CP violation in the 2HDM and EFT: the ZZZ vertex

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Outline

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Motivation for 2HDM and ZZZ vertex

- 2HDM: simple SM extension realized by some motivated BSM models: e.g. type-II by SUSY models, other types in composite Higgs models (see [Stefano Moretti's talk]).
- Amongst $\neq$ signatures, a possible one concerns deviations in ZZ production via contributions from ZZZ vertex (see [Grządkowski–2016]).
- The ZZZ tensor structure contains an observable CP-odd part.
- Comparing wrt. an EFT model-matching and an SM-EFT approach (top-down vs. bottom-up), allowing us to understand how well NP can be described with EFT & how much information is lost (see also [HBM–2016]).

Complex 2HDM in a nutshell [Gunion–1989, Branco–2011] (1/3)

- Original Lagrangian $\mathcal{L}$ with two scalar doublets $\Phi_{1,2}$ (VEVs: $v_{1,2}/\sqrt{2}$).
- $\mathbb{Z}_2$ symm. imposed to avoid FCNCs at tree-level: $(\Phi_1, \Phi_2) \to (\Phi_1, -\Phi_2)$.
- 4 types of 2HDM depending on H_i couplings to fermions.

"Higgs basis" [Lavoura–1994]: only 1st one has a VEV, $v = \sqrt{v_1^2 + v_2^2}$.

$$\Phi_{1,2} \to H_1 = \begin{pmatrix} -iG^+ \\ \frac{1}{\sqrt{2}}(v+h+iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(R+iI) \end{pmatrix}.$$

$\mathcal{L}$ then becomes [Bernon–2015] ($Y_3, Z_{5,6,7} \in \mathbb{C}$):

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{\text{no Higgs}} + |D_\mu H_1|^2 + |D_\mu H_2|^2 + \mathcal{L}_Y - V_H\,, \quad -\mathcal{L}_Y = Y_f \overline{f_R} H_1^\dagger f_L + \frac{\eta_f}{t_\beta} Y_f \overline{f_R} H_2^\dagger f_L + \text{h.c.}\,,$$

$$V_H = Y_1|H_1|^2 + Y_2|H_2|^2 + (Y_3 H_1^\dagger H_2 + \text{h.c.}) + \frac{Z_1}{2}|H_1|^4 + \frac{Z_2}{2}|H_2|^4 + Z_3|H_1|^2|H_2|^2$$
$$+ Z_4(H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{\frac{Z_5}{2}(H_1^\dagger H_2)^2 + (Z_6|H_1|^2 + Z_7|H_2|^2)(H_1^\dagger H_2) + \text{h.c.}\right\}$$

(Sum over $f = u, d, l$, and $\eta_f = 1$ or $-t_\beta^2$ depending on the 2HDM type.)

Complex 2HDM in a nutshell [Gunion–1989, Branco–2011] (2/3)

- Neutral scalars $\{h, R, I\}$ "Higgs basis" $\rightarrow$ neutral mass-eigenstate scalars $\{h_1, h_2, h_3\}$ via rotation matrix T [Branco–2011, Fontes–2014].
- E.g. for the real 2HDM, couplings to vector bosons $g_{h_i VV}$ are $\propto \sin_{\beta-\alpha}$ for h_1, $\propto \cos_{\beta-\alpha}$ for h_2 and none for h_3 (α, β: rotation angles).

Two limits (similar to ℝ2HDM)

- Alignment limit: $\cos_{\beta-\alpha} \ll 1$, i.e. h_1 lives in H_1 and corresponds to the SM Higgs boson, while $h_{2,3}$ can be almost degenerated.
- Decoupling limit: $Y_2 \gg v^2$, so that $m_{h_{2,3},H^\pm} \gg m_{h_1}$.

Stationarity conditions (← potential minimization)

$$Y_1 = \frac{-Z_1 v^2}{2}, \quad Y_3 = \frac{-Z_6 v^2}{2}.$$

$\Rightarrow$ Only Z_5, Z_6, Z_7 are independently complex.
$\Rightarrow$ The invariants source of CP violation must be related to $\mathrm{Im}(Z_7 Z_6^*)$, $\mathrm{Im}(Z_6^2 Z_5^*)$ and $\mathrm{Im}(Z_7^2 Z_5^*)$ [Lavoura–1994].

