DO PRECISION ELECTROWEAK CONSTRAINTS GUARANTEE THAT THE NLC CAN FIND AT LEAST ONE HIGGS BOSON OF A TYPE-II 2HDM?

J. F Gunion, RADCOR (Carmel, Sept. 11 – 15, 2000)

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OUTLINE

● Define the problematical \([m_h, \tan \beta]\) parameter space wedges.
● Show the \(\Delta \chi^2\) relative to SM fit.
● How fine-tuned are the parameters.
● What is happening analytically?
● What is the required potential form?
● What are discovery possibilities with increased LC \(\sqrt{s}\), or at LHC, or in \(\gamma\gamma\) collisions.
The Model
Type-II CP conserving 2HDM with Higgs bosons $h^0$, $H^0$, $A^0$ and $H^\pm$.

The No-Discovery Wedges
The Scenario: There is only one light Higgs boson, $h$, with $m_h < \sqrt{s} - 2m_t$ in particular (so that $b\bar{b}h$ and $t\bar{t}h$ are both allowed), and it has zero tree-level $WW/ZZ$ coupling. Either

- $h = A^0$; or
- $h = h^0$ and $\sin(\beta - \alpha) = 0$.

All other Higgs bosons with substantial tree-level $WW/ZZ$ couplings are too heavy to be produced.

Will we see the $h$?

One-loop induced couplings are too small.

$WW \rightarrow h$ is best (no off-shell $s$ in loop) and one finds $\sigma(WW \rightarrow A^0)/\sigma(WW \rightarrow h_{SM}) \sim \alpha_W^2 \cot^2 \beta$. $\Rightarrow < 50$ events for $L = 2500$ fb$^{-1}$.

Need to consider $t\bar{t}h$ and $b\bar{b}h$

- Sum rules for fermionic couplings imply one or both couplings are ok.

\[(\hat{S}_h^t)^2 + (\hat{P}_h^t)^2 = \left(\frac{\cos \beta}{\sin \beta}\right)^2, \quad (\hat{S}_h^b)^2 + (\hat{P}_h^b)^2 = \left(\frac{\sin \beta}{\cos \beta}\right)^2 \]  

(1)

where $(f = t, b)$ couplings are $\bar{f}(S_h^f + i\gamma_5 P_h^f)f h$ and

\[\hat{S}_h^f \equiv \frac{S_h^f v}{m_f}, \quad \hat{P}_h^f \equiv \frac{P_h^f v}{m_f}, \]  

(2)

- But, even $L = 2500$ fb$^{-1}$ is insufficient even at $\sqrt{s} = 800$ GeV for 50 events if $\tan \beta$ is in moderate wedge region.
Figure 1: For $\sqrt{s} = 500$ GeV and $\sqrt{s} = 800$ GeV, the solid lines show as a function of $m_{A^0}$ the maximum and minimum $\tan \beta$ values between which $t\bar{t}A^0$, $b\bar{b}A^0$ final states will both have fewer than 50 events assuming $L = 2500$ fb$^{-1}$. The different types of bars indicate the best $\chi^2$ values obtained for fits to precision electroweak data after scanning: over the masses of the remaining Higgs bosons subject to the constraint they are too heavy to be directly produced; and over the mixing angle in the CP-even sector.
Figure 2: The same as for Fig. 1, except for $h = h^0$. The CP-even sector mixing angle is fixed by the requirement $\sin(\beta - \alpha) = 0$.

**Conclusion:** the fermionic coupling sum rules do not yield any guarantees. They only restrict the problematical region.
What about precision electroweak data?

I.e., are wedges ruled out because of bad $\chi^2$? One might think so since the neutral Higgs with $WW/ZZ$ coupling is required to be heavy. But, $\Delta \chi^2$ relative to best SM fit is small once $\tan \beta \gtrsim 1$ (see figures). The large $\Delta \chi^2$'s found for $\tan \beta < 1$ come from too large an $R_b$, although the deviation of $\Gamma^{Z}_{\text{tot}}$ also increases.

**Typical case:**

$m_{A^0} = 90 \text{ GeV}$, $\tan \beta = 2.3$.

For $\sqrt{s} = 500 \text{ GeV}$, $\Delta \chi^2_{\text{min}} = 0.78$ is achieved for $m_{h^0} = \sqrt{s} - 10 \text{ GeV} = 490 \text{ GeV}$ (i.e. as small as we allow), $m_{H^0} = 830 \text{ GeV}$, $m_{H^\pm} = 850 \text{ GeV}$, and $\alpha \sim -0.1\pi$ (corresponding to $\beta - \alpha \sim \pi/2 \rightarrow h^0=\text{SM-like}$).

