Implication of LHC Higgs Signal for the MSSM Parameter Regions

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In collaboration with N. Christensen, T. Han, L. Carpenter
work ongoing...

S. Su
Outline

Higgs signal as light CP-even Higgs $h^0$
- $m_h$ around 125 GeV (or 115 - 130 GeV)
- $\sigma(gg\rightarrow h^0)\text{Br}(h^0\rightarrow \gamma\gamma/WW/ZZ)$ close to the SM value

Higgs signal as heavy CP-even Higgs $H^0$

Direct collider search limits

Indirect constraints: $b\rightarrow s\gamma$, $B_s\rightarrow \mu^+\mu^-$, ...

Collider signatures: superparticles

Collider signatures: other MSSM Higgses
Outline

- Higgs signal as light \( \text{CP-even Higgs} \ h^0 \)
  - \( m_h \) around 125 GeV (or 115 -130 GeV)
  - \( \sigma (gg \to h^0) Br(h^0 \to \gamma\gamma/WW/ZZ) \) close to the SM value

- Higgs signal as heavy \( \text{CP-even Higgs} \ H^0 \)

- Direct collider search limits

- Indirect constraints: \( b \to s\gamma, B_s \to \mu^+\mu^- \), ...

- Collider signatures: superparticles

- Collider signatures: other MSSM Higgses
Current LHC Indication of 125 GeV Higgs

ATLAS Preliminary

Best fit

±1σ

2011 Data

\[ \int L dt = 1.0-4.9 \text{ fb}^{-1} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

ATLAS

ATLAS-CONG-2011-163 (b)

OBS Preliminary, \( \sqrt{s} = 7 \text{ TeV} \)

Combined, \( L_{\text{int}} = 4.6-4.7 \text{ fb}^{-1} \)

CMS

CMS PAS HIG-11-032

Higgs boson mass (GeV/c²)

Best fit \( \sigma/\sigma_{\text{SM}} \)

±1σ from fit

S. Su
Identify regions in MSSM parameter space that gives

\[
m_H \text{ around 125 GeV (or 115 - 130 GeV)}
\]

\[
\sigma(gg \to H) Br(H \to \gamma\gamma/WW/ZZ) \text{ around SM value}
\]

Consistent with direct/indirect exp bounds
(consider those relevant to the Higgs sector)
- Tevatron/LHC $h^0/H^0/A^0 \to \tau\tau$ search, $H^\pm$ search
- $b \to s\gamma$, $B_s \to \mu^+\mu^-$, ...
- dark matter (funnel region?)
Consider 125 GeV Higgs as light CP-even $h^0$  

Dominant loop correction to $m_{h^0}$ from stop sector

\[
m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[ \frac{1}{2} \tilde{X}_t + t + \frac{1}{16\pi^2} \left( \frac{3 m_t^2}{2 v^2} - 32\pi\alpha_3 \right) \left( \tilde{X}_t t + t^2 \right) \right]
\]

\[
t = \log \frac{M_{\text{SUSY}}^2}{m_t^2}
\]

\[
\tilde{X}_t = \frac{2\tilde{A}_t^2}{M_{\text{SUSY}}^2} \left( 1 - \frac{\tilde{A}_t^2}{12 M_{\text{SUSY}}^2} \right),
\]

\[
\tilde{A}_t = A_t - \mu \cot \beta,
\]

Small stop mixing $A_t$ ($m_{h^0}^{\text{min}}$): need stop mass VERY large (5-10 TeV, FP region).

large stop mixing $A_t$ ($m_{h^0}^{\text{max}}$): ...

S. Heinemeyer et. al., 1112.3026  
A. Arbey et. al., 1112.3028;  
A. Arbey et. al., 1112.3032;  
P. Draper et. al., 1112.3068  
M. Carena et, al., 1112.3336;  
A. Arvanitaki and G. Villadoro, 1112.4835

...
- st1 could be as light as 200-300 GeV
- large stop mass splittings between $m_{st1}$ and $m_{st2}$.
  - $st2 \rightarrow st1 + Z$?
Stop Contribution

Figure 1: Contour plots of the Higgs mass in the $m_{Q_3} - m_{U_3}$ plane, for different values of $A_t$ and $\tan \beta$. The stau soft masses have been fixed at $m_{\tilde{L}_3} = m_{\tilde{e}_3} = (350 \text{ GeV})^2$, while $\mu = 10^{30} \text{ GeV}$ and $A_{\tilde{\tau}} = 500 \text{ GeV}$, leading to a lightest stau mass of about $135 \text{ GeV}$ for $\tan \beta = 60$.

