HIGGS AT e^+e^- LINEAR COLLIDERS
(Theor. Part)

1. INTRODUCTION

- general physics scenario
- 2-phase LC project

2. THE BASE: SM HIGGS MECHANISM

- establ. Higgs mechanism for elw SB
- precision analyses: looking beyond SM

3. SM EXTENSION: SUPERSYMMETRY

- MSSM as a framework
- generalized scenarios

4. ALTERNATIVE: STRONG ELW SYMMETRY BREAKING

- composite Higgs particles
- "no" Higgs

5. CONCLUSIONS

1. INTRODUCTION

LC target : precision analysis of Higgs mechanism / elw SB

$\downarrow$

telescope for exploring new physics areas

Scales :

- $v \approx 246$ GeV elw SB scale : energy range $\lesssim \mathcal{O}(1\,\text{TeV})$
  expected crucial for elw SB

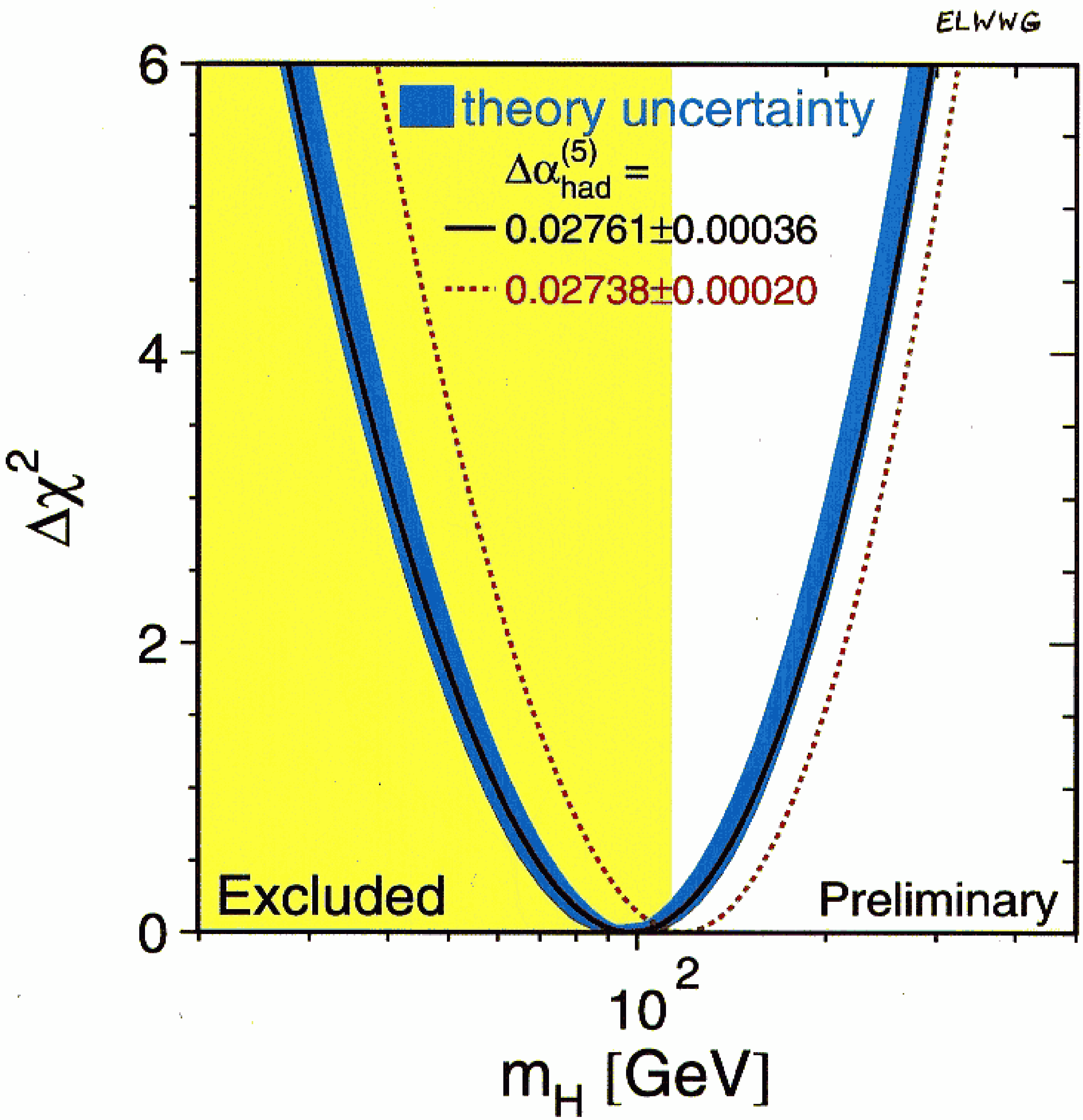
- Λ_* scale of new [stg] interactions :

  $\Lambda_* \lesssim M_{PL}$: light fundamental Higgs boson
  naturalness : SM $\to$ SUSY at $\mathcal{O}$(TeV)

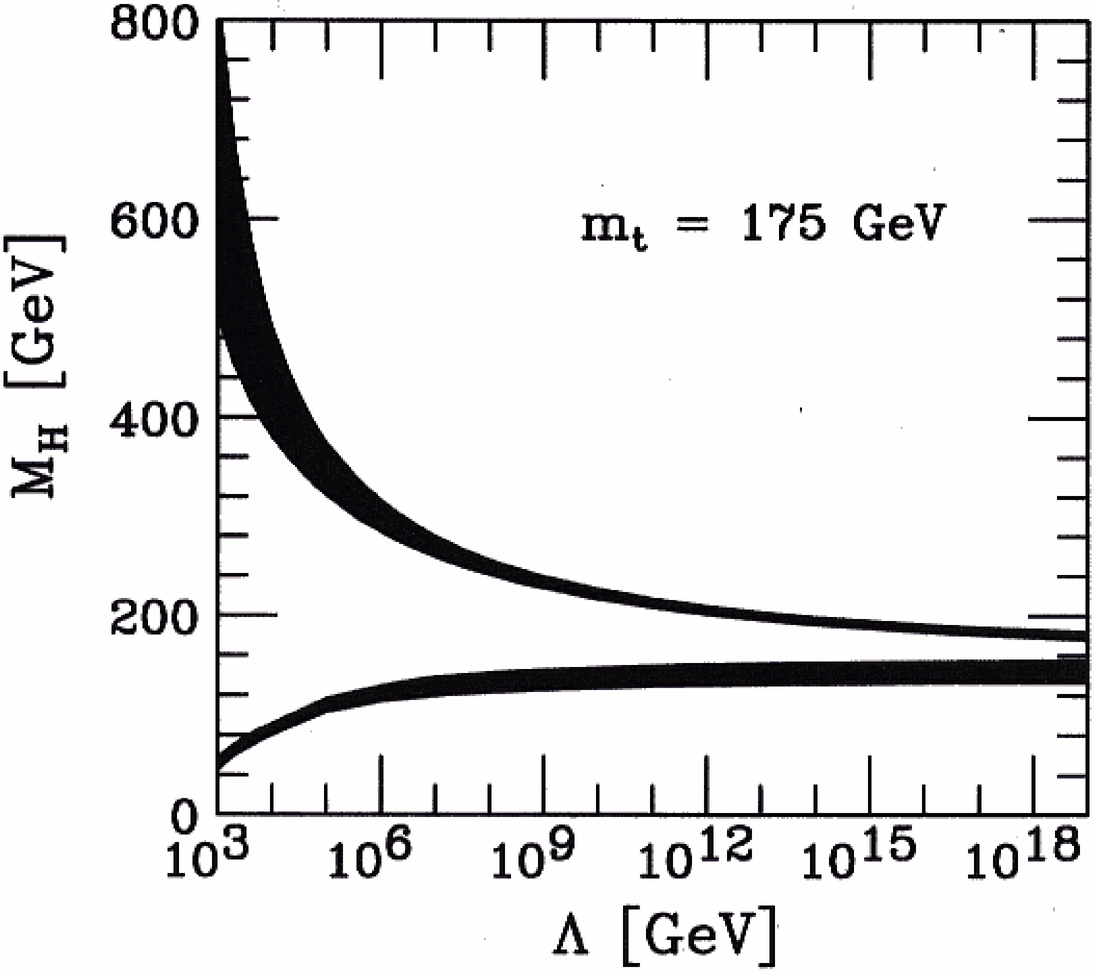
  $\Lambda_* \ll M_{PL}$: composite Higgs particle [inter. scale]
  "no" Higgs : strong WW interaction

LC PROJECT :

		$\sqrt{s}$	$\int \mathcal{L}$ p.a.	
Phase I	TESLA	M_Z ... 500 ... 800 GeV	300 ... 500 fb^{-1}	TDR
	JLC/NLC	M_Z ... 500 ... 888 GeV	.. 200 ... 340 fb^{-1}	
Phase II	CLIC	... 3 ... 5 TeV	0.3 / 1 ab^{-1}	2nd g.


ELWWG
theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02761±0.00036
0.02738±0.00020
Excluded
Preliminary
6
4
2
0
$\Delta\chi^2$
10^2
m_H [GeV]

Riesselmann



doubling e^- arm : 1.2 TeV]

LC $\gamma\gamma$ mode : monochromatic $\Delta \sim 10\%$

luminosity $\sim 1/2\, \mathcal{L}_{e^+e^-}$

Giga Z : LE operation $\gtrsim 10^9$ Z per a

Project-band-with : M_Z to several TeV

high luminosity

clean exp. environment

→ high-resolution picture of elw symmetry breaking

→ extrapolation to scales not accessible directly

2. THE BASE: SM HIGGS MECHANISM

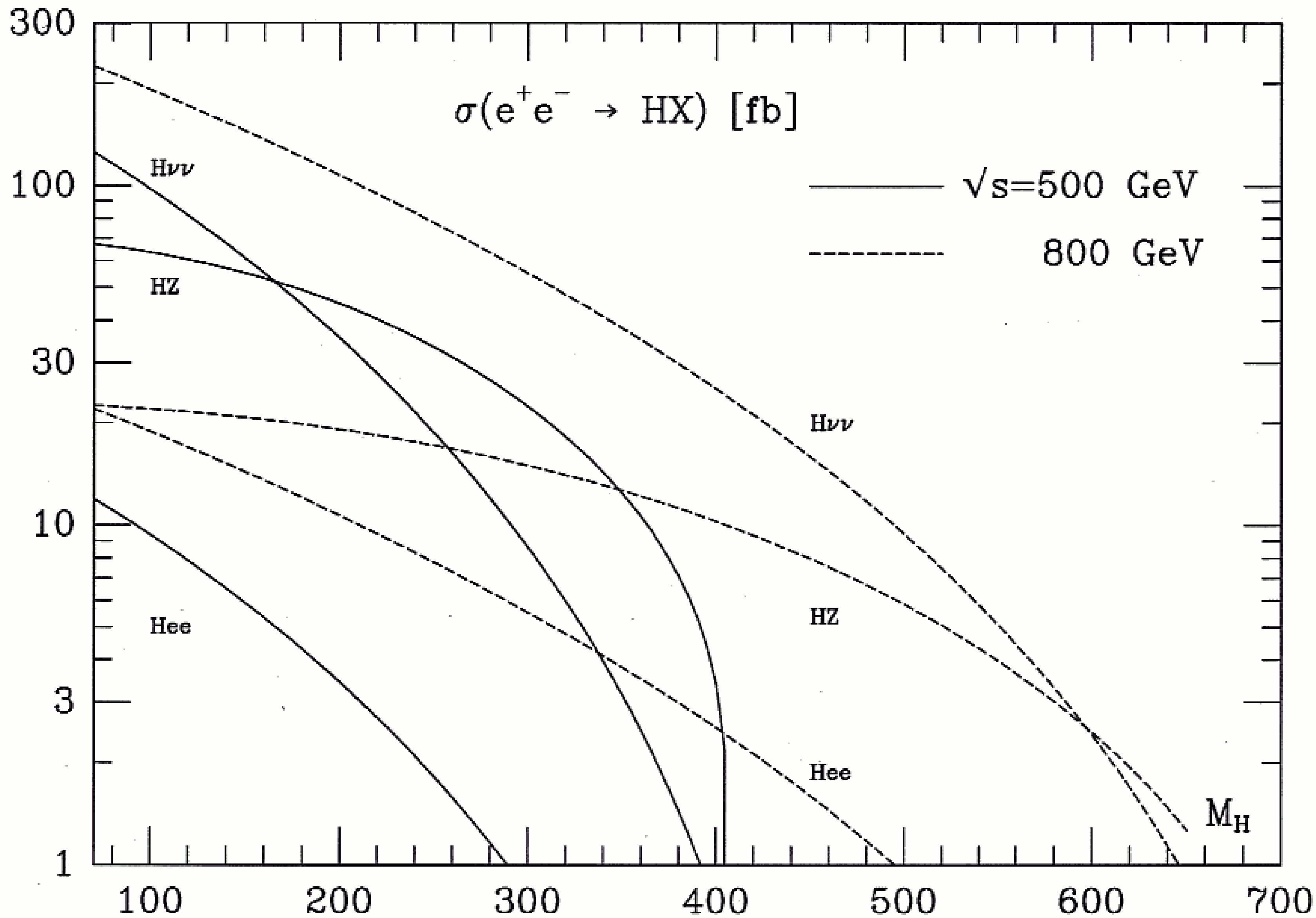
ElwSB in fundamental scalar iso-doublet sector:

Higgs boson : all properties determined if mass fixed

$M_H \lessapprox 200$ GeV ← analysis of precision exp.

