125 GeV Higgs Scenarios in the NMSSM and 2HDM Perspectives

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based on arXiv:1207.1545, 1207.1817, 1208.4952, 1210.1976
with G. Belanger, U. Ellwanger, J.F. Gunion, S. Kraml, J. Schwarz

based on arXiv:1211.3580 with A. Drozd, B. Grzadkowski, J.F. Gunion

Outline

1. SM Higgs Boson Physics
   - Higgs boson in the SM
   - 125 GeV Higgs-like signal at the LHC and the Tevatron
2. 125 GeV Higgs in the NMSSM
   - Single Higgs Scenarios: h_1 or $h_2 \sim 125$ GeV
   - Degenerate Higgs Scenarios: h_1 and $h_2 \sim 125$ GeV
   - 98 GeV + 125 GeV LEP-LHC Higgs Scenario
3. Enhanced Signals of 125 GeV Higgs in the 2HDM
   - Single Higgs Scenarios: h or $H \sim 125$ GeV
   - Degenerate Higgs Scenarios
4. Conclusion and Outlook

Higgs – God particle – has been attracting worldwide attention over the years.

上帝，你真的存在!

A faded Chinese article published in the public daily newspaper in 1980s.

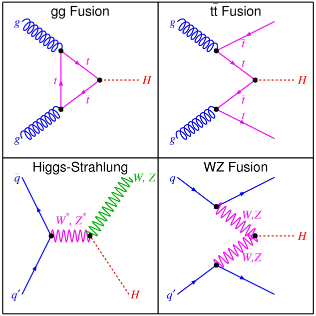
The title is "God, you **DO** really exist!"

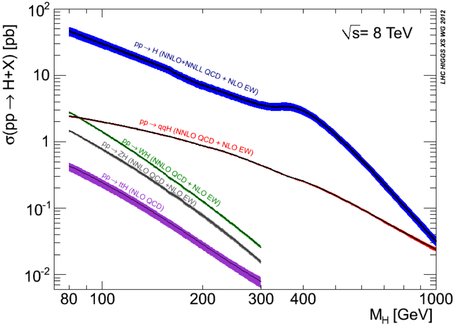
SM Higgs Boson Production

LHC:

- gluon fusion (ggF) and vector boson fusion (VBF) – main production.
- $V^* \to VH$ ($V = W$ or Z) with $H \to b\bar{b}$ and $VBF \to H$ with $H \to \tau^+\tau^-$.

Tevatron: $V^* \to VH$ ($V = W$ or Z) with $H \to b\bar{b}$ only.

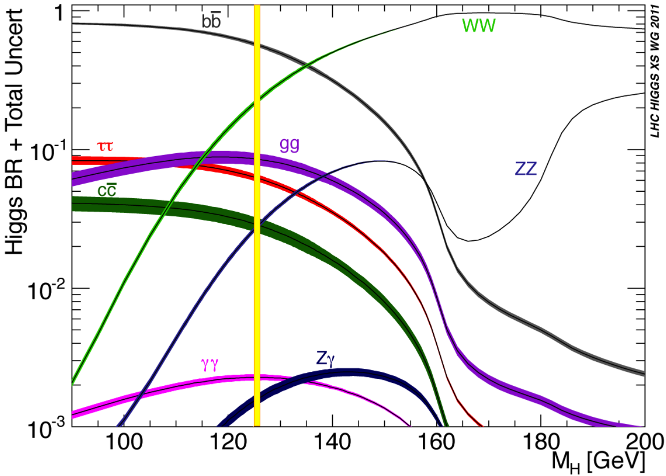




$gg \to H$: Good for WW, ZZ, $\gamma\gamma$ final states; Bad for $H \to b\bar{b}$ (overwhelming QCD backgrounds!)

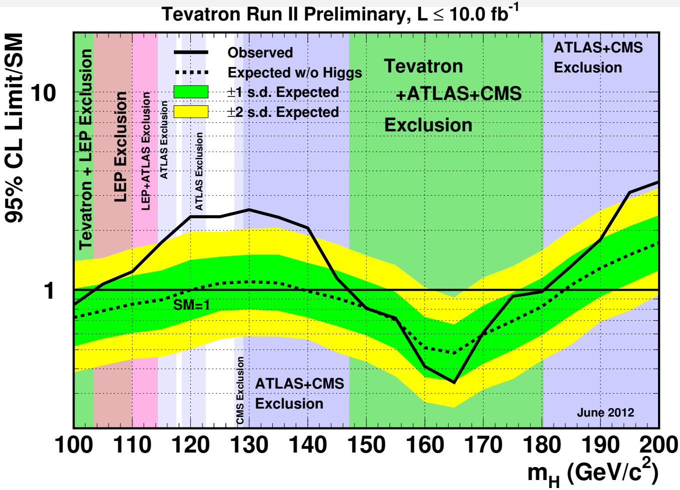
$qq \to V^* \to VH$: Good for $H \to b\bar{b}$ final states in the Leptons + Jets search (W/Z boson decays to leptons which are straightforward to select).

SM Higgs Boson Decay



ZZ, $\gamma\gamma$, $Z\gamma$: small branching ratio but clean signatures and NO missing energy.
WW: more sizable branching ratio; two leptons + missing energy.
$b\bar{b}$: largest branching ratio; quark hadronization into jets.

SM Higgs Search Overview (Prior to July 4th, 2012)



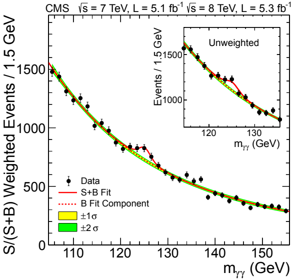
SM Higgs mass m_H excluded regions:

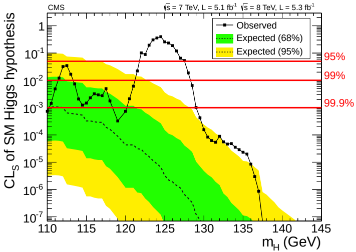
LEP: < 114 GeV (1989-2000).
Tevatron: 100 GeV – 106 GeV and 147 GeV – 179 GeV.
CMS: 127.5 GeV – 600 GeV.

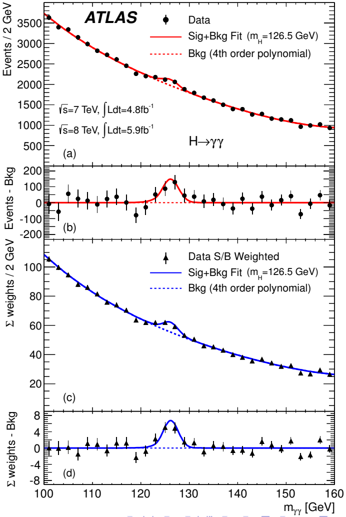
ATLAS: 110 GeV – 117.5 GeV, 118.5 GeV – 122.5 GeV and 129 GeV – 539 GeV.

125 GeV Higgs-like signal at the LHC

After over thirty years of waiting, this summer, CMS and ATLAS both saw a "new boson" decaying into two photons, with a mass at around 126 GeV:







A HISTORIC moment in science.

It is a privilege to witness the Higgs discovery, on July 4th, 2012.


国际新闻

INTERNATIONAL NEWS

新快报

A29

天哪！这真是"上帝粒子"吗？

欧洲核子中心激动宣布可能发现希格斯－玻色子："我们对宇宙的理解，将要改变！"

物理学家们纷纷发博表期待

83岁希格斯：未想过有生之年等到

还需时间确认 意义堪比阿波罗登月

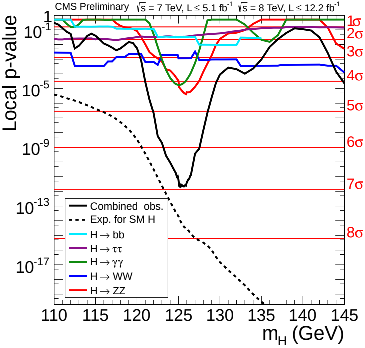
网友围观：好像很牛 但是不懂

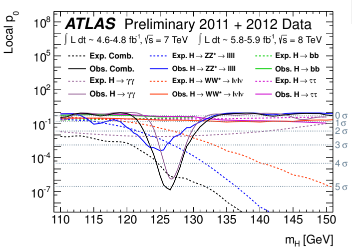
希格斯－玻色子是个啥？

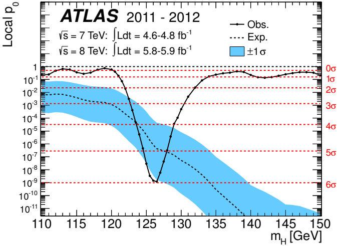
"这该死的粒子！"

125 GeV Higgs-like signal at the LHC

Local p-values was updated shortly after HCP 2012 for both collaborations.







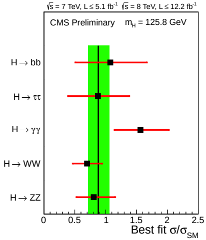
CMS and ATLAS provide an essentially 7σ and 6σ signal, respectively, for a Higgs-like resonance with mass at 125.8 GeV and 126.5 GeV, respectively.

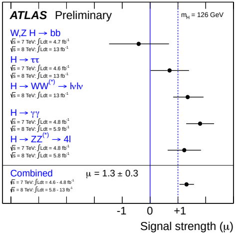
With the new data, "Seeing is believing" !

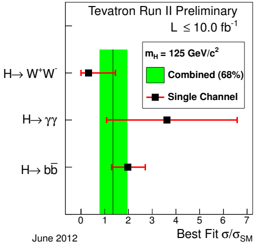
125 GeV Higgs-like signal (shortly after HCP 2012)

Question: whether or not it *is* the SM Higgs? how to distinguish?

- reduced coupling
- signal strength as defined $R_Y^{h_i}(X) \equiv \frac{\sigma(Y \to h_i)\ \mathrm{BR}(h_i \to X)}{\sigma(Y \to h_{\mathrm{SM}})\ \mathrm{BR}(h_{\mathrm{SM}} \to X)}$







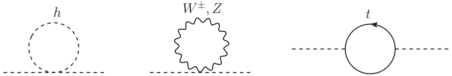
	gg fusion			VBF		VH
$m_h = 125$	$\gamma\gamma$	$ZZ^* \to 4\ell$	$WW^* \to 2\ell 2\nu$	$\gamma\gamma$	$\tau^+\tau^-$	$b\bar{b}$
ATLAS	1.8 ± 0.5	1.2 ± 0.6	1.4 ± 0.6			-0.4 ± 1.1
CMS	$1.564^{+0.46}_{-0.419}$	$0.807^{+0.349}_{-0.28}$	$0.699^{+0.245}_{-0.232}$	$2.256^{+1.286}_{-1.017}$	$0.819^{+0.824}_{-0.746}$	$1.309^{+0.654}_{-0.601}$
	high resolution		poor resolution			

Tevatron: the evidence for the Higgs boson is based principally on the $W + H$ with $H \to b\bar{b}$ decay mode, the observed enhancements relative to the SM rate by a factor of $1.56^{+0.72}_{-0.73}$.

