Phenomenology of 2HDM with real singlet

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Based on: work in progress with R. Benbrik, S. Semlali and L. Rahili and A, Benbrik, Moretti, Rouchad, Q.S. Yan and X. Zhang, JHEP'18

Multi-Higgs Workshop 4-7th September 2018, Lisbon

Outlines

- Introduction: Higgs at LHC
- The 2HDM with real singlet (2HDMS or N2HDM): parameters, sum rules and constraints
- Exotic decays of the SM Higgs
- Multi-photons signature at 2HDM-I, 2HDMS-I: $pp \to H_{125} \to hh \to 4\gamma$
- Bosonic decays of charged Higgs $H^{\pm} \to WS$ $pp \to W^* \to hH^+ \to Whh \to W + 4\gamma$
- Conclusions

Higgs at LHC: Prologue

- 1964: Brout-Englert-Higgs: Higgs mechanism to explain the origine of masses
- 2001: Search started at LEP-II: $e^+e^- \to ZH$, $H \to b\bar{b}$, $m_H > 114.4$ GeV, LEP Working group for Higgs: PLB'2003
- 2004-(2008)-2011: Search continue at Tevatron run II
- 4th July 2012: discovery of Higgs-like particle at LHC by ATLAS and CMS, PLB'2012;
  more than 8600 citations (in average $\approx$ 4 citations per day)

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- August 2012: The combined CDF and D0 search for $H \to b\bar{b}$ revealed evidence for a particle consistent with the SM prediction CDF-D0 PRL'2012
- December 2013: Nobel prize to Englert-Higgs

What do we learn from Higgs discovery?

1. The Higgs mechanism is operating: from $\Phi\Phi VV$ we get HVV.
2. Observation of bosonic decays: $H \to \gamma\gamma, ZZ, WW$
   Observation of Yuhawa interactions: $H \to \tau^+\tau^-, t\bar{t}$ and $b\bar{b}$
   All observations are consistant with SM (errors within $\approx 10 - 15\%$).

   Still missing $h \to \gamma Z$, $\mu^+\mu^-$, triple and quartic couplings hhh, hhhh

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3. The Higgs vev is full strength, HWW, HZZ are SM-like (BUT; data has large errors and it may be possible the vev strength is shared by other Higgs like in Multi-Higgs models, SUSY...).
4. A precise measurement program is needed at Future LHC-HL/ILC/CLIC in order to pine down the nature of the Higgs-like particle.

Motivations for 2HDM with real/complex singlet

- Dark Matter:
  Drozd, Grzadkowski, Gunion, Yun Jiang; JHEP'2014 ;
  L. Wang, R. Shi and X. F. Han, PRD'2017
- Dark matter and neutrino masses:
  A.A, C. Boem, E. Ma , T.C. Yuan JCAP'2016
- Special case of the Next-to-MSSM:
  Muhlleitner, Sampaio, Santos, Wittbrodt, JHEP'2017
- CP violation and dark matter:
  Azevedo, Ferreira, Muhlleitner, Patel, Santos, Wittbrodt, arXiv:1807.10322
- CP violation :
  V. Keus, N. Koivunen and K. Tuominen, arXiv:1712.09613

Scalar Potential

The scalar sector of 2HDMS consists of two doublets H_i (i = 1,2), with $Y = 1$ and real singlet

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

$$\begin{aligned} V &= m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - \mu^2 \left(H_1^\dagger H_2 + h.c\right) + \frac{m_S^2}{2} S^2 \\ &+ \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 \\ &+ \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \left(H_2^\dagger H_1\right)^2\right] \\ &+ \frac{1}{8}\lambda_6 S^4 + \frac{1}{2}\lambda_7 \left(H_1^\dagger H_1\right) S^2 + \frac{1}{2}\lambda_8 \left(H_2^\dagger H_2\right) S^2 \end{aligned}$$

- 6 physical Higgs: 3 CP-even h_1, h_2 and h_3, 1 CP-odd A^0 and one charged Higgs pair $H^\pm$.

- The scalar potential have 15 independent parameters: m^2_{11}, m^2_{22}, m^2_S, μ^2, v_1, v_2, v_s and $\lambda_{1,\ldots,8}$.

