Search Strategies for non-Standard Higgses at e^+e^- Colliders

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(ICHEP 2000), PA 11

Motivation:

SM: if no new physics below M_U, M_{Pl}
$\Rightarrow$ $m_H \sim 130 - 200$ GeV, in perfect agreement with EW data

$m_H \sim 130 - 200$ GeV:

* difficult for Tevatron („3σ")
* OK for LHC $gg \to H \to \gamma\gamma$ or $t\bar{t}H + WH$
* easy for e^+e^- LC $e^+e^- \to Z + X$
  even for a SM-like Higgs with invisible (fermiophobic) decays

LEP $\Rightarrow$ $m_H \gtrsim 113$ GeV
for lower m_H – limit on g_{ZZh}

However: Higgs sector may be more complicated

Main Concern – a light „bosophobic" Higgs with suppressed ZZh ??

- adding singlets
- adding doublets
- conclusions

☆ Adding singlets $(\rho = 1)$

no particular benefit but
can get diluted ZZh couplings

Suppose many singlets that mix with the SM Higgs and share ZZh coupling, e.g.

$$g_{ZZh_i} = \frac{g\, m_Z}{\cos\theta_W}\, C_i\,, \qquad |C_i| \ll 1$$

which spread over a mass range, $\Delta m_{ij} < \delta_{exp}$

crucial sum rule (Espinosa Gunion PRL 82(99))

$$\sum_i C_i^2\, m_{h_i}^2 \leq (200 - 250\ \mathrm{GeV})^2$$

if no extra physics below M_U.

- very difficult for hadron colliders
- at $\sqrt{s} = 500$ GeV e^+e^- LC
  $L \sim 200\ fb^{-1}$ enough to see a broad excess in M_X in $e^+e^- \to Z + X$

☆ Adding doublets (again $g = 1$)

ex MSSM contains two doublets

$\Rightarrow \underbrace{h, H}, \underbrace{A}, H^{\pm}$

CP +1 −1

$m_h \lesssim 130-135$ GeV

adding more singlets, e.g. NMSSM may push up to ~150 GeV

LEP2 limits significant: $m_{h,A} \gtrsim 90$ GeV

low tan β excluded

- Allowing for CP violation in SUSY sector
  $\Rightarrow$ brought in loops to Higgs
  limits may be weakened
- if $C_h \simeq 0 \Rightarrow |C_{hA}| \simeq 1$, $m_h \sim m_A$
  Higgs pair production
- invisible decays ($h \to \chi\chi$)
  rely more heavily on
  $Zh + ZH$ contributions to $Z + X$

$\Rightarrow$ SUSY: quite constrained Higgs sector
will allow discovery of a Higgs.

Generic 2HDM – type II

- $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}$ $\qquad$ $\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$

- Z_2: $\Phi_2 \to -\Phi_2$, $u_{R_i} \to -u_{R_i}$
  to avoid FCNC

- Z_2 broken softly by $\mu^2 \Phi_1^\dagger \Phi_2$ + h.c.

  → CP can be broken (Weinberg)

  3x3 mixing

- $(\mathrm{Re}\,\phi_1^0, \mathrm{Re}\,\phi_2^0, s_\beta \mathrm{Im}\,\phi_1^0 - c_\beta \mathrm{Im}\,\phi_2^0) \to (h_1, h_2, h_3)$

  ↑ no definite CP

- Yukawas not invariant under CP

  $$\mathcal{L} = \frac{m_f}{v} h_i \bar{f} (S_i^f + P_i^f \gamma_5) f$$

- couplings to gauge bosons

  $$g_{ZZh_i} = \frac{g m_Z}{\cos\theta_W} C_i$$

  $$g_{Zh_ih_j} = \frac{g}{2\cos\theta_W} C_{ij}$$

C_i, C_{ij}, S_i^f, P_i^f depend on $\tan\beta$

and $\alpha_1, \alpha_2, \alpha_3$ mixing angles

★ Sum rules for the couplings:

suppose that the lightest Higgs boson h_1 has suppressed couplings to Z-boson

$$|C_1| \ll 1.$$

Sum rule

Mendez Pomarol '91
Gunion Grzadkowski Haber, JK '97

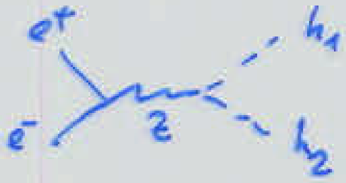
$$\boxed{C_i^2 + C_j^2 + C_{ij}^2 = 1.}$$