Part I: 125 GeV Higgs in the NMSSM

Hierarchy Problem with the Standard Model

The Higgs mass is essentially a **free** parameter, but the Higgs boson hasn't been discovered yet ...⟶ Quantum correction to the Higgs mass



$$\underbrace{m_H^2}_{\sim \lambda v^2} = m_{\text{bare}}^2 + \underbrace{\frac{1}{16\pi^2}\lambda\Lambda^2 + \frac{1}{16\pi^2}g^2\Lambda^2 - \frac{3}{8\pi^2}y_t^2\Lambda^2}_{\text{quadratically-divergent radiative correction}}$$

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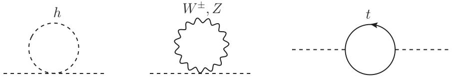

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- If $\Lambda \sim \mathcal{O}(v)$, $\surd$
- However, the SM is assumed to be an EFT with very heavy particles, so $\Lambda \gg v$ (i.e., $\Lambda \sim M_{\text{GUT}}, M_{\text{Pl}}$).

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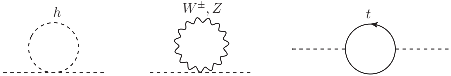

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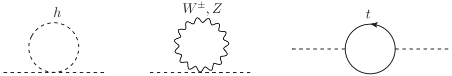

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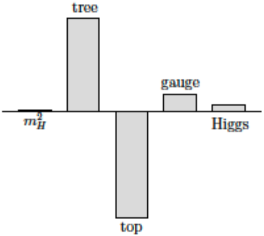
Fine-tuning

- The fine-tuning is needed for example, $\Lambda = 10$ TeV $\longrightarrow$
- The fine-tuning required is much greater as Λ increases
- The fine-tuning completely disappeared at $\Lambda = 1$ TeV.



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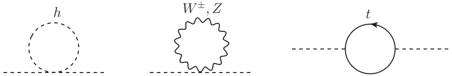

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- The fine-tuning is needed for example, $\Lambda = 10$ TeV $\longrightarrow$
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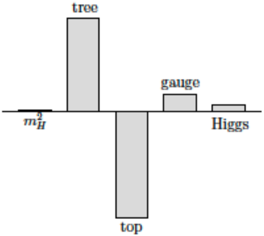

Supersymmetry and MSSM

Supersymmetry is a generalization of the space-time symmetries of quantum field theory that transforms fermions into bosons and vice versa.

- allows the unification of gauge couplings.
- solves the hierarchy problem by introducing superpartners

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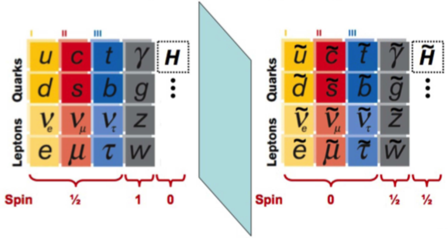
In a theory with unbroken supersymmetry, for every type of fermion there exists a corresponding type of boson with the same mass and internal quantum numbers, and vice-versa.

MSSM=SM+SM-Superpartners

fermion	$\longleftrightarrow$	sfermion
gauge boson	$\longleftrightarrow$	gaugino
Higgs	$\longleftrightarrow$	Higgsino



NMSSM=MSSM+Singlet Brief Review

I will focus on the discussion within the (semi-unified)[1] NMSSM perspective in which both a Higgs mass of order 125 GeV and significant $\gamma\gamma$ mode enhancements are easily obtained.

$$W_{NMSSM} = W_{MSSM} + \cancel{\mu H_u H_d} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

with the additional $m_S^2|S|^2$, $\lambda A_\lambda H_u H_d S$ and $\frac{1}{3}\kappa A_\kappa S^3$ terms in the soft SUSY-breaking Lagrangian. The NMSSM is very attractive:

1. it solves the μ problem of the MSSM: $\mu_{\text{eff}} = \lambda\langle S\rangle \longrightarrow M_{\text{SUSY}}$ $\surd$.
2. The three CP-even Higgs fields, H_u, H_d and S mix and yield

NMSSM Higgs Sector
3 CP-even neutral scalars: h_1, h_2, h_3
2 CP-odd neutral pseudoscalar: a_1, a_2
2 charged scalars: $H^\pm$

3. The lightest CP-even Higgs mass ($m_S^2 \sim m_{Q_3}^2$)

$$m_{h_1}^2 \approxeq \overbrace{M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta}^{\text{tree level}} - \frac{\lambda^2}{\kappa^2} v^2 (\lambda - \kappa \sin 2\beta)^2 + \frac{3 m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{m_S^2}{m_t^2}\right) + \frac{A_t^2}{m_S^2}\left(1 - \frac{A_t^2}{12 m_S^2}\right)\right]$$

[1] "Semi-unified" we mean a model which has universal m_0, $m_{1/2}$, and A_0 at the GUT scale with NUHM relaxation for $m_{H_u}^2$, $m_{H_d}^2$ and m_S^2, and general A_λ and A_κ, together with the parameters v, $\tan\beta$, λ.

Basic Constraints

- Having a proper RGE solution, no Landau pole and a neutralino LSP.
- Higgs mass limits are from LEP, TEVATRON, and early LHC data; SUSY mass limits are essentially from LEP.
- B-physics constraints

Observables	Constraints
ΔM_d	0.507 ± 0.008 (2σ)
ΔM_s	17.77 ± 0.24 (2σ)
BR($B \to X_s\gamma$)	3.55 ± 0.51 (2σ)
BR($B^+ \to \tau^+\nu$)	$(1.67 \pm 0.78) \times 10^{-4}$ (2σ)
BR($B_s \to \mu^+\mu^-$)	$< 4.5 \times 10^{-9}$ (95% C.L.)

- Regarding dark matter constraints, we accept all points that have the relic density $\Omega h^2 < 0.136$, particularly, $0.094 \leq \Omega h^2 \leq 0.136$ is the 'WMAP window'.
- 2011 XENON100 bound on the spin-independent LSP–proton scattering cross section. [2]
- the anomalous magnetic moment of the muon δa_μ (discussed shortly).

[2] For points with $\Omega h^2 < 0.094$, we rescale these bounds by a factor of $0.11/\Omega h^2$.

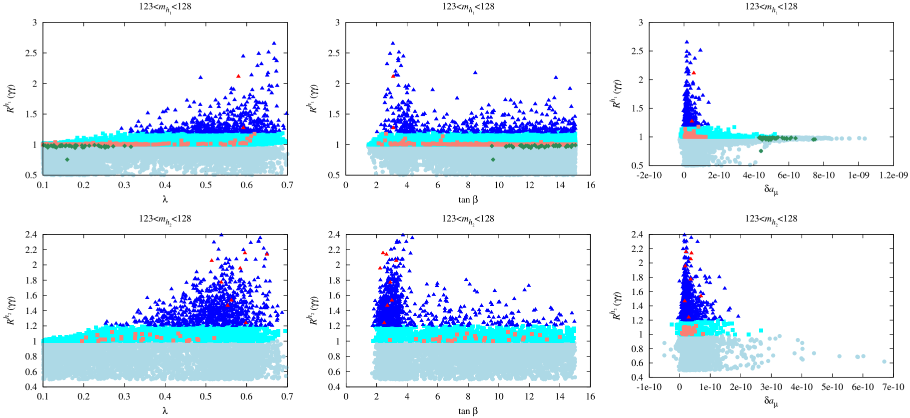
Scenario I: Single 125 Higgs

- h_1 or h_2 either lies in the 123–128 GeV mass window.

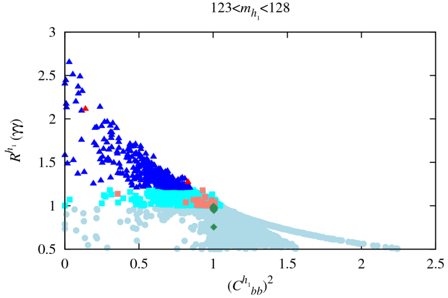
$\gamma\gamma$ Enhancement Realization

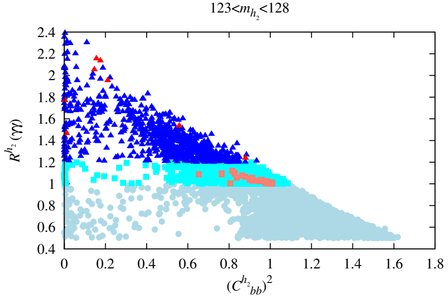
$\gamma\gamma$ enhancements appear to be possible only if

- the superpotential coupling λ is large (and $\tan\beta$ is preferably small)
- the δa_μ constraint is greatly relaxed



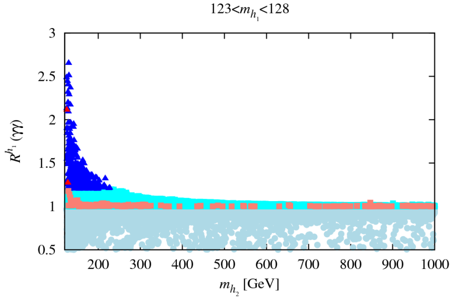
$\gamma\gamma$ Enhancement Mechanism

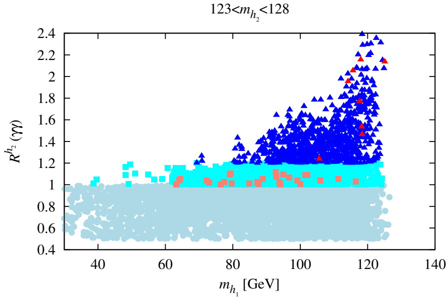




The enhancement happens when the partial width of a 125 GeV Higgs boson into $b\bar{b}$ is strongly reduced.

$\gamma\gamma$ Enhancement Dependence on the Higgs Mass



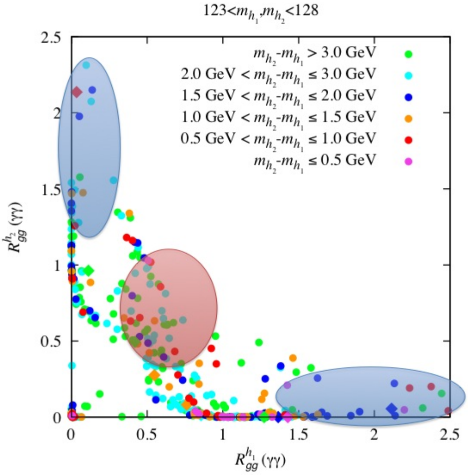


In addition to large λ (and preferably small $\tan\beta$), enhanced $\gamma\gamma$ rates are most natural when the h_1 has mass similar to the second lightest CP-even Higgs, h_2, (with one of them being primarily the doublet-like H_u while the other has a large singlet S component) with enhancement particularly likely if the h_1 and h_2 are degenerate.

