Neutrinoless double beta decay from the RG-improved dim-7 SMEFT interactions

South China Normal University

Xiao-Dong Ma (马小东)

中微子及相关新物理研讨会（NuPhyR）
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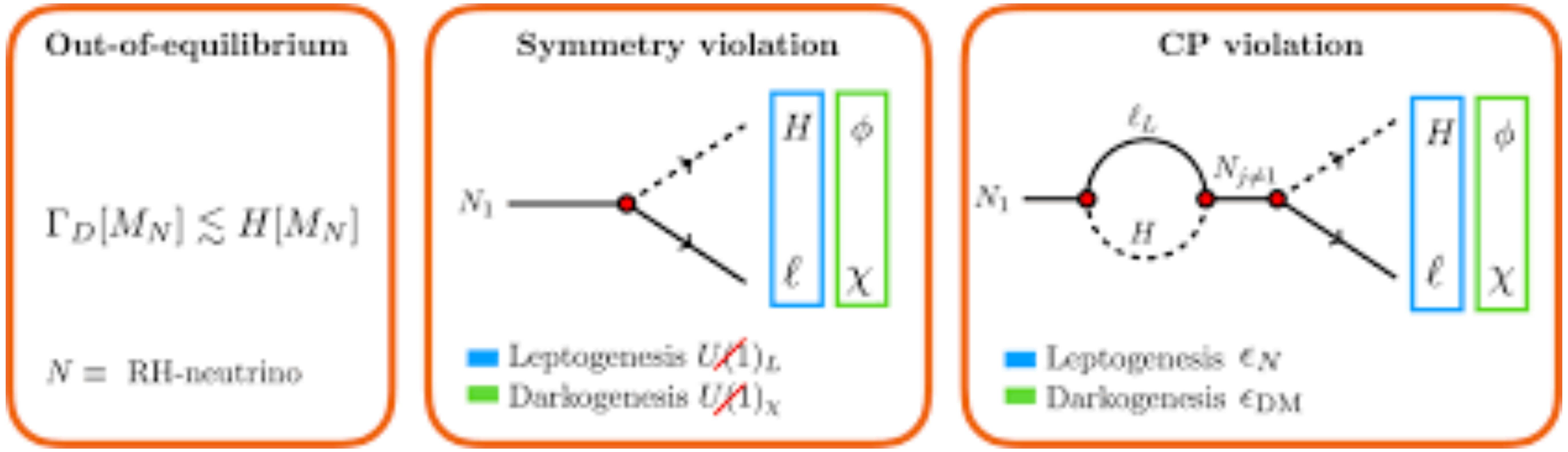
Yi Liao, Xiao-Dong Ma, Hao-Lin Wang, Xiang Zhao,
2505.06499, JHEP08(2025)138

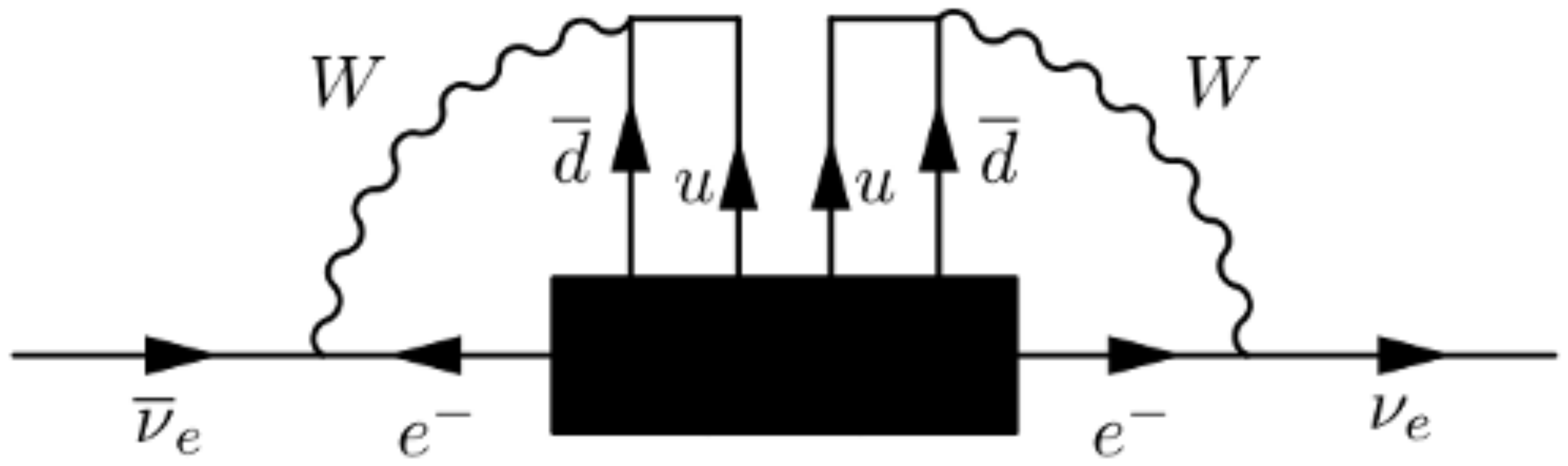
Lepton number violation

- Neutrino oscillation $\Rightarrow$ neutrino mass
- Majorana nature of neutrinos is a well-motivated picture for massive neutrinos
- Baryogenesis via leptogenesis
- Dark matter

https://neutrino.syr.edu/research/neutrino-oscillations/



https://x.com/higgsinocat/status/1375404211974893570



Black box theorem

LNV signals as a test of Majorana nature of ν

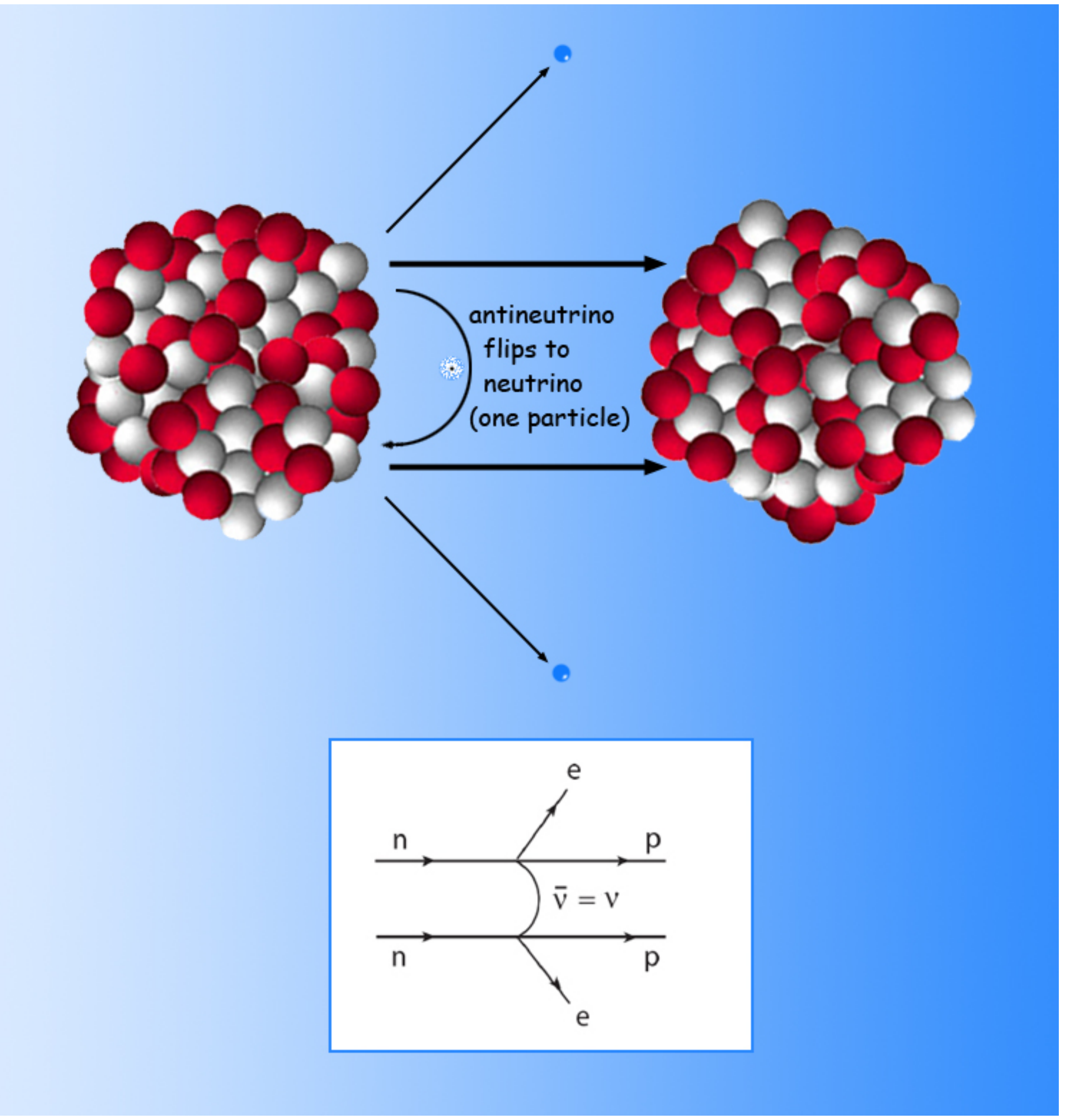
Schechter, Valle, Phys.Rev. D25 (1982) 774

Nuclear and collider test of LNV

- Neutrinoless double beta decay(0vββ)

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^{-} $$

Gerda, Majorana, LEGEND, CUPID, NEXT, CUORE, nEXO, KamLAND-ZenSNO, DARWIN, PandaX, etc



- Muon-positron conversion in nuclei

$$ \mu^{-} + {}^{A}_{Z}X \rightarrow {}^{A}_{Z-2}X + e^{+} $$

Pontecorvo, 1967 **COMET, Mu2e**

- Neutrinoless Double-Electron Capture (0v2EC)

$$ e_b^{-} + e_b^{-} + (A,Z) \rightarrow (A,Z-2)** $$

2007.14908

- Trimuon production from neutrino-neutron collision

$$ \nu_\mu N \rightarrow \mu^{-}\mu^{+}\mu^{+}X $$

Flanz, Rodejohann, Zuber, 9907203

- $e-p$ collider:

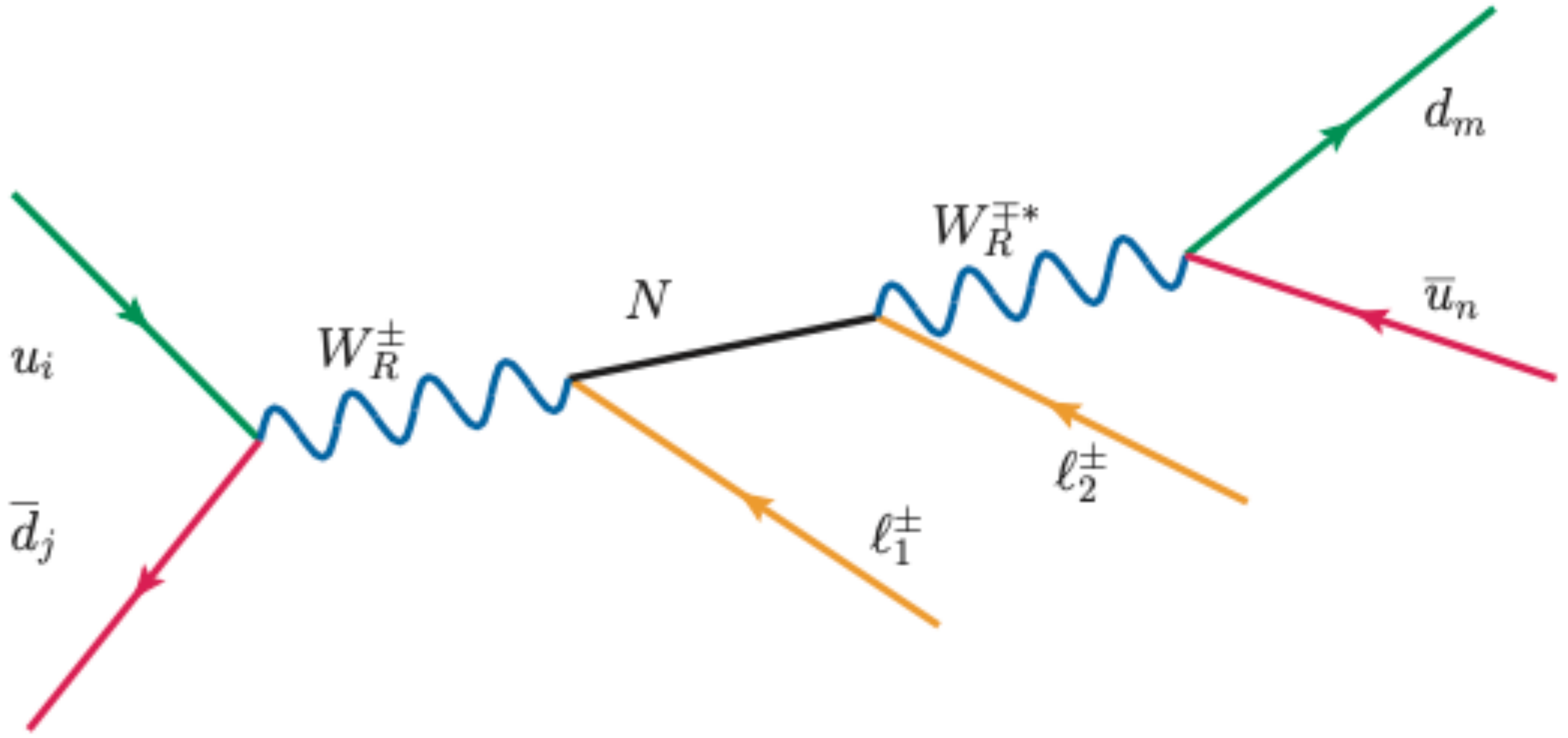
$$ e^{\pm}p \rightarrow \bar{\nu}_e(\nu_e)\ell^{\pm}\ell'^{\pm}X $$

