Two-Higgs-Doublet Model Effective Field Theory

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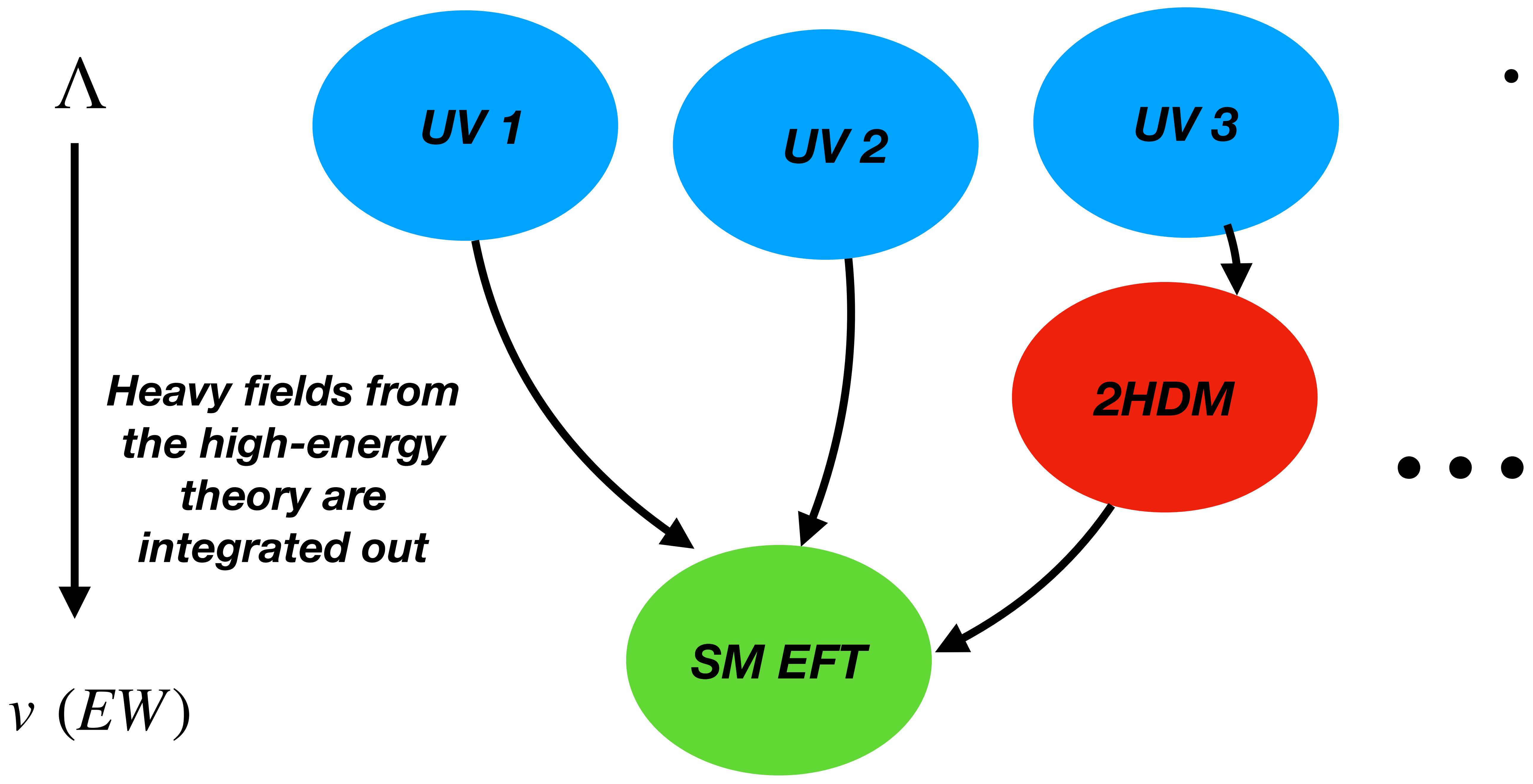
Effective Field Theories

- New physics affects ***low energy*** observables from **non-renormalizable operators with Wilson coefficients** $C_i \propto \Lambda^{4-d}$ **for** $d > 4$



Leptons, quarks, $\gamma, Z, W^{\pm}, h$

$$\mathscr{L} = \mathscr{L}_{\textbf{SM}} + \sum C_i^{(5)} \mathscr{O}_i^{(5)} + \sum C_i^{(6)} \mathscr{O}_i^{(6)}$$

- Some UV theory can describe at low energies the SM (SMEFT)
- Maybe some other theory can contain additional Higgs scalars $H, A, H^{\pm}$ and can be integrated out $v \ll M_2 \simeq \Lambda$
  - This has been realized in the non-linear Higgs Effective Theory

J. High Energy Phys. 10 036 (2015)

Phys. Rev. D 109, 075022 (2024)

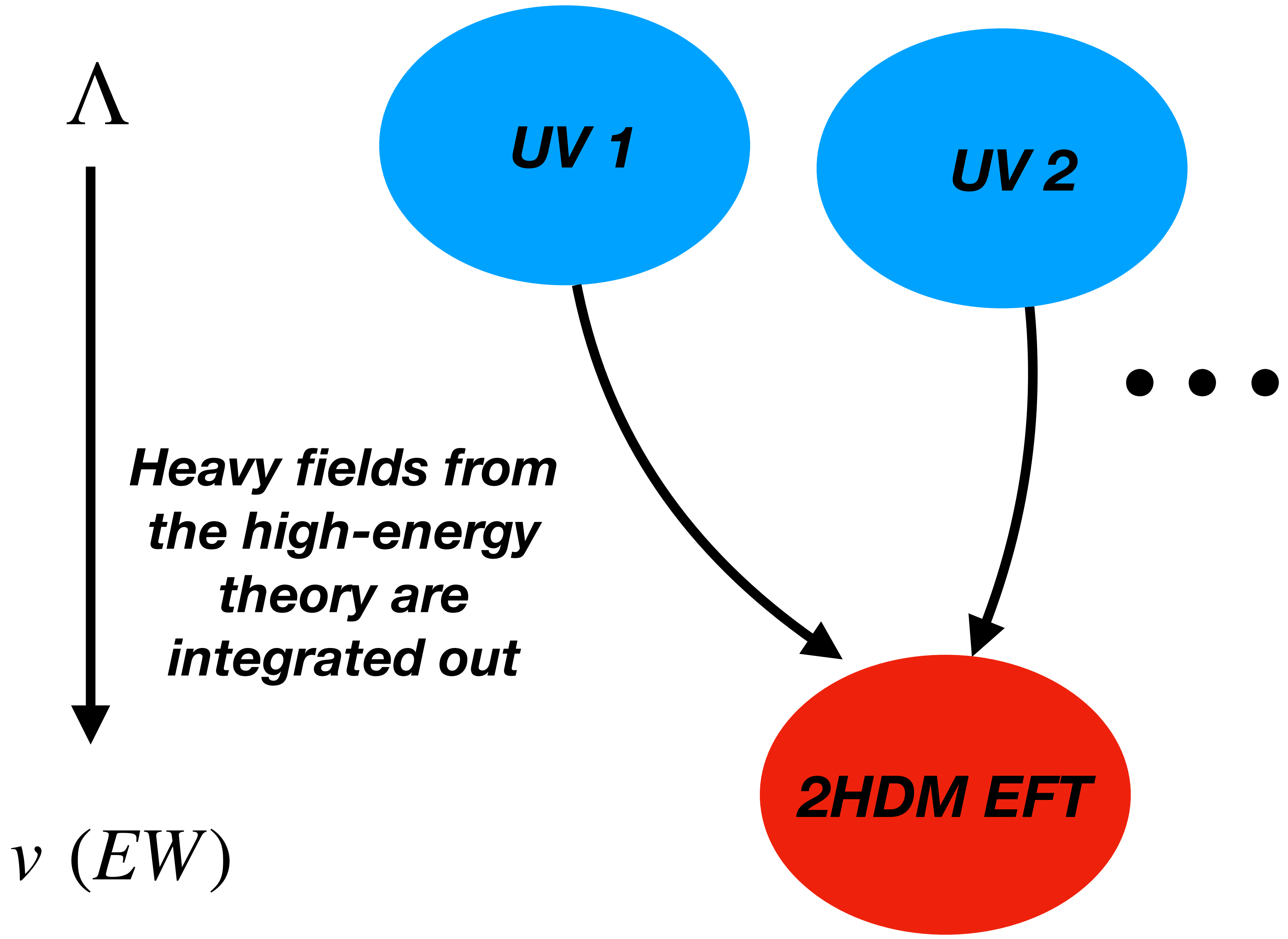
Motivation

- Now, let's assume that the low energy theory is described by not only the SM particles **but new Higgses** $H, A, H^{\pm}$

- Why? The 2HDM is one of the simplest extensions of the SM by adding one additional Higgs doublet

    - Can also be specified further by how the Higgs doublets couple to fermions (type-I, II, X, and Y)

- Although there are new neutral and charged Higgses, their masses **could be heavy (and integrated out) or light and should be kept in the low energy theory**



SM + new Higgses: $H, A, H^{\pm}$

$$\mathscr{L} = \mathscr{L}_{\textbf{2HDM}} + \sum C_i^{(5)} \mathcal{O}_i^{(5)} + \sum C_i^{(6)} \mathcal{O}_i^{(6)}$$

- Previous groups have looked at the CP-conserving case with Z_2 symmetry only, however, misidentified operators that are unique in the types of 2HDMs

J. High Energy Phys. 09 160 (2016)

- Other groups have attempted to construct the general 2HDM EFT, but couldn't find some sets of linearly independent operators

J. High Energy Phys. 10 048 (2017)
J. High Energy Phys. 09 035 (2019)

Higgs Doublets

- If there's CP conservation in the scalar sector, then the doublets have the following components:

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

$$\Phi_1^{\pm} = G^{\pm} \cos \hat{\beta}^{\pm} - H^{\pm} \sin \hat{\beta}^{\pm}$$

$$\Phi_2^{\pm} = G^{\pm} \sin \hat{\beta}^{\pm} + H^{\pm} \cos \hat{\beta}^{\pm}$$

$$\Phi_1^0 = v_1 + \frac{1}{\sqrt{2}}(-h \sin \hat{\alpha} + H \cos \hat{\alpha} + iG \cos \hat{\beta} - iA \sin \hat{\beta})$$

$$\Phi_2^0 = v_2 + \frac{1}{\sqrt{2}}(h \cos \hat{\alpha} + H \sin \hat{\alpha} + iG \sin \hat{\beta} + iA \cos \hat{\beta})$$

New Higgs scalars

$$\{H, A, H^{\pm}\}$$

$$v = 174 \ GeV \qquad v_1 \equiv v \cos \beta \qquad v_2 \equiv v \sin \beta$$

- β is the **vacuum angle**
- $\hat{\beta}, \hat{\beta}^{\pm}$ rotate the CP-odd and charged scalars to the $\{G, A\}$ and $\{G^{\pm}, H^{\pm}\}$ basis
- $\hat{\alpha}$ rotates the CP-even scalars to the $\{h, H\}$ basis

The Complete Set of Effective Operators

(Warsaw-like basis) J. High Energy Phys. 10 085 (2010)

$$\mathcal{O}_{\nu\nu\Phi}^{(11)} = (\Phi_1 \cdot l_L)^T \mathbf{C} (\Phi_1 \cdot l_L),$$
$$\mathcal{O}_{\nu\nu\Phi}^{(22)} = (\Phi_2 \cdot l_L)^T \mathbf{C} (\Phi_2 \cdot l_L),$$
$$\mathcal{O}_{\nu\nu\Phi}^{(12)} = (\Phi_1 \cdot l_L)^T \mathbf{C} (\Phi_2 \cdot l_L),$$

