SEARCH FOR HIGGS BOSONS AT FUTURE COLLIDERS

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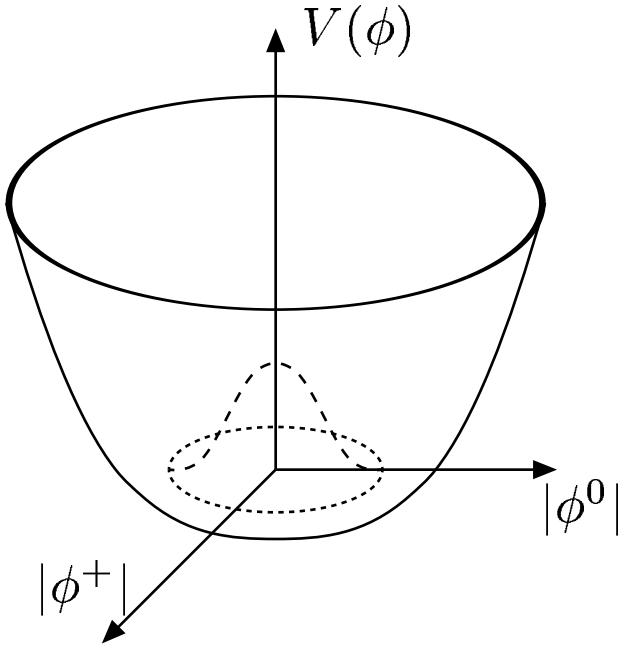
I INTRODUCTION

(i) Standard Model

- Higgs potential:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \underbrace{\exp\left[i\vec{\Theta}\frac{\vec{\tau}}{2}\right]}_{\Rightarrow W^\pm, Z} \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix}$$



$$V(\phi) = \frac{\lambda}{2}\left[|\phi|^2 - \frac{v^2}{2}\right]^2 = \frac{M_H^2}{2}H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4$$

Higgs
Englert, Brout
Guralnik, Hagen, Kibble

$\Rightarrow$ one scalar Higgs boson

$v = 1/\sqrt{\sqrt{2}G_F} \approx 246$ GeV

- fermions [unitary gauge]:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad e^-_R \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \mu^-_R \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \quad \tau^-_R$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{matrix} u_R \\ d_R \end{matrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{matrix} c_R \\ s_R \end{matrix} \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad \begin{matrix} t_R \\ b_R \end{matrix}$$

isospin: $\pm\frac{1}{2}$ 0 $\pm\frac{1}{2}$ 0 $\pm\frac{1}{2}$ 0

hypercharge: $Y = 2(Q - I_3)$
[Gell-Mann–Nishijima relation]

gauge bosons: hypercharge $B_\mu \dfrac{Y}{2}$

isospin $W_\mu = W^a_\mu \dfrac{\sigma^a}{2}$

color $G_\mu = G^a_\mu \dfrac{\lambda^a}{2}$

$$W^\pm_\mu = \frac{W^1_\mu \mp i W^2_\mu}{\sqrt{2}}$$

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix}$$

[θ_W = Weinberg angle]

• mass generation:

$$\begin{aligned}\mathcal{L}_{int} &= |(\partial_\mu - gW_\mu^a \frac{\tau^a}{2} - g' B_\mu \frac{Y}{2})\phi|^2 \\ &- \sum_d g_d \bar{L}\phi d_R - \sum_u g_u \bar{L}\phi^c u_R + h.c.\end{aligned}$$

unitary gauge:

$$\phi = \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix} \qquad \phi^c = i\tau^2\phi^* = \begin{pmatrix} \frac{v+H}{\sqrt{2}} \\ 0 \end{pmatrix}$$

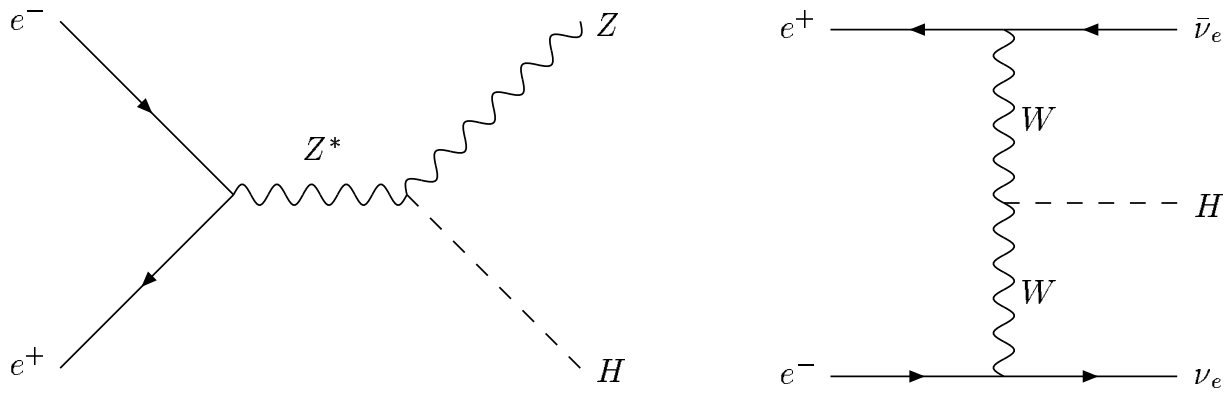
$$\Rightarrow M_W = \frac{g}{2}v \qquad \begin{aligned} M_Z &= \frac{\sqrt{g^2+g'^2}}{2}v \\ m_f &= \frac{g_f}{\sqrt{2}}v \end{aligned} \qquad M_\gamma = 0$$

$\Rightarrow$ $SU(2)_L \times U(1)_Y \to U(1)_{elm}$ [QED]

• couplings to gauge bosons $V = W^\pm, Z$ and fermions:

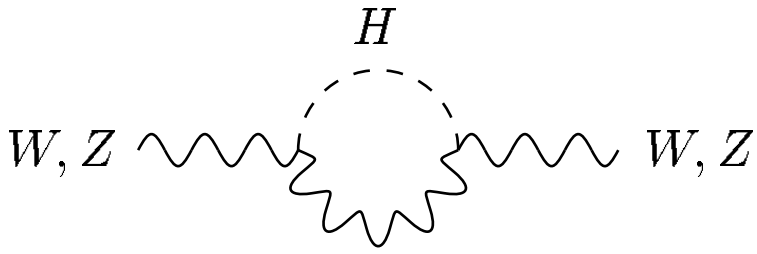
$$g_{VVH} = 2\frac{M_V^2}{v} \qquad g_{ffH} = \frac{m_f}{v} \text{ [} \leftarrow \text{ Yukawa]}$$

- direct search at LEP2:



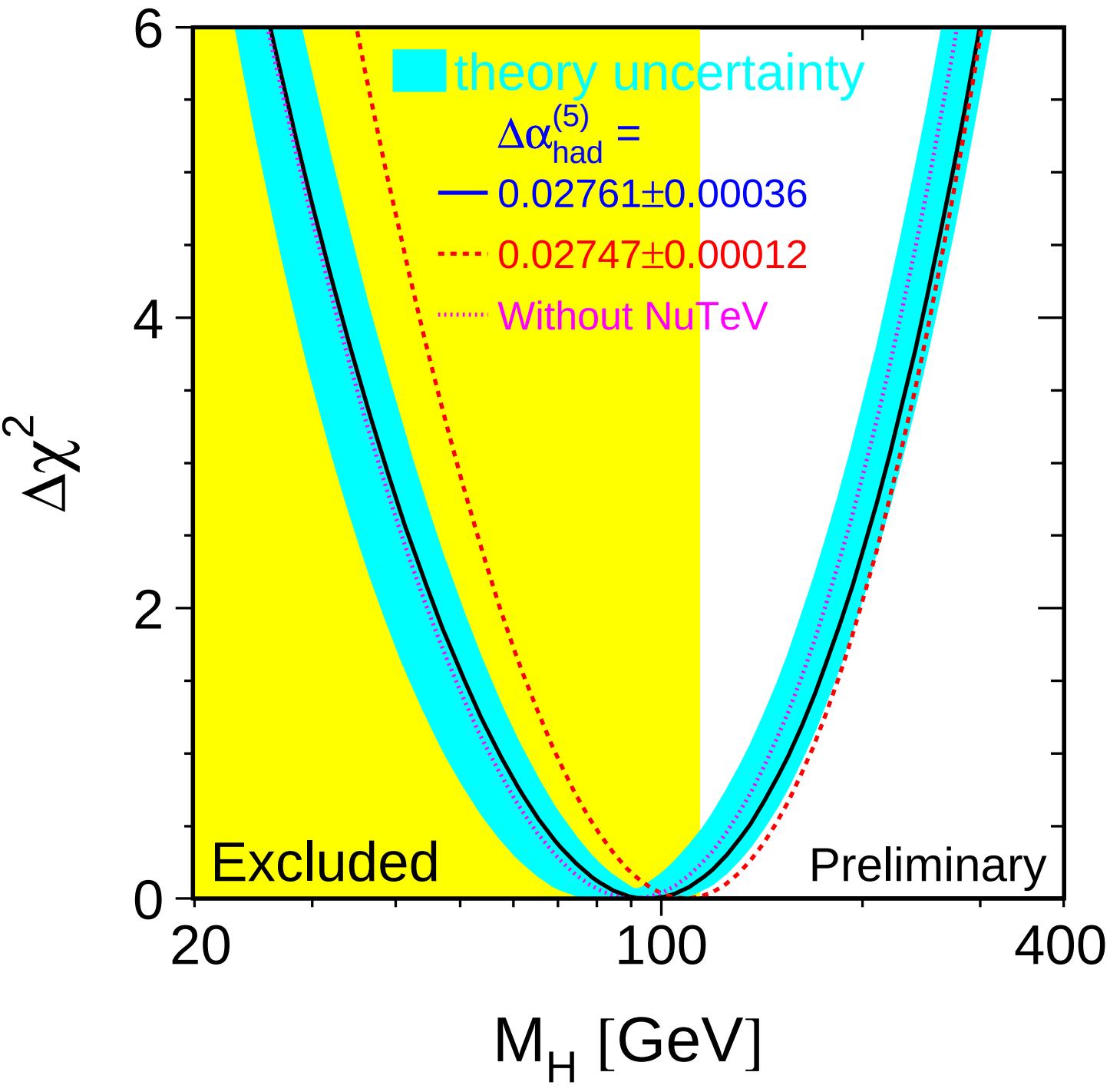
$$e^+e^- \to ZH, \nu_e\bar{\nu}_e H \Rightarrow M_H > 114.4 \text{ GeV}$$