- 3 minimization conditions and $v_1^2 + v_2^2$ is fixed from m_W. we are left with 11 free parameters

$$\alpha_{1,2,3},\ \tan\beta,\ v_S,\ m_{h_1} < m_{h_2} = 125 \text{ GeV} < m_{h_3},\ m_A,\ m_{H^\pm}\ ,\ \mu^2$$

2HDM limit: $\alpha_1 \to \alpha + \frac{\pi}{2}$, $\alpha_2 \to 0$ *and* $\alpha_3 \to 0$

Higgs Couplings to Vector gauge bosons and sum rules

Gunion, Haber, Wudka, PRD'91; Bento,Haber, Romao, Silva: JHEP'2017 ; arXiv:1808.07123 [hep-ph].

$$
\begin{aligned}
g_{h_1 VV} &: \quad c_{\alpha_2} c_{\beta-\alpha_1}, \\
g_{h_2 VV} &: \quad c_{\alpha_3} s_{\beta-\alpha_1} - s_{\alpha_2} s_{\alpha_3} c_{\beta-\alpha_1}, \\
g_{h_3 VV} &: \quad -s_{\alpha_3} s_{\beta-\alpha_1} - s_{\alpha_2} c_{\alpha_3} c_{\beta-\alpha_1},
\end{aligned}
$$

$$
\sum_{i=1}^{3} g^2_{h_i VV} = 1 \ , \ \Longrightarrow \mid g_{h_i VV} \mid \leq 1
$$

$$\begin{aligned} g_{h_1 VS} &: \quad -c_{\alpha_2} s_{\beta-\alpha_1}, \\ g_{h_2 VS} &: \quad c_{\alpha_3} c_{\beta-\alpha_1} + s_{\alpha_2} s_{\alpha_3} s_{\beta-\alpha_1}, \\ g_{h_3 VS} &: \quad -s_{\alpha_3} c_{\beta-\alpha_1} + s_{\alpha_2} c_{\alpha_3} s_{\beta-\alpha_1}, \end{aligned}$$

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

for $S = A^0, V = Z$; $S = H^\pm, V = W^\mp$;

R_{i3} is the singlet component of the Higgs h_i

If $R_{i3} = 1$, h_i is pure singlet then $g_{h_i VV} = g_{h_i VS} = 0$

Higgs couplings and Sum rules

Bento,Haber, Romao, Silva: arXiv:1808.07123 [hep-ph].

$$\sum_{i=1}^{3} g_{h_i VV} g_{h_i f\bar{f}} = 1$$

$$\Longrightarrow if \quad | g_{h_i VV} | = 1 \ ; \ g_{h_j VV} = 0 \ for \ j \neq i \quad then \ g_{h_i f\bar{f}} = 1$$

$i = 1, 2, 3$

Constraints

- Tree level perturbative unitarity à la Lee-Quigg-Thacker
  S. Kanemura, T. Kubota and E. Takasugi, PLB'1993 and
  A. Akeroyd, A. A and E. M. Naimi PLB'2000.
  Sensitive to the new parameters $\lambda_{6,7,8}$

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- EWPT constraints: S, T and U
  Grimus, Lavoura, M. Ogreid and Osland, NPB'2008
- LHC and LEP constraints from Higgsbounds and HiggsSignals (8 TeV and 13 TeV)

Inputs: h_2 is the SM-like Higgs

$$m_{h_1} \in [10, 120]\ \text{GeV}, \quad m_{h_3} \in [200, 700]\ \text{GeV}, \quad m_{H^\pm} \in [80, 700]\ \text{GeV},$$
$$m_A \in [62.5, 700]\ \text{GeV}, \quad m_{12}^2 \in [0, 1.5 \times 10^3]\ \text{GeV}, \quad v_S = 300\ \text{GeV},$$
$$\frac{-\pi}{2} < \alpha_1 < \frac{\pi}{2}, \quad \frac{-\pi}{6} < \alpha_{2,3} < \frac{\pi}{6}, \quad \text{and } 0.5 < \tan\beta < 25,$$

- case with $h_1 \sim 125$ GeV was considered by Muhlleitner, Sampaio, Santos, Wittbrodt, JHEP'2017.
- Scenario with $m_h < 125$ GeV$=m_H$ is viable in 2HDM, MSSM (Sven, Klemm talks) and other models .
- We concentrate only on 2HDMS-I : $h_1 ff \propto \sin\alpha_1 \cos\alpha_2 / \sin\beta$
- $\alpha_1 \approx 0$, h_1 is fermiophobic

S and T

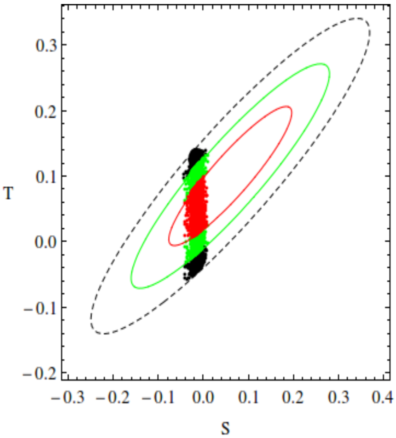


Figure: Correlation between S and T. The errors for χ^{ST}-square fit are 99.7% CL (black), 95.5% CL (green) and 68% CL (red)

