Multiple/Degenerate 125 GeV Higgs Scenarios within the NMSSM Perspective

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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

Outline

1. Preliminary Background
   - 125 GeV Higgs-like signal at the LHC and the Tevatron
   - NMSSM review
2. Single 125 GeV Higgs Scenarios
3. Degenerate 125 GeV Higgs Scenarios
   - $h_1 \sim 125 + h_2 \sim 125$ phenomenology
   - Diagnosing tools
4. Multiple 125 GeV Higgs Scenarios
   - $h_1 \sim 125 + h_2 \sim 136$ LHC–Tevatron scenario
   - $h_1 \sim 98 + h_2 \sim 125$ LEP–LHC scenario
   - Future test
5. Conclusion and Outlook

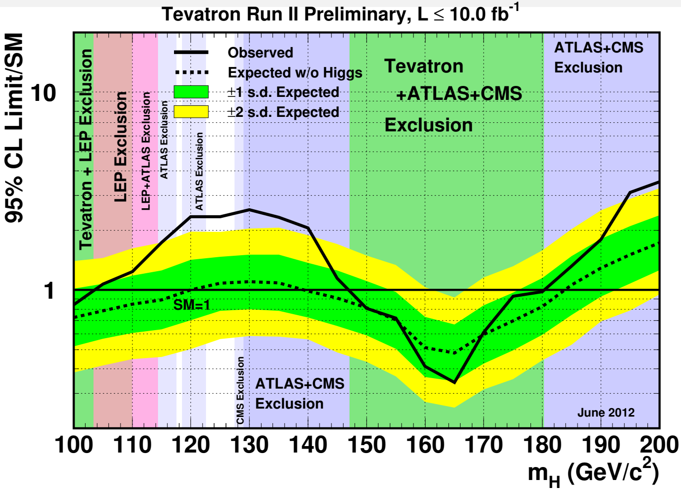
Higgs – God particle – has been attracting worldwide attention over the years.

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 Search Overview (Prior to July 4th, 2012)

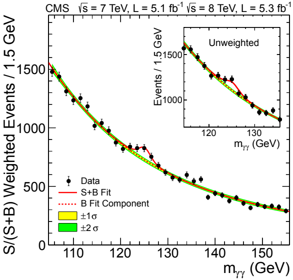


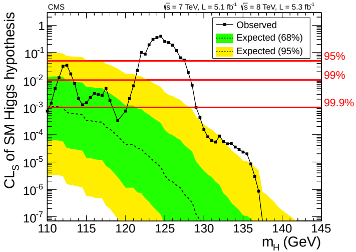
SM Higgs mass m_H excluded regions:

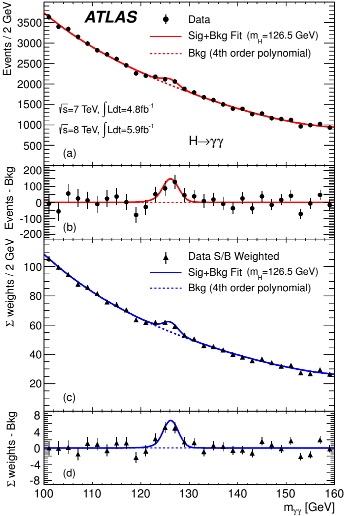
LEP: < 114 GeV (1989-2000).
Tevatron: 100 GeV – 106 GeV and 147 GeV – 179 GeV.
CMS: 127.5 GeV – 600 GeV.
ATLAS: 110 GeV – 117.5 GeV, 118.5 GeV – 122.5 GeV and 129 GeV – 539 GeV.

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！”

网友围观：好像很牛 但是不懂

“这该死的粒子！”

希格斯－玻色子是个啥？

"Higgs" Announcement webcast link for later tonight. (webca
311 发布时间：7 小时 发布者：Phantom_Symmetry
64 评论 分享 保存 hide report

一共 64 条评论
sorted by: best

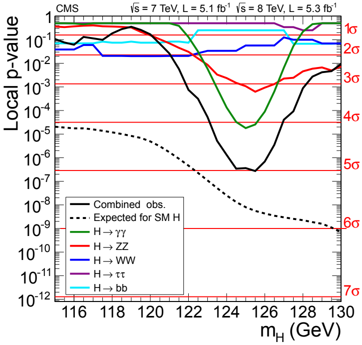
[–] jbjr3 28 分/分 15 分钟 ago
I have no idea whats goin on 我完全不知道现场发生了什么。
permalink report 回复 {verb}

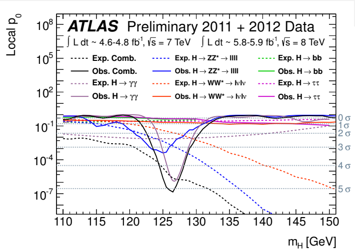
[–] nomoon_ 24 分/分 14 分钟 ago 嘿有几个词我好像认识！
I know some of these words!
permalink parent report 回复 {verb}

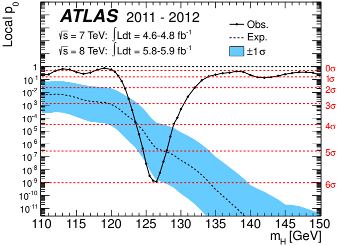
Note: Top-level comments will be removed if they are jokes, memes, or otherwise off-topic.

125 GeV Higgs-like signal at the LHC

Local p-values was updated on July 31st, 2012 for both collaborations.







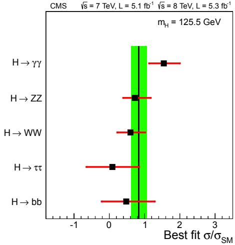
CMS and ATLAS provide an essentially 5σ and 6σ signal, respectively, for a Higgs-like resonance with mass of order 123–128 GeV.

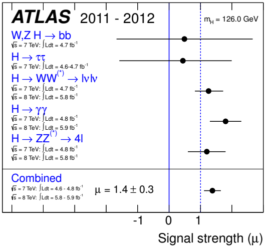
With the new data, “Seeing is believing” !

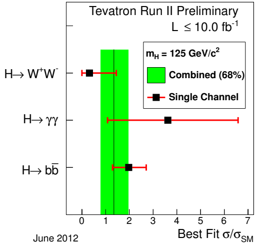
125 GeV Higgs-like signal

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	1.26 ± 0.45	2.7 ± 1.5	$0.44^{+1.55}_{-2}$	0.5 ± 2
CMS	$1.55^{+0.47}_{-0.45}$	$0.73^{+0.47}_{-0.36}$	$0.6^{+0.45}_{-0.4}$	2.6 ± 1.3	$0.09^{+0.78}_{-0.76}$	$0.5^{+0.8}_{-0.7}$
Combined	1.66 ± 0.36	1.02 ± 0.38	×	> 1	very small	×
	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 $1.97^{+0.74}_{-0.69}$.

NMSSM=MSSM+Singlet Brief Review

I will focus on the discussion within the NMSSM perspective in which both a Higgs mass of order 125 GeV and significant $\gamma\gamma$ mode enhancements are easily obtained.

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

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: $\mu_{\text{eff}} = \lambda\langle S\rangle \longrightarrow M_{\text{SUSY}}$ $\quad\surd$.
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

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

where $m_S^2 \sim m_{Q_3}^2$

Purpose

Study the semi-unified version of the NMSSM consistent with *at least* a fairly SM-like Higgs at 125 GeV and implications thereof.

- “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 $m^2_{H_u}$, $m^2_{H_d}$ and m^2_S, and general A_λ and A_κ, together with the parameters v, $\tan\beta$, λ.
- The constraints are imposed at the GUT scale and then low-scale parameters are obtained by RGE evolution.

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

- Regarding dark matter constraints, we accept all points that have the relic density $\Omega h^2 < 0.136$, particularly, $0.094 \le \Omega h^2 \le 0.136$ is the 'WMAP window'.
- 2011 XENON100 bound on the spin-independent LSP–proton scattering cross section. [1]
- the anomalous magnetic moment of the muon δa_μ (discussed shortly).

