Higgs and SUSY Higgs (Theory)

Working Group Summary Report

Yasuhiro Okada (KEK)

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Higgs Physics at LC.

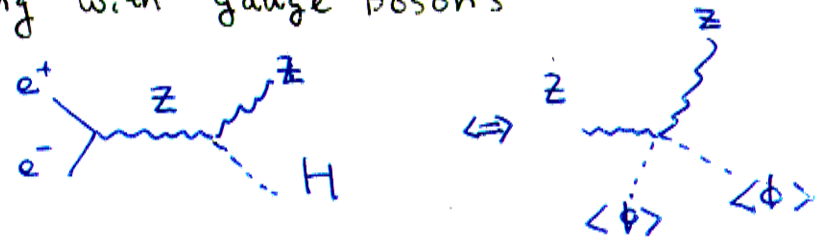
Light Higgs boson (100 - 200 GeV) production at $\sqrt{s} = 300 - 500$ GeV e^+e^- LC.

$$50 - 200\ \mathrm{fb} \times 100 - 1000\ \mathrm{fb}^{-1}$$

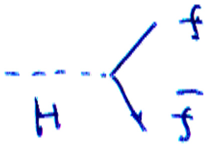
$$\Rightarrow 10^4 - 10^5 \text{ Higgs bosons}$$

- Study its properties

Coupling with gauge bosons

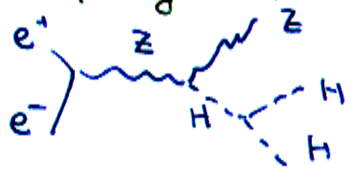


Coupling with fermions



$$\propto m_f = \frac{y_f \langle\phi\rangle}{\sqrt{2}}$$

Self coupling constant



$$, V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

Fundermental questions of particle physics

- How well can these coupling constants be determined?
- Can we distinguish various models,

  the minimal Standard Model (SM),

  two Higgs doublet model (THDM),

  MSSM, extended version of SUSY models?
- Within a specific model, for example, MSSM, how well can various parameters be determined?

1. Theoretical consideration on Higgs boson mass

J. Gunion

2. MSSM Higgs Sector

- SUSY correction to y_b — S. Mrenna, H. Logan, G. Weiglein, S. Kiyoura, C. Kolda
- $\tan\beta$ determination — J. Jiang
- Single $H^{\pm}$ production — S. Kanemura

3 Anomalous ZZH, $Z\gamma H$ coupling.

J. Kamoshita

4 $\gamma\gamma$ collider

O. Yakavlov
M. Melles
M. Krawczyk

C.P. Yuan "ν mass and Higgs"

[1.] Theoretical Consideration on the Higgs boson mass

Higgs boson mass ⇔ Higgs self coupling

$m_h = \sqrt{2\lambda}\,v$ (in SM)

Light Higgs boson ⟷ perturbative

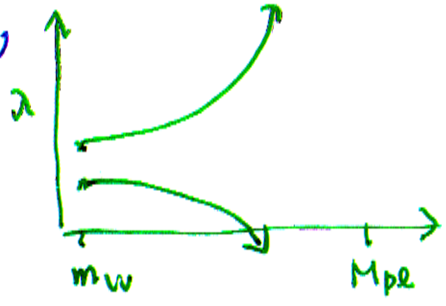
Heavy Higgs boson ⟷ Strong interaction

Theoretical upper and lower bounds on m_h

① The minimal SM

If the SM is valid up to $\Lambda = M_{pl}$ ($= 10^{19}$ GeV)

$135 \lesssim m_h \lesssim 180$ GeV



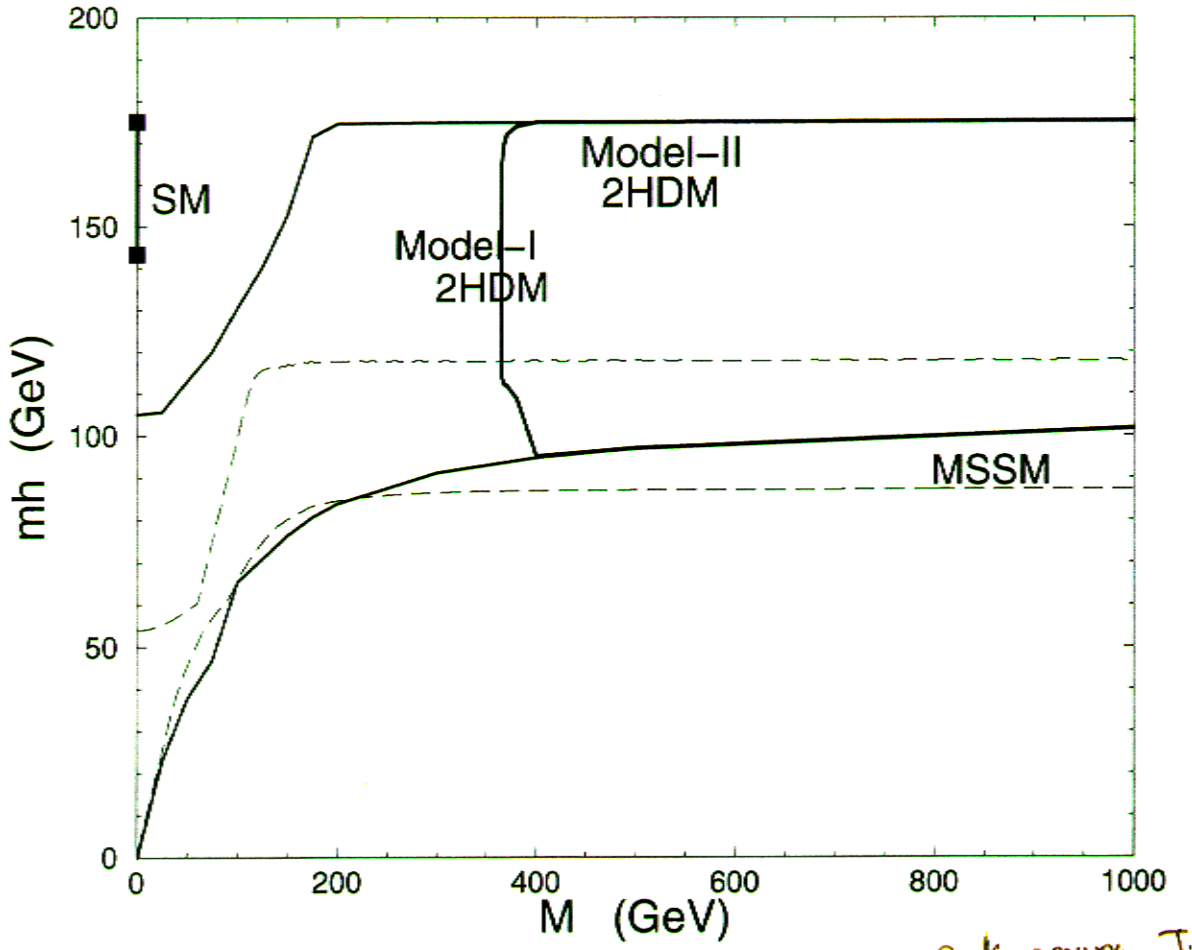
② Two Higgs doublet model

For $\Lambda = M_{pl}$,

$100 \lesssim m_h \lesssim 180$ GeV

for the lightest CP even Higgs boson (h) in the decoupling limit. ($m_h \ll m_{H,A,H^\pm}$)

S. Kanemura. T. Kasai Y.O. 1999



S. Kanemura T. Kasai Y. Okada

③ MSSM Higgs Sector

2HDM $\left(\underbrace{h, H}_{\substack{\text{CP even} \\ (m_h < m_H)}}, \underset{\substack{\uparrow \\ \text{CP odd}}}{A}, H^{\pm} \right)$

The upper bound of m_h exists without reference to the cutoff scale Λ.

$$m_h^2 \leq \underset{\substack{\uparrow \\ \text{tree}}}{m_Z^2 \cos^2 2\beta} + \underset{\substack{\uparrow \\ \text{One loop}}}{\frac{3}{2\pi^2} \frac{m_t^4}{v^2} \log \frac{m_{\text{stop}}^2}{m_t^2}}$$

$\frac{(g^2 + g'^2)}{8}$,

$$\tan\beta \equiv \frac{\langle H_2^0 \rangle}{\langle H_1^0 \rangle}$$

$$m_h \lesssim 130 \text{ GeV}$$

④ general SUSY models

The upperbound of the lightest CP even Higgs boson is obtained if we require any of dimensionless coupling constant does not blow up below the cutoff scale (M_{pl})

- MSSM ⊕ a singlet Higgs field
  $m_h \lesssim 150$ GeV
- MSSM ⊕ a triplet Higgs field (J. Espinosa. M. Quiros 1998)
  $m_h \lesssim 210$ GeV
- MSSM ⊕ vectorlike matters (T. Moroi. Y.O. 1992)
  $m_h \lesssim 180$ GeV

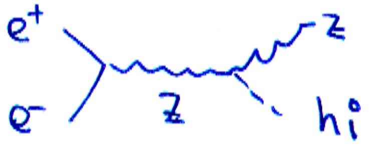
Detectability of at least one Higgs boson at LC,

- MSSM

At least one of h and H. can be detectable through the $e^+e^- \to Z h_0$ process with a low ($\sim 10\,fb^{-1}$) laminocity.