if for the next-to-lightest $|C_2| \ll 1$

$$\Rightarrow \quad |C_{12}| \simeq 1$$

a) if $m_1 + m_2 \lesssim \sqrt{s}$

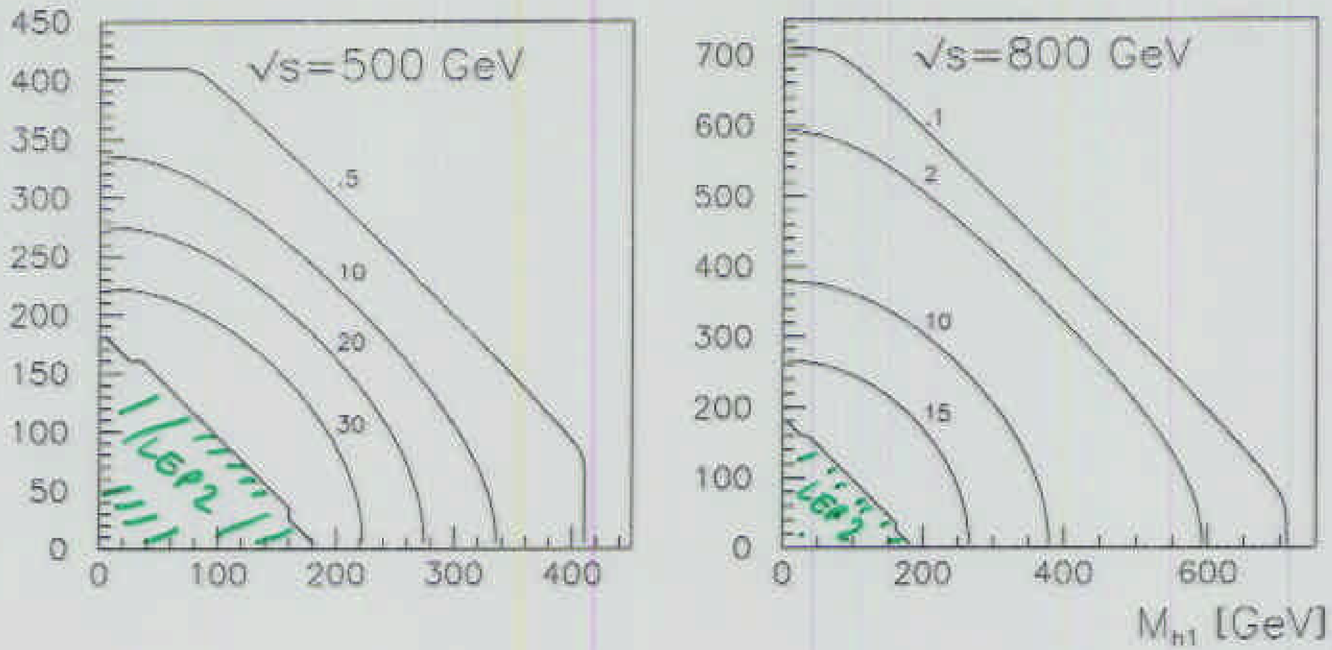
$\Rightarrow$ Higgs pair production



Grzadkowski, Gunion, JK, PL B 480

$m_{h_1} + m_{h_2} < \sqrt{s}$

$\sigma(h_1 h_2)$ in fb



both can be seen up to the kinematical limit

b) two light Higgses with one $C_i = 1$

can we see the other ?

or only one light Higgs* with $C_1 \neq 0$

sum rules for Yukawa couplings

Gunion, Grzadkowski, Kalinowski PRD 60 (99)

$$\mathcal{L} \ni \frac{m_f}{v} h_i \bar{f} \left(S_i^f + i P_i^f \gamma_5 \right) f$$

$$(S_i^t)^2 + (P_i^t)^2 = \cot^2\beta \left[1 + \frac{C_i}{\cos^2\beta} \left(2 S_i^b \cos^2\beta + C_i \right) \right]$$

$$(S_i^b)^2 + (P_i^b)^2 = \tan^2\beta \left[1 + \frac{C_i}{\sin^2\beta} \left(2 S_i^t \sin^2\beta + C_i \right) \right]$$

