Alternative futures for the Higgs data: are we approaching or receding from the decoupling limit?

Howard E. Haber

Outline

- Properties of the Higgs boson observed by ATLAS and CMS (with a cameo appearance by the Tevatron)

- The decoupling limit of the Higgs sector
  - Three independent mechanisms for departures from the decoupling limit
  - The decoupling limit of the general 2HDM
  - The decoupling limit of the MSSM Higgs sector
  - Are we approaching the decoupling limit?

- Hints of an excess in the $\gamma\gamma$ channel
  - Are we receding from the decoupling limit?
  - A model of nearly mass-degenerate scalars in the context of the two-Higgs doublet model (2HDM)
  - Scanning the 2HDM parameter space for viable regions consistent with an enhanced $\gamma\gamma$ signal
  - Testable consequences (an enhanced $\tau^+\tau^-$ signal and slightly different invariant masses in the $\gamma\gamma$ and the $ZZ^* \to$ 4 lepton channels)

- Conclusions

The LHC Discovery of 4 July 2012

The CERN update of the search for the Higgs boson, simulcast at ICHEP-2012 in Melbourne, Australia

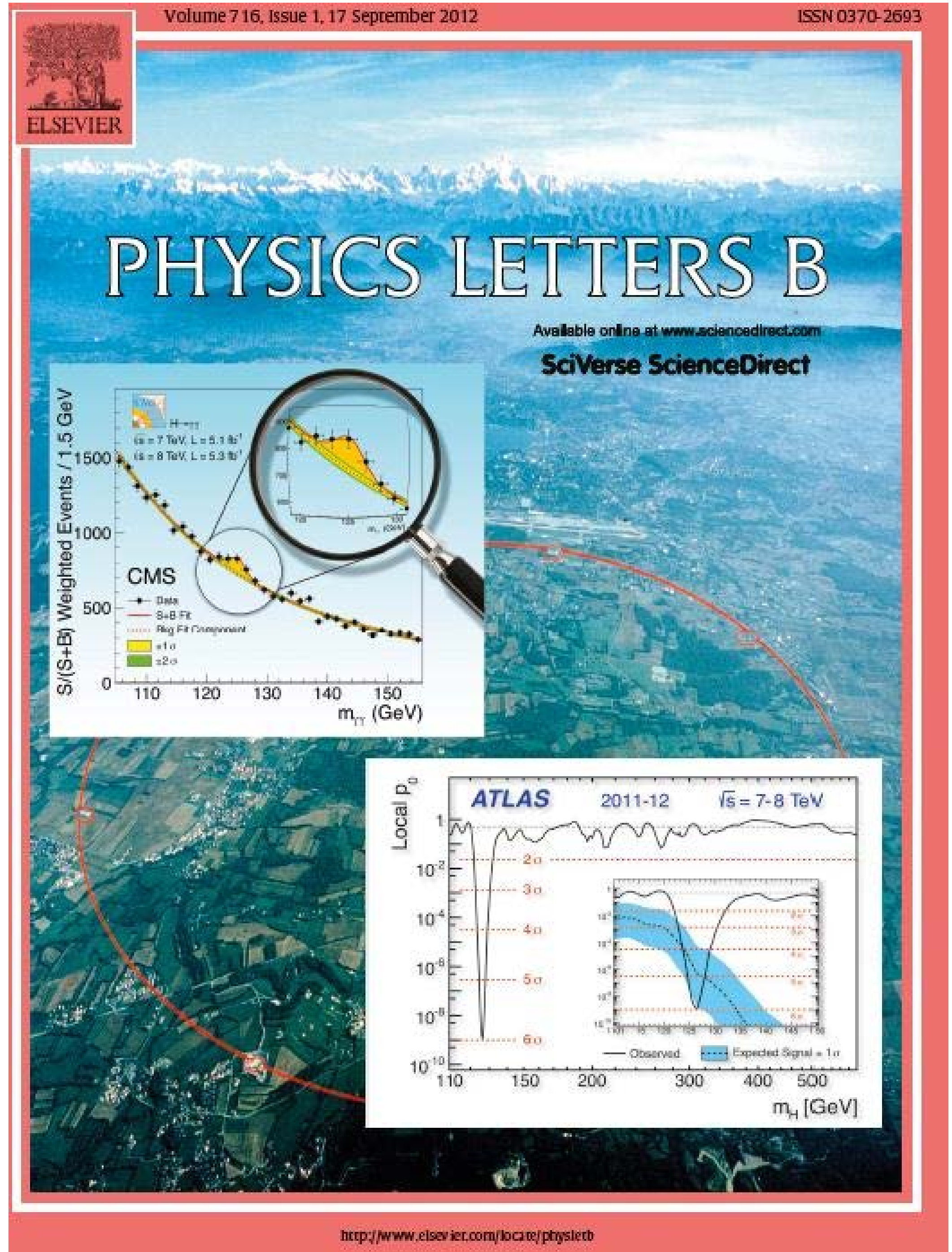
The discovery of the new boson is published in Physics Letters B.

<u>ATLAS Collaboration:</u>

Physics Letters B716 (2012) 1—29

<u>CMS Collaboration:</u>

Physics Letters B716 (2012) 30—61



A Higgs boson of mass 125 GeV

A new boson was born on the 4^{th} of July 2012. Its properties seem to be close to the ones predicted for the Standard Model (SM) Higgs boson. As further data comes in, some key questions must be addressed:

1. Is the spin of the new boson 0?

   - It cannot be spin 1, since the $\gamma\gamma$ decay mode is observed. In principle, it could be spin 2 (or higher). Fans of Kaluza-Klein excitations of the graviton would be thrilled if it turned out to be spin 2, although initial indications do not favor this spin assignment.

2. Is the new boson CP-even?

   - Ruling out a mixed-CP scalar may take a while.
   - A CP-odd assignment is presently disfavored by the data (although it is unlikely in light of its observed couplings to vector boson pairs).

3. Is it a Higgs boson?

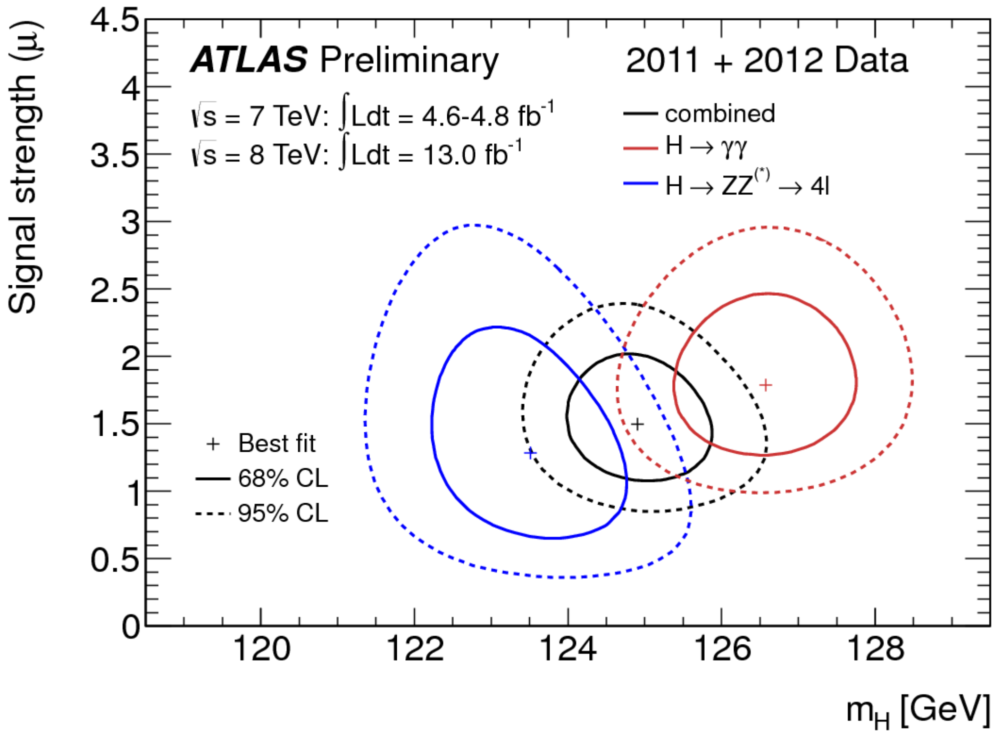
4. Is it *the* Higgs boson?

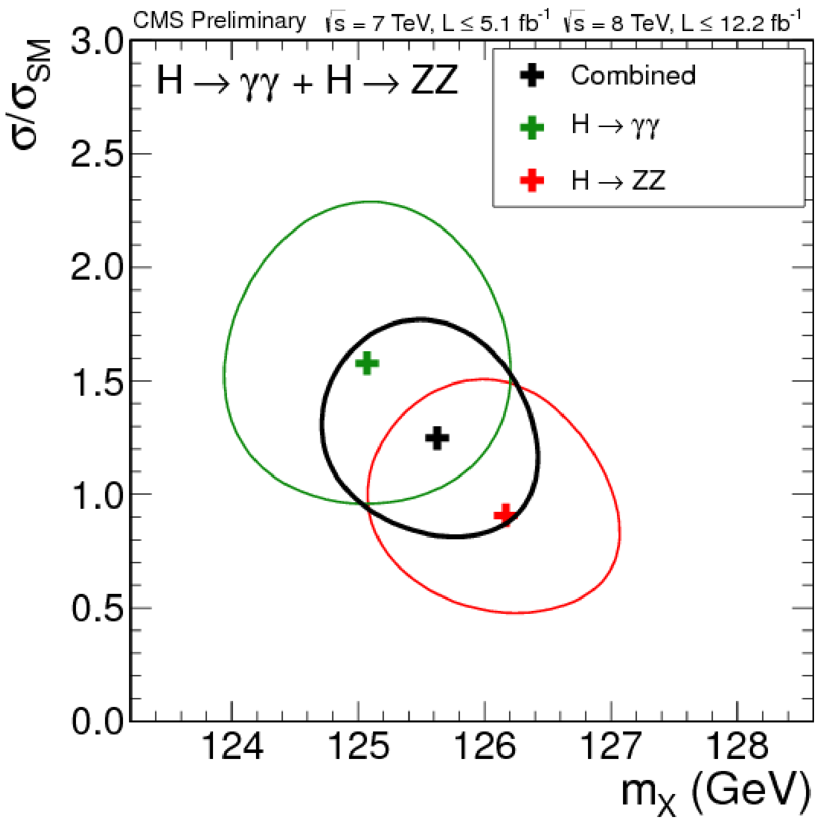
- We really want to know whether this state is completely responsible for repairing unitarity in the scattering of longitudinal gauge bosons, or whether it is one of a number of scalar states.

- We would also like to clarify the role of the new boson in the fermion mass mechanism.

The limited Higgs data set (as of December 2012) does not permit us to answer any of these questions definitively. Nevertheless, let us see what the present data indicates for the properties of the new boson, normalized to the corresponding properties of the SM Higgs boson.

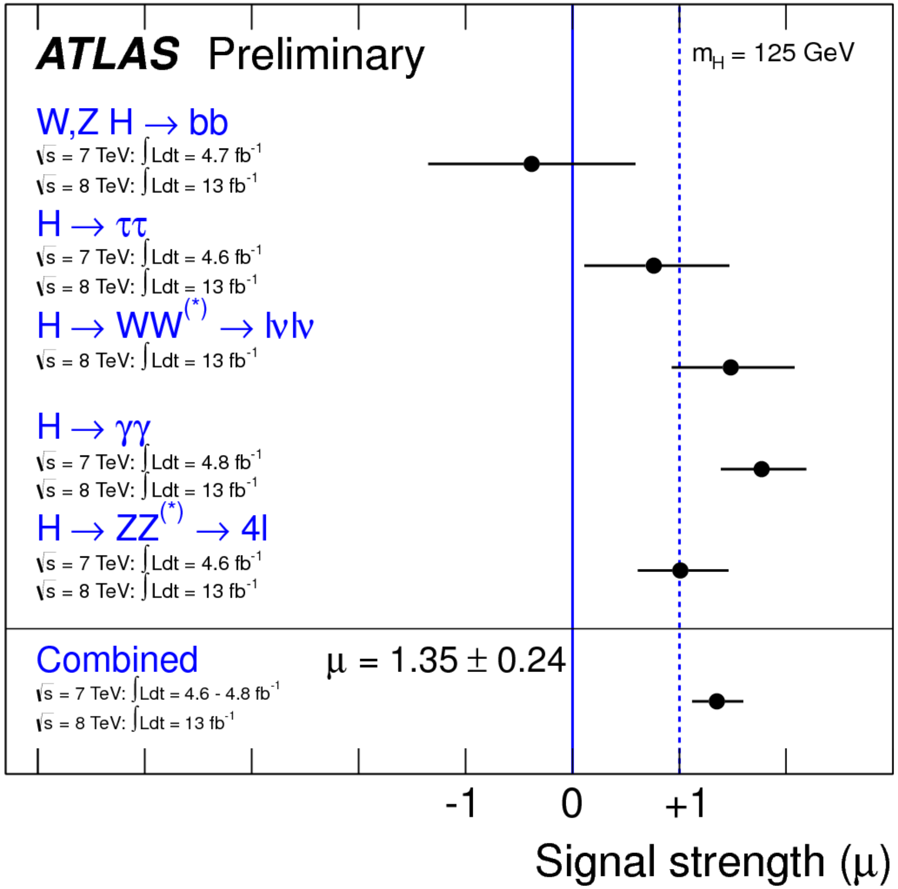
ATLAS and CMS mass determinations of the newly discovered boson