h_1 Couplings

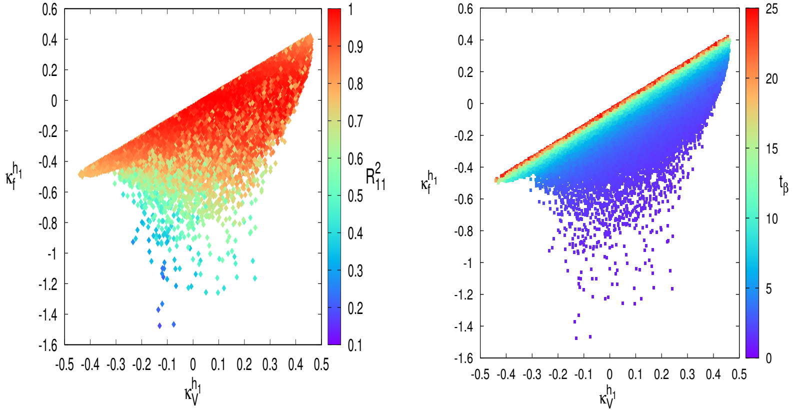


Figure: $\kappa_f^{h_1}$ as a function of $\kappa_V^{h_1}$ with R^2_{11} and $\tan\beta$ at 95% C.L

$h_1 \to bb, WW, \gamma\gamma$ decays

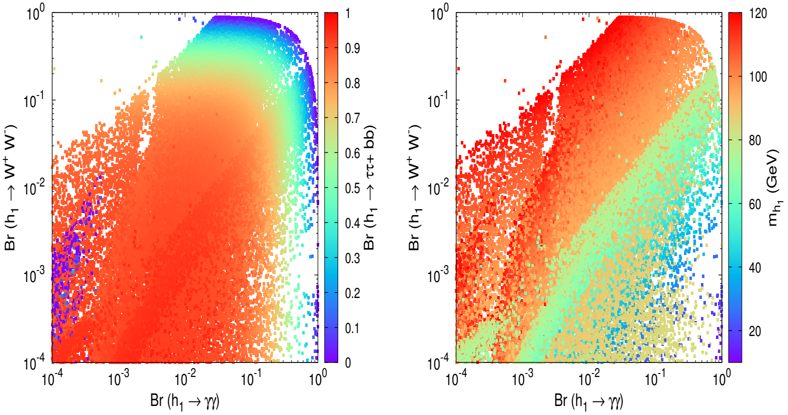


Figure: $Br(h_1 \to W^+W^-)$ and $Br(h_1 \to \gamma\gamma)$ vs. $Br(h_1 \to b\bar{b})$ (left), and m_{h_1} (right) at 95% .CL, in 2HDMS type I

Exotic decays of h_1

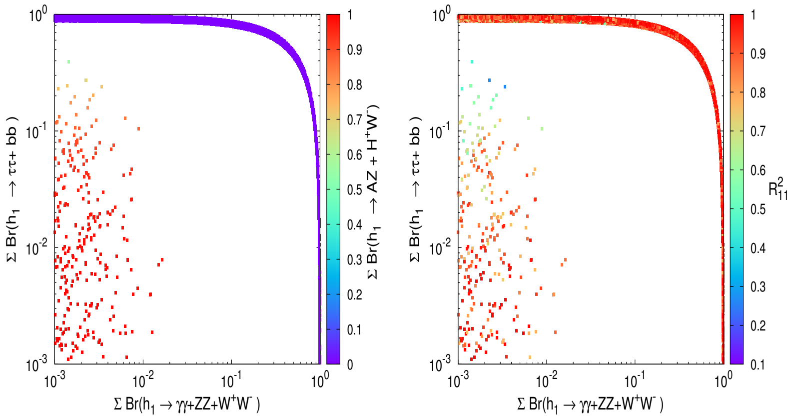
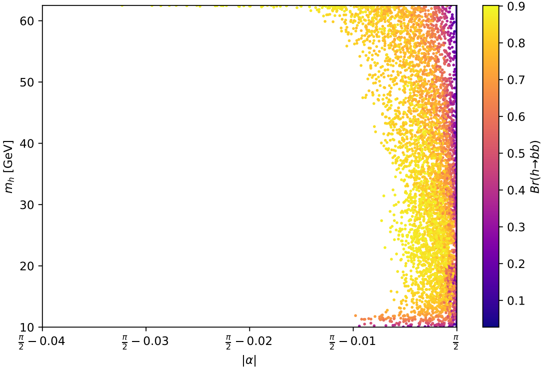


Figure: $\sum Br(h_1 \to f\bar{f})$ as a function of $\sum Br(h_1 \to VV)$ vs $Br(h_1 \to SV)$ and R_{11}^2 at 95% $.CL$ in 2HDMS-I.

