1st Mediterranean Conference on Higgs Physics

Extended Higgs sector of 2HDM with real singlet facing LHC data

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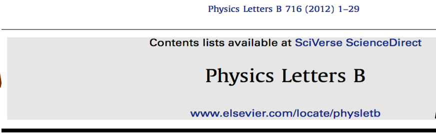
OUTLINE

Parametrization of N2HDM

Numerical results

CONCLUSION



Physics Letters B 716 (2012) 1–29

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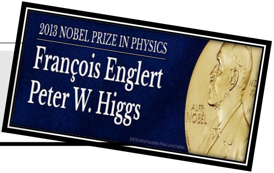
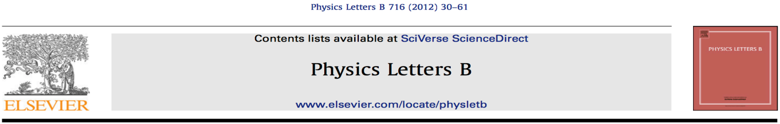


Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.



Physics Letters B 716 (2012) 30–61

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Physics Letters B

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Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

MOTIVATIONS :

- Dark matter :
  Drozd, Grzadkowski, Gunion, Yun Jiang ; JHEP'2014 ;
  L. Wang, R. Shi and X. F. Han, PRD'2017
- Dark matter and CP violation :
  D. Azeved, P.M Ferreira, M. Muhlleitner, J. Wittbrodtl arXiv :1807.10322
- Special case of the Next-to-MSSM :
  M. Muhlleitner, M. O. P. Sampaio, R. Santos JHEP03(2017)094
  M. Muhlleitner, M. O. P. Sampaio, R. Santos JHEP08(2017)132
- $h_i \to h_j h_j$, $h_i \to h_j h_k$, $h_i \to AZ$, $h_i \to W^{\pm}H^{\mp}$,
  A. Arhrib, R. Benbrik, M. El Kacimi, L. Rahili and S. Semlali, **arXiv : 1811.12431**

PARAMETRIZATION OF N2HDM

The scalar sector of N2HDM consists of two doublets, $H_i \;\; (i = 1,\ 2)$ with weak hyperchage $Y = 1$, and a real singlet scalar with $Y = 0$:

$$H_i \quad = \begin{pmatrix} \phi_i^{\pm} \\ \frac{1}{\sqrt{2}}(v_i + \phi_i + i\chi_i) \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}(v_s + \phi_s) \qquad (1)$$

2HDM Contribution

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

Singlet Contribution

PARAMETRIZATION OF N2HDM

The scalar sector of N2HDM consists of two doublets, $H_i \;\; (i = 1,\, 2)$ with weak hyperchage $Y = 1$, and a real singlet scalar with $Y = 0$:

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2HDM Contribution

$$V(H_1, H_2, S) = m_{11}^2\, H_1^\dagger H_1 + m_{22}^2\, H_2^\dagger H_2 - \mu^2 \left(H_1^\dagger H_2 + H_2^\dagger H_1\right)$$

EWSB

$$\boxed{\begin{aligned} m_{11}^2 &= \mu^2 \tan\beta - \frac{1}{2}\lambda_1 v^2 \cos^2\beta - \frac{1}{2}\lambda_{345} v^2 \sin^2\beta - \frac{1}{4}\lambda_7 v_S^2 \\ m_{22}^2 &= \mu^2 \cot\beta - \frac{1}{2}\lambda_1 v^2 \sin^2\beta - \frac{1}{2}\lambda_{345} v^2 \cos^2\beta - \frac{1}{4}\lambda_8 v_S^2 \\ m_S^2 &= -\frac{1}{2}\lambda_7 v^2 \cos^2\beta - \frac{1}{2}\lambda_8 v^2 \sin^2\beta - \frac{1}{4}\lambda_6 v_S^2 \end{aligned}}$$

$$- \tfrac{1}{2}\lambda_8 \left(H_2^\dagger H_2\right)(S^\dagger S)$$

Singlet Contribution

MODEL PARAMETER

6 physical Higgs : 3 Cp-even h_1, h_2 et h_3, 1 CP-odd A^0 and 2 charged Higgs $H^{\pm}$.

The scalar potential has : 15 independent parameters : m_{11}^2, m_{22}^2, m_S^2, μ^2, v_1, v_2, v_s et $\lambda_{1,\ldots,8}$.

