HIDING THE 2HDM HIGGS BOSONS – THE IMPORTANCE OF GIGA-Z AND/OR HIGHER ENERGY

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OUTLINE

- Motivation.
- The problematical $[m_h, \tan\beta]$ parameter space wedges.
- Does $e^+e^- \to hhZ$ help?
- The $\Delta\chi^2$ relative to SM fit.
- How fine-tuned are the parameters.
- What is happening analytically?
- What is the required potential form?
- The S, T plane picture and the Giga-Z option.
- 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 $H^\pm$.

- Many models with 2HDM as effective Higgs sector below some scale Λ, set by scale of: extra dimension; strong coupling (technicolor or other) regime, . . .

  Λ as low as a few TeV possible.

- Higgs self couplings λ_i need only remain perturbative up to Λ, so not a big constraint in general case.

- λ_i not related to gauge couplings in the general case, so only real constraint is the perturbativity 'prejudice'.

  2HDM masses of order 1 TeV are consistent with $\alpha_i \equiv \frac{\lambda_i^2}{4\pi} \lesssim 1$.

  Only if $\alpha_i \lesssim 1$ after evolving to $\Lambda \sim 10^{19}$ GeV does 2HDM predict 90 GeV $\lesssim m_{h^0} \lesssim$ 175 GeV with h^0 SM-like, e.g. $\sim$ SM-like g_{ZZh^0} coupling.

- Net result: the decoupling limit defined by $\alpha_i \leq \mathcal{O}(1)$, $m_{H^0}, m_{A^0}, m_{H^\pm} \sim M$ large (in which limit the h^0 is SM like), need not be nature's choice.

  One can have any Higgs masses and couplings that are consistent with $\alpha_i \leq \mathcal{O}(1)$ (assuming we want to retain perturbativity).

The No-Discovery Wedges

The Scenario: There is only one light Higgs boson, h, e.g. with $m_h < \sqrt{s} - 2m_t$ (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.

For $m_{A^0}^2 \ll m_t^2, s$, the dominant t-loop diagram for $e^+e^- \to ZA^0$ is off-shell suppressed and gives $\sigma^{1-\mathrm{loop}}(ZA^0) \times \tan^2\beta \sim 3.6$ ab (~ 1.6 ab) at $\sqrt{s} = 500$ GeV (800 GeV) $\Rightarrow < 10$ events for $L = 2500~\mathrm{fb}^{-1}$.

WW fusion does not have $1/s$ suppression, but the 1-loop induced cross section is also too small at these energies.

Four important production mechanisms: $e^+e^- \to hhZ$, $b\bar{b}h$, $t\bar{t}h$ and $\gamma\gamma \to h$.

***hhZ* and $W^+W^- \to hh$:**

Guaranteed to have contributions from the purely gauge $hhZZ$ and hhW^+W^- couplings, respectively. (Additional diagrams involving Higgs exchanges tend to suppress the cross section.) Assuming (optimistically) that 50 events will be adequate for discovery with $L = 2.5~\mathrm{ab}^{-1}$, $m_{h^0} < 145$ GeV (< 225 GeV) and $m_{A^0} < 155$ GeV (< 250 GeV) will be probed by $e^+e^- \to hhZ$ at $\sqrt{s} = 500$ GeV (800 GeV). $e^+e^- \to hh$ (WW fusion) may reach a bit higher.

