A 125 GeV Higgs, Light $\tilde{\tau}$ and the $\gamma\gamma$ Rate in the MSSM

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FNAL

Outline

- Motivation:
  - Recent Atlas/CMS Results
  - MSSM:
    - Higgs Mass
    - 125 GeV Higgs
  - Production Cross-Sections
  - Constraints on MSSM parameter space:
    - EWPT.
    - Dark Matter.
  - Assuming $M_{mess}$ flavor universality, $M_{mess}/m_{soft}$?
  - Collider Prospects.
- Conclusions and Outlook
Motivation

Recent Experimental Results
The $h \rightarrow \gamma \gamma$ rate looks high at this point, but more data is necessary in order to reach a robust conclusion.
Goals

- $m_h \sim 125$ GeV

- $\gamma\gamma$ rate decoupled from $WW$ and $ZZ$ rate
Supersymmetry

Fermion-Boson Symmetry
For every fermion there is a boson of equal mass and couplings and visa versa.
No new dimensionless couplings.
Couplings of SUSY particles equal to couplings of SM particles.
Helps stabilize the weak scale-Planck scale hierarchy.
Provides a good Dark Matter candidate (the lightest SUSY Particle).
Allows for gauge coupling unification.
Radiatively Induces electroweak symmetry breaking.
Higgs Mass

Dependence on MSSM Parameters
What does SUSY imply for the Higgs Sector?

- 2 Higgs $SU(2)$ doublets: $\phi_1$ and $\phi_2$
- 2 CP-even ($h, H$) with mixing angle $\alpha$.
- 1 CP-odd ($A$) and a charged pair $H^+$
- $\tan \beta = v_2/v_1$, $v^2 = v_1^2 + v_2^2 = 246$ GeV

- At tree level, one Higgs doublet couples only to down quarks and the other couples only to up quarks:

$$-L = \overline{\psi}_L \begin{pmatrix} h_+^i \phi_1 d^i_R + \hat{h}_u^i \phi_2 u^i_R \end{pmatrix} + h.c.$$  

- Up and down sectors diagonalized independently:
  - Higgs interactions remain flavor diagonal at tree-level.

- Couplings:
  - Gauge bosons and fermions (SM normalized)
    - $hZZ, hWW, ZHA, WH^\pm H \rightarrow \sin(\beta - \alpha)$
    - $HZZ, HWW, ZhA, WH^\pm h \rightarrow \cos(\beta - \alpha)$
    - $(h, H, A) u \bar{u} \rightarrow \cos \alpha / \sin \beta, \sin \alpha / \sin \beta, \ 1 / \tan \beta$
    - $(h, H, A) d \bar{d}/l^+l^- \rightarrow - \sin \alpha / \cos \beta, \cos \alpha / \cos \beta, \tan \beta$

- Lightest (SM-like) Higgs naturally light due to SUSY, $m_h \leq m_Z$.
- Others may be heavy and roughly degenerate (decoupling limit).
Radiative Corrections to the SM-like Higgs Boson Mass

- Important quantum corrections due to incomplete cancellation of particles and sparticles in loops.
- Main effect due to stops: 
  \[ X_t = A_t - \mu^* / \tan \beta \]

\[ M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + m_{\tilde{t}}^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_{\tilde{t}}^2 + D_R \end{pmatrix} \]

- For moderate to large values of \( \tan \beta \), large non-standard Higgs masses and 
  \( M_{\text{SUSY}} \sim m_Q \sim m_u \): 
  \[ m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_{\tilde{t}}^4}{v^2} \left[ \frac{1}{2} \tilde{X}_t + t + \frac{1}{16\pi^2} \left( \frac{3}{2} \frac{m_t^2}{v^2} - 32\pi\alpha_3 \right) (\tilde{X}_t t + t^2) \right] \]
  \[ t = \log \frac{M_{\text{SUSY}}^2}{m_{\tilde{t}}^2} \]
  \[ \tilde{A}_t = A_t - \mu \cot \beta \]
  \[ \tilde{X}_t = \frac{2\tilde{A}_t^2}{M_{\text{SUSY}}^2} \left( 1 - \frac{\tilde{A}_t^2}{12M_{\text{SUSY}}^2} \right) \]