- **M3SQ ≠ M3SU:** one stop could be light
  - light M3SQ: light st1 mostly left-handed? sbL?
  - light M3SU: light st1 mostly right-handed?

M. Carena et al., 1112.3336;
Consider \( \tilde{t}_1 \tilde{t}_1^* \) pair production at the LHC

\[
\begin{align*}
\chi_1^\pm &\rightarrow W^{(*)} \chi_1^0 \\
\chi_2^0 &\rightarrow Z^{(*)} \chi_1^0 \\
\chi_2^0 &\rightarrow h \chi_1^0
\end{align*}
\]

Collider Signatures:
- \( bbWW+MET \)
- \( bbWW+ZZ+MET \)
- \( bbWW+hh+MET \)
- ...
Stop Contribution

![Figure 1: Tree-level Higgs sector parameters ($M_A$, $\tan\beta$) for the case where the parameters governing the higher-order corrections are chosen such that a maximum value for $M_h$ is obtained ($m_{h\text{max}}$) benchmark scenario). The different colours correspond to the regions excluded by LEP (blue) and Tevatron/LHC (red). The gray area is the allowed parameter space prior to the latest LHC results. The green band shows the region compatible with the assumed Higgs signal (see text). With the assumed Higgs signal, interpreted as the lighter CP-even MSSM Higgs mass, implies in particular that $M_h > 122$ GeV (including theoretical uncertainties), which is significantly higher than the limit observed for a SM-like Higgs at LEP of $M_h > 114.4 \pm 2$ GeV. From Fig. 1 it is therefore possible to extract lower (one parameter) limits on $M_A$ and $\tan\beta$ from the edges of the green band. Note that these bounds, by deriving them in the $m_{h\text{max}}$ scenario, are conservative and apply generically in the MSSM. To address the (small) residual $M_{\text{SUSY}}$ dependence of these bounds, we extract limits for the three different values $M_{\text{SUSY}} = \{0.5, 1, 2\}$ TeV. The results are given in Table 1, where for comparison we also show the previous limits derived from the LEP Higgs searches [22], i.e. before the incorporation of the new LHC results reported in Ref. [10]. The bounds on $M_A$ translate directly into lower limits on $M_{H\pm}$, which are also given in the table. A phenomenological consequence of the bound $M_{H\pm} \gtrsim 155$ GeV (for $M_{\text{SUSY}} = 1$ TeV) is that it would leave only a very small kinematic window open for the possibility that MSSM charged Higgs bosons are produced in the decay of top quarks.

### Table 1: Lower limits on the MSSM Higgs sector tree-level parameters $M_A$ and $\tan\beta$ obtained with and without the assumed Higgs signal of $M_h \sim 125$ GeV, see Eq. (1). The mass limits have been rounded to 1 GeV.

<table>
<thead>
<tr>
<th>$M_{\text{SUSY}}$ (GeV)</th>
<th>$\tan\beta$</th>
<th>$M_A$ (GeV)</th>
<th>$M_{H\pm}$ (GeV)</th>
<th>$\tan\beta$</th>
<th>$M_A$ (GeV)</th>
<th>$M_{H\pm}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>2.7</td>
<td>95</td>
<td>123</td>
<td>4.5</td>
<td>140</td>
<td>161</td>
</tr>
<tr>
<td>1000</td>
<td>2.2</td>
<td>95</td>
<td>123</td>
<td>3.2</td>
<td>133</td>
<td>155</td>
</tr>
<tr>
<td>2000</td>
<td>2.0</td>
<td>95</td>
<td>123</td>
<td>2.9</td>
<td>130</td>
<td>152</td>
</tr>
</tbody>
</table>

S. Heinemeyer et. al., 1112.3026

- little dependence on $\mu$ and $\tan\beta$
- little dependence on $m_A$ except for small $m_A$
- $\tan\beta$ in a narrow region.
Stop Contribution

Figure 2: Allowed ranges of $\tan\beta$ for $M_A = 400$ GeV, shown as a function of the stop mixing parameter $X_t$. The colour coding is as in Fig. 1. The three plots correspond to $M_{\text{SUSY}} = 500$ GeV (left), $M_{\text{SUSY}} = 1$ TeV (centre), and $M_{\text{SUSY}} = 2$ TeV (right).