Flanz, Rodejohann, Zuber, 9911298

- LHC search:

$$ pp \rightarrow \ell^{\pm}\ell'^{\pm} + nj + X $$

Cai, Han, Li, Ruiz, 1711.02180



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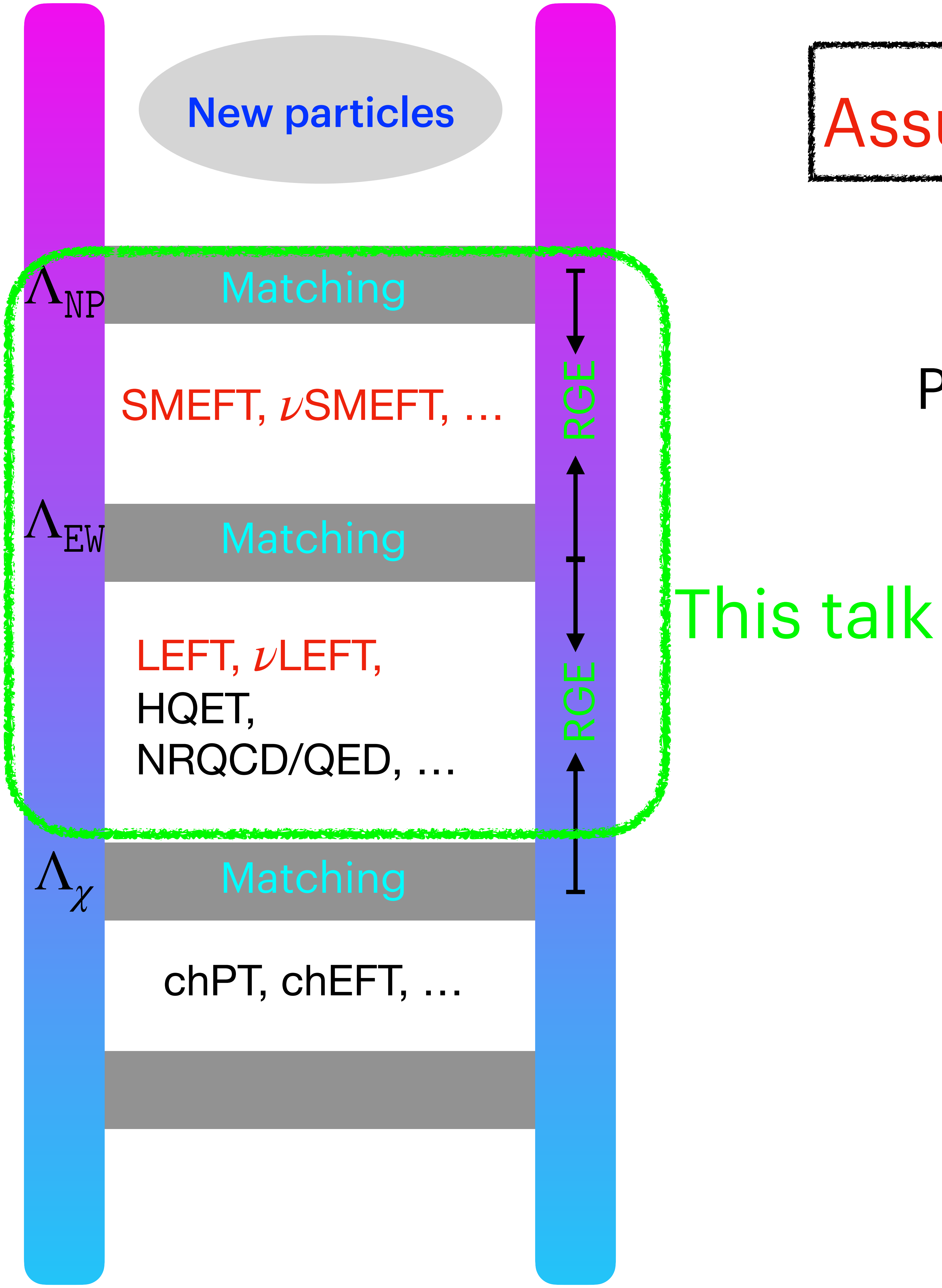
More will be covered by Michael's talk tomorrow

EFT as a powerful tool for low-energy LNV processes



Assumption: scales are well separated with $\Lambda_{\mathrm{NP}} \gg \Lambda_{\mathrm{EW}}$

Parametrize the derivation of low energy observables w.r.t. the SM prediction by non-SM interactions based on SM particles and symmetries

SMEFT-like framework

Study NP effect in low energy observables indirectly

SMEFT framework

Weinberg, 1979 | Buchmuller & Wyler, 1986 Warsaw basis, 2010 | Lehman, 2014 **Liao & Ma, 2016** | Murphy, 2020 Li et al, 2020 | Li et al, 2020 **Liao & Ma, 2020** | Harlander et al, 2023

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \boxed{\mathscr{L}_{\rm dim5}} + \boxed{\mathscr{L}_{\rm dim6}} + \boxed{\mathscr{L}_{\rm dim7}} + \boxed{\mathscr{L}_{\rm dim8}} + \boxed{\mathscr{L}_{\rm dim9}} + \boxed{\mathscr{L}_{\rm dim10-12}} \cdots$$

$$\mathscr{L}_{\rm dim5} = \frac{\hat{C}_{LH}}{\Lambda}\epsilon_{im}\epsilon_{jn}(\overline{L_i^{\rm C}}L_j)\tilde{H}_n\tilde{H}_m + {\rm h.c.},$$

Hilbert series method: *Henning, Lu, Melia, Murayama 2015, 2017*

- Matter fields: $Q, L; u, d, e; H$
- Gauge symmetry: $\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$
- $D \in$ even (odd) if $|B-L|/2$ is even (odd)
- $D = 6 : |B-L| = 0$ vs $D = 5, 7 : |B-L| = 2$
- $D \in$ odd: B/L is violated Kobach, 1604.05726

$\Delta L = 2$ processes such as $0\nu\beta\beta$ are described by odd-D operators

Operator basis @ dim 7

	$\psi^2 H^4$ + h.c.		$\psi^2 H^3 D$ + h.c.
$\mathcal{O}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(L^i C L^m)H^j H^n(H^\dagger H)$	$\mathcal{O}_{LeHD}$	$\epsilon_{ij}\epsilon_{mn}(L^i C\gamma_\mu e)H^j H^m iD^\mu H^n$
	$\psi^2 H^2 D^2$ + h.c.		$\psi^2 H^2 X$ + h.c.
$\mathcal{O}_{LHD1}$	$\epsilon_{ij}\epsilon_{mn}(L^i C D^\mu L^j)H^m(D_\mu H^n)$	$\mathcal{O}_{LHB}$	$\epsilon_{ij}\epsilon_{mn}(L^i C\sigma_{\mu\nu}L^m)H^j H^n B^{\mu\nu}$
$\mathcal{O}_{LHD2}$	$\epsilon_{im}\epsilon_{jn}(L^i C D^\mu L^j)H^m(D_\mu H^n)$	$\mathcal{O}_{LHW}$	$\epsilon_{ij}(\epsilon\tau^I)_{mn}(L^i C\sigma_{\mu\nu}L^m)H^j H^n W^{I\mu\nu}$
	$\psi^4 D$ + h.c.		$\psi^4 H$ + h.c.
$\mathcal{O}_{\bar{d}uLLD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L^i CiD^\mu L^j)$	$\mathcal{O}_{\bar{e}LLLH}$	$\epsilon_{ij}\epsilon_{mn}(\bar{e}L^i)(L^j CL^m)H^n$
$\mathcal{O}_{\bar{L}QddD}$	$(\bar{L}\gamma_\mu Q)(dCiD^\mu d)$	$\mathcal{O}_{\bar{d}LQLH1}$	$\epsilon_{ij}\epsilon_{mn}(\bar{d}L^i)(Q^j CL^m)H^n$
$\mathcal{O}_{\bar{e}dddD}$	$(\bar{e}\gamma_\mu d)(dCiD^\mu d)$	$\mathcal{O}_{\bar{d}LQLH2}$	$\epsilon_{im}\epsilon_{jn}(\bar{d}L^i)(Q^j CL^m)H^n$
		$\mathcal{O}_{\bar{d}LueH}$	$\epsilon_{ij}(\bar{d}L^i)(uCe)H^j$
		$\mathcal{O}_{\bar{Q}uLLH}$	$\epsilon_{ij}(\bar{Q}u)(LCL^i)H^j$
		$\mathcal{O}_{\bar{L}dud\tilde{H}}$	$(\bar{L}d)(uCd)\tilde{H}$
		$\mathcal{O}_{\bar{L}dddH}$	$(\bar{L}d)(dCd)H$
		$\mathcal{O}_{\bar{e}Qdd\tilde{H}}$	$\epsilon_{ij}(\bar{e}Q^i)(dCd)\tilde{H}^j$
		$\mathcal{O}_{\bar{L}dQQ\tilde{H}}$	$\epsilon_{ij}(\bar{L}d)(QCQ^i)\tilde{H}^j$
$\mathcal{O}^{(2)}_{\bar{d}uLLD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L^i C\sigma^{\mu\nu}D_\nu L^j)$	$\mathcal{O}_{\bar{L}dQdD}$	$(\bar{L}iD^\mu d)(QC\gamma_\mu d)$

Counting operators depend on flavors

Provide leading-order $\Delta L = 2$ interactions beyond the Weinberg operator

$13(\not B) + 7(\not{B})$ given by [L. Lehman:1410.4193]. Yi Liao & XDM 1607.07309

Dim-7 Majorana neutrino mass operator;

Baryon number violating operators with $\Delta B = -\Delta L = 1$;

Redundant operators.

