}\\ \hat{C}_{5,6}^{8u/d}\end{pmatrix},$$

New Physics Applications

Coherent elastic neutrino-nucleus scattering

$$
\begin{aligned}
\mathcal{L}_\pi \;=\; & \frac{f^2}{2}\hat{\mathcal{C}}_{1,2}^{6u/d}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\langle Q_\mp u_\mu\rangle + \frac{f^2 B_0 m_q}{2}\hat{\mathcal{C}}_{4,5}^{7u/d}(\nu_{L\alpha}^T C\nu_{L\beta})\langle\Sigma_\pm\rangle \\
& +\hat{\mathcal{C}}_3^{7u/d} m_q \Lambda_2(\nu_{L\alpha}^T C\sigma^{\mu\nu}\nu_{L\beta})\langle\Sigma_+[u_\mu,u_\nu]\rangle \\
& +\hat{\mathcal{C}}_{1,2}^{7u/d}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\Big\{g_1^\pi\langle\Sigma_\pm[\nabla^\nu u_\mu,u_\nu]\rangle + g_2^\pi\langle\nabla^\nu\Sigma_\pm[u_\mu,u_\nu]\rangle \\
& \qquad +g_3^\pi\langle\Sigma_\pm[u_\mu,\chi_-]\rangle + g_4^\pi\langle\Sigma_\mp[u_\mu,\chi_+]\rangle + g_5^\pi\varepsilon_{\mu\nu\rho\lambda}\langle u^\nu u^\rho\nabla^\lambda\Sigma_\mp\rangle\Big\} \\
& +\hat{\mathcal{C}}_6^{7}(\nu_{L\alpha}^T C\nu_{L\beta})\Big\{a_1\frac{f^2}{4}\langle u_\mu u^\mu\rangle + a_2\frac{f^2}{4}\langle\chi_+\rangle\Big\} \\
& +\hat{\mathcal{C}}_{1,2}^{8u/d} g_6^\pi(\bar{\nu}_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})\langle Q_\pm\chi_+\rangle\langle u_\mu u_\nu\rangle \\
& +\hat{\mathcal{C}}_{3,4}^{8u/d} g_7^\pi(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\langle u_\mu[Q_\mp,\chi_+]\rangle \\
& +\hat{\mathcal{C}}_9^{8} g_8^\pi(\bar{\nu}_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})\langle u_\mu u_\nu\rangle + \ldots,
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\pi N} \;=\; & \hat{\mathcal{C}}_1^{6u/d}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\Big\{(\bar{N}\gamma_\mu Q_+ N) + (\bar{N}\gamma_\mu N)\langle Q_+\rangle + \frac{L_1}{m_N}\partial^\nu(\bar{N}\sigma_{\mu\nu}Q_+ N) \\
& \quad +\frac{L_2}{m_N}\partial^\nu(\bar{N}\sigma_{\mu\nu}N)\langle Q_+\rangle\Big\} + \hat{\mathcal{C}}_2^{6u/d}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\Big\{L_3(\bar{N}\gamma^5\gamma_\mu Q_+ N) + L_4(\bar{N}\gamma^5\gamma_\mu N)\langle Q_+\rangle\Big\} \\
& +\hat{\mathcal{C}}_3^{7u/d}(\nu_{L\alpha}^T C\sigma^{\mu\nu}\nu_{L\beta})\Big\{L_5(\bar{N}\sigma_{\mu\nu}\Sigma_+ N) + L_6(\bar{N}\sigma_{\mu\nu}N)\langle\Sigma_+\rangle + \frac{L_7}{m_N}\partial_\nu(\bar{N}\gamma_\mu\Sigma_+ N) \\
& \quad +\frac{L_8}{m_N}\partial_\nu(\bar{N}\gamma_\mu N)\langle\Sigma_+\rangle\Big\} + \hat{\mathcal{C}}_4^{7u/d}(\nu_{L\alpha}^T C\nu_{L\beta})\Big\{L_9(\bar{N}\Sigma_+ N) + L_{10}(\bar{N}N)\langle\Sigma_+\rangle\Big\} \\
& +\hat{\mathcal{C}}_5^{7u/d}(\nu_{L\alpha}^T C\nu_{L\beta})\Big\{L_{11}(\bar{N}\gamma^5\Sigma_+ N) + L_{12}(\bar{N}\gamma^5 N)\langle\Sigma_+\rangle\Big\} \\
& +\hat{\mathcal{C}}_6^{7} L_{13}(\nu_{L\alpha}^T C\nu_{L\beta})(\bar{N}N) + \hat{\mathcal{C}}_7^{7} L_{14}(\nu_{L\alpha}^T C\nu_{L\beta})(\bar{N}\gamma^5 N) \\
& +\hat{\mathcal{C}}_1^{7u/d}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\Big\{g_1(\bar{N}\gamma_\mu\Sigma_+ N) + g_2(\bar{N}\gamma_\mu N)\langle\Sigma_+\rangle\Big\} \\
& +\hat{\mathcal{C}}_2^{7u/d}(\bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})\Big\{\frac{g_3}{m_N}\partial^\nu(\bar{N}i\gamma^5\sigma_{\mu\nu}\Sigma_+ N) + \frac{g_4}{m_N}\partial^\nu(\bar{N}i\gamma^5\sigma_{\mu\nu}N)\langle\Sigma_+\rangle\Big\} \\
& +\hat{\mathcal{C}}_1^{8u/d}(\bar{\nu}_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})\Big\{g_5(\bar{N}\gamma_\mu\overleftrightarrow{\partial}_\nu Q_+ N) + g_6(\bar{N}\gamma^\mu\overleftrightarrow{\partial}_\nu N)\langle Q_+\rangle\Big\} \\
& +\hat{\mathcal{C}}_2^{8u/d}(\bar{\nu}_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})\Big\{g_7(\bar{N}\gamma^5\gamma_\mu\overleftrightarrow{\partial}_\nu Q_+ N) + g_8(\bar{N}\gamma^5\gamma_\mu\overleftrightarrow{\partial}_\nu N)\langle Q_+\rangle\Big\} \\
& +\hat{\mathcal{C}}_9^{8} g_9(\bar{\nu}_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})(\bar{N}\gamma_\mu\overleftrightarrow{\partial}_\nu N) + \ldots,
\end{aligned}
$$