but in contrast to the lower bound which is scenario-independent, this limit will only apply to the specific case of the $m_{\max}^h$ scenario. In fact, the allowed range for $\tan\beta$ depends sensitively on the other parameters, as can be seen from Fig. 2, where we show the $(X_t, \tan\beta)$ plane for $M_A = 400$ GeV, but the results are qualitatively similar for other values of $M_A$ in the decoupling limit. The main difference is the LHC exclusion limit (in red), which goes down to lower values of $\tan\beta$ for lower $M_A$. On the other hand, for $M_A$ in the non-decoupling regime, even before the new results $\tan\beta$ was already quite restricted, from above by the the LHC limits, and from below by the LEP limits, which can also be seen from Fig. 1. The $m_{\max}^h$ value of $X_t = -2M_{\text{SUSY}}$ turns out to be quite special, since this parameter region (at least for $M_{\text{SUSY}} = 1$ TeV and $M_{\text{SUSY}} = 2$ TeV) actually shows the highest sensitivity to variations of $\tan\beta$ when $m_h \sim 125$ GeV. This would result in only a narrow allowed $\tan\beta$ region. For other regions of $X_t$, however, $\tan\beta$ values all the way up to the LHC bound are compatible with an assumed signal at $m_h \sim 125$ GeV. Further progress could obviously be made if direct information on the stop sector became available from the LHC or a future Linear Collider.

Having established lower limits on the tree-level parameters $M_A$ and $\tan\beta$, we now investigate instead what can be inferred from the assumed Higgs signal about the higher-order corrections in the Higgs sector. Similarly to the previous case, we can obtain an absolute lower limit on the stop mass scale $M_{\text{SUSY}}$ by considering the maximal tree-level contribution to $M_h$. We therefore perform this analysis in the decoupling limit (fixing $M_A = 1$ TeV, $\tan\beta = 20$). The resulting constraints for $M_{\text{SUSY}}$ and $X_t$ are shown in Fig. 3 (left) using the same colour coding as before. Several favoured branches develop in this plane, centred around $X_t \sim -1.5 M_{\text{SUSY}}$, $X_t \sim 1.2 M_{\text{SUSY}}$, and $X_t \sim 2.5 M_{\text{SUSY}}$. The minimal allowed stop mass scale is $M_{\text{SUSY}} \sim 300$ GeV with positive $X_t$ and $M_{\text{SUSY}} \sim 500$ GeV for negative $X_t$ (which is in general preferred by BR($b \to s\gamma$), see above).

The results on the stop sector can also be interpreted as a lower limit on the mass $m_{\tilde{t}_1}$ of the lightest stop squark. This is shown in Fig. 3 (right). It is interesting to note from the figure that without the assumed Higgs signal, there is essentially no lower bound on the lightest stop mass coming from the Higgs sector. Taking the new results into account, we obtain the lower bounds $m_{\tilde{t}_1} > 100$ GeV ($X_t > 0$) and $m_{\tilde{t}_1} > 250$ GeV ($X_t < 0$). These bounds can be compared to those from direct searches, where the LEP limit $m_{\tilde{t}_1} > \sim 95$ GeV is still valid [23]. Results from stop searches at the Tevatron can also be found in this reference. No new stop limits have been established so far from the SUSY searches at the LHC [16].
Stop Contribution

MA = 1 TeV, tanβ = 20

Positive $M_3 A_t$ gives larger contributions comparing to positive $M_3 A_t$.

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\[ \Delta m_h^2 \simeq -\frac{h_b^4 v^2}{16\pi^2} \frac{\mu^4_{\text{SUSY}}}{M_{\text{SUSY}}^4} \left( 1 + \frac{t}{16\pi^2} \left( 9h_b^2 - 5\frac{m_t^2}{v^2} - 64\pi\alpha_3 \right) \right) \]

\[ h_b \simeq \frac{m_b}{v \cos\beta(1 + \tan\beta \Delta h_b)} \]

- small \( m_{\text{sb}} \), large \( \mu \)
- negative and large \( \Delta h_b \) (\( \mu M_3 \) large and negative) \( \rightarrow \) large \( h_b \)
  (but then enhanced \( h^0 \rightarrow bb \) and suppressed \( h^0 \rightarrow \gamma\gamma/WW/ZZ \))

\[ \Delta m_{h^2}^2 \simeq -\frac{h^4_{\tau} v^2}{48\pi^2} \frac{\mu^4_{\tau}}{M_{\tau}^4} \]

\[ h_{\tau} \simeq \frac{m_{\tau}}{v \cos\beta(1 + \tan\beta \Delta h_{\tau})} \]

- small \( m_{\text{stau}} \), large \( \mu \)
- negative and large \( \Delta h_{\text{tau}} \) (\( \mu M_2 \) large and negative) \( \rightarrow \) large \( h_{\text{tau}} \)
  muon g-2?
Region I: Decoupling Region