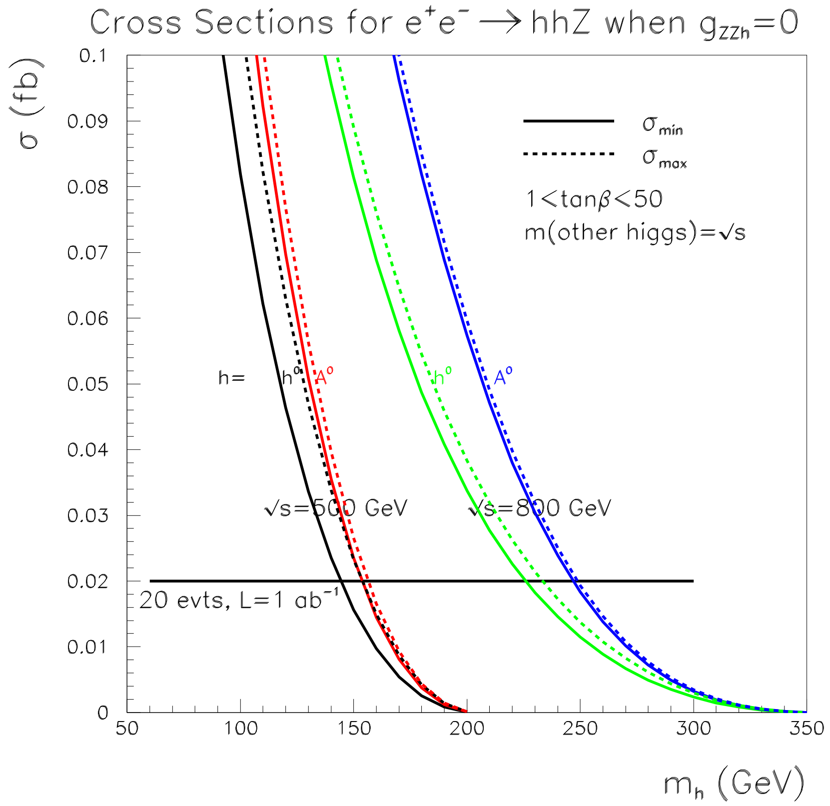

Figure 1: For $\sqrt{s} = 500$ GeV and $\sqrt{s} = 800$ GeV and for $h = h^0$ and $h = A^0$, we plot as a function of m_h the maximum and minimum values of $\sigma(e^+e^- \to hhZ)$ found after scanning $1 < \tan\beta < 50$ taking all other higgs masses equal to $\sqrt{s}$. For $h = h^0$, we require $\sin(\beta - \alpha) = 0$ during the scan. The 20 event level for $L = 1$ ab^{-1} is indicated. Other Higgs masses taken $= \sqrt{s}$.

What about $t\bar{t}h$ and $b\bar{b}h$?

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

$$(\hat{S}^t_h)^2 + (\hat{P}^t_h)^2 = \left(\frac{\cos\beta}{\sin\beta}\right)^2 , \quad (\hat{S}^b_h)^2 + (\hat{P}^b_h)^2 = \left(\frac{\sin\beta}{\cos\beta}\right)^2 \qquad (1)$$

where $(f = t, b)$ couplings are $\frac{v}{m_f}\overline{f}(\hat{S}^f_h + i\gamma_5\hat{P}^f_h)fh$.

