Standard Model Higgs Effective Field Theory and extensions to the Two Higgs Doublet Model

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LNF Spring Institute 2017
Frascati, 12th May 2017

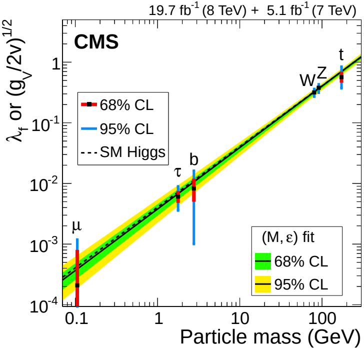
Outline

Introduction

After the discovery of the Higgs boson, we are looking for New Physics signals

It is reasonable to think that NP is related to the EW symmetry breaking

Compatibility of data with the SM



Scaling coupling $\propto$ mass follows naturally if the new boson is part of the sector that breaks the EW symmetry

$$\lambda_\psi \propto \frac{m_\psi}{v}$$

$$\lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

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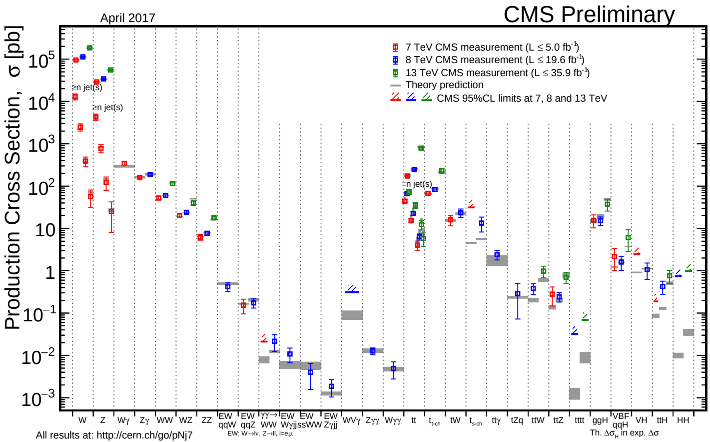

We look for small deviations from the SM: precision physics era

Introduction

- The focus now is on a region of the parameter space around the SM point.
- Following a bottom-up approach, our ignorance of the EWSB sector can be parametrized in terms of an effective Lagrangian.
- The Effective Field Theory approach is possible if there is a gap between m_H and the New Physics scale.
- The couplings of the operators are free parameters.
- The fields correspond to the particles of the SM.
- In case new (not-so-heavy) particles are discovered they can be included in the Lagrangian
  - Example: add a second light Higgs doublet $\longrightarrow$ 2HDM-EFT

Outline

Higgs 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

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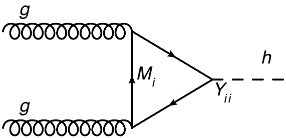
Effective Field Theories

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.

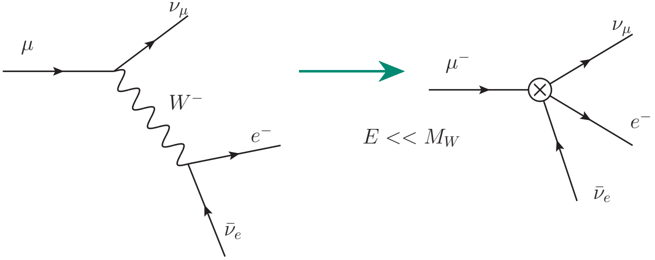
SM example: the limit of infinite top mass

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

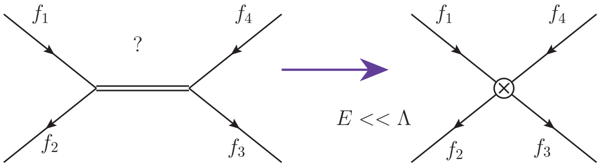
The coefficient is determined by matching the full theory with the effective theory.

