EFFECTIVE THEORIES OF HIGGS SECTOR VACUUM STATES

Daniel Egana-Ugrinovic
Rutgers University

In collaboration with Scott Thomas

UC Davis
Sept. 28th, 2015
A new era of discovery: the Higgs sector

- Possible deviations from the SM Higgs couplings could be found (e.g. Craig, Galloway, Thomas 1305.2424).

- New scalars extending the Higgs sector could be found (e.g. Craig, D’Eramo, Draper, Thomas, Zhang, 1504.04630).

- Flavor physics could provide hints to new scalars, that could be charged (e.g. Crivellin 1412.2512).

- Which one(s) would be the possible extension(s) of the Higgs sector corresponding to a particular signature?
EW Precision

- First experimental constraint: EW precision

\[ \rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 1.0008^{+0.0017}_{-0.0007} \]

*Easily achieved only with a vacuum parametrized by SU(2) singlets and doublets (*)

Alignment

• Second experimental constraint, *alignment*:

  The Higgs seems to couple to SM particles with similar strength than the Higgs condensate (experimental fact) (*)

  (* at least to gauge bosons and 3rd gen. fermions)

  Naturally achieved in the decoupling limit
The EFT's of the Higgs sector

- These experimental facts are very constraining.

- The aligned xSM and 2HDM are the simplest UV completions fulfilling these principles.

*The objective*

Be as general as possible and derive the xSM and 2HDM EFT (at tree level).

*Leave no effect behind.*
Outline

1. The effective theory of the xSM. Democratic dilution of couplings?


3. The low energy theory of the 2HDM.

4. Comments. The complex alignment parameter. Examples of applications of the EFT.
The xSM
The xSM

- The most general renormalizable potential contains 7 parameters

\[ V = \frac{\mu^2}{2} S^2 + \frac{\zeta}{3} S^3 + \frac{\lambda S}{8} S^4 + m^2 H^\dagger H + \frac{\lambda}{2} (H^\dagger H)^2 + \xi S H^\dagger H + \frac{\lambda'}{2} S^2 H^\dagger H \]

without loss of generality, we write no tadpole term

- There are 4 mass scales \( \zeta, \xi, \mu, m \). Define the decoupling limit as

\[ \lambda_i v^2 \ll \mu^2 \]

- We allow for the remaining mass scales to be as large as \( \mu \)

\[ \xi, \zeta \leq \mu \]

That is it: *this is very general*
The vacuum states. Fermionic interactions.

- Define the vacuum states

\[ H_0 = \frac{1}{\sqrt{2}} (v + h) \quad S = v_s + s \]

- And standard fermionic interactions

\[ -\mathcal{L}_Y = \lambda_{ij}^u Q_i H \bar{u}_j - \lambda_{ij}^d Q_i H^c \bar{d}_j - \lambda_{ij}^\ell L_i H^c \bar{\ell}_j + h.c. \]

\[ \lambda_{ij}^f = \frac{\sqrt{2} m_{ij}^f}{v} = \frac{\sqrt{2} m_i^f}{v} \delta_{ij}^f \]
Very short review: the mixing language

The interaction term $\xi S H^\dagger H$ induces mixing. The Higgs mass eigenstate is

$$\varphi_1 = h \cos \gamma + s \sin \gamma$$

$$\cos \gamma = 1 - \frac{\xi^2}{2\mu^2} \left( \frac{v}{\mu} \right)^2 + \mathcal{O} \left( \frac{v^4}{\mu^4} \right)$$

Couplings of the higgs mass eigenstate are *democratically diluted* with respect to SM value *

$$g_{\varphi_1VV} = \frac{2m_V^2}{v} \cos \gamma$$

$$g_{\varphi_1^2VV} = \frac{2m_V^2}{v^2} \cos^2 \gamma$$

$$\chi^f_{\varphi_1ij} = \frac{m_i^f}{v} \cos \gamma \delta_{ij}$$

* Self couplings are more complicated
Deriving the xSM EFT

- An example diagram is

\[ \frac{\xi^2}{\mu^2} (H^\dagger H)^2 \]

\[ \frac{\xi^2}{\mu^4} \partial_\mu (H^\dagger H)^2 \partial_\mu (H^\dagger H)^2 \]

- EFT organizes the effects in an expansion in a small parameter.

- To get this expansion right, need to identify the operator’s effective dimension.

