Extension of Standard Model to Two Higgs Doublets Model plus a Singlet Scalar Field

Under Direction Of:

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Motivation

- The Higgs mass m_h is around $125.09 \pm 0.24(\pm 0.24 \pm 0.21 \pm 0.11)$ GeV.
- Many models could explain the LHC results (2HDM, Susy, Inert Higgs, composite Higgs).
- Several theoretical issues still unexplained (δ_ρ, S, T, B-physics).
- From LHC data, there are deviations of reduced coupling κ_V and κ_F.
- Excess at 750 GeV ? ? ? Hard to explain within in MSSM or even in 2HDM.

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Motivation

What is the nature of the Higgs ? Is it a doublet ? Or a mixing between a doublet and singlet ?

Our motivation is to study the 2HDMS in the light of LHC results

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In order to study the new physics effects on the LHC measurements for some specific Higgs decay modes, we define the signal strength as the ratio of Higgs signal to the SM prediction as :

$$\mu_i^f = \frac{\sigma_i(h) \cdot Br(h \to f)}{\sigma_i^{SM}(h) \cdot Br^{SM}(h \to f)} \equiv \bar{\sigma}_i \cdot \mu_f \, , \tag{1}$$

where $\sigma_i(h)$ denotes the Higgs production cross section by channel i and $Br(h \to f)$ is the BR for the Higgs decay $h \to f$.

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Production	Loops	Interference	Expression in terms of fundamental coupling strengths
$\sigma(\mathrm{ggF})$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	-	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	-	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	$W-t$	$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width			
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

FIGURE 1 : Overview of Higgs boson production cross sections σ_i and Higgs boson partial decay widths Γ_f. For each production or decay mode the scaling of the corresponding rate in terms of Higgs boson coupling strength scale factors.

In order to study the influence of new free parameters and to understand their correlations, we perform the χ-square fitting by using the LHC data for Higgs searches.

For a given channel $f = \gamma\gamma, WW^*, ZZ^*, \tau\tau$, we define the χ_f^2 as :

$$\chi_f^2 = \frac{1}{\hat{\sigma}_1^2(1-\rho^2)}(\mu_1^f - \hat{\mu}_1^f)^2 + \frac{1}{\hat{\sigma}_1^2(1-\rho^2)}(\mu_2^f - \hat{\mu}_2^f)^2 - \frac{2\rho}{\hat{\sigma}_1\hat{\sigma}_2(1-\rho^2)}(\mu_1^f - \hat{\mu}_1^f)(\mu_2^f - \hat{\mu}_2^f)\,, \quad (2)$$

where $\hat{\mu}_{1,2}^f$, $\hat{\sigma}_{1,2}$ and ρ are the measured Higgs signal strengths, their one-sigma errors, and their correlation.

the indices 1 and 2 in turn stand for $\mathrm{ggF} + \mathrm{tth}$ and $\mathrm{VBF} + \mathrm{Vh}$, and $\mu_{1,2}^f$ are the results in the 2HDMS.

The global χ-square is defined by :

$$\chi^2 = \sum_f \chi_f^2 + \chi_{ST}^2\,, \quad (3)$$

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the Higgs potential

The most general 2HDMS scalar potential is [Chien-yi chen,Michael freic and Marc sher arXiv :[1312.3949v1]] :

$$
\begin{aligned}
V(H_1, H_2, S) &= m_{11}^2\, H_1^\dagger H_1 + m_{22}^2\, H_2^\dagger H_2 - \mu^2 \left(H_1^\dagger H_2 + H_2^\dagger H_1\right) \\
&+ \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3\, H_1^\dagger H_1\, H_2^\dagger H_2 \\
&+ \lambda_4\, H_1^\dagger H_2\, H_2^\dagger H_1 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \left(H_2^\dagger H_1\right)^2\right] \\
&+ \frac{1}{2} m_S^2 (S^\dagger S) + \frac{1}{8}\lambda_6 (S^\dagger S)^2 + \frac{1}{2}\lambda_7 \left(H_1^\dagger H_1\right)(S^\dagger S) \\
&+ \frac{1}{2}\lambda_8 \left(H_2^\dagger H_2\right)(S^\dagger S)
\end{aligned} \tag{4}
$$

avec :

m_{11}^2 , m_{22}^2 et m_S^2 : mass parameters.
$\lambda_{i=1,4}$: real parameters.
λ_5, μ^2 : complex parameters.

