Exploring Higgs-like Resonant Signals within a 2HDM Framework

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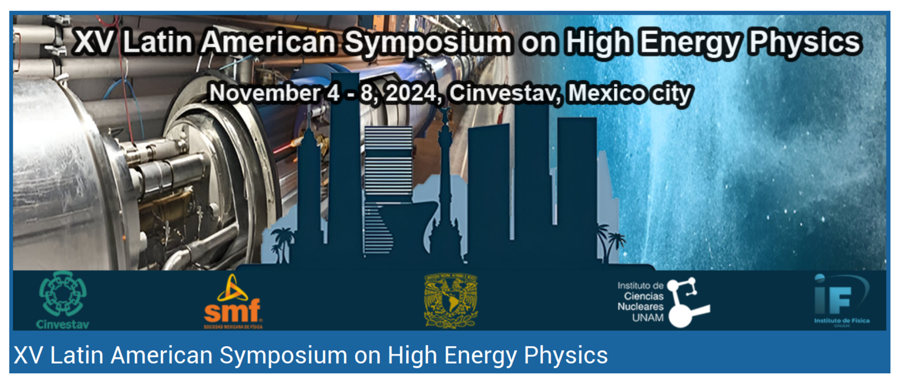

Abstract

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 σ. 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 $H \to Sh$ or $H \to SS$.

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.

Δ2HDMS 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	ℓ_i, ν_{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	Φ_a, σ	$1,\ 0$	$(1,0),\ 0$

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:

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

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

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

- 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: $M_{H_1} < M_{H_2} < M_{H_3}$

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:

$$M_A^2 = \begin{cases} -\dfrac{\mu(v_1^2v_2^2 + v^2v_\sigma^2)}{\sqrt{2}v_1v_2v_\sigma} & \text{(cubic case)} \\ -\dfrac{\lambda(4v_1^2v_2^2 + v^2v_\sigma^2)}{2v_1v_2} & \text{(quartic case)} \end{cases}$$

Mass Spectrum of the Charged Scalar Sector

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

$$M_{C^\pm}^2 = \begin{cases} -\dfrac{v^2}{2}\left(\sqrt{2}\dfrac{\mu v_\sigma}{v_1v_2} + \lambda_4\right) & \text{(cubic case)} \\ -\dfrac{v^2}{2}\left(\dfrac{\lambda v_\sigma^2}{v_1v_2} + \lambda_4\right) & \text{(quartic case)} \end{cases}$$

Conclusions

- Recent anomalies observed at the LHC can be explained through extensions of the SM, specifically 2HDMs.
- The inclusion of a scalar singlet σ 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.

Numerical Results (cubic term)