- Region I: decoupling region of large $m_A (> 2 m_Z)$.
  - $h^0$ is SM like.
  - slightly suppressed $gg \rightarrow h^0$ and $h^0 \rightarrow \gamma\gamma$, WW and ZZ
Avoid Intense Coupling Region

- Avoid the intense coupling region: small $m_A$, large $\tan\beta$.
  - $h^0, H^0, A^0$ masses close to each other
  - $h^0bb, h^0\tau\tau$ enhanced, $h^0\to\gamma\gamma, WW, ZZ$ suppressed

![Graph](image-url)
Avoid Intense Coupling Region

- avoid the intense coupling region: small $m_A$, large $\tan\beta$.
- $h^0, H^0, A^0$ masses close to each other
- $h^0 bb, h^0 \tau\tau$ enhanced, $h^0 \rightarrow \gamma\gamma, WW, ZZ$ suppressed

there are exceptions…
**Region II: suppressed \( h^0 \rightarrow bb \)**

- suppressed \( h^0 \rightarrow bb \) leads to enhanced \( h^0 \rightarrow \gamma\gamma, WW, ZZ \)

\[
\frac{-\sin\alpha}{\cos\beta} \left[ 1 - \frac{\Delta h_b \tan\beta}{1 + \Delta h_b \tan\beta} \left( 1 + \frac{1}{\tan\alpha \tan\beta} \right) \right]
\]
**Region II: suppressed $h^0 \to bb$**

- Suppressed $h^0 \to bb$ leads to enhanced $h^0 \to \gamma\gamma, WW, ZZ$

\[
h_{bb} : \frac{\sin \alpha}{\cos \beta} \left[ 1 - \frac{\Delta h_b \tan \beta}{1 + \Delta h_b \tan \beta} \left( 1 + \frac{1}{\tan \alpha \tan \beta} \right) \right]
\]

**Region IIA:**
Small $\alpha_{\text{eff}}$ region
suppressed $h^0 \rightarrow bb$ leads to enhanced $h^0 \rightarrow \gamma\gamma, WW, ZZ$

region IIA: small $\alpha_{\text{eff}}$ region

region IIB: suppressed bottom Yukawa coupling

$h^{\pm} b \bar{b}$:
$$h^{\pm} b \bar{b} : \frac{\sin \alpha}{\cos \beta} \left[ 1 - \frac{\Delta h_b \tan \beta}{1 + \Delta h_b \tan \beta} \left( 1 + \frac{1}{\tan \alpha \tan \beta} \right) \right]$$

For large values of $\tan \beta$ and moderate values of $m_A$ the values of $\sin \alpha$ tend to be very small, of order $\cos \beta$. A decrease of the bottom quark coupling can be obtained, for instance, if $|\sin \alpha| < \cos \beta$, which can be obtained by making the loop corrections $\Delta h_b$ positive and sizable. Since the tree-level contribution for $E_{\text{M}}^2 H_{12}$ is suppressed by $\Delta h_b \tan \beta$, the loop corrections may be significant in the large $\tan \beta$ regime. It is well known that a suppression of the Higgs mixing can be achieved for large values of $\mu A_t < n e \mu A_t > n f$ for $A_t < \sqrt{t M_{\text{SUSY}}}$, as follows from Eq. (5). Sizable values of $A_t$ are necessary to achieve a large modification of the Higgs mixing, what leads to values of the Higgs mass of about $\Delta$--$\Delta$ GeV for stops masses of about $\Delta$ TeV. A benchmark scenario for Higgs searches at hadron colliders, named the "small $\alpha_{\text{eff}}$ scenario," has been constructed due to this property. Large values of $\mu_3 A_b, \tau > n$ may also lead to a significant effect for very large values of $\tan \beta$.
Region IIA: Small $\alpha_{\text{eff}}$

- Suppression of $h^0b\bar{b}$ coupling due to the mixing effects in the CP-even Higgs sector

$$h\bar{b}b : -\frac{\sin\alpha}{\cos\beta} \left[ 1 - \frac{\Delta h_b \tan\beta}{1 + \Delta h_b \tan\beta} \left( 1 + \frac{1}{\tan\alpha \tan\beta} \right) \right]$$

