Possible New Higgs Bosons at ~ 400 GeV

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Abstract

Several searches for Beyond the Standard Model (BSM) Higgs bosons at the LHC show an excess at the level of $2 - 3\,\sigma$ at a mass scale of $m_\phi \sim 400$ GeV. ϕ can either be a CP-even Higgs boson, H, or a CP-odd Higgs boson, A. The respective search channels are $pp \to H/A \to t\bar{t}$, $pp \to H/A \to \tau^+\tau^-$ and $pp \to A \to Zh$, observed at CMS, ATLAS and ATLAS/CMS, respectively. We derive/obtain best-fit cross sections and uncertainties for these excesses. Within the Next-to-2 Higgs Doublet Model (N2HDM) and the Next-to Minimal Supersymmetric Standard Model (NMSSM) we analyze to what extent one, two or three of these excesses can be fit simultaneously in the two models. We find ...

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1 Introduction

- Higgs is a big success, fits in the SM, but also in BSM models.
- Possible BSM models: 2HDM, N2HDM, ..., MSSM, NMSSM, ...
- LHC searches for BSM Higgs bosons. Excesses in various channels at the $2-3\,\sigma$ level. List channels etc.
- Main idea of the paper: check whether the N2HDM and NMSSM can accomodate one, two or three of these excesses simultaneously.

2 The Excesses

More details on the excesses, best-fit cross sections and uncertainties, χ^2 function.

$$\chi^2_{400} := \dots \tag{1}$$

3 The models

We list the models and the codes that are used to evaluate them.
Maybe we can put some general considerations about which parameter spaces are preferred to accomodate the excesses.

3.1 The N2HDM

The simplest extension of the two Higgs doublet model (2HDM) that conserves CP is achieved by adding a real scalar singlet Higgs field which gives rise to the so-called N2HDM. The scalar potential when the scalar singlet is added can be written as [2, 3]

$$\begin{aligned} V = {} & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}] \\ & + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2, \end{aligned} \tag{2}$$

the two $SU(2)_L$ doublets are Φ_1 and Φ_2 while Φ_S the real scalar singlet. One of the most problematic point when dealing with two Higgs doublet models is the appearance of flavour changing neutral currents (FCNC) at tree level. In order to avoid such phenomenon a Z_2 symmetry is imposed on the scalar potential in such a way that the scalar fields transform as

$$\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2,\ \Phi_S \to \Phi_S. \tag{3}$$

However, we can see from Eq. (2) that this Z_2 symmetry is softly broken by the m_{12}^2 term. Despite this fact the extension of this symmetry to the Yukawa sector forbids strictly FCNSs at tree level. In the Yukawa sector there are four variants of the N2HDM that depends on the configuration of the fermions with respect to the Z_2 symmetry. These four types are listed in Tab. 1.

	u-type	d-type	leptons
type I	Φ_2	Φ_2	Φ_2
type II	Φ_2	Φ_1	Φ_1
type III (lepton specific)	Φ_2	Φ_2	Φ_1
type IV (flipped)	Φ_2	Φ_1	Φ_2

Table 1: Allowed fermion couplings in the four types of N2HDM.

After electroweak symmetry breaking (EWSB) takes place, the scalar fields can be parameterised as

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \ \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \ \Phi_S = v_S + \rho_S, \tag{4}$$

where v_1, v_2 and v_S are the real vacuum expectation values (vev) acquired by the fields Φ_1, Φ_2 and Φ_S respectively. We can define $\tan\beta = v_2/v1$ as it is usually done in the 2HDM. The configuration of the scalar fields after EWSB occurs, *i.e.* Eq. (4), makes the charged and CP-odd Higgs sector remain unaltered with respecto to the 2HDM counterpart. However, that is not the case in the CP-even scalar sector due to the mixing of the three fields, ρ_1, ρ_2 and ρ_S. Such mixing configures the physical eigenstates under a 3×3 orthogonal matrix, R, of the interaction basis,