- MSSM ⊕ a singlet Higgs (J.Kamoshita. Y.O. M.Tanaka 1996 / S.King .PWhite 1996)

when the lightest Higgs boson becomes singlet-dominated, the production cross section is suppressed.



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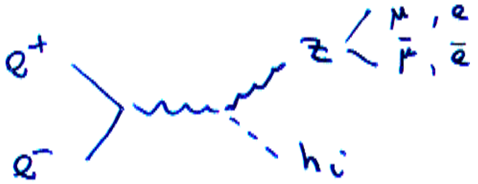
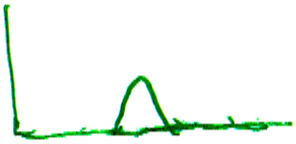
Even in such a case at least one of three CP even Higgs bosons is detectable.

$$\mathrm{Min}\{\sigma_{h_1}, \sigma_{h_2}, \sigma_{h_3}\} \geq \frac{\sigma_{SH}(m = m_{\text{upper bound}})}{3}$$

- More general SUSY model (J.Espinosa. J.Gunion 1998)

Independent of numbers of extra Higgs field, and decay modes, the Higgs signal is observable at LC with $\sqrt{s} = 500$ GeV and $500\,fb^{-1}$.





recoil mass spectrum $M_h^2 = (P_e + P_{\bar{e}} - P_Z)^2$

Precision Electroweak measurement V.S. Higgs boson mass ?

- **In the SM,** the constraint on the Higgs boson mass is obtained from the electroweak measurements. (without any assumption on cut off scale etc.)

$$m_h \lesssim 210 \text{ GeV} \qquad (95\% \text{ CL})$$

⇒ detectable at LC

- **Two Higgs doublet model.** Chankowski Farris Grzadkowski Gunion. Kalinowski Krawczyk

It is possible, that

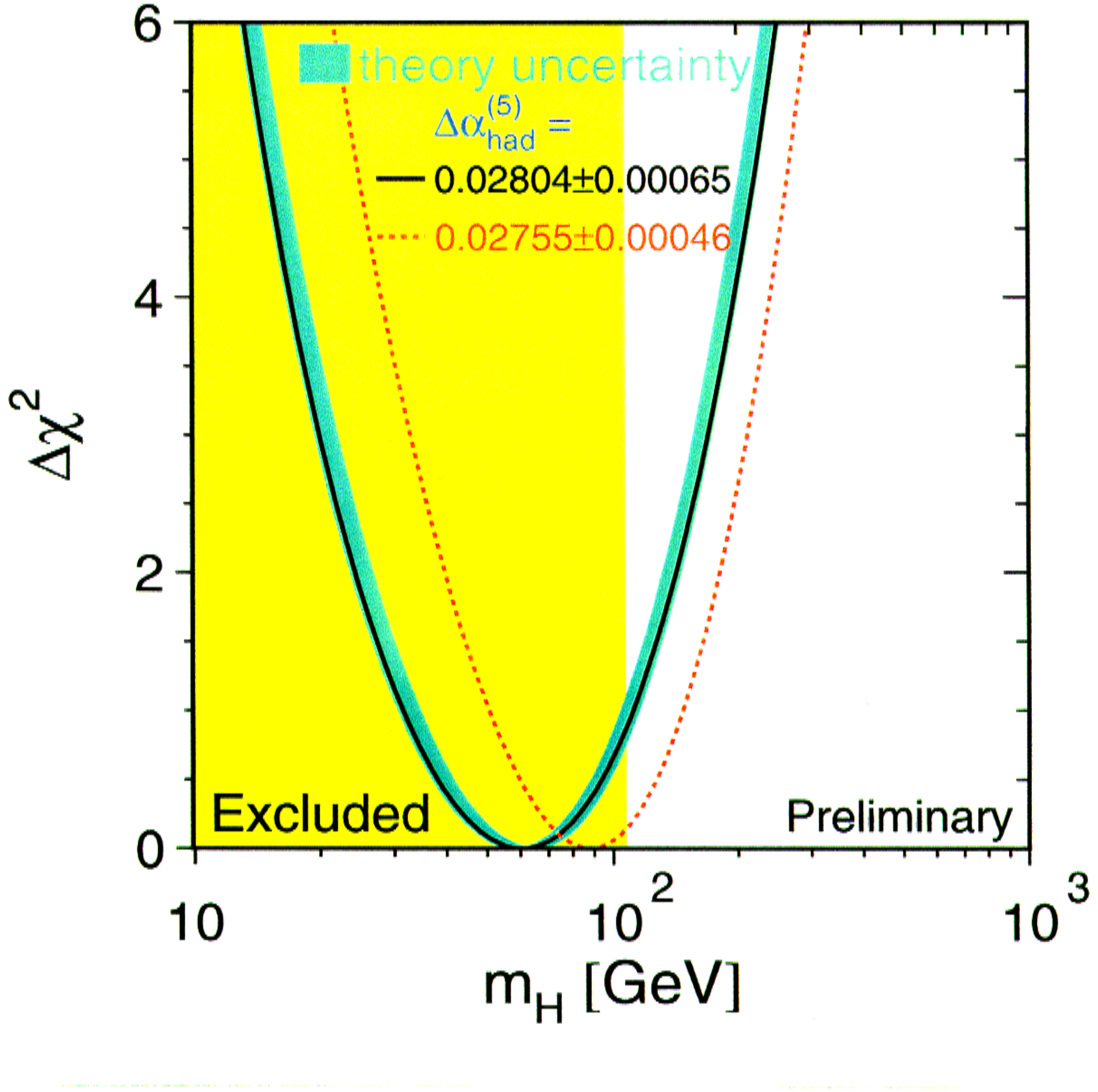
① the light Higgs boson: (A or h.) has no ZZ/WW coupling

② the heavy Higgs boson (H) is too heavy at $\sqrt{s} = 500\text{–}800$ GeV

③ not enough $e^+e^- \to t\bar{t}h, b\bar{b}\ h$ ($t\bar{t}\ A, b\bar{b}A$) production with $L = 2500\ \text{fb}^{-1}$

④ still the electroweak precision test is reasonable good.

⇒ Giga-Z can distinguish this case.



6
4
2
0
$\Delta\chi^2$
theory uncertainty
$\Delta\alpha_{had}^{(5)} =$
0.02804±0.00065
0.02755±0.00046
Excluded
Preliminary
10
10^2
10^3
m_H [GeV]

The S, T Plane Picture and Giga-Z.