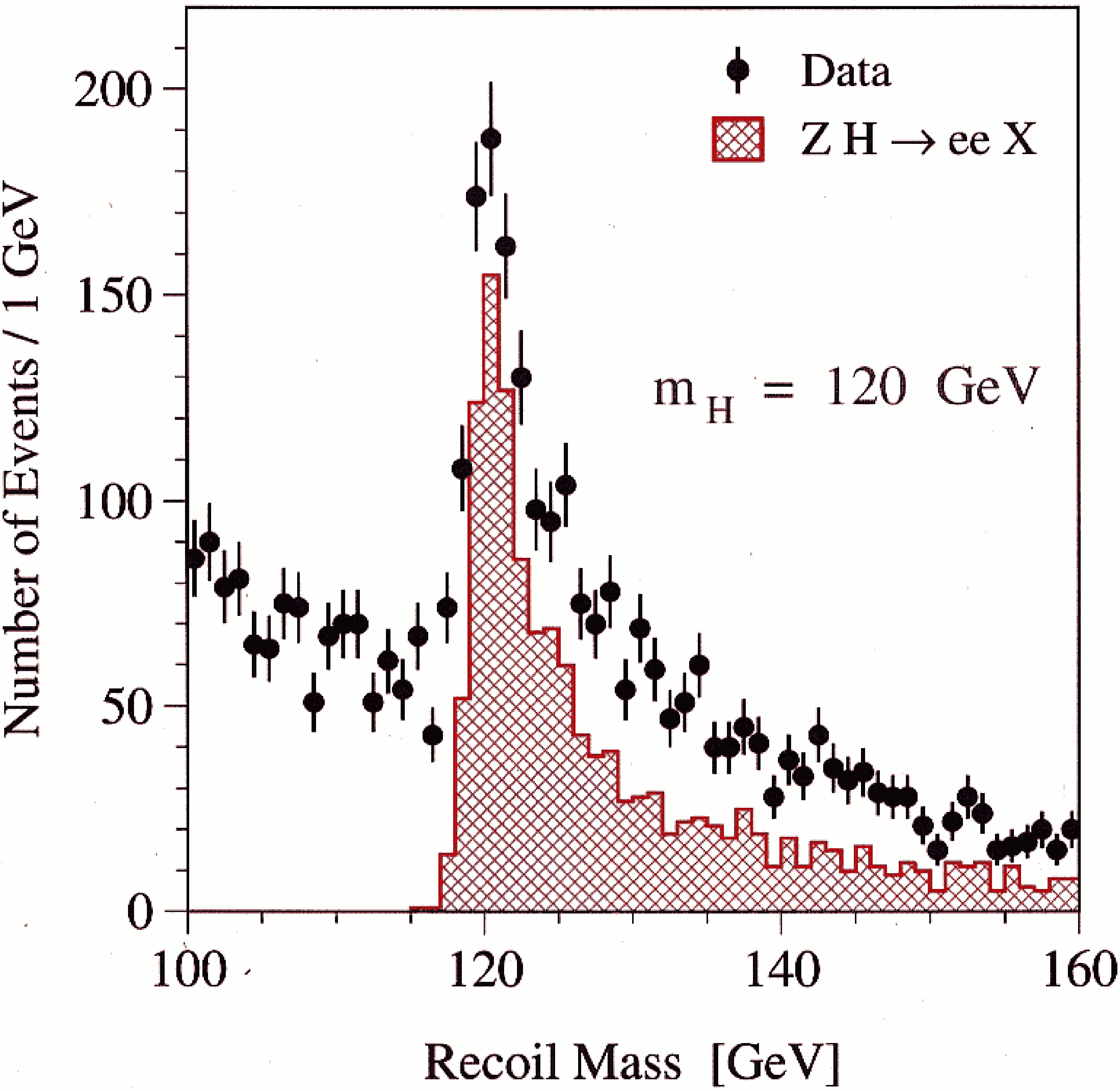
← extdg up to M_{PL}
prerequisite $s_W^2 \sim 0.2$]

Djouadi ea



$\sigma(e^+e^- \to HX)$ [fb]
$\sqrt{s}$=500 GeV
800 GeV
H$\nu\nu$
HZ
Hee
H$\nu\nu$
HZ
Hee
M_H
300
100
30
10
3
1
100
200
300
400
500
600
700

Garcia-Abia
Lohmann



TASK: establish Higgs mechanism experimentally in three steps

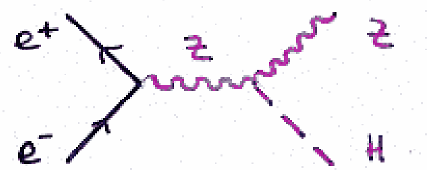
(1) Higgs excitation ≡ Higgs boson must be discovered [LEP2?] Tevatron LHC

(2) generating masses by interaction with Higgs field: coupling ~ mass [LHC] LC

(3) Higgs field in vacuum generated by spont. sym. brkg: reconstruction of Higgs potential LC

LC PRODUCTION OF SM HIGGS BOSON

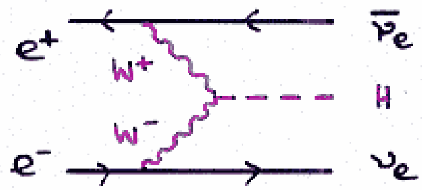
(a) Higgs-strahlung:



$$\sigma = \frac{G_F^2 M_Z^4}{96\pi s} k_s \beta$$

$\sqrt{s}$ lower part

(b) W fusion:



$$\sigma \simeq \frac{G_F^3 M_W^4}{4\sqrt{2}\pi^3} \log \frac{s}{M_H^2}$$

$\sqrt{s}$ upper part

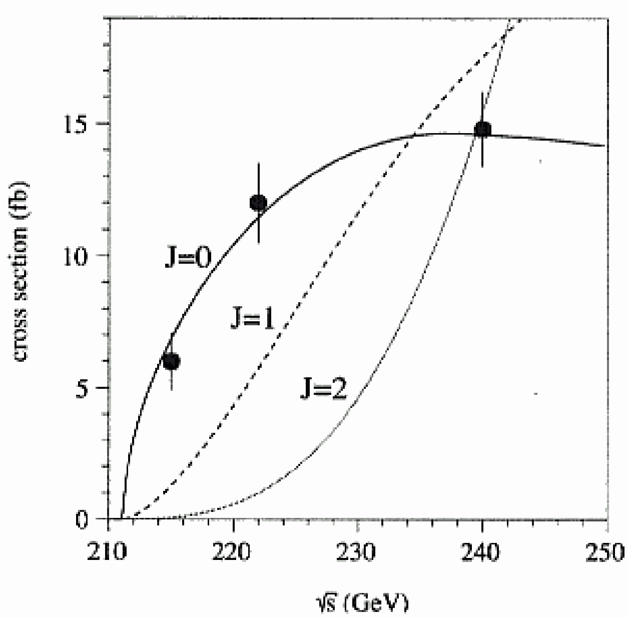
F: $\sqrt{s} \sim 300$ GeV / $\int\mathcal{L} \sim 500$ fb^{-1}

$M_H \sim$ intermediate mass range: 10^5 Higgs bosons

F: almost background-free

Coupling	$M_H = 120\,\text{GeV}$	$140\,\text{GeV}$
g_{HWW}	$\pm\, 0.012$	$\pm\, 0.020$
g_{HZZ}	$\pm\, 0.012$	$\pm\, 0.013$
g_{Htt}	$\pm\, 0.030$	$\pm\, 0.061$
g_{Hbb}	$\pm\, 0.022$	$\pm\, 0.022$
g_{Hcc}	$\pm\, 0.037$	$\pm\, 0.102$
$g_{H\tau\tau}$	$\pm\, 0.033$	$\pm\, 0.048$
g_{HWW}/g_{HZZ}	$\pm\, 0.017$	$\pm\, 0.024$
g_{Htt}/g_{HWW}	$\pm\, 0.029$	$\pm\, 0.052$
g_{Hbb}/g_{HWW}	$\pm\, 0.012$	$\pm\, 0.022$
$g_{H\tau\tau}/g_{HWW}$	$\pm\, 0.033$	$\pm\, 0.041$
g_{Htt}/g_{Hbb}	$\pm\, 0.026$	$\pm\, 0.057$
g_{Hcc}/g_{Hbb}	$\pm\, 0.041$	$\pm\, 0.100$
$g_{H\tau\tau}/g_{Hbb}$	$\pm\, 0.027$	$\pm\, 0.042$

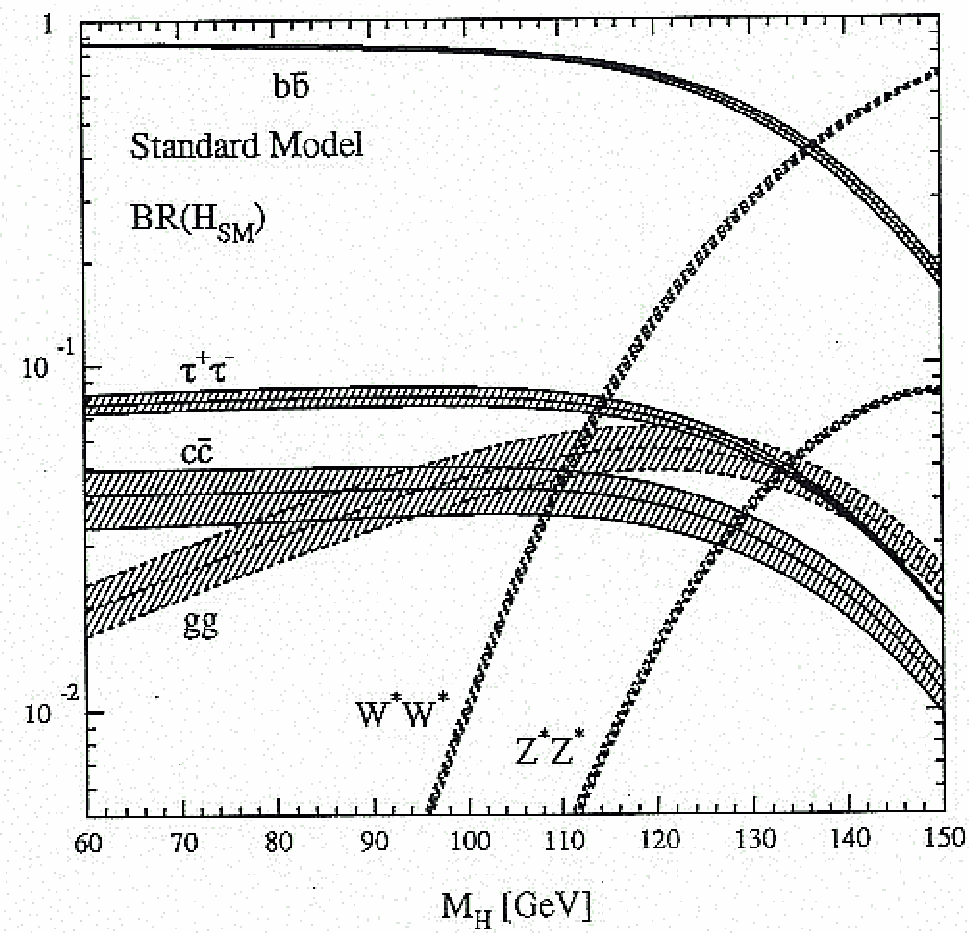
Table 2.2.6: *Relative accuracy on Higgs couplings and their ratios obtained from a global fit (see text). An integrated luminosity of $500\,fb^{-1}$ at $\sqrt{s} = 500$ GeV is assumed except for the measurement of g_{Htt}, which assumes $1000\,fb^{-1}$ at $\sqrt{s} = 800\,GeV$ in addition.*



TESLA TDR

Figure 2.2.7: *Simulated measurement of the $e^+e^- \to H^0Z$ cross section for $M_H = 120\,GeV$ with $20\,fb^{-1}$/point at three centre-of-mass energies compared to the predictions for a spin-0 (full line) and examples of spin-1 (dashed line) and spin-2 (dotted line) particles.*

Djouadi ea

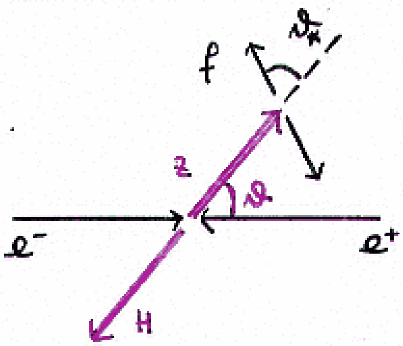


bb̄
Standard Model
BR(H_SM)
τ+τ-
cc̄
gg
W*W*
Z*Z*
1
10^-1
10^-2
60
70
80
90
100
110
120
130
140
150
M_H [GeV]

lifetime

Hagiwara ea
Para
Schumacher

$\underline{\underline{J^{PC} = 0^{++}}}$:



threshold : $\sigma \sim \beta \sim \sqrt{s-(m_H+m_Z)^2}$

$\quad$ ang $[1+\cos^2\vartheta]\cdot[\sin^2\vartheta_*]$ $\quad$ V.V.

