Fermiophobic Higgs boson and supersymmetry

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based on 1204.0080
in collaboration with

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Outline

Motivation

Why fermiophobia?

- **Theo**: Chiral Symmetry Breaking (m_f) and EW symmetry breaking (M_W, M_Z) may have a different origin.
  $\langle h \rangle$ could be only responsible of M_W and M_Z but not of m_f
- **Exp1**: not (yet) any strong evidence supporting tree-level y_f
- **Exp2**:
  - **a.** FP scenarios are among those giving the best fit to LHC data available after Moriond 2012 (Giardino, Kannike, Raidal and Strumia, 1203.4254)
  - **b.** local excess in $\gamma\gamma$ at LHC $\overset{?}{\Longrightarrow}$ FP h, $M_h \simeq 125$ GeV
    CMS-PAS-HIG-12-002,008; ATLAS-CONF-2012-013

Why supersymmetry?

- Only **NON** susy fermiophobic Higgs models in the past

Motivation

Pros:

- vacuum stability bound is lowered
- sfermions can be naturally in the 2-3 TeV range
- the usual flavor and CP problems are relaxed
- no more constraints from $b \to s\gamma$ and $B_s \to \mu\mu$
  $\Rightarrow$ $H^{\pm}$ can be light
- relax constraints on DM

Cons:

- No mechanism for generating SM m_f (added by hand)
  $\Rightarrow$ it is only an effective theory

MSSM & Higgs mass loop correction

In the MSSM $M_h^{\mathrm{tree}} < M_Z$. But

$$\Delta M_h^2 = 3y_t^4 \frac{v^2 \sin^4 \beta}{8\pi^2} \left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12 M_S^2} \right) \right]$$

- M_S is the average stop mass
- X_t is the stop mass mixing parameter, $X_t = \frac{a_t}{y_t} - \mu \cot \beta$
- a_t is the trilinear coupling of the soft term $a_t \tilde{Q} H_u \tilde{u}^c$

The failure of the MSSM

Fermiophobic limit: $y_t \to 0$

$$\Delta M_h^2 = 3y_t^4 \frac{v^2 \sin^4 \beta}{8\pi^2} \left[\log \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12 M_S^2} \right) \right]$$

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The failure of the MSSM

Fermiophobic limit: $y_t \to 0$

$$\Delta M_h^2 = -\frac{3v^2 \sin^4\beta}{8\pi^2}\frac{a_t^4}{12M_S^4} < 0$$

- so we cannot get $M_h > M_Z$ and even more so $M_h \simeq 125$ GeV
- $M_h < M_Z$ is already ruled out
- **Fermiophobic Higgs if SUSY, cannot be just MSSM-like**

Setup

Z_3 symmetric NMSSM superpotential.

$$\mathcal{W} = \lambda S H_u H_d + \frac{k}{3} S^3 + y_u Q H_u u^c + y_d H_d Q d^c + y_e H_d L e^c$$

and S, H_u, H_d soft terms

$$\begin{aligned}\mathcal{L}_{\text{soft}} = &- \left(m_{h_u}^2 h_u^\dagger h_u + m_{h_d}^2 h_d^\dagger h_d + m_s^2 s^\dagger s \right) - \left(a_\lambda s h_u h_d + \frac{1}{3} a_k s^3 + h.c. \right) \\ &- \left(m_{Q_{ij}}^2 \tilde{Q}_i \tilde{Q}_j^\dagger + m_{U_{ij}}^2 \tilde{U}_i^c \tilde{U}_j^{c\dagger} + m_{D_{ij}}^2 \tilde{D}_i^c \tilde{D}_j^{c\dagger} + m_{L_{ij}}^2 \tilde{L}_i \tilde{L}_j^\dagger + m_{E_{ij}}^2 \tilde{E}_i^c \tilde{E}_j^{c\dagger} \right) \\ &- \left(a_u^{ij} \tilde{Q}_i \tilde{U}_j^c h_u - a_d^{ij} \tilde{Q}_i \tilde{D}_j^c h_d - a_e^{ij} \tilde{L}_i \tilde{E}_j^c h_d + h.c. \right) \\ &- \frac{1}{2} \sum_{a=1}^{3} \left(M_a \lambda_a \lambda_a + h.c. \right)\end{aligned}$$

Setup

Z_3 symmetric **FP** NMSSM superpotential.