- **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.**

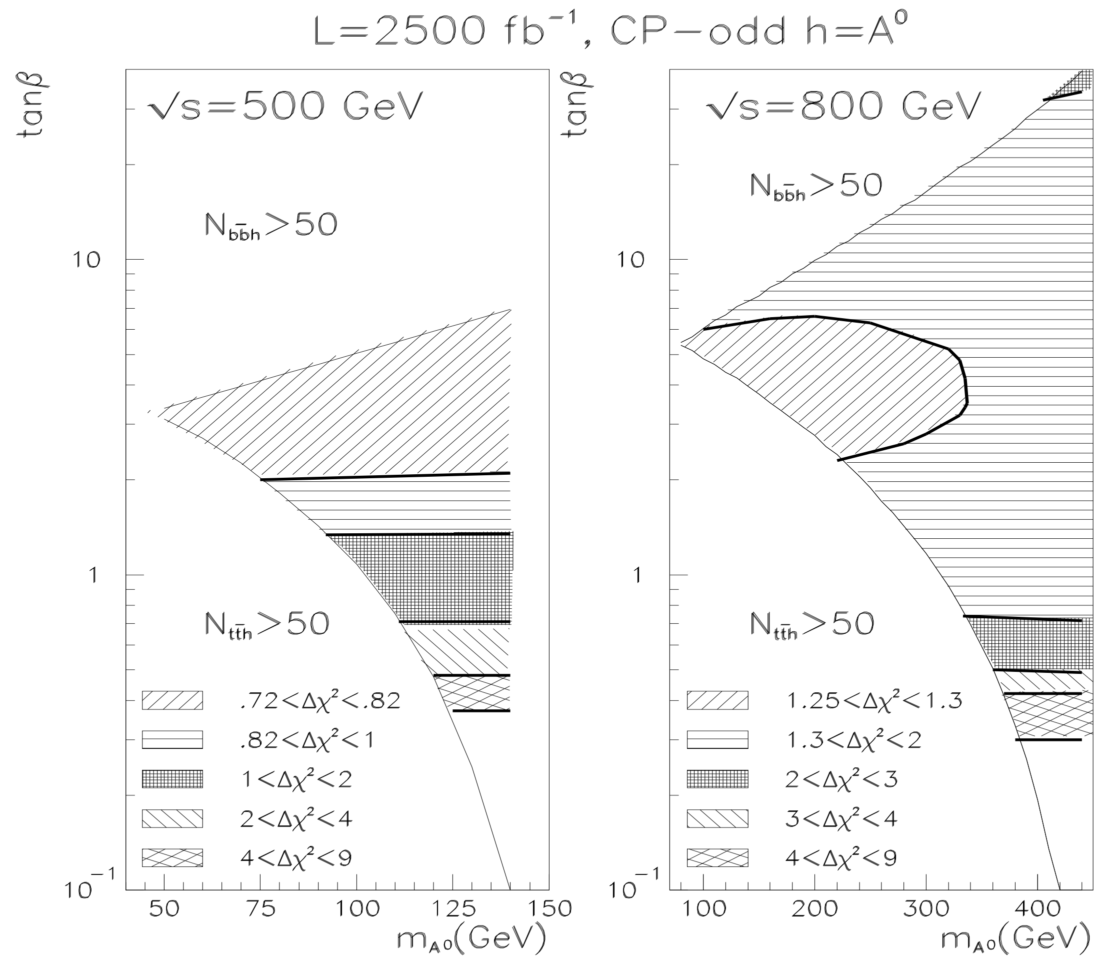

Figure 2: For $\sqrt{s} = 500$ GeV and $\sqrt{s} = 800$ GeV, the solid lines show as a function of m_{A^0} the maximum and minimum $\tan\beta$ values between which $t\bar{t}A^0$, $b\bar{b}A^0$ final states will both have fewer than 50 events assuming $L = 2500$ fb^{-1}.The different types of bars indicate the best χ^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.

For m_{h^0} larger than plotted, no lower bound to wedge and upper bound continues upward; i.e., 'wedges' continue into the $m_{h^0} > 160$ GeV ($\sqrt{s} = 500$ GeV) and $m_{h^0} > 250$ GeV ($\sqrt{s} = 800$ GeV) regions for which h^0h^0Z has < 20 events ($L = 2500$ fb^{-1}).