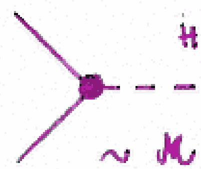
$\Longrightarrow$ ruling out : $J^P = 0^-, 1^\pm, 2^\pm, \ldots$

CP admix : $\quad H = [0^{++}] + i\eta\,[0^{+-}]$

$$\frac{d\sigma}{d\cos\vartheta} \simeq \sin^2\vartheta + 8\eta\,p\cos\vartheta \Longrightarrow \text{sens. } \eta \lesssim 0.03$$

HIGGS COUPLINGS

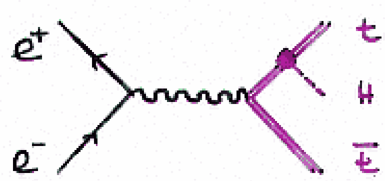
SM masses generated by interaction
with Higgs field : $g \sim M$



← production : $\sigma(H) \sim g^2(HZZ)$ etc

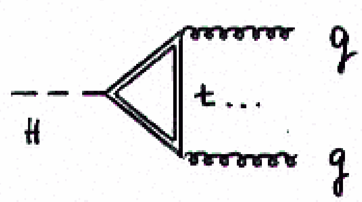
← decay : $BR(f) \sim g^2(Hff)$ etc

← top couplg :



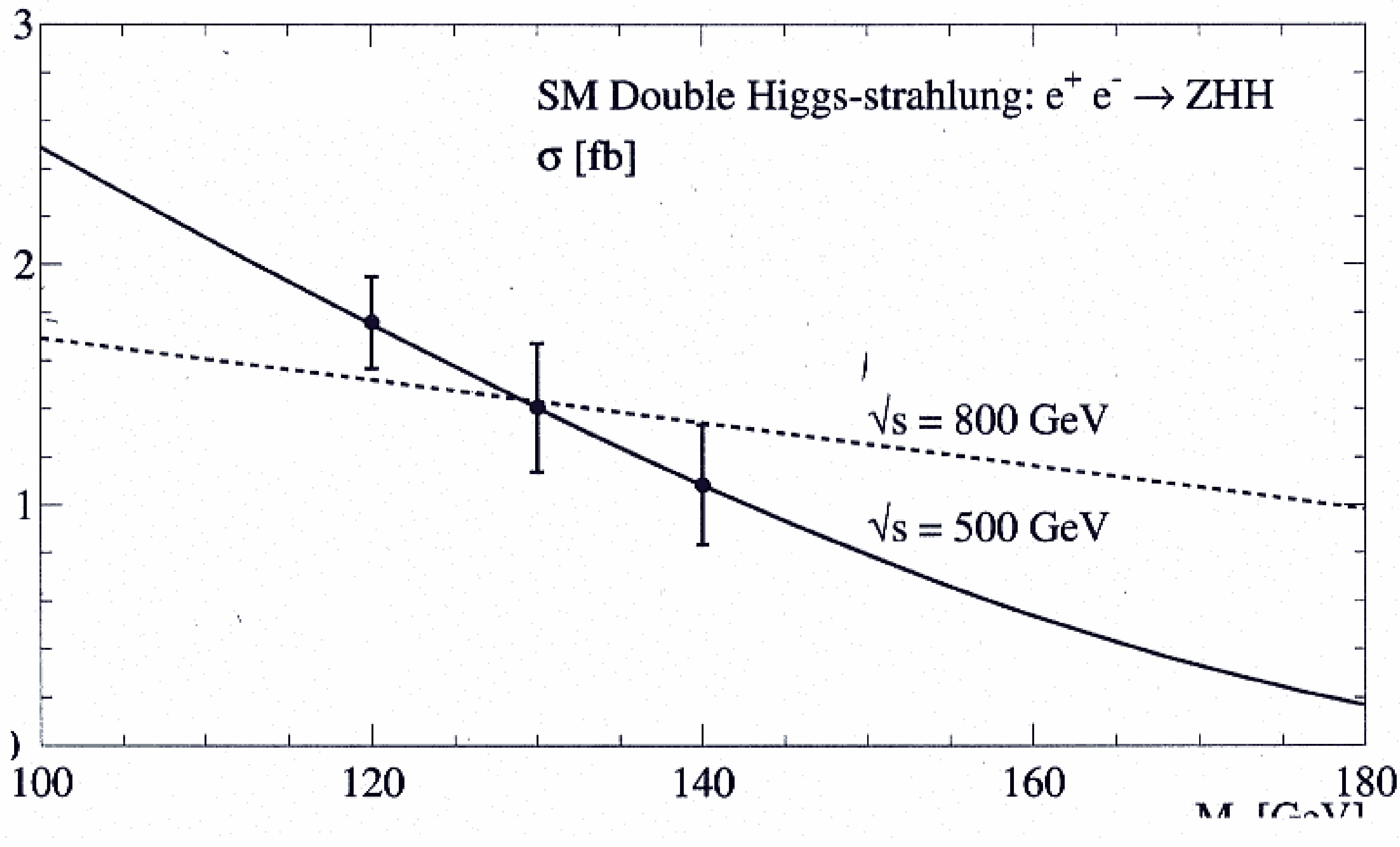
Djouadi ea
Dawson ea
Dittmaier ea

← loop cplgs :



and $H \to \gamma\gamma$ decay
$\gamma\gamma \to H$ production

MÜHLLEITNER ER
GAY ER



SUMMARY:

coupling	M_H = 120 GeV	140 GeV
HWW	0.012	0.020
HZZ	0.012	0.013
$Hb\bar{b}$	0.022	0.022
$Hc\bar{c}$	0.037	0.102
$H\tau\tau$	0.033	0.048
$Ht\bar{t}$	0.030	0.061

Battaglia
Desch ea

Zerwas ea
Baur ea

(i) same mechanism for gauge bosons and fermions

(ii) up/down ratio: $\dfrac{c}{b} = \dfrac{m_c^2(M_H)}{m_b^2(M_H)}$

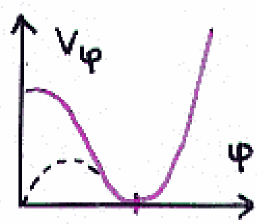
(iii) lepton/quark ratio: $\dfrac{\tau}{b} = \dfrac{m_\tau^2}{3 m_b^2(M_H)}$

HIGGS POTENTIAL

self-interactions of scalar fields

→ shift of minimum $v/\sqrt{2} \neq 0$

→ electroweak symmetry breaking



$$V = \lambda\left[\varphi^2 - \tfrac{1}{2}v^2\right]^2 \Rightarrow \lambda_2 = M_H^2/2 \quad \rightarrow \text{ oscill about min.}$$

$$\Rightarrow \lambda_3 = M_H^2/2v \quad \rightarrow \text{ dampg at } \varphi = 0$$

$$\lambda_4 = M_H^2/8v^2 \quad \rightarrow \text{ final form}$$

HHH:

double Higgs-strahlung:

$\sigma \sim \alpha^2 g^2 (HHH) \lessapprox 1\,\text{fb}$

sensitivity ≈ 0.18

Carena ea

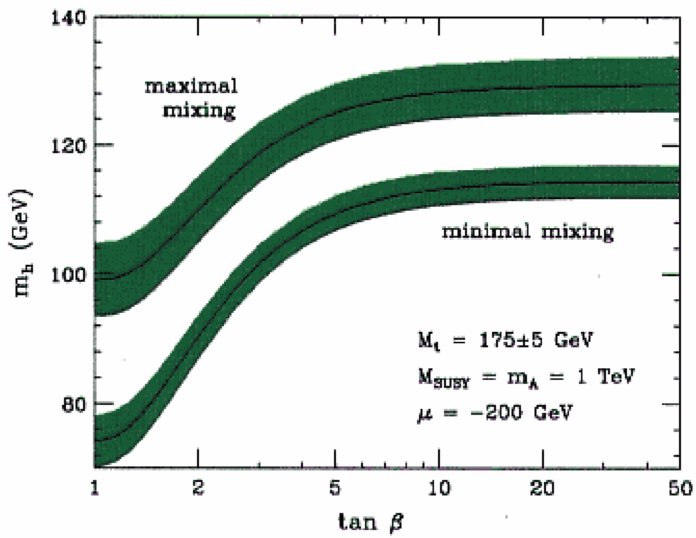
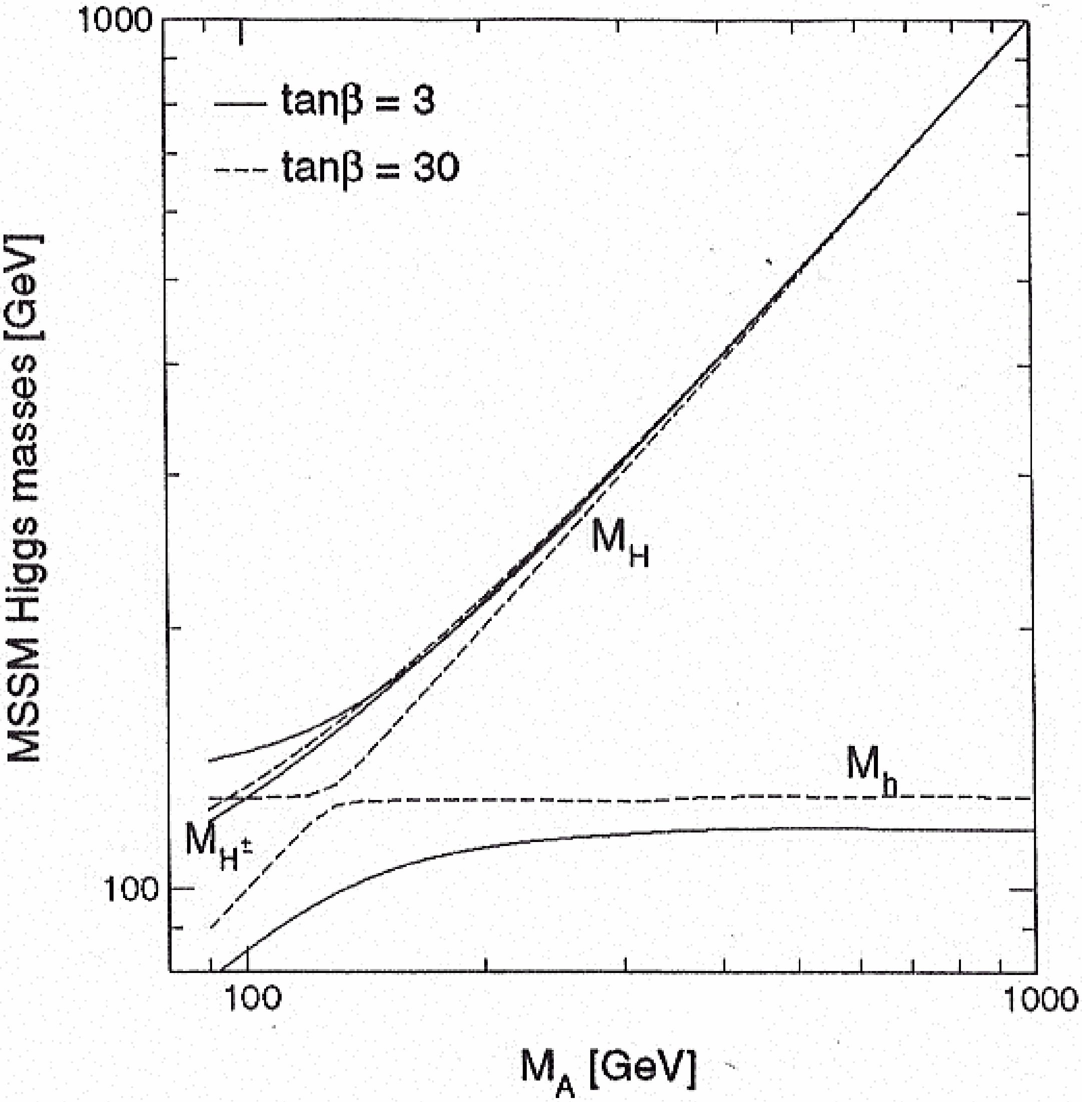


Figure 11: The radiatively corrected light CP-even Higgs mass is plotted as a function of $\tan\beta$, for $M_{\rm SUSY} \equiv M_Q = M_U = M_D = 1$ TeV and $m_A = 1$ TeV, for the maximal mixing [upper band] and minimal mixing [lower band] benchmark cases [see caption to fig. 10]. The impact of the top quark mass is exhibited by the shaded bands; the central value corresponds to $M_t = 175$ GeV, while the upper [lower] edge of the bands correspond to increasing [decreasing] M_t by 5 GeV.


