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

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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 $b\overline{b}h$ and $t\overline{t}h$ 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.

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

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

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

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

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

$$\hat{S}_h^f \equiv \frac{S_h^f v}{m_f} , \qquad \hat{P}_h^f \equiv \frac{P_h^f v}{m_f} , \qquad (2)$$

- 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.

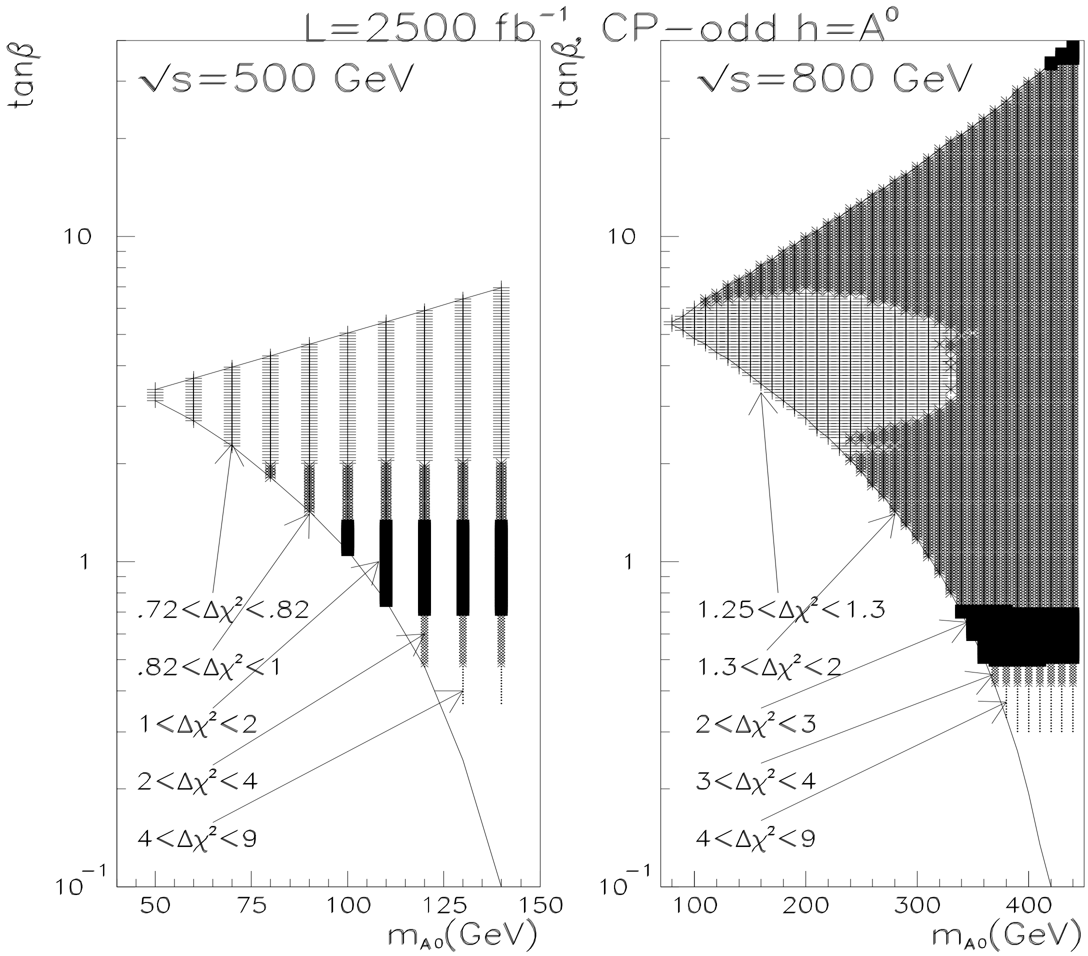

Figure 1: For $\sqrt{s}$ = 500 GeV and $\sqrt{s}$ = 800 GeV, the solid lines show as a function of m_{A^0} the maximum and minimum $\tan\beta$ values between which $t\bar{t}A^0$, $b\bar{b}A^0$ final states will both have fewer than 50 events assuming L = 2500 fb^{-1}.The different types of bars indicate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