$(\cdot \cdot)$ Tells us which Higgs doublets are being contracted together

Lepton-violating (Weinberg) operators

Mass operators $\psi^2\phi^3$ ***(48)***

Dipole operators $\psi^2 X\phi$ ***(32)***

$\psi^2\phi^3$	$\mathcal{O}_{l\Phi_1}^{(11)} = \bar{l}_L e_R \Phi_1 (\Phi_1^\dagger \Phi_1)$	$\mathcal{O}_{d\Phi_1}^{(11)} = \bar{q}_L d_R \Phi_1 (\Phi_1^\dagger \Phi_1)$	$\mathcal{O}_{u\Phi_1}^{(11)} = \bar{q}_L u_R \cdot \Phi_1^\dagger (\Phi_1^\dagger \Phi_1)$
	$\mathcal{O}_{l\Phi_1}^{(22)} = \bar{l}_L e_R \Phi_1 (\Phi_2^\dagger \Phi_2)$	$\mathcal{O}_{d\Phi_1}^{(22)} = \bar{q}_L d_R \Phi_1 (\Phi_2^\dagger \Phi_2)$	$\mathcal{O}_{u\Phi_1}^{(22)} = \bar{q}_L u_R \cdot \Phi_1^\dagger (\Phi_2^\dagger \Phi_2)$
	$\mathcal{O}_{l\Phi_1}^{(21)} = \bar{l}_L e_R \Phi_1 (\Phi_2^\dagger \Phi_1)$	$\mathcal{O}_{d\Phi_1}^{(21)} = \bar{q}_L d_R \Phi_1 (\Phi_2^\dagger \Phi_1)$	$\mathcal{O}_{u\Phi_1}^{(21)} = \bar{q}_L u_R \cdot \Phi_1^\dagger (\Phi_2^\dagger \Phi_1)$
	$\mathcal{O}_{l\Phi_1}^{(12)} = \bar{l}_L e_R \Phi_1 (\Phi_1^\dagger \Phi_2)$	$\mathcal{O}_{d\Phi_1}^{(12)} = \bar{q}_L d_R \Phi_1 (\Phi_1^\dagger \Phi_2)$	$\mathcal{O}_{u\Phi_1}^{(12)} = \bar{q}_L u_R \cdot \Phi_1^\dagger (\Phi_1^\dagger \Phi_2)$
	$\mathcal{O}_{l\Phi_2}^{(22)} = \bar{l}_L e_R \Phi_2 (\Phi_2^\dagger \Phi_2)$	$\mathcal{O}_{d\Phi_2}^{(22)} = \bar{q}_L d_R \Phi_2 (\Phi_2^\dagger \Phi_2)$	$\mathcal{O}_{u\Phi_2}^{(22)} = \bar{q}_L u_R \cdot \Phi_2^\dagger (\Phi_2^\dagger \Phi_2)$
	$\mathcal{O}_{l\Phi_2}^{(11)} = \bar{l}_L e_R \Phi_2 (\Phi_1^\dagger \Phi_1)$	$\mathcal{O}_{d\Phi_2}^{(11)} = \bar{q}_L d_R \Phi_2 (\Phi_1^\dagger \Phi_1)$	$\mathcal{O}_{u\Phi_2}^{(11)} = \bar{q}_L u_R \cdot \Phi_2^\dagger (\Phi_1^\dagger \Phi_1)$
	$\mathcal{O}_{l\Phi_2}^{(21)} = \bar{l}_L e_R \Phi_2 (\Phi_2^\dagger \Phi_1)$	$\mathcal{O}_{d\Phi_2}^{(21)} = \bar{q}_L d_R \Phi_2 (\Phi_2^\dagger \Phi_1)$	$\mathcal{O}_{u\Phi_2}^{(21)} = \bar{q}_L u_R \cdot \Phi_2^\dagger (\Phi_2^\dagger \Phi_1)$
	$\mathcal{O}_{l\Phi_2}^{(12)} = \bar{l}_L e_R \Phi_2 (\Phi_1^\dagger \Phi_2)$	$\mathcal{O}_{d\Phi_2}^{(12)} = \bar{q}_L d_R \Phi_2 (\Phi_1^\dagger \Phi_2)$	$\mathcal{O}_{u\Phi_2}^{(12)} = \bar{q}_L u_R \cdot \Phi_2^\dagger (\Phi_1^\dagger \Phi_2)$
$\psi^2 X\phi$	$\mathcal{O}_{lB\Phi_1} = \bar{l}_L \sigma^{\mu\nu} e_R \Phi_1 B_{\mu\nu}$	$\mathcal{O}_{dB\Phi_1} = \bar{q}_L \sigma^{\mu\nu} d_R \Phi_1 B_{\mu\nu}$	$\mathcal{O}_{uB\Phi_1} = \bar{q}_L \sigma^{\mu\nu} u_R \cdot \Phi_1^\dagger B_{\mu\nu}$
	$\mathcal{O}_{lW\Phi_1} = \bar{l}_L \sigma^{\mu\nu} e_R \tau^a \Phi_1 W_{\mu\nu}^a$	$\mathcal{O}_{dW\Phi_1} = \bar{q}_L \sigma^{\mu\nu} d_R \tau^a \Phi_1 W_{\mu\nu}^a$	$\mathcal{O}_{uW\Phi_1} = \bar{q}_L \sigma^{\mu\nu} u_R \tau^a \cdot \Phi_1^\dagger W_{\mu\nu}^a$
	$\mathcal{O}_{lB\Phi_2} = \bar{l}_L \sigma^{\mu\nu} e_R \Phi_2 B_{\mu\nu}$	$\mathcal{O}_{dG\Phi_1} = \bar{q}_L \sigma^{\mu\nu} \lambda^a d_R \Phi_1 G_{\mu\nu}^a$	$\mathcal{O}_{uG\Phi_1} = \bar{q}_L \sigma^{\mu\nu} \lambda^a u_R \cdot \Phi_1^\dagger G_{\mu\nu}^a$
	$\mathcal{O}_{lW\Phi_2} = \bar{l}_L \sigma^{\mu\nu} e_R \tau^a \Phi_2 W_{\mu\nu}^a$	$\mathcal{O}_{dB\Phi_2} = \bar{q}_L \sigma^{\mu\nu} d_R \Phi_2 B_{\mu\nu}$	$\mathcal{O}_{uB\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \cdot \Phi_2^\dagger B_{\mu\nu}$
		$\mathcal{O}_{dW\Phi_2} = \bar{q}_L \sigma^{\mu\nu} d_R \tau^a \Phi_2 W_{\mu\nu}^a$	$\mathcal{O}_{uW\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \tau^a \cdot \Phi_2^\dagger W_{\mu\nu}^a$
		$\mathcal{O}_{dG\Phi_2} = \bar{q}_L \sigma^{\mu\nu} \lambda^a d_R \Phi_2 G_{\mu\nu}^a$	$\mathcal{O}_{uG\Phi_2} = \bar{q}_L \sigma^{\mu\nu} \lambda^a u_R \cdot \Phi_2^\dagger G_{\mu\nu}^a$

The Complete Set of Effective Operators

$\psi^2\phi^2 D$

$$\mathcal{O}_{\Phi e}^{(11)} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_1)(\bar{e}_R\gamma^\mu e_R)$$
$$\mathcal{O}_{\Phi e}^{(22)} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{e}_R\gamma^\mu e_R)$$
$$\mathcal{O}_{\Phi e}^{(12)} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{e}_R\gamma^\mu e_R) + \text{H.c.}$$
$$\mathcal{O}_{\Phi l}^{(11)[1]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_1)(\bar{l}_L\gamma^\mu l_L)$$
$$\mathcal{O}_{\Phi l}^{(22)[1]} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{l}_L\gamma^\mu l_L)$$
$$\mathcal{O}_{\Phi l}^{(12)[1]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{l}_L\gamma^\mu l_L) + \text{H.c.}$$
$$\mathcal{O}_{\Phi l}^{(11)[3]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu^a \Phi_1)(\bar{l}_L\tau^a\gamma^\mu l_L)$$
$$\mathcal{O}_{\Phi l}^{(22)[3]} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu^a \Phi_2)(\bar{l}_L\tau^a\gamma^\mu l_L)$$
$$\mathcal{O}_{\Phi l}^{(12)[3]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu^a \Phi_2)(\bar{l}_L\tau^a\gamma^\mu l_L) + \text{H.c.}$$

$$\mathcal{O}_{\Phi d}^{(11)} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_1)(\bar{d}_R\gamma^\mu d_R)$$
$$\mathcal{O}_{\Phi d}^{(22)} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{d}_R\gamma^\mu d_R)$$
$$\mathcal{O}_{\Phi d}^{(12)} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{d}_R\gamma^\mu d_R) + \text{H.c.}$$
$$\mathcal{O}_{\Phi u}^{(11)} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_1)(\bar{u}_R\gamma^\mu u_R)$$
$$\mathcal{O}_{\Phi u}^{(22)} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{u}_R\gamma^\mu u_R)$$
$$\mathcal{O}_{\Phi u}^{(12)} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{u}_R\gamma^\mu u_R) + \text{H.c.}$$
$$\mathcal{O}_{\Phi q}^{(11)[1]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_1)(\bar{q}_L\gamma^\mu q_L)$$
$$\mathcal{O}_{\Phi q}^{(22)[1]} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{q}_L\gamma^\mu q_L)$$
$$\mathcal{O}_{\Phi q}^{(12)[1]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu \Phi_2)(\bar{q}_L\gamma^\mu q_L) + \text{H.c.}$$
$$\mathcal{O}_{\Phi q}^{(11)[3]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu^a \Phi_1)(\bar{q}_L\tau^a\gamma^\mu q_L)$$
$$\mathcal{O}_{\Phi q}^{(22)[3]} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu^a \Phi_2)(\bar{q}_L\tau^a\gamma^\mu q_L)$$
$$\mathcal{O}_{\Phi q}^{(12)[3]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu^a \Phi_2)(\bar{q}_L\tau^a\gamma^\mu q_L) + \text{H.c.}$$
$$\mathcal{O}_{\Phi ud}^{(11)} = (\Phi_1 \cdot iD_\mu \Phi_1)(\bar{u}_R\gamma^\mu d_R) + \text{H.c.}$$
$$\mathcal{O}_{\Phi ud}^{(22)} = (\Phi_2 \cdot iD_\mu \Phi_2)(\bar{u}_R\gamma^\mu d_R) + \text{H.c.}$$
$$\mathcal{O}_{\Phi ud}^{(21)} = (\Phi_2 i \cdot \overleftrightarrow{D}_\mu \Phi_1)(\bar{u}_R\gamma^\mu d_R) + \text{H.c.}$$

Left- or right-handed covariant derivative operators $\psi^2\phi^2 D$ (34)

$$\Phi_{1,2}^\dagger \overleftrightarrow{D}_\mu \Phi_{1,2} \equiv \left(\Phi_{1,2}^\dagger (D_\mu \Phi_{1,2}) - (D_\mu \Phi_{1,2})^\dagger \Phi_{1,2}\right)$$

$$\Phi_{1,2}^\dagger \overleftrightarrow{D}_\mu^a \Phi_{1,2} \equiv \left(\Phi_{1,2}^\dagger \tau^a (D_\mu \Phi_{1,2}) - (D_\mu \Phi_{1,2})^\dagger \tau^a \Phi_{1,2}\right)$$

Antisymmetric combinations of covariant derivatives

The Complete Set of Effective Operators

Scalar derivative operators $\phi^4 D^2$ (20)

$\phi^4 D^2$

$$\mathcal{O}_{\Phi\partial^2}^{(11)(11)} = \partial_\mu(\Phi_1^\dagger\Phi_1)\partial^\mu(\Phi_1^\dagger\Phi_1)$$
$$\mathcal{O}_{\Phi\partial^2}^{(22)(22)} = \partial_\mu(\Phi_2^\dagger\Phi_2)\partial^\mu(\Phi_2^\dagger\Phi_2)$$
$$\mathcal{O}_{\Phi\partial^2}^{(11)(22)} = \partial_\mu(\Phi_1^\dagger\Phi_1)\partial^\mu(\Phi_2^\dagger\Phi_2)$$
$$\mathcal{O}_{\Phi\partial^2}^{(21)(21)} = \partial_\mu(\Phi_2^\dagger\Phi_1)\partial^\mu(\Phi_2^\dagger\Phi_1) + \text{H.c.}$$
$$\mathcal{O}_{\Phi\partial^2}^{(21)(12)} = \partial_\mu(\Phi_2^\dagger\Phi_1)\partial^\mu(\Phi_1^\dagger\Phi_2)$$
$$\mathcal{O}_{\Phi\partial^2}^{(21)(11)} = \partial_\mu(\Phi_2^\dagger\Phi_1)\partial^\mu(\Phi_1^\dagger\Phi_1) + \text{H.c.}$$
$$\mathcal{O}_{\Phi\partial^2}^{(21)(22)} = \partial_\mu(\Phi_2^\dagger\Phi_1)\partial^\mu(\Phi_2^\dagger\Phi_2) + \text{H.c.}$$

$$\mathcal{O}_{\Phi D}^{(11)(11)} = (\Phi_1^\dagger \overleftrightarrow{D}_\mu \Phi_1)(\Phi_1^\dagger \overleftrightarrow{D}^\mu \Phi_1)$$
$$\mathcal{O}_{\Phi D}^{(22)(22)} = (\Phi_2^\dagger \overleftrightarrow{D}_\mu \Phi_2)(\Phi_2^\dagger \overleftrightarrow{D}^\mu \Phi_2)$$
$$\mathcal{O}_{\Phi D}^{(11)(22)} = (\Phi_1^\dagger \overleftrightarrow{D}_\mu \Phi_1)(\Phi_2^\dagger \overleftrightarrow{D}^\mu \Phi_2)$$
$$\mathcal{O}_{\Phi D}^{(21)(21)} = (\Phi_2^\dagger \overleftrightarrow{D}_\mu \Phi_1)(\Phi_2^\dagger \overleftrightarrow{D}^\mu \Phi_1) + \text{H.c.}$$
$$\mathcal{O}_{\Phi D}^{(21)(12)} = (\Phi_2^\dagger \overleftrightarrow{D}_\mu \Phi_1)(\Phi_1^\dagger \overleftrightarrow{D}^\mu \Phi_2)$$
$$\mathcal{O}_{\Phi D}^{(21)(11)} = (\Phi_2^\dagger \overleftrightarrow{D}_\mu \Phi_1)(\Phi_1^\dagger \overleftrightarrow{D}^\mu \Phi_1) + \text{H.c.}$$
$$\mathcal{O}_{\Phi D}^{(21)(22)} = (\Phi_2^\dagger \overleftrightarrow{D}_\mu \Phi_1)(\Phi_2^\dagger \overleftrightarrow{D}^\mu \Phi_2) + \text{H.c.}$$

Scalar operators ϕ^6 (20)