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

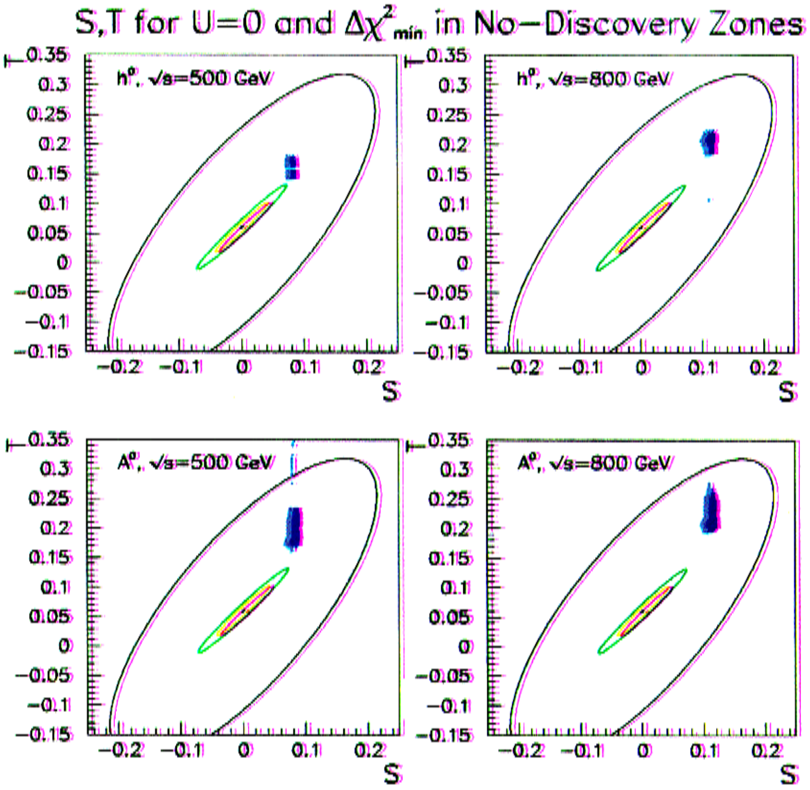


Figure 5: We plot the $U=0$ 90% CL ellipse in the S, T plane for a SM Higgs of mass 115 GeV from the latest Erler/Langacker analysis. Also shown are 90% and 99.9% ellipses for Giga-Z using U=0 and error analyses (including correlations) from Erler and from Moenig. **The blobs of blue are where our 2HDM 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.

[2] MSSM Higgs Sector

- Parameters of the Higgs Sector

$$m_A, \quad \tan\beta, \quad m_t, \quad m_{stop}$$

$$(m_{\tilde{t}_L}, m_{\tilde{t}_R}, A_t, m_{\tilde{b}_L} \cdots\cdots)$$

Neutral Higgs boson mixing angle

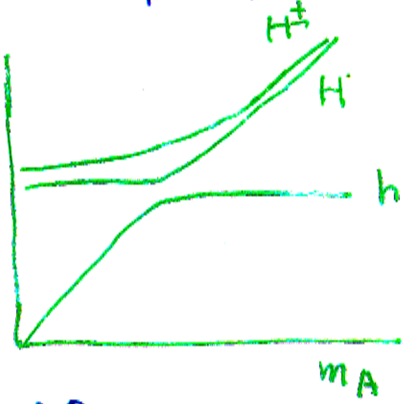
$$\mathrm{Re}\, H_1^0 = \frac{1}{\sqrt{2}}(v\cos\beta - h\sin\alpha + H\cos\alpha)$$

$$\mathrm{Re}\, H_2^0 = \frac{1}{\sqrt{2}}(v\sin\beta + h\cos\alpha + H\sin\alpha)$$

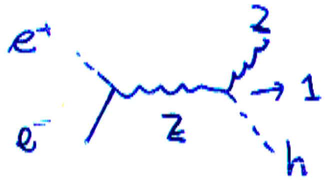
$$\alpha = \alpha(m_A, \tan\beta, m_t, m_{stop} \cdots)$$

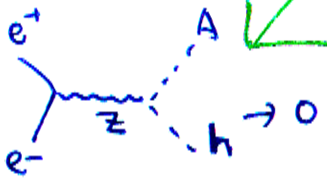
- Decoupling limit

$m_A >> 150$ GeV

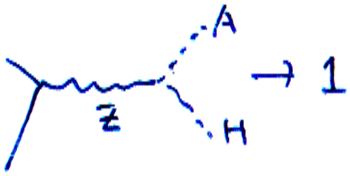


∴ h → SM like Higgs boson



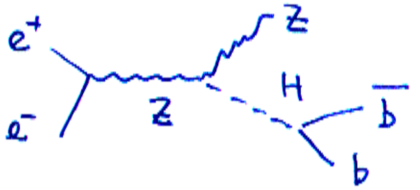


- H, A, $H^\pm$ degenerate in mass



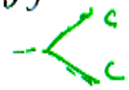
① Non-minimality contour

$\sigma(e^+e^- \to Zh) \cdot Br(h \to b\bar{b})$



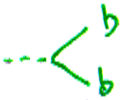
② $\dfrac{B(h \to c\bar{c}) + B(h \to gg)}{B(h \to b\bar{b})}$ vs. m_A

