IF LIGHT HIGGS BOSON(S) EXIST, IS THE NLC GUARANTEED TO FIND THEM?

J. F Gunion, NLC Berkeley Workshop (March 29 – March 31, 2000)

OUTLINE

- The CP-Violating General Two-Higgs Doublet Model
  - How a light Higgs boson can evade discovery.
- The RGE/Supersymmetry Context
  - What if there are many Higgs bosons?

1 The CP-Violating 2HDM

Two Particularly Unsettling Situations

- There is only one light Higgs boson, and it has weak WW/ZZ couplings.

  Higgs bosons with substantial WW/ZZ couplings are too heavy. (Precision EW constraints? — extra operators, e.g. from KK sector, might be present to fix up problems for otherwise-excluded portions of parameter space.)

  Will we see it?

  NB: This scenario is inconsistent with perturbativity up to high scales in SUSY context.

- There are two light Higgs bosons, one of which carries essentially all of the WW/ZZ coupling, the other one having mainly fermionic couplings.

  Will we see the 2nd Higgs?

  NB: Completely consistent with high-scale perturbativity and certainly no precision EW issue.

In either case ⇒ **need to consider $t\bar{t}h$ and $b\bar{b}h$**

Issues:

- Sum rules for fermionic couplings.
- Energy.
- Luminosity.

The Fermionic Couplings:

$$\mathcal{L} = h_i \bar{f}(S_i^f + iP_i^f \gamma_5) f \tag{1.1}$$

where the scalar (S_i^f) and pseudoscalar (P_i^f) couplings are

$$S_i^u = -\frac{m_u}{v s_\beta} R_{i2}, \qquad P_i^u = -\frac{m_u}{v s_\beta} c_\beta R_{i3}, \tag{1.2}$$

$$S_i^d = -\frac{m_d}{v c_\beta} R_{i1}, \qquad P_i^d = -\frac{m_d}{v c_\beta} s_\beta R_{i3}\,, \tag{1.3}$$

For the 2HDM, the R_{ij} are elements of the orthogonal rotation matrix

$$h = R\varphi = \begin{pmatrix} c_1 & -s_1 c_2 & s_1 s_2 \\ s_1 c_3 & c_1 c_2 c_3 - s_2 s_3 & -c_1 s_2 c_3 - c_2 s_3 \\ s_1 s_3 & c_1 c_2 s_3 + s_2 c_3 & -c_1 s_2 s_3 + c_2 c_3 \end{pmatrix} \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \end{pmatrix}, \tag{1.4}$$

[$s_i \equiv \sin\alpha_i$ and $c_i \equiv \cos\alpha_i$] which relates the original neutral degrees of freedom

$$(\varphi_1, \varphi_2, \varphi_3) \equiv \sqrt{2}(\mathrm{Re}\phi_1^0,\ \mathrm{Re}\phi_2^0,\ s_\beta \mathrm{Im}\phi_1^0 - c_\beta \mathrm{Im}\phi_2^0) \tag{1.5}$$

of $\Phi_1 = (\phi_1^+, \phi_1^0)$ and $\Phi_2 = (\phi_2^+, \phi_2^0)$ to the physical mass eigenstates h_i ($i = 1, 2, 3$). Convention: $m_{h_1} \leq m_{h_2} \leq m_{h_3}$.

The Bosonic Couplings:

$$g_{ZZh_i} \equiv \frac{g m_Z}{c_W} C_i\,, \quad g_{Zh_i h_j} \equiv \frac{g}{2c_W} C_{ij}\,. \tag{1.6}$$

$$C_i = s_\beta R_{i2} + c_\beta R_{i1} \tag{1.7}$$

$$C_{ij} = w_i R_{j3} - w_j R_{i3} \tag{1.8}$$

where $w_i = s_\beta R_{i1} - c_\beta R_{i2}$.

The Sum Rules:

Bosonic

$$C_i^2 + C_j^2 + C_{ij}^2 = 1 \quad \text{any } i, j \tag{1.9}$$

$\Rightarrow C_1 = 1$ implies $C_2 = 0$ and $C_{12} = 0$

$\Rightarrow Zh_2$ and h_1h_2 are absent even if both h_1 and h_2 are light.

Fermionic

If $C_i \to 0 \Rightarrow$

$$(\hat{S}_i^t)^2 + (\hat{P}_i^t)^2 = \left(\frac{\cos\beta}{\sin\beta}\right)^2, \quad (\hat{S}_i^b)^2 + (\hat{P}_i^b)^2 = \left(\frac{\sin\beta}{\cos\beta}\right)^2 \tag{1.10}$$

where $(f = t, b)$

$$\hat{S}_i^f \equiv \frac{S_i^f v}{m_f}, \qquad \hat{P}_i^f \equiv \frac{P_i^f v}{m_f}, \tag{1.11}$$

$\Rightarrow$ either $t\bar{t}$ or $b\bar{b}$ coupling of h_i must be big.

Independent of C_i, we have

$$\sin^2\beta[(\hat{S}_i^t)^2 + (\hat{P}_i^t)^2] + \cos^2\beta[(\hat{S}_i^b)^2 + (\hat{P}_i^b)^2] = 1\,, \tag{1.12}$$

$\Rightarrow$ **guarantee of $\boldsymbol{h_i}$ detection IF**

- $\sqrt{s} > 2m_t + m_{h_i}$ (substantially)
- luminosity is adequate.

