Preparatory project: Supersymmetric Four Higgs Doublet Models

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INTRODUCTION: EXCESSES IN EXPERIMENTAL DATA [3]

excesses in experimental data at 400 GeV

- $A \to t\bar{t}$
  - CMS reported a local excess of 3.5σ (1st year Run 2)
  - no ATLAS data
- $\Phi \to \tau^+\tau^-$
  - ATLAS reported a local excess of 2.7σ (full Run 2)
  - no excess in CMS data (possibly due to lower sensitivity)
- $A \to ZH_{SM}$
  - ATLAS reported a local excess of 3.6σ (1st year Run 2)
  - at mass 440 GeV in b-quark associated production channel
  - updated ATLAS Run 2 in ggF channel in agreement with SM predictions

INTRODUCTION: EXCESSES IN EXPERIMENTAL DATA [3, 2]

excesses in experimental data at 95 GeV

- $pp \to \Phi \to \gamma\gamma$
  - CMS reported a local excess of about 3σ (1st year Run 2) with 2σ local in Run 1 data at comparable mass
  - compatible with ATLAS results
- $e^+e^- \to Z\Phi \to Zb\bar{b}$
  - LEP reported a local excess of about 2σ
- $\Phi \to \tau^+\tau^-$
  - CMS has observed an excess with a local significance of about 3σ
  - compatible with corresponding ATLAS limits

INTRODUCTION: 4HDM [3, 2]

- Idea: explain all the excesses at 95 GeV within one theoretical framework and ideally the ones at 400 GeV too
  - possible candidates: 2HDM type IV
  - type IV can describe the excesses in $\gamma\gamma$ ans $\tau^+\tau^-$ at 95 GeV
- Goal: find a supersymmetric description for the excesses
  - Problem: SUSY has Higgs sector with the same structure as 2HDM type II
  - find a supersymmetric model with Higgs sector equivalent to 2HDM type IV
- Model based on: M. A. Arroyo-Urena et al. A Private SUSY 4HDM with FCNC in the Up-sector. 2019.

$\rightarrow$ **supersymmetric four Higgs doublet model (SS4HDM)**

DERIVATION OF MASS MATRIX [1]

- 4 Higgs doublets with neutral and charged components

$$H_{u1} = \begin{pmatrix} H_{u1}^{+} \\ H_{u1}^{0} \end{pmatrix} \qquad H_{u2} = \begin{pmatrix} H_{u2}^{+} \\ H_{u2}^{0} \end{pmatrix} \qquad H_{d} = \begin{pmatrix} H_{d}^{0} \\ H_{d}^{-} \end{pmatrix} \qquad H_{l} = \begin{pmatrix} H_{l}^{0} \\ H_{l}^{-} \end{pmatrix} \tag{1}$$

- parametrization of neutral component $H_k^0 = \frac{1}{\sqrt{2}}(v_k + \eta_k + i\chi_k)$
- scalar potential for Higgs field

$$\begin{aligned} V = & \sum_{i=1}^{2} \Big[\big(|\mu_{i1}|^2 + |\mu_{i2}|^2 + \tilde{m_{ui}}^2\big)\big(|H_{ui}^0|^2 + |H_{ui}^+|^2\big) + \big(|\mu_{1i}|^2 + |\mu_{2i}|^2 + \tilde{m_{di}}^2\big)\big(|H_{di}^0|^2 + |H_{di}^-|^2\big)\Big] \\ & + \Big[\big(\mu_{11}^*\mu_{21} + \mu_{12}^*\mu_{22}\big)\big(H_{u1}^{0*}H_{u2}^0 + H_{u1}^{+*}H_{u2}^+\big) + \big(\mu_{11}^*\mu_{21} + \mu_{12}^*\mu_{22}\big)\big(H_{d1}^{0*}H_{d2}^0 + H_{d1}^{-*}H_{d2}^-\big) + \text{c.c.}\Big] \\ & + \Big[\sum_{i=1}^{2}\sum_{j=1}^{2} b_{ij}^2\big(H_{ui}^+H_{dj}^- - H_{ui}^0H_{di}^0\big) + \text{c.c.}\Big] + \frac{g^2 + g'^2}{8}\Big[\sum_{i=1}^{2}\big(|H_{ui}^0|^2 + |H_{ui}^+|^2 - |H_{di}^0|^2 + |H_{di}^-|^2\big)\Big]^2 \\ & + \frac{g^2}{2}\Big[\sum_{i=1}^{2}|H_{ui}^{+*}H_{ui}^0 + H_{di}^{0*}H_{di}^-|^2 - \sum_{i=1}^{2}\sum_{j=1}^{2}\big(|H_{ui}^0|^2 - |H_{di}^0|^2\big)\big(|H_{uj}^+|^2 - |H_{dj}^-|^2\big)\Big] \end{aligned} \tag{2}$$