Flavor-specific basis

Dim-7 SMEFT operators: $(\Delta B, \Delta L) = (0, 2)$				
Classes	Original operator basis in [17, 18]	Basis in [19, 20]	Relations of the two different notations	WC name in `D7RGESolver`
$\psi^2 H^4$	$\mathcal{O}_{LH}^{pr} = \epsilon_{ij}\epsilon_{mn}(\overline{L_p^{i\mathtt{C}}} L_r^m) H^j H^n (H^\dagger H)$	$\mathcal{O}_{LH}^{pr}$	same	`LH_pr`
$\psi^2 H^3 D$	$\mathcal{O}_{LeHD}^{pr} = \epsilon_{ij}\epsilon_{mn}(\overline{L_p^{i\mathtt{C}}} \gamma_\mu e_r) H^j H^m iD^\mu H^n$	$\mathcal{O}_{LeDH}^{pr}$	$= \mathcal{O}_{LeHD}^{pr}$	`LeDH_pr`
$\psi^2 H^2 D^2$	$\mathcal{O}_{LHD1}^{pr} = \epsilon_{ij}\epsilon_{mn}(\overline{L_p^{i\mathtt{C}}} D^\mu L_r^j) H^m D_\mu H^n$	$\mathcal{O}_{DLDH1}^{pr}$	$= \frac{1}{2}(\mathcal{O}_{LHD1}^{pr} + \mathcal{O}_{LHD1}^{rp})$	`DLDH1_pr`
	$\mathcal{O}_{LHD2}^{pr} = \epsilon_{im}\epsilon_{jn}(\overline{L_p^{i\mathtt{C}}} D^\mu L_r^j) H^m D_\mu H^n$	$\mathcal{O}_{DLDH2}^{pr}$	$= \frac{1}{2}(\mathcal{O}_{LHD2}^{pr} + \mathcal{O}_{LHD2}^{rp})$	`DLDH2_pr`
$\psi^2 H^2 X$	$\mathcal{O}_{LHB}^{pr} = \epsilon_{ij}\epsilon_{mn}(\overline{L_p^{i\mathtt{C}}} \sigma_{\mu\nu} L_r^m) H^j H^n B^{\mu\nu}$	$\mathcal{O}_{LHB}^{pr}$	same	`LHB_pr`
	$\mathcal{O}_{LHW}^{pr} = \epsilon_{ij}(\epsilon\tau^I)_{mn}(\overline{L_p^{i\mathtt{C}}} \sigma_{\mu\nu} L_r^m) H^j H^n W^{I\mu\nu}$	$\mathcal{O}_{LHW}^{pr}$	same	`LHW_pr`
$\psi^4 H$	$\mathcal{O}_{\bar{e}LLLH}^{prst} = \epsilon_{ij}\epsilon_{mn}(\overline{e_p} L_r^i)(\overline{L_s^{j\mathtt{C}}} L_t^m) H^n$	$\mathcal{O}_{\bar{e}LLLH}^{(\mathtt{S}),prst}$	$= \frac{1}{6}(\mathcal{O}_{\bar{e}LLLH}^{prst} + \mathcal{O}_{\bar{e}LLLH}^{pstr} + \mathcal{O}_{\bar{e}LLLH}^{ptrs}) + s \leftrightarrow t$	`eLLLHS_prst`
		$\mathcal{O}_{\bar{e}LLLH}^{(\mathtt{A}),prst}$	$= \frac{1}{6}(\mathcal{O}_{\bar{e}LLLH}^{prst} + \mathcal{O}_{\bar{e}LLLH}^{pstr} + \mathcal{O}_{\bar{e}LLLH}^{ptrs}) - s \leftrightarrow t$	`eLLLHA_prst`
		$\mathcal{O}_{\bar{e}LLLH}^{(\mathtt{M}),prst}$	$= \frac{1}{3}(\mathcal{O}_{\bar{e}LLLH}^{prst} + \mathcal{O}_{\bar{e}LLLH}^{psrt}) - t \leftrightarrow r$	`eLLLHM_prst`
	$\mathcal{O}_{\bar{d}LQLH1}^{prst} = \epsilon_{ij}\epsilon_{mn}(\overline{d_p} L_r^i)(\overline{Q_s^{j\mathtt{C}}} L_t^m) H^n$	$\mathcal{O}_{\bar{d}LQLH1}^{prst}$	same	`dLQLH1_prst`
	$\mathcal{O}_{\bar{d}LQLH2}^{prst} = \epsilon_{im}\epsilon_{jn}(\overline{d_p} L_r^i)(\overline{Q_s^{j\mathtt{C}}} L_t^m) H^n$	$\mathcal{O}_{\bar{d}LQLH2}^{prst}$	same	`dLQLH2_prst`
	$\mathcal{O}_{\bar{d}LueH}^{prst} = \epsilon_{ij}(\overline{d_p} L_r^i)(\overline{u_s^{\mathtt{C}}} e_t) H^j$	$\mathcal{O}_{\bar{d}LueH}^{prst}$	same	`dLueH_prst`
	$\mathcal{O}_{\bar{Q}uLLH}^{prst} = \epsilon_{ij}(\overline{Q_p} u_r)(\overline{L_s^{\mathtt{C}}} L_t^i) H^j$	$\mathcal{O}_{\bar{Q}uLLH}^{prst}$	same	`QuLLH_prst`
$\psi^4 D$	$\mathcal{O}_{\bar{d}uLLD}^{prst} = \epsilon_{ij}(\overline{d_p} \gamma_\mu u_r)(\overline{L_s^{i\mathtt{C}}} iD^\mu L_t^j)$	$\mathcal{O}_{\bar{d}uLDL}^{prst}$	$= \frac{1}{2}(\mathcal{O}_{\bar{d}uLLD}^{prst} + \mathcal{O}_{\bar{d}uLLD}^{prts})$	`duLDL_prst`
Dim-7 SMEFT operators: $(\Delta B, \Delta L) = (1, -1)$				
$\psi^4 H$	$\mathcal{O}_{\bar{L}dud\tilde{H}}^{prst} = \epsilon_{\alpha\beta\gamma}(\overline{L_p} d_r^\alpha)(\overline{u_s^{\beta\mathtt{C}}} d_t^\gamma)\tilde{H}$	$\mathcal{O}_{\bar{L}dud\tilde{H}}^{prst}$	same	`LdudH_prst`
	$\mathcal{O}_{\bar{L}dddH}^{prst} = \epsilon_{\alpha\beta\gamma}(\overline{L_p} d_r^\alpha)(\overline{d_s^{\beta\mathtt{C}}} d_t^\gamma) H$	$\mathcal{O}_{\bar{L}dddH}^{(\mathtt{M}),prst}$	$= \frac{1}{3}(\mathcal{O}_{\bar{L}dddH}^{prst} + \mathcal{O}_{\bar{L}dddH}^{psrt}) - s \leftrightarrow t$	`LdddHM_prst`
	$\mathcal{O}_{\bar{e}Qdd\tilde{H}}^{prst} = \epsilon_{ij}\epsilon_{\alpha\beta\gamma}(\overline{e_p} Q_r^{i\alpha})(\overline{d_s^{\beta\mathtt{C}}} d_t^\gamma)\tilde{H}^j$	$\mathcal{O}_{\bar{e}Qdd\tilde{H}}^{prst}$	same	`eQddH_prst`
	$\mathcal{O}_{\bar{L}dQQ\tilde{H}}^{prst} = \epsilon_{ij}\epsilon_{\alpha\beta\gamma}(\overline{L_p} d_r^\alpha)(\overline{Q_s^{\beta\mathtt{C}}} Q_t^{i\gamma})\tilde{H}^j$	$\mathcal{O}_{\bar{L}dQQ\tilde{H}}^{prst}$	same	`LdQQH_prst`
$\psi^4 D$	$\mathcal{O}_{\bar{e}dddD}^{prst} = \epsilon_{\alpha\beta\gamma}(\overline{e_p} \gamma_\mu d_r^\alpha)(\overline{d_s^{\beta\mathtt{C}}} iD^\mu d_t^\gamma)$	$\mathcal{O}_{\bar{e}ddDd}^{prst}$	$= \frac{1}{6}(\mathcal{O}_{\bar{e}dddD}^{prst} + \mathcal{O}_{\bar{e}dddD}^{ptrs} + \mathcal{O}_{\bar{e}dddD}^{pstr}) + s \leftrightarrow t$	`eddDd_prst`
	$\mathcal{O}_{\bar{L}QddD}^{prst} = \epsilon_{\alpha\beta\gamma}(\overline{L_p} \gamma_\mu Q_r^\alpha)(\overline{d_s^{\beta\mathtt{C}}} iD^\mu d_t^\gamma)$	$\mathcal{O}_{\bar{L}QdDd}^{prst}$	$= \frac{1}{2}(\mathcal{O}_{\bar{L}QddD}^{prst} + \mathcal{O}_{\bar{L}QddD}^{prts})$	`LQdDd_prst`

- Organized in terms of operators with manifest flavor symmetries
- Easy to write down the RGEs in a non-redundant way
- Adopted notation in our code

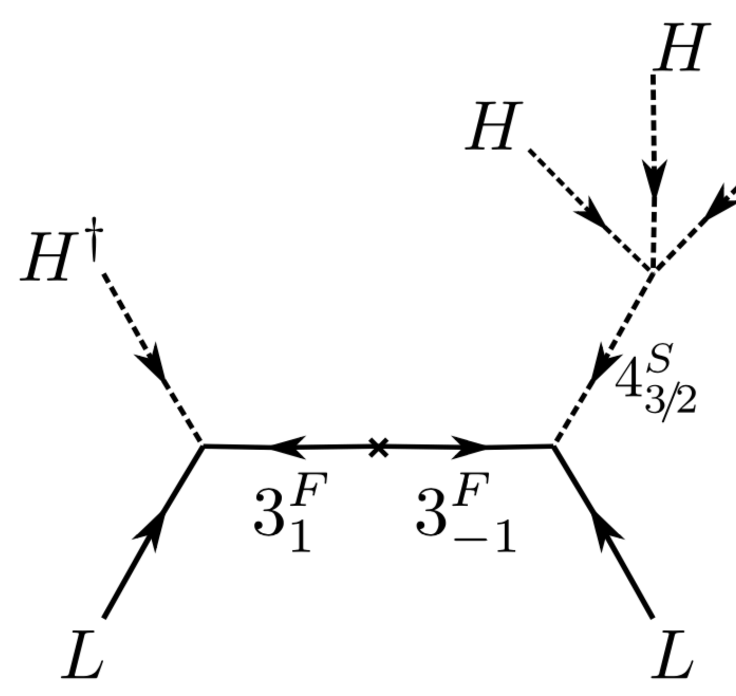
Yi Liao, XDM: 1901.10302
D. Zhang: 2310.11055