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}. \tag{5}$$

The subindex i, where $i = 1, 2, 3$ respect the following order $m_{h_1} < m_{h_2} < m_{h_3}$ that we use in the rest of the paper. The form of the rotation matrix R can be written as

$$R = \begin{pmatrix} c_{\alpha_1}c_{\alpha_2} & s_{\alpha_1}c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1}s_{\alpha_2}s_{\alpha_3} + s_{\alpha_1}c_{\alpha_3}) & c_{\alpha_1}c_{\alpha_3} - s_{\alpha_1}s_{\alpha_2}s_{\alpha_3} & c_{\alpha_2}s_{\alpha_3} \\ -c_{\alpha_1}s_{\alpha_2}c_{\alpha_3} + s_{\alpha_1}s_{\alpha_3} & -(c_{\alpha_1}s_{\alpha_3} + s_{\alpha_1}s_{\alpha_2}c_{\alpha_3}) & c_{\alpha_2}c_{\alpha_3} \end{pmatrix}, \tag{6}$$

where $s_\alpha = \sin\alpha$, $c_\alpha = \cos\alpha$ and α_1, α_2,α_3 are the three mixing angles.

3.2 The NMSSM

3.3 Experimental constraints

- Theoretical constraints

- LHC rate measurements of h_{125}: `HiggsSignals`
- BSM Higgs searches: `HiggsBounds`
- Flavor constraints: `SuperIso`
  Do we really take this into account?
- Not taken into account: DM constraints. Explain why.

3.4 Prediction of χ^2_{400} in the N2HDM and NMSSM

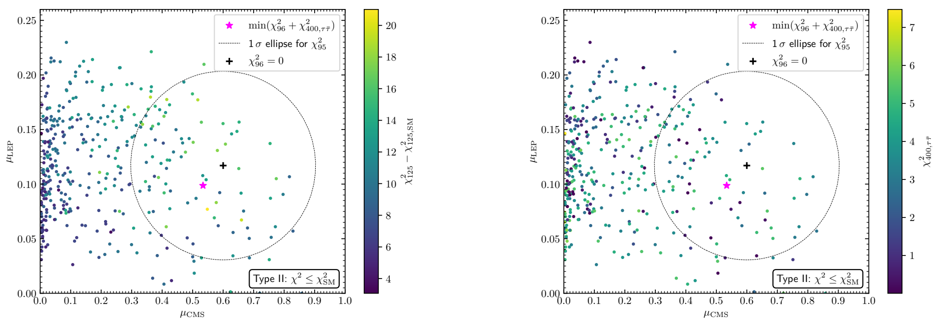

Figure 1: .

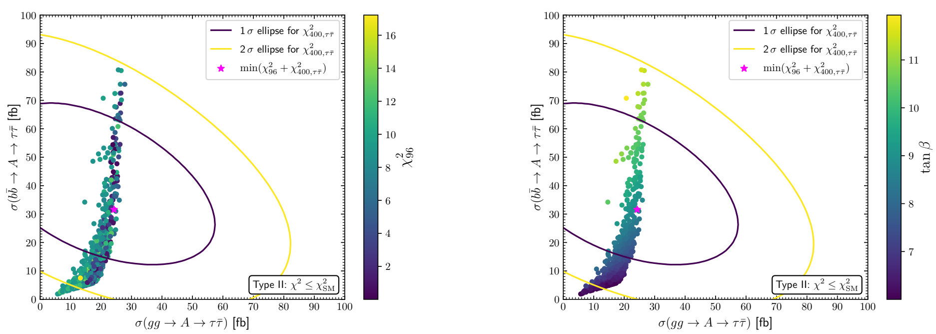

Figure 2: .

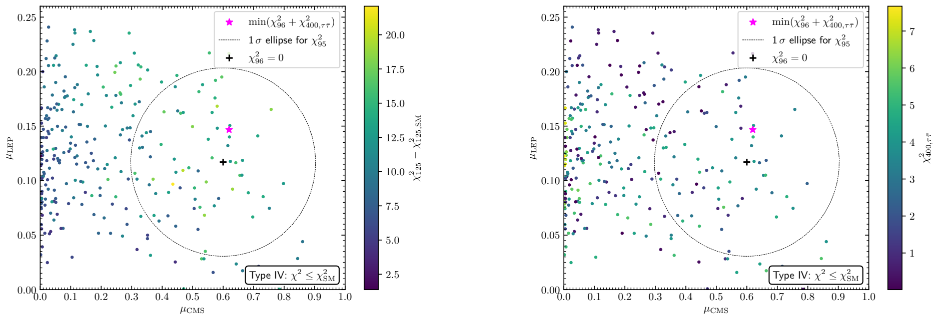

Figure 3: .