- \( m_h \) depends logarithmically on averaged stop mass scale, \( M_{\text{SUSY}} \), and has a quadratic and quartic dependence on the stop mixing parameter, \( A_t \).
Standard Model-like Higgs Mass

- Long list of 2-loop computations:
  - Carena, Degrassi, Ellis, Espinoza, Haber, Harlander, Heinemeyer, Hempfling, Hoang, Hollik, Hahn, Martin, Pilaftsis, Quiros, Ridolfi, Rzehak, Slavich, Wagner, Weiglein, Zhang, Zwirner.

- 2-loop corrections: $m_h \leq 130$ GeV
  - $M_S = 1 - 2$ TeV, $\Delta m_h \sim 2 - 5$ GeV

- $m_h \sim 125$ GeV: Large $X_t$ and Moderate/Large $\tan \beta$

- $X_t = A_t - \mu / \tan \beta$, $X_t = 0$: No mixing; $X_t = \sqrt{6}M_S$: Max. Mixing

Carena and Haber, hep-ph/0208209
Contours of $A_t$ needed to obtain $124 \text{ GeV} < m_h < 126 \text{ GeV}$.

- Associated stop mass contours in black.

- Illustrates the requirement for large $A_t$.

- No hard lower bound for stop masses.
Cross-sections and Rates

Higgs Production Mechanisms at the LHC
The event rate depends on 3 quantities:

\[ B\sigma(p\bar{p} \rightarrow h \rightarrow X_{SM}) \equiv \sigma(p\bar{p} \rightarrow h) \frac{\Gamma(h \rightarrow X_{SM})}{\Gamma_{total}} \]

These may be affected by new physics.

If SM rate modified \( \Rightarrow \) total width is modified as well.

Particularly true for \( WW \) rate for high Higgs masses and for \( bb \) rate for low Higgs masses.
Mixing effects in CP-even Higgs Sector

Mixing can have very relevant effects on the production rates and decay branching ratios.

In most regions of parameter space, mixing effects conspire to enhance the branching ratio into $b\bar{b}$, thus suppressing the decay into photons and gauge bosons.

\[
\mathcal{M}_H^2 = \begin{bmatrix}
    m_A^2 \sin^2 \beta + M_Z^2 \cos^2 \beta & -(m_A^2 + M_Z^2) \sin \beta \cos \beta + \text{Loop}_{12} \\
    -(m_A^2 + M_Z^2) \sin \beta \cos \beta + \text{Loop}_{12} & m_A^2 \cos^2 \beta + M_Z^2 \sin^2 \beta + \text{Loop}_{22}
\end{bmatrix}
\]

\[
hWW : \quad \sin(\beta - \alpha),
\]
\[
h\bar{t}\bar{t} : \quad \frac{\cos \alpha}{\sin \beta},
\]
\[
hbb : \quad \frac{-\sin \alpha}{\cos \beta} \left[ 1 - \frac{\Delta h_b \tan \beta}{1 + \Delta h_b \tan \beta} \left( 1 + \frac{1}{\tan \alpha \tan \beta} \right) \right]
\]

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

\[
\cos(2\alpha) = \frac{(\mathcal{M}_H^2)_{11} - (\mathcal{M}_H^2)_{22}}{\sqrt{\text{Tr}[\mathcal{M}_H^2]^2 - \text{det}[\mathcal{M}_H^2]}}.
\]
$m_h \sim 125$ GeV: Squarks and the Di-Photon Production Rate

- **Gluon fusion:**
  - Receives contributions from $t\bar{b}$ and $\tilde{t}\tilde{b}$.
  - Light 3rd generation squarks can **increase** gluon fusion rate, but large mixing is required for $m_h$ masses of interest:
    - Leads to suppression.