$$\mathcal{W} = \lambda S H_u H_d + \frac{k}{3} S^3 + y_u Q H_u u^c + y_d H_d Q d^c + y_e H_d L e^c$$

and S, H_u, H_d soft terms

$$\mathcal{L}_{\rm soft} = -\left(m^2_{h_u} h_u^\dagger h_u + m^2_{h_d} h_d^\dagger h_d + m_s^2 s^\dagger s\right) - \left(a_\lambda s h_u h_d + \frac{1}{3} a_k s^3 + h.c.\right)$$
$$- \left(m^2_{Q_{ij}} \tilde{Q}_i \tilde{Q}_j^\dagger + m^2_{U_{ij}} \tilde{U}_i^c \tilde{U}_j^{c\dagger} + m^2_{D_{ij}} \tilde{D}_i^c \tilde{D}_j^{c\dagger} + m^2_{L_{ij}} \tilde{L}_i \tilde{L}_j^\dagger + m^2_{E_{ij}} \tilde{E}_i^c \tilde{E}_j^{c\dagger}\right)$$
$$- \left(a_u^{ij} \tilde{Q}_i \tilde{U}_j^c h_u - a_d^{ij} \tilde{Q}_i \tilde{D}_j^c h_d - a_e^{ij} \tilde{L}_i \tilde{E}_j^c h_d + h.c.\right)$$
$$-\frac{1}{2} \sum_{a=1}^{3} \left(M_a \lambda_a \lambda_a + h.c.\right)$$

- Z_3 is also used in order to get fermiophobia:
  $X_{H_u} = X_{H_d} = X_S = 1$ and $X_f = 0 \Rightarrow \boxed{y_f, a_f = 0}$
  But also other possible configurations (see 1204.0080)

Scalar potential

$$\begin{aligned}
V &= \left(m_{h_u}^2 + |\lambda s|^2\right)\left(\left|h_u^0\right|^2 + \left|h_u^+\right|^2\right) + \left(m_{h_d}^2 + |\lambda s|^2\right)\left(\left|h_d^0\right|^2 + \left|h_d^-\right|^2\right) \\
&+ m_s^2|s|^2 + \left(a_\lambda\left(h_u^+h_d^- - h_u^0h_d^0\right)s + \frac{1}{3}a_k s^3 + \mathrm{h.c.}\right) \\
&+ \left|\lambda\left(h_u^+h_d^- - h_u^0h_d^0\right) + ks^2\right|^2 \\
&+ \frac{g_1^2+g_2^2}{8}\left(\left|h_u^0\right|^2 + \left|h_u^+\right|^2 - \left|h_d^0\right|^2 - \left|h_d^-\right|^2\right)^2 + \frac{g_2^2}{2}\left|h_u^+h_d^{0*} + h_u^0h_d^{-*}\right|^2
\end{aligned}$$

Parametrization:

$$\begin{aligned}
h_d^0 &= \frac{1}{\sqrt{2}}\left(v_d + h_{dR}^0 + ih_{dI}^0\right) \\
h_u^0 &= \frac{1}{\sqrt{2}}\left(v_u + h_{uR}^0 + ih_{uI}^0\right) \\
s &= \frac{1}{\sqrt{2}}\left(v_S + s_R + is_I\right)
\end{aligned}$$

$$\begin{aligned}
v^2 &= v_u^2 + v_d^2 \\
\tan\beta &= \frac{v_u}{v_d}
\end{aligned}$$

CP even scalars

$$M_S^2 = \begin{pmatrix} M^2_{S,11} & M^2_{S,12} & M^2_{S,13} \\ \dots & M^2_{S,22} & M^2_{S,23} \\ \dots & \dots & M^2_{S,33} \end{pmatrix} \quad \text{in the basis } (h^0_{dR}, h^0_{uR}, s_R)$$

$$\begin{aligned} M^2_{S,13} &= v v_S \left(\lambda^2 \cos\beta - k\lambda \sin\beta\right) - \frac{a_\lambda v \sin\beta}{\sqrt{2}} \\ M^2_{S,23} &= v v_S \left(\lambda^2 \sin\beta - k\lambda \cos\beta\right) - \frac{a_\lambda v \cos\beta}{\sqrt{2}} \end{aligned}$$

There is a choice that allows no mixing between s_R and $h^0_{uR,dR}$,

$$\boxed{\begin{aligned} a_\lambda &= 0 \\ k &= \lambda \\ \tan\beta &= 1 \end{aligned}}$$

N.B. $\tan\beta = 1$ is allowed in this model because no constraints occur from the Yukawa sector. Therefore this choice is the most natural one.