Effective Field Theories

Fermi Theory



SMEFT



Higgs Effective Lagrangian

Higgs doublet - EW symmetry is linearly realized

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

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

- $\mathcal{L}^{D=5}$ 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
Buchmüller and Wyler, NPB 268 (1986) 621
Grzadkowski, Iskrzynski, Misiak and Rosiek, JHEP 1010 (2010) 085
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Effective Lagrangian for a Higgs doublet

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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		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

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

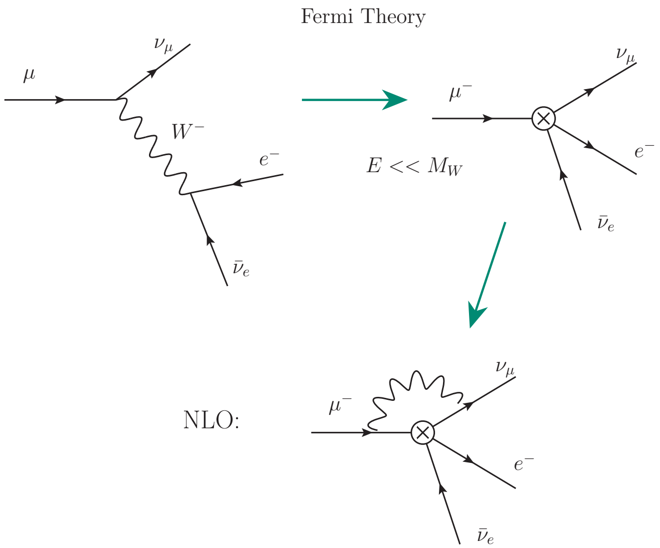
Class	N_{op}	CP-even n_g	1	3	CP-odd n_g	1	3
1	4	2	2	2	2	2	2
2	1	1	1	1	0	0	0
3	2	2	2	2	0	0	0
4	8	4	4	4	4	4	4
5	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
8 : $(\overline{L}L)(\overline{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	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

NLO EFT


Fermi Theory
ν_μ
μ
W^-
e^-
$\bar{\nu}_e$
μ^-
ν_μ
$E << M_W$
e^-
$\bar{\nu}_e$
NLO:
ν_μ
μ^-
e^-
$\bar{\nu}_e$

NLO Higgs EFT

One-loop calculations in linear Higgs EFT

Complete anomalous dimension matrix:

(Warsaw basis)

- Grojean, Jenkins, Manohar, Trott 2013
- Jenkins, Manohar, Trott 2013 & 2014
- Alonso, Jenkins, Manohar, Trott 2014

(SILH basis)

- Elias-Miró, Espinosa, Masso and Pomarol 2013
- Elias-Miró, Grojean, Gupta, Marzocca 2014

Some Higgs decays, finite renormalization:

- MG, Gomez-Ambrosio, Passarino and Uccirati 2015 ($h \to \gamma\gamma, Z\gamma, WW, ZZ$)
- Hartmann,Trott 2015 ($h \to \gamma\gamma$ in detail)

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NLO Higgs EFT

Conventions

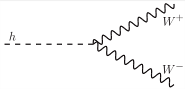
Warsaw basis

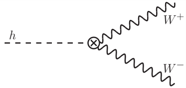
Each term of the d = 6 Lagrangian is of the form:

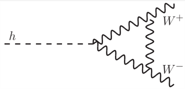
$$\frac{c_i}{M_W^2}\, g_6\, g^{n_i}\, \mathcal{O}_i \qquad\qquad g_6 \equiv \frac{1}{\sqrt{2}G_F\Lambda^2} \simeq 0.0606\left(\frac{\text{TeV}}{\Lambda}\right)^2$$

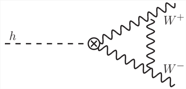
Insertion of 1-loop corrections in the EFT

Processes starting at tree-level in the SM e.g. $h \to W^+W^-$:

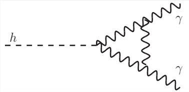


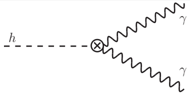


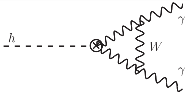




Processes starting at 1-loop in the SM e.g. $h \to \gamma\gamma$:







MG, Gomez-Ambrosio, Passarino and Uccirati, JHEP 1507 (2015) 175

NLO Higgs EFT

Preliminary steps

Vanishing of the linear H-term

In the SM there is a contribution to the linear H-term from the Higgs potential:

$$V(\phi) = \mu^2 \phi^\dagger \phi - \frac{\lambda}{2} \left(\phi^\dagger \phi\right)^2 \qquad \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} -i\sqrt{2}G^+ \\ h + v + iG^0 \end{pmatrix}$$

Its cancellation implies:

$$\mu^2 = -\lambda v^2 + \beta_h \qquad (\beta_h = 0 \text{ at tree level})$$

In the dim-6 SMEFT also the operator $\mathcal{O}_\phi = \left(\phi^\dagger \phi\right)^3$ contributes.

Hence, the cancellation implies:

$$\mu^2 = -\lambda v^2 + 3M_W^2 g_6 a_\phi + \beta_h$$

MG, Gomez-Ambrosio, Passarino and Uccirati, JHEP 1507 (2015) 175

NLO Higgs EFT

Preliminary steps

Redefinition of fields and parameters

All the operators with at least 2 powers of ϕ contribute to the quadratic terms.

All the fields and parameters must be redefined.

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

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

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

Redefinition of the gauge parameters

$$\mathcal{L}_{\rm gf} = -\mathcal{C}^+\,\mathcal{C}^- - \frac{1}{2}\,\mathcal{C}_{\rm Z}^2 - \frac{1}{2}\,\mathcal{C}_{\rm A}^2$$

$$\mathcal{C}^\pm = -\xi_{\rm W}\,\partial_\mu\,W_\mu^\pm + \xi_\pm\,M\,\phi^\pm \qquad \mathcal{C}_{\rm Z} = -\xi_{\rm Z}\,\partial_\mu\,Z_\mu + \xi_0\,\frac{M}{c_\theta}\,\phi^0 \qquad \mathcal{C}_{\rm A} = \xi_{\rm A}\,\partial_\mu\,A_\mu$$

Redefinition of the ξ_i parameters normalized to 1: $\xi_i = 1 + g_6\Delta R_{\xi_i}$

MG, Gomez-Ambrosio, Passarino and Uccirati, JHEP 1507 (2015) 175

NLO Higgs EFT

Renormalization

Counterterms for fields and parameters

Define UV-divergent counterterms for the fields:

$$F = \left(1 + \frac{1}{2}\frac{g^2}{16\pi^2} dZ_F \Delta_{UV}\right) F_{ren}$$

and for the parameters:

$$P = \left(1 + \frac{1}{2}\frac{g^2}{16\pi^2} dZ_P \Delta_{UV}\right) P_{ren}$$

$$\Delta_{UV} = \frac{2}{\varepsilon} - \gamma_E - \ln\pi - ln\frac{\mu_R^2}{\mu^2} \qquad dZ_i = dZ_i^{(4)} + g_6 dZ_i^{(6)}$$

Calculate the self-energies and determine the counterterms

$$\Sigma_{ii} = \frac{g^2}{16\pi^2}\left(\Sigma_{ii}^{(4)} + g_6\Sigma_{ii}^{(6)}\right) \qquad \Sigma_{ii}^{(n)} = \Sigma_{ii;UV}^{(n)}\Delta_{UV}(M_W^2) + \Sigma_{ii;fin}^{(n)}$$

Require that the HH, ZZ, $\gamma\gamma$, γZ, WW, ff self-energies are UV-finite.

MG, Gomez-Ambrosio, Passarino and Uccirati, JHEP 1507 (2015) 175

NLO Higgs EFT

Running of the Wilson coefficients

Construct the 3-point (and higher) functions:

- they are $\mathcal{O}^{(4)}$-finite
- remove the $\mathcal{O}^{(6)}$ UV divergencies by mixing the Wilson coefficients

Running and mixing of Wilson coefficients

$$\bar{c}_i(\mu) = \left(\delta_{ij} + \gamma_{ij}^{(0)} \frac{g_{SM}^2}{16\pi^2} \log\left(\frac{\mu}{M}\right)\right) \bar{c}_j(M)$$

- Compared to the SM, additional logarithmic divergences are present;
- these divergences are absorbed by the running of the coefficients of the local operators;
- the matrix $\gamma_{ij}^{(0)}$ mixes the coefficients;
- the only one-loop diagrams which generate logarithmic divergences are the ones containing one insertion of effective vertices;
- A selection of the operators *a priori* is not possible.