ϕ^6

$$\mathcal{O}_{\Phi}^{(11)(11)(11)} = (\Phi_1^\dagger\Phi_1)^3$$
$$\mathcal{O}_{\Phi}^{(11)(11)(22)} = (\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2)$$
$$\mathcal{O}_{\Phi}^{(11)(22)(22)} = (\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2$$
$$\mathcal{O}_{\Phi}^{(11)(11)(21)} = (\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_1) + \text{H.c.}$$
$$\mathcal{O}_{\Phi}^{(22)(22)(21)} = (\Phi_2^\dagger\Phi_2)^2(\Phi_2^\dagger\Phi_1) + \text{H.c.}$$
$$\mathcal{O}_{\Phi}^{(22)(22)(22)} = (\Phi_2^\dagger\Phi_2)^3$$

$$\mathcal{O}_{\Phi}^{(11)(21)(21)} = (\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1)^2 + \text{H.c.}$$
$$\mathcal{O}_{\Phi}^{(11)(21)(12)} = (\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)$$
$$\mathcal{O}_{\Phi}^{(22)(21)(21)} = (\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)^2 + \text{H.c.}$$
$$\mathcal{O}_{\Phi}^{(22)(21)(12)} = (\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)$$
$$\mathcal{O}_{\Phi}^{(21)(21)(21)} = (\Phi_2^\dagger\Phi_1)^3 + \text{H.c.}$$
$$\mathcal{O}_{\Phi}^{(21)(21)(12)} = (\Phi_2^\dagger\Phi_1)^2(\Phi_1^\dagger\Phi_2) + \text{H.c.}$$
$$\mathcal{O}_{\Phi}^{(11)(22)(21)} = (\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \text{H.c.}$$

Symmetric combinations of covariant derivatives

$$\left(\Phi_{1,2}^\dagger(D_\mu\Phi_{1,2}) + (D_\mu\Phi_{1,2})^\dagger\Phi_{1,2}\right) = \partial_\mu(\Phi_{1,2}^\dagger\Phi_{1,2})$$

ϕ^6 operators affect the vacuum stability and scalar masses

$\phi^4 D^2$ operators affect the gauge masses and kinetic terms of the scalars

The Complete Set of Effective Operators

X^3 operators SAME as in SMEFT (4)

X^3	$\mathcal{O}_W = \epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\sigma} W_\sigma^{c\mu}$	$\mathcal{O}_{\tilde{W}} = \epsilon^{abc} \tilde{W}_\mu^{a\nu} W_\nu^{b\sigma} W_\sigma^{c\mu}$
	$\mathcal{O}_G = f^{abc} G_\mu^{a\nu} G_\nu^{b\sigma} G_\sigma^{c\mu}$	$\mathcal{O}_{\tilde{G}} = f^{abc} \tilde{G}_\mu^{a\nu} G_\nu^{b\sigma} G_\sigma^{c\mu}$
$X^2\phi^2$	$\mathcal{O}_{\Phi G}^{(11)} = (\Phi_1^\dagger \Phi_1) G_{\mu\nu}^a G^{a\mu\nu}$	$\mathcal{O}_{\Phi W}^{(11)} = (\Phi_1^\dagger \Phi_1) W_{\mu\nu}^a W^{a\mu\nu}$
	$\mathcal{O}_{\Phi G}^{(22)} = (\Phi_2^\dagger \Phi_2) G_{\mu\nu}^a G^{a\mu\nu}$	$\mathcal{O}_{\Phi W}^{(22)} = (\Phi_2^\dagger \Phi_2) W_{\mu\nu}^a W^{a\mu\nu}$
	$\mathcal{O}_{\Phi G}^{(21)} = (\Phi_2^\dagger \Phi_1) G_{\mu\nu}^a G^{a\mu\nu} + \text{H.c.}$	$\mathcal{O}_{\Phi W}^{(21)} = (\Phi_2^\dagger \Phi_1) W_{\mu\nu}^a W^{a\mu\nu} + \text{H.c.}$
	$\mathcal{O}_{\Phi \tilde{G}}^{(11)} = (\Phi_1^\dagger \Phi_1) \tilde{G}_{\mu\nu}^a G^{a\mu\nu}$	$\mathcal{O}_{\Phi \tilde{W}}^{(11)} = (\Phi_1^\dagger \Phi_1) \tilde{W}_{\mu\nu}^a W^{a\mu\nu}$
	$\mathcal{O}_{\Phi \tilde{G}}^{(22)} = (\Phi_2^\dagger \Phi_2) \tilde{G}_{\mu\nu}^a G^{a\mu\nu}$	$\mathcal{O}_{\Phi \tilde{W}}^{(22)} = (\Phi_2^\dagger \Phi_2) \tilde{W}_{\mu\nu}^a W^{a\mu\nu}$
	$\mathcal{O}_{\Phi \tilde{G}}^{(21)} = (\Phi_2^\dagger \Phi_1) \tilde{G}_{\mu\nu}^a G^{a\mu\nu} + \text{H.c.}$	$\mathcal{O}_{\Phi \tilde{W}}^{(21)} = (\Phi_2^\dagger \Phi_1) \tilde{W}_{\mu\nu}^a W^{a\mu\nu} + \text{H.c.}$
	$\mathcal{O}_{\Phi B}^{(11)} = (\Phi_1^\dagger \Phi_1) B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{\Phi WB}^{(11)} = (\Phi_1^\dagger \tau^a \Phi_1) W_{\mu\nu}^a B^{\mu\nu}$
	$\mathcal{O}_{\Phi B}^{(22)} = (\Phi_2^\dagger \Phi_2) B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{\Phi WB}^{(22)} = (\Phi_2^\dagger \tau^a \Phi_2) W_{\mu\nu}^a B^{\mu\nu}$
	$\mathcal{O}_{\Phi B}^{(21)} = (\Phi_2^\dagger \Phi_1) B_{\mu\nu} B^{\mu\nu} + \text{H.c.}$	$\mathcal{O}_{\Phi WB}^{(21)} = (\Phi_2^\dagger \tau^a \Phi_1) W_{\mu\nu}^a B^{\mu\nu} + \text{H.c.}$
	$\mathcal{O}_{\Phi \tilde{B}}^{(11)} = (\Phi_1^\dagger \Phi_1) \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{\Phi \tilde{W}B}^{(11)} = (\Phi_1^\dagger \tau^a \Phi_1) \tilde{W}_{\mu\nu}^a B^{\mu\nu}$
	$\mathcal{O}_{\Phi \tilde{B}}^{(22)} = (\Phi_2^\dagger \Phi_2) \tilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{\Phi \tilde{W}B}^{(22)} = (\Phi_2^\dagger \tau^a \Phi_2) \tilde{W}_{\mu\nu}^a B^{\mu\nu}$
	$\mathcal{O}_{\Phi \tilde{B}}^{(21)} = (\Phi_2^\dagger \Phi_1) \tilde{B}_{\mu\nu} B^{\mu\nu} + \text{H.c.}$	$\mathcal{O}_{\Phi \tilde{W}B}^{(21)} = (\Phi_2^\dagger \tau^a \Phi_1) \tilde{W}_{\mu\nu}^a B^{\mu\nu} + \text{H.c.}$

Scalar-gauge operators
$X^2\phi^2$ (32)

$X^2\phi^2$ operators affects kinetic terms of gauge bosons

ψ^4 operators SAME as in SMEFT (38)

ψ^4	$\mathcal{O}_{ll} = (\bar{l}_L\gamma^\mu l_L)(\bar{l}_L\gamma_\mu l_L)$	$\mathcal{O}_{ee} = (\bar{e}_R\gamma^\mu e_R)(\bar{e}_R\gamma_\mu e_R)$
	$\mathcal{O}_{qq}^{(1)} = (\bar{q}_L\gamma^\mu q_L)(\bar{q}_L\gamma_\mu q_L)$	$\mathcal{O}_{dd} = (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma_\mu d_R)$
	$\mathcal{O}_{qq}^{(3)} = (\bar{q}_L\tau^a\gamma^\mu q_L)(\bar{q}_L\tau^a\gamma_\mu q_L)$	$\mathcal{O}_{uu} = (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma_\mu u_R)$
	$\mathcal{O}_{lq}^{(1)} = (\bar{l}_L\gamma^\mu l_L)(\bar{q}_L\gamma_\mu q_L)$	$\mathcal{O}_{ed} = (\bar{e}_R\gamma^\mu e_R)(\bar{d}_R\gamma_\mu d_R)$
	$\mathcal{O}_{le} = (\bar{l}_L\gamma^\mu l_L)(\bar{e}_R\gamma_\mu e_R)$	$\mathcal{O}_{eu} = (\bar{e}_R\gamma^\mu e_R)(\bar{u}_R\gamma_\mu u_R)$
	$\mathcal{O}_{ld} = (\bar{l}_L\gamma^\mu l_L)(\bar{d}_R\gamma_\mu d_R)$	$\mathcal{O}_{ud}^{(1)} = (\bar{u}_R\gamma^\mu u_R)(\bar{d}_R\gamma_\mu d_R)$
	$\mathcal{O}_{lu} = (\bar{l}_L\gamma^\mu l_L)(\bar{u}_R\gamma_\mu u_R)$	$\mathcal{O}_{ud}^{(8)} = (\bar{u}_R\lambda^a\gamma^\mu u_R)(\bar{d}_R\lambda^a\gamma_\mu d_R)$
	$\mathcal{O}_{qe} = (\bar{q}_L\gamma^\mu q_L)(\bar{e}_R\gamma_\mu e_R)$	$\mathcal{O}_{qd}^{(1)} = (\bar{q}_L\gamma^\mu q_L)(\bar{d}_R\gamma_\mu d_R)$
	$\mathcal{O}_{lq}^{(3)} = (\bar{l}_L\tau^a\gamma^\mu l_L)(\bar{q}_L\tau^a\gamma_\mu q_L)$	$\mathcal{O}_{qd}^{(8)} = (\bar{q}_L\lambda^a\gamma^\mu q_L)(\bar{d}_R\lambda^a\gamma_\mu d_R)$
		$\mathcal{O}_{qu}^{(1)} = (\bar{q}_L\gamma^\mu q_L)(\bar{u}_R\gamma_\mu u_R)$
		$\mathcal{O}_{qu}^{(8)} = (\bar{q}_L\lambda^a\gamma^\mu q_L)(\bar{u}_R\lambda^a\gamma_\mu u_R)$
	$\mathcal{O}_{ledq} = (\bar{l}_L e_R)(\bar{d}_R q_L) + \text{H.c.}$	$\mathcal{O}_{duq} = \epsilon^{\alpha\beta\gamma}\epsilon_{jk}((d_R^\alpha)^T\mathbf{C}u_R^\beta)((q_{Lj}^\gamma)^T\mathbf{C}l_{Lk}) + \text{H.c.}$
	$\mathcal{O}_{quqd}^{(1)} = (\bar{q}_L u_R)\cdot(\bar{q}_L d_R) + \text{H.c.}$	$\mathcal{O}_{qqu} = \epsilon^{\alpha\beta\gamma}\epsilon_{jk}((q_{Lj}^\alpha)^T\mathbf{C}q_{Lk}^\beta)((u_R^\gamma)^T\mathbf{C}e_R) + \text{H.c.}$
	$\mathcal{O}_{quqd}^{(8)} = (\bar{q}_L\lambda^a u_R)\cdot(\bar{q}_L\lambda^a d_R) + \text{H.c.}$	$\mathcal{O}_{qqq} = \epsilon^{\alpha\beta\gamma}\epsilon_{jn}\epsilon_{km}((q_{Lj}^\alpha)^T\mathbf{C}q_{Lk}^\beta)((q_{Lm}^\gamma)^T\mathbf{C}l_{Ln}) + \text{H.c.}$
	$\mathcal{O}_{lequ}^{(1)} = (\bar{l}_L e_R)\cdot(\bar{q}_L u_R) + \text{H.c.}$	$\mathcal{O}_{duu} = \epsilon^{\alpha\beta\gamma}((d_R^\alpha)^T\mathbf{C}u_R^\beta)((u_R^\gamma)^T\mathbf{C}e_R) + \text{H.c.}$
	$\mathcal{O}_{lequ}^{(3)} = (\bar{l}_L\sigma^{\mu\nu}e_R)\cdot(\bar{q}_L\sigma_{\mu\nu}u_R) + \text{H.c.}$	

Total: $48 + 32 + 34 + 20 + 20 + 32 + 4 + 38 = 228$

Matches Hilbert series counting
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Types of 2HDM EFTs

- Avoid flavor changing neutral currents with fermions by imposing Z_2 symmetry on the fields:

Model	u	d	e	l_L	e_R	q_L	u_R	d_R	Φ_1	Φ_2
Type-I	Φ_2	Φ_2	Φ_2	$+$	$+$	$+$	$+$	$+$	$-$	$+$
Type-II	Φ_2	Φ_1	Φ_1	$+$	$-$	$+$	$+$	$-$	$-$	$+$
Type-X (Lepton-specific)	Φ_2	Φ_2	Φ_1	$+$	$-$	$+$	$+$	$+$	$-$	$+$
Type-Y (Flipped)	Φ_2	Φ_1	Φ_2	$+$	$+$	$+$	$+$	$-$	$-$	$+$