*In the xSM*

Effective dimension = Operator dimension
The xSM EFT

- Up to operator dimension six:

\[ D_\mu H^\dagger D^\mu H + \frac{1}{2} \zeta_H \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) - V'(H) \]

- By any means not the most general EFT you could write.

- Most coefficients (but not all) controlled exclusively by one parameter: \( \frac{\xi^2}{\mu^2} \)
The analogue of mixing in EFT terms

Let us expand the kinetic operator

\[ \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) = v^2 \partial_\mu h \partial^\mu h + 2vh \partial_\mu h \partial^\mu h + h^2 \partial_\mu h \partial^\mu h \]

„Mixing“ is encoded in WF renormalization.

The remaining two operators can be replaced in favor of operators with no derivatives using e.o.m., and they lead to additional modifications of the Higgs couplings.
Fermionic and Gauge Couplings

- All couplings are modified \textit{at the same operator dimension}.

\[
\lambda^{f}_{\varphi_{ij}} = \frac{m^{f}_{i}}{v} \left[ 1 - \frac{\xi^2}{2\mu^2} \frac{v^2}{\mu^2} \right] \delta_{ij} + \mathcal{O} \left( \frac{v^4}{\mu^4} \right)
\]

\[
g^{3}_{\varphi} = \frac{-3m^{2}_{\varphi}}{v^2} + \left( \frac{9\lambda \xi^2}{2\mu^2} - \frac{3\lambda^{'} \xi^2}{\mu^2} - \frac{9\xi^4}{2\mu^4} + \frac{2\xi \xi^3}{\mu^4} \right) \frac{v^2}{\mu^2} + \mathcal{O} \left( \frac{v^4}{\mu^4} \right)
\]

\[
g^{VV}_{\varphi} = \frac{2m^{2}_{V}}{v} \left[ 1 - \frac{\xi^2}{2\mu^2} \frac{v^2}{\mu^2} \right] + \mathcal{O} \left( \frac{v^4}{\mu^4} \right)
\]

\[
g^{2VV}_{\varphi} = \frac{2m^{2}_{V}}{v^2} \left[ 1 - \frac{2\xi^2}{\mu^2} \frac{v^2}{\mu^2} \right] + \mathcal{O} \left( \frac{v^4}{\mu^4} \right) \neq \frac{2m^{2}_{V}}{v^2} \cos^2 \gamma
\]

\textit{The last coupling is not just dilution!}
Four linear couplings do not match

- Amplitudes match, couplings do not necessarily match. Consider the short distance piece of the amplitude.

\[ g_{EFT}^{\phi\phiVV} = g_{Mixing}^{\phi_1\phi_1VV} + \]

(Short distance only)

- This diagram cannot be neglected: it leads to effects of order \( v^2/\mu^2 \)
Trilinear couplings must match

- This ensures the equality of the long distance pieces of the amplitudes.
  \[ \text{(Long distance only)} \]
  \[ \frac{1}{s-m_\phi^2} \]

- Long distance pieces of amplitudes are controlled by trilinear couplings.

Trilinear couplings in the mixing and EFT languages always match.
The 2HDM: an unconventional review
The Most General 2HDM

- It is a theory of two identical doublets with a condensate specified by

\[ \frac{v_1^2}{2} = \langle \Phi_1^\dagger \Phi_1 \rangle \quad \frac{v_2^2}{2} = \langle \Phi_2^\dagger \Phi_2 \rangle \]

\[ \xi = \text{Arg} \langle \Phi_1^\dagger \Phi_2 \rangle \]

- As such

\[ \tan \beta = \frac{v_1}{v_2} \]

does not have physical meaning at this point

(see for instance Haber, O’Neil, 0602242)
The Higgs Basis

- We can always perform a rotation

\[
e^{-i\xi/2} H_1 = \cos \beta \ \Phi_1 + \sin \beta \ e^{-i\xi} \ \Phi_2
\]

\[
H_2 = - \sin \beta \ e^{i\xi} \ \Phi_1 + \cos \beta \ \Phi_2
\]

\[
\frac{v^2}{2} = \langle H_1^\dagger H_1 \rangle \quad 0 = \langle H_2^\dagger H_2 \rangle
\]

- This is the Higgs basis (e.g. Davidson, Haber 0504050). Useful in the alignment limit, so we work in this basis.
The potential in the Higgs basis