DERIVATION OF MASS MATRIX [1]

- general form of the mass matrix $\mathcal{M}^2 = \begin{bmatrix} m^2_{u1,u1} & m^2_{u1,d1} & m^2_{u1,d2} & m^2_{u1,u2} \\ m^2_{d1,u1} & m^2_{d1,d1} & m^2_{d1,d2} & m^2_{d1,u2} \\ m^2_{d2,u1} & m^2_{d2,d1} & m^2_{d2,d2} & m^2_{d2,u2} \\ m^2_{u2,u1} & m^2_{u2,d1} & m^2_{u2,d2} & m^2_{u2,u2} \end{bmatrix}$
- vacuum expectation values

$$v_{u1} = \frac{2M_Z}{\sqrt{(g^2 + g'^2) \cdot (1 + \tan\omega^2)}} \cdot \cos\beta \tag{3}$$

$$v_{u2} = \frac{2M_Z}{\sqrt{(g^2 + g'^2) \cdot (1 + \tan\omega^2)}} \cdot \tan\omega \sin\alpha \tag{4}$$

$$v_{d} = \frac{2M_Z}{\sqrt{(g^2 + g'^2) \cdot (1 + \tan\omega^2)}} \cdot \sin\beta \tag{5}$$

$$v_{u2} = \frac{2M_Z}{\sqrt{(g^2 + g'^2) \cdot (1 + \tan\omega^2)}} \cdot \tan\omega \cos\alpha \tag{6}$$

- mass matrix elements $\mathcal{M}^2_{i,j} = \frac{1}{2} \frac{\partial^2 V}{\partial H_{\nu,i} \partial H_{\sigma,j}}$
- minimalization conditions $\frac{\partial V}{\partial H_{\nu i}} = 0$
- deviations from results in *A Private SUSY 4HDM with FCNC in the Up-sector*

PARAMETER DEPENDENCE OF MASS VALUES: ANGLES α, β, ω

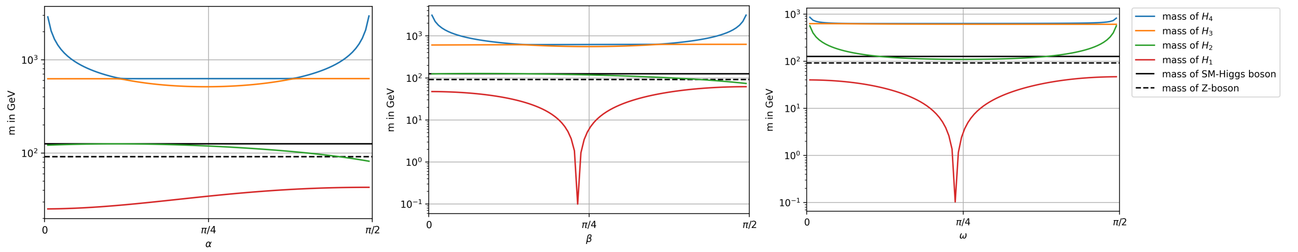


Figure. Dependence of the four mass eigenvalues of the CP even neutral Higgs on the angles α, β and ω for fixed values of $\mu_{11} = 200\,\text{GeV}$, $\mu_{12} = 0\,\text{GeV}$, $\mu_{21} = 0\,\text{GeV}$, $\mu_{22} = 200\,\text{GeV}$, $b_{11} = 550$, $b_{12} = 100\,\text{GeV}$, $b_{21} = 100\,\text{GeV}$, $b_{22} = 500\,\text{GeV}$, $\alpha = 0.38$, $\beta = 0.45$, $\omega = 0.37$.