$$\boxed{\sin^2\beta \left((S_i^t)^2 + (P_i^t)^2 \right) + \cos^2\beta \left((S_i^b)^2 + (P_i^b)^2 \right) = 1.}$$

for $C_i = 0$, $S_i^2 + P_i^2 \longrightarrow P_{A^0}^2$

for $|C_i| = 1$ $S_i^2 + P_i^2 \longrightarrow 1$

$\tan\beta \to 0, \infty$

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* such a scenario consistent with EW precision fits
Chankowski, Krawczyk, Zochowski EPJ 11 (99) 661

Chankowski, Krawczyk, Zochowski
EPJ 11 (99) 661

$m_h = 20$ GeV

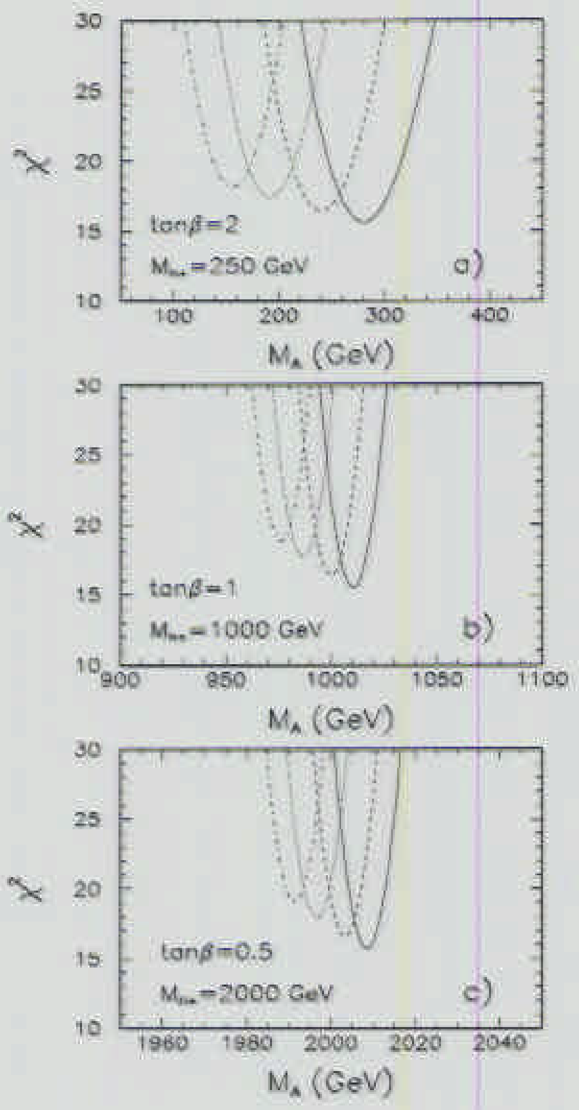


Figure 5: χ^2 for $M_h = 20$ GeV and $\sin^2(\beta - \alpha) = 0$ as a function of M_A for different low and intermediate values of $\tan\beta$ and different H^+ masses. Solid, dashed, dotted and dot-dashed lines correspond to M_H =90, 200, 500 and 1000 GeV, respectively; $m_t = 174$ GeV.

