Workshop on Multi-Higgs Models

Footprints of a vectophobic 2HDM at the LHC?

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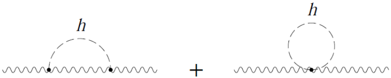
The Custodial Symmetry in the SM

- Accidental symmetry of the scalar potential

$$SU(2)_L \times SU(2)_R \xrightarrow{SSB} SU(2)_V$$

- Protects the tree-level mass relation $\rho = \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$
- Broken by $g' \neq 0 \Rightarrow g'^2$ corrections

$$\rho = 1 - F(g') \log \frac{m_h^2}{M_Z^2} \xrightarrow[g' \to 0]{\text{Custodial limit}} 1$$

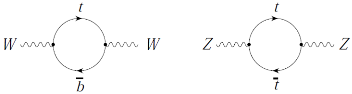


- Broken by Yukawa Lagrangian terms:

$$\mathcal{L}_{Yukawa} = -\bar{Q}_L^i Y_d^{ij} H d_R^j - \bar{Q}_L^i Y_u^{ij} \tilde{H} u_R^j \xrightarrow[Y_u = Y_d]{\text{Custodial Limit}} -\bar{Q}_L^i Y^{ij} \Phi Q_R^j$$

$\Rightarrow Y_u \neq Y_d$ corrections:

$$\rho = 1 + F(m_b^2, m_t^2) \xrightarrow[m_b^2 = m_t^2]{\text{Custodial Limit}} 1$$



The Custodial Symmetry in the 2HDM

SM

Accidental symmetry of the scalar potential

$$SU(2)_L \times SU(2)_R \xrightarrow{SSB} SU(2)_V$$

Protects the tree-level mass relation

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

Broken by $g' \neq 0$ and $m_b \ll m_t$

Custodial 2HDM

Needs to be imposed $\Rightarrow$ constrains new parameters

(CP invariant)

$$\Phi_1 \ni \left\{ \begin{array}{c} G^+ \\ G^0 \\ G^- \end{array} \right\} \oplus \{h^0 + \frac{v}{\sqrt{2}}\};$$

$$\Phi_2 \ni \left\{ \begin{array}{c} H^+ \\ A^0 \\ H^- \end{array} \right\} \oplus \{H^0\} \text{ or } \left\{ \begin{array}{c} H^+ \\ H^0 \\ H^- \end{array} \right\} \oplus \{A^0\}$$

$$\alpha = \beta - \frac{\pi}{2} \text{ and } \left\{ \begin{array}{l} m_{H^0} < m_{A^0} \approx m_{H^\pm} \\ m_{A^0} < m_{H^0} \approx m_{H^\pm} \end{array} \right.$$

Custodial symmetry violated in a "minimal" way as in the SM

The flavour symmetry

SM

Accidental Symmetry of the matter lagrangian

$$\mathcal{L}_{Matter} = \sum_{k,i} \bar{\Psi}_k^i (i \not{D}_k) \Psi_k^i \quad \begin{cases} k = Q, u, d \\ i = 1, \ldots, n \end{cases}$$

$$U(n)^3 = U(n)_Q \times U(n)_u \times U(n)_d$$

Yukawa couplings mass hierarchy breaks the Flavour Symmetry

After SSB, misalignment $\begin{cases} \text{ew eigenstates} \\ \text{mass eigenstates} \end{cases}$

Flavour Mixing in CC : $\bar{u}'_L \gamma_\mu d'_L = \bar{u}_L \gamma_\mu V_{CKM} d_L$,

Flavour Conservation in NC : $\bar{q}'_L \gamma^\mu q'_L = \bar{q}_L \gamma^\mu q_L$.

2HDM with MFV

Introduces new sources of flavour Violation in NC

$$\mathcal{L}_{Yukawa} = -\bar{Q}_L (Y_d \Phi_1 + Z_d \Phi_2) d_R - \bar{Q}_L (Y_u \tilde{\Phi}_1 + Z_u \tilde{\Phi}_2) u_R$$

$Y_{u,d}$ = SM-like Yukawas (generate masses),

$Z_{u,d}$ generate A^0 and H^0 mediated FCNC.

