Workshop Summary: Revisiting the Higgs Wishlist

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Higgs Identification Workshop
KITP, Santa Barbara
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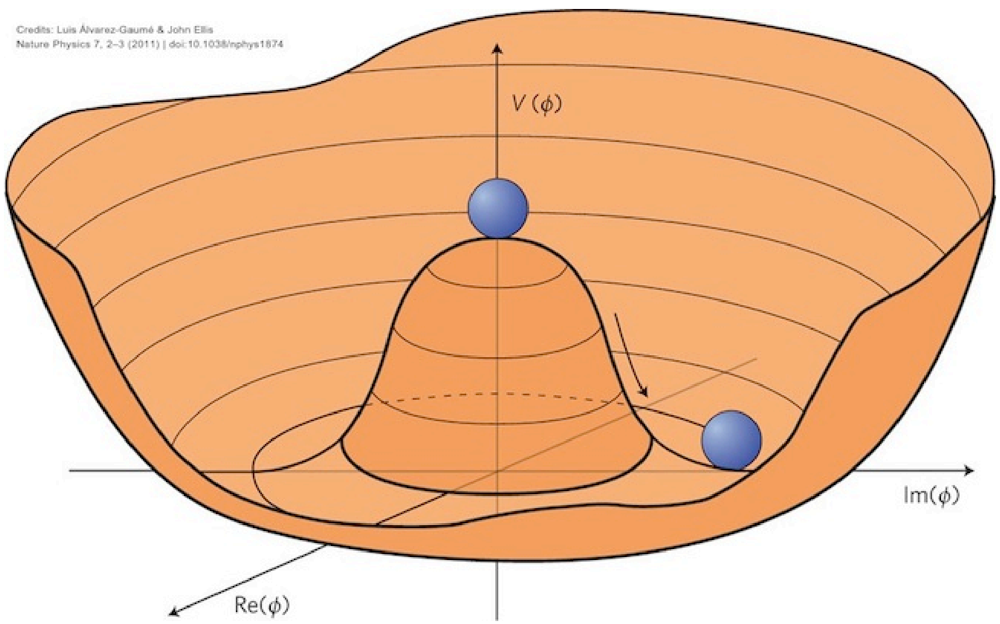


Theory Questions

➢Is the observable Higgs state responsible for the unitarization of W_LW_L scattering?

$$W_LW_L \to W_LW_L, Z_LZ_L, hZ_L \quad \Rightarrow \quad g_{hWW}\ ,\ g_{hZZ}$$
$$W_LW_L \to t\bar{t} \quad \Rightarrow \quad g_{ht\bar{t}}$$

For example, in an SU(2)×U(1) gauge theory with a CP-conserving Higgs sector, no doubly charged Higgs bosons and $\rho \equiv m_W^2/m_Z^2\cos^2\theta_W = 1$, we have[1]

$$\sum_{\text{CP}-\text{even }k} g^2_{W^+W^-\phi_k^0} = g^2 m_W^2\,,$$
$$\sum_{\text{CP}-\text{even }k} g^2_{ZZ\phi_k^0} = \frac{g^2 m_Z^2}{\cos^2\theta_W}\,,$$
$$\sum_{\text{CP}-\text{even }k} g_{W^+W^-\phi_k^0}\, g^S_{kff} = -\tfrac{1}{2} g^2 m_f\,.$$

Are these unitary sum rules saturated by the experimentally observed Higgs state?

[1] For more general results, see J.F. Gunion, H.E. Haber and J. Wudka, Phys. Rev. **D43**, 904 (1991).

- How close to the decoupling limit is the experimentally observed Higgs boson?

  - There are two decoupling limits:

    - Higgs sector decoupling: enters at tree-level
    - Decoupling of new BSM physics: enters at loop-level.

  - Higgs decoupling limit governs the mass scale of the non-minimal Higgs states.

  - BSM physics decoupling governs the mass scale of of the new BSM interactions.

Here, BSM physics refers to all new physics beyond the Standard Model with a possible extended Higgs sector.

➢What if deviations from SM Higgs couplings are confirmed?

