EFFECTIVE THEORIES OF HIGGS SECTOR VACUUM STATES

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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*

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

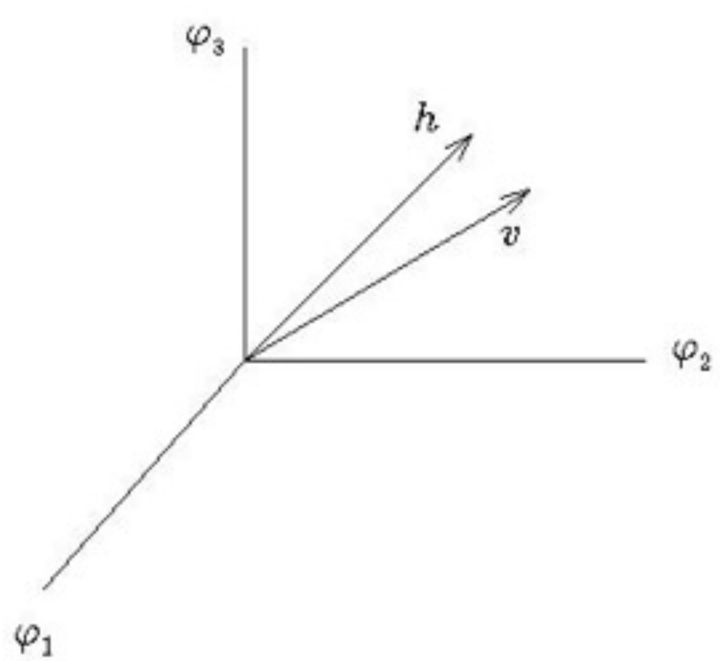
Easily achieved only with a vacuum parametrized by SU(2) singlets and doublets (*)

(* Exceptions: see Gunion, Haber, Kane, Dawson, *The Higgs Hunter's Guide*, or Georgi, Machacek, Nucl. Phys. B 262, 463)

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?
2. The 2HDM: an unconventional review. Challenges of the mixing language.
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 ζ, ξ, μ, 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 μ

$$\xi, \zeta \leq \mu$$

That is it: *this is very general*

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The vacuum states. Fermionic interactions.

- Define the vacuum states

$$H_0 = \frac{1}{\sqrt{2}}(v+h) \qquad S = v_s + s$$

- And standard fermionic interactions

$$-\mathcal{L}_Y = \ \lambda^u_{ij}\ Q_i H \bar{u}_j - \lambda^d_{ij} Q_i H^c \bar{d}_j - \lambda^\ell_{ij} L_i H^c \bar{\ell}_j + \mathrm{h.c.}$$

$$\lambda^f_{ij} = \frac{\sqrt{2} m^f_{ij}}{v} = \frac{\sqrt{2} m^f_i}{v}\ \delta^f_{ij}$$

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Very short review: the mixing language

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

$$\varphi_1 = h\cos\gamma + s\sin\gamma \qquad\qquad \cos\gamma = 1 - \frac{\xi^2}{2\mu^2}\left(\frac{v}{\mu}\right)^2 + \mathcal{O}\left(\frac{v^4}{\mu^4}\right)$$

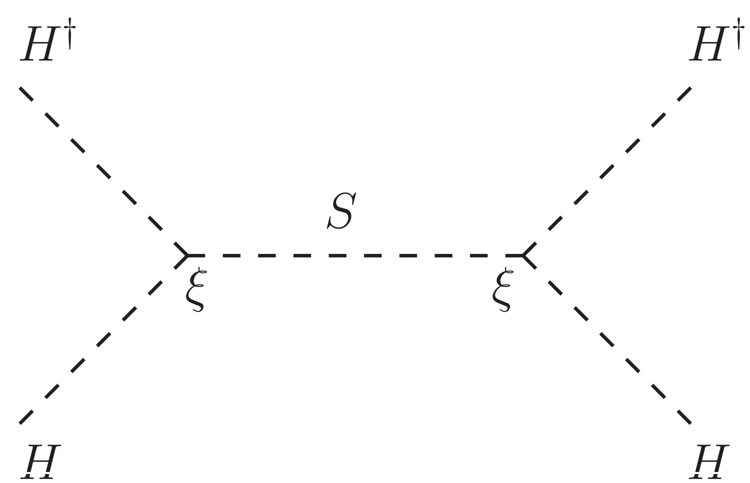
- Couplings of the higgs mass eigenstate are *democratically diluted* with respect to SM value *

$$\begin{aligned} g_{\varphi_1 VV} &= \frac{2m_V^2}{v}\cos\gamma \\ g_{\varphi_1^2 VV} &= \frac{2m_V^2}{v^2}\cos^2\gamma \\ \lambda^f_{\varphi_1 ij} &= \frac{m_i^f}{v}\cos\gamma\ \delta_{ij} \end{aligned}$$

* 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 <u>not</u> the most general EFT you could write.

