The Effective Field Theory approach to new physics: two explicit examples

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Outline

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Standard Model Effective Field Theory

In searches for new physics we can distinguish among:

- Direct searches

  Searches for new resonances.

- Top-down approach: BSM models (model-dependent)

  Unknowns: model parameters.

- Bottom-up approach: EFT ("model-independent")

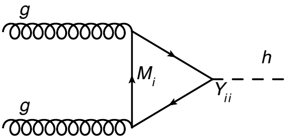
  Unknowns: Wilson coefficients

Assumptions:

- The dynamical degrees of freedom at the EW scale are those of the SM
- New Physics appears at some high scale $\Lambda >> v$ (decoupling)
- Absence of mixing of new heavy scalars with the SM Higgs doublet
- $SU(2)_L \times U(1)_Y$ is linearly realized at high energies

Effective Field Theories

Local operators parametrize the effects of the exchange of new heavy particles:



$$\longrightarrow \qquad G^a_{\mu\nu} G^{a\mu\nu} H^\dagger H$$

Integrate out the heavy fields and obtain the effective operator.

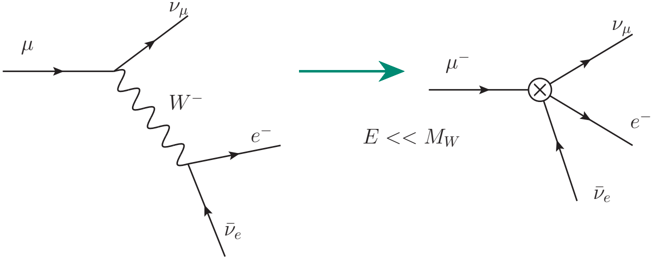
SM example: the limit of infinite top mass

$$\Delta\mathcal{L}_{ggh} = \frac{g_S^2}{48\pi^2} G^a_{\mu\nu} G^{a\mu\nu} \frac{h}{v}$$

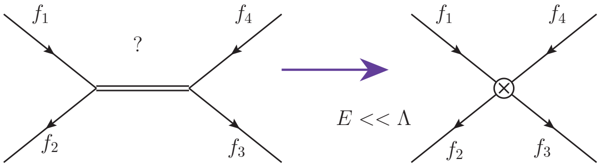
The coefficient is determined by matching the full theory with the effective theory.

Effective Field Theories

Fermi Theory



SMEFT



SMEFT Lagrangian

Higgs doublet - EW symmetry is linearly realized

$$\mathcal{L}_{HEFT} = \mathcal{L}_{SM} + \sum_{n>4} \sum_{i} \frac{c_i}{\Lambda^{n-4}} O_i^{D=n}$$

$$\mathcal{L}_{HEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}^{D=5} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6} + \frac{1}{\Lambda^3}\mathcal{L}^{D=7} + \frac{1}{\Lambda^4}\mathcal{L}^{D=8} + \ldots$$

- $\mathcal{L}^{D=5}$ and $\mathcal{L}^{D=7}$: lepton number violating
- $\mathcal{L}^{D=8}$ and higher: parametrically subleading
- $\mathcal{L}^{D=6}$: leading effect

$$\mathcal{L}_{HEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6}$$

C. N. Leung, S. T. Love and S. Rao, Z. Phys. C 31 (1986) 433
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$$\boxed{\mathcal{L}_{HEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\mathcal{L}^{D=6}}$$

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SMEFT

GIMR/Warsaw basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger \varphi\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger \varphi\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger \varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger \tau^I \varphi\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- 15 bosonic operators
- 19 single-fermionic-current operators
- 25 four-fermion operators (assuming barionic number conservation)

15+19+25=59 independent operators (for 1 fermion generation)

Grzadkowski, Iskrzynski, Misiak, Rosiek, JHEP 1010 (2010) 085

SMEFT - From 1 to 3 fermion generations

- Add flavour indices to all operators
- From 59 to 2499 operators!
- Assume some flavour structure to avoid severe constraints from FCNC

Class	$N_{\rm op}$	CP-even n_g	1	3	CP-odd n_g	1	3
1	4	2	2	2	2	2	2
2	1	1	1	1	0	0	0
3	2	2	2	2	0	0	0
4	8	4	4	4	4	4	4
5	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
8 : $(\overline{L}L)(\overline{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
8 : $(\overline{R}R)(\overline{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
8 : $(\overline{L}L)(\overline{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
8 : $(\overline{L}R)(\overline{R}L)$	1	n_g^4	1	81	n_g^4	1	81
8 : $(\overline{L}R)(\overline{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total	59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

$1 = F^3 \quad 2 = H^6 \quad 3 = H^4D^2 \quad 4 = F^2H^2 \quad 5 = \phi^2H^3 \quad 6 = \psi^2FH \quad 7 = \psi^2H^2D$

Alonso, Jenkins, Manohar and Trott, JHEP 1404 (2014) 159

Outline

The EFT of the 2HDM

Suppose that a new particle is discovered around the EW scale.
We still do not know the UV complete theory, and we would like to extend the EFT approach to include the new field.

Is it a viable option? 2 possibilities:

- there is a gap between the new d.o.f. and the other NP resonances $\longrightarrow$ YES
- the new d.o.f. is heavy and we suppose that it is at the same scale of the rest of the NP particles $\longrightarrow$ NO

In the following:

- We suppose the existence of a second Higgs doublet, not so far from the EW scale, and of a gap w.r.t. the other NP resonances;
- we parametrize our ignorance of the UV-complete theory building an EFT with the dynamical degrees of freedom of the 2HDM.

