Probing the flavor of New Physics with dipoles

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UNIVERSITY
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Work in collaboration with **S. Jäger** and **K. Leslie** (U. Sussex)
Portorož 2019: Precision era in High Energy Physics

Outline

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Radiative processes

$\rightarrow$ Address the structure of flavor, sources of CP violation

E.M. form factors: Magnetic Dipole Moment (MDM),
Electric Dipole Moment (EDM), etc.

Flavor transitions: $\mu \to e\gamma$, $\tau \to (e,\mu)\gamma$, $\nu' \to \nu\gamma$,
$s \to d\gamma$, $b \to (s,d)\gamma$, etc.

$\rightarrow$ Dipole operators: $\mathcal{L} = \frac{e v_{\rm EW}}{\sqrt{2}} \mathcal{C}^{\beta\alpha}_{\psi\gamma} \bar{\psi}_\beta \sigma^{\mu\nu} P_R \psi_\alpha F_{\mu\nu} + \text{h.c.}$

$\rightarrow$ **Reach to NP scales**:

eEDM:	$\lvert\text{Im}[\mathcal{C}^{ee}_{e\gamma}]\rvert \lesssim (8 \times 10^5\ \text{TeV})^{-2}$	[ACME]
$\mu \to e\gamma$:	$\sqrt{\lvert\mathcal{C}^{e\mu}_{e\gamma}\rvert^2 + \lvert\mathcal{C}^{\mu e}_{e\gamma}\rvert^2} \lesssim (4 \times 10^4\ \text{TeV})^{-2}$	[MEG]
nEDM:	$\left\lvert\text{Im}[\mathcal{C}^{dd}_{d\gamma}]\right\rvert, \left\lvert\text{Im}[\mathcal{C}^{uu}_{u\gamma}]\right\rvert \lesssim (2 \times 10^5\ \text{TeV})^{-2}$	[PRD92, 092003 (2015)]

SMEFT way

→ Higher dimensional operators respecting SM local symmetries and containing SM d.o.f. only, suppressed by $\Lambda_{\rm NP} \gg v_{\rm EW}$

→ Equations Of Motion (EOMs) eliminate redundant cases:
59 linearly independent operators of dimension six,
with 1350 CP-even + 1149 CP-odd couplings,
assuming SM global symmetries, B and L

$$X^3,\ H^6,\ H^4D^2,\ \psi^2H^3,\ X^2H^2,\ \psi^2XH,\ \psi^2H^2D,\ \psi^4$$

[ψ fermions; D cov. derivative; X field strengths]

[Buchmüller, Wyler '86; Grzadkowski, Iskrzyński, Misiak, Rosiek '10]

→ I assume that ops. of dim. > 6 can be neglected ($\sim \Lambda_{\rm NP}^{-4}$, etc.)

Probing non-dipole operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i C_i Q_i, \qquad C_i \text{ scales as } \Lambda_{\rm NP}^{-2}$$

Mixing with dipole:

$$16\pi^2 \frac{d}{d\ell n(\mu)} C_{\psi^2 XH}(\mu) = \Sigma_i (C_{\psi^2 XH}, C_{\psi^4}, C_{X^3}, C_{X^2H^2})_i(\mu) \gamma^{(1\text{-loop})}_{i,\psi^2 XH}$$

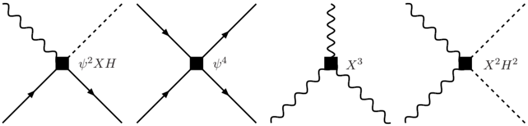
[Alonso, Jenkins, Manohar, Trott '13]

[Pruna, Signer '14; Davidson '16; Crivellin, Davidson, Pruna, Signer '17]

Ex. of bound: [ACME]

$$\left|\frac{m_t}{m_e} {\rm Im}\, C^{(3),eett}_{\ell equ}\right| \lesssim 3 \times 10^{-6}\ {\rm TeV}^{-2}$$

[■: possible vertices]



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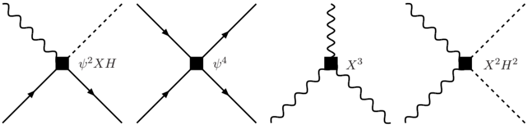