- electroweak observables:



$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W}[1 + \Delta r]$$

$$\Delta r_{Higgs} = \frac{G_F M_W^2}{8\sqrt{2}\pi^2}\frac{11}{3}\left[\log\frac{M_H^2}{M_W^2} - \frac{5}{6}\right]$$



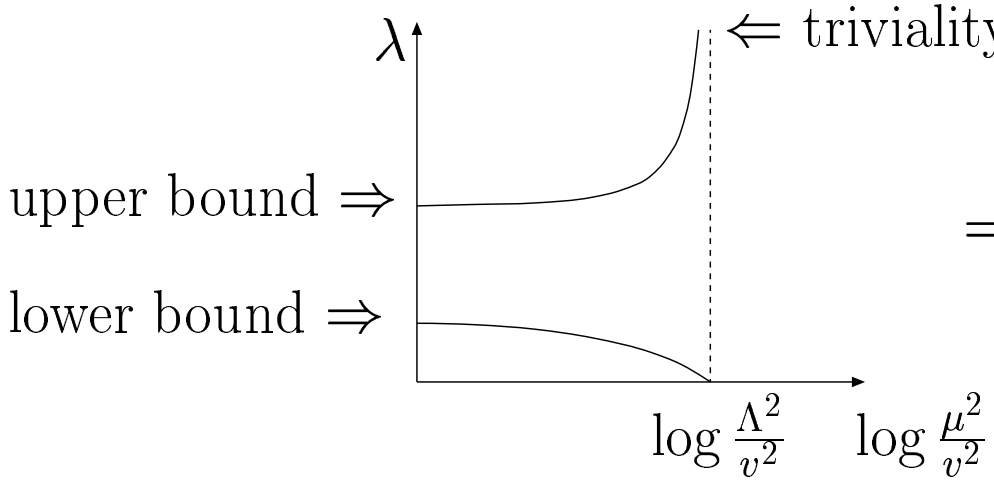
$$M_H = 96^{+60}_{-38}\ \text{GeV}$$

$$\Rightarrow M_H \lesssim 219\ \text{GeV (95\% CL)}$$

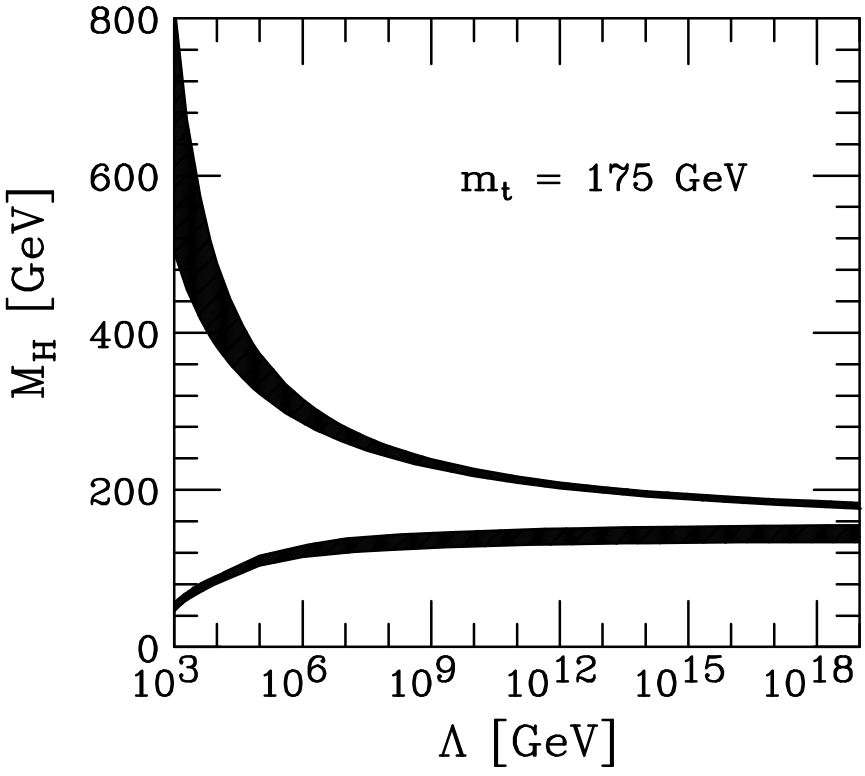
LEP/SLC

- triviality and vacuum stability:

$$\frac{d\lambda}{d\log\frac{\mu^2}{v^2}} = \frac{3}{8\pi^2}\left[+\lambda^2 + \lambda g_t^2 - g_t^4\right]$$



$\Rightarrow \Lambda \gtrsim 1$ TeV



Hambye
Riesselmann

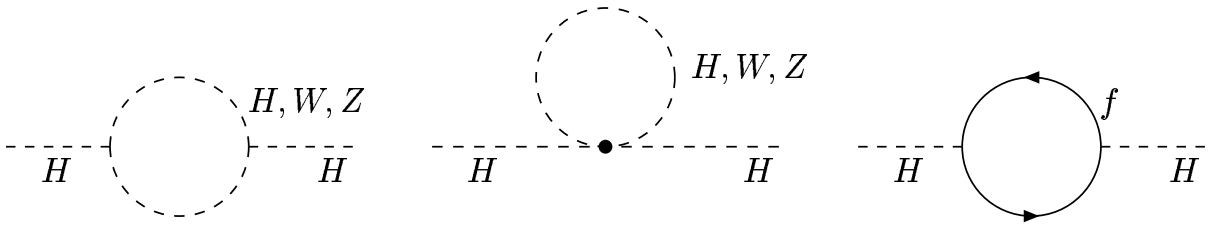
$\Lambda = 1$ TeV : 55 GeV $\lesssim M_H \lesssim$ 700 GeV

$\Lambda = M_{GUT}$: 130 GeV $\lesssim M_H \lesssim$ 190 GeV

Cabibbo
Sher
Lindner
Lüscher, Weisz
Hasenfratz, . . .
etc.

$\Rightarrow$ light Higgs boson

- GUT: hierarchy problem



$$\Delta M_H^2 \sim \Lambda^2 \sim \mathcal{O}(M_{GUT}^2) \gg M_H^2$$

[quadratic divergence]

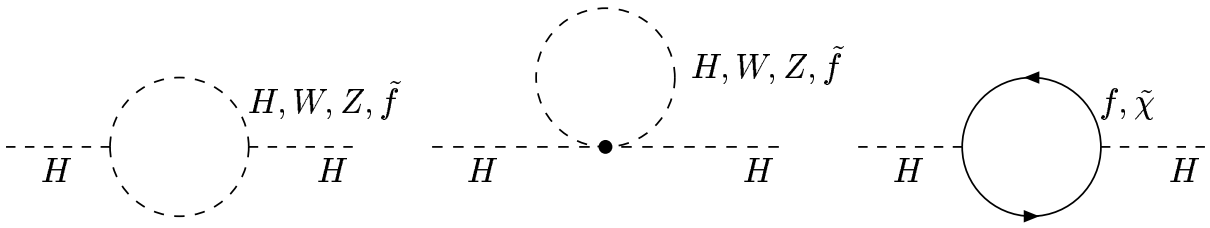
absorbed in counter term: $M_H^2 \to M_H^2 + \Delta M_H^2 - \delta M_H^2$

$\Rightarrow$ unnatural fine tuning [$\sim$ 28 digits]