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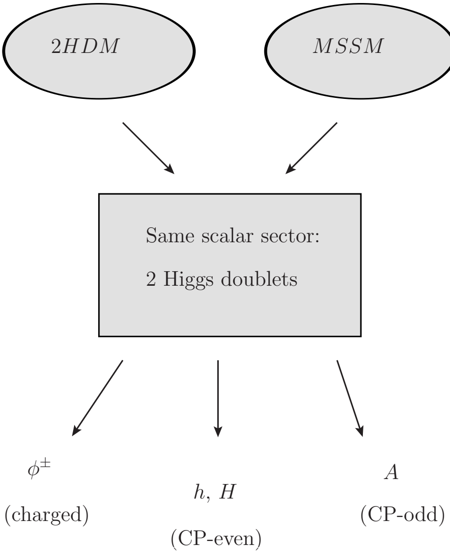
The Two Higgs Doublet Model



Motivations:

- MSSM
- Axion models
- Models explaining baryon asymmetry

Vector boson and fermion content of the 2HDM: the same as the SM.

The Two Higgs Doublet Model

$$\begin{aligned}
\mathcal{L}^{(4)}_{2HDM} &= -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
&+ (D_\mu\varphi_1)^\dagger(D^\mu\varphi_1) + (D_\mu\varphi_2)^\dagger(D^\mu\varphi_2) \\
&- V(\varphi_1,\varphi_2) + i\left(\bar{l}\not{D}l + \bar{q}\not{D}q + \bar{u}\not{D}u + \bar{d}\not{D}d\right) + \mathcal{L}_Y\,,
\end{aligned}$$

$$\begin{aligned}
V(\varphi_1,\varphi_2) &= m^2_{11}\,\varphi_1^\dagger\varphi_1 + m^2_{22}\,\varphi_2^\dagger\varphi_2 - m^2_{12}\left(\varphi_1^\dagger\varphi_2 + \varphi_2^\dagger\varphi_1\right) + \frac{\lambda_1}{2}\left(\varphi_1^\dagger\varphi_1\right)^2 + \frac{\lambda_2}{2}\left(\varphi_2^\dagger\varphi_2\right)^2 \\
&+\lambda_3\,\varphi_1^\dagger\varphi_1\,\varphi_2^\dagger\varphi_2 + \lambda_4\,\varphi_1^\dagger\varphi_2\,\varphi_2^\dagger\varphi_1 + \frac{\lambda_5}{2}\left[\left(\varphi_1^\dagger\varphi_2\right)^2 + \left(\varphi_2^\dagger\varphi_1\right)^2\right] \\
&+ \lambda_6\left(\varphi_1^\dagger\varphi_1\right)\left(\varphi_1^\dagger\varphi_2\right) + \lambda_7\left(\varphi_2^\dagger\varphi_2\right)\left(\varphi_1^\dagger\varphi_2\right)
\end{aligned}$$

$m^2_{11},\ m^2_{22},\ \lambda_{1,2,3,4}$ real

$m^2_{12},\ \lambda_{5,6,7}$ complex

The Two Higgs Doublet Model

FCNC can be avoided imposing an appropriate Z_2 symmetry:

$$Z_2: \qquad \phi_1 \to -\phi_1 \qquad \text{or} \qquad \phi_2 \to -\phi_2$$

We keep the m_{12}-term, that softly breaks the symmetry.

$$\begin{aligned} V(\varphi_1, \varphi_2) = \; & m_{11}^2\, \varphi_1^\dagger \varphi_1 + m_{22}^2\, \varphi_2^\dagger \varphi_2 - m_{12}^2 \left(\varphi_1^\dagger \varphi_2 + \varphi_2^\dagger \varphi_1\right) + \frac{\lambda_1}{2}\left(\varphi_1^\dagger \varphi_1\right)^2 + \frac{\lambda_2}{2}\left(\varphi_2^\dagger \varphi_2\right)^2 \\ & + \lambda_3\, \varphi_1^\dagger \varphi_1\, \varphi_2^\dagger \varphi_2 + \lambda_4\, \varphi_1^\dagger \varphi_2\, \varphi_2^\dagger \varphi_1 + \frac{\lambda_5}{2}\left[\left(\varphi_1^\dagger \varphi_2\right)^2 + \left(\varphi_2^\dagger \varphi_1\right)^2\right] \\ & + \lambda_6 \left(\varphi_1^\dagger \varphi_1\right)\left(\varphi_1^\dagger \varphi_2\right) + \lambda_7 \left(\varphi_2^\dagger \varphi_2\right)\left(\varphi_1^\dagger \varphi_2\right) \end{aligned}$$

$m_{11}^2,\ m_{22}^2,\ \lambda_{1,2,3,4}$ real

$m_{12}^2,\ \lambda_{5,6,7}$ complex

Rotation to the physical basis (2HDM)

Lagrangian for the mass terms of the CP-odd (η_a), CP-even (ρ_a) and charged (ϕ_a^+) Higgses:

$$L_{M_H}^{(4)} = \frac{1}{2}\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}^T m_\eta^2 \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} + \begin{pmatrix} \phi_1^- \\ \phi_2^- \end{pmatrix}^T m_{\phi^\pm}^2 \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} + \frac{1}{2}\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}^T m_\rho^2 \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

with

$$m_\eta^2 = (v_1 v_2 \lambda_5 - m_{12}^2)\begin{pmatrix} -\frac{v_2}{v_1} & 1 \\ 1 & -\frac{v_1}{v_2} \end{pmatrix}$$

$$m_\rho^2 = \begin{pmatrix} \lambda_1 v_1^2 + m_{12}^2 \frac{v_2}{v_1} & v_1 v_2 (\lambda_3 + \lambda_4 + \lambda_5) - m_{12}^2 \\ v_1 v_2 (\lambda_3 + \lambda_4 + \lambda_5) - m_{12}^2 & \lambda_2 v_2^2 + m_{12}^2 \frac{v_1}{v_2} \end{pmatrix}$$

$$m_{\phi^\pm}^2 = \left[\frac{v_1 v_2}{2}(\lambda_4 + \lambda_5) - m_{12}^2\right]\begin{pmatrix} -\frac{v_2}{v_1} & 1 \\ 1 & -\frac{v_1}{v_2} \end{pmatrix}$$