In the following table, the observables considered and their pulls are compared for the best fit in this non-discovery case vs. the usual SM fit.

⇒ Some observables are better fit by non-discovery 2HDM parameter choices and some worse. Biggest pull increases are for $\Gamma^{Z}_{\text{tot}}$ and $\Gamma^{Z}_{\text{had}}/\Gamma^{Z}_{\text{lep}}$.

**Sensitivity to inputs:**

We have varied inputs such as: • Whether or not we use running $m_b$.

• The value of $\alpha_s$. • The value of $m_t$. • Changing input observable measurements; e.g. using $m_W^{\text{LEP}}$ from CERN-EXP-2000-016 instead of including LEP2 results of Moriond or Osaka.

⇒ $\Delta \chi^2$ changes resulting from such changes are all $< 0.1$.

⇒ We think our results are quite reliable when using SM fit as basis for comparison.
Table 1: Observables considered (TEV stands for Tevatron data) and typical pulls for a 2HDM fit. Pulls are defined as \( \Delta O_i = \frac{O_i - O_i^{\text{min}}}{\Delta O_i} \), where \( O_i \) is the measured value of a given observable, \( O_i^{\text{min}} \) is the value for the observable for the best fit choice of parameters, and \( \Delta O_i \) is the full error (including systematic error) for that observable. The pull results are for \( m_t = 174 \text{ GeV}, \alpha_s = 0.117, m_{A^0} = 90 \text{ GeV}, \tan\beta = 2.3, m_{h^0} = 490 \text{ GeV}, m_{H^0} = 830 \text{ GeV} \) and \( m_{H^+} = 850 \text{ GeV} \), yielding \( \Delta \chi^2 = 0.78 \) relative to the best \( \chi^2 \) achieved in the SM-like limit of the 2HDM, for which we also give the pulls for the same \( m_t \) and \( \alpha_s \). These latter results are quite close to those given in CERN-EXP-2000-016 with the exception of \( m_W^{\text{LEP}} \) for which we have used the Moriond result including LEP2 running. The SM-like 2HDM pulls are essentially identical to those of CERN-EXP-2000-016 if we use \( m_W^{\text{LEP}} \) as quoted there.

<table>
<thead>
<tr>
<th>( O )</th>
<th>( m_W^{\text{LEP}} )</th>
<th>( m_W^{\text{TEV}} )</th>
<th>( \sin^2 \theta_W^{\text{TEV}} )</th>
<th>( \Delta Z_{\text{tot}} )</th>
<th>( \sigma_{\text{had}} )</th>
<th>( A_e^{\text{LEP}} )</th>
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<tr>
<td>2HDM</td>
<td>0.157</td>
<td>0.880</td>
<td>1.32</td>
<td>-0.972</td>
<td>1.61</td>
<td>0.338</td>
</tr>
<tr>
<td>SM</td>
<td>0.370</td>
<td>1.04</td>
<td>1.23</td>
<td>-0.508</td>
<td>1.73</td>
<td>0.167</td>
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<table>
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<tr>
<th>( O )</th>
<th>( A_t^{\text{LEP}} )</th>
<th>( \sin^2 \theta^*_\text{LEP} )</th>
<th>( G^Z_{\text{had}} / G^Z_{\text{lep}} )</th>
<th>( A^l_{\text{lep}} )</th>
<th>( R_b^{\text{LEP}} )</th>
<th>( R_c^{\text{LEP}} )</th>
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<tr>
<td>2HDM</td>
<td>-0.927</td>
<td>0.522</td>
<td>1.42</td>
<td>0.944</td>
<td>0.733</td>
<td>-0.744</td>
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<tr>
<td>SM</td>
<td>-1.12</td>
<td>0.632</td>
<td>1.13</td>
<td>0.742</td>
<td>0.668</td>
<td>-0.743</td>
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</table>

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<tr>
<th>( O )</th>
<th>( A_{FB}^{b\text{LEP}} )</th>
<th>( A_{FB}^{c\text{LEP}} )</th>
<th>( A_{LR}^{b\text{SLD}} )</th>
<th>( A_{LR}^{c\text{SLD}} )</th>
<th>( \sin^2 \theta_{\text{SLD}} )</th>
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<tr>
<td>2HDM</td>
<td>-1.98</td>
<td>-1.22</td>
<td>-0.948</td>
<td>-1.45</td>
<td>-2.26</td>
</tr>
<tr>
<td>SM</td>
<td>-2.29</td>
<td>-1.34</td>
<td>-0.950</td>
<td>-1.46</td>
<td>-1.83</td>
</tr>
</tbody>
</table>

**Giga-Z?**

To increase \( \Delta \chi^2_{\text{min}} \sim 1 \) to \( \Delta \chi^2_{\text{min}} \sim 3 \) need factor of three improvement in both statistical and systematic errors.