CP even scalars

Then the minimization equations read

$$\begin{aligned}\left(4m_{h_d}^2+\lambda^2 v^2\right) &= 0\\ \left(4m_{h_u}^2+\lambda^2 v^2\right) &= 0\\ \frac{a_k v_S^2}{\sqrt{2}}+m_S^2 v_S+\lambda^2 v_S^3 &= 0\end{aligned}$$

leading to the CP-even neutral Higgs boson mass matrix

$$M_S^2=\begin{pmatrix}\frac{1}{2}\left(M_Z^2+v_S^2\lambda^2\right) & \frac{1}{2}\left((v-v_S)(v+v_S)\lambda^2-M_Z^2\right) & 0\\ \dots & \frac{1}{2}\left(M_Z^2+v_S^2\lambda^2\right) & 0\\ \dots & \dots & 2v_S^2\lambda^2+\frac{a_k v_S}{\sqrt{2}}\end{pmatrix}$$

where $M_Z^2=\frac{1}{4}\left(g_1^2+g_2^2\right)v^2$.

CP even scalars

The corresponding eigenvectors and eigenvalues

$$h = \frac{1}{\sqrt{2}}\left(h^0_{dR} + h^0_{uR}\right) \qquad M_h^2 = \frac{(\lambda v)^2}{2} \simeq (125\text{GeV})^2$$

$$H = \frac{1}{\sqrt{2}}\left(h^0_{dR} - h^0_{uR}\right) \qquad M_H^2 = (\lambda v_S)^2 + M_Z^2 - M_h^2$$

$$M_{s_R}^2 = \frac{a_k v_S}{\sqrt{2}} + 2(\lambda v_S)^2$$

MSSM notation $\rightarrow \alpha = -\pi/4$

$\Downarrow$

$\beta = \pi/4 \Rightarrow$ no direct tree level couplings HWW and HZZ

$\Downarrow$

OK with LHC seeing no other "resonance" but $\simeq$ 125GeV.

CP odd scalars

$$M'^2_P = \begin{pmatrix} \frac{v_S^2\lambda^2}{2} & \frac{v_S^2\lambda^2}{2} & -\frac{vv_S\lambda^2}{\sqrt{2}} \\ \frac{v_S^2\lambda^2}{2} & \frac{v_S^2\lambda^2}{2} & -\frac{vv_S\lambda^2}{\sqrt{2}} \\ -\frac{vv_S\lambda^2}{\sqrt{2}} & -\frac{vv_S\lambda^2}{\sqrt{2}} & v^2\lambda^2 - \frac{3a_k v_S}{\sqrt{2}} \end{pmatrix} \quad \text{in the basis } (h^0_{dI}, h^0_{uI}, s_I)$$

and the corresponding eigenvalues

$$\begin{aligned} M^2_{G^0} &= 0 \\ M^2_{A^0_{1,2}} &= \frac{1}{4}\left(2\lambda^2\left(v^2+v_S^2\right) - 3\sqrt{2}a_k v_S \mp \sqrt{\Delta}\right) \end{aligned}$$

where

$$\Delta = \left(3\sqrt{2}a_k v_S - 2\lambda^2\left(v^2+v_S^2\right)\right)^2 + 24\sqrt{2}a_k\lambda^2 v_S^3$$

Charged scalars

$$M'^2_{\pm} = \left(M_W^2 + \frac{1}{2}\lambda^2 \left(2v_S^2 - v^2\right) \right) \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \quad \text{in the basis } (h_u^+, h_d^{-*})$$

where $M_W^2 = \frac{1}{4} g_2^2 v^2$.

