On the way to Maroon Lake
The reward was/is the same for all.
The first paper with Howie: "Heavy Particle Production At The Ssc" S. J. Brodsky, H. E. Haber and J. F. Gunion. (Mar 1984)


The book:
find a gunion and a haber - Search Results - INSPIRE-HEP

Citations summary

Generated on 2013-01-05

66 papers found, 45 of them citeable (published or arXiv)

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Breakdown of papers by citations:
- Renowned papers (500+): 3
- Famous papers (250-499): 5
- Very well-known papers (100-249): 13
- Well-known papers (50-99): 9
- Known papers (10-49): 2
- Less known papers (1-9): 4
- Unknown papers (0): 2

\[ h_{\text{HEP}} \text{ index} \]

32

See additional metrics

Exclude self-citations or RPP

Warning: The citation search should be used and interpreted with great care. Read the fine print
## Citations summary

Generated on 2013-01-05

35 papers found, 29 of them citeable (published or arXiv)

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**Breakdown of papers by citations:**

- Renowned papers (500+): 2
- Famous papers (250-499): 3
- Very well-known papers (100-249): 6
- Well-known papers (50-99): 9
- Known papers (10-49): 6
- Less known papers (1-9): 3
- Unknown papers (0): 0

**h<sub>HEP</sub> index**: 22

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**Warning:** The citation search should be used and interpreted with great care. [Read the fine print](http://inspirehep.net/search?ln=en&ln=en&p=find+a+gunion+a...).
Determining the nature of the 126 GeV ‘Higgs’ signal

Jack Gunion
U.C. Davis

The Search for Fundamental Physics: Higgs Bosons & Supersymmetry, January, 6 2013


2HDM Collaborators: Alexandra Drozd, Bohdan Grzadkowski, Yun Jiang

Higgs couplings Collaborators: Belanger, Beranger, Ellwanger, Kraml

Higgs-like LHC Excesses at $125 - 126$ GeV

- Experimental Higgs-like excesses: define

$$R_Y^h(X) = \frac{\sigma(pp \rightarrow Y \rightarrow h)\text{BR}(h \rightarrow X)}{\sigma(pp \rightarrow Y \rightarrow h_{SM})\text{BR}(h_{SM} \rightarrow X)} , \quad R^h(X) = \sum_Y R_Y^h , \quad (1)$$

where $Y = gg, VV, Vh$ or $t\bar{t}h$. The notation $\mu \equiv R$ is sometimes employed.

Experimental results are now available for many channels, where the experimental channel is usually a mixture of the theoretical channels.

$$\mu_k = \sum T_k^i \hat{\mu}_i , \quad (2)$$

where the $T_k^i$ give the amount of contribution to the experimental channel $k$ coming from the theoretically defined channel $i$ and $\hat{\mu}_i$ is the prediction for a given theoretical channel. The observed $\mu_k$ values and $T_k^i$ values are summarized in the following tables.
<table>
<thead>
<tr>
<th>Channel</th>
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<th>$m_H$ (GeV)</th>
<th>Production mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$ (4.8 fb$^{-1}$ at 7 TeV + 13.0 fb$^{-1}$ at 8 TeV)</td>
<td>$\mu$ (ggF + ttH, $\gamma\gamma$)</td>
<td>$1.85 \pm 0.52$</td>
<td>126.6</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$ (4.8 fb$^{-1}$ at 7 TeV + 13.0 fb$^{-1}$ at 8 TeV)</td>
<td>$\mu$ (VBF + VH, $\gamma\gamma$)</td>
<td>$2.01 \pm 1.23$</td>
<td>126.6</td>
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<tr>
<td>$H \rightarrow ZZ$ (4.6 fb$^{-1}$ at 7 TeV + 13.0 fb$^{-1}$ at 8 TeV)</td>
<td>Inclusive</td>
<td>$1.01^{+0.45}<em>{-0.40} \rightarrow 0.97^{+0.45}</em>{-0.40}$</td>
<td>125</td>
</tr>
<tr>
<td>$H \rightarrow WW$ (13.0 fb$^{-1}$ at 8 TeV)</td>
<td>$\mu$ (ggF, $\tau\tau$)</td>
<td>$2.41 \pm 1.57$</td>
<td>125</td>
</tr>
<tr>
<td>$H \rightarrow WW$ (13.0 fb$^{-1}$ at 8 TeV)</td>
<td>$\mu$ (VBF + VH, $\tau\tau$)</td>
<td>$-0.26 \pm 1.02$</td>
<td>125</td>
</tr>
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</table>