Giga-Z factory would probably do the job.
What if we push up the lightest Higgs mass to $m_h \gtrsim \sqrt{s}$?

Table 2: Lower and upper values of $\tan \beta$, using the notation $[\tan \beta_{\text{min}}, \tan \beta_{\text{max}}]$, at which the given $\Delta \chi^2_{\text{min}}$ value is crossed for the $m_h = \sqrt{s} - 10$ GeV cases.

<table>
<thead>
<tr>
<th>$\Delta \chi^2_{\text{min}}$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>9</th>
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</thead>
<tbody>
<tr>
<td>$h = A^0$, $\sqrt{s} = 500$</td>
<td>[1.8,14]</td>
<td>[0.63,56]</td>
<td>[0.49,75]</td>
<td>[0.44,89]</td>
<td>[0.30, &gt; 110]</td>
</tr>
<tr>
<td>$h = A^0$, $\sqrt{s} = 800$</td>
<td>no</td>
<td>[0.75,47]</td>
<td>[0.46,85]</td>
<td>[0.39,107]</td>
<td>[0.27, &gt; 110]</td>
</tr>
<tr>
<td>$h = h^0$, $\sqrt{s} = 500$</td>
<td>no</td>
<td>[0.92,51]</td>
<td>[0.73,73]</td>
<td>[0.63,86]</td>
<td>[0.45, &gt; 110]</td>
</tr>
<tr>
<td>$h = h^0$, $\sqrt{s} = 800$</td>
<td>no</td>
<td>[1.4,33]</td>
<td>[0.68,78]</td>
<td>[0.55,102]</td>
<td>[0.35, &gt; 110]</td>
</tr>
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While the $\Delta \chi^2_{\text{min}}$ values increase with increasing $m_h$, the $\Delta \chi^2_{\text{min}}$ values are not bad even if all Higgs are heavy, so long as the other Higgs masses are correlated with one another and $m_h$ in the best way and $\alpha$ is chosen appropriately.

**How closely correlated?** i.e. how much fine tuning?

While the very best $\Delta \chi^2$ values require careful parameter choices, there are many quite different parameter choices with $\Delta \chi^2$ not much worse.

Future Notation: $H$ is the neutral Higgs that is next-lightest; $H = h^0$ for $h = A^0$ and $H = H^0$ for $h = h^0$.

In the $h = A^0$ case, very often the $H = h^0$ is SM-like for $\Delta \chi^2_{\text{min}}$.

In the $h = h^0$ case, $H = H^0$ is automatically SM-like.
Figure 3: For $m_{A^0} = 90$ GeV, $\tan\beta = 2.3$ and $m_{h^0} = 490$ GeV, we plot $m_{H^\pm}$ vs. $m_{h^0}$ for various ranges of $\Delta \chi^2$. Scans in $m_{h^0}$ and $m_{H^\pm}$ were done using 10 GeV steps, which leads to some incompleteness in the points for each $\Delta \chi^2$ range. The scan in $m_{h^0}$ was limited to $m_{h^0} < 980$ GeV. Multiple entries at the same $m_{h^0}, m_{H^\pm}$ location correspond to different $\alpha$ values.

Note how expanding to $\Delta \chi^2 = 1$ brings in many very different solutions.
Figure 4: For $m_{A^0} = 90$ GeV and $\tan \beta = 2.3$, we plot vs. $m_{h^0}$: a) $\Delta \chi^2_{\text{min}}$ after scanning over all $m_{h^0}, m_{H^\pm} > m_{h^0}$ and all $\alpha$; b) the corresponding $m_{H^0}$ and $m_{H^\pm}$ values; c) the values of $m_{H^0}$ for which $\Delta \chi^2 < \Delta \chi^2_{\text{min}} + 0.05$ is achieved; d) the closely correlated values of $m_{H^\pm}$ for which $\Delta \chi^2 < \Delta \chi^2_{\text{min}} + 0.05$ is achieved. Here, $\Delta \chi^2_{\text{min}}$ is always achieved for $\alpha = -0.1\pi$ i.e. $\beta - \alpha \sim \pi/2$ → maximal $h^0$ coupling to $ZZ$.

