



# Investigating Resonant Higgs Signatures in the Context of a Two Higgs Doublet Model (2HDM)

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Abstract

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In this work, we explore Higgs-like resonant signals within the framework of Two-Higgs-Doublet Models (2HDM). We address the recent anomalies observed at the LHC and propose extensions to the Standard Model that could explain them, focusing on the inclusion of a scalar singlet  $\sigma$ . We analyze the resulting particle spectrum and how it aligns with experimental observations without the need for fine-tuning the model parameters.

## Beyond the Standard Model Motivations

- Existence of neutrino mass.
- Evidence for dark matter.
- Observed matter-antimatter asymmetry of the universe.

This requires extending the Standard Model (SM) either in the scalar, gauge, or fermion sector.

## Search for Higgs Bosons Beyond the SM at the LHC

- **ATLAS and CMS** have intensively searched for new Higgs bosons beyond the SM.
- Analyzing various decay channels and production processes to detect new scalar particles.
- **Decays into two photons ( $\gamma\gamma$ ):** Excesses around 95 GeV and 151 GeV.
- **Decays into  $Z\gamma$ :** Observed in combinations of associated production channels.
- **Decays into pairs of bottom quarks ( $b\bar{b}$ ):** Indicative in the excess around 95 GeV.
- **Decays into pairs of  $W^+W^-$  and  $ZZ$  bosons:** Suggest heavy scalar bosons.
- **Production of Higgs pairs (di-Higgs):** Especially in asymmetric processes like  $H \rightarrow S h$  or  $H \rightarrow S S$ .

## Mass Range of Scalar Resonances

### Around 95 GeV:

- Indications of a possible new scalar boson.
- Observed in channels like  $\gamma\gamma$ ,  $\tau^+\tau^-$ , and  $b\bar{b}$ .
- Local and global significances in ATLAS and CMS.

### Around 151 GeV:

- Significant deviations in  $\gamma\gamma$  and  $Z\gamma$  channels.
- Suggest the existence of a new scalar in this mass range.

## Two-Higgs-Doublet Models (2HDM) and Extensions

### 2HDM Type II and Type IV:

- Can accommodate an additional scalar boson around 95 GeV.
- Compatible with excesses in  $\gamma\gamma$  and  $\tau^+\tau^-$ .

### N2HDM (Next-to-Minimal Two-Higgs-Doublet Model):

- Includes an additional doublet or scalar singlet.
- Allows interactions between multiple scalars.

### S2HDM (2HDM Extended with a Singlet):

- Explains simultaneously the excesses in  $\gamma\gamma$  and  $b\bar{b}$  around 95 GeV.

### $\Delta$ 2HDMs Model:

- Extension with two Higgs doublets, a real singlet, and a real triplet.
- Explains observed excesses in multiple channels.

## The Proposed Model:

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_\alpha \otimes U(1)_\beta$$

### Fermion and Scalar Content:

	Fields	$\hat{Y}$	$\hat{Q}$
Leptons	$\ell_i, \nu_{iR}, e_{iR}$	$-1, 0, -2$	$(0, -1), 0, -1$
Quarks	$q_i, u_{iR}, d_{iR}$	$\frac{1}{3}, \frac{4}{3}, -\frac{2}{3}$	$(\frac{2}{3}, -\frac{1}{3}), \frac{2}{3}, -\frac{1}{3}$
Scalars	$\Phi_\alpha, \sigma$	$1, 0$	$(1, 0), 0$

### Spontaneous Symmetry Breaking:

$$SU(2)_L \otimes U(1)_\alpha \otimes U(1)_\beta \xrightarrow{\langle \sigma \rangle} SU(2)_L \otimes U(1)_Y \xrightarrow{\langle \Phi_1, \Phi_2 \rangle} U(1)_Q$$

## Scalar Potential

- Scalar content:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ v_i + h_i + i\eta_i \end{pmatrix}, \quad \sigma = \frac{v_\sigma + \xi + i\zeta}{\sqrt{2}}$$

- VEV hierarchy:  $v_\sigma > v_2 \gg v_1$
- General scalar potential:

$$V(\Phi_1, \Phi_2, \sigma) = \mu_1^2 |\Phi_1|^2 + \mu_2^2 |\Phi_2|^2 + \mu_\sigma^2 |\sigma|^2 + \lambda_1 |\Phi_1|^4 + \lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \lambda_{1\sigma} |\Phi_1|^2 |\sigma|^2 + \lambda_{2\sigma} |\Phi_2|^2 |\sigma|^2 + \text{cubic or quartic terms in } \sigma$$

- Cubic term:  $\mu[(\Phi_1^\dagger \Phi_2)\sigma + \text{h.c.}]$
- Quartic term:  $\lambda[(\Phi_1^\dagger \Phi_2)\sigma^2 + \text{h.c.}]$

## Mass Spectrum of the Neutral Scalar Sector

- After minimizing the potential, the mass matrix for neutral scalars is obtained.
- Two cases are considered: potential with cubic term and with quartic term.
- Mass hierarchy:  $M_{H_1} < M_{H_2} < M_{H_3}$