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

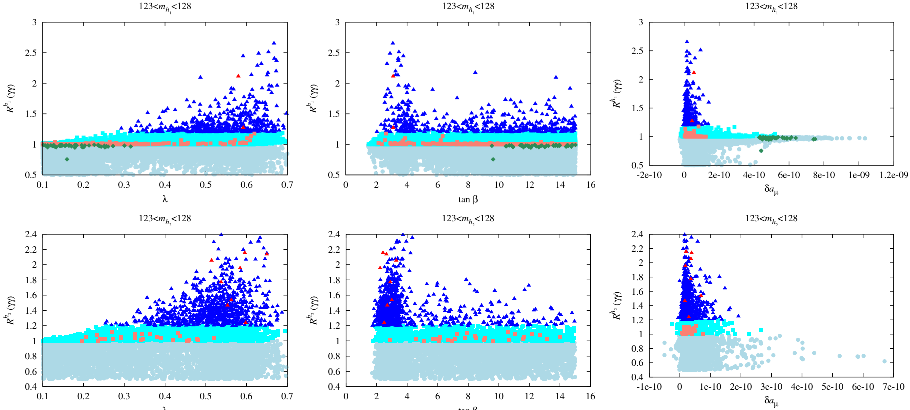
Part I: Single Higgs Scenarios

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

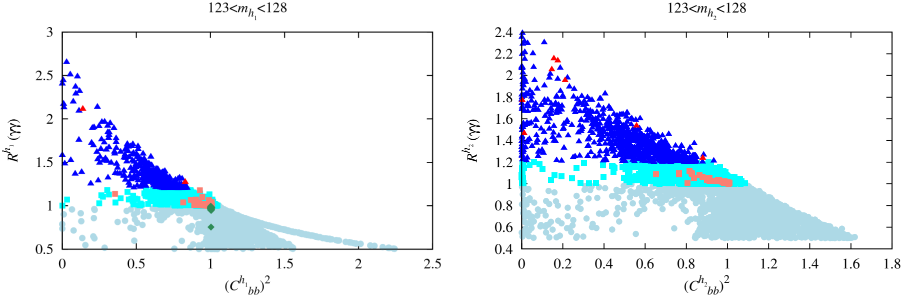
$\gamma\gamma$ Enhancement Realization

$\gamma\gamma$ 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

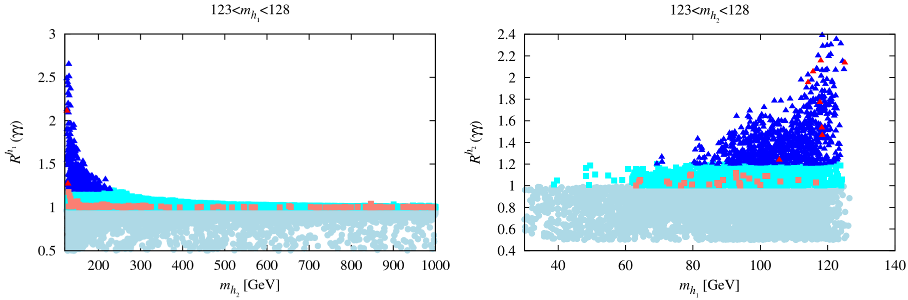


$\gamma\gamma$ Enhancement Mechanism



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

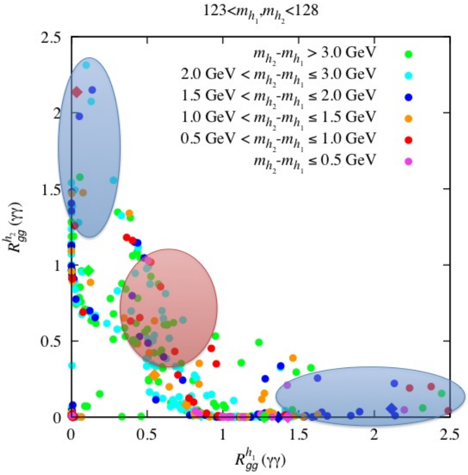


In addition to large λ (and preferably small $\tan\beta$), enhanced $\gamma\gamma$ rates are most natural when the h_1 has mass similar to the second lightest CP-even Higgs, h_2, (with one of them being primarily the doublet-like H_u while the other has a large singlet S component) with enhancement particularly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

Part II: Degenerate Higgs Scenarios

- 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:

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

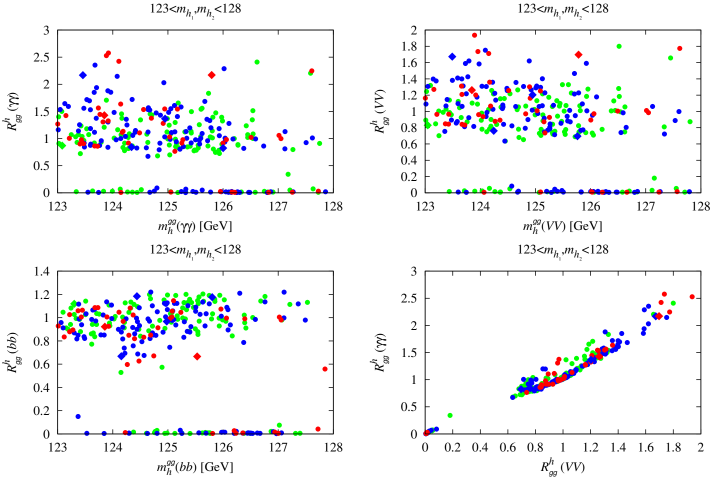
- effective Higgs signal:

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

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 $\sigma_{\text{res}} \sim 1.5$ GeV. The widths of the h_1 and h_2 are very much smaller than this resolution.

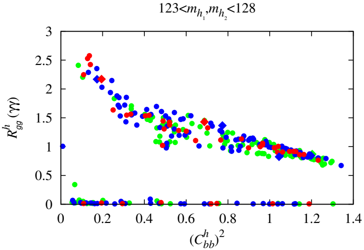
Combined Signal Rates

●$m_{h_2} - m_{h_1} \le 1$ GeV; ●1 GeV $< m_{h_2} - m_{h_1} \le 2$ GeV; ●2 GeV $< m_{h_2} - m_{h_1} \le 3$ GeV



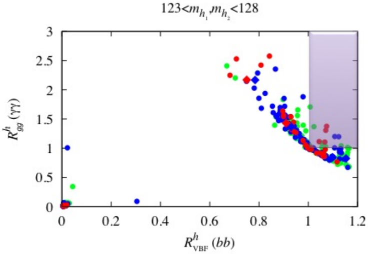
- Enhanced $\gamma\gamma$ and VV rates from gluon fusion are very common.
- There is a very strong correlation between $R^{h}_{gg}(\gamma\gamma)$ and $R^{h}_{gg}(VV)$ described approximately by $R^{h}_{gg}(\gamma\gamma) \sim 1.25\, R^{h}_{gg}(VV)$. In particular, if $R^{h}_{gg}(\gamma\gamma) \sim 1.5$,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

Enhancement Mechanism – Degenerate Scenarios



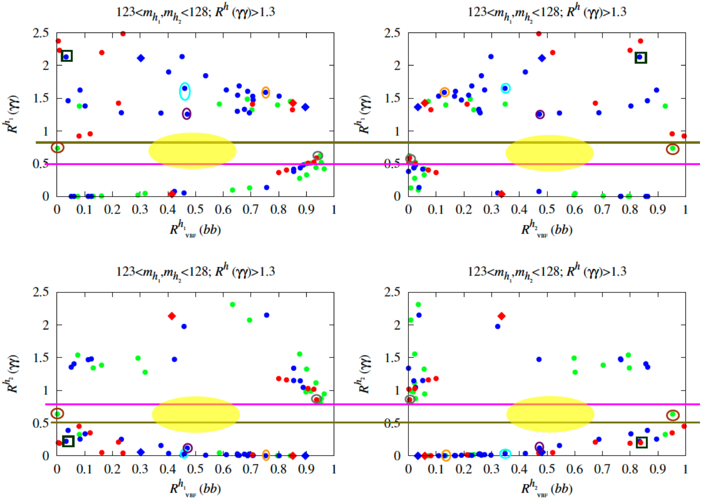
The primary mechanism:

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



- In general, the larger $R^h_{gg}(\gamma\gamma)$ is, the smaller the value of $R^h_{W^*\to Wh}(b\overline{b})$.
- Enhancement of Wh production with $h \to b\overline{b}$ is rather limited; indeed the maximal value of $R^h_{\rm VBF}(b\overline{b}) = R^h_{W^*\to Wh}(b\overline{b})$ is of order 1.2.
- There *are* parameter choices for which both the $\gamma\gamma$ rate and the $W^* \to Wh(\to b\overline{b})$ 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.

Various Types of Enhancement II

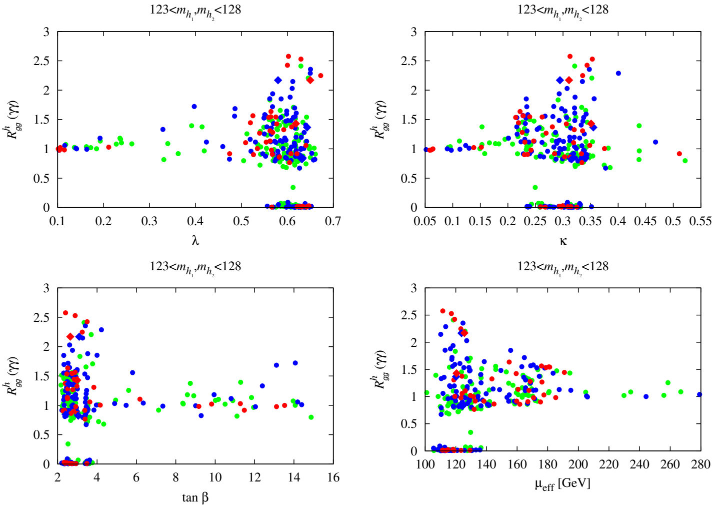


Two mechanisms to realize the enhancement:

1. one Higgs "steals" (through mixing) some of the $b\bar{b}$ width of the other Higgs to make the latter enhanced.
2. either the $\gamma\gamma$ or the $b\bar{b}$ signal receives substantial contributions from both the h_1 and the h_2 for the $\gamma\gamma$ final state) while the other final state is dominated by just one of the two Higgses.

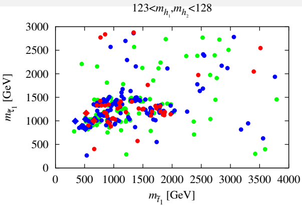
NO points where the $\gamma\gamma$ and $b\bar{b}$ rates *both* receive substantial contributions from *both* h_1 and h_2.