J. Kamoshita
Y.O. M.Tanaka
1995



$$R_{cc+gg/bb} = \frac{B(h \to c\bar{c}) + B(h \to gg)}{B(h \to b\bar{b})}$$

⇒ up-type Yukawa



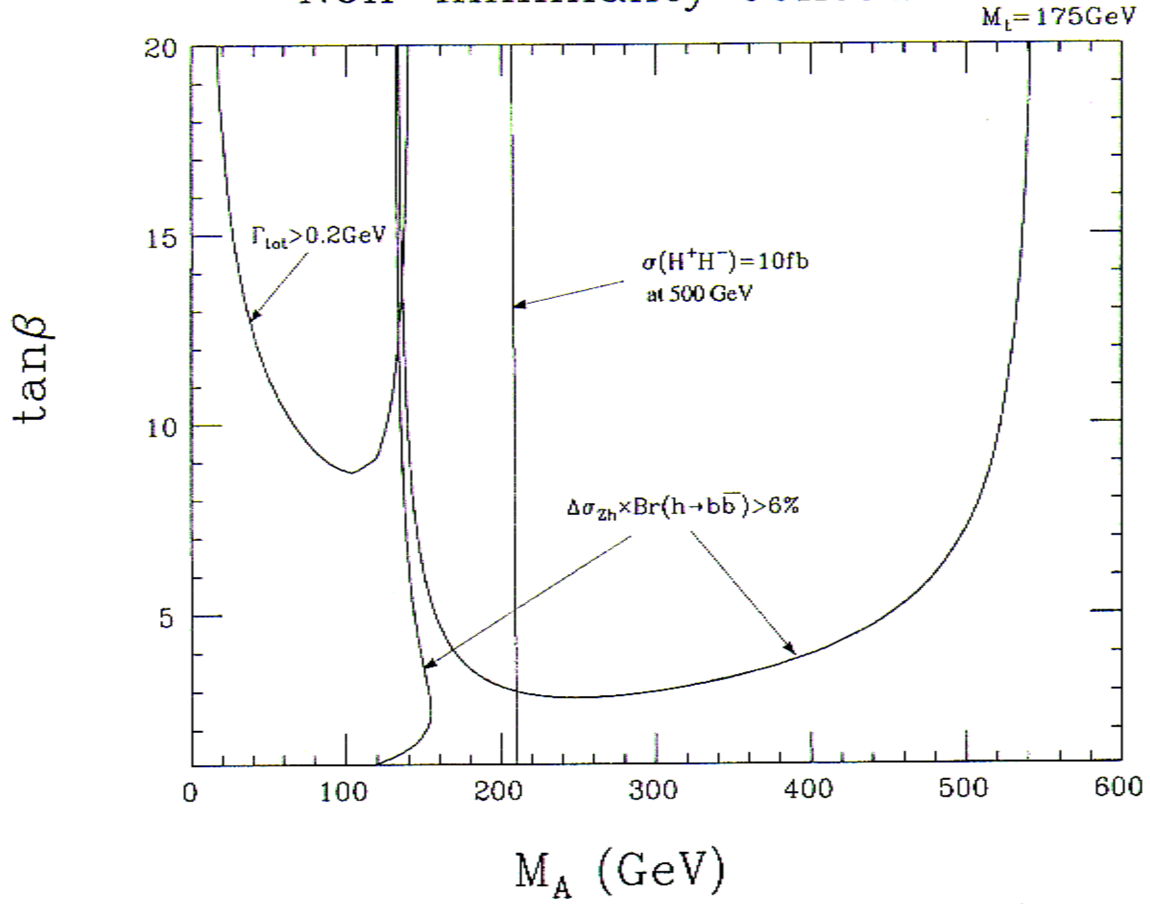
⇒ down-type Yukawa

$$= \left(\frac{1}{\tan\alpha \tan\beta}\right)^2 R_{cc+gg/bb}(SM)$$

$$\simeq \left(\frac{m_A^2 - m_h^2}{m_A^2 + m_Z^2}\right)^2 R_{cc+gg/bb}(SM)$$

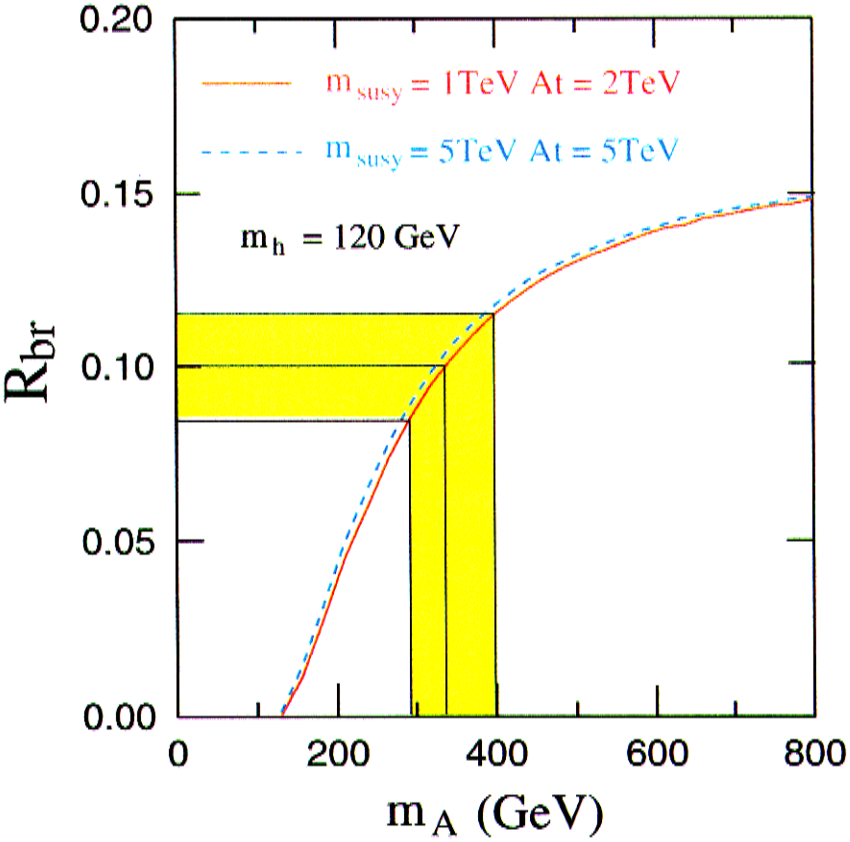
⇒ A probe to m_A.

Non−minimality Contour



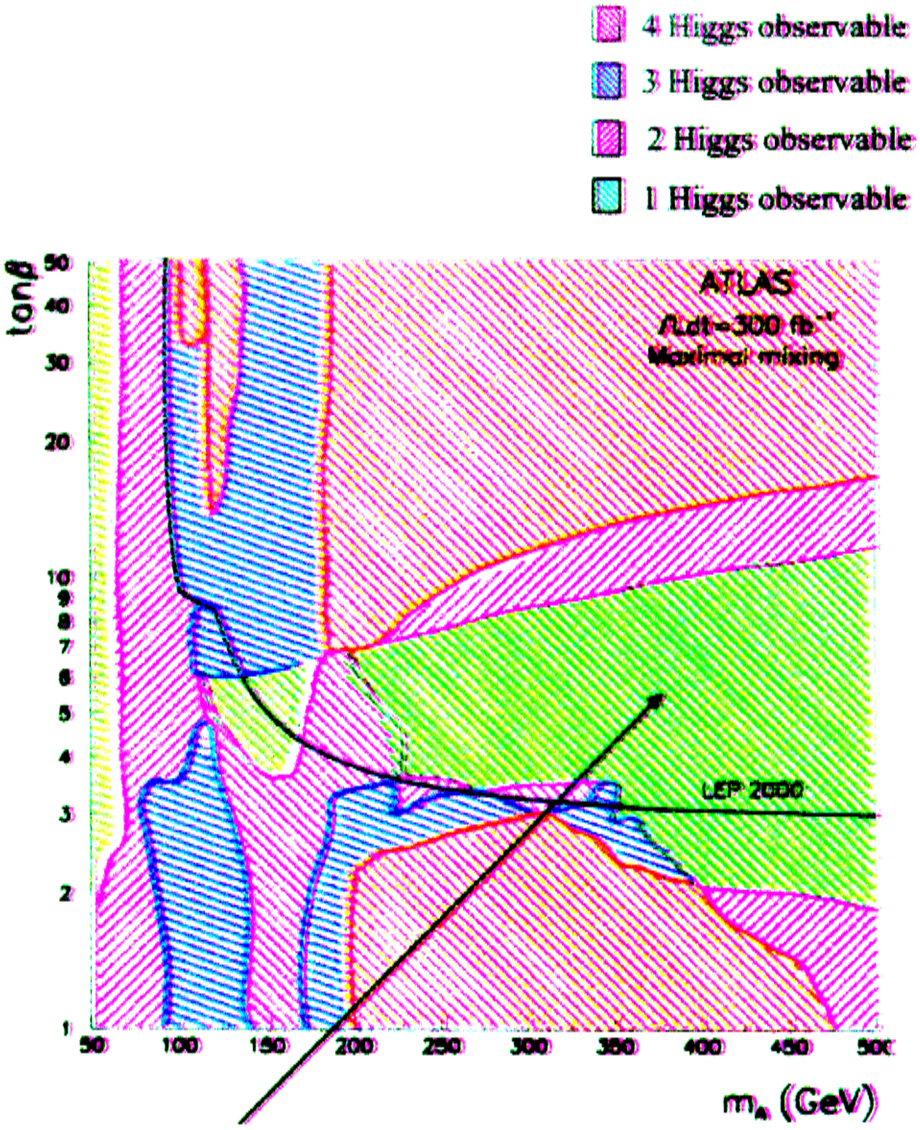
A. Miyamoto
JLC study

$$R_{br} = \frac{B(h\text{->}c\bar{c}) + B(h\text{->}gg)}{B(h\text{->}b\bar{b})}$$



J.Kamoshita,Y.Okada,M.Tanaka, LCWS95 & PLB391(97)124

I.Nakamura, Kawagoe, LCWS95 & PRD54(96)3634, I.Nakamura, LCWS99



Here:

-- only h observable
-- h ≈ SM Higgs

} → disentangle SM /MSSM ?

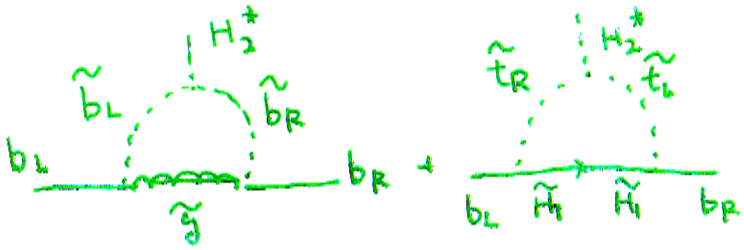
③ SUSY loop correction to Y_b at large $\tan\beta$

when $\tan\beta$ is large ($\simeq 50$), a sizable $b\bar{b}H_2^*$ coupling can be induced by SUSY loop effect.

. Carena Mrenna Wagner 1999
. Babu Kolda 1999

⇒ Beyond type II model.

$$\mathcal{L}_{Yukawa} = y_t \bar{t}_L t_R H_2^0 + y_b \bar{b}_L b_R H_1^0 + \epsilon_b y_b \bar{b}_L b_R H_2^{0*}$$