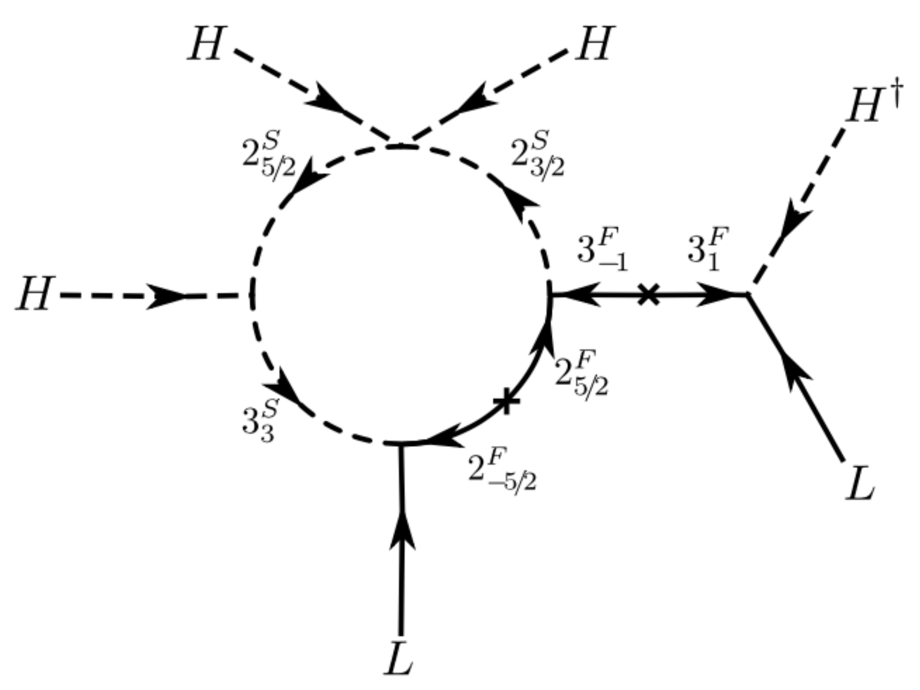
UV completion of dim-7 operators

EFT operators ⇔ UV models

Tree-level ⇒ 1-loop ⇒ 2-loop

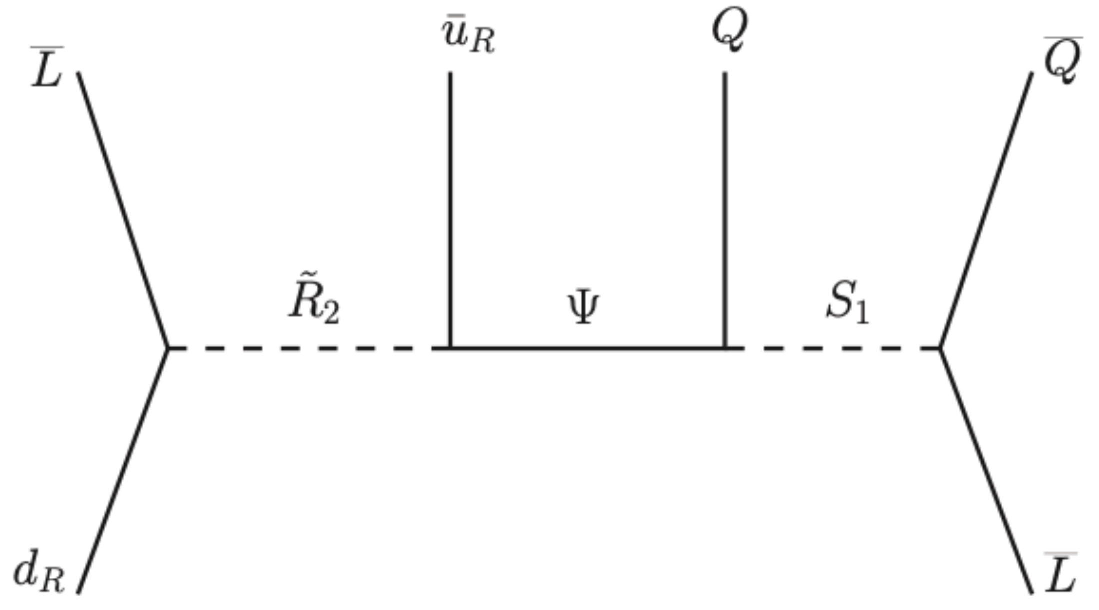
- Usually, assume the SM gauge symmetry intact
- Internal heavy fields: scalar, fermion, vector





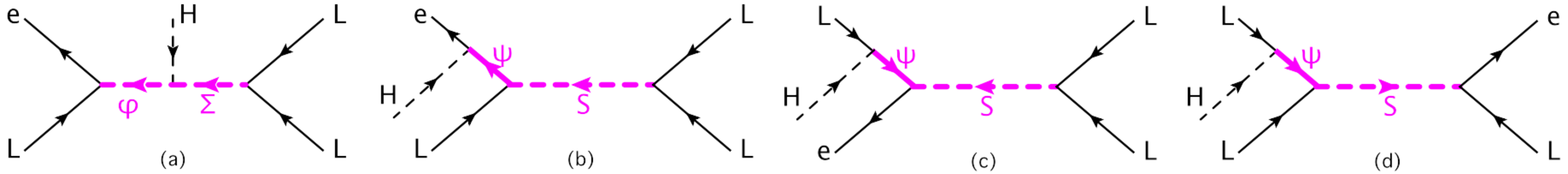
Anamiati et al: 1806.07264
Bonnet et al: 1204.5862
Cai et a : 1706.08524
Hirsch: 1411.7038, ...

- Generate topologies and diagrams
- Assign external and internal fields
- Select genuine topologies



Chen, Ding, Yao: 2110.15347, 2301.02503

Li, Zhao, Yu: 2311.10079



Yi Liao, XDM, Quan-Yu Wnag: 2005.08013

RG running effects in phenomenological studies

- Improve perturbative calculation
- Operator renormalization ⇒ **operator mixing effects**
- RGE effects are crucial for precise low energy analyses

- Dim-6 RGEs: 1308.2627, 1310.4838, 1312.2014
- Automatic RGE solver: DsixTools (1704.04504), wilson (1804.05033)
- Extensive phenomenological analyses incorporating RGEs

- Dim-5 RGEs: hep-ph/9309223, hep-ph/0108005
- Dim-7 RGEs: 1607.07309 , 1901.10302, 2306.03008, 2310.11055

Process relevant to dim-5/7 SMEFT
•Neutrino masses
•Neutrinoless double beta decay
•LNV signals at collider
•LNV meson and charged lepton decay
•Majorana neutrino magnetic moment
……

Automatic RGE solver: D7RGESolver

Yi Liao, XDM, Hao-Lin Wang, Xiang Zhao, 2505.06499

The accurate solutions of dim-5&7 RGEs are necessary for physical analysis

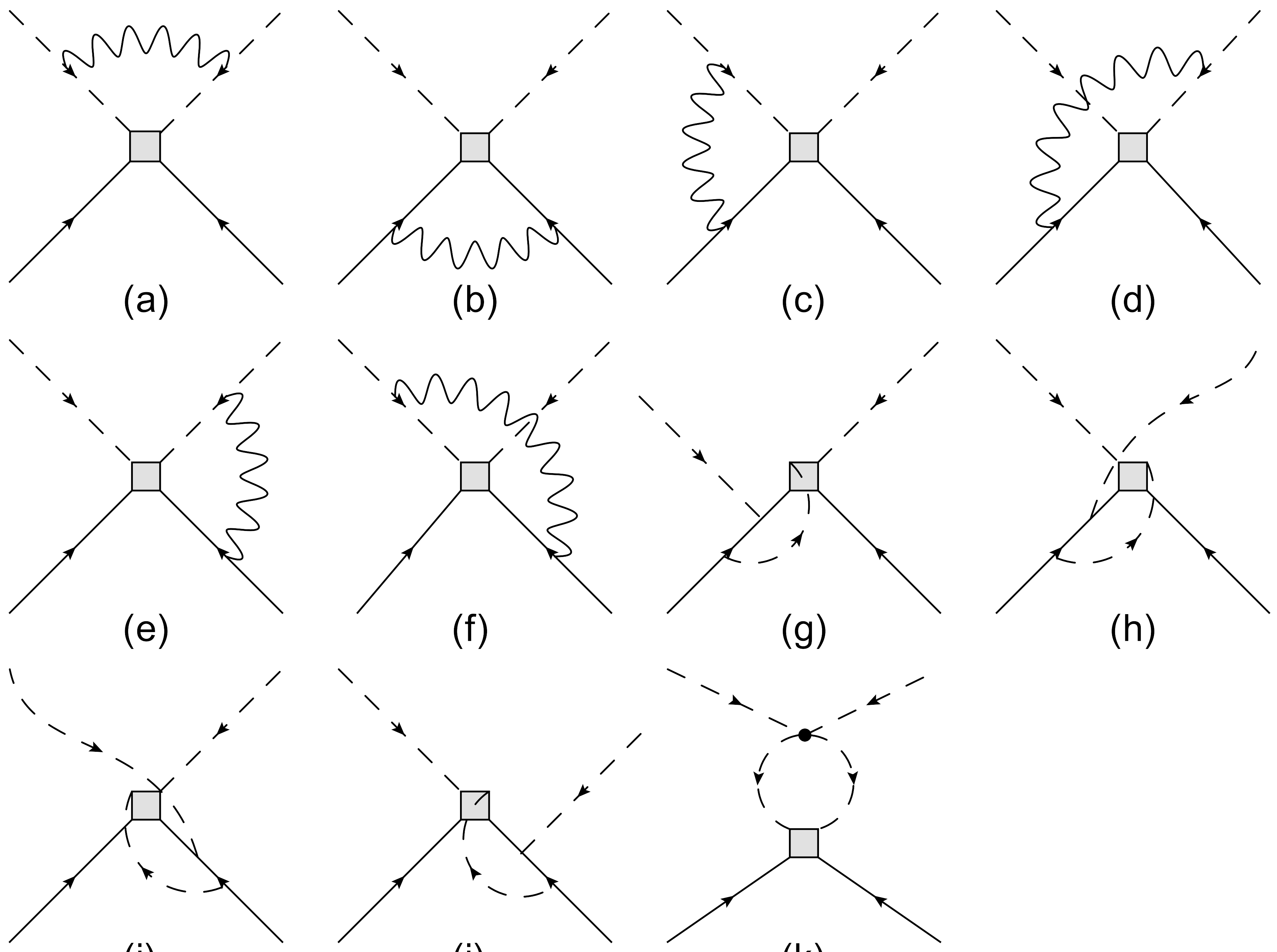
RGEs of dim-5 Weinberg operator

$\mathcal{O}_5 = \epsilon_{ij}\epsilon_{mn}(L^i C L^m) H^j H^n$

$$16\pi^2 \mu \frac{d}{d\mu} C_5^{pr} = (4\lambda + 2Y - 3g_2^2) C_5^{pr} - \frac{3}{2}\left[(Y_e Y_e^\dagger)_{vp} C_5^{vr} + p \to r\right]$$

$$Y \equiv \mathrm{Tr}\left[3(Y_u^\dagger Y_u) + 3(Y_d^\dagger Y_d) + (Y_e^\dagger Y_e)\right]$$

K. S. Babu et al: hep-ph/9309223
S. Antusch et al: hep-ph/0108005



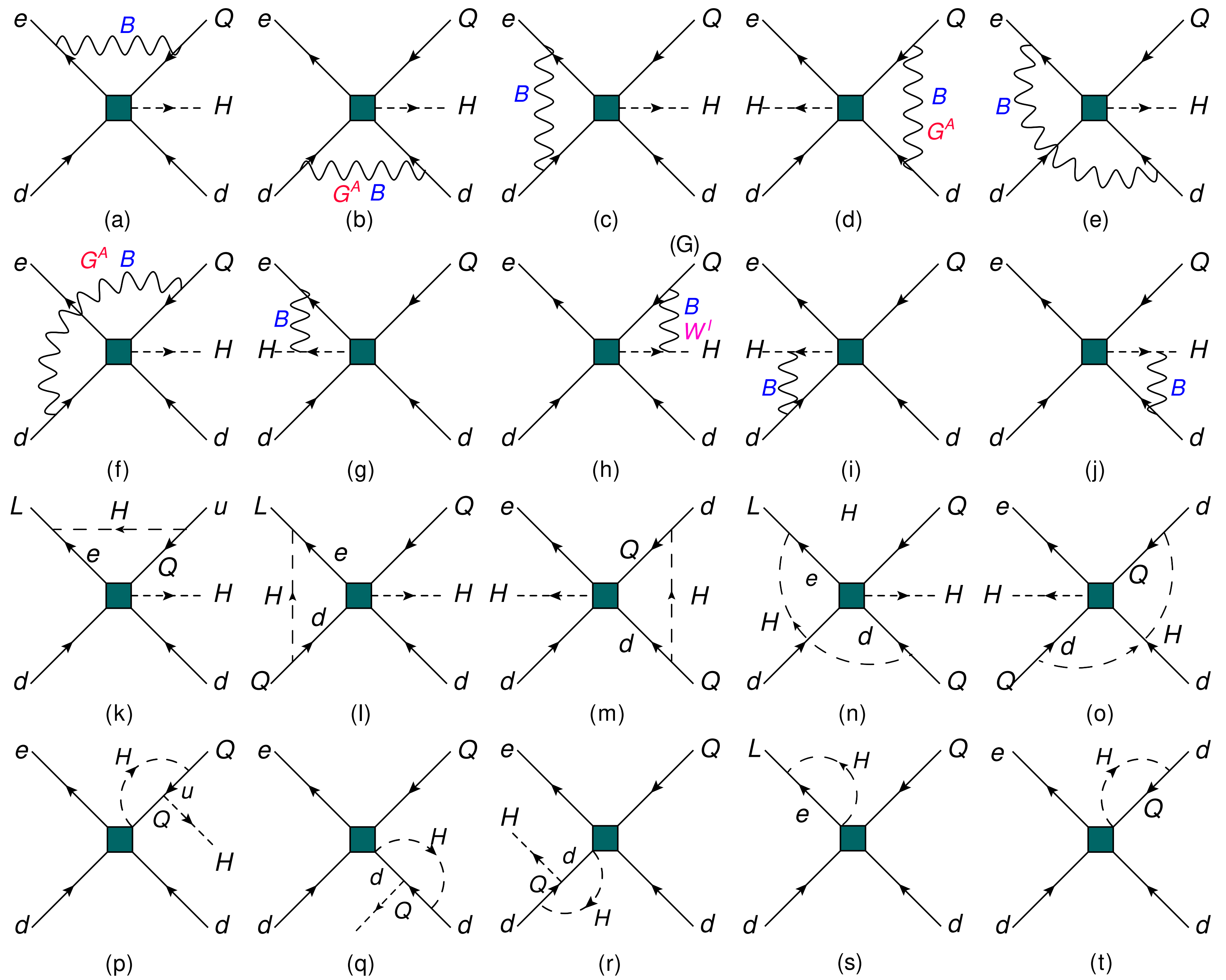
No g_1^2 terms—cancelled

$$16\pi^2 \mu \frac{d}{d\mu} C_{LH}^{d\,pr} = \left[(3d^2 - 18d + 19)\lambda - \frac{3}{4}(d-5)g_1^2 - \frac{3}{4}(3d-11)g_2^2 + (d-3)W_H\right] C_{LH}^{d\,pr} - \frac{3}{2}\left[(Y_e Y_e^\dagger)_{vp} C_{LH}^{d\,vr} + (Y_e Y_e^\dagger)_{vr} C_{LH}^{d\,pv}\right],$$