NLO Higgs EFT

Finite renormalization

On-shell finite renormalization

After removal of the UV poles we have replaced $M_{bare} \to M_{ren}$.

Now we establish the connection to the on-shell masses:

$$M^2_{ren} = M^2_{OS} \left[1 + \frac{g^2_{ren}}{16\pi^2} \left(d\mathcal{Z}^{(4)}_M + g_6 \, d\mathcal{Z}^{(6)}_M \right) \right] \qquad \text{etc.}$$

G_F and α renormalization schemes

Choose input observables:

- $\{G_F \,, M_Z \,, M_W\}$
- $\{\alpha \,, G_F \,, M_Z\}$
- $\dots$

and write the corresponding equations that connect renormalized parameters to experimental measurements.

MG, Gomez-Ambrosio, Passarino and Uccirati, JHEP 1507 (2015) 175

NLO Higgs EFT

Finite renormalization

Example: $\{G_F\,, M_Z\,, M_W\}$ scheme

- Establish a connection between g_{ren} and G_F

$$\text{th.} \qquad \frac{1}{\tau_\mu} = \frac{m_\mu^5}{192\pi^3}\frac{g^4}{32M_W^4}\left(1+\delta_\mu\right)$$

$$\text{exp.} \qquad \frac{1}{\tau_\mu} = \frac{m_\mu^5}{192\pi^3}G_F^2$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}\left[1+\frac{g^2}{16\pi^2}\left(\delta_G+\frac{\Sigma_{WW}(0)}{M_W^2}\right)\right]$$

$$g_{ren}^2 = 4\sqrt{2}G_F M_{W;ren}^2\left[1-\frac{G_F M_{W;ren}^2}{2\sqrt{2}\pi^2}\left(\delta_G+\frac{\Sigma_{WW;fin}(0)}{M_W^2}\right)\right]$$

MG, Gomez-Ambrosio, Passarino and Uccirati, JHEP 1507 (2015) 175

Example: Higgs decay to a photon pair

$h \to \gamma\gamma$

$$A^{\mu\nu}_{H\gamma\gamma} = \mathcal{T}_{H\gamma\gamma} T^{\mu\nu} \qquad M_H^2 T^{\mu\nu} = p_2^\mu p_1^\nu - p_1 \cdot p_2 \delta^{\mu\nu}$$

$$\mathcal{T}_{H\gamma\gamma} = \kappa_W^{H\gamma\gamma} \mathcal{T}^W_{H\gamma\gamma} + \kappa_t^{H\gamma\gamma} \mathcal{T}^t_{H\gamma\gamma} + \kappa_b^{H\gamma\gamma} \mathcal{T}^b_{H\gamma\gamma} + \mathcal{T}^{NF}_{H\gamma\gamma}$$

The SM contribution

$\kappa_W^{H\gamma\gamma} = \kappa_t^{H\gamma\gamma} = \kappa_b^{H\gamma\gamma} = 1$

$$\mathcal{T}^x_{H\gamma\gamma} = \frac{i g^3 s_W^2}{8\pi^2} \frac{M_x^2}{M_W} T^x_{H\gamma\gamma} \qquad C_0^x \equiv C_0(-M_H^2, 0, 0; M_X, M_x, M_x)$$

$$T^W_{H\gamma\gamma} = -6 - 6(M_H^2 - 2M_W^2) C_0^W$$

$$T^t_{H\gamma\gamma} = \frac{16}{3} + \frac{8}{3}(M_H^2 - 4M_t^2) C_0^t \qquad T^b_{H\gamma\gamma} = \frac{4}{9} + \frac{2}{9}(M_H^2 - 4M_b^2) C_0^b$$