Region IIA: small $\alpha_{\text{eff}}$ region

$$\mathcal{M}_H^2 = \begin{bmatrix}
m_A^2 \sin^2\beta + M_Z^2 \cos^2\beta \\
-(m_A^2 + M_Z^2) \sin\beta \cos\beta + \text{Loop}_{12} \\
-(m_A^2 + M_Z^2) \sin\beta \cos\beta + \text{Loop}_{12} \\
-(m_A^2 + M_Z^2) \sin\beta \cos\beta + \text{Loop}_{12}
\end{bmatrix}
$$

$$\sin(2\alpha) = \frac{2 (\mathcal{M}_H^2)_{12}}{\sqrt{\text{Tr}[\mathcal{M}_H^2]^2 - \text{det}[\mathcal{M}_H^2]}}$$

- moderate for large $\tan\beta$
- small to moderate $m_A$
Region IIA: Small $\alpha_{\text{eff}}$

- suppression of $h^0 bb$ coupling due to the mixing effects in the CP-even Higgs sector

\[
\text{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2 \beta M_{\text{SUSY}}^2} \left[ \frac{A_t \tilde{A}_t}{M_{\text{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2 \beta \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_{\tau}^4 v^2}{48\pi^2} \sin^2 \beta \frac{\mu^3 A_{\tau}}{M_{\tilde{\tau}}^4}
\]

Carena et. al., hep-ph/9808312
Carena et. al., hep-ph/9907422
**Region IIA: Small \( \alpha_{\text{eff}} \)**

- **Suppression of** \( h^0 \)bb **coupling due to the mixing effects in the CP-even Higgs sector**

\[
\text{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2 \beta M_{\text{SUSY}}^2} \frac{\mu \tilde{A}_t}{M_{\text{SUSY}}^2} \left[ \frac{A_t \tilde{A}_t}{M_{\text{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2 \beta \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_\tau^4 v^2}{48\pi^2} \sin^2 \beta \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}
\]

*stop contribution*

- **light stop, large** \( \mu A_t \)
- **\( \mu A_t < 0 \) for** \( A_t < \sqrt{6} m_{{\text{st}}} \)
- **\( \mu A_t > 0 \) for** \( A_t > \sqrt{6} m_{{\text{st}}} \)

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Carena et. al., hep-ph/9808312
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Region IIA: Small $\alpha_{\text{eff}}$

- Suppression of $h^0bb$ coupling due to the mixing effects in the CP-even Higgs sector

\[
\text{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2 \beta M_{\text{SUSY}}^2} \frac{\mu \tilde{A}_t}{M_{\text{SUSY}}^2} \left[ \frac{A_t \tilde{A}_t}{M_{\text{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2 \beta \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_{\tau}^4 v^2}{48\pi^2} \sin^2 \beta \frac{\mu^3 A_\tau}{M_{\text{SUSY}}^4}
\]

- **Stop contribution**
  - light stop, large $\mu A_t$
  - $\mu A_t < 0$ for $A_t < \sqrt{6} m_{\text{st}}$
  - $\mu A_t > 0$ for $A_t > \sqrt{6} m_{\text{st}}$

- **Sb contribution**
  - light sbottom
  - large $\mu^3 A_b$
  - large $h_b$

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Carena et. al., hep-ph/9808312
Carena et. al., hep-ph/9907422

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Region IIA: Small $\alpha_{\text{eff}}$

- Suppression of $h^0\bb$ coupling due to the mixing effects in the CP-even Higgs sector

\[
\text{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2 \beta M_{\text{SUSY}}^2} \left[ \frac{A_t \tilde{A}_t}{M_{\text{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2 \beta \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_{\tau}^4 v^2}{48\pi^2} \sin^2 \beta \frac{\mu^3 A_{\tau}}{M_{\tilde{\tau}}^4}
\]

**stop contribution**
- light stop, large $\mu A_t$
- $\mu A_t < 0$ for $A_t < \sqrt{6} \, m_{st}$
- $\mu A_t > 0$ for $A_t > \sqrt{6} \, m_{st}$

**sb contribution**
- light sbottom
- large $\mu^3 A_b$
- large $h_b$

**stau contribution**
- light stau
- large $\mu^3 A_{\tau}$
- large $h_{\tau}$

Carena et. al., hep-ph/9808312
Carena et. al., hep-ph/9907422
Region IIA: Small $\alpha_{\text{eff}}$

$M_{3SL}=M_{3SE}=340, \mu =1030$
$A_{\tau}=1500, A_t=2500$
$M_1=100, M_2=1000, M_3=1200$
$MSUSY=1000$

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Region IIA: Small $\alpha_{\text{eff}}$

M3SL=M3SE=340, $\mu = 1030$
A$\tau$=1500, At=2500
M1=100, M2=1000, M3=1200
MSUSY=1000