The most general renormalizable potential in the Higgs basis is

\[
V(H_1, H_2) = \tilde{m}_1^2 H_1^\dagger H_1 + \tilde{m}_2^2 H_2^\dagger H_2 + (\tilde{m}_{12}^2 H_1^\dagger H_2 + \text{h.c.}) \\
+ \frac{1}{2} \tilde{\lambda}_1 (H_1^\dagger H_1)^2 + \frac{1}{2} \tilde{\lambda}_2 (H_2^\dagger H_2)^2 + \tilde{\lambda}_3 (H_2^\dagger H_2)(H_1^\dagger H_1) + \tilde{\lambda}_4 (H_2^\dagger H_1)(H_1^\dagger H_2) \\
+ \left[ \frac{1}{2} \tilde{\lambda}_5 (H_1^\dagger H_2)^2 + \tilde{\lambda}_6 (H_1^\dagger H_1 H_2^\dagger H_2) + \tilde{\lambda}_7 (H_2^\dagger H_2)(H_1^\dagger H_2) + \text{h.c.} \right]
\]

The EWSB conditions are

\[
v^2 = -2 \frac{\tilde{m}_1^2}{\tilde{\lambda}_1} \\
\tilde{m}_{12}^2 = -\frac{1}{2} \tilde{\lambda}_6 v^2
\]

No-tadpole condition

The only limitation we will impose, is that we work in the decouplings limit \( \tilde{\lambda}_i v^2 \ll \tilde{m}_2^2 \)
The observables in the Higgs potential

The potential contains a $U(1)$ background symmetry

<table>
<thead>
<tr>
<th></th>
<th>$U(1)_{PQ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_1$</td>
<td>0</td>
</tr>
<tr>
<td>$H_2$</td>
<td>-1</td>
</tr>
<tr>
<td>$\tilde{m}_1^2$, $\tilde{m}_2^2$, $\tilde{\lambda}_1$, $\tilde{\lambda}_2$, $\tilde{\lambda}_3$, $\tilde{\lambda}_4$</td>
<td>0</td>
</tr>
<tr>
<td>$\tilde{m}_{12}^2$, $\tilde{\lambda}_6$, $\tilde{\lambda}_7$</td>
<td>+1</td>
</tr>
<tr>
<td>$\tilde{\lambda}_5$</td>
<td>+2</td>
</tr>
</tbody>
</table>

There are 11 invariants under the background symmetry in the potential: 11 physical observables (examples: $\tilde{\lambda}_2$, $\tilde{\lambda}_6^*\tilde{\lambda}_6$, $\nu$)

The background symmetry is unbroken by the Higgs vev.
The Yukawas. CP violation.

The most general Yukawas are

\[
\begin{bmatrix}
\tilde{\lambda}_{aij}^u & Q_i H_a \bar{u}_j - \tilde{\lambda}_{aij}^{d\dagger} Q_i H_a^c \bar{d}_j - \tilde{\lambda}_{aij}^{\ell\dagger} L_i H_a^c \bar{\ell}_j + \text{h.c.}
\end{bmatrix}
\]

\[
\tilde{\lambda}_{1ij}^f = \frac{\sqrt{2} m_{ij}^f}{v}
\]

The physical CP violating phases are

\[
\theta_1 = \text{Arg}(\tilde{\lambda}_6^2 \tilde{\lambda}_5^*)
\]

\[
\theta_2 = \text{Arg}(\tilde{\lambda}_7^2 \tilde{\lambda}_5^*)
\]

CP violation in the potential

CP violation in the potential or Yukawas

CP violation in the potential or Yukawas
Review of the mixing language

- Normally you would write the mass matrix and diagonalize it.

\[
M^2 = \begin{pmatrix}
\tilde{\lambda}_1 v^2 & |\tilde{\lambda}_6| \cos(\theta_1/2) v^2 & -|\tilde{\lambda}_6| \sin(\theta_1/2) v^2 \\
|\tilde{\lambda}_6| \cos(\theta_1/2) v^2 & \tilde{m}_2^2 + \frac{1}{2} v^2 \left( \tilde{\lambda}_3 + \tilde{\lambda}_4 + |\tilde{\lambda}_5| \right) & 0 \\
-|\tilde{\lambda}_6| \sin(\theta_1/2) v^2 & 0 & \tilde{m}_2^2 + \frac{1}{2} v^2 \left( \tilde{\lambda}_3 + \tilde{\lambda}_4 - |\tilde{\lambda}_5| \right)
\end{pmatrix}
\]

- In the CP violating case this leads to cumbersome expressions for the couplings (e.g. Haber, O’Neil 0602242v6). Can this be improved?