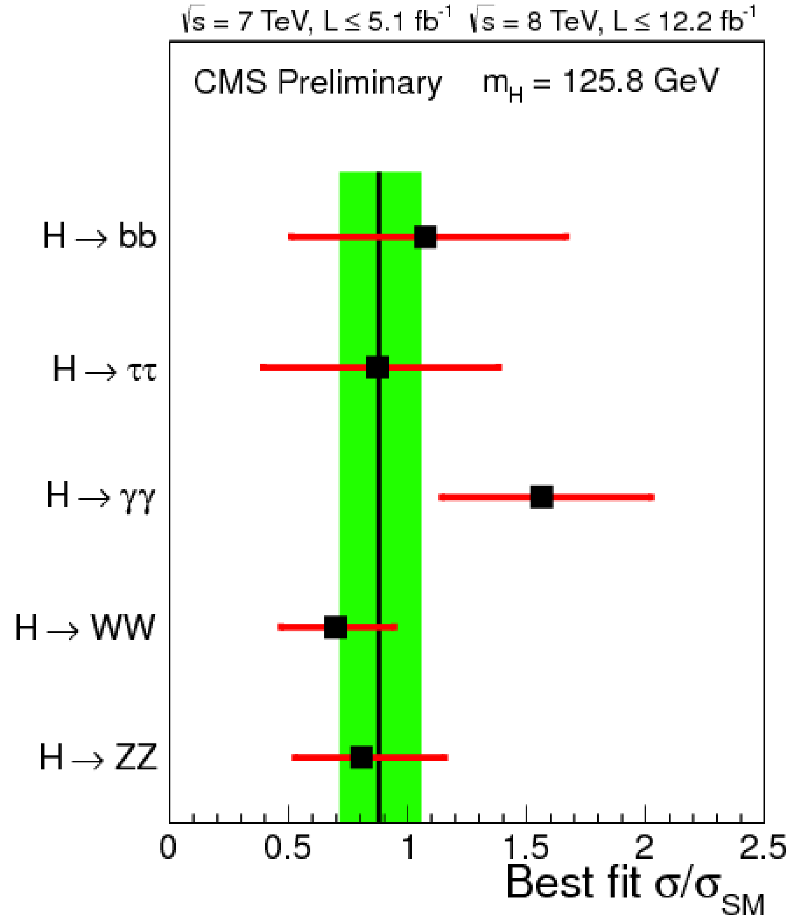




m_h = 125.2 ± 0.3 (stat) ± 0.6 (syst) GeV

m_h = 125.8 ± 0.4 (stat) ± 0.4 (syst) GeV



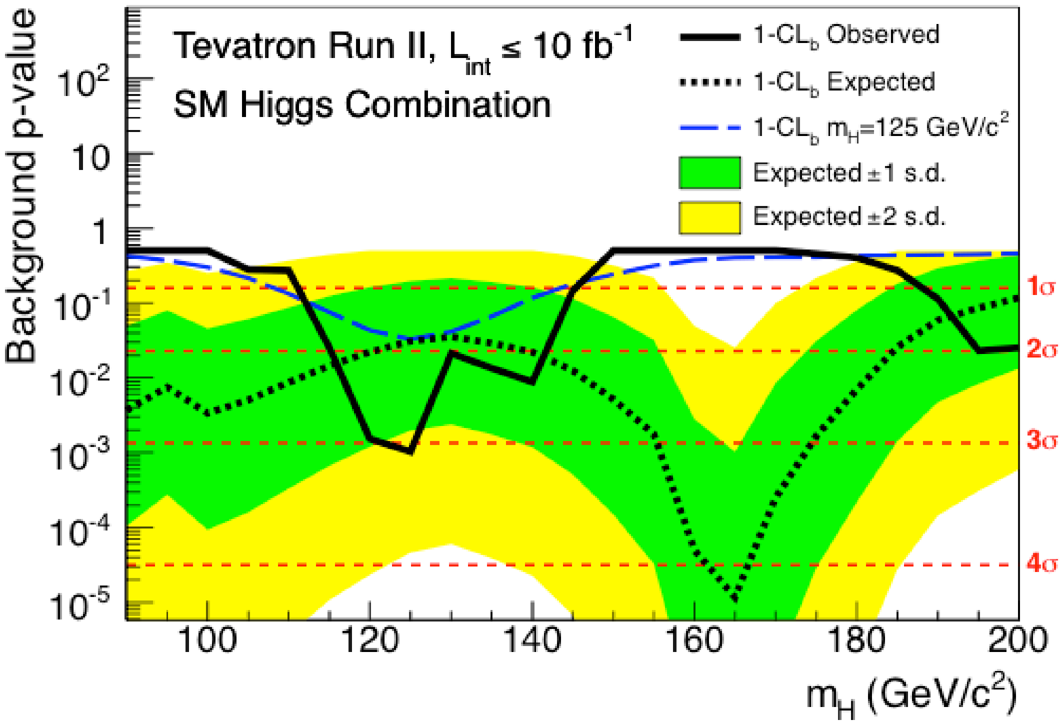


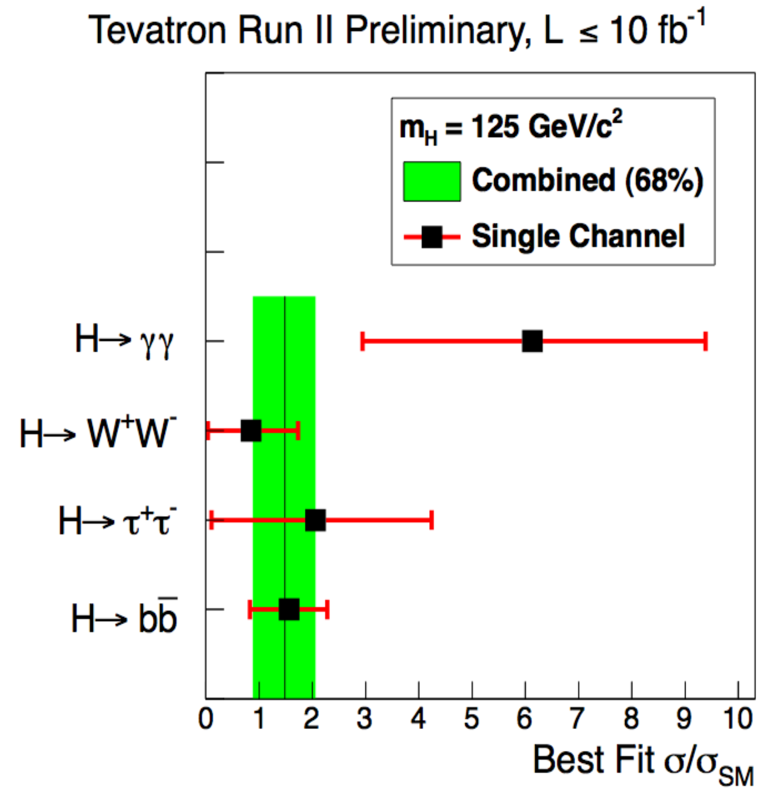
Summary of the individual and combined best-fit values of the strength parameter for a Higgs boson mass hypothesis of 125 GeV. Taken from ATLAS-CONF-2012-170, 13 December 2012.

The ATLAS γγ signal strength deviates from the Standard Model prediction by 2.4 σ.

Values of $\hat{\mu} = \sigma/\sigma_{SM}$ for the combination (solid vertical line) and for sub-combinations grouped by decay mode (points). The vertical band shows the overall $\hat{\mu}$ value 0.88 ± 0.21. The horizontal bars indicate the ±1σ uncertainties (both statistical and systematic) on the $\hat{\mu}$ values for individual channels. Taken from CMS-PAS-HIG-12-045, 16 November 2012.

Even the Tevatron has something to contribute





The local p-value distribution for background-only hypothesis, for the combination of the CDF and D0 analyses. The green and yellow bands correspond to the regions enclosing 1 σ and 2σ fluctuations around the median predicted value in the background-only hypothesis, respectively.

Best fit signal strength for a hypothesized Higgs boson mass of 125 GeV for the combination (black line) and for the three sub-combinations. The band corresponds to the ± 1σ uncertainties on the full combination.

Reference: Aurelio Juste, presentation at the HCP Symposium in Kyoto, Japan, November 15, 2012.

Interpretation of the Higgs coupling data

T. Plehn and M. Rauch,
"Higgs Couplings after the Discovery,"
Europhys.Lett. **100,** 11002 (2012).

Abstract

Following the ATLAS and CMS analyses presented around ICHEP 2012 we determine the individual Higgs couplings. The new data allow us to specifically test the effective coupling to photons. We find no significant deviation from the Standard Model in any of the Higgs couplings.

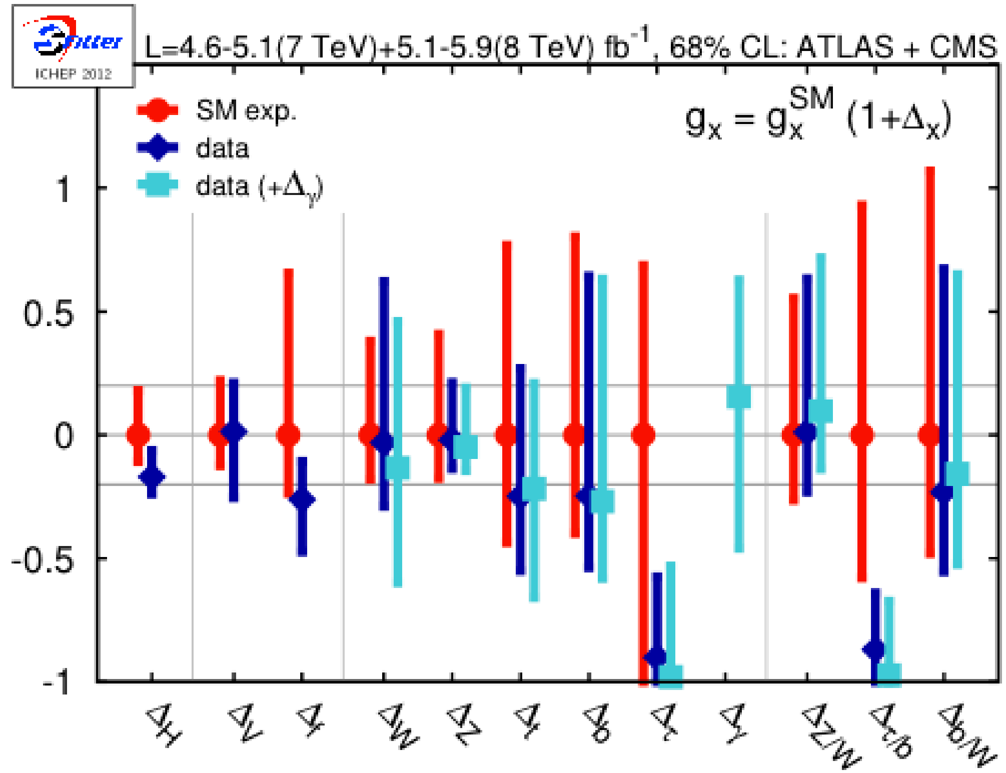
SFitter Higgs analyses — the general Higgs coupling analysis and its first application on data is comprehensively documented in Refs. [9, 10, 16]. * All tree-level Higgs couplings and their ratios are parameterized as

$$g_{xxH} \equiv g_x = (1+\Delta_x)\ g_x^{\mathrm{SM}}$$

$$\frac{g_{xxH}}{g_{yyH}} \equiv \frac{g_x}{g_y} = (1+\Delta_{x/y})\ \left(\frac{g_x}{g_y}\right)^{\mathrm{SM}} . \qquad (1)$$

For the loop-induced Higgs-photon coupling this means

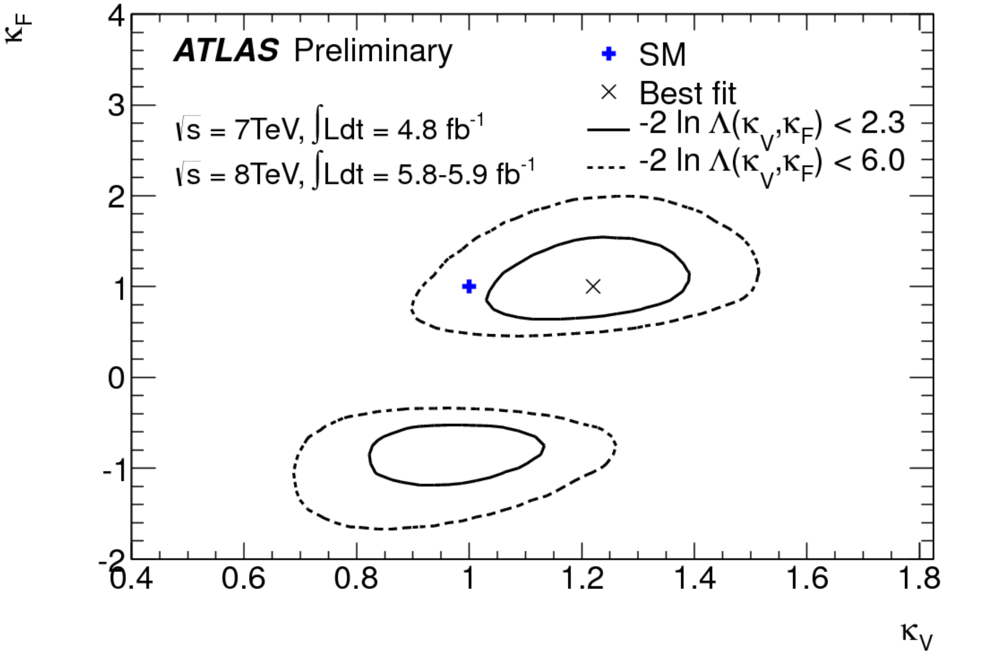
$$g_{\gamma\gamma H} \equiv g_\gamma = \left(1+\Delta_\gamma^{\mathrm{SM}}+\Delta_\gamma\right)\ g_\gamma^{\mathrm{SM}} . \qquad (2)$$



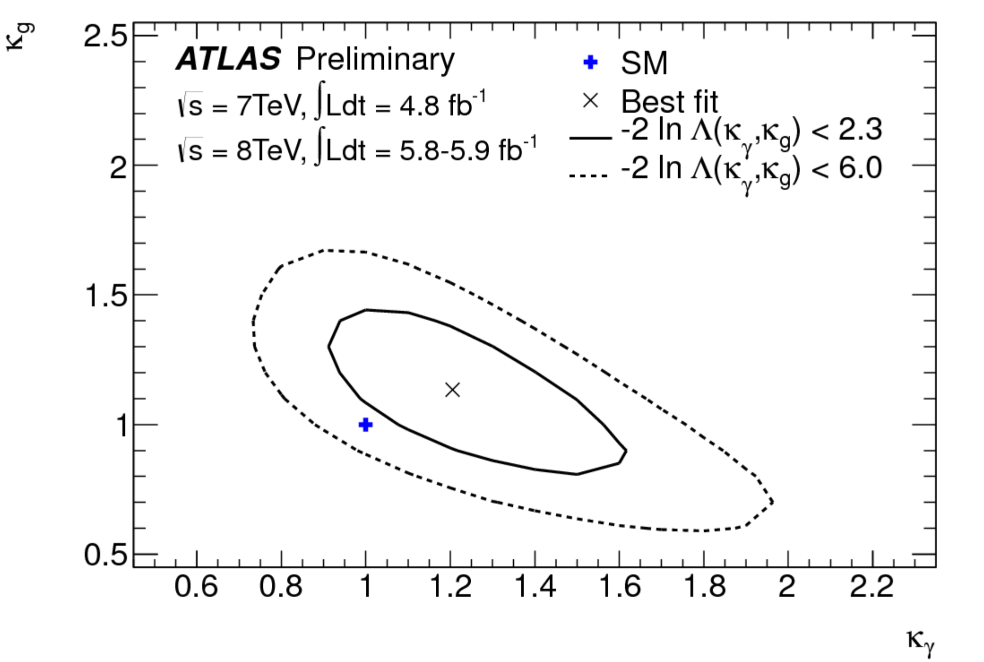
Results based on 2011 and initial 2012 data, for the SM signal expectation and for the data (m_H = 126 GeV). We also show the form factor result Δ_H and universal fermion and boson couplings $\Delta_{V;f}$. The band indicates a ±20% variation.

How well does ATLAS Higgs data fit the Standard Model expectations for Higgs couplings?

Top figure: Fits for 2-parameter benchmark models probing different Higgs coupling strength scale factors for fermions and vector bosons, under the assumption that there is a single coupling for all fermions t, b, τ (κ_F) and a single coupling for vector bosons (κ_V).

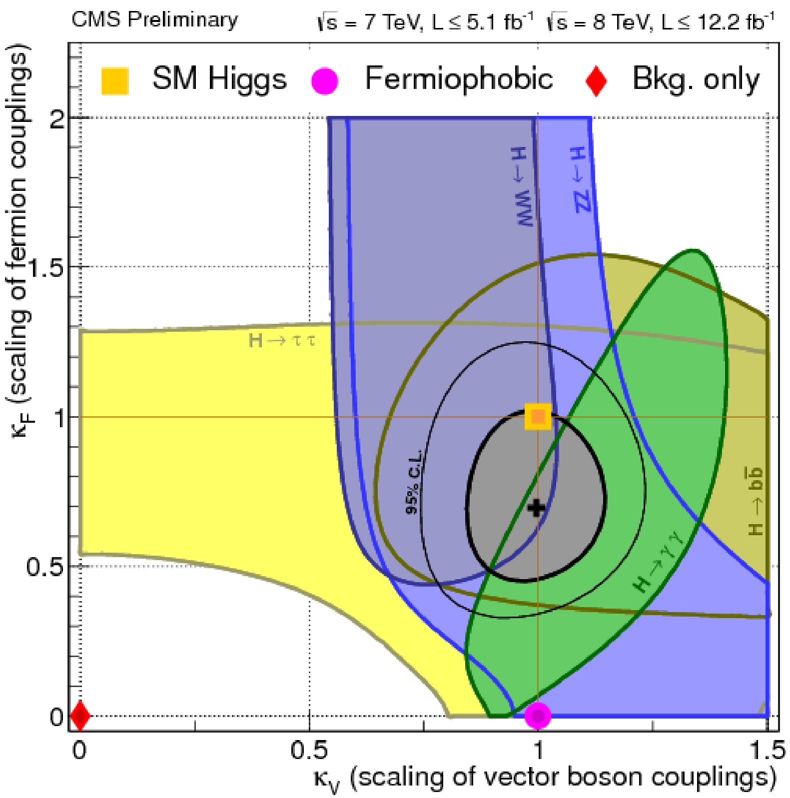


Bottom figure: Fits for benchmark models probing for contributions from non-Standard Model particles: probing only the gg → H and H→ γγ loops, assuming no sizable extra contribution to the total width. The magnitudes of the ggH and γγH couplings relative to their Standard Model values are denoted by κ_g and κ_γ.