Type-I (31 + H.c. = 62)			
$\psi^2\phi^3$	$\mathcal{O}^{(21)}_{l\Phi_1} = \bar{l}_L e_R \Phi_1(\Phi_2^\dagger\Phi_1)$	$\mathcal{O}^{(21)}_{d\Phi_1} = \bar{q}_L d_R \Phi_1(\Phi_2^\dagger\Phi_1)$	$\mathcal{O}^{(21)}_{u\Phi_1} = \bar{q}_L u_R \cdot \Phi_1^\dagger(\Phi_2^\dagger\Phi_1)$
	$\mathcal{O}^{(12)}_{l\Phi_1} = \bar{l}_L e_R \Phi_1(\Phi_1^\dagger\Phi_2)$	$\mathcal{O}^{(12)}_{d\Phi_1} = \bar{q}_L d_R \Phi_1(\Phi_1^\dagger\Phi_2)$	$\mathcal{O}^{(12)}_{u\Phi_1} = \bar{q}_L u_R \cdot \Phi_1^\dagger(\Phi_1^\dagger\Phi_2)$
	$\mathcal{O}^{(22)}_{l\Phi_2} = \bar{l}_L e_R \Phi_2(\Phi_2^\dagger\Phi_2)$	$\mathcal{O}^{(22)}_{d\Phi_2} = \bar{q}_L d_R \Phi_2(\Phi_2^\dagger\Phi_2)$	$\mathcal{O}^{(22)}_{u\Phi_2} = \bar{q}_L u_R \cdot \Phi_2^\dagger(\Phi_2^\dagger\Phi_2)$
	$\mathcal{O}^{(11)}_{l\Phi_2} = \bar{l}_L e_R \Phi_2(\Phi_1^\dagger\Phi_1)$	$\mathcal{O}^{(11)}_{d\Phi_2} = \bar{q}_L d_R \Phi_2(\Phi_1^\dagger\Phi_1)$	$\mathcal{O}^{(11)}_{u\Phi_2} = \bar{q}_L u_R \cdot \Phi_2^\dagger(\Phi_1^\dagger\Phi_1)$
$\psi^2 X\phi$	$\mathcal{O}_{lB\Phi_2} = \bar{l}_L \sigma^{\mu\nu} e_R \Phi_2 B_{\mu\nu}$	$\mathcal{O}_{dB\Phi_2} = \bar{q}_L \sigma^{\mu\nu} d_R \Phi_2 B_{\mu\nu}$	$\mathcal{O}_{uB\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \cdot \Phi_2^\dagger B_{\mu\nu}$
	$\mathcal{O}_{lW\Phi_2} = \bar{l}_L \sigma^{\mu\nu} e_R \tau^a \Phi_2 W^a_{\mu\nu}$	$\mathcal{O}_{dW\Phi_2} = \bar{q}_L \sigma^{\mu\nu} d_R \tau^a \Phi_2 W^a_{\mu\nu}$	$\mathcal{O}_{uW\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \tau^a \cdot \Phi_2^\dagger W^a_{\mu\nu}$
		$\mathcal{O}_{dG\Phi_2} = \bar{q}_L \sigma^{\mu\nu} \lambda^a d_R \Phi_2 G^a_{\mu\nu}$	$\mathcal{O}_{uG\Phi_2} = \bar{q}_L \sigma^{\mu\nu} \lambda^a u_R \cdot \Phi_2^\dagger G^a_{\mu\nu}$
$\psi^2\phi^2 D$	$\mathcal{O}^{(11)}_{\Phi ud} = (\Phi_1 \cdot iD_\mu \Phi_1)(\bar{u}_R \gamma^\mu d_R)$		$\mathcal{O}^{(22)}_{\Phi ud} = (\Phi_2 \cdot iD_\mu \Phi_2)(\bar{u}_R \gamma^\mu d_R)$
ψ^4	$\mathcal{O}_{ledq} = (\bar{l}_L e_R)(\bar{d}_R q_L)$		$\mathcal{O}_{duq} = \epsilon^{\alpha\beta\gamma}\epsilon_{jk}((d_R^\alpha)^T \mathbf{C} u_R^\beta)((q_{Lj}^\gamma)^T \mathbf{C} l_{Lk})$
	$\mathcal{O}^{(1)}_{quqd} = (\bar{q}_L u_R) \cdot (\bar{q}_L d_R)$		$\mathcal{O}_{qqu} = \epsilon^{\alpha\beta\gamma}\epsilon_{jk}((q_{Lj}^\alpha)^T \mathbf{C} q_{Lk}^\beta)((u_R^\gamma)^T \mathbf{C} e_R)$
	$\mathcal{O}^{(8)}_{quqd} = (\bar{q}_L \lambda^a u_R) \cdot (\bar{q}_L \lambda^a d_R)$		$\mathcal{O}_{qqq} = \epsilon^{\alpha\beta\gamma}\epsilon_{jn}((q_{Lj}^\alpha)^T \mathbf{C} q_L^\beta) \cdot ((q_L^\gamma)^T \mathbf{C} l_{Ln})$
	$\mathcal{O}^{(1)}_{lequ} = (\bar{l}_L e_R) \cdot (\bar{q}_L u_R)$		$\mathcal{O}_{duu} = \epsilon^{\alpha\beta\gamma}((d_R^\alpha)^T \mathbf{C} u_R^\beta)((u_R^\gamma)^T \mathbf{C} e_R)$
	$\mathcal{O}^{(3)}_{lequ} = (\bar{l}_L \sigma^{\mu\nu} e_R) \cdot (\bar{q}_L \sigma_{\mu\nu} u_R)$		

Type-II (24 + H.c. = 48)			
$\psi^2\phi^3$	$\mathcal{O}^{(11)}_{l\Phi_1} = \bar{l}_L e_R \Phi_1(\Phi_1^\dagger\Phi_1)$	$\mathcal{O}^{(11)}_{d\Phi_1} = \bar{q}_L d_R \Phi_1(\Phi_1^\dagger\Phi_1)$	$\mathcal{O}^{(21)}_{u\Phi_1} = \bar{q}_L u_R \cdot \Phi_1^\dagger(\Phi_2^\dagger\Phi_1)$
	$\mathcal{O}^{(22)}_{l\Phi_1} = \bar{l}_L e_R \Phi_1(\Phi_2^\dagger\Phi_2)$	$\mathcal{O}^{(22)}_{d\Phi_1} = \bar{q}_L d_R \Phi_1(\Phi_2^\dagger\Phi_2)$	$\mathcal{O}^{(12)}_{u\Phi_1} = \bar{q}_L u_R \cdot \Phi_1^\dagger(\Phi_1^\dagger\Phi_2)$
	$\mathcal{O}^{(21)}_{l\Phi_2} = \bar{l}_L e_R \Phi_2(\Phi_2^\dagger\Phi_1)$	$\mathcal{O}^{(21)}_{d\Phi_2} = \bar{q}_L d_R \Phi_2(\Phi_2^\dagger\Phi_1)$	$\mathcal{O}^{(22)}_{u\Phi_2} = \bar{q}_L u_R \cdot \Phi_2^\dagger(\Phi_2^\dagger\Phi_2)$
	$\mathcal{O}^{(12)}_{l\Phi_2} = \bar{l}_L e_R \Phi_2(\Phi_1^\dagger\Phi_2)$	$\mathcal{O}^{(12)}_{d\Phi_2} = \bar{q}_L d_R \Phi_2(\Phi_1^\dagger\Phi_2)$	$\mathcal{O}^{(11)}_{u\Phi_2} = \bar{q}_L u_R \cdot \Phi_2^\dagger(\Phi_1^\dagger\Phi_1)$
$\psi^2 X\phi$	$\mathcal{O}_{lB\Phi_1} = \bar{l}_L \sigma^{\mu\nu} e_R \Phi_1 B_{\mu\nu}$	$\mathcal{O}_{dB\Phi_1} = \bar{q}_L \sigma^{\mu\nu} d_R \Phi_1 B_{\mu\nu}$	$\mathcal{O}_{uB\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \cdot \Phi_2^\dagger B_{\mu\nu}$
	$\mathcal{O}_{lW\Phi_1} = \bar{l}_L \sigma^{\mu\nu} e_R \tau^a \Phi_1 W^a_{\mu\nu}$	$\mathcal{O}_{dW\Phi_1} = \bar{q}_L \sigma^{\mu\nu} d_R \tau^a \Phi_1 W^a_{\mu\nu}$	$\mathcal{O}_{uW\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \tau^a \cdot \Phi_2^\dagger W^a_{\mu\nu}$
		$\mathcal{O}_{dG\Phi_1} = \bar{q}_L \sigma^{\mu\nu} \lambda^a d_R \Phi_1 G^a_{\mu\nu}$	$\mathcal{O}_{uG\Phi_2} = \bar{q}_L \sigma^{\mu\nu} \lambda^a u_R \cdot \Phi_2^\dagger G^a_{\mu\nu}$
$\psi^2\phi^2 D$	$\mathcal{O}^{(21)}_{\Phi ud} = (\Phi_2 i \cdot \overleftrightarrow{D}_\mu \Phi_1)(\bar{u}_R \gamma^\mu d_R)$		
ψ^4	$\mathcal{O}_{ledq} = (\bar{l}_L e_R)(\bar{d}_R q_L)$		$\mathcal{O}_{qqq} = \epsilon^{\alpha\beta\gamma}\epsilon_{jn}((q_{Lj}^\alpha)^T \mathbf{C} q_L^\beta) \cdot ((q_L^\gamma)^T \mathbf{C} l_{Ln})$
			$\mathcal{O}_{duu} = \epsilon^{\alpha\beta\gamma}((d_R^\alpha)^T \mathbf{C} u_R^\beta)((u_R^\gamma)^T \mathbf{C} e_R)$

Types of 2HDM EFTs

Type-X ($26 + \text{H.c.} = 52$)			
$\psi^2\phi^3$	$\mathcal{O}^{(11)}_{l\Phi_1} = \bar{l}_L e_R \Phi_1 (\Phi_1^\dagger \Phi_1)$	$\mathcal{O}^{(21)}_{d\Phi_1} = \bar{q}_L d_R \Phi_1 (\Phi_2^\dagger \Phi_1)$	$\mathcal{O}^{(21)}_{u\Phi_1} = \bar{q}_L u_R \cdot \Phi_1^\dagger (\Phi_2^\dagger \Phi_1)$
	$\mathcal{O}^{(22)}_{l\Phi_1} = \bar{l}_L e_R \Phi_1 (\Phi_2^\dagger \Phi_2)$	$\mathcal{O}^{(12)}_{d\Phi_1} = \bar{q}_L d_R \Phi_1 (\Phi_1^\dagger \Phi_2)$	$\mathcal{O}^{(12)}_{u\Phi_1} = \bar{q}_L u_R \cdot \Phi_1^\dagger (\Phi_1^\dagger \Phi_2)$
	$\mathcal{O}^{(21)}_{l\Phi_2} = \bar{l}_L e_R \Phi_2 (\Phi_2^\dagger \Phi_1)$	$\mathcal{O}^{(22)}_{d\Phi_2} = \bar{q}_L d_R \Phi_2 (\Phi_2^\dagger \Phi_2)$	$\mathcal{O}^{(22)}_{u\Phi_2} = \bar{q}_L u_R \cdot \Phi_2^\dagger (\Phi_2^\dagger \Phi_2)$
	$\mathcal{O}^{(12)}_{l\Phi_2} = \bar{l}_L e_R \Phi_2 (\Phi_1^\dagger \Phi_2)$	$\mathcal{O}^{(11)}_{d\Phi_2} = \bar{q}_L d_R \Phi_2 (\Phi_1^\dagger \Phi_1)$	$\mathcal{O}^{(11)}_{u\Phi_2} = \bar{q}_L u_R \cdot \Phi_2^\dagger (\Phi_1^\dagger \Phi_1)$
$\psi^2 X\phi$	$\mathcal{O}_{lB\Phi_1} = \bar{l}_L \sigma^{\mu\nu} e_R \Phi_1 B_{\mu\nu}$	$\mathcal{O}_{dB\Phi_2} = \bar{q}_L \sigma^{\mu\nu} d_R \Phi_2 B_{\mu\nu}$	$\mathcal{O}_{uB\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \cdot \Phi_2^\dagger B_{\mu\nu}$
	$\mathcal{O}_{lW\Phi_1} = \bar{l}_L \sigma^{\mu\nu} e_R \tau^a \Phi_1 W^a_{\mu\nu}$	$\mathcal{O}_{dW\Phi_2} = \bar{q}_L \sigma^{\mu\nu} d_R \tau^a \Phi_2 W^a_{\mu\nu}$	$\mathcal{O}_{uW\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \tau^a \cdot \Phi_2^\dagger W^a_{\mu\nu}$
		$\mathcal{O}_{dG\Phi_2} = \bar{q}_L \sigma^{\mu\nu} \lambda^a d_R \Phi_2 G^a_{\mu\nu}$	$\mathcal{O}_{uG\Phi_2} = \bar{q}_L \sigma^{\mu\nu} \lambda^a u_R \cdot \Phi_2^\dagger G^a_{\mu\nu}$
$\psi^2\phi^2 D$	$\mathcal{O}^{(11)}_{\Phi ud} = (\Phi_1 \cdot iD_\mu \Phi_1)(\bar{u}_R \gamma^\mu d_R)$		$\mathcal{O}^{(22)}_{\Phi ud} = (\Phi_2 \cdot iD_\mu \Phi_2)(\bar{u}_R \gamma^\mu d_R)$
ψ^4	$\mathcal{O}^{(1)}_{quqd} = (\bar{q}_L u_R) \cdot (\bar{q}_L d_R)$		$\mathcal{O}_{duq} = \epsilon^{\alpha\beta\gamma} \epsilon_{jk} ((d_R^\alpha)^T \mathbf{C} u_R^\beta)((q_{Lj}^\gamma)^T \mathbf{C} l_{Lk})$
	$\mathcal{O}^{(8)}_{quqd} = (\bar{q}_L \lambda^a u_R) \cdot (\bar{q}_L \lambda^a d_R)$		$\mathcal{O}_{qqq} = \epsilon^{\alpha\beta\gamma} \epsilon_{jn} ((q_{Lj}^\alpha)^T \mathbf{C} q_L^\beta) \cdot ((q_L^\gamma)^T \mathbf{C} l_{Ln})$