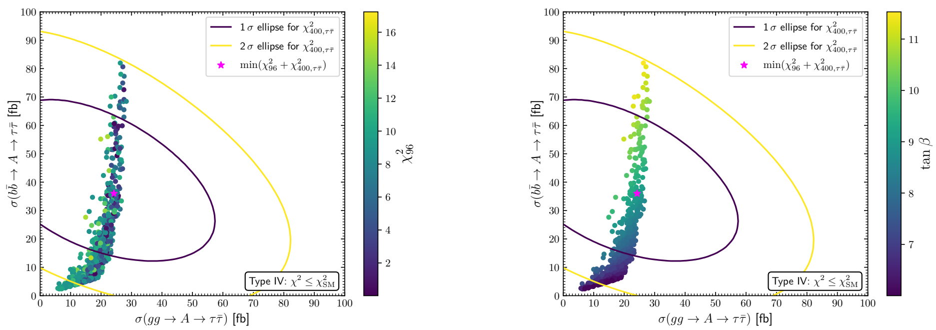

Figure 4: .

4 Results

5 Conclusions

Acknowledgments

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A Derivation of best-fit cross sections and uncertainties

A.1 The very simple recipe

Assuming a gaussian signal, one can extract the expected signal from the value of the 95% CL exclusion limit $L^{95}_{\rm exp}$ and the corresponding $1\,\sigma$ uncertainty $s^{95}_{\rm exp}$. The one-sided 95% CL for a normal distribution lies 1.64 standard deviations from the mean, so that the central value for the expected signal cross section $\sigma_{\rm exp}$ is given by

$$\sigma_{\rm exp} = L^{95}_{\rm exp} - 1.64 s^{95}_{\rm exp}\,. \tag{7}$$

The same is true for the central value of the observed signal cross section $\sigma_{\rm obs}$. Given the observed 95% CL exclusion limit $L^{95}_{\rm obs}$ together with the $1\,\sigma$ uncertainty $s^{95}_{\rm obs}$, and again assuming a gaussian signal shape, we can write down the relation

$$\sigma_{\rm obs} = L^{95}_{\rm obs} - 1.64 s^{95}_{\rm obs}\,. \tag{8}$$

Unfortunately, the uncertainty of the observed signal is not shown in the plots. However, under the conservative assumption that

$$s^{95}_{\rm obs} = s^{95}_{\rm exp}\,, \tag{9}$$

we can still derive a value for the signal cross section $\sigma_{\rm sig}$, i.e., the cross section from BSM physics that amounts for the excess between observed events and expected events based on the SM hypothesis. In our analysis, $\sigma_{\rm sig}$ is the cross section given by the NMSSM pseudoscalar and scalar resonances. Under the assumption that interference of NMSSM contributions and SM background is negligible, we know that

$$\sigma_{\rm obs} = \sigma_{\rm exp} + \sigma_{\rm sig}\,. \tag{10}$$

Thus, we find that $\sigma_{\rm obs}$ is simply given by the difference between the observed and expected exclusion limits,

$$\sigma_{\rm sig} = L^{95}_{\rm obs} - L^{95}_{\rm exp}\,. \tag{11}$$

Note that this definition has the intuitively desired properties. On the one hand it grows with the number of excess events, and on the other hand it is exactly zero in case the expected and the observed exclusion limits coincide, meaning that there is no excess to be explained by BSM physics.

For the uncertainty of the signal cross section $s_{\rm sig}$ we will assume that it is given by

$$s_{\rm sig} = \frac{s^{95}_{\rm exp}}{1.64}\,, \tag{12}$$

because [insert explanation here].

Based on this simple recipe, we find for the Zh excess the signal cross sections as shown in Tab. 2, given for the mass range in which the excess was observed.

m [GeV]	$\sigma^{gg}_{\rm sig}$ [fb]	$\sigma^{b\bar{b}}_{\rm sig}$ [fb]
400	89 ± 33	103 ± 37
420	118 ± 27	171 ± 27
440	114 ± 23	183 ± 27
460	50 ± 20	109 ± 21
480	11 ± 17	50 ± 19

Table 2: Signal cross sections for the Zh excess assuming gg production or $b\bar{b}$ production as derived following the very simple recipe.