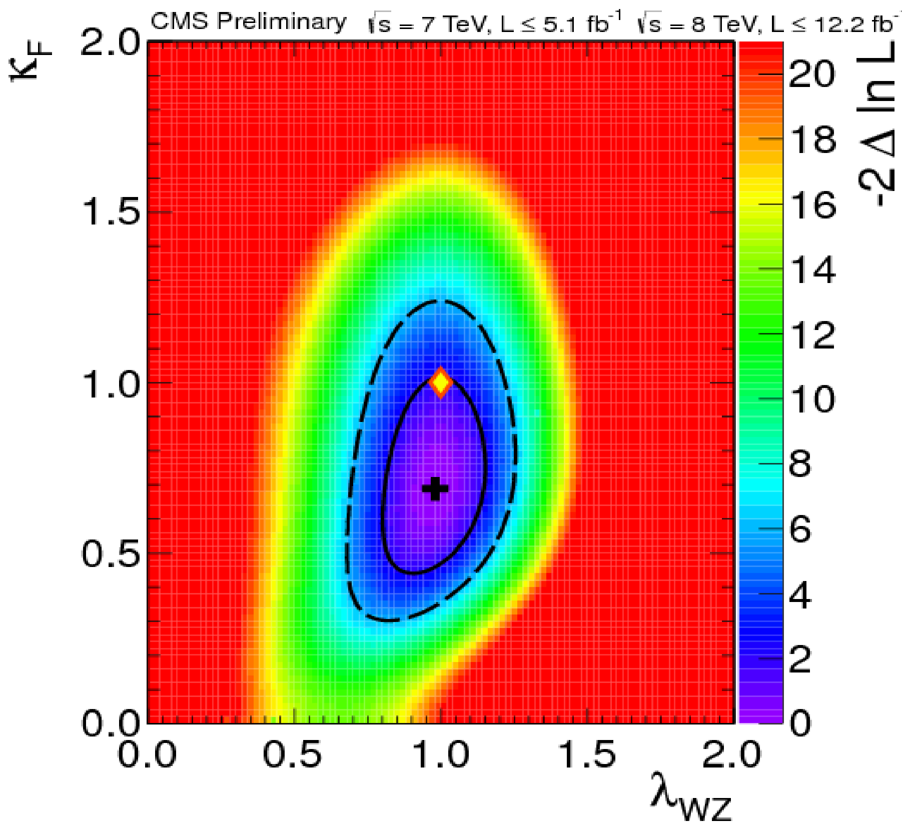


Reference:
ATLAS-CONF-2012-127 (September 9, 2012)

How well does CMS Higgs data fit the Standard Model expectations for Higgs couplings?



Tests of fermion and vector boson couplings of the Higgs boson. The Standard Model (SM) expectation is (κ_V , κ_F)=(1,1).



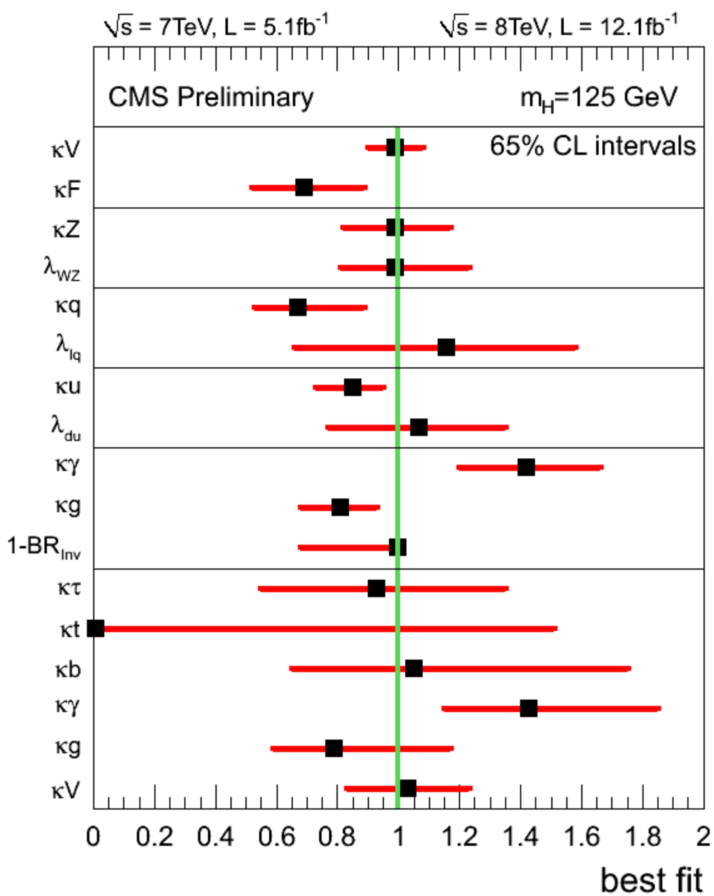
Test of custodial symmetry: the Standard Model expectation is $\lambda_{WZ} = \kappa_W / \kappa_Z = 1$.

Taken from: CMS-PAS-HIG-12-045, 16 November 2012.

CMS Higgs couplings summary

- Overall good compatibility with SM predictions
- Still limited precision

Marco Zanetti, presentation at HCP 2012, Kyoto



Model parameters	Assessed scaling factors (95% CL intervals)	
λ_{WZ}, κ_Z	λ_{WZ}	[0.57–1.65]
$\lambda_{WZ}, \kappa_Z, \kappa_f$	λ_{WZ}	[0.67–1.55]
κ_V	κ_V	[0.78–1.19]
κ_f	κ_f	[0.40–1.12]
κ_γ, κ_g	κ_γ	[0.98–1.92]
	κ_g	[0.55–1.07]
$\mathcal{B}(H \to BSM), \kappa_\gamma, \kappa_g$	$\mathcal{B}(H \to BSM)$	[0.00–0.62]
$\lambda_{du}, \kappa_V, \kappa_u$	λ_{du}	[0.45–1.66]
$\lambda_{\ell q}, \kappa_V, \kappa_q$	$\lambda_{\ell q}$	[0.00–2.11]
$\kappa_V, \kappa_b, \kappa_\tau, \kappa_t, \kappa_g, \kappa_\gamma$	κ_V	[0.58–1.41]
	κ_b	[not constrained]
	κ_τ	[0.00–1.80]
	κ_t	[not constrained]
	κ_g	[0.43–1.92]
	κ_γ	[0.81–2.27]

From G. Bélanger et al., arXiv 1212.5244, based on Higgs data through December, 2012.

"While the Standard Model does not provide a bad fit (χ^2/d.o.f.=0.96), it is more than 2σ away from our best fit solutions."

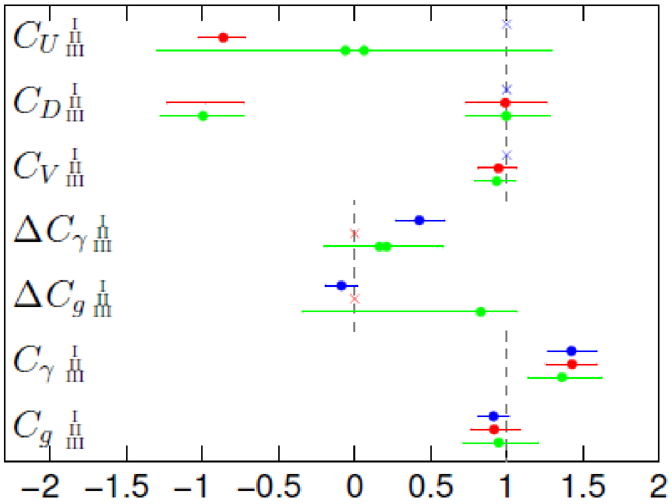


Figure 11: Graphical representation of the best fit values for C_U, C_D, C_V, ΔC_γ and ΔC_g of Table 4. The labels refer to the fits discussed in the text. The dashed lines indicate the SM value for the given quantity. The ×'s indicate cases where the parameter in question was fixed to its SM value.

Fit	I	II, $C_U < 0$	II, $C_U > 0$	III
$\widehat{\mu}(\text{ggF}, \gamma\gamma)$	$1.71^{+0.33}_{-0.32}$	$1.81^{+0.43}_{-0.41}$	1.07 ± 0.18	$1.79^{+0.36}_{-0.34}$
$\widehat{\mu}(\text{ggF}, ZZ)$	$0.84^{+0.18}_{-0.17}$	0.79 ± 0.15	0.97 ± 0.20	$0.84^{+0.21}_{-0.18}$
$\widehat{\mu}(\text{ggF}, b\bar{b})$	$0.84^{+0.18}_{-0.17}$	$0.87^{+0.57}_{-0.40}$	$0.63^{+0.36}_{-0.26}$	$0.96^{+0.59}_{-0.43}$
$\widehat{\mu}(\text{VBF}, \gamma\gamma)$	$2.05^{+0.54}_{-0.44}$	$1.92^{+0.78}_{-0.68}$	$1.66^{+0.70}_{-0.63}$	$1.74^{+0.84}_{-0.73}$
$\widehat{\mu}(\text{VBF}, ZZ)$	1.00 ± 0.02	$0.84^{+0.42}_{-0.36}$	$1.50^{+0.50}_{-0.46}$	$0.82^{+0.38}_{-0.35}$
$\widehat{\mu}(\text{VBF}, b\bar{b})$	1.00 ± 0.02	0.92 ± 0.30	0.98 ± 0.32	$0.93^{+0.25}_{-0.29}$

Table 8: Summary of $\widehat{\mu}$ results for Fits I–III. For Fit II, the tabulated results are for the best fit with $C_U < 0$, column 1 of Table 5, and for the case $C_U, C_D > 0$, column 3 of Table 5.

The Decoupling Limit of the Higgs sector

The Higgs boson serves as a window to physics beyond the Standard Model (SM) only if one can experimentally establish deviations of Higgs couplings from their SM values, or discover new scalar degrees of freedom beyond the SM-like Higgs boson. The prospects to achieve this are challenging in general due to the decoupling limit.

In extended Higgs models (as well as in some alternative models of electroweak symmetry breaking), most of the parameter space typically yields a neutral CP-even Higgs boson with SM-like tree-level couplings and additional scalar states that are somewhat heavier in mass (of order Λ_H), with small mass splittings of order $(m_Z/\Lambda_H)\, m_Z$. Below the scale Λ_H, the effective Higgs theory is the SM.

Interpreting the LHC Higgs data and the decoupling limit

- It is important to distinguish two energy scales:

  - Λ_H : the scale of the heavy non-minimal Higgs bosons.
  - Λ_{NP} : the scale of new physics beyond the Higgs-extended SM.

- The departure from the decoupling limit can receive contributions from both the heavy Higgs states via tree-level mixing and from new physics via one-loop radiative correction effects.

  - Separating out these two effects if deviations from SM Higgs couplings are confirmed will be important (and challenging).

Other mechanisms for departures from SM-like behavior

- Since $H^\dagger H$ is an singlet with respect to the electroweak gauge group, the effective Lagrangian
$$\mathscr{L}_{\rm int} = \lambda H^\dagger H f(\phi, \psi, A_\mu)$$
can exhibit both renormalizable and nonrenormalizable interactions with electrowek gauge singlet fields ϕ, ψ and A_μ. This is the Higgs portal.

- Decoupling is achieved in the limit of $\lambda \to 0$. Thus, small deviations from decoupling can result from small λ as well as from effects of new physics associated with higher mass scales.

- The Higgs boson can also couple to new light states with electroweak quantum numbers (e.g. the lightest neutralino of SUSY).

- For example, the decay properties of the SM-like Higgs boson would be modified if a new decay channel into invisible states is present.

The two-Higgs doublet model (2HDM) provides a laboratory for studying the phenomenology of an extended Higgs sector and possible departures from the decoupling limit.

- It is often motivated by the MSSM, which requires a second Higgs doublet in order to cancel anomalies that arise from Higgsino partners.

- The MSSM also provides a scale of new physics beyond the Higgs-extended Standard Model that can also generate deviations from SM-like Higgs behavior.

Start with the 2HDM fields, Φ_1 and Φ_2, in a generic basis, where $\langle\Phi_i\rangle = v_i$, and $v^2 \equiv |v_1|^2 + |v_2|^2 = (246\ \text{GeV})^2$. It is convenient to define new Higgs doublet fields:

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1^*\Phi_1 + v_2^*\Phi_2}{v}\,, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v}\,.$$

It follows that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$. This is the *Higgs basis*, which is uniquely defined up to an overall rephasing, $H_2 \to e^{i\chi} H_2$. In the Higgs basis, the scalar potential is given by:

$$\begin{aligned}\mathcal{V} = {} & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 \\ & + \tfrac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{ \tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \left[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2)\right] H_1^\dagger H_2 + \text{h.c.} \right\}\,,\end{aligned}$$

where Y_1, Y_2 and $Z_1, \ldots, Z_4$ are real and uniquely defined, whereas Y_3, Z_5, Z_6 and Z_7 are complex and transform under the rephasing of H_2,

$$[Y_3, Z_6, Z_7] \to e^{-i\chi}[Y_3, Z_6, Z_7] \quad \text{and} \quad Z_5 \to e^{-2i\chi} Z_5\,.$$

The Higgs mass-eigenstate basis

The physical charged Higgs boson is the charged component of the Higgs-basis doublet H_2, and its mass is given by $m^2_{H^\pm} = Y_2 + \frac{1}{2}Z_3 v^2$.

The three physical neutral Higgs boson mass-eigenstates are determined by diagonalizing a 3×3 real symmetric squared-mass matrix that is defined in the Higgs basis.

$$\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & \mathrm{Re}(Z_6) & -\mathrm{Im}(Z_6) \\ \mathrm{Re}(Z_6) & \frac{1}{2}Z_{345} + Y_2/v^2 & -\frac{1}{2}\mathrm{Im}(Z_5) \\ -\mathrm{Im}(Z_6) & -\frac{1}{2}\mathrm{Im}(Z_5) & \frac{1}{2}Z_{345} - \mathrm{Re}(Z_5) + Y_2/v^2 \end{pmatrix},$$

where $Z_{345} \equiv Z_3 + Z_4 + \mathrm{Re}(Z_5)$.The diagonalizing matrix is a 3×3 real orthogonal matrix that depends on three angles: θ_{12}, θ_{13} and θ_{23}. Under the rephasing $H_2 \to e^{i\chi} H_2$,

$$\theta_{12}\,,\ \theta_{13} \text{ are invariant, and} \quad \theta_{23} \to \theta_{23} - \chi\,.$$

The Decoupling Limit of the 2HDM

In the decoupling limit, one of the two Higgs doublets of the 2HDM receives a very large mass which then decouples from the theory. This is achieved when $Y_2 \gg v^2$ and $|Z_i| \lesssim \mathcal{O}(1)$ [for all i]. The effective low energy theory is a one-Higgs-doublet model, which yields the SM Higgs boson.

We order the neutral scalar masses according to $m_1 < m_{2,3}$ and define the Higgs mixing angles accordingly. The conditions for the decoupling limit are:

$$|\sin\theta_{12}| \lesssim \mathcal{O}\left(\frac{v^2}{m_2^2}\right) \ll 1\,, \qquad |\sin\theta_{13}| \lesssim \mathcal{O}\left(\frac{v^2}{m_3^2}\right) \ll 1\,,$$

$$\operatorname{Im}(Z_5\, e^{-2i\theta_{23}}) \lesssim \mathcal{O}\left(\frac{v^2}{m_3^2}\right) \ll 1\,.$$

In the decoupling limit, $m_1 \ll m_2, m_3, m_{H^\pm}$. In particular, the properties of h_1 coincide with the SM Higgs boson with $m_1^2 = Z_1 v^2$ up to corrections of $\mathcal{O}(v^4/m_{2,3}^2)$, and $m_2 \simeq m_3 \simeq m_{H^\pm}$ with squared mass splittings of $\mathcal{O}(v^2)$.

Higgs-fermion Yukawa couplings in the 2HDM

In the Higgs basis, $\kappa^{U,D}$ and $\rho^{U,D}$, are the 3×3 Yukawa coupling matrices,

$$-\mathscr{L}_{\rm Y} = \overline{U}_L(\kappa^U H_1^{0\,\dagger} + \rho^U H_2^{0\,\dagger})U_R - \overline{D}_L K^\dagger(\kappa^U H_1^- + \rho^U H_2^-)U_R$$
$$+\overline{U}_L K(\kappa^{D\,\dagger} H_1^+ + \rho^{D\,\dagger} H_2^+)D_R + \overline{D}_L(\kappa^{D\,\dagger} H_1^0 + \rho^{D\,\dagger} H_2^0)D_R + \text{h.c.},$$

where $U=(u,c,t)$ and $D=(d,s,b)$ are the physical quark fields and K is the CKM mixing matrix. (Repeat for the leptons.)