$$m_b = y_b(1+\epsilon_b\tan\beta)\frac{v}{\sqrt{2}}\cos\beta$$

$$\epsilon_b \sim O(0.01)$$

$$\epsilon_b\tan\beta \sim 0.5$$

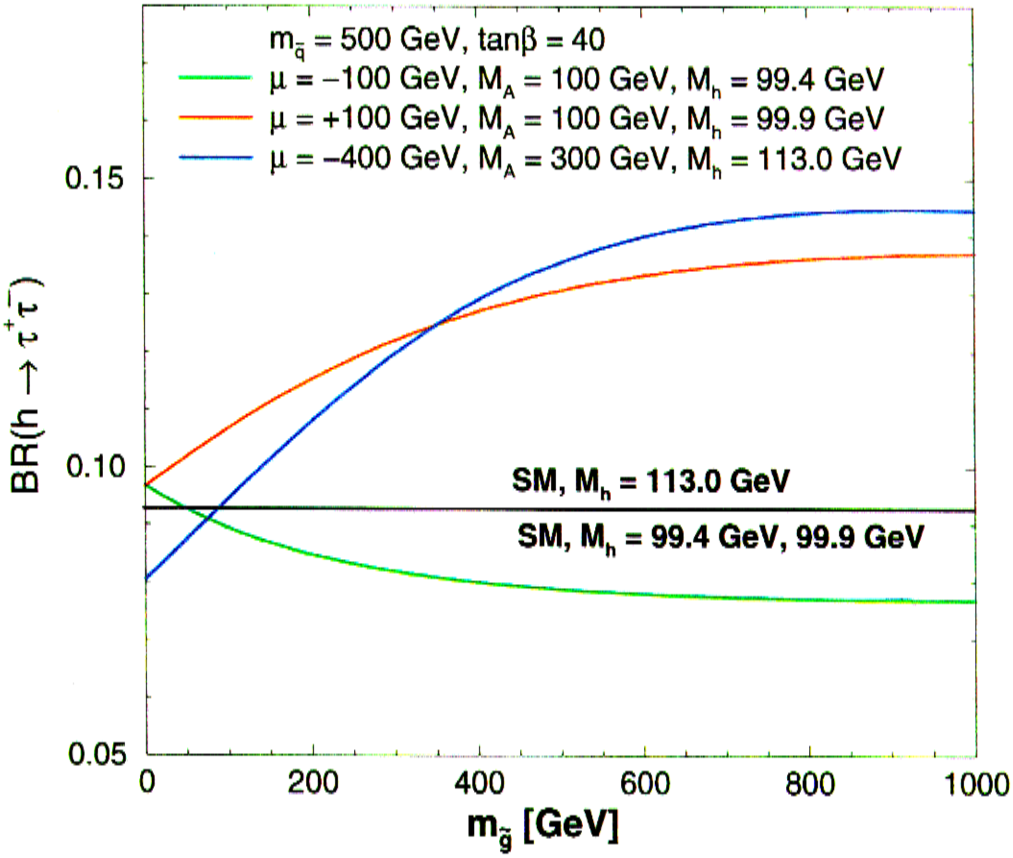
$$R_{\tau/b} \equiv \frac{B(h\to\tau\bar{\tau})}{B(h\to b\bar{b})} = \left(\frac{1+\epsilon_b\tan\beta}{1-\epsilon_b/\tan\beta}\right)^2 R_{\tau/b}(SM)$$

$R_{\tau/b}$ can be different from the SM and type II THDM.

$R_{cc+gg/bb}$ is also affected by the same factor

Effect of gluino vertex corrections to $h \to q\bar{q}$ on BR($h \to \tau^+\tau^-$):

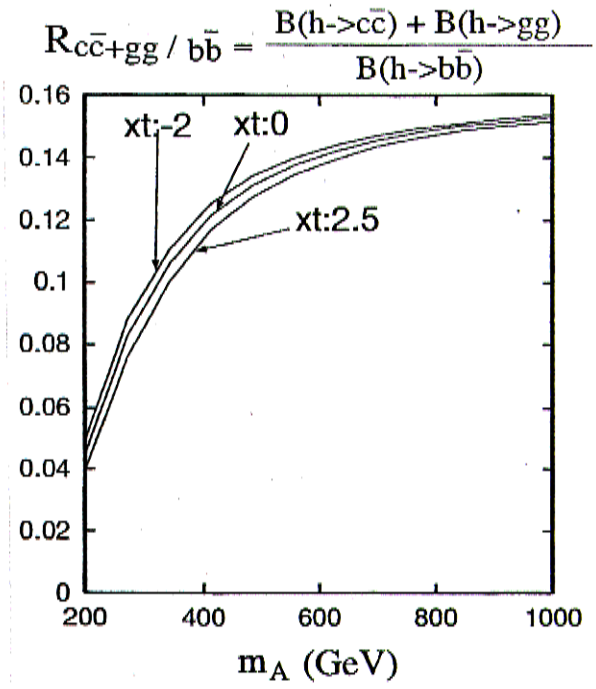
[S. Heinemeyer, W. Hollik, G. W. '00]



⇒ Large effects possible for large tan β,

even for relatively large M_A

S.Kiyoura Y.Okada.



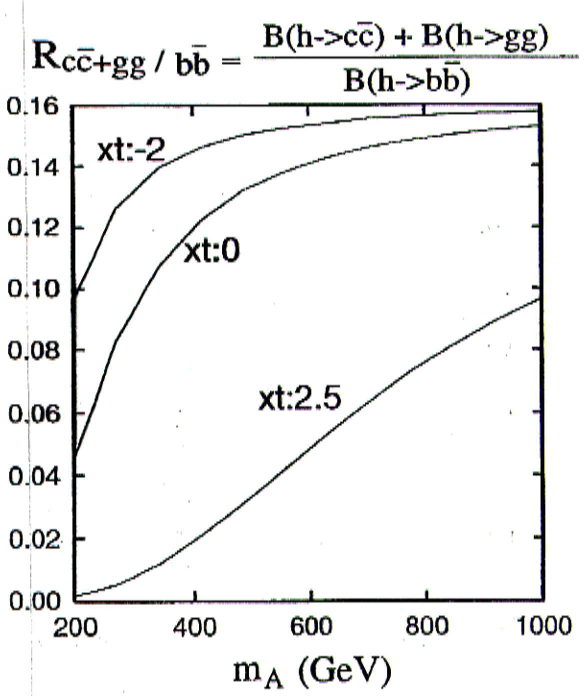
$xt = At / M_{Susy}$

m_h = 120 GeV

$\tan\beta = 10$

M3 = 300GeV

μ = 300GeV



$Xt = At / M_{Susy}$

m_h = 120 GeV

$\tan\beta = 50$

M3 = 300GeV

μ = 300GeV

- From $B(h \to b\bar{b})$, $B(h \to c\bar{c})$, $B(h \to \tau\bar{\tau})$

we can determine $\Delta(m_b) \equiv \epsilon_b \tan\beta$.

$$x \equiv \frac{B(h\to b\bar{b})}{B(h\to\tau\bar{\tau})} \Big/ \frac{B(h\to b\bar{b})}{B(h\to\tau\bar{\tau})}\Big|_{SM}$$

$$y \equiv \frac{B(h\to c\bar{c})}{B(h\to\tau\bar{\tau})} \Big/ \frac{B(h\to c\bar{c})}{B(h\to\tau\bar{\tau})}\Big|_{SM}$$

$$\Delta(m_b) = \frac{1-\sqrt{x}}{\sqrt{x}-\sqrt{y}}$$

H. Logan. M. Carena
- H. Haber. S. Mrenna

- Effects on heavy Higgs boson production / decay

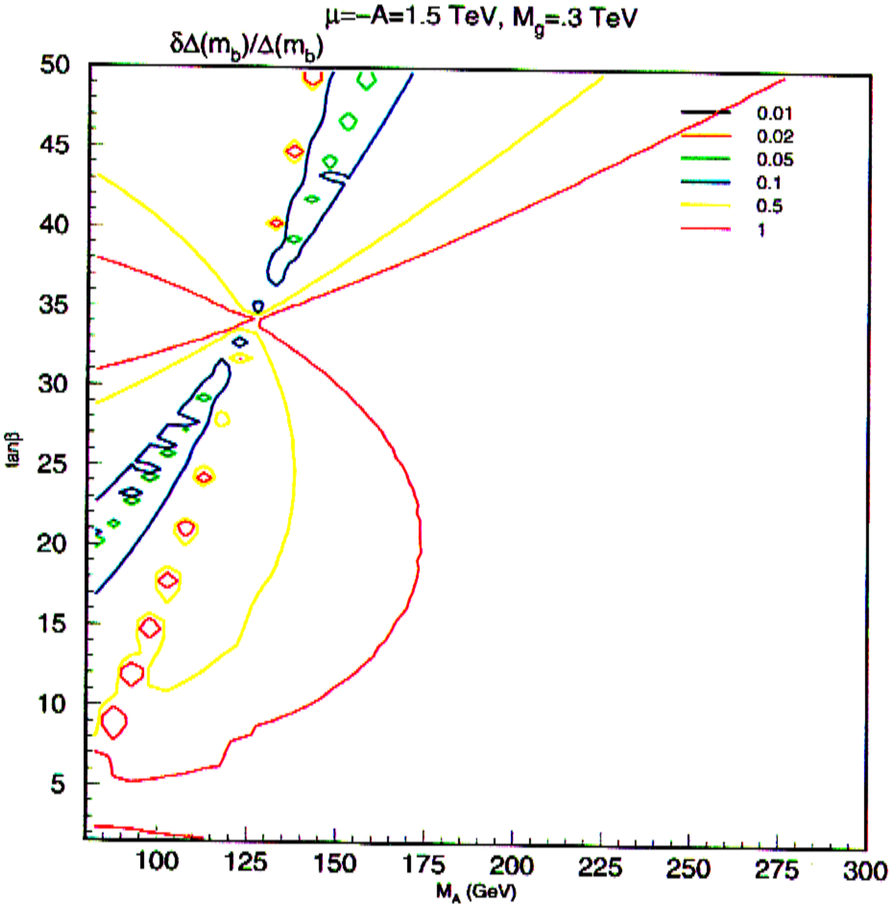
C Kolda

$$\mathcal{L} = \frac{m_b}{\sqrt{2}v\sin\beta}\left(\frac{1}{1+\epsilon_b\tan\beta}\right)\left(\tan\beta A^0 + \frac{\cos\alpha}{\cos\beta}H^0\right)\bar{b}_R b_L + h.c.$$