$g_{h_i ZZ}^2 + g_{h_i ZA}^2 + R_{i3}^2 = 1$

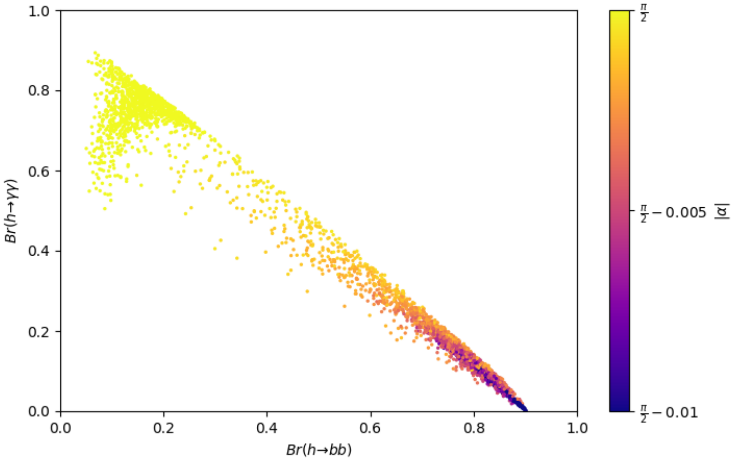
Similar result in 2HDM type I

- $h^0 f\bar{f} \propto \frac{\cos\alpha}{\sin\beta} \to 0$ for $\alpha \to \pi/2$, h^0 becomes fermiophobic.
- $h^0 \to \gamma\gamma$ mediated by $H^\pm/W^\pm$ loops could reach 100%
- in the fermiophobic limit $h^0 \to b\bar{b}$, $h^0 \to s\bar{b}$ would compete with $h^0 \to \gamma\gamma$: Barroso, Brucher, Santos PRD'99, A.A PLB'05



Quasi-fermiophobic h^0 in 2HDM type I

- $h^0 \to \gamma\gamma$ vs $h^0 \to b\bar{b}$ at one-loop:



h_2 Couplings

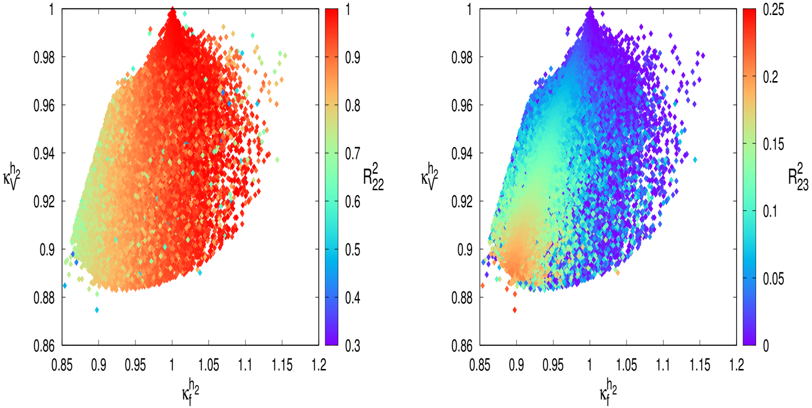


Figure: $(\kappa_V^{h_2}, \kappa_f^{h_2})$ as a function of $R^2_{22,23}$

$\sum_{i=1}^{3} g_{h_i VV} g_{h_i f\bar{f}} = 1$

h_2 Couplings

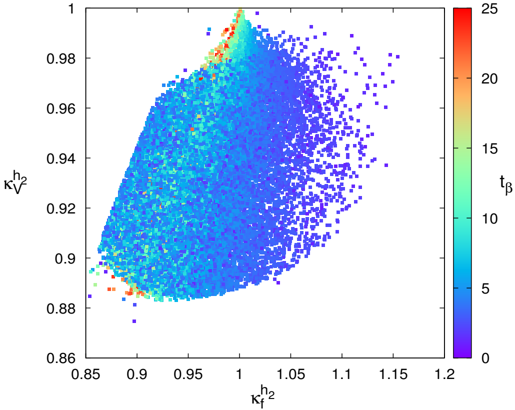


Figure: $(\kappa_V^{h_2}, \kappa_f^{h_2})$ vs $\tan\beta$

h_2 Couplings

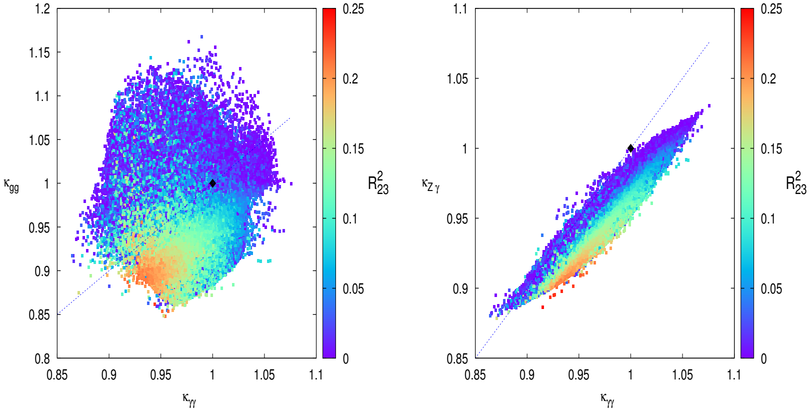


Figure: $\kappa_{gg}^{h_2}$ versus R_{23}^2 and $\kappa_{\gamma\gamma}^{h_2}$ as a function of $\kappa_{Z\gamma}^{h_2}$ as a function of singlet component R_{23}^2 in 2HDMS type-I at 95% $C.L$

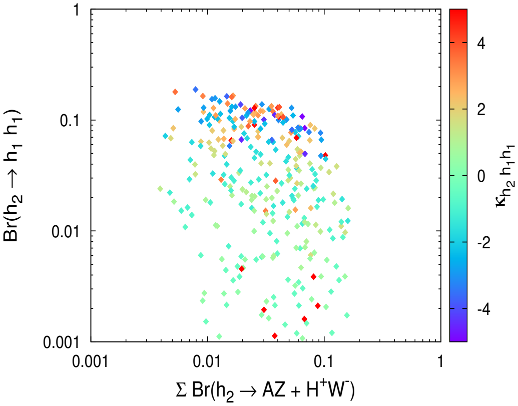
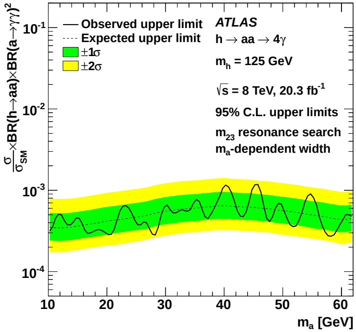


Figure: $Br(h_2 \to h_1 h_1)$ and $Br(h_2 \to AZ + H^+W^-)$ vs $\kappa_{h_2 h_1 h_1}$

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

- The search channel that mostly enabled Higgs discovery was $gg \to H \to \gamma\gamma$ decay.
- Because photons final states are clean at hadronic environment LHC
- Also because of sharp resolution in the di-photon invariant mass achievable by the LHC detectors
- knowledge of $m_H = 125$ GeV, one can enforce $m_{4\gamma} = m_H$
- One can reconstruct in each event photon pairs: $m_{\gamma\gamma} = m'_{\gamma\gamma}$

- G. Aad *et al.* [ATLAS Collaboration], "*Search for new phenomena in events with at least three photons collected in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,*" EPJC**76**(2016)
- ATLAS study was motivated and applied to the Next-MSSM case with light CP-odd $gg \to H \to a_1 a_1 \to \gamma\gamma\gamma\gamma$.

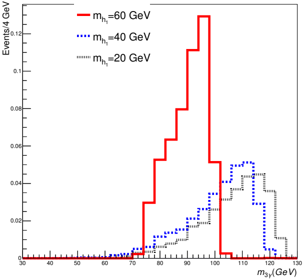


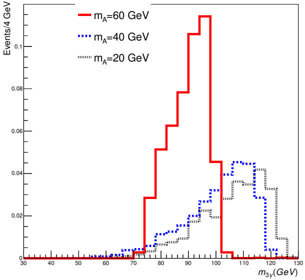
- $gg \to H \to hh \to 4\gamma$ and $gg \to H \to AA \to 4\gamma$ have the same differential cross section,
- The matrix elements can be put as

$$\begin{aligned}\mathcal{M}^h &= C(k_1 \cdot k_2 \eta^{\mu\nu} - k_2^\mu k_1^\nu)\epsilon_\mu^*(k_1)\epsilon_\nu^*(k_2)(k_3 \cdot k_4 \eta^{\rho\sigma} - k_4^\rho k_3^\sigma) \\ &\quad \times \epsilon_\rho^*(k_3)\epsilon_\sigma^*(k_4)\delta^{ab}\epsilon(p_1) \cdot \epsilon(p_2)\,, \\ \mathcal{M}^A &= D\epsilon_\alpha^*(k_1)\epsilon_\beta^*(k_2)\epsilon^{\alpha\beta\mu\nu}k_\mu^1 k_\nu^2 \epsilon_\rho^*(k_3)\epsilon_\sigma^*(k_4)\epsilon^{\rho\sigma\gamma\delta}k_\gamma^3 k_\delta^4 \delta^{ab}\epsilon_{p_1}.\epsilon_{p_2}\end{aligned}$$

  p_1 and p_2 is the momentum of the initial gluons, $k_1 - k_4$ are momentum of 4 photons in the final state.
- $\mid \mathcal{M}^{h,A} \mid^2 \propto \{C^2, D^2\}(k_1.k_2)^2(k_3.k_4)^2$