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Rotation to the physical basis:

	eigenvalues	physical states	Goldstone bosons	rotation angle
$m_{\phi^\pm}^2$	$0;\ m_\pm^2$	$H^\pm$ (charged)	$G^\pm$	$\beta \equiv \arctan \frac{v_2}{v_1}$
m_η^2	$0;\ m_A^2$	A (CP-odd)	G_0	$\beta \equiv \arctan \frac{v_2}{v_1}$
m_ρ^2	$m_h^2;\ m_H^2$	$h,\ H$ (CP-even)	–	α

2HDM-EFT

Assumptions for the effective theory of the 2HDM:

$$\mathcal{L}_{2HDM} = \mathcal{L}^{(4)}_{2HDM} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

- Its gauge group contains the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ as a subgroup.
- It contains two Higgs doublets as dynamical degrees of freedom, either as fundamental or composite fields.
- At low energies it reproduces the 2HDM, barring the existence of weakly coupled *light* particles, like axions or sterile neutrinos.

Dim-5 the generalization of the Weinberg operator:

$$Q^{11}_{\nu\nu} = (\tilde{\varphi}_1^\dagger l_p)^T C (\tilde{\varphi}_1^\dagger l_r)\,, \quad Q^{22}_{\nu\nu} = (\tilde{\varphi}_2^\dagger l_p)^T C (\tilde{\varphi}_2^\dagger l_r)$$

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2HDM-EFT operators

φ^6
$Q_\varphi^{111} = (\varphi_1^\dagger \varphi_1)^3$
$Q_\varphi^{112} = (\varphi_1^\dagger \varphi_1)^2 (\varphi_2^\dagger \varphi_2)$
$Q_\varphi^{122} = (\varphi_1^\dagger \varphi_1) (\varphi_2^\dagger \varphi_2)^2$
$Q_\varphi^{222} = (\varphi_2^\dagger \varphi_2)^3$
$Q_\varphi^{(1221)1} = (\varphi_1^\dagger \varphi_2)(\varphi_2^\dagger \varphi_1)(\varphi_1^\dagger \varphi_1)$
$Q_\varphi^{(1221)2} = (\varphi_1^\dagger \varphi_2)(\varphi_2^\dagger \varphi_1)(\varphi_2^\dagger \varphi_2)$
$Q_\varphi^{(1212)1} = (\varphi_1^\dagger \varphi_2)^2(\varphi_1^\dagger \varphi_1) + h.c.$
$Q_\varphi^{(1212)2} = (\varphi_1^\dagger \varphi_2)^2(\varphi_2^\dagger \varphi_2) + h.c.$

- Higgs doublets only
- They modify the Higgs potential

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2HDM-EFT operators

$\varphi^4 D^2$	
$\Box$	φD
$Q_{\Box}^{1(1)} = (\varphi_1^\dagger \varphi_1)\Box(\varphi_1^\dagger \varphi_1)$	$Q_{\varphi D}^{(1)11(1)} = \left[(D_\mu \varphi_1)^\dagger \varphi_1\right]\left[\varphi_1^\dagger (D^\mu \varphi_1)\right]$ $\quad Q_{\varphi D}^{(1)21(2)} = \left[(D_\mu \varphi_1)^\dagger \varphi_2\right]\left[\varphi_1^\dagger (D^\mu \varphi_2)\right] + h.c.$
$Q_{\Box}^{2(2)} = (\varphi_2^\dagger \varphi_2)\Box(\varphi_2^\dagger \varphi_2)$	$Q_{\varphi D}^{(2)22(2)} = \left[(D_\mu \varphi_2)^\dagger \varphi_2\right]\left[\varphi_2^\dagger (D^\mu \varphi_2)\right]$ $\quad Q_{\varphi D}^{(1)12(2)} = \left[(D_\mu \varphi_1)^\dagger \varphi_1\right]\left[\varphi_2^\dagger (D^\mu \varphi_2)\right] + h.c.$
$Q_{\Box}^{1(2)} = (\varphi_1^\dagger \varphi_1)\Box(\varphi_2^\dagger \varphi_2)$	$Q_{\varphi D}^{(1)22(1)} = \left[(D_\mu \varphi_1)^\dagger \varphi_2\right]\left[\varphi_2^\dagger (D^\mu \varphi_1)\right]$ $\quad Q_{\varphi D}^{12(12)} = \left[{\varphi_1}^\dagger \varphi_2\right]\left[(D_\mu \varphi_1)^\dagger (D^\mu \varphi_2)\right] + h.c.$
	$Q_{\varphi D}^{(2)11(2)} = \left[(D_\mu \varphi_2)^\dagger \varphi_1\right]\left[\varphi_1^\dagger (D^\mu \varphi_2)\right]$ $\quad Q_{\varphi D}^{12(21)} = \left[{\varphi_1}^\dagger \varphi_2\right]\left[(D_\mu \varphi_2)^\dagger (D^\mu \varphi_1)\right] + h.c.$

- Four Higgs doublets and two derivatives
- They modify the kinetic terms of the Higgs fields, the Higgs-gauge boson interactions and the W and Z masses

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2HDM-EFT operators

$\varphi^2 X^2$	
GG, WW, BB	WB
$Q_{\varphi X}^{11} = (\varphi_1^\dagger \varphi_1) X_{\mu\nu} X^{\mu\nu}$	$Q_{\varphi WB}^{11} = (\varphi_1^\dagger \tau^I \varphi_1) W_{\mu\nu}^I B^{\mu\nu}$
$Q_{\varphi X}^{22} = (\varphi_2^\dagger \varphi_2) X_{\mu\nu} X^{\mu\nu}$	$Q_{\varphi WB}^{22} = (\varphi_2^\dagger \tau^I \varphi_2) W_{\mu\nu}^I B^{\mu\nu}$
$Q_{\varphi \tilde{X}}^{11} = (\varphi_1^\dagger \varphi_1) \tilde{X}_{\mu\nu} X^{\mu\nu}$	$Q_{\varphi \tilde{W} B}^{11} = (\varphi_1^\dagger \tau^I \varphi_1) \tilde{W}_{\mu\nu}^I B^{\mu\nu}$
$Q_{\varphi \tilde{X}}^{22} = (\varphi_2^\dagger \varphi_2) \tilde{X}_{\mu\nu} X^{\mu\nu}$	$Q_{\varphi \tilde{W} B}^{22} = (\varphi_2^\dagger \tau^I \varphi_2) \tilde{W}_{\mu\nu}^I B^{\mu\nu}$