New Physics Applications

Coherent elastic neutrino-nucleus scattering

LEC	value	LEC	value
f	92.21(14) MeV	g_A	1.2754(13)
$B_0 m_u$	6200(400) MeV^2	$B_0 m_d$	13300(400) MeV^2
L_1	1.855(14)	L_2	−1.017(15)
L_3	0.6377(7)	L_4	−0.220(10)
L_5	1.38(17) MeV	L_6	−0.49(8) MeV
L_7	−6.76(37) MeV	L_8	2.65(18) MeV
L_9	11.52(25) MeV	L_{10}	24.05(48) MeV
L_{11}	−17.7(20) MeV	L_{12}	−13.9(15) MeV
L_{13}	−50.4(6) MeV	L_{14}	−0.306(28) GeV
g_1^π	$\mathcal{O}(\Lambda_\chi)$	g_2^π	$\mathcal{O}(\Lambda_\chi)$
g_3^π	$\mathcal{O}(\Lambda_\chi)$	g_4^π	$\mathcal{O}(\Lambda_\chi)$
g_5^π	$\mathcal{O}(\Lambda_\chi)$	g_6^π	$\mathcal{O}(1)$
g_7^π	$\mathcal{O}(\Lambda_\chi^2)$	g_8^π	$\mathcal{O}(\Lambda_\chi^2)$
g_1	$\mathcal{O}(\Lambda_\chi)$	g_2	$\mathcal{O}(\Lambda_\chi)$
g_3	$\mathcal{O}(\Lambda_\chi)$	g_4	$\mathcal{O}(\Lambda_\chi)$
g_5	$\mathcal{O}(1)$	g_6	$\mathcal{O}(1)$
g_7	$\mathcal{O}(1)$	g_8	$\mathcal{O}(1)$
g_9	$\mathcal{O}(1)$		

$$2L_1 + 2L_2 = 2(\mu_p - 1) + \mu_n = 1.676(29)\,,$$

$$2L_2 = 2\mu_n + (\mu_p - 1) = -2.034(29)\,,$$

$$2L_3 = g_A = 1.2754(13)\,, \quad 2L_3 + 4L_4 = \Sigma_{ud} = 0.397(40)\,,$$

$$2(L_5 + L_6) = m_u \hat{F}^{u/p}_{T,0} = 1.79(30)\ \text{MeV}\,,$$

$$2L_6 = m_d \hat{F}^{d/p}_{T,0} = -0.97(15)\ \text{MeV}\,,$$

$$2(L_5 + L_6 + L_7 + L_8) = m_u \hat{F}^{u/p}_{T,1} = -6.44(54)\ \text{MeV}\,,$$

$$2(L_6 + L_8) = m_d \hat{F}^{d/p}_{T,1} = 4.32(32)\ \text{MeV}\,.$$

$$L_{10} = B_0 c_1 (m_d + m_u) = 24.05(48)\ \text{MeV}\,,$$

$$L_9 - \frac{1}{2} L_{10} = B_0 c_5 (m_d - m_u) = -0.51(8)\ \text{MeV}\,.$$

$$L_{11} = m_N B_0 d_{18} (m_d + m_u) = -17.7(20)\ \text{MeV}\,,$$

$$L_{12} = m_N B_0 d_{19} (m_d + m_u) = -13.9(15)\ \text{MeV}\,,$$

$$L_{13} = F^N_G = -50.4(6)\ \text{MeV}\,, \quad L_{14} = F^N_{\tilde{G}} = -0.306(28)\ \text{GeV}\,.$$

New Physics Applications

Interactions of Neutrinos with Non-relativistic Nucleons

$$\mathcal{O}_{1,p} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta}) v_\mu (\bar{p}_v p_v)\,, \qquad \mathcal{O}_{2,p} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{p}_v S_\mu p_v)\,,$$

$$\mathcal{O}_{3,p} = (\nu^T_{L\alpha} C \nu_{L\beta})(\bar{p}_v p_v)\,, \qquad \mathcal{O}_{4,p} = (\nu^T_{L\alpha} C \sigma^{\mu\nu} \nu_{L\beta}) v_\nu (\bar{p}_v S_\mu p_v)\,,$$

$$\mathcal{O}_{5,p} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta})(\bar{p}_v \frac{K^\mu}{2m_N} p_v)\,, \qquad \mathcal{O}_{6,p} = \varepsilon_{\mu\nu\rho\lambda}(\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta}) v^\rho (\bar{p}_v \frac{q^\nu S^\lambda}{m_N} p_v)\,,$$

