THE EFFECTIVE FIELD THEORIES OF THE VACUUM

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What if in the near future…

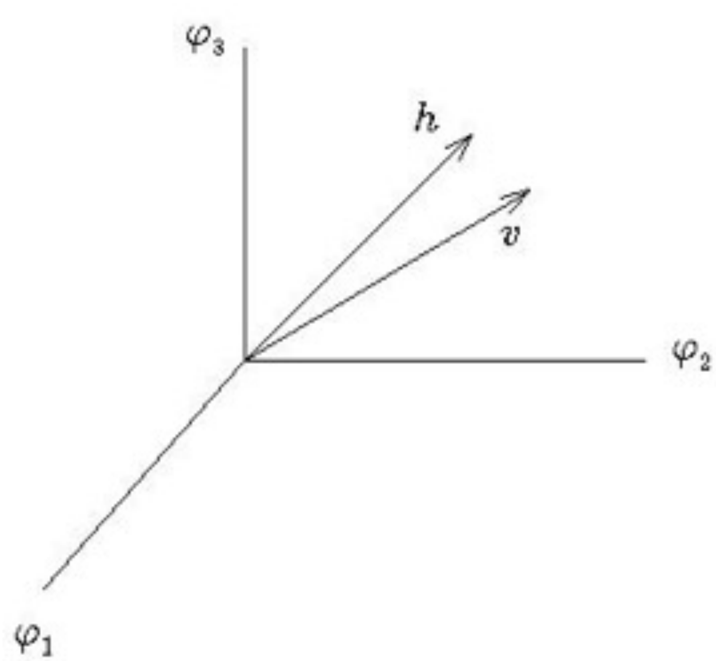
- Significant deviations from the SM Higgs couplings are found (e.g. Craig, Galloway, Thomas 1305.2424).
- New scalars are found (e.g. Craig, D'Eramo, Draper, Thomas, Zhang, 1504.04630).
- Flavor physics points to new scalars, that could be charged (e.g. Crivellin 1412.2512).
- What would we theorists say about the low energy physics?

I. Alignment

How do we build the map of theories?

- Guiding principle 1, *alignment*:

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



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

Naturally achieved in the decoupling limit

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II. EW Precision

- Guiding principle II, *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 (*)

(* Exceptions with more complicated representations and some assumptions exist, e.g. Georgi, Machacek, Nucl. Phys. B 262, 463)

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III. Generality

- Guiding principle III, *be as general as possible, while being consistent with I and II.*

The EFT's of the Higgs sector

- These guiding principles 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.

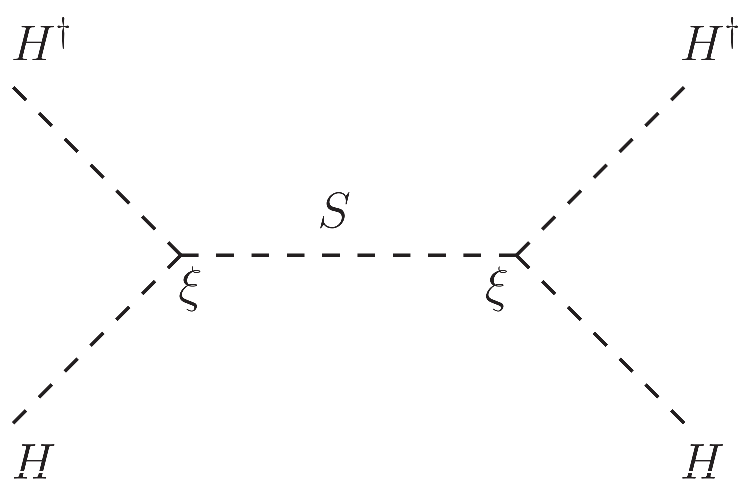
Leave no effect behind.

The xSM EFT

- The most general potential contains 7 parameters.