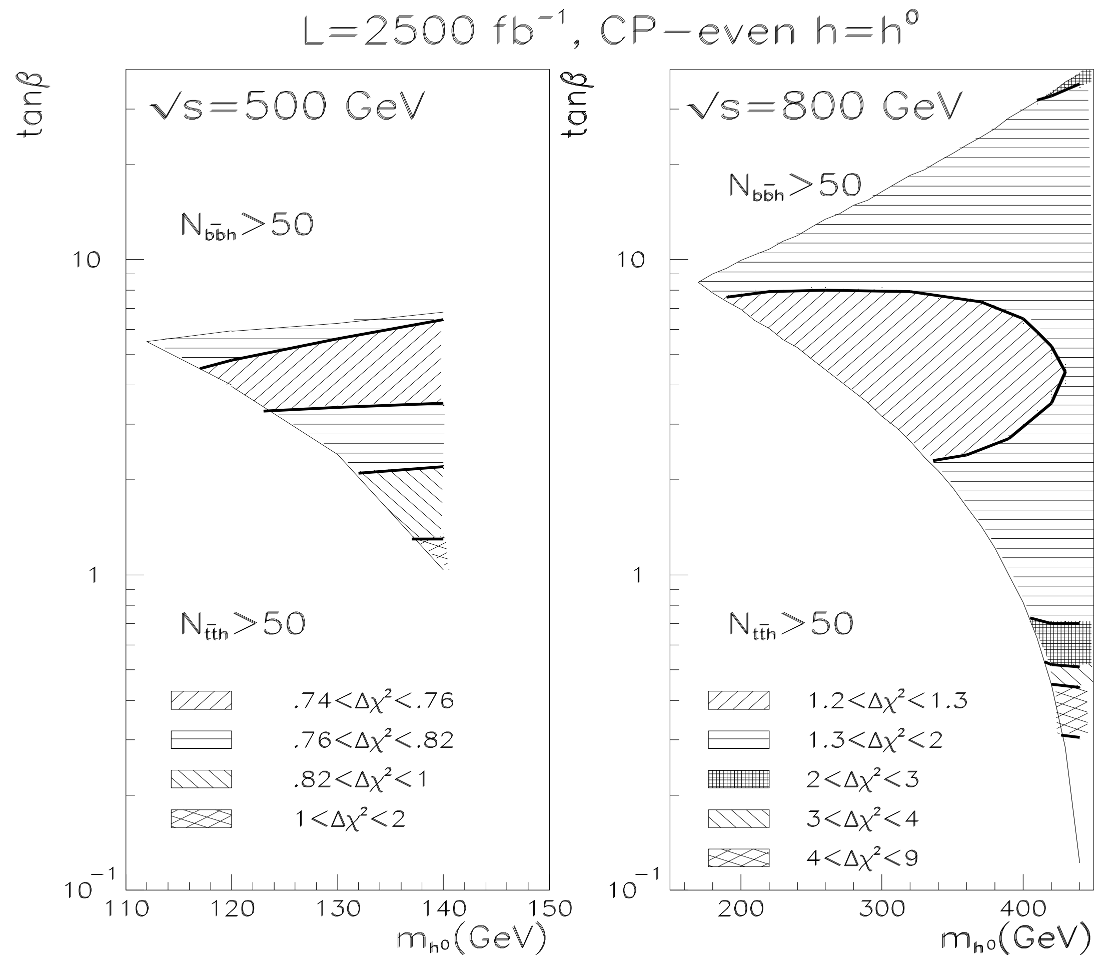

Figure 3: The same as for Fig. 2, except for $h = h^0$. The CP-even sector mixing angle is fixed by the requirement $\sin(\beta - \alpha) = 0$.

Again, 'wedges' continue into $m_{A^0} > 170$ GeV ($\sqrt{s} = 500$ GeV) and $m_{A^0} > 280$ GeV ($\sqrt{s} = 800$ GeV) regions for which $A^0A^0Z \Rightarrow < 20$ events for $L = 2500$ fb^{-1}.

Conclusion: the fermionic coupling sum rules do not yield any guarantees. They only restrict the problematical region.

Future Notation: H is the neutral Higgs that is next-lightest; to have best precision fits, $H = h^0$ (with h^0 typically SM-like) for $h = A^0$ and $H = H^0$ (guaranteed SM-like) for $h = h^0$.

What about precision electroweak data?

I.e., are wedges ruled out because of bad χ^2? One might think so since the neutral Higgs with WW/ZZ coupling is required to be heavy. But, best $\Delta\chi^2$ 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 $\Gamma^Z_{\rm tot}$ also increases.

Typical case:

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

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

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

Giga-Z factory could do the job. More later.

What if we push up the lightest Higgs mass to $m_h \gtrsim \sqrt{s}$?

Table 1: Lower and upper values of $\tan\beta$, using the notation $[\tan\beta_{\rm min}, \tan\beta_{\rm max}]$, at which the given $\Delta\chi^2_{\rm min}$ value is crossed for the $m_h = \sqrt{s} - 10$ GeV cases.

$\Delta\chi^2_{\rm min}$	1	2	3	4	9
$h = A^0, \sqrt{s} = 500$	[1.8,14]	[0.63,56]	[0.49,75]	[0.44,89]	[0.30, >110]
$h = A^0, \sqrt{s} = 800$	no	[0.75,47]	[0.46,85]	[0.39,107]	[0.27, >110]
$h = h^0, \sqrt{s} = 500$	no	[0.92,51]	[0.73,73]	[0.63,86]	[0.45, >110]
$h = h^0, \sqrt{s} = 800$	no	[1.4,33]	[0.68,78]	[0.55,102]	[0.35, >110]

While the $\Delta\chi^2_{\rm min}$ values increase with increasing m_h, the $\Delta\chi^2_{\rm min}$ values are not bad even if all Higgs are heavy.

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

Must maintain small (positive) $m_{H^\pm} - m_{H^0}$ 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 $\Delta\chi^2_{\rm min}$ possible?

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

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

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

$\Rightarrow$

- For light $h = A^0$ (h^0), small (positive) $m_{H^\pm}^2 - m_{H^0}^2$ ($m_{H^\pm}^2 - m_{A^0}^2$) allows good χ^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,

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

  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) α of CP-even mixing, many other solutions are very nearby.

Is the required form of the potential natural for small $\Delta\chi^2_{\rm min}$?