$$\mathcal{O}_{7,p} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta}) v_\mu (\bar{p}_v \frac{K_\nu S^\nu}{2m_N} p_v)\,, \qquad \mathcal{O}_{8,p} = \varepsilon_{\mu\rho\lambda\sigma}(\nu^T_{L\alpha} C \sigma^{\mu\nu} \nu_{L\beta}) v_\nu v_\sigma (\bar{p}_v \frac{K^\rho S^\lambda}{m_N} p_v)\,,$$

$$\mathcal{O}_{9,p} = (\nu^T_{L\alpha} C \sigma^{\mu\nu} \nu_{L\beta}) v_\nu (\bar{p}_v \frac{q_\mu}{m_N} p_v)\,, \qquad \mathcal{O}_{10,p} = (\nu^T_{L\alpha} C \nu_{L\beta})(\bar{p}_v \frac{S^\mu q_\mu}{m_N} p_v)\,,$$

$$\mathcal{O}_{11,p} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta}) v_\mu (\bar{p}_v \frac{q^\nu S_\nu}{m_N} p_v)\,, \qquad \mathcal{O}_{12,p} = \varepsilon_{\mu\nu\rho\lambda}(\nu^T_{L\alpha} C \nu_{L\beta}) \frac{P^\mu q^\nu}{m_N^2} v^\rho (\bar{p}_v S^\lambda p_v)\,,$$

$$\mathcal{O}_{13,p} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta}) P^\nu v_\mu v_\nu (\bar{p}_v p_v)\,, \qquad \mathcal{O}_{14,p} = (\bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta}) P^\nu v_\nu (\bar{p}_v S_\mu p_v)\,.$$

Spin-averaged squared amplitude

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

New Physics Applications

	LEFT operator	Response function	Overall scaling
$\mathcal{O}_1^{6u/d}$	$(\bar\nu_{L\alpha}\gamma^\mu\nu_{L\beta})(\bar q\gamma_\mu\tau^{u/d}q)$	W_{MM}	A
		$W_{\Sigma'\Sigma'}$	1
		$W_{\Delta\Delta}$	$\varepsilon\cdot 1$
		$W_{\Delta\Sigma'}$	$\varepsilon\cdot 1$
$\mathcal{O}_2^{6u/d}$	$(\bar\nu_{L\alpha}\gamma^\mu\nu_{L\beta})(\bar q\gamma^5\gamma_\mu\tau^{u/d}q)$	$W_{\Sigma'\Sigma'}$	1
$\mathcal{O}_1^{7u/d}$	$(\bar\nu_{L\alpha}\gamma^\mu\nu_{L\beta})(\bar q\overleftrightarrow{\partial}_\mu\tau^{u/d}q)$	W_{MM}	A
$\mathcal{O}_2^{7u/d}$	$(\bar\nu_{L\alpha}\gamma^\mu\nu_{L\beta})(\bar q\gamma^5\overleftrightarrow{\partial}_\mu\tau^{u/d}q)$	$W_{\Sigma''\Sigma''}$	$\varepsilon\cdot 1$
$\mathcal{O}_3^{7u/d}$	$m_q(\nu_{L\alpha}^T C\sigma^{\mu\nu}\nu_{L\beta})(\bar q\sigma_{\mu\nu}\tau^{u/d}q)$	W_{MM}	$\varepsilon^3\cdot A$
		$W_{\Sigma'\Sigma'}, W_{\Sigma''\Sigma''}$	$\varepsilon^2\cdot 1$
		$W_{\Phi''\Phi''}$	$\varepsilon^3\cdot A$
		$W_{\tilde\Phi'\tilde\Phi'}$	$\varepsilon^3\cdot 1$
		$W_{\Phi''M}$	$\varepsilon^3\cdot A$
$\mathcal{O}_4^{7u/d}$	$m_q(\nu_{L\alpha}^T C\nu_{L\beta})(\bar q\tau^{u/d}q)$	W_{MM}	$\varepsilon^2\cdot A$
$\mathcal{O}_5^{7u/d}$	$m_q(\nu_{L\alpha}^T C\nu_{L\beta})(\bar q\gamma^5\tau^{u/d}q)$	$W_{\Sigma''\Sigma''}$	$\varepsilon^3\cdot 1$
$\mathcal{O}_6^7$	$(\nu_{L\alpha}^T C\nu_{L\beta})G^A_{\mu\nu}G^{A\mu\nu}$	W_{MM}	$\varepsilon^2\cdot A$
$\mathcal{O}_7^7$	$(\nu_{L\alpha}^T C\nu_{L\beta})\tilde G^A_{\mu\nu}G^{A\mu\nu}$	$W_{\Sigma''\Sigma''}$	$\varepsilon^3\cdot 1$
$\mathcal{O}_1^{8u/d}$	$(\bar\nu_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})(\bar q\gamma_\mu\overleftrightarrow{\partial}_\nu\tau^{u/d}q)$	W_{MM}	A
$\mathcal{O}_2^{8u/d}$	$(\bar\nu_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})(\bar q\gamma^5\gamma_\mu\overleftrightarrow{\partial}_\nu\tau^{u/d}q)$	$W_{\Sigma'\Sigma'}$	1
$\mathcal{O}_9^8$	$(\bar\nu_{L\alpha}\gamma^\mu\overleftrightarrow{\partial}^\nu\nu_{L\beta})G^A_{\mu\rho}G^{A\rho}_\nu$	W_{MM}	A