$gg \to H \to hh \to 4\gamma$ vs $gg \to H \to AA \to 4\gamma$

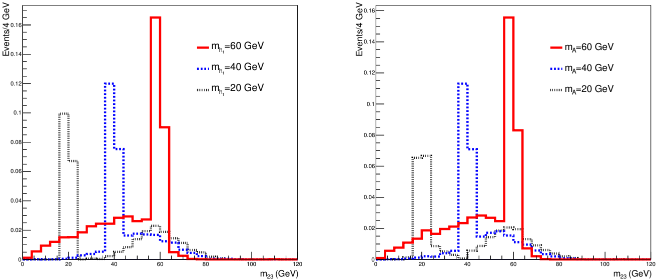




Distributions at detector level: (a) $m_{3\gamma}$ for $gg \to H \to hh \to 4\gamma$, (b) $m_{3\gamma}$ for $gg \to H \to AA \to 4\gamma$,

$m_{3\gamma}$: the invariant mass of the 3 leading P_T-ordered photons

$gg \to H \to hh \to 4\gamma$ vs $gg \to H \to AA \to 4\gamma$



Distributions at detector level: (a) m_{23} for $gg \to H \to hh \to 4\gamma$ and (b) m_{23} for $gg \to H \to AA \to 4\gamma$.

m_{23}: the invariant mass of the 2nd and 3rd P_T-ordered photons.

Projection from 8 TeV to 14 TeV sensitivity

- In order to project the sensitivity of the future LHC run at $\sqrt{s} = 14$ TeV, we have to rescale 8 TeV results.
- The 'boost factors', for both signal and background processes is calculated using MC tools: (MadGraph 5, PYTHIA: simulate showering, hadonisation and decays and PGS to perform the fast detector simulations).

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- The 'boost factors', for both signal and background processes is calculated using MC tools: (MadGraph 5, PYTHIA: simulate showering, hadonisation and decays and PGS to perform the fast detector simulations).
- we adopt the same selection cuts of the ATLAS collaboration,
  - i) $n_\gamma \geq 3$: we consider inclusive 3 photon events.
  - ii) The two leading photons should have a $P_t(\gamma) > 22$ GeV and the third one should have a $P_t(\gamma) > 17$ GeV
  - iii) The photons should be resolved in the range $|\eta| < 2.37$ and do not fall in the end-cap region $1.37 < |\eta| < 1.52$.
  - iv) $\Delta R(\gamma\gamma) > 0.4$.

Invisible decay of h_2

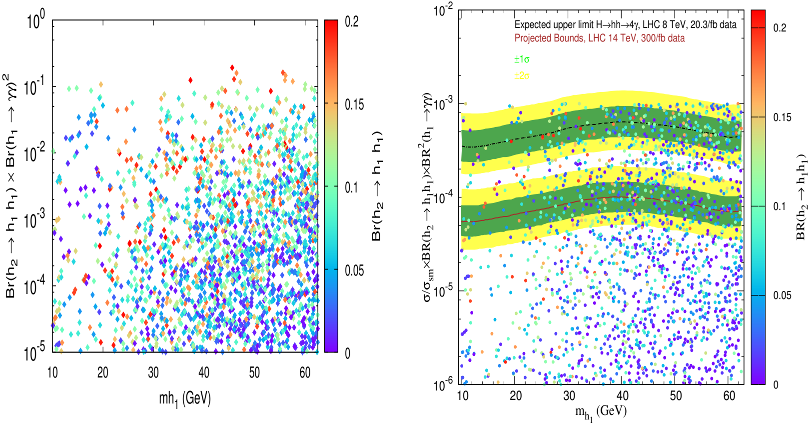
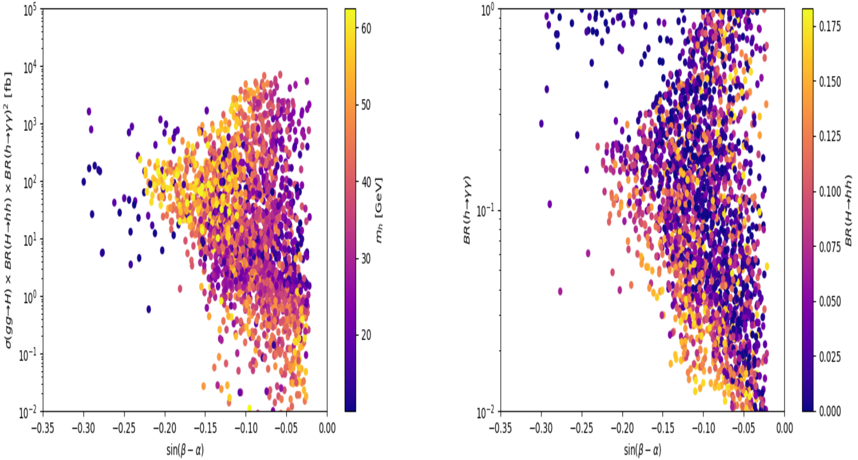
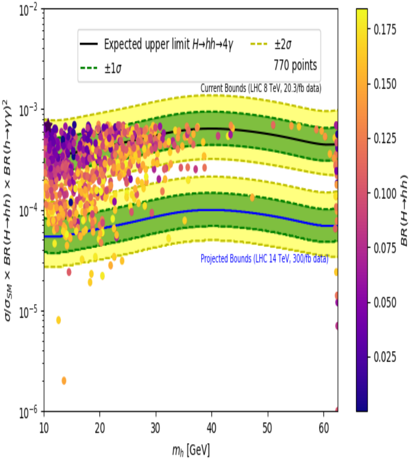