$m_A = 10$ GeV

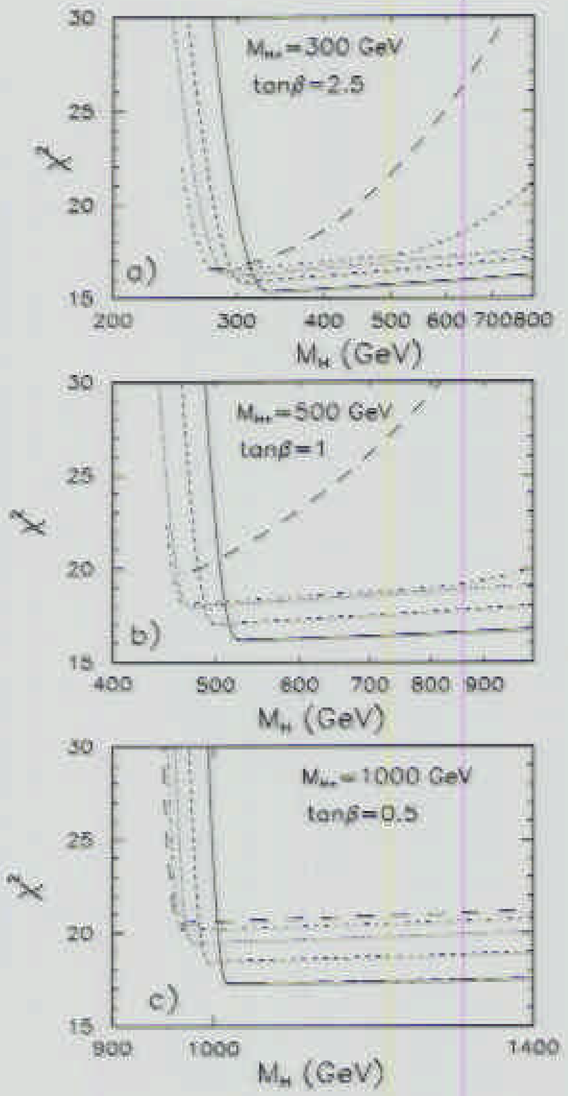


Figure 10: χ^2 as a function of M_H for different low and intermediate values of $\tan\beta$ and different H^+ masses, for $M_A = 10$ GeV. Solid, dashed, dotted, dot-dashed and long-dashed lines correspond to M_h equal (90, 150, 200, 250, 275) GeV, (90, 200, 400, 450, 475) GeV and (90, 250, 500, 750, 940) GeV for panels a, b and c, respectively.

in a general search must consider

three processes

a) $e^+e^- \to Z h_1$ ($\hookrightarrow f\bar{f}$)

b) $e^+e^- \to h_1 h_2$ ($\hookrightarrow f\bar{f}$)