The hierarchy of nuclear responses

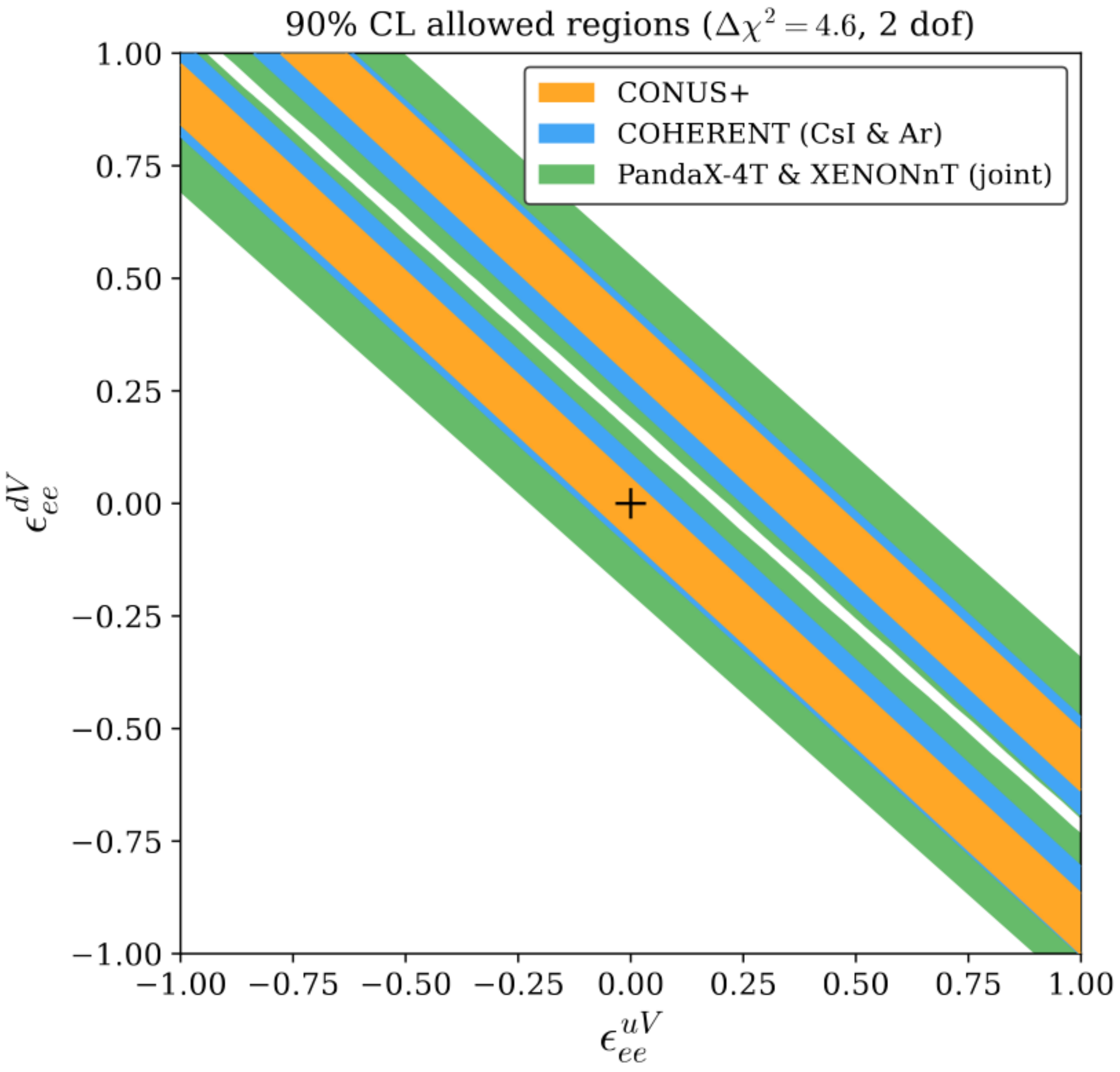
$$W_{MM}\gg\frac{q}{m_N}W_{\Phi''M}\gg\left\{W_{\Sigma'\Sigma'},\,W_{\Sigma''\Sigma''},\,\frac{q^2}{m_N^2}W_{MM},\,\frac{q^2}{m_N^2}W_{\Phi''\Phi''}\right\}$$
$$\gg\left\{\frac{q}{m_N}W_{\Delta\Sigma'},\,\frac{q^2}{m_N^2}W_{\Delta\Delta},\,\frac{q^2}{m_N^2}W_{\tilde\Phi'\tilde\Phi'}\right\}.$$