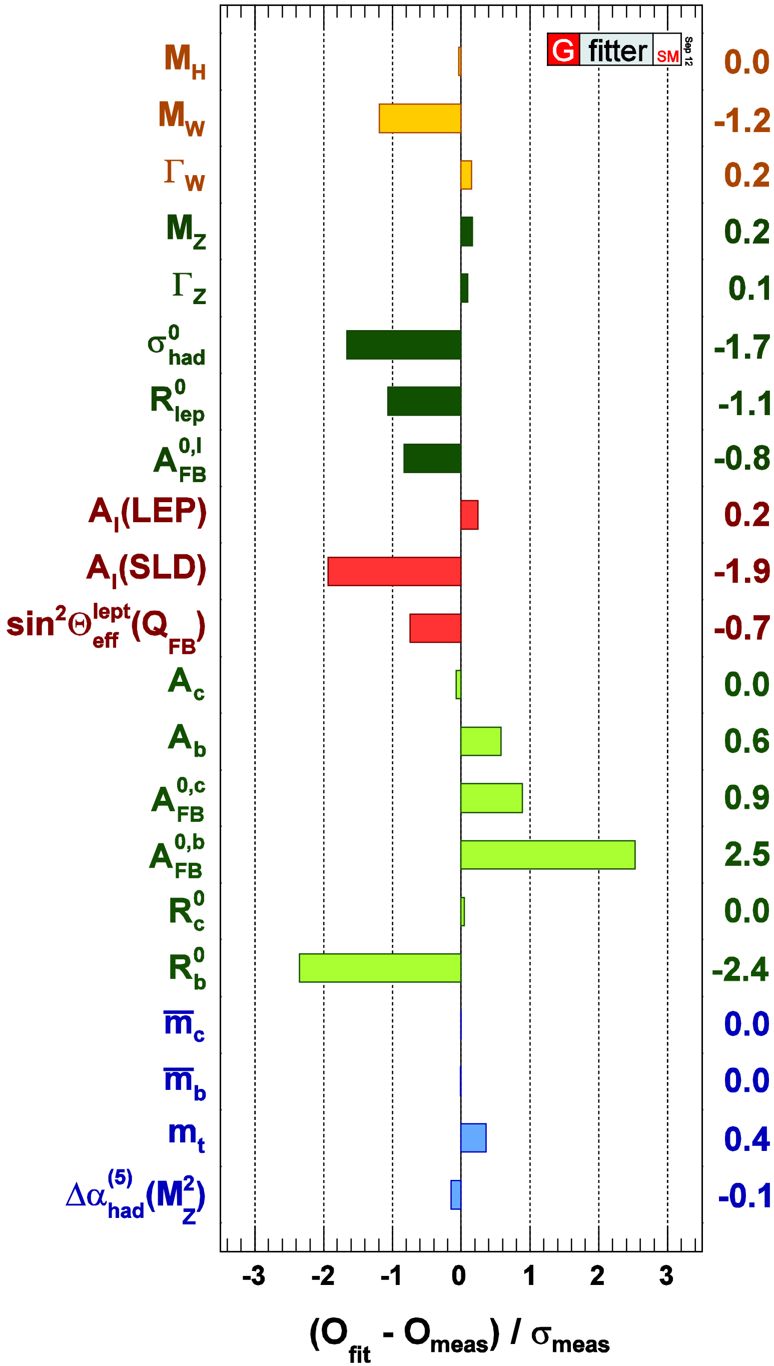
- ❑ If large deviations are detected is there a compelling source of new physics beyond the Standard Model that can account for the deviations? How can one discriminate among different choices of the BSM physics?

- ❑ If small deviations from SM couplings are eventually established (highly suggestive of the near-decoupling regime), what are the systematics of the deviations, and do they point to a particular BSM scenario and/or extended Higgs sector?

  - o The answer is known in the pure 2HDM model [e.g. if CP is conserved, then deviations from decoupling depend on one parameter, cos(β-α)]. But, how to generalize? To include BSM effects, you must distinguish between tree and loop contributions that contribute to the deviations.

➢ Precision Higgs observables as a probe of new physics

- ❑ How well can the LHC do in the asymptotic limit?
- ❑ What is the value added by the ILC?
- ❑ If deviations from SM Higgs couplings are detected can one extract a value for the mass scale of the new physics (Λ_{BSM})?
- ❑ How reliable is the determination of Λ_{BSM}, and how is this quantity related to a measurable quantity?
- ❑ How many standard deviations are required for the deviations to be convincing [cf. $(g\text{-}2)_\mu$, A_L , $A_{FB}(b)$]?



G fitter SM
Sep 12
M_H 0.0
M_W -1.2
Γ_W 0.2
M_Z 0.2
Γ_Z 0.1
σ^0_{had} -1.7
R^0_{lep} -1.1
$A^{0,l}_{FB}$ -0.8
A_l(LEP) 0.2
A_l(SLD) -1.9
$\sin^2\Theta^{lept}_{eff}(Q_{FB})$ -0.7
A_c 0.0
A_b 0.6
$A^{0,c}_{FB}$ 0.9
$A^{0,b}_{FB}$ 2.5
R^0_c 0.0
R^0_b -2.4
$\overline{m}_c$ 0.0
$\overline{m}_b$ 0.0
m_t 0.4
$\Delta\alpha^{(5)}_{had}(M^2_Z)$ -0.1
-3 -2 -1 0 1 2 3
$(O_{fit} - O_{meas}) / \sigma_{meas}$

- Fate of the Higgs self-coupling $\lambda(Q)$ as $Q \to M_{PL}$?