3 minimization conditions and the combination $v_1^2 + v_2^2$
$\Rightarrow$ 11 free parameters

We can write the quartic couplings in terms of :

$$\alpha_{1,2,3},\ \tan\beta,\ v_S,\ m_{h_{1,2,3}},\ m_A,\ m_{H\pm} \quad \text{and} \quad \mu^2$$

où, $m_{h_1} < m_{h_2} < m_{h_3}$.

2HDM limit :

- $\alpha_1 \to \alpha + \frac{\pi}{2}$, $\alpha_2 \to 0$ and $\alpha_3 \to 0$,
- $\lambda_6,\ \lambda_7,\ \lambda_8 \to 0$.

HIGGS COUPLINGS TO GAUGE BOSONS AND SUM RULES

The normalized couplings of neutral Higgs to a pair of gauge bosons $V = Z, W$ are given by :

$$\begin{aligned} \kappa_V^{h_1} &: \quad c_\beta \mathcal{R}_{11} + s_\beta \mathcal{R}_{12} = c_{\alpha_2} c_{\beta-\alpha_1} \\ \kappa_V^{h_2} &: \quad c_\beta \mathcal{R}_{21} + s_\beta \mathcal{R}_{22} = c_{\alpha_3} s_{\beta-\alpha_1} - s_{\alpha_2} s_{\alpha_3} c_{\beta-\alpha_1} \\ \kappa_V^{h_3} &: \quad c_\beta \mathcal{R}_{31} + s_\beta \mathcal{R}_{32} = -s_{\alpha_3} s_{\beta-\alpha_1} - s_{\alpha_2} c_{\alpha_3} c_{\beta-\alpha_1} \end{aligned}$$

which satisfy the following sum rule :

$$\sum_{i=1}^{3} (\kappa_V^{h_i})^2 = 1$$

- $(\kappa_V^{h_1})^2 + (\kappa_V^{h_2})^2 + (\kappa_V^{h_3})^2 = 1 \implies |\kappa_V^{h_i}| \leqslant 1$

$$\sum_{i=1}^{3} \kappa_V^{h_i} \, \kappa_f^{h_i} = 1$$

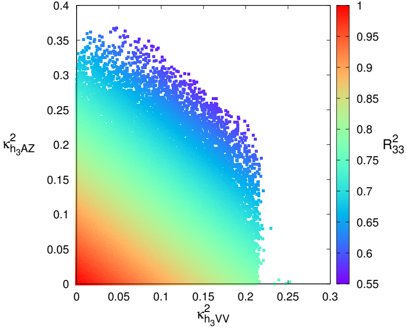
- If $\kappa_V^{h_i} = 1$; $\kappa_V^{h_j} = 0$ for $i \neq j$ then $\kappa_f^{h_i} = 1$.

HIGGS COUPLINGS TO GAUGE BOSONS AND SUM RULES

The couplings between two Higgs bosons and one gauge boson,

$$\begin{aligned} \kappa_{h_1 VS} &: \quad -c_{\alpha_2} s_{\beta-\alpha_1} \\ \kappa_{h_2 VS} &: \quad c_{\alpha_3} c_{\beta-\alpha_1} + s_{\alpha_2} s_{\alpha_3} s_{\beta-\alpha_1} \qquad V = Z(W^\pm) \text{ and } S = A(H^\mp) \\ \kappa_{h_3 VS} &: \quad -s_{\alpha_3} c_{\beta-\alpha_1} + s_{\alpha_2} c_{\alpha_3} s_{\beta-\alpha_1} \end{aligned}$$

In the N2HDM, one can easily derive the following sum rules :



$i = (1,\ 2,\ 3)$

$$\kappa^2_{h_i ZZ} + \kappa^2_{h_i ZA} + R^2_{i3} = 1$$

$$\kappa^2_{h_i W^\pm W^\mp} + \kappa^2_{h_i W^\pm H^\mp} + R^2_{i3} = 1$$

THEORETICAL AND EXPERIMENTAL CONSTRAINTS

- Unitarity constraint ,
  S. Kanemura, T. Kubota and E. Takasugi, PLB'1993 and
  A. Akeroyd, A. A and E. M. Naimi PLB'2000
- Boundedness from below (BFB) of the scalar potential,
  Kaffas, Khater, Ogreid and Osland, NPB2007
- Oblic parameters : S, T et U,
  Grimus, Lavoura, M. Ogreid and Osland, NPB'2008
- HiggsBounds and HiggsSignal
  P. Bechtle and al, EPJC 74 (2014) no.3, 2693
  P. Bechtle and al EPJC 74 (2014) no.2, 2711