Table 1: ATLAS results as employed in this analysis. The correlations included in the fits are $\rho = -0.37$ for the $\gamma\gamma$ and $\rho = -0.50$ for the $\tau\tau$ channels.
<table>
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<td></td>
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<td>$H \to \gamma\gamma$ (5.1 fb$^{-1}$ at 7 TeV + 5.3 fb$^{-1}$ at 8 TeV) [?, ?, ?]</td>
<td>$\mu$(ggF + ttH, $\gamma\gamma$)</td>
<td>$0.95 \pm 0.65$</td>
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<td></td>
<td>$\mu$(VBF + VH, $\gamma\gamma$)</td>
<td>$3.77 \pm 1.75$</td>
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<td>$H \to ZZ$ (up to 4.9 fb$^{-1}$ at 7 TeV + 12.1 fb$^{-1}$ at 8 TeV) [?, ?, ?]</td>
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<td>$0.81^{+0.35}_{-0.28}$</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>VH tag</td>
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</tr>
<tr>
<td>$H \to b\bar{b}$ (up to 5.0 fb$^{-1}$ at 7 TeV + 12.1 fb$^{-1}$ at 8 TeV) [?, ?, ?]</td>
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<td>$1.31^{+0.65}_{-0.60}$</td>
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<tr>
<td></td>
<td>ttH tag</td>
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<td>$H \to \tau\tau$ (up to 5.0 fb$^{-1}$ at 7 TeV + 12.1 fb$^{-1}$ at 8 TeV) [?, ?, ?]</td>
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<td>VBF tag</td>
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<td></td>
<td>VH tag</td>
<td>$0.86^{+1.92}_{-1.68}$</td>
<td>125.8</td>
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Table 2: CMS results as employed in this analysis. The correlation included for the $\gamma\gamma$ channel is $\rho = -0.54$. 

J. Gunion, The Search for Fundamental Physics: Higgs Bosons & Supersymmetry, January, 6 2013
<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal strength $\mu$</th>
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<th>Production mode</th>
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<td>$H \rightarrow WW$</td>
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<td>-</td>
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<tr>
<td>$H \rightarrow bb$</td>
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<td></td>
<td>-</td>
<td>-</td>
<td>100%</td>
<td>-</td>
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Table 3: Tevatron results for up to $10\text{ fb}^{-1}$ at $\sqrt{s} = 1.96$ TeV, as employed in this analysis.

Note: general enhancement of $\gamma\gamma$ final states in both ggF (not CMS) and especially VBF.

Note: $R(ZZ,WW) \gtrsim 1$ for ATLAS, whereas $R(ZZ,WW) < 1$ for CMS.

- **The big questions:**
  1. If the deviations from a single SM Higgs survive what is the model?
  2. If they do survive, how far beyond the "standard" model must we go to describe them?
Suppose the signal derives from just one Higgs boson — we assume $0^+$.  

The structure we will test is

$$\mathcal{L} = g \left[ C_V \left( m_W W_\mu W^\mu + \frac{m_Z}{\cos \theta_W} Z_\mu Z^\mu \right) 
- C_U \frac{m_t}{2m_W} \bar{t}t - C_D \frac{m_b}{2m_W} \bar{b}b 
- C_D \frac{m_{\tau}}{2m_W} \bar{\tau}\tau \right] H. \ (3)$$

In general, the $C_I$ can take on negative as well as positive values; there is one overall sign ambiguity which we fix by taking $C_V > 0$.  

We will be fitting the data given earlier.  

In addition to the tree-level couplings given above, the $H$ has couplings to $gg$ and $\gamma\gamma$ that are first induced at one loop and
are completely computable in terms of $C_U$, $C_D$ and $C_V$ if only loops containing SM particles are present. We define $\bar{C}_g$ and $\bar{C}_\gamma$ to be the ratio of these couplings so computed to the SM (i.e. $C_U = C_D = C_V = 1$) values.

- However, in some of our fits we will also allow for additional loop contributions $\Delta C_g$ and $\Delta C_\gamma$ from new particles; in this case $C_g = \bar{C}_g + \Delta C_g$ and $C_\gamma = \bar{C}_\gamma + \Delta C_\gamma$.

- The largest set of independent parameters in our fits is thus

$$C_U, \ C_D, \ C_V, \ \Delta C_g, \ \Delta C_\gamma.$$  (4)
Fit I: $C_U = C_D = C_V = 1$, $\Delta C_g$ and $\Delta C_{\gamma}$ free.

Figure 1: Two parameter fit of $\Delta C_{\gamma}$ and $\Delta C_g$, assuming $C_U = C_D = C_V = 1$ (Fit I). The red, orange and yellow ellipses show the 68%, 95% and 99.7% CL regions, respectively. The white star marks the best-fit point $\Delta C_{\gamma} = 0.426$, $\Delta C_g = -0.086$. It has $\chi^2 = 12.3$ vs. SM $\chi^2 = 20.2$. i.e. SM is $\sim 2\sigma$ worse.
● Fit II: varying $C_U$, $C_D$, and $C_V$ ($\Delta C_\gamma = \Delta C_g = 0$)

![Graphs showing two-dimensional $\chi^2$ distributions for $C_U$, $C_D$, $C_V$ with $C_\gamma = C_\gamma$ and $C_g = C_g$ as computed in terms of $C_U$, $C_D$, $C_V$. Details on the minima in different sectors of the ($C_U$, $C_D$) plane can be found in Table 5. Note strong preference for negative $C_U = -1$ ($\gamma\gamma$ $t$-loop adds to $W$ loop). Negative $C_U$ is hard in most models. But, $\chi^2 = 11.6$ is much better than for SM.]