Complex 2HDM in a nutshell [Gunion–1989, Branco–2011] (3/3)

From the rotation matrix T:

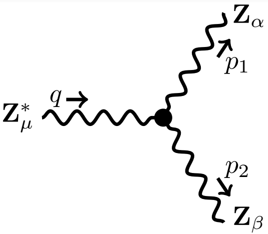
- h couples to gauge bosons, coupling coincides with the SM one g^{SM}_{hVV}
  $\Rightarrow g_{h_i VV} = T_{1i} \times g^{\text{SM}}_{hVV}$.
- T is orthogonal $\Rightarrow$ **Sum rule:** $\sum_i |g_{h_i VV}|^2 = |g^{\text{SM}}_{hVV}|^2$:
  ensures that each $|g_{h_i VV}|$ is always $< |g^{\text{SM}}_{hVV}|$ (generalizes for any n-HDM).

Nota bene

Finding a $|g_{h_i VV}| > |g^{\text{SM}}_{hVV}|$ would exclude SM *and all* of these models.
Experimental measurements consistent with SM predictions $\rightarrow$ the mixing angles in T are in the *alignment limit* and $h_1 \sim h$ in the "Higgs basis".

Outline

ZZZ vertex structure [Hagiwara–1986, Gounaris–1999] (1/2)



Z_α, Z_β on-shell; Z_μ off-shell; $q = p_1 + p_2$.

CP properties via: $\mathbb{C} : Z_\mu \to -Z_\mu$, and $\mathbb{P} : (Z_0, Z_i) \to (Z_0, -Z_i)$ and $(\partial_0, \partial_i) \to (\partial_0, -\partial_i)$.

Lorentz + Bose symmetries constrain Z^3 vertex function $\Gamma_{\mu\alpha\beta}$:

$$
\begin{aligned}
i\Gamma_{\mu\alpha\beta} = & -e\frac{q^2 - m_Z^2}{m_Z^2} f_4^Z(q^2)(\eta_{\mu\alpha}p_{1,\beta} + \eta_{\mu\beta}p_{2,\alpha}) - e\frac{q^2 - m_Z^2}{m_Z^2} f_5^Z(q^2)\epsilon_{\mu\alpha\beta\rho}(p_1 - p_2)^\rho \\
& + \tilde{f}_1(q^2)(\eta_{\mu\alpha}p_{2,\beta} + \eta_{\mu\beta}p_{1,\alpha}) + \tilde{f}_2(q^2)\eta_{\alpha\beta}q_\mu + \tilde{f}_3(q^2)q_\mu p_{1,\beta}p_{2,\alpha} \\
& + \tilde{f}_4(q^2)q_\mu p_{1,\alpha}p_{2,\beta} + \tilde{f}_5(q^2)q_\mu(p_{1,\alpha}p_{1,\beta} + p_{2,\alpha}p_{2,\beta}) \,.
\end{aligned}
$$

$f_4^Z(q^2)$ term is CP-odd: e.g. effective interaction $\frac{\tilde{\kappa}_{ZZZ}}{m_Z^2}\partial_\mu Z_\nu \partial^\mu Z^\rho \partial_\rho Z^\nu$ provides $f_4^Z(q^2) = \tilde{\kappa}_{ZZZ}$. $f_5^Z(q^2)$ term is CP-even.

ZZZ vertex structure [Hagiwara–1986, Gounaris–1999] (2/2)

$$i\Gamma_{\mu\alpha\beta} = -e\frac{q^2 - m_Z^2}{m_Z^2} f_4^Z(q^2)(\eta_{\mu\alpha}p_{1,\beta} + \eta_{\mu\beta}p_{2,\alpha}) - e\frac{q^2 - m_Z^2}{m_Z^2} f_5^Z(q^2)\epsilon_{\mu\alpha\beta\rho}(p_1 - p_2)^\rho$$
$$+ \tilde{f}_1(q^2)(\eta_{\mu\alpha}p_{2,\beta} + \eta_{\mu\beta}p_{1,\alpha}) + \tilde{f}_2(q^2)\eta_{\alpha\beta}q_\mu + \tilde{f}_3(q^2)q_\mu p_{1,\beta}p_{2,\alpha}$$
$$+ \tilde{f}_4(q^2)q_\mu p_{1,\alpha}p_{2,\beta} + \tilde{f}_5(q^2)q_\mu(p_{1,\alpha}p_{1,\beta} + p_{2,\alpha}p_{2,\beta}) .$$

Remarks:

- $f_4^Z(q^2)$ and $f_5^Z(q^2)$ are related to observables, the $\tilde{f}_i(q^2)$ are not.
- Example of $\bar{f}f \to ZZ$ with a Z^* in s-channel.
- The $\tilde{f}_i(q^2)$ may be gauge-dependent in specific calculations.