$X = G^A$, W^I or B

- Operators with two Higgs doublets and two field strength tensors
- They modify the Higgs-gauge boson interactions

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2HDM-EFT operators

$\Psi^2\varphi^2 D$	
(1)	(3)
$Q^1_{\varphi ud} = i(\tilde{\varphi}_1^\dagger i \overleftrightarrow{D}_\mu \varphi_1)(\bar{u}_p \gamma^\mu d_r)$	
$Q^2_{\varphi ud} = i(\tilde{\varphi}_2^\dagger i \overleftrightarrow{D}_\mu \varphi_2)(\bar{u}_p \gamma^\mu d_r)$	
$Q^{(1)1}_{\varphi l} = (\varphi_1^\dagger i \overleftrightarrow{D}_\mu \varphi_1)(\bar{l}_p \gamma^\mu l_r)$	$Q^{(3)1}_{\varphi l} = (\varphi_1^\dagger i \overleftrightarrow{D}^I_\mu \varphi_1)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q^{(1)2}_{\varphi l} = (\varphi_2^\dagger i \overleftrightarrow{D}_\mu \varphi_2)(\bar{l}_p \gamma^\mu l_r)$	$Q^{(3)2}_{\varphi l} = (\varphi_2^\dagger i \overleftrightarrow{D}^I_\mu \varphi_2)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q^1_{\varphi e} = (\varphi_1^\dagger i \overleftrightarrow{D}_\mu \varphi_1)(\bar{e}_p \gamma^\mu e_r)$	
$Q^2_{\varphi e} = (\varphi_2^\dagger i \overleftrightarrow{D}_\mu \varphi_2)(\bar{e}_p \gamma^\mu e_r)$	
$Q^{(1)1}_{\varphi q} = (\varphi_1^\dagger i \overleftrightarrow{D}_\mu \varphi_1)(\bar{q}_p \gamma^\mu q_r)$	$Q^{(3)1}_{\varphi q} = (\varphi_1^\dagger i \overleftrightarrow{D}^I_\mu \varphi_1)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q^{(1)2}_{\varphi q} = (\varphi_2^\dagger i \overleftrightarrow{D}_\mu \varphi_2)(\bar{q}_p \gamma^\mu q_r)$	$Q^{(3)2}_{\varphi q} = (\varphi_2^\dagger i \overleftrightarrow{D}^I_\mu \varphi_2)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q^1_{\varphi u} = (\varphi_1^\dagger i \overleftrightarrow{D}_\mu \varphi_1)(\bar{u}_p \gamma^\mu u_r)$	
$Q^2_{\varphi u} = (\varphi_2^\dagger i \overleftrightarrow{D}_\mu \varphi_2)(\bar{u}_p \gamma^\mu u_r)$	
$Q^1_{\varphi d} = (\varphi_1^\dagger i \overleftrightarrow{D}_\mu \varphi_1)(\bar{d}_p \gamma^\mu d_r)$	
$Q^2_{\varphi d} = (\varphi_2^\dagger i \overleftrightarrow{D}_\mu \varphi_2)(\bar{d}_p \gamma^\mu d_r)$	

- Operators containing two fermions, two Higgs doublets and a covariant derivative
- They contribute to the fermion-Z and fermion-W couplings after EWSB

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2HDM-EFT operators

$\Psi^2\varphi X$		
G	W	B
$Q^1_{dG} = (\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi_1\, G^A_{\mu\nu}$	$Q^1_{dW} = (\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi_1\, W^I_{\mu\nu}$	$Q^1_{dB} = (\bar{q}_p\sigma^{\mu\nu}d_r)\varphi_1 B_{\mu\nu}$
$Q^2_{dG} = (\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi_2 G^A_{\mu\nu}$	$Q^2_{dW} = (\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi_2\, W^I_{\mu\nu}$	$Q^2_{dB} = (\bar{q}_p\sigma^{\mu\nu}d_r)\varphi_2 B_{\mu\nu}$
$Q^1_{uG} = (\bar{q}_p\sigma^{\mu\nu}T^A u_r)\tilde{\varphi}_1 G^A_{\mu\nu}$	$Q^1_{uW} = (\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\tilde{\varphi}_1\, W^I_{\mu\nu}$	$Q^1_{uB} = (\bar{q}_p\sigma^{\mu\nu}u_r)\tilde{\varphi}_1 B_{\mu\nu}$
$Q^2_{uG} = (\bar{q}_p\sigma^{\mu\nu}T^A u_r)\tilde{\varphi}_2 G^A_{\mu\nu}$	$Q^2_{uW} = (\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\tilde{\varphi}_2\, W^I_{\mu\nu}$	$Q^2_{uB} = (\bar{q}_p\sigma^{\mu\nu}u_r)\tilde{\varphi}_2 B_{\mu\nu}$
	$Q^1_{eW} = (\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi_1 W^I_{\mu\nu}$	$Q^1_{eB} = (\bar{l}_p\sigma^{\mu\nu}e_r)\varphi_1 B_{\mu\nu}$
	$Q^2_{eW} = (\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi_2 W^I_{\mu\nu}$	$Q^2_{eB} = (\bar{l}_p\sigma^{\mu\nu}e_r)\varphi_2 B_{\mu\nu}$

$$\sigma^{\mu\nu} = i\,[\gamma^\mu, \gamma^\nu]/2$$

- Operators containing two fermion fields, one Higgs doublet and a field strength tensor
- They give rise to dipole interactions after EWSB