h_1 COUPLINGS

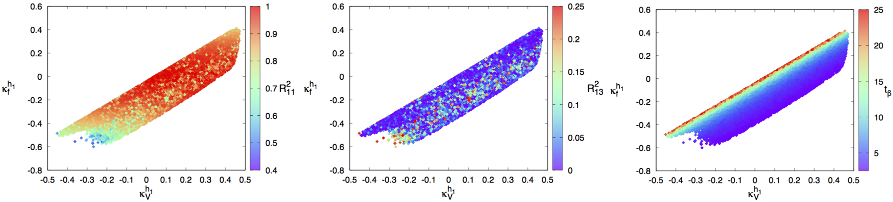


FIGURE – Correlation between $\kappa_f^{h_1}$ et $\kappa_V^{h_1}$ as a function of R^2_{11}, R^2_{13} and $\tan\beta$ at 95%C.L

- The contribution of the doublet is very large
- $|\kappa_f^{h_1}| \leqslant 1$ in a large area of parameter space while one can have a scenario with $|\kappa_f^{h_1}| \geqslant 1$.
- Linear correlation between $\kappa_f^{h_1}$ and $\kappa_V^{h_1}$ at large $\tan\beta$.

h_1 DECAY

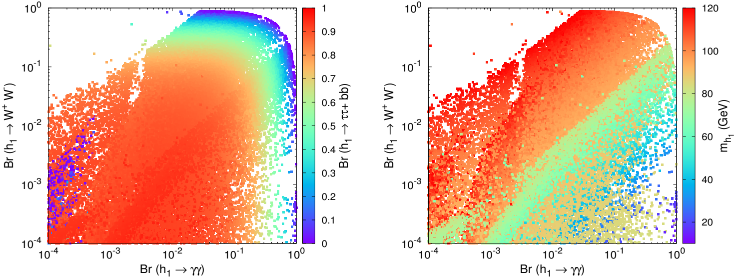


FIGURE – Correlation between $Br(h_1 \to \gamma\gamma)$ and $Br(h_1 \to W^+W^-)$ vs. $Br(h_1 \to f\bar{f})$ and m_{h_1} at 95% .CL

- $h_1 \to W^+W^-$ will proceed with one or both W being off-shell
- In most cases h_1 would decay significantly into $b\bar{b}$
- Fermiophobic scenario if $\kappa_f^{h_1} \propto \cos\alpha_2 \sin\alpha_1 \to 0$.
- $h_1 \to WW^{(*)}$ can compete with $h_1 \to \gamma\gamma$.

h_1 DECAY

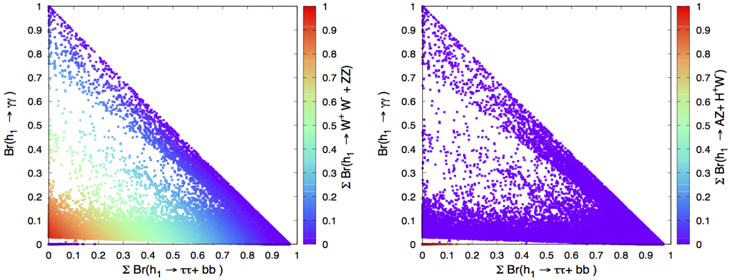


FIGURE – $Br(h_1 \to \gamma\gamma)$ as a function of $Br(h_1 \to \tau^+\tau^- + b\bar{b})$ vs. $Br(h_1 \to W^+W^- + ZZ)$ (left panel) and $Br(h_1 \to H^+W^- + AZ)$ (right panel) at 95%C.L

- The scenario where $Br(h_1 \to SV)$ can become significant
- $\kappa^2_{h_i VV} + \kappa^2_{h_i SV} + R^2_{i3} = 1$

h_2 COUPLINGS

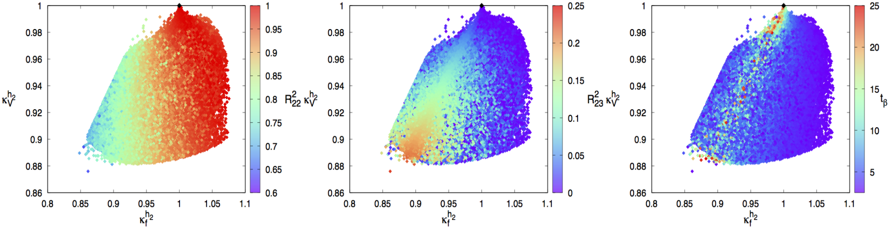


FIGURE – $(\kappa_V^{h_2}, \kappa_f^{h_2})$ as a function of $R^2_{22,23}$ and tan β

- ☐ The suppression of $\kappa_V^{h_2}$ could be of the order of 12%and it could happen both for $\kappa_f^{h_2} < 1$ or $\kappa_f^{h_2} > 1$
- ☐ An enhancement of $\kappa_f^{h_2}$ in the range of $[1.05 - 1.15]$ for small singlet component of h_2 ($R^2_{23} \approx 0.1$) and moderate tan β.

