Asymmetric Di-Higgs Signals of the N2HDM

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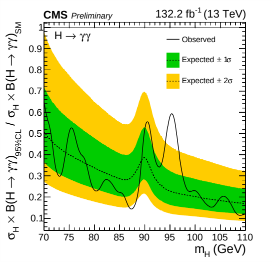
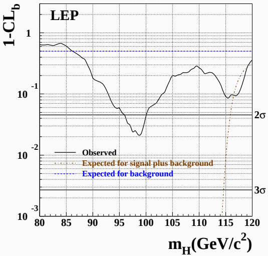
Outline

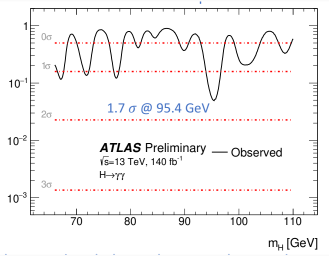
1. Motivation
2. Next-to-minimal two-Higgs-doublet model (N2HDM-Z_2) with a Z_2 symmetry
3. Next-to-minimal two-Higgs-doublet model (N2HDM-$U(1)'$) with a $U(1)'$ symmetry
4. Phenomenology
5. Conclusions

Motivation

- The CMS, ATLAS and LEP hints for a new resonance decaying to $\gamma\gamma$ at 95 GeV.

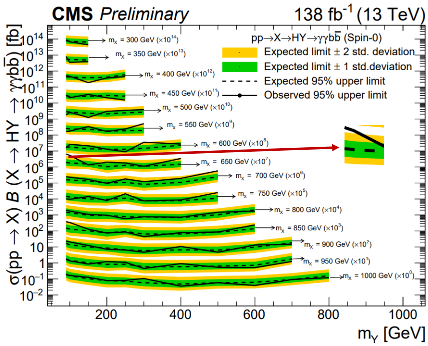






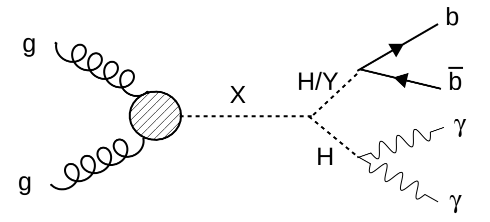
Motivation

- CMS excess in decay of a new resonance to two scalar: $X(650) \to (h(125) \to \gamma\gamma)(Y(95) \to \bar{b}b)$.



Asymmetric Higgs decays are small in most models.

Motivation



- At least three CP-even scalars needed to explain the excesses.
- Study the singlet extended version of the two-Higgs doublet model (N2HDM-$U(1)'$).
- Three CP-even, one CP-odd and two charged Higgs.
- Focus on two different versions: N2HDM-Z_2 and N2HDM-$U(1)_H$.

N2HDM-Z_2

- N2HDM-Z_2 is the standard and more studied version.
- Two Z_2 global symmetry: $\phi \to -\phi$ and $H_2 \to -H_2$.
- The scalar potential is

  a) Doublet Terms

$$\mathcal{V}_H = m_{11}^2 |H_1|^2 + m_{22}^2 |H_2|^2 + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)\,. \tag{1}$$

  b) Singlet Terms

$$\mathcal{V}_\phi = |\phi|^2 \left(m_\phi^2 + \frac{\lambda_\phi}{2}|\phi|^2 + \lambda_{\phi 1}|H_1|^2 + \lambda_{\phi 2}|H_2|^2 \right)\,. \tag{2}$$

  c) Additional Terms

$$\mathcal{V}_{CP} = -m_{12}^2 (H_1^\dagger H_2 + \text{h.c.}) + \lambda_5 ((H_1^\dagger H_2)^2 + \text{h.c.}) \tag{3}$$

- No terms like $H_1 H_2 \phi$, etc.

N2HDM-$U(1)'$

Motivations for a $U(1)'$ symmetry.

- The Z_2 version of N2HDM does not allow for sizable asymmetric di-Higgs decay as it is mixing suppressed.
- Instead introduce a single $U(1)_H$ gauge symmetry in N2HDM.
- No *CP*-violating terms and one less free parameter.
- Like the SM, the N2HDM–$U(1)'$ is built on local gauge symmetries and spontaneous symmetry breaking.

N2HDM-$U(1)'$

- Scalar sector of N2HDM-$U(1)'$ has the terms $\mathcal{V}_H$ and $\mathcal{V}_\phi$, but not $\mathcal{V}_{\mathcal{CP}}$.
- Two possible ways to get an effective m_{12} term depending on the charge assignment under the $U(1)_H$ gauge symmetry:

  Case 1: $|Q_H(\phi)| = |Q_H(H_1) - Q_H(H_2)|$

  $$\mathcal{V}^1_{\phi H} = \sqrt{2}\mu H_1^\dagger H_2 \phi + \mathrm{h.c.} \tag{4}$$

  Case 2: $|Q_H(\phi)| = \dfrac{|Q_H(H_1) - Q_H(H_2)|}{2}$

  $$\mathcal{V}^2_{\phi H} = \lambda_{\phi 12}(H_1^\dagger H_2)\phi^2 + \mathrm{h.c.} \tag{5}$$

  where $Q_H(\Phi)$ denotes the $U(1)_H$ charge of field Φ.
- Case 2 is novel to the best of our knowledge.