- **Di-photon width:**
  - $W$ loop is partially suppressed by $t$ loop.
  - Light $\tilde{t}\tilde{b}$:
    - Can add to this suppression
    - Can produce enhancement if mixing large.
    - Usually overcompensated by suppression of gluon fusion.

\[
\sigma(gg \rightarrow h) BR(h \rightarrow \gamma\gamma) \leq \sigma(gg \rightarrow h)_{SM} BR(h \rightarrow \gamma\gamma)_{SM}
\]
The ratio of BR(h → b b) to its SM value, in the (mA, Aτ) plane.

- tan β = 60, m_{e3} = m_{L3} = 250 GeV.
- We fix m_{t1} = 90 GeV, hence μ varies in the range 500-550 GeV.
- Relevant squark parameters are A_t = 1.8 TeV, m_{Q3} = m_{u3} = 1.5 TeV corresponding to m_{t1,2} = 1.4, 1.6 TeV and m_h ~ 125 GeV.
- bb suppressed → γγ, ZZ/WW enhanced.

\[ \text{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2 \beta M_{\text{SUSY}}^2} \left[ \frac{A_t \tilde{A}_t}{M_{\text{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2 \beta \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_{\tau_1}^4 v^2}{48\pi^2} \sin^2 \beta \frac{\mu^3 A_\tau}{M_{\text{SUSY}}^4} . \]

\[ m_A, A_\tau \text{ and } BR(h \rightarrow bb) \]
Is it Possible to Enhance Di-Photon Rate Without Affecting the Higgs into WW and ZZ Rate?

- Higgs decay into photons proceeds via charged particle loops.
- Light \( \tilde{\tau} \) would have the same effect as light \( \tilde{t} \):
  - Enhancement for large mixing.
- Do not effect the gluon fusion rate.

\[
M_{\tau}^2 \simeq \begin{bmatrix}
  m_{L_3}^2 + m_{\tau}^2 + D_L & h_{\tau} \nu (A_\tau \cos \beta - \mu \sin \beta) \\
  h_{\tau} \nu (A_\tau \cos \beta - \mu \sin \beta) & m_{E_3}^2 + m_{\tau}^2 + D_R
\end{bmatrix}
\]

- Large mixing here means:
  - Large \( \mu \) and Large \( \tan \beta \)
Light staus with large mixing may induce relevant enhancement of the BR of the decay of a SM-like Higgs into two photons, without affecting other decays too much.

$A_\tau$ changes BR into $bb$, impacting $\gamma\gamma$, $WW$ and $ZZ$ together.

Dashed lines denote contours of stau masses.
ZZ Production Minimally Impacted

$m_A = 1$ TeV GeV, $A_T = 500$ GeV

\[
\frac{\sigma (gg \rightarrow h) \text{Br}(h \rightarrow ZZ)}{\sigma (gg \rightarrow h)^{SM} \text{Br}(h \rightarrow ZZ)^{SM}}
\]

\[
\mu \text{ (GeV)}
\]

\[
m_{L_3} \text{ (GeV)}
\]

$m_A = 1$ TeV GeV, $A_T = 500$ GeV

\[
\frac{\sigma (gg \rightarrow h) \text{Br}(h \rightarrow ZZ)}{\sigma (gg \rightarrow h)^{SM} \text{Br}(h \rightarrow ZZ)^{SM}}
\]

\[
m \text{ (GeV)}
\]

\[
m_{L_3} \text{ (GeV)}
\]
Top:
- $m_t \sim 140$ GeV
- $m_{Q3} \sim 2.5$ TeV
- $A_t \sim 2$ TeV
- $m_A \sim 1.5$ TeV

Right:
- $m_t \sim 500$ GeV
- $m_{Q3} \sim 1.5$ TeV
- $A_t \sim 1.4$ TeV
- $m_A \sim 1$ TeV

$\tan \beta = 60$ and $\mu$ such that light $m_{\tau} = 90$ GeV.