PARAMETER DEPENDENCE OF MASS VALUES: BILINEAR TERMS b_{11}, b_{22}

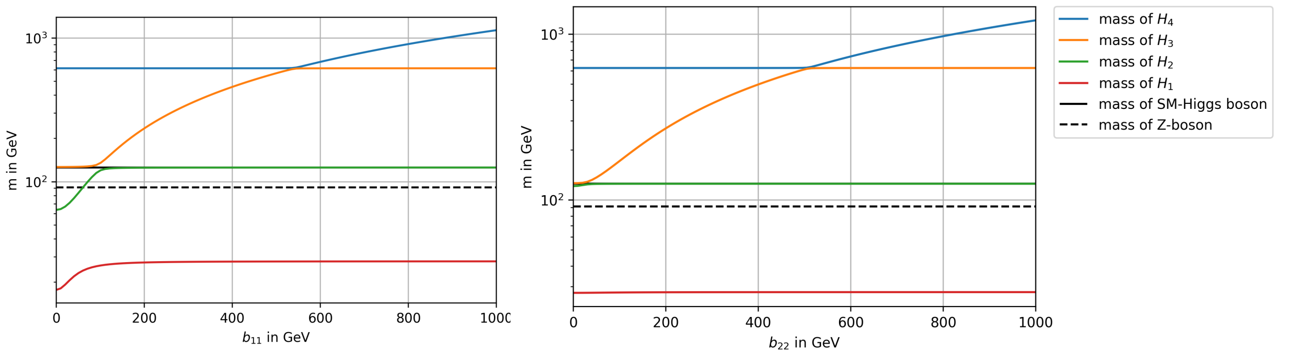


Figure. Dependence of the four mass eigenvalues of the CP even neutral Higgs on b_{11} and b_{22} for fixed values of $\mu_{11} = 200\,\text{GeV}$, $\mu_{12} = 0\,\text{GeV}$, $\mu_{21} = 0\,\text{GeV}$, $\mu_{22} = 200\,\text{GeV}$, $b_{11} = 550$, $b_{12} = 100\,\text{GeV}$, $b_{21} = 100\,\text{GeV}$, $b_{22} = 500\,\text{GeV}$, $\alpha = 0.38$, $\beta = 0.45$, $\omega = 0.37$.

PARAMETER DEPENDENCE OF MASS VALUES: BILINEAR TERMS b_{12}, b_{21}

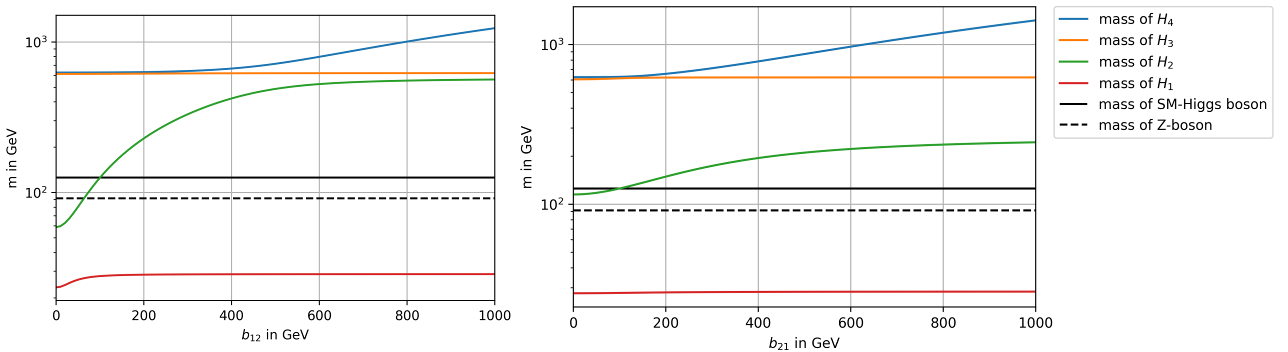


Figure. Dependence of the four mass eigenvalues of the CP even neutral Higgs on b_{12} and b_{21} for fixed values of $\mu_{11} = 200\,\text{GeV}$, $\mu_{12} = 0\,\text{GeV}$, $\mu_{21} = 0\,\text{GeV}$, $\mu_{22} = 200\,\text{GeV}$, $b_{11} = 550$, $b_{12} = 100\,\text{GeV}$, $b_{21} = 100\,\text{GeV}$, $b_{22} = 500\,\text{GeV}$, $\alpha = 0.38$, $\beta = 0.45$, $\omega = 0.37$.