HERE: Leading Order mixing with the dipole arriving at two-loops

Outline

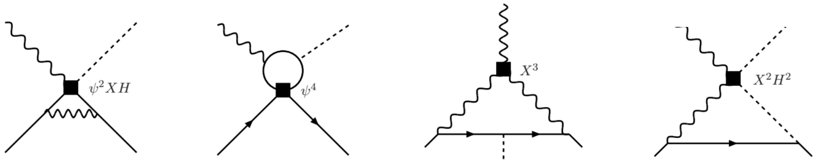
Renormalization of SM + dim.=6 ops.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i C_i Q_i, \qquad C_i \text{ scales as } \Lambda_{\rm NP}^{-2}$$

$$\mathcal{L}_{\rm SM} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{I\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,\ell,e} \bar{\psi} i \not{D} \psi$$
$$-\lambda \left(H^\dagger H - \frac{1}{2} v_{\rm EW}^2\right)^2 - \left[H^{\dagger j} \bar{d} Y_d q_j + \tilde{H}^{\dagger j} \bar{u} Y_u q_j + H^{\dagger j} \bar{e} Y_e \ell_j + \text{h.c.}\right]$$

[plus gauge fixing and ghost terms]

Full set of local operators required in the renormalization program?



Full basis of operators

class $\mathcal{O}$: gauge-invariant operators, e.g., Warsaw basis
class **A**: BRST-exact operators, i.e., $A = \delta_{BRST} A'$
class **B**: vanish via the equations of motion

$$\begin{pmatrix} [\mathcal{O}]^{\rm ren} \\ [\mathbf{A}]^{\rm ren} \\ [\mathbf{B}]^{\rm ren} \end{pmatrix} = \begin{pmatrix} Z_{\mathcal{O}\mathcal{O}} & Z_{\mathcal{O}A} & Z_{\mathcal{O}B} \\ 0 & Z_{AA} & Z_{AB} \\ 0 & 0 & Z_{BB} \end{pmatrix} \begin{pmatrix} \mathcal{O} \\ \mathbf{A} \\ \mathbf{B} \end{pmatrix}$$

with
$$\langle 0 | T\{A\Phi\} | 0 \rangle_{\text{on-shell}} = 0$$
$$\langle 0 | T\{B\Phi\} | 0 \rangle_{\text{on-shell}} = 0$$
Φ: set of local fields

[Dixon, Taylor '74; Kluberg-Stern, Zuber '75; Joglekar, Lee '76; Joglekar '77; Collins '84]

[cf. Herrlich, Nierste '96 for double insertions]

$\rightarrow$ Non-phys. ops. are generated systematically by extending BRST

[Henneaux '93; Barnich, Brandt, Henneaux '00]

$\rightarrow$ Typically, large set required for renormalizing dim.=6 operators

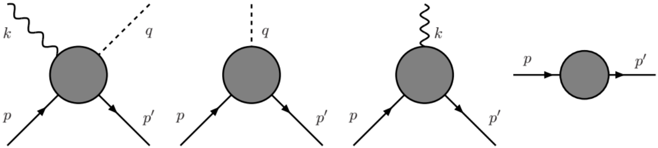
Renormalization of dipole operators

Consider all operators Q that contribute to $\Sigma_Q Z_{OQ} \mathcal{G}_Q^{\rm tree}(\Phi) = \mathcal{G}_O(\Phi)$

$\Rightarrow Z_{OQ} =$ linear combination of $\mathcal{G}_O(\psi^2 A^\mu H), \mathcal{G}_O(\psi^2 H), \mathcal{G}_O(\psi^2 A^\mu), \mathcal{G}_O(\psi^2)$

[$\mathcal{G}_O$: Green's functions of single insertions of (bare) operator O]

[cf., e.g., Grinstein, Springer, Wise '88 on $b \to s\gamma$]



Ex. of structures from non-physical operators:

$$g_A[(\partial_\nu \bar{\psi}_L)\Gamma^{\mu\nu} t^I \xi_R \varphi] A^I_\mu,\ \bar{\psi}_L \gamma_\mu (i \not{D} \xi_R)(D^\mu \varphi),\ \ldots$$

Outline

Renormalization of $\psi^2 H^3$ operators

$\rightarrow$ Case we will be focusing upon: $\psi^2 H^3$,
generated in many concrete extensions of the SM