We now consider cross sections etc. for

$$e^+e^- \to f\overline{f}h_1\,. \tag{1.13}$$

Plot **maximal** and **minimal** cross sections at fixed $\tan\beta$.

Note: $\sigma(b\bar{b}h)_{\max} \sim \sigma(b\bar{b}h)_{\min}$

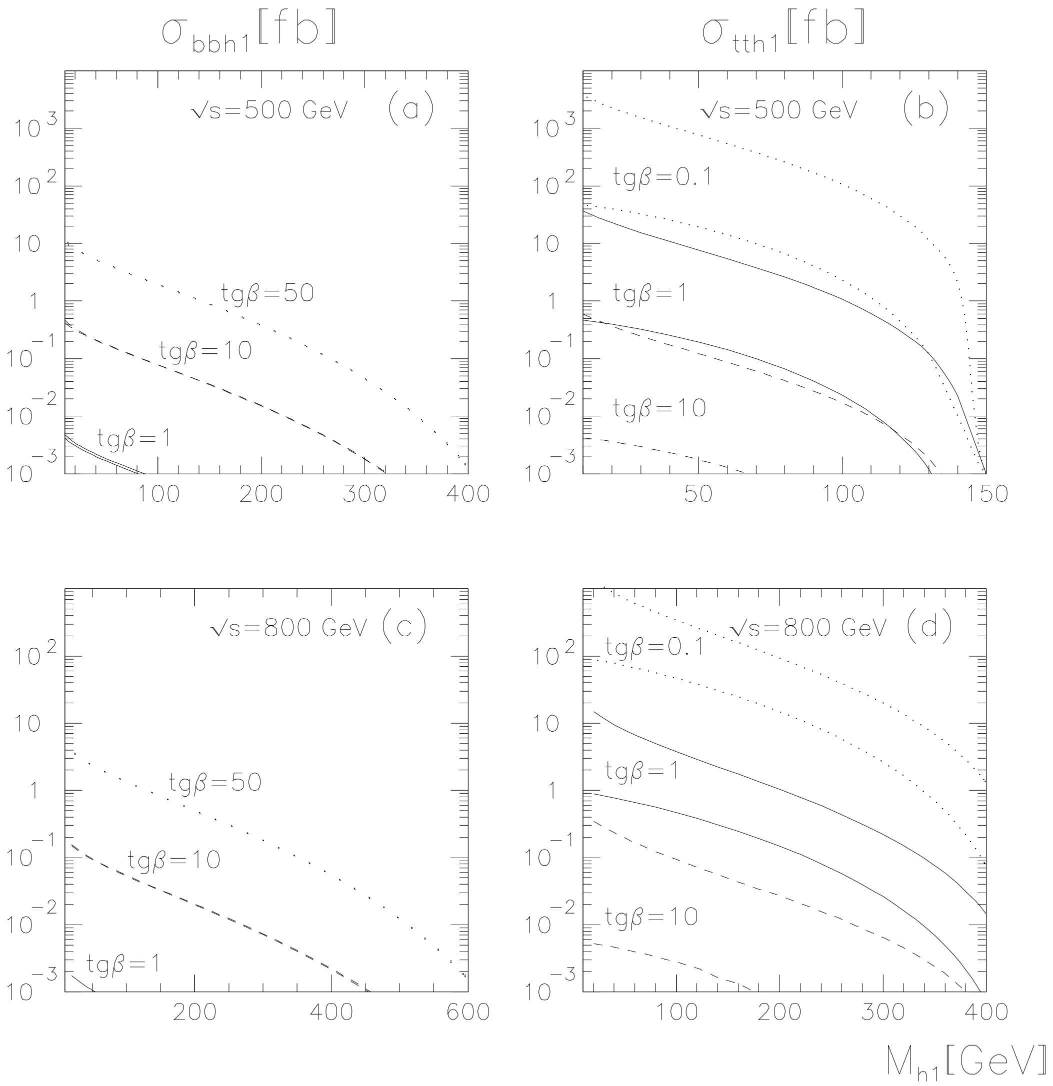

Figure 1: The minimal and maximal values of $\sigma(b\bar{b}h_1)$ and $\sigma(t\bar{t}h_1)$, obtained by scanning over α_1 and α_2 while requiring ≤ 50 Zh_1 events for $L = 500$ fb^{-1}, are plotted for $\sqrt{s} = 500$ and 800 GeV. dots: $\tan\beta = 0.1$ and $t\bar{t}h_1$; solid: $\tan\beta = 1$; dashes: $\tan\beta = 10$; dots: $\tan\beta = 50$ and $b\bar{b}h_1$. In the case of $b\bar{b}h_1$, the minimal and maximal values of the cross sections are almost the same.

Summary of Results

Inputs:

- Assume $L = 500$ fb^{-1} (optimistic/TESLA).
- Keep only α_i's such that ≤ 50 Zh_1 events.
- Assume 50 events for discovery.

Outputs:

- $\tan\beta \gg 1 \Rightarrow b\overline{b}h_1$ good.
- $\tan\beta \ll 1 \Rightarrow t\overline{t}h_1$ good subject to phase space suppression.
- $\tan\beta$ moderate? For $L = 500$ fb^{-1}, ≥ 50 events $\Rightarrow \sigma \geq 0.1$ fb. Fig. 1 $\Rightarrow$

  $\sqrt{s} = 500$ GeV

  - At $\tan\beta = 1$,

    $\sigma(b\overline{b}h_1) \ll 0.1$ fb for all m_{h_1}

    $\sigma_{\rm min}(t\overline{t}h_1)$ falls below 0.1 fb for $m_{h_1} > 70$ GeV.