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2HDM-EFT operators

$\Psi^2\varphi^3$		
e	d	u
$Q_{e\varphi}^{111} = (\bar{l}_p e_r \varphi_1)(\varphi_1^\dagger \varphi_1)$	$Q_{d\varphi}^{111} = (\bar{q}_p d_r \varphi_1)(\varphi_1^\dagger \varphi_1)$	$Q_{u\varphi}^{111} = (\bar{q}_p u_r \tilde{\varphi}_1)(\varphi_1^\dagger \varphi_1)$
$Q_{e\varphi}^{122} = (\bar{l}_p e_r \varphi_1)(\varphi_2^\dagger \varphi_2)$	$Q_{d\varphi}^{122} = (\bar{q}_p d_r \varphi_1)(\varphi_2^\dagger \varphi_2)$	$Q_{u\varphi}^{122} = (\bar{q}_p u_r \tilde{\varphi}_1)(\varphi_2^\dagger \varphi_2)$
$Q_{e\varphi}^{222} = (\bar{l}_p e_r \varphi_2)(\varphi_2^\dagger \varphi_2)$	$Q_{d\varphi}^{222} = (\bar{q}_p d_r \varphi_2)(\varphi_2^\dagger \varphi_2)$	$Q_{u\varphi}^{222} = (\bar{q}_p u_r \tilde{\varphi}_2)(\varphi_2^\dagger \varphi_2)$
$Q_{e\varphi}^{211} = (\bar{l}_p e_r \varphi_2)(\varphi_1^\dagger \varphi_1)$	$Q_{d\varphi}^{211} = (\bar{q}_p d_r \varphi_2)(\varphi_1^\dagger \varphi_1)$	$Q_{u\varphi}^{211} = (\bar{q}_p u_r \tilde{\varphi}_2)(\varphi_1^\dagger \varphi_1)$

- Operators with two fermion fields and three Higgs doublets
- They modify the relation between fermion masses and Higgs-fermion couplings

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2HDM-EFT: kinetic terms

$$L_{H_{\rm kin}}^{(4)+(6)} = \frac{1}{2}\begin{pmatrix}\partial_\mu\rho_1\\ \partial_\mu\rho_2\end{pmatrix}^T \begin{pmatrix} 1+\frac{2\Delta_{\Box}^{11}}{\Lambda^2}+\frac{\Delta_{\varphi D}^{11}}{2\Lambda^2} & \frac{\Delta_{\Box}^{12}}{\Lambda^2}+\frac{\Delta_{\varphi D}^{12}}{2\Lambda^2}\\ \frac{\Delta_{\Box}^{12}}{\Lambda^2}+\frac{\Delta_{\varphi D}^{12}}{2\Lambda^2} & 1+\frac{2\Delta_{\Box}^{22}}{\Lambda^2}+\frac{\Delta_{\varphi D}^{22}}{2\Lambda^2}\end{pmatrix}\begin{pmatrix}\partial_\mu\rho_1\\ \partial_\mu\rho_2\end{pmatrix}$$

$$+\frac{1}{2}\begin{pmatrix}\partial_\mu\eta_1\\ \partial_\mu\eta_2\end{pmatrix}^T \begin{pmatrix} 1+\frac{\Delta_{\varphi D}^{11}}{2\Lambda^2} & \frac{\Delta_{\varphi D}^{12}}{2\Lambda^2}\\ \frac{\Delta_{\varphi D}^{12}}{2\Lambda^2} & 1+\frac{\Delta_{\varphi D}^{22}}{2\Lambda^2}\end{pmatrix}\begin{pmatrix}\partial_\mu\eta_1\\ \partial_\mu\eta_2\end{pmatrix}$$

$$+\begin{pmatrix}\partial_\mu\phi_1^+\\ \partial_\mu\phi_2^+\end{pmatrix}^\dagger \begin{pmatrix} 1 & \frac{\Delta_{\varphi D}^{+}}{2\Lambda^2}\\ \frac{\Delta_{\varphi D}^{+}}{2\Lambda^2} & 1\end{pmatrix}\begin{pmatrix}\partial_\mu\phi_1^+\\ \partial_\mu\phi_2^+\end{pmatrix}$$

Example: $\mathcal{O}_{\phi\Box} = \partial_\mu(\phi^\dagger\phi)\partial^\mu(\phi^\dagger\phi)$

$$\frac{c_{\phi\Box}}{v^2}\mathcal{O}_{\phi\Box} = c_{\phi\Box}\partial_\mu h\partial^\mu h + \dots$$

$$\Delta\mathcal{L}_h = \frac{1}{2}(1+2c_{\phi\Box})\partial_\mu h\partial^\mu h + \dots \qquad \Rightarrow \qquad \bar{h} = (1+2c_{\phi\Box})^{\frac{1}{2}} h$$

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2HDM-EFT: kinetic terms

$$
L_{H_{\rm kin}}^{(4)+(6)} = \frac{1}{2}\begin{pmatrix}\partial_\mu\rho_1\\ \partial_\mu\rho_2\end{pmatrix}^T \begin{pmatrix} 1+\frac{2\Delta_\Box^{11}}{\Lambda^2}+\frac{\Delta_{\varphi D}^{11}}{2\Lambda^2} & \frac{\Delta_\Box^{12}}{\Lambda^2}+\frac{\Delta_{\varphi D}^{12}}{2\Lambda^2}\\ \frac{\Delta_\Box^{12}}{\Lambda^2}+\frac{\Delta_{\varphi D}^{12}}{2\Lambda^2} & 1+\frac{2\Delta_\Box^{22}}{\Lambda^2}+\frac{\Delta_{\varphi D}^{22}}{2\Lambda^2}\end{pmatrix}\begin{pmatrix}\partial_\mu\rho_1\\ \partial_\mu\rho_2\end{pmatrix}
$$