Dependence on NMSSM Parameters

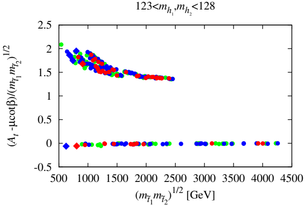


The largest $R^h_{gg}(\gamma\gamma)$ values arise at large λ, moderate κ, small $\tan\beta < 5$ (but note that $R^h_{gg}(\gamma\gamma) > 1.5$ is possible even for $\tan\beta = 15$) and small $\mu_{\rm eff} < 150$ GeV. Such low values of $\mu_{\rm eff}$ are very favorable in point of fine tuning, in particular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

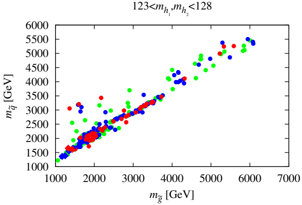
Implication for SUSY Particles



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

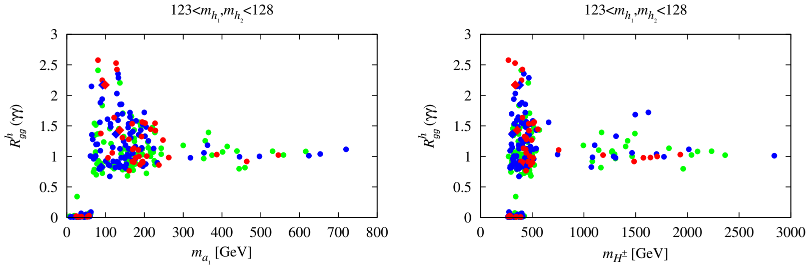


2. A good fraction of our points with degenerate h_1, h_2 and $R(\gamma\gamma) > 1.3$ features light stops with $M_{\mathrm{SUSY}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \lesssim 1$ TeV. The stop mixing is typically large in these cases, $(A_t - \mu_{\mathrm{eff}} \cot\beta)/M_{\mathrm{SUSY}} \approx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



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

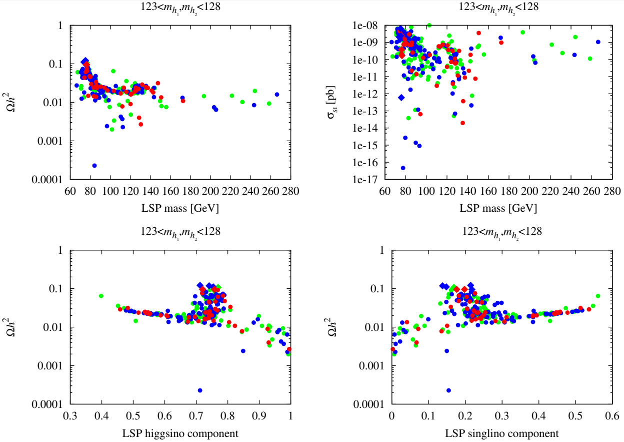
Correlation on Other Higgs Bosons



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

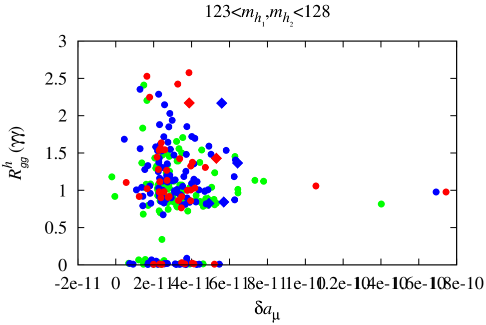
- The general trend is that the maximum $R^h_{gg}(\gamma\gamma)$ possible decreases rapidly as m_{a_1} and $m_{H^\pm}$ increase.
- Values above 1.7 are associated with masses for the a_2, h_3 and $H^\pm$ of order $\lesssim 500$ GeV and for the a_1 of order $70 \lesssim m_{a_1} \lesssim 150$ GeV, 250 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

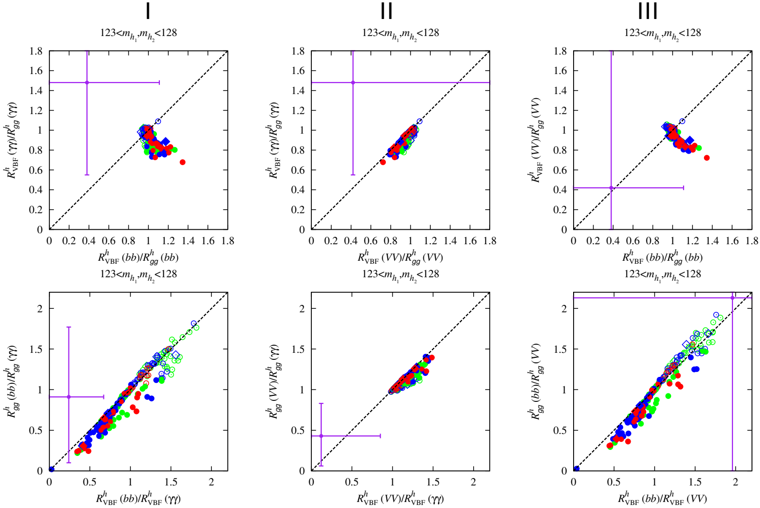
we propose the **double ratios** to reveal the existence of a second, quasi-degenerate (but non-interfering in the small width approximation) Higgs state are :

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

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 $R^h_{gg}(\gamma\gamma) > 1$.

What does current LHC data say about these various double ratios?

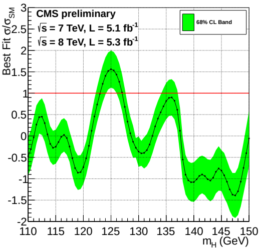
- Obviously, current statistics are inadequate to discriminate whether or not the double ratios deviate from unity.
- For a $\sqrt{s} = 14\ \mathrm{TeV}$ run with $L = 100\ \mathrm{fb}^{-1}$ ($300\ \mathrm{fb}^{-1}$), the number of Higgs events will be about a factor of 25 (77) larger than the number produced for $L \sim 5\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7\ \mathrm{TeV}$ plus $L \sim 6\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8\ \mathrm{TeV}$. It means the error bars should be reduced by roughly a factor of 5 (9), levels that could indeed reveal a deviation from unity, or at least remove some model points if no deviation within that error is seen.
- Of course improvements in the experimental analyses may further increase the sensitivity.

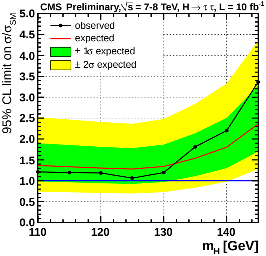
We thus conclude that our diagnostic tools will ultimately prove viable and perhaps crucial for determining if the $\sim 125\ \mathrm{GeV}$ Higgs signal is really only due to a single Higgs-like resonance or if two resonances are contributing, the latter having significant probability in model contexts if enhanced $\gamma\gamma$ rates are indeed confirmed at higher statistics.

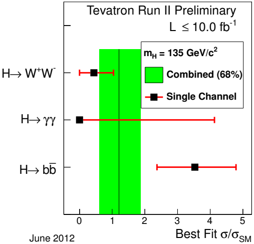
Part III: Multiple Higgs Scenarios

- $h_1 \sim 98$ GeV (LEP) and $h_2 \sim 125$ GeV
- $h_1 \sim 125$ GeV and $h_2 \sim 136$ GeV (Tevatron)

136 GeV Higgs-like signal







1. CMS observed an additional excess corresponding to $M_H \sim 136$ GeV in the $\gamma\gamma$ decay mode.
2. CMS observed a deficit for $M_H \sim 125$ GeV for the *VBF*-tag class of events, but an excess for $M_H \gtrsim 132$ GeV in the $\tau^+\tau^-$ decay mode.
3. The best fit to the measurement of M_H at the Tevatron corresponds to $M_H \sim 135$ GeV with an enhanced signal rate $3.53^{+1.26}_{-1.16}$ in the $b\bar{b}$ decay mode with *WH*-tag.

	gg fusion			VBF	VH
$m_h = 136$	$\gamma\gamma$	$ZZ^* \to 4\ell$	$WW^* \to \ell\nu\ell\nu$	$\tau^+\tau^-$	$b\bar{b}$
ATLAS	$0.0^{+0.4}$				
CMS	0.9 ± 0.4				
Combined	0.45 ± 0.3	≤ 0.2	$\times$	< 1.81	$\times$
	high resolution		poor resolution		

$WW^{(*)}$ channel (with *VH*-tag) is ignored due to its low mass resolution.

Effective $b\bar{b}$ Signal

The central value 3.53 in the $b\bar{b}$ is difficult to explain.

- the VH production cross section $\propto (C^{h_i}_{VV})^2$ cannot be enhanced with respect to the SM.
- the SM Higgs branching fraction of $\sim 40\%$ for $m_{h_{\rm SM}} = 135$ GeV can be enhanced at most by a factor of 2.5 in the unphysical limit $C^{h_i}_{dd} \to \infty$.

125+136 LHC–Tevatron scenario

- If $R^{h_1}_{VBF}(\tau\tau)$ is as small as observed by CMS, the values for $R_{VH}(b\bar{b})$ measured at the Tevatron should originate primarily from h_2 with $m_{h_2} \sim 135$–136 GeV. $\surd$

This possibility is one of the main advantages.

- However, the contribution of h_1 to the signal rate $R_{VH}(b\bar{b})$ obtained assuming $m_{h_{\rm SM}} \sim 135$ GeV can still be sizable, since the production cross section of h_1 is $\sim 30\%$ larger.

$$R^{\rm eff}_{VH}(b\bar{b}) \simeq R^{h_2}_{VH}(b\bar{b}) + 1.3 \times R^{h_1}_{VH}(b\bar{b})$$

- In addition, the contribution from h_2 to the signal rate $R_{VH}(b\bar{b})$ assuming $m_{h_{\rm SM}} \sim 125$ GeV should be as large as possible.