More on increasing $m_H$ keeping $m_h$ and $\tan \beta$ fixed. Consider case of $h = A^0$ and $H = h^0$.

As $m_{h^0}$ increases ⇒ slow increase of $\Delta \chi^2_{\text{min}}$.

Must maintain small $m_{H^\pm} - m_{H^0}$ for very best $\Delta \chi^2$.

Overall mass scale of $m_{H^0} \sim m_{H^\pm}$ is quite flexible if allow for just a little extra $\Delta \chi^2$; e.g., $m_{H^0} \sim m_{H^\pm} \sim m_{h^0}$ solutions appear.
How is small $\Delta \chi^2_{\text{min}}$ possible?

Consider $h = A^0$ and $H = h^0$, $m_{h^0} > \sqrt{s} - 10$ GeV. For cases such that $\Delta \chi^2_{\text{min}}$ is achieved with $\sin^2(\beta - \alpha) \sim 1$,

$$\Delta \rho = \frac{\alpha}{16\pi m_W^2 c_W^2} \left\{ \frac{c_W^2 m_{H^\pm}^2 - m_{H^0}^2}{s_W^2} - 3 m_W^2 \left[ \log \frac{m_{H^0}^2}{m_W^2} + \frac{1}{6} + \frac{1}{s_W^2} \log \frac{m_W^2}{m_Z^2} \right] \right\}$$

(3)

For $h = h^0$ and $H = H^0$, replace $m_{H^0} \rightarrow m_{A^0}$, $m_{h^0} \rightarrow m_{H^0}$.

$\Rightarrow$

- For light $h = A^0$ ($h^0$), small $m_{H^\pm}^2 - m_{H^0}^2$ ($m_{H^\pm}^2 - m_{A^0}^2$) is always needed for good $\chi^2$ fits.

- $\Delta \chi^2$ slowly worsens with increasing mass for next lightest Higgs because $S$ parameter is growing logarithmically.

To good approximation for situations of relevance,

$$S(0) \sim \frac{1}{12\pi} \left( -\frac{5}{3} + \log \frac{m_H^2}{m_W^2} \right),$$

(4)

where $H = h^0$ ($H = H^0$) for $h = A^0$ ($h = h^0$), respectively.

- But, to repeat: while the best $\Delta \chi^2$ requires tuning the $m_{H^\pm}$ mass scale (keeping small splitting with heaviest neutral Higgs) and (for $h = A^0$ case) $\alpha$ of CP-even mixing, many other solutions are very nearby.
Is the required form of the potential natural for small $\Delta \chi_{\text{min}}^2$?

The 2HDM potential can be written in terms of the two SU(2) Higgs doublets $\Phi_1 = (\phi_1^+, \phi_1^0)$ and $\Phi_2 = (\phi_2^+, \phi_2^0)$ in the form (assuming only soft FCNC-protecting $Z_2$ symmetry breaking):

$$
V(\Phi_1, \Phi_2) = -\mu_1^2 \Phi_1^\dagger \Phi_1 - \mu_2^2 \Phi_2^\dagger \Phi_2 - (\mu_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.})
+ \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)
+ \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \frac{1}{2} \left[ \lambda_5 (\Phi_1^\dagger \Phi_1)^2 + \text{h.c.} \right],
$$

(5)

where $\mu_{12}^2$ and $\lambda_5$ should be chosen real for a CP-conserving Higgs potential. The resulting Higgs masses or mass matrices are then

$$
m_{A_0}^2 = \frac{\mu_{12}^2}{s_\beta c_\beta} - v^2 \lambda_5, \quad m_{H^\pm}^2 = m_{A_0}^2 + \frac{1}{2} v^2 (\lambda_5 - \lambda_4)
$$

$$
\mathcal{M}^2 = m_{A_0}^2 \begin{pmatrix}
     s_\beta^2 & -s_\beta c_\beta \\
     -s_\beta c_\beta & c_\beta^2 
\end{pmatrix} + v^2 \begin{pmatrix}
     \lambda_1 c_\beta^2 + \lambda_5 s_\beta^2 & (\lambda_3 + \lambda_4) s_\beta c_\beta \\
     (\lambda_3 + \lambda_4) s_\beta c_\beta & \lambda_2 s_\beta^2 + \lambda_5 c_\beta^2 
\end{pmatrix}
$$

(6)

So long as $m_{A_0}^2 > 0$, the CP-conserving minimum is either the only minimum ($\lambda_5 > 0$) or the preferred minimum ($\lambda_5 < 0$).

