The low energy theories of the Higgs sector

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- The LHC is turning on: it is time to probe the Higgs sector.

- Recall that

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\ \theta_W} = 1.0008^{+0.0017}_{-0.0007} \quad (1)$$

- Delicate relation $\rho = 1$ only preserved "*easily*" if the BSM Higgs sector contains only *singlets or doublets*. (or no mixing with the Higgs).

- Since LHC data is consistent with SM like Higgs couplings (alignment limit), the decoupling limit is a very attractive possibility: $\rightarrow$ *Use EFT's!!*

- For simplicity we will *work at tree level*.

- Example: Higgs mixing with a heavy real singlet. Fermionic and gauge higgs couplings must be diluted accordingly.

- In EFT this is packaged in WF renormalization through operators

$$\frac{\eta}{m_s^2}\,\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) \tag{2}$$

The 2HDM

- General 2HDM: 11 parameters *only in the potential!*.

- Work in the *Higgs basis*, $< H_2 >= 0$

$$V = \tilde{m}_1^2 H_1^\dagger H_1 + \tilde{m}_2^2 H_2^\dagger H_2 + \left(\tilde{m}_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.}\right) + \frac{1}{2}\tilde{\lambda}_1 (H_1^\dagger H_1)^2 + \tilde{\lambda}_6 H_1^\dagger H_1 H_1^\dagger H_2 + \dots \quad (3)$$

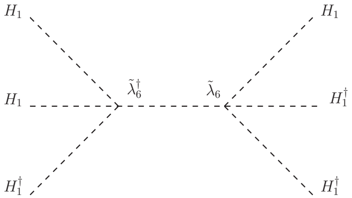
- From EWSB conditions

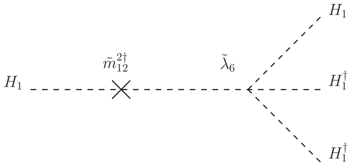
$$\tilde{m}_{12}^2 = -\frac{1}{2}\tilde{\lambda}_6 v^2$$

$$\to ED := n_D + 2n_{\tilde{m}_{12}^2} \qquad \textit{Effective dimension}$$

Example 1: Modifications to the Higgs potential

Consider the following diagrams at zero momentum

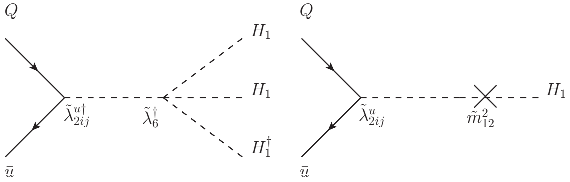




$$\frac{\tilde{\lambda}_6^* \tilde{\lambda}_6}{\tilde{m}_2^2}(H_1^\dagger H_1)^3 \qquad \frac{(\tilde{\lambda}_6^* \tilde{m}_{12}^2 + h.c.)}{\tilde{m}_2^2}(H_1^\dagger H_1)^2$$

They are of the same effective dimension (six)

Example 2: Modifications to Higgs-fermion interaction Lagrangian and four fermion interactions



$$-Q_i H_1 \left(\frac{\tilde{\lambda}^u_{2ij} \tilde{\lambda}^*_6}{\tilde{m}^2_2} H_1^\dagger H_1 + \frac{\tilde{\lambda}^u_{2ij} \tilde{\lambda}^*_6}{\tilde{m}^2_2} \right) \bar{u}_j \qquad (4)$$

They are of the same effective dimension (six)

Summary of effects

- We work at ED 6 in the fermionic sector, and 8 in the bosonic sector.
- After calculating $\approx$ 20 diagrams we get

	Is modified at effective dimension:
Higgs potential	≥ 6
Higgs-fermion interactions *	≥ 6
Four-fermion interactions *	≥ 6
Higgs kinetic lagrangian	≥ 8
Higgs-gauge boson interactions	≥ 8

$*$ carries CP and/or flavor violation.

- Compare with the xSM: in that case, Higgs-gauge boson interactions are modified at effective dimension 6.