  - Is the Higgs vacuum stable or metastable?

  - What is the theoretical origin of λ?

How does BSM physics impact these questions?

- For example, in the MSSM, λ is determined by gauge couplings, and the Higgs vacuum is therefore stable.

- In other BSM models, the corresponding answers may not be so straightforward.

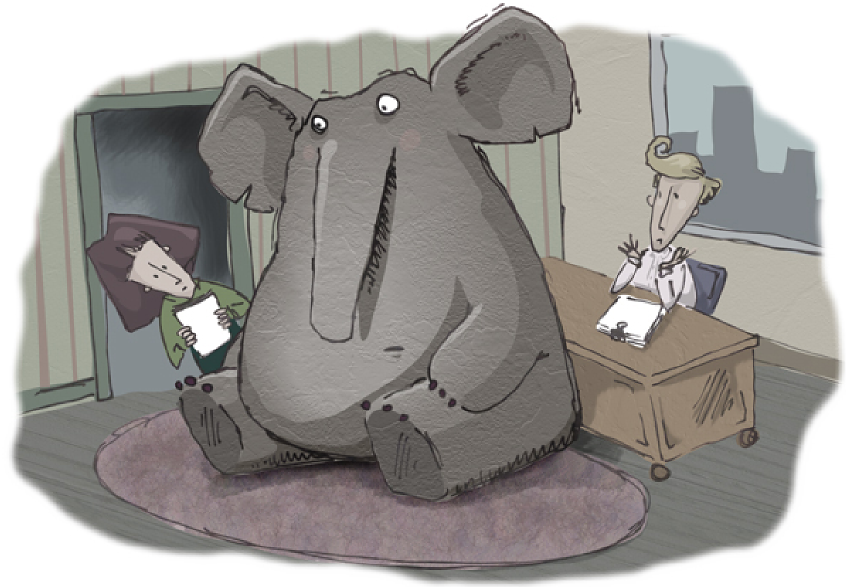
- Is the gauge hierarchy problem resolved by TeV-scale physics? If yes, does this new physics provide us with a more fundamental understanding of the origin of electroweak symmetry breaking?

Supersymmetry remains the favored candidate, but if and when new physics is discovered, avoid the temptation to drive a square peg into a round hole.

Nevertheless, the SUSY wishlist for Higgs physics includes:

- A resolution to the μ problem.
- An more accurate computation of the Higgs mass to reduce the uncertainty below 1 GeV.

Higgs Wishlist for the Experiments



- Is the γγ excess statistically significant?
- Do the $ZZ^* \rightarrow$ 4 lepton events provide a consistent story (relative to γγ)?
- Will ATLAS and CMS converge by Moriond?
- How much tension is there with the SM expectations?

- We are eager for some clarifications…

  - Can custodial symmetry in the Higgs couplings be verified (ultimately with a similar accuracy to the ρ-parameter)?

  - Can we experimentally verify that fermion masses arise from the same mechanism as the gauge boson masses? That is, show the expected dependence of Higgs couplings on masses.

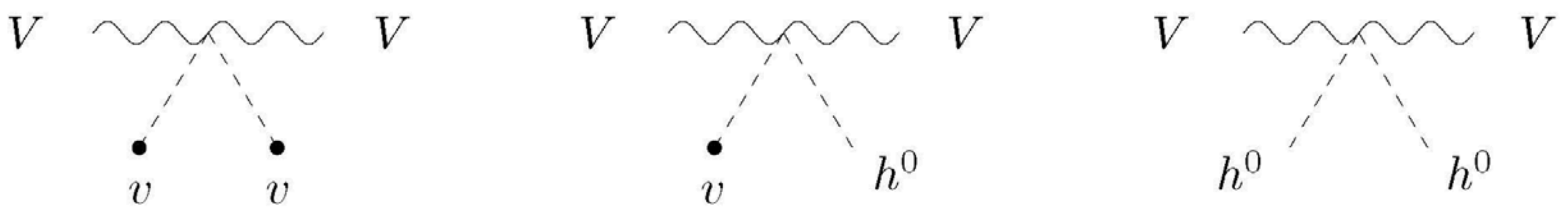
  - Is BR($h \rightarrow \gamma Z$) consistent with BR($h \rightarrow \gamma\gamma$)?

  - What is BR($h \rightarrow$ non-SM channels)?

  - What is BR($h \rightarrow$ invisble)?

Standard Model masses and Higgs couplings

Gauge bosons ($V = W^\pm$ or Z) acquire mass via interaction with the Higgs vacuum condensate.