Carena, Gori, N.S., Wagner, Wang

**$\gamma\gamma$/ZZ Rates**

- $A_t = 1500$ GeV
- $A_t = 0$ GeV
- $A_t = -1500$ GeV
Electroweak Constraints

$m_W$ and $(g_\mu - 2)$
\( m_W = 80.385 \pm 0.015 \text{ GeV} \)

- \( m_{L_3} = m_{e_3} \),
- \( \mu > 500 \text{ GeV} \).
- \( m_{L_3} \) and \( m_{e_3} \) \( \sim \) few hundred GeV,
- \( m_{L_3} < m_{e_3} \).
$2 \times 10^{-9} < \frac{(g_\mu-2)}{2} < 4 \times 10^{-9}$

$m_{L^2} \sim m_{e^2} \sim 500 \text{ GeV}$
Dark Matter

LSP-NLSP Co-annihilation
Neutralino LSP and stau NLSP

\[ m_\tau \sim 90 \text{ GeV} \Rightarrow m_{\chi_1} \sim 30 - 40 \text{ GeV} \]
Messenger Scale
Light Sleptons

Assuming
- Flavor blindness
- 1\textsuperscript{st}/2\textsuperscript{nd} and 3\textsuperscript{rd} generations light at TeV scale
  - 3\textsuperscript{rd} generation sleptons run strongly with Yukawas
  - Yukawas scaled by tan $\beta$
  - 1\textsuperscript{st}/2\textsuperscript{nd} generation barely affected by running.

Large tan $\beta$ and Low Messenger scale

OR

Moderate tan $\beta$ and High Messenger scale $\sim M_{\text{GUT}}$
Running of $m_L$ with scale, $t = \log(Q / m_Z)$

(a): $M \simeq 10^7$ GeV, $\tan \beta = 60$

$m_e$ runs similarly

$m_{L3}$ running $>> m_{L2}/m_{L1}$ running.

$m_{L2}$ (TeV) $\sim m_{L2}$ (M)

(b): $M \simeq 10^{16}$ GeV

FLAVOR BLINDNESS

Large $\tan \beta$:
small $m_{L2}$ forces low unification scale.

Lowering $\tan \beta$:
reduces running of $m_{L3}$
Can have unification at $\sim M_{GUT}$
Collider Prospects

Preliminary Results for Light Staus

June 8, 2012
Nausheen R. Shah
PLHC2012
Probing Light Staus:
Direct weak production of a \textit{stau + tau sneutrino} through the s-channel exchange of a $W$.

- Quite model independent:
  - Depends only on masses and mixings of staus and sneutrinos.
  - Would be open even in scenario with very heavy squarks/gluinos.

- Typical signature:
  - Multi-taus,
  - Missing energy and
  - Weak gauge bosons, giving rise to additional leptons.

- We used parton level results from Madgraph 5.

- A more realistic simulation should include:
  - Parton showering,
  - Hadronization, and
  - Detector simulation.

- Properly matched matrix element + parton shower simulation particularly important for estimation of $W+jets$ background.

- However, our analysis sufficient to obtain a rough order of magnitude estimate of the discovery reach.
Current LHC Search Status

- Final states containing taus, leptons, hard jets and large missing energy, arising from (relatively light) squarks/gluinos decaying directly or through cascades into the stau NLSP.
- This channel complementary to the ones we investigate, but more model dependent.
- Final states similar to the ones we analyze have been investigated in the context of searches for charginos and neutralinos.
- Comparing the cross sections of the LHC searches, we note that the multilepton searches are still not sensitive to our scenario.