## Numerical Results (cubic-quartic term)

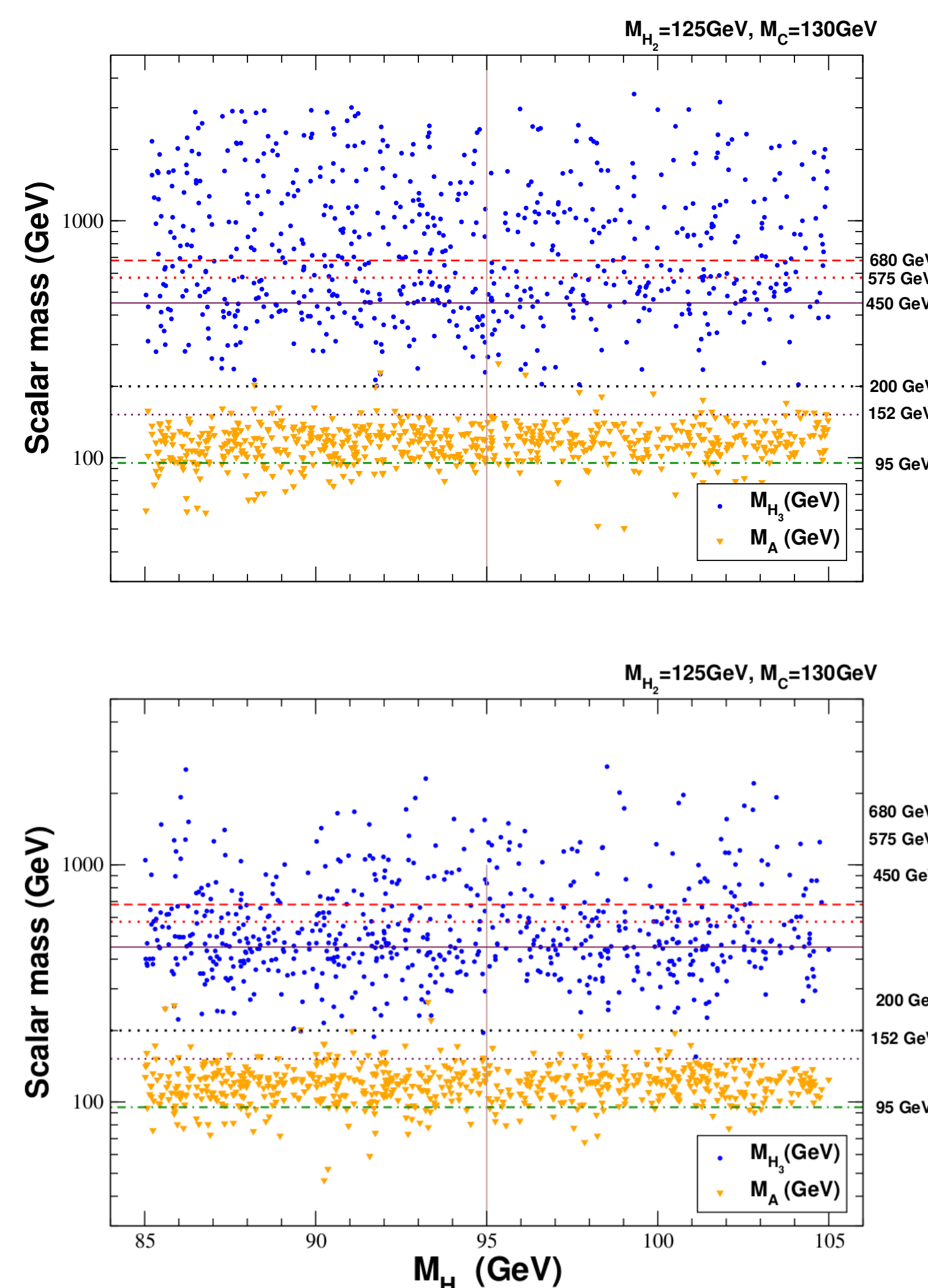


Figure: Distribution of the scalar masses  $M_{H_3}$  (blue dots) and the pseudoscalar  $M_A$  (orange triangles) for the potential with cubic and quartic term.

## Mass Spectrum of the Neutral Pseudoscalar Sector

- Mass matrix for neutral pseudoscalars in both cases (cubic and quartic).
- The mass of the pseudoscalar  $A$  is:

$$M_A^2 = \begin{cases} \frac{\mu(v_1^2 v_2^2 + v^2 v_\sigma^2)}{\sqrt{2} v_1 v_2 v_\sigma} & (\text{cubic case}) \\ \frac{\lambda(4v_1^2 v_2^2 + v^2 v_\sigma^2)}{2v_1 v_2} & (\text{quartic case}) \end{cases}$$

## Mass Spectrum of the Charged Scalar Sector

- Mass matrix for charged scalars in both cases.
- The mass of the charged Higgs  $C^\pm$  is:

$$M_{C^\pm}^2 = \begin{cases} -\frac{v^2}{2} \left( \sqrt{2} \frac{\mu v_\sigma}{v_1 v_2} + \lambda_4 \right) & (\text{cubic case}) \\ -\frac{v^2}{2} \left( \frac{\lambda v_\sigma^2}{v_1 v_2} + \lambda_4 \right) & (\text{quartic case}) \end{cases}$$