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The allowed regions in the (λ_7, λ_8) parameter space after sequentially imposing the various theoretical constraints (Unitarity, BFB and EW) .

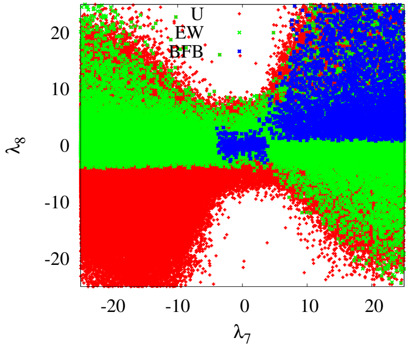

FIGURE 2 : The impact of Unitarity(U), electroweak symmetry breaking (EW) and Vaccum stability (BFB) on the (λ_7, λ_8) plane

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2HDMS-Oblic Parameters

The oblique parameters are a useful way to parametrize the effects of new physics (NP) on electroweak observables. the NP effects may be parametrized by thoses quantities [M.E. Peskin and T. Takeuchi, [A new constraint on a strongly interacting Higgs sector]] :

$$\frac{\alpha}{4s_W^2c_W^2}S = \frac{A_{ZZ}\left(m_Z^2\right)-A_{ZZ}(0)}{m_Z^2} - \left.\frac{\partial A_{\gamma\gamma}\left(q^2\right)}{\partial q^2}\right|_{q^2=0} + \frac{c_W^2-s_W^2}{c_Ws_W}\left.\frac{\partial A_{\gamma Z}\left(q^2\right)}{\partial q^2}\right|_{q^2=0}, \quad (5)$$

$$\alpha T = \frac{A_{WW}(0)}{m_W^2} - \frac{A_{ZZ}(0)}{m_Z^2}, \quad (6)$$

$$\frac{\alpha}{4s_W^2}U = \frac{A_{WW}\left(m_W^2\right)-A_{WW}(0)}{m_W^2} - c_W^2\frac{A_{ZZ}\left(m_Z^2\right)-A_{ZZ}(0)}{m_Z^2} - s_W^2\left.\frac{\partial A_{\gamma\gamma}\left(q^2\right)}{\partial q^2}\right|_{q^2=0} + 2c_Ws_W\left.\frac{\partial A_{\gamma Z}\left(q^2\right)}{\partial q^2}\right|_{q^2=0}, \quad (7)$$

(8)

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Experimental Constraints

We have introduced the oblique parameters S, T and U [W.Grimus, L.Lavoura et al [arXiv :0802.4353v1]] :

$$
\begin{aligned}
S^{2HDMS} = & \frac{1}{24\pi}[(2s_w^2-1)^2 G(m_{H^+}^2, m_{H^+}^2, m_z^2) + R_{21}^2 G(m_{h_1}^2, m_A^2, m_z^2) \\
& + R_{22}^2 G(m_{h_2}^2, m_A^2, m_z^2) + R_{23}^2 G(m_{h_3}^2, m_A^2, m_z^2) + (R_{11}^2 + R_{21}^2)\ln(m_{h_1}^2) \\
& + (R_{12}^2 + R_{22}^2)\ln(m_{h_2}^2) + (R_{13}^2 + R_{23}^2)\ln(m_{h_3}^3) + \ln(m_A^2) - 2\ln(m_{H^+}^2) - \ln(m_{h_{ref}}^2) \\
& + R_{11}^2 \hat{G}(m_{h_1^2}, m_z^2) + R_{12}^2 \hat{G}(m_{h_2}^2, m_z^2) + R_{13}^2 \hat{G}(m_{h_3}^2, m_z^2) - \hat{G}(m_{h_{ref}}^2, m_z^2)]
\end{aligned}
$$