$$
+\frac{1}{2}\begin{pmatrix}\partial_\mu\eta_1\\ \partial_\mu\eta_2\end{pmatrix}^T \begin{pmatrix} 1+\frac{\Delta_{\varphi D}^{11}}{2\Lambda^2} & \frac{\Delta_{\varphi D}^{12}}{2\Lambda^2}\\ \frac{\Delta_{\varphi D}^{12}}{2\Lambda^2} & 1+\frac{\Delta_{\varphi D}^{22}}{2\Lambda^2}\end{pmatrix}\begin{pmatrix}\partial_\mu\eta_1\\ \partial_\mu\eta_2\end{pmatrix}
$$

$$
+\begin{pmatrix}\partial_\mu\phi_1^+\\ \partial_\mu\phi_2^+\end{pmatrix}^\dagger \begin{pmatrix} 1 & \frac{\Delta_{\varphi D}^{+}}{2\Lambda^2}\\ \frac{\Delta_{\varphi D}^{+}}{2\Lambda^2} & 1\end{pmatrix}\begin{pmatrix}\partial_\mu\phi_1^+\\ \partial_\mu\phi_2^+\end{pmatrix}
$$

$$
\rho_1 \to \rho_1\left(1-\frac{\Delta_{\varphi D}^{11}+4\Delta_\Box^{11}}{4\Lambda^2}\right)-\left(\frac{\Delta_{\varphi D}^{12}+4\Delta_\Box^{12}}{4\Lambda^2}\right)\rho_2
$$

$$
\rho_2 \to \rho_2\left(1-\frac{\Delta_{\varphi D}^{22}+4\Delta_\Box^{22}}{4\Lambda^2}\right)-\frac{\Delta_{\varphi D}^{12}+4\Delta_\Box^{12}}{4\Lambda^2}\rho_1
$$

$$
\eta_1 \to \eta_1\left(1-\frac{\Delta_{\varphi D}^{11}}{4\Lambda^2}\right)-\frac{\Delta_{\varphi D}^{12}}{4\Lambda^2}\eta_2
$$

$$
\phi_1^+ \to \phi_1^+ - \frac{\Delta_{\varphi D}^{+}}{4\Lambda^2}\phi_2^+
$$

$$
\phi_2^+ \to \phi_2^+ - \frac{\Delta_{\varphi D}^{+}}{4\Lambda^2}\phi_1^+
$$

$$
\eta_2 \to \eta_2\left(1-\frac{\Delta_{\varphi D}^{22}}{4\Lambda^2}\right)-\frac{\Delta_{\varphi D}^{12}}{4\Lambda^2}\eta_1
$$

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2HDM-EFT: mass terms

$$L_{M_H}^{(4)+(6)} = \frac{1}{2}\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}^T (m_\eta^2 + \Delta m_\eta^2) \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$
$$+\begin{pmatrix} \phi_1^- \\ \phi_2^- \end{pmatrix}^T \left(m_{\phi^\pm}^2 + \Delta m_{\phi^\pm}^2\right) \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$
$$+\frac{1}{2}\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}^T (m_\rho^2 + \Delta m_\rho^2) \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

$$\Delta m_\eta^2 = \Delta m_{\varphi D \eta}{}^2 + \Delta m^2_{\varphi^6 \eta}$$
$$\Delta m_\rho^2 = \Delta m_{\varphi D \rho}{}^2 + \Delta m^2_{\varphi^6 \rho}$$
$$\Delta m_{\phi^\pm}^2 = \Delta m_{\varphi D \phi^\pm}{}^2 + \Delta m^2_{\varphi^6 \phi^\pm}$$

2HDM:

$m_{\phi^\pm}^2$ and m_η^2
$\downarrow$
$\beta \equiv \arctan \frac{v_2}{v_1}$

m_ρ^2
$\downarrow$
α

2HDM-EFT:

$m_{\phi^\pm}^2 + \Delta m_{\phi^\pm}$ and
$m_\rho^2 + \Delta m_\rho^2$
$\downarrow$
$\beta_\phi^\pm,\ \beta_\eta \neq \beta$

$m_\rho^2 + \Delta m_\rho^2$
$\downarrow$
$\alpha' \neq \alpha$

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Yukawa sector

The couplings of the Higgs doublets with fermions in the 2HDM

$$\mathcal{L}_Y = -Y_1^e\,\bar{l}\varphi_1 e - Y_2^e\,\bar{l}\varphi_2 e - Y_1^d\,\bar{q}\varphi_1 d - Y_2^d\,\bar{q}\varphi_2 d - Y_1^u\,\bar{q}\tilde{\varphi}_1 u - Y_2^u\,\bar{q}\tilde{\varphi}_2 u + h.c.$$

(Require $Y_1^f = 0$ or $Y_2^f = 0$ to avoid FCNC)

Paschos-Glashow-Weinberg theorem:

If all right-handed fermions with the same quantum numbers couple to the same Higgs multiplet, then FCNC are absent.

model	u_R	d_R	e_R
Type I	φ_2	φ_2	φ_2
Type II	φ_2	φ_1	φ_1
Lepton − specific	φ_2	φ_2	φ_1
Flipped	φ_2	φ_1	φ_2

Yukawa sector

The couplings of the Higgs doublets with fermions in the 2HDM-EFT

$$\mathcal{L}_Y + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i \qquad \mathcal{O}_{ijk} \sim \left(\bar{f}_L f_R \phi_i\right)\left(\phi_j^\dagger \phi_k\right) \qquad i,j,k = 1,2$$

After the EW symmetry breaking:

- new contributions to the fermion masses

$$m^f = \frac{v_1 Y_1^f}{\sqrt{2}} + \frac{v_2 Y_2^f}{\sqrt{2}} + \frac{1}{2\sqrt{2}\,\Lambda^2}\left(v_1^3\, C_{f\varphi}^{111} + v_1 v_2^2\, C_{f\varphi}^{122} + v_2^3\, C_{f\varphi}^{222} + v_1^2 v_2\, C_{f\varphi}^{211}\right)$$

- Modifications to the Higgs-fermion-fermion and Higgs-Higgs-fermion-fermion couplings