[Davidson '16; Panico, Pomarol, Riembau '18]

$\rightarrow$ At 1-loop: $\psi^2 H^3$ mix only into $\psi^2 H$; $H^6, \psi^2 H^3$

$\rightarrow$ Mixing with the dipole: Leading Order at 2-loops

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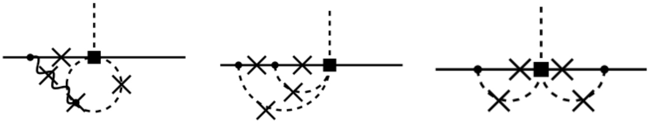
Ex. of diagrams necessary to determine the mixing with dipoles:



[$\times$: different possibilities for attaching an external gauge boson]

$Z_{\psi^2 H^3, \psi^2 XH} \overset{MS}{=} \underset{1/\varepsilon}{\text{Coef.}}[\mathcal{G}_{\psi^2 H^3}(\psi^2 AH), \not{k}\not{\epsilon}(k)]$, neglecting Yukawa couplings

[Kinetic basis: $p \cdot \epsilon(k)$, $p' \cdot \epsilon(k)$, $k \cdot \epsilon(k)$, $\not{p}\not{\epsilon}(k)$, $\not{p}'\not{\epsilon}(k)$, $\not{k}\not{\epsilon}(k)$]

Anomalous Dimension Matrix

Dipole: $g_X(\bar{\psi}_L \sigma^{\mu\nu} t^I \xi_R \varphi) X^I_{\mu\nu}$, $(q_L, u_R), (q_L, d_R), (\ell_L, e_R), (\ell_L, \nu_R)$

$$(16\pi^2)^2 \frac{d}{d\ell n(\mu)} C_{\psi^2 XH}(\mu) = \left(g_Y^2 \gamma_Y^X + g_L^2 \gamma_L^X + g_C^2 \gamma_c^X \right) C_{\psi^2 H^3}(\mu)$$

	$X = B$	$X = W$	$X = G$
γ_Y^X	$3 Q_\varphi^Y Q_\varphi^Y (Q_L^Y + Q_R^Y)$	$\frac{1}{2} Q_\varphi^Y (Q_L^Y + Q_R^Y)$	0
γ_L^X	$\frac{3}{4} Q_\varphi^Y$	$\frac{3}{8}$	0
γ_c^X	0	0	0

$Q_\phi^Y = -Q_{\tilde{\phi}}^Y = 1/2$; $Q_{\ell_L}^Y = -1/2$, $Q_{e_R}^Y = -1$, $Q_{\nu_R}^Y = 0$; $Q_{q_L}^Y = 1/6$, $Q_{u_R}^Y = +2/3$, $Q_{d_R}^Y = -1/3$

Cases involving dim.=4 Yukawas not relevant for light fermions

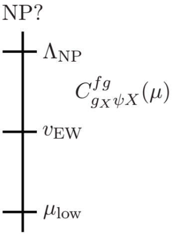
Checks: arbitrary Feynman gauge $\surd$
independence of specific set of Green's functions $\surd$

Also, results agree with hep-ph/1810.09413 [Panico, Pomarol, Riembau '18]

Contributions to the dipole Wilson coef.

→ Solution of the RGE:

$$C^{fg}_{g_X \psi X}(\mu) = C^{fg}_{g_X \psi X}(\Lambda_{\rm NP}) - \ell n \left(\frac{\Lambda_{\rm NP}}{\mu} \right) \times C^{fg}_{\psi H}(\Lambda_{\rm NP}) \times \left(\frac{g_Y^2}{(4\pi)^4} \gamma_Y^X + \frac{g_L^2}{(4\pi)^4} \gamma_L^X \right) + \ldots$$