Differential event rate per target nucleus

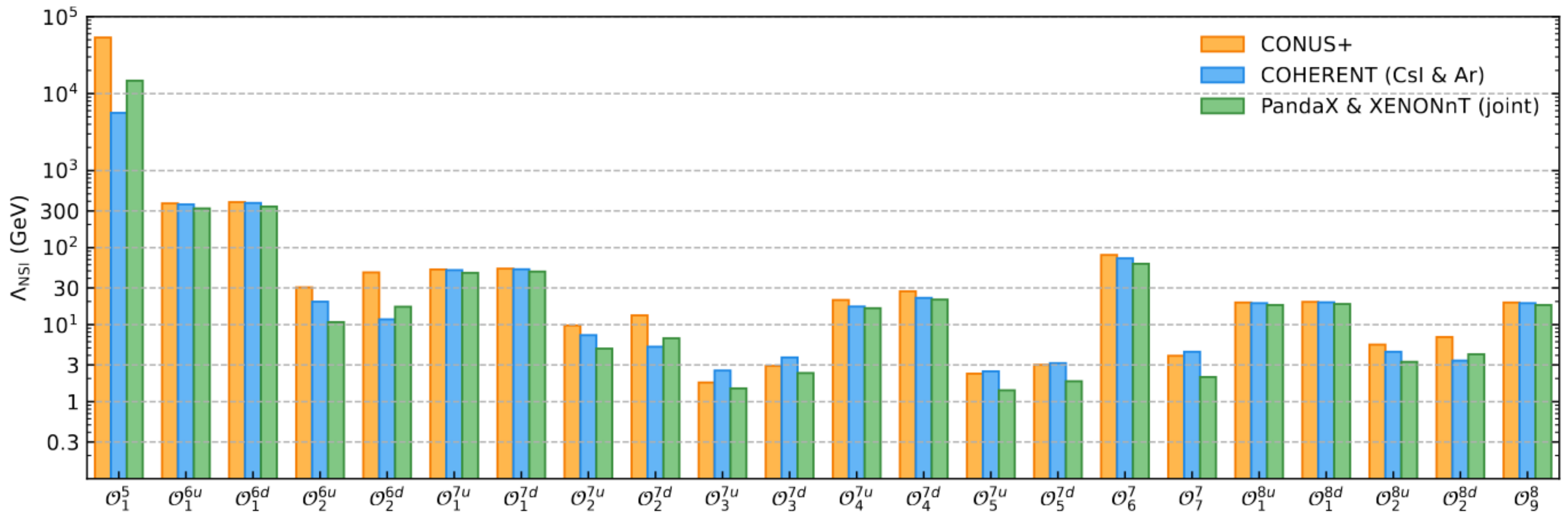
$$\frac{\mathrm{d}R_{\nu_\alpha}}{\mathrm{d}T_{\rm nr}}=\int_{E_{\nu,\min}(T_{\rm nr})}^{E_{\nu,\max}}\mathrm{d}E_\nu\,\Phi_{\nu_\alpha}(E_\nu)\,\frac{\mathrm{d}\sigma}{\mathrm{d}T_{\rm nr}}(E_\nu,T_{\rm nr})\,,$$

New Physics Applications

NSI analysis at the 90% confidence level



Lower limits on the energy scale corresponding to the Wilson coefficients of LEFT at the 90% confidence level



New Physics Applications

SMEFT Operators

Dimension-6	
O_H	$(H^\dagger H)^3$
O_{HW}	$H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$
O_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$
O_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
O_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D^\mu H)$
$O^{(1)}_{H\ell}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu \ell)$
$O^{(3)}_{H\ell}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{\ell}\tau^I\gamma^\mu \ell)$
$O^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$
$O^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$
O_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$
O_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$
O_{uB}	$(\bar{Q}\sigma^{\mu\nu} u_R)\tilde{H} B_{\mu\nu}$
O_{uW}	$(\bar{Q}\sigma^{\mu\nu} u_R)\tau^I \tilde{H} W^I_{\mu\nu}$
O_{dB}	$(\bar{Q}\sigma^{\mu\nu} d_R) H B_{\mu\nu}$
O_{dW}	$(\bar{Q}\sigma^{\mu\nu} d_R)\tau^I H W^I_{\mu\nu}$
$O^{(1)}_{\ell q}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{Q}\gamma_\mu Q)$
$O^{(3)}_{\ell q}$	$(\bar{\ell}\gamma^\mu \tau^I \ell)(\bar{Q}\gamma_\mu \tau^I Q)$
$O_{\ell u}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{u}_R\gamma_\mu u_R)$
$O_{\ell d}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{d}_R\gamma_\mu d_R)$

Dimension-5	
O_5	$\epsilon^{ik}\epsilon^{jl}(\ell_i^T C \ell_j) H_k H_l$

Dimension-7	
O_{QuLLH}	$\epsilon^{ij}(\overline{Q}^k u_R)(\ell_k^T C \ell_i) H_j$
O_{dLQLH1}	$\epsilon^{ij}\epsilon^{kl}(\overline{d}_R \ell_i)(Q_j^T C \ell_k) H_l$
O_{dLQLH2}	$\epsilon^{ik}\epsilon^{jl}(\overline{d}_R \ell_i)(Q_j^T C \ell_k) H_l$

Dimension-8	
$O_{l^2G^2D}$	$(\bar{\ell}\gamma^\mu i \overleftrightarrow{D}^\nu \ell) G^A_{\mu\rho} G^{A\rho}_\nu$
$O^{(1)}_{l^2q^2G}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{Q}\gamma^\nu T^A Q) G^A_{\mu\nu}$
$O^{(2)}_{l^2q^2G}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{Q}\gamma^\nu T^A Q) \widetilde{G}^A_{\mu\nu}$
$O^{(3)}_{l^2q^2G}$	$(\bar{\ell}\gamma^\mu \tau^I \ell)(\bar{Q}\gamma^\nu T^A \tau^I Q) G^A_{\mu\nu}$
$O^{(4)}_{l^2q^2G}$	$(\bar{\ell}\gamma^\mu \tau^I \ell)(\bar{Q}\gamma^\nu T^A \tau^I Q) \widetilde{G}^A_{\mu\nu}$
$O^{(1)}_{l^2u^2G}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{u}_R\gamma^\nu T^A u_R) G^A_{\mu\nu}$
$O^{(2)}_{l^2u^2G}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{u}_R\gamma^\nu T^A u_R) \widetilde{G}^A_{\mu\nu}$
$O^{(1)}_{l^2d^2G}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{d}_R\gamma^\nu T^A d_R) G^A_{\mu\nu}$
$O^{(2)}_{l^2d^2G}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{d}_R\gamma^\nu T^A d_R) \widetilde{G}^A_{\mu\nu}$
$O^{(2)}_{l^2q^2D^2}$	$(\bar{\ell}\gamma^\mu \overleftrightarrow{D}^\nu \ell)(\bar{Q}\gamma_\mu \overleftrightarrow{D}_\nu Q)$
$O^{(4)}_{l^2q^2D^2}$	$(\bar{\ell}\gamma^\mu \overleftrightarrow{D}^{I\nu} \ell)(\bar{Q}\gamma_\mu \overleftrightarrow{D}^I_\nu Q)$
$O^{(2)}_{l^2u^2D^2}$	$(\bar{\ell}\gamma^\mu \overleftrightarrow{D}^\nu \ell)(\bar{u}_R\gamma_\mu \overleftrightarrow{D}_\nu u_R)$
$O^{(2)}_{l^2d^2D^2}$	$(\bar{\ell}\gamma^\mu \overleftrightarrow{D}^\nu \ell)(\bar{d}_R\gamma_\mu \overleftrightarrow{D}_\nu d_R)$