c) $e^+e^- \to f\bar{f} h_1$

Pokorski, JK '89

Calculate $\frac{d\sigma}{dx_1\,dx_2}$

$x_1 = 2E_f/\sqrt{s}$

$x_2 = \frac{2E_{\bar{f}}}{\sqrt{s}}$

and assuming that Zh_1 suppressed

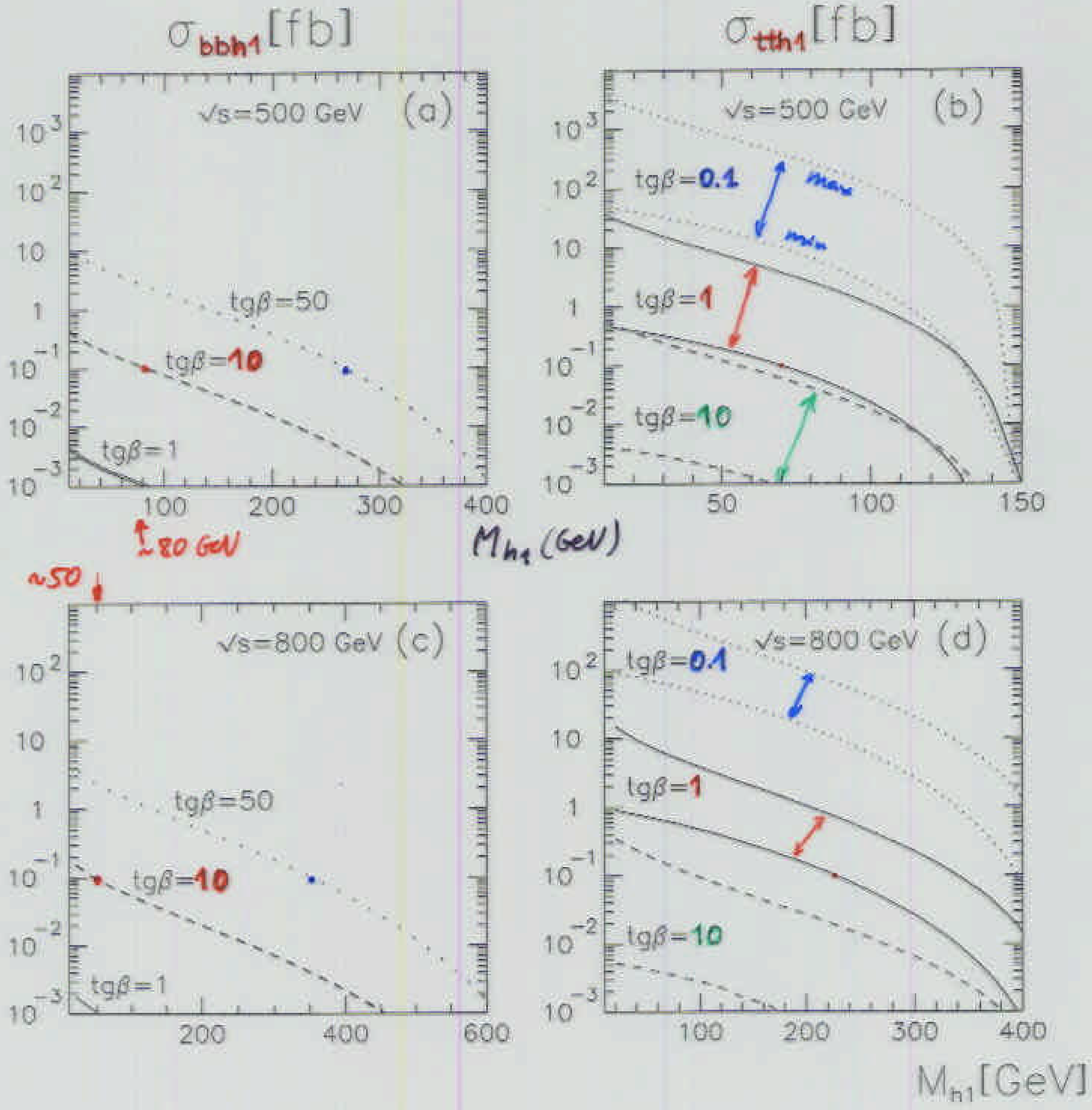
derive σ_{min} and σ_{max}

scanning the mixing angles $(\alpha_1, \alpha_2, \alpha_3)$

assuming $|\epsilon_i| < \Delta$ (i.e. # Zh_i events ≤ 50 for $\mathcal{L} = 500\ fb^{-1}$)

calculate σ_{min} and σ_{max} scanning over mixing angles

take $\sigma = 0.1$ fb as an observability criteria



how much luminosity needed to discover h_1 ?

the worst-case scenario:

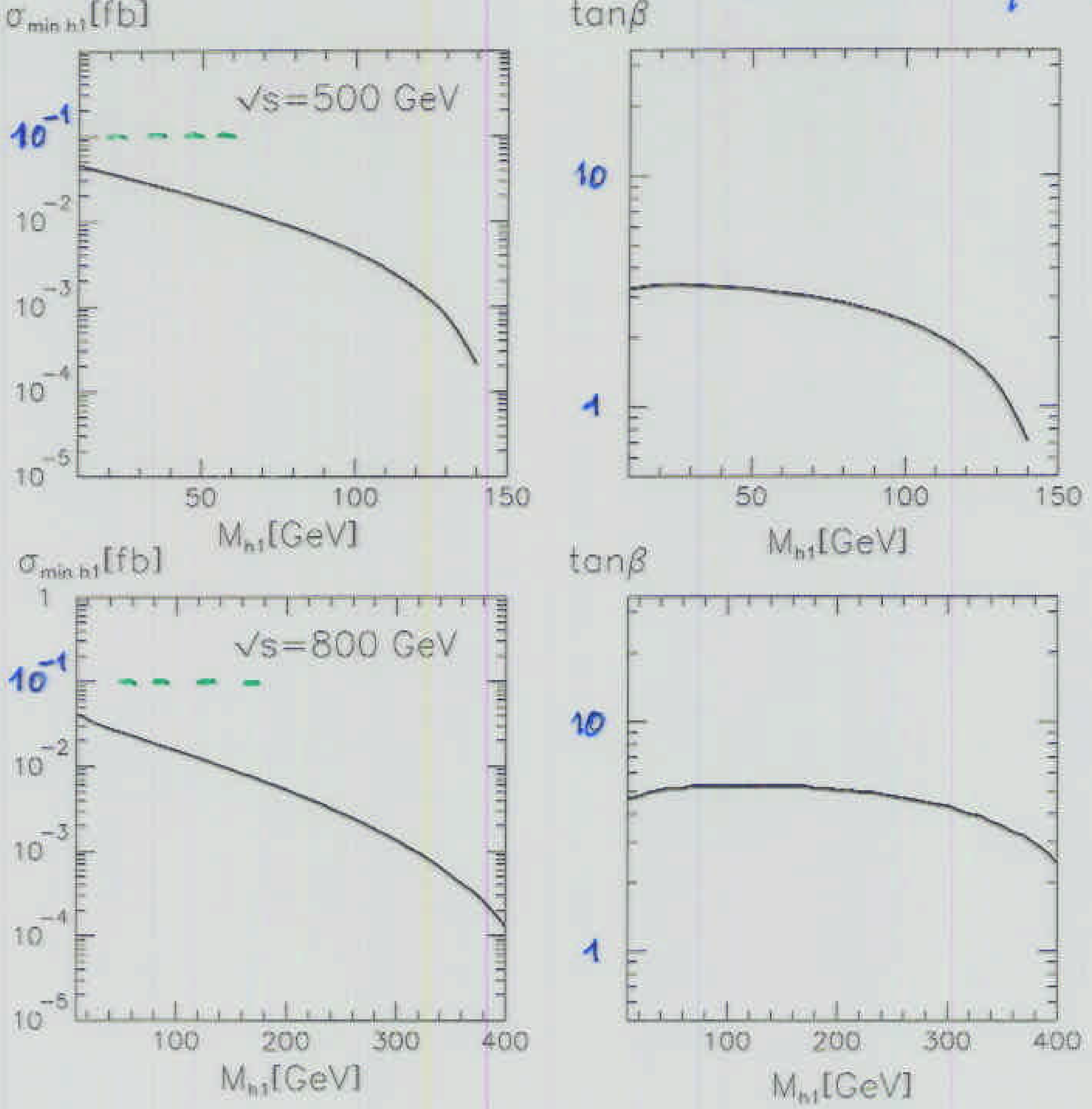
$$\sigma_{min} \equiv \min_{\alpha_i} \left(\max \sigma(b\bar{b}h_1), \sigma(t\bar{t}h_1) \right)$$