PARAMETER DEPENDENCE OF MASS VALUES: μ_{11}, μ_{22}

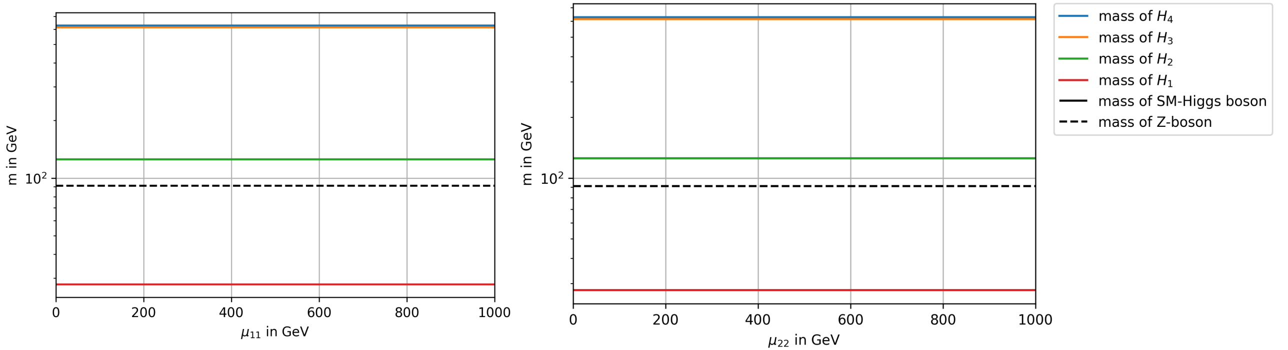


Figure. Dependence of the four mass eigenvalues of the CP even neutral Higgs on μ_{11} and μ_{22} for fixed values of $\mu_{11} = 200\,\text{GeV}$, $\mu_{12} = 0\,\text{GeV}$, $\mu_{21} = 0\,\text{GeV}$, $\mu_{22} = 200\,\text{GeV}$, $b_{11} = 550$, $b_{12} = 100\,\text{GeV}$, $b_{21} = 100\,\text{GeV}$, $b_{22} = 500\,\text{GeV}$, $\alpha = 0.38$, $\beta = 0.45$, $\omega = 0.37$.

PARAMETER DEPENDENCE OF MASS VALUES: μ_{12}, μ_{21}

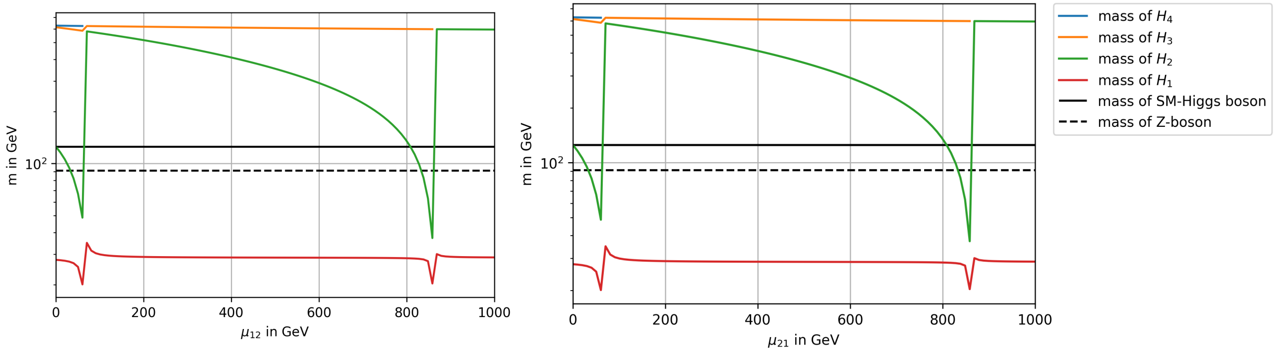


Figure. Dependence of the four mass eigenvalues of the CP even neutral Higgs on μ_{12} and μ_{21} for fixed values of $\mu_{11} = 200\,\text{GeV}$, $\mu_{12} = 0\,\text{GeV}$, $\mu_{21} = 0\,\text{GeV}$, $\mu_{22} = 200\,\text{GeV}$, $b_{11} = 550$, $b_{12} = 100\,\text{GeV}$, $b_{21} = 100\,\text{GeV}$, $b_{22} = 500\,\text{GeV}$, $\alpha = 0.38$, $\beta = 0.45$, $\omega = 0.37$.