UV Completion

Dim-6

$\mathcal{O}_H$	$S_1(\mathbf{1},\mathbf{1})_0, S_4(\mathbf{1},\mathbf{2})_{\frac{1}{2}}, S_5(\mathbf{1},\mathbf{3})_0, S_6(\mathbf{1},\mathbf{3})_1, S_7(\mathbf{1},\mathbf{4})_{\frac{1}{2}}, S_8(\mathbf{1},\mathbf{4})_{\frac{3}{2}}, V_2(\mathbf{1},\mathbf{1})_1, V_4(\mathbf{1},\mathbf{3})_0$
$\mathcal{O}_{HD}$	$S_5(\mathbf{1},\mathbf{3})_0, S_6(\mathbf{1},\mathbf{3})_1, V_1(\mathbf{1},\mathbf{1})_0, V_2(\mathbf{1},\mathbf{1})_1, V_4(\mathbf{1},\mathbf{3})_0$
$\mathcal{O}^{(1)}_{H\ell}$	$F_1(\mathbf{1},\mathbf{1})_0, F_2(\mathbf{1},\mathbf{1})_1, F_5(\mathbf{1},\mathbf{3})_0, F_6(\mathbf{1},\mathbf{3})_1, V_1(\mathbf{1},\mathbf{1})_0$
$\mathcal{O}^{(3)}_{H\ell}$	$F_1(\mathbf{1},\mathbf{1})_0, F_2(\mathbf{1},\mathbf{1})_1, F_5(\mathbf{1},\mathbf{3})_0, F_6(\mathbf{1},\mathbf{3})_1, V_4(\mathbf{1},\mathbf{3})_0$
$\mathcal{O}^{(1)}_{Hq}$	$F_8(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}, F_9(\mathbf{3},\mathbf{1})_{\frac{2}{3}}, F_{13}(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}, F_{14}(\mathbf{3},\mathbf{3})_{\frac{2}{3}}, V_1(\mathbf{1},\mathbf{1})_0$
$\mathcal{O}^{(3)}_{Hq}$	$F_8(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}, F_9(\mathbf{3},\mathbf{1})_{\frac{2}{3}}, F_{13}(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}, F_{14}(\mathbf{3},\mathbf{3})_{\frac{2}{3}}, V_4(\mathbf{1},\mathbf{3})_0$
$\mathcal{O}_{Hu}$	$F_{11}(\mathbf{3},\mathbf{2})_{\frac{1}{6}}, F_{12}(\mathbf{3},\mathbf{2})_{\frac{7}{6}}, V_1(\mathbf{1},\mathbf{1})_0$
$\mathcal{O}_{Hd}$	$F_{10}(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}, F_{11}(\mathbf{3},\mathbf{2})_{\frac{1}{6}}, V_1(\mathbf{1},\mathbf{1})_0$
$\mathcal{O}^{(1)}_{\ell q}$	$S_{10}(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}, S_{14}(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}, V_1(\mathbf{1},\mathbf{1})_0, V_5(\mathbf{3},\mathbf{1})_{\frac{2}{3}}, V_9(\mathbf{3},\mathbf{1})_{\frac{2}{3}}$
$\mathcal{O}^{(3)}_{\ell q}$	$S_{10}(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}, S_{14}(\mathbf{3},\mathbf{3})_{-\frac{1}{3}}, V_4(\mathbf{1},\mathbf{3})_0, V_5(\mathbf{3},\mathbf{1})_{\frac{2}{3}}, V_9(\mathbf{3},\mathbf{3})_{\frac{2}{3}}$
$\mathcal{O}_{\ell u}$	$S_{13}(\mathbf{3},\mathbf{2})_{\frac{7}{6}}, V_1(\mathbf{1},\mathbf{1})_0, V_8(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$
$\mathcal{O}_{\ell d}$	$S_{12}(\mathbf{3},\mathbf{2})_{\frac{1}{6}}, V_1(\mathbf{1},\mathbf{1})_0, V_7(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$