(ii) MSSM

- SUSY: fermions $\leftrightarrow$ bosons

- no quadratic divergences
  $\Rightarrow$ solution to the hierarchy problem



$$\Delta M_H^2 \sim (\tilde{m}^2 - m^2) \log \frac{\Lambda^2}{m^2} \Rightarrow \tilde{m} \lesssim \mathcal{O}(1 \text{ TeV})$$

- SUSY-GUT: $\sin^2 \theta_W = 0.2334 \pm 0.0026$ Langacker
  LEP: $\sin^2 \theta_W = 0.2317 \pm 0.0002$ LEP/SLC

- minimal model: 2 Higgs doubletts ϕ_1, ϕ_2

$$\begin{aligned} V_\phi &= m_1^2 |\phi_1|^2 + m_2^2 |\phi_2|^2 - m_{12}^2 \left[\phi_1^+ \phi_2 + h.c.\right] \\ &+ \frac{g^2 + g'^2}{8} \left[|\phi_1|^2 - |\phi_2|^2\right]^2 + \frac{g^2}{2} |\phi_1^+ \phi_2|^2 \end{aligned}$$

ESB $\rightarrow$ 5 Higgs bosons:

h, H	neutral, $\mathcal{CP}$ even
A	neutral, $\mathcal{CP}$ odd
$H^{\pm}$	charged

LO: 2 input parameters: $M_A, \mathrm{tg}\beta = \frac{v_2}{v_1}$

$$M_h^2 = \frac{1}{2}\{M_A^2 + M_Z^2 + \epsilon - \sqrt{(M_A^2 + M_Z^2 + \epsilon)^2 - 4M_A^2 M_Z^2 c_{2\beta}^2 - 4\epsilon(M_A^2 s_\beta^2 + M_Z^2 c_\beta^2)}\}$$

- large radiative corrections:

$$\epsilon = \frac{3G_F}{\sqrt{2}\pi^2}\frac{m_t^4}{s_\beta^2}\log\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

$$M_h < M_Z \rightarrow \boxed{M_h \lesssim 135 \text{ GeV}}$$

Haber
Carena,...
Heinemeyer,...
Zhang
etc.

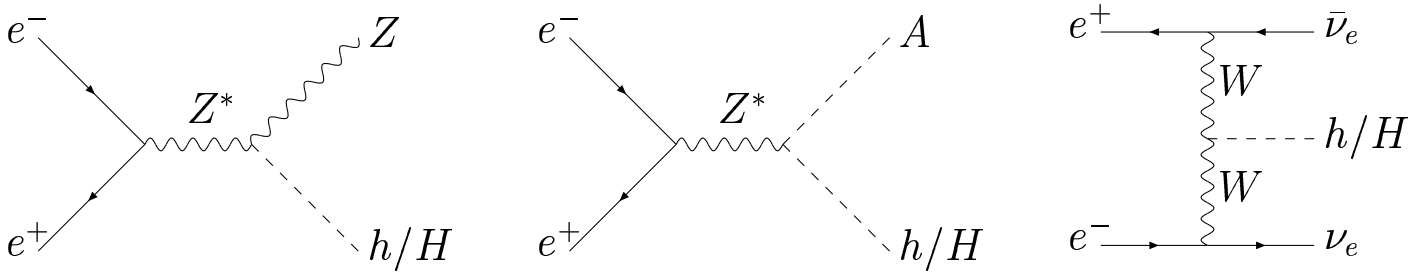
- modified couplings:

ϕ	g_u^ϕ	g_d^ϕ	g_V^ϕ
h	c_α/s_β	$-s_\alpha/c_\beta$	$s_{\beta-\alpha}$
H	s_α/s_β	c_α/c_β	$c_{\beta-\alpha}$
A	$\mathrm{ctg}\beta$	$\mathrm{tg}\beta$	0

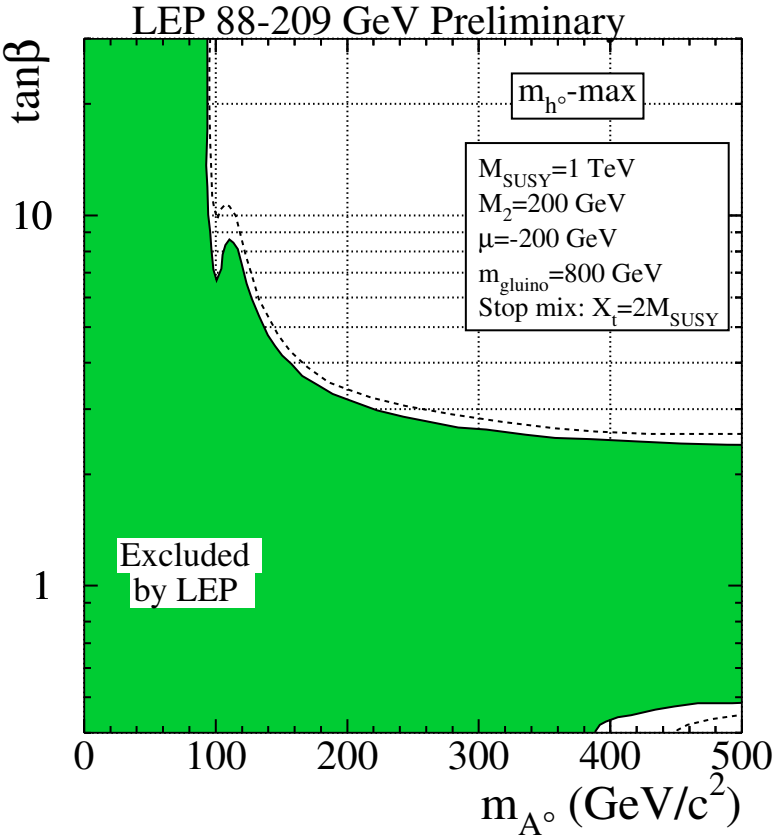
- mixing: $\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$

- Yukawa couplings: $\mathrm{tg}\beta\uparrow \quad \Rightarrow \quad g_u^\phi\downarrow \quad g_d^\phi\uparrow \quad g_V^\phi\downarrow$

- direct search at LEP2:



$$e^+e^- \to Z + h/H, A + h/H, \nu_e\bar{\nu}_e + h/H$$



$M_{h/H} > 91$ GeV, $M_A \gtrsim 91.9$ GeV, $M_{H^\pm} > 78.6$ GeV

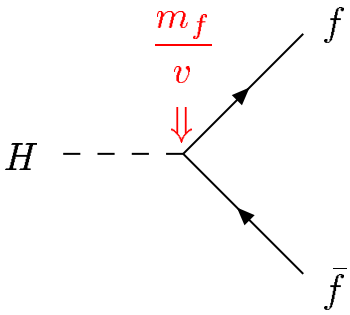
$0.5 < \text{tg}\beta < 2.4$ excluded

[only for $m_t = 175$ GeV]

- large M_A: $h \sim H_{SM}$ [decoupling regime]
  $M_A \sim M_H \sim M_{H^\pm}$

II *HIGGS BOSON DECAYS*

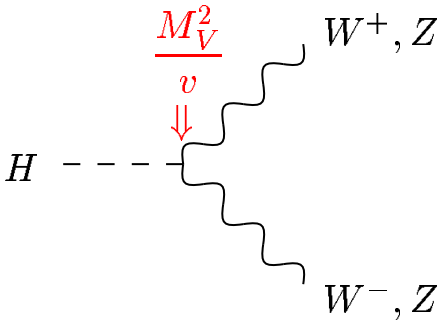
(i) Standard Model



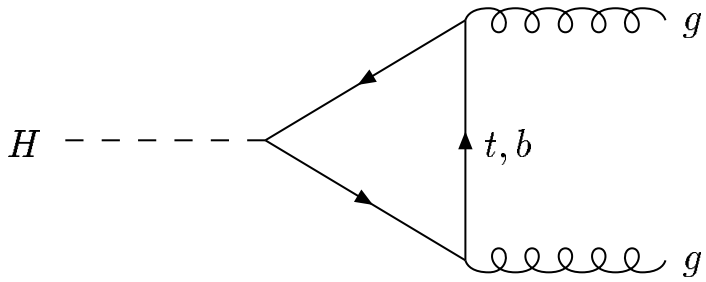
$$BR(H \to b\bar{b}) \lesssim 85\%$$
$$BR(H \to \tau^+\tau^-) \lesssim 8\%$$
$$BR(H \to c\bar{c}) \lesssim 4\%$$
$$BR(H \to t\bar{t}) \lesssim 20\%$$

Braaten, Leveille
Drees, Hikasa
etc.