- Moreover, in the singlet case couplings in the mixing and EFT language did not match.
The 2HDM and the power of EFT
Deriving the EFT: effective dimension

Examples:

\[ \lambda^* \lambda_6 (H^\dagger H)^3 \]

\[ (\tilde{m}_{12}^2)^* \lambda_6 (H^\dagger H)^2 \sim v^2 \text{ No tadpole condition} \]

In the 2HDM

Effective dimension ≠ Operator dimension

\[ ED = 4 - n\tilde{m}_2 \]
The low energy theory of the 2HDM

This is just to show you how does the EFT look.

\[ Z_H D_\mu H^\dagger D^\mu H + \zeta_H \left[ \frac{1}{2} \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) + H^\dagger H D_\mu H^\dagger D^\mu H \right] \]
\[ + \zeta'_H \left[ 2H^\dagger H \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) + (H^\dagger H)^2 D_\mu H^\dagger D^\mu H \right] - V(H) \]
\[ - \left[ Q_i H (\lambda^u_{ij} + \eta^u_{ij} H^\dagger H) \bar{u}_j - Q_i H^c (\lambda^d_{ij} + \eta^d_{ij} H^\dagger H) \bar{d}_j \right] \]
\[ - L_i H^c (\lambda^\ell_{ij} + \eta^\ell_{ij} H^\dagger H) \bar{\ell}_j + \text{h.c.} \]

... plus many four fermion operators

\[ \Omega^{uu(0)}_{ijmn} (Q_i \bar{u}_j)(\bar{u}_m Q_n) + \Omega^{dd(0)}_{ijmn} (Q_i \bar{d}_j)(\bar{d}_m Q_n) + \Omega^{\ell\ell(0)}_{ijmn} (L_i \bar{\ell}_j)(\bar{\ell}_m L_n) \]
\[ + \left[ \Omega^{d\ell(0)}_{ijmn} (Q_i \bar{d}_j)(\bar{\ell}_m L_n) + \Omega^{ud(2)}_{ijmn} (Q_i \bar{u}_j)(Q_m \bar{d}_n) + \Omega^{u\ell(2)}_{ijmn} (Q_i \bar{u}_j)(L_m \bar{\ell}_n) + \text{h.c.} \right] \]
The 2HDM EFT: Higgs and fermions

The Higgs-fermion sector contains

\[
\begin{align*}
\lambda_{ij}^u Q_i H \bar{u}_j + \eta_{ij}^u Q_i H H^\dagger H \bar{u}_j + \cdots + \text{h.c.}
\end{align*}
\]

**Effective dimension six**

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

- Controlled by the heavy doublet Yukawa and $\tilde{\lambda}^*_6$
- Source of flavor violating processes ($\Delta F = 1$ only)
- CP violation directly measurable in EDM’s
The 2HDM EFT: fermions

- The fermionic sector contains

\[
\frac{\tilde{\lambda}_u^{2ij} \tilde{\lambda}_u^{2\dagger mn}}{\tilde{m}_2^2} (Q_i \bar{u}_j) (\bar{u}_m^\dagger Q_n^\dagger) + \cdots
\]

- Controlled by the heavy doublet Yukawa.
- Source of CP and flavor violation ($\Delta F = 1$ & $\Delta F = 2$)
The 2HDM EFT: Higgs and gauge bosons

The gauge-kinetic sector contains

$$\frac{\tilde{\lambda}_6^* \tilde{\lambda}_6}{\tilde{m}_2^4} (H^\dagger H)^2 D_\mu H^\dagger D^{\mu} H + \ldots$$

All operators show up first at effective dimension eight

Controlled again by $\tilde{\lambda}_6$ ...!

$$g_{\varphi^2 VV} = \frac{2m_V^2}{v^2} \left[ 1 - 3\tilde{\lambda}_6^* \tilde{\lambda}_6 \frac{v^4}{\tilde{m}_2^4} + \mathcal{O}\left(\frac{v^6}{\tilde{m}_2^6}\right) \right]$$
The 2HDM EFT: self couplings

The Higgs potential contains

\[ m_H^2 H \dagger H + \frac{1}{2} \lambda_H (H \dagger H)^2 - \frac{\tilde{\lambda}_6^* \tilde{\lambda}_6}{\tilde{m}_2^2} (H \dagger H)^3 + \ldots \]  