1000
100
tanβ = 3
tanβ = 30
MSSM Higgs masses [GeV]
M_H
M_h
$M_{H^\pm}$
100
1000
M_A [GeV]

HIGH PRECISION :

a) establish exp. elw SB in SM etc: valuta physica sui generis

b) consequences BYSM examples :

- new strong interactions at intermediate scale :
  changing fermion cplgs, self-interactions, ..?
  affecting loop couplings? — Snowman

- only top mass generated by Higgs mechanism,
  other fermion mass "radiatively" :
  $H \not\to b\bar{b}$
  $H \to gg$ dominant for low Higgs masses — Fritzsch ea

- xtra dimensions :
  new scalars mixing with Higgs boson — Csaki ea, Cheung
  RS : radion $\leftrightarrow$ Higgs
  $\quad\llcorner gg \qquad \llcorner b\bar{b}$: change BR(H)

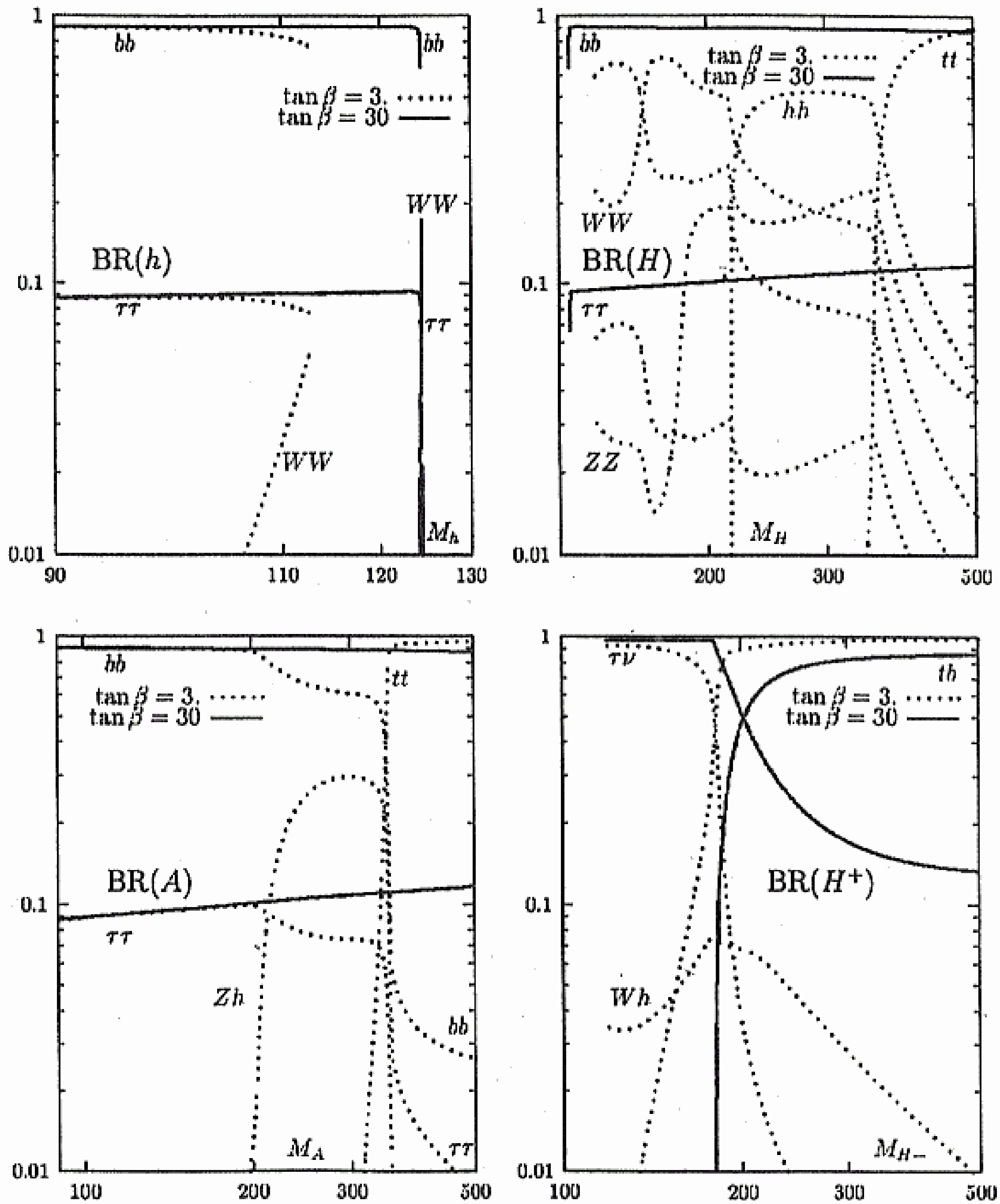
3. SUPERSYMMETRY

MSSM : 2 doublets $\to$ spectrum of 5 states :

$h^0 \quad \lesssim 135$ GeV
$H^0, A^0, H^\pm \quad \sim \mathcal{O}(v)$ to $\mathcal{O}(\mathrm{TeV})$

parameters: M_A, $\mathrm{tg}\,\beta$

large : degen


BR(h)
bb
tan β = 3
tan β = 30
WW
ττ
M_h
BR(H)
hh
tt
ZZ
M_H
BR(A)
Zh
M_A
BR(H⁺)
τν
tb
Wh
M_H−
1
0.1
0.01
90
110
120
130
100
200
300
500

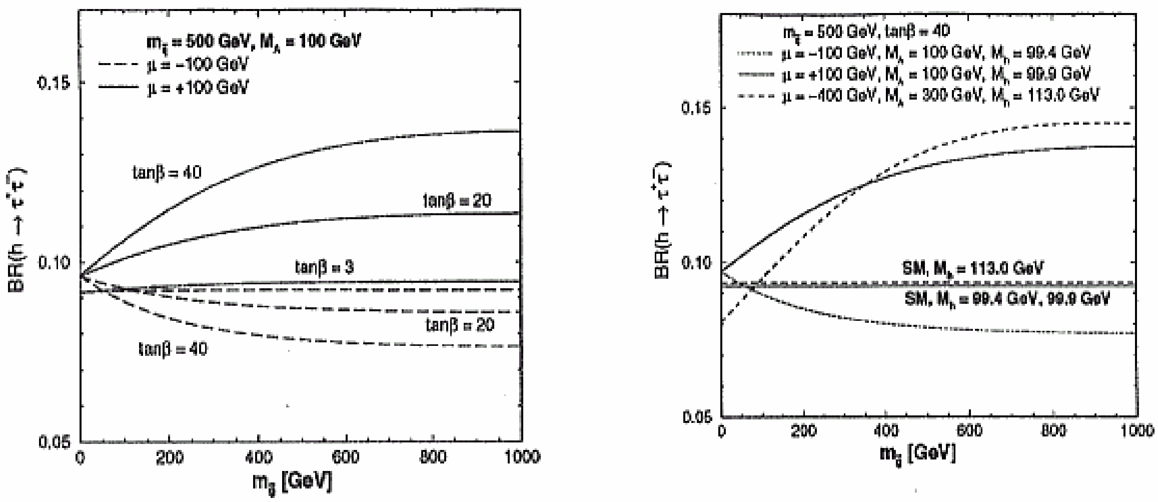
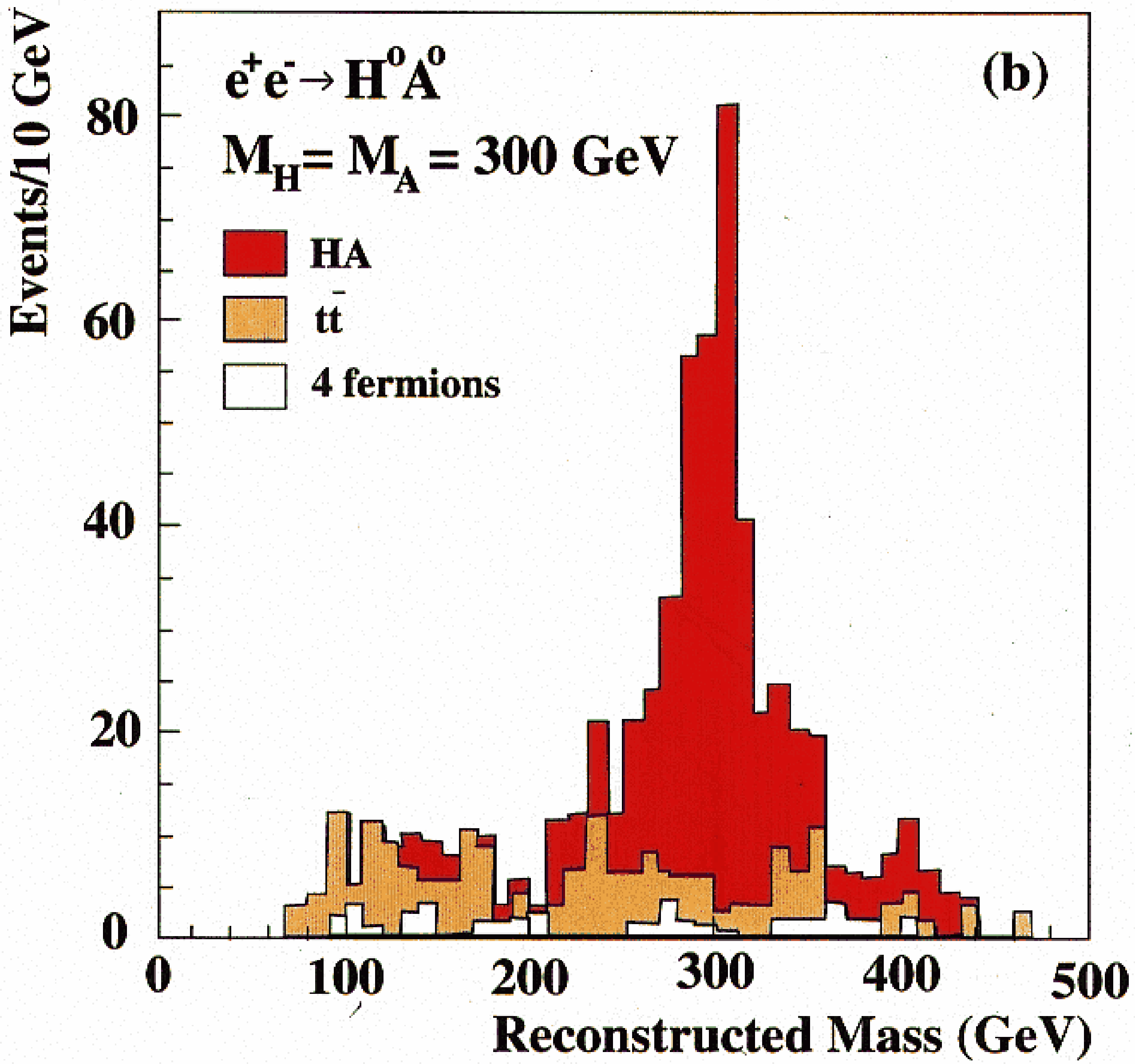


Figure 7: *$BR(h \to \tau^+\tau^-)$ is shown as a function of $m_{\tilde{g}}$. The left plot corresponds to three different values of $\tan\beta$ and $\mu = \pm 100$ GeV. The right plot corresponds to $\tan\beta = 40$ and the two scenarios $M_A = 100$ GeV$, \mu = \pm 100$ GeV and $M_A = 300$ GeV$, \mu = -400$ GeV. The other parameters in both plots are $m_{\tilde{q}} = 500$ GeV$, X_t = 500$ GeV$, M_A = 100$ GeV, $M_2 = 500$ GeV, $A_b = A_t$. The Higgs boson masses given in the legend are averaged masses over the interval $0 < m_{\tilde{g}} < 1000$ GeV where the variation of M_h is about ± 1 GeV for the above considered parameters. The horizontal lines represent the SM result using the corresponding Higgs boson masses.*

Heinemeyer

TESLA TDR


e+e- → H°A°
(b)
M_H = M_A = 300 GeV
HA
tt̄
4 fermions
Events/10 GeV
0
20
40
60
80
0
100
200
300
400
500
Reconstructed Mass (GeV)

DECAY MODES:

Higgs → SM particles $\qquad h^0 \to b\bar{b}$ ..