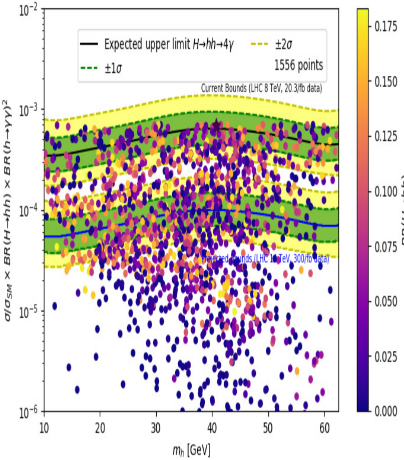
Figure: $Br(h_2 \to h_1 h_1) \times Br(h_1 \to \gamma\gamma)^2$ (left) and $\sigma(gg \to h_2) \times Br(h_2 \to h_1 h_1) \times Br(h_1 \to \gamma\gamma)^2$ (right) as a function of m_{h_1} at 95% $C.L$ in 2HDMS type-I

$\sigma(gg \to H \to hh \to 4\gamma)$ in 2HDM-I



$\sigma(gg \to H \to hh \to \gamma\gamma\gamma\gamma)$





fermionic decays

- $H^\pm \to \tau\nu \quad , \quad cs \quad , \quad cb$
- $H^\pm \to tb$

Bosonic decays of $H^\pm$

fermionic decays

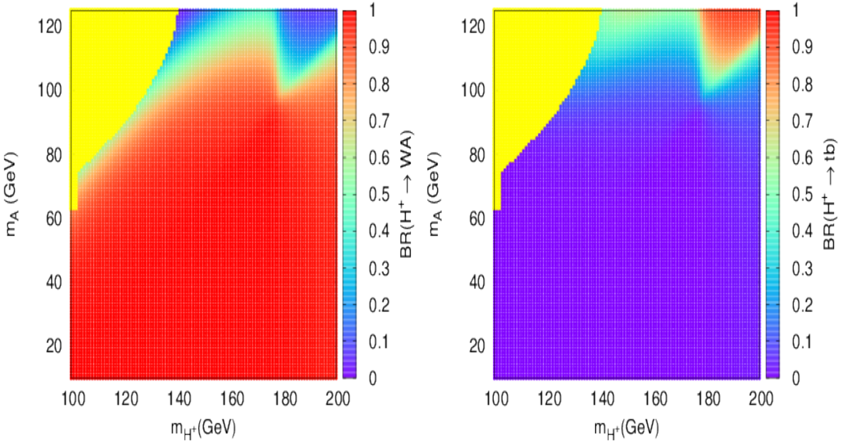
- $H^\pm \to \tau\nu \quad , \quad cs \quad , \quad cb$
- $H^\pm \to tb$

bosonic decays

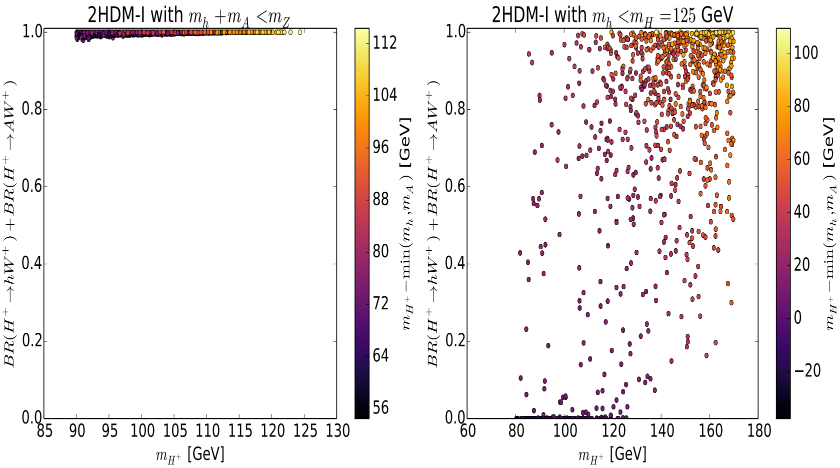
- $H^\pm \to W^\pm \phi^0 \quad , \quad \phi^0 = h^0, A^0, H^0$
- $H^\pm \to W^\pm \gamma, W^\pm Z$: small (loop mediated).
- $H^\pm \to W^\pm Z$ exists at tree level in triplet models. (production through WZ fusion)