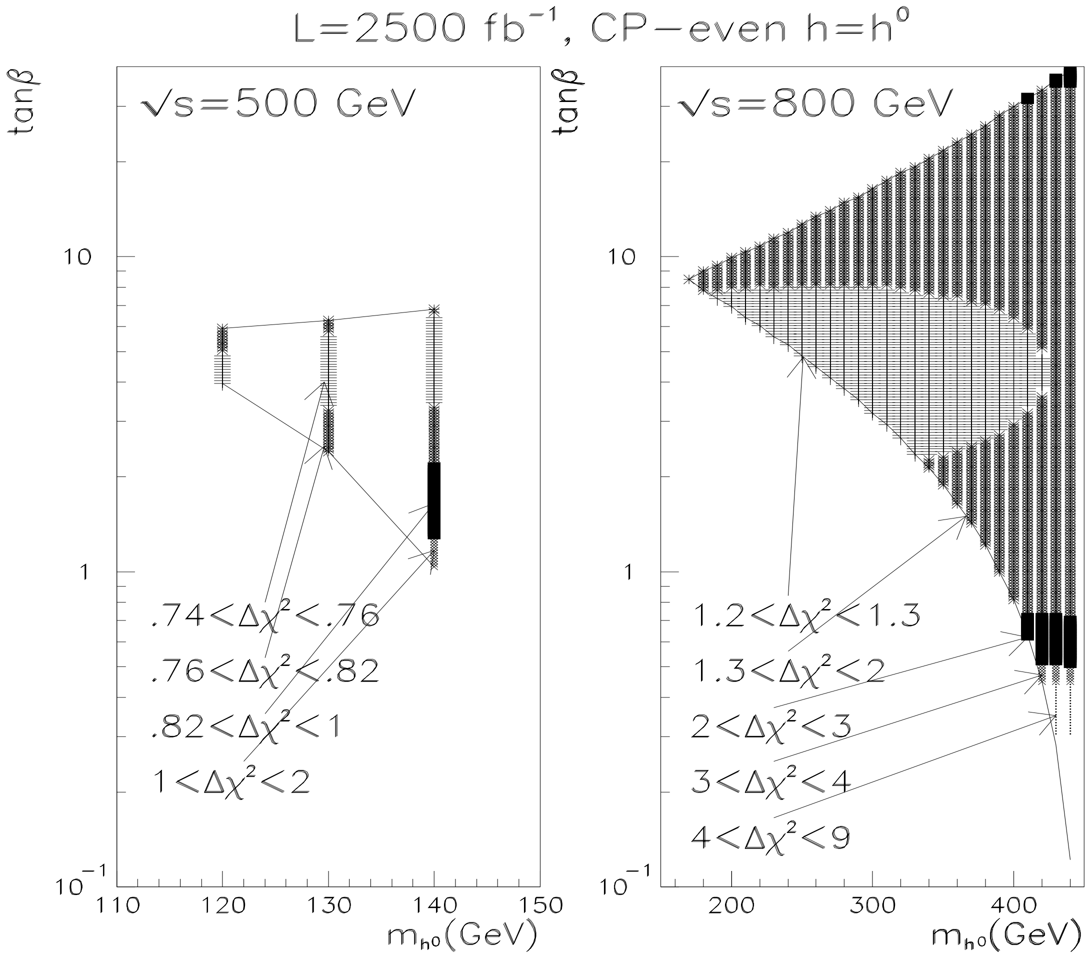

Figure 2: The same as for Fig. 1, except for $h = h^0$. The CP-even sector mixing angle is fixed by the requirement $\sin(\beta - \alpha) = 0$.

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 χ^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 $\Gamma^Z_{\rm tot}$ 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 $\beta - \alpha \sim \pi/2 \rightarrow h^0$=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.

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

Sensitivity to inputs:

We have varied inputs such as: • Whether or not we use running m_b. • The value of α_s. • The value of m_t. • Changing input observable measurements; e.g. using $m_W^{\rm LEP}$ from CERN-EXP-2000-016 instead of including LEP2 results of Moriond or Osaka.