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Region IIA: Small $\alpha_{\text{eff}}$

Masses for Higgses, $M_{3\text{SL}}=M_{3\text{SE}}=1000$ GeV, $A_T=1500$, $A_t=2500$, $M_1=M_2=M_3=1000$ GeV

$M_{3\text{SUSY}}=1000$

$M_{3\text{SL}}=M_{3\text{SE}}=340$, $\mu =1030$

$A_T=1500$, $A_t=2500$

$M_1=100$, $M_2=1000$, $M_3=1200$

$S. \text{ Su}$
Region IIA: Small $\alpha_{\text{eff}}$

M3SL=M3SE=340, $\mu$ =1030
At=1500, At=2500
M1=100, M2=1000, M3=1200
MSUSY=1000

S. Su
Region IIA: Small $\alpha_{\text{eff}}$

- Masses for Higgses, $M_{3SL}=M_{3SE}=1000$ GeV, $\mu =1030$
- $\tan\beta =1500$, $A_\tau =2500$
- $M_1=100$, $M_2=1000$, $M_3=1200$
- $M_{\text{SUSY}}=1000$

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Region IIB: Suppressed $h_b$

- suppressed $h^0bb$ coupling due to suppression of bottom Yukawa:
  - $\Delta h_b$ large and positive

\[
   h\bar{b}\bar{b} : -\frac{\sin \alpha}{\cos \beta} \left[ 1 - \frac{\Delta h_b \tan \beta}{1 + \Delta h_b \tan \beta} \left( 1 + \frac{1}{\tan \alpha \tan \beta} \right) \right]
\]

- $\mu M_3$ large and positive, small $m_{\tilde{b}}$
  - $\Rightarrow$ large $\Delta h_b > 0 \Rightarrow$ suppressed $h^0bb$ coupling

Carena et. al., hep-ph/9808312
Carena et. al., hep-ph/0202167
Region III: Enhanced $h \rightarrow \gamma \gamma$

- SM contribution usually suppressed.
  dominantly from $W$, subdominantly from top (bottom).

MSSM extra stop/sbottom/stau contribution (enhancement)
- stop contribution: small $m_{st}$, large $A_t$
- sbottom/stau contribution: small $m_{sb}$, $m_{ST}$, large $\mu$, large $\tan\beta$
- chargino contribution is only important for chargino lighter than 100 GeV.
Region III: Enhanced \( h \rightarrow \gamma \gamma \)

- stop/sbottom also leads to suppressed \( gg \rightarrow h^0 \):
  - combined \( gg \rightarrow h^0 \rightarrow \gamma \gamma \) usually suppressed.

\[ A_t = 2.5 \text{ TeV}, \tan \beta = 10, \quad \frac{\sigma (gg \rightarrow h)}{\sigma (gg \rightarrow h)_{SM}} \times \frac{\text{Br}(h \rightarrow \gamma \gamma)}{\text{Br}(h \rightarrow \gamma \gamma)_{SM}} \]

![Contour plot](image)

M. Carena et al., 1112.3336;
Region III: Enhanced $h\rightarrow \gamma\gamma$

- **Stau contribution:** small $m_{\text{st}}$, large $\mu$, large $\tan\beta$

Contour plots of the ratio of the $\sigma_{\text{BR}}$ for which the stau mixing becomes relevant and the lightest stau mass is close to its SM value—in the $m_{L3} - \mu$ plane—for $\tan\beta = 10$ and $\tan\beta = 60$.

Experimental limit—of about 100 GeV.

M. Carena et al., 1112.3336; 22
gg→h Not Too Much Suppressed

- usually suppressed \( h\bar{t}\bar{t} : \frac{\cos \alpha}{\sin \beta} < 1 \)
- small suppression in the decoupling region.
- bottom contribution opposite to top contribution.
- large bottom Yukawa leads to suppressed gg→h^0.

- light stop without mixing leads to enhancement of gg→h^0. not good for large \( m_{h^0} \).
- light stop with large \( A_t \), light sbottom with large \( \mu \) and tanβ leads to suppression of gg→h^0.
125 GeV Higgs as Heavy CP-even Higgs $H^0$

- heavy CP-even Higgs $H^0$ SM like
- light CP-even Higgs $h^0$ (<114 GeV), evade LEP bound by reduced $ZZh^0$ coupling
- Region IV: $m_A$: 95 - 100 GeV, $\tan\beta$: 8-10 (near $m_{h_{\text{max}}}$ region?)