Most stringent constraint on the stau mass given by LEP bound ~ 85-90 GeV for the case of the split stau-neutralino spectrum.
\[ m_{L3} = m_{e3} = 280 \text{ GeV}, \tan \beta = 60, \ \mu = 650 \text{ GeV}, M_1 = 35 \text{ GeV}, \]
giving a light stau, \( m_{\tilde{\tau}_1} \sim 95 \text{ GeV}, \) a very light LSP, \( m_{\chi_1} \sim 35 \text{ GeV} \) and a light sneutrino, \( m_{\nu_\tau} \sim 270 \text{ GeV} \) for 8 TeV LHC.

\[ pp \rightarrow \tilde{\tau}_1 \tilde{\nu}_{\tau} \rightarrow \tilde{\tau}_1 (W \tilde{\tau}_1) \rightarrow \tau \chi_1 W \tau \chi_1 \]

- \( \tilde{\tau}_1 \tilde{\tau}_1 \) production overwhelmed by background.

- Better situation: \( \tilde{\tau}_1 \nu_{\tau} \) with leptonically decaying \( W. \)

- 2 loose \( \tau \) tags:
  - 60% \( \tau \) identification
  - Jet Background rejection factor: 20-50

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<tr>
<td>Signal</td>
<td>1.6</td>
<td>0.26</td>
<td>0.11</td>
</tr>
<tr>
<td>Physical background, ( W + Z/\gamma^* )</td>
<td>27</td>
<td>0.32</td>
<td>( \lesssim 10^{-3} )</td>
</tr>
<tr>
<td>( W + ) jets background</td>
<td>( 10^4 )</td>
<td>39</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Cross sections for the signal and the physical and fake background after \( \tau \)-tags at the 14 TeV LHC: after imposing \( p_T^{\tau(j)} > 10 \text{ GeV}, \Delta R > 0.4 \) and and \( |\eta| < 2.5 \) (second column); with the additional requirement \( p_T^{\ell} > 85 \text{ GeV} \) and \( E_T > 85 \) (third column); imposing that the \( \tau \) is not too boosted \( p_T^{\tau} < 80 \text{ GeV} \) (fourth column).

Similar cuts for 14 TeV LHC:
Can get \( S/B \sim 1 \) with \( \sigma \sim 1 \text{ fb} \) (low statistics).
Conclusions and Outlook

- 125 GeV Higgs boson mass consistent with stops ~ 1 TeV and **large stop mixing**: 
  - No hard bound on the lightest stop mass.

- Rates may be modified by mixing or by light sfermions.
  - Stops tend to slightly suppress the photon rate.
  - **Light staus.**
    - Large \( \mu \tan \beta \) can enhance diphoton rate without modifying other rates in a significant way
    - Suppression of the bottom quark rates \((m_A, A_t)\).
    - Further enhancement of the photon rate.
    - Less dramatic enhancement of the \(WW\) and \(ZZ\) rates.

- EWPT combined with recent Higgs results favor light sleptons for all generations:
  - Either large \( \tan \beta \) with low messenger scale or moderate \( \tan \beta \) with high messenger scale.

- Collider prospects for **light staus**
  - Low statistics
  - Can get \( S/B \sim 1 \) with \( \sigma \sim 1 \text{ fb} \) => high luminosity LHC can have \( \sim \text{tens of events} \).
Backup Slides
We are living in very interesting times: A light SM-like Higgs is beginning to be probed by present data.

Excluded at 95% CL

**CMS:**
- 127.5-600 GeV

**ATLAS:**
- 110-117.5 GeV
- 118.5-122.5 GeV
- 129-539 GeV
Allowed region also overlaps with region preferred by SM Precision Electroweak Data
If the Higgs is SM-like, mass range between ~ 115 – 130 GeV is preferred both from direct searches as well as from indirect precision tests.

Interesting excess in the region of the Higgs masses close to 125 GeV.