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

$\Rightarrow$ 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 $(\mathcal{O}_i - \mathcal{O}_i^{\rm min})/\Delta\mathcal{O}_i$, where $\mathcal{O}_i$ is the measured value of a given observable, $\mathcal{O}_i^{\rm min}$ is the value for the observable for the best fit choice of parameters, and $\Delta\mathcal{O}_i$ is the full error (including systematic error) for that observable. The pull results are for $m_t = 174$ GeV, $\alpha_s = 0.117$, $m_{A^0} = 90$ GeV, $\tan\beta = 2.3$, $m_{h^0} = 490$ GeV, $m_{H^0} = 830$ GeV and $m_{H^\pm} = 850$ GeV, yielding $\Delta\chi^2 = 0.78$ relative to the best χ^2 achieved in the SM-like limit of the 2HDM, for which we also give the pulls for the same m_t and α_s. These latter results are quite close to those given in CERN-EXP-2000-016 with the exception of $m_W^{\rm LEP}$ 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 $m_W^{\rm LEP}$ as quoted there.

$\mathcal{O}$	$m_W^{\rm LEP}$	$m_W^{\rm TEV}$	$\sin^2\theta_W^{\rm TEV}$	$\Gamma_{\rm tot}^Z$	$\sigma_{\rm had}^Z$	$\mathcal{A}_e^{\rm LEP}$
2HDM	0.157	0.880	1.32	-0.972	1.61	0.338
SM	0.370	1.04	1.23	-0.508	1.73	0.167
$\mathcal{O}$	$\mathcal{A}_\tau^{\rm LEP}$	$\sin^2\theta_{\rm LEP}^*$	$\Gamma_{\rm had}^Z/\Gamma_{\rm lep}^Z$	$A_{FB}^{l\ \rm LEP}$	$R_b^{\rm LEP}$	$R_c^{\rm LEP}$
2HDM	-0.927	0.522	1.42	0.944	0.733	-0.744
SM	-1.12	0.632	1.13	0.742	0.668	-0.743
$\mathcal{O}$	$A_{FB}^{b\ \rm LEP}$	$A_{FB}^{c\ \rm LEP}$	$A_{LR}^{b\ \rm SLD}$	$A_{LR}^{c\ \rm SLD}$	$\sin^2\theta_{\rm SLD}$	
2HDM	-1.98	-1.22	-0.948	-1.45	-2.26	
SM	-2.29	-1.34	-0.950	-1.46	-1.83	

Giga-Z?

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 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 $[\tan\beta_{\rm min}, \tan\beta_{\rm max}]$, 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, so long as the other Higgs masses are correlated with one another and m_h in the best way and α 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 $\Delta\chi^2_{\rm min}$.

In the $h = h^0$ case, $H = H^0$ is automatically SM-like.