very light A^0: $\tan\beta = 5$, $m_H = 300$ GeV, $\sin(\beta - \alpha) = 1$

Yellow excluded by data

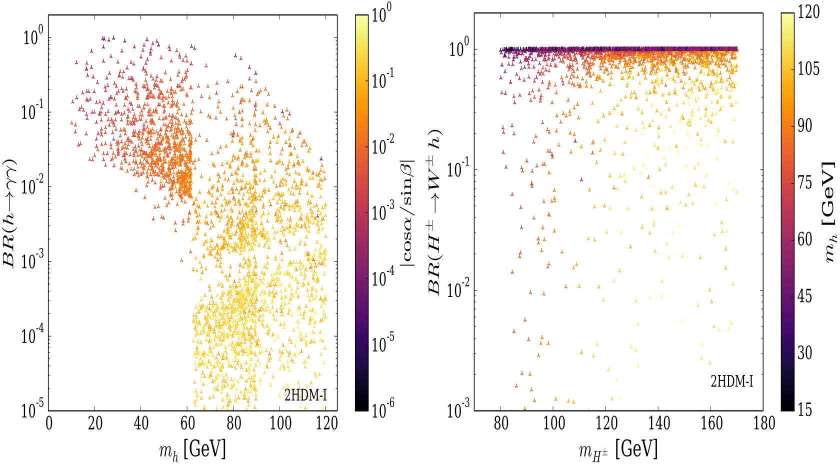


$\mathrm{Br}(H^{\pm} \to W^{\pm}S)$; H SM-like, $\cos(\beta - \alpha) = 1$

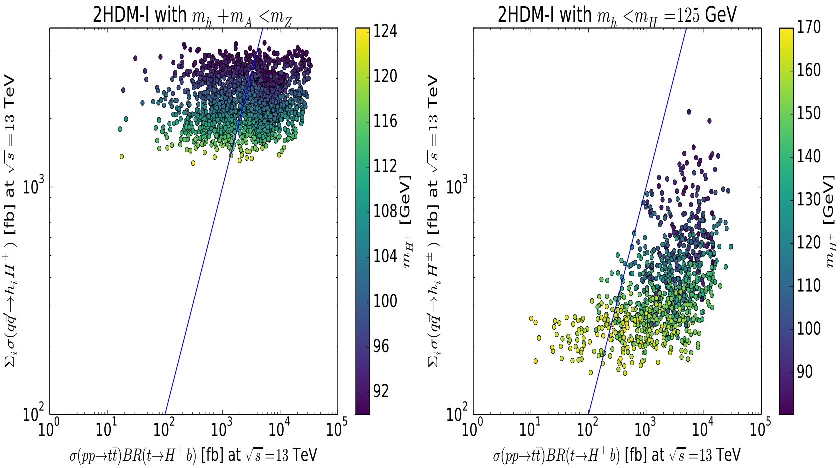


$$pp \to hH^{\pm} \to Whh \to W4\gamma$$
$$pp \to AH^{\pm} \to WhA$$

Br($h^0 \to \gamma\gamma$) and Br($H^\pm \to W^\pm h^0$)



Comparison: $\sigma(pp \to t\bar{t}) \times BR(t \to H^+ b)$ vs. $\Sigma_i \sigma(q\bar{q}' \to H^\pm h_i)$



Conclusions

- In the 2HDM and 2HDMS a scenario with one higgs < 125 GeV is still alive, leading to exotic decays of h_1 and/or h_2 such as $h_{1,2} \to Z^* A$, $h_{1,2} \to W^* H^{\pm}$.
- In 2HDM and 2HDMS-I there is regions of the parameter space compliant with theoretical and experimental constraints yielding substantial $Br(h \to \gamma\gamma)$ as well as $Br(H \to hh)$.
- The cross section for $gg \to H \to hh \to 4\gamma$ is at pb level and is sensitive to ATLAS exclusion.
- In 2HDM-I, the bosonic decays $H^{\pm} \to W^* h/W^* A$, for $m_{H^{\pm}} \leq m_t - m_b$ wherein $W \to l\nu$., could be substantial.