Scenario II: Degenerate Higgs

- h_1 and h_2 both lie in the 123–128 GeV mass window.

Individual $\gamma\gamma$ Rates



We combine h_1 and h_2 signals as follows in defining

- effective Higgs mass:

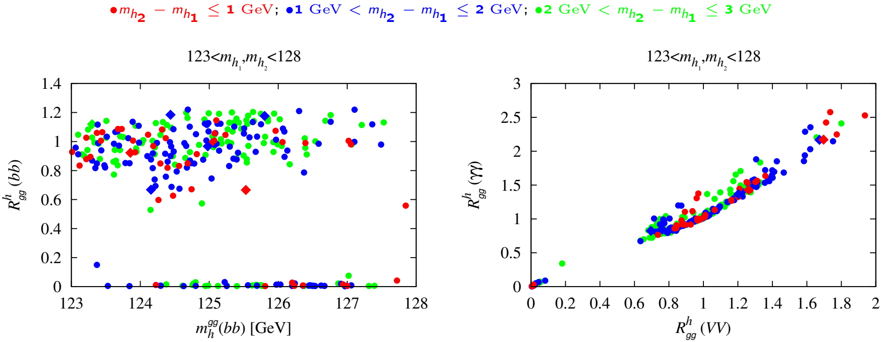
$$m_h^Y(X) \equiv \frac{R_Y^{h_1}(X) m_{h_1} + R_Y^{h_2}(X) m_{h_2}}{R_Y^{h_1}(X) + R_Y^{h_2}(X)}$$

- effective Higgs signal:

$$R_Y^h(X) = R_Y^{h_1}(X) + R_Y^{h_2}(X)$$

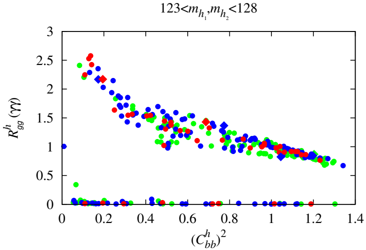
The extent to which it is appropriate to combine the rates from the h_1 and h_2 depends upon the degree of degeneracy and the experimental resolution, estimated to be of order $\sigma_{\rm res} \sim 1.5$ GeV. The widths of the h_1 and h_2 are very much smaller than this resolution.

Combined Signal Rates



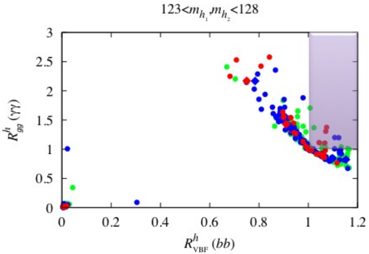
- Enhanced $\gamma\gamma$ and VV rates from gluon fusion are very common.
- There is a very strong correlation between $R^h_{gg}(\gamma\gamma)$ and $R^h_{gg}(VV)$ described approximately by $R^h_{gg}(\gamma\gamma) \sim 1.25\, R^h_{gg}(VV)$. In particular, if $R^h_{gg}(\gamma\gamma) \sim 1.5$, as suggested by current experimental results, then in this model $R^h_{gg}(VV) \geq 1.2$.

Enhancement Mechanism – Degenerate Scenarios



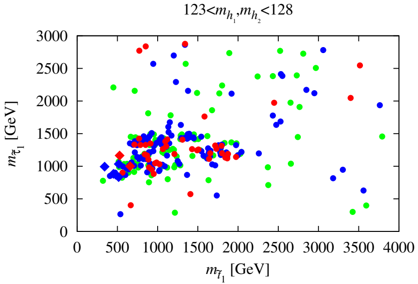
The primary mechanism:

- large net $\gamma\gamma$ branching ratio is achieved by reducing the average total width by reducing the average $b\bar{b}$ coupling strength.
- aniti-correlation between $R^h_{gg}(\gamma\gamma)$ and $R^h_{W*\to Wh}(b\bar{b}) = R^h_{\rm VBF}(b\bar{b})$.

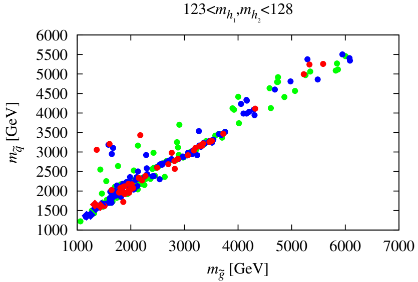


- In general, the larger $R^h_{gg}(\gamma\gamma)$ is, the smaller the value of $R^h_{W*\to Wh}(b\bar{b})$.
- Enhancement of Wh production with $h \to b\bar{b}$ is rather limited; indeed the maximal value of $R^h_{\rm VBF}(b\bar{b}) = R^h_{W*\to Wh}(b\bar{b})$ is of order 1.2.
- There *are* parameter choices for which both the $\gamma\gamma$ rate and the $W^* \to Wh(\to b\bar{b})$ rate can be enhanced relative to the SM. This is an **unique** feature as a result of there being contributions to these rates from both the h_1 and h_2.

Implication for SUSY Particles

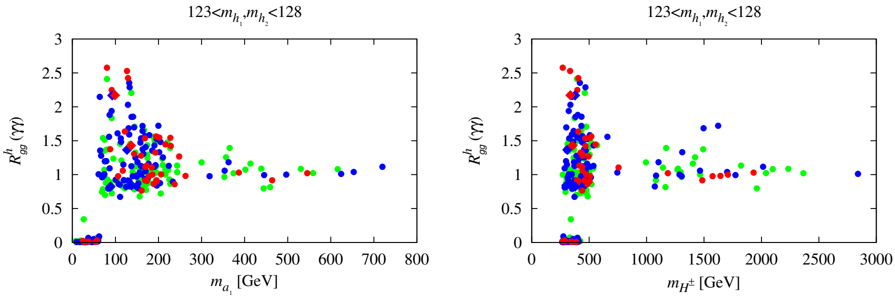


1. Indeed, the few points which we found in the WMAP window always have $m_{\tilde{t}_1} < 700$ GeV.



2. Squark and gluino masses are above about 1.25 TeV ranging up to as high as 6 TeV (where our scanning more or less ended). The WMAP-window points with large $R^h_{gg}(\gamma\gamma)$ are located at low masses of $m_{\tilde{g}} \sim 1.3$ TeV and $m_{\tilde{q}} \sim 1.6$ TeV.

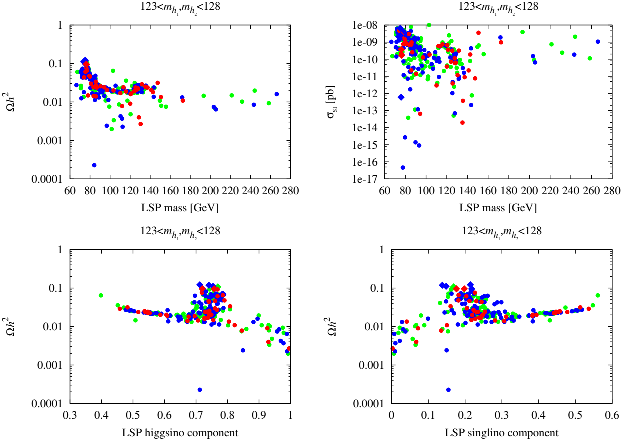
Correlation on Other Higgs Bosons



(note that $m_{a_2} \simeq m_{h_3} \simeq m_{H^\pm}$)

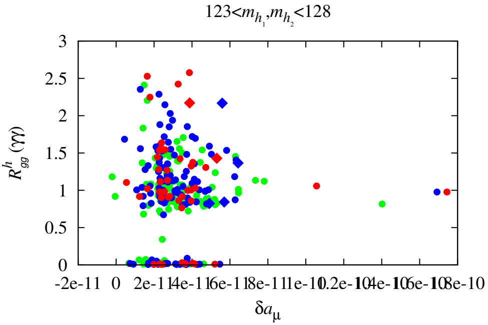
- The general trend is that the maximum $R^h_{gg}(\gamma\gamma)$ possible decreases rapidly as m_{a_1} and $m_{H^\pm}$ increase.
- Values above 1.7 are associated with masses for the a_2, h_3 and $H^\pm$ of order $\lesssim 500$ GeV and for the a_1 of order $70 \lesssim m_{a_1} \lesssim 150$ GeV, 250 GeV being the lowest allowed $m_{H^\pm}$.
- Although $m_{a_1} \sim 125$ GeV is common for points with $R^h_{gg}(\gamma\gamma) > 1$, the contribution of the a_1 to the $\gamma\gamma$ signal is always small, typically $R^{a_1}_{gg}(\gamma\gamma) \lesssim 0.01$ (due to large singlet component of the a_1 for all $R^h_{gg}(\gamma\gamma) > 1$ points).

Dark Matter Properties



- WMAP-window points have a rather limited range of LSP masses, roughly $m_{\widetilde{\chi}_1^0} \in [60, 80]$ GeV.
- Corresponding $\sigma_{\rm SI}$ values range from *few* $\times\, 10^{-9}$ pb to as low as *few* $\times\, 10^{-11}$ pb.
- large Ωh^2: mixed higgsino–singlino, with a singlino component of the order of 20%. low Ωh^2: the LSP is dominantly higgsino (owing to small $\mu_{\rm eff}$).

What is the Status on δa_μ?



It is not possible to find scenarios of this degenerate/enhanced type while predicting a value of δa_μ consistent with that needed to explain the current discrepancy. In particular, the very largest value of δa_μ achieved is of order 1.8×10^{-10} ($\delta a_\mu < 6 \times 10^{-11}$ for the WMAP-window).

Large δa_μ only be possible if $\lambda < 0.1$, for which the Higgs signal in the $\gamma\gamma$ and VV^* $(V = W, Z)$ final states for Higgs in the 123–128 GeV window is very SM-like.