MFV $\Rightarrow$ Sources of Flavour Violation = SM ones

Impose transformation laws under $G_F = SU(3)_Q \times SU(3)_u \times SU(3)_d$ to

$$Y_u \sim (3, \bar{3}, 1) \qquad Y_d \sim (3, 1, \bar{3})$$

New flavour structures in terms of the Yukawas in a G_f invariant way

$$\begin{aligned} Z_d &= \{\delta_0 + \delta_1 Y_u Y_u^\dagger + \ldots\} Y_d \\ Z_u &= \{\upsilon_0 + \upsilon_1 Y_u Y_u^\dagger + \ldots\} Y_u \end{aligned}$$

Suppressed FCNCs

$\Delta F = 2$ mixings

Tree-level A^0 and H^0 mediated FCNC $\Rightarrow (Z_d)_{ij} = 4 G_F \delta_1 (V^*_{ti} V_{tj}) m_t^2 \frac{m_{d_j}}{v}$

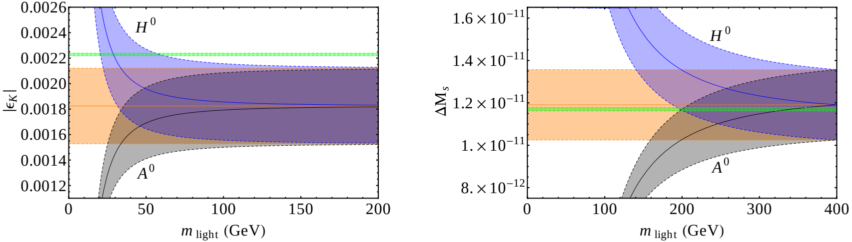


Figure: ϵ_K and ΔM_s as a function of the H^0 and A^0 masses

$$\langle \bar{M}^0 | \mathcal{H}_{eff}^{\Delta F=2} | M^0 \rangle \simeq \langle \bar{M}^0 | \mathcal{H}_{eff}^{\Delta F=2} | M^0 \rangle^{SM} \left[1 + 16\pi^2 x \delta_1^2 m_M^2 \left(\frac{1}{m_{H^0}^2} - \frac{1}{m_{A^0}^2} \right) \right]$$

$B_s \to \mu^+\mu^-$ decay

SM operator $Q_A = (\bar{b}_L \gamma^\mu s_L)(\bar{\mu}\gamma_\mu\gamma_5\mu)$; new operators $\begin{cases} H^0 \to Q_S = m_b(\bar{b}_R s_L)(\bar{\mu}\mu) \\ A^0 \to Q_P = m_b(\bar{b}_R s_L)(\bar{\mu}\gamma_5\mu) \end{cases}$

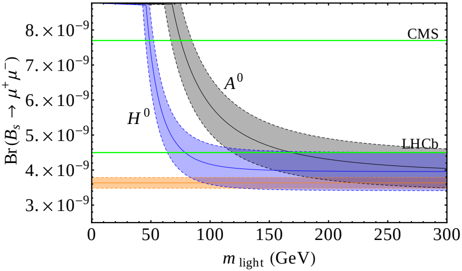


Figure: The $B_s \to \mu^+\mu^-$ branching ratio as a function of the H^0 and A^0 masses

$$\mathcal{B}(B_s \to \mu^+\mu^-) = \mathcal{B}(B_s \to \mu^+\mu^-)^{SM} \left[\left(1 + m_{B_s}^2 \frac{C_P}{C_A}\right)^2 + \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) m_{B_s}^4 \frac{C_S^2}{C_A^2} \right]$$

$$C_{S(P)} = \frac{\Delta}{m^2_{H^0(A^0)}}; \qquad \Delta = \frac{4\pi^2 \delta_1 \lambda_0 m_t^2}{M_W^2}.$$