→ At one-loop, $C_{\psi^2 XH}, C_{\psi^4}, C_{X^3}, C_{X^2 H^2}$

→ Consider the pheno. effects of $C^{fg}_{\psi H}(\Lambda_{\rm NP}) \neq 0$, $C^{fg}_{g_X \psi X}(\Lambda_{\rm NP}) = 0$

$$\mathcal{L} = \frac{e v_{\rm EW}}{\sqrt{2}} \mathcal{C}^{\beta\alpha}_{\psi\gamma} \bar{\psi}_\beta \sigma^{\mu\nu} P_R \psi_\alpha F_{\mu\nu} + {\rm h.c.}$$

$$\mathcal{C}_{e\gamma} = C_{g_Y eB} - C_{g_L eW} \,, \qquad \mathcal{C}_{d\gamma} = C_{g_Y dB} - C_{g_L dW}$$
$$\mathcal{C}_{\nu\gamma} = C_{g_Y \nu B} + C_{g_L \nu W} \,, \qquad \mathcal{C}_{u\gamma} = C_{g_Y uB} + C_{g_L uW}$$

[ex. pheno: Crivellin, Najjari, Rosiek '13; Panico, Pomarol, Riembau '18]

Tree-level constraints on $\psi^2 H^3$

$\psi^2 H^3$ changes couplings of the physical Higgs h:

$$\mathcal{L} = -\bar{u}' M_u u' - h \bar{u}' Y_u u' + \ldots$$

$$[M_\psi]_{ij} \simeq \frac{v_{\rm EW}}{\sqrt{2}} \left([Y_\psi^{\rm dim.=4}]_{ij} - \frac{1}{2} v_{\rm EW}^2 [C_{\psi H}^\dagger]_{ij} \right) ,$$

$$[Y_\psi]_{ij} \simeq \frac{1}{v_{\rm EW}} [M_\psi]_{ij} - \frac{v_{\rm EW}^2}{\sqrt{2}} [C_{\psi H}^\dagger]_{ij} , \quad \psi = u, d, e$$

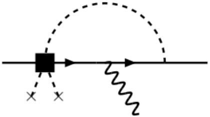
→ M_ψ combines the Wilson coefficients of $\psi^2 H$ and $\psi^2 H^3$; almost-exact cancellations are not usually expected to happen

→ Meson-mixing (K^0, D^0, B_d^0, B_s^0 oscillations) dominates constraints on flavor-changing currents involving s, c, b or t

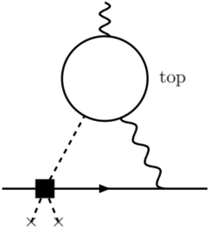
Finite parts of loop diagrams

→ Loop-induced bounds on flavor violating Higgs couplings:

Ex. of 1-loop diagram:



Ex. of Barr-Zee diagram:



[cf. Barr, Zee '90; Harnik, Kopp, Zupan '12; Brod, Haisch, Zupan '13]

→ By avoiding a small Yukawa coupling, two-loop diagrams may (over)compensate for the loop-suppression

→ Analogously, the two-loop mixing-induced effect will also be enhanced compared to one-loop finite terms

Two-loop bounds

$\rightarrow$ Enhancements in the finite corrections (such as $N_c = 3$) compared to mixing-induced effects (for which $\gamma^X \sim 1/4$)

$\rightarrow$ Pheno. results, comparison with Barr-Zee ($\tilde{C}_{\psi H} = V_\psi^\dagger C_{\psi H}$):

eEDM: $|\mathrm{Im}[\tilde{C}_{eH}^{ee}(\Lambda_{\mathrm{NP}})]| \lesssim \mathcal{F} \times 0.004 \times \frac{\sqrt{2} m_e}{v_{\mathrm{EW}}^3}$ [ACME]

$\mu \to e\gamma$: $(|\tilde{C}_{eH}^{e\mu}(\Lambda_{\mathrm{NP}})|^2 + |\tilde{C}_{eH}^{\mu e}(\Lambda_{\mathrm{NP}})|^2)^{1/2} \lesssim \mathcal{F} \times 0.1 \times \frac{\sqrt{2 m_e m_\mu}}{v_{\mathrm{EW}}^3}$ [MEG]

nEDM: $\left|\mathrm{Im}[\tilde{C}_{dH}^{dd}(\Lambda_{\mathrm{NP}})]\right|, \left|\mathrm{Im}[\tilde{C}_{uH}^{uu}(\Lambda_{\mathrm{NP}})]\right| \lesssim \mathcal{F} \times 10 \times \frac{\sqrt{2} m_d}{v_{\mathrm{EW}}^3}$ [PRD92, 092003 (2015)]

[for nEDM, see, e.g., Pospelov, Ritz '05]

[Values for $\Lambda_{\mathrm{NP}} = 1$ TeV, and $\mu = M_H$: further RGE corrections are omitted]

where $\mathcal{F} \sim 0.3$ from Barr-Zee contributions

Renormalization of four-fermion ops.