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**Figure 4:** Parameter space in the alternative $M_{H^0} \sim 125$ GeV scenario. The colour coding is similar to Fig. 1, with a new region (cyan) compatible with the assumed $H^0$ signal. For the plot of tree-level parameters (left) we have assumed $M_{\text{SUSY}} = X_t = 1$ TeV, and for the stop parameters (right) we fix $M_A = 100$ GeV, $\tan\beta = 10$.

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**4 Conclusions**

An excess in the SM-like Higgs searches at ATLAS and CMS has recently been reported [10] around $M_{SM}H \approx 125$ GeV, which within the experimental uncertainties appears to be remarkably consistent between ATLAS and CMS and is supported by several search channels. While it would be premature to assign more significance to this result than regarding it as a possible (exciting) hint at this stage, it is certainly very interesting to note that this excess has appeared precisely in the region favoured by the global fit within the SM, and within the range predicted in the MSSM. Concerning the MSSM, it is remarkable that the mass region above the upper MSSM bound on a light SM-like Higgs is meanwhile ruled out [10]. Observing a state compatible with a SM-like Higgs boson with $M_{SM}H > 135$ GeV would have unambiguously ruled out the MSSM (but would have been viable in the SM and in non-minimal supersymmetric extensions of it). We therefore regard the reported results as a strong motivation for studying the possible interpretation of an assumed (still hypothetical, of course) signal at $125$ GeV $\pm 1$ GeV. In this paper we have discussed the possible implications of such an assumed signal within the MSSM, where we have investigated both the possibilities that the assumed signal is associated with the light CP-even Higgs boson of the MSSM, $h^0$, and the (slightly more exotic) possibility that the assumed signal in fact corresponds to the heavier CP-even Higgs boson $H^0$.

Investigating the interpretation $M_h = 125 \pm 1$ GeV first, we have demonstrated that there is a significant parameter space of the MSSM compatible with the interpretation that the assumed signal corresponds to the lighter CP-even MSSM Higgs boson. While it would not be appropriate to assign any physical significance to point densities in MSSM parameter space, our scans nevertheless do not seem to indicate a strong case for going from the MSSM to non-minimal SUSY models even though the reported excess is not very far away from the upper bound on the lightest Higgs mass in the MSSM. It should be noted that the question to what extent the scenarios discussed in this paper can be realized in constrained GUT-based models of SUSY breaking is of a very different nature. We do not pursue this any further here, besides mentioning that it has already been shown to be rather difficult to get to such high $M_h$ values in models such as the CMSSM, mGMSB, mAMSB, or NUHM1 [24].
Direct Experimental Constraints

- LEP/Tevatron $H^\pm$ searches

![Graph showing constraints on $m_{H^\pm}$ versus $\tan \beta$](image)

**Figure 13:** Summary of the 95% C.L. exclusions in the $(m_{H^\pm}, \tan \beta)$ plane obtained by LEP [195] and CDF [214]. The benchmark scenario parameters used to interpret the CDF results are very close to those of the $m_{max}$ scenario, and $m_t$ is assumed to be 175 GeV. The full lines indicate the median limits expected in the absence of a $H^\pm$ signal, and the horizontal hatching represents the $\pm 1 \sigma$ bands about this expectation. Color version at end of book.
Direct Experimental Constraints

CMS $pp \rightarrow h^0/H^0/A^0 + X$ with $h^0/H^0/A^0 \rightarrow \tau\tau$

Figure 3: The expected one- and two-standard-deviation ranges and the observed 95% CL upper limits on $\sigma \phi \cdot B_{\tau\tau}$ as a function of $m_A$. The signal acceptance is based on the MSSM model described in the text, assuming $\tan \beta = 30$.

Figure 4: Region in the parameter space of $\tan \beta$ versus $m_A$ excluded at 95% CL in the context of the MSSM $m_{\text{max}}$ scenario with the effect of $\pm \sigma$ theoretical uncertainties shown:

Table 5: Expected range and observed 95% CL upper limits on the cross section normalized to the SM expectation as functions of $m_{H^0}$ for the SM search:
Direct Experimental Constraints

- CMS \( pp \rightarrow h^0/H^0/A^0 + X \) with \( h^0/H^0/A^0 \rightarrow \tau \tau \)

![Graph 1: 95% CL limits on \( \sigma(\phi \rightarrow \tau \tau) \) vs. \( m_A \) for CMS Preliminary with 4.6 fb\(^{-1}\) at \( \sqrt{s} = 7 \) TeV.](image1)

![Graph 2: Region in the parameter space of \( \tan \beta \) vs. \( m_A \) excluded at 95% CL in the context of the MSSM scenario with the effect of theoretical uncertainties shown.](image2)

![Graph 3: Table 5: Expected range and observed 95% CL upper limits on the cross section normalized to the SM expectation as functions of \( m_{H^0} \) for the SM search:](image3)
Indirect Experimental Constraints

Only consider those get contribution from the Higgs sector

- **b → sγ**

  \[
  \text{Br}(b \to s\gamma) = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}, \quad \text{EXP}(2010);
  \]

  \[
  \text{Br}(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}, \quad \text{QCDNNLO}.
  \]

- **H^± loop**: always positive.