Type-Y ($25 + \text{H.c.} = 50$)			
$\psi^2\phi^3$	$\mathcal{O}^{(21)}_{l\Phi_1} = \bar{l}_L e_R \Phi_1 (\Phi_2^\dagger \Phi_1)$	$\mathcal{O}^{(11)}_{d\Phi_1} = \bar{q}_L d_R \Phi_1 (\Phi_1^\dagger \Phi_1)$	$\mathcal{O}^{(21)}_{u\Phi_1} = \bar{q}_L u_R \cdot \Phi_1^\dagger (\Phi_2^\dagger \Phi_1)$
	$\mathcal{O}^{(12)}_{l\Phi_1} = \bar{l}_L e_R \Phi_1 (\Phi_1^\dagger \Phi_2)$	$\mathcal{O}^{(22)}_{d\Phi_1} = \bar{q}_L d_R \Phi_1 (\Phi_2^\dagger \Phi_2)$	$\mathcal{O}^{(12)}_{u\Phi_1} = \bar{q}_L u_R \cdot \Phi_1^\dagger (\Phi_1^\dagger \Phi_2)$
	$\mathcal{O}^{(22)}_{l\Phi_2} = \bar{l}_L e_R \Phi_2 (\Phi_2^\dagger \Phi_2)$	$\mathcal{O}^{(21)}_{d\Phi_2} = \bar{q}_L d_R \Phi_2 (\Phi_2^\dagger \Phi_1)$	$\mathcal{O}^{(22)}_{u\Phi_2} = \bar{q}_L u_R \cdot \Phi_2^\dagger (\Phi_2^\dagger \Phi_2)$
	$\mathcal{O}^{(11)}_{l\Phi_2} = \bar{l}_L e_R \Phi_2 (\Phi_1^\dagger \Phi_1)$	$\mathcal{O}^{(12)}_{d\Phi_2} = \bar{q}_L d_R \Phi_2 (\Phi_1^\dagger \Phi_2)$	$\mathcal{O}^{(11)}_{u\Phi_2} = \bar{q}_L u_R \cdot \Phi_2^\dagger (\Phi_1^\dagger \Phi_1)$
$\psi^2 X\phi$	$\mathcal{O}_{lB\Phi_2} = \bar{l}_L \sigma^{\mu\nu} e_R \Phi_2 B_{\mu\nu}$	$\mathcal{O}_{dB\Phi_1} = \bar{q}_L \sigma^{\mu\nu} d_R \Phi_1 B_{\mu\nu}$	$\mathcal{O}_{uB\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \cdot \Phi_2^\dagger B_{\mu\nu}$
	$\mathcal{O}_{lW\Phi_2} = \bar{l}_L \sigma^{\mu\nu} e_R \tau^a \Phi_2 W^a_{\mu\nu}$	$\mathcal{O}_{dW\Phi_1} = \bar{q}_L \sigma^{\mu\nu} d_R \tau^a \Phi_1 W^a_{\mu\nu}$	$\mathcal{O}_{uW\Phi_2} = \bar{q}_L \sigma^{\mu\nu} u_R \tau^a \cdot \Phi_2^\dagger W^a_{\mu\nu}$
		$\mathcal{O}_{dG\Phi_1} = \bar{q}_L \sigma^{\mu\nu} \lambda^a d_R \Phi_1 G^a_{\mu\nu}$	$\mathcal{O}_{uG\Phi_2} = \bar{q}_L \sigma^{\mu\nu} \lambda^a u_R \cdot \Phi_2^\dagger G^a_{\mu\nu}$
$\psi^2\phi^2 D$	$\mathcal{O}^{(21)}_{\Phi ud} = (\Phi_2 i \cdot \overleftrightarrow{D}_\mu \Phi_1)(\bar{u}_R \gamma^\mu d_R)$		
ψ^4	$\mathcal{O}^{(1)}_{lequ} = (\bar{l}_L e_R) \cdot (\bar{q}_L u_R)$		$\mathcal{O}_{qqu} = \epsilon^{\alpha\beta\gamma} \epsilon_{jk} ((q_{Lj}^\alpha)^T \mathbf{C} q_{Lk}^\beta)((u_R^\gamma)^T \mathbf{C} e_R)$
	$\mathcal{O}^{(3)}_{lequ} = (\bar{l}_L \sigma^{\mu\nu} e_R) \cdot (\bar{q}_L \sigma_{\mu\nu} u_R)$		$\mathcal{O}_{qqq} = \epsilon^{\alpha\beta\gamma} \epsilon_{jn} ((q_{Lj}^\alpha)^T \mathbf{C} q_L^\beta) \cdot ((q_L^\gamma)^T \mathbf{C} l_{Ln})$

Notice that ψ^4 operators aren't affected by the new scalars, but are affected if a Z_2 symmetry is imposed

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predicts half of the $\psi^2\phi^3$ operators and in each type of 2HDM since they impose their Z_2 symmetry by restricting mixed pairs of $\Phi^\dagger_{1,2}\Phi_{2,1}$

Types of 2HDM EFTs

$\phi^4 D^2$	$\mathcal{O}_{\Phi\partial^2}^{(11)(11)} = \partial_\mu(\Phi_1^\dagger\Phi_1)\partial^\mu(\Phi_1^\dagger\Phi_1)$	$\mathcal{O}_{\Phi\partial^2}^{(21)(12)} = \partial_\mu(\Phi_2^\dagger\Phi_1)\partial^\mu(\Phi_1^\dagger\Phi_2)$
	$\mathcal{O}_{\Phi\partial^2}^{(22)(22)} = \partial_\mu(\Phi_2^\dagger\Phi_2)\partial^\mu(\Phi_2^\dagger\Phi_2)$	$\mathcal{O}_{\Phi\partial^2}^{(21)(21)} = \partial_\mu(\Phi_2^\dagger\Phi_1)\partial^\mu(\Phi_2^\dagger\Phi_1) + \text{H.c.}$
	$\mathcal{O}_{\Phi\partial^2}^{(11)(22)} = \partial_\mu(\Phi_1^\dagger\Phi_1)\partial^\mu(\Phi_2^\dagger\Phi_2)$	
	$\mathcal{O}_{\Phi D}^{(11)(11)} = (\Phi_1^\dagger \overleftrightarrow{D}_\mu\Phi_1)(\Phi_1^\dagger \overleftrightarrow{D}^\mu\Phi_1)$	$\mathcal{O}_{\Phi D}^{(21)(12)} = (\Phi_2^\dagger \overleftrightarrow{D}_\mu\Phi_1)(\Phi_1^\dagger \overleftrightarrow{D}^\mu\Phi_2)$
	$\mathcal{O}_{\Phi D}^{(22)(22)} = (\Phi_2^\dagger \overleftrightarrow{D}_\mu\Phi_2)(\Phi_2^\dagger \overleftrightarrow{D}^\mu\Phi_2)$	$\mathcal{O}_{\Phi D}^{(21)(21)} = (\Phi_2^\dagger \overleftrightarrow{D}_\mu\Phi_1)(\Phi_2^\dagger \overleftrightarrow{D}^\mu\Phi_1) + \text{H.c.}$
	$\mathcal{O}_{\Phi D}^{(11)(22)} = (\Phi_1^\dagger \overleftrightarrow{D}_\mu\Phi_1)(\Phi_2^\dagger \overleftrightarrow{D}^\mu\Phi_2)$	
ϕ^6	$\mathcal{O}_{\Phi}^{(11)(11)(11)} = (\Phi_1^\dagger\Phi_1)^3$	$\mathcal{O}_{\Phi}^{(11)(21)(21)} = (\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1)^2 + \text{H.c.}$
	$\mathcal{O}_{\Phi}^{(22)(22)(22)} = (\Phi_2^\dagger\Phi_2)^3$	$\mathcal{O}_{\Phi}^{(22)(21)(21)} = (\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)^2 + \text{H.c.}$
	$\mathcal{O}_{\Phi}^{(11)(11)(22)} = (\Phi_1^\dagger\Phi_1)^2(\Phi_2^\dagger\Phi_2)$	$\mathcal{O}_{\Phi}^{(11)(21)(12)} = (\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)$
	$\mathcal{O}_{\Phi}^{(11)(22)(22)} = (\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)^2$	$\mathcal{O}_{\Phi}^{(22)(21)(12)} = (\Phi_2^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2)$

$X^2\phi^2$	$\mathcal{O}_{\Phi G}^{(11)} = (\Phi_1^\dagger\Phi_1)G_{\mu\nu}^a G^{a\mu\nu}$	$\mathcal{O}_{\Phi\tilde{G}}^{(11)} = (\Phi_1^\dagger\Phi_1)\tilde{G}_{\mu\nu}^a G^{a\mu\nu}$
	$\mathcal{O}_{\Phi G}^{(22)} = (\Phi_2^\dagger\Phi_2)G_{\mu\nu}^a G^{a\mu\nu}$	$\mathcal{O}_{\Phi\tilde{G}}^{(22)} = (\Phi_2^\dagger\Phi_2)\tilde{G}_{\mu\nu}^a G^{a\mu\nu}$
	$\mathcal{O}_{\Phi W}^{(11)} = (\Phi_1^\dagger\Phi_1)W_{\mu\nu}^a W^{a\mu\nu}$	$\mathcal{O}_{\Phi\tilde{W}}^{(11)} = (\Phi_1^\dagger\Phi_1)\tilde{W}_{\mu\nu}^a W^{a\mu\nu}$
	$\mathcal{O}_{\Phi W}^{(22)} = (\Phi_2^\dagger\Phi_2)W_{\mu\nu}^a W^{a\mu\nu}$	$\mathcal{O}_{\Phi\tilde{W}}^{(22)} = (\Phi_2^\dagger\Phi_2)\tilde{W}_{\mu\nu}^a W^{a\mu\nu}$
	$\mathcal{O}_{\Phi B}^{(11)} = (\Phi_1^\dagger\Phi_1)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\Phi\tilde{B}}^{(11)} = (\Phi_1^\dagger\Phi_1)\tilde{B}_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\Phi B}^{(22)} = (\Phi_2^\dagger\Phi_2)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\Phi\tilde{B}}^{(22)} = (\Phi_2^\dagger\Phi_2)\tilde{B}_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\Phi WB}^{(11)} = (\Phi_1^\dagger\tau^a\Phi_1)W_{\mu\nu}^a B^{\mu\nu}$	$\mathcal{O}_{\Phi\tilde{W}B}^{(11)} = (\Phi_1^\dagger\tau^a\Phi_1)\tilde{W}_{\mu\nu}^a B^{\mu\nu}$
	$\mathcal{O}_{\Phi WB}^{(22)} = (\Phi_2^\dagger\tau^a\Phi_2)W_{\mu\nu}^a B^{\mu\nu}$	$\mathcal{O}_{\Phi\tilde{W}B}^{(22)} = (\Phi_2^\dagger\tau^a\Phi_2)\tilde{W}_{\mu\nu}^a B^{\mu\nu}$
$\psi^2\phi^2 D$	$\mathcal{O}_{\Phi e}^{(11)} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu\Phi_1)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{\Phi l}^{(11)[1]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu\Phi_1)(\bar{l}_L\gamma^\mu l_L)$
	$\mathcal{O}_{\Phi e}^{(22)} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu\Phi_2)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{\Phi l}^{(22)[1]} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu\Phi_2)(\bar{l}_L\gamma^\mu l_L)$
	$\mathcal{O}_{\Phi d}^{(11)} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu\Phi_1)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{\Phi q}^{(11)[1]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu\Phi_1)(\bar{q}_L\gamma^\mu q_L)$
	$\mathcal{O}_{\Phi d}^{(22)} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu\Phi_2)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{\Phi q}^{(22)[1]} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu\Phi_2)(\bar{q}_L\gamma^\mu q_L)$
	$\mathcal{O}_{\Phi u}^{(11)} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu\Phi_1)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{\Phi l}^{(11)[3]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu^a\Phi_1)(\bar{l}_L\tau^a\gamma^\mu l_L)$
	$\mathcal{O}_{\Phi u}^{(22)} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu\Phi_2)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{\Phi l}^{(22)[3]} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu^a\Phi_2)(\bar{l}_L\tau^a\gamma^\mu l_L)$
		$\mathcal{O}_{\Phi q}^{(11)[3]} = (\Phi_1^\dagger i\overleftrightarrow{D}_\mu^a\Phi_1)(\bar{q}_L\tau^a\gamma^\mu q_L)$
		$\mathcal{O}_{\Phi q}^{(22)[3]} = (\Phi_2^\dagger i\overleftrightarrow{D}_\mu^a\Phi_2)(\bar{q}_L\tau^a\gamma^\mu q_L)$