What are the consequences on the reduced couplings?

	gg fusion			VBF		VH
$m_{h_1} = 125$	$\gamma\gamma$	$ZZ^* \to 4\ell$	$WW^* \to 2\ell 2\nu$	$\gamma\gamma$	$\tau^+\tau^-$	$b\bar{b}$
Combined	1.66 ± 0.36	1.02 ± 0.38	×	> 1	very small	$1.97^{+0.74}_{-0.69}$
	high resolution		poor resolution			

① keeping $C^{h_1}_{gg} \sim C^{h_1}_{uu}$ not be small, $C^{h_1}_{dd}$ reduced $\Longrightarrow \Gamma(h_1 \to b\bar{b}) \Longrightarrow \Gamma_{\rm tot}(h_1)$

$$\Longrightarrow \begin{cases} \text{enhanced } R^{h_1}_{gg}(\gamma\gamma) \quad \surd \\ \text{enhanced } R^{h_1}_{gg}(ZZ), \text{together with a slightly reduced } C^{h_1}_{ZZ} \quad \surd \end{cases}$$

② $C^{h_1}_{dd}$ reduced $\Longrightarrow C^{h_1}_{\tau\tau}$ reduced $\Longrightarrow$ small $R^{h_1}_{VBF}(\tau\tau)$ $\surd$ $\Longrightarrow$ small $R^{h_1}_{VH}(b\bar{b})$ ✗

	gg fusion			VBF	VH
$m_{h_2} = 136$	$\gamma\gamma$	$ZZ^* \to 4\ell$	$WW^* \to \ell\nu\ell\nu$	$\tau^+\tau^-$	$b\bar{b}$
Combined	0.45 ± 0.3	≤ 0.2	×	< 1.81	$3.53^{+1.26}_{-1.16}$
	high resolution		poor resolution		

③ then need $C^{h_2}_{dd}$ enhanced $\Longrightarrow$ large $R^{\rm eff}_{VH}(b\bar{b})$ $\surd$, in addition that $C^{h_2}_{VV}$ is not small.

④ small $C^{h_2}_{gg} \sim C^{h_2}_{uu} \Longrightarrow$ small $R^{h_2}_{gg}(\gamma\gamma)$ and $R^{h_2}_{gg}(ZZ)$ $\surd$

General NMSSM DOES Work–an exemplary point

NMSSM parameters (The dimensionful parameters are given in GeV):

λ	κ	$\tan\beta$	μ_{eff}	A_λ	A_κ
0.617	0.253	1.77	143	164	337

general NMSSM specific:

M_1	M_2	M_3	$m_{\tilde q_{1,2}}, m_{\tilde b_R}$	$m_{\tilde\ell}, m_{\tilde q_3}$	$A_t = A_b$	A_τ
220	400	1100	1500	1000	-2500	-1000

Higgs masses and component decompositions:

m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	$m_{H^\pm}$
125	136	289	95	282	272

Higgs	$S_{i,d}$	$S_{i,u}$	$S_{i,s}$	$C^{h_i}_{dd}$	$C^{h_i}_{uu}$	$C^{h_i}_{VV}$	$C^{h_i}_{gg}$	$C^{h_i}_{\gamma\gamma}$
h_1	-0.24	-0.67	0.70	-0.48	-0.77	-0.70	0.77	0.85
h_2	0.54	0.51	0.67	1.09	0.58	0.71	0.54	0.66
h_3	0.81	-0.54	-0.24	1.64	-0.62	-0.07	0.65	0.28

Signal rates:

Higgs	$R_{gg}(\gamma\gamma)$	$R_{VBF}(\gamma\gamma)$	$R_{gg}(VV)$	$R_{VH}(VV)$	$R_{VH}(b\bar b)$	$R_{gg}(\tau\tau)$
h_1	1.30	1.09	0.90	0.75	0.36	0.42
h_2	0.16	0.27	0.18	0.31	0.74	0.43
h_3	0.58	0.01	0.04	0.004	0.23	19.6

$R^{\mathrm{eff}}_{VH}(b\bar b) \sim 1.20$. Note that $R_{VBF}(VV) = R_{VH}(VV)$ and $R_{VBF}(\tau\tau) \sim R_{VH}(b\bar b)$.

How about in the semi-constrained NMSSM?

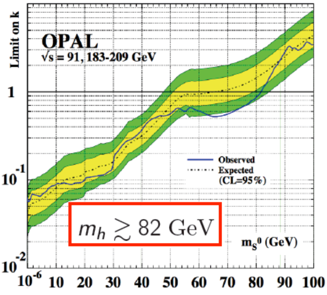
- Can find scenarios where h_1 and h_2 have masses of about 125 and 136 GeV, respectively.
- However, we did NOT find any points where the slightly enhanced $R^{h_1}_{gg}(ZZ)$, the substantially enhanced $R^{h_1}_{gg}(\gamma\gamma)$, the suppressed $R^{h_2}_{gg}(\gamma\gamma)$ and very small $R^{h_2}_{gg}(ZZ)$ are all satisfied simultaneously. at least one of the last three conditions has to be relaxed to find valid points.

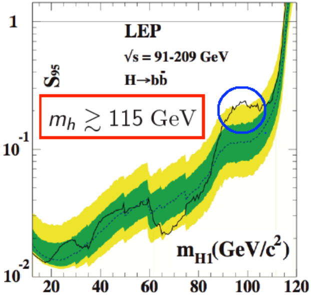
	$R^{h_1}_{gg}(\gamma\gamma)$	$R^{h_1}_{gg}(ZZ)$	$R^{h_2}_{gg}(\gamma\gamma)$	$R^{h_2}_{gg}(ZZ)$	$R^{h_2}_{VBF}(\tau\tau)$	$R^{h_2}_{VH}(b\bar{b})$
case I	$\surd$	$\surd$	$\lesssim 0.06$	$\surd$	$\surd$	
case II	$\lesssim 1.3$	$\surd$	$\surd$	$\surd$	$\surd$	never large

Maybe case I is a good thing in the end?

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:

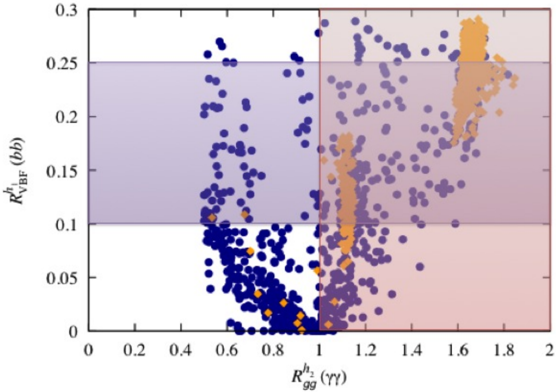
whether the LHC signal and the small ($\sim 2\sigma$) LEP excess in $e^+e^- \to Zb\overline{b}$ in the vicinity of $M_{b\overline{b}} \sim 98$ GeV using the h' with $m_{h'} \sim 98$ GeV could be **simultaneously** explained?

$98 + 125\ \mathrm{GeV}$ 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 $m_{h_1} \sim 98\ \mathrm{GeV}$ and $m_{h_2} \sim 125\ \mathrm{GeV}$, respectively, with the h_1 being largely singlet and the h_2 being primarily doublet (mainly H_u for the scenarios we consider).
- A $125\ \mathrm{GeV}$ Higgs state h_2 with enhanced $\gamma\gamma$ signal rate is easily obtained for large λ and small $\tan\beta$.

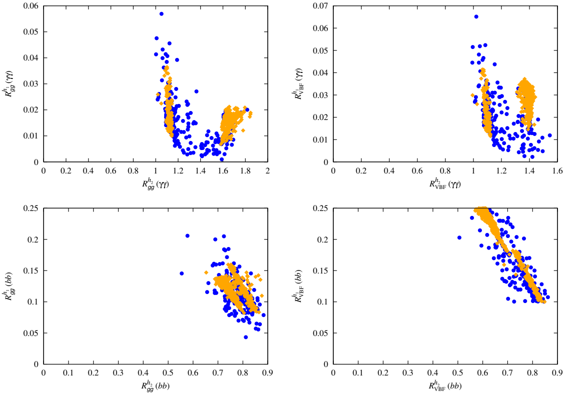
LEP–LHC Fit $(m_{h_1} \in [96, 100]\ \mathrm{GeV},\ m_{h_2} \in [123, 128]\ \mathrm{GeV})$



- 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

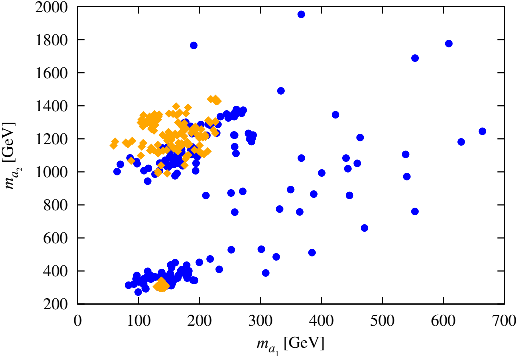


	$R^{h_2}_{gg}(\gamma\gamma)$	$m_{\widetilde{\chi}^0_1}$	$m_{\tilde{t}_1}$	
I	~ 1.1	> 93 GeV	> 1.8 TeV	
II	~ 1.6	~ 77 GeV	197 GeV – 1 TeV	✓

If $R^{h_2}_{gg}(\gamma\gamma)$ 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.

- 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.
- $R^{h_2}_{gg}(bb)$ and $R^{h_2}_{VBF}(bb)$ values that are associated with reduced $b\overline{b}$ 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.
- For WMAP-window points the largest $R^{h_1}_{VBF}(bb)$ values occur for the light-$m_{\widetilde{\chi}^0_1}$ point group II.

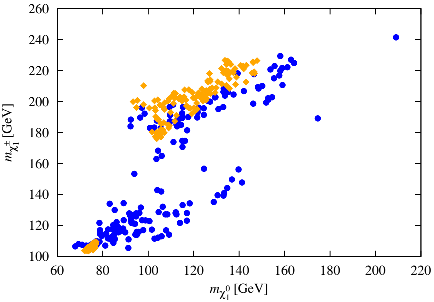
Expectation for Other NMSSM Higgses



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

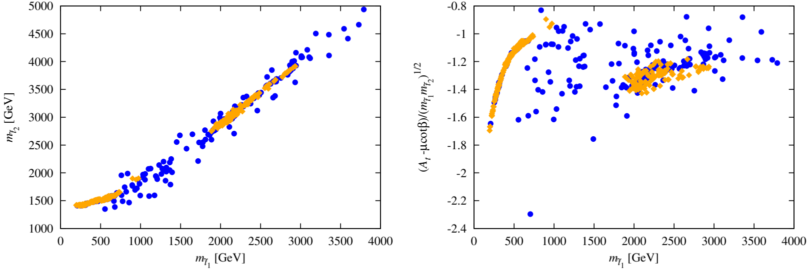
Small m_{a_1} is typical of the WMAP-window points.