Couplings & Propagators

Vertices [Fontes–2017] (momenta incoming, Feynman rules' 'i' included):[1]

$$[h_i, h_j, Z^\mu] = \frac{g}{2c_W}\,(p_i - p_j)^\mu\,\epsilon_{ijk}\,x_k\,, \quad [Z^\mu, G^0, h_i] = \frac{g}{2c_W}\,(p_i - p_0)^\mu\;x_i\,,$$

$$[h_i, Z^\mu, Z^\nu] = i\,\frac{g}{c_W}\,m_Z\,g^{\mu\nu}\,x_i\,, \quad \text{where:} \quad x_i \equiv T_{1i} = \frac{g_{h_iVV}}{g^{\mathrm{SM}}_{hVV}}\,, \quad c_W \equiv \cos\theta_W\,.$$

In generic R_ξ gauge, Goldstone G^0 and Z propagators read [Romao–2012]:

$$[G^0, G^0] = \frac{i}{p^2 - \xi m_Z^2 + i\epsilon}\,, \quad [Z^\mu, Z^\nu] = \frac{-i}{k^2 - m_Z^2 + i\epsilon}\left[g^{\mu\nu} - (1-\xi)\frac{k^\mu k^\nu}{k^2 - \xi m_Z^2}\right]$$

Calculations performed with `Mathematica` and package `FeynCalc` [Mertig–1990, Shtabovenko–2016], cross-checked with `Package-X` [Patel–2015].

Loop-functions conventions from `LoopTools` [Hahn–1998].

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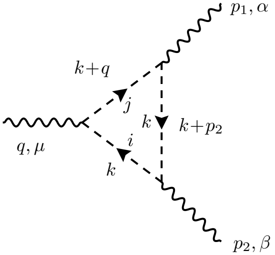
[1] The gauge couplings convention $D_\mu = \partial_\mu + igA_\mu$ is used. If $D_\mu = \partial_\mu - igA_\mu$ is used instead, the sign of $[h_i, h_j, Z^\mu]$ and $[Z^\mu, G^0, h_i]$ is flipped and the Z^3 form factor picks up an overall minus sign.

h_i, h_j, h_k loop

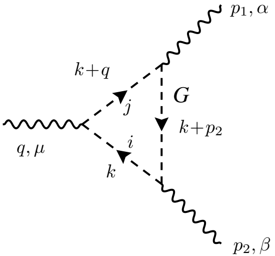
Each scalar in the loop is different ($\leftarrow \epsilon_{ijk}$ in the couplings).



$$e\frac{q^2 - m_Z^2}{m_Z^2}\, f_4^{Z,hhh} = -\frac{8}{16\pi^2}\left(\frac{g}{2c_W}\right)^3 x_1 x_2 x_3 \sum_{i,j,k} \epsilon_{ijk} C_{001}(q^2, m_Z^2, m_Z^2, m_i^2, m_j^2, m_k^2)\,.$$

h_i, h_j, G^0 loop

The Goldstone can be on each of the internal lines.
All combinations of h_i, h_j with $i \neq j$ appear.



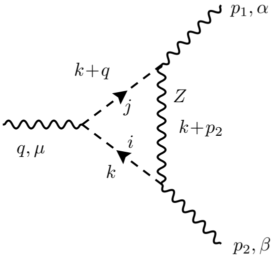
$$e\frac{q^2 - m_Z^2}{m_Z^2}\, f_4^{Z,hhG} = \frac{8}{16\pi^2}\left(\frac{g}{2c_W}\right)^3 x_1 x_2 x_3 \sum_{i,j,k} \epsilon_{ijk} \left[C_{001}(q^2, m_Z^2, m_Z^2, m_i^2, m_j^2, \xi m_Z^2)\right.$$

$$\left. + C_{001}(q^2, m_Z^2, m_Z^2, \xi m_Z^2, m_j^2, m_k^2) + C_{001}(q^2, m_Z^2, m_Z^2, m_i^2, \xi m_Z^2, m_k^2)\right]$$

$$\equiv F_4^{Z,hhG}(\xi)\,.$$

h_i, h_j, Z loop

The Z can be on each of the internal lines.
All combinations of h_i, h_j with $i \neq j$ appear.