N2HDM-$U(1)'$

- Field content:

$$H_1 = \begin{pmatrix} w_1^+ \\ \frac{v_1 + H + i\eta_1}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} w_2^+ \\ \frac{v_2 + h + i\eta_2}{\sqrt{2}} \end{pmatrix}, \qquad \phi = \frac{v_S + S + i\eta_S}{\sqrt{2}}. \tag{6}$$

- 11 parameters in our model:

$$m_h, m_H, m_S, m_A, m_{H^\pm}, \alpha_1, \alpha_2, \alpha_3, \tan\beta, v_S, v \tag{7}$$

α_i are the CP-even mixing angles, $\tan\beta = \frac{v_2}{v_1}$ and $v = \sqrt{v_1^2 + v_2^2}$.

- In the absence of mixing, the mass eigenstates within H_2, H_1, and ϕ are h, H, and S, respectively

- CP-even mass matrix,

$$M_\rho^2 \approx \begin{pmatrix} -\mu v_S \tan\beta & \mu v_S & \mu v \\ \mu v_S & \lambda_2 v^2 & 0 \\ \mu v & 0 & \lambda_\phi v_S^2 \end{pmatrix}, \tag{8}$$

  for vanishing $\lambda_{\phi 2}$, and assuming v_1 is very small such that $\tan\beta$ is very large.

- In this limit, the mixing of $H - h$ and $H - S$ is negligible

- Only unsuppressed decay of H, in the absence of Yukawa couplings of H_1, is $H \to Sh$ for Case 1, and in addition $H \to SS$ for Case 2, if $m_H \gg m_S$

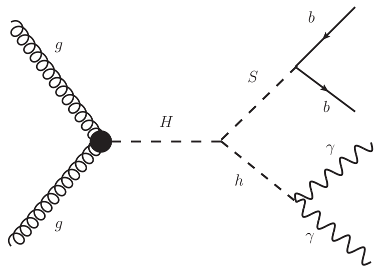
Phenomenology

- Asymmetric Higgs decays are useful in the context of CMS di-Higgs analysis.
- Here, X $\approx 650\,\text{GeV}$ boson decay into Y $\approx 95\,\text{GeV}$ scalar and the SM Higgs, and then Y decays into $b\bar{b}$ and the SM Higgs into $\gamma\gamma$
- $\sigma(pp \to b\bar{b}\gamma\gamma)$ is $\approx 0.35^{+0.17}_{-0.13}$ fb
- Taking $\text{BR}(h \to \gamma\gamma) \approx 0.23\%$ and the upper-limit of $pp \to b\bar{b}\tau\bar{\tau}$ is ≈ 4 fb, we aim to explain within $2\,\sigma$

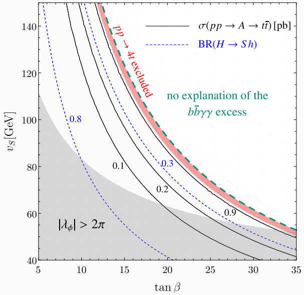
$$\sigma(pp \to (650) \to (95)\,h) \times \mathrm{BR}((95) \to b\bar{b}) \approx 70\,\mathrm{fb}\,. \qquad (9)$$

Phenomenology

- There are two options within the N2HDM; identify the $\approx 95\,\text{GeV}$ state with H and the $\approx 650\,\text{GeV}$ one with S or vice versa
- If H is lighter, then μ is small ($m_H \approx -\mu v_S \tan\beta$), and therefore the branching ratio is suppressed (due to $\mu H_1^\dagger H_2 \phi$)
- Consider the second case, i.e. $pp \to H \to Sh$, for a larger branching ratio



Phenomenology



- Grey region is excluded from having positive eigenvalues of the mass matrix as well as perturbative couplings
- For sufficient production cross-section of H, assume effective coupling $-\tilde{Y}^t \bar{Q}_L \tilde{H}_1 t_R$
- Predict the cross-section of $H \to tt$, $A \to tt$ and $pp \to t\bar{t}A \to t\bar{t}t\bar{t}$
- Red region excluded by the $pp \to t\bar{t}t\bar{t}$ search of ATLAS

Summary

- In comparison to N2HDM-Z_2, our model is

  1. More predictive as it contains one less free parameter
  2. Built on local gauge symmetries and spontaneous symmetry breaking
  3. Large branching ratios for asymmetry decays $H \to Sh$ even in the limit of small mixing angles.
  4. No CP violation

- $Z - Z'$ mixing can naturally account for the higher than expected W mass, as suggested by CDF II
- Detailed phenomenological studies are left for future work