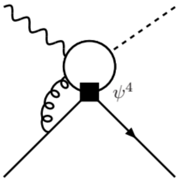
$\rightarrow$ Ongoing analysis of four-fermion operators

eEDM: $Q^{(1)}_{\ell equ}$, $Q^{(3)}_{\ell equ}$; $Q_{\ell edq}$, $Q_{\ell e}$

$|\mathrm{Im}\, C^{eett}_{\ell edq,\ell e}| \lesssim 10^{-5}, 10^{-6}\ \mathrm{TeV}^{-2}$

[Panico, Pomarol, Riembau '18]

nEDM: $Q^{(1)}_{\ell equ}$, $Q^{(3)}_{\ell equ}$; $Q^{(1)}_{qu}$, $Q^{(8)}_{qu}$, $Q^{(1)}_{qd}$, $Q^{(8)}_{qd}$, $Q^{(1)}_{quqd}$, $Q^{(8)}_{quqd}$, $Q_{\ell edq}$



$\rightarrow$ Analogously to Barr-Zee type of contributions: top in loops

$\rightarrow$ Typically, constraints at the level of $< \mathcal{O}(0.1)\,\mathrm{TeV}^{-2}$ **w/o** considering mixing with dipoles

[Falkowski, González-Alonso, Mimouni '17]

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1. Introduction
2. Renormalization of SMEFT
3. Dim. 6 corrections to Yukawa couplings
4. Conclusions

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$\rightarrow$ **Generic tool** for improving our understanding of flavor and CPV

$\rightarrow$ SMEFT: systematic approach in the absence of new d.o.f. (so far)

$\rightarrow$ Mainly discussed here: constraints on corrections to Yukawa couplings from mixing with dipole

$\rightarrow$ Finite contributions dominate bounds on $\psi^2 H^3$ W.C.

$\rightarrow$ Prospects: constraining four-fermion contact interactions

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Hvala!

Lake Bohinj, Slovenia

Extended BRST-variation

$\rightarrow$ Extend BRST-variation to "anti-fields"; $\delta_{BRST} = \delta + \gamma$ increases the mass power counting and the ghost number by one unit

$\rightarrow$ Consider all polynomials of dim. ≤ 5, and ghost number -1

Z	δZ	γZ
A_μ^I	0	$D_\mu C^I$
ξ^i	0	$-eC^I T^i_{Ij} \xi^j$
C^I	0	$\frac{1}{2} e f^I_{KJ} C^J C^K$
$C^\ddagger_I$	$-D_\mu A_I^{\ddagger\mu} - e\xi^\ddagger_i T^i_{Ij} \xi^j$	$e f^K_{JI} C^J C^\ddagger_K$
$A_I^{\ddagger\mu}$	L^μ_I	$e f^K_{JI} C^J A_K^{\ddagger\mu}$
$\xi^\ddagger_i$	L_i	$eC^I \xi^\ddagger_j T^j_{Ii}$

$D_\mu C^I = \partial_\mu C^I + e f^I_{JK} A^J_\mu C^K$, $D_\mu A_I^{\ddagger\mu} = \partial_\mu A_I^{\ddagger\mu} - e f^K_{JI} A^J_\mu A_K^{\ddagger\mu}$, and $L^\mu_I = \frac{\delta L}{\delta A^I_\mu}$,

$L_i = (-1)^{\epsilon_i} \frac{\delta L}{\delta \xi^i}$, where L is the action.

The field ξ designates a fermion or a scalar.