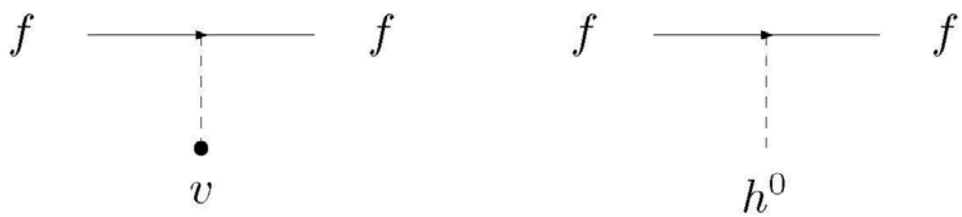
Thus,

$$g_{hVV} = 2m_V^2/v\,, \qquad \text{and} \qquad g_{hhVV} = 2m_V^2/v^2\,,$$

i.e., the Higgs couplings to vector bosons are proportional to the corresponding boson squared-mass.

Likewise, by replacing V with the Higgs field h^0 in the above diagrams, the Higgs self-couplings are also proportional to the square of the Higgs mass:

$$g_{hhh} = \tfrac{3}{2}\lambda v = \frac{3m_h^2}{v}\,, \qquad \text{and} \qquad g_{hhhh} = \tfrac{3}{2}\lambda = \frac{3m_h^2}{v^2}\,.$$



Thus,

$$g_{hf\bar{f}} = m_f/v\,,$$

i.e., Higgs–fermion couplings are proportional to the corresponding fermion mass.

<u>The bottom line</u>

- Higgs bosons couple to other bosons with strength proportional to the boson squared mass
- Higgs bosons couple to fermions with strength proportional to the fermion mass
- The Higgs mass itself is the only undetermined parameter.

➢ Further clarifications…

- ❑ Confirm spin and CP quantum numbers of the boson.
- ❑ Measure the htt coupling (better yet: h coupling to the top partners, if they exist!)
- ❑ Double Higgs production: in the far future of a higher luminosity and/or higher energy LHC. Still, beyond the hhh coupling, one can try to detect the WWhh coupling, and identify potential BSM physics effects in the gghh box diagram.
- ❑ Should we perhaps worry about detecting the WWWW quartic vertex and make sure that the gauge structure is preserved?

➢ Beyond the SM Higgs boson---more wishes

- ❑ Find the charged Higgs boson.
- ❑ Measure tan β (if you are absolutely certain that the Higgs sector corresponds to a Type-I or II 2HDM).
- ❑ Even better---if you suspect that the Higgs sector corresponds to a 2HDM, measure the basis-independent Yukawa matrix (since a priori, tan β is a meaningless quantity) and experimentally determine the structure of the Higgs-fermion coupling.

Reference: H.E. Haber and D. O'Neil, ``Basis-independent methods for the two-Higgs-doublet model. II. The Significance of tan β," Phys. Rev. **D74**, 015018 (2006).

➢ Are there two nearly mass-degenerate scalars with mass around 125 GeV?

- In the NMSSM, see:

J.F. Gunion, Y. Jiang and S. Kraml, Phys. Rev. **D86**, 071702 (2012); and arXiv:1208.1817 [hep-ph].

- In the 2HDM, see

P.M. Ferreira, Howard E. Haber, João P. Silva and Rui Santos, arXiv:1211.3131[hep-ph].

and

A. Drozd, B. Grzadkowski, J.F. Gunion and Y. Jiang, arXiv:1211.3580 [hep-ph].

Enhanced final state Higgs channels

We define

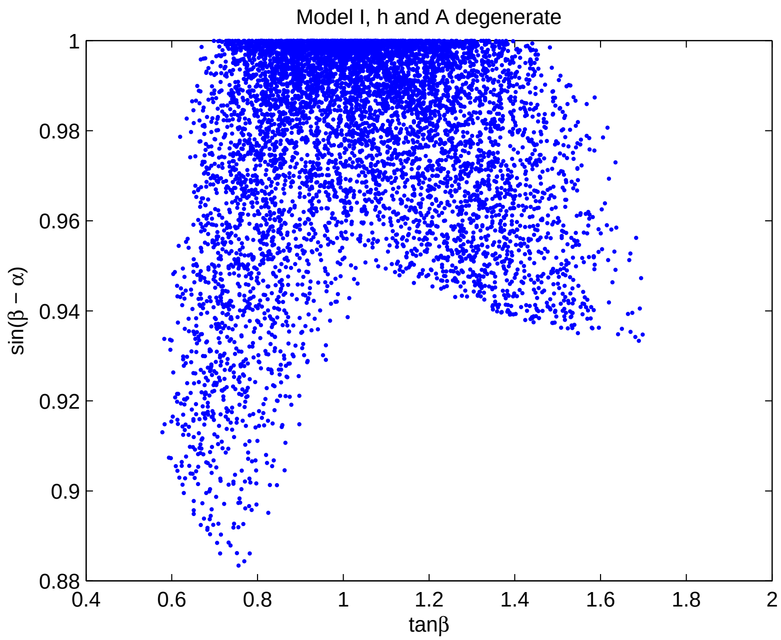
$$R_f^H = \frac{\sigma(pp \to H)_{\rm 2HDM} \times {\rm BR}(H \to f)_{\rm 2HDM}}{\sigma(pp \to h_{\rm SM}) \times {\rm BR}(h_{\rm SM} \to f)}\,,$$