Figure 2: Two-dimensional $\chi^2$ distributions for the three parameter fit, Fit II, of $C_U$, $C_D$, $C_V$ with $C_\gamma = C_\gamma$ and $C_g = C_g$ as computed in terms of $C_U$, $C_D$, $C_V$. Details on the minima in different sectors of the ($C_U$, $C_D$) plane can be found in Table 5. Note strong preference for negative $C_U = -1$ ($\gamma\gamma$ $t$-loop adds to $W$ loop). Negative $C_U$ is hard in most models. But, $\chi^2 = 11.6$ is much better than for SM.
Fit II: varying $C_U$, $C_D$ and $C_V$ ($\Delta C_\gamma = \Delta C_g = 0$) requiring $C_U, C_D > 0$ (and $C_V > 0$ by convention)

Figure 3: Two-dimensional $\chi^2$ distributions for the three parameter fit, Fit II, as in Fig. 2 but with $C_U > 0$, $C_D > 0$, $C_V > 0$. The upper row of plots allows for $C_V > 1$, while in the lower row of plots $C_V \leq 1$ is imposed. The best fit point has $\chi^2 = 18.66$, a value that is not much lower than that for the SM.
Fit III: varying $C_U$, $C_D$, $C_V$, $\Delta C_\gamma$ and $\Delta C_g$

Figure 4: Two-dimensional distributions for the five parameter fit of $C_U$, $C_D$, $C_V$, $\Delta C_\gamma$ and $\Delta C_g$ (Fit III). Details regarding the best fit point are given in Table 4. Note from top middle plot how $\Delta C_g$ can be traded for $C_U$. 

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J. Gunion, The Search for Fundamental Physics: Higgs Bosons & Supersymmetry, January, 6 2013 12
<table>
<thead>
<tr>
<th>Fit</th>
<th>I</th>
<th>II</th>
<th>III, 1st min.</th>
<th>III, 2nd min.</th>
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<tr>
<td>$C_U$</td>
<td>1</td>
<td>$-0.864^{+0.142}_{-0.163}$</td>
<td>$-0.06 \pm 1.3$</td>
<td>$0.06 \pm 1.3$</td>
</tr>
<tr>
<td>$C_D$</td>
<td>1</td>
<td>$0.991^{+0.277}_{-0.261}$</td>
<td>$0.996^{+0.284}_{-0.264}$</td>
<td>$-0.996^{+0.263}_{-0.284}$</td>
</tr>
<tr>
<td>$C_V$</td>
<td>1</td>
<td>$0.947^{+0.119}_{-0.132}$</td>
<td>$0.934^{+0.124}_{-0.140}$</td>
<td>$0.934^{+0.124}_{-0.140}$</td>
</tr>
<tr>
<td>$\Delta C_{\gamma}$</td>
<td>$0.426^{+0.167}_{-0.157}$</td>
<td>$1.431^{+0.165}_{-0.173}$</td>
<td>$1.364^{+0.263}_{-0.225}$</td>
<td>$1.364^{+0.263}_{-0.225}$</td>
</tr>
<tr>
<td>$\Delta C_g$</td>
<td>$-0.086^{+0.102}_{-0.103}$</td>
<td>$0.918^{+0.173}_{-0.153}$</td>
<td>$0.948^{+0.26}_{-0.23}$</td>
<td>$0.948^{+0.26}_{-0.23}$</td>
</tr>
<tr>
<td>$C_{\gamma}$</td>
<td>$1.426^{+0.167}_{-0.157}$</td>
<td>$1.431^{+0.165}_{-0.173}$</td>
<td>$1.364^{+0.263}_{-0.225}$</td>
<td>$1.364^{+0.263}_{-0.225}$</td>
</tr>
<tr>
<td>$C_g$</td>
<td>$0.914^{+0.102}_{-0.103}$</td>
<td>$0.918^{+0.173}_{-0.153}$</td>
<td>$0.948^{+0.26}_{-0.23}$</td>
<td>$0.948^{+0.26}_{-0.23}$</td>
</tr>
<tr>
<td>$\chi^2_{\text{min}}$</td>
<td>12.31</td>
<td>11.95</td>
<td>11.46</td>
<td>11.46</td>
</tr>
<tr>
<td>$\chi^2_{\text{min}}/\text{d.o.f.}$</td>
<td>0.648</td>
<td>0.664</td>
<td>0.716</td>
<td>0.716</td>
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Table 4: Summary of results for Fits I–III. For Fit II, the tabulated results are from the best fit, cf. column 1 of Table 5.
<table>
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<th>Sector</th>
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<th>$C_U, C_D &lt; 0$</th>
<th>$C_U, C_D &gt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_U$</td>
<td>$-0.864^{+0.142}_{-0.163}$</td>
<td>$-0.911^{+0.150}_{-0.171}$</td>
<td>$0.847^{+0.152}_{-0.133}$</td>
</tr>
<tr>
<td>$C_D$</td>
<td>$0.991^{+0.277}_{-0.261}$</td>
<td>$-0.980^{+0.258}_{-0.273}$</td>
<td>$0.851^{+0.221}_{-0.213}$</td>
</tr>
<tr>
<td>$C_V$</td>
<td>$0.947^{+0.120}_{-0.132}$</td>
<td>$0.943^{+0.119}_{-0.133}$</td>
<td>$1.055^{+0.109}_{-0.118}$</td>
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<tr>
<td>$C_\gamma$</td>
<td>$1.431^{+0.165}_{-0.173}$</td>
<td>$1.425^{+0.163}_{-0.173}$</td>
<td>$1.110^{+0.145}_{-0.159}$</td>
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<tr>
<td>$C_g$</td>
<td>$0.918^{+0.173}_{-0.153}$</td>
<td>$0.909^{+0.168}_{-0.150}$</td>
<td>$0.847^{+0.159}_{-0.128}$</td>
</tr>
</tbody>
</table>