QCD corrections large: $\sim -50\%$



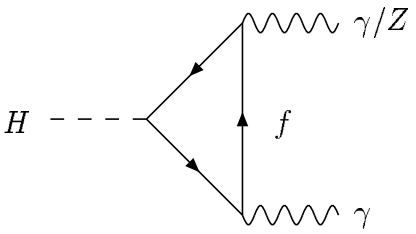
$$BR(H \to W^+W^-) \lesssim 60 - 95\%$$
$$BR(H \to ZZ) \lesssim 30\%$$

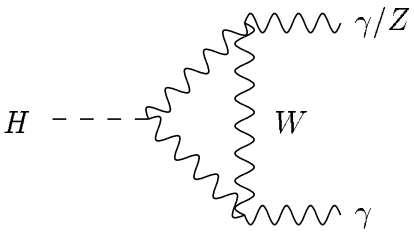


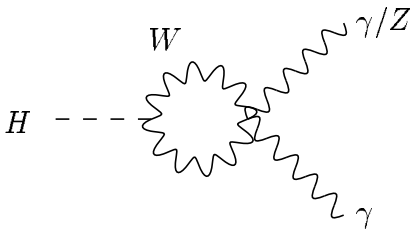
$$BR(H \to gg) \lesssim 6\%$$

Inami,. . .
S.,. . .
etc.

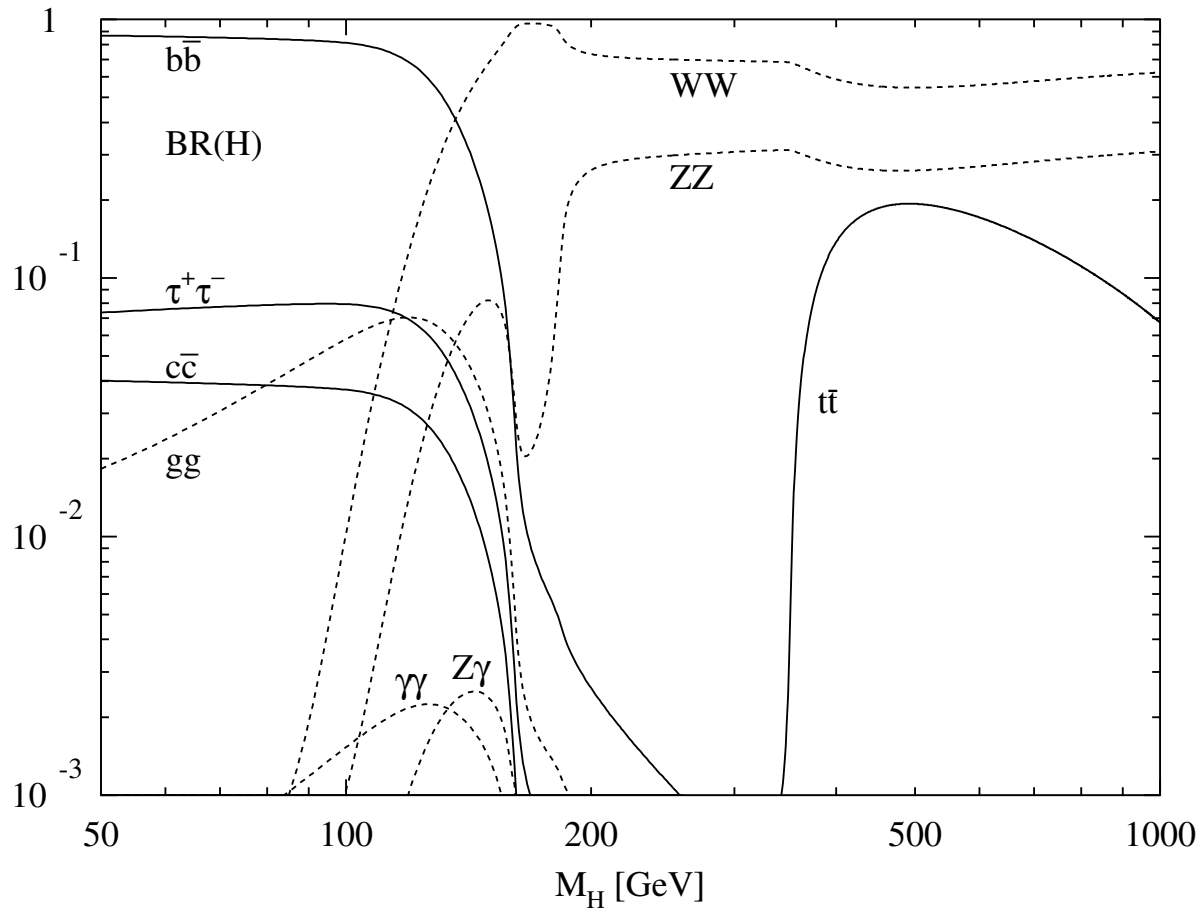
QCD corrections large: $\sim +70\%$

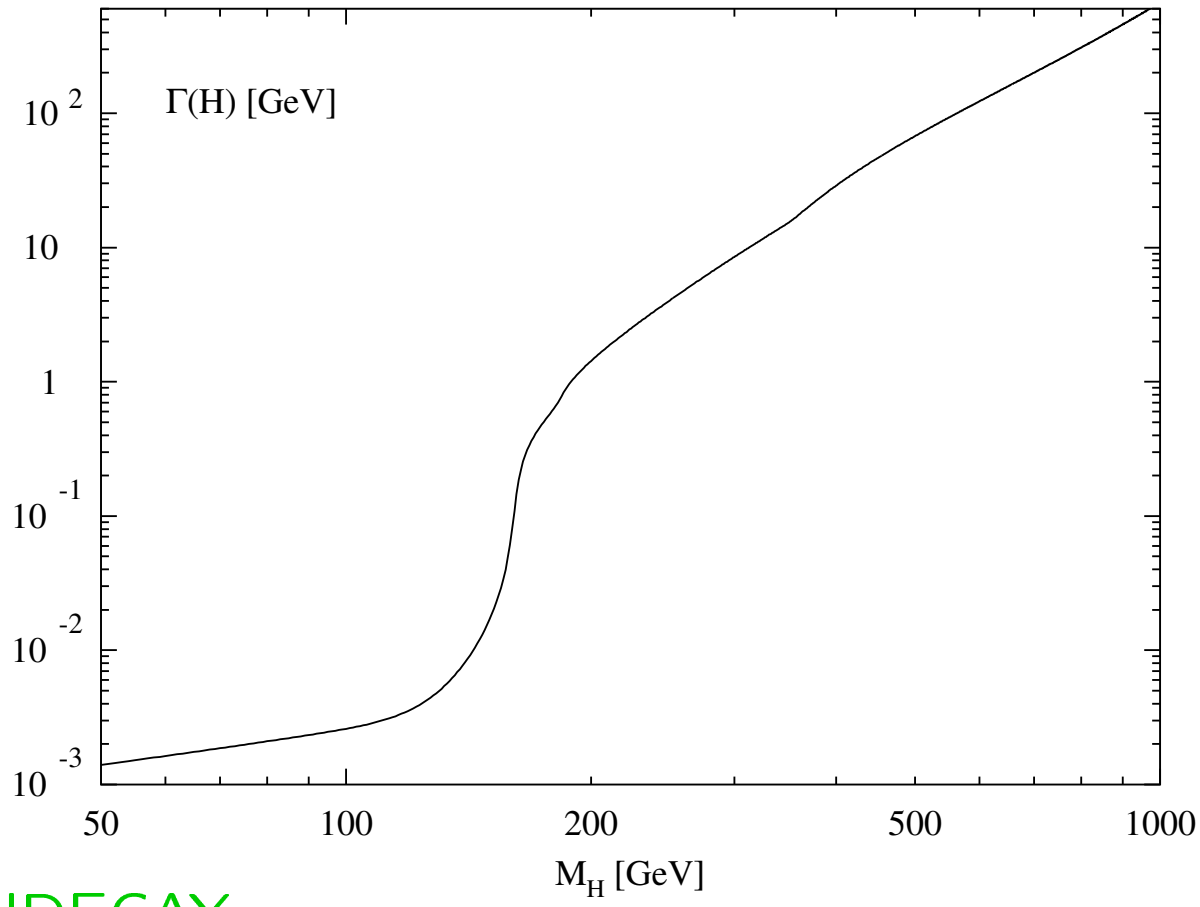






$$BR(H \to \gamma\gamma, Z\gamma) \lesssim 2 \times 10^{-3}$$


1
10 -1
10 -2
10 -3
bb̄
BR(H)
WW
ZZ
τ+τ−
cc̄
tt̄
gg
γγ
Zγ
50
100
200
500
1000
M_H [GeV]

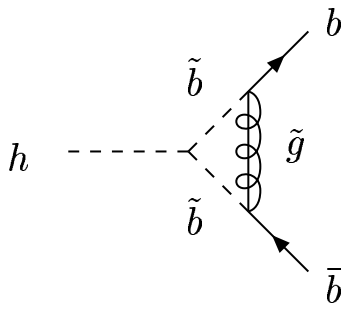

10 2
10
1
10 -1
10 -2
10 -3
Γ(H) [GeV]
50
100
200
500
1000
M_H [GeV]

HDECAY

(ii) MSSM

- modification due to additional MSSM factors
  $\Rightarrow$ suppression of $\phi^0 \to VV, t\bar{t}$