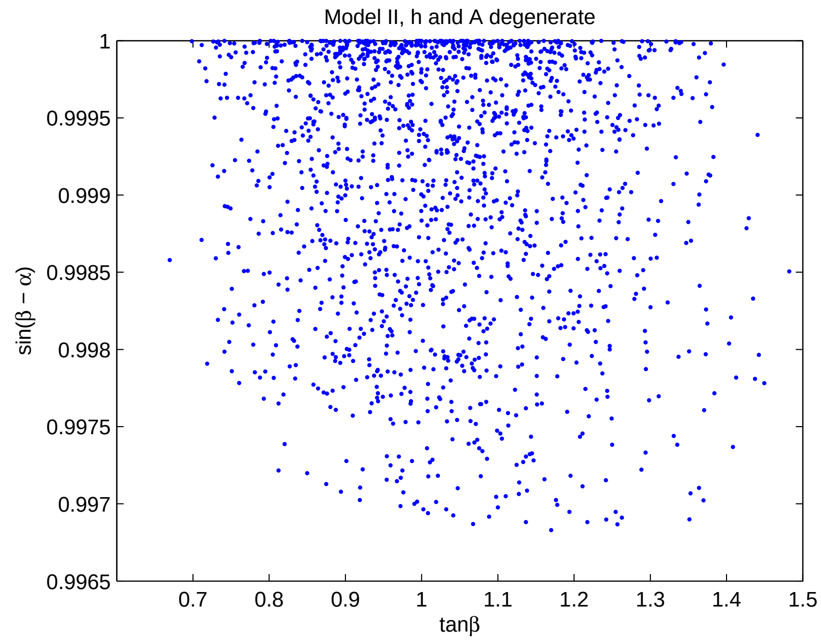
where f is the final state of interest, and H is one of the two 125 GeV mass-degenerate scalars. The observed ratio of f production relative to the SM expectation is

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

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.

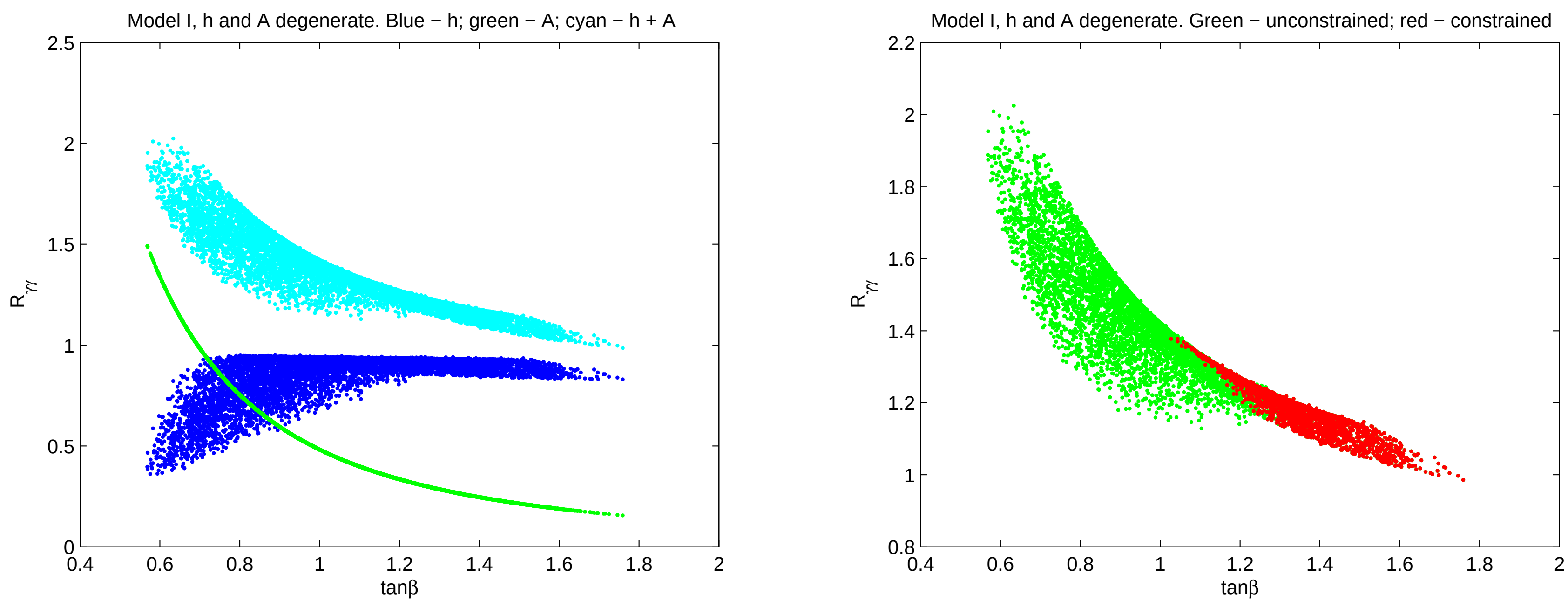
In our analysis, we assume that $R_{WW} \simeq R_{ZZ} \simeq 1 \pm 0.2$.