Remarks: mass values

- lightest Higgs needs to be restricted $\rightarrow$ Higgs boson with mass $m < m_{SM}$ would have been detected at LEP
  - must have reduced coupling to gauge bosons
- in this model: lightest Higgs has mass $m_{H1} < m_Z$
  - same as in MSSM (at tree-level)
- investigate: H_2 or H_3 SM-like Higgs

DERIVATION OF COUPLING

- derivation of couplings from Lagrangian

$$\mathcal{L}_{\text{kin}} = \sum_i (\mathcal{D}_\mu H_i)^\dagger (\mathcal{D}^\mu H_i) \tag{7}$$

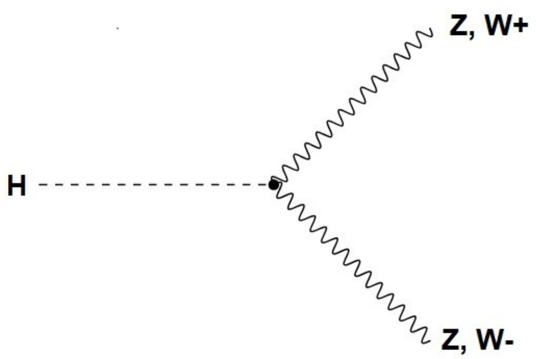
- covariant derivative

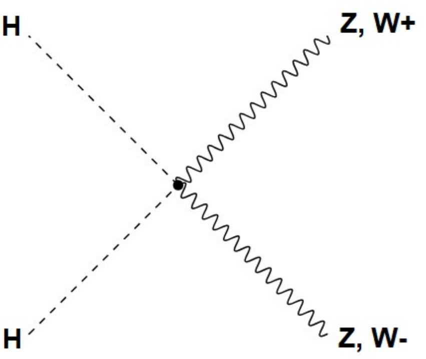
$$i\mathcal{D}_\mu = i\partial_\mu - \frac{g}{2}(\tau_+ W_\mu^+ + \tau_- W_\mu^-) - eQA_\mu - \frac{g}{\cos\Theta_W}\left(\frac{\tau_3}{2} - Q\sin^2\Theta_W\right)Z_\mu \tag{8}$$

with

$$\tau_+ = \begin{pmatrix} 0 & \sqrt{2} \\ 0 & 0 \end{pmatrix} \qquad \tau_- = \begin{pmatrix} 0 & 0 \\ \sqrt{2} & 0 \end{pmatrix} \qquad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{9}$$

COUPLING OF CP-EVEN NEUTRAL HIGGS TO GAUGE BOSONS: RESULTS





- still a problem with the lightest Higgs, because the calculated coupling is too big $\rightarrow$ requires further investigation
- coupling of two different Higgs to gauge boson(s) vanishes

SUM RULE FOR *HWW*- AND *HZZ*-COUPLING

- Sum Rule

$$\sum_{i=1}^{4}\left(\frac{g_i}{g}\right)^2 = 1 \tag{10}$$

- for HWW-processes $\mathcal{L} \supset \frac{g^2}{2}\sum_{i=1}^{4}\sum_{j=1}^{4}\xi_{ij}v_j H_i W^+ W^-$
- to prove sum rule, show that

$$\sum_{i=1}^{4}\left(\sum_{j=1}^{4}\xi_{ij}v_j\right)^2 = v^2 \tag{11}$$

- take the square and use the unitarity of the rotation matrix with entries ξ_{ij}
- result:

$$\sum_{i=1}^{4}\left(\sum_{j=1}^{4}\xi_{ij}v_j\right)^2 = \sum_{j=1}^{4}v_j^2 = v^2\Box \tag{12}$$

- proof analogous for $HZZ-$coupling

SUMMARY AND OUTLOOK

Summary

- mass spectrum for CP even neutral Higgs bososns
- Coupling of CP even neutral Higgs to gauge bosons
- sum rule is fulfilled due to the unitarity of eigenvector-matrix
- lightest Higgs boson H_1 has mass $m_{H1} < m_Z$

Outlook

- mass spectrum and coupling of CP-odd and charged Higgs sector
- restrictions on the lightest Higgs
- study SUSY particle sector
- Yukawa sector $\rightarrow$ hopefully: explanation of excess at 95 GeV (and 400 GeV)

References I

[1] M. A. Arroyo-Urena et al. *A Private SUSY 4HDM with FCNC in the Up-sector*. 2019. DOI: 10.48550/ARXIV.1901.01304.

[2] T. Biekötter, S. Heinemeyer, and G. Weiglein. "Excesses in the low-mass Higgs-boson search and the \varvec{W}-boson mass measurement". In: *The European Physical Journal C* 83.5 (May 2023). DOI: 10.1140/epjc/s10052-023-11635-3.

[3] T. Biekötter et al. "Possible indications for new Higgs bosons in the reach of the LHC: N2HDM and NMSSM interpretations". In: *The European Physical Journal C* 82.2 (Feb. 2022). DOI: 10.1140/epjc/s10052-022-10099-1.