[Batalin-Vilkovisky; Henneaux '93; Collins, Scalise '94; Barnich, Brandt, Henneaux '00]

Some calculation aspects

$$\int f[\text{internal momenta } q, \text{ external momenta } p, \text{ masses } M]$$

Expansion in external momenta for simplifying integrals:

$$\underbrace{\frac{1}{(q+p)^2 - M^2}}_{\text{sup. deg. of div. } +2} \overset{exact}{=} \underbrace{\frac{1}{q^2 - m_R^2}}_{\text{sup. deg. of div. } +2} + \underbrace{\frac{M^2 - p^2 - 2q \cdot p - m_R^2}{q^2 - m_R^2} \frac{1}{(q+p)^2 - M^2}}_{\text{sup. deg. of div. } +3}$$

[Chetyrkin, Misiak, Münz '97; Gambino, Gorbahn, Haisch '03; Zoller '14]

Basic formulas

$$\frac{dC^T}{d\ell n(\mu)} = -C^T \left(\frac{dZ}{d\ell n(\mu)} Z^{-1} - Z(\epsilon\Delta + \gamma_M N) Z^{-1} \right) \equiv C^T \gamma$$

for $\psi^2 H^3$: $\Delta = -3, n = 2$;
for ψ^4: $\Delta = -2, n = 2$;
for $g\psi^2 XH$: $\Delta = -1, n = 2$.

$$\mathcal{L}^{(6)}(\beta\alpha) = \Sigma_i M^{-2} \mu^{-\Delta_i \epsilon} [C_i(\mu)]^{\beta\alpha} [Q_i^{bare}]^{\beta\alpha} + \Sigma_{i,j,f,g} M^{-2} \mu^{-\Delta_j \epsilon} [C_i(\mu)]^{\beta\alpha} [(Z_{ij}^X - \delta_{ij})]^{\beta\alpha fg} [Q_j^{bare}]^{fg} + \ldots + \mathrm{h.c.}$$

$$Z^{X,\ \beta\alpha fg}_{\psi^2 H^3, g\psi^2 XH} = \Bigg[\bigg(\frac{g_Y^2}{(4\pi)^4} (Z_Y^X)_1^{(1)} + \frac{g_L^2}{(4\pi)^4} (Z_L^X)_1^{(1)} + \frac{g_c^2}{(4\pi)^4} (Z_c^X)_1^{(1)} + \frac{\lambda}{(4\pi)^4} (Z_\lambda^X)_1^{(1)} + \frac{\Sigma_{k,l} Y_{kl}^* \times Y_{lk}}{(4\pi)^4} (Z_{\mathrm{det}^2}^X)_1^{(1)} \bigg) \delta_{f\beta} \delta_{g\alpha} + \frac{\Sigma_l (Y^\dagger)_{fl} \times Y_{l\beta}}{(4\pi)^4} \delta_{g\alpha} (Z_{y,y}^X)_1^{(1)} + \frac{(Y^\dagger)_{g\beta} \times (Y^\dagger)_{\alpha f}}{(4\pi)^4} (Z_{Y,y}^X)_1^{(1)} + \frac{\Sigma_k Y_{\alpha k} \times (Y^\dagger)_{kg}}{(4\pi)^4} \delta_{f\beta} (Z_{Y,Y}^X)_1^{(1)} \Bigg] \frac{1}{\epsilon} + \ldots$$

Dipole: $g_X(\bar{\psi}_L \sigma^{\mu\nu} t^I \xi_R \varphi) X^I_{\mu\nu}$, $(q_L, u_R), (q_L, d_R), (\ell_L, e_R), (\ell_L, \nu_R)$

	$X = B$	$X = W$	$X = G$
$(Z^X_Y)^{(1)}_1$	$\frac{3}{4} Q^Y_\varphi Q^Y_\varphi (Q^Y_L + Q^Y_R)$	$\frac{1}{8} Q^Y_\varphi (Q^Y_L + Q^Y_R)$	0
$(Z^X_L)^{(1)}_1$	$\frac{3}{16} Q^Y_\varphi$	$\frac{3}{32}$	0
$(Z^X_c)^{(1)}_1$	0	0	0
$(Z^X_\lambda)^{(1)}_1$	0	0	0
$(Z^X_{y,y})^{(1)}_1$	$\frac{1}{16}(5\, Q^Y_L + Q^Y_R)$	$\frac{1}{32}$	$\frac{3}{8}$
$(Z^X_{Y,y})^{(1)}_1$	0	0	0
$(Z^X_{Y,Y})^{(1)}_1$	$\frac{1}{16}(Q^Y_L + 5\, Q^Y_R)$	$\frac{1}{96}$	$\frac{3}{8}$
$(Z^X_{\det^2})^{(1)}_1$	0	0	0