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$$\mathcal{T}_{H\gamma\gamma} = \kappa_W^{H\gamma\gamma} \mathcal{T}^W_{H\gamma\gamma} + \kappa_t^{H\gamma\gamma} \mathcal{T}^t_{H\gamma\gamma} + \kappa_b^{H\gamma\gamma} \mathcal{T}^b_{H\gamma\gamma} + \mathcal{T}^{NF}_{H\gamma\gamma}$$

The factorizable $d = 6$ contributions: $\kappa_x^{H\gamma\gamma} = 1 + g_6 \Delta\kappa_x^{H\gamma\gamma} \qquad (x = W, t, b)$

$$\Delta\kappa_W^{H\gamma\gamma} = 2a_{\phi\Box} - \frac{1}{2s_W^2} a_{\phi D} + (6 - s_W^2) a_{AA} + c_W^2 a_{ZZ} + (2 + s_W^2) \frac{c_W}{s_W} a_{AZ}$$

$$\Delta\kappa_t H\gamma\gamma = (6 + s_W^2) a_{AA} - c_W^2 a_{ZZ} + (2 - s_W^2) \frac{c_W}{s_W} a_{AZ} + \frac{3}{16} \frac{M_H^2}{s_W M_W^2} a_{tWB} + a_{t\phi}$$

$$\Delta\kappa_b^{H\gamma\gamma} = (6 - s_W^2) a_{AA} - c_W^2 a_{ZZ} + (2 - s_W^2) \frac{c_W}{s_W} a_{AZ} - \frac{3}{8} \frac{M_H^2}{s_W M_W^2} a_{bWB} - a_{b\phi}$$

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$$\mathcal{T}_{H\gamma\gamma} = \kappa_W^{H\gamma\gamma}\mathcal{T}^W_{H\gamma\gamma} + \kappa_t^{H\gamma\gamma}\mathcal{T}^t_{H\gamma\gamma} + \kappa_b^{H\gamma\gamma}\mathcal{T}^b_{H\gamma\gamma} + \mathcal{T}^{NF}_{H\gamma\gamma}$$

The non-factorizable $d = 6$ contributions:

$$\mathcal{T}^{NF}_{H\gamma\gamma} = i g g_6 \frac{M_H^2}{M_W} a_{AA} + 1\,\frac{g^3 g_6}{16\pi^2}\left[a_{AA}\mathcal{T}^{AA}_{H\gamma\gamma}(\mu) + a_{ZZ}\mathcal{T}^{ZZ}_{H\gamma\gamma}(\mu) + a_{AZ}\mathcal{T}^{AZ}_{H\gamma\gamma}(\mu) + a_{tWB}\mathcal{T}^{tWB}_{H\gamma\gamma}(\mu) + a_{bWB}\mathcal{T}^{bWB}_{H\gamma\gamma}(\mu)\right]$$

$$\mathcal{T}^{AA}_{H\gamma\gamma}(\mu) = -\frac{x_H^2}{32}\left[8(1-3s_W^2)s_W^2 + (3-4s_W^2 c_W^2)x_H^2\right]\ln\frac{\mu^2}{M_H^2} + \dots$$

$$\mathcal{T}^{ZZ}_{H\gamma\gamma} = \frac{s_W^2 c_W^2 x_H^2}{8}(6 - x_H^2)\ln\frac{\mu^2}{M_H^2} + \dots$$

$$\mathcal{T}^{AZ}_{H\gamma\gamma} = -\frac{s_W c_W x_H^2}{16}\left[2(1-6s_W^2) - (1-2s_W^2)x_H^2\right]\ln\frac{\mu^2}{M_H^2} + \dots$$

$$x_H = \frac{M_H}{M_W}$$

MG, Gomez-Ambrosio, Passarino and Uccirati, JHEP 1507 (2015) 175

Summary and Outlook - SMEFT

Summary

- We have shown the effective Lagrangian for a Higgs doublet. In the spirit of a bottom-up approach, it is an essential framework to perform searches for new physics in a model-independent way.
- In view of a precision Higgs physics phase, NLO calculations are in need. The whole anomalous dimension matrix is now known and some Higgs processes have been calculated.