    $\Rightarrow$ all but quite light h_1's could elude discovery.
  - At $\tan\beta = 10$,

    $\sigma_{\rm min}(t\overline{t}h_1) \ll 0.1$ fb

    $\sigma_{\rm min}(b\overline{b}h_1) \simeq \sigma_{\rm max}(b\overline{b}h_1)$ falls below 0.1 fb for $m_{h_1} > 80$ GeV.

    $\Rightarrow$ again, all but quite light h_1's could elude discovery.

$\sqrt{s} = 800$ GeV

– At $\tan\beta = 1$,

$t\bar{t}h_1$ observable for $m_{h_1} \lesssim 230$ GeV

– At $\tan\beta = 10$,

$\sigma_{\rm min}(t\bar{t}h_1)$ very small

$\sigma(b\bar{b}h_1) < 0.1$ fb for $m_{h_1} \sim 50$ GeV.

$\Rightarrow$ for $\tan\beta \sim 10$, only a very light h_1 is guaranteed to be observable with $L = 500$ fb^{-1}.

- **Worst case scenarios**

Impose:

(I) ≤ 50 Zh_1 events for $L = 500$ fb^{-1}

(II) LEP/LEPII upper bounds on the ZZh_1 coupling.

Seek $\tan\beta$, α_i values that minimize the maximum of $\sigma(t\bar{t}h_1)$ and $\sigma(b\bar{b}h_1)$

Find:

$\sqrt{s} = 500$ GeV:

$L > 1000$ fb^{-1} needed for 50 events even for small m_{h_1}.

As m_{h_1} increases, worst case σ_{WC} for $\sqrt{s} = 500$ GeV falls dramatically: detection of h_1 impossible for any reasonable L.

$\sqrt{s} = 800$ GeV:

$\sigma_{WC} \geq 1.7 \times 10^{-2}$ fb for $m_{h_1} \leq 100$ GeV.

$L = 3000$ fb^{-1} $\Rightarrow \sim 50$ events in the $b\bar{b}h_1$ and $t\bar{t}h_1$ modes, each.