Interpretation: implicitly assume that the observed discrepancy in a_μ comes, at least in part, from a source other than the NMSSM.

double ratio

Let us now take a look in more detail.

$$R_Y^{h_i}(X) = \frac{\sigma(Y \to h_i)\mathrm{BR}(h_i \to X)}{\sigma(Y \to h_{\mathrm{SM}})\mathrm{BR}(h_{\mathrm{SM}} \to X)} = (C_Y^{h_i})^2 \frac{\Gamma(h_i \to X)}{\Gamma(h_{\mathrm{SM}} \to X)} \frac{\Gamma_{\mathrm{tot}}(h_{\mathrm{SM}})}{\Gamma_{\mathrm{tot}}(h_i)} = (C_Y^{h_i})^2 (C_X^{h_i})^2 \ldots$$

where $Y = gg$ for gluon fusion and $Y = WW, ZZ$ for W, Z fusion and W, Z strahlung, this latter also implies $R_{VBF}^{h_i}(X) = R_{V^* \to VH}^{h_i}(X)$ and $C_\Gamma^{h_i}$ is the ratio of the h_i total width the SM Higgs total width.

The diagnostic tools

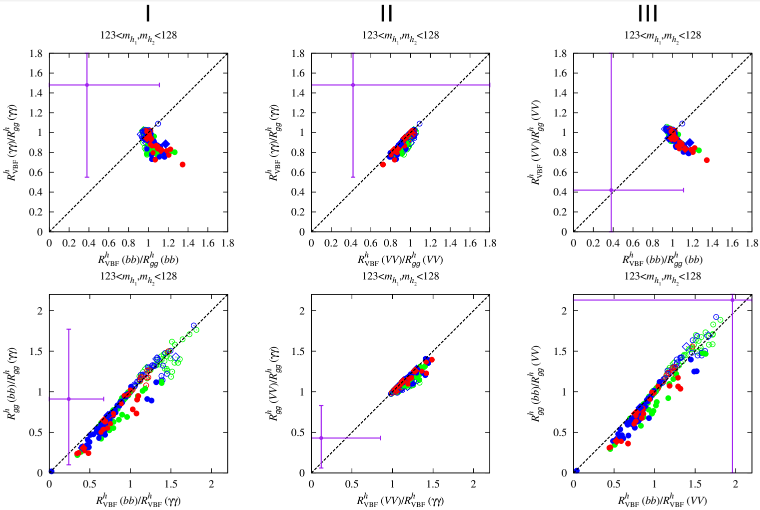
we propose the **double ratios** to reveal the existence of a second, quasi-degenerate (but non-interfering in the small width approximation) Higgs state are :

I): $\frac{R_{VBF}^{h}(\gamma\gamma)/R_{gg}^{h}(\gamma\gamma)}{R_{VBF}^{h}(bb)/R_{gg}^{h}(bb)}$, II): $\frac{R_{VBF}^{h}(\gamma\gamma)/R_{gg}^{h}(\gamma\gamma)}{R_{VBF}^{h}(WW)/R_{gg}^{h}(WW)}$, III): $\frac{R_{VBF}^{h}(WW)/R_{gg}^{h}(WW)}{R_{VBF}^{h}(bb)/R_{gg}^{h}(bb)}$

each of which should be unity if only a single Higgs boson is present but, due to the non-factorizing nature of the sum, are generally expected to **deviate from 1** if two (or more) Higgs bosons are contributing to the net h signals.

Of course, the above three double ratios are not all independent. Which will be most useful depends upon the precision with which the R^h's for different initial/final states can be measured.

double ratio examination – NMSSM (i)

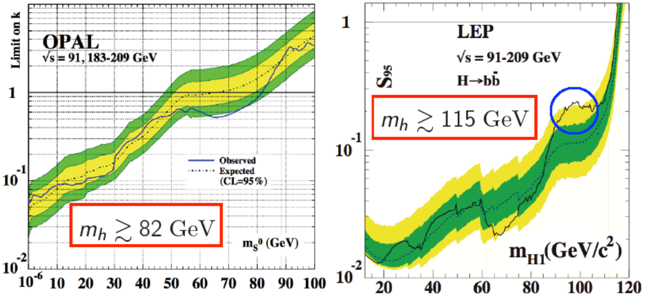


- III) is very like I) due to the correlation between the $R^h_{gg}(\gamma\gamma)$ and $R^h_{gg}(WW)$ values.
- Any one of these double ratios will often, but not always, deviate from unity.
- The probability of such deviation increases dramatically if we require $R^h_{gg}(\gamma\gamma) > 1$.

Scenario III: 98 +125 LEP – LHC

LEP Excess around 98 GeV

The LEP excess is clearly inconsistent with a SM-like Higgs boson around 98 GeV, being only about 10 – 20% of the rate predicted for the $h_{\rm SM}$.



An interesting question:

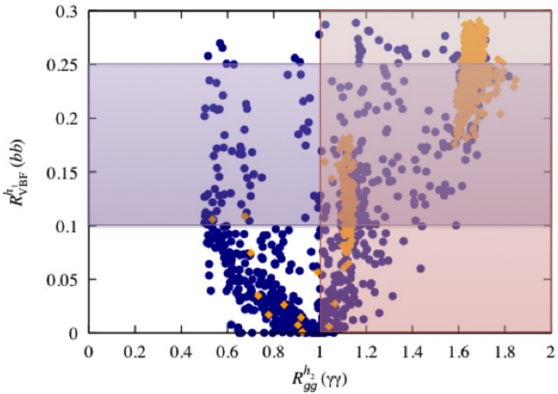
whether the LHC signal and the small ($\sim 2\sigma$) LEP excess in $e^+e^- \to Zb\overline{b}$ in the vicinity of $M_{b\bar{b}} \sim 98$ GeV using the h' with $m_{h'} \sim 98$ GeV could be **simultaneously** explained?

$98 + 125$ GeV LEP–LHC scenarios

98 +125 LEP–LHC scenario

- Consistency with such a result for the h' is natural if the h' couples at a reduced level to ZZ, which, in turn, is automatic if the h has substantial ZZ coupling, as required by the observed LHC signals.
- To describe the LEP and LHC data under the NMSSM framework, the h_1 and h_2 must have $m_{h_1} \sim 98$ GeV and $m_{h_2} \sim 125$ GeV, respectively, with the h_1 being largely singlet and the h_2 being primarily doublet (mainly H_u for the scenarios we consider).
- A 125 GeV Higgs state h_2 with enhanced $\gamma\gamma$ signal rate is easily obtained for large λ and small $\tan\beta$.

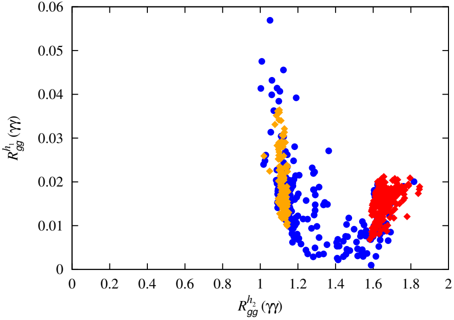
LEP–LHC Fit $(m_{h_1} \in [96, 100]\ \mathrm{GeV},\ m_{h_2} \in [123, 128]\ \mathrm{GeV})$

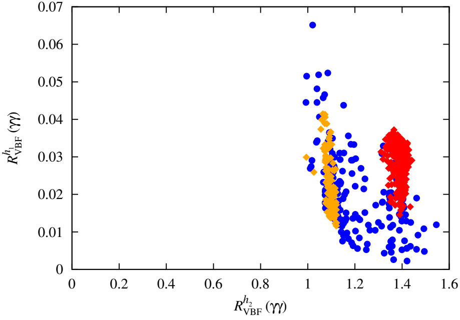


- Those points with $R^{h_1}_{VBF}(bb)$ between about 0.1 and 0.25 would provide the best fit to the LEP excess. ($R^{h_1}_{VBF}(bb)$ is equivalent to $R^{h_1}_{Vh_1}(bb)$ as relevant for LEP.)
- A large portion of such points have $R^{h_2}_{gg}(\gamma\gamma) > 1$ as preferred by LHC data.

In all the remaining plots: $R^{h_2}_{gg}(\gamma\gamma) > 1$ and $0.1 \le R^{h_1}_{VBF}(bb) \le 0.25$.

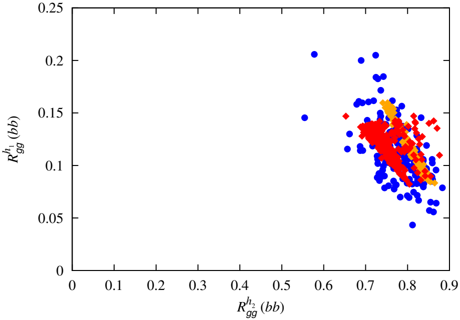
Enhanced $\gamma\gamma$ Rates

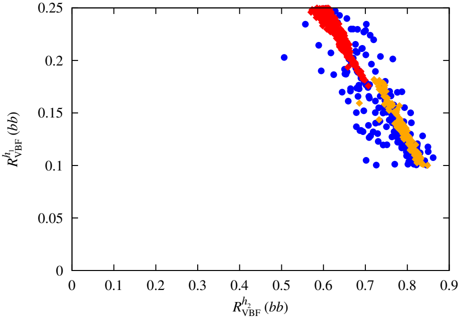




- h_2 can easily have an enhanced $\gamma\gamma$ signal for both gg and VBF production.
- The $\gamma\gamma$ signal arising from the h_1 for both production mechanisms is quite small and unlikely to be observable.

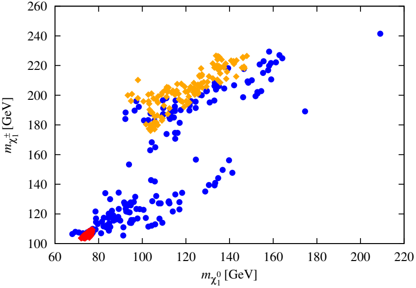
SM-like $b\bar{b}$ Rates

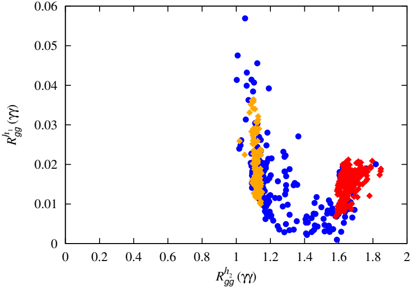


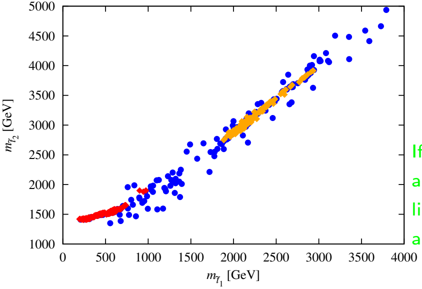


- $R^{h_2}_{gg}(bb)$ and $R^{h_2}_{VBF}(bb)$ values that are associated with reduced $b\bar{b}$ width (relative to the SM) are reduced to have enhanced $R^{h_2}_{gg}(\gamma\gamma)$ and $R^{h_2}_{VBF}(\gamma\gamma)$.
- $R^{h_1}_{gg}(bb)$ and $R^{h_1}_{VBF}(bb)$ values are such that the h_1 could not yet have been seen at the Tevatron or LHC.