This gives us a total of 76 operators common in all four types of 2HDMs

2HDM EFT in the Higgs Basis

- We can always perform a rotation on the Higgs doublets: rotate by the vacuum angle β:

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

This is called the **Higgs basis**

$$H_1 = \begin{pmatrix} G^+ \cos(\beta - \hat{\beta}^\pm) + H^+ \sin(\beta - \hat{\beta}^\pm) \\ v + \frac{1}{\sqrt{2}}(h \sin(\beta - \hat{\alpha}) + H \cos(\beta - \hat{\alpha}) + iG \cos(\beta - \hat{\beta}) + iA \sin(\beta - \hat{\beta})) \end{pmatrix}$$

In the tree-level 2HDM, $\beta = \hat{\beta} = \hat{\beta}^\pm$
but dim. 6 contributions break this

$$H_2 = \begin{pmatrix} -G^+ \sin(\beta - \hat{\beta}^\pm) + H^+ \cos(\beta - \hat{\beta}^\pm) \\ \frac{1}{\sqrt{2}}(h \cos(\beta - \hat{\alpha}) - H \sin(\beta - \hat{\alpha}) - iG \sin(\beta - \hat{\beta}) + iA \cos(\beta - \hat{\beta})) \end{pmatrix}$$

$\beta - \hat{\beta} = \mathcal{O}(v^4/\Lambda^2 m_A^2)$ for the CP-odd scalars

$\beta - \hat{\beta}^\pm = \mathcal{O}(v^4/\Lambda^2 m_{H^\pm}^2)$ for the charged sector

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but dim. 6 contributions break this

*In the **alignment limit:** $\beta - \hat{\alpha} \to \pi/2$*

$$H_2 = \begin{pmatrix} -G^+ \sin(\beta - \hat{\beta}^\pm) + H^+ \cos(\beta - \hat{\beta}^\pm) \\ \frac{1}{\sqrt{2}}(h \cos(\beta - \hat{\alpha}) - H \sin(\beta - \hat{\alpha}) - iG \sin(\beta - \hat{\beta}) + iA \cos(\beta - \hat{\beta})) \end{pmatrix} \to \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(-H + iA) \end{pmatrix} + \mathcal{O}\left(\frac{v^4}{\Lambda^2 M^2}\right)$$

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SM fields are approx. decoupled from new scalars

2HDM EFT in the Higgs Basis

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H_1 **contains VEV** $\quad M_1 \sim v$

$$H_2 = \begin{pmatrix} -G^+ \sin(\beta - \hat{\beta}^{\pm}) + H^+ \cos(\beta - \hat{\beta}^{\pm}) \\ \frac{1}{\sqrt{2}}(h \cos(\beta - \hat{\alpha}) - H \sin(\beta - \hat{\alpha}) - iG \sin(\beta - \hat{\beta}) + iA \cos(\beta - \hat{\beta})) \end{pmatrix} \rightarrow \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(-H + iA) \end{pmatrix} + \mathcal{O}\left(\frac{v^4}{\Lambda^2 M^2}\right)$$

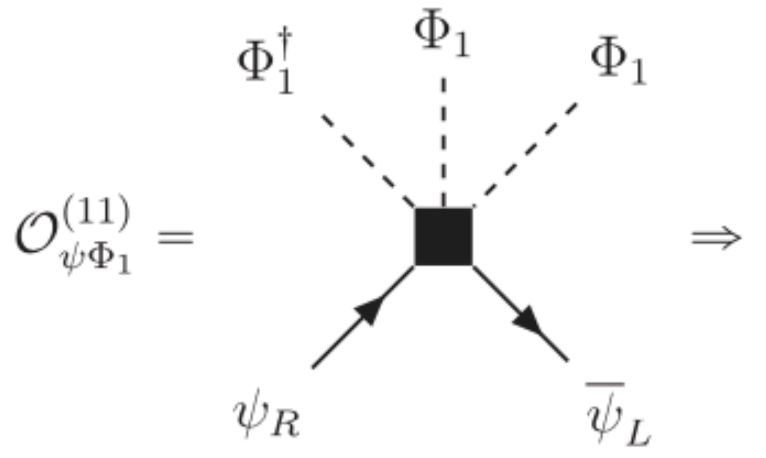
$v \lesssim M_2$

The Higgs basis has the same number (228) of operators as in the standard basis, and all operators can be obtained by replacing $\Phi \rightarrow H$

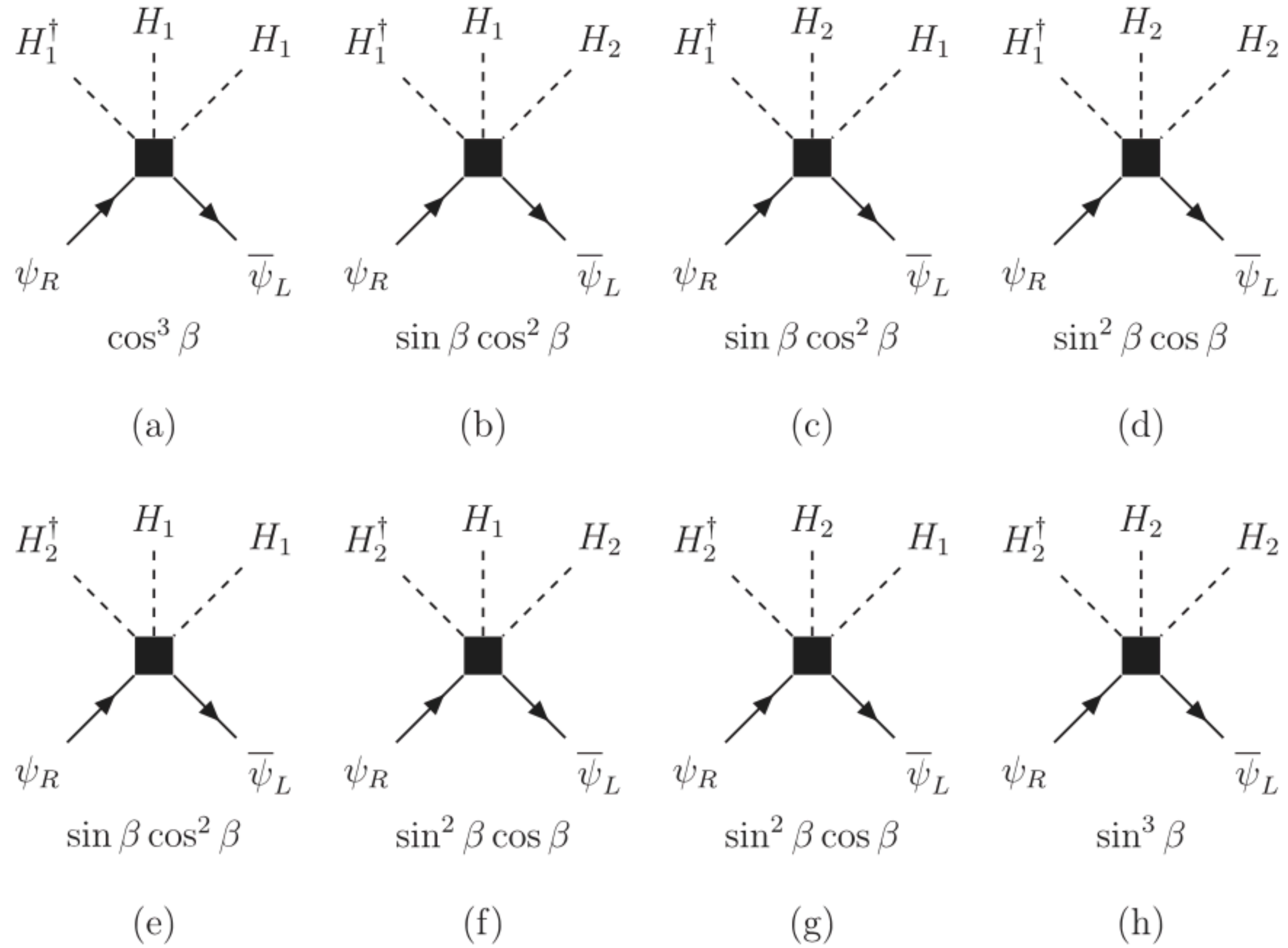
2HDM EFT Higgs Basis Advantages

Let's suppose some theory generates the operator $\mathcal{O}^{(11)}_{\psi\Phi_1} = \overline{\psi}_L \psi_R \Phi_1 \left(\Phi_1^\dagger \Phi_1\right)$

Standard basis:



In the Higgs basis: 8 operators are present w/ combinations of $H_1(H_2)$:



Factors of $\cos\beta$ or $\sin\beta$ are to compare the proportionality between diagrams

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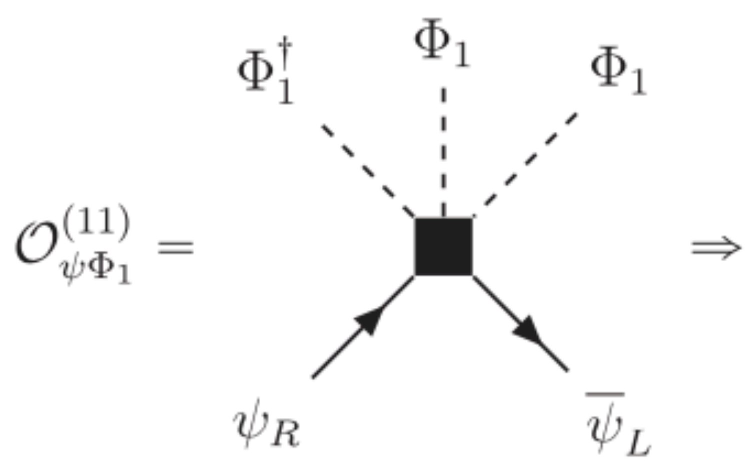
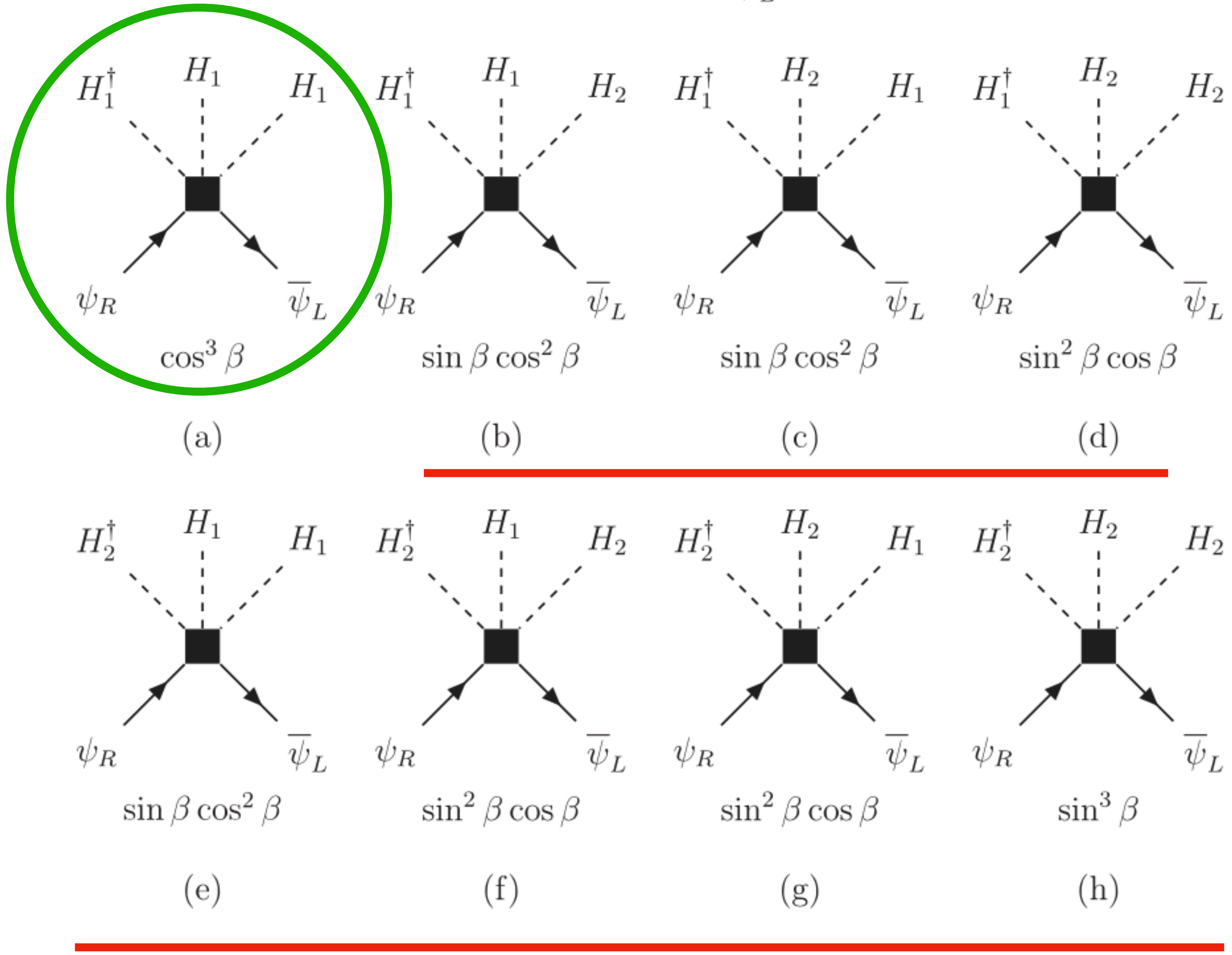