June 8, 2012
Nausheen R. Shah
PLHC2012
Additional Affects at Large $\tan \beta$

Sbottoms:  \[ \Delta m^2_{h_b} \simeq -\frac{h^4_b v^2}{16\pi^2} \frac{\mu^4}{M^4_{\text{SUSY}}} \left( 1 + \frac{t}{16\pi^2} \left( 9h^2_b - 5 \frac{m^2_t}{v^2} - 64\pi\alpha_3 \right) \right) \]

$h_b$ receives 1-loop corrections that depend on sign of $\mu M_{\tilde{g}}$

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

Staus:  \[ \Delta m^2_{h_{\tau}} \simeq -\frac{h^4_{\tau} v^2}{48\pi^2} \frac{\mu^4}{M^4_{\tilde{\tau}}} \]

$h_{\tau}$ corrections depend on the sign of $\mu M_2$

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

Both corrections give negative contributions to the Higgs mass

Positive values of $\mu M_{\tilde{g}}$ and $\mu M_2$ enhance the value of the Higgs mass.
Contour plots of Higgs and stop masses in $m_{Q_3}$-$m_{\tilde{u}_3}$ plane, for two values of $A_t$ and $\tan \beta$.

- Lightest stau mass is $\sim 135$ GeV for $\tan \beta = 60$.
- Large splitting: heaviest stop mass is of the order of the heaviest soft stop parameter.
- Light stop $\sim 100$ GeV can be obtained.
- No hard lower bound on the stop mass.

Large value of $A_t \sim 1.5$ TeV always necessary to achieve $m_h \sim 123 - 127$ GeV.

Larger for larger $\tan \beta$ to compensate for the negative corrections from the sbottom/staus.
Intermediate $\tan \beta$ leads to largest $m_h$ for same values of soft stop mass parameters.

Gain in tree-level Higgs mass from moving $\tan \beta$ from 5 to 60 compensated by the negative stau effects.

In case of degenerate soft masses,

- $A_t$ above $\sim 1.5$ TeV needed to achieve $m_h \sim 125$ GeV.
- The lightest stop mass is naturally above $\sim 500$ GeV.
Sleptons

- Moderate values of $\tan \beta$ and small stau mixing:
- Light $\tilde{\tau}$ tend to induce slight suppression in $\gamma\gamma$ production:

\[ A_t = 2.5 \text{ TeV, } \tan \beta = 10 \]

\[ \frac{\sigma(gg \rightarrow h) \text{ Br}(h \rightarrow \gamma\gamma)}{\sigma(gg \rightarrow h)_{\text{SM}} \text{ Br}(h \rightarrow \gamma\gamma)_{\text{SM}}} \]

Carena, Gori, N.S., Wagner
Higgs mixing effects depend relevantly on $A_\tau$ for $m_A \sim < 1$ TeV

- $\tan \beta = 60$;  $A_\tau = 1500$ GeV;  $m_A = 700$ GeV;  $\mu = 1030$ GeV;
- $m_{e3} = m_{L3} = 340$ GeV
- $m_{\tau} = 106$ GeV

**CONSEQUENCE**

- Further enhancement of $\gamma\gamma$ and also $WW$ and $ZZ$!

\[
\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{SM}} \cdot \frac{BR(h \to \gamma\gamma)}{BR(h \to \gamma\gamma)_{SM}} = 1.96
\]
\[
\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{SM}} \cdot \frac{BR(h \to VV^*)}{BR(h \to VV^*)_{SM}} = 1.25 \quad (V = W, Z)
\]
Figure 9: $p_T$ distribution for the leading jet faking a tau of the $W+$ jets background (in blue) and for the leading tau of the signal (black dashed) at the 8 TeV LHC. The events shown satisfy the basic set of cuts ($p_T^\ell > 70$ GeV and $\not E_T > 70$ GeV). The signal has been scaled by a factor of 100 for visibility.
<table>
<thead>
<tr>
<th>Signature</th>
<th>8 TeV LHC (fb)</th>
<th>14 TeV LHC (fb)</th>
</tr>
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<tbody>
<tr>
<td>$pp \rightarrow \tilde{\tau}_1 \tilde{\tau}_1$</td>
<td>2$\tau$, $E_T$</td>
<td>55.3</td>
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<td>2$\tau$, 2$W$, $E_T$</td>
<td>1.6</td>
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**Table 1:** Possible stau and sneutrino direct production channels with their signatures at the LHC. The cross sections shown are computed for $m_{L3} = m_{e3} = 280$ GeV, $\tan \beta = 60$, $\mu = 650$ GeV and $M_1 = 35$ GeV.