Correlation between enhanced $\gamma\gamma$ rates and SUSY particle properties



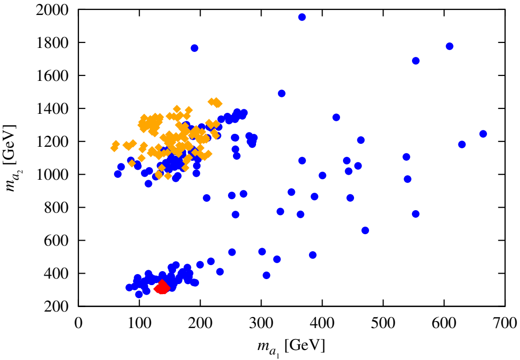




	$R_{gg}^{h_2}(\gamma\gamma)$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{t}_1}$	
I	~ 1.1	> 93 GeV	> 1.8 TeV	
II	~ 1.6	~ 77 GeV	197 GeV – 1 TeV	$\surd$

If $R_{gg}^{h_2}(\gamma\gamma)$ ends up converging to a large value, then masses for all strongly interacting SUSY particles would be close to current limits if the present $98 + 125$ GeV LEP–LHC Higgs scenario applies.

Expectation for Other NMSSM Higgses

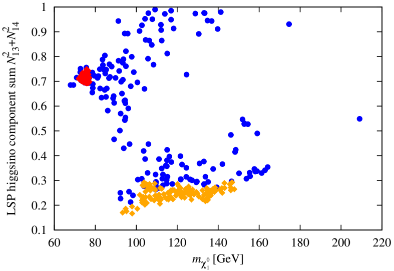


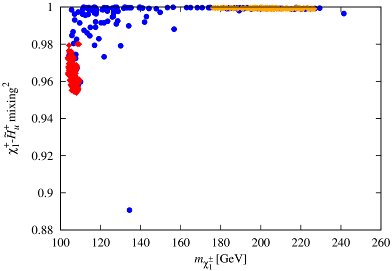
$m_{h_3} \simeq m_{H^\pm} \simeq m_{a_2}$ for the scenarios considered.

Small m_{a_1} is typical of the WMAP-window points.

LSP Composition

The composition of the $\widetilde{\chi}_1^0$ and the $\widetilde{\chi}_1^\pm$ are crucial when it comes to the relic density of the $\widetilde{\chi}_1^0$ (LSP dark matter candidate).

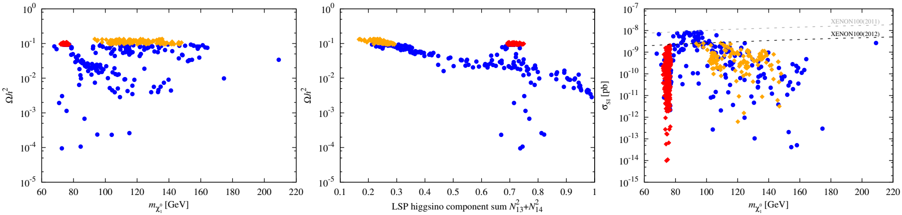




in the WMAP window

- Low $m_{\widetilde{\chi}_1^0}$ group (I) , the $\widetilde{\chi}_1^0$ can have a large Higgsino fraction since the $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to W^+W^-$ annihilation mode (mainly via t-channel exchange of the light Higgsino-like chargino) is below threshold.
- $m_{\widetilde{\chi}_1^0} > 93$ GeV group (II), the points can lie in the WMAP window only if the $\widetilde{\chi}_1^0$ does **NOT** have a large Higgsino fraction, in the other words, the LSP is dominantly singlino (under the approximation that the singlino fraction = 1 - Higgsino fraction).

Dark Matter Properties



Why the relic density Ωh^2 too small?

- The main mechanism is rapid $\tilde{\chi}_1^0\tilde{\chi}_1^0$ annihilation to W^+W^- due to a substantial Higgsino component of the $\tilde{\chi}_1^0$. Indeed, the relic density of a Higgsino LSP is typically of order $\Omega h^2 \approx 10^{-3} - 10^{-2}$.
- Ωh^2 increases as the Higgsino component declines.

Incidentally, the 2012 XENON100 limits on the spin-independent cross section $\sigma_{\rm SI}$ are obeyed by all the WMAP points. Experiments will probe some of the $\sigma_{\rm SI}$ values that survive 2012 limits relatively soon, especially the $m_{\tilde{\chi}_1^0} > 93~{\rm GeV}$ points that are in the WMAP window. However, it is also noteworthy that the $m_{\tilde{\chi}_1^0} \sim 75~{\rm GeV}$ WMAP-window points can have very small $\sigma_{\rm SI}$.

Part II: 125 GeV Higgs in the 2HDM

Two Higgs-Doublet Model (2HDM)

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right]$$
$$+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$
$$+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right]\left(\Phi_1^\dagger \Phi_2\right) + \text{h.c.} \right\},$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v\cos\beta + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (e^{i\xi} v\sin\beta + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix}$$

$0 \le \beta \le \pi/2$, $-\pi/2 \le \alpha \le \pi/2$.

1. NO $\mathcal{CP}$ violation: all λ_i and m_{12}^2 are assumed to be real.
2. NO spontaneous $\mathcal{CP}$ breaking: take $\xi = 0$.
3. NO severe tree-level FCNC.
4. "soft" Z_2 symmetry ($\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$) breaking: $m_{12}^2 \neq 0$.
5.

	2HDM Higgs Sector
5	2 CP-even neutral scalars: $h = -\rho_1 \sin\alpha + \rho_2 \cos\alpha$, $H = \rho_1 \cos\alpha + \rho_2 \sin\alpha$
	1 CP-odd neutral pseudoscalar: $A = -\eta_1 \sin\beta + \eta_2 \cos\beta$
	2 charged scalars: $H^\pm$

Basic Constraints

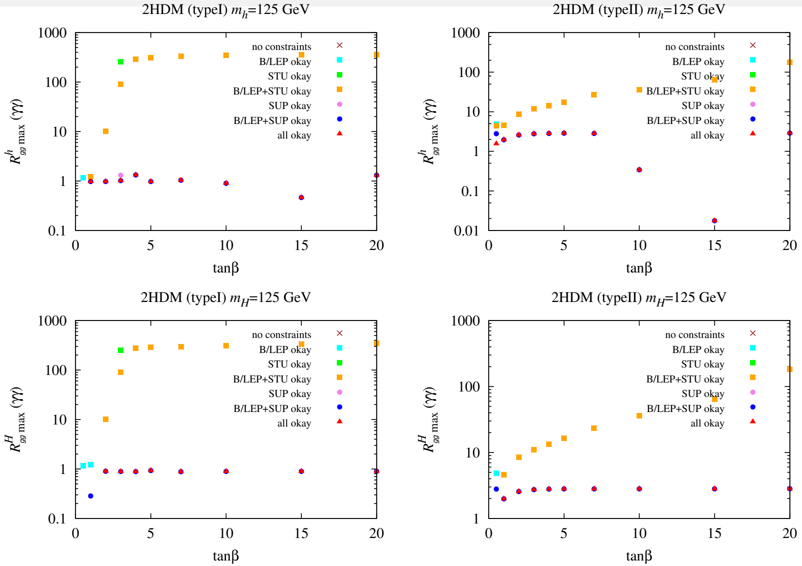
- implements precision electroweak constraints (denoted STU). $-0.3 < S < 0.33$; $-0.34 < T < 0.35$ and $-0.25 < U < 0.41$ (3σ)
- limits coming from requiring vacuum stability, unitarity and coupling-constant perturbativity (denoted jointly as SUP).
- LEP constraints on Higgs mass limits.
- B-physics constraints (from $\mathrm{BR}(B_s \to X_s\gamma)$, R_b, ΔM_{B_s}, ϵ_K, $\mathrm{BR}(B^+ \to \tau^+\nu_\tau)$ and $\mathrm{BR}(B^+ \to D\tau^+\nu_\tau)$).
- the anomalous magnetic moment of the muon δa_μ.

Single Higgs Scenarios

- h or H either lies at 125 GeV.

The signal at 125 GeV cannot be pure A since the A does not couple to ZZ, a final state that is definitely present at 125 GeV.

$\gamma\gamma$ Enhancement dependence on the levels of constraints imposed



The B/LEP and STU leave the maximum $R^h_{gg}(\gamma\gamma)$ unchanged. In contrast, the SUP constraints greatly reduce the maximum value of $R^h_{gg}(\gamma\gamma)$ that can be achieved .

$\gamma\gamma$ enhancement achieved (Type I)

$H \sim 125$

$\tan\beta$	$R^H_{gg\max}(\gamma\gamma)$	$R^H_{gg}(ZZ)$	$R^H_{gg}(b\bar{b})$	$R^H_{\rm VBF}(\gamma\gamma)$	$R^H_{\rm VBF}(ZZ)$	$R^H_{\rm VBF}(b\bar{b})$	m_h	m_A	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^H_{H^\pm}/\mathcal{A}$	δa_μ
2.0	0.90	1.00	1.02	0.89	0.99	1.00	125	400	350	50	0.9	-0.05	-2.1
3.0	0.89	0.96	0.88	0.97	1.05	0.96	125	400	350	50	0.9	-0.05	-1.8
4.0	0.89	0.97	1.09	0.79	0.86	0.97	105	500	90	50	1.0	-0.03	-1.7
5.0	0.93	0.98	1.06	0.86	0.90	0.98	125	500	90	50	1.0	-0.01	-1.6
7.0	0.88	0.99	1.03	0.85	0.95	0.99	65	400	350	10	1.0	-0.05	-1.6
10.0	0.89	1.00	1.02	0.87	0.98	1.00	45	400	350	0	1.0	-0.05	-1.6
15.0	0.90	1.00	1.01	0.89	0.99	1.00	5	400	350	0	-1.0	-0.05	-1.6
20.0	0.90	1.00	1.00	0.89	0.99	1.00	25	400	350	0	-1.0	-0.05	-1.5

NO ENHANCEMENT

TABLE V: Table of maximum $R^H_{gg}(\gamma\gamma)$ values for the Type I 2HDM with $m_H = 125$ GeV and associated R values for other initial and/or final states. The input parameters that give the maximal $R^H_{gg}(\gamma\gamma)$ value are also tabulated.