Prediction for SUSY Particles



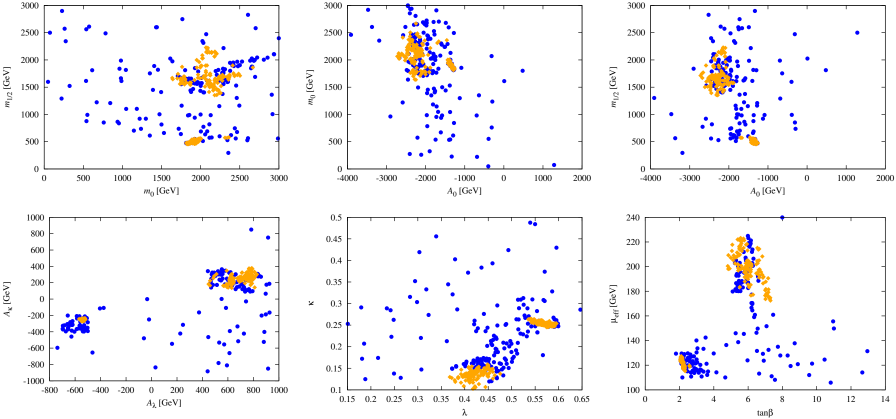
- Low values of $m_{\widetilde{\chi}_1^0}$ are typical for the scan points, but more particular to this model are the rather low values of $m_{\widetilde{\chi}_1^\pm}$.
- ATLAS and CMS are currently performing analyses, but the difficulty in isolating the leptons or jets associated with $\widetilde{\chi}_1^\pm \to \widetilde{\chi}_1^0 + X$ decays would arise when $m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0}$ is small.
- For the WMAP-window points $m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0}$ is typically quite substantial, at least $35~\mathrm{GeV}$ for the low-$m_{\widetilde{\chi}_1^0}$ points.

Prediction for SUSY Particles



- Of particular interest is the very large range of $m_{\tilde{t}_1}$. We observed the possibility of $m_{\tilde{t}_1}$ as small as 197 GeV and mostly modest values of the mixing parameter $(A_t - \mu\cot\beta)/\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$.
- For lighter values of $m_{\tilde{t}_1}$ (typical of the low-$m_{\widetilde{\chi}_1^0}$ WMAP points), the $\tilde{t}_1$ always decays via $\tilde{t}_1 \to \widetilde{\chi}_1^+ b$ or $\tilde{t}_1 \to \widetilde{\chi}_1^0 t$, the latter being absent when $m_{\tilde{t}_1} < m_{\widetilde{\chi}_1^0} + m_t$.
- At high $m_{\tilde{t}_1}$, these same channels are present but also $\tilde{t}_1 \to \widetilde{\chi}_{2,3,4,5}^0 t$ can be important, which channels being present depending upon whether $m_{\tilde{t}_1} - m_{\chi_{2,3,4,5}^0} - m_t > 0$ or not.

NMSSM Parameters



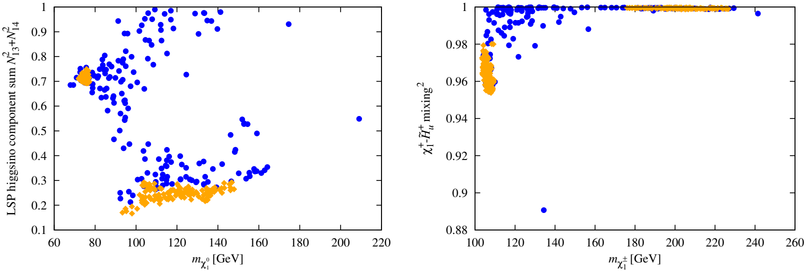
No particular regions of these parameters appear to be singled out aside from some preference for negative values of A_0.

Low $\mu_{\rm eff} \Longrightarrow$ not much fine-tuning.

- Large $m_{\tilde{\chi}_1^0}$ group (II): $\tan\beta \in [5, 7]$ and $\lambda \in [0.37, 0.48]$.
- Low $m_{\tilde{\chi}_1^0}$ group (I): large Higgsino component with $\tan\beta \in [2, 2.6]$ and $\lambda \in [0.53, 0.6]$.

LSP Composition

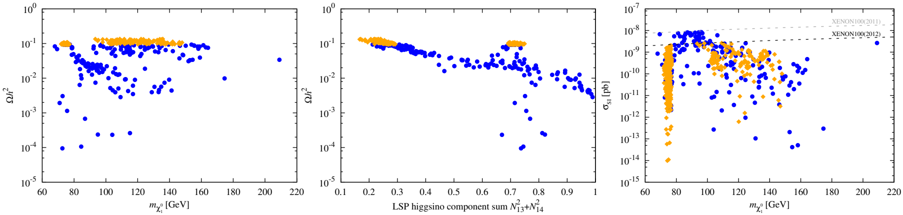
The composition of the $\widetilde{\chi}_1^0$ and the $\widetilde{\chi}_1^\pm$ are crucial when it comes to the relic density of the $\widetilde{\chi}_1^0$ (LSP dark matter candidate).



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



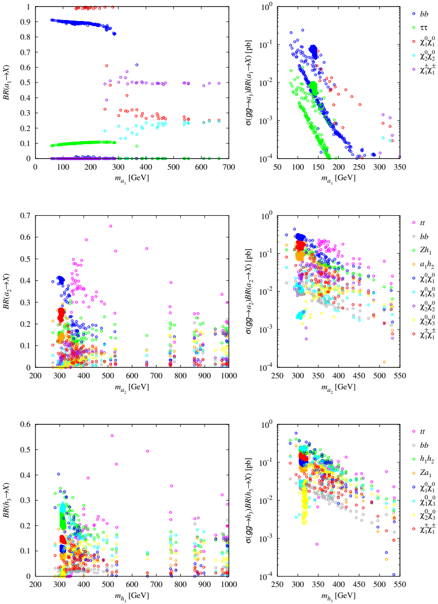
Why the relic density Ωh^2 too small?

- The main mechanism is rapid $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ annihilation to W^+W^- due to a substantial Higgsino component of the $\widetilde{\chi}_1^0$. 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 $m_{\widetilde{\chi}_1^0} > 93~\mathrm{GeV}$ points that are in the WMAP window. However, it is also noteworthy that the $m_{\widetilde{\chi}_1^0} \sim 75~\mathrm{GeV}$ WMAP-window points can have very small $\sigma_{\rm SI}$.

Future Test: Comfirm or Rule out?

LHC Test – Direct Higgs Production and Decay



a_1

- singlet dominant, so rather small production rates
- The largest $\sigma\mathrm{BR}(X)$: $X = b\bar{b}$ final state (have huge backgrounds)
- $\sigma\mathrm{BR}(X)$ for $X = \tilde{\chi}_1^0\tilde{\chi}_1^0$ can be significant (when allowed)

a_2

- doublet dominant, so better discovery prospects
- $m_{a_2} > 2m_t$, $t\bar{t}$ final state: $\sigma\mathrm{BR} > 0.01$ pb for $m_{a_2} < 550$ GeV
- $m_{a_2} < 2m_t$, $a_1 h_2$ final state with both a_1 and h_2 decaying to $b\bar{b}$ might be visible.

h_3

- the possibly visible final states are $t\bar{t}$ for $m_{h_3} > 2m_t$ and $h_1 h_2$ for $m_{h_3} < 2m_t$

For both the a_2 and h_3, $\sigma\mathrm{BR}(X)$ is substantial for $X = \tilde{\chi}_1^0\tilde{\chi}_1^0$, but to isolate this invisible final state would require an additional photon or jet tag.

Conclusions

We have assessed the extent to which various semi-constrained NMSSM (scNMSSM) scenarios with *at least* a $\sim$125 GeV Higgs h_1 are able to describe this LHC signal.

- we proposed a novel idea — "degenerate Higgs" and examined scNMSSM scenarios in which both h_1 and h_2 have mass near 125 GeV. As what we expected, very substantially enhanced $\gamma\gamma$ and other signals are possible.
- we developed diagnostic tools that would provide incontrovertible evidence for the presence of more than one Higgs near 125 GeV in the LHC data.
- In addition, we studied interesting multiple Higgs scenarios: (i) 125+136 LHC–Tevatron scenario, the best fit to the Tevatron results in the $b\bar{b}$ channel and the mild excesses at CMS in the $\gamma\gamma$ channel at 136 GeV and in the $\tau\tau$ channel above 132 GeV can be explained by h_2 in this mass range, together with h_1 at 125 GeV discovered at the LHC. (ii) 98+125 LEP–LHC scenario, h_1 is consistent with the small LEP excess at 98 GeV and h_2 has the primary features of the LHC Higgs-like signals at 125 GeV, including an enhanced $\gamma\gamma$ rate.

Future Work and Outlook

- The phenomenological NMSSM is a natural extension.

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 for your attention!

Thanks to Profs. Gunion and Kraml (and etc.) for their patient guidance and help, and also for their strong recommendations for my 2013 LHC-TI Fellowship application.

Happy Thanksgiving!