$$e\frac{q^2 - m_Z^2}{m_Z^2}\, f_4^{Z,hhZ} = F_4^{Z,hhG}(1) - F_4^{Z,hhG}(\xi) - \frac{8}{16\pi^2}\left(\frac{g}{2c_W}\right)^3 x_1 x_2 x_3 m_Z^2 \sum_{i,j,k} \epsilon_{ijk} C_1(q^2, m_Z^2, m_Z^2, m_i^2, m_Z^2, m_k^2)\,.$$

The result (1-loop) – ℂ2HDM

- $f_4^Z = f_4^{Z,hhh} + f_4^{Z,hhZ} + f_4^{Z,hhG}$: the ξ-dependent parts cancel out each other: **Result is gauge-invariant**.
- Due to the antisymmetric ϵ_{ijk} the UV-divergences of the PaVe C_{001} cancel out: **Result is finite**.

$$e\frac{q^2 - m_Z^2}{m_Z^2} f_4^Z(q^2) \left[\frac{1}{16\pi^2} \left(\frac{g}{c_W} \right)^3 x_1 x_2 x_3 \right]^{-1} \equiv \hat{f}_4^{\,Z} =$$

$$\sum_{i,j,k} \epsilon_{ijk} \left[-C_{001}(q^2, m_Z^2, m_Z^2, m_i^2, m_j^2, m_k^2) + C_{001}(q^2, m_Z^2, m_Z^2, m_i^2, m_j^2, m_Z^2) \right.$$

$$+ C_{001}(q^2, m_Z^2, m_Z^2, m_Z^2, m_j^2, m_k^2) + C_{001}(q^2, m_Z^2, m_Z^2, m_i^2, m_Z^2, m_k^2)$$

$$\left. - m_Z^2 C_1(q^2, m_Z^2, m_Z^2, m_i^2, m_Z^2, m_k^2) \right] .$$

(Note: Each diagram agrees with [Grządkowski–2016] when $\xi = 1$.)

Phenomenological discussion (1/2)

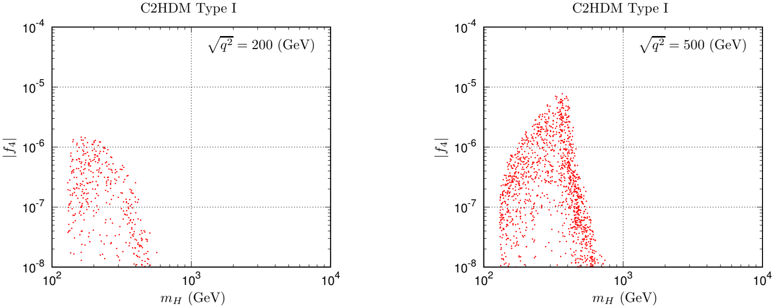


Figure: $|f_4|$ scatter plots in ℂ2HDM for two ≠ CM energies, satisfying theoretical (unitarity, V_H bounded from below) and experimental (LHC Higgs, EDM, EW precision meas.) constraints.

- $|f_4^Z|$ can reach values of $\mathcal{O}(10^{-5})$ in realistic parameter space of ℂ2HDM.
- Compare with recent ATLAS [Aaboud–2017] and CMS [Sirunyan–2017] analyses of ZZ production at the LHC: upper bound on $|f_4^Z|$ (assumed ℝ) of $\mathcal{O}(10^{-3})$.

Phenomenological discussion (2/2)

However when considering a generic BSM framework, one must check whether effects other than f_4^Z may contribute to the actual experimental observable being measured (and from which f_4^Z is inferred): example with $h \to ZZ$ production:

- Not a problem with SM Higgs: $\approx 5\%$ contribution to σ_{ZZ}; for measuring f_4^Z each Z in final state is required to have a $m_Z \in [60; 120]$ GeV.
- Problem happens if *heavier* Higgs decays to ZZ. Mitigated in ℂ2HDM because: 1) from $h_{125} \to ZZ$ measurements the corresponding coupling in ℂ2HDM lies very close to SM value ($\to$ alignment limit), 2) ℂ2HDM sum rule guarantees that any heavier scalar has a very small coupling to ZZ.