A.2 Advanced approach and its connection to the simple ansatz

The observed 95% CL exclusion limit on a given cross section, $\sigma_{\rm obs,95}$, can be used to estimate its central value. Assuming that the signal uncertainty is dominated by statistical fluctuations, i.e. $\sqrt{N_{\rm evt}} = \sqrt{\alpha\ \sigma_{\rm obs,95}}$, the total uncertainty reads

$$\Delta_{\rm obs,95} = \sqrt{\alpha\ \sigma_{\rm obs,95} + \Delta^2_{\rm bkg}} \tag{13}$$

where $\Delta_{\rm bkg}$denotes the background uncertainty. As the one-sided 95% CL of a normal distribution lies 1.645 standard deviations from its mean the central value for the expected signal cross section $\sigma_{\rm obs}$and its uncertainty are given by

$$\begin{aligned} \sigma_{\rm obs} &= \sigma_{\rm obs,95} - 1.645\ \Delta_{\rm obs,95} && (14)\\ \Delta_{\rm obs} &= \sqrt{\alpha\ \sigma_{\rm obs} + \Delta^2_{\rm bkg}}\,. && (15) \end{aligned}$$

In order to estimate α and $\Delta_{\rm bkg}$, we can construct the following set of equations

$$\begin{aligned} \sigma_{95} &= 1.645\ \Delta_{95} && (16)\\ \Delta^2_{95} &= \alpha\ \sigma_{95} + \Delta^2_{\rm bkg} && (17)\\ \sigma_{95,+1} &= 1.645\ \Delta_{95,+1} + \Delta_{\rm bkg} && (18)\\ \Delta^2_{95,+1} &= \alpha\ \sigma_{95,+1} + \Delta^2_{\rm bkg} && (19)\\ \sigma_{95,+2} &= 1.645\ \Delta_{95,+2} + 2\ \Delta_{\rm bkg} && (20)\\ \Delta^2_{95,+2} &= \alpha\ \sigma_{95,+2} + \Delta^2_{\rm bkg}\,. && (21) \end{aligned}$$

Equations (14) and (15) obtain a very simple form if we are assuming that the signal uncertainty can be neglected compared to that of the background. In this case, σ_{95}= 1.645 $\Delta_{\rm bkg}$, and so

$$\begin{aligned} \sigma_{\rm obs} &= \sigma_{\rm obs,95} - \sigma_{95} && (22)\\ \Delta_{\rm obs} &= \Delta_{\rm bkg} = \sigma_{95}/1.645\,. && (23) \end{aligned}$$

References

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	$ggH\tau\tau$ (ATLAS)	$bbH\tau\tau$ (ATLAS)	$ggZH$ (ATLAS)	$bbZH$ (ATLAS)
σ_{95}[fb]	40.0	30.6	139	155
$\sigma_{95,+1}$[fb]	53.8	41.9	185	207
$\sigma_{95,+2}$[fb]	67.9	54.9	231	258
$\sigma_{\mathrm{obs},95}$[fb]	82.9	77.2	228	258
$\sigma_{\mathrm{obs}} \pm \Delta_{\mathrm{obs}}$(full) [fb]	27.0 ± 20.5	30.6 ± 18.6	53 ± 56	62 ± 64
$\sigma_{\mathrm{obs}} \pm \Delta_{\mathrm{obs}}$(1.645) [fb]	60.2 ± 24.3	58.6 ± 18.6	152 ± 85	173 ± 94
$\sigma_{\mathrm{obs}} \pm \Delta_{\mathrm{obs}}$(diff) [fb]	42.9 ± 13.8	46.6 ± 11.3	89 ± 64	103 ± 52
$\sigma_{\mathrm{obs}} \pm \Delta_{\mathrm{obs}}$(georg) [fb]	30.3 ± 22.2	34.3 ± 19.3	60.6 ± 65.6	70.6 ± 74.2

Table 3: Observed signal cross sections

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