Dim-7

$\mathcal{O}_{QuLLH}$	$\{S_2(\mathbf{1},\mathbf{1})_1, S_4(\mathbf{1},\mathbf{2})_{\frac{1}{2}}\}$ $\{S_2(\mathbf{1},\mathbf{1})_1, F_8(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}\}$ $\{S_2(\mathbf{1},\mathbf{1})_1, F_{12}(\mathbf{3},\mathbf{2})_{\frac{7}{6}}\}$ $\{F_{12}(\mathbf{3},\mathbf{2})_{\frac{7}{6}}, V_5(\mathbf{3},\mathbf{1})_{\frac{2}{3}}\}$ $\{F_{12}(\mathbf{3},\mathbf{2})_{\frac{7}{6}}, V_9(\mathbf{3},\mathbf{3})_{\frac{2}{3}}\}$
$\mathcal{O}_{dLQLH1}$	$\{S_{12}(\mathbf{3},\mathbf{2})_{\frac{1}{6}}, F_{14}(\mathbf{3},\mathbf{3})_{\frac{2}{3}}\}$
$\mathcal{O}_{dLQLH2}$	$\{S_2(\mathbf{1},\mathbf{1})_1, S_4(\mathbf{1},\mathbf{2})_{\frac{1}{2}}\}$ $\{S_2(\mathbf{1},\mathbf{1})_1, F_9(\mathbf{3},\mathbf{1})_{\frac{2}{3}}\}$ $\{S_2(\mathbf{1},\mathbf{1})_1, F_{10}(\mathbf{3},\mathbf{2})_{-\frac{5}{6}}\}$ $\{S_{12}(\mathbf{3},\mathbf{2})_{\frac{1}{6}}, F_9(\mathbf{3},\mathbf{1})_{\frac{2}{3}}\}$ $\{S_{12}(\mathbf{3},\mathbf{2})_{\frac{1}{6}}, F_{14}(\mathbf{3},\mathbf{3})_{\frac{2}{3}}\}$

Dim-8

$\mathcal{O}_{\ell^2G^2D}$	$F_{18}(\mathbf{8},\mathbf{2})_{-\frac{1}{2}}, R_{18}(\mathbf{8},\mathbf{2})_{\frac{1}{2}}, T_1(\mathbf{1},\mathbf{1})_0$
$\mathcal{O}^{(2)}_{\ell^2q^2D^2}$	$T_1(\mathbf{1},\mathbf{1})_0, T_2(\mathbf{1},\mathbf{3})_0, T_3(\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}}, T_4(\bar{\mathbf{3}},\mathbf{3})_{-\frac{2}{3}}$
$\mathcal{O}^{(4)}_{\ell^2q^2D^2}$	$T_1(\mathbf{1},\mathbf{1})_0, T_2(\mathbf{1},\mathbf{3})_0, T_3(\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}}, T_4(\bar{\mathbf{3}},\mathbf{3})_{-\frac{2}{3}}$
$\mathcal{O}^{(2)}_{\ell^2u^2D^2}$	$T_1(\mathbf{1},\mathbf{1})_0, T_6(\mathbf{3},\mathbf{2})_{\frac{1}{6}}$
$\mathcal{O}^{(2)}_{\ell^2d^2D^2}$	$T_1(\mathbf{1},\mathbf{1})_0, T_7(\bar{\mathbf{3}},\mathbf{2})_{\frac{5}{6}}$

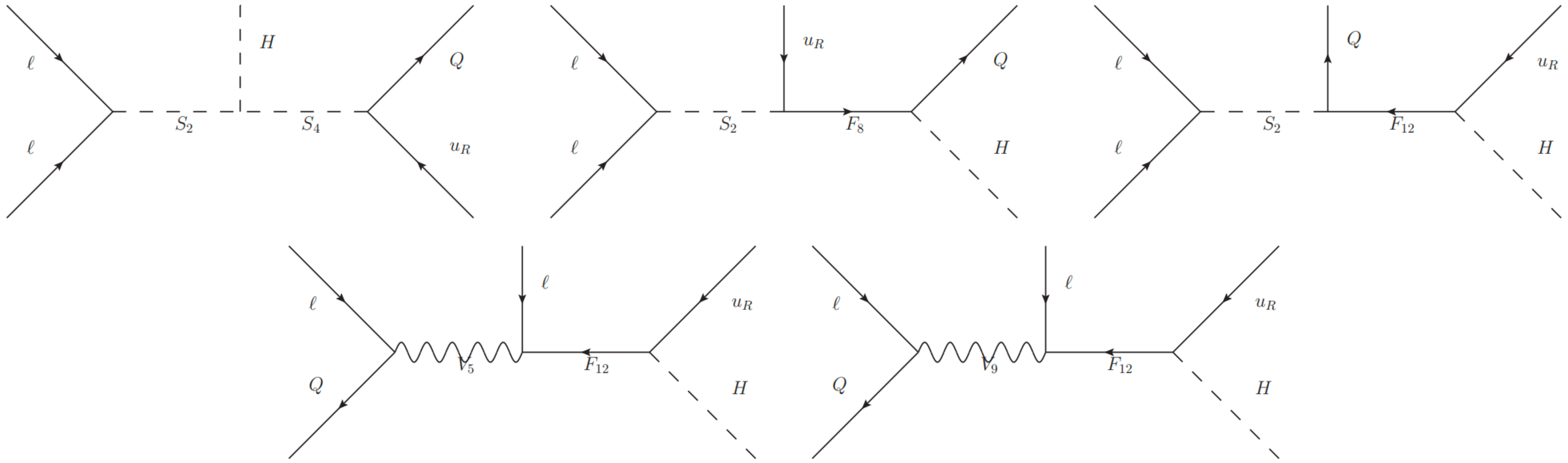
Li, Ni, Xiao, Yu, 2204.03660 (JHEP)
Li, Ren, Yu, 2307.10380 (PRD)
Li, Ni, Xiao, Yu, 2309.15933 (JHEP)