Outline

EFT intro (simplified!)

- Suppose new degrees of freedom @ high energy
  ⇒ Separation of scales: $m(\text{NP}) \gg m(\text{EW})$.
- At lower energies, NP modifies interactions of SM fields (modify SM predictions).
  Formally: NP fields are integrated out, generation of non-renormalizable dim. ≥ 5 effective operators.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{d \geq 5} \frac{\mathcal{C}^{(d)}}{\Lambda_{\text{NP}}^{d-4}} \mathcal{O}^{(d)}(\{\text{SM fields}\}) = \mathcal{L}_{D=5} + \mathcal{L}_{D=6} + \dots ,$$

- $\mathcal{L}_{\text{SM}}$: the Standard-Model Lagrangian.
- Λ_{NP}: energy scale(s) of NP;
  $\mathcal{C}^{(d)}$: dimensionless effective coupling ("Wilson coefficient");
  $\mathcal{O}^{(d)}$: effective operator, *function of SM fields only*.
- $\mathcal{L}_{D=5}$ ("Weinberg operator"): masses for neutrinos.
- $\mathcal{L}_{D\geq 6}$: the part of interest!

Matching $\mathbb{C}$2HDM result with EFT

"Naive" expansion of loop functions in terms of $1/m_H$?
$\rightarrow$ Not tractable due to complicated form and non-analytic behaviour.

$\Rightarrow$ Method of regions [Beneke–1997]

In our 1-loop integrals case with two $\neq$ mass scales $m_{\text{light}} \ll m_{\text{heavy}}$:
1) expand integrand for *soft* momenta and compute integral; 2) expand integrand for *hard* momenta and compute integral, and 3) sum both contribs. together.

With $m_1 = m_h = 125$ GeV, $m_2 = m_H$ and $m_3 = \sqrt{m_H^2 + \delta}$ with $\delta \sim v$, in decoupling limit $m_h \ll m_H$ (and $q^2 \ll m_H^2$), we find:

- leading contributions are $\mathcal{O}(m_H^{-4})$, from diagrams with 1 heavy scalar and 2 SM particles (h, Z, G^0) in the loop, correspond to the soft region ($k \ll m_H$) of the integrals;
- other regions / diagrams are $\mathcal{O}(m_H^{-6})$ or higher.

Matching result

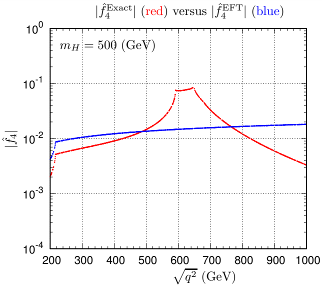
The form of the expansion is found to be (when $m_h \ll m_H$ and $q^2 \ll m_H^2$):

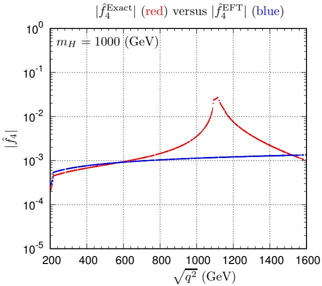
$$ef_4^Z(q^2) \sim \frac{\delta^2 x_1 x_2 x_3}{m_H^4} \left(\frac{g}{c_W}\right)^3 \times \mathsf{func}(q^2, m_h, m_Z)\,,$$

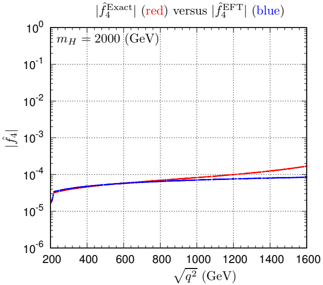
where $\mathsf{func}(q^2, m_h, m_Z)$ is some complicated kinematical function.
In the decoupling limit the Higgs mixing angles are also suppressed:
$\delta^2 x_1 x_2 x_3 \approx \frac{v^6}{2m_H^4} \operatorname{Im}(Z_5^* Z_6^2)$.