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

- Derive the EFT by integrating out S. Example:



$$\longrightarrow$$

$$(H^\dagger H)^2$$

$$\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)$$

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 controlled exclusively by one parameter: $\frac{\xi^2}{\mu^2}$

- „Mixing“ is encoded in WF renormalization.

Mixing ⟷ *WF renormalization*

Fermionic and Gauge Couplings

- Fermionic and gauge couplings are modified *at the same operator dimension.*

$$\lambda^f_{\varphi ij} = \frac{m^f_i}{v}\left[1 - \boxed{\frac{\xi^2}{2\mu^2}\frac{v^2}{\mu^2}} + \mathcal{O}\left(\frac{v^4}{\mu^4}\right)\right]\delta_{ij}$$

$$g_{\varphi VV} = \frac{2m_V^2}{v}\left[1 - \boxed{\frac{\xi^2}{2\mu^2}\frac{v^2}{\mu^2}} + \mathcal{O}\left(\frac{v^4}{\mu^4}\right)\right]$$

$$g_{\varphi^2 VV} = \frac{2m_V^2}{v^2}\left[1 - \boxed{2\frac{\xi^2}{\mu^2}\frac{v^2}{\mu^2}} + \mathcal{O}\left(\frac{v^4}{\mu^4}\right)\right]$$

The last coupling is not just due to mixing with the singlet!

The Most General 2HDM

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

$$\frac{v_1^2}{2} = \langle \Phi_1^\dagger \Phi_1 \rangle \qquad \frac{v_2^2}{2} = \langle \Phi_2^\dagger \Phi_2 \rangle$$

$$\xi = \mathrm{Arg}\langle \Phi_1^\dagger \Phi_2 \rangle$$

- As such

$$\tan\beta = \frac{v_1}{v_2}$$

does not have physical meaning *at this point*

(see for instance Haber, O'Neil, 0602242)

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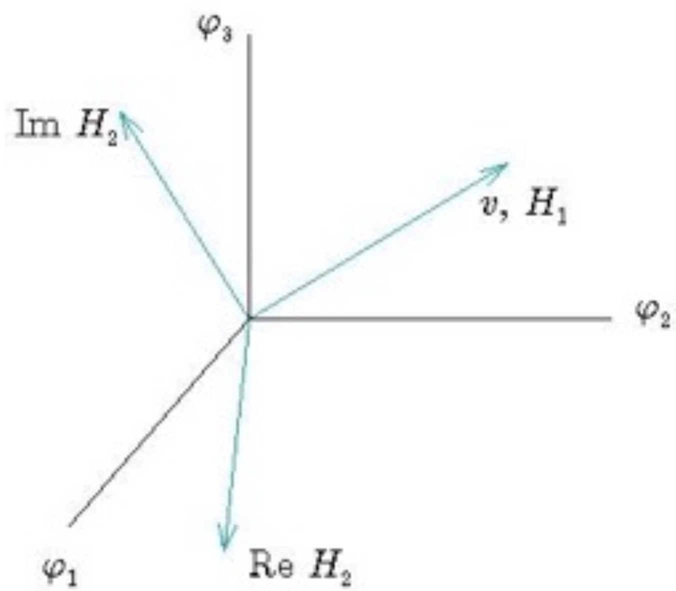
The Higgs Basis

- We can *always* perform a rotation

$$e^{-i\xi/2}H_1 = \cos\beta\ \Phi_1 + \sin\beta\ e^{-i\xi}\ \Phi_2$$
$$H_2 = -\sin\beta\ e^{i\xi}\ \Phi_1 + \cos\beta\ \Phi_2$$

$$\frac{v^2}{2} = \langle H_1^\dagger H_1 \rangle \qquad 0 = \langle H_2^\dagger H_2 \rangle$$

- This is the *Higgs basis* *(e.g. Davidson, Haber 0504050).* Useful in the *alignment limit*.