It contains one massless Goldstone mode $G^{\pm}$, and

$$\begin{aligned} M_{H^\pm}^2 &= (\lambda v_S)^2 + M_W^2 - M_h^2 \quad \lessapprox \quad M_H^2 = (\lambda v_S)^2 + M_Z^2 - M_h^2 \\ H^+ &= \frac{1}{\sqrt{2}} \left(h_u^+ + h_d^{-*} \right) \end{aligned}$$

Neutralinos & Charginos

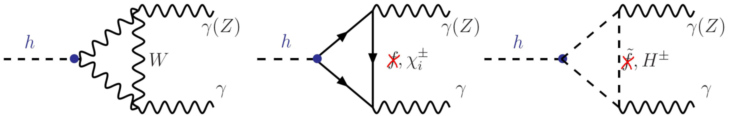
$$M_0 = \begin{pmatrix} M_1 & 0 & -M_Z \sin\theta_W & M_Z \sin\theta_W & 0 \\ \dots & M_2 & M_Z \cos\theta_W & -M_Z \cos\theta_W & 0 \\ \dots & \dots & 0 & -\frac{1}{\sqrt{2}}\lambda v_S & -\frac{\lambda v}{2} \\ \dots & \dots & \dots & 0 & -\frac{\lambda v}{2} \\ \dots & \dots & \dots & \dots & \sqrt{2} v_S \end{pmatrix}$$

in the basis $\psi^0 = (\lambda_1, \lambda_2^3, \tilde{h}_d^0, \tilde{h}_u^0, \tilde{s})$

$$M_{\tilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix}$$ in the basis $\psi^\pm = (\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)$

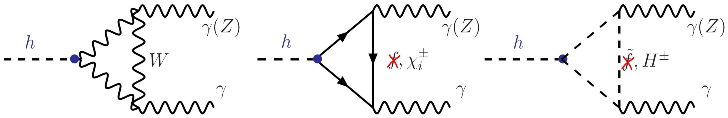
$$\mathbf{X} = \begin{pmatrix} M_2 & M_W \\ M_W & \frac{1}{\sqrt{2}}\lambda v_S \end{pmatrix}$$

Strategy



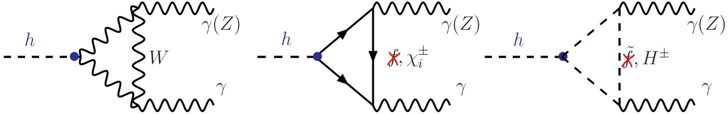
- relevant free parameters:
  $M_1 > 0, \; M_2 > 0, \; |\lambda|, \; |\mu| \equiv |\lambda v_S| / \sqrt{2}, \; \mathrm{sign}(\mu)$

Strategy



- relevant free parameters:
  $M_1 > 0$, $M_2 > 0$, $|\lambda|$, $|\mu| \equiv |\lambda v_S| / \sqrt{2}$, $\mathrm{sign}(\mu)$
- $M_h = \frac{|\lambda| v}{\sqrt{2}} = 125$ GeV, $M_1 = 100$ GeV
-
-

Strategy



- relevant free parameters:
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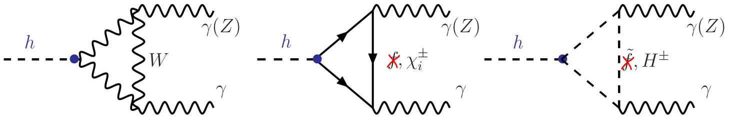
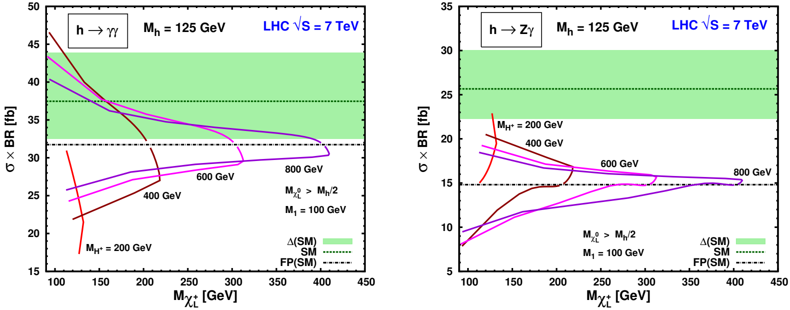
- $M_h = \frac{|\lambda| v}{\sqrt{2}} = 125$ GeV, $M_1 = 100$ GeV
- $(M_{H^\pm}, M_{\chi_L^+}) \to (|\mu|, M_2)$
-