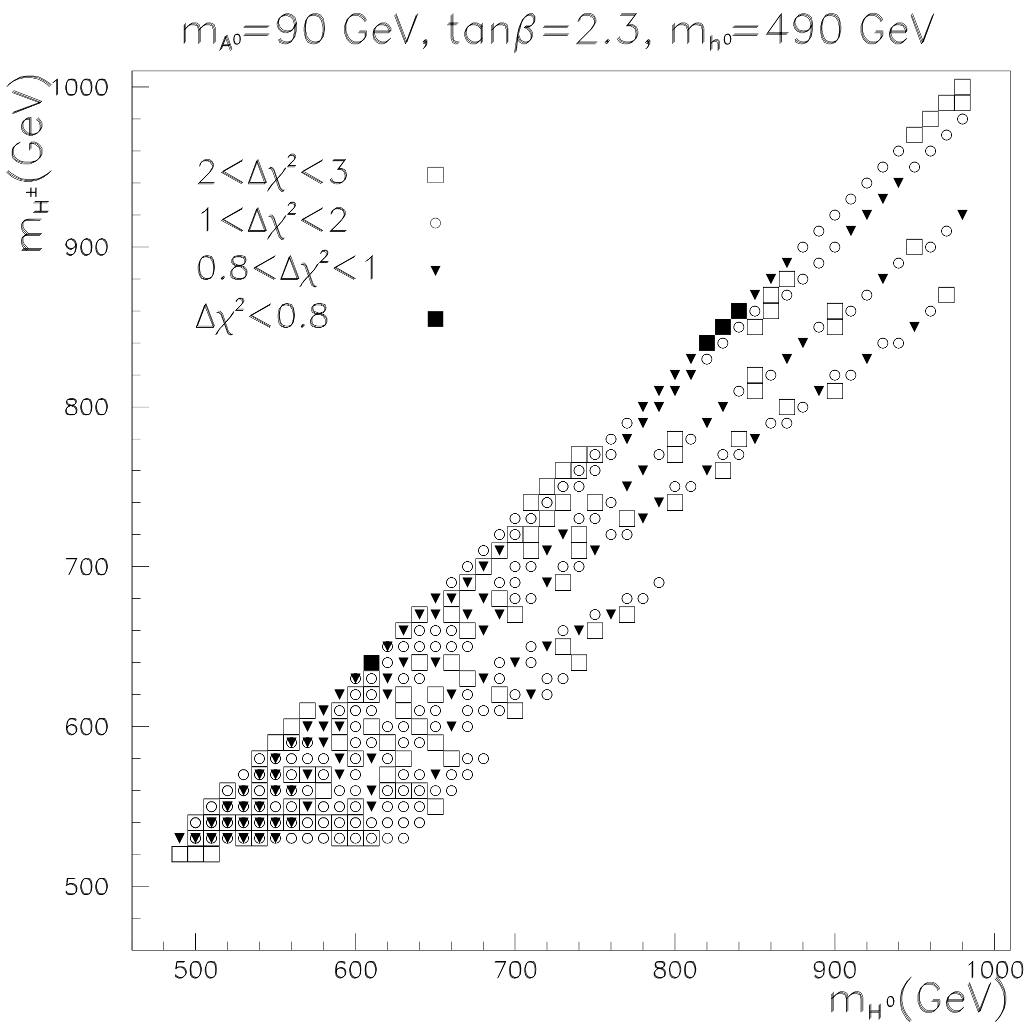

Figure 3: For $m_{A^0} = 90$ GeV, $\tan\beta = 2.3$ and $m_{h^0} = 490$ GeV, we plot $m_{H^\pm}$ vs. m_{H^0} for various ranges of $\Delta\chi^2$. Scans in m_{H^0} and $m_{H^\pm}$ were done using 10 GeV steps, which leads to some incompleteness in the points for each $\Delta\chi^2$ range. The scan in 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 α values.

Note how expanding to $\Delta\chi^2 = 1$ brings in many very different solutions.