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<td>Physical background, $W + Z/\gamma^*$</td>
<td>0.6</td>
<td>0.16</td>
<td>0.07</td>
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<tr>
<td>$W$ + jets background</td>
<td>$4 \times 10^3$</td>
<td>26</td>
<td>0.3</td>
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**Table 2:** Cross sections for the signal and the physical and fake backgrounds after $\tau$-tags at the 8 TeV LHC: after imposing acceptance cuts $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^{\ell} > 70$ GeV and $E_T > 70$ (third column); imposing that the $\tau$ is not too boosted $p_T^\tau < 75$ GeV (fourth column).

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**Table 3:** Cross sections for the signal and the physical and fake background after $\tau$-tags at the 14 TeV LHC: after imposing $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^{\ell} > 85$ GeV and $E_T > 85$ (third column); imposing that the $\tau$ is not too boosted $p_T^\tau < 80$ GeV (fourth column).
Atlas results zoomed in the Low Mass region

We observe an excess of events around $m_H \sim 126$ GeV:

- local significance $3.6 \sigma$, with contributions from the $H \rightarrow \gamma\gamma$ ($2.8 \sigma$), $H \rightarrow ZZ^* \rightarrow 4l$ ($2.1 \sigma$), $H \rightarrow WW^* \rightarrow l\nu l\nu$ ($1.4 \sigma$) analyses
- SM Higgs expectation: $2.4 \sigma$ local \rightarrow observed excess compatible with signal strength within $+1\sigma$
- the global significance (taking into account Look-Elsewhere-Effect) is $\sim 2.3 \sigma$
For large values of $\mu$ and $A_t$ one can get suppression of the Higgs decay into bottom quarks and therefore enhancement of photon decay branching ratio.

Carena, Mrenna, Wagner'99
Carena, Heinemeyer, Wagner, Weiglein'02

Such scenario, however, demands small values of the the CP-odd Higgs mass and large tan\beta and seems to be in conflict with non-standard Higgs boson searches.

Carena, Draper, Liu, Wagner'11
Results did not change significantly with the datea update. Interestingly, the observed limit is somewhat weaker than the expected one.
Loop induced gluon and gamma widths

\[
\Gamma_{H \rightarrow gg} = \frac{G_\mu \alpha_s^2 m_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_f A_f(\tau_f) \right|^2
\]

\[
\Gamma_{H \rightarrow \gamma\gamma} = \frac{G_\mu \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 A_f(\tau_f) + A_W(\tau_W) \right|^2
\]

\[
A_f(\tau) = 2 \left[ \tau + (\tau - 1)f(\tau) \right] \tau^{-2}
\]

\[
A_W(\tau) = - \left[ 2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau) \right] \tau^{-2}
\]

\[
f(\tau) = \begin{cases} 
\arcsin^2 \sqrt{\tau} & \tau \leq 1 \\
-\frac{1}{4} \left[ \ln \frac{1 + \sqrt{1 - \tau^{-1}}}{1 - \sqrt{1 - \tau^{-1}}} - i\pi \right]^2 & \tau > 1
\end{cases}
\]
Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to both Higgs fields arise after radiative corrections.

\[ \mathcal{L} = \bar{d}_L (h_d H_1^0 + \Delta h_d H_2^0) d_R \]

- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

\[
\frac{\Delta_b}{\tan \beta} = \frac{\Delta h_b}{h_b} \approx \frac{2 \alpha_s}{3 \pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_1}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16 \pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_1}^2, \mu^2)}
\]

\[ X_t = A_t - \mu / \tan \beta \approx A_t \quad \Delta_b = (E_g + E_t h_t^2) \tan \beta \]

Resummation: Carena, Garcia, Nierste, C.W.'00