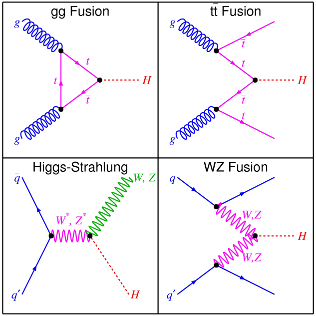
Back Up

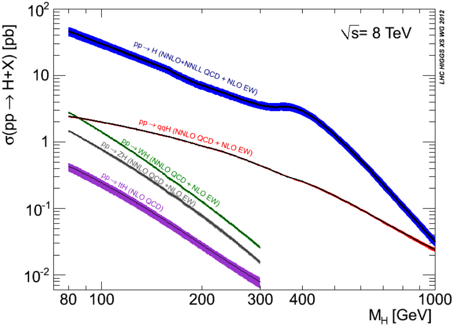
SM Higgs Boson Production

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.

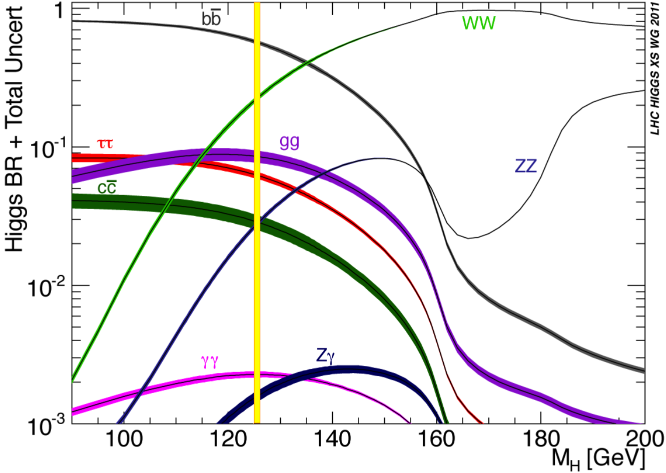




$gg \to H$: Good for WW, ZZ, $\gamma\gamma$ final states; Bad for $H \to b\bar{b}$ (overwhelming QCD backgrounds!)

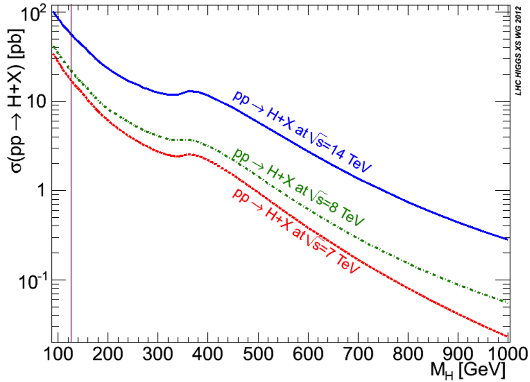
$qq \to V^* \to VH$: Good for $H \to b\bar{b}$ final states in the Leptons + Jets search (W/Z boson decays to leptons which are straightforward to select).

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.

Higgs Production Comparison



the expected increase in the number of Higgs events at $\sqrt{s} = 14~\mathrm{TeV}$ for integrated luminosity of $100~\mathrm{fb}^{-1}$ will be a factor of roughly

$$100 \times 49.85/(5 \times 15.32 + 6 \times 19.52) = 25$$

larger than for the $(5~\mathrm{fb}^{-1}, 7~\mathrm{TeV} + 6~\mathrm{fb}^{-1}, 8~\mathrm{TeV})$ results.

This implies a decrease in the error bars by a factor of order $1/\sqrt{25} \sim 1/5$ based just on

More on Rs in the doublets+singlets Models

$$R^{h_i}_Y(X) = \frac{\sigma(Y\to h_i)\mathrm{BR}(h_i\to X)}{\sigma(Y\to h_{\mathrm{SM}})\mathrm{BR}(h_{\mathrm{SM}}\to X)} = (C^{h_i}_Y)^2\,\frac{\Gamma(h_i\to X)}{\Gamma(h_{\mathrm{SM}}\to X)}\,\frac{\Gamma_{\mathrm{tot}}(h_{\mathrm{SM}})}{\Gamma_{\mathrm{tot}}(h_i)} = (C^{h_i}_Y)^2(C^{h_i}_X)^2\ldots$$

where $Y = gg$ for gluon fusion and $Y = WW, ZZ$ for W, Z fusion and W, Z strahlung, this latter also implies $R^{h_i}_{VBF}(X) = R^{h_i}_{V^*\to VH}(X)$.

Assumptions:

1. in SUSY models, $C_{\tau\tau} \approx C_{dd}$ (up to radiative corrections relevant for very large $\tan\beta$).
2. $C^{h_i}_{WW} = C^{h_i}_{ZZ} \leq 1$ (the custodial symmetry stored in any doublets+singlets models).
3. The radiatively induced coupling to gluons originates mostly from top quark loops, $C^{h_i}_{gg} \approx C^{h_i}_{tt}$.
4. The radiatively induced coupling to photons originates mostly from the W loop, $C^{h_i}_{\gamma\gamma} \approx C^{h_i}_{WW}$, neglecting the much smaller top loop contribution and loops involving non-SM particles.

NOT all the R^{h_i}'s in the context of any doublets plus singlets model are independent.

A complete set: $R^h_{gg}(WW)$, $R^h_{gg}(bb)$, $R^h_{gg}(\gamma\gamma)$, $R^h_{VBF}(WW)$, $R^h_{VBF}(bb)$, $R^h_{VBF}(\gamma\gamma)$

The Scale-invariant NMSSM

NMSSM solves μ-problem by adding one singlet S, at the cost of adding 3 more particles

$$\mathcal{L}_{\mathrm{NMSSM}} = \mathcal{L}_{\mathrm{kinetic}} + \mathcal{L}_{\mathrm{int}} + \mathcal{L}_{\mathrm{soft}}^{\mathrm{NMSSM}}$$

The interactions are generated by the superpotential

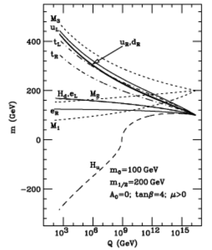
$$W_{NMSSM} = \bar{u}\mathbf{Y_u}QH_u - \bar{d}\mathbf{Y_d}QH_d - \bar{e}\mathbf{Y_e}LH_d + \lambda SH_uH_d + \frac{\kappa}{3}S^3$$

and the soft SUSY breaking terms are

$$\mathcal{L}_{\mathbf{soft}} \begin{cases} \mathcal{L}_{\mathbf{gaugino}} = -\frac{1}{2}\left(M_3\tilde{G}^a\tilde{G}_a + M_2\tilde{W}^\alpha\tilde{W}_\alpha + M_1\tilde{B}\tilde{B}\right) + \mathrm{h.c.} \\ \mathcal{L}_{\mathbf{sfermions}} = -\tilde{Q}_L^* \mathrm{m}_{\tilde{\mathrm{Q}}}^2 \tilde{Q}_L - \tilde{L}_L^* \mathrm{m}_{\tilde{\mathrm{L}}}^2 \tilde{L}_L - \tilde{u}_R^* \mathrm{m}_{\tilde{\mathrm{u}}}^2 \tilde{u}_R - \tilde{d}_R^* \mathrm{m}_{\tilde{\mathrm{d}}}^2 \tilde{d}_R - \tilde{e}_R^* \mathrm{m}_{\tilde{\mathrm{e}}}^2 \tilde{e}_R \\ \mathcal{L}_{\mathbf{Higgs}} = -m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - m_S^2 S^* S \\ \mathcal{L}_{\mathbf{trilinear}} = -\left(\tilde{u}_R \mathrm{A_u} \tilde{Q}_L H_u - \tilde{d}_R \mathrm{A_d} \tilde{Q}_L H_d - \tilde{e}_R \mathrm{A_e} \tilde{L}_L H_d + \lambda A_\lambda H_u H_d S + \frac{1}{3}\kappa A_\kappa S^3\right) \\ \qquad + \mathrm{h.c.} \end{cases}$$

$\mathbb{Z}_3$-symmetry: a multiplication of all components of chiral superfields by a phase $e^{2\pi i/3}$.

NMSSM Parameters



- GUT scale parameters (assume unification)
  1. Gaugino masses: $m_{1/2} \longrightarrow M_1, M_2, M_3$
  2. Squark masses: $m_0 \longrightarrow \mathbf{m^2_{\tilde{Q}}, m^2_{\tilde{L}}, m^2_{\tilde{u}}, m^2_{\tilde{d}}, m^2_{\tilde{e}}}$
  3. Trilinear couplings: $A_0 \longrightarrow \mathbf{A_u, A_d, A_e}$
- SUSY scale parameters

$\lambda, A_\lambda, A_\kappa, \kappa, m_S^2, m_{H_u}^2, m_{H_d}^2$

v_u, v_d, s

$$v_u\left(m_{H_u}^2 + \mu_{\text{eff}}^2 + \lambda^2 v_d^2 + \frac{g_1^2+g_2^2}{4}(v_u^2 - v_d^2)\right) - v_d\,\mu_{\text{eff}}(A_\lambda + \kappa s) = 0$$

$$v_d\left(m_{H_d}^2 + \mu_{\text{eff}}^2 + \lambda^2 v_u^2 - \frac{g_1^2+g_2^2}{4}(v_u^2 - v_d^2)\right) - v_u\,\mu_{\text{eff}}(A_\lambda + \kappa s) = 0$$

Higgs VEV Minimizations

$$s\left(m_S^2 + \kappa A_\kappa s + 2\kappa^2 s^2 + \lambda^2(v_u^2 + v_d^2) - 2\lambda\kappa v_u v_d\right) - \lambda v_u v_d A_\lambda = 0$$