Strategy



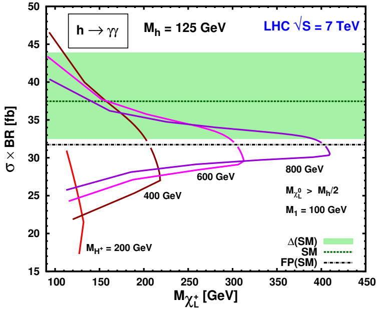
- relevant free parameters:
  $M_1 > 0, \;\; M_2 > 0, \;\; |\lambda|, \;\; |\mu| \equiv |\lambda v_S| / \sqrt{2}, \;\; \text{sign}(\mu)$
- $M_h = \frac{|\lambda| v}{\sqrt{2}} = 125 \text{ GeV}, \; M_1 = 100 \text{ GeV}$
- $(M_{H^\pm}, M_{\chi_L^+}) \to (|\mu|, M_2)$
- $M_{\chi_L^0} > M_h/2 \Rightarrow h \nrightarrow \chi_i \chi_j$
  $\Rightarrow R - \text{parity} \Rightarrow h \nrightarrow \chi_i^* \chi_j, \chi_i^* \chi_j^*$

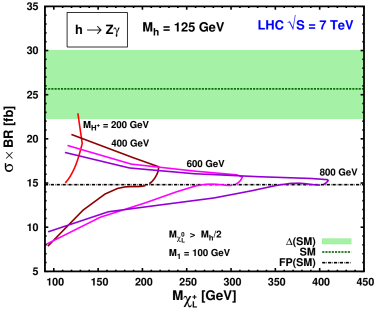
Signal rates @ LHC7



1. The lines above (below) the FP SM prediction for $h \to \gamma\gamma$ correspond to positive (negative) values the μ. For $h \to Z\gamma$ is the opposite.
2. For fixed $M_{\chi_L^+}$ two non-degenerates values of $M_{\chi_H^+}$ are possible. So there are always two solutions for the one-loop SUSY contribution.

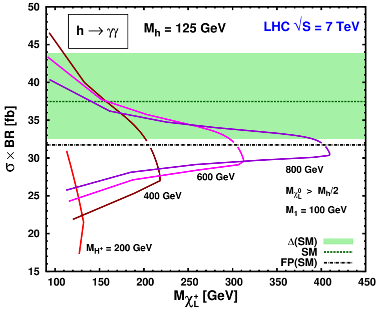
Signal rates @ LHC7





3. The dominant SUSY contribution comes from the $\chi^{\pm}$
4. The absence of points in the half-plane above (below) the FP(SM) line for $M_{H^+} = 200$ GeV in the case of $h \to \gamma\gamma$ ($h \to Z\gamma$), is due to the constraint $M_{\chi^0_L} > M_h/2$ and depends on our choice for $M_1 = 100$ GeV.

Signal rates @ LHC7



5. The present fits (1203.4254) indicate that the LHC observes fewer $\gamma\gamma$ events than predicted by the pure FP SM. FP NMSSM signal rates can be smaller than the FP SM predictions, so FP NMSSM allows a better fit to LHC data.

Conclusions

Results:

- Fermiophobic Higgs boson in MSSM is ruled out
- FP NMSSM is viable and Z_3 could explain fermiophobia
- 1-loop Higgs boson branching fractions and production rates in $\gamma\gamma$ and $Z\gamma$ can be sizably modified with respect to the FP SM, allowing a better fit to present collider data

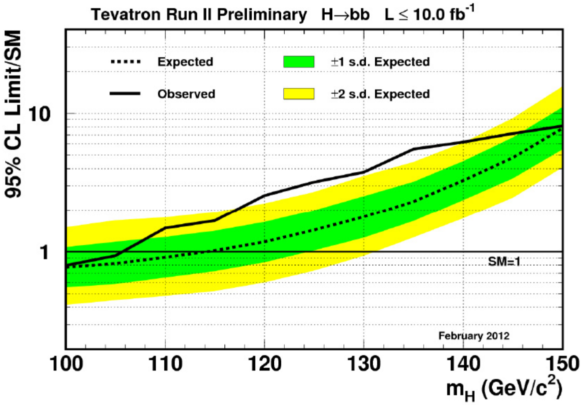
Future:

- Admitting the $s_R - h^0_{uR,dR}$ mixing the Higgs coupling to weak gauge boson WW and ZZ can be modified, and a suppression of the rates for $h \to WW^*$ and $h \to ZZ^*$ with respect to the pure FP model expectations can be achieved.
- Most of the previous analyses on SUSY particle searches should be revised in the light of the fact that the large top-Yukawa coupling is absent or strongly suppressed.

Thank you!