## Conclusions

- Recent anomalies observed at the LHC can be explained through extensions of the SM, specifically 2HDMs.
- The inclusion of a scalar singlet  $\sigma$  that provides mass to a new boson  $Z'$  enhances the model's ability to explain these anomalies.
- The model predicts a particle spectrum consistent with experimental observations, including:
  - Three CP-even scalar bosons:  $H_1, H_2, H_3$ .
  - One CP-odd scalar boson:  $A$ .
  - One charged scalar boson:  $C^\pm$ .
- The masses and parameters of the model naturally align with the observed anomalies without the need for fine-tuning.

## Coupling upper limit

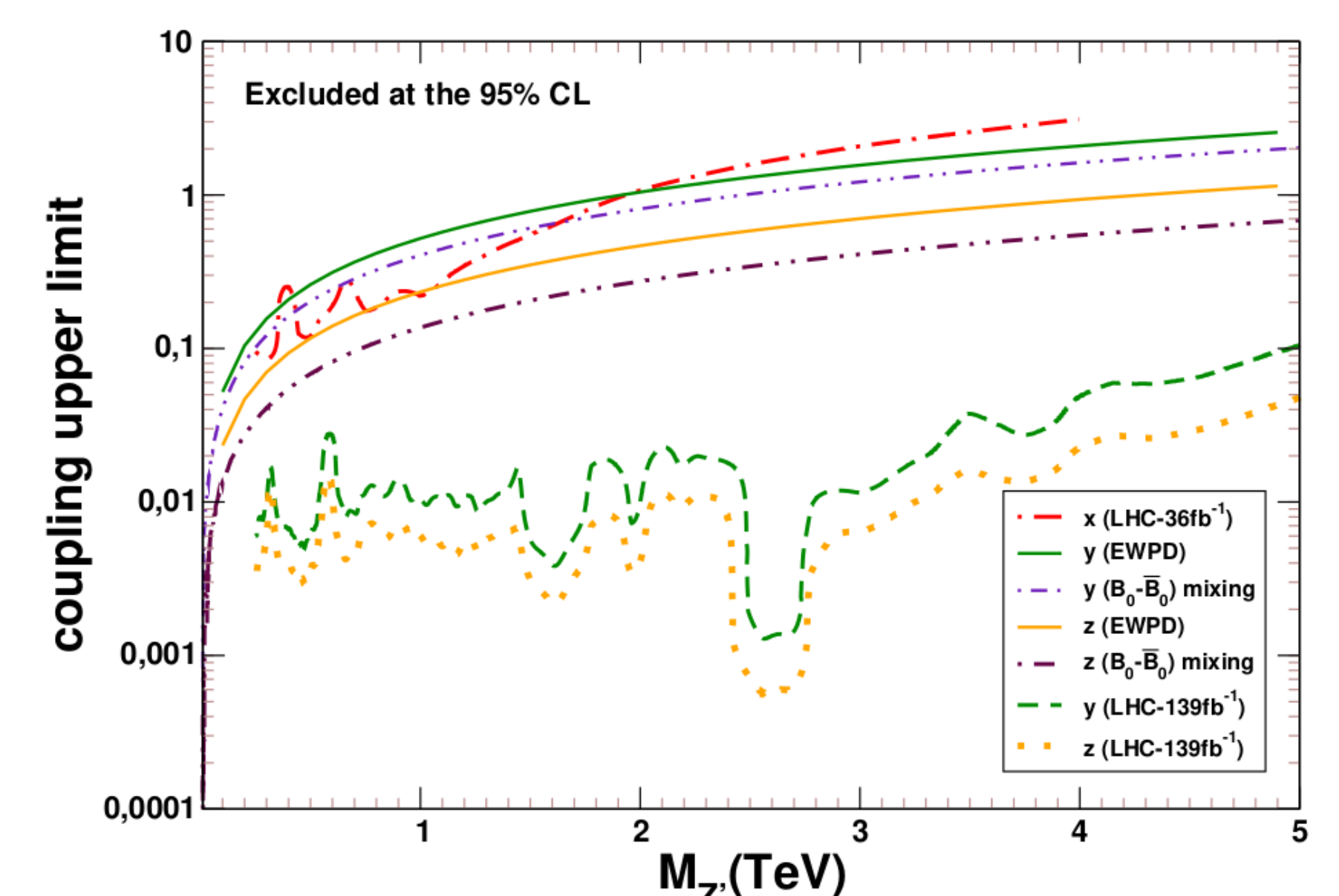


Figure: Left: Upper limit on the model parameters  $x, y, z$ . Right: 95% CL upper limits on the fiducial  $Z'$  production cross-section times the  $Z' \rightarrow \ell^+ \ell^-$  branching [?] (green continuous line) and the corresponding upper limits on the  $Z'$  decaying to  $\tau\tau$  pairs (red continuous line).