$-25\% \lesssim \epsilon_b \tan\beta \lesssim -18\%$ for SO(10)-like GUT

⇒ increase the below-threshold production of $e^+e^- \to Ab\bar{b}$, $Hb\bar{b}$

suppress $B(A/H \to \tau\bar{\tau})$, $B(A/H \to c\bar{c})$


μ=−A=1.5 TeV, M_g=.3 TeV
δΔ(m_b)/Δ(m_b)
0.01
0.02
0.05
0.1
0.5
1
tanβ
50
45
40
35
30
25
20
15
10
5
100
125
150
175
200
225
250
275
300
M_A (GeV)

④ $\tan\beta$ determination from Heavy Higgs boson

V. Barger T. Han, J. Jiang

- Branching ratio

  Small $\tan\beta$

  $A, H \rightarrow t\bar{t}$,

  $H^- \rightarrow b\bar{t}$

  Large $\tan\beta$.

  $A, H \rightarrow b\bar{b}, \tau^+\tau^-$

  $H^- \rightarrow \tau\bar{\nu}, b\bar{t}$.

- Enhancement of the production at large $\tan\beta$.

  $e^+e^- \rightarrow t\bar{b}H^-$

  $e^+e^- \rightarrow b\bar{b}H, b\bar{b}A$

⇒ $\tan\beta$ determination.

$e^+e^- \rightarrow H\bar{t}t, H\bar{b}b, A\bar{t}t, A\bar{b}b$

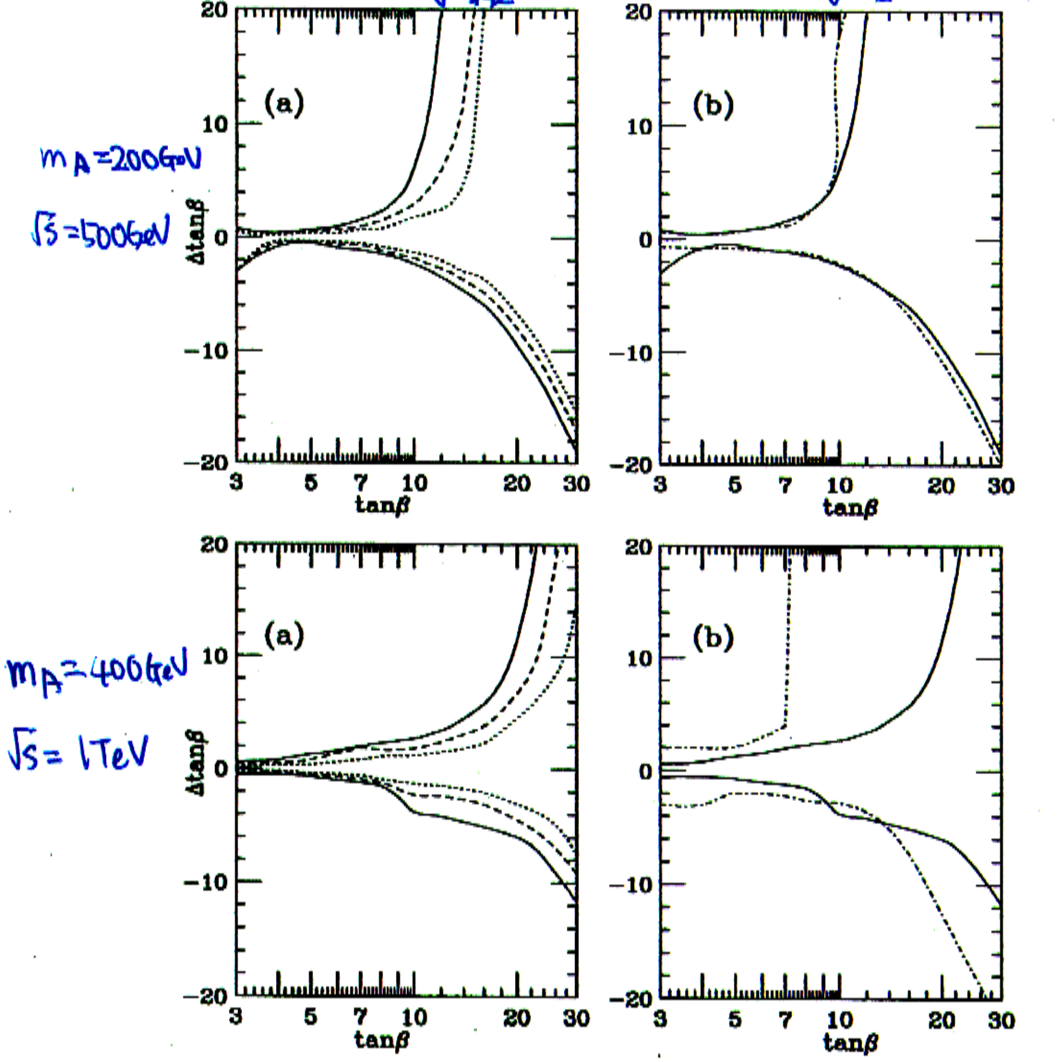
at $\sqrt{s} = 500 - 1000$ GeV

($e^+e^- \rightarrow H^{\pm}tb$ v.s. $\tan\beta$ J. Feng T. Moroi (1997))

V. Barger, T Han, J. Jiang

tan β determination

- In MSSM:



⇒ typically, $\tan\beta \approx 3 \pm 2$ or 10 ± 4

⑤ Single charged Higgs boson production in MSSM

S. Kanemura S. Moretti K. Odagiri

For $m_{H^\pm} \lesssim \frac{\sqrt{s}}{2}$

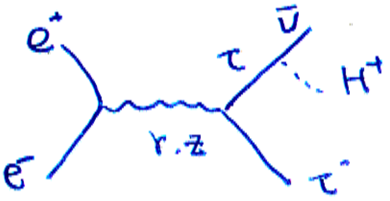
$e^+e^- \to \tau^-\bar{\nu} H^+$, $e^+e^- \to \bar{t}bH^+$, $e^+e^- \to h^0 W^- H^+$

can be 1 – 100 fb due to H^+H^- production

For $m_{H^\pm} > \frac{\sqrt{s}}{2}$

Useful modes (10^{-2} – 1 fb)

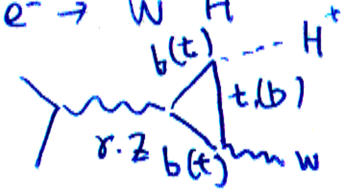
$e^+e^- \to \tau^-\bar{\nu} H^+$ (large $\tan\beta$)



$\propto m_\tau \tan\beta$

(small $\tan\beta$)

$e^+e^- \to W^- H^+$



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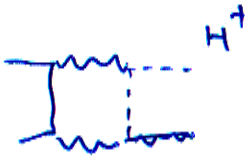