- large SUSY–QCD corrections to $\phi^0 \to b\bar{b}$

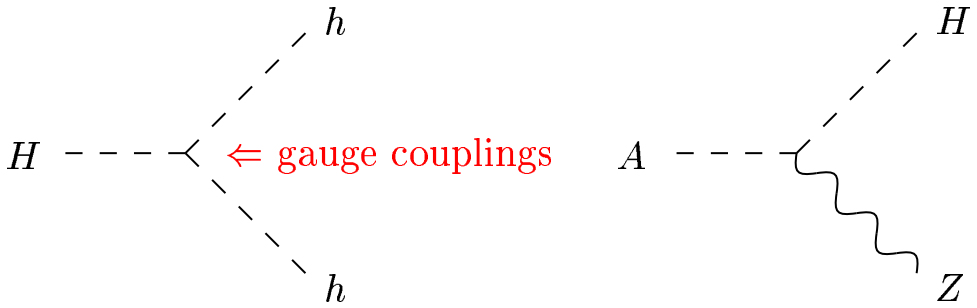


$+ \cdots \qquad \propto \frac{m_{\tilde{g}} \mu \, \mathrm{tg}\beta}{m^2_{\tilde{b}}}$

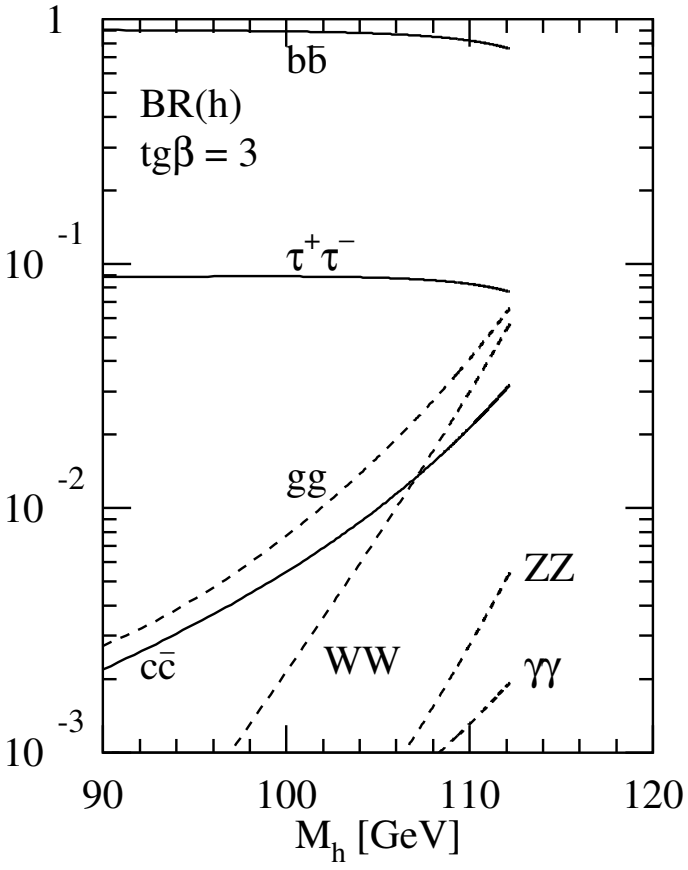
Hall,. . .
Carena,. . .
Nierste,. . .
Häfliger,. . .
etc.

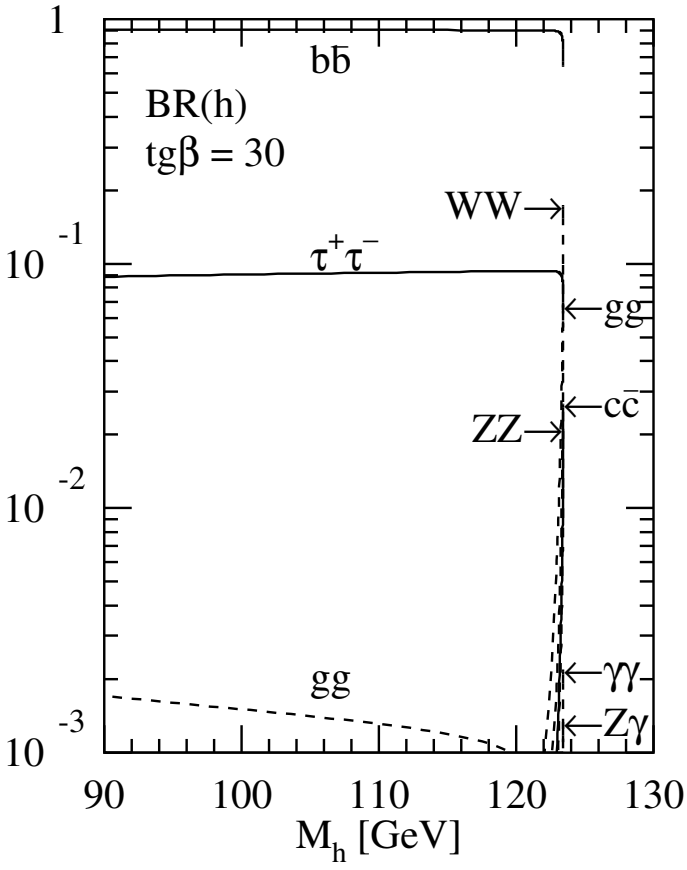
- $\phi^0 \to gg, \gamma\gamma, Z\gamma$: $\tilde{t}, \tilde{b}$ loops
  $\gamma\gamma, Z\gamma$: $H^\pm, \tilde{\chi}$ loops

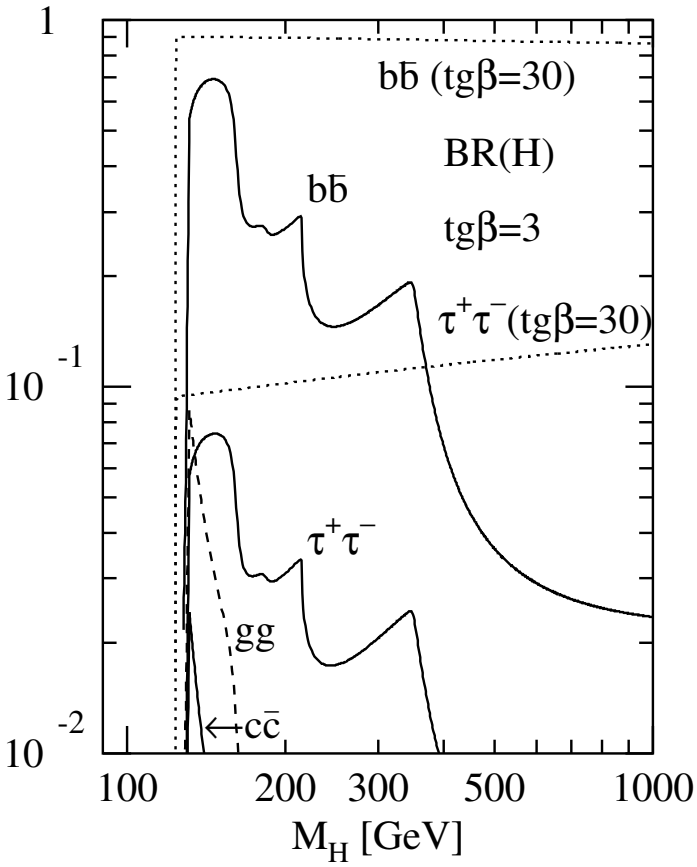
- new decay modes: $H \to hh, AA, ZA$, $A \to ZH$, $H^\pm \to W^\pm + h/A$

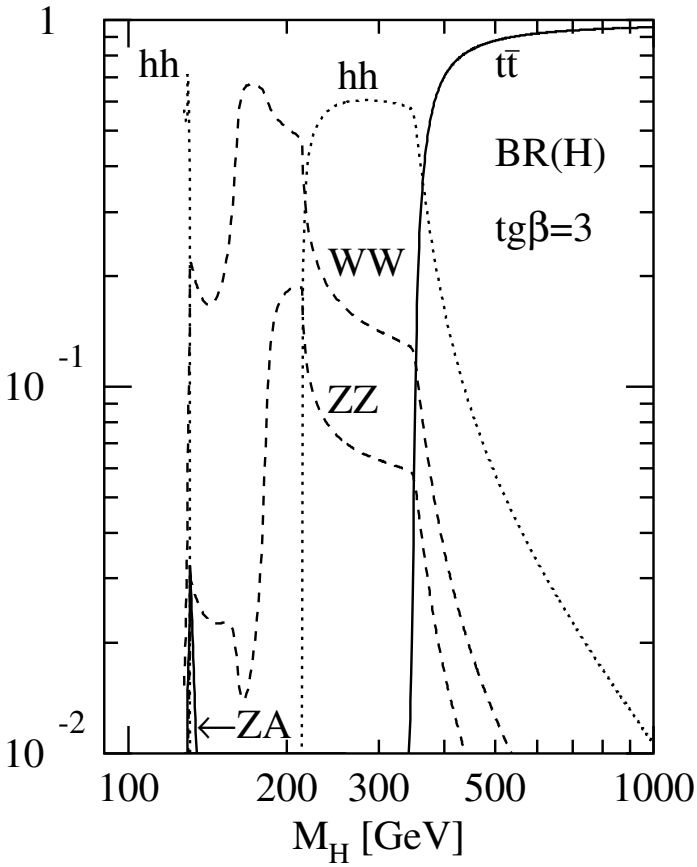


- new decay modes into SUSY particles: $\phi \to \tilde{\chi}\tilde{\chi}, \tilde{q}\bar{\tilde{q}}$