Backup slides

Tevatron


Tevatron Run II Preliminary H→bb L ≤ 10.0 fb-1
95% CL Limit/SM
Expected
Observed
±1 s.d. Expected
±2 s.d. Expected
SM=1
February 2012
mH (GeV/c2)
10
1
100
110
120
130
140
150

Fermion mass

The obvious question in any FP Higgs boson scenario is what is the alternative mechanism for generating the observed fermion masses. Because the top quark mass is so large, it cannot be generated radiatively. The most plausible scenario for generating such large fermion masses is strong dynamics above the electroweak scale. In such a scenario both the composite Higgs boson fermiophobia and fermion masses might originate from the same new physics. See: hep-ph/0703164, 1002.1011, 1012.1562, 1110.1613

A generic prediction of strong electroweak symmetry breaking scenarios, including composite Higgs models, is the appearance of new resonances at 2–3 TeV. We assume that such or any other new physics scenario above the electroweak scale generates the top quark mass.

XENON100

- In the MSSM the spin-independent dark matter scattering off nuclei is dominated by tree level Higgs boson exchange. Now this process is suppressed. The dominant dark matter scattering process is through WW exchange at one loop level. Scattering due to W-loops is too weak to be observed in the present stage of XENON100. As the SUSY scale could now be large, higgsino or wino relic abundance would become a natural explanation to the dark matter of the Universe.

Z_3 charge assignment

- $\mu H_u H_d$, S, S^2, $y_u Q H_u u^c$, $y_d H_d Q d^c$, $y_e H_d L e^c$ forbidden by:

$$\begin{aligned} X_Q + X_{H_u} + X_{u^c} &\neq 0 \mod N, \\ X_Q + X_{H_d} + X_{d^c} &\neq 0 \mod N, \\ X_L + X_{H_d} + X_{e^c} &\neq 0 \mod N, \\ X_{H_u} + X_{H_d} &\neq 0 \mod N, \\ X_S &\neq 0 \mod N, \\ 2X_S &\neq 0 \mod N, \end{aligned}$$

- $\lambda S H_u H_d$, $\frac{k}{3} S^3$ allowed by

$$\begin{aligned} 3X_S &= 0 \mod N, \\ X_S + X_{H_u} + X_{H_d} &= 0 \mod N \end{aligned}$$

Easiest: $X_{H_u} = X_{H_d} = X_S = 1$ and $X_{\rm fermion} = 0 \Rightarrow$ Yukawas via $\frac{H_u H_d}{\Lambda^2} Q H_d d^c \ldots$
Other: $X_{H_u} = X_{H_d} = X_S = 1$ and $X_{\rm fermion} = 2 \Rightarrow$ Yukawas via $\frac{S}{\Lambda} Q H_d d^c \ldots$.

Scalar potential minimization

Parametrization:

$$h_d^0 = \frac{1}{\sqrt{2}}\left(v_d + h_{dR}^0 + i h_{dI}^0\right) \qquad v^2 = v_u^2 + v_d^2$$

$$h_u^0 = \frac{1}{\sqrt{2}}\left(v_u + h_{uR}^0 + i h_{uI}^0\right) \qquad \tan\beta = \frac{v_u}{v_d}$$

$$s = \frac{1}{\sqrt{2}}\left(v_S + s_R + i s_I\right)$$

Minima equations:

$$v\Big(-4v_S \sin\beta\left(\sqrt{2}a_\lambda + k\lambda v_S\right) + \cos\beta\left(v^2\cos^3\beta\left(g_1^2+g_2^2\right) + 8m_{h_d}^2 + 4\lambda^2 v_S^2\right) - v^2\sin^2\beta\left(g_1^2+g_2^2-4\lambda^2\right)\Big) = 0$$

$$v\Big(-4v_S \cos\beta\left(\sqrt{2}a_\lambda + k\lambda v_S\right) + \sin\beta\left(v^2\sin^2\beta\left(g_1^2+g_2^2\right) + 8m_{h_u}^2 + 4\lambda^2 v_S^2\right) - v^2\sin\beta\cos^2\beta\left(g_1^2+g_2^2-4\lambda^2\right)\Big) = 0$$

$$v_S\left(\sqrt{2}a_k v_S + 2k^2 v_S^2 + \lambda^2 v^2 + 2m_S^2\right) - \frac{1}{4}v^2\sin 2\beta\left(\sqrt{2}a_\lambda + 2k\lambda v_S\right) = 0$$