$$ef_4^Z(q^2) \sim \operatorname{Im}(Z_5^* Z_6^2)\frac{v^6}{2m_H^8}\left(\frac{g}{c_W}\right)^3 \times \mathsf{func}(q^2, m_h, m_Z).$$

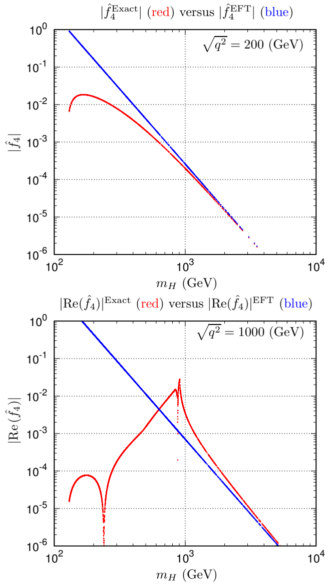
Comparing exact vs. matched EFT (1/2)







Comparing exact vs. matched EFT (2/2)



Prerequisites for SM-EFT

General assumptions

- The operators are $G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$ invariant.
- The 125 GeV Higgs boson h_1 belongs to the Higgs scalar $SU(2)$ doublet H that transforms as $(\mathbf{1}, \mathbf{2})_{1/2}$ of G_{SM} and acquires a VEV v. (OK since we already work with such doublets in the 2HDM.)

Start from $\mathcal{L}_{\text{C2HDM}}$ (terms not relevant here are dropped) and work in the "Higgs basis" where $\langle H_1 \rangle = v/\sqrt{2}$ while $\langle H_2 \rangle = 0$, $\oplus$ Stationarity conditions:

$$\mathcal{L}_{\text{C2HDM}} \supset |D_\mu H_1|^2 - Z_1 \frac{|H_1|^2 - v^2}{2} |H_1|^2 + |D_\mu H_2|^2 - Y_2 |H_2|^2 - Z_3 |H_1|^2 |H_2|^2$$
$$- Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) - \left\{ \frac{Z_5}{2} (H_1^\dagger H_2)^2 + Z_6 X_0 (H_1^\dagger H_2) + \text{h.c.} \right\} + \ldots ,$$

where: $\quad X_0 = |H_1|^2 - \dfrac{v^2}{2}$.

Procedure

Write EOM for $H_2^{(\dagger)}$ & search for perturbative solution $H_2 = \sum_{n=1}^{+\infty} Y_2^{-n} H_2^{(n)}$;
$Y_2 \equiv$ large mass^2 scale Λ_{NP} (we implicitly suppose the **decoupling limit**):

$$Y_2 H_2 + D^2 H_2 + Z_6^* X_0 H_1 + Z_5^* (H_2^\dagger H_1) H_1 + \cdots = 0.$$

$\Rightarrow$ Recursive equations:

$$H_2^{(1)} = -Z_6^* X_0 H_1 \,, \quad H_2^{(n+1)} = -D^2 H_2^{(n)} - Z_5^* (H_2^{(n)\,\dagger} H_1) H_1 + \ldots \,,$$

and we need to go up to $n = 4$. Replace all the $H_2^{(n)}$ values recursively into the expanded ansatz and back into $\mathcal{L}_{\text{C2HDM}}$, to obtain a tree-level-generated EFT expressed only in terms of the $H_1 \equiv H$ doublet and D_μ:

$$\mathcal{L}_{\text{C2HDM}}^{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{n=1}^{+\infty} Y_2^{-n} \mathcal{L}^{(2n+4)} \,.$$

Identifying the operator(s) in the SM-EFT (1/2)

Examples (note: $X_0 = |H_1|^2 - \frac{v^2}{2}$):

Operator	Properties
$\mathcal{L}^{(6)} \supset \|Z_6\|^2 X_0^2 \|H\|^2$	Shifts triple-h coupling.
$\mathcal{L}^{(8)} \supset \|Z_6 D_\mu (X_0 H)\|^2$	Renormalizes h kinetic term.
$\mathcal{L}^{(10)} \supset\propto D_\mu (H^\dagger X_0) D_\mu (X_0 \|H\|^2 H) +$ h.c.	CP-odd interactions $\propto \mathrm{Im}(Z_5^* Z_6^2) h^{\geq 3} \partial_\mu Z^\mu$, does not generate ZZZ simply.