By setting $H_1^0 = v/\sqrt{2}$ and $H_2^0=0$, one obtains the quark mass terms. Hence, κ^U and κ^D are proportional to the diagonal quark mass matrices M_U and M_D, respectively,

$$M_U = \frac{v}{\sqrt{2}}\kappa^U = \text{diag}(m_u\,,\,m_c\,,\,m_t)\,, \qquad M_D = \frac{v}{\sqrt{2}}\kappa^{D\,\dagger} = \text{diag}(m_d\,,\,m_s\,,\,m_b)\,.$$

Note that $\rho^Q \to e^{-i\chi}\rho^Q$ under the rephasing $H_2 \to e^{i\chi}H_2$, (for $Q=U,D$).

In general ρ^Q is a complex non-digaonal matrix. As a result, the most general 2HDM exhibits tree-level Higgs-mediated FCNCs and new sources of CP-violation in the interactions of the neutral Higgs bosons.

In the decoupling limit where $m_1 \ll m_{2,3}$, CP-violating and tree-level Higgs-mediated FCNCs are suppreseed by factors of $\mathcal{O}(v^2/m^2_{2,3})$. In contrast, the interactions of the heavy neutral Higgs bosons (h_2 and h_3) and the charge Higgs bosons ($H^\pm$) in the decoupling limit can exhibit both CP-violating and quark flavor non-diagonal couplings (proportional to ρ^Q).

How to avoid tree-level Higgs-mediated FCNCs

- Arbitrarily declare ρ^U and ρ^D to be diagonal matrices. This is an unnaturally fine-tuned solution.

- Impose a discrete symmetry or supersymmetry (e.g."Type-I" or "Type-II" Higgs-fermion interactions), which selects out a special basis of the 2HDM scalar fields. In this case, ρ^Q is automatically proportional to M_Q (for $Q = U, D, L$), and is hence diagonal.

- Impose alignment without a symmetry: $\rho^Q = \alpha^Q \kappa^Q \,, (Q = U, D, L)\,$, where the α^Q are complex scalar parameters [e.g. see Pich and Tuzon (2009)].

- Impose the decoupling limit. Tree-level Higgs-mediated FCNCs will be suppressed by factors of squared-masses of heavy Higgs states. (How heavy is sufficient?)

The CP-conserving 2HDM with Type I or II Yukawa couplings

The scalar potential exhibits a $\mathbb{Z}_2$ symmetry that is at most softly broken,

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \tfrac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \tfrac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2$$
$$+\lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \left[\tfrac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right],$$

where m_{12}^2 and λ_5 are real. The most general Yukawa Lagrangian, in terms of the quark mass-eigenstate fields, is:

$$-\mathscr{L}_Y = \overline{U}_L \widetilde{\Phi}_a^0 \eta_a^U U_R + \overline{D}_L K^\dagger \widetilde{\Phi}_a^- \eta_a^U U_R + \overline{U}_L K \Phi_a^+ \eta_a^{D\,\dagger} D_R + \overline{D}_L \Phi_a^0 \eta_a^{D\,\dagger} D_R + \text{h.c.},$$

where $a = 1, 2$, $\widetilde{\Phi}_a \equiv (\widetilde{\Phi}^0\,,\,\widetilde{\Phi}^-) = i\sigma_2 \Phi_a^*$ and K is the CKM mixing matrix. The $\eta^{U,D}$ are 3×3 Yukawa coupling matrices.

Type-I Yukawa couplings: $\eta_1^U = \eta_1^D = 0$.

	h^0	A^0	H^0
up-type quarks	$\cos\alpha/\sin\beta$	$\cot\beta$	$\sin\alpha/\sin\beta$
down-type quarks and leptons	$\cos\alpha/\sin\beta$	$-\cot\beta$	$\sin\alpha/\sin\beta$

Type-II Yukawa couplings: $\eta_1^U = \eta_2^D = 0$ [employed by the MSSM].

	h^0	A^0	H^0
up-type quarks	$\cos\alpha/\sin\beta$	$\cot\beta$	$\sin\alpha/\sin\beta$
down-type quarks and leptons	$-\sin\alpha/\cos\beta$	$\tan\beta$	$\cos\alpha/\cos\beta$

Here, α is the CP-even Higgs mixing angle and $\tan\beta = v_u/v_d$. The h^0 and H^0 are CP-even neutral Higgs bosons with $m_{h^0} \leq m_{H^0}$ and A^0 is a CP-odd neutral Higgs boson.

Example: decoupling of the non-minimal Higgs bosons of the MSSM Higgs sector (tree-level analysis)

In the limit of $m_A \gg m_Z$, the expressions for the Higgs masses and mixing angle simplify and one finds

$$
\begin{aligned}
m_h^2 &\simeq m_Z^2 \cos^2 2\beta \,, \\
m_H^2 &\simeq m_A^2 + m_Z^2 \sin^2 2\beta \,, \\
m_{H^\pm}^2 &= m_A^2 + m_W^2 \,, \\
\cos^2(\beta - \alpha) &\simeq \frac{m_Z^4 \sin^2 4\beta}{4m_A^4} \,.
\end{aligned}
$$

Two consequences are immediately apparent. First, $m_A \simeq m_H \simeq m_{H^\pm}$, up to corrections of $\mathcal{O}(m_Z^2/m_A)$. Second, $\cos(\beta - \alpha) = 0$ up to corrections of $\mathcal{O}(m_Z^2/m_A^2)$. This is the decoupling limit, since at energy scales below approximately common mass of the heavy Higgs bosons $H^\pm$ H^0, A^0, the effective Higgs theory is precisely that of the SM.

In the limit of $\cos(\beta-\alpha)\to 0$, all the h^0 couplings to SM particles approach their SM limits. In particular, if λ_V is a Higgs coupling to vector bosons and λ_f is a Higgs couplings to fermions, then

$$\frac{\lambda_V}{[\lambda_V]_{\rm SM}} = \sin(\beta-\alpha) = 1+\mathcal{O}\left(m_Z^4/m_A^4\right)\,, \qquad \frac{\lambda_f}{[\lambda_f]_{\rm SM}} = 1+\mathcal{O}\left(m_Z^2/m_A^2\right)\,.$$

The MSSM employs Type-II Higgs-fermion interactions. The behavior of the $h^0 ff$ couplings is:

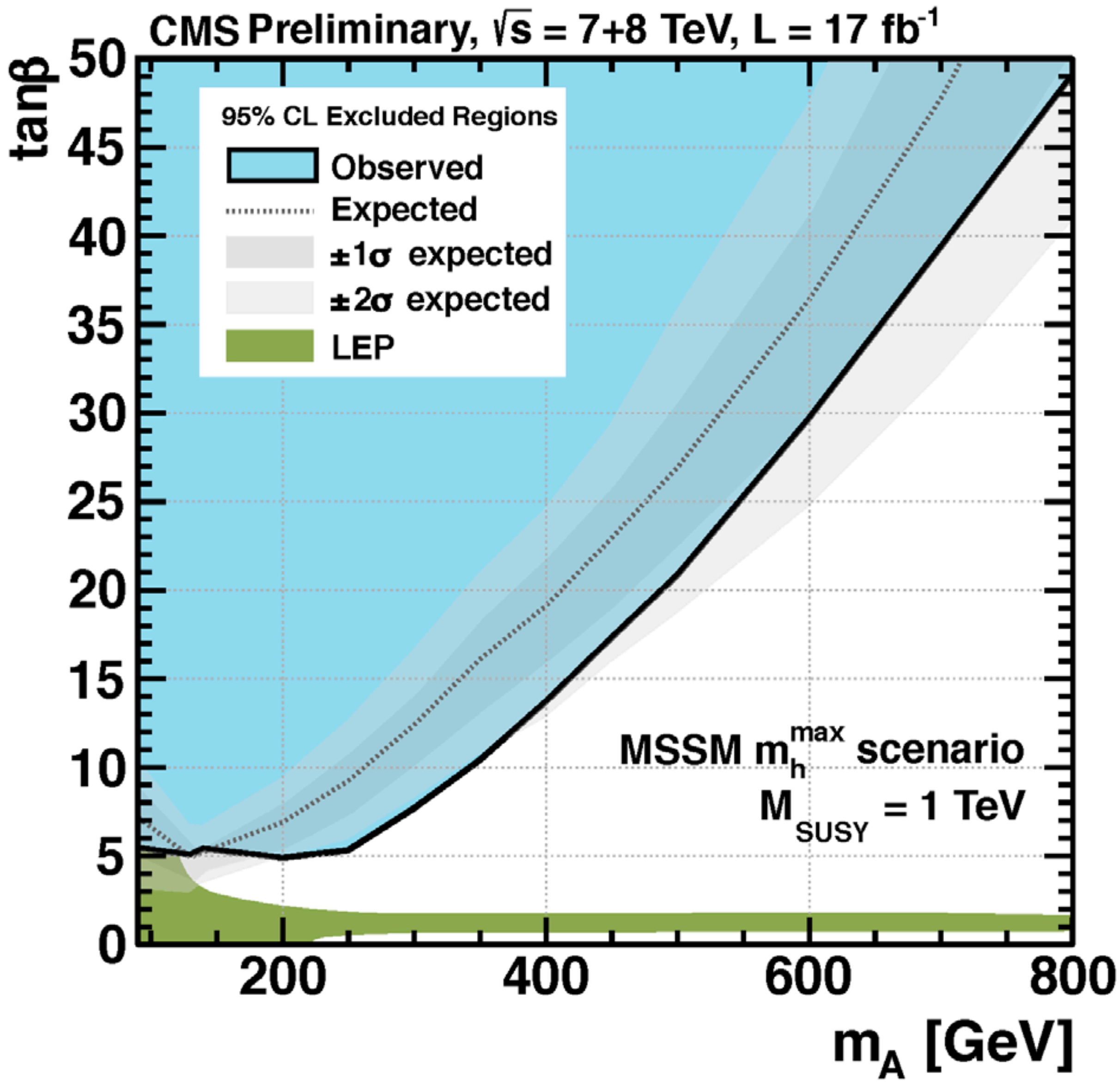
$$h^0 b\bar{b} \quad (\text{or } h^0\tau^+\tau^-): \qquad -\frac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\,,$$

$$h^0 t\bar{t}: \qquad \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\,.$$

Note the extra $\tan\beta$ enhancement in the deviation of λ_{hbb} from $[\lambda_{hbb}]_{\rm SM}$.

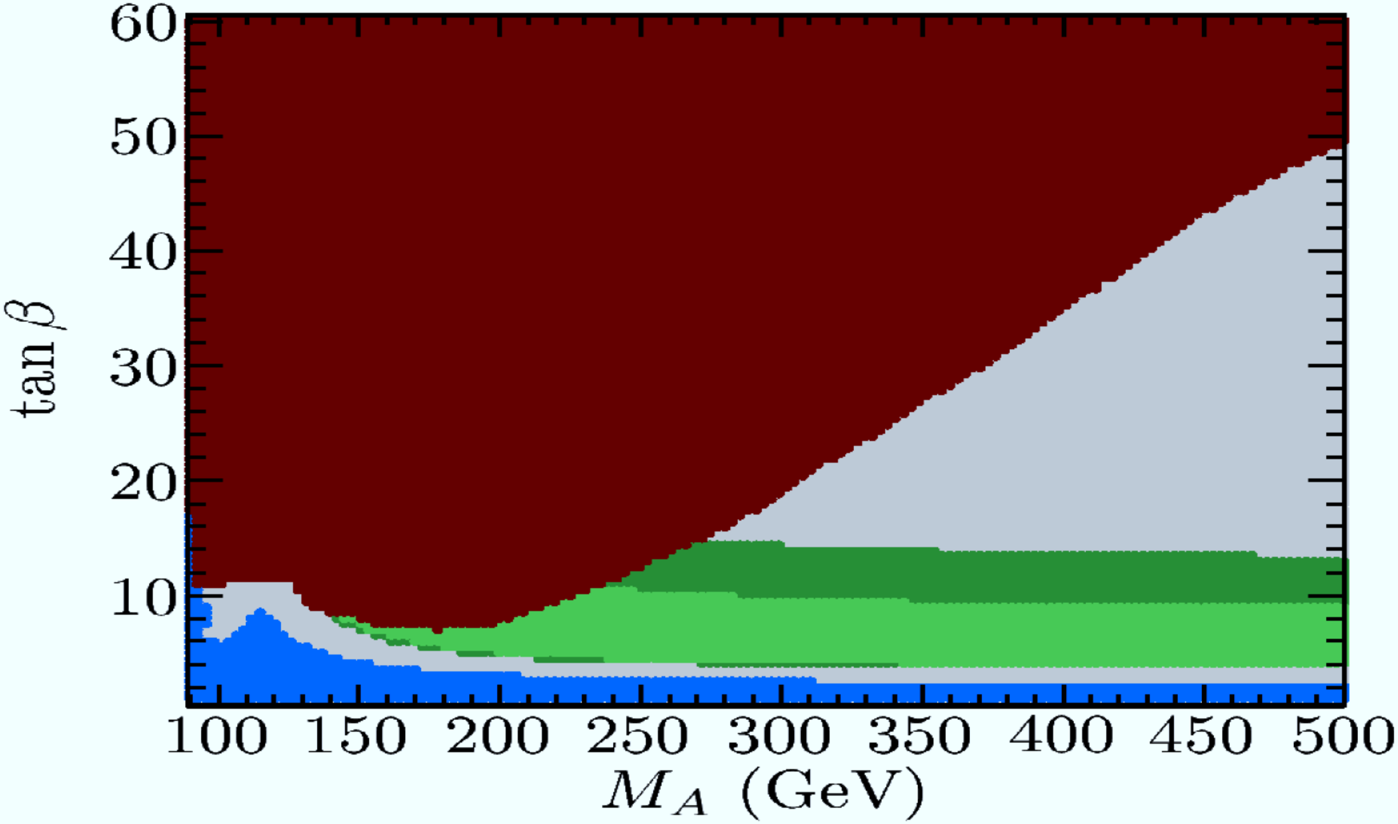
Thus, the approach to decoupling is fastest for the h^0VV couplings, and slowest for the couplings of h^0 to down-type quarks and leptons (if $\tan\beta$ is large).

More evidence for the decoupling limit?



Lower bounds on M_A *and* $\tan\beta$ *from interpreting signal at* ~ 126 GeV *as light MSSM Higgs boson* h

Red: LHC limits from $H, A \to \tau^+\tau^-$ search; Blue: LEP limits
Green: compatible with interpreting signal at 126 GeV as light MSSM Higgs h ($+\, m_t$ variation) [*S. Heinemeyer, O. Stål, G. W. '11, '12*]



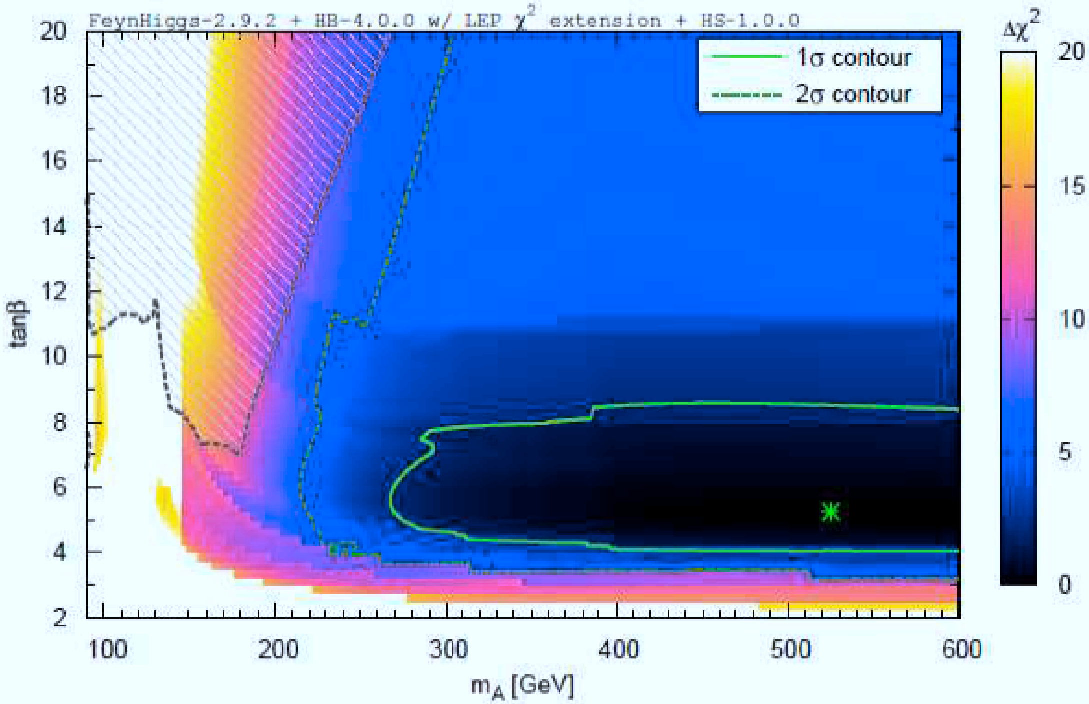
$\Rightarrow \tan\beta \gtrsim 4,\ M_A \gtrsim 140$ GeV, $M_{H^\pm} \gtrsim 160$ GeV

Analysis in $m_{\rm h}^{\rm max}$ benchmark scenario

The $m_h^{\rm max}$ scenario

$(M_{\rm SUSY} = 1$ TeV, $|X_t| = 2$ TeV, $\mu = 200$ GeV, $M_1 = 100$ GeV, $M_2 = 200$ GeV, $M_3 = 1200$ GeV$)$

5. Take into account $\Delta m_h^{\rm th} = \Delta m_H^{\rm th} = 2$ GeV in HiggsBounds.



- Exclusion in large m_A region vanishes (now, $m_h \lesssim 130$ GeV is allowed).