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.

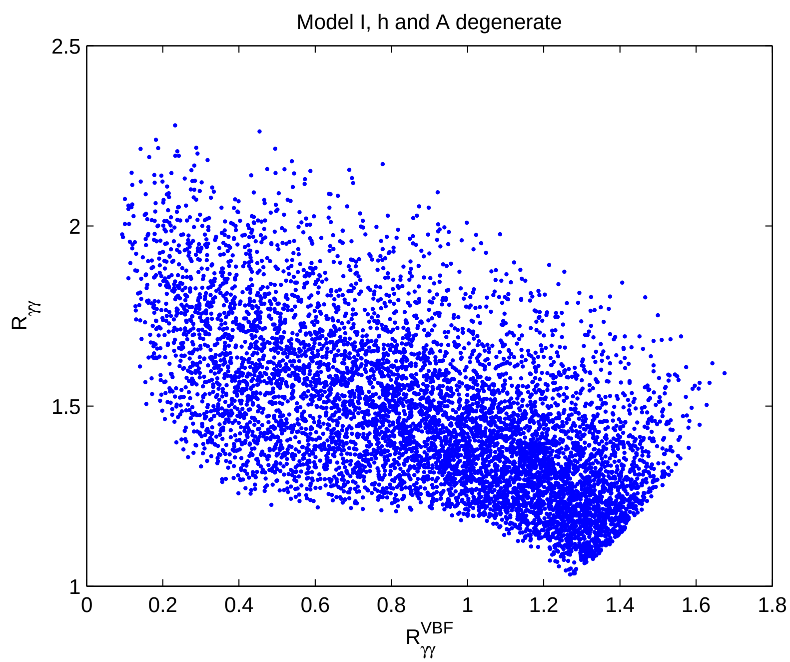
Right panel: Total rate for $R_{\gamma\gamma}$ as a function of $\tan\beta$ for the constrained (red) and unconstrained (green) scenarios.

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:

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

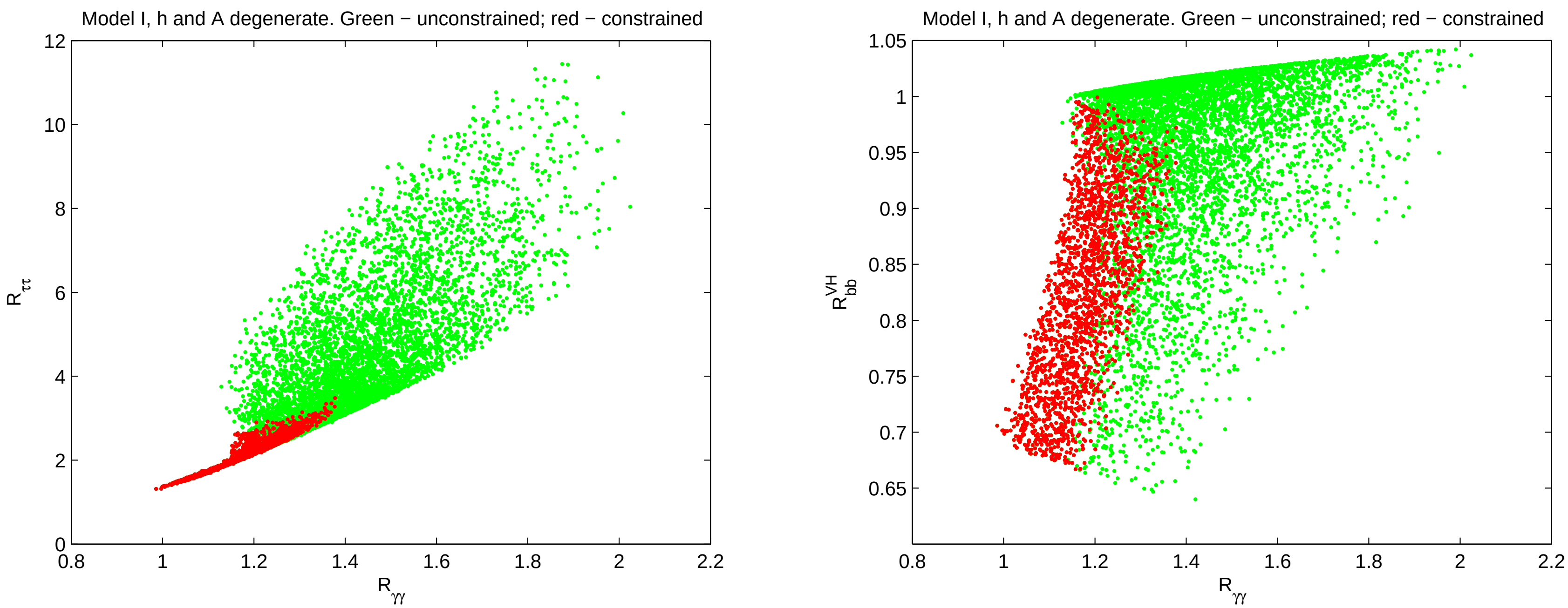


Allowed region in the $R_{\gamma\gamma}^{\rm VBF} - R_{\gamma\gamma}$ plane with (red) and without (green) the B-physics constraints.

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.

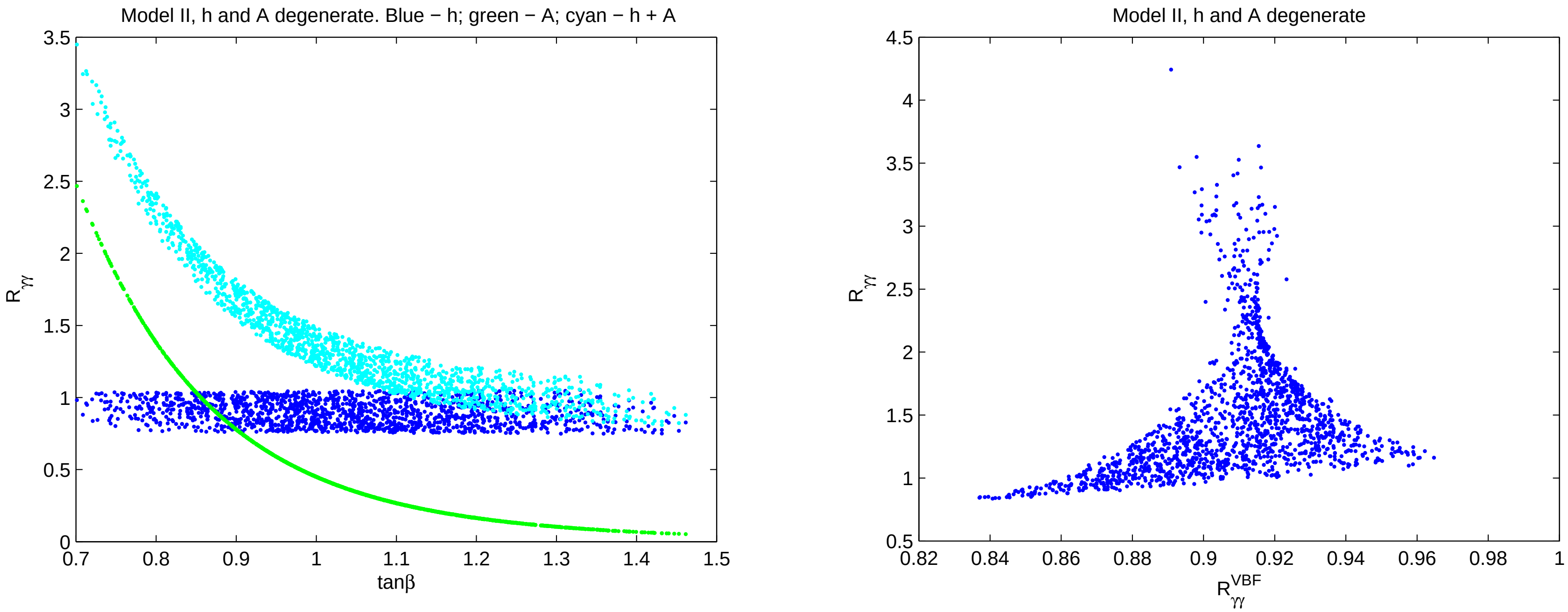
1. The inclusive $\tau^+\tau^-$ signal is enhanced with respect to the SM due to the production of A via gg fusion.