→ cascade decays $\qquad A^0 \to Z h^0$ ..

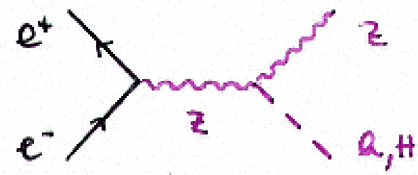
→ supersym. particles $\qquad h^0 \to \tilde{\chi}\tilde{\chi}$ ..

potentially large effects of radiative corrections

PRODUCTION CHANNELS:

Heinemeyer ea

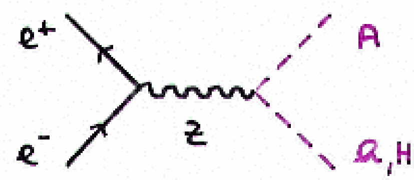
a) Higgs-strahlung:



$\sigma_{Zh} = \sigma_0 \times \sin^2(\beta-\alpha)$

$\sigma_{ZH} = \sigma_0 \times \cos^2(\beta-\alpha)$

b) assoc. production:



$\sigma_{Ah} = \sigma_0 \lambda \times \cos^2(\beta-\alpha)$

$\sigma_{AH} = \sigma_0 \lambda \times \sin^2(\beta-\alpha)$

light h^0 boson:

$\left.\begin{array}{l}\text{mutual } \sin^2/\cos^2 \text{ in } Zh \text{ and } Ah \\ \sin^2 \text{ small} \to \cos^2 \text{ large, } M_A \text{ small}\end{array}\right\}$

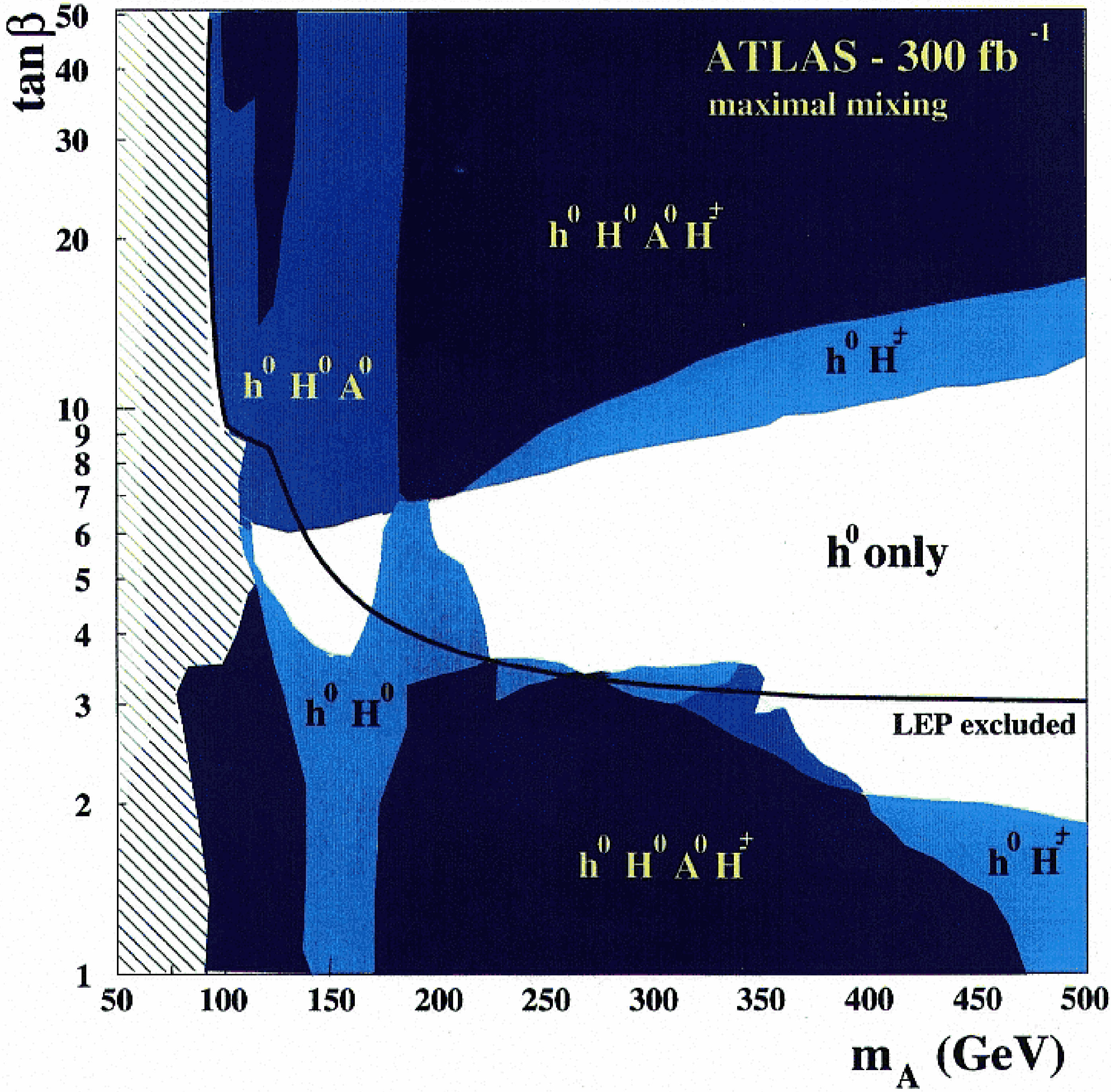
h^0 must be found / at ~ 250 GeV

indep. of decay mode

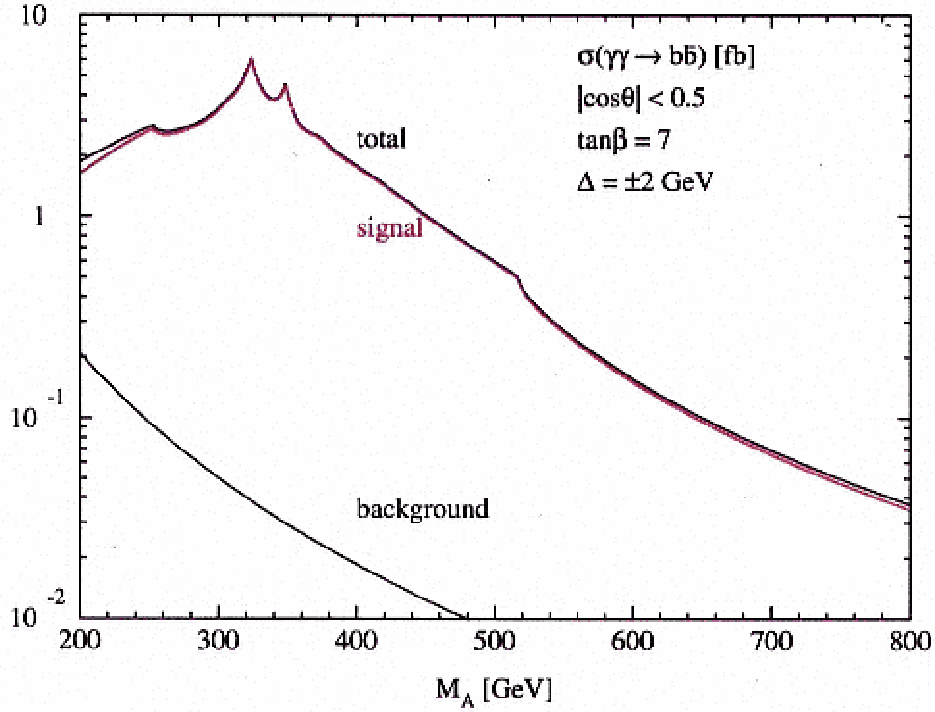
heavy $H^0, A^0, H^\pm$: pair production in decpl. regime

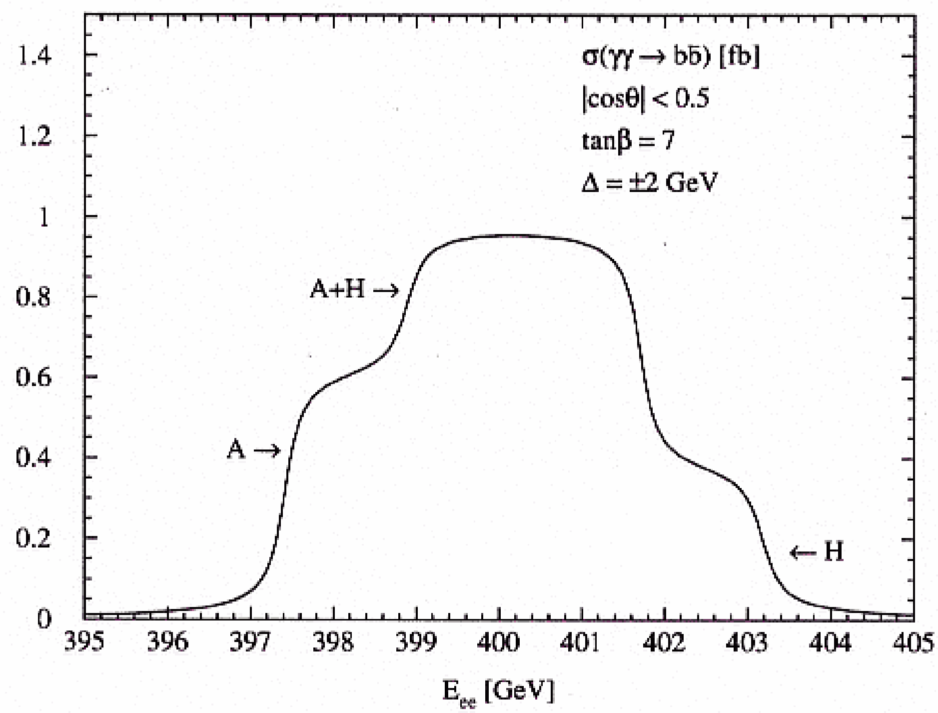
$e^+e^- \to A^0H^0,\ H^+H^-$ with $M \lesssim \frac{1}{2}\sqrt{s}$