List of results

- **Only one coupling** (some sort of “complex” alignment parameter) and the yukawas of the heavy higgs control most of the modifications to the SM Higgs couplings at first order.

$$g_{\varphi VV} = \frac{2m_V^2}{v}\left[1 - \frac{1}{2}\tilde{\lambda}_6^*\tilde{\lambda}_6\,\frac{v^4}{\tilde{m}_2^4} + \mathcal{O}\left(\frac{v^6}{\tilde{m}_2^6}\right)\right]$$

$$g_{\varphi^2 VV} = \frac{2m_V^2}{v^2}\left[1 - 3\tilde{\lambda}_6^\dagger\tilde{\lambda}_6\,\frac{v^4}{\tilde{m}_2^4} + \mathcal{O}\left(\frac{v^6}{\tilde{m}_2^6}\right)\right] \qquad (5)$$

$$\lambda^f_{\varphi ij} = \frac{m_i^f}{v}\,\delta_{ij} - 2\left(\frac{\tilde{\lambda}^f_{2ij}\tilde{\lambda}_6^*}{2\sqrt{2}}\right)\left(\frac{v^2}{\tilde{m}_2^2}\right) + \mathcal{O}\left(\frac{v^4}{\tilde{m}_2^4}\right)$$

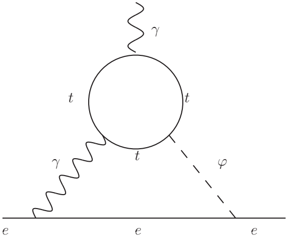
- **No CP violation in the bosonic interactions** up to at least effective dimension 10 (or more). Background invariants $\mathrm{Arg}(\tilde{\lambda}_6^2\tilde{\lambda}_5^*), \mathrm{Arg}(\tilde{\lambda}_7^2\tilde{\lambda}_5^*)$ are irrelevant at ED 6.

Further applications: CP violation.

- In any 2HDM with Glashow-Weinberg conditions, *there is only* **one** *relevant CP violating phase at ED 6*, carried **exclusively** in the higgs-fermion interactions.

$$\theta := \frac{v^2}{\tilde{m}_2^2} \sin\left[\arg\left(\tilde{\lambda}_6^* e^{-i\xi/2}\right)\right] + \mathcal{O}\left(\frac{v^4}{\tilde{m}_2^2}\right)$$

- Important for EDM's. *We can directly relate an EDM measurement with a higgs-fermion coupling measurement.*



Example: type II 2HDM

- At large $\tan\beta$, only significant deviation from SM couplings is in down type yukawas.

$$\lambda^{d,\ell}_{\varphi ij} = \delta_{ij}\,\frac{m_i^{d,\ell}}{v}\left[1+\tilde{\lambda}_6^* e^{-i\xi/2}\tan\beta\,\frac{v^2}{\tilde{m}_2^2}+\mathcal{O}\left(\frac{v^4}{\tilde{m}_2^4}\right)\right]$$

$$v\lambda^{d,\ell}_{\varphi^2 ij} = v^2\lambda^{d,\ell}_{\varphi^3 ij} = \delta_{ij}\,\frac{m_i^{d,\ell}}{v}\left[3\tilde{\lambda}_6^* e^{-\frac{i\xi}{2}}\tan\beta\,\frac{v^2}{\tilde{m}_2^2}+\mathcal{O}\left(\frac{v^4}{\tilde{m}_2^4}\right)\right] \tag{6}$$

Further applications: flavor physics.

- Flavor physics: flavor violation in four fermion operators from integrating out the heavy doublet and the higgs boson come at **the same order**.

$$\frac{\tilde{\lambda}^{u}_{2ij}\tilde{\lambda}^{u\dagger}_{2mn}}{\tilde{m}_2^2}(Q_i\bar{u}_j)(\bar{u}^\dagger_m Q^\dagger_n) \qquad \frac{\lambda^{u}_{\varphi ij}\lambda^{u}_{\varphi mn}}{m_\varphi^2}(u_i\bar{u}_j)(u_m\bar{u}_n)$$

From heavy higgs   From light higgs

- But they have a **different chiral**, **parametric** and **flavor violating** structure. *Important* for flavor observables.

- If we are in the exact alignment limit, **only deviation to SM** is in four fermion operators induced by integrating out the heavy Higgs.

Conclusions

- The results presented here, unless stated otherise **are valid for the most general 2HDM with heavy BSM higgses**.

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