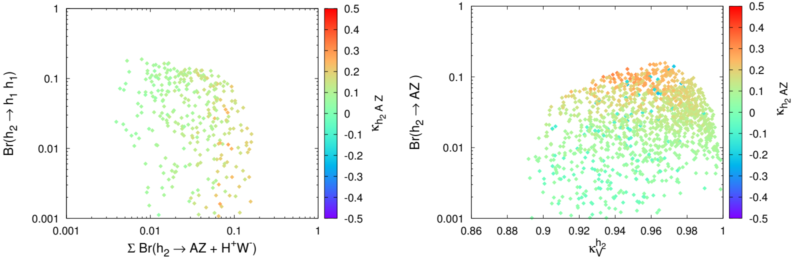


FIGURE – $Br(h_2 \to h_1 h_1)$ and $Br(h_2 \to AZ + H^+W^-)$ versus κ_{h_2AZ} (left panel) and $Br(h_2 \to AZ)$ vs. $\kappa_V^{h_2}$ as a function of κ_{h_2AZ} at 95% $C.L$

- $Br(h_2 \to Z^*A)$ is suppressed when h_2VV is full strength.
- $Br(h_2 \to h_1h_1)$ is maximized when $Br(h_2 \to Z^*A) + Br(h_2 \to W^{*\mp}H^{\pm})$ is minimal and vice verse.

$gg \to h_2^{SM} \to h_1 h_1 \to 4\gamma$

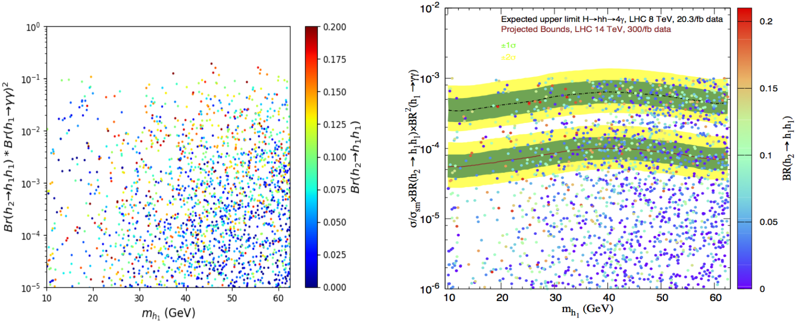


FIGURE – $\sigma(gg \to h_2) \times Br(h_2 \to h_1 h_1) \times Br(h_1 \to \gamma\gamma)^2$ and $Br(h_2 \to h_1 h_1) \times Br(h_1 \to \gamma\gamma)^2$ as a function of m_{h_1} and $Br(h_2 \to h_1 h_1)$ at 95% C.L

$\sigma(gg \to h_3) \times Br(h_3 \to h_i h_i,\ h_i h_j)$

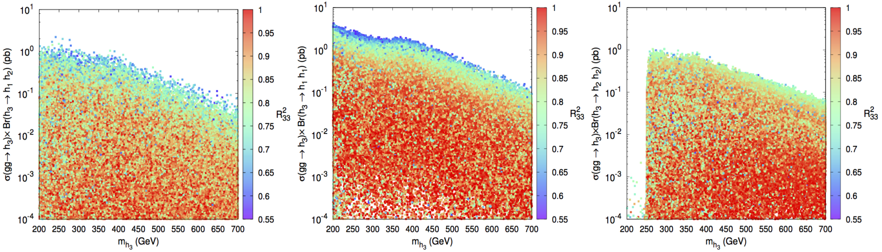


FIGURE – $\sigma(gg \to h_3) \times Br(h_3 \to h_i h_j)$ as a function of R^2_{33} in N2HDM type-I at 95% C.L

CONCLUSION

- h1 can be quasi-fermiophobic and would decay domi- nantly into two photons
- LHC data still allow a room for the non-detected decays of the SM-Higgs $h_2 \to h_1 h_1$ and others with a branching ratio of the order which can reach 24%. Such decay followed by two photons decay of h_1 could lead to four photons signature, namely $pp \to h_2 \to h_1 h_1 \to 4\gamma$.
- Comparison of ATLAS data with our four photons signal show that there is a large area of parameter space that still escapes ATLAS data

Thanks for listening