and find $\tan\beta$ for which σ_{min} is smallest.

Gunion Grzadkowski Kalinowski, PLB 480

$\sigma_{min} \leq 0.1$ fb

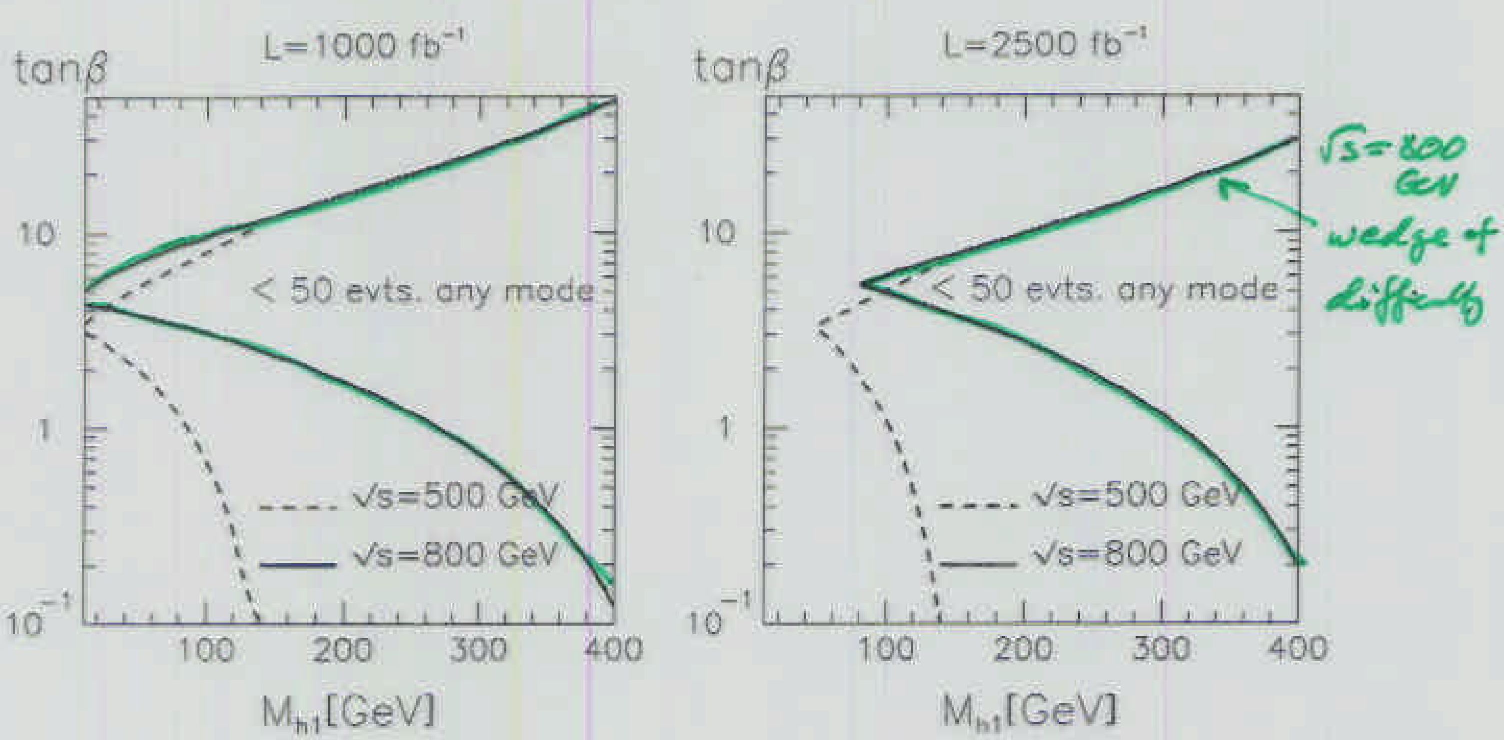
intermediate $\tan\beta$ difficult.