- Most coefficients (but not all) controlled exclusively by one parameter: $\boxed{\dfrac{\xi^2}{\mu^2}}$

The analogue of mixing in EFT terms

- Let us expand the kinetic operator

$$\partial_\mu \left(H^\dagger H\right) \partial^\mu (H^\dagger H) = \boxed{v^2 \partial_\mu h \partial^\mu h} + 2vh\partial_\mu h \partial^\mu h + h^2 \partial_\mu h \partial^\mu h$$

- „Mixing“ is encoded in WF renormalization.

Mixing $\longleftrightarrow$ *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 *at the same operator dimension.*

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

$$\frac{g_{\varphi^3}}{v} = -\frac{3m^2_\varphi}{v^2} + \left(\frac{9\lambda\xi^2}{2\mu^2} - \frac{3\lambda'\xi^2}{\mu^2} - \frac{9\xi^4}{2\mu^4} + \frac{2\zeta\xi^3}{\mu^4}\right)\boxed{\frac{v^2}{\mu^2}} + \mathcal{O}\left(\frac{v^4}{\mu^4}\right)$$

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

$$g_{\varphi^2 VV} = \frac{2m^2_V}{v^2}\left[1 - \boxed{2\frac{\xi^2}{\mu^2}\frac{v^2}{\mu^2}} + \mathcal{O}\left(\frac{v^4}{\mu^4}\right)\right] \neq \underline{\frac{2m^2_V}{v^2}\cos^2\gamma}$$

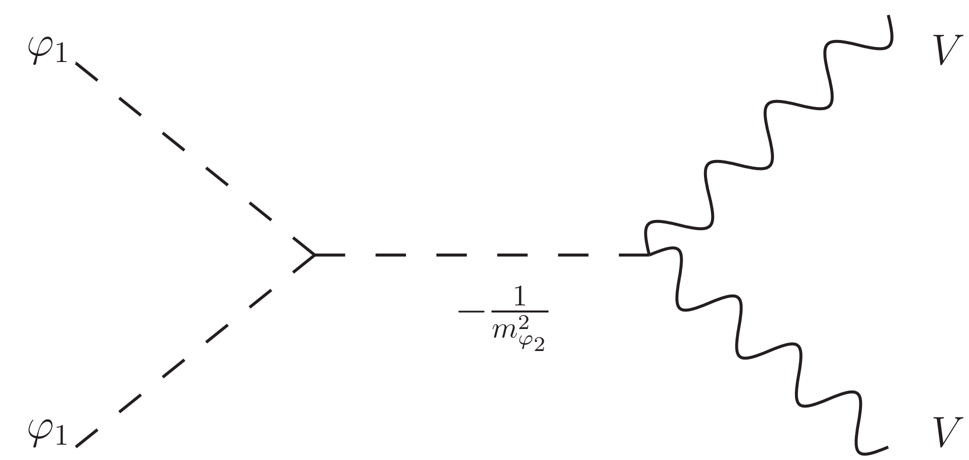
The last coupling is not just dilution!

Four linear couplings do not match

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

(Short distance only)

$$g^{EFT}_{\varphi\varphi VV} \quad = \quad g^{Mixing}_{\varphi_1\varphi_1 VV} \quad +$$



- This diagram cannot be neglected: it leads to effects of order v^2/μ^2

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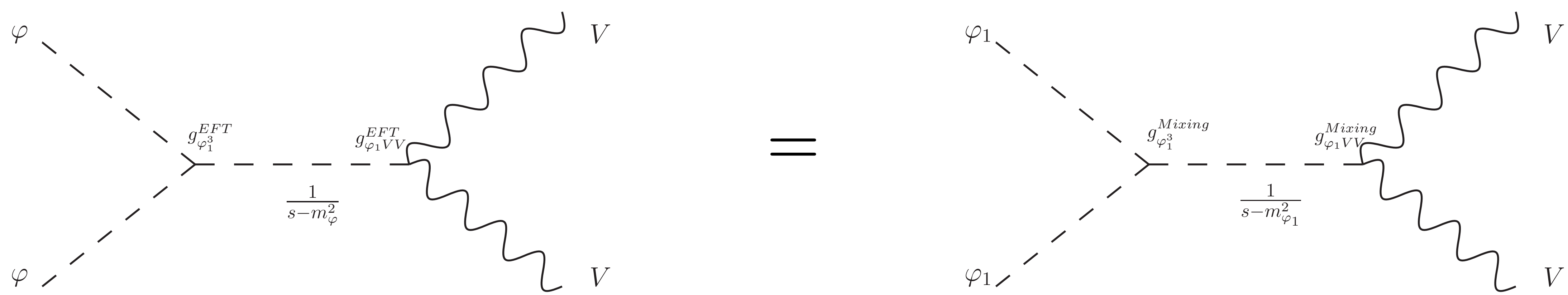
Trilinear couplings must match

- This ensures the equality of the long distance pieces of the amplitudes.