For the configurations that minimize $\Delta \chi^2$, we always find that $V$ is close to the form (where $\lambda_5$ is $< 0$ in some cases and $> 0$ in others):

$$
V_{\text{quartic}}(\Phi_1, \Phi_2) = \frac{1}{2} \lambda_1 \left| \Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 \right|^2 - \frac{1}{2} \lambda_5 \left| \Phi_1^\dagger \Phi_2 - \Phi_2^\dagger \Phi_1 \right|^2,
$$

(7)

i.e. a weighted sum of the (absolute) squares of the natural symmetric and antisymmetric combinations of the two Higgs doublet fields. This form of the potential guarantees absence of quadratic growth of $\Delta \rho$ with the masses of the heavier Higgs bosons, i.e. it incorporates a hidden custodial SU(2) symmetry.
Higher energy LC and LHC.
Will increased LC energy or LHC running allow Higgs discovery?
The $h$?

- First, by comparing the $\sqrt{s} = 500 \text{ GeV}$ and $\sqrt{s} = 800 \text{ GeV}$ no-discovery wedges, we see that although the $\tan \beta$ extent of the wedge narrows considerably with increasing $\sqrt{s}$, the smallest no-discovery value of $m_h$ increases rather slowly; thus, one cannot absolutely rely on $h$ detection at higher LC energy in these scenarios.

- Also, the absence of $ZZ$ coupling and the moderate value of $\tan \beta$ implies that the $h$ will not be detectable at the LHC.

The other Higgs bosons?
Since $\chi^2_{\text{min}}$ is always achieved for $m_H$ at the $Hb\bar{b}$ threshold and for masses of the other Higgs bosons often much larger than $m_H$, the discovery possibilities for the $H = h^0 (H^0)$ deserve particular attention in the $h = A^0 (h^0)$ cases.

Cases:

- **Case I:** $h = A^0$ and $\Delta \chi^2_{\text{min}}$ when $H = h^0$ is SM-like.
  - The SM-like $H = h^0$.
    - For the $\Delta \chi^2_{\text{min}}$ values of $m_{h^0}$ and for a substantial range above, the LHC would detect the $h^0$ in the gold plated $ZZ \rightarrow 4\ell$ channel.
    - As $e^+e^- \sqrt{s} \rightarrow > 1 \text{ TeV}$ and if $Zh^0$ and $\nu\bar{\nu}h^0$ not seen, $m_{h^0} \gtrsim 1 \text{ TeV}$ ⇒ strong $WW$ scattering at LHC and LC.
* Precision electroweak fits do not necessarily have particularly bad $\chi^2$ for such large $m_{h^0}$ — $\Delta\chi^2_{\text{min}}$ only increases by $< 1 - 2$ compared to values obtained for $m_{h^0} \sim 800$ GeV. (Couplings begin to become non-perturbative and calculations not entirely trustworthy for $m_{h^0}$ values much above $800 - 900$ GeV.)

* Although $b\bar{b}h^0$ opens up as $\sqrt{s}$ of the LC is increased, $\sigma(b\bar{b}h^0)$ for a SM-like $h^0$ is very small at high mass and $b\bar{b}h^0$ production would not be detectable.

$\Rightarrow$ Need LC with $\sqrt{s}$ large enough to probe a strongly interacting $WW$ sector to be certain of seeing $H = h^0$ signal.

- For $h = A^0$, the two heaviest Higgs bosons $H^0$ and $H^\pm$ have fairly large masses for $\Delta\chi^2_{\text{min}}$: $600 - 800$ GeV for $\sqrt{s} = 500$ GeV and $> 1$ TeV for $\sqrt{s} = 800$ GeV.

* $\Rightarrow$ Although $Z \rightarrow A^0H^0 = $ full strength, $A^0H^0$ production would become kinematically allowed only with a substantial increase in $\sqrt{s}$.

* Small cross sections for Yukawa processes at moderate tan $\beta$,

$\Rightarrow$ much larger $\sqrt{s}$ would be needed for $b\bar{b}H^0$ and $b\bar{t}H^+ + \bar{b}tH^-$ production. And, much larger $\sqrt{s}$ would also be required for $H^+H^-$ and $t\bar{t}H^0$ production.

* For $\sqrt{s} = 800$ GeV $\Delta\chi^2_{\text{min}}$ cases,

$\Rightarrow$ A $\sqrt{s} > 2$ TeV LC needed to see in pair production.