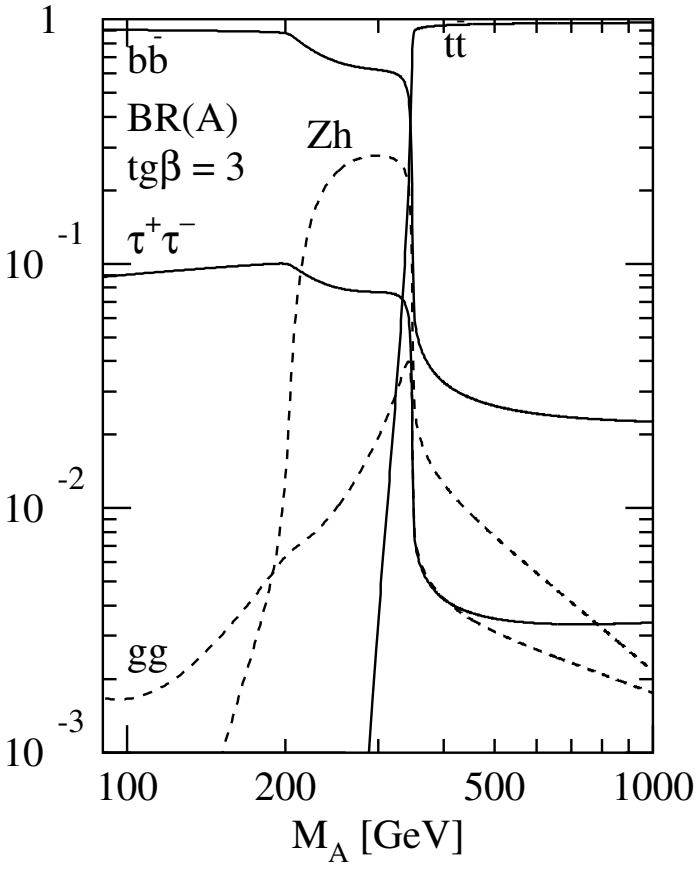

1
10 -1
10 -2
10 -3
bb̄
BR(h)
tgβ = 3
τ+τ−
gg
cc̄
WW
ZZ
γγ
90
100
110
120
M_h [GeV]

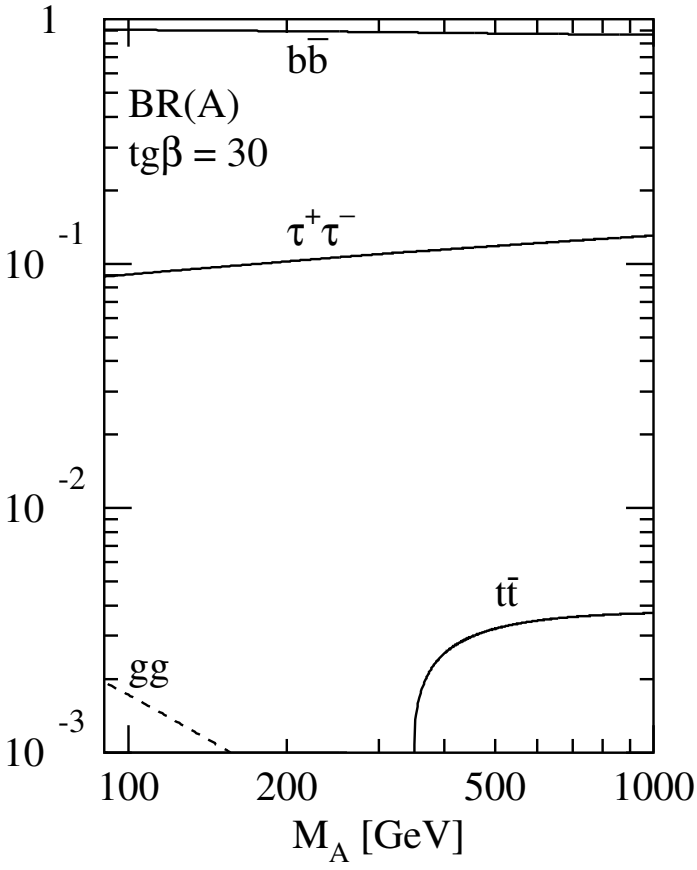

1
10 -1
10 -2
10 -3
bb̄
BR(h)
tgβ = 30
WW→
τ+τ−
←gg
←cc̄
ZZ→
gg
←γγ
←Zγ
90
100
110
120
130
M_h [GeV]

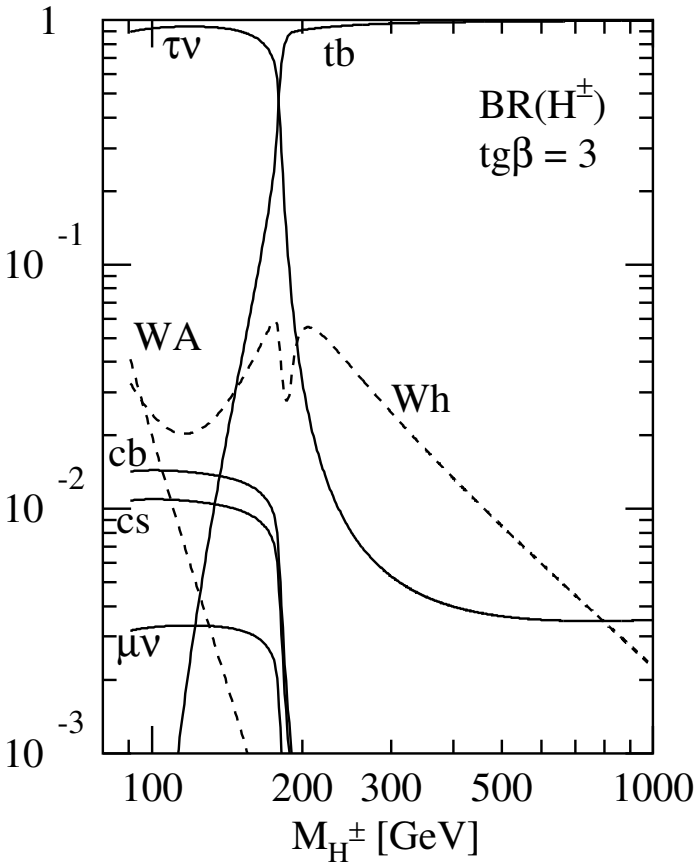

1
10 -1
10 -2
bb̄ (tgβ=30)
BR(H)
bb̄
tgβ=3
τ+τ−(tgβ=30)
τ+τ−
gg
←cc̄
100
200
300
500
1000
M_H [GeV]

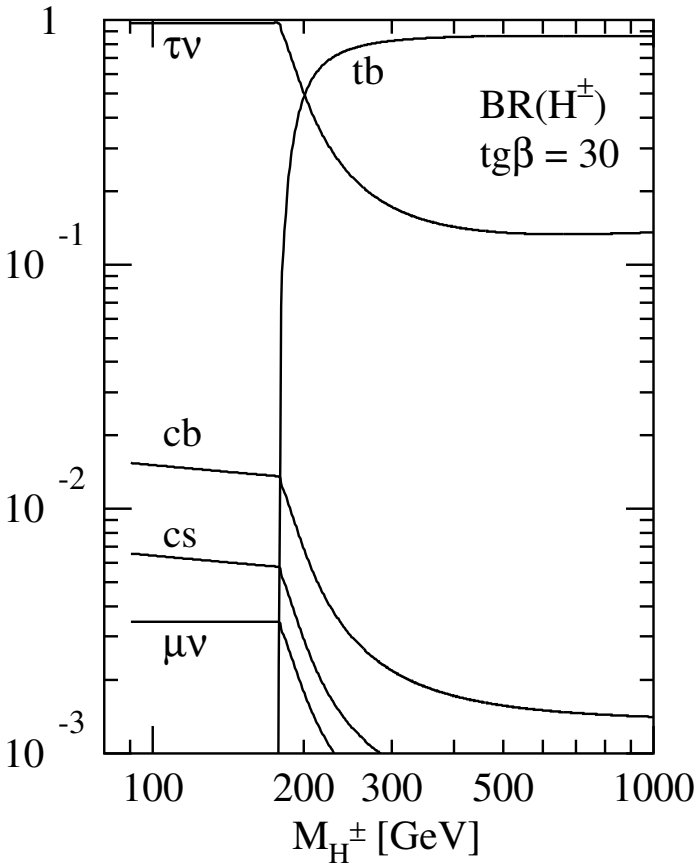

1
10 -1
10 -2
hh
hh
tt̄
BR(H)
tgβ=3
WW
ZZ
←ZA
100
200
300
500
1000
M_H [GeV]