The Higgs Basis

- The new potential contains *eleven physical parameters! (keeping track of BG symmetries)*

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

- The EWSB conditions are

$$v^2 = -2\frac{\tilde{m}_1^2}{\tilde{\lambda}_1}$$

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

No-tadpole condition

The Higgs Basis

- The most general Yukawas are

$$\Big[\,\tilde\lambda^{u}_{aij}\;Q_iH_a\bar u_j-\tilde\lambda^{d\dagger}_{aij}Q_iH^c_a\bar d_j-\tilde\lambda^{\ell\dagger}_{aij}L_iH^c_a\bar\ell_j+\text{h.c.}\Big]$$

$$\tilde\lambda^f_{1ij}=\frac{\sqrt2 m^f_{ij}}{v}$$

- The *physical* CP violating phases are

$$\theta_1=\text{Arg}\big(\tilde\lambda_6^2\tilde\lambda_5^*\big)$$
$$\theta_2=\text{Arg}\big(\tilde\lambda_7^2\tilde\lambda_5^*\big)$$

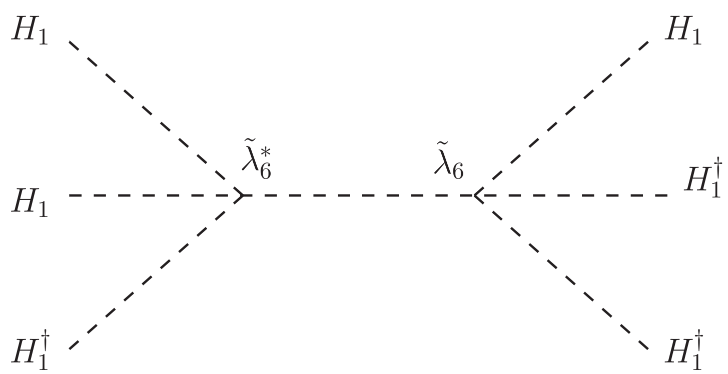
CP violation in the potential

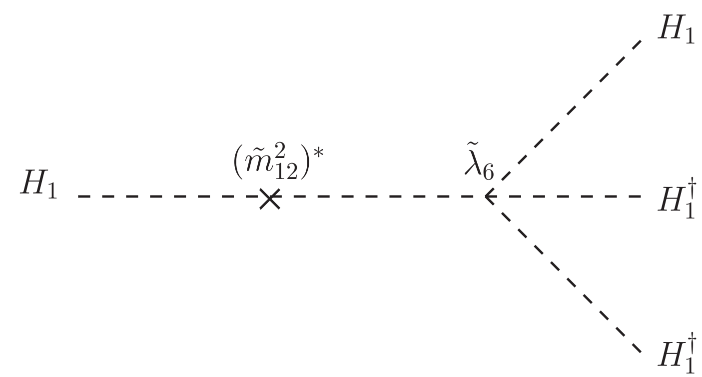
$$\text{Arg}\,\tilde\lambda^*_{5,6,7}(\tilde\lambda^f_{2ij})^2$$

CP violation in the potential or Yukawas

Effective Dimension

- Examples:





$$\lambda_6^*\lambda_6(H^\dagger H)^3$$

$$(\tilde m_{12}^2)^*\lambda_6(H^\dagger H)^2$$

$\sim v^2$ *No tadpole condition*

Operator dimension $\neq$ *Effective dimension*

$$ED = 4 - n_{\tilde m_2^2}$$

The 2HDM EFT: Higgs and fermions

- The Higgs-fermion sector contains, as an example

$$\left[\lambda^u_{ij} Q_i H \bar{u}_j + \eta^u_{ij} Q_i H H^\dagger H \bar{u}_j + \cdots + \text{h.c.}\right]$$

Effective dimension six

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

- *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, as an example

$$\frac{\tilde{\lambda}^{u}_{2ij}\tilde{\lambda}^{u\dagger}_{2mn}}{\tilde{m}_2^2}(Q_i\bar{u}_j)(\bar{u}^\dagger_m Q^\dagger_n) + \cdots$$