Effective dimension six

Controlled by \( \tilde{\lambda}_6 \)

\[ g_{\varphi_1^4} = -\frac{3 m_{\varphi_1}^2}{v^2} + 36 \frac{\tilde{\lambda}_6^* \tilde{\lambda}_6 v^2}{\tilde{m}_2^2} + O \left( \frac{v^4}{\tilde{m}_2^4} \right) \]
Comparing the different couplings

- Fermionic and gauge couplings are modified at different effective dimension.

\[ \lambda_{\phi ij}^f = \frac{m_i^f}{v} \delta_{ij} - 2 \left( \frac{\tilde{\lambda}_{2ij}^f \tilde{\lambda}_6^*}{2\sqrt{2}} \right) \left( \frac{v^2}{m_2^2} \right) + \mathcal{O} \left( \frac{v^4}{m_2^4} \right) \]

\[ g_{\phi_1 V V} = \frac{2m_V^2}{v} \left[ 1 - \frac{1}{2} \tilde{\lambda}_6^* \tilde{\lambda}_6 \left( \frac{v^4}{m_2^4} \right) + \mathcal{O} \left( \frac{v^6}{m_2^6} \right) \right] \]

\[ g_{\phi^2 V V} = \frac{2m_V^2}{v^2} \left[ 1 - 3 \tilde{\lambda}_6^* \tilde{\lambda}_6 \left( \frac{v^4}{m_2^4} \right) + \mathcal{O} \left( \frac{v^6}{m_2^6} \right) \right] \]

\[ g_{\phi_1^4} = -\frac{3m_{\phi_1}^2}{v^2} + 36 \tilde{\lambda}_6^* \tilde{\lambda}_6 \left( \frac{v^2}{m_2^2} \right) + \mathcal{O} \left( \frac{v^4}{m_2^4} \right) \]

Very different from the mixing result
Interesting facts, an example application and a scorecard for LHC and flavor
CP violation

- We found CP violation at ED 6 in higgs-fermion interactions.

- What about the **bosonic** CP violating phases $\theta_1$ & $\theta_2$ ??

\[ \begin{align*}
\theta_1 &= \text{Arg}(\tilde{\lambda}_6^2\tilde{\lambda}_5^*) \\
\theta_2 &= \text{Arg}(\tilde{\lambda}_7^2\tilde{\lambda}_5^*)
\end{align*} \]

The CP violation associated with these phases does not appear at ED 6.

All CP violation in Higgs-fermion interactions!
The complex alignment parameter

What is this $\tilde{\lambda}_6^*$ controlling the deviations from the SM couplings? It is related to a complex alignment parameter $\Xi$.

- It is a physical quantity (it is measurable)
- No need to diagonalize the mass matrix!

$$\Xi = -|\tilde{\lambda}_6| e^{-i\theta_1/2} \frac{v^2}{\tilde{m}_2^2} + \mathcal{O}\left(\frac{v^4}{\tilde{m}_2^4}\right)$$

Example of use: $g_{\varphi_1 H^\pm W} = -\frac{im_W}{v} \Xi$
How to detect a perfectly aligned 2HDM

- If all couplings are measured to be SM like, can we get hints of the 2HDM in low energy data?

\[
\frac{\tilde{\lambda}_2^{ij} \tilde{\lambda}_2^{mn}}{\tilde{m}_2^2} (Q_i \bar{u}_j)(\bar{u}_m Q_n) + \cdots
\]

There will still be hope to find hints of a second doublet in flavor experiments.
This is a large effect: ED 6, couplings can be order one.
Where is $\tan \beta$?

- If you work with a general 2HDM you should not make any reference to $\tan \beta$. It artificially extends your parameter space.

- Where is $\tan \beta$? It is a direction singled out by particular models:
  - In the MSSM: direction relative to the flat direction $H_u=H_d$.
  - In type I, II, III, IV 2HDM: direction relative to the coupled doublet.
What is so special about types I-IV?