HDECAY

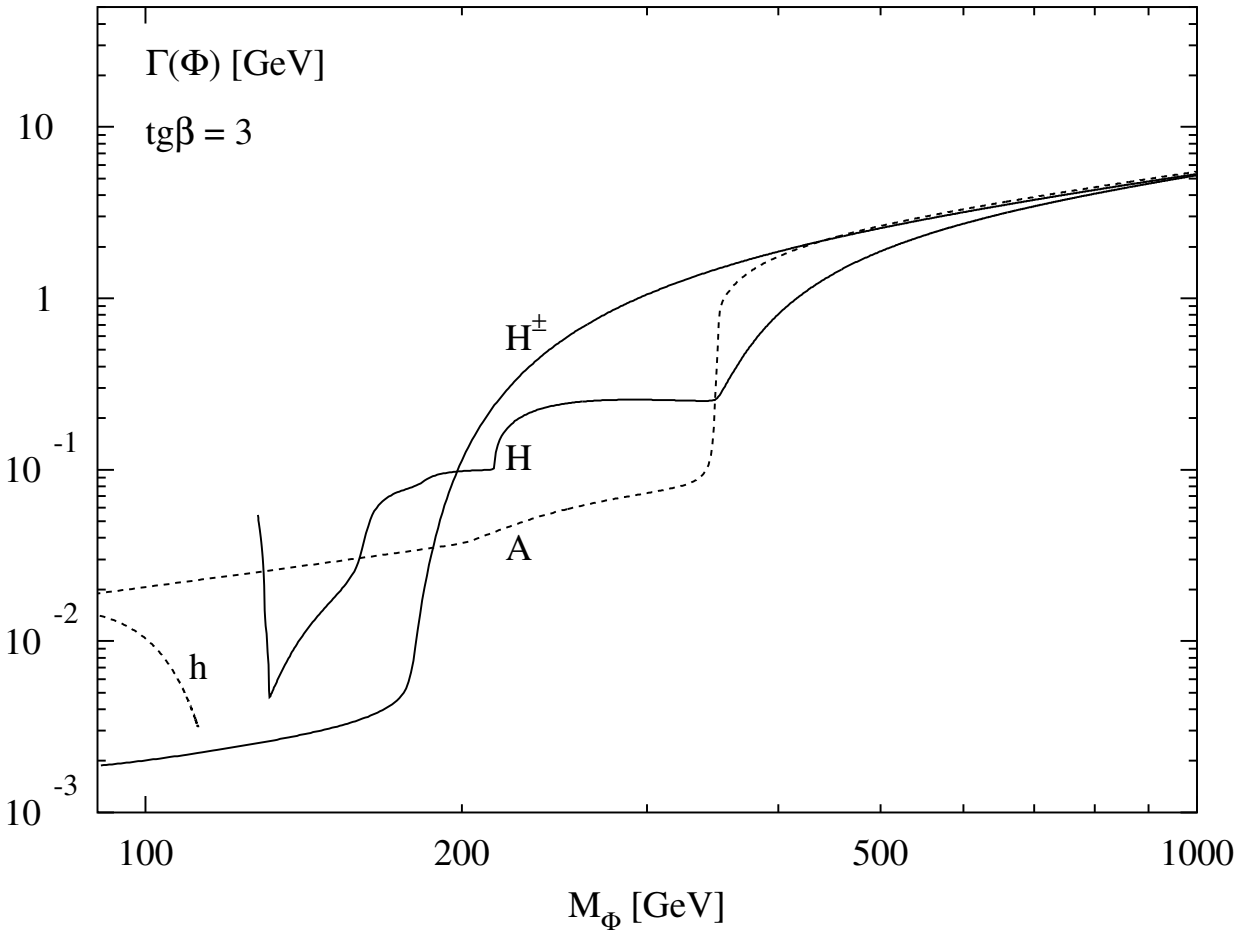

1
10 -1
10 -2
10 -3
bb
tt
BR(A)
tgβ = 3
Zh
τ+τ−
gg
100
200
500
1000
M_A [GeV]

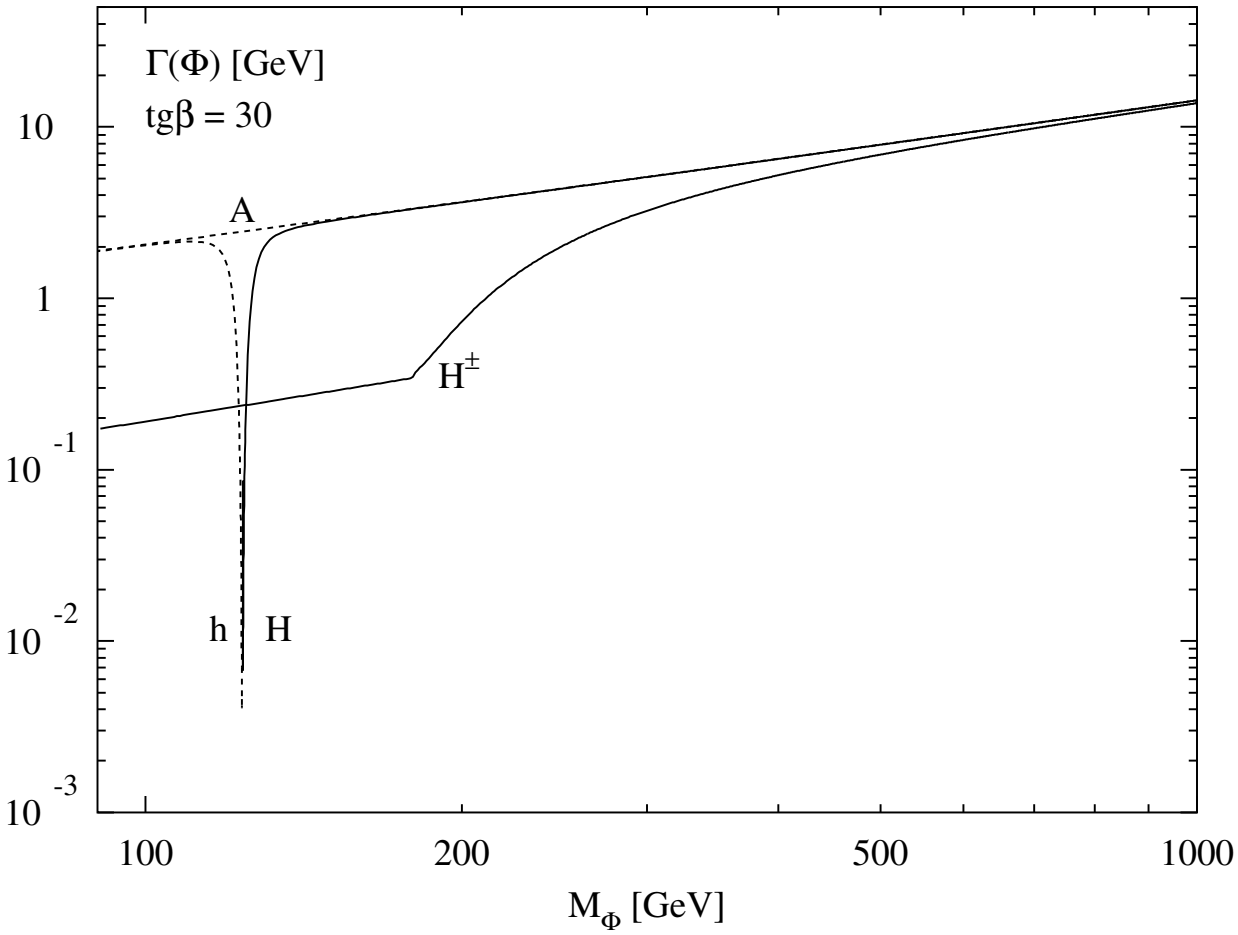

1
10 -1
10 -2
10 -3
bb
BR(A)
tgβ = 30
τ+τ−
tt
gg
100
200
500
1000
M_A [GeV]


1
10 -1
10 -2
10 -3
τν
tb
BR(H±)
tgβ = 3
WA
Wh
cb
cs
μν
100
200
300
500
1000
M_H± [GeV]


1
10 -1
10 -2
10 -3
τν
tb
BR(H±)
tgβ = 30
cb
cs
μν
100
200
300
500
1000
M_H± [GeV]