Are we approaching or receding from the decoupling limit?

Although the limited statistics of the Higgs data set does not yield any significant deviations from SM Higgs boson predictions, it is difficult to ignore the fact that both ATLAS and CMS report enhancements in the $\gamma\gamma$ channel.

Consider then the following exercise. Assume that with more data, the enhanced signal in the $\gamma\gamma$ channel persists, whereas the Higgs boson couplings to WW and ZZ are observed at or near their SM predicted values. This would imply new physics beyond the SM. But, what sort of new physics? What are the possibilities?

Keeping in mind that the Higgs boson couples to WW and ZZ at tree-level, but couples to γγ (and Zγ) at loop-level, three possible scenarios are:

1. Add new uncolored charged particles to the SM that couple to the Higgs boson, which can appear in the $H \to \gamma\gamma$ loop and modify its branching ratio. The Higgs production cross sections and their coupling to WW and ZZ are unaffected.

2. Suppress the $H \to bb$ partial width (due to new physics), which would increase the $H \to \gamma\gamma$ branching ratio.

3. Add a new spin 0 particle approximately mass-degenerate with the Higgs boson (m_H=125 GeV) with suppressed couplings to WW and ZZ. (For example, a CP-odd Higgs boson only couples to WW and ZZ at the loop-level). Such a scalar can also decay into γγ. This would be observed as an enhanced γγ signal.

An approximately mass-degenerate Higgs boson pair

- The NMSSM has three neutral CP-even states and two neutral CP-odd states. This motivated a study of a parameter regime in which two of the neutral states were approximately degenerate in mass: J.F. Gunion, Y. Jiang and S. Kraml, *Could two NMSSM Higgs bosons be present near 125 GeV*?, Phys. Rev. **D86**, 071702 (2012); *Diagnosing Degenerate Higgs Bosons at 125 GeV*, arXiv:1208.1817 [hep-ph].

- Pedro Ferreira, Rui Santos, João Silva and I wanted to know whether the $\gamma\gamma$ excess could be explained by two nearly mass-degenerate Higgs states in the (non-supersymmetric) two-Higgs-doublet model (2HDM). In the rest of this talk, I will show you the results of our analysis, which now appears in P.M. Ferreira, Howard E. Haber, João P. Silva and Rui Santos, arXiv:1211.3131

- In the 2HDM, degenerate Higgs states were considered independently by A. Drozd, B. Grzadkowski, J.F. Gunion and Y. Jiang, ``Two-Higgs-Doublet Models and Enhanced Rates for a 125 GeV Higgs," arXiv:1211.3580 [hep-ph].

Constraints on a scan of the 2HDM-I and 2HDM-II parameter space

We vary the model parameters under the assumptions that

- The scalar potential is bounded from below and the quartic Higgs couplings lie below their unitarity limits;
- $m_{h^0} \simeq 125$ GeV;
- the couplings of h^0 to VV ($V = W$ or Z) are within 20% of their SM-values;
- Precision electroweak constraints (contributions to S, T and U) are satisfied;

subject to the constraints imposed by the following experimental observables:

1. $b \to s\gamma$
2. B_d^0–$\overline{B}_d^0$ and B_s^0–$\overline{B}_s^0$ mixing
3. $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$
4. $B^+ \to \tau^+\nu_\tau$

These experimental observables place constraints on the value of $\tan\beta/m_{H^\pm}$. We do not make use of the recent BABAR data on $\overline{B} \to D\tau^-\overline{\nu}_\tau \,/\, D^*\tau^-\overline{\nu}_\tau$, which is not compatible with the 2HDM.

BaBar observes a 3.4 σ deviation in $B \to D\tau\nu$ / $D^*\tau\nu$. However this data is inconsistent with the type II 2HDM at the 99.8% CL.

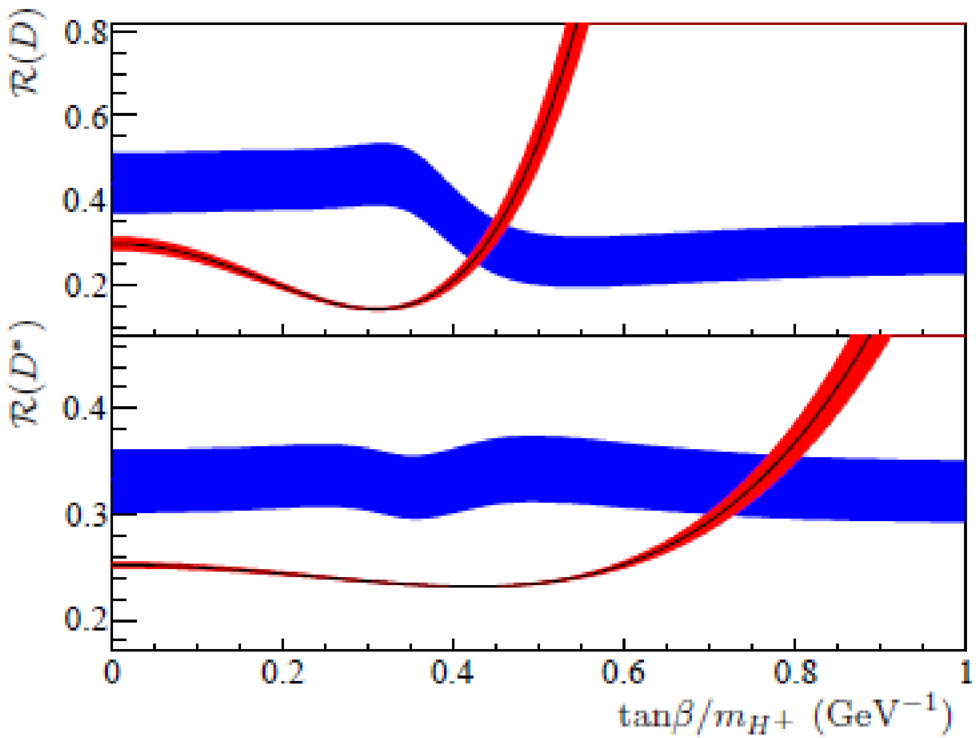
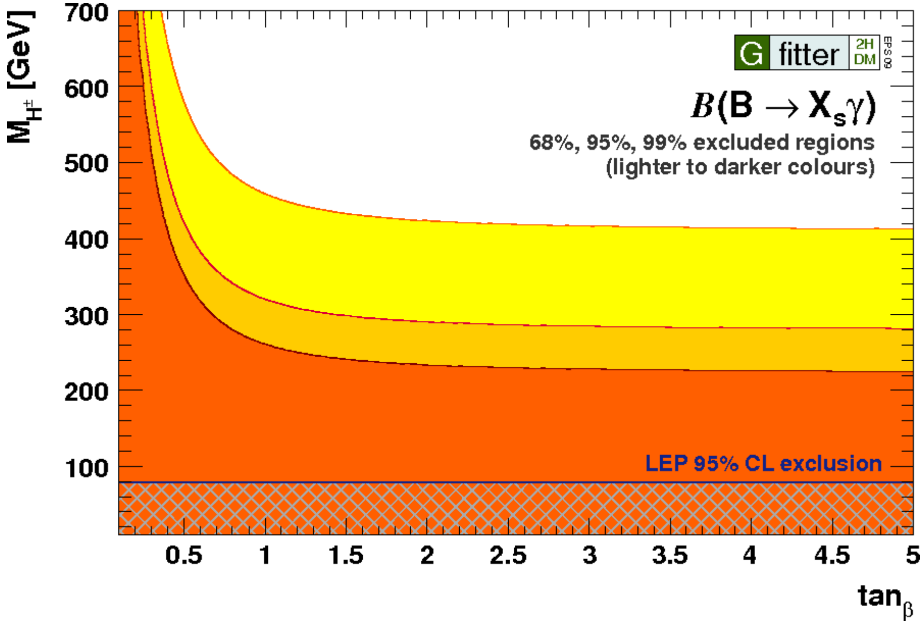
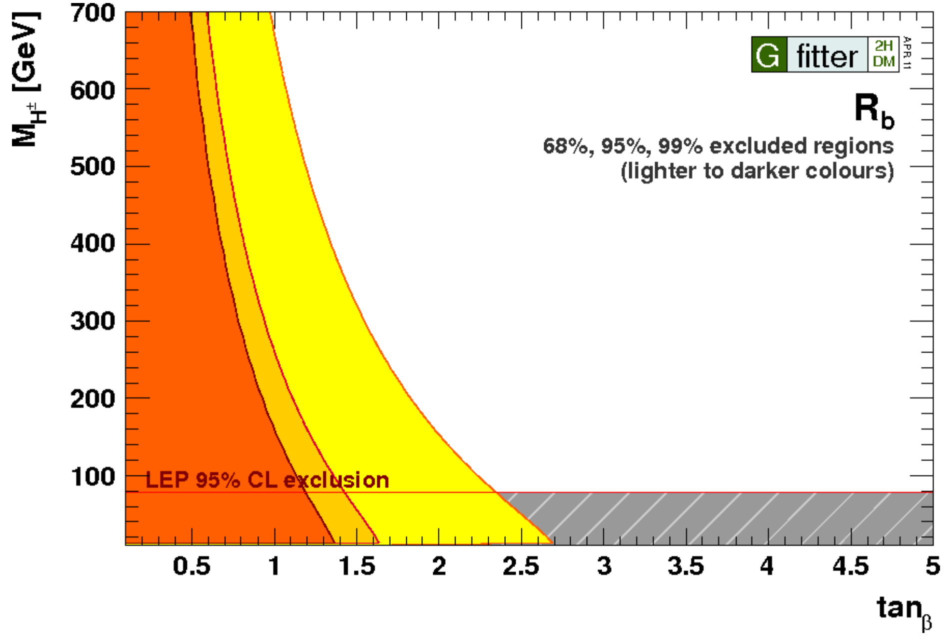


FIG. 2. (Color online) Comparison of the results of this analysis (light grey, blue) with predictions that include a charged Higgs boson of type II 2HDM (dark grey, red). The SM corresponds to $\tan\beta/m_{H^+} = 0$.

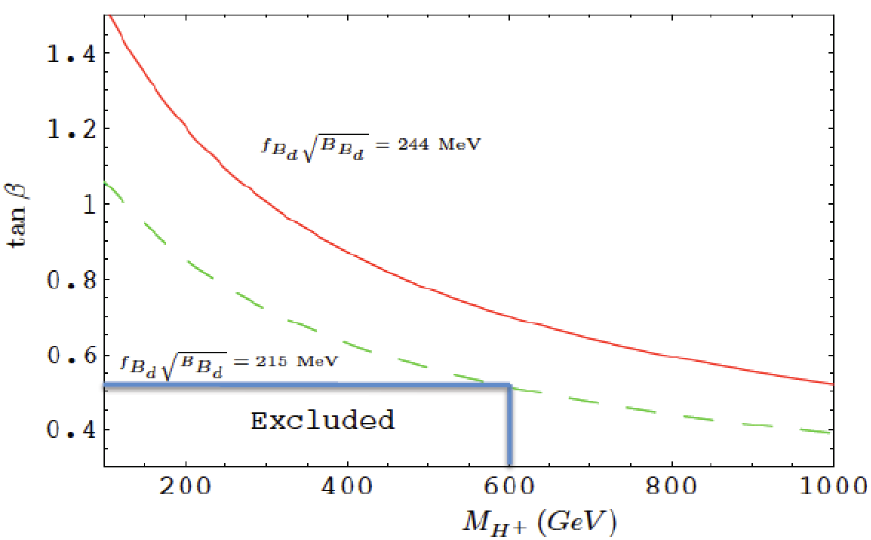
Taken from J.P. Lees et al. [BaBar Collaboration], *Evidence for an excess of* B → *$D^{(*)}\tau\nu$ decays*, Phys. Rev. Lett. **109**, 101802 (2012)

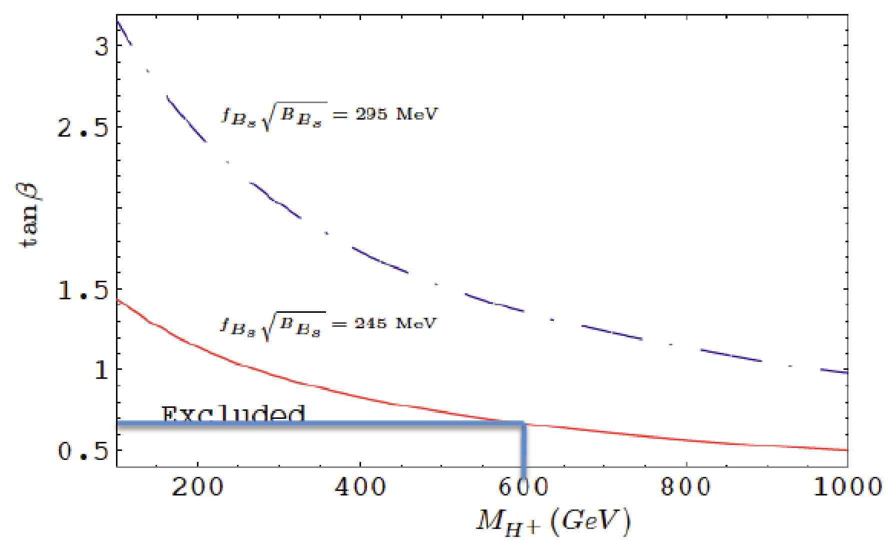
Constraints on tan β/ m_{H^+} from the 2HDM-II model



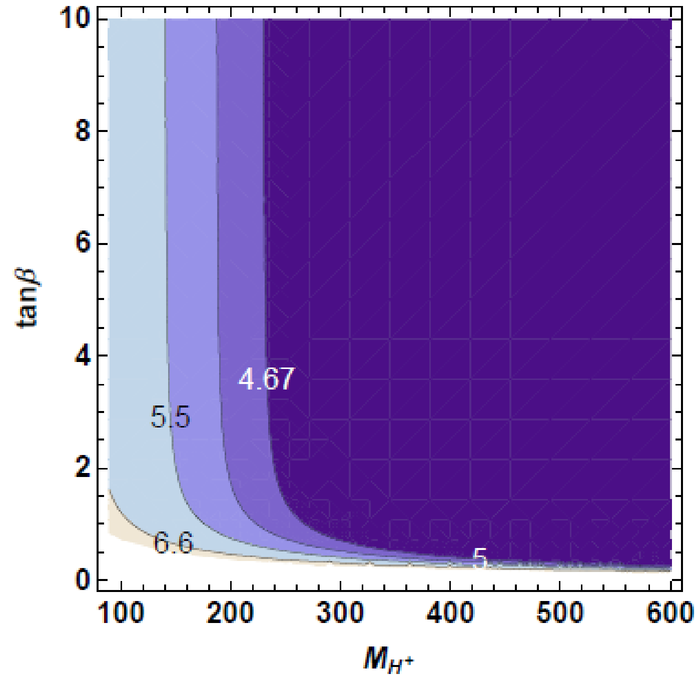


Below (from Rui Santos): 2σ bounds on tan β/ m_{H^+} from B_d--$\bar{B}_d$ and B_s--$\bar{B}_s$ mixing

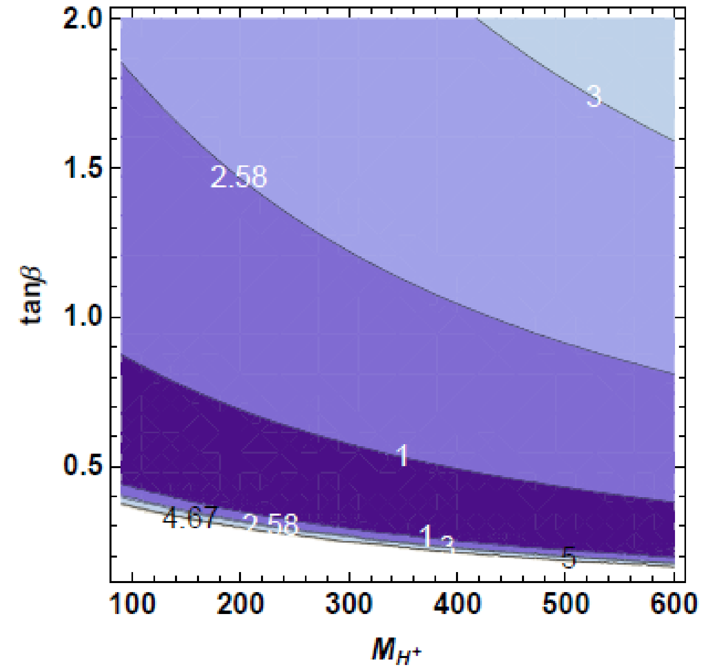




In the 2HDM-I for values of tan β $\lesssim$ 1.5, b → sγ provides the more stringent constraint on the value of tan β/ m_{H^+}.