CLIC: M up to 2.5 TeV

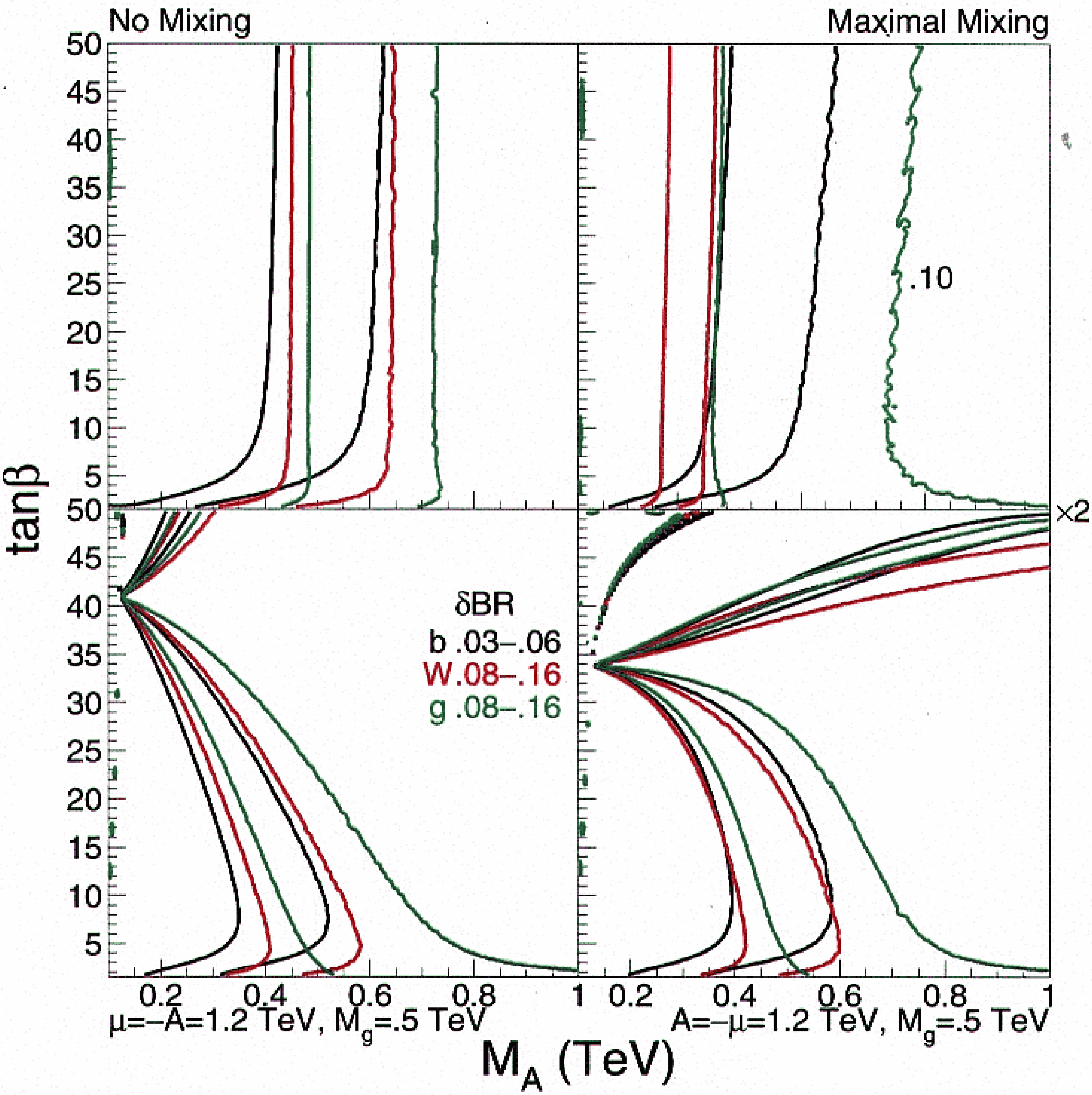

ATLAS - 300 fb^{-1}
maximal mixing
h^0 H^0 A^0 $H^\pm$
h^0 H^0 A^0
h^0 $H^\pm$
h^0 only
h^0 H^0
LEP excluded
h^0 H^0 A^0 $H^\pm$
h^0 $H^\pm$
$\tan\beta$
m_A (GeV)
1
2
3
4
5
6
7
8
9
10
20
30
40
50
50
100
150
200
250
300
350
400
450
500

Mühlleitner
Krämer, Spira, Z





Carena ea


No Mixing
Maximal Mixing
tanβ
.10
×2
δBR
b .03–.06
W.08–.16
g .08–.16
μ=−A=1.2 TeV, M_g=.5 TeV
A=−μ=1.2 TeV, M_g=.5 TeV
M_A (TeV)

Erler ea

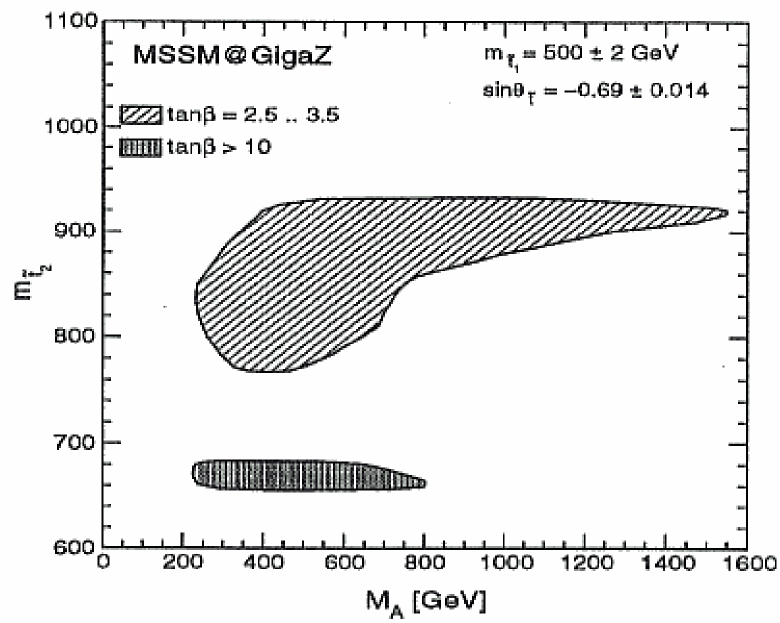
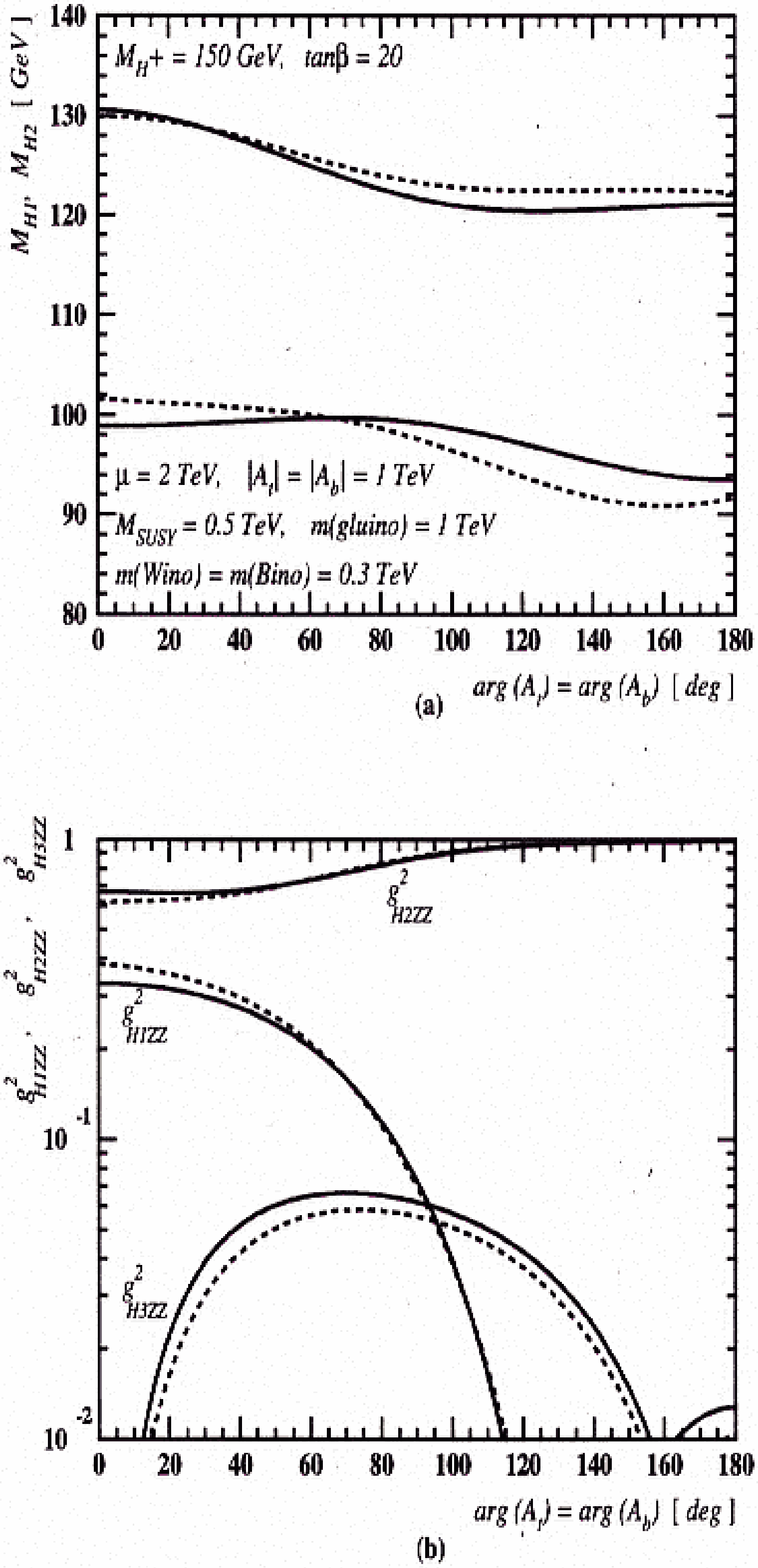


Figure 19: The region in the $m_A - m_{\tilde{t}_2}$ plane, allowed by $1\,\sigma$ errors obtained from the Giga-Z measurements of m_W and $\sin^2\theta_{\rm eff}$: $m_W = 80.400 \pm 0.006$ GeV, $\sin^2\theta_{\rm eff} = 0.23140 \pm 0.00001$, and from the LC measurement of m_h: $m_h = 115 \pm 0.05$ (exp.) $\pm\, 0.5$ (theo.) GeV. $\tan\beta$ is assumed to be $\tan\beta = 3 \pm 0.5$ or $\tan\beta > 10$. The other parameters including their uncertainties are given by $m_{\tilde{t}_1} = 500 \pm 2$ GeV, $\sin\theta_{\tilde{t}} = -0.69 \pm 0.014$, $A_b = A_t \pm 10\%$, $m_{\tilde{g}} = 500 \pm 10$ GeV, $\mu = -200 \pm 1$ GeV and $M_2 = 400 \pm 2$ GeV.

Couplings and Masses of Neutral Higgs $(\tan\beta = 20)$

Carena et al.



(INDIRECT) ACCESS TO HEAVY MASSES :

note : LHC blind in wedge : centered at $tg\beta \sim 8$
opening up at $M_A \sim 250$ GeV

a) $\gamma\gamma \to H^0$ and A^0 : resonances in Compton collider
$M \lesssim 600$ GeV at LC of 800 GeV

b) BR($h^0 \to b\bar{b}$) etc : $hbb = -\sin\alpha / \cos\beta$: $\alpha \to M_A$ Okada Battaglia

no mix : reach ~ 700 GeV Carena et
mixing : reach up to 1 to 2 TeV
[depdg on SUSY params]

c) Giga Z : $\sin^2\vartheta_{eff}$, M_W, $m(h^0)$, $M(\tilde{t}_1)$ and ϑ_t } small $tg\beta$: reach $\lesssim 1.6$ TeV
large $tg\beta$: $\lesssim 0.8$ TeV

DISENTANGLING A^0 from H^0 :