CP even scalars

$$M_S^2 = \begin{pmatrix} M_{S,11}^2 & M_{S,12}^2 & M_{S,13}^2 \\ \dots & M_{S,22}^2 & M_{S,23}^2 \\ \dots & \dots & M_{S,33}^2 \end{pmatrix} \quad \text{in the basis } (h_{dR}^0, h_{uR}^0, s_R)$$

where

$$\begin{aligned}
M_{S,11}^2 &= m_{h_d}^2 + \frac{v_S^2\lambda^2}{2} + \frac{1}{8}v^2\left(g_1^2 + g_2^2 + 2\lambda^2 + 2\left(g_1^2 + g_2^2 - \lambda^2\right)\cos 2\beta\right) \\
M_{S,22}^2 &= m_{h_u}^2 + \frac{v_S^2\lambda^2}{2} + \frac{1}{8}v^2\left(g_1^2 + g_2^2 + 2\lambda^2 - 2\left(g_1^2 + g_2^2 - \lambda^2\right)\cos 2\beta\right) \\
M_{S,33}^2 &= m_S^2 + 3k^2v_S^2 + \sqrt{2}a_k v_S + v^2\left(\frac{\lambda^2}{2} - k\lambda\cos\beta\sin\beta\right) \\
M_{S,12}^2 &= \frac{1}{8}\left(-g_1^2 - g_2^2 + 4\lambda^2\right)\sin 2\beta v^2 - \frac{1}{2}kv_S^2\lambda - \frac{a_\lambda v_S}{\sqrt{2}} \\
M_{S,13}^2 &= vv_S\left(\lambda^2\cos\beta - k\lambda\sin\beta\right) - \frac{a_\lambda v\sin\beta}{\sqrt{2}} \\
M_{S,23}^2 &= vv_S\left(\lambda^2\sin\beta - k\lambda\cos\beta\right) - \frac{a_\lambda v\cos\beta}{\sqrt{2}}
\end{aligned}$$

CP even scalars eigenstates

$$h_1^0 = \frac{1}{\sqrt{2}}\left(h_{dR}^0 + h_{uR}^0\right) \qquad M_{h_1^0}^2 = \frac{\lambda^2 v^2}{2}$$

$$h_2^0 = \frac{1}{\sqrt{2}}\left(h_{dR}^0 - h_{uR}^0\right) \qquad M_{h_2^0}^2 = M_Z^2 + \frac{1}{2}\lambda^2\left(2v_S^2 - v^2\right)$$

$$M_{s_R}^2 = \frac{a_k v_S}{\sqrt{2}} + 2\lambda^2 v_S^2$$

Two distinct phenomenologically viable scenarios occur.

1. $M_{h_1^0}^2 < M_{h_2^0}^2 \quad \Rightarrow \quad h = h_1^0,\ H = h_2^0 \quad \Rightarrow \quad \alpha = -\pi/4 = \beta - \pi/2.$
   H does not have any direct tree level coupling to WW and ZZ that explains why the LHC does not see presently any other resonance but the lightest one at 125 GeV.
2. $M_{h_1^0}^2 > M_{h_2^0}^2 \quad \Rightarrow \quad h = h_2^0,\ H = h_1^0 \quad \Rightarrow \quad \alpha = \pi/4 = \beta.$
   LHC observed the second heaviest CP-even state because the couplings of the lightest one to fermions and to gauge bosons are strongly suppressed. Discovering such a light "sterile" Higgs boson is very difficult at the LHC.

Stable minimum conditions

We must ensure that all physical square masses are positive, which is equivalent to checking that our solution is a minimum of the potential. Moreover the constraint on $M^2_{H^\pm}$ implies that we are not breaking the $U(1)_{\rm em}$. So such a requirement will impose further constraints on the free parameters, that can be summarized as follows:

$$\text{sign}(a_k) = -\text{sign}(v_S), \quad |a_k| < 2\sqrt{2}\lambda^2 |v_S|$$

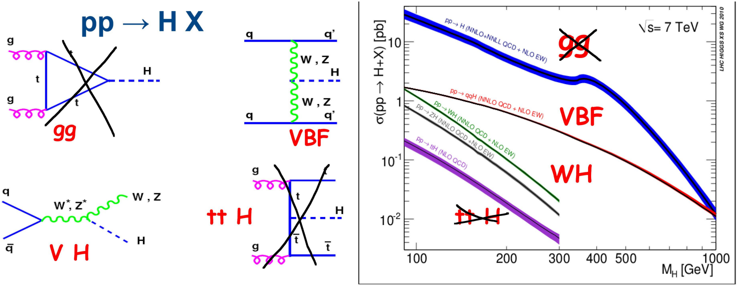
and one of the two following options

a) $v_S^2 > \frac{1}{2} v^2$,

b) $\frac{1}{2}\lambda^2 \left(v^2 - 2v_S^2\right) < M_W^2$.