(a) The Type II model branching ratio is always greater than the SM value. As one can exclude all $\mathcal{B} \times 10^4 \geq 4.67$ at 2 σ, values of $M_{H\pm} \leq 260$ GeV are excluded independent of $\tan\beta$.



(b) The Type I model branching ratio is always smaller than the SM value for $\tan\beta \geq 0.4$. For $\tan\beta \ll 1$ the branching ratio rises like $\mathcal{B} \propto \cot^4\beta$.

Taken from Paul Posch, University of Vienna Ph.D. thesis (2009).

2HDM constraints in the m_{H^+} vs. tan β plane, from F. Mahmoudi and O. Stal, *Flavor constraints on the two-Higgs-doublet model with general Yukawa couplings*, Phys. Rev. **D81**, 035016 (2010).

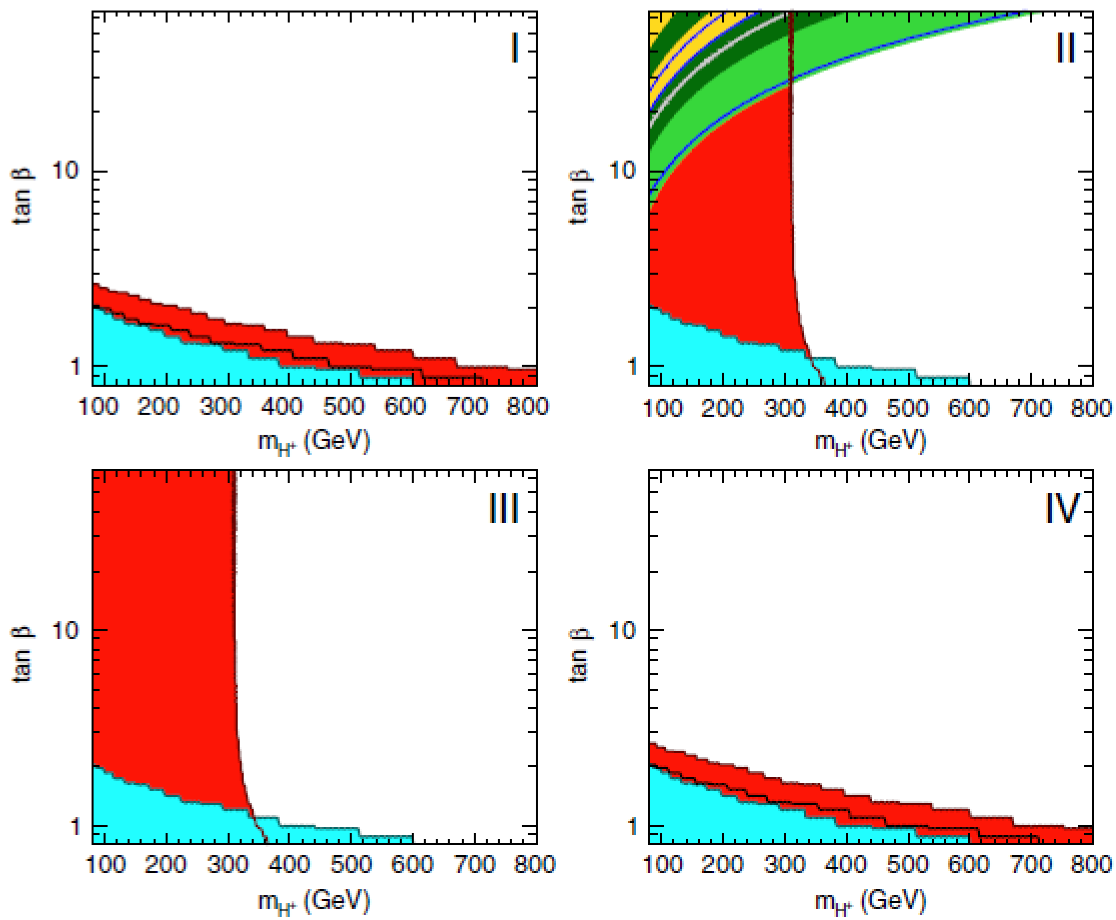


FIG. 10 (color online). Excluded regions of the $(m_{H^+}, \tan\beta)$ parameter space for Z_2-symmetric 2HDM types. The color coding is as follows: $\mathrm{BR}(B \to X_s \gamma)$ (red), Δ_{0-} (black contour), ΔM_{B_d} (cyan), $B_u \to \tau\nu_\tau$ (blue), $B \to D\tau\nu_\tau$ (yellow), $K \to \mu\nu_\mu$ (gray contour), $D_s \to \tau\nu_\tau$ (light green), and $D_s \to \mu\nu_\mu$ (dark green). The white region is not excluded by any of these constraints.

Scanning the 2HDM parameter space for an enhanced γγ signal in a region with mass-degenerate neutral Higgs bosons

- Choices for the degenerate Higgs pair: (h^0, A^0), (h^0, H^0), or (H^0, A^0)
- Degenerate Higgs mass of 125 GeV
- One of the neutral Higgs boson has SM-like couplings (±20%) to the W and Z gauge bosons
- Impose 2HDM constraints
- Focus on the parameter regime where $0.5 \lesssim \tan\beta \lesssim 2.0$
- Take $m_{H^+} > 600$ GeV, to avoid all 2HDM-II constraints

Expectations for the parameter scan

- The SM-like Higgs boson (h_{SM}) is produced with SM-like cross-sections and decay branching ratios.

- The coupling of the degenerate neutral state (h_{deg}) to VV (V=W or Z) is highly suppressed.

- The h_{deg} is produced in gg fusion (but not WW fusion nor in associated Vh_{deg} production) at a rate that is comparable to that of $h_{SM.}$ Since the coupling of h_{deg} to tt pairs is enhanced for tan $\beta<1$, and the loop-coupling of h_{deg} to $\gamma\gamma$ is suppressed due to the absence of the WW loop, the presence of h_{deg} can add an O(1) contribution to the observed $\gamma\gamma$ signal.

- The $\tau\tau$ signal should also be enhanced due to h_{deg} production via gg fusion. The branching ratio of h_{deg} to $\tau\tau$ is slightly enhanced for m_h =125 GeV, due to the strong suppression of the WW* final state.

Hence, we expect that the tan $\beta \lesssim 1$ regime will be our main focus.

Enhanced final state Higgs channels

We define

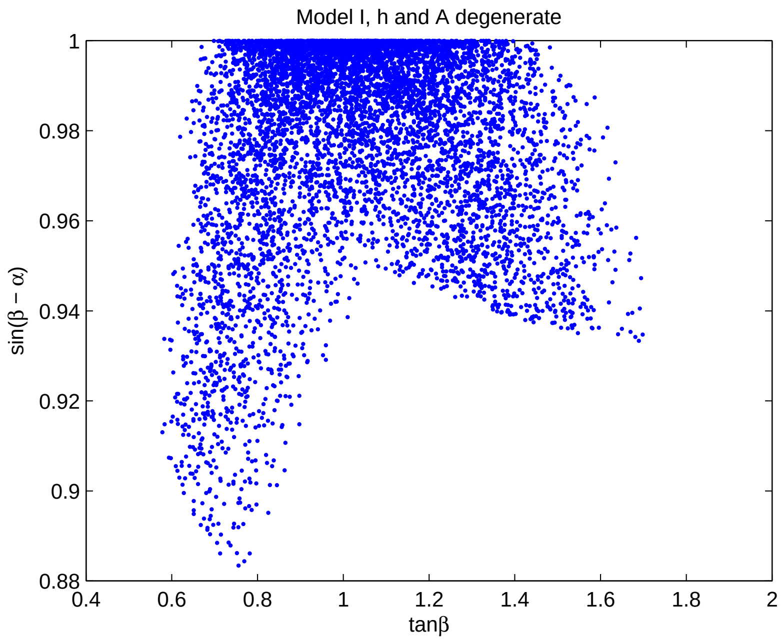
$$R_f^H = \frac{\sigma(pp \to H)_{\rm 2HDM} \times {\rm BR}(H \to f)_{\rm 2HDM}}{\sigma(pp \to h_{\rm SM}) \times {\rm BR}(h_{\rm SM} \to f)}\,,$$

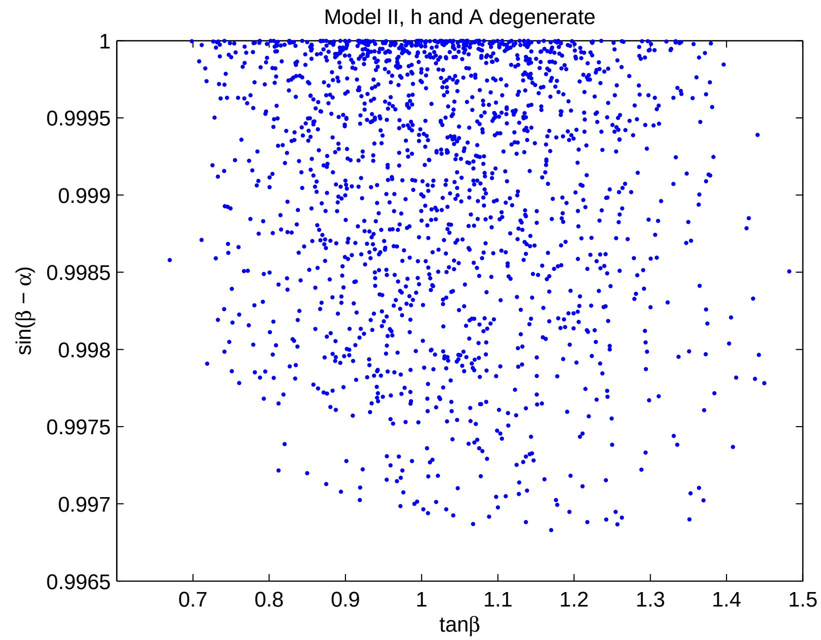
where f is the final state of interest, and H is one of the two 125 GeV mass-degenerate scalars. The observed ratio of f production relative to the SM expectation is

$$R_f \equiv \sum_H R_f^H\,.$$

In obtaining $\sigma(pp \to S)$, we include the two main Higgs production mechanisms: gg fusion and vector boson (W^+W^- and ZZ) fusion. The final states of interest are $f = \gamma\gamma$, ZZ^*, WW^* and $\tau^+\tau^-$. Note that the LHC is (eventually) sensitive to the $b\bar{b}$ final state primarily in associated $V + H$ production, which is less relevant to our analysis.

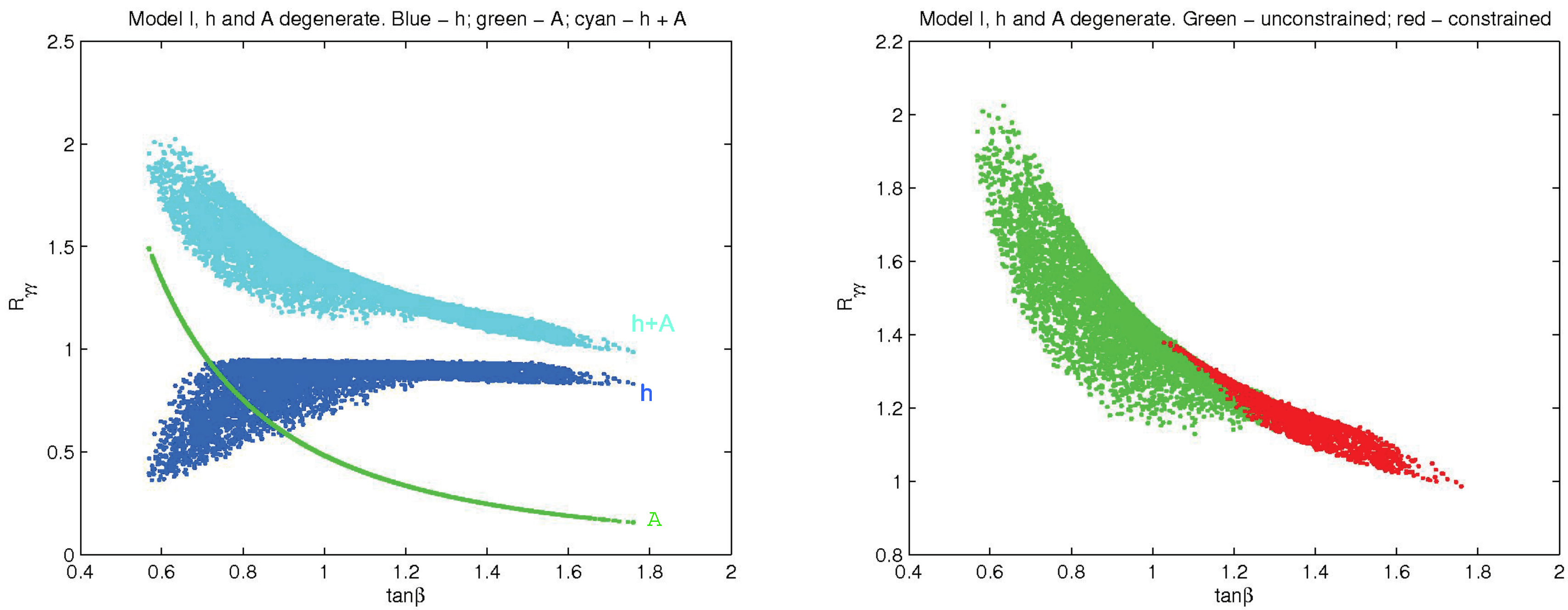
In our analysis, we assume that $R_{WW} \simeq R_{ZZ} \simeq 1 \pm 0.2$.





By imposing the constraints of the mass-degenerate h^0, A^0 pair, we find that $\sin(\beta - \alpha)$ is necessarily near 1. Hence, it follows that the couplings of h^0 to the massive gauge boson pairs are close to their SM values. Similar result follow for other degenerate pair choices.

An enhanced $\gamma\gamma$ signal due to mass-degenerate h^0 and A^0:



Left panel: $R_{\gamma\gamma}$ as a function of $\tan\beta$ for h (blue), A (green), and the total observable rate (cyan), obtained by summing the rates with intermediate h and A, for the unconstrained scenario.