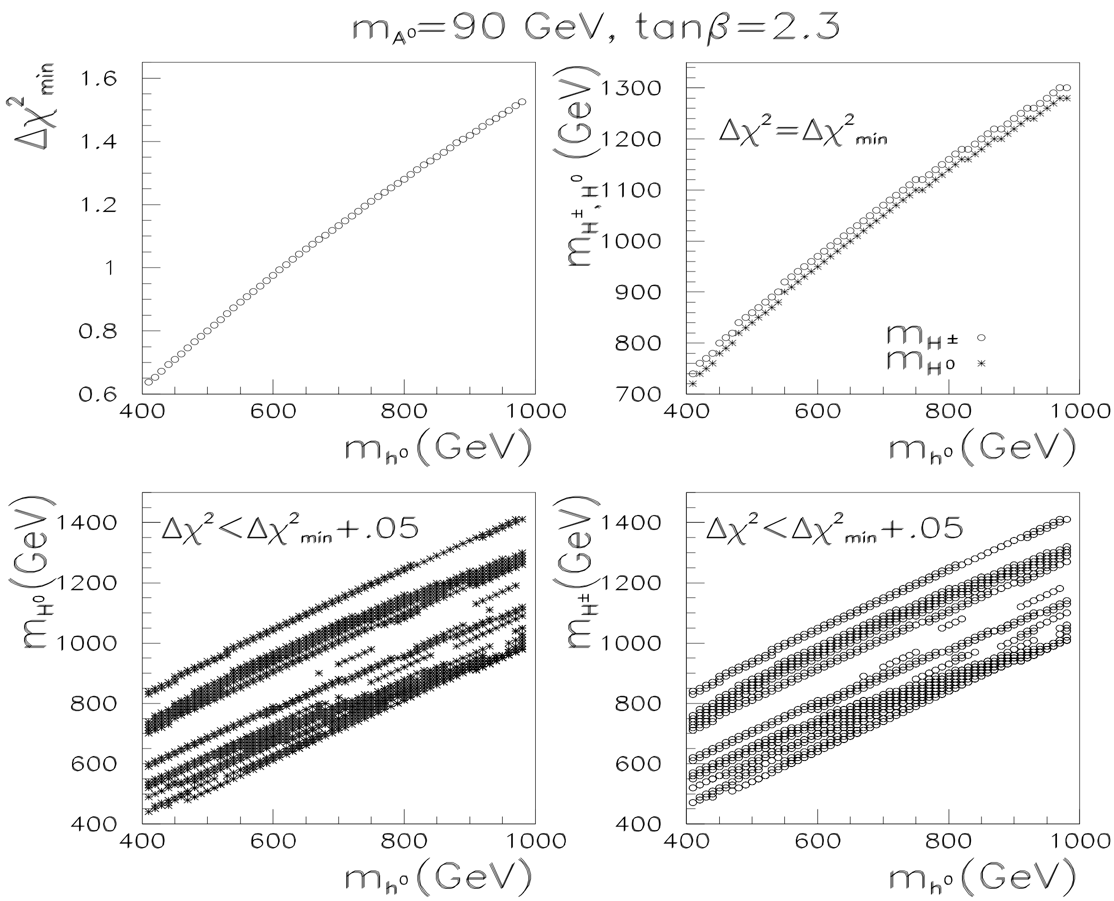

Figure 4: For $m_{A^0} = 90$ GeV and $\tan\beta = 2.3$, we plot vs. m_{h^0}: a) $\Delta\chi^2_{\rm min}$ after scanning over all $m_{H^0}, m_{H^\pm} > m_{h^0}$ and all α; b) the corresponding m_{H^0} and $m_{H^\pm}$ values; c) the values of m_{H^0} for which $\Delta\chi^2 < \Delta\chi^2_{\rm min} + 0.05$ is achieved; d) the closely correlated values of $m_{H^\pm}$ for which $\Delta\chi^2 < \Delta\chi^2_{\rm min} + 0.05$ is achieved. Here, $\Delta\chi^2_{\rm min}$ is always achieved for $\alpha = -0.1\pi$ i.e. $\beta - \alpha \sim \pi/2$ $\rightarrow$ 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 $\Rightarrow$ slow increase of $\Delta\chi^2_{\rm min}$.

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 $\Delta\chi^2_{\rm min}$ 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 $\sin^2(\beta-\alpha) \sim 1$,

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

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 $m_{H^\pm}^2 - m_{H^0}^2$ ($m_{H^\pm}^2 - m_{A^0}^2$) is always needed for good χ^2 fits.
- $\Delta\chi^2$ slowly worsens with increasing mass for next lightest Higgs because S parameter is growing logarthmically.

  To good approximation for situations of relevance,

  $$S(0) \sim \frac{1}{12\pi}\left(-\frac{5}{3} + \log\frac{m_H^2}{m_W^2}\right), \quad (4)$$

  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) 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):

$$\begin{aligned} V(\Phi_1,\Phi_2) &= -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - (\mu_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ &+ \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &+ \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right] , \end{aligned} \tag{5}$$

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

$$\begin{aligned} m_{A^0}^2 &= \frac{\mu_{12}^2}{s_\beta c_\beta} - v^2\lambda_5\,, \quad m_{H^\pm}^2 = m_{A^0}^2 + \frac{1}{2}v^2(\lambda_5 - \lambda_4) \\ \mathcal{M}^2 &= m_{A^0}^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + \lambda_5 s_\beta^2 & (\lambda_3+\lambda_4)s_\beta c_\beta \\ (\lambda_3+\lambda_4)s_\beta c_\beta & \lambda_2 s_\beta^2 + \lambda_5 c_\beta^2 \end{pmatrix} \end{aligned} \tag{6}$$

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 λ_5 is < 0 in some cases and > 0 in others):

$$V_{\rm quartic}(\Phi_1,\Phi_2) = \frac{1}{2}\lambda_1\left|\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2\right|^2 - \frac{1}{2}\lambda_5\left|\Phi_1^\dagger\Phi_2 - \Phi_2^\dagger\Phi_1\right|^2 , \tag{7}$$

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 $\sqrt{s} = 500$ 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 at the $Hb\overline{b}$ 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 $\Delta\chi^2_{\rm min}$ 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 and if Zh^0 and $\nu\overline{\nu}h^0$ not seen, $\Rightarrow$ $m_{h^0} \gtrsim 1$ 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.