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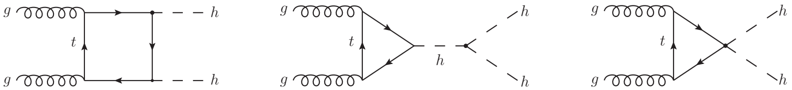
Application: Higgs pair production



SMEFT

$$\mathcal{O} \sim (\bar{f}_L f_R \phi)\left(\phi^\dagger \phi\right)$$

- The same operator controls $f\bar{f}h$ and $f\bar{f}hh$ couplings;
- it contributes also to the $f\bar{f}Z$ vertex
- hence, it is strongly constrained by the EWPT at LEP

2HDM-EFT

$$\mathcal{O}_{ijk} \sim (\bar{f}_L f_R \phi_i)\left(\phi_j^\dagger \phi_k\right) \quad i,j,k = 1,2$$

- Many operators, that enter in different combinations in the $f\bar{f}h$ and $f\bar{f}hh$ vertices;
- the $f\bar{f}hh$ vertex is not constrained by EWPT;
- enhancements of the $gghh$ cross section are possible.

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Summary and Outlook - 2HDM-EFT

Summary

- We have discussed in which cases the EFT approach can be extended to include new degrees of freedom.
- We have built the effective Lagrangian for the dynamical degrees of freedom of the 2HDM.
- We have shown that the rotations to the physical basis are affected by the dim-6 operators and $\tan\beta$ gets modifications.

Outlook

This is just the beginning:

- Calculate contributions from the effective operators to the observables.
- Set new bounds on the 2HDM and on (linear combination of) Wilson coefficients.
- Study the impact of the Z_2 symmetry and of FCNC in the effective sector.
- ...

Outline

The Doubly Charged $SU(2)_L$-singlet Scalar

Motivation: good candidate for the generation of the neutrino masses

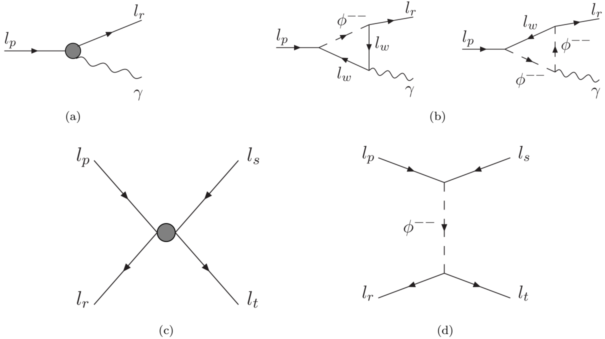
It couples only with R-handed charged leptons

$$\begin{aligned}\mathcal{L}_{UV} &= \mathcal{L}_{\rm SM} + (D_\mu S^{++})^\dagger (D^\mu S^{++}) \\ &\quad + \left(\lambda_{ab}\, \overline{(\ell_R)^c_a} \ell_{Rb}\, S^{++} + \text{h.c.}\right)\end{aligned}$$

λ_{ab} consist of 6 independent parameters and allow for LFV processes

Low-energy effective Lagrangian and the matching

Feynman diagrams representing the UV-complete contributions that match to the dipole and four-fermion operators.



- Diagrams in Fig. (b) match into the diagram in Fig. (a) (dipole interaction)
- Diagram in Fig. (d) matches into the diagram in Fig. (c) (contact interaction)

Crivellin, MG, Panizzi, Pruna, Signer, work in progress

Low-energy effective Lagrangian and the matching

Dipole			
$Q_{e\gamma}$	$em_r(\bar{l}_p\sigma^{\mu\nu}P_L l_r)F_{\mu\nu} + \text{H.c.}$		
Scalar/Tensorial		**Vectorial**	
Q_S	$(\bar{l}_p P_L l_r)(\bar{l}_s P_L l_t) + \text{H.c.}$	Q_{VLL}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{l}_s\gamma_\mu P_L l_t)$
		Q_{VLR}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{l}_s\gamma_\mu P_R l_t)$
		Q_{VRR}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{l}_s\gamma_\mu P_R l_t)$
$Q_{Slq(1)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_L q_t) + \text{H.c.}$	Q_{VlqLL}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{q}_s\gamma_\mu P_L q_t)$
$Q_{Slq(2)}$	$(\bar{l}_p P_L l_r)(\bar{q}_s P_R q_t) + \text{H.c.}$	Q_{VlqLR}	$(\bar{l}_p\gamma^\mu P_L l_r)(\bar{q}_s\gamma_\mu P_R q_t)$
Q_{Tlq}	$(\bar{l}_p\sigma^{\mu\nu} P_L l_r)(\bar{q}_s\sigma_{\mu\nu} P_L q_t) + \text{H.c.}$	Q_{VlqRL}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{q}_s\gamma_\mu P_L q_t)$
		Q_{VlqRR}	$(\bar{l}_p\gamma^\mu P_R l_r)(\bar{q}_s\gamma_\mu P_R q_t)$

Dimension-six operators that allow for effective leptonic transitions below the EW scale

Current low-energy experimental limits

$$\begin{aligned}
\mathrm{Br}\left[\tau^\mp \to e^\mp e^\pm e^\mp\right] &\leq 1.4\times 10^{-8}\\
\mathrm{Br}\left[\tau^\mp \to \mu^\mp \mu^\pm \mu^\mp\right] &\leq 1.2\times 10^{-8}\\
\mathrm{Br}\left[\tau^\mp \to e^\mp \mu^\pm \mu^\mp\right] &\leq 1.6\times 10^{-8}\\
\mathrm{Br}\left[\tau^\mp \to \mu^\mp e^\pm \mu^\mp\right] &\leq 9.8\times 10^{-9}\\
\mathrm{Br}\left[\tau^\mp \to \mu^\mp e^\pm e^\mp\right] &\leq 1.1\times 10^{-8}\\
\mathrm{Br}\left[\tau^\mp \to e^\mp \mu^\pm e^\mp\right] &\leq 8.4\times 10^{-8}\\
\mathrm{Br}\left[\mu^\mp \to e^\mp e^\pm e^\mp\right] &\leq 1.0\times 10^{-12}
\end{aligned}$$