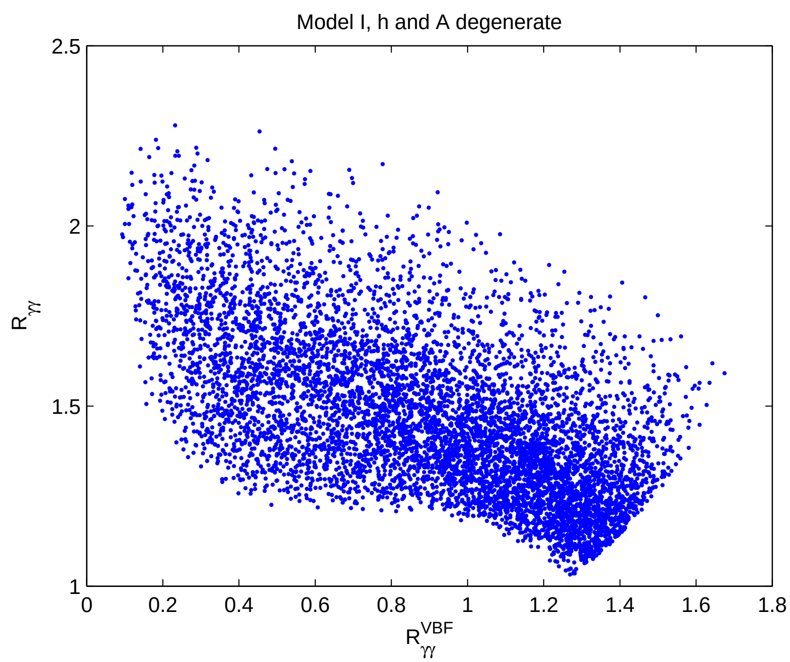
Right panel: Total rate for $R_{\gamma\gamma}$ as a function of $\tan\beta$ for the constrained (red) and unconstrained (green) scenarios.

The enhancement occurs in the parameter regime of $\tan\beta \lesssim 1.5$ and $\sin(\beta-\alpha)$ near 1.

Indeed, we see that the scenario of a mass-degenerate h^0 and A^0 (and more generally any mass-degenerate Higgs pair) that yields an enhanced $\gamma\gamma$ signal is *incompatible* with the MSSM Higgs sector, since such low values of $\tan\beta$ in the MSSM are ruled out by LEP data.

It is possible to experimentally separate out $\gamma\gamma$ events that arise from Higgs bosons produced by WW-fusion. (In practice, there is typically a 30% contamination from the gluon-gluon fusion production channel.) We define:

$$R_{\gamma\gamma}^{\rm VBF} = \frac{\sigma(pp \to VV \to h)_{\rm 2HDM}\,{\rm BR}(h \to \gamma\gamma)_{\rm 2HDM}}{\sigma(pp \to VV \to h_{\rm SM})\,{\rm BR}(h_{\rm SM} \to \gamma\gamma)}\,,$$

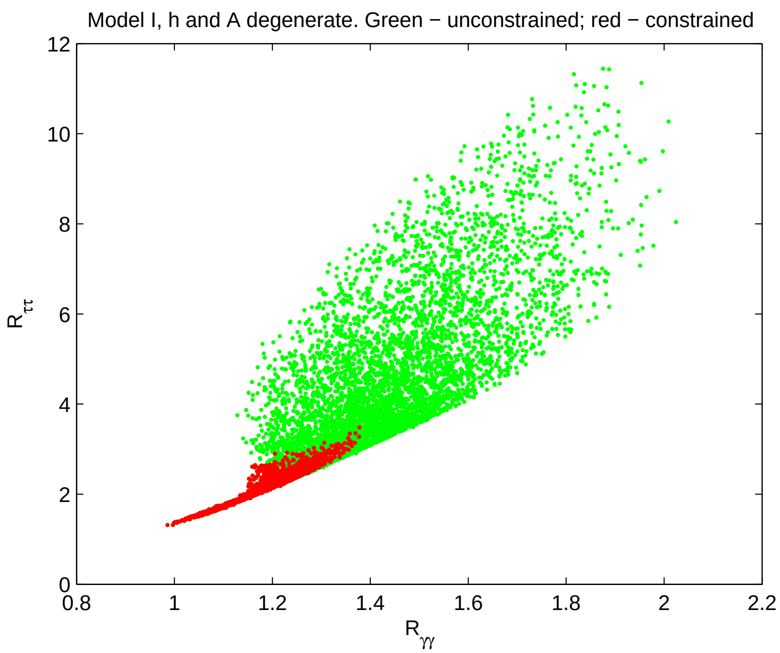


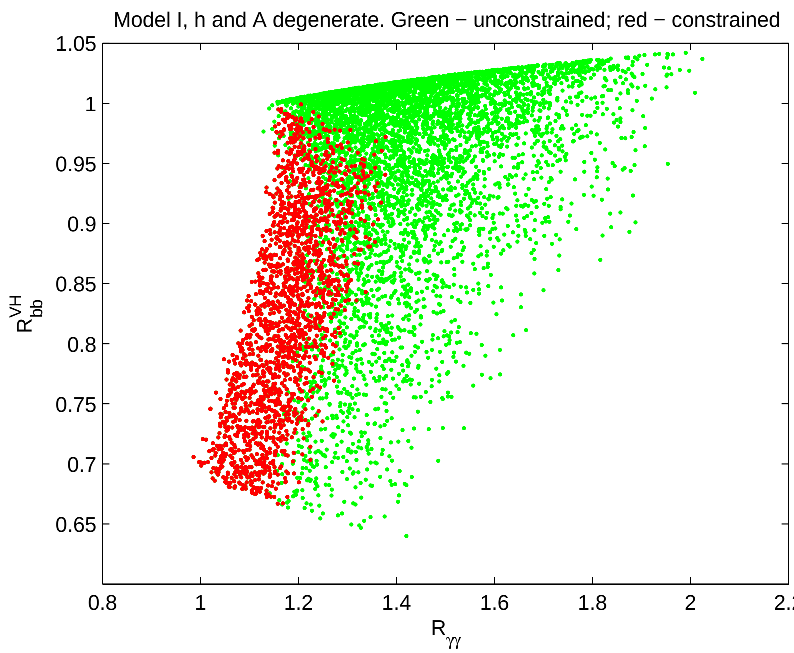
Allowed region in the $R_{\gamma\gamma}^{\rm VBF} - R_{\gamma\gamma}$ plane with (red) and without (green) the B-physics constraints.

An enhanced $\gamma\gamma$ signal in the mass-degenerate scenario yields two associated predictions that must be confirmed by experiment if this framework is to be consistent.

1. The inclusive $\tau^+\tau^-$ signal is enhanced with respect to the SM due to the production of A via gg fusion.

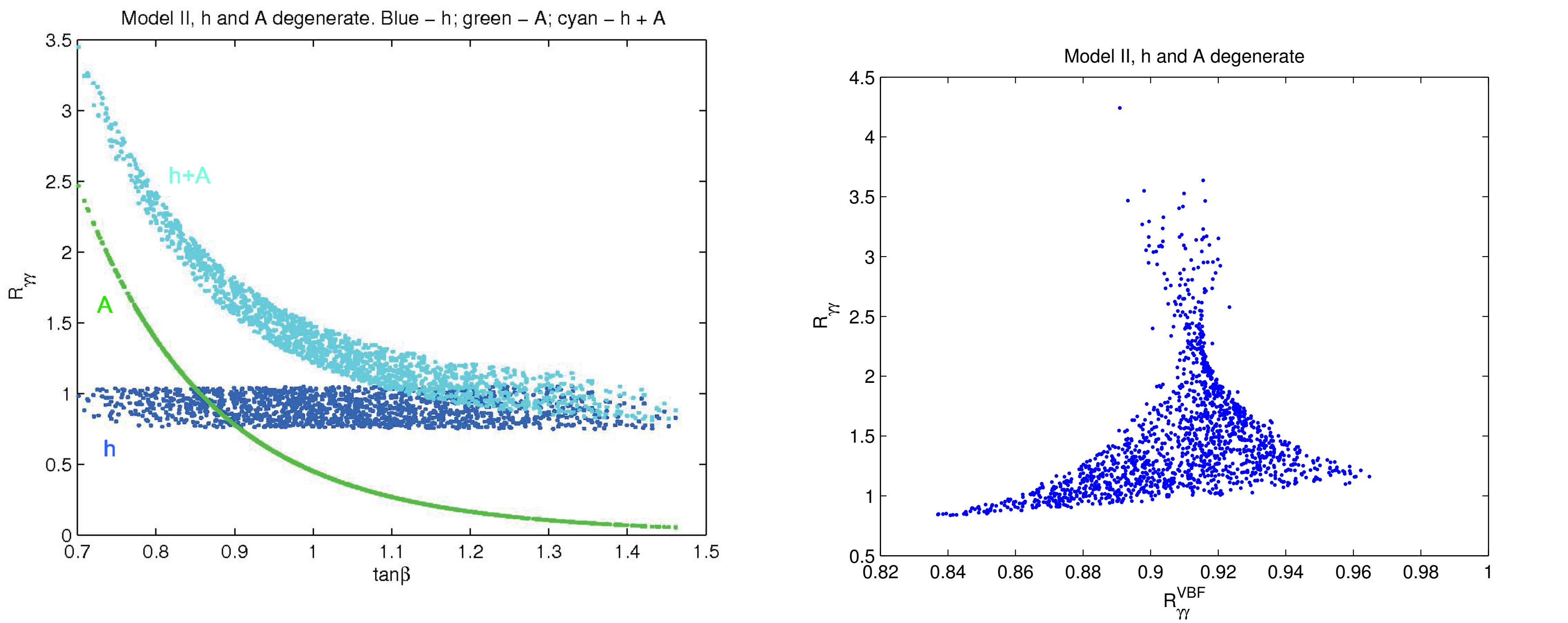
2. The exclusive $b\bar{b}$ signal due to the production of Higgs bosons in association with W or Z is close to its SM value but is not enhanced.





Left panel: Total $R_{\tau\tau}$ (h and A summed) as a function of $R_{\gamma\gamma}$ for the constrained (red) and unconstrained (green) scenarios. Right panel: $R_{bb}^{\rm VH}$ (h and A summed) as a function of $R_{\gamma\gamma}$ for the constrained (red) and unconstrained (green) scenarios.

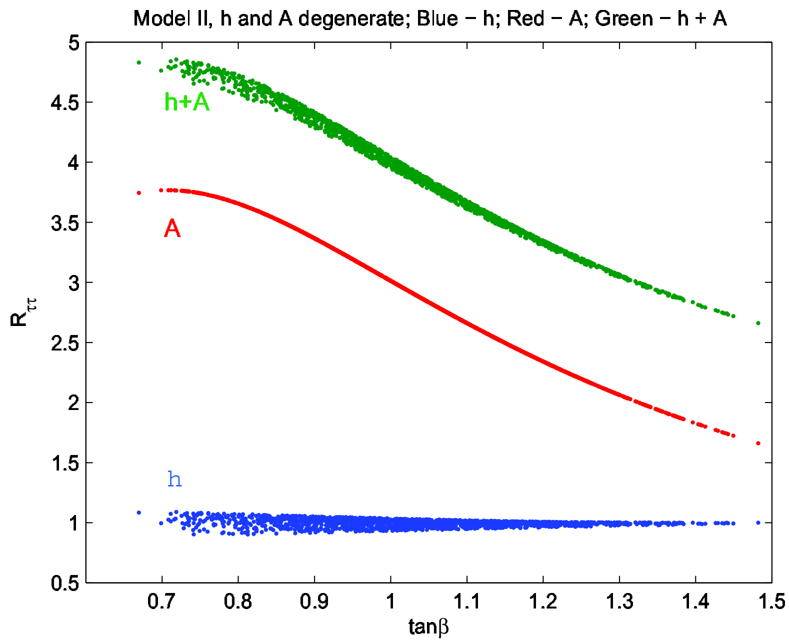
We can repeat the exercise for the Type-II 2HDM. Once we assume a heavy charged Higgs mass, there are no further constraints from B physics.

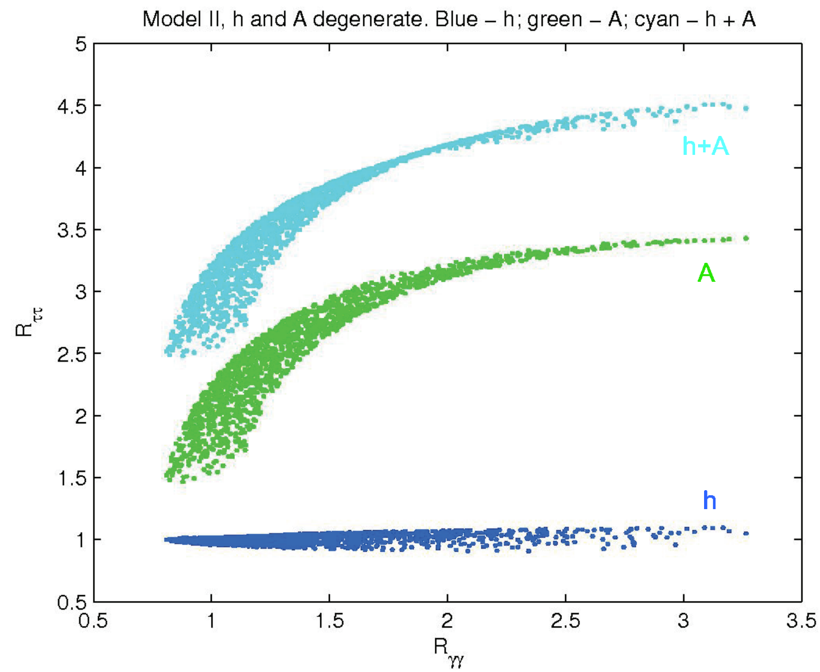


Left panel: $R_{\gamma\gamma}$ as a function of $\tan\beta$ for h (blue), A (green), and the total observable rate, obtained by summing the rates with intermediate h and A (cyan). Right panel: Allowed region in the $R^{\mathrm{VBF}}_{\gamma\gamma} - R_{\gamma\gamma}$. Right panel: $R_{\tau\tau}$ as a function of $R_{\gamma\gamma}$ for h (blue), A (green), and the total observable rate, obtained by summing the rates with intermediate h and A (cyan).

For the Type-II case, $R^{\mathrm{VBF}}_{\gamma\gamma}$ can never be enhanced above 1, since it only receives contributions from h production, which has nearly exact SM couplings since $\sin(\beta - \alpha)$ is extremely close to 1.

As in the Type-I case, the $\tau^+\tau^-$ signal is enhanced, which is a critical prediction of the mass-degenerate scenario.



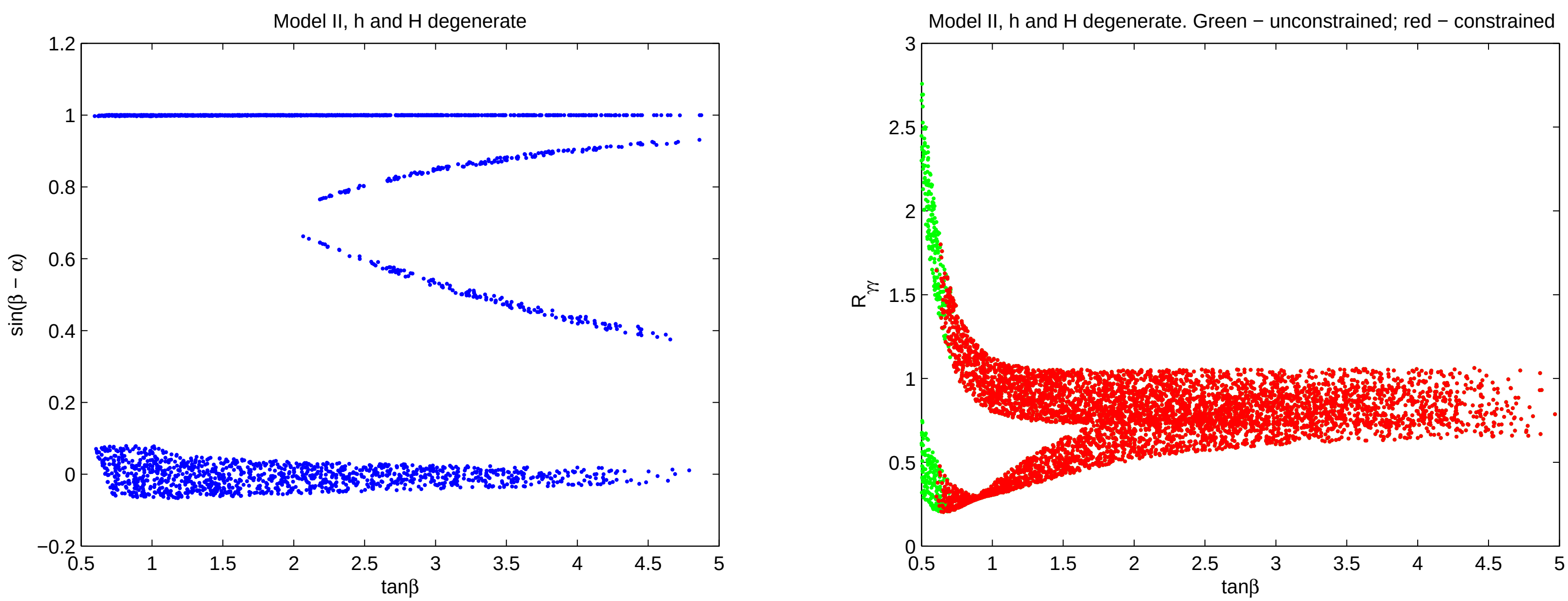


Left panel: $R_{\mathcal{T}\mathcal{T}}$ as a function of $\tan\beta$ for h (blue), A (red), and the total observable rate, obtained by summing the rates with intermediate h and A (green). Right panel: $R_{\mathcal{T}\mathcal{T}}$ as a function of $R_{\gamma\gamma}$ for h (blue), A (green), and the total observable rate, obtained by summing the rates with intermediate h and A (cyan).