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):

$$\begin{aligned} V(\Phi_1,\Phi_2) &= -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - (\mu_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ &+ \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &+ \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right] , \end{aligned} \tag{4}$$

where μ_{12}^2 and λ_5 should be chosen real for a CP-conserving Higgs potential. The resulting Higgs masses or mass matrices are then

$$\begin{aligned} m_{A^0}^2 &= \frac{\mu_{12}^2}{s_\beta c_\beta} - v^2\lambda_5 , \quad m_{H^\pm}^2 = m_{A^0}^2 + \frac{1}{2}v^2(\lambda_5 - \lambda_4) \\ \mathcal{M}^2 &= m_{A^0}^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + \lambda_5 s_\beta^2 & (\lambda_3+\lambda_4)s_\beta c_\beta \\ (\lambda_3+\lambda_4)s_\beta c_\beta & \lambda_2 s_\beta^2 + \lambda_5 c_\beta^2 \end{pmatrix} \end{aligned} \tag{5}$$

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 small $m_{A^0}^2$ configurations that minimize $\Delta\chi^2$, we always find that V is close to the form (where λ_5 is < 0 in some cases and > 0 in others):

$$V_{\rm quartic}(\Phi_1,\Phi_2) = \frac{1}{2}\lambda_1 \left|\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2\right|^2 - \frac{1}{2}\lambda_5 \left|\Phi_1^\dagger\Phi_2 - \Phi_2^\dagger\Phi_1\right|^2 , \tag{6}$$

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.

The S, T Plane Picture and Giga-Z.

The 'success' of the 2HDM no-discovery scenarios is easily understood in the S, T plane.