Worst Case Plots

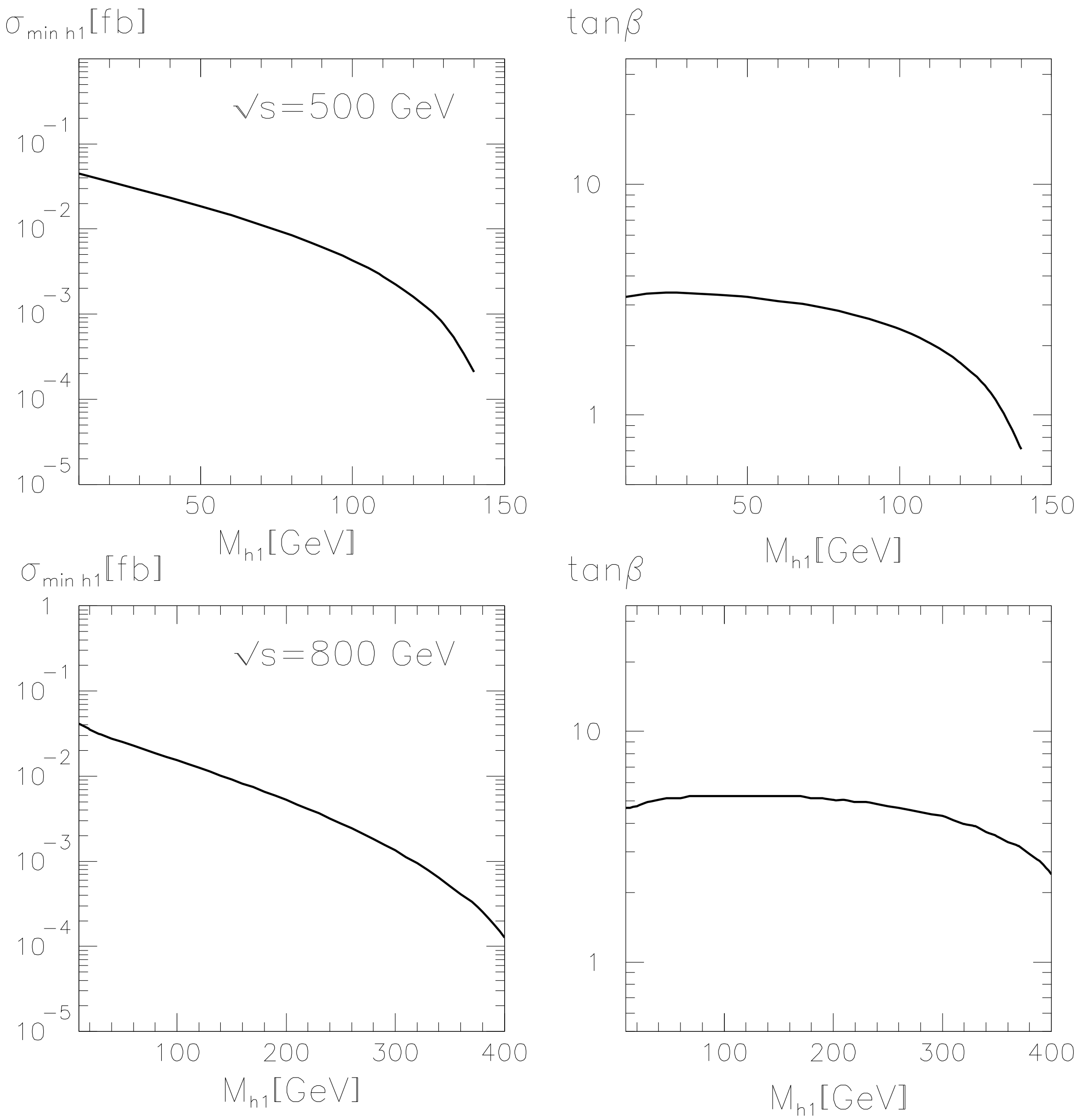

Figure 2: For $\sqrt{s} = 500$ GeV and $\sqrt{s} = 800$ GeV, $\sigma_{\rm min} \equiv \min_{\tan\beta}\left(\min_{(\alpha_1,\alpha_2)}\left\{\max[\sigma_{\rm min}(b\overline{b}h_1), \sigma_{\rm min}(t\overline{t}h_1)]\right\}\right)$ and corresponding $\tan\beta$ vs. m_{h_1} from scanning over $\tan\beta$ and (α_1, α_2) subject to constraints (I) and (II).

Moderate $\tan\beta$ is the killer. Often (not always) h_1 is nearly pure CP-odd in worst case.

Determine the $\tan\beta$ range for which light Higgs could evade discovery in any mode for a given L.

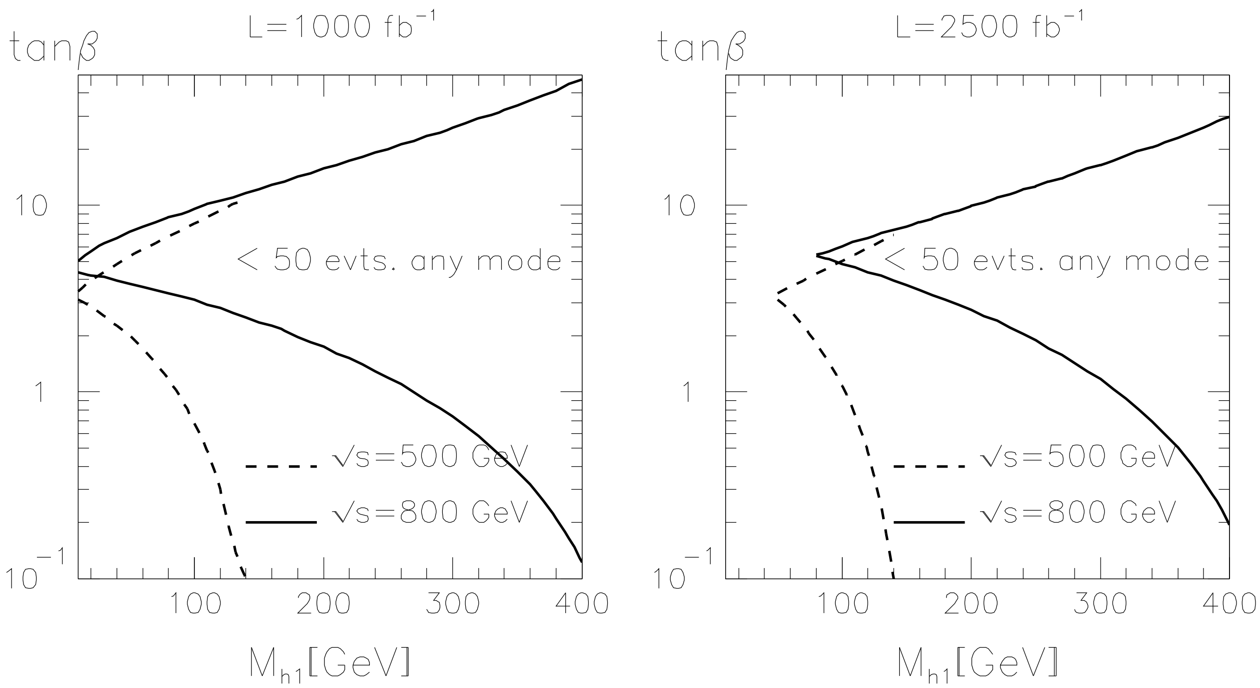

Figure 3: For $\sqrt{s} = 500$ GeV (dashes) and $\sqrt{s} = 800$ GeV (solid) the maximum and minimum $\tan\beta$ values between which $t\bar{t}h_1$, $b\bar{b}h_1$ and Zh_1 final states can (for some choice of (α_1, α_2) consistent with constraint (II)) all have fewer than 50 events assuming (a) $L = 1000$ fb^{-1} or (b) $L = 2500$ fb^{-1}.

The $L = 1000$ fb^{-1} wedge begins at $m_{h_1} \sim 25$ GeV

The $L = 2500$ fb^{-1} wedge begins at $m_{h_1} \sim 80$ GeV for $\sqrt{s} = 800$ GeV.

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

2 The General SUSY Context

MSSM

- One Higgs guaranteed to be light. Guaranteed to be observable if other Higgs bosons are heavy ($C_1 \to 1$).
- If a 2nd Higgs is light, $\Rightarrow$ will find one or both ($C_1^2 + C_2^2 + C_{12}^2 = 1$). Need to know only a few other Higgs and rely on $b\overline{b}$ decays.