$\chi^2_{\text{min}}$ | 11.95 | 12.06 | 18.66 |

$\chi^2_{\text{min}}$/d.o.f. | 0.66 | 0.67 | 1.04 |

**Table 5:** Results for Fit II in different sectors of the $(C_U, C_D)$ plane.
Figure 5: Graphical representation of the best fit values for $C_U$, $C_D$, $C_V$, $\Delta C_{\gamma}$ and $\Delta C_g$ of Table 4. The labels refer to the fits discussed in the text. The dashed lines indicate the SM value for the given quantity. The $\times$'s indicate cases where the parameter in question was fixed to its SM value. If the $\gamma\gamma$ mode excesses persist, it would appear necessary to have $C_{\gamma} \sim 1.4$ by some means or other ($C_U$ negative with $\Delta C_{\gamma}$ small, or $C_U$ normal with $\Delta C_{\gamma} \sim 0.4$.) Note that $C_g \sim 1$ and $C_V \sim 1$ for all fits.
Impact on Two-Higgs-Doublet Models

- Only $\alpha$ and $\beta$ needed to describe a single Higgs. So good fit is not exactly guaranteed.

Figure 6: 2HDM fits for the $h$ in the Type I (left) and Type II (right) models. Note: $\beta - \pi/2 = \alpha - 2\pi$ is SM limit. Fit is far from SM limit and requires small $\tan \beta$, the latter being problematical for perturbativity of top-quark coupling. If we require $\tan \beta > 1$, must move to ‘long valley’ which is near SM-like limit and has much higher $\chi^2$. 
Summary of Fitting Results

Best $\chi^2$’s are achieved pretty far from SM limit and would have to involve exotic parameters. Only cure: light charged Higgs, but then other constraints become a problem.
Enhanced Higgs signals in the NMSSM

- NMSSM = MSSM + $\hat{S}$.
- The extra complex $S$ component of $\hat{S}$ ⇒ the NMSSM has $h_1, h_2, a_1, a_2$.
- The new NMSSM parameters of the superpotential ($\lambda$ and $\kappa$) and scalar potential ($A_\lambda$ and $A_\kappa$) appear as:

$$ W \ni \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{\kappa}{3} \hat{S}^3, \quad V_{\text{soft}} \ni \lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 \quad (5) $$

- $\langle S \rangle \neq 0$ is generated by SUSY breakng and solves $\mu$ problem:

$$ \mu_{\text{eff}} = \lambda \langle S \rangle. $$

- First question: Can the NMSSM give a Higgs mass as large as 125 GeV?

**Answer:** Yes, so long as it is not a highly unified model. For our studies, we employed universal $m_0$, except for NUHM ($m_{H_u}^2$,
Can this model achieve rates in $\gamma \gamma$ and $4\ell$ that are $>\text{SM}$? Answer: it depends on whether or not we insist on getting good $a_\mu$.  

The possible mechanism (arXiv:1112.3548, Ellwanger) is to reduce the $b \bar{b}$ width of the mainly SM-like Higgs by giving it some singlet component. The $gg$ and $\gamma \gamma$ couplings are less affected.  

Typically, this requires $m_{h_1}$ and $m_{h_2}$ to have similar masses (for singlet-doublet mixing) and large $\lambda$ (to enhance Higgs mass). Large $\lambda$ (by which we mean $\lambda > 0.1$) is only possible while retaining perturbativity up to $m_{Pl}$ if $\tan \beta$ is modest in size. In the semi-unified model we employ, enhanced rates and/or large $\lambda$ cannot be made consistent with decent $\delta a_\mu$. (J. F. Gunion, Y. Jiang and S. Kraml.arXiv:1201.0982 [hep-ph])
• The "enhanced" SM-like Higgs can be either $h_1$ or $h_2$.

$$R_{gg}^{h_i}(X) \equiv (C_{gg}^{h_i})^2 \frac{\text{BR}(h_i \rightarrow X)}{\text{BR}(h_{SM} \rightarrow X)}, \quad R_{VBF}^{h_i}(X) \equiv (C_{VV}^{h_i})^2 \frac{\text{BR}(h_i \rightarrow X)}{\text{BR}(h_{SM} \rightarrow X)}, \quad (6)$$

where $h_i$ is the $i^{th}$ NMSSM scalar Higgs, and $h_{SM}$ is the SM Higgs boson. $C_{Y}^{h_i} = g_Y h_i / g_Y h_{SM}$ and $R_{Vh}$ for $V^* \rightarrow V h_i$ ($V = W, Z$) with $h_i \rightarrow X$ is equal to $R_{VBF}^{h_i}(X)$ in doublets + singlets models.