(a) is the only operator which can contribute to the mass: $\overline{\psi}_L \psi_R C^{(11)}_{\psi\Phi_1} (v\cos\beta)^3$

In the Higgs basis: 8 operators are present w/ combinations of $H_1(H_2)$:

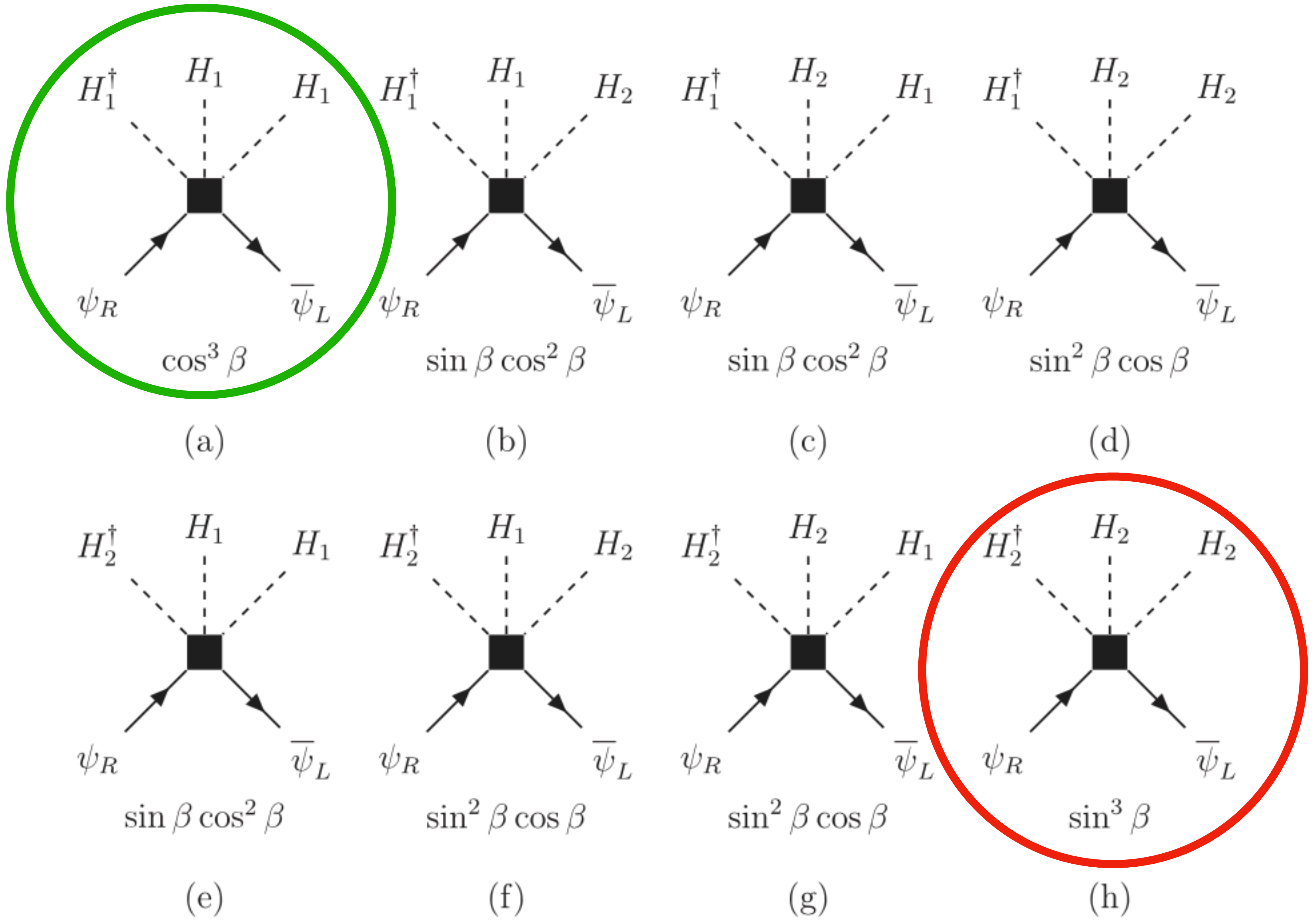


(b-h) are operators which only contribute to scattering of at least 1 new Higgs scalar

Factors of $\cos\beta$ or $\sin\beta$ are to compare the proportionality between diagrams

2HDM EFT Higgs Basis Advantages

Let's suppose some theory generates the operator $\mathcal{O}_{\psi\Phi_1}^{(11)} = \overline{\psi}_L \psi_R \Phi_1 \left(\Phi_1^\dagger \Phi_1\right)$



We can also learn something about scattering. Say I want to compare the cross section of $\overline{\psi}\psi \to hhh$ to $\overline{\psi}\psi \to HHH$

$$\frac{\sigma(\overline{\psi}\psi \to HHH)}{\sigma(\overline{\psi}\psi \to hhh)} \propto \frac{|\sin^3\beta C_{\psi\Phi_1}^{(11)}|^2}{|\cos^3\beta C_{\psi\Phi_1}^{(11)}|^2} = \tan^6\beta$$

The process $\overline{\psi}\psi \to hhh$ is contained only in the first operator

The process $\overline{\psi}\psi \to HHH$ is contained in the last operator

(Also HHH, HAA, HHA, H^+H^-H, and H^+H^-A)

$\tan\beta$ enhancements are a general feature of a 2HDM and are clear in the 2HDM EFT Higgs basis

Other Advantages: An Example UV-Completion

Let's suppose we have a UV theory where new leptons couple to the Higgs doublets and muon in a type-II 2HDM:

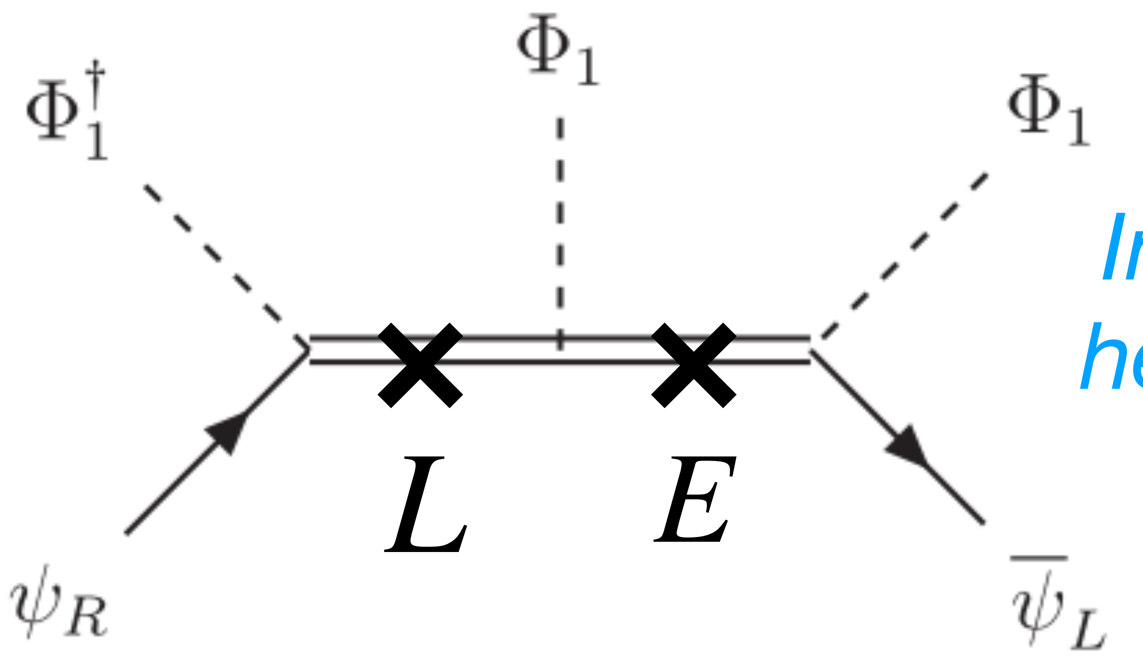
	l_L	μ_R	Φ_1	Φ_2	$L_{L,R}$	$E_{L,R}$
$SU(2)_L$	**2**	**1**	**2**	**2**	**2**	**1**
$U(1)_Y$	$\frac{1}{2}$	-1	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{3}{2}$	-1
Z_2	$+$	$-$	$-$	$+$	$+$	$-$

$$\mathscr{L} = -y_\mu \bar{l}_L \mu_R \Phi_1 - \lambda_E \bar{l}_L E_R \Phi_1 - \lambda_L \bar{L}_L \mu_R \cdot \Phi_1^\dagger - \lambda \bar{L}_L \cdot E_R \Phi_1^\dagger - \bar{\lambda} \bar{E}_L L_R \cdot \Phi_1$$
$$-M_L \bar{L}_L L_R - M_E \bar{E}_L E_R - m_1^2 \Phi_1^\dagger \Phi_1 - m_2^2 \Phi_2^\dagger \Phi_2 + h.c.$$