$h \sim 125$

$\tan\beta$	$R^h_{gg\max}(\gamma\gamma)$	$R^h_{gg}(ZZ)$	$R^h_{gg}(b\bar{b})$	$R^h_{\rm VBF}(\gamma\gamma)$	$R^h_{\rm VBF}(ZZ)$	$R^h_{\rm VBF}(b\bar{b})$	m_H	m_A	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^h_{H^\pm}/\mathcal{A}$	δa_μ
1.0	0.98	1.00	1.02	0.96	0.98	1.00	875	750	800	500	-0.7	-0.01	-2.3
2.0	0.98	0.98	0.92	1.04	1.04	0.98	425	500	350	200	-0.5	-0.01	-1.8
3.0	1.02	0.98	0.92	1.08	1.04	0.98	225	400	150	100	-0.4	0.01	-1.7
4.0	1.33	0.99	1.07	1.24	0.93	0.99	225	200	90	100	-0.1	0.14	-1.7
5.0	0.98	0.98	1.06	0.90	0.91	0.98	225	400	150	100	-0.0	0.01	-1.6
7.0	1.04	0.99	0.98	1.06	1.01	0.99	135	500	90	50	-0.2	0.02	-1.6
10.0	0.90	0.81	0.74	0.99	0.89	0.81	175	500	150	50	-0.5	0.04	-1.5
15.0	0.46	0.59	0.66	0.41	0.53	0.59	225	400	350	50	0.6	-0.11	-1.4
20.0	1.31	1.00	1.00	1.30	0.99	1.00	225	200	90	50	-0.0	0.13	-1.5

TABLE III: Table of maximum $R^h_{gg}(\gamma\gamma)$ values for the Type I 2HDM with $m_h = 125$ GeV and associated R values for other initial and/or final states. The input parameters that give the maximal $R^h_{gg}(\gamma\gamma)$ value are also tabulated.

The maximal $R^h_{gg}(\gamma\gamma)$ is of order of 1.3, as found if $\tan\beta = 4$ or 20. In these cases, $R^h_{gg}(ZZ)$ and $R^h_{gg}(b\bar{b})$ are of order 1 as fairly consistent with current data.

$\gamma\gamma$ enhancement achieved (Type II)

$h \sim 125$

$\tan\beta$	$R^h_{gg\max}(\gamma\gamma)$	$R^h_{gg}(ZZ)$	$R^h_{gg}(b\bar{b})$	$R^h_{\rm VBF}(\gamma\gamma)$	$R^h_{\rm VBF}(ZZ)$	$R^h_{\rm VBF}(b\bar{b})$	m_H	m_A	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$A^h_{H^\pm}/A$	δa_μ
0.5	1.56	2.69	1.84	0.52	0.89	0.61	425	500	600	100	-0.7	-0.06	-0.5
1.0	1.97	3.36	0.39	0.65	1.11	0.13	125	500	500	100	-0.2	-0.06	0.7
2.0	2.59	3.36	0.00	1.48	1.92	0.00	225	200	340	100	-0.0	-0.05	1.6
3.0	2.78	3.29	0.00	2.01	2.37	0.00	225	200	320	100	-0.0	-0.05	1.6
4.0	2.84	3.25	0.00	2.24	2.57	0.00	225	200	320	100	-0.0	-0.04	1.6
5.0	2.87	3.23	0.00	2.37	2.66	0.00	225	200	320	100	-0.0	-0.04	1.6
7.0	2.83	3.21	0.00	2.42	2.75	0.00	135	300	320	50	-0.0	-0.05	0.8
10.0	0.34	0.43	1.89	0.22	0.28	1.23	325	200	320	100	0.2	-0.08	3.5
15.0	0.02	0.03	4.06	0.00	0.01	0.87	225	200	320	50	0.6	-0.14	5.3
20.0	2.89	3.19	0.00	2.57	2.83	0.00	225	200	320	50	-0.0	-0.04	2.4

TABLE IV: Table of maximum $R^h_{gg}(\gamma\gamma)$ values for the Type II 2HDM with $m_h = 125$ GeV and associated R values for other initial and/or final states. The input parameters that give the maximal $R^h_{gg}(\gamma\gamma)$ value are also tabulated.

$H \sim 125$

$\tan\beta$	$R^H_{gg\max}(\gamma\gamma)$	$R^H_{gg}(ZZ)$	$R^H_{gg}(b\bar{b})$	$R^H_{\rm VBF}(\gamma\gamma)$	$R^H_{\rm VBF}(ZZ)$	$R^H_{\rm VBF}(b\bar{b})$	m_h	m_A	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$A^H_{H^\pm}/A$	δa_μ
1.0	1.99	3.24	0.52	0.71	1.16	0.19	125	500	500	100	1.0	-0.06	0.7
2.0	2.56	3.36	0.00	1.46	1.92	0.00	125	300	340	50	1.0	-0.06	1.1
3.0	2.73	3.29	0.00	1.97	2.37	0.00	125	300	320	50	1.0	-0.05	1.0
4.0	2.78	3.25	0.00	2.20	2.57	0.00	125	300	320	50	-1.0	-0.05	1.0
5.0	2.81	3.23	0.00	2.32	2.66	0.00	125	300	320	50	-1.0	-0.05	0.9
7.0	2.80	3.21	0.00	2.40	2.75	0.00	65	300	320	10	-1.0	-0.06	-0.0
10.0	2.81	3.20	0.00	2.46	2.79	0.00	45	300	320	0	-1.0	-0.06	-2.8
15.0	2.82	3.19	0.00	2.49	2.82	0.00	25	300	320	0	-1.0	-0.05	-16.9
20.0	2.82	3.19	0.00	2.50	2.83	0.00	25	300	320	0	-1.0	-0.05	-30.8

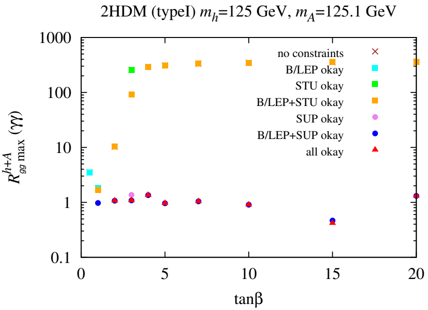
TABLE VI: Table of maximum $R^H_{gg}(\gamma\gamma)$ values for the Type II 2HDM with $m_H = 125$ GeV and associated R values for other initial and/or final states. The input parameters that give the maximal $R^H_{gg}(\gamma\gamma)$ value are also tabulated.

At the points that maximize $R_{gg}(\gamma\gamma)$ in the Type II model, $R_{gg}(ZZ)$ is typically large. In fact, $R^h_{gg}(ZZ) > R^h_{gg}(\gamma\gamma)$, thus the Type II models seem to be disfavored.

Degenerate Higgs Scenarios

- h and A both lie at the 125 GeV mass.
- H and A both lie at the 125 GeV mass.
- h and H both lie at the 125 GeV mass.

$\gamma\gamma$ Enhancement achieved (Type I)

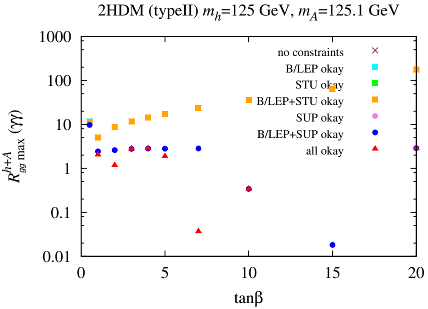


- For the Type I model, $R^h_{gg}(\gamma\gamma)$ is significantly enhanced only at $\tan\beta = 4$ and $\tan\beta = 20$ that the pseudoscalar contribution $R^A_{gg}(\gamma\gamma)$ turns out to be tiny.
- The A can contribute even more to the $b\bar{b}$ final state rate than the h if $\tan\beta$ is small.
- **Only** $\tan\beta = 20$ **yields both an enhanced** $\gamma\gamma$ **rate,** $R^{h+A}_{gg\,\max}(\gamma\gamma) = 1.31$**, and SM-like rates for the** ZZ **and** $b\bar{b}$ **final states!!!**

$\tan\beta$	$R^{h+A}_{gg\max}(\gamma\gamma)$	$R^h_{gg}(\gamma\gamma)$	$R^A_{gg}(\gamma\gamma)$	$R^{h+A}_{gg}(ZZ)$	$R^{h+A}_{gg}(b\bar b)$	$R^h_{VBF}(\gamma\gamma)$	$R^h_{VBF}(ZZ)$	$R^h_{VBF}(b\bar b)$	m_H	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$\mathcal{A}^h_{H^\pm}/\mathcal{A}$	δa_μ
2.0	1.07	0.92	0.15	0.98	1.73	0.98	1.04	0.98	325	250	100	-0.5	-0.04	-2.2
3.0	1.08	1.02	0.07	0.98	1.28	1.08	1.04	0.98	225	150	100	-0.4	0.01	-1.9
4.0	1.35	1.33	0.03	0.99	1.21	1.24	0.93	0.99	225	90	100	-0.1	0.14	-1.8
5.0	0.96	0.95	0.01	1.00	1.07	0.95	1.00	1.00	135	90	50	-0.2	-0.03	-1.7
7.0	1.04	1.04	0.01	0.99	1.00	1.06	1.01	0.99	135	90	50	-0.2	0.02	-1.6
10.0	0.91	0.90	0.01	0.81	0.77	0.99	0.89	0.81	175	150	50	-0.5	0.04	-1.5
15.0	0.42	0.42	0.00	0.59	0.67	0.37	0.53	0.59	225	250	50	0.6	-0.17	-1.4
20.0	1.31	1.31	0.00	1.00	1.00	1.30	0.99	1.00	225	90	50	-0.0	0.13	-1.6

TABLE VII: Table of maximum $R^{h+A}_{gg}(\gamma\gamma)$ values for the Type I 2HDM with $m_h = m_A = 125$ GeV and associated R values for other initial and/or final states. The input parameters that give the maximal $R^{h+A}_{gg}(\gamma\gamma)$ value are also tabulated.

$\gamma\gamma$ Enhancement achieved (Type II)



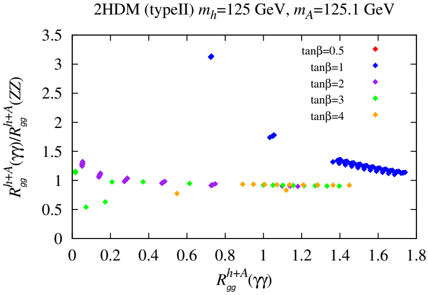
- For the Type II model, $R^{h+A}_{gg}(\gamma\gamma)$ reaches maximum values of order $2-3$. The pseudoscalar contribution $R^{A}_{gg}(\gamma\gamma)$ is also negligible.
- A substantial enhancement of $R^{h+A}_{gg}(\gamma\gamma)$ is most often associated with $R^{h+A}_{gg}(ZZ) > R^{h+A}_{gg}(\gamma\gamma)$ (contrary to the LHC observations). But this is not *always* the case.