Just that the Yukawas of the heavy doublets are proportional to the mass matrix. Example: type I

\[ \tilde{\lambda}_{2ij}^{u,d,\ell} = \sqrt{2} e^{-\frac{i\xi}{2}} \cot \beta \frac{m_{ij}^{u,d,\ell}}{v} \]

\[ \lambda_{\varphi ij}^{u,d,\ell} = \frac{m_{ij}^{u,d,\ell}}{v} \left[ 1 - e^{-i\xi/2} \cot \beta \frac{v^2}{\tilde{m}_2^2} + O \left( \frac{v^4}{\tilde{m}_2^4} \right) \right] \]

**Type I**

*Unique CP violating phase in the low energy theory at ED 6.*
The CP violating phase does not show up on four fermion operators. Consider as an example

$$\tilde{N}_{ijmn}^{uu(0)}(u_i\bar{u}_j)(\bar{u}_m^\dagger u_n^\dagger)$$

$$\tilde{N}_{ijmn}^{uu\pm(0)}(d_i\bar{u}_j)(\bar{u}_m^\dagger d_n^\dagger)$$

$$\tilde{N}_{ijmn}^{uu(0)} = 2 \frac{1}{\tilde{m}_2^2} \delta_{ij} \delta_{mn} \frac{m_i^u m_m^{u*}}{v^2} \cot^2 \beta$$

$$\tilde{N}_{ijmn}^{uu\pm(0)} = 2 \frac{1}{\tilde{m}_2^2} V_{ij}^T m_j^u m_m^{u*} V_{mn}^* \cot^2 \beta$$
An example application: EDM’s and the 2HDM

- The electron dipole moment is strongly constrained from experiment

\[ d_e \lesssim 10^{-29} \text{e cm} \]

ACME, 1310.7534 atom-ph

- All the contributions at effective dimension six come from Barr-zee diagrams

Only diagrams with light higgses. All masses in the loops are known.
EDM’s in types I-IV

- Places bound on the unique CP violating phase at ED six.

\[
\sin \theta = \frac{v^2}{\tilde{m}_2^2} |\tilde{\lambda}_6| \sin \left[ \text{Arg} \left( \tilde{\lambda}_6^* e^{-i\xi/2} \right) \right] \left[ 1 + \mathcal{O} \left( \frac{v^2}{\tilde{m}_2^2} \right) \right]
\]

- Examples (numbers are estimates, work in progress):

\[
d_e \approx 10^{-28} \sin \theta \cot \beta \text{ e cm} \quad \text{Types I, IV}
\]

\[
d_e \approx 10^{-26} \sin \theta \tan \beta \text{ e cm} \quad \text{Types II, III at large } \tan \beta
\]
### A scorecard for LHC and flavor experiments

#### The effective theories of the vacuum

<table>
<thead>
<tr>
<th></th>
<th>The xSM</th>
<th>The 2HDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in fermionic couplings</td>
<td>ED 6 and always smaller than SM</td>
<td>ED 6</td>
</tr>
<tr>
<td>Change in couplings to gauge bosons</td>
<td>ED 6 and always smaller than SM</td>
<td>ED 8 and always smaller than SM</td>
</tr>
<tr>
<td>Change in self couplings</td>
<td>ED 6</td>
<td>ED 6 and always smaller than SM</td>
</tr>
<tr>
<td>Changes parametrized mostly by (*) (correlations!)</td>
<td>A single real number</td>
<td>The complex alignment parameter and a complex matrix ( \tilde{\lambda}_{2ij} )</td>
</tr>
<tr>
<td>Flavor violation</td>
<td>✗</td>
<td>( \Delta F = 1, \Delta F' = 2 ) chirality violating &amp; chirality preserving</td>
</tr>
<tr>
<td>CP violation</td>
<td>✗</td>
<td>ED 6 and only in fermionic interactions</td>
</tr>
</tbody>
</table>

(* Higgs self couplings are controlled by a larger set of the UV completion parameters)
Effective dimensions at LHC

The plot below is an exclusion plot for the alignment parameter in type I 2HDM. Large exclusion: ED 6 effect. Poor exclusion: only ED 8 in action.