Outlook

A lot still to be done:

- The other Higgs decay and production channels
- S , T , U parameters
- Implement $\mathcal{L}_{d=6}$ in automatic tools for NLO calculations
- Fit experimental data!

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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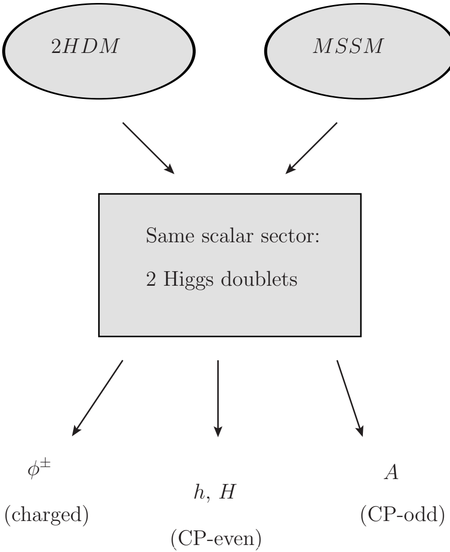
The Two Higgs Doublet Model



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

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

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

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

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

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:

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

Crivellin, MG, Procura, JHEP 1609 (2016) 160

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

- 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

Crivellin, MG, Procura, JHEP 1609 (2016) 160

2HDM-EFT operators

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

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

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

Crivellin, MG, Procura, JHEP 1609 (2016) 160

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

Crivellin, MG, Procura, JHEP 1609 (2016) 160

2HDM-EFT: kinetic terms

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

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

$$+\begin{pmatrix}\partial_\mu\phi^+_1\\ \partial_\mu\phi^+_2\end{pmatrix}^\dagger \begin{pmatrix} 1 & \frac{\Delta^{+}_{\varphi D}}{2\Lambda^2} \\ \frac{\Delta^{+}_{\varphi D}}{2\Lambda^2} & 1\end{pmatrix}\begin{pmatrix}\partial_\mu\phi^+_1\\ \partial_\mu\phi^+_2\end{pmatrix}$$

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

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

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

Crivellin, MG, Procura, JHEP 1609 (2016) 160

2HDM-EFT: kinetic terms

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

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

$$+\begin{pmatrix}\partial_\mu\phi^+_1\\ \partial_\mu\phi^+_2\end{pmatrix}^\dagger \begin{pmatrix} 1 & \frac{\Delta^{+}_{\varphi D}}{2\Lambda^2}\\ \frac{\Delta^{+}_{\varphi D}}{2\Lambda^2} & 1\end{pmatrix}\begin{pmatrix}\partial_\mu\phi^+_1\\ \partial_\mu\phi^+_2\end{pmatrix}$$

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

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

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

$$\phi^+_1 \to \phi^+_1-\frac{\Delta^{+}_{\varphi D}}{4\Lambda^2}\phi^+_2$$

$$\phi^+_2 \to \phi^+_2-\frac{\Delta^{+}_{\varphi D}}{4\Lambda^2}\phi^+_1$$

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

Crivellin, MG, Procura, JHEP 1609 (2016) 160

2HDM-EFT: mass terms

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

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

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 $m_\rho^2 + \Delta m_\rho^2$

$\downarrow$

$\beta_\phi^\pm,\ \beta_\eta \neq \beta$

$m_\rho^2 + \Delta m_\rho^2$

$\downarrow$

$\alpha' \neq \alpha$

Crivellin, MG, Procura, JHEP 1609 (2016) 160

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:

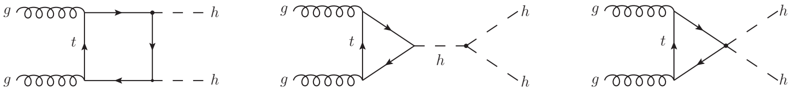
- new contributions to the fermion masses

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

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

Crivellin, MG, Procura, JHEP 1609 (2016) 160

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.

Crivellin, MG, Procura, JHEP 1609 (2016) 160

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.
- ...