And (red: term that generates CP-violating interactions):

$$\mathcal{L}^{(12)} \supset \frac{-Z_5^* Z_6^2}{m_H^8} \left[D^2 (H^\dagger X_0) D^2 (X_0 |H|^2 H) + (D^2 (H^\dagger X_0) H)^2 / 2 \right] + \text{h.c.},$$

leading to (using classical EOM for h: $v\Box h = \ldots$):

$$\mathcal{L}^{(12)} \supset \frac{\mathrm{Im}(Z_5^* Z_6^2)}{m_H^8} \frac{g v^6}{2 c_W} Z^\nu \partial_\nu h \Box h + \mathcal{O}(Z h^3)$$

$$\to \frac{\mathrm{Im}(Z_5^* Z_6^2)}{m_H^8} \frac{g v^5}{2 c_W} Z^\nu \partial_\nu h (m_Z^2 Z_\mu Z^\mu + 2 m_W^2 W_\mu^+ W^{-\,\mu}) \,.$$

Identifying the operator(s) in the SM-EFT (2/2)

$$\mathrm{Im}(Z_5^* Z_6^2) \left(\frac{g}{c_W}\right)^3 \frac{v^7}{8m_H^8} Z^\nu \partial_\nu h Z_\mu Z^\mu$$ at $d = 12$ and is CP-odd.

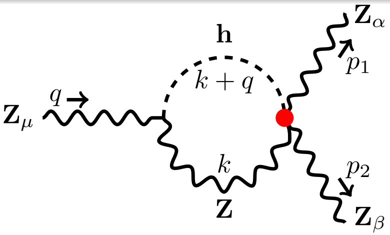


Figure: 1-loop diagram contributing to the Z^3 vertex in EFT, with insertion of the $d = 12$ operator. (+ 2 other diags. with permutations of external legs.)

Personal comment! Alternative computation: use "Universal 1-Loop Effective Action" (UOLEA) technique, extended at $d = 12$ and including light/heavy fields mixing? ([Cheyette,Gaillard (1980); Henning, Lu, Murayama (2014); Drozd, Ellis, Quevillon, You (2014-2015), + Zhang (2017); et al.], and [HBM talk @ 2HDM-Workshop 2016].)

Discussion

- In ℂ2HDM the ZZZ vertex arises from a $d=12$ operator inserted at 1-loop level.
- While ZZZ cannot be generated at $d=6$, it could be a priori generated at $d \geq 8$, e.g. $\mathcal{L}_{d=8} = \frac{ic_8}{\Lambda^4} B_{\mu\nu} B^{\mu\rho} H^\dagger \{D^\nu, D_\rho\} H$ (and $B_{\mu\nu} \to W^i_{\mu\nu}$) [Degrande–2013], and contribute to f_4^Z.
- However these cannot be generated in the ℂ2HDM at 1-loop, because all the CP-violating effects are $\propto$ to the **Jarlskog-type invariant** (see [Lavoura–1994]) $J_{\text{CP}} = \frac{(m_{h_3}^2 - m_{h_2}^2)(m_{h_3}^2 - m_{h_1}^2)(m_{h_2}^2 - m_{h_1}^2)}{m_{h_1}^2 m_{h_2}^2 m_{h_3}^2} x_1 x_2 x_3 \propto \text{Im}(Z_5^* Z_6^2)$.
- $\hbar$ power-counting (see refs. in [HBM–2018]) show that the $d=12$ operator is allowed within the ℂ2HDM at tree-level, while the $d=8$ one cannot appear before 3-loop level in the matching.

Outline

Summary

- The CP-violating ZZZ vertex has been studied in the ℂ2HDM and in its matching within the SM-EFT framework.
- The CP-odd form-factor f_4^Z has been evaluated at 1-loop in R_ξ gauge and is gauge-independent; the leading contribs. arise from triangle diagrams with SM particles and heavy Higgses.
- It probes one of the Jarlskog J_{CP} invariants in the extended Higgs sector.
- Using the f_4^Z approximation in decoupling limit we found the dominant diagrams and operator responsible for CP-violating ZZZ vertex in the low-energy EFT where the heavy scalars are integrated out.
- Via power-counting and J_{CP}, we confirmed that the operator appears in the EFT at $d = 12$ in the matching at 1-loop. $\Rightarrow$ CP-violating effects in ZZ production are extremely suppressed when $v \ll m_H$.

Thank you for your attention!

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