Most General SUSY

- **Sum Rule:**

$$\sum_i C_i^2 m_{h_i}^2 = \langle M^2 \rangle \,. \tag{2.1}$$

Constraints on $\langle M^2 \rangle$

– Precision electroweak suggests $\langle M^2 \rangle \lesssim 200 - 250$ GeV.

– In the SUSY context,

$$\langle M^2 \rangle = \lambda^2 v^2 \equiv m_B^2 \,, \tag{2.2}$$

λ is a quartic-style coupling constant and $v = 246$ GeV.

∗ RGE $\Rightarrow$ λ grows with energy scale
$\Rightarrow$ bound it by assuming it remains perturbative up to Λ.

∗ In general SUSY models with arbitrary particle content and Higgs triplet as well as singlet fields, $m_B \leq 200$ GeV for $\Lambda \sim 10^{17}$ GeV.

But, even this may not guarantee discovery in the Worst Case.

Defining the worst case

- Many Higgs fields that are singlets under the ordinary gauge groups.

  e.g. string model with many extra U(1)'s or multi-singlet Higgs sector.

  (Singlets are good since they maintain $\rho = 1$, do not influence gauge unification, *etc.*.)

- Arrange for all mass eigenstates to decay to many channels ($b\overline{b}$, invisible, $c\overline{c}$, gg, $\tau^+\tau^-$, $\ldots$).

  $\Rightarrow$ signal in any one channel smaller compared to background than when $b\overline{b}$ decay is dominant.

  For appropriate mass matrix, one can realize this ugly possibility.

- Imagine that the Higgs eigenstates are spread out in mass at intervals smaller than the experimental mass resolution that can be achieved.

  $\Rightarrow$ roughly, a Higgs boson every $10 - 15$ GeV for planned resolutions.

  ($\Rightarrow$ improve if sufficiently concerned about this scenario?)

- $\Rightarrow$ broad continuum excess in $e^+e^- \to ZX$ as a function of m_X in many different final states X.

  In the very worst case, this continuum would have a shape that mimics the relevant background.

- Note: worst case us **not** when all the SUSY Higgs bosons are pushed to maximum mass (allowed by above sum rule) and share equally the ZZ coupling-squared, $\Rightarrow$ sum to apparent single Higgs with SM coupling.

The WC signal and Analysis

- Consider the (Zh) $e^+e^- \to ZX$, $Z \to e^+e^-, \mu^+\mu^-$, and (ZZ-fusion) $e^+e^- \to e^+e^-X$ channels with X treated inclusively.

  In the e^+e^-X final state, Zh and ZZ-fusion are separated by cuts on the e^+e^- mass.

- Assume $\sqrt{s} = 500$ GeV, for which $\sigma_{\rm SM}$ (Zh mode) is substantial out to $m_h \sim 200$ GeV. ($\sigma_{\rm SM}$ falls from 70 fb at low m_h to 42 fb at $m_h \sim 200$ GeV.)

  We will confine ourselves to the ≤ 200 GeV window in m_h in discussing experimental sensitivity.

- Since it seems overly perverse to assume that $C_i^2\sigma_{\rm SM}(m_{h_i})$ follows the background, assume C_i^2 constant from $m_h^{\rm min}$ to $m_h^{\rm max}$ (taking continuum limit, $C^2(m_h)$, of discrete overlapping spectrum) $\Rightarrow$

$$\langle M^2\rangle = \frac{1}{3}\left([m_h^{\rm max}]^2 + m_h^{\rm max}m_h^{\rm min} + [m_h^{\rm min}]^2\right) . \qquad (2.3)$$

  – maximal spread: $m_h^{\rm min} = 0$, (2.3) with $\langle M^2\rangle \leq [200~{\rm GeV}]^2 \Rightarrow m_h^{\rm max} = \sqrt{3\langle M^2\rangle} = 340$ GeV.

  – If LEP2 data eventually allows us to say that $C^2(m_h)$ is small for $m_h \leq 70$ GeV (say) **in continuum spread-out sense**, then (2.3) with $\langle M^2\rangle = [200~{\rm GeV}]^2$ requires $m_h^{\rm max} = 300$ GeV.

- Use JFG, Han Sobey analysis (Phys. Lett. **B429**, 79 (1998); hep-ph/9801317) available for $70-200$ GeV region.

  Various resolutions in EM calorimetry and tracking were considered: Electromagnetic calorimeter:

  I: NLC/EM $\Delta E/E = 12\%/\sqrt{E} \oplus 1\%$;

  II: CMS/EM $\Delta E/E = 2\%/\sqrt{E} \oplus 0.5\%$.

  Tracking:

  III: NLC/tracking $\Delta p/p = 2\times 10^{-4} p \oplus 1.5\times 10^{-3}/\sqrt{p}\sin^2\theta$;

  IV: SJLC/tracking $\Delta p/p = 5\times 10^{-5} p \oplus 10^{-3}$,

  with p in GeV. SJLC denotes "super-JLC" detector design.