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}^{VH} (h and A summed) as a function of $R_{\gamma\gamma}$ for the constrained (red) and unconstrained (green) scenarios.

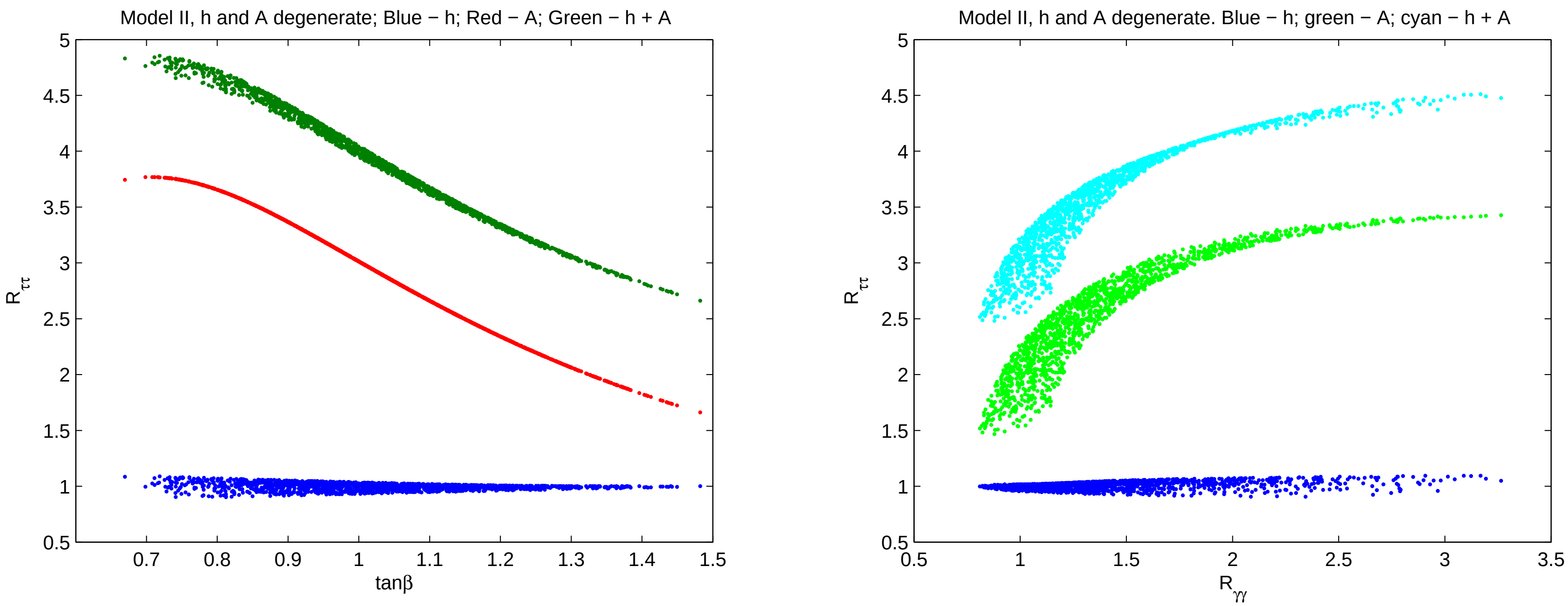
We can repeat the exercise for the Type-II 2HDM. Once we assume a heavy charged Higgs mass, there are no further constraints from B physics.



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 $R_{\gamma\gamma}^{\rm VBF} - R_{\gamma\gamma}$. 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, $R_{\gamma\gamma}^{\rm VBF}$ 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: $R_{\tau\tau}$ 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: $R_{\tau\tau}$ 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).

We are at the dawn of an exciting era for Higgs Hunters.

Meanwhile in 2013, be sure to contribute to the Higgs Working Group of the Energy Frontier Group for the Snowmass 2013 Study [see http://www.snowmass2013.org/tikiindex.php?page=The+Higgs+Boson]

Also, if you are available, remember to apply to the Aspen summer Program (deadline for applications is January 31, 2013):

Workshop: Implications of Higgs-like LHC signals
Organizers: John Gunion, Howard Haber, Andrey Korytov, Laura Reina
Dates: August 11, 2013 to September 1, 2013

http://www.aspenphys.org/physicists/summer/program/applications.html.

Apparently, there was a mistranslation of a Mayan document that purported to predict the end of the world on December 21, 2012. In fact, what was actually predicted was the end of the KITP Higgs Identification Workshop on December 21, 2012.

Thus, I officially declare that this Workshop is now over. Safe travels and happy holidays to all!