- **Chargino loop**: negative for \(\mu A_t > 0\), positive for \(\mu A_t < 0\)
\[ b \rightarrow s \gamma \]

- smaller \( M_2 \) with \( \mu A_t > 0 \) could possibly cancel \( H^\pm \) contribution.
The strongest constraints on a light stop/Higgs sector come from indirect bounds from rare $B$ decays, in particular for the moderate values of $\tan \beta$ considered in this work the constraints are dominated by $b \rightarrow s \gamma$. The main contributions come from the charged Higgs/top and the chargino/stop loops. The charged Higgs increases the amplitude of $b \rightarrow s \gamma$ and varies mildly with $\tan \beta$ unless $\tan \beta \lesssim \sqrt{2}$ when all other SUSY particles are decoupled. The charged Higgs is constrained to be heavier than $\sim 200$ GeV when all other SUSY particles are decoupled. This bound changes drastically when charginos and stops are light. Chargino contributions interfere destructively or constructively with the SM depending on the relative sign of the $\mu$ and $A_t$ terms. They significantly affect $b \rightarrow s \gamma$ at large $\tan \beta$. Their effect is minimized when the rest of the squarks are also light and the $A_t$ term are small due to the GIM mechanism. A natural spectrum requires light Higgsinos and stops, and large cancellations from a light charged Higgs or from $A_t$ terms are necessary to satisfy the current experimental bounds.

To illustrate the impact of the different contributions, Fig. 1 plots $BR(B \rightarrow X_s \gamma)$ with respect to $\tan \beta$ for the three cases where pg only the charged Higgs contribution is important, qg only the chargino/stop loop without $A_t$ terms is important, rg only the chargino/stop loop with $A_t$ terms is important.
Indirect Experimental Constraints

\[ \text{Br}(B_s \rightarrow \mu^+ \mu^-) < 1.08 \times 10^{-8}, \text{ CMS + LHCb}; \]

\[ \text{Br}(B_s \rightarrow \mu^+ \mu^-) < 3.9 \times 10^{-8}, \text{ CDF}; \]

\[ \text{Br}(B_s \rightarrow \mu^+ \mu^-) = (3.19 \pm 0.19) \times 10^{-9}, \text{ SM}, \]

**B_s \rightarrow \mu^+ \mu^-**

- FeynHiggs does not give correct decoupling behavior. Correct the FH value by offset of \( 0.76 \times 10^{-4} \).
- SUSY has two dominant contributions, charged Higgs loop and chargino loop. Charged Higgs (with top) always gives a positive contribution. Chargino loop gives a negative contribution for \( \mu_A t > 0 \) (chargino-stop loop), which makes the deviation worse; positive contribution for \( \mu_A t < 0 \) \[17\].
Implication for Future LHC Searches

- In those identified MSSM regions
  - What are the discovery channels for superparticles?
  - What are the discovery channels for other MSSM Higgses?

Work in Progress...
Conclusions

- LHC Higgs search indication:
  - $m_H$ around 125 GeV (or 115 - 130 GeV)
  - $\sigma(gg\rightarrow H)Br(H\rightarrow \gamma\gamma/WW/ZZ)$ around the SM value

- Interpret $H$ as MSSM light CP-even Higgs
  - $m_{h^0}$: large stop sector mixing $\Rightarrow$ large mass splitting, one stop could be light

- Region I: decoupling region ($m_A > 2m_Z$)
- Region IIA: small $\alpha_{\text{eff}}$
- Region IIB: suppressed bottom Yukawa $h_b$
- Region III: enhanced $h^0 \rightarrow \gamma\gamma$ by stau with large mixing (stop/sbottom contribution leads to the suppression of $gg\rightarrow h^0$)
Conclusions

Interpret 125 GeV Higgs as the heavy CP-even Higgs.

Region IV: $m_A: 95 - 100$ GeV, $\tan \beta: 8-10$

Exp indirect constraints and direct constraints

Implication for LHC searches: superparticles and Higgses
(work in progress...)