Effective dimension six

↑

- *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, as an example

$$\frac{\tilde{\lambda}_6^* \tilde{\lambda}_6}{\tilde{m}_2^4} H^\dagger H \, D_\mu H^\dagger D^\mu H + \cdots$$

<u>All</u> operators show up first at effective dimension <u>eight</u>

↑

Controlled again by this same $\tilde{\lambda}_6^*$ *…!*

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

Comparing the couplings

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

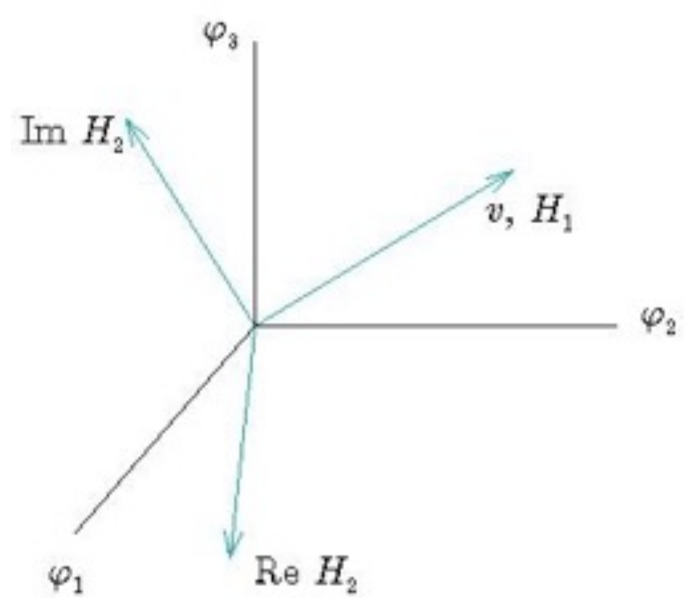
$$g_{\varphi^2 VV} = \frac{2m_V^2}{v^2}\left[1 - 3\tilde{\lambda}_6^\dagger \tilde{\lambda}_6 \boxed{\frac{v^4}{\tilde{m}_2^4}} + \mathcal{O}\left(\frac{v^6}{\tilde{m}_2^6}\right)\right]$$

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

Comments

- What is this $\tilde{\lambda}_6^*$ controlling the deviations from the SM couplings?

It is related to a complex alignment parameter Ξ *.*



Useful tool to analyze
a general 2HDM.
More of it on the paper.
No need to diagonalize the mass matrix!

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

Comments

- What if we live too close to the alignment limit?

There will still be hope to find hints of a second doublet in flavor experiments

$$\boxed{\frac{\tilde{\lambda}^{u}_{2ij}\tilde{\lambda}^{u\dagger}_{2mn}}{\tilde{m}_2^2}}(Q_i\bar{u}_j)(\bar{u}^\dagger_m Q^\dagger_n) + \cdots$$

- What about the bosonic CP violating phases θ_1 & θ_2 ??

They do not show up at to at least ED10
<u>All</u> CP violation in Higgs-fermion interactions!

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Where is *tanβ*?

- If you work with a general 2HDM *you should not make any reference to tanβ*. It artificially extends your parameter space.

- Where is *tanβ?* It is a direction singled out by particular models:

    - In the MSSM: direction relative to the flat direction Hu=Hd.

    - In type I 2HDM: direction relative to the coupled doublet (similar in types II,III,IV)

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

Summary

The effective theories of the vacuum

	The xSM	The 2HDM
Change in fermionic couplings	ED 6	ED 6
Change in couplings to gauge bosons	ED 6	ED 8
Parametrized mostly by (*) (correlations!)	*A single real number*	*The complex alignment parameter and* $\tilde{\lambda}^f_{2ij}$
Flavor violation	✘	$\Delta F = 1, \Delta F = 2$ *chirality violating & chirality preserving*
CP violation	✘	*Only in fermionic interactions*

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

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