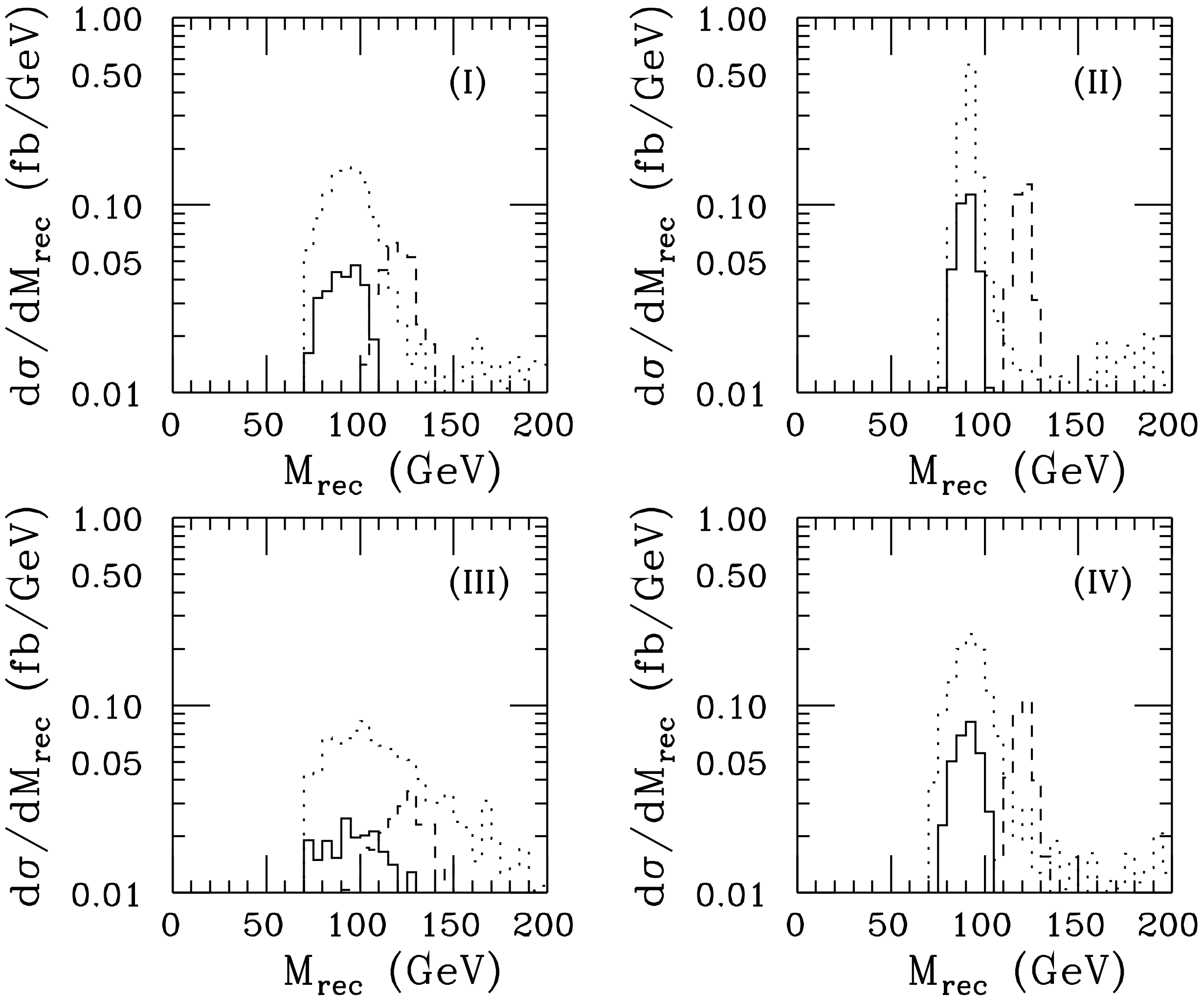

Figure 4: Recoil mass distributions for $e^+e^- \to e^+e^-X$ at $\sqrt{s} = 500$ GeV. The solid and dashed curves give the Zh signal for $m_h = 90$ and 120 GeV, respectively. The dotted line is the summed SM background. Results for the different energy/momentum resolution, cases I-IV, are shown in the four different panels. Strong Cuts have been imposed.

Note how much even the $m_h = 90$ and 120 GeV signals overlap for standard NLC EM resolution for the e^+e^- channel and the very poor $\mu^+\mu^-$ channel result for NLC tracking! **SJLC tracking and/or CMS EM is needed to get resolution down even close to ~ 10 GeV.**