$Q^Y_\phi = -Q^Y_{\tilde{\phi}} = 1/2$; $Q^Y_{\ell_L} = -1/2$, $Q^Y_{e_R} = -1$, $Q^Y_{\nu_R} = 0$; $Q^Y_{q_L} = 1/6$, $Q^Y_{u_R} = +2/3$, $Q^Y_{d_R} = -1/3$

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 0.63 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu} Y_{\mu e})$	-0.0022 ... -0.0009
electron EDM	$\lvert\mathrm{Im}(Y_{e\mu} Y_{\mu e})\rvert$	$< 0.10 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 1.2 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y^*_{e\mu}\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau} Y_{\tau e})$	[-0.24 ... -0.10] $\times 10^{-3}$
electron EDM	$\lvert\mathrm{Im}(Y_{e\tau} Y_{\tau e})\rvert$	$< 0.01 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.5 \pm 0.71) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau} Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$(\lvert Y_{\tau\mu} Y_{e\tau}\rvert^2 + \lvert Y_{\mu\tau} Y_{\tau e}\rvert^2)^{1/4}$	$< 0.60 \times 10^{-4}$

neutron EDM [37, 52]	$\lvert\mathrm{Im}(Y_{ut} Y_{tu})\rvert$	$< 4.4 \times 10^{-7}$
	$\lvert\mathrm{Im}(Y_{ct} Y_{tc})\rvert$	$< 5.2 \times 10^{-4}$

[Table adapted from Harnik, Kopp, Zupan '12]

$\mathcal{B}(h \to \ell\ell')$ @ 95% CL:

$$\sqrt{\lvert\tilde{C}^{e\mu}_{eH}\rvert^2 + \lvert\tilde{C}^{\mu e}_{eH}\rvert^2} < 1.3 \times 10^{-2}\ \mathrm{TeV}^{-2}$$

$$\sqrt{\lvert\tilde{C}^{e\tau}_{eH}\rvert^2 + \lvert\tilde{C}^{\tau e}_{eH}\rvert^2} < 5.6 \times 10^{-2}\ \mathrm{TeV}^{-2}$$

$$\sqrt{\lvert\tilde{C}^{\mu\tau}_{eH}\rvert^2 + \lvert\tilde{C}^{\tau\mu}_{eH}\rvert^2} < 8.1 \times 10^{-2}\ \mathrm{TeV}^{-2}$$

$$Y^{HKZ}_{ij} \to -\frac{v^2_{\mathrm{EW}}}{\sqrt{2}}[\tilde{C}^\dagger]_{ij}$$

$$\mathcal{B}(h \to e\mu) < 3.5 \times 10^{-4} \text{ (95\% CL)}$$ [Khachatryan:2016rke]

$$\mathcal{B}(h \to e\tau) < 6.9 \times 10^{-3} \text{ (95\% CL)}$$ [Khachatryan:2016rke]

$$\mathcal{B}(h \to \mu\tau) < 1.43\% \text{ (95\% CL)}$$ [Aad:2016blu]

$$\mathcal{B}(\mu \to e\gamma) < 4.2 \times 10^{-13} \text{ (90\% CL)}$$ [TheMEG:2016wtm]

$$\mathcal{B}(\tau \to e\gamma) < 3.3 \times 10^{-8} \text{ (90\% CL)}$$ [Aubert:2009ag]

$$\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8} \text{ (90\% CL)}$$ [Aubert:2009ag]

$$\Delta a_e = a_e^{\rm exp} - a_e^{\rm SM} = -0.88(0.36) \times 10^{-12} \text{ @ } 1\sigma$$ [Parker:2018]

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 268(63)(43) \times 10^{-11} \text{ @ } 1\sigma$$ [Tanabashi:2018oca]

$$|d_e|/e < 1.1 \times 10^{-29} \text{ cm (90\% CL)}$$ [Andreev:2018ayy]

$$|d_\mu|/e < 1.9 \times 10^{-19} \text{ cm (95\% CL)}$$ [Bennett:2008dy]

$$d_\tau/e \in [-2.2, 4.5] \times 10^{-17} \text{ cm (95\% CL)}$$ [Inami:2002ah]

$$|d_N|/e < 3.0 \times 10^{-26} \text{ cm (90\% CL)}$$ [Afach:2015sja]