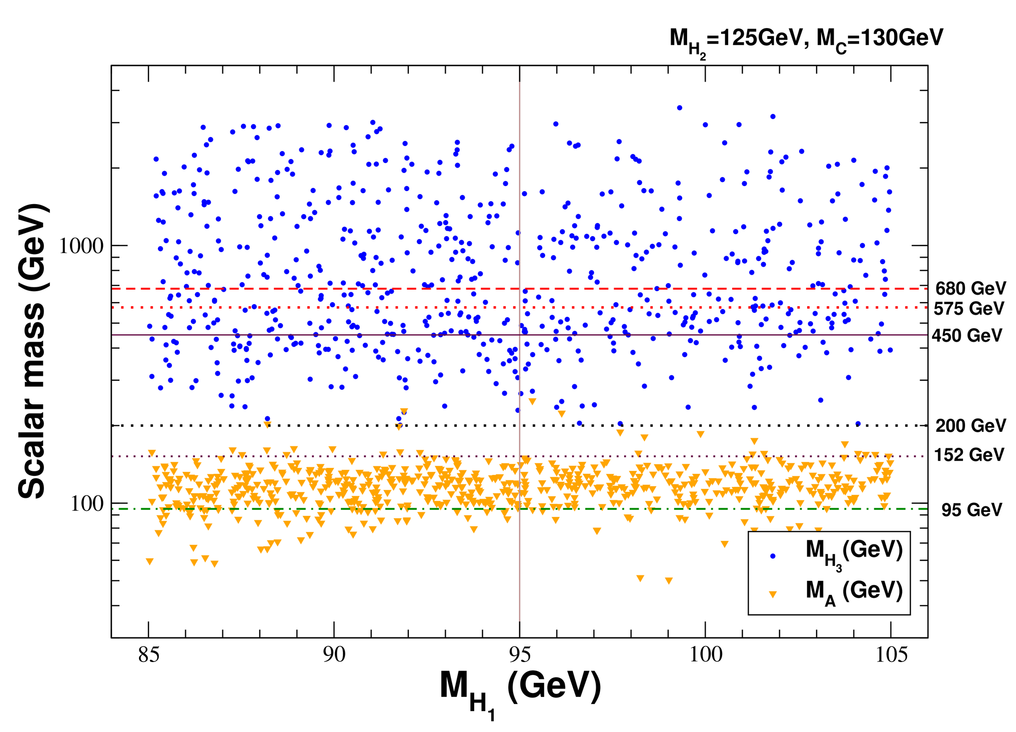

Figure: Distribution of the scalar masses M_{H_3} (blue dots) and the pseudoscalar M_A (orange triangles) for the potential with cubic term.

Numerical Results (quartic term)

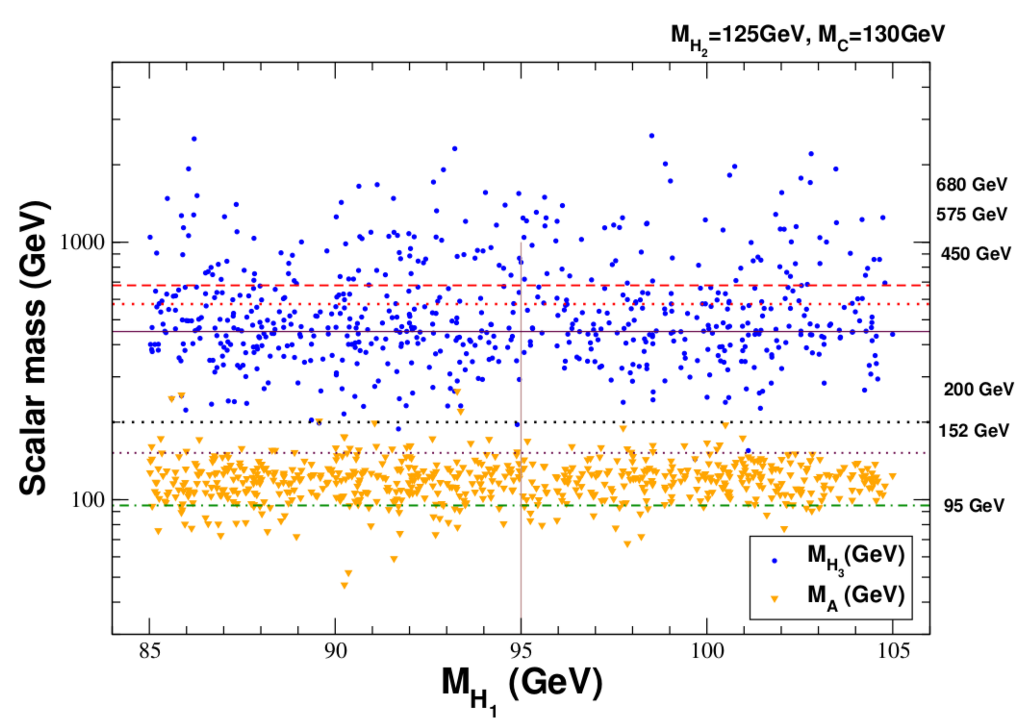

Figure: Distribution of the scalar masses M_{H_3} (blue dots) and the pseudoscalar M_A (orange triangles) for the potential with quartic term.

Work in progress, in collaboration with E. Rojas, W. Ponce, R. Benavides, and O. Rodríguez, based in part on arXiv:2408.16177 [hep-ph]

"The Standard Model of Particle Physics as an effective theory from two non-universal U(1)'s"