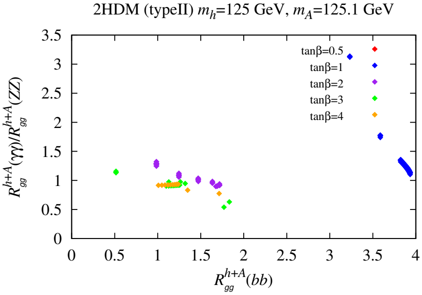
$\tan\beta$	$R^{h+A}_{gg\,max}(\gamma\gamma)$	$R^h_{gg}(\gamma\gamma)$	$R^A_{gg}(\gamma\gamma)$	$R^{h+A}_{gg}(ZZ)$	$R^{h+A}_{gg}(b\bar b)$	$R^h_{VBF}(\gamma\gamma)$	$R^h_{VBF}(ZZ)$	$R^h_{VBF}(b\bar b)$	m_H	$m_{H^\pm}$	m_{12}	$\sin\alpha$	$A^h_{H^\pm}/A$	δa_μ
1.0	2.05	1.58	0.47	2.05	3.91	0.93	1.22	0.65	525	500	100	-0.5	-0.06	1.3
2.0	1.18	1.17	0.01	1.31	1.68	1.07	1.20	0.87	325	340	100	-0.4	-0.05	1.5
3.0	2.78	2.78	0.00	3.29	0.27	2.01	2.37	0.00	225	320	100	-0.0	-0.05	2.3
4.0	2.84	2.84	0.00	3.25	0.23	2.24	2.57	0.00	225	320	100	-0.0	-0.04	2.3
5.0	1.89	1.89	0.00	2.19	0.95	1.41	1.64	0.47	225	320	100	0.1	-0.05	2.7
7.0	0.04	0.04	0.00	0.06	2.85	0.01	0.02	0.75	325	320	100	0.6	-0.15	5.2
10.0	0.34	0.34	0.00	0.43	3.66	0.22	0.28	1.23	325	320	100	0.2	-0.08	4.7
20.0	2.89	2.89	0.00	3.19	8.03	2.57	2.83	0.00	225	320	50	-0.0	-0.04	5.6

TABLE VIII: Table of maximum $R^{h+A}_{gg}(\gamma\gamma)$ values for the Type II 2HDM with $m_h = m_A = 125$ GeV and associated R values for other initial and/or final states. The input parameters that give the maximal $R^{h+A}_{gg}(\gamma\gamma)$ value are also tabulated.

$\gamma\gamma$ – ZZ rate correlation (Type II)

Only the points having $R_{gg}^{h+A}(ZZ) < 1.6$ are plotted.



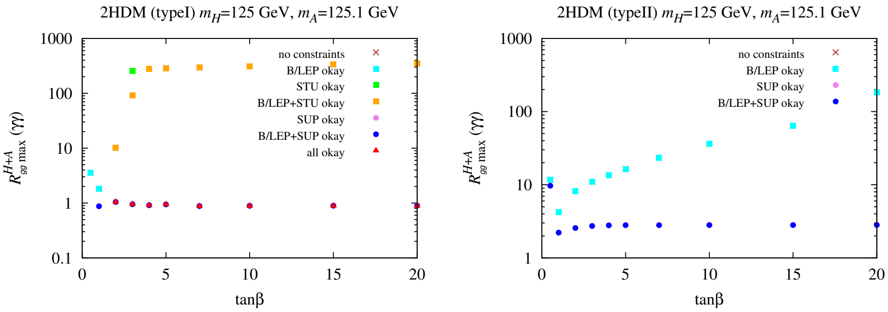


- As seen here, for $\tan\beta = 1$ there exist points (blue diamonds) such that $r_h > 1$ and $R_{gg}^{h+A}(\gamma\gamma) > 1$ (or even > 1.5). However, the $R_{gg}^{h+A}(b\bar{b})$ values that correspond to those points are **greater than** 3.5, a result that is disfavored by the LHC data.

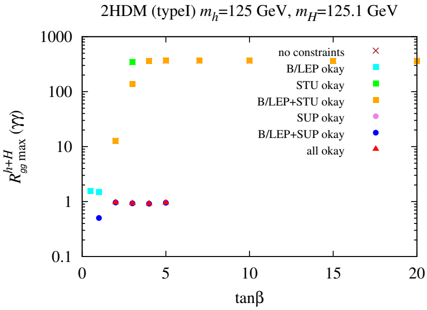
$H = 125$ and $A \sim 125$

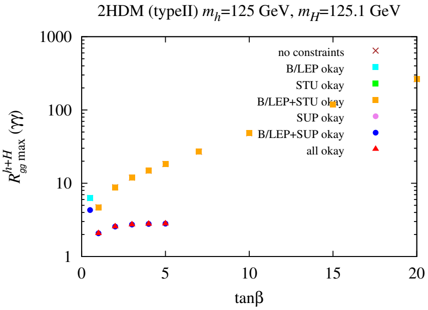
The case with $m_A \sim 125$ GeV and $m_H = 125$ GeV is less attractive.

1. For the Type I model, the maximum value achieved for $R^{H+A}_{gg\,\max}(\gamma\gamma)$ is rather modest reaching only 1.04 at small $\tan\beta$.
2. For the Type II model, there are **NO** parameter choices for which the H and A have a mass of 125 GeV while all other constraints are satisfied.



$h = 125$ and $H \sim 125$





We find that some of the previously available $\tan\beta$ values are ruled out by the full set of constraints.

1. In the Type I, there is NO gain in maximal $R^{h+H}_{gg}(\gamma\gamma)$ values, and often some loss, relative to the cases where only the h or only the H was required to have mass of $125~\mathrm{GeV}$.
2. Type II models suffer from that the ZZ signal is badly larger than the $\gamma\gamma$ signal.

Conclusions

- It seems likely that the Higgs responsible for EWSB has emerged. Perhaps, other Higgs-like objects are emerging.
- We have assessed the extent to which various semi-unified NMSSM scenarios with *at least* a $\sim$125 GeV Higgs h_1 are able to describe this LHC signal.
- We have also analyzed the Type I and Type II pure 2HDM with regard to consistency with a significant enhancement of the gluon-fusion-induced $\gamma\gamma$ signal observed at the LHC at $\sim 125~\mathrm{GeV}$.
  - The SUP play the key role in limiting the maximal possible enhancement in the Higgs to di-photon decay rate.
  - The Type II model is unable to give a significantly enhanced $gg \to$ Higgs $\to \gamma\gamma$ signal while maintaining consistency with other channels, particularly with the SM-like ZZ rate and somehow suppressed $b\bar{b}$ rate.
  - While the Type I models could provide a consistent picture if the LHC results converge to only a modest enhancement for $R^h_{gg}(\gamma\gamma) \lesssim 1.3$.

Future Work and Outlook

- The phenomenological NMSSM is a natural extension.
- But, if $R^h_{gg}(\gamma\gamma)$ is definitively measured to have a value much above 1.3 while the ZZ and $b\bar{b}$ channels show little enhancement then there is no consistent 2HDM description. One must go beyond the 2HDM to include new physics such as supersymmetry.
- 2HDM+singlets and 2HDM+triplets with a dark matter candidate is also an natural extension that worths studying.

Instead of being the end of story, the recent discovery of the 125 GeV Higgs-like signal has brought particle physics research into the start of a new era. We are in the midst of an exciting debate on the nature of the 125 GeV state.

We are currently waiting to see if the future LHC data supports the various multi-Higgs proposals outlined earlier, or, alternatively, suggests that alternative theories are Nature's choice.


Thank you
Thanks to Prof. Gunion for his patient guidance and help,
and strong recommendations for my US NSF 2013 LHC-TI Fellowship application.
To me, this is a productive year.
It is just the start of my research career, wish your staying tuned.

Back Up

μ Problem of the MSSM

The MSSM superpotential contains the bilinear coupling $\mu H_u H_d$ of the two Higgs MSSM doublet superfields and. The b parameter arises from the soft SUSY breaking term $bH_u H_d$.

Higgs VEV Minimization conditions

$$\begin{cases} |\mu|^2 + m_{H_u}^2 = b\cot\beta + (M_Z^2/2)\cos 2\beta \\ |\mu|^2 + m_{H_d}^2 = b\tan\beta - (M_Z^2/2)\cos 2\beta \end{cases}$$

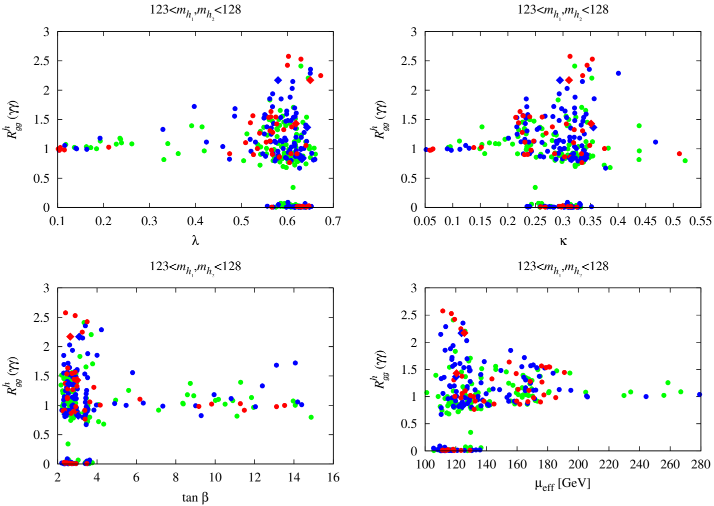
- If $\mu \sim \mathcal{O}(M_Z)$, $\surd$
- However, if SUSY derives from an underlying string theory, then

$$\mu \sim M_{\rm Pl}, M_{\rm string} \gg M_{\rm SUSY},$$ FINE-TUNING

$\Longrightarrow$ large $m_{H_u}^2, m_{H_d}^2$ $\Longrightarrow$ large cancellation

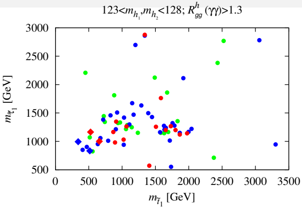
μ PROBLEM

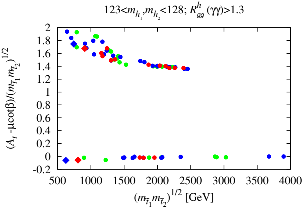
Dependence on NMSSM Parameters

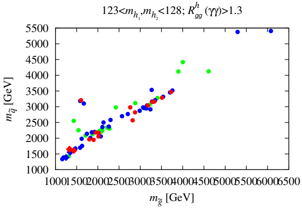


The largest $R^h_{gg}(\gamma\gamma)$ values arise at large λ, moderate κ, small $\tan\beta < 5$ (but note that $R^h_{gg}(\gamma\gamma) > 1.5$ is possible even for $\tan\beta = 15$) and small $\mu_{\rm eff} < 150$ GeV. Such low values of $\mu_{\rm eff}$ are very favorable in point of fine tuning, in particular if stops are also light.