Figure 7: The plot shows $R_{gg}(\gamma\gamma)$ for the cases of $123 < m_{h_1} < 128$ GeV and $123 < m_{h_2} < 128$ GeV. Note: red triangle (orange square) is for WMAP window with $R_{gg}(\gamma\gamma) > 1.2$ ($R_{gg}(\gamma\gamma) = [1, 1.2]$).
Figure 8: Observe the clear general increase in maximum $R_{gg}(\gamma\gamma)$ with increasing $\lambda$. Green points have good $\delta a_\mu$, $m_{h_2} > 1$ TeV BUT $R_{gg}(\gamma\gamma) \sim 1$.

Figure 9: The lightest stop has mass $\sim 300 - 700$ GeV for red-triangle points.
• If we ignore $\delta a_\mu$, then $R_{gg}(\gamma\gamma) > 1.2$ (even $> 2$) is possible while satisfying all other constraints provided $h_1$ and $h_2$ are close in mass, especially in the case where $m_{h_2} \in [123, 128]$ GeV window.

• This raises the issue of scenarios in which both $m_{h_1}$ and $m_{h_2}$ are in the $[123, 128]$ GeV window where the experiments see the Higgs signal.

Supporting reasons:

- If $h_1$ and $h_2$ are sufficiently degenerate, the experimentalists might not have resolved the two distinct peaks, even in the $\gamma\gamma$ channel.
- The rates for the $h_1$ and $h_2$ could then add together to give an enhanced $\gamma\gamma$, for example, signal.
- The apparent width or shape of the $\gamma\gamma$ mass distribution could be altered.
- There is more room for an apparent mismatch between the
\( \gamma \gamma \) channel and other channels, such as \( b\bar{b} \) or \( 4\ell \), than in non-degenerate situation.

In particular, the \( h_1 \) and \( h_2 \) will generally have different \( gg \) and \( VV \) production rates and branching ratios.

- The general coupling analysis suggests that suppressing the \( VV \) coupling and the \( b\bar{b} \) coupling through mixing does not provide a wonderful fit if only one of the \( h_1 \) or \( h_2 \) is identified as the 126 GeV resonance.
Degenerate NMSSM Higgs Scenarios:

(arXiv:1207.1545, JFG, Jiang, Kraml)

- For the numerical analysis, we use NMSSMTools version 3.2.0, which has improved convergence of RGEs in the case of large Yukawa couplings.
- The precise constraints imposed are the following.
  1. Basic constraints: proper RGE solution, no Landau pole, neutralino LSP, Higgs and SUSY mass limits as implemented in NMSSMTools-3.2.0.
  2. $B$ physics: $\text{BR}(B_s \to X_s \gamma)$, $\Delta M_s$, $\Delta M_d$, $\text{BR}(B_s \to \mu^+\mu^-)$ (old upper limit), $\text{BR}(B^+ \to \tau^+\nu_{\tau})$ and $\text{BR}(B \to X_s\mu^+\mu^-)$ at $2\sigma$ as encoded in NMSSMTools-3.2.0, plus updates.
  3. Dark Matter: $\Omega h^2 < 0.136$, thus allowing for scenarios in which the relic density arises at least in part from some other source.
However, we single out points with $0.094 \leq \Omega h^2 \leq 0.136$, which is the ‘WMAP window’ defined in NMSSMTools-3.2.0.

4. 2011 XENON 100: spin-independent LSP–proton scattering cross section bounds implied by the neutralino-mass-dependent XENON100 bound. (For points with $\Omega h^2 < 0.094$, we rescale these bounds by a factor of $0.11/\Omega h^2$.) (2012 XENON 100 has little additional impact.)

5. $\delta a_\mu$ ignored: impossible to satisfy for scenarios we study here.

- Compute the effective Higgs mass in given production and final decay channels $Y$ and $X$, respectively, and $R_{gg}^h$ as

$$m_h^Y(X) \equiv \frac{R_{Y1}^h(X)m_{h1} + R_{Y2}^h(X)m_{h2}}{R_{Y1}^h(X) + R_{Y2}^h(X)} \quad R_Y^h(X) = R_{Y1}^h(X) + R_{Y2}^h(X).$$

- 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. Very roughly, one should probably think of $\sigma_{\text{res}} \sim 1.5$ GeV or larger. The widths of the $h_1$ and $h_2$ are very much smaller than this resolution.