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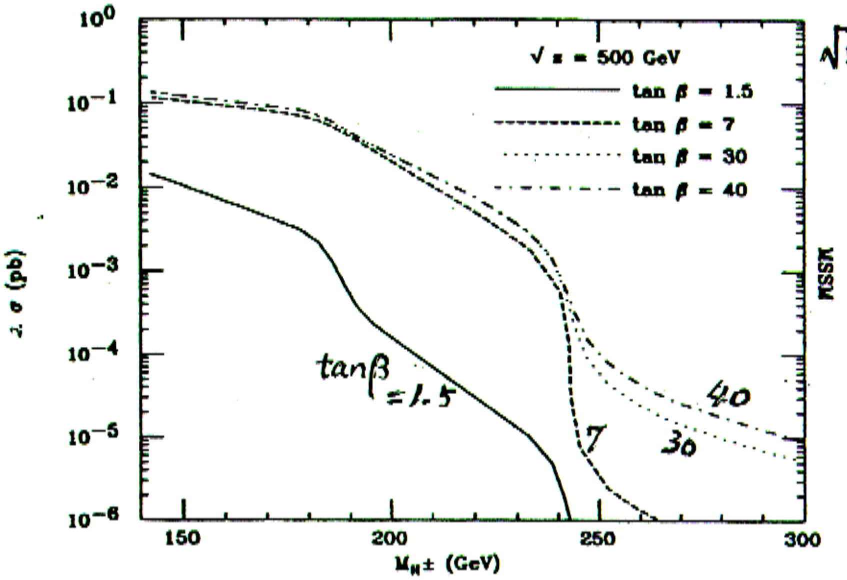
e+ e- → τ- ν̄ H+ $e^+e^- \to \tau^-\bar{\nu}H^+$

$\sqrt{s} = 500$ GeV

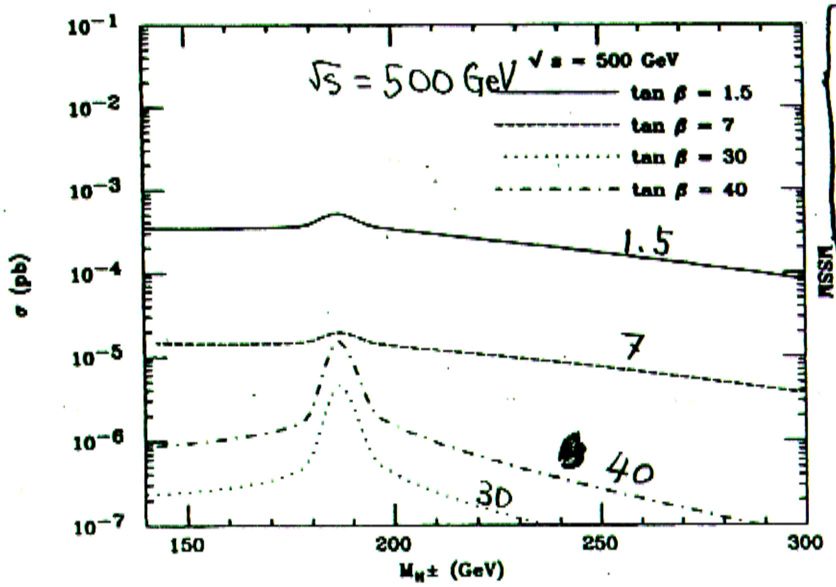


coupling ~ $g_W^2 \left[m_t^2 \cot\beta \pm m_b^2 \tan\beta \right]$ $e^+e^- \to W^-H^+$

w

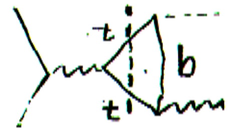
~ w

e+ e- → W- H+



threshold ef

$\sqrt{s} \sim 2m_t$



One order greater

$m_{H^\pm} \sim m_t$

S.Kanemura S.Moretti. K.Odagiri

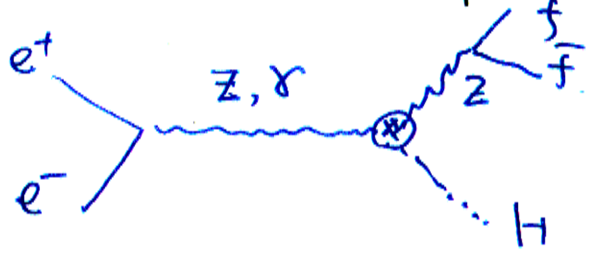
[3] ZZH , ZγH anomalous couplings

K.Hagiwara S.Ishihara. J.Kamoshita. B.Kniehl

$$\mathcal{L}_{eff} = (1+a_Z)\frac{g_Z m_Z}{2} H Z_\mu Z^\mu + \frac{g_Z}{m_Z}\sum_{V,\gamma}\Big[b_V H Z_{\mu\nu} V^{\mu\nu} + c_V(\partial_\mu H Z_\nu - \partial_\nu H Z_\mu) V^{\mu\nu} + \tilde{b}_V H Z_{\mu\nu}\tilde{V}^{\mu\nu}\Big]$$

$$\left(V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \ , \ \tilde{V}_{\mu\nu} = \epsilon_{\mu\nu\alpha\beta} V^{\alpha\beta} \right)$$

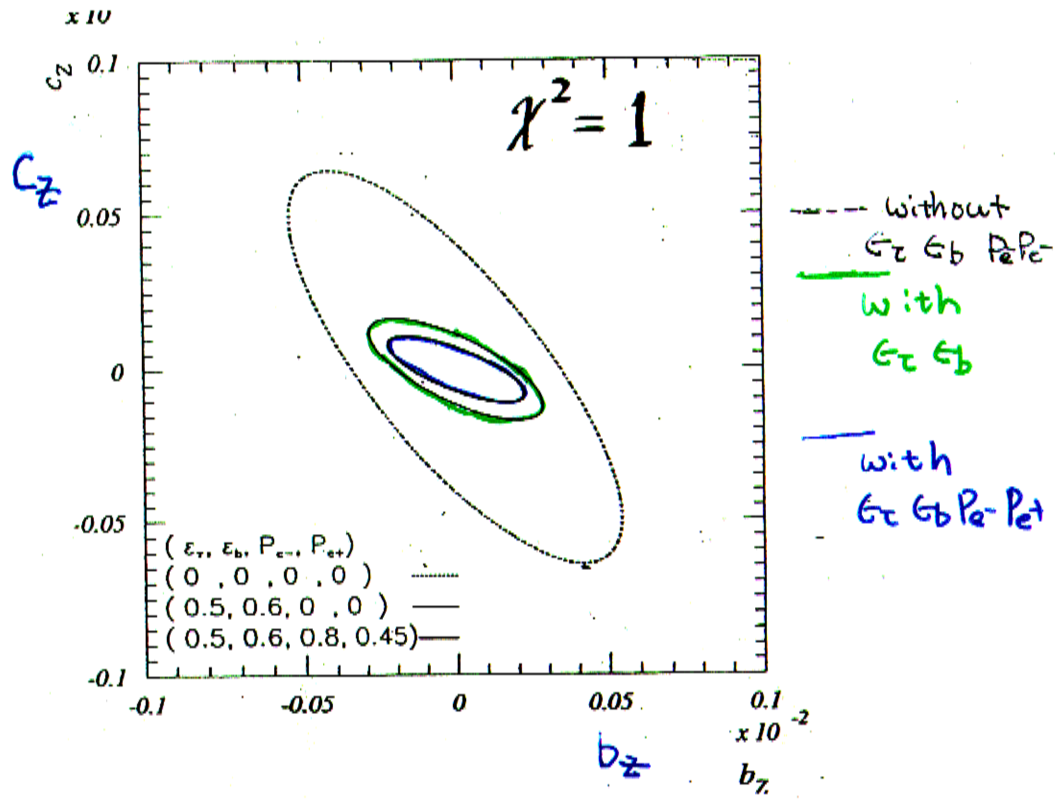
Expected constraints on a_Z, b_V, c_V $\tilde{b}_V$ from $e^+e^- \to Hf\bar{f}$ process