Yi Liao, XDM: 1701.08019

$$\mathcal{O}^D_{\text{n.m.}} = \left[(L^T \epsilon H) C (L^T \epsilon H)^T\right] (H^\dagger H)^{\frac{D-5}{2}} + \text{h.c.}$$

RGEs of dim-7 $\Delta L = 2$ operators



$(\omega,\bar{\omega})\vert\chi$	$(\omega,\bar{\omega})\vert\chi$	$(5,3)\vert 3$	$(5,3)\vert 3$	$(5,3)\vert 3$	$(5,5)\vert 2$	$(5,5)\vert 2$	$(5,5)\vert 2$	$(7,3)\vert 2$	$(7,3)\vert 2$	$(7,3)\vert 2$	$(7,3)\vert 3$	$(7,3)\vert 3$	$(7,5)\vert 1$
$(\omega,\bar{\omega})\vert\chi$	γ_{ij}	$\mathcal{O}_{LHD1}$	$\mathcal{O}_{LHD2}$	$\mathcal{O}_{\bar{d}uLLD}$	$\mathcal{O}_{LeHD}$	$\mathcal{O}_{\bar{d}LueH}$	$\mathcal{O}_{\bar{Q}uLLH}$	$\mathcal{O}_{\bar{e}LLLH}$	$\mathcal{O}_{\bar{d}LQLH1}$	$\mathcal{O}_{\bar{d}LQLH2}$	$\mathcal{O}_{LHB}$	$\mathcal{O}_{LHW}$	$\mathcal{O}_{LH}$
$(5,3)\vert 3$	$\mathcal{O}_{LHD1}$	g^2	g^2	g^2	0	0	0	0	0	0	0	0	0
$(5,3)\vert 3$	$\mathcal{O}_{LHD2}$	g^2	g^2	0	0	0	0	0	0	0	0	0	0
$(5,3)\vert 3$	$\mathcal{O}_{\bar{d}uLLD}$	g^2	g^2	g^2	0	0	0	0	0	0	0	0	0
$(5,5)\vert 2$	$\mathcal{O}_{LeHD}$	g^3	g^3	0	g^2	g^2	0	0	0	0	$\Sigma\to 0$	$\Sigma\to 0$	0
$(5,5)\vert 2$	$\mathcal{O}_{\bar{d}LueH}$	g^3	g^3	g^3	g^2	g^2	g^2	0	Y_uY_e	Y_uY_e	0	0	0
$(5,5)\vert 2$	$\mathcal{O}_{\bar{Q}uLLH}$	g^3	g^3	g^3	0	g^2	g^2	Y_uY_e	Y_uY_d	Y_uY_d	0	0	0
$(7,3)\vert 2$	$\mathcal{O}_{\bar{e}LLLH}$	g^3	g^3	0	0	0	$Y_u^\dagger Y_e^\dagger$	g^2	g^2	g^2	g^3	g^3	0
$(7,3)\vert 2$	$\mathcal{O}_{\bar{d}LQLH1}$	g^3	g^3	g^3	0	$Y_u^\dagger Y_e^\dagger$	$Y_u^\dagger Y_d^\dagger$	g^2	g^2	g^2	g^3	g^3	0
$(7,3)\vert 2$	$\mathcal{O}_{\bar{d}LQLH2}$	g^3	g^3	g^3	0	$Y_u^\dagger Y_e^\dagger$	$Y_u^\dagger Y_d^\dagger$	g^2	g^2	g^2	g^3	g^3	0
$(7,3)\vert 3$	$\mathcal{O}_{LHB}$	g^2	g^2	0	$\Sigma\to 0$	0	0	g^1	g^1	0	g^2	g^2	0
$(7,3)\vert 3$	$\mathcal{O}_{LHW}$	g^2	g^2	0	$\Sigma\to 0$	0	0	g^1	g^1	g^1	g^2	g^2	0
$(7,5)\vert 1$	$\mathcal{O}_{LH}$	g^4	g^4	0	g^3	0	g^3	g^3	g^3	0	0	g^4	g^2

Rich operator mixing effects

$$\langle (C\mathcal{O})_{\bar{d}LueH}\rangle^{(k)}\delta = -\frac{1}{2}(Y_d)_{pv}(Y_e^\dagger)_{ws}C_{\bar{d}LueH}^{vtrw}\mathcal{O}_{\bar{d}LueH}^{prst},$$

$$\langle (C\mathcal{O})_{\bar{d}LueH}\rangle^{(l)}\delta = (Y_u^\dagger)_{vs}(Y_e^\dagger)_{wt}C_{\bar{d}LueH}^{prvw}\left(\mathcal{O}_{\bar{d}LQLH1}^{prst} - \mathcal{O}_{\bar{d}LQLH2}^{prst}\right),$$

$$\langle (C\mathcal{O})_{\bar{d}LueH}\rangle^{(m)}\delta = -\frac{1}{2}(Y_e)_{vt}(Y_e^\dagger)_{wr}C_{\bar{d}LueH}^{pvsw}\mathcal{O}_{\bar{d}LueH}^{prst},$$

$$\langle (C\mathcal{O})_{\bar{d}LueH}\rangle^{(n)}\delta = -(Y_d^\dagger Y_d)_{pv}C_{\bar{d}LueH}^{vrst}\mathcal{O}_{\bar{d}LueH}^{prst},$$

$$\langle (C\mathcal{O})_{\bar{d}LueH}\rangle^{(o)}\delta = -(Y_u^\dagger Y_u)_{vs}C_{\bar{d}LueH}^{prvt}\mathcal{O}_{\bar{d}LueH}^{prst},$$

$$\langle (C\mathcal{O})_{\bar{d}LueH}\rangle^{(p)}\delta = (Y_e Y_e^\dagger)_{vr}C_{\bar{d}LueH}^{pvst}\mathcal{O}_{\bar{d}LueH}^{prst},$$

$$\langle (C\mathcal{O})_{\bar{d}LueH}\rangle^{(q)}\delta = -\frac{1}{2}(Y_e^\dagger Y_e)_{vt}C_{\bar{d}LueH}^{prsv}\mathcal{O}_{\bar{d}LueH}^{prst},$$

$$\langle (C\mathcal{O})_{\bar{d}LueH}\rangle^{(r)}\delta = 3(Y_u^\dagger Y_d)_{vw}C_{\bar{d}LueH}^{wpvr}\mathcal{O}_{LeHD}^{pr},$$

Yi Liao, XDM: 1901.10302

RG mixing between dim-5 and dim-7 operators

$$\dot{C}_{LH5}^{pr} = \frac{1}{2}(-3g^2 + 4\lambda + 2W_H)C_{LH5}^{pr} - \frac{3}{2}[C_{LH5}Y_lY_l^\dagger]^{pr} + \mu_h^2\{8C_{LH}^{pr} + 2[C_{LeDH}Y_l^\dagger]^{pr} + \frac{3}{2}g^2\left(2C_{DLDH1}^{pr} + C_{DLDH2}^{pr}\right) + [C_{DLDH1}Y_lY_l^\dagger]^{pr} - \frac{1}{2}[C_{DLDH2}Y_lY_l^\dagger]^{pr} - [Y_l]_{ts}\left(3C_{\bar{e}LLLH}^{(\mathtt{S}),stpr} + 2C_{\bar{e}LLLH}^{(\mathtt{M}),stpr}\right) - 3[Y_d]_{ts}C_{\bar{d}LQLH1}^{sptr} + 6[Y_u^\dagger]_{st}C_{\bar{Q}uLLH}^{tspr}\} + p \leftrightarrow r\,.$$

D. Zhang: 2310.11055; 2306.03008

D7RGESolver — a python package for solving dim5&7 RGEs

https://github.com/ZhaoXiang210/D7RGESolver

Yi Liao, XDM, Hao-Lin Wang, Xiang Zhao, 2505.06499

Solve the complete RGEs of dim-5&7 operators

- D7RGESolver
  - RGE_dim7.py — Functions to solve RGEs
  - beta_function.py — Store the RGEs
  - WCs_dic.py — All independent WCs
  - SM_parameters.py — The SM inputs
  - ovbb.py — Study the $0\nu\beta\beta$ decay
  - example — Example to use
  - external_tools
    - nudobe — An external tool to study the $0\nu\beta\beta$ decay

Oliver Scholer et al., 2304.05415

```
for p, r in indices:
    Beta[f"LH5_{p}{r}"] = (
        ###### dim-5 contribution to LH5
        1/2*(-3*g**2 + 4*Lambda + 2*WH)*C_LH5[p-1,r-1]
        +1/2*(-3*g**2 + 4*Lambda + 2*WH)*C_LH5[r-1,p-1]
        -3/2*(C_LH5 @ Yl @ Yl.conj().T)[p-1,r-1]
        -3/2*(C_LH5 @ Yl @ Yl.conj().T)[r-1,p-1]
```

```
"LH5_11": 0,
"LH5_12": 0,
"LH5_13": 0,
"LH5_22": 0,
"LH5_23": 0,
"LH5_33": 0,
```

The structure of the D7RGESolver package.

D7RGESolver — a python package for solving dim5&7 RGEs

- SM inputs at electroweak scale
- The RGEs of the SM parameters:

  one loop + two loop

- Dim-5&7 operators: only focus on independent flavors
- Two choices of quark flavor basis:

Up-quark flavor basis: $Y_u = \frac{\sqrt{2}}{v} M_u, \quad Y_d = \frac{\sqrt{2}}{v} V_{\rm CKM} M_d.$

Down-quark flavor basis: $Y_u = \frac{\sqrt{2}}{v} V^\dagger_{\rm CKM} M_u, \quad Y_d = \frac{\sqrt{2}}{v} M_d.$

$$Y_l = \frac{\sqrt{2}}{v} M_e$$

Input notation in the code

Class	2F	2FS	2FA	4F3S	4F3A	4F2S
#	9	6	3	30	3	54
WC in the code	LeDH_pr LHW_pr	LH5_pr LH_pr DLDH1_pr DLDH2_pr	LHB_pr	eLLLHS_prst eddDd_prst	eLLLHA_prst	duLDL_prst LQdDd_prst
sym.	\	pr = rp	pr = −rp	prst = prts = ptsr	prst = −prts = −ptsr	prst = prts
Adopted flavors	{p, r}	{1, 1} {1, 2} {1, 3} {2, 2} {2, 3} {3, 3}	{1, 2} {1, 3} {2, 3}	{p, 1, 1, 1} {p, 1, 1, 2} {p, 1, 1, 3} {p, 1, 2, 2} {p, 1, 2, 3} {p, 1, 3, 3} {p, 2, 2, 2} {p, 2, 2, 3} {p, 2, 3, 3} {p, 3, 3, 3}	{p, 1, 2, 3}	{p, r, 1, 1} {p, r, 1, 2} {p, r, 1, 3} {p, r, 2, 2} {p, r, 2, 3} {p, r, 3, 3}