From now on we shall assume that the lightest CP even scalar is the one coupled to the W's, thus $M^2_{h_1^0} < M^2_{h_2^0}$. Moreover we want also $M^2_{h_1^0} > M^2_Z$. This implies that the only available option is **a)**.

Higgs production. 7 TeV



inclusive x-sections (fb)

Heavy chargino double degeneracy

$$M_{\tilde{C}} = \begin{pmatrix} \mathbf{0} & \mathbf{X}^T \\ \mathbf{X} & \mathbf{0} \end{pmatrix} \qquad \mathbf{X} = \begin{pmatrix} M_2 & M_W \\ M_W & \mu \end{pmatrix} \qquad M^2_{H^\pm} \to \mu$$

$$M^2_{\chi^+_{L,H}} = \text{Eigenvalues}(\mathbf{X}^T\mathbf{X}) = \frac{1}{2}\left(\mu^2 + M_2^2 + 2M_W^2 \pm (\mu + M_2)\sqrt{(M_2 - \mu)^2 + 4M_W^2}\right)$$

$$\downarrow$$

Solve $M^2_{\chi^+_L}$ in function of M_2: 2nd degree eq. $\to$ 2 sols

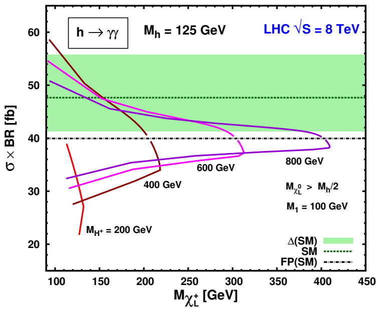
$$\downarrow$$

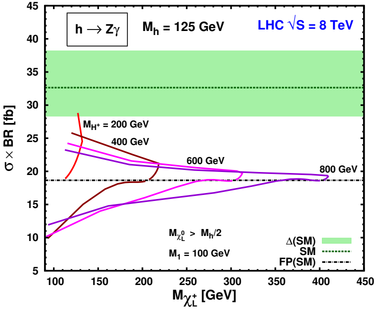
$$M_2 = \frac{M^4_{\chi^+_L} - M_W^2 \mp \mu M^2_{\chi^+_L}}{\pm M^2_{\chi^+_L} - \mu}$$

$$\Downarrow$$

$$\boxed{M^2_{\chi^+_H} = \frac{\left(\mu(\mu \pm M^2_{\chi^+_L}) + M_W^2\right)^2}{(\mu \pm M^2_{\chi^+_L})^2}}$$

Signal rates 8 TeV





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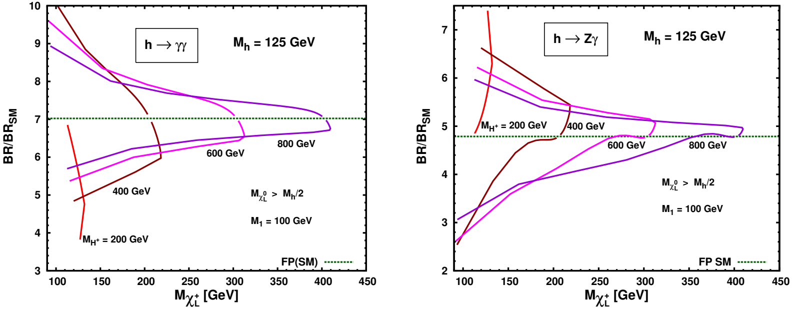
h → γγ
M_h = 125 GeV
BR/BR_SM
M_χL+ [GeV]
800 GeV
600 GeV
400 GeV
M_H+ = 200 GeV
M_χL0 > M_h/2
M_1 = 100 GeV
FP(SM)
h → Zγ
M_h = 125 GeV
BR/BR_SM
M_χL+ [GeV]
M_H+ = 200 GeV
400 GeV
600 GeV
800 GeV
M_χL0 > M_h/2
M_1 = 100 GeV
FP SM