Enhanced $\gamma\gamma$ and $\tau^+\tau^-$ signals due to mass-degenerate h^0 and H^0:

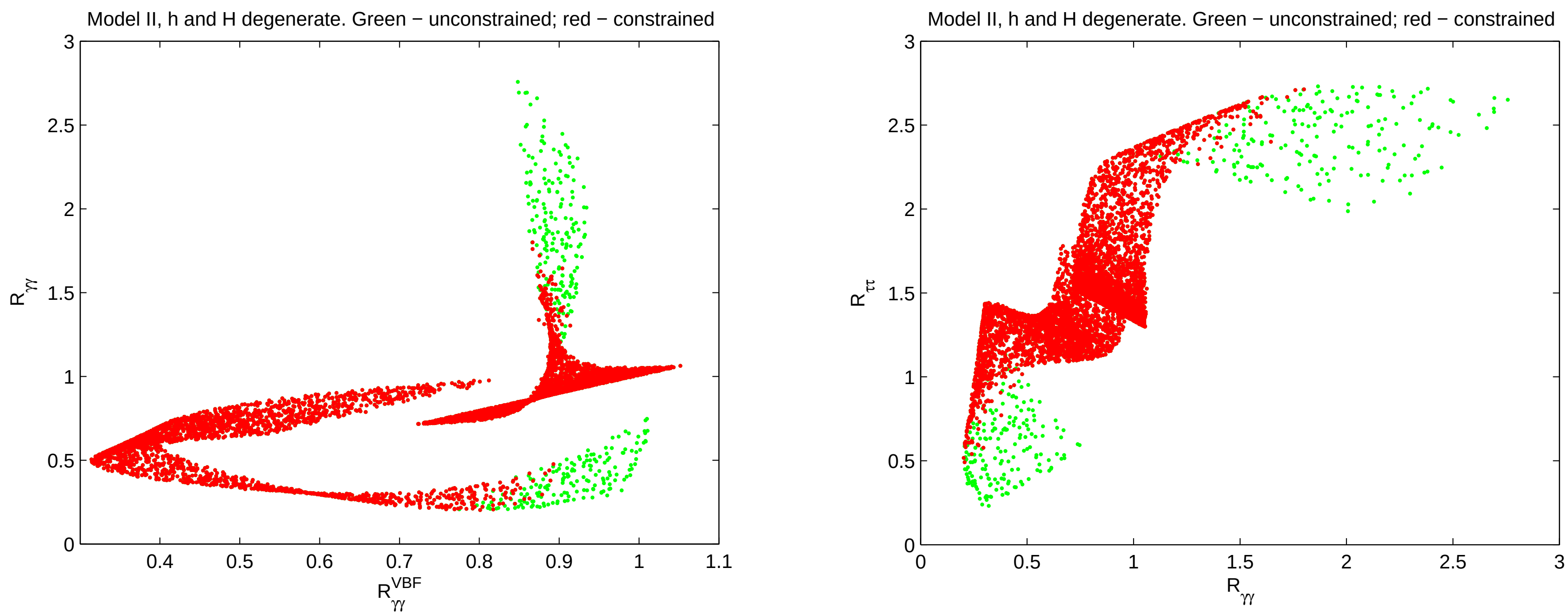
In Type-I models, there is no longer a constraint on $\sin(\beta - \alpha)$ since both h and H can couple to vector boson pairs. It turns out that after imposing B-constraints, it is not possible to enhance the $\gamma\gamma$ signal.

In Type-II models, the constraint on $\sin(\beta - \alpha)$ is rather complicated. We find that an enhanced $\gamma\gamma$ signal is possible.



Left panel: Values obtained in the $\tan\beta - \sin(\beta - \alpha)$ plane for the points generated, which satisfy $0.8 < R_{\gamma\gamma} < 1.5$.
Right panel: Values for $R_{\gamma\gamma}$ as a function of $\tan\beta$ for the constrained (red) and unconstrained (green) scenarios.

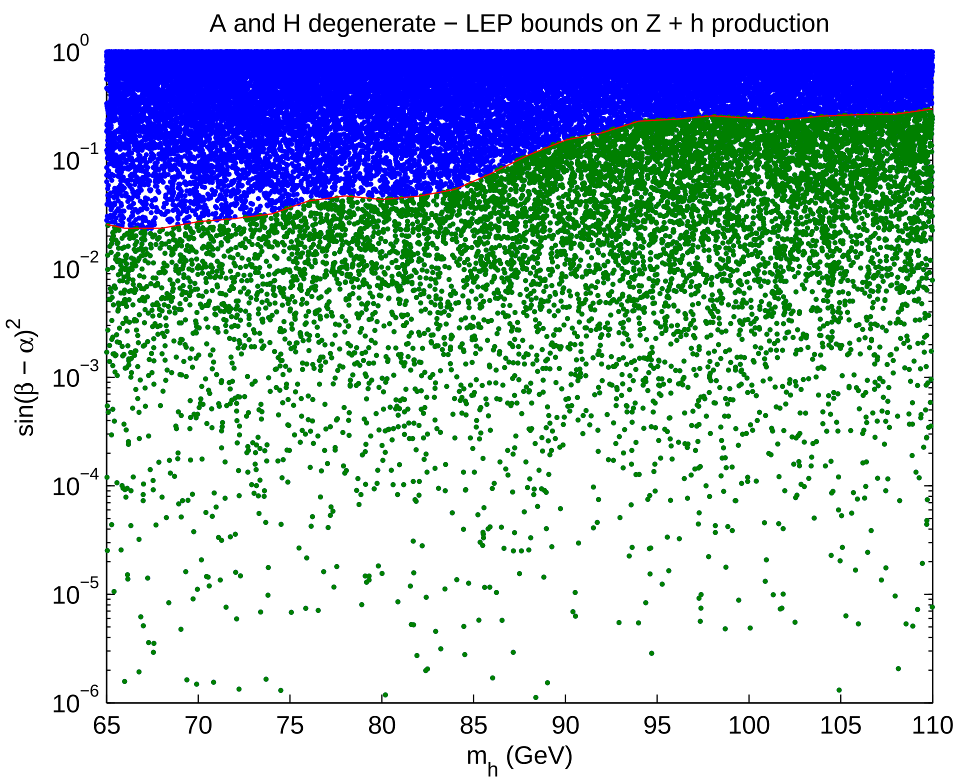
As in the previous case of mass-degenerate scalars in the Type-II model, the $\gamma\gamma$ signal resulting from Higgs bosons produced in vector boson fusion is slightly suppressed, whereas the $\tau^+\tau^-$ signal is enhanced in regions of the enhanced $\gamma\gamma$ signal.



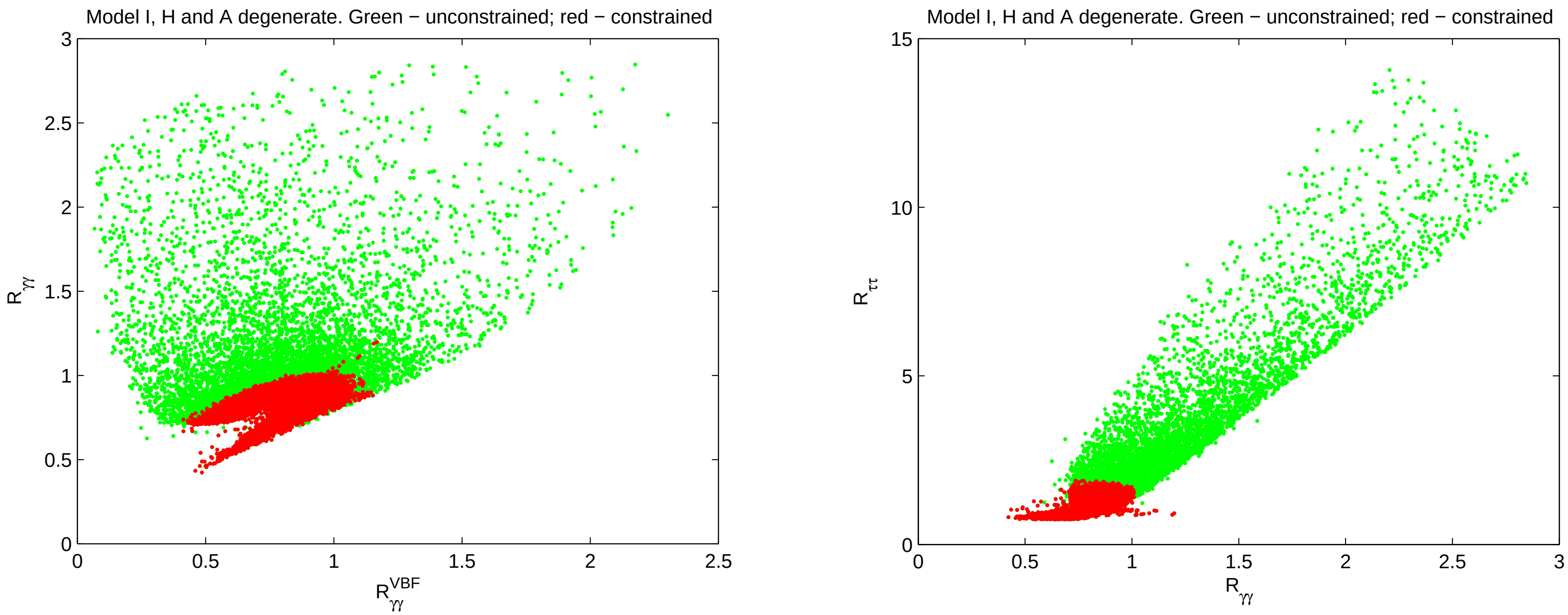
Left panel: Allowed region in the $R_{\gamma\gamma}^{\rm VBF}$–$R_{\gamma\gamma}$ plane for the constrained (red) and unconstrained (green) scenarios.
Right panel: Allowed region in the $R_{\gamma\gamma}$–$R_{\tau\tau}$ plane for the constrained (red) and unconstrained (green) scenarios.

Enhanced $\gamma\gamma$ and $\tau^+\tau^-$ signals due to mass-degenerate H^0 and A^0:

This is a peculiar case, as it would imply that a lighter h^0 was missed at LEP. But, this is possible if the $h^0 ZZ$ coupling is sufficiently suppressed. We assume that $m_{H^0} < 2m_h$; otherwise $H^0 \to h^0 h^0$ would be a significant decay mode and the $H^0 \to ZZ^* \to \ell\ell\ell'\ell'$ signal would be suppressed. Assuming that $m_h \simeq m_A \simeq 126$ GeV and $m_h > \frac{1}{2} m_H$, the LEP Higgs search cannot probe regions of $\sin(\beta - \alpha) \simeq 0.1$ [the latter is the suppression of the $h^0 ZZ$ coupling strength)].



In the case of the mass-degenerate H^0 and A^0, we find that charged Higgs masses must lie below about 200 GeV; otherwise, the Higgs corrections to the electroweak ρ-parameter are too large. This rules out the Type-II 2HDM (due to $b \to s\gamma$ constraints), so we consider 2HDM-I.

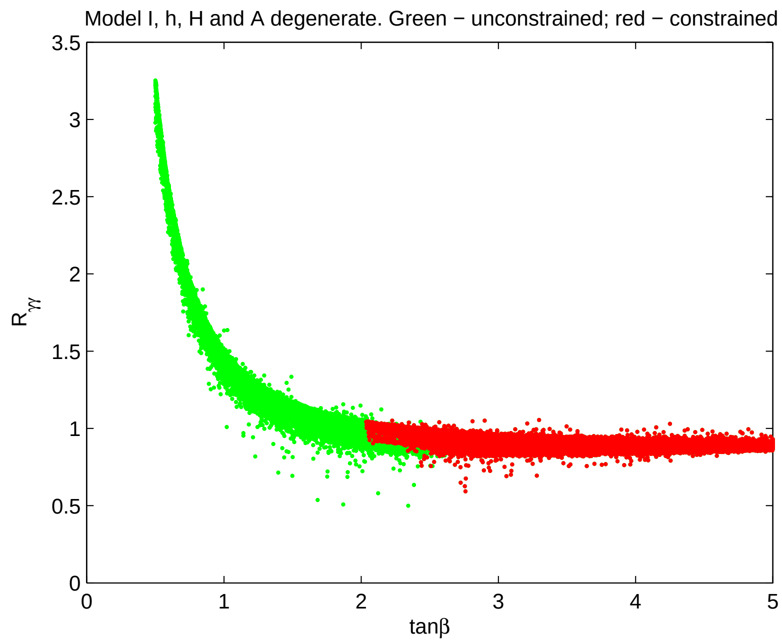


Left panel: Allowed region in the $R_{\gamma\gamma}^{\rm VBF}$–$R_{\gamma\gamma}$ plane for the constrained (red) and unconstrained (green) scenarios.
Right panel: Allowed region in the $R_{\gamma\gamma}$–$R_{\tau\tau}$ plane for the constrained (red) and unconstrained (green) scenarios.

Only a few points with an enhanced $\gamma\gamma$ signal survive. These points need to be examined more closely to see whether they are realistic.

The mass-degenerate threesome h^0, H^0 and A^0

As in the degenerate H^0, A^0 case, the charged Higgs masses must lie below about 200 GeV. Hence, the Type-II 2HDM is ruled out (due to $b \to s\gamma$ constraints). In the Type-I 2HDM, regions of an enhanced $\gamma\gamma$ signal are ruled out by other B-physics constraints.



Total $R_{\gamma\gamma}$ (h, H and A summed) as a function of $\tan\beta$ for the constrained (red) and unconstrained (green) scenarios.

A mass difference in the $\gamma\gamma$ and the $ZZ^* \to 4$ lepton channels?

In the mass-degenerate Higgs scenario, all we really require is a near-degeneracy of the two masses. Since the ATLAS and CMS Higgs mass measurements in the $\gamma\gamma$ and the $ZZ^* \to 4$ lepton channels have resolutions of 1–2 GeV, it is possible that with more data a difference in the invariant masses measured in these two channels could be discerned.

In our models of an enhanced $\gamma\gamma$ signal due to nearly-degenerate states, the $ZZ^* \to 4$ lepton channel arises entirely from one SM-like Higgs boson state, whereas the $\gamma\gamma$ signal is made up of contributions from both scalar states. Thus, the average mass inferred from the $\gamma\gamma$ channel can be slightly different from that of the $ZZ^* \to 4$ lepton channel.

Conclusions

- The current LHC Higgs data sets are limited in statistics. Despite some intriguing variations, the present data is consistent with a SM-like Higgs boson.
- If further data reveals no statistically significant deviations from SM Higgs behavior, then we are in the domain of the decoupling limit. A precision Higgs program is then required to elucidate the possibility of new Higgs physics beyond the SM.
- The enhancement of the $\gamma\gamma$ signal in LHC Higgs data is not yet statistically significant, Nevertheless, this could be the first hint of new Higgs physics beyond the SM.
- P. Ferreira, R. Santos, J. Silva, and I have examined the possibility that an enhancement in the $\gamma\gamma$ channel (while maintaining SM-like Higgs couplings to W^+W^- and ZZ) is due to a mass-degenerate pair of neutral Higgs bosons in the 2HDM. We find that a 50% (or larger) enhancement can occur in the 2HDM with Type-I and Type-II Yukawa couplings for values of $\tan\beta$ near 1 (or below).
- Such a scenario is easily tested, as it would almost certainly require:
  - Enhanced production of $\tau^+\tau^-$ (which is not yet ruled out by LHC Higgs data due to large statistical uncertainties in the current $\tau^+\tau^-$ coupling measurements).
  - The possibility of a measurable difference in the Higgs mass measurement via the $\gamma\gamma$ and the $ZZ^* \to 4$ lepton channels.