Diagonal at the electroweak scale ⇒ become non-diagonal at other scales

D7RGESolver — Example for its basic usage

Run $\mathcal{O}_{LH5}^{11}$ and $\mathcal{O}_{DLDH1}^{11}$ from 10 TeV to 80 GeV

```
from RGE_dim7 import solve_rge, print_WCs
C_in = {"LH5_11": 1e-15+0j,"DLDH1_11": 1e-15+0j}        # Input the WCs
scale_in = 1e4                       # Input energy scale in units of GeV
scale_out = 80                       # Output energy scale in units of GeV
```

```
C_out = solve_rge(scale_in, scale_out, C_in, basis="down", method="integrate")
```

Main function

```
print_WCs(C_out)
```

method="leadinglog" for fast calculation

```
## Wilson coefficients

**EFT:** 'SMEFT'
| WC name | Value |
|------------------|----------------------------------------------|
| 'LH5_11' | (5.51729127984111e-13-1.1697182471147425e-28j) |
| 'LH_11' | (-2.727147726710258 5e-18+1.963932185687201 6e-33j) |
| 'DLDH1_11' | (8.183376576714679e-16+1.539722194653356e-39j) |
| 'DLDH2_11' | (8.253541710427263e-17-3.157387110573996e-39j) |
| 'QuLLH_3311' | (-2.976790814412032e-17+6.616906663619594e-33j) |
| 'LHW_11' | (-3.399190512252408e-18-1.1024467172929897e-33j) |
| ... | ... |
```

Enhanced due to mixing from $\mathcal{O}_{DLDH1}^{11}$

- Dim-5 and -7 Weinberg operators on top
- Other dim-7 ones are in descending order of absolute values

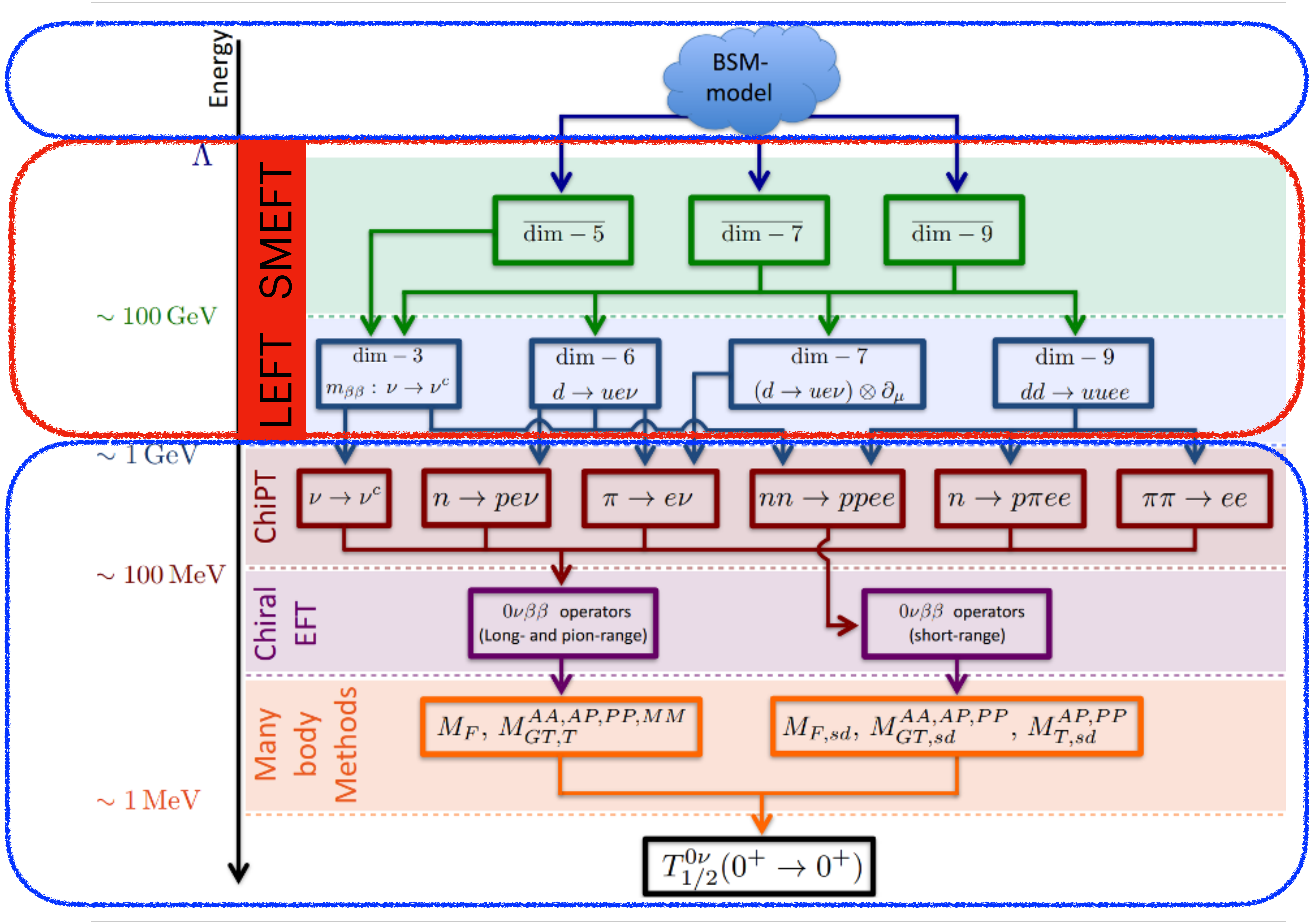
Application to $0\nu\beta\beta$

Skip these sectors

See tomorrow's talk by Frank and Jiangming

Focus on SM/L-EFT

Implemented into vDoBe



V. Cirigliano et al.,1806.02780
O. Scholer, J. de Vries and L. Gráf, vDoBe, 2306.08709

Low-energy EFT (LEFT) below electroweak scale

$$\boxed{u,\ d,\ s,\ c,\ b;\ \ e,\ \mu,\ \tau;\ \ \nu_e,\ \nu_\mu,\ \nu_\tau}$$

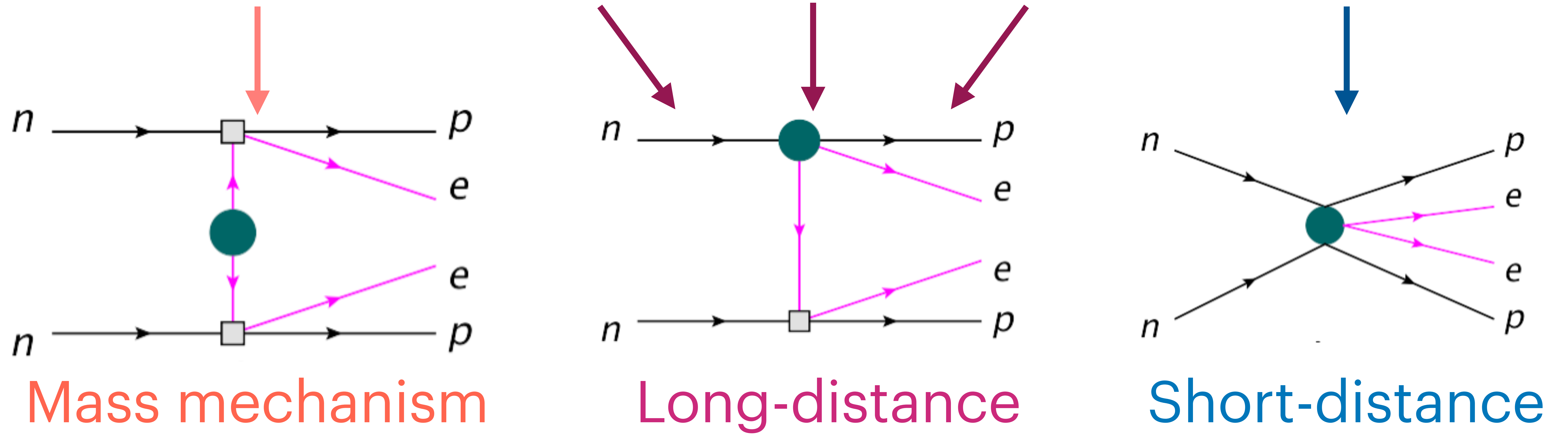
$$SU(3)_c \times SU(2)_L \times U(1)_Y \to SU(3)_c \times U(1)_{em}$$

Jenkins, Manohar, Stoffer, 2018 — *Li, Ren, Xiao, Yu, Zheng, 2020*

$$\mathscr{L}_{\text{LEFT}} = \mathscr{L}_{\dim\leq 4} + \sum_{\dim 5,i} \frac{\hat{C}_{5,i}}{\Lambda}\mathscr{Q}^i_{\dim-5} + \sum_{\dim 6,i} \frac{\hat{C}_{6,i}}{\Lambda^2}\mathscr{Q}^i_{\dim-6} + \sum_{\dim 7,i} \frac{\hat{C}_{7,i}}{\Lambda^3}\mathscr{Q}^i_{\dim-7} + \sum_{\dim 8,i} \frac{\hat{C}_{8,i}}{\Lambda^4}\mathscr{Q}^i_{\dim-8} + \sum_{\dim 9,i} \frac{\hat{C}_{9,i}}{\Lambda^5}\mathscr{Q}^i_{\dim-9} + \cdots$$

Liao, XDM, Wang, 2020 — *Murphy, 2020* — *Liao, XDM, Wang, 2019*

$$\mathcal{L}^{0\nu\beta\beta}_{\text{LEFT}} = \mathcal{L}^{(3)}_{\Delta L=2} + \mathcal{L}^{(6)}_{\Delta L=2} + \mathcal{L}^{(7)}_{\Delta L=2} + \mathcal{L}^{(8)}_{\Delta L=2} + \mathcal{L}^{(9)}_{\Delta L=2} + \cdots,$$



G. Prezeau, M. Ramsey-Musolf, P. Vogel, hep-ph/0303205
L.Graf, F. Deppisch, F. Iachello, J. Kotila:1806.06058
V. Cirigliano et al.,1806.02780

LEFT description of $0\nu\beta\beta$ process due to dim-7 operators

V. Cirigliano et al.,1806.02780

$$\mathcal{L}^{(3)}_{\Delta L=2} = -\frac{1}{2} m_{\beta\beta}\, \overline{\nu^{c}_{L,e}} \nu_{L,e} + \text{h.c.}\,, \qquad 1$$

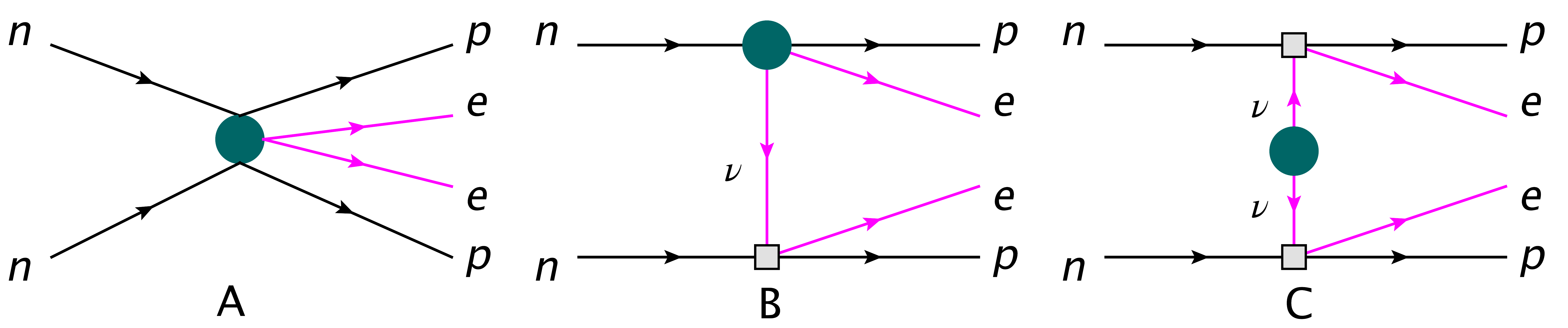
$$\mathcal{L}^{(6)}_{\Delta L=2} = \sqrt{2} G_F \Big[C^{(6)}_{\rm VL} (\overline{u}_{\rm L}\gamma^{\mu} d_{\rm L})(\overline{e}_{\rm R}\gamma_{\mu}\nu^{c}_{{\rm L},e}) + C^{(6)}_{\rm VR}(\overline{u}_{\rm R}\gamma^{\mu} d_{\rm R})(\overline{e}_{\rm R}\gamma_{\mu}\nu^{c}_{{\rm L},e}) \qquad 6$$
$$+ C^{(6)}_{\rm SR}(\overline{u}_{\rm L} d_{\rm R})(\overline{e}_{\rm L}\nu^{c}_{{\rm L},e}) + C^{(6)}_{\rm SL}(\overline{u}_{\rm R} d_{\rm L})(\overline{e}_{\rm L}\nu^{c}_{{\rm L},e}) + C^{(6)}_{\rm T}(\overline{u}_{\rm L}\sigma^{\mu\nu} d_{\rm R})(\overline{e}_{\rm L}\sigma_{\mu\nu}\nu^{c}_{{\rm L},e})\Big] + \text{h.c.}\,,$$