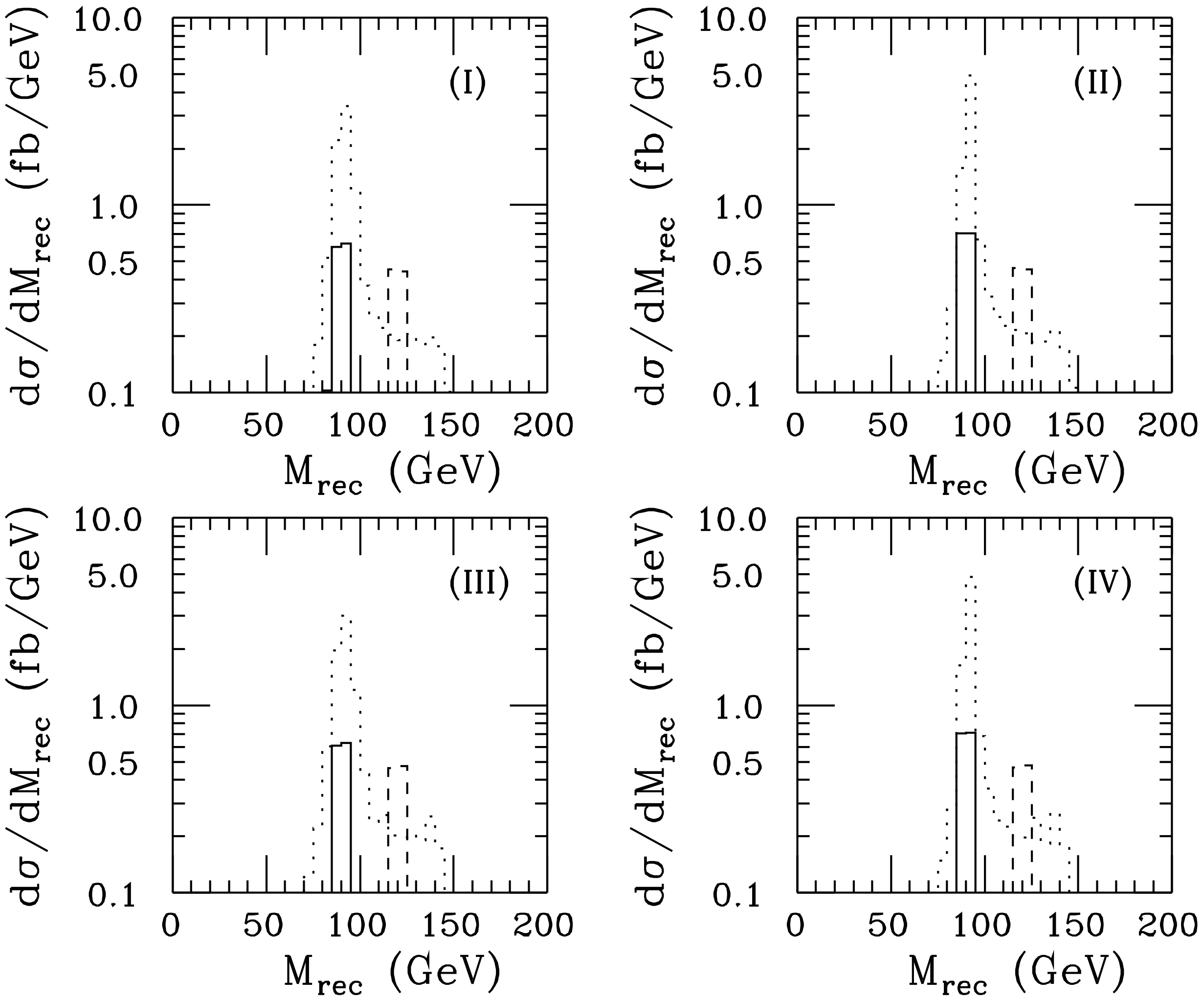

Figure 5: Recoil mass distributions for $e^+e^- \to e^+e^-X$ at $\sqrt{s} = 250$ GeV. The solid and dashed curves give the Zh signal for $m_h = 90$ and 120 GeV, respectively. The dotted line is the summed SM background. Results for the different energy/momentum resolution, cases I-IV, are shown in the four different panels. Strong Cuts have been imposed.

Resolutions at $\sqrt{s} = 250$ GeV are much better. If upper bound on $\langle M^2 \rangle$ could be sufficiently lowered that running at lower energy would not miss much of the spectrum, $\Rightarrow$ use $\sqrt{s} = 250$ GeV.

We have resolutions of order 10 GeV for standard NLC EM and NLC tracking choices.

- For $C^2(m_h)$ =constant,
  - Without limits on $C^2(m_h)$ from LEP2, $m_h^{\max} = 340$ GeV $\Rightarrow$ a fraction $\boldsymbol{f = 0.4}$ of uniform spectrum (with significant ZZ coupling) would lie in the **70 − 200 GeV** region.
  - If LEP2 limits strong, then $m_h^{\min} = 70$ GeV and $m_h^{\max} = 300$ GeV $\Rightarrow$ $\boldsymbol{f = 0.55}$ in **70 − 200 GeV** mass region.
  - Alternatively, consider only **100 − 200 GeV** mass interval (so as to avoid Z region with largest background) $\Rightarrow$ $\boldsymbol{f \sim 0.3}$ for $m_h^{\min} = 0$ and $\boldsymbol{f \sim 0.43}$ for $m_h^{\min} = 70$ GeV, respectively, for $\langle M^2 \rangle = [200 \text{ GeV}]^2$.
- Table 1 shows results for $L = 500\ \text{fb}^{-1}$ in $e^+e^- \to e^+e^-X$ channel assuming all $C^2(m_h)$ weight is in indicated window.

Table 1: Approximate S, B and $S/\sqrt{B}$ values for the Zh and ZZ-fusion contributions to $e^+e^- \to e^+e^-h$, after integrating the M_X recoil mass spectrum from (a) 70 GeV to 200 GeV and (b) 100 GeV to 200 GeV, assuming that many Higgs bosons are distributed evenly throughout the interval and have $\sum_h g^2_{ZZh} = g^2_{ZZh_{SM}}$. Results are for $\sqrt{s} = 500$ GeV, $L = 500\ \text{fb}^{-1}$.

M_X	Zh			ZZ-fusion		
Interval	S	B	$S/\sqrt{B}$	S	B	$S/\sqrt{B}$
70 − 200	**675**	**3170**	**12.0**	**2615**	**80100**	**9.2**
100 − 200	**678**	**1350**	**18.5**	**2300**	**39600**	**11.5**

ZZ-fusion channel not good because of very small S/B.