$$
\begin{aligned}
T^{2HDMS} = & \frac{1}{16\pi m_w^2 s_w^2}(R_{21}^2 F(m_{H^+}^2, m_{h_1}^2) + R_{22}^2 F(m_{H^+}^2, m_{h_2}^2) + R_{23}^2 F(m_{H^+}^2, m_{h_3}^2) \\
& + F(m_{H^+}^2, m_A^2) - R_{21}^2 F(m_{h_1}^2, m_A^2) - R_{22}^2 F(m_{h_2}^2, m_A^2) - R_{23}^2 F(m_{h_3}^2, m_A^2) \\
& + 3(R_{11}^2(F(m_z^2, m_{h_1}^2) - F(m_w^2, m_{h_1}^2)) + R_{12}^2(F(m_z^2, m_{h_2}^2) - F(m_w^2, m_{h_2}^2)) \\
& + R_{13}^2(F(m_z^2, m_{h_3}^2) - F(m_w^2, m_{h_3}^2))) - 3(F(m_z^2, m_{h_{ref}}^2) - F(m_w^2, m_{h_{ref}}^2)))
\end{aligned}
$$

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$$
\begin{aligned}
U^{2HDMS} = & \frac{1}{24\pi}[R_{21}^2 G(m_{H^+}^2, m_{h_1}^2, m_w^2) + R_{22}^2 G(m_{H^+}^2, m_{h_2}^2, m_w^2) \\
& + R_{23}^2 G(m_{H^+}^2, m_{h_3}^2, m_w^2) + G(m_{H^+}^2, m_A^2, m_w^2) - (2s_w^2 - 1)^2 G(m_{H^+}^2, m_{H^+}^2, m_z^2) \\
& - (R_{21}^2 G(m_{h_1}^2, m_A^2, m_z^2) - R_{22}^2 G(m_{h_2}^2, m_A^2, m_z^2) - R_{23}^2 G(m_{h_3}^2, m_A^2, m_z^2) \\
& + R_{11}^2(\hat{G}(m_{h_1}^2, m_w^2) - \hat{G}(m_{h_1}^2, m_z^2)) + R_{12}^2(\hat{G}(m_{h_2}^2, m_w^2) \\
& - \hat{G}(m_{h_2}^2, m_z^2)) + R_{13}^2(\hat{G}(m_{h_3}^2, m_w^2) - \hat{G}(m_{h_3}^2, m_z^2)) \\
& - G(m_{h_{ref}}^2, m_w^2) + G(m_{h_{ref}}^2, m_z^2)]
\end{aligned}
$$

with :

$$
\begin{aligned}
R_{11} &= S_{11}c_\beta + s_\beta S_{12}\ , \ R_{21} = S_{12}c_\beta - s_\beta S_{11}, R_{13} = S_{13} \\
R_{12} &= S_{21}c_\beta + S_{22}s_\beta\ , \ R_{22} = S_{22}c_\beta - s_\beta S_{21}, R_{32} = S_{23} \\
R_{13} &= c_\beta S_{31} + s_\beta S_{32}\ , \ R_{23} = S_{32}c_\beta - s_\beta S_{31}, R_{33} = S_{33}
\end{aligned}
$$

β is defined trough the ratio of the vev's of the two doublets.

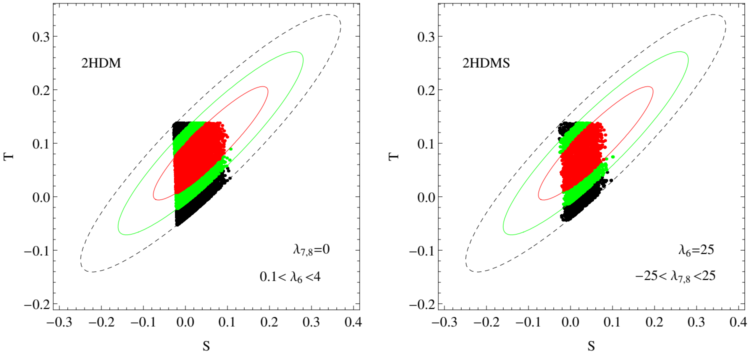

FIGURE 3 : Correlation between S and T after imposing theoretical and experimental constraintes,the left and right panels stand for the case where 2HDMS goes to 2HDM for $\lambda_7 = \lambda_8 = 0$ and $v_s = 10^7$ and 2HDMS respectively. The errors for χ-square fit are 99.7% CL (black), 95.5% CL (green) and 68% CL (red).