$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{\sqrt{2} G_F}{v} \Big[C^{(7)}_{\rm VL}(\overline{u}_{\rm L}\gamma^{\mu} d_{\rm L})(\overline{e}_{\rm L} i \overleftrightarrow{\partial}_{\mu} \nu^{c}_{{\rm L},e}) + C^{(7)}_{\rm VR}(\overline{u}_{\rm R}\gamma^{\mu} d_{\rm R})(\overline{e}_{\rm L} i \overleftrightarrow{\partial}_{\mu} \nu^{c}_{{\rm L},e})\Big] + \text{h.c.}\,, \qquad 2$$

$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5} \Big[C^{(9)}_{\rm 1L}(\overline{u}_{\rm L}\gamma_{\mu} d_{\rm L})(\overline{u}_{\rm L}\gamma^{\mu} d_{\rm L})(\overline{e_{\rm L}} e^{c}_{\rm L}) + C^{(9)}_{\rm 4L}(\overline{u}_{\rm L}\gamma_{\mu} d_{\rm L})(\overline{u}_{\rm R}\gamma^{\mu} d_{\rm R})(\overline{e_{\rm L}} e^{c}_{\rm L})\Big] + \text{h.c.}\,, \qquad 2$$

SMEFT @dim 7

A limited number of LEFT operators are required.



Short-distance

Long-distance

Mass mechanism

Matching onto the LEFT

Tree-level matching: 1 dim-5 and 11 dim-7 operators $\Rightarrow 0\nu\beta\beta$

Basis	LEFT operators	Matching results at electroweak scale $\Lambda_{\rm EW}$
Up	$\mathcal{O}^{(6)}_{\rm SL} = \sqrt{2}G_F(\overline{u_{\rm R}}d_{\rm L})(\overline{e_{\rm L}}\nu^{\rm c}_{{\rm L},e})$	$C^{(6)}_{\rm SL} = v^3\left(\frac{1}{\sqrt{2}}V_{w1}C^{w111*}_{QuLLH} + \frac{1}{2v}m_u V_{ud}C^{11*}_{DLDH2}\right)$
flavor	$\mathcal{O}^{(6)}_{\rm SR} = \sqrt{2}G_F(\overline{u_{\rm L}}d_{\rm R})(\overline{e_{\rm L}}\nu^{\rm c}_{{\rm L},e})$	$C^{(6)}_{\rm SR} = v^3\left(\frac{1}{2\sqrt{2}}C^{1111*}_{dLQLH1} - \frac{1}{2v}m_d V_{ud}C^{11*}_{DLDH2}\right)$
basis	$\mathcal{O}^{(6)}_{\rm T} = \sqrt{2}G_F(\overline{u_{\rm L}}\sigma^{\mu\nu}d_{\rm R})(\overline{e_{\rm L}}\sigma_{\mu\nu}\nu^{\rm c}_{{\rm L},e})$	$C^{(6)}_{\rm T} = v^3\left(\frac{1}{8\sqrt{2}}C^{1111*}_{dLQLH1} + \frac{1}{4\sqrt{2}}C^{1111*}_{dLQLH2}\right)$
	$\mathcal{O}_{m\beta\beta} = -\frac{1}{2}m_{\beta\beta}\overline{\nu^{\rm c}_{{\rm L},e}}\nu_{L,e}$	$m_{\beta\beta} = -v^2C^{11}_{LH5} - \frac{1}{2}v^4C^{11}_{LH}$
	$\mathcal{O}^{(6)}_{\rm VL} = \sqrt{2}G_F(\overline{u_{\rm L}}\gamma^\mu d_{\rm L})(\overline{e_{\rm R}}\gamma_\mu\nu^{\rm c}_{{\rm L},e})$	$C^{(6)}_{\rm VL} = v^3V_{ud}\left(-\frac{1}{\sqrt{2}}C^{11*}_{LeDH} + 4\frac{m_e}{v}g^{-1}C^{11*}_{LHW}\right)$
	$\mathcal{O}^{(6)}_{\rm VR} = \sqrt{2}G_F(\overline{u_{\rm R}}\gamma^\mu d_{\rm R})(\overline{e_{\rm R}}\gamma_\mu\nu^{\rm c}_{{\rm L},e})$	$C^{(6)}_{\rm VR} = \frac{v^3}{2\sqrt{2}}C^{1111*}_{dLueH}$
	$\mathcal{O}^{(7)}_{\rm VL} = \frac{\sqrt{2}}{v}G_F(\overline{u_{\rm L}}\gamma^\mu d_{\rm L})(\overline{e_{\rm L}}\overleftrightarrow{\partial}_\mu\nu^{\rm c}_{{\rm L},e})$	$C^{(7)}_{\rm VL} = -v^3V_{ud}\left(C^{11*}_{DLDH1} + \frac{1}{2}C^{11*}_{DLDH2} + 4g^{-1}C^{11*}_{LHW}\right)$
	$\mathcal{O}^{(7)}_{\rm VR} = \frac{\sqrt{2}}{v}G_F(\overline{u_{\rm R}}\gamma^\mu d_{\rm R})(\overline{e_{\rm L}}\overleftrightarrow{\partial}_\mu\nu^{\rm c}_{{\rm L},e})$	$C^{(7)}_{\rm VR} = -v^3C^{1111*}_{duLDL}$
	$\mathcal{O}^{(9)}_{\rm 1L} = \frac{1}{v^5}(\overline{u_{\rm L}}\gamma_\mu d_{\rm L})(\overline{u_{\rm L}}\gamma^\mu d_{\rm L})(\overline{e_{\rm L}}e^{\rm c}_{\rm L})$	$C^{(9)}_{\rm 1L} = -v^3V^2_{ud}\left(2C^{11*}_{DLDH1} + 8g^{-1}C^{11*}_{LHW}\right)$
	$\mathcal{O}^{(9)}_{\rm 4L} = \frac{1}{v^5}(\overline{u_{\rm L}}\gamma_\mu d_{\rm L})(\overline{u_{\rm R}}\gamma^\mu d_{\rm R})(\overline{e_{\rm L}}e^{\rm c}_{\rm L})$	$C^{(9)}_{\rm 4L} = -2v^3V_{ud}C^{1111*}_{duLDL}$
Down	$\mathcal{O}^{(6)}_{\rm SL} = \sqrt{2}G_F(\overline{u_{\rm R}}d_{\rm L})(\overline{e_{\rm L}}\nu^{\rm c}_{{\rm L},e})$	$C^{(6)}_{\rm SL} = v^3\left(\frac{1}{\sqrt{2}}C^{1111*}_{QuLLH} + \frac{1}{2v}m_u V_{ud}C^{11*}_{DLDH2}\right)$
flavor	$\mathcal{O}^{(6)}_{\rm SR} = \sqrt{2}G_F(\overline{u_{\rm L}}d_{\rm R})(\overline{e_{\rm L}}\nu^{\rm c}_{{\rm L},e})$	$C^{(6)}_{\rm SR} = v^3\left(\frac{1}{2\sqrt{2}}V_{1w}C^{11w1*}_{dLQLH1} - \frac{1}{2v}m_d V_{ud}C^{11*}_{DLDH2}\right)$
basis	$\mathcal{O}^{(6)}_{\rm T} = \sqrt{2}G_F(\overline{u_{\rm L}}\sigma^{\mu\nu}d_{\rm R})(\overline{e_{\rm L}}\sigma_{\mu\nu}\nu^{\rm c}_{{\rm L},e})$	$C^{(6)}_{\rm T} = v^3V_{1w}\left(\frac{1}{8\sqrt{2}}C^{11w1*}_{dLQLH1} + \frac{1}{4\sqrt{2}}C^{11w1*}_{dLQLH2}\right)$

Depending on the convention of the relationship between mass vs flavor eigenstates

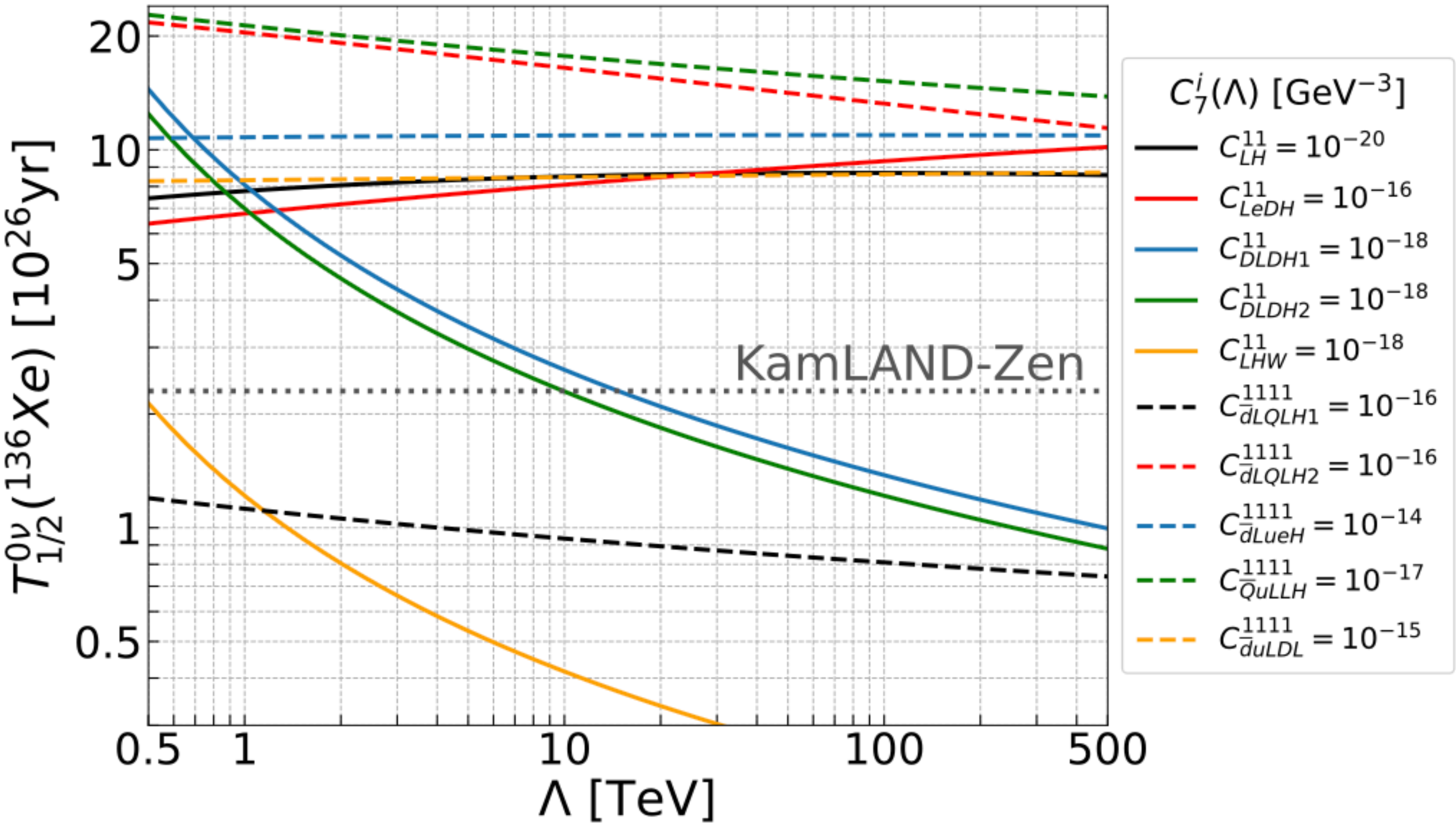
Up-quark flavor basis

$$Y_u = \frac{\sqrt{2}}{v}M_u, \quad Y_d = \frac{\sqrt{2}}{v}V_{\rm CKM}M_d\,.$$

Up-quark flavor basis

$$Y_u = \frac{\sqrt{2}}{v}V^\dagger_{\rm CKM}M_u, \quad Y_d = \frac{\sqrt{2}}{v}M_d\,.$$