e^+e^- LC

high luminosity needed

Gunion Grzadkowski
[illegible] PLB 480



even at $\mathcal{L} = 2500\ fb^{-1}$, wedge begins at $m_{h_1} \sim 80$ GeV @ $\sqrt{s} = 800$ GeV

hadron colliders ⇒ even more difficult

Let's hope that EW data really do indicate a relatively light Higgs

★ Measuring Yukawas

1. if $\tan\beta \ll 1$ or $\tan\beta \gg 10$

* then $c_i \approx 0$ is the most optimistic

either top or bottom Yukawa enhanced

* for $|c_i| \approx 1$, both Yukawa → SM

$\sigma(b\bar{b}h)$ too small

$\sigma(t\bar{t}h) > 0.1$ for $m_H < 70$, 230

$\sqrt{s} = 500$, 800

2. $\tan\beta \sim$ moderate

* if $c_i \approx 0$, Higgs may not be observed

* for $|c_i| \sim 1$, σ_{min} approach $\tan\beta = 1$ values.

similar mass range like above.

Adding extra singlet

Φ_1, Φ_2, S

$$\left(\mathrm{Re}\,\phi_1^0,\ \mathrm{Re}\,\phi_2^0,\ s_\beta\,\mathrm{Im}\,\phi_1^0 - c_\beta\,\mathrm{Im}\,\phi_2^0,\ \mathrm{Re}\,S,\ \mathrm{Im}\,S\right) \to$$

$$\to \left(h_1, h_2, h_3, h_4, h_5\right)$$

↑ 5×5 mixing

Sum rules:

$$C_i^2 + C_j^2 + C_{ij}^2 = \delta_{ij}$$ can be $\ll 1$

$$\sin^2\beta\left[(S_i^t)^2 + (P_i^t)^2\right] + \cos^2\beta\left[(S_i^b)^2 + (P_i^b)^2\right] = R_i^2$$

↑ SU(2) content of h_i
can be $\ll 1$

summing the above for at least three neutral Higgs bosons $\Rightarrow \geq 1$.

for 2D + N singlets $\Rightarrow$
need at least 2 + 2N light Higgses to guarantee discovery

☆ Conclusions :

- a light Higgs boson of a general 2HDM not experimentally excluded
- Higgs search strategies should include

- for moderate $\tan\beta \sim 1 - 10$
  Higgs may escape detection even at e^+e^- colliders
- if two Higgses light $\Rightarrow$ both observable at e^+e^- LC
- for 2 doublets + N singlets :
  need 2 + 2N light to guarantee discovery
- enough freedom , need not take Higgs discovery at the Tevatron or LC for granted
- keep working on every possible signature