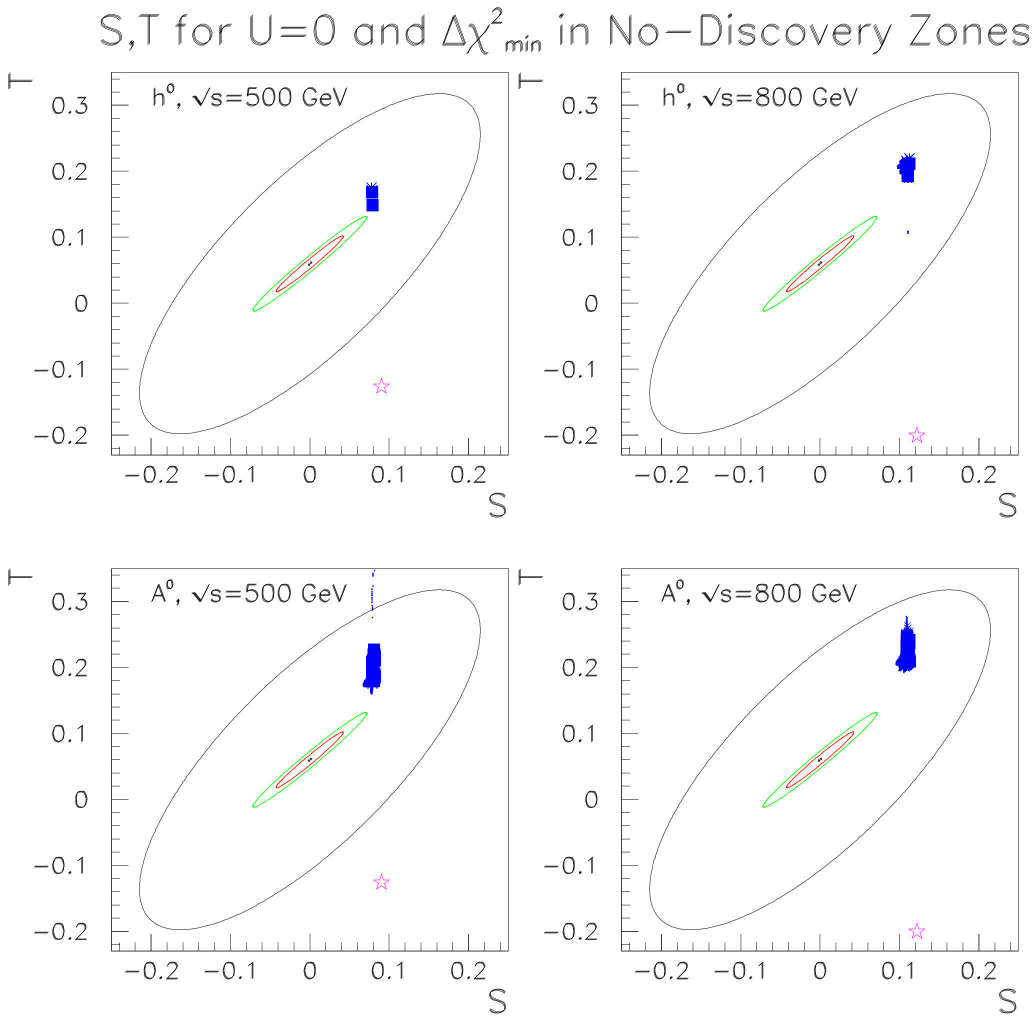

Figure 4: We plot the $U = 0$ 90% CL ellipse in the S, T plane for a SM Higgs of mass 115 GeV from the latest Erler/Langacker analysis. Also shown are 90% and 99.9% ellipses for Giga-Z using U=0 and error analyses (including correlations) from Erler and from Moenig. **The blobs of blue are where our 2HDM no-discovery $\Delta\chi^2_{\rm min}$ solutions fall.**

Note:

- 2HDM no-discovery solutions well within current 90% CL ellipse.
- Giga-Z will distinguish, **especially if there is no Higgs discovery at $\sqrt{s} = 800$.**
- **Knowing U will be crucial.** Giga-Z errors shown assume m_W is measured to 6 MeV using threshold scan.

Higher energy LC and LHC.

Will increased LC energy or LHC running allow Higgs discovery?

The h?

- First, by comparing the $\sqrt{s} = 500$ GeV and $\sqrt{s} = 800$ 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 $\chi^2_{\rm min}$ is always achieved for m_H fairly low (near $\sqrt{s}$), and 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 $\Delta\chi^2_{\rm min}$ when $H = h^0$ is SM-like.

  The SM-like $H = h^0$.

  - For the $\Delta\chi^2_{\rm min}$ values of m_{h^0} and for a substantial range above, the LHC would detect the h^0 in the gold plated $ZZ \to 4\ell$ channel.
  - As e^+e^- $\sqrt{s} \to > 1$ TeV either Zh^0 and/or $\nu\overline{\nu}h^0$ are seen, or $m_{h^0} \gtrsim 1$ TeV $\Rightarrow$ strong WW scattering at LHC and LC.

- Precision electroweak fits do not necessarily have particularly bad χ^2 for such large m_{h^0} — $\Delta\chi^2_{\rm min}$ 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 $b\overline{b}h^0$ opens up as $\sqrt{s}$ of the LC is increased, $\sigma(b\overline{b}h^0)$ for a SM-like h^0 is very small at high mass and $b\overline{b}h^0$ 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.

The other Higgses, H^0 and $H^\pm$? $\Rightarrow$ harder to see.

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

- **Case II:** $h = A^0$, $\Delta\chi^2_{\rm min}$ 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.
  - 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 $\sim \sqrt{s}$ for $\Delta\chi^2_{\rm min}$).

$\Rightarrow$ H^0 detection in the gold-plated modes at the LHC or at a $\sqrt{s} \gtrsim 1$ 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 a 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.

The most probable future scenario:

- Discovery of the H (or strong WW) at the LHC (in the gold-plated $H \to ZZ \to 4\ell$ mode) $\Rightarrow$ need Giga-Z measurements of S, T to pin down possibilities for heavier $H^\pm$ and 2nd neutral Higgs boson that are nearly, but not quite, degenerate in mass.
- There could still be a light h. An LC with sufficient $\sqrt{s}$ could then completely reveal the Higgs states by observing not only ZH and/or $WW \to H$ production but also $h^0 A^0$ production (regardless of which is the light h) and possibly $H^+ H^-$ production.

What about $\gamma\gamma$ collisions?

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

$\Rightarrow$ 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 $b\overline{b}$ final state.

Of course, the $m_h \gtrsim 0.8\sqrt{s}$ scenarios (which have somewhat higher $\Delta\chi^2_{\rm min}$) will certainly not be accessible in $\gamma\gamma$ collisions.

CONCLUSIONS

- **2HDM can present unpleasant possibilities.**
- **If no light Higgs observable at LC, $\Rightarrow$ discovery of SM-like heavy Higgs (or strong WW scattering) at LHC (and, eventually, higher $\sqrt{s}$ LC) almost certain.**
- **If heavy SM-like Higgs (or strong WW) seen at LHC, $\Rightarrow$ need conspiracy for precision electroweak. In 2HDM context, Giga-Z very useful to constrain arrangement of other 2HDM Higgs bosons,** `if` m_W `threshold scan or other gives` m_W `error below` **6 MeV.**

  Very possible that other Higgs will not be directly observable at either LHC or LC.