RG effects on the half lifetime of $^{136}\mathrm{Xe}$ $0\nu\beta\beta$ decay



Yi Liao, XDM, Hao-Lin Wang, Xiang Zhao, 2505.06499

Large impact from

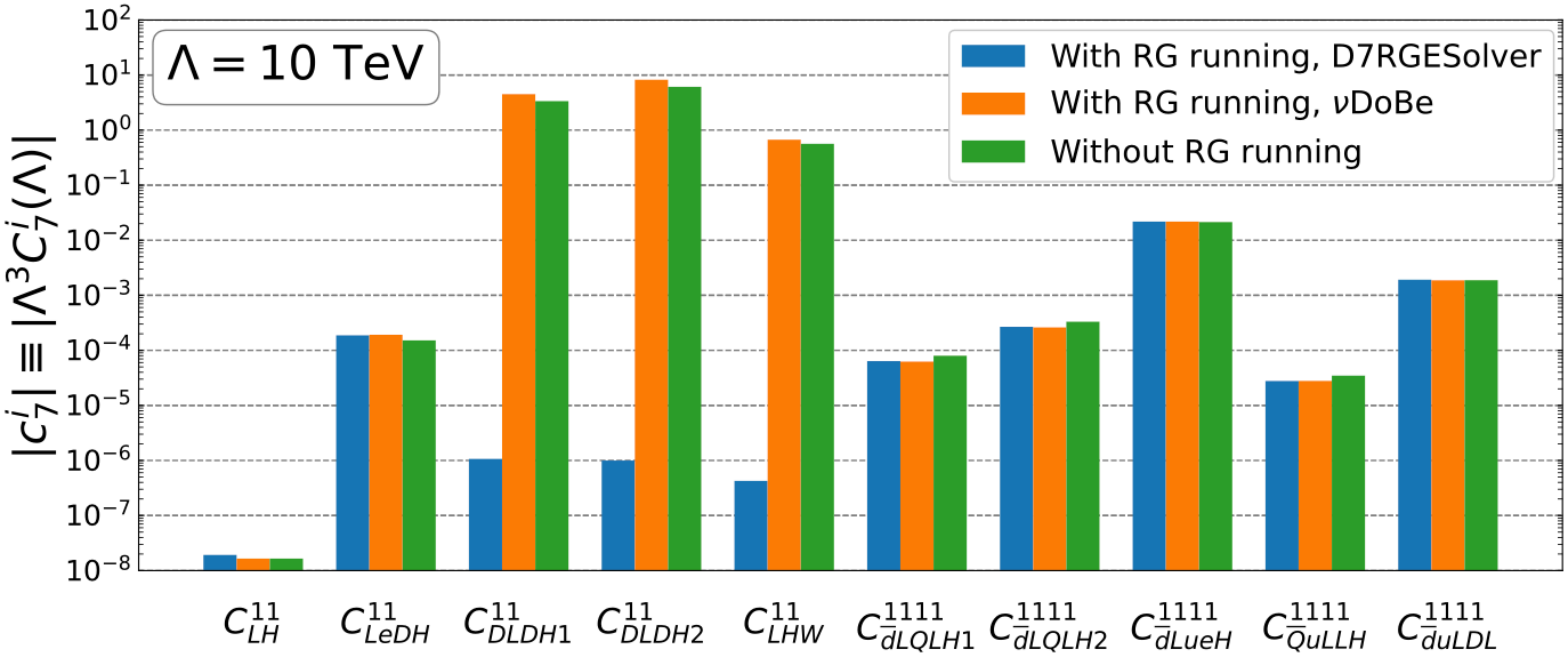
$\mathcal{O}^{11}_{DLDH1,2}$, $\mathcal{O}^{11}_{LHW}$

Mixing into $\mathcal{O}_{LH(5)}$ operator

RGE effect plays a significant role in predicting the $0\nu\beta\beta$ decay half lifetime

L. Gráf, C. Hati, A. Martín-Galán and O. Scholer, 2504.00081

Constraints on 10 1st generation operators



- KamLAND-Zen experimental limit $[T_{1/2}^{0\nu}]_{\texttt{SMEFT}}(c_i) \gtrsim [T_{1/2}^{0\nu}]_{\texttt{KamLAND}}^{90\,\%} = 2.3 \times 10^{26}\,\mathrm{yr}.$
- The full and precise RGE evolution of these operators has a significant impact on their numerical constraints
- Mainly from their contributions to the $\mathcal{O}_{LH(5)}$ through RGE mixing

Operator	$\lvert c_7^i\rvert \equiv \lvert\Lambda^3 C_7^i(\Lambda)\rvert$ Same in both bases	Operator	$\lvert c_7^i\rvert \equiv \lvert\Lambda^3 C_7^i(\Lambda)\rvert$ Up-quark flavor basis	Down-quark flavor basis
RGE-improved constraints on the dimensionless WCs c_7^i at $\Lambda = 10$ TeV				
$\mathcal{O}_{LH}^{11}$	1.92×10^{-8}	$\mathcal{O}_{\bar{Q}uLLH}^{1111}$	2.85×10^{-5}	2.78×10^{-5}
$\mathcal{O}_{LeDH}^{11}$	1.88×10^{-4}	$\mathcal{O}_{\bar{Q}uLLH}^{1211}$	8.58×10^{5}	4.48×10^{-4}
$\mathcal{O}_{DLDH1}^{11}$	1.07×10^{-6}	$\mathcal{O}_{\bar{Q}uLLH}^{1311}$	3.51	6.50×10^{-6}
$\mathcal{O}_{DLDH2}^{11}$	9.99×10^{-7}	$\mathcal{O}_{\bar{Q}uLLH}^{2111}$	1.24×10^{-4}	2.65×10^{-1}
$\mathcal{O}_{LHW}^{11}$	4.26×10^{-7}	$\mathcal{O}_{\bar{Q}uLLH}^{2211}$	1.00×10^{-4}	1.03×10^{-4}
$\mathcal{O}_{\bar{e}LLLH}^{(M),2112}$	1.76×10^{-3}	$\mathcal{O}_{\bar{Q}uLLH}^{2311}$	3.01×10^{-1}	1.43×10^{-6}
$\mathcal{O}_{\bar{e}LLLH}^{(M),3113}$	1.05×10^{-4}	$\mathcal{O}_{\bar{Q}uLLH}^{3111}$	3.24×10^{-3}	5.38×10^{-2}
$\mathcal{O}_{\bar{e}LLLH}^{(S),1111}$	2.59×10^{-1}	$\mathcal{O}_{\bar{Q}uLLH}^{3211}$	5.65×10^{1}	2.38×10^{-3}
$\mathcal{O}_{\bar{e}LLLH}^{(S),2112}$	1.25×10^{-3}	$\mathcal{O}_{\bar{Q}uLLH}^{3311}$	5.90×10^{-8}	5.90×10^{-8}
$\mathcal{O}_{\bar{e}LLLH}^{(S),3113}$	7.44×10^{-5}			
$\mathcal{O}_{\bar{d}uLDL}^{1111}$	1.92×10^{-3}	$\mathcal{O}_{\bar{d}LQLH1}^{1111}$	6.22×10^{-5}	6.38×10^{-5}
$\mathcal{O}_{\bar{d}uLDL}^{1211}$	3.58×10^{2}	$\mathcal{O}_{\bar{d}LQLH1}^{1121}$	2.17×10^{-1}	2.77×10^{-4}
$\mathcal{O}_{\bar{d}uLDL}^{1311}$	1.54×10^{1}	$\mathcal{O}_{\bar{d}LQLH1}^{1131}$	4.69	1.72×10^{-2}
$\mathcal{O}_{\bar{d}uLDL}^{2111}$	9.21×10^{3}	$\mathcal{O}_{\bar{d}LQLH1}^{2111}$	1.06×10^{-2}	4.50×10^{1}
$\mathcal{O}_{\bar{d}uLDL}^{2211}$	4.04	$\mathcal{O}_{\bar{d}LQLH1}^{2121}$	2.45×10^{-3}	2.39×10^{-3}
$\mathcal{O}_{\bar{d}uLDL}^{2311}$	1.66×10^{-1}	$\mathcal{O}_{\bar{d}LQLH1}^{2131}$	5.05×10^{-2}	4.09×10^{-1}
$\mathcal{O}_{\bar{d}uLDL}^{3111}$	1.34×10^{2}	$\mathcal{O}_{\bar{d}LQLH1}^{3111}$	1.27×10^{-2}	3.61×10^{-2}
$\mathcal{O}_{\bar{d}uLDL}^{3211}$	1.80	$\mathcal{O}_{\bar{d}LQLH1}^{3121}$	1.09×10^{-3}	7.91×10^{-3}
$\mathcal{O}_{\bar{d}uLDL}^{3311}$	1.33×10^{-4}	$\mathcal{O}_{\bar{d}LQLH1}^{3131}$	4.04×10^{-5}	4.04×10^{-5}
$\mathcal{O}_{\bar{d}LueH}^{1111}$	2.18×10^{-2}	$\mathcal{O}_{\bar{d}LQLH2}^{1111}$	2.61×10^{-4}	2.68×10^{-4}
$\mathcal{O}_{\bar{d}LueH}^{1121}$	9.27×10^{4}	$\mathcal{O}_{\bar{d}LQLH2}^{1121}$	3.57	1.16×10^{-3}
$\mathcal{O}_{\bar{d}LueH}^{1131}$	8.92×10^{3}	$\mathcal{O}_{\bar{d}LQLH2}^{1131}$	8.56×10^{1}	7.20×10^{-2}
$\mathcal{O}_{\bar{d}LueH}^{2111}$	2.27×10^{6}	$\mathcal{O}_{\bar{d}LQLH2}^{2111}$	1.75×10^{-1}	2.94×10^{3}
$\mathcal{O}_{\bar{d}LueH}^{2121}$	1.05×10^{3}	$\mathcal{O}_{\bar{d}LQLH2}^{2121}$	4.03×10^{-2}	3.93×10^{-2}
$\mathcal{O}_{\bar{d}LueH}^{2131}$	9.58×10^{1}	$\mathcal{O}_{\bar{d}LQLH2}^{2131}$	9.16×10^{-1}	2.66×10^{1}
$\mathcal{O}_{\bar{d}LueH}^{3111}$	2.72×10^{6}	$\mathcal{O}_{\bar{d}LQLH2}^{3111}$	2.09×10^{-1}	2.35
$\mathcal{O}_{\bar{d}LueH}^{3121}$	4.67×10^{2}	$\mathcal{O}_{\bar{d}LQLH2}^{3121}$	1.80×10^{-2}	5.14×10^{-1}
$\mathcal{O}_{\bar{d}LueH}^{3131}$	7.67×10^{-2}	$\mathcal{O}_{\bar{d}LQLH2}^{3131}$	7.33×10^{-4}	7.32×10^{-4}

Full RGE improved constraints

RG mixing effects are important to constrain operators that cannot directly contribute to $0\nu\beta\beta$, especially the operators involving 3rd or 2nd generation quarks

55 dim-7 SMEFT operators are constrained vs 10 operators through tree-level contributions

Yi Liao, XDM, Hao-Lin Wang, Xiang Zhao, 2505.06499

Summary

- We provide an automatic tool D7RGESolver to solve the full one-loop RGEs of dim-5&7 SMEFT operators;
- The running effects of dim-5&7 interactions can significantly affect the $0\nu\beta\beta$ rate;
- Current $0\nu\beta\beta$ half lifetime bound can contrain 55 dim-7 operators due to RGEs;
- The mixing through dim-5&7 Weinberg operators has the leading contribution to $0\nu\beta\beta$ process;
- The mixing via Yukawa couplings involving 3rd generation quarks is significant.

Thank you for your time!