$\lambda, A_\lambda, A_\kappa, v, \tan\beta, m_{H_u}^2, m_{H_d}^2$

Various choices for different scenarios

NMSSM Higgs sector

$$D^a|_{\text{Higgs}} = -g\left[(H_u^*)^\alpha(\tau^a)_\alpha^\beta(H_u)_\beta + (H_d^*)^\alpha(\tau^a)_\alpha^\beta(H_d)_\beta + |S|^2\right],$$

$$D'|_{\text{Higgs}} = -\frac{g'}{2}\left(|H_u^+|^2 + |H_u^0|^2 - |H_d^0|^2 - |H_d^-|^2\right)$$

$$\begin{aligned} V =\ & (|\mu+\lambda S|^2 + m_{H_u}^2)\left(|H_u^+|^2 + |H_u^0|^2\right) + (|\mu+\lambda S|^2 + m_{H_d}^2)\left(|H_d^-|^2 + |H_d^0|^2\right) \\ & + \frac{g^2}{2}|H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 + \frac{g^2+g'^2}{8}\left(|H_u^+|^2 + |H_u^0|^2 - |H_d^0|^2 - |H_d^-|^2\right)^2 \\ & + m_S^2|S|^2 + \left|\kappa S^2 + \lambda\left(H_u^+ H_d^- - H_u^0 H_d^0\right)\right|^2 + \left[(b+\lambda A_\lambda S)\left(H_u^+ H_d^- - H_u^0 H_d^0\right) + \frac{1}{3}\kappa A_\kappa S^3 + h.c.\right] \end{aligned}$$

Expanding the Higgs fields around the VEVs

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \longrightarrow \begin{pmatrix} 0 \\ v_u/\sqrt{2} \end{pmatrix} + \begin{pmatrix} H_u^+ \\ \text{Re}H_u^0 + i\text{Im}H_u^0 \end{pmatrix}$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \longrightarrow \begin{pmatrix} v_u/\sqrt{2} \\ 0 \end{pmatrix} + \begin{pmatrix} \text{Re}H_d^0 + i\text{Im}H_d^0 \\ H_d^- \end{pmatrix}$$

$$S \longrightarrow v_u/\sqrt{2} + \text{Re}S + i\text{Im}S$$

Higge mass eigenstates

$$\begin{pmatrix} \text{Re}H_d^0 \\ \text{Re}H_u^0 \\ \text{Re}S \end{pmatrix} \xrightarrow{\alpha} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}, \qquad \begin{pmatrix} \text{Im}H_d^0 \\ \text{Im}H_u^0 \\ \text{Im}S \end{pmatrix} \xrightarrow{\beta} \begin{pmatrix} a_1 \\ \text{N.G.B} \\ a_2 \end{pmatrix}, \qquad \begin{pmatrix} H_u^+ \\ H_d^{-*} = H_d^+ \end{pmatrix} \xrightarrow{\beta} \begin{pmatrix} \text{N.G.B} \\ H^+ \end{pmatrix}.$$

NMSSM Higgs Sector

The Higgs sector of the NMSSM is described by the six parameters

$$\lambda\ ,\ \kappa\ ,\ A_\lambda\ ,\ A_\kappa,\ \tan\beta\ = v_u/v_d\ ,\ \mu_{\rm eff}\ .$$

The couplings of the Higgs states depend on their decompositions into the CP-even weak eigenstates H_d, H_u and S, which are given by

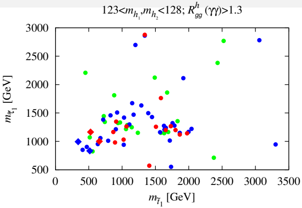
$$\begin{aligned} h_1 &= S_{1,d}\ H_d + S_{1,u}\ H_u + S_{1,s}\ S\ , \\ h_2 &= S_{2,d}\ H_d + S_{2,u}\ H_u + S_{2,s}\ S\ . \end{aligned}$$

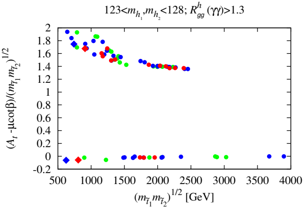
Then, the reduced couplings of h_i are

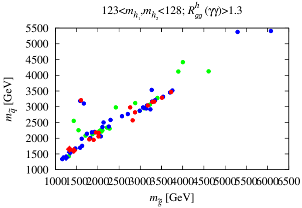
$$C_{dd}^{h_i} = \frac{S_{i,d}}{\cos\beta}\ , \qquad C_{uu}^{h_i} = \frac{S_{i,u}}{\sin\beta}\ , \qquad C_{VV}^{h_i} = \cos\beta\, S_{i,d} + \sin\beta\, S_{i,u}\ .$$

The loop-induced reduced couplings $C_{gg}^{h_i}$ and $C_{\gamma\gamma}^{h_i}$ have to be computed including contributions from SUSY particles in the loops, including scalar τ-leptons, charginos and more.

Implication for SUSY Particles





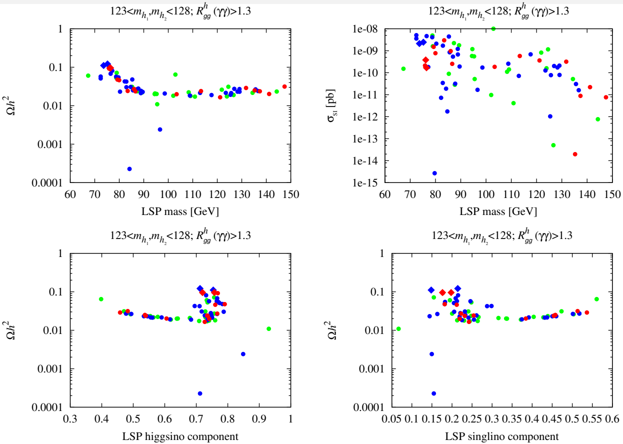


① Indeed, the few points which we found in the WMAP window always have $m_{\tilde{t}_1} < 700\ \mathrm{GeV}$.

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

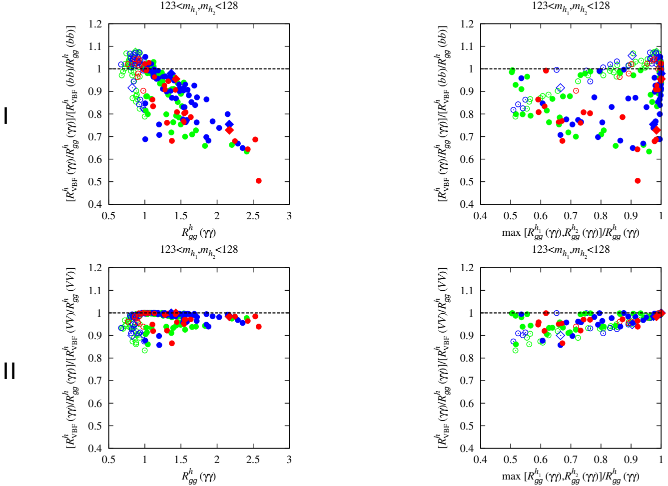
③ Squark and gluino masses are above about $1.25\ \mathrm{TeV}$ ranging up to as high as $6\ \mathrm{TeV}$ (where our scanning more or less ended). The WMAP-window points with large $R^h_{gg}(\gamma\gamma)$ are located at low masses of $m_{\tilde{g}} \sim 1.3\ \mathrm{TeV}$ and $m_{\tilde{q}} \sim 1.6\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

Dark Matter Properties



- WMAP-window points have a rather limited range of LSP masses, roughly $m_{\widetilde{\chi}^0_1} \in [60, 80]$ 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 $\mu_{\rm eff}$).

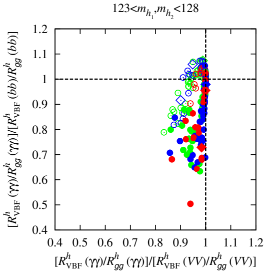
double ratio examination – NMSSM (ii)

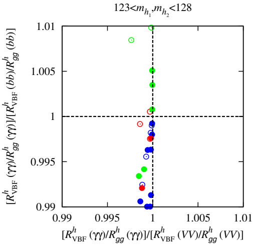


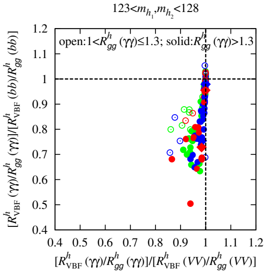
- For the NMSSM, it seems that double ratio I) provides the greatest discrimination for the majority of the degenerate scenarios that have enhanced $\gamma\gamma$ rates.
- It particularly, being sensitive to the $b\overline{b}$ final state, singles out degenerate Higgs scenarios even when one or the other of h_1 or h_2 dominates the $gg \to \gamma\gamma$ rate.
- In comparison, double ratio II) is most useful for scenarios with $R^h_{gg}(\gamma\gamma) \sim 1$.

double ratio examination – NMSSM (iii)

As illustrated below, the greatest discriminating power is clearly obtained by measuring both double ratios.



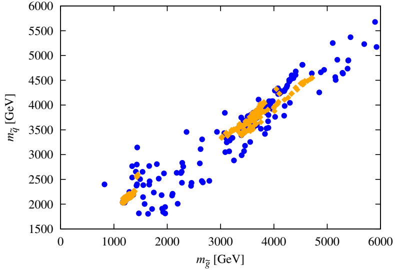


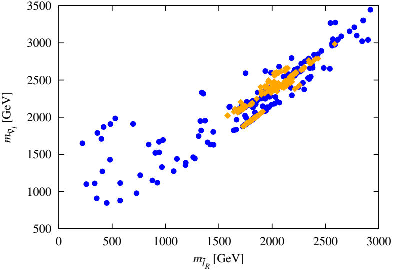


In fact, a close examination reveals that there are no points for which *both* double ratios are exactly 1!

Of course, experimental errors may lead to a region containing a certain number of points in which both double ratios are merely consistent with 1 within the errors.