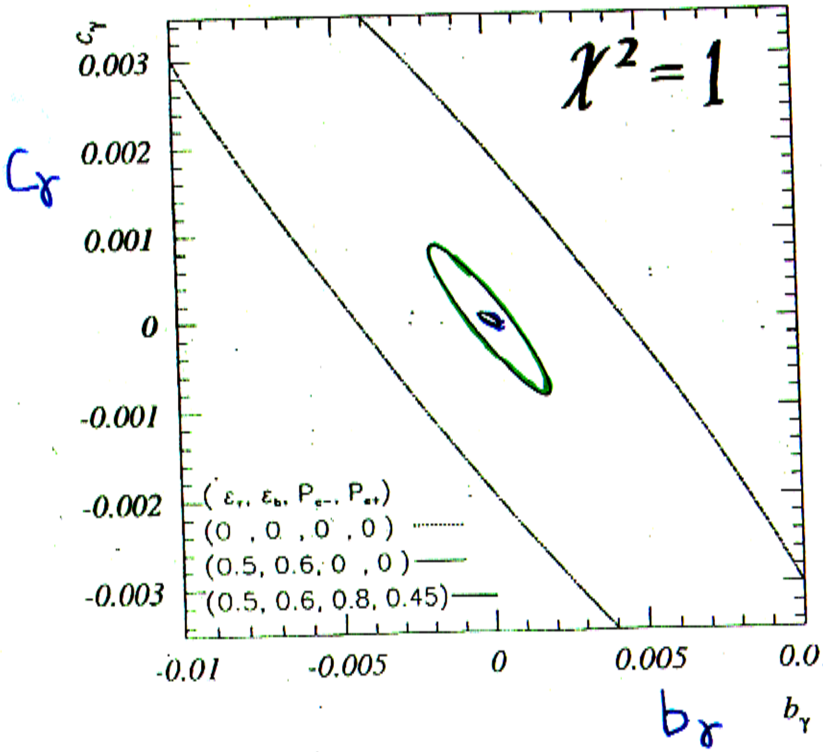


For $\sqrt{s}=500$ GeV $L = 300\ fb^{-1}$, $m_H = 115$ GeV

- Helicity measurement of τ lepton ($\epsilon_\tau = 50\%$)
- charge identification of b ($\epsilon_b = 60\%$)
- Beam polarization ($|P_{e^-}| = 80\%$ $|P_{e^+}| = 45\%$)

Significant improvement on determination of the ZγH couplings

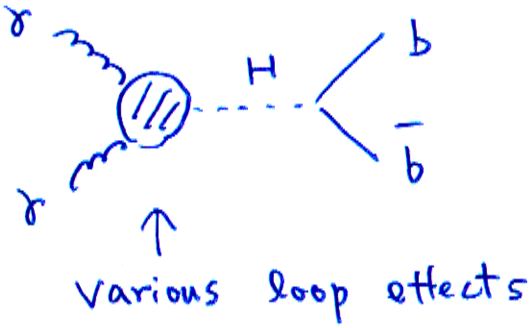




K. Hagiwara
S. Ishihara
J. Kamoshita
B.A. Kniehl

[4] photon - photon collider

Measurement of $\Gamma(H\to\gamma\gamma)$



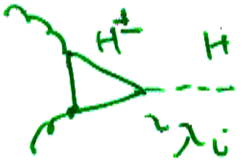
Radiative corrections to signal and background processes ($\gamma\gamma\to b\bar{b}$) are under control · M. Melles · O. Yakovlev

⇒ Determination $\Gamma(H\to\gamma\gamma)$ at $\lesssim 2\%$ level is possible for four years. for $m_H \lesssim 140\text{GeV}$

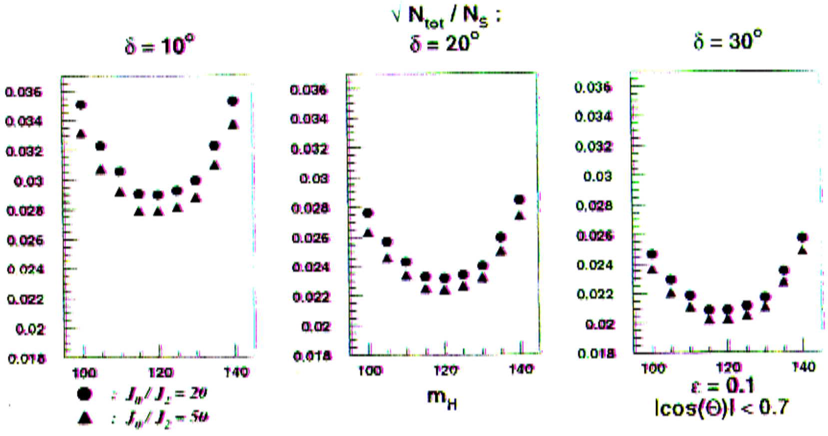
⊙ Resolving 2HDM and SM by $\Gamma(H\to\gamma\gamma)$ I. Ginzburg M. Krawczyk P. Osland.

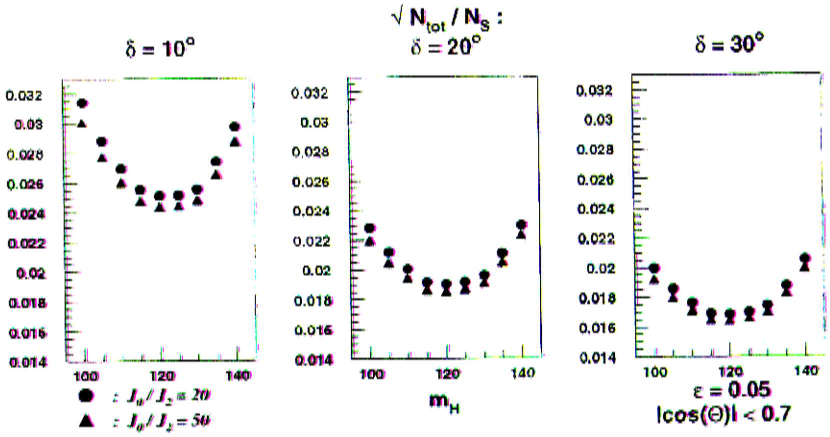
Suppose the light Higgs boson found at LHC and e^+e^- LC is a SM-like couplings to gauge bosons and fermions.

In 2HDM, the deviation of $\Gamma(H\to\gamma\gamma)$ from the SM value can be ~10% because of the non-decoupling effect of $H^\pm$.



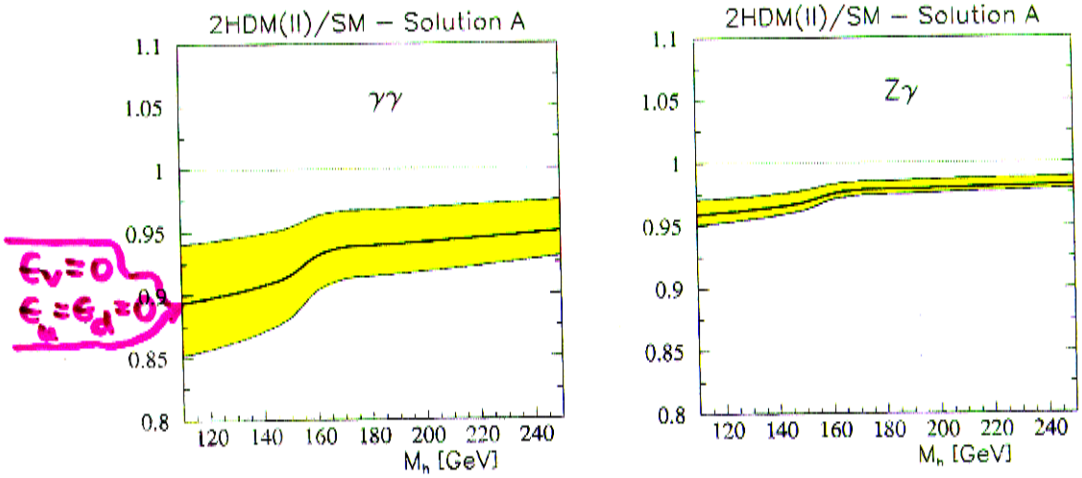
Include new Tesla parameters with better charm suppression:





Assumptions (Battaglia): 70 % double b-tagging efficiency, 1% probability of counting $c\bar{c}$ as $b\bar{b}$.

Deviation from 1 due to
$H^{\pm}$ contribution!



Results are shown for $\lambda_5 = 0$ and $M_{H^\pm} = 800$ GeV. The regions above and below the thick curves correspond to 1 sigma error in couplings:

$\hookrightarrow \delta_u, \delta_d$

$$1 - \chi^2_{\gamma\gamma} \sim 0.10 - 0.05$$

$$1 - \chi^2_{Z\gamma} \sim 0.04 - 0.02$$

Summary

There are many oppotunities to learn about physics beyond the SM from Higgs physics at LC

- Precise determinations of the production cross section and the branching fractions
  - ⇒ MSSM parameters
- Heavy Higgs production / decay
- Anomalous ZZH, $Z\gamma H$ couplings
- $\Gamma(H\to\gamma\gamma)$ at photon collider

These measurements are important to astablish/distinguish the SM / MSSM / THDM or others.