Diphoton signal at the LHC

H^0 and A^0 are vectophobic $g_{HVV} = g_{AVV} = 0$ with $V = W^{\pm}, Z^0$

$$R = \frac{\sigma \times \mathcal{B}(H^0, A^0 \to \gamma\gamma)}{\sigma \times \mathcal{B}(h^0 \to \gamma\gamma)^{SM}}$$

$$R_{H^0/h^0}(m_{H^0} = 0 \to 125 \text{ GeV}) = (0.12 \to 0.08)\frac{(\upsilon_0 + \upsilon_1 y_t^2)^4}{(\delta_0 + \delta_1 y_t^2)^2}$$

$$R_{A^0/h^0}(m_{A^0} = 0 \to 125 \text{ GeV}) = (0.59 \to 0.44)\frac{(\upsilon_0 + \upsilon_1 y_t^2)^4}{(\delta_0 + \delta_1 y_t^2)^2}$$

Two possible hierarchies with light (pseudo)scalar

1. $m_{A^0(H^0)} < m_{H^0(A^0)} \approx m_{H^\pm} < m_{h^0}$

   with $m_{h^0} > 2m_{H^0(A^0)}$

2. $m_{h^0}, m_{A^0(H^0)} < m_{H^0(A^0)} = m_{H^\pm}$

Role of Higgs W^+W^- and Z^0Z^0 production and decay observations

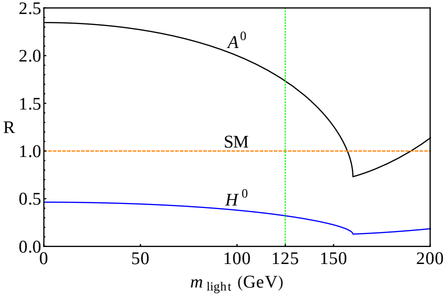


Figure: The ratio R as a function of the H^0 and A^0 masses

Conclusions

- 2HDM with minimally broken custodial and flavour symmetries can show unexpected phenomenology.
- Flavour observables are able to disentangle A^0-induced FCNC from H^0. They impose big constraints on light (pseudo)scalars, but show that FCNC are efficiently suppressed for scalar masses well below the TeV scale.
- The diphoton signal at the LHC at 125 GeV can be enhanced with respect to the SM in the case of a pseudosclarar.
- However LHC data on ZZ decays seem incompatible with a vectophobic model with light (pseudo)scalar.
- In that case the usual decoupling limit can still be applied to this model

$$m_{h^0} \ll m_{H^0,A^0,H^\pm}$$

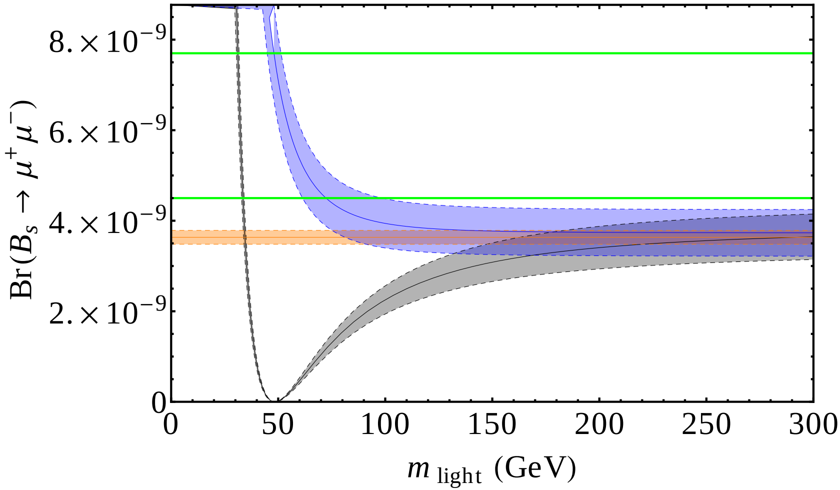


Figure: The $B_s \to \mu^+\mu^-$ branching ratio as a function of the H^0 and A^0 masses with negative values of the MFV coefficients