- We perform scans covering the following parameter ranges:

\begin{align*}
0 &\leq m_0 \leq 3000; & 100 &\leq m_{1/2} \leq 3000; & 1 &\leq \tan \beta \leq 40; \\
-6000 &\leq A_0 \leq 6000; & 0.1 &\leq \lambda \leq 0.7; & 0.05 &\leq \kappa \leq 0.5; \\
-1000 &\leq A_\lambda \leq 1000; & -1000 &\leq A_\kappa \leq 1000; & 100 &\leq \mu_{\text{eff}} \leq 500. \quad (8)
\end{align*}

We only display points which pass the basic constraints, satisfy $B$-physics constraints, have $\Omega h^2 < 0.136$, obey the 2011 XENON100 limit on the LSP scattering cross-section off protons and have both $h_1$ and $h_2$ in the desired mass range: $123$ GeV $< m_{h_1}, m_{h_2} < 128$ GeV.

- In Fig. 10, points are color coded according to $m_{h_2} - m_{h_1}$. Circular points have $\Omega h^2 < 0.094$, while diamond points have $0.094 \leq \Omega h^2 \leq 0.136$ (i.e. lie within the WMAP window).
• Many of the displayed points are such that $R_{gg}^{h_1}(\gamma\gamma) + R_{gg}^{h_2}(\gamma\gamma) > 1$.

• A few such points have $\Omega h^2$ in the WMAP window. These points are such that either $R_{gg}^{h_1}(\gamma\gamma) > 2$ or $R_{gg}^{h_2}(\gamma\gamma) > 2$, with the $R_{gg}^h(\gamma\gamma)$ for the other Higgs being small.

• However, the majority of the points with $R_{gg}^{h_1}(\gamma\gamma) + R_{gg}^{h_2}(\gamma\gamma) > 1$ have $\Omega h^2 < 0.094$ and the $\gamma\gamma$ signal is often shared between the $h_1$ and the $h_2$. 

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Figure 10: Correlation of \( gg \rightarrow (h_1, h_2) \rightarrow \gamma \gamma \) signal strengths when both \( h_1 \) and \( h_2 \) lie in the 123–128 GeV mass range. The circular points have \( \Omega h^2 < 0.094 \), while diamond points have \( 0.094 \leq \Omega h^2 \leq 0.136 \). Points are color coded according to \( m_{h_2} - m_{h_1} \). Probably green and cyan points can be resolved in mass.

Now combine the \( h_1 \) and \( h_2 \) signals as described above. Recall:
circular (diamond) points have $\Omega h^2 < 0.094 \ (0.094 \leq \Omega h^2 \leq 0.136)$. Color code:

1. red for $m_{h_2} - m_{h_1} \leq 1 \text{ GeV}$;
2. blue for $1 \text{ GeV} < m_{h_2} - m_{h_1} \leq 2 \text{ GeV}$;
3. green for $2 \text{ GeV} < m_{h_2} - m_{h_1} \leq 3 \text{ GeV}$.

- For current statistics and $\sigma_{\text{res}} \gtrsim 1.5 \text{ GeV}$ we estimate that the $h_1$ and $h_2$ signals will not be seen separately for $m_{h_2} - m_{h_1} \leq 2 \text{ GeV}$.

- In Fig. 11, we show results for $R_{gg}^h (X)$ for $X = \gamma\gamma, VV, b\bar{b}$. Enhanced $\gamma\gamma$ and $VV$ rates from gluon fusion are very common.

- The bottom-right plot shows that enhancement in $Vh$ with $h \rightarrow b\bar{b}$ rate is also natural, though not as large as the best fit value suggested by the new Tevatron analysis.

- Diamond points $\text{ i.e. }$ those in the WMAP window) are rare, but typically show enhanced rates.
Figure 11: $R_{gg}^h(X)$ for $X = \gamma\gamma$, $VV$, $b\bar{b}$, and $R_{VBF}^h(b\bar{b})$ versus $m_h$. For application to the Tevatron, note that $R_{VBF}^h(b\bar{b}) = R_{V^* \rightarrow Vh}^h(b\bar{b})$. 
Figure 12: Left: correlation between the gluon fusion induced $\gamma\gamma$ and $VV$ rates relative to the SM. Right: correlation between the gluon fusion induced $\gamma\gamma$ rate and the $VV$ fusion induced $b\bar{b}$ rates relative to the SM; the relative rate for $V^* \rightarrow Vh$ with $h \rightarrow b\bar{b}$ (relevant for the Tevatron) is equal to the latter.

- Comments on Fig. 12:
  1. Left-hand plot shows the strong correlation between $R_{gg}^h(\gamma\gamma)$ and $R_{gg}^h(VV)$. 
Note that if $R_{gg}^h(\gamma \gamma) \sim 1.5$, as suggested by current experimental results, then in this model $R_{gg}^h(VV) \geq 1.2$.

2. The right-hand plot shows the (anti) correlation between $R_{gg}^h(\gamma \gamma)$ and $R_{V^* \rightarrow Vh}(b\bar{b}) = R_{VBF}^h(b\bar{b})$.

In general, the larger $R_{gg}^h(\gamma \gamma)$ is, the smaller the value of $R_{V^* \rightarrow Vh}(b\bar{b})$.

However, this latter plot shows that there are parameter choices for which both the $\gamma \gamma$ rate at the LHC and the $V^* \rightarrow Vh(\rightarrow b\bar{b})$ rate at the Tevatron (and LHC) can be enhanced relative to the SM as a result of there being contributions to these rates from both the $h_1$ and $h_2$.