Craig, Galloway, Thomas 1305.2424

-1.0 -0.5 0.0 0.5 1.0
0

cos(β−α)

Type 1: Combined Fit [68, 95% CL]

β

0 0.5 1.0
-1.0 -0.5 0.0 0.5 1.0

cos(β−α)

Type 1: Fit Breakdown

β

-1.0 -0.5 0.0 0.5 1.0
0

cos(β−α)
## A scorecard for LHC and flavor experiments

### The effective theories of the vacuum

<table>
<thead>
<tr>
<th></th>
<th>The xSM</th>
<th>The 2HDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in fermionic couplings</td>
<td>ED 6 and always smaller than SM</td>
<td>ED 6</td>
</tr>
<tr>
<td>Change in couplings to gauge bosons</td>
<td>ED 6 and always smaller than SM</td>
<td>ED 8 and always smaller than SM</td>
</tr>
<tr>
<td>Change in self couplings</td>
<td>ED 6</td>
<td>ED 6 and always smaller than SM</td>
</tr>
<tr>
<td>Changes parametrized mostly by (*) (correlations!)</td>
<td>A single real number</td>
<td>The complex alignment parameter and a complex matrix $\lambda_{2i,j}^f$</td>
</tr>
<tr>
<td>Flavor violation</td>
<td>✗</td>
<td>$\Delta F' = 1$, $\Delta F' = 2$ chirality violating &amp; chirality preserving</td>
</tr>
<tr>
<td>CP violation</td>
<td>✗</td>
<td>ED 6 and only in fermionic interactions</td>
</tr>
</tbody>
</table>

(* Higgs self couplings are controlled by a larger set of the UV completion parameters)
Backup: four fermion operators

From integrating out the heavy Higgs

$$
\Omega_{ijmn}^{uu}(0)(Q_i\bar{u}_j)(\bar{u}_m Q_n) + \Omega_{ijmn}^{dd}(0)(Q_i\bar{d}_j)(\bar{d}_m Q_n) + \Omega_{ijmn}^{l\ell}(0)(L_i\ell_j)(\bar{\ell}_m L_n)
$$

$$
+ \left[ \Omega_{ijmn}^{d\ell}(0)(Q_i\bar{d}_j)(\bar{\ell}_m L_n) + \Omega_{ijmn}^{ud}(2)(Q_i\bar{u}_j)(Q_m d_n) + \Omega_{ijmn}^{u\ell}(2)(Q_i\bar{u}_j)(L_m \bar{\ell}_n) + \text{h.c.} \right]
$$

From the light Higgs

$$
\omega_{ijmn}^{uu}(0)(u_i\bar{u}_j)(\bar{u}_m u_n) + \omega_{ijmn}^{dd}(0)(d_i\bar{d}_j)(\bar{d}_m d_n) + \omega_{ijmn}^{l\ell}(0)(\ell_i\bar{\ell}_j)(\bar{\ell}_m \ell_n)
$$

$$
+ \left[ \omega_{ijmn}^{d\ell}(0)(d_i\bar{d}_j)(\bar{\ell}_m L_n) + \omega_{ijmn}^{ud}(2)(u_i\bar{u}_j)(d_m \bar{d}_n) + \omega_{ijmn}^{u\ell}(2)(u_i\bar{u}_j)(L_m \bar{\ell}_n)

+ \omega_{ijmn}^{uu}(2)(u_i\bar{u}_j)(u_m \bar{u}_n) + \omega_{ijmn}^{ud}(0)(u_i\bar{u}_j)(\bar{d}_m d_n) + \omega_{ijmn}^{u\ell}(0)(u_i\bar{u}_j)(\bar{\ell}_m \ell_n)

+ \omega_{ijmn}^{dd}(2)(d_i\bar{d}_j)(d_m \bar{d}_n) + \omega_{ijmn}^{d\ell}(2)(d_i\bar{d}_j)(L_m \bar{\ell}_n) + \omega_{ijmn}^{u\ell}(2)(\ell_i\bar{\ell}_j)(L_m \bar{\ell}_n) + \text{h.c.} \right]
$$
Comparison of four fermion operators

- Take a particular example. For the Heavy Higgs mediated operators

\[(d_i \bar{d}_j)(\bar{d}_m^\dagger d_n^\dagger) \frac{\tilde{\lambda}_{2ij}^{d^\dagger} \tilde{\lambda}_2^{d}}{\tilde{m}_2^2}\]

- The same operator coming from the light Higgs is

\[(d_i \bar{d}_j)(\bar{d}_m^\dagger d_n^\dagger) \left[ \delta_{ij} \delta_{mn} \frac{m_i^{d^\dagger} m_m^d}{\lambda_1 v^4} - \frac{1}{\sqrt{2}} \delta_{ij} \tilde{\lambda}_{2mn}^{d} \frac{\tilde{\lambda}_6^{*}}{\lambda_1} \frac{m_i^{d^\dagger}}{v} \frac{1}{\tilde{m}_2^2} \right.\]

- The parametric dependence is different, the ED is the same.