Non-decoupling of charged scalars in Higgs decay and symmetries of the scalar potential

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Introduction

- It is not yet settled whether the 125 GeV Higgs is alone or it has any sibling(s)?
- Extension of scalar sector by additional doublets is attractive because (i) Rho parameter remains unity at tree level, (ii) MSSM is based on 2HDM, (iii) it is straightforward to find a combination

$$h \equiv v^{-1} \sum_{i=1}^{n} v_i h_i$$

==> SM-like coupling with fermions and gauge bosons : Alignment limit

- Non-decoupling:
    * In $h \to \gamma\gamma$ charged Higgs contributions do not necessarily decouple.
    * Symmetries of potential play a role in ensuring decoupling.

- We demonstrate non-decoupling vs decoupling in 2HDM context with underlying reasons, and show results for 3HDM also.

Essential points

- If V(2HDM) has exact Z2 symmetry AND both scalars receive vevs, the charged Higgs contributions do NOT decouple in diphoton decay width.
- If Z2 is softly broken in V, then decoupling is achieved, but with fine-tuning.
- If V has global U(1) symmetry, then its soft breaking can ensure decoupling without fine-tuning.
- For 3-(or more)-HDM, enhanced global symmetries and their soft breaking are necessary to ensure decoupling.
- Unless decoupling is ensured, high precision measurements of higgs to diphoton decay width can restrict number of such doublets regardless of how heavy the charged Higgs masses are.

Working formulae

$$\mu_{\gamma\gamma} \equiv \frac{\sigma(pp \to h)}{\sigma^{SM}(pp \to h)} \frac{Br(h \to \gamma\gamma)}{Br^{SM}(h \to \gamma\gamma)} = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma^{SM}(h \to \gamma\gamma)}$$

$$g_{hH^+H^-} \equiv \kappa \frac{g M_{H^+}^2}{M_W}$$

For Convenience

Root of decoupling / non-decoupling

$$\Gamma\left(h \to \gamma\gamma\right) \propto \frac{m_h^3}{M_W^2} \left| A_W + \frac{4}{3} A_t + \sum_i \kappa_i A_{H_i^+} \right|^2$$

where

$$A_{H_i^+} = -\tau_i \left[1 - \tau_i \left(\sin^{-1} \sqrt{1/\tau_i} \right)^2 \right] \quad ; \qquad \tau_i \equiv \left(2 M_{H_i^+} / m_h \right)^2$$

When $\quad M_{H_i^+} \to \infty \quad \Rightarrow \quad A_{H_i^+} \to \frac{1}{3}$

Two Higgs-doublet Models

$$V_{2\mathrm{HDM}} = \lambda_1 \left(\phi_1^\dagger \phi_1 - \frac{v_1^2}{2}\right)^2 + \lambda_2 \left(\phi_2^\dagger \phi_2 - \frac{v_2^2}{2}\right)^2 + \lambda_3 \left(\phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2 - \frac{v_1^2 + v_2^2}{2}\right)^2$$

$$+\lambda_4 \left((\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) - (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1)\right) + \lambda_5 \left(\mathrm{Re}\ \phi_1^\dagger \phi_2 - \frac{v_1 v_2}{2}\right)^2 + \lambda_6 \left(\mathrm{Im}\ \phi_1^\dagger \phi_2\right)^2$$

Assumed: i) Z2 symmetry: $\phi_1 \to \phi_1 \quad , \quad \phi_2 \to -\phi_2$
(ii) Both scalars receive vevs, (iii) Soft breaking of Z2, (iv) All lambdas real

How many parameters? 8

Started with: v1, v2, lam(1-6)
Traded for: v (246 GeV), tanB, mh (125 GeV), mH, mA, mH+, alpha, lam5
Alignment limit: alpha = beta – pi/2

Hence, 5 unknown free parameters.

Decoupling vs Non-decoupling

$$\kappa = -\frac{1}{m_{H^+}^2}\left(m_{H^+}^2 - \lambda_5\frac{v^2}{2} + \frac{m_h^2}{2}\right)$$

- If Z2 is exact, ƛ5 = 0, which means ϰ = - 1 : Non-decoupling
- For ƛ5 ≠ 0, decoupling at the expense of F.T. : $m^2(H+) \sim ƛ5\, v^2/2$
- If, instead of Z2, we have U(1) symmetry in quartic,

ƛ5 = ƛ6 = 2 $m^2(A) / v^2$

$$\kappa = -\frac{1}{m_{H^+}^2}\left(m_{H^+}^2 - m_A^2 + \frac{m_h^2}{2}\right)$$

- | m(H+) - m(A) | « m(H+) , m(A) by unitarity and T parameter.

  which implies Decoupling without F.T.

Different parametrization and underlying dynamics

$$V'_{\rm 2HDM} = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - \left(m_{12}^2\phi_1^\dagger\phi_2 + {\rm h.c.}\right) + \frac{\beta_1}{2}\left(\phi_1^\dagger\phi_1\right)^2 + \frac{\beta_2}{2}\left(\phi_2^\dagger\phi_2\right)^2 + \beta_3\left(\phi_1^\dagger\phi_1\right)\left(\phi_2^\dagger\phi_2\right) + \beta_4\left(\phi_1^\dagger\phi_2\right)\left(\phi_2^\dagger\phi_1\right) + \left\{\frac{\beta_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + {\rm h.c.}\right\}$$

- This is a more general parametrization than V(2HDM).
- No *a priori* assumption that both scalars receive vevs.
- When β2 = β3 = β4 = β5 = 0 , m²(12) = 0 and m²(22) > 0

  ==> Inert Doublet Model with **perfect Z2 symmetry**

  ==> Smooth **decoupling** when m²(22) → ∞

  as m²(22) doesnt have SSB origin.
- Note : 2 m²(12) = λ5 v1 v2 , 2 β5 = λ5 – λ6

  Regulator for decoupling

Three Higgs-Doublet Models

- S3 or A4 symmetric flavor models employ 3 doublets (ϕ1, ϕ2, ϕ3).
- For exact symmetry:

$$\kappa_i = -\frac{1}{m^2_{H_i^+}}\left(m^2_{H_i^+} + \frac{m_h^2}{2}\right)$$

- Apply a global continuous symmetry SO(2) on (ϕ1, ϕ2) and allow its soft breaking:

$$\kappa_1 = -\frac{1}{m^2_{H_1^+}}\left(m^2_{H_1^+} - m^2_{H_1} + \frac{m_h^2}{2}\right) \Rightarrow \text{Decoupling}$$

$$\kappa_2 = -\frac{1}{m^2_{H_2^+}}\left(m^2_{H_2^+} + \frac{m_h^2}{2}\right) \Rightarrow \text{Non-decoupling}$$

- Need extended symmetry SO(2) X U(1) with an extra soft breaking parameter to ensure full decoupling.

Conclusions

- If both scalars in 2HDM receive vevs, then charged Higgs will **decouple** from higgs to diphoton decay width, even with perfect **alignment**, provided there is an additional symmetry and its soft breaking.
- In 3(or more)HDM, the same logic can be extended.
- Otherwise, diphoton decay width can sense the number of such multiplets regardless of how heavy they are.

Thank you