3. It is often the case that one of the $h_1$ or $h_2$ dominates $R_{gg}^h(\gamma \gamma)$ while the other dominates $R_{V^* \rightarrow Vh}(b\bar{b})$. This is typical of the diamond WMAP-window points.

However, a significant number of the circular $\Omega h^2 < 0.094$ points are such that either the $\gamma \gamma$ or the $b\bar{b}$ signal receives
substantial contributions from both the $h_1$ and the $h_2$. We did not find points where the $\gamma\gamma$ and $b\bar{b}$ final states both receive substantial contributions from both the $h_1$ and $h_2$.

Figure 13: Left: effective Higgs masses obtained from different channels: $m_{h}^{gg}(\gamma\gamma)$ versus $m_{h}^{gg}(VV)$. Right: $\gamma\gamma$ signal strength $R_{hgg}^{\gamma\gamma}$ versus effective coupling to $b\bar{b}$ quarks $(C_{bb}^{h})^2$. Here, $C_{bb}^{h} \equiv \left[ R_{hgg}^{h_1}(\gamma\gamma)C_{bb}^{h_1^2} + R_{hgg}^{h_2}(\gamma\gamma)C_{bb}^{h_2^2} \right] / \left[ R_{hgg}^{h_1}(\gamma\gamma) + R_{hgg}^{h_2}(\gamma\gamma) \right]$.
Comments on Fig. 13

1. The $m_h$ values for the gluon fusion induced $\gamma\gamma$ and $VV$ cases are also strongly correlated — in fact, they differ by no more than a fraction of a GeV and are most often much closer, see the left plot of Fig. 13.

2. The right plot of Fig. 13 illustrates the mechanism behind enhanced rates, namely that large net $\gamma\gamma$ branching ratio is achieved by reducing the average total width by reducing the average $b\bar{b}$ coupling strength.
Let us take seriously the ATLAS preference of a lower apparent mass in the $4\ell$ channel compared to $\gamma\gamma$ channel.

Can this be accommodated in nearly degenerate scenarios?

• Return to scenarios of previous section and analyze more closely.

• $h_1$ should have $ZZ$ rate not too much smaller than SM-like rate, but suppressed $\gamma\gamma$ rate.

• $h_2$ should have enhanced $\gamma\gamma$ and somewhat suppressed $ZZ$ rate.

The basic issue is encapsulated in the following plots. The green and cyan points have $m_{h_2} - m_{h_1} > 3$ GeV and $m_{h_2} - m_{h_1} \in [2, 3]$ GeV, respectively. So, pay most attention to these colors.
• Left-hand figure shows that $R_{h_1}^{\gamma\gamma} \lesssim R_{h_1}^{ZZ}$ along lower part of upper branch (the best branch).

• Right-hand figure shows that $R_{h_2}^{\gamma\gamma} > R_{h_2}^{ZZ}$ by a substantial amount along the upper branch.

• Net result would be to shift $ZZ$ mass lower and $\gamma\gamma$ mass higher.
Detailed fit needed to see if ATLAS mass discrepancy can be described.
Diagnosing the presence of degenerate Higgses

• Given that enhanced $R_{gg}^h$ is very natural if there are degenerate Higgs mass eigenstates, how do we detect degeneracy if closely degenerate? Must look at correlations among different $R^h$’s.

• In the context of any doublets plus singlets model not all the $R^{h_i}$’s are independent; a complete independent set of $R^h$’s can be taken to be:

$$R_{gg}^h(VV), \quad R_{gg}^h(bb), \quad R_{gg}^h(\gamma\gamma), \quad R^h_{VBF}(VV), \quad R^h_{VBF}(bb), \quad R^h_{VBF}(\gamma\gamma).$$ (9)

• Let us now look in more detail at a given $R_Y^h(X)$. It takes the form

$$R^h_Y(X) = \sum_{i=1,2} \frac{(C^{h_i}_Y)^2(C^{h_i}_X)^2}{C_{\Gamma}^{h_i}}$$ (10)

where $C^{h_i}_X$ for $X = \gamma\gamma, WW, ZZ, \ldots$ is the ratio of the $h_iX$
to $h_{SM} X$ coupling and $C_{\Gamma}^{h_i}$ is the ratio of the total width of the $h_i$ to the SM Higgs total width.

- The diagnostic tools that can reveal the existence of a second, quasi-degenerate (but non-interfering in the small width approximation) Higgs state are the double ratios:

$$
\begin{align*}
\text{I): } & \frac{R_{VBF}^h(\gamma\gamma)}{R_{VBF}^h(bb)} / \frac{R_{gg}^h(\gamma\gamma)}{R_{gg}^h(bb)}, \\
\text{II): } & \frac{R_{VBF}^h(\gamma\gamma)}{R_{VBF}^h(VV)} / \frac{R_{gg}^h(\gamma\gamma)}{R_{gg}^h(VV)}, \\
\text{III): } & \frac{R_{VBF}^h(VV)}{R_{VBF}^h(bb)} / \frac{R_{gg}^h(VV)}{R_{gg}^h(bb)},
\end{align*}
(11)
$$

each of which should be unity if only a single Higgs boson is present but, due to the non-factorizing nature of the sum in Eq. (10), are generally expected to deviate from 1 if two (or more) Higgs bosons are contributing to the net $h$ signals.