Bottom up EFT

New Physics Applications

UV completion of dimension 7 SMEFT operators

$$
\begin{aligned}
\mathcal{L}_{\rm UV} = \Big\{ & - S_2^\dagger (D^2 + M_{S_2}^2) S_2 - S_4^{\dagger i}(D^2 + M_{S_4}^2) S_{4i} - S_{12}^{\dagger ai}(D^2 + M_{S_{12}}^2) S_{12ai} \\
& + \bar{F}_8^a (i\not{D} - M_{F_8}) F_{8a} + \bar{F}_9^a (i\not{D} - M_{F_9}) F_{9a} + \bar{F}_{12}^{ai}(i\not{D} - M_{F_{12}}) F_{12ai} \\
& + \bar{F}_{14}^{aI}(i\not{D} - M_{F_{14}}) F_{14a}^I + V_5^{\dagger\mu}(g_{\mu\nu} D^2 - D_\nu D_\mu + g_{\mu\nu} M_{V_5}^2) V_5^\nu \\
& + V_9^{\dagger\mu}(g_{\mu\nu} D^2 - D_\nu D_\mu + g_{\mu\nu} M_{V_9}^2) V_9^\nu \Big\} \\
+ \Big\{ & \mathcal{D}_{S_2\ell^2} \epsilon^{ij} (\ell_i^T C \ell_j) S_2 + \mathcal{D}_{S_4 uQ} \epsilon^{ij} (\bar{u}_R Q_j) S_{4i} + \mathcal{D}_{S_4 Qd} (\bar{d}_R Q_i) S_4^{\dagger i} \\
& + \mathcal{D}_{S_{12}\ell d} \epsilon^{ij} (\bar{d}_R^a \ell_j) S_{12ai} + \mathcal{D}_{F_8 HQ} (\bar{F}_8^a Q_{ai}) H^{\dagger i} + \mathcal{D}_{F_9 HQ} \epsilon^{ij} (\bar{F}_9^a Q_{ai}) H_j \\
& + \mathcal{D}_{F_{10} Hd} \epsilon^{ij} (\bar{d}_R^a F_{10ai}) H_j + \mathcal{D}_{F_{12} Hu} (\bar{u}_R^a F_{12ai}) H^{\dagger i} + \mathcal{D}_{F_{14} HQ} \epsilon^{kj} (\tau^I)^i_k (\bar{F}_{14}^{aI} Q_{ai}) H_j \,, \\
& + \mathcal{D}_{V_5 \ell Q} (\bar{\ell} \gamma_\mu Q) V_5^{\dagger a\mu} - \sqrt{2} \mathcal{D}_{V_9 \ell Q} (\bar{\ell} \tau^I Q) V_9^{\dagger aI\mu} + \text{h.c.} \Big\} \\
+ \Big\{ & \mathcal{C}_{S_2 S_4 H} \epsilon^{ij} H_j S_{4i} S_2^\dagger + \mathcal{D}_{S_2 F_8 u} (\bar{u}_R^a F_{8a}) S_2 + \mathcal{D}_{S_2 F_9 d} (\bar{d}_R^a F_{9a}) S_2^\dagger \\
& + \mathcal{D}_{S_2 F_{10} Q} (F_{10}^{aiT} C Q_{ai}) S_2^\dagger + \mathcal{D}_{S_2 F_{12} Q} (F_{12ai}^T C Q^{ai}) S_2 + \mathcal{D}_{S_{12} F_9 \ell} (F_{9a}^T C \ell_i) S_{12}^{\dagger ai} \\
& + \mathcal{D}_{S_{12} F_{14} \ell} (\tau^I)^i_j (F_{14a}^{IT} C \ell_j) S_{12}^{\dagger ai} + \mathcal{D}_{F_{12} V_5 \ell} \epsilon_{ij} (\ell^j \gamma_\mu F_{12a}^i) (V_5)^{a\mu} \\
& + \mathcal{D}_{F_{12} V_9 \ell} \epsilon_{kj} (\tau^I)^k_i (\ell^j \gamma_\mu F_{12a}^i) V_9^{aI\mu} + \text{h.c.} \Big\} \,,
\end{aligned}
$$



$$
\frac{C_{QuLLH}}{\Lambda^3} = \frac{\mathcal{C}_{S_2 S_4 H} \mathcal{D}_{S_2 \ell^2} \mathcal{D}_{S_4 uQ}}{M_{S_2}^2 M_{S_4}^2} + \frac{\mathcal{D}_{S_2 F_8 u} \mathcal{D}_{S_2 \ell^2} \mathcal{D}_{F_8 HQ}}{M_{S_2}^2 M_{F_8}} + \frac{\mathcal{D}_{S_2 F_{12} Q} \mathcal{D}_{S_2 \ell^2} \mathcal{D}_{F_{12} Hu}}{M_{S_2}^2 M_{F_{12}}} + \frac{\mathcal{D}_{F_{12} V_5 \ell} \mathcal{D}_{V_5 \ell Q} \mathcal{D}_{F_{12} Hu}}{M_{V_5}^2 M_{F_{12}}} + \frac{\mathcal{D}_{F_{12} V_9 \ell} \mathcal{D}_{V_9 \ell Q} \mathcal{D}_{F_{12} Hu}}{M_{V_9}^2 M_{F_{12}}} \,.
$$

Summary

- We construct the full set of chiral operators via the Young tensor method.
- We propose a systematic spurion method for the matching of LEFT to ChPT, which is particularly useful for LEFT at higher dimensions and for ChPT at higher orders of p.
- We establish a complete EFT framework bridging high scales down to nuclear probes for CEvNS.

Thank you