Effective field theory for Higgs Physics

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Higgs Hunting 2016
Paris, 1st September 2016

Higgs Effective Lagrangian

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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Higgs Effective Lagrangian

Compatibility with the SM

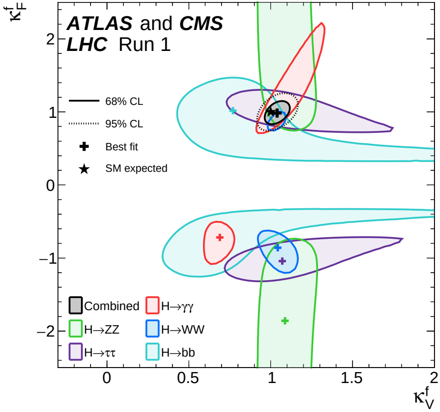
The Higgs boson looks like a doublet

Gap between m_H and the New Physics scale

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

NLO is the new standard @LHC

- Many calculations at NNLO QCD
- Many calculations at NLO EW



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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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	$N_{\rm op}$	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

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

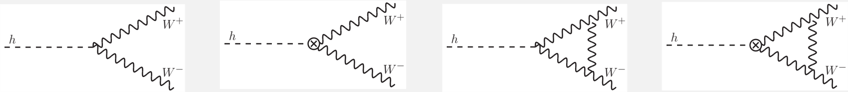
Warsaw basis

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

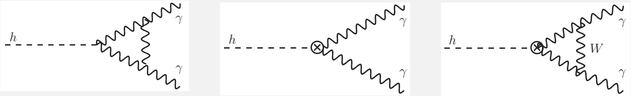
$$\frac{c_i}{M_W^2}\, g_6\, g^{n_i}\, \mathcal{O}_i \qquad\qquad g_6 \equiv \frac{1}{\sqrt{2} G_F \Lambda^2} \simeq 0.0606 \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

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:

$$\mu^2 = -\lambda v^2 + 3M_W^2 g_6 a_\phi + \beta_h \qquad (\beta_h = 0 \text{ at tree level})$$

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

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 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

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!