- In a doublets+singlets model all other double ratios that are equal to unity for single Higgs exchange are not independent of the above three.

- 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. E.g measurements of $R^h$ for the $bb$ final state may continue to be somewhat imprecise and it is then double ratio II) that might prove most discriminating. Or, it could be that one of the double ratios deviates from unity by a much larger amount than the others, in which case it might be most discriminating even if the $R^h$'s involved are not measured with great precision.

- In Fig. 14, we plot the numerator versus the denominator of the double ratios I) and II), [III) being very like I) due to the correlation between the $R^h_{gg}(\gamma\gamma)$ and $R^h_{gg}(VV)$ values discussed earlier).
- We observe that any one of these double ratios will often, but not always, deviate from unity (the diagonal dashed line in the figure).
- The probability of such deviation increases dramatically if we
require (as apparently preferred by LHC data) $R_{gg}^{h}(\gamma\gamma) > 1$, see the solid (vs. open) symbols of Fig. 14.

- This is further elucidated in Fig. 15 where we display the double ratios I) and II) as functions of $R_{gg}^{h}(\gamma\gamma)$ (left plots).

For the NMSSM, it seems that the double ratio I) provides the greatest discrimination between degenerate vs. non-degenerate scenarios with values very substantially different from unity (the dashed line) for the majority of the degenerate NMSSM scenarios explored in the earlier section of this talk that have enhanced $\gamma\gamma$ rates.

Note in particular that I), being sensitive to the $b\bar{b}$ final state, singles out degenerate Higgs scenarios even when one or the other of $h_1$ or $h_2$ dominates the $gg \rightarrow \gamma\gamma$ rate, see the top right plot of Fig. 15.

In comparison, double ratio II) is most useful for scenarios with $R_{gg}^{h}(\gamma\gamma) \sim 1$, as illustrated by the bottom left plot of Fig. 15.
Thus, as illustrated by the bottom right plot of Fig. 15, 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.
Figure 14: Comparisons of pairs of event rate ratios that should be equal if only a single Higgs boson is present. The color code is green for points with $2 \text{ GeV} < m_{h_2} - m_{h_1} \leq 3 \text{ GeV}$, blue for $1 \text{ GeV} < m_{h_2} - m_{h_1} \leq 2 \text{ GeV}$, and red for $m_{h_2} - m_{h_1} \leq 1 \text{ GeV}$. Large diamond points have $\Omega h^2$ in the WMAP window of $[0.094, 0.136]$, while circular points have $\Omega h^2 < 0.094$. Solid points are those with $R_{gg}^h(\gamma\gamma) > 1$ and open symbols have $R_{gg}^h(\gamma\gamma) \leq 1$. Current experimental values for the ratios from CMS data along with their $1\sigma$ error bars are also shown.
Figure 15: Double ratios I) and II) of Eq. (11) as functions of $R_{gg}^{h}(\gamma\gamma)$ (on the left). On the right we show (top) double ratio I) vs. $\max \left[ R_{gg}^{h_{1}}(\gamma\gamma), R_{gg}^{h_{2}}(\gamma\gamma) \right] / R_{gg}^{h}(\gamma\gamma)$ and (bottom) double ratio I) vs. double ratio II) for the points displayed in Fig. 14. Colors and symbols are the same as in Fig. 14.
• What does current LHC data say about these various double ratios?

The central values and $1\sigma$ error bars for the numerator and denominator of double ratios I) and II) obtained from CMS data (CMS-PAS-HIG-12-020) are also shown in Fig. 14. Obviously, current statistics are inadequate to discriminate whether or not the double ratios deviate from unity. About 100 times increased statistics will be needed. This will not be achieved until the $\sqrt{s} = 14$ TeV run with $\geq 100$ fb$^{-1}$ of accumulated luminosity.

Nonetheless, it is clear that the double-ratio diagnostic tools will ultimately prove viable and perhaps crucial for determining if the $\sim 125$ GeV Higgs signal is really only due to a single Higgs-like resonance or if two resonances are contributing.

• Degeneracy has significant probability in model contexts if enhanced $\gamma\gamma$ rates are indeed confirmed at higher statistics.
The pure 2HDM

- There are some differences.

NMSSM-like degeneracy can be explored in this context also, but no time to discuss.
Conclusions

• It seems likely that the Higgs responsible for EWSB has emerged.
• Perhaps, other Higgs-like objects are emerging.
• Survival of enhanced signals for one or more Higgs boson would be one of the most exciting outcomes of the current LHC run and would guarantee years of theoretical and experimental exploration of BSM models with elementary scalars.
• >SM signals would appear to guarantee the importance of a linear collider or LEP3 or muon collider in order to understand fully the responsible BSM physics.
• In any case, the current situation illustrates the fact that we must never assume we have uncovered all the Higgs.
Certainly, I will continue watching and waiting