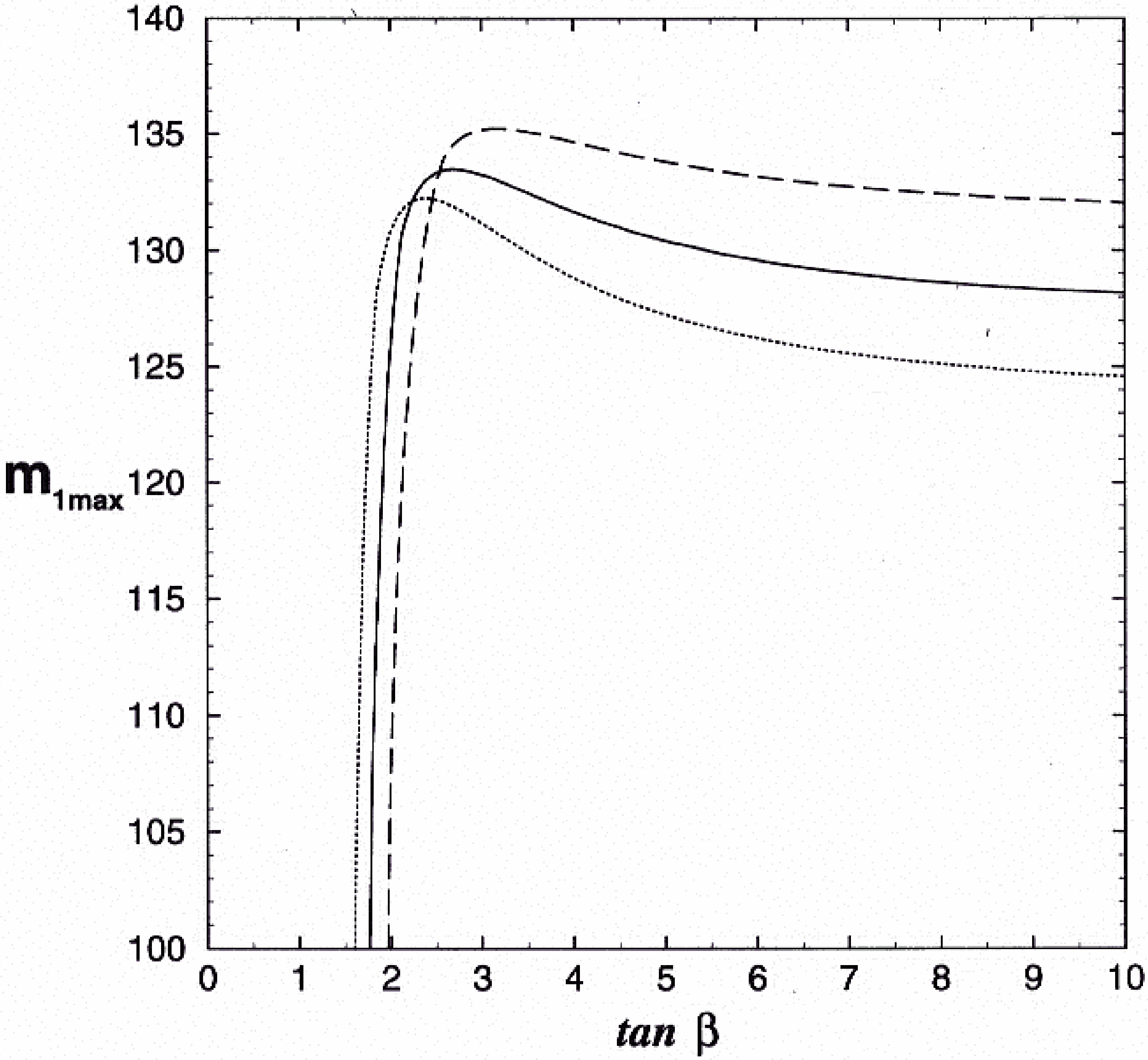
decay : $H, A \to t\bar{t}$: $\frac{d\sigma}{d\varphi_{WW}} \sim 1 \mp \left(\frac{\pi}{4}\right)^2 \cos\varphi$

$\gamma\gamma$ prod : threshold scan

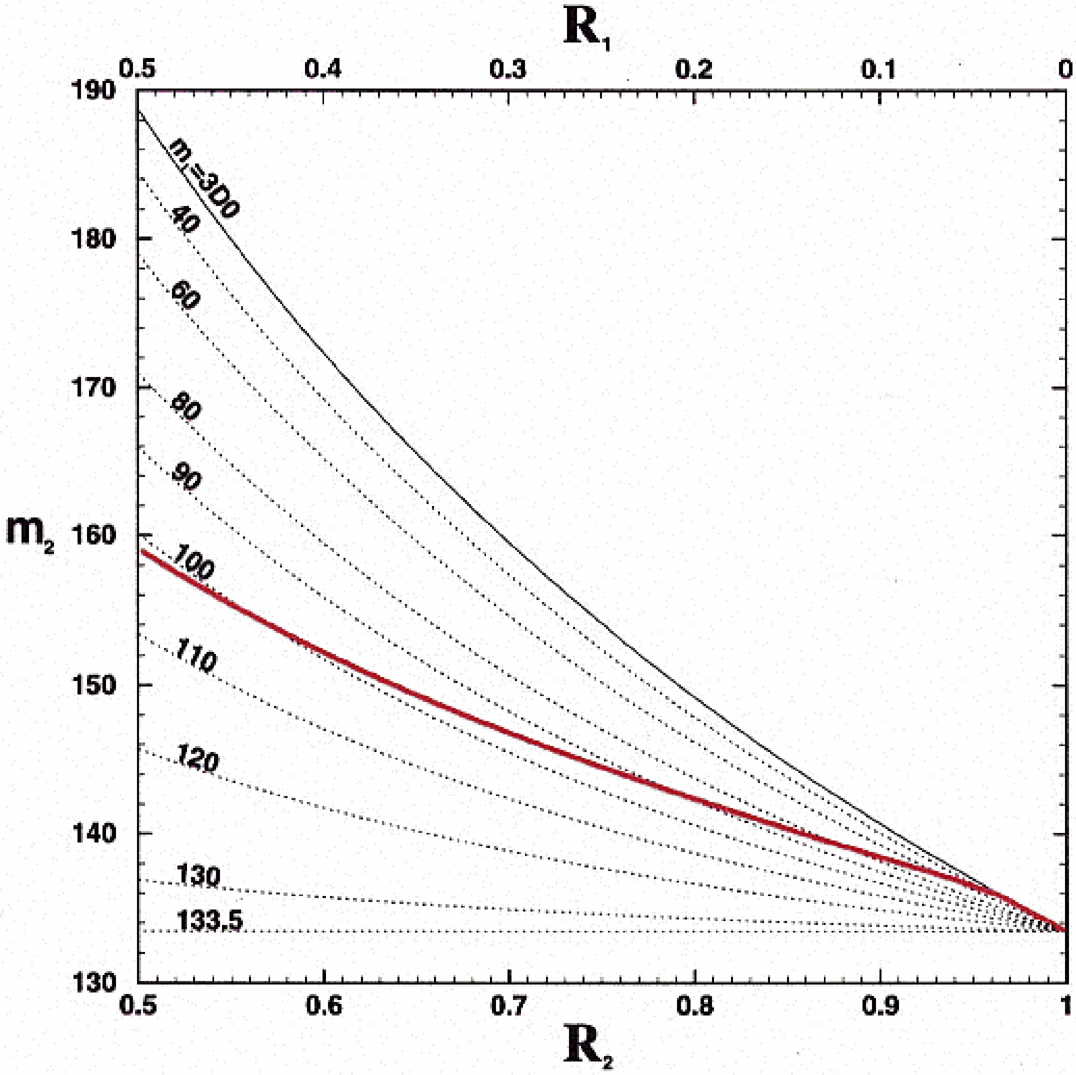
lin. pol. parallel : $\gamma\gamma_{\parallel} \to H^0$
perpend. : $\gamma\gamma_{\perp} \to A^0$

CP : strongly affecting MSSM Higgs sector Carena et
$h^0, H^0, A^0 \to$ CP mixtures 1, 2, 3

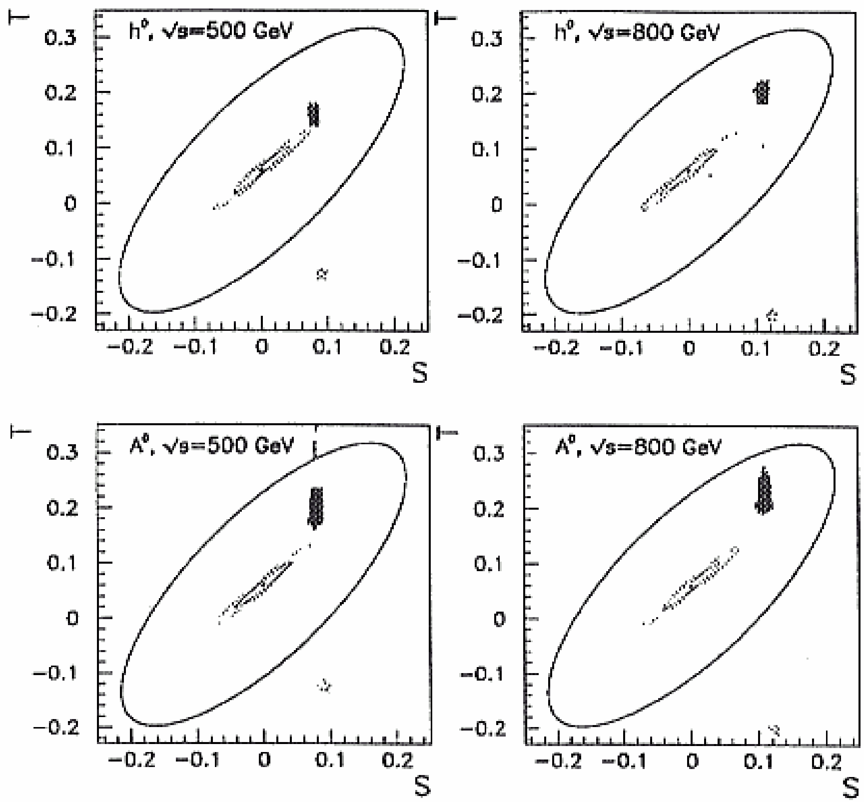
Ellwanger ea



Ellwanger ca



S,T for U=0 and $\Delta\chi^2_{min}$ in No–Discovery Zones



guuion ea

(M+1) SSM : motivated by μ problem superstring theories ... Ellwanger

2 doublets + 1 singlet : $h^0, H^0 \oplus H'^0 \Rightarrow H_1^0, H_2^0, H_3^0$

$A^0 \oplus A'^0 \Rightarrow A_1^0, A_2^0$

$H^\pm \Rightarrow H_1^\pm$

mass pattern ← Yukawa interaction $\lambda H_1 H_2 S$:

- λ bounded : $M^2_{H_1^0} \leq M_Z^2 \cos^2 2\beta + \frac{2\lambda^2 M_Z^2}{g_1^2+g_2^2} \sin^2 2\beta \to 135$ GeV
- $H^\pm$ below $W^\pm$: $M^2_{H^\pm} = M^2_{W^\pm} + M_A^2 - \lambda^2 v^2$

production :

- if $H_1^0 \sim S$ dcplg $\Rightarrow H_2^0$ light $\Rightarrow$ MSSM
- general no-lose theorem — Espinosa Gunion

  ↑ not valid in non-SUSY 2HDM : — Krawczyk ea
  S, T, U analysis in GigaZ

REMARK : Hall ea

Higgs pattern in general SUSY may be quite different from MSSM

Scherk-Schwarz SUSY breaking ~ compactification of xtra dim.

→ one light Higgs boson in dim = 4

$M(h) \lesssim 180$ GeV $\oplus$ non-std SUSY properties

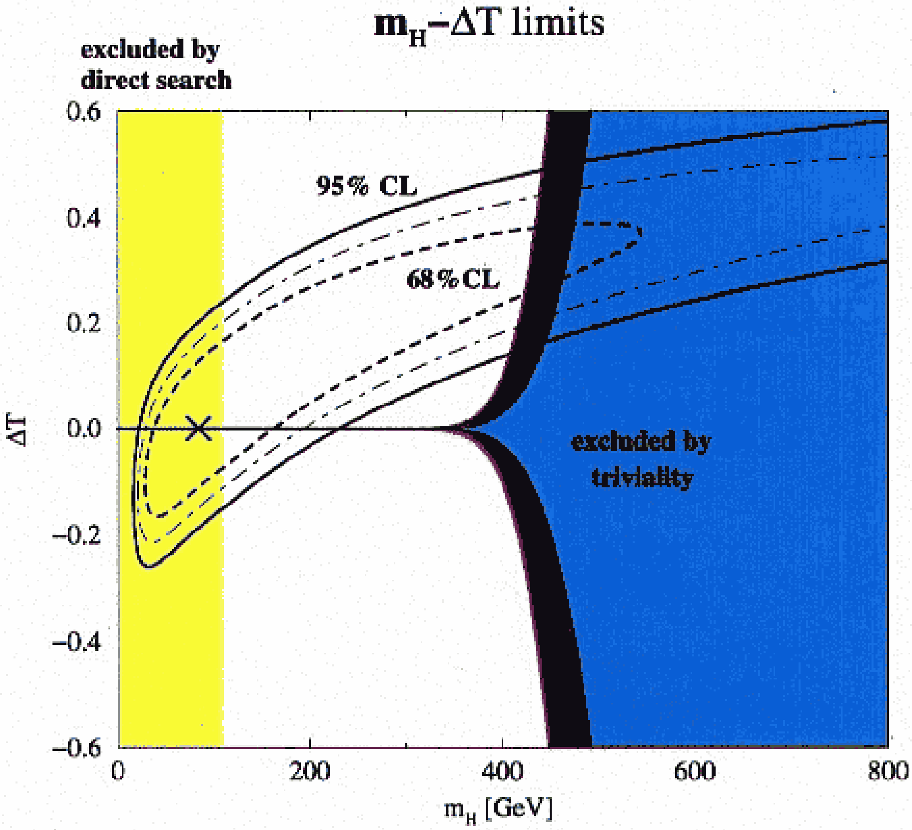


Figure 1: 68% and 95% CL bounds in the $(m_H, \Delta T)$ plane allowed by a fit to precision electroweak data [1, 2]. The best fit "standard model" value is shown by the cross on the $\Delta T = 0$ line. (Also shown by the dot-dash curve is the contour corresponding to $\Delta\chi^2 = 4$, whose intersection with the line $\Delta T = 0$ – at approximately 190 GeV – corresponds to the usual 95% CL upper bound quoted on the Higgs boson mass in the standard model.) The light region to the right is excluded by eqn. 1.3 for $b\kappa^2 = 4\pi$. The dark region denotes the additional area excluded for $b\kappa^2 = 4\pi^2$. The positive branches of the curves bounding these regions are lower bounds for ΔT in the top-seesaw and composite higgs models described in the text. Any $(m_H, \Delta T)$ with positive ΔT and to the left of the appropriate triviality curve can be realized in the corresponding model.