$\Rightarrow$ Because of the moderate value of tan $\beta$, $\sqrt{s} > 2$ TeV also needed for Yukawa processes.
* For moderate tan \( \beta \) and such large masses, \( H^0 \) and \( H^\pm \) detection at the LHC would not be possible due to the smallness of the \( ZZ H^0 \) and \( WW H^0 \) couplings and the very modest size of \( b \bar{b} H^0 \) production.

Overall, for the \( h = A^0 \) and \( H = h^0 = \text{SM-like} \) \( \Delta \chi^2_{\text{min}} \) cases, the first focus should be on LHC observation of the \( h^0 \) as a resonance or in strong \( WW \) scattering.

- **Case II:** \( h = A^0 \), \( \Delta \chi^2_{\text{min}} \) achieved for small \( \sin^2(\beta - \alpha) \), as typified by the moderate tan \( \beta \), \( \alpha \sim 0 \) cases.

  - The \( H = h^0 \) will be hard to detect in the SM-like discovery modes.
  - \( A^0 h^0 = \text{full strength; observation would be possible when kinematically allowed.} \)

Since our searches required \( \sqrt{s} < m_{h^0} + 10 \text{ GeV} \), \( \Rightarrow \) need very substantially larger \( \sqrt{s} \) than the assumed value.

- However, in these cases the \( H^0 \) has SM-like \( ZZ, WW \) coupling and \( m_{H^0} \) is usually not much larger than \( m_{h^0} \) (which is always \( \sqrt{s} - 10 \text{ GeV for } \Delta \chi^2_{\text{min}} \)).

  \( \Rightarrow H^0 \) detection in the gold-plated modes at the LHC or at a \( \sqrt{s} \gtrsim 1 \text{ TeV} \) LC would be possible.
• **Case III:** $h = h^0, H = H^0$ (with $H^0$ SM-like); the two heaviest Higgs bosons are the $A^0$ and $H^\pm$.

  - $H^0$ detection in gold plated channels should be possible.
  
  - As $\sqrt{s}$ at the LC is increased, $h^0 A^0$ production would become kinematically allowed (and be full strength), followed by $H^+ H^-$ pair production.
  
  - For the moderate tan $\beta$ values in question, the Yukawa processes would not be useful (either at the LC or the LHC).

**General Rule:** Good chance of seeing the heavier neutral Higgs with SM-like couplings at $\sqrt{s} > 1 - 1.5$ TeV LC or at LHC. But, no guarantees for $\sqrt{s} = 800$ GeV.
What about $\gamma\gamma$ collisions?

- Assume extreme $L_{\text{eff}} = 2500$ fb$^{-1}$.
- Assume superb final state resolution $\Gamma_{\text{exp}} = 5$ GeV.
- Assume ability to isolate $b\bar{b}$ final state with no extra jets with high efficiency (included in above $L_{\text{eff}}$).

⇒ Even for low $h = A^0$ masses (have not yet studied $h = h^0$), there are portions of the wedges for which the $\gamma\gamma$ signal will be unobservable in the $b\bar{b}$ final state.

![Graph showing $\gamma\gamma$ collisions, $L_{\text{eff}} = 2500$ fb$^{-1}$, CP-odd $h = A^0$](image)

Figure 5: For $h = A^0$, we show regions of $N_{SD}$ levels achieved for a $b\bar{b}$ signal in $\gamma\gamma$ collisions assuming $L_{\text{eff}} = 2500$ fb$^{-1}$ (including tagging and two-jet final state isolation) and an extremely good final state mass resolution of $\Gamma_{\text{exp}} = 5$ GeV. At each $[m_{\gamma\gamma}, \tan \beta]$ point, other 2HDM parameters are taken equal to those that yield $\Delta \chi^2_{\text{min}}$. 
CONCLUSIONS

- CP-violating 2HDM can present unpleasant possibilities.

- Giga-Z operation of LC could distinguish between 2HDM no-$e^+e^-$ discovery scenarios and SM or SM-like 2HDM at $\gtrsim 3\sigma$ level.

- $\gamma\gamma$ collisions could allow discovery of the $h$ (for $m_h \lesssim 0.8\sqrt{s}$) in all but the higher tan $\beta$ parts of the no-$e^+e^-$-discovery wedges.

Of course, the $m_h \sim \sqrt{s}$ scenarios (which have somewhat higher $\Delta\chi^2_{\text{min}}$) will not be accessible in $\gamma\gamma$ collisions.