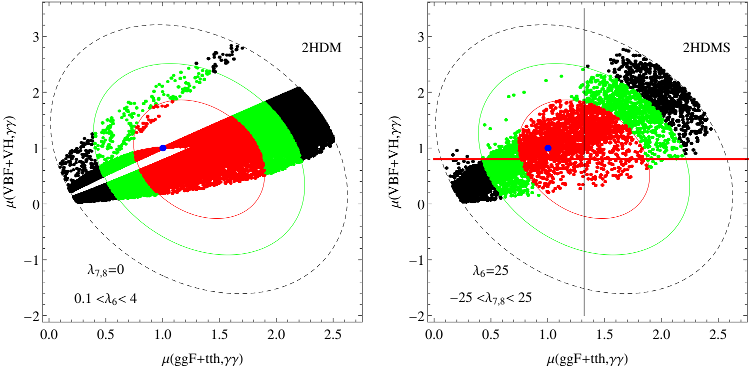

FIGURE 4 : Combined signal strength ellipses for $\gamma\gamma$, the left and right panels stand for the case where 2HDMS goes to 2HDM for $\lambda_7 = \lambda_8 = 0$ and $v_s = 10^7$ and 2HDMS respectively. The errors for χ-square fit are 99.7% CL (black), 95.5% CL (green) and 68% CL (red).

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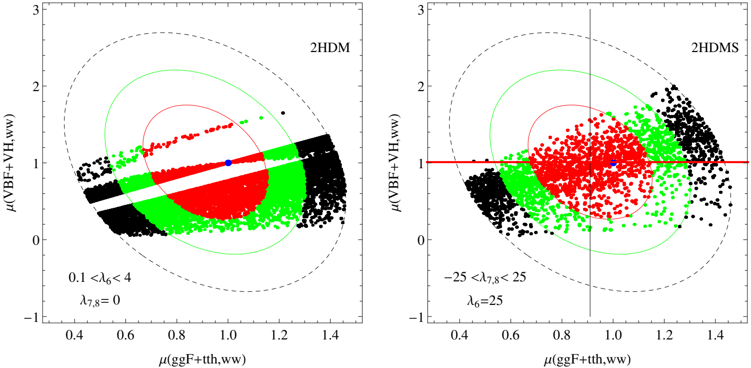

FIGURE 5 : Combined signal strength ellipses for w^+w^-, the left and right panels stand for the case where 2HDMS goes to 2HDM for $\lambda_7 = \lambda_8 = 0$ and $v_s = 10^7$ and 2HDMS respectively. The errors for χ-square fit are 99.7% CL (black), 95.5%CL (green) and 68%CL (red).

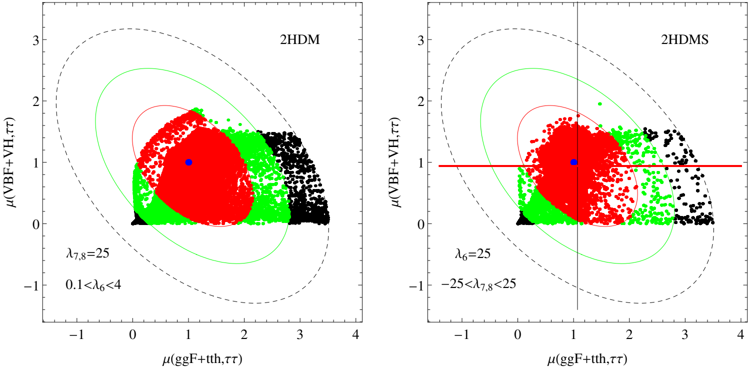

FIGURE 6 : Combined signal strength ellipses for $\tau^+\tau^-$, the left and right panels stand for the case where 2HDMS goes to 2HDM for $\lambda_7 = \lambda_8 = 0$ and $v_s = 10^7$ and 2HDMS respectively. The errors for χ-square fit are 99.7% CL (black), 95.5%CL (green) and 68%CL (red).

Conclusion

The mixing between the singlet and the two doublets has changed the gauge and Yukawa couplings of our model.
As a result, the model predicts a significant enhancement of the $\gamma\gamma$ rate compatible with the signal strengths observed by ATLAS and CMS due to the presence of a singlet scalar.

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Thanks for your attention

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