Chivukula et al

4. ALTERNATIVE : STRONG ELW SB

Bardeen ea
Hill ea
Chivukula ea

a) COMPOSITE HIGGS BOSON

motivation : M_t large $\Rightarrow$ t interrelated with elwSB ?

top seesaw mechanism:

$\oplus$ χ singlet : $\begin{bmatrix} t \\ b \end{bmatrix}_L$ $\begin{matrix} t_R \\ b_R \end{matrix}$ χ_L χ_R : $\varphi = \begin{bmatrix} \bar{\chi}_R t_L \\ \bar{\chi}_R b_L \end{bmatrix}$

precision data $\Delta\rho$: $M_H \underset{\sim}{<} 500$ GeV
$M_\chi \gtrsim 5$ TeV

$\oplus$ χ, ω singlets : spectrum of new scalar / pseudoscalar states, some with potentially small masses :

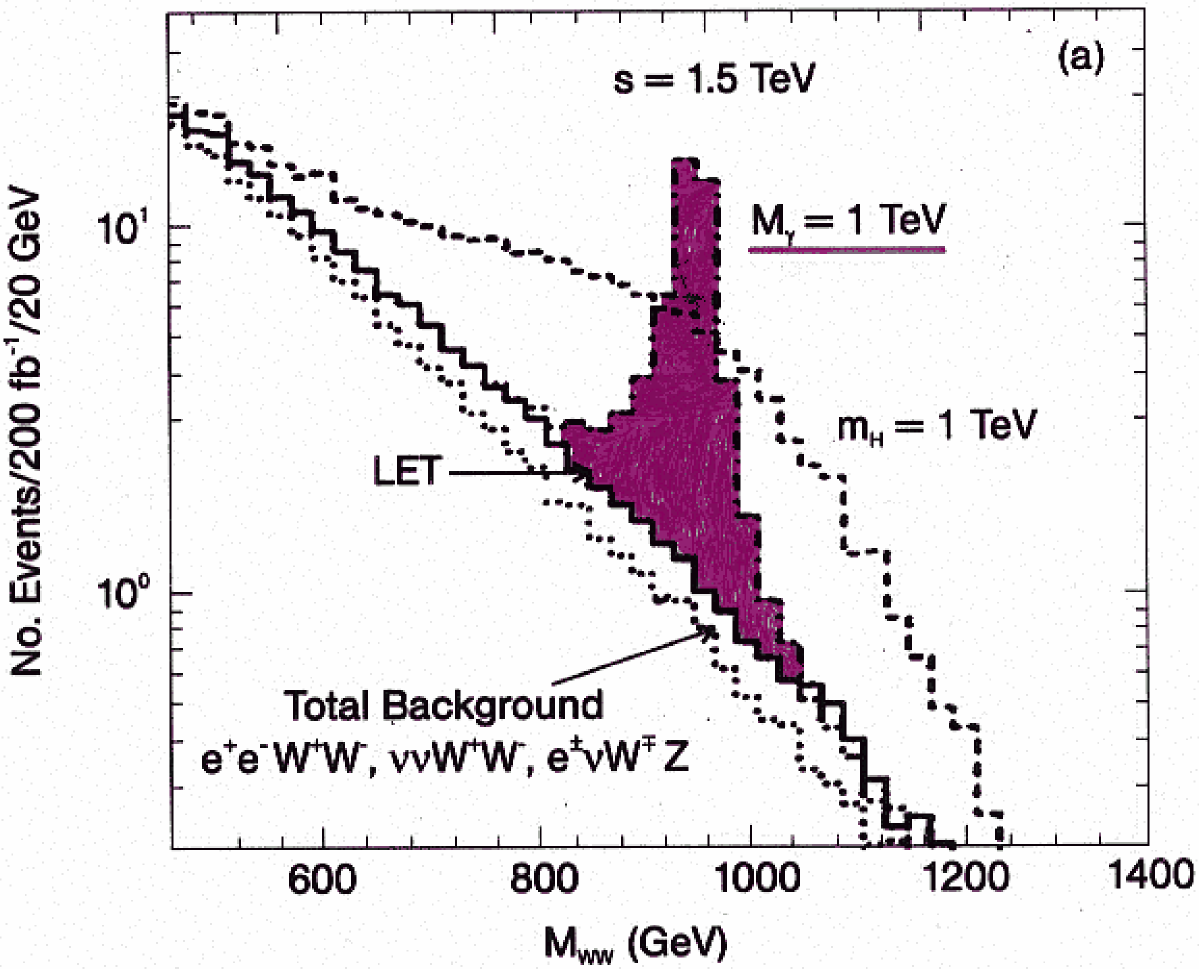
$$\left.\begin{array}{ll} \text{light scalar} & : h^0 \\ \text{light pseudoscalar} & : A^0 \end{array}\right\}$$

$M_{h^0} > 2 M_{A^0}$: dominant h^0 decay : $h^0 \to A^0 A^0$

$e^+e^- \to Z h^0$ — Dobrescu ea
$\hookrightarrow A^0 A^0$
$\hookrightarrow \gamma\gamma, 3\pi, \ldots$

easy to detect at LC

Barger et al



(a)
s = 1.5 TeV
M_γ = 1 TeV
m_H = 1 TeV
LET
Total Background
$e^+e^-W^+W^-$, $\nu\nu W^+W^-$, $e^\pm\nu W^\mp Z$
No. Events/200 fb^{-1}/20 GeV
10^1
10^0
600
800
1000
1200
1400
M_{ww} (GeV)

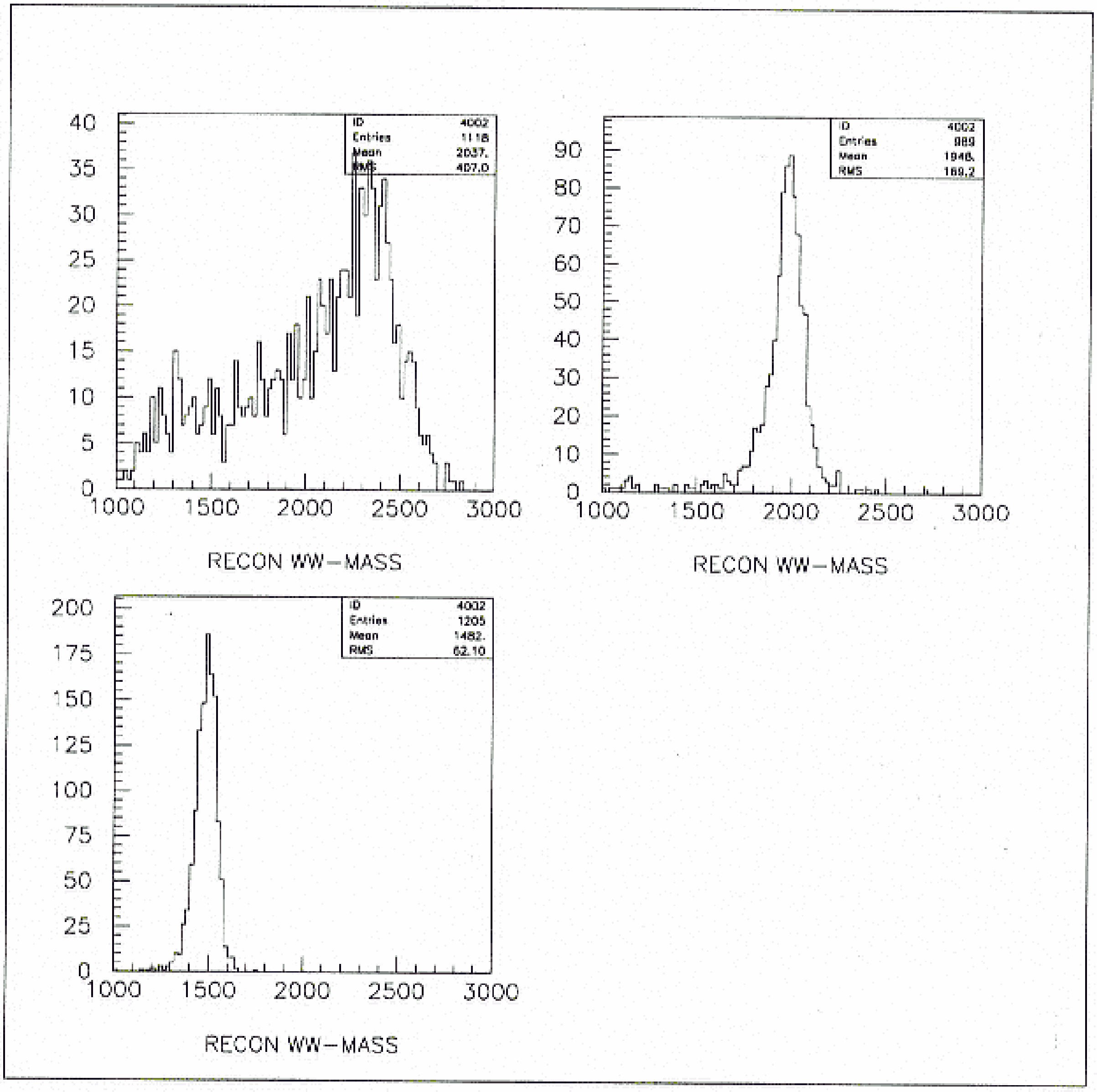
RECONSTRUCTED MASS

CLIC

$M_{WW} = 1.5$ TeV, $\Gamma = 35$ GeV

$M_{WW} = 2$ TeV, $\Gamma = 85$ GeV

$M_{WW} = 2.5$ TeV, $\Gamma = 250$ GeV



b) STRONGLY INTERACTING W BOSONS

no fundam. Higgs boson : strong WW interactions ~ 1 TeV

← new strong interactions $\Lambda_* \lesssim 4\pi v \sim 3$ TeV
global chiral symmetry : spontaneously broken
Goldstone bosons ~ longit. W states

:: deviations from SM predictions for energies below Λ_*
in precision analyses :

Barklow
Ohl ea
Casalbuoni

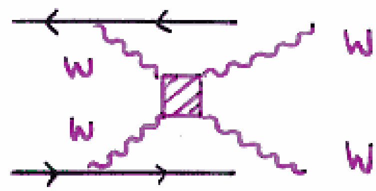
■ anom. trilin. cplg :

$\sqrt{s}$ = 500 GeV

Λ_* up to 3 TeV

■ strong WW scattg :

thresh below res.



$\sqrt{s}$ = 800 GeV

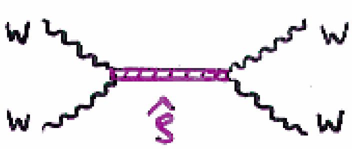
Λ_* up to 2.5 TeV

■ pseudo-Goldstone bosons : $e^+e^- \to \gamma P^0$ $\qquad M_0 \lesssim 400$ GeV

$\gamma\gamma \to P^0$ $\qquad \lesssim 0.7\sqrt{s}$

:: resonance formation : $WW \to R \to WW$ in CLIC range

Barger ea
De Roeck



optimal environm. for res. studies

5. CONCLUSIONS

1.) Essential elements of SM Higgs mechanism can be reconstructed in LC / phase I:

- profile of Higgs boson
- 3 lin. component of Higgs potential

2.) In supersymmetric theories, in LC / phase I access to

- light Higgs boson and its properties
- heavy Higgs bosons in e^+e^- mode : mass up to $\sqrt{s}/2$

  in $\gamma\gamma$ mode : up to $\sim 0.7\sqrt{s}_{ee}$

  and measurement of properties
- no-lose theorem for SUSY Higgs discovery

in LC / phase II : access up to $\lesssim 2.5$ TeV

3.) Strong elw symmetry breaking and new strong interactions

- covered in LC / phase I throughout threshold region
- in LC / phase II : resonance formation covered

The central alternative scenarios, fundamental Higgs sector and strong elw symmetry breaking, can be reconstructed at e^+e^- linear colliders with unique completeness and precision.