- For $h=A^0$, the two heaviest Higgs bosons H^0 and $H^\pm$ have fairly large masses for $\Delta\chi^2_{\rm min}$: $600-800$ GeV for $\sqrt{s}=500$ GeV and >1 TeV for $\sqrt{s}=800$ GeV.
  * $\Rightarrow$ Although $Z\to A^0H^0$ = 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 $b\overline{b}H^0$ and $b\overline{t}H^+ + \overline{b}tH^-$ production. And, much larger $\sqrt{s}$ would also be required for H^+H^- and $t\overline{t}H^0$ production.
  * For $\sqrt{s}=800$ GeV $\Delta\chi^2_{\rm min}$ 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 ZZH^0 and WWH^0 couplings and the very modest size of $b\overline{b}H^0$ production.

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.
  - A^0h^0 = full strength; observation would be possible when kinematically allowed.

    Since our searches required $\sqrt{s} < m_{h^0} + 10$ 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 $\sqrt{s} - 10$ GeV 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 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 $L_{\rm eff} = 2500~{\rm fb}^{-1}$.
- 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.

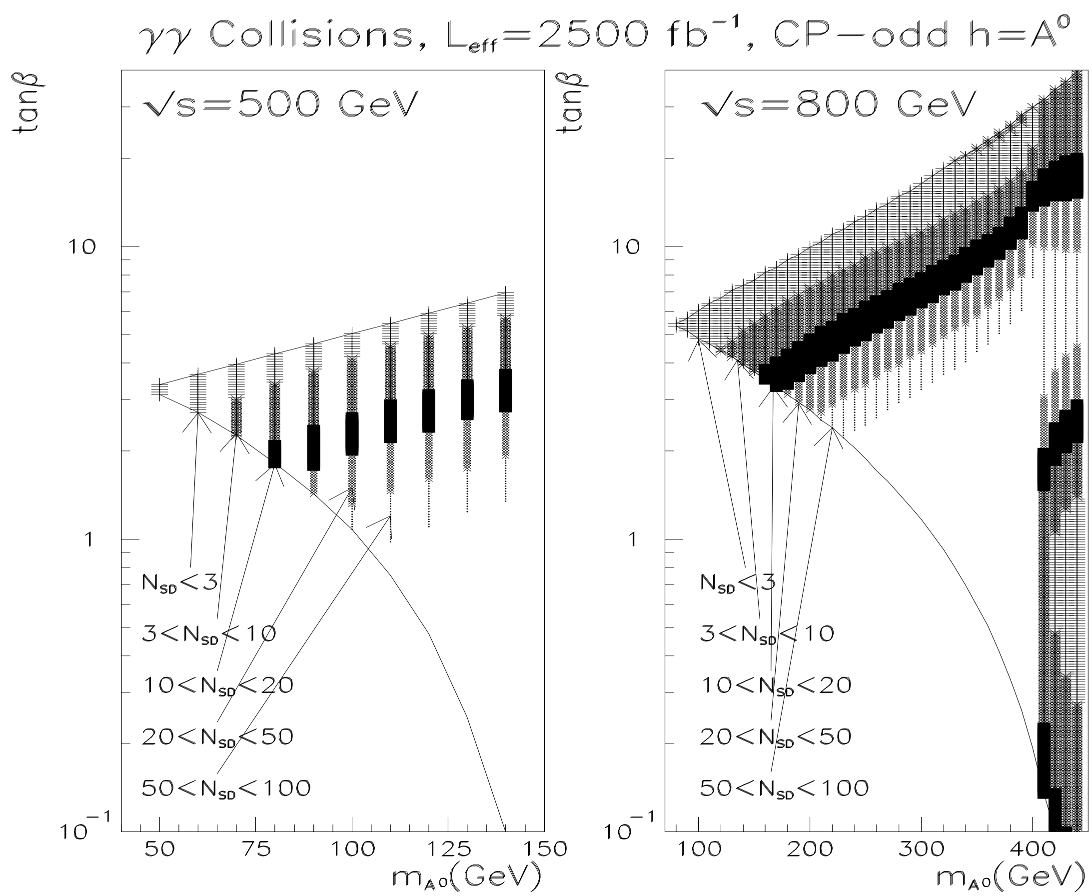

Figure 5: For $h = A^0$, we show regions of N_{SD} levels achieved for a $b\overline{b}$ signal in $\gamma\gamma$ collisions assuming $L_{\rm eff} = 2500~{\rm fb}^{-1}$ (including tagging and two-jet final state isolation) and an extremely good final state mass resolution of $\Gamma_{\rm exp} = 5$ GeV.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

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 $\Delta\chi^2_{\rm min}$) will not be accessible in $\gamma\gamma$ collisions.