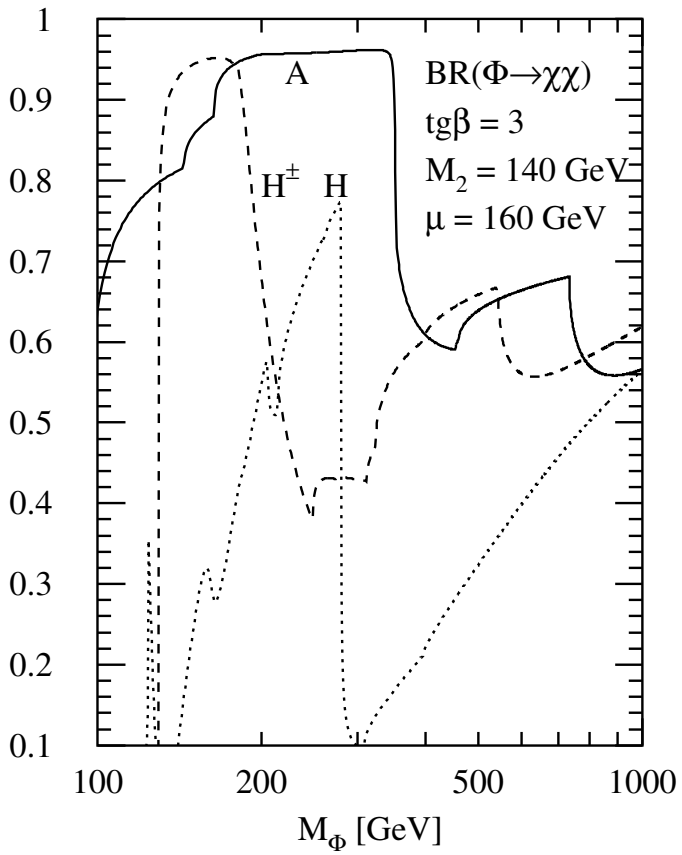
HDECAY

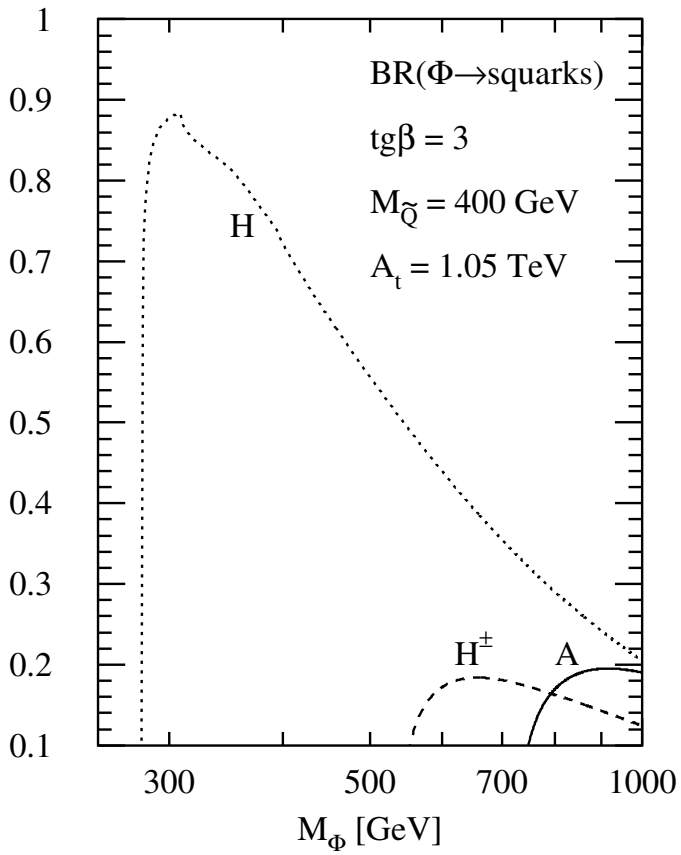

Γ(Φ) [GeV]
tgβ = 3
10
1
10 -1
10 -2
10 -3
H±
H
A
h
100
200
500
1000
M_Φ [GeV]


Γ(Φ) [GeV]
tgβ = 30
10
1
10 -1
10 -2
10 -3
A
H±
h
H
100
200
500
1000
M_Φ [GeV]

HDECAY

SUSY Decays





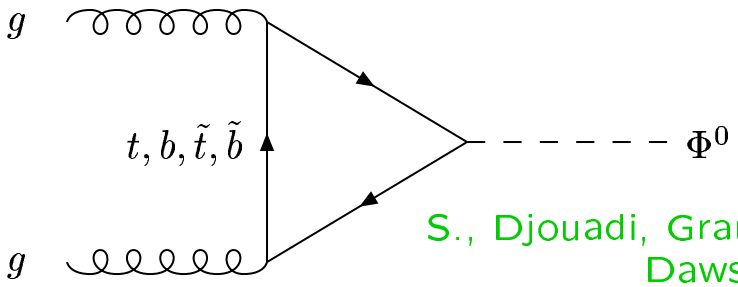
HDECAY

- if kinematically possible → important

III *HIGGS SEARCH @ LHC*

Higgs boson production in SM/MSSM:

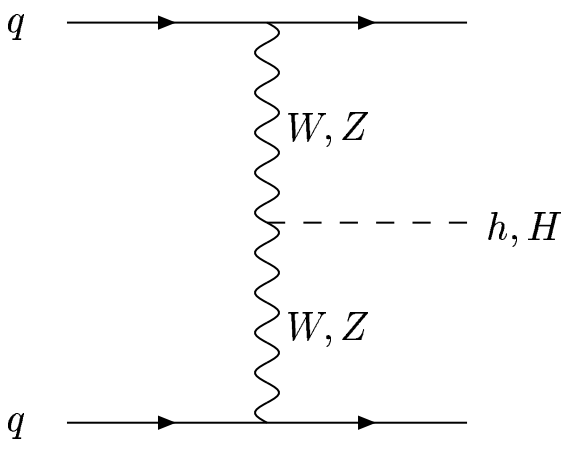
- Gluon fusion: $pp \to gg \to h/H/A$



S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman
Harlander, Kilgore
Anastasiou, Melnikov

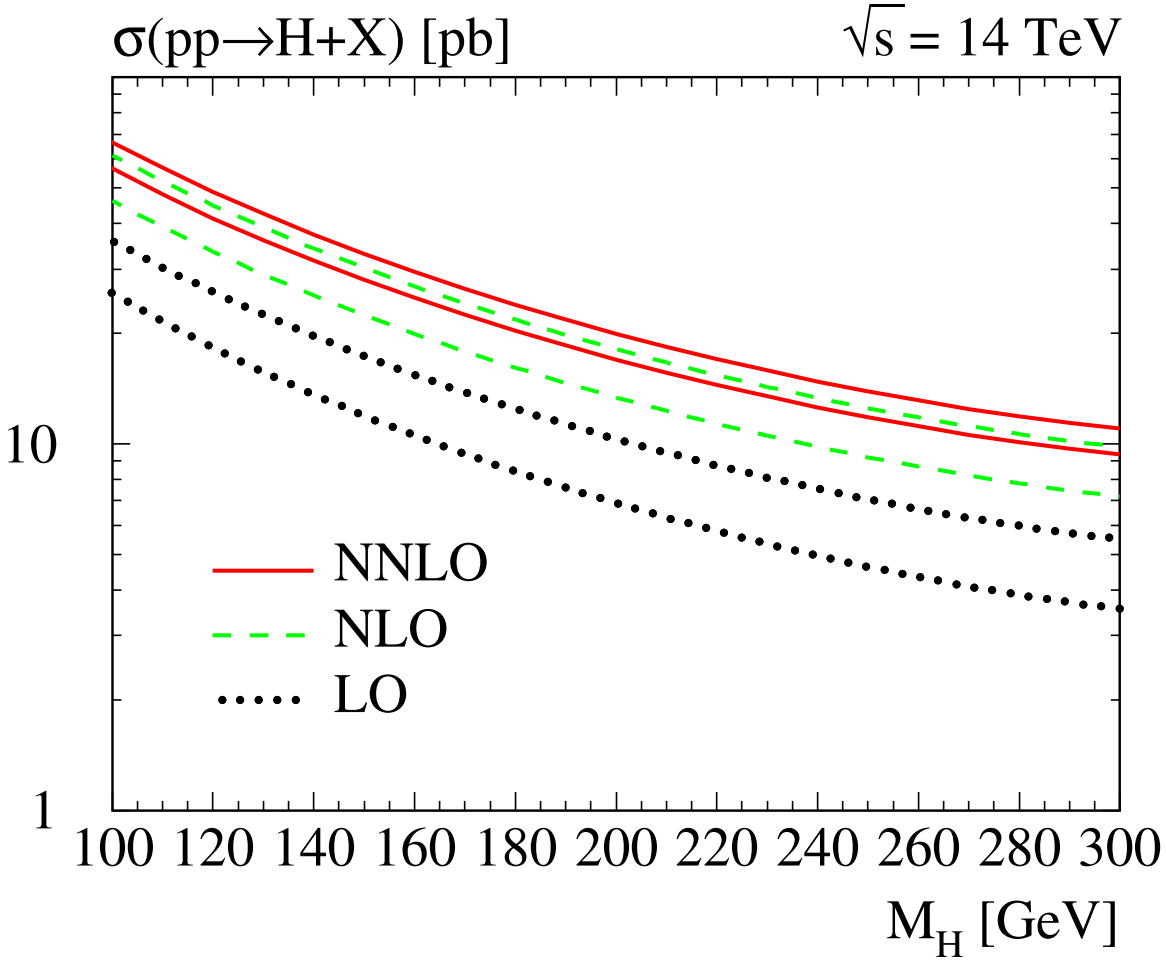
QCD corrections: $\sim 10 \ldots 100\%$ F