For Zh channel, must **now include fraction $\boldsymbol{f}$ in the interval and sum over $\boldsymbol{Z \to e^+e^-}$ and $\boldsymbol{Z \to \mu^+\mu^-}$.**

- Including the fraction f and summing the e^+e^- and $\mu^+\mu^-$ Zh channels, $\boldsymbol{L = 500\ \mathrm{fb}^{-1}}$ $\Rightarrow$:
  - $S \sim 1350f$ with a background of either $\boldsymbol{B = 6350}$ or $\boldsymbol{B = 2700}$, for $\mathbf{70 - 200\ GeV}$ and $\mathbf{100 - 200\ GeV}$ windows, respectively.
  - $\Rightarrow$ we have to detect the presence of a broad $\boldsymbol{\sim 21\% f}$ $\boldsymbol{(\sim 50\% f)}$ excess over background, respectively.

    For $\boldsymbol{f \sim 0.4 - 0.55}$ in 1st case and $\boldsymbol{f \sim 0.3 - 0.43}$ in 2nd case, $\Rightarrow$ probably ok.
  - Nominally, $S/\sqrt{B} \sim$ **17f** and $\boldsymbol{\sim 26f}$ for the $\mathbf{70 - 200\ GeV}$ and $\mathbf{100 - 200\ GeV}$ windows in M_X, respectively.
- $\boldsymbol{L = 50\ \mathrm{fb}^{-1}}$ $\Rightarrow \sqrt{10}$ loss:
  - $S/\sqrt{B} =$ **5.3f** and $\boldsymbol{8.2f}$ level in the Zh (with $Z \to e^+e^- + \mu^+\mu^-$) channel for the $\mathbf{70 - 200\ GeV}$ and $\mathbf{100 - 200\ GeV}$ intervals, respectively, which is borderline for $\boldsymbol{f \sim 0.4 - 0.55}$ and $\boldsymbol{f \sim 0.3 - 0.43}$, respectively.
- **Need $\boldsymbol{L = 200\ \mathrm{fb}^{-1}}$ to have a $\boldsymbol{S/\sqrt{B} > 5}$ broad enhancement signal for $\boldsymbol{f \sim 0.5}$.**

- Could we analyze the spectrum bin-by-bin?

Table 2: Approximate S, B and $S/\sqrt{B}$ values for Zh (with $Z \to e^+e^- + \mu^+\mu^-$) in each of the thirteen 10 GeV bins in M_X from 70 to 200 GeV, assuming that $S \sim 1350$ events, from Higgs bosons with $\sum_h g^2_{ZZh} = g^2_{ZZh_{SM}}$, are distributed equally among these bins. We assume $\sqrt{s} = 500$ GeV, $L = 500$ fb^{-1}.

Bin No.	1	2	3	4	5	6	7	8–13
S	104	104	104	104	104	104	104	104
B	1020	1560	1440	734	296	162	125	~ 130
$S/\sqrt{B}$	3.3	2.6	2.7	3.8	6.0	8.2	9.3	9.1

Distribute the roughly 1350f signal events (for Zh with $Z \to e^+e^-$ and $\mu^+\mu^-$) equally in the thirteen 10 GeV bins from 70 to 200 GeV. S for $f = 1$, B and corresponding $S/\sqrt{B}$ values are given in Table 2, assuming all $C^2(m_h)$ weight is between 70 and 200 GeV.

Note that both S and $S/\sqrt{B}$ must be reduced by f.

- **$L = 500$ fb^{-1} would yield $S/\sqrt{B} > 3$ only for the $M_X \gtrsim 120$ GeV bins when $f \sim 0.5$.**
- **With only $L = 200$ fb^{-1}** (as might be achieved after a few years of running at a lower luminosity design), this **bin-by-bin type of analysis would not be possible for 10 GeV bins if $f \sim 0.5$.**

  $\Rightarrow$ need 500 fb^{-1}.

Detector Implications

- A closer look at advantages associated with improving the planned resolutions for electrons and muons is probably worthwhile.
- Perhaps one could look for the broad overall signal, and if seen then upgrade the detectors so that a refined m_X bin-by-bin analysis would be easier.
- Of course, it could be that the Higgs are spaced so that a 20 GeV resolution would not resolve them whereas a 10 GeV resolution would. $\Rightarrow$ In this case it would have been nice to have the resolution all along!

Discussion

- How many Higgs force us into the continuum scenario?

  For resolutions planned for electrons and muons $\Delta M > 20$ GeV.

  $\Rightarrow$ something like 5 Higgs distributed from 70 to 200 GeV would be a problem.

  The Cvetic, Langacker, ... analysis of the Lykken *et al.* models suggests that such a number is very possible, perhaps even likely, in string models.

- Still, for $L \geq 200~\text{fb}^{-1}$ we have a no-lose theorem for seeing the broad overall excess at a $\sqrt{s} = 500$ GeV NLC.

  For bin-by-bin analysis we really would need $L = 500~\text{fb}^{-1}$.

- It would be good to extend the background calculations to higher m_X to see if the high mass interval adds much to the signal.

- Can we improve by using non-leptonic Z decays? *i.e.* are backgrounds really too large.

  $\Rightarrow$ need very complex and detailed study.

  A study of the $b\bar{b}X$ mode might be worthwhile. One needs to look at what cuts will optimize S/B.

3 CONCLUSIONS

- CP-violating 2HDM can present unpleasant possibilities.
- Even SUSY/RGE context with many Higgs could require **high** luminosity.