Prediction for SUSY Particles



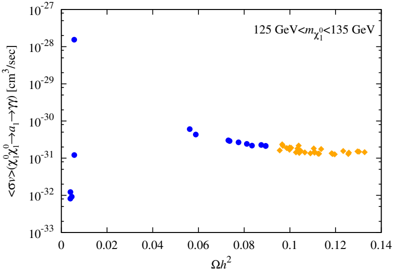


- The predicted $m_{\tilde{q}}$ and $m_{\tilde{g}}$ are beyond current experimental limits, although the lowest values (as found in particular in the low-$m_{\widetilde{\chi}_1^0}$ WMAP-window scenarios) may soon be probed.

- Note that $m_{\tilde{g}}$ can be below $m_{\widetilde{\ell}_R}$ (as common in constrained models when m_0 is large) for some points, including the low-$m_{\widetilde{\chi}_1^0}$ points in the WMAP window.

Able to describe the Fermi-LAT data?

Whether or not any of the points are such as to describe the monochromatic signal $\langle\sigma v\rangle(\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to \gamma\gamma) \sim 10^{-27}\mathrm{cm}^3/\mathrm{sec}$ *at* $130~\mathrm{GeV}$ *observed in the Fermi-LAT data?*



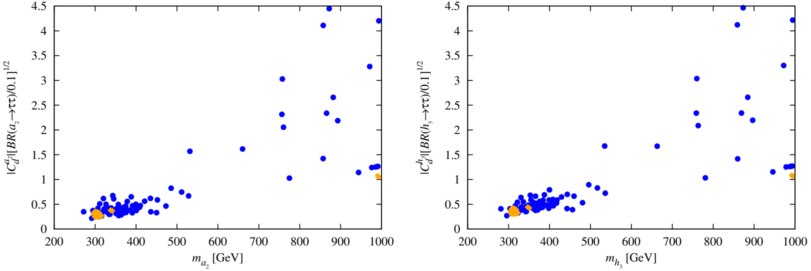
For points with $m_{\widetilde{\chi}_1^0} \in [125, 135]~\mathrm{GeV}$, it is the *s*-channel a_1 diagram that can give a large $\langle\sigma v\rangle$.

- In the WMAP window, they have values of $\langle\sigma v\rangle$ four orders of magnitude below that required to explain the excess.
- Those points with the largest $\langle\sigma v\rangle$ always have quite small Ωh^2 and hence ρ_{DM}.
- Incidentally, all the points in our plots are fully consistent with the current bounds from the continuum γ spectrum as measured by Fermi-LAT.

If the $130~\mathrm{GeV}$ gamma ray line is confirmed, then a fully general NMSSM model (no GUT scale unifications) might be simultaneously consistent with all experiment measurements.

LHC Test – Direct Higgs Production and Decay

A final possible detection mode is $gg \to a_2, h_3 \to \tau^+\tau^-$.



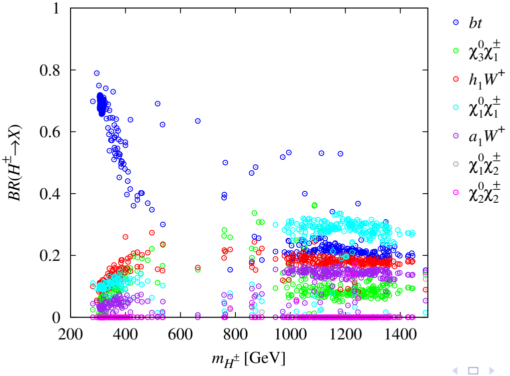
in the effective down-quark coupling, 0.1 is a reference value of $\mathrm{BR}(H, A \to \tau^+\tau^-)$ implicit in the MSSM limit plots discussed below.

- Noting that $m_{a_2} \simeq m_{h_3}$ and the fact that the two plots are nearly identical shows that we may sum the a_2 and h_3 signals together in the same manner as the H and A signals are summed together in the case of the analogous plot of $\tan\beta$ vs. $m_A \simeq m_H$ in the case of the MSSM.
- Limits from CMS 4.6 fb^{-1} data are of order $C_d^{a_2,h_3}(\mathrm{eff}) \lesssim 7-8$ for $m_{a_2} \simeq m_{h_3} \in [150, 220]$ GeV rising rapidly to reach ~ 50 at degenerate mass of order 500 GeV.

LHC Test – Charged Higgs Decay

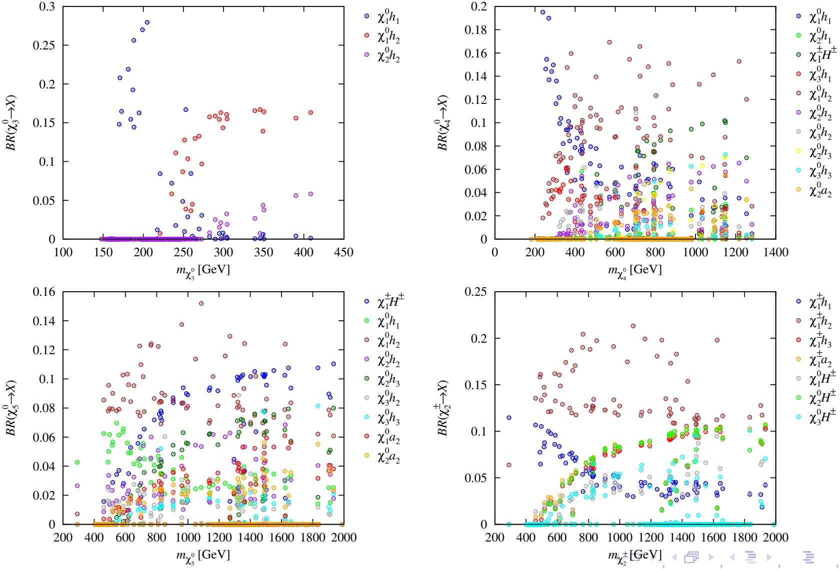
Regarding the $H^\pm$, prospects for its discovery at masses for which H^+H^- production has substantial cross section appear to be promising in the bt final state provided reconstruction of the bt mass is possible with good efficiency and one or more b tags are sufficient to reject SM background.

Also very interesting would be detection of $H^\pm \to h_1 W^\pm$ in the $h_1 \to b\overline{b}$ final state using mass reconstruction for the $b\overline{b}$ and a leptonic trigger from the $W^\pm$ to reject backgrounds.



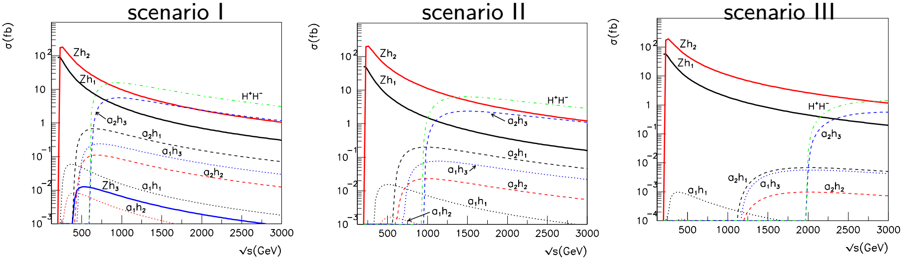
LHC Test – Higgses from Neutralino Decays

Whether some of the Higgs bosons can be detected via ino-pair production?



Linear Collider Test

An e^+e^- collider would be the ideal machine to produce the additional Higgs states and resolve the scenario.



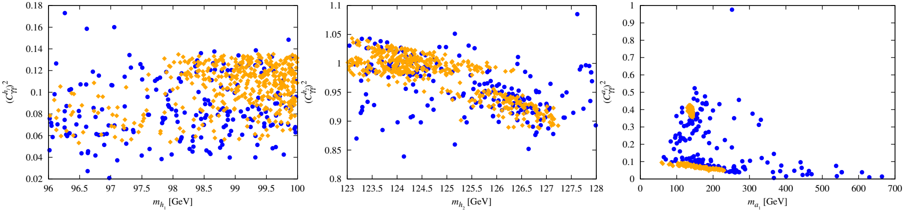
Sce.	m_{h_1}	m_{h_2}	m_{h_3}	m_{a_1}	m_{a_2}	$m_{H^\pm}$	$m_{\tilde{\chi}^0_1}$	Ωh^2	LSP-S	LSP-$\widetilde{H}$	$R^{h_2}_{gg}(\gamma\gamma)$
I	99	124	311	140	302	295	76	0.099	18%	75%	1.62
II	97	124	481	217	473	466	92	0.026	20%	74%	1.53
III	99	126	993	147	991	989	115	0.099	75%	25%	1.14

With an integrated luminosity of 1000 fb^{-1}, substantial event rates for many Z+Higgs and Higgs pair final states are predicted. Of course, Zh_1 and Zh_2 production have the largest cross sections and lowest thresholds. The next lowest thresholds are for $a_1 h_1$ production, but the cross sections are quite small.

In the e^+e^- collider case, it would be easy to isolate signals in many final states.

Photon Collider Test

In the $\gamma\gamma$ collider, the γ's are obtained by backscattering of laser photons off the energetic e's. A huge range of energies is possible for such a $\gamma\gamma$ collider, ranging from low to high center of mass energies depending upon the center of mass energy of the underlying electron collider.



- The fairly SM-like h_2 at $\sim 125\ \mathrm{GeV}$ can be studied easily at such a collider since its $\gamma\gamma$ coupling is close to SM strength.
- Even though the h_1 and a_1 are largely singlet, both have $\gamma\gamma$ couplings-squared that are often of order 0.1×SM and above (at the same mass). Indeed, this coupling becomes stronger as λ is increased.

Muon Collider Test

A muon-collider with $\sqrt{s}$ close to the Higgs mass in question would be a particularly ideal machine to study any Higgs boson with $\mu^+\mu^-$ coupling that is not too different from that of a SM Higgs boson of similar mass.