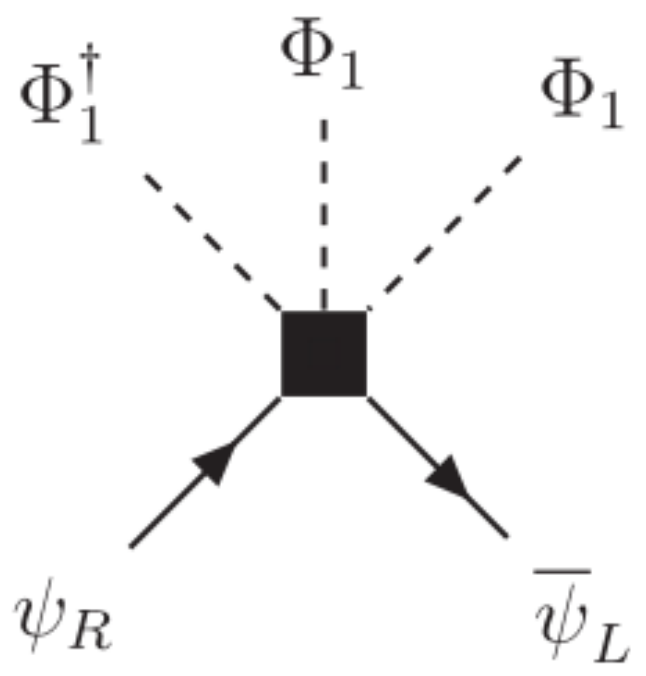
Vector-like lepton doublet L

Vector-like lepton singlet E

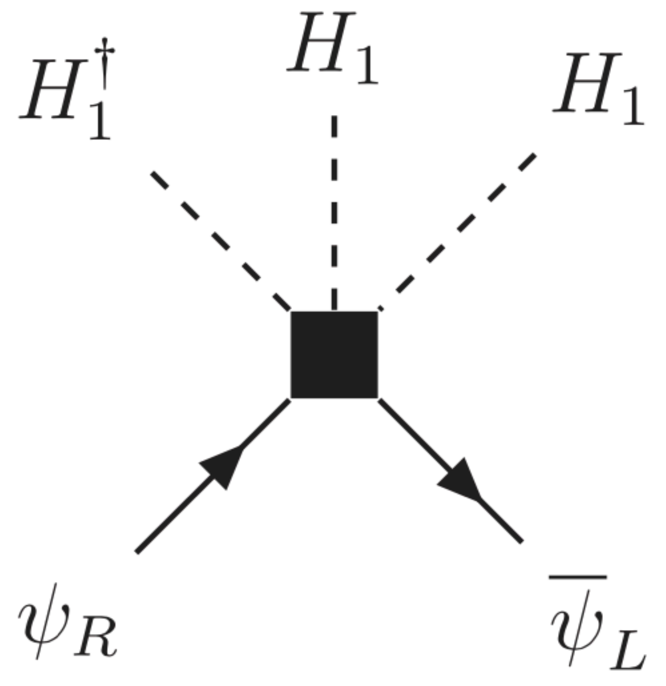
$$M_{L,E} \gg v$$



Integrate out heavy leptons



Rotate to Higgs Basis; contribution to the muon mass



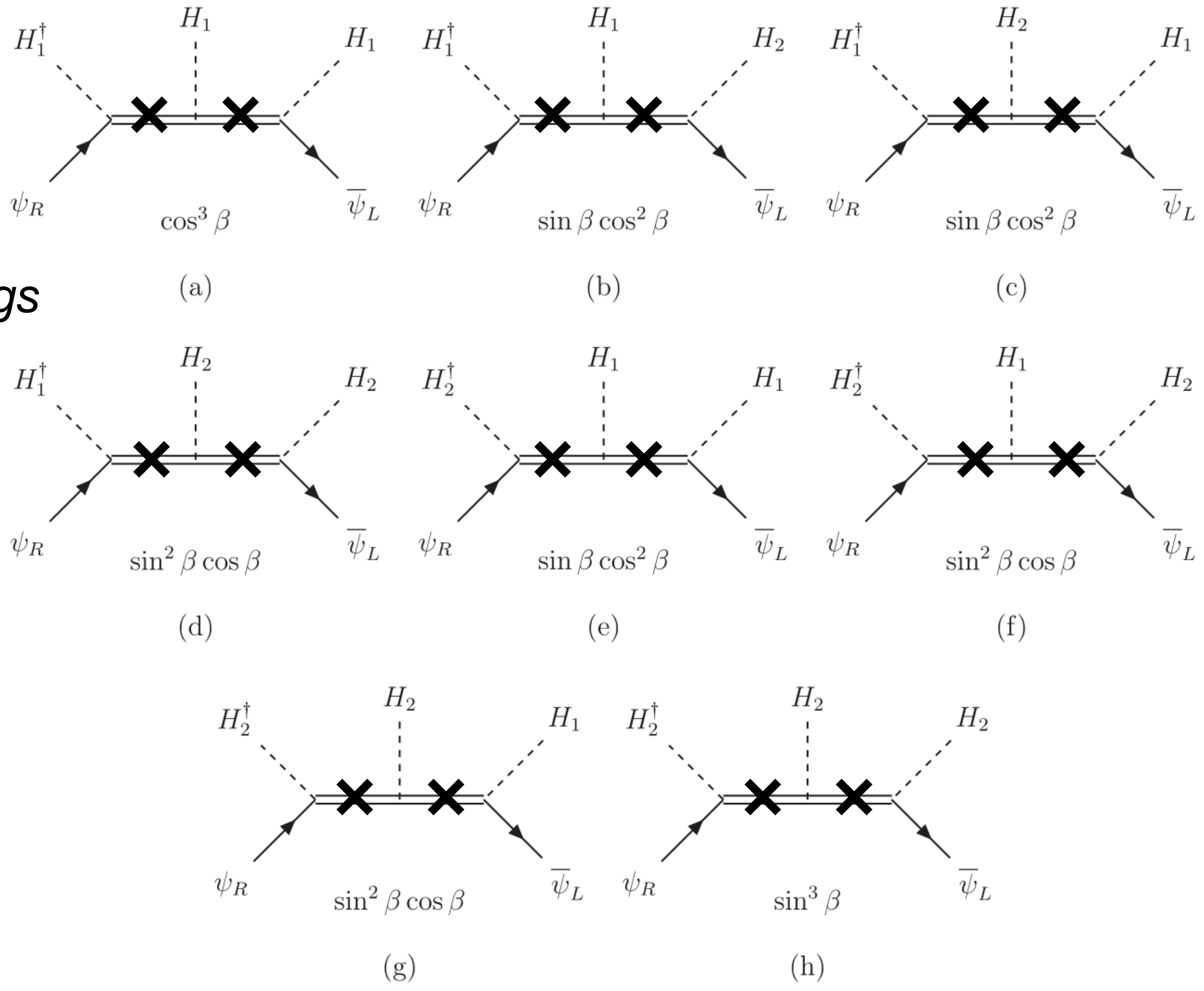
✖ = mass insertion

$$C_{\mu\Phi_1}^{(11)} \bar{l}_L \mu_R \Phi_1 \left(\Phi_1^\dagger \Phi_1\right)$$

$$C_{\mu H_1}^{(11)} = C_{\mu\Phi_1}^{(11)} \cos^3\beta = \left(\frac{\lambda_L \lambda_E \bar{\lambda}}{M_L M_E}\right) \cos^3\beta$$

Other Advantages: An Example UV-Completion

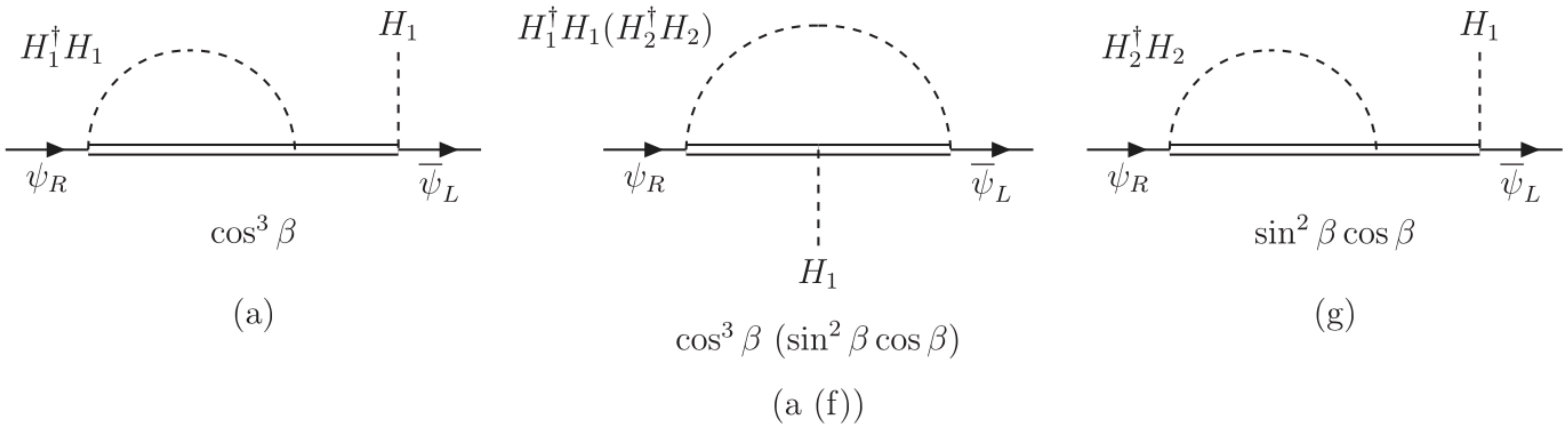
In the Higgs basis:



Let's see what happens *if I close all doublets in* $H_1^\dagger H_1$ $(H_2^\dagger H_2)$ *invariant pairs (but leave one* H_1 *outside)*

Other Advantages: An Example UV-Completion

The external H_1 is needed so it doesn't vanish after EWSB



Other Advantages: An Example UV-Completion

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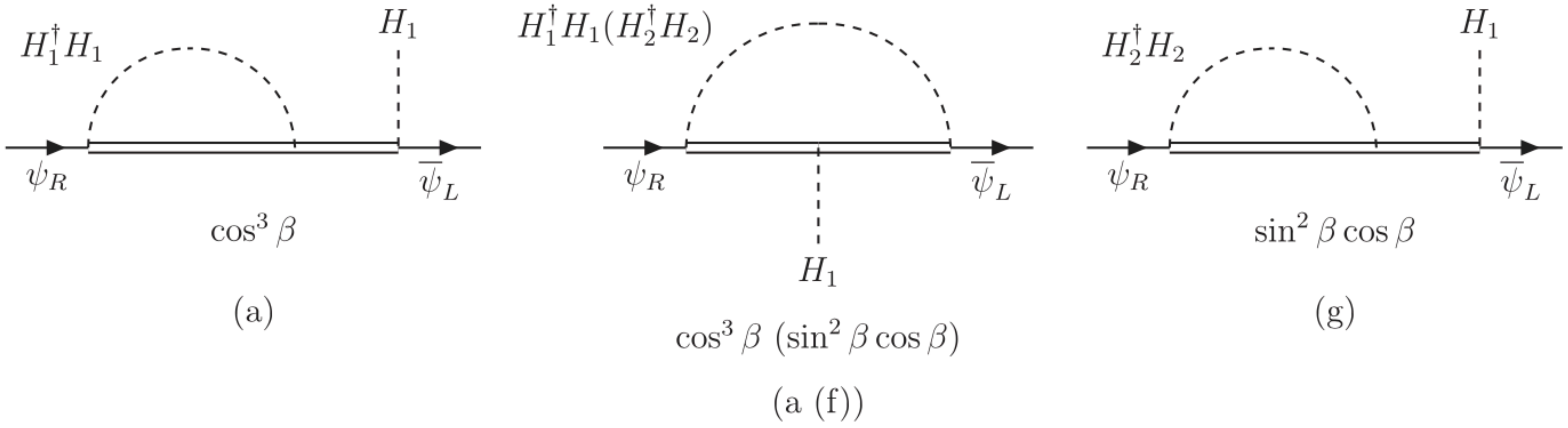
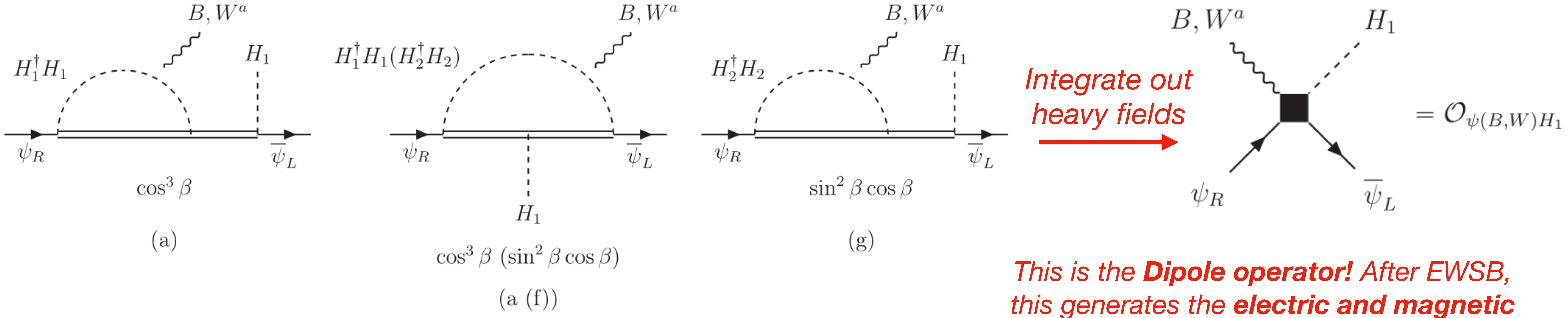


Dress diagram with $B,\ W^a$ gauge fields:



H_2 **loops are** $\tan^2\beta$ **enhanced compared to** H_1 **loops**

This is the ***Dipole operator!*** *After EWSB, this generates the* ***electric and magnetic dipole moments of the muon***

Other Advantages: An Example UV-Completion

- We see that in this UV completion, generating the operator $C^{(11)}_{\mu\Phi_1}\bar{l}_L\mu_R\Phi_1\left(\Phi_1^\dagger\Phi_1\right)$ **is directly correlated to the dipole operators**

$$C_{lBH_1}\bar{l}_L\sigma^{\mu\nu}\mu_R H_1 B_{\mu\nu} \qquad\qquad C_{lWH_1}\bar{l}_L\sigma^{\mu\nu}\mu_R\tau^a H_1 W^a_{\mu\nu}$$

$$C_{\mu\gamma} = \cos\theta_W C_{lBH_1} - \sin\theta_W C_{lWH_1}$$

Phys. Rev. Lett 129, 221801 (2022)
Phys. Rev. D 107, 095043 (2023)

$$\Delta a_\mu = -\left(\frac{4m_\mu v}{e}\right)\mathbf{Re}[C_{\mu\gamma}]$$ **(muon $g-2$)**

$$d_\mu = 2v\,\mathbf{Im}[C_{\mu\gamma}]$$ **(muon EDM)**

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In this model, $C_{\mu\gamma}$ is

$$C^{(11)}_{\mu\Phi_1} = \left(\frac{\lambda_L\lambda_E\bar{\lambda}}{M_L M_E}\right)$$

Very different answers depending what the scale of H_2 is!

$$C_{\mu\gamma} = 5e\left(\frac{\lambda_L\lambda_E\bar{\lambda}}{64\pi^2 M_L M_E}\right)\cos^3\beta\left(1+\tan^2\beta\right) \qquad M_{L,E} \gg M_{1,2}$$

Much easier to obtain than the entire calculation in the mass eigenstate basis

$$C_{\mu\gamma} = e\left(\frac{\lambda_L\lambda_E\bar{\lambda}}{64\pi^2 M_L M_E}\right)\cos^3\beta\left(5+\frac{17}{6}\tan^2\beta\right) + e\left(\frac{\lambda_L\lambda_E\lambda^*}{64\pi^2 M_L M_E}\right)\cos^3\beta\left(\frac{1}{6}\tan^2\beta\right) \qquad M_{L,E}\sim M_2 \gg M_1$$

Phys. Rev. D 108, 055019 (2023)

Takeaways

- There are 228 operators in the general 2HDM EFT, where the low-energy theory contains the SM fields and new Higgs scalars

- Imposing a Z_2 symmetry on the fields will give 76 common operators in all types of 2HDMs, and model-specific ones for each type

- The **Higgs basis** is useful when separating the SM d.o.f from the new Higgses where the characteristic scales might be different

  - This is advantageous since operators **only containing** H_1 can contribute to physical parameters of the particles or SM processes while ones with H_2 can only ever contribute to scattering

  - This provides a simple scaling between scattering processes involving any number of new Higgses and the SM fields

  - In UV theories, connections between different observables can be made clear in this basis

Thank you for listening!

INDIANA UNIVERSITY BLOOMINGTON

Sidenote

arXiv:2411.07337 [hep-ph]

- Just recently in here, we calculate all couplings and masses of the physical scalars and SM particles, including exact formulas for the case of explicit CP-violation
- We show selected Feynman rules for the CP-conserving type-II 2HDM EFT in the alignment limit
- We've developed a FeynRules code that can work in many limits of the 2HDM EFT presented here, such as alignment limit, types of 2HDMs, CP-violation, etc.