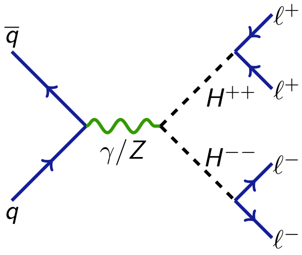
$$\begin{aligned}
\mathrm{Br}\left[\tau \to e\gamma\right] &\leq 3.3\times 10^{-8}\\
\mathrm{Br}\left[\tau \to \mu\gamma\right] &\leq 4.4\times 10^{-8}\\
\mathrm{Br}\left[\mu \to e\gamma\right] &\leq 4.2\times 10^{-13}
\end{aligned}$$

$$\mathrm{BR}(l_p^\pm \to l_r^\pm \gamma) \simeq \frac{\alpha\, m_p^5}{(24\pi^2)^2 m_\phi^4 \Gamma_p} \left| \sum_{w=1}^{3} \lambda_{pw}\lambda_{rw}^* \right|^2$$

$$\mathrm{BR}(l_p^\pm \to l_r^\pm l_s^\mp l_t^\pm) \simeq \frac{m_p^5 |\lambda_{ps}|^2 |\lambda_{rt}|^2}{s_{rt} 6(4\pi)^3 m_\phi^4 \Gamma_p}$$

Direct production

Current limits from LHC



- Direct searches at LHC (7 TeV and 13 Tev)
- Signature: same-sign lepton pairs

Current limits from ATLAS:

$m_\phi > 700$ GeV (R-handed)
$m_\phi > 800$ GeV (L-handed)
assuming $Br(H^{\pm\pm} \to l^\pm l^\pm) = 100\%$

Current limits from CMS:

$m_\phi > 800$ GeV
assuming
$\mathrm{Br}(H^{\pm\pm} \to e^\pm e^\pm) = 100\%$

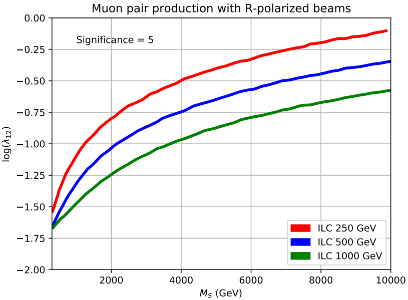
CERN-EP-2017-198

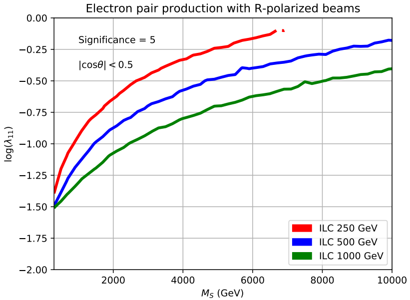
CMS-PAS-HIG-16-036

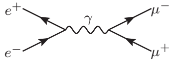
Perspective of searches at future colliders

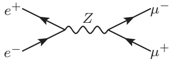
Crivellin, MG, Panizzi, Pruna, Signer, work in progress

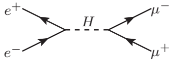
(Preliminary plots)

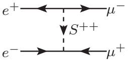




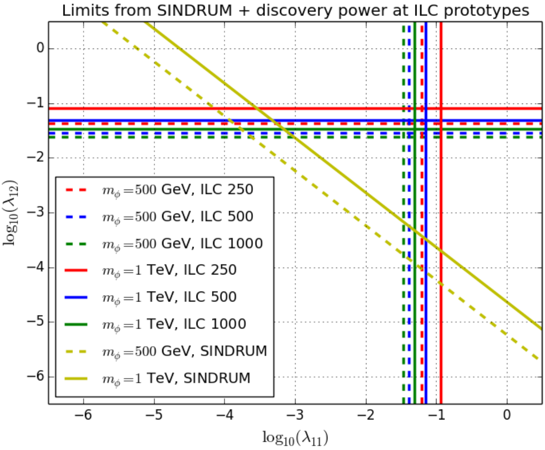








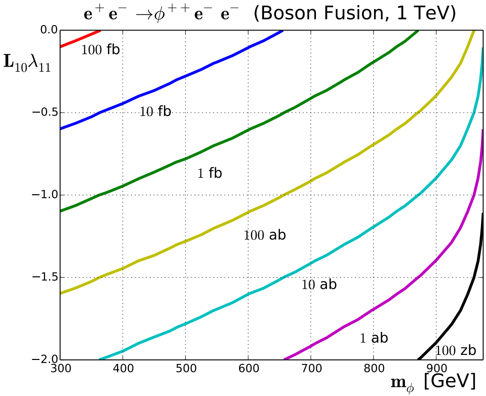
Limits from low energy and future colliders



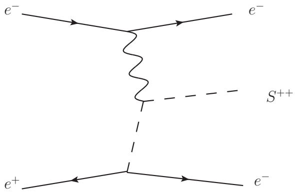
Crivellin, MG, Panizzi, Pruna, Signer, work in progress

Direct production

Single production at ILC



$e^+e^- \to \phi^{++}e^-e^-$



Crivellin, MG, Panizzi, Pruna, Signer, work in progress

Summary and Outllook - Doubly Charged Scalar

Summary

- The DCS is a minimal extension of the SM that accounts for the neutrino mass generation and allows LFV processes.
- Preliminary studies show that low energy physics and future e^+e^- colliders provide complementary bounds.
- Due to the production of the DCS in the t-channel, future e^+e^- colliders can be sensitive to mass scales of several TeV.

Outlook

This presentation is just a preliminary study:

- Perform a complete collider analysis of direct DCS production at future colliders.
- Study the possibility to improve current bounds at LHC.
- Study the interplay between low- and high-energy limits.
- . . .