Implication for SUSY Particles





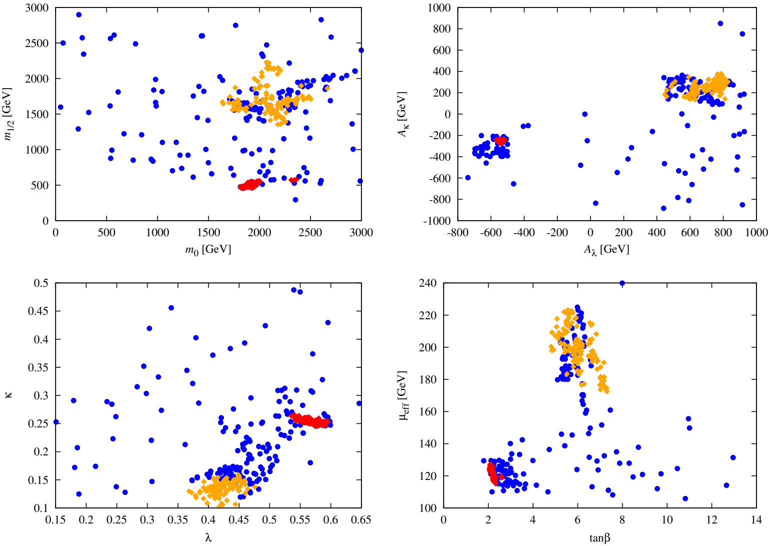


1. Indeed, the few points which we found in the WMAP window always have $m_{\tilde{t}_1} < 700$ GeV.

2. A good fraction of our points with degenerate h_1, h_2 and $R(\gamma\gamma) > 1.3$ features light stops with $M_{\rm SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \lesssim 1$ TeV.
   The stop mixing is typically large in these cases, $(A_t - \mu_{\rm eff} \cot\beta)/M_{\rm SUSY} \approx 1.5$–$2$.

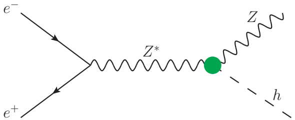
3. Squark and gluino masses are above about 1.25 TeV ranging up to as high as 6 TeV (where our scanning more or less ended).
   The WMAP-window points with large $R^h_{gg}(\gamma\gamma)$ are located at low masses of $m_{\tilde{g}} \sim 1.3$ TeV and $m_{\tilde{q}} \sim 1.6$ TeV.

NMSSM Parameters

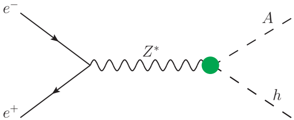


No particular regions of these parameters appear to be singled out aside from some preference for negative values of A_0. Low $\mu_{\rm eff} \Longrightarrow$ not much fine-tuning.

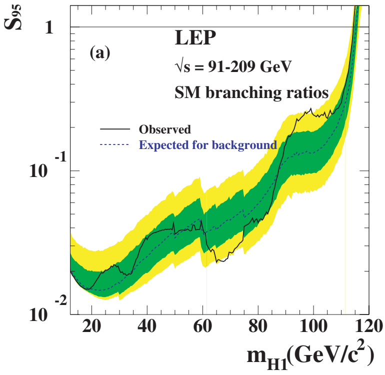
LEP Constraints

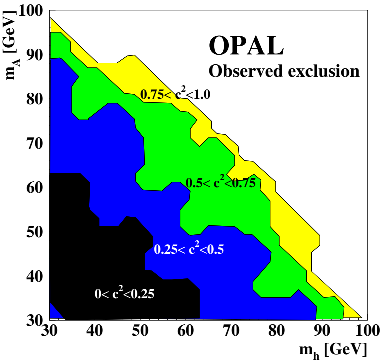


$$\frac{\sigma(e^+e^- \to Z\,h)}{\sigma(e^+e^- \to Z\,h_{\rm SM})} \sim \sin^2(\alpha - \beta)$$



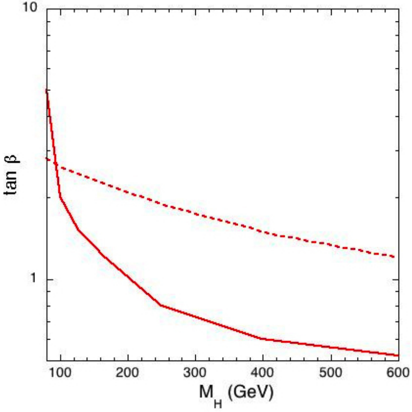
$$\frac{\sigma(e^+e^- \to A\,h)}{\sigma(e^+e^- \to Z\,h_{\rm SM})} \sim \cos^2(\alpha - \beta)$$



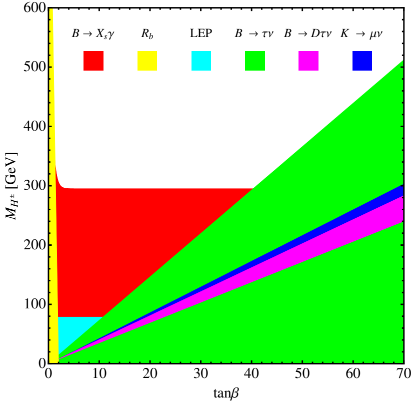


Flavor Physics Constraints

Type I



Type II



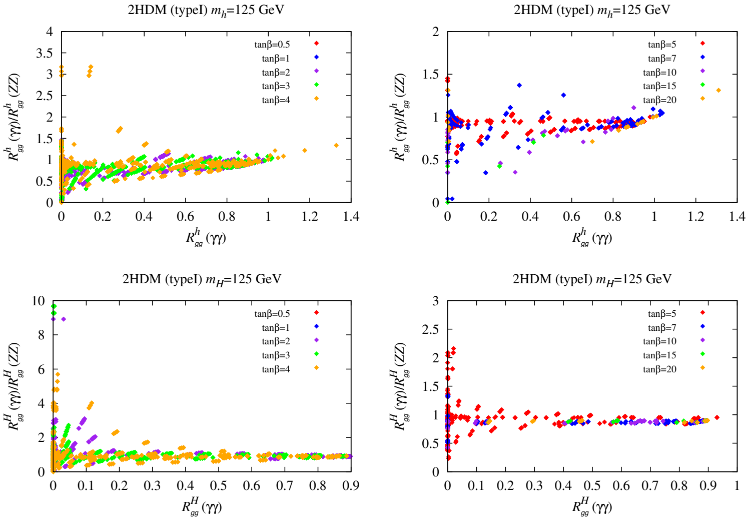
Solid: R_b for $Z \to b\bar{b}$, ϵ_K and Δm_{B_s}
Dash: $\bar{B} \to X_s\gamma$ in models with FCNC

Various Types of the 2HDM

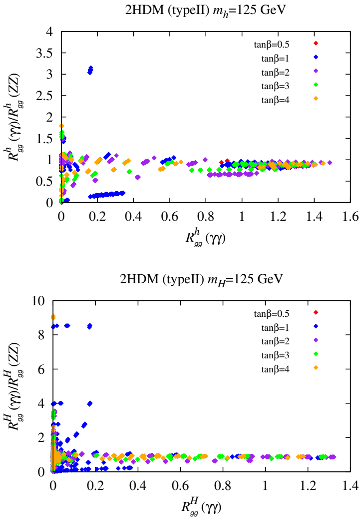
Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific (X)	Φ_2	Φ_2	Φ_1
Flipped (Y)	Φ_2	Φ_1	Φ_2

	Type I	Type II	Lepton-specific (X)	Flipped (Y)
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$
$\xi_{H^\pm}^u$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
$\xi_{H^\pm}^d$	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
$\xi_{H^\pm}^\ell$	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$

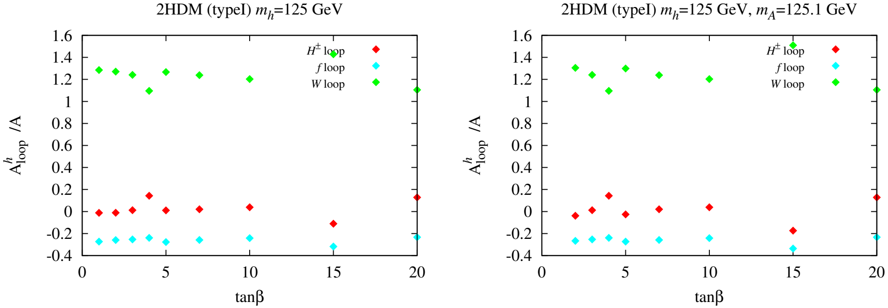
$\gamma\gamma$ – ZZ rate correlation (Type I)



$\gamma\gamma$ – ZZ rate correlation (Type II)



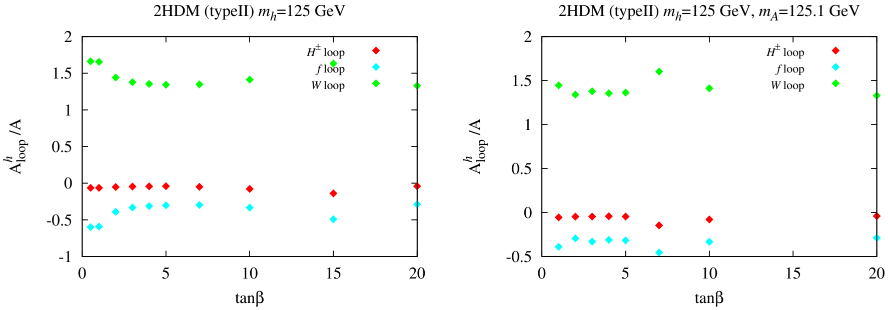
$\gamma\gamma$ Enhancement mechanism in the 2HDM



One sees that the tan β values of 4 and 20 associated with $R^h_{gg}(\gamma\gamma) \sim 1.3$ are associated with large $A_{H^{\pm}}/A$. Indeed, in these two cases, the relative charged Higgs contribution reaches nearly ~ 0.2 and is as large as the fermionic contribution, but of the opposite sign.

In fact, although the dominant loop is the W loop, the $H^{\pm}$ loop may contribute as much as the dominant (top quark) fermionic loop.

$\gamma\gamma$ Enhancement mechanism in the 2HDM



The charged Higgs contributions are small when SUP constraints are imposed, preventing the quartic couplings from violating the perturbativity condition.
In fact, the enhancement of $R^h_{gg}(\gamma\gamma)$ observed in the plots earlier prior to imposing SUP is caused just by the charged Higgs loop.