(Long distance only) *(Long distance only)*



- 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

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

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

- As such

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

does not have physical meaning <u>*at this point*</u>

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

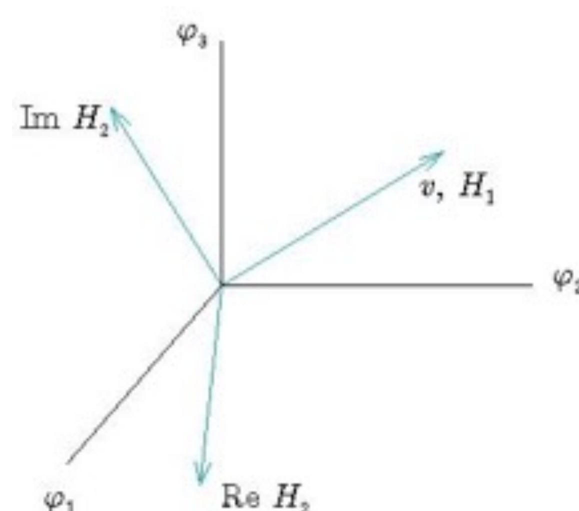
The Higgs Basis

- We can *always* perform a rotation

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

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

- 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

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

- 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 only limitation we will impose, is that we work in the decouplings limit $\tilde{\lambda}_i v^2 << \tilde{m}_2^2$

The observables in the Higgs potential

- The potential contains a U(1) background symmetry

	$U(1)_{PQ}$
H_1	0
H_2	-1
$\tilde{m}_1^2, \tilde{m}_2^2, \tilde{\lambda}_1, \tilde{\lambda}_2, \tilde{\lambda}_3, \tilde{\lambda}_4$	0
$\tilde{m}_{12}^2, \tilde{\lambda}_6, \tilde{\lambda}_7$	$+1$
$\tilde{\lambda}_5$	$+2$

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

- The background symmetry is unbroken by the Higgs vev.

The Yukawas. CP violation.

- The most general Yukawas are

$$\left[\, \tilde{\lambda}^{u}_{aij}\; Q_i H_a \bar{u}_j - \tilde{\lambda}^{d\dagger}_{aij} Q_i H^c_a \bar{d}_j - \tilde{\lambda}^{\ell\dagger}_{aij} L_i H^c_a \bar{\ell}_j + \text{h.c.} \right]$$

$$\tilde{\lambda}^{f}_{1ij} = \frac{\sqrt{2} m^{f}_{ij}}{v}$$

- The *physical* CP violating phases are

$$\theta_1 = \mathrm{Arg}\big(\tilde{\lambda}_6^2 \tilde{\lambda}_5^*\big)$$

$$\theta_2 = \mathrm{Arg}\big(\tilde{\lambda}_7^2 \tilde{\lambda}_5^*\big)$$

CP violation in the potential

$$\mathrm{Arg}(\tilde{\lambda}_6^* \tilde{\lambda}^{f}_{2ij})$$

CP violation in the potential or Yukawas

Review of the mixing language

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

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

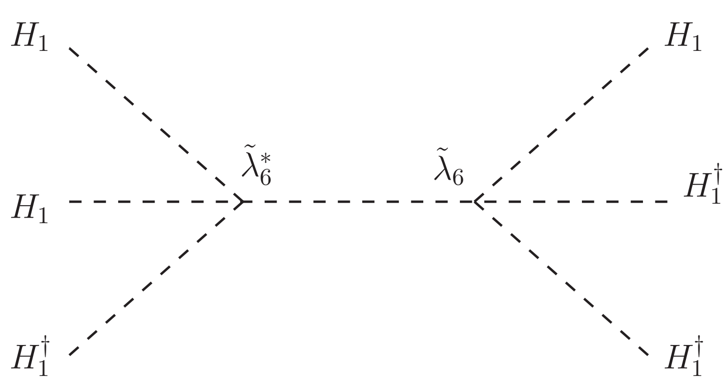
- In the CP violating case this leads to cumbersome expressions for the couplings *(e.g. Haber, O'Neil 0602242v6).* Can this be improved?

- Moreover, in the singlet case couplings in the mixing and EFT language did not match.

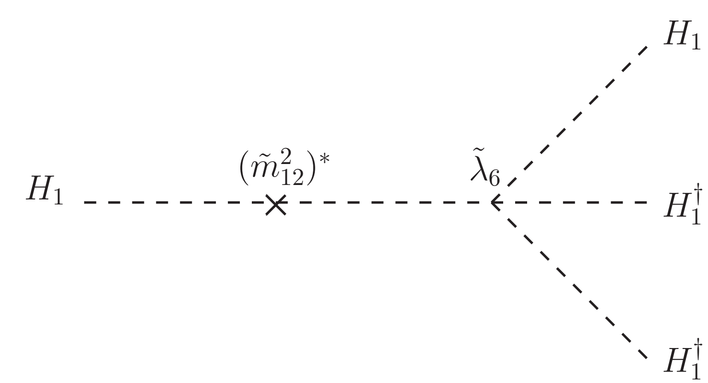
The 2HDM and the power of EFT

Deriving the EFT: effective dimension

- Examples:



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



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

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

In the 2HDM
Effective dimension ≠ Operator dimension

$$ED = 4 - n_{\tilde{m}_2^2}$$

The low energy theory of the 2HDM

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

$$
\begin{aligned}
& Z_H\, D_\mu H^\dagger D^\mu H + \zeta_H \left[\frac{1}{2} \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) + H^\dagger H\, D_\mu H^\dagger D^\mu H \right] \\
& + \zeta'_H \left[2 H^\dagger H\, \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) + (H^\dagger H)^2\, D_\mu H^\dagger D^\mu H \right] - V(H) \\
& - \Big[Q_i H \big(\lambda^u_{ij} + \eta^u_{ij} H^\dagger H \big) \bar{u}_j - Q_i H^c \big(\lambda^{d\dagger}_{ij} + \eta^{d\dagger}_{ij} H^\dagger H \big) \bar{d}_j \\
& - L_i H^c \big(\lambda^{\ell\dagger}_{ij} + \eta^{\ell\dagger}_{ij} H^\dagger H \big) \bar{\ell}_j + \text{h.c.} \Big]
\end{aligned}
$$

… plus many four fermion operators

$$
\begin{aligned}
& \Omega^{uu\,(0)}_{ijmn} (Q_i \bar{u}_j)(\bar{u}^\dagger_m Q^\dagger_n) + \Omega^{dd\,(0)}_{ijmn} (Q_i \bar{d}_j)(\bar{d}^\dagger_m Q^\dagger_n) + \Omega^{\ell\ell\,(0)}_{ijmn} (L_i \bar{\ell}_j)(\bar{\ell}^\dagger_m L^\dagger_n) \\
& + \Big[\Omega^{d\ell\,(0)}_{ijmn} (Q_i \bar{d}_j)(\bar{\ell}^\dagger_m L^\dagger_n) + \Omega^{ud\,(2)}_{ijmn} (Q_i \bar{u}_j)(Q_m \bar{d}_n) + \Omega^{u\ell\,(2)}_{ijmn} (Q_i \bar{u}_j)(L_m \bar{\ell}_n) + \text{h.c.} \Big]
\end{aligned}
$$

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The 2HDM EFT: Higgs and fermions

- The Higgs-fermion sector contains

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

Effective dimension six

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

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

The 2HDM EFT: fermions

- The fermionic sector contains

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

Effective dimension *<u>six</u>*

- *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

$\uparrow$

Controlled again by $\tilde{\lambda}_6 \ldots$*!*

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

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 $\tilde{\lambda}_6$

$$g_{\varphi_1^4} = -\frac{3m_{\varphi_1}^2}{v^2} + 36\tilde{\lambda}_6^* \tilde{\lambda}_6 \boxed{\frac{v^2}{\tilde{m}_2^2}} + \mathcal{O}\left(\frac{v^4}{\tilde{m}_2^4}\right)$$

Comparing the different couplings

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

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

$$g_{\varphi_1 VV} = \frac{2m_V^2}{v}\left[1 - \frac{1}{2}\tilde{\lambda}^*_6\tilde{\lambda}_6\boxed{\frac{v^4}{\tilde{m}_2^4}} + \mathcal{O}\left(\frac{v^6}{\tilde{m}_2^6}\right)\right]$$

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

$$g_{\varphi_1^4} = -\frac{3m^2_{\varphi_1}}{v^2} + 36\tilde{\lambda}^*_6\tilde{\lambda}_6\boxed{\frac{v^2}{\tilde{m}_2^2}} + \mathcal{O}\left(\frac{v^4}{\tilde{m}_2^4}\right)$$

Very different from the mixing result

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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 $\theta_1 \ \& \ \theta_2$??

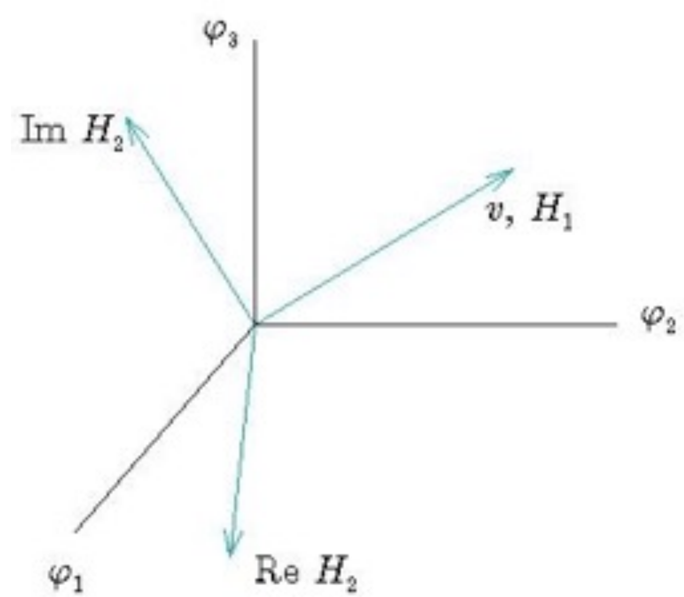
$$\theta_1 = \mathrm{Arg}\big(\tilde{\lambda}_6^2 \tilde{\lambda}_5^*\big)$$
$$\theta_2 = \mathrm{Arg}\big(\tilde{\lambda}_7^2 \tilde{\lambda}_5^*\big)$$

The CP violation associated with this 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 <u>complex alignment parameter Ξ .</u>



- It is a physical quantity *(it is <u>measurable</u>)*
- *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: $$g_{\varphi_1 H^\pm W} = -\frac{i m_W}{v}\,\Xi$$

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?

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

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 *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, 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

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

Type I

$$\lambda^{u,d,\ell}_{\varphi ij} = \frac{m^{u,d,\ell}_{ij}}{v}\left[1 - \boxed{\tilde{\lambda}^{*}_{6} e^{-i\xi/2}} \cot\beta \, \frac{v^2}{\tilde{m}^2_2} + \mathcal{O}\left(\frac{v^4}{\tilde{m}^4_2}\right)\right]$$

<u>Unique</u> CP violating phase
in the low energy theory at ED 6.

Four fermion operators in types I-IV

- The CP violating phase <u>does not</u> show up on four fermion operators. Consider as an example

$$\tilde{\Omega}^{uu\,(0)}_{ijmn}\,(u_i\bar{u}_j)(\bar{u}^\dagger_m u^\dagger_n) \quad , \quad \tilde{\Omega}^{uu\pm\,(0)}_{ijmn}\,(d_i\bar{u}_j)(\bar{u}^\dagger_m d^\dagger_n)$$

$$\tilde{\Omega}^{uu\,(0)}_{ijmn} = 2\,\frac{1}{\tilde{m}_2^2}\delta_{ij}\delta_{mn}\frac{m^u_i m^{u*}_m}{v^2}\cot^2\beta$$

$$\tilde{\Omega}^{uu\pm\,(0)}_{ijmn} = 2\,\frac{1}{\tilde{m}_2^2}\frac{V^T_{ij}m^u_j m^{u*}_m V^*_{mn}}{v^2}\cot^2\beta$$

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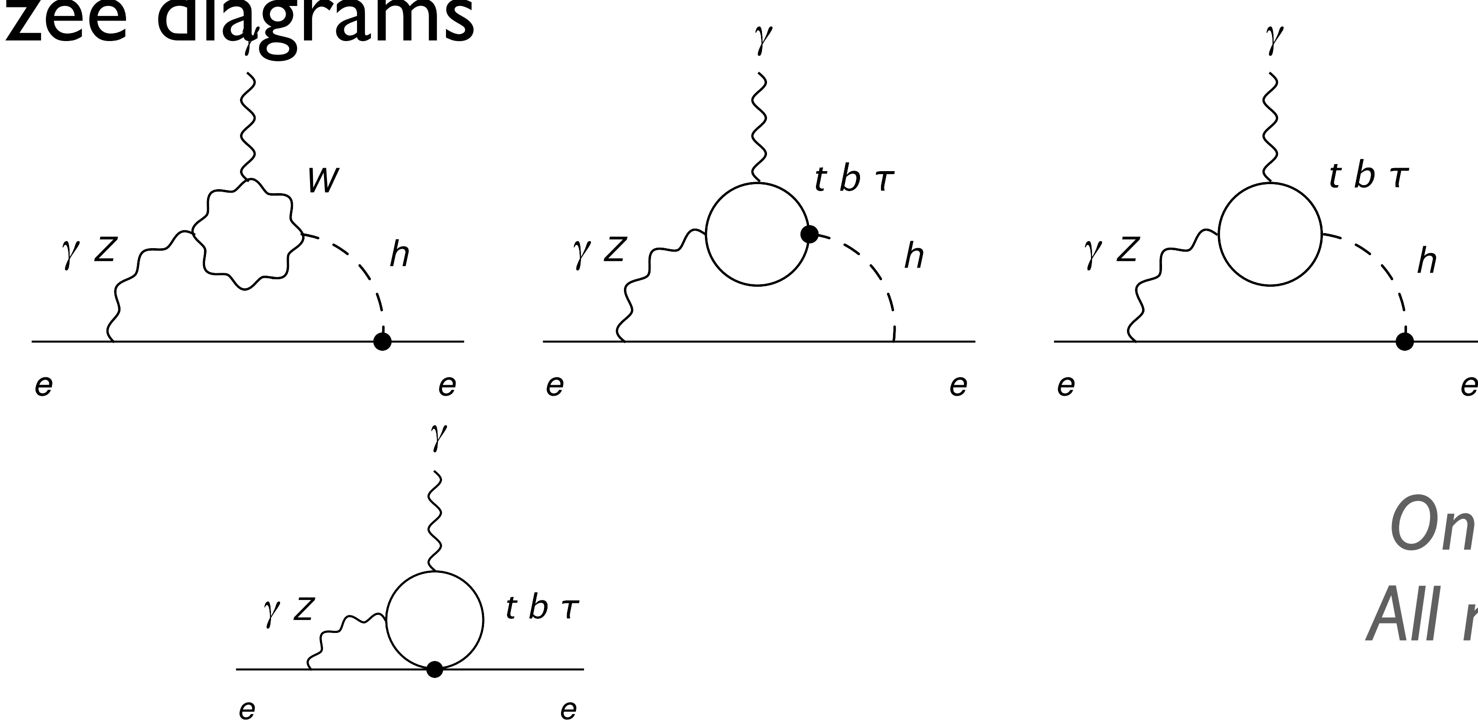
An example application: EDM’s and the 2HDM

- 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.

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

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

$$d_e \approx 10^{-28} \sin\theta \cot\beta \quad \mathrm{e\ cm}$$

Types I, IV

$$d_e \approx 10^{-26} \sin\theta \tan\beta \quad \mathrm{e\ cm}$$

Types II, III *at large* $\tan\beta$

A scorecard for LHC and flavor experiments

The effective theories of the vacuum

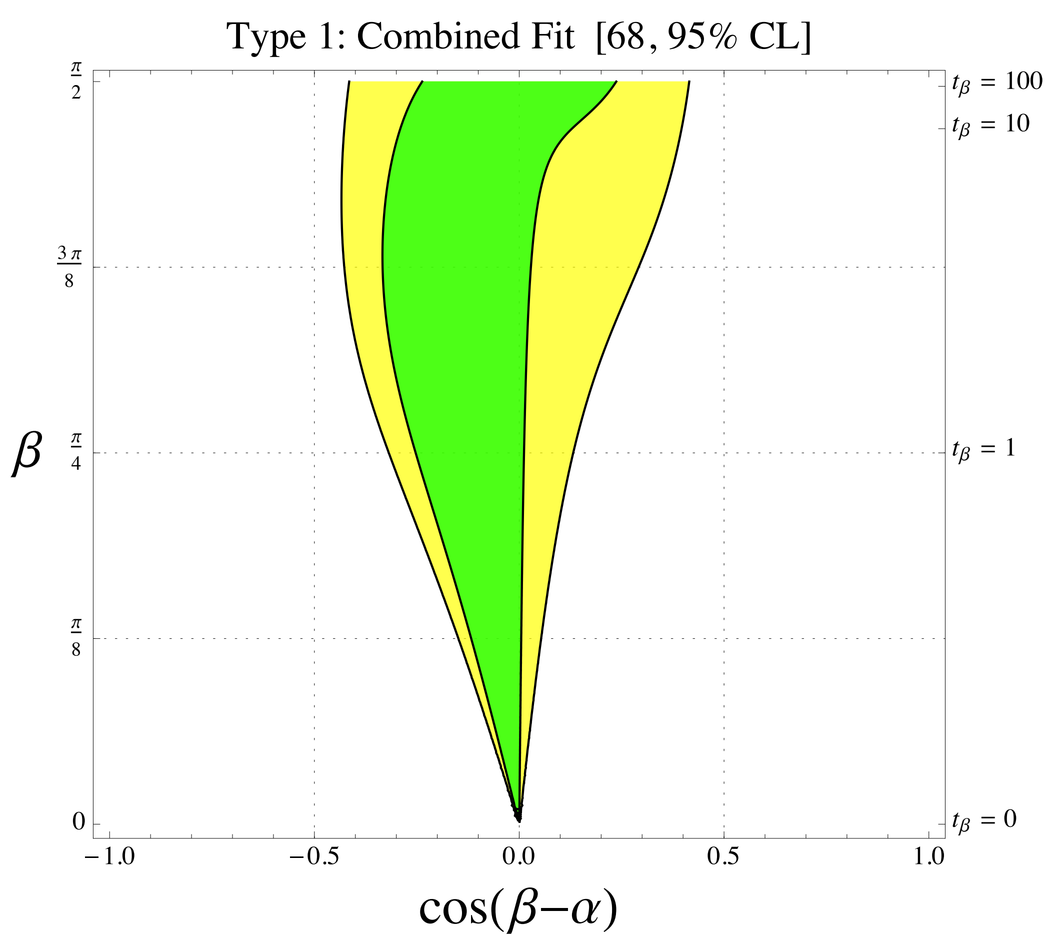
	The xSM	The 2HDM
Change in fermionic couplings	ED 6 and always smaller than SM	ED 6
Change in couplings to gauge bosons	ED 6 and always smaller than SM	ED 8 and always smaller than SM
Change in self couplings	ED 6	ED 6 and always smaller than SM
Changes parametrized mostly by (*) (correlations!)	A single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

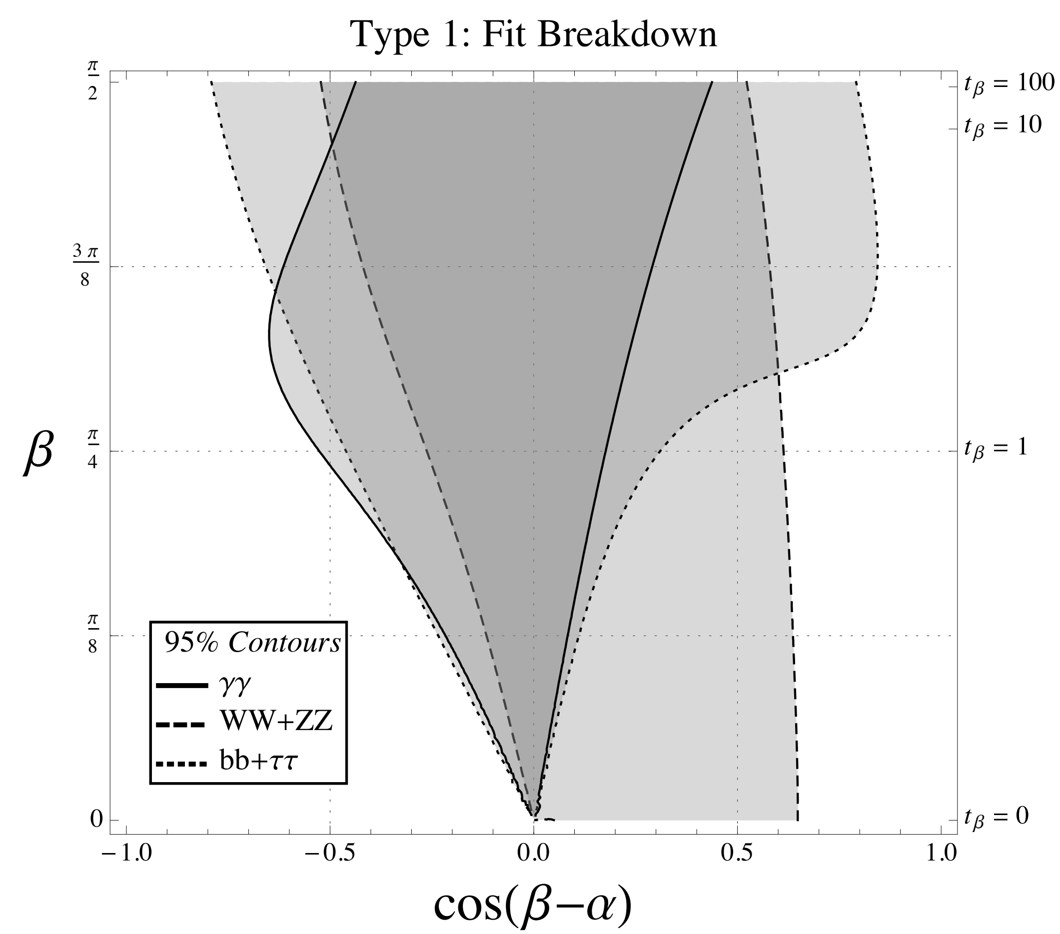
(* Higgs self couplings are controlled by a larger set of the UV completion parameters)

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





A scorecard for LHC and flavor experiments

The effective theories of the vacuum

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

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

Daniel Egana-Ugrinovic, Scott Thomas, Rutgers University.

Backup: four fermion operators

- From integrating out the heavy Higgs

$$\Omega^{uu\,(0)}_{ijmn}(Q_i\bar{u}_j)(\bar{u}^\dagger_m Q^\dagger_n) + \Omega^{dd\,(0)}_{ijmn}(Q_i\bar{d}_j)(\bar{d}^\dagger_m Q^\dagger_n) + \Omega^{\ell\ell\,(0)}_{ijmn}(L_i\bar{\ell}_j)(\bar{\ell}^\dagger_m L^\dagger_n)$$
$$+ \left[\Omega^{d\ell\,(0)}_{ijmn}(Q_i\bar{d}_j)(\bar{\ell}^\dagger_m L^\dagger_n) + \Omega^{ud\,(2)}_{ijmn}(Q_i\bar{u}_j)(Q_m\bar{d}_n) + \Omega^{u\ell\,(2)}_{ijmn}(Q_i\bar{u}_j)(L_m\bar{\ell}_n) + \text{h.c.}\right]$$

- From the light Higgs

$$\omega^{uu\,(0)}_{ijmn}(u_i\bar{u}_j)(\bar{u}^\dagger_m u^\dagger_n) + \omega^{dd\,(0)}_{ijmn}(d_i\bar{d}_j)(\bar{d}^\dagger_m d^\dagger_n) + \omega^{\ell\ell\,(0)}_{ijmn}(\ell_i\bar{\ell}_j)(\bar{\ell}^\dagger_m \ell^\dagger_n)$$
$$+ \Big[\omega^{d\ell\,(0)}_{ijmn}(d_i\bar{d}_j)(\bar{\ell}^\dagger_m \ell^\dagger_n) + \omega^{ud\,(2)}_{ijmn}(u_i\bar{u}_j)(d_m\bar{d}_n) + \omega^{u\ell\,(2)}_{ijmn}(u_i\bar{u}_j)(\ell_m\bar{\ell}_n)$$
$$+ \omega^{uu\,(2)}_{ijmn}(u_i\bar{u}_j)(u_m\bar{u}_n) + \omega^{ud\,(0)}_{ijmn}(u_i\bar{u}_j)(\bar{d}^\dagger_m d^\dagger_n) + \omega^{u\ell\,(0)}_{ijmn}(u_i\bar{u}_j)(\bar{\ell}^\dagger_m \ell^\dagger_n)$$
$$+ \omega^{dd\,(2)}_{ijmn}(d_i\bar{d}_j)(d_m\bar{d}_n) + \omega^{d\ell\,(2)}_{ijmn}(d_i\bar{d}_j)(\ell_m\bar{\ell}_n) + \omega^{\ell\ell\,(2)}_{ijmn}(\ell_i\bar{\ell}_j)(\ell_m\bar{\ell}_n) + \text{h.c.}\Big]$$

Comparison of four fermion operators

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

$$(d_i \bar{d}_j)(\bar{d}^\dagger_m d^\dagger_n)\,\frac{\tilde{\lambda}^{d\dagger}_{2ij}\tilde{\lambda}^{d}_{2mn}}{\tilde{m}_2^2}$$

- The same operator coming from the light Higgs is

$$(d_i \bar{d}_j)(\bar{d}^\dagger_m d^\dagger_n)\Big[\delta_{ij}\delta_{mn}\,\frac{m_i^{d\dagger} m_m^{d}}{\lambda_1 v^4} - \ \frac{1}{\sqrt{2}}\,\delta_{ij}\,\tilde{\lambda}^{d}_{2mn}\,\frac{\tilde{\lambda}_6^*}{\lambda_1}\,\frac{m_i^{d\dagger}}{v}\,\frac{1}{\tilde{m}_2^2}$$
$$-\frac{1}{\sqrt{2}}\,\delta_{mn}\,\tilde{\lambda}^{d\dagger}_{2ij}\,\frac{\tilde{\lambda}_6}{\lambda_1}\,\frac{m_m^{d\dagger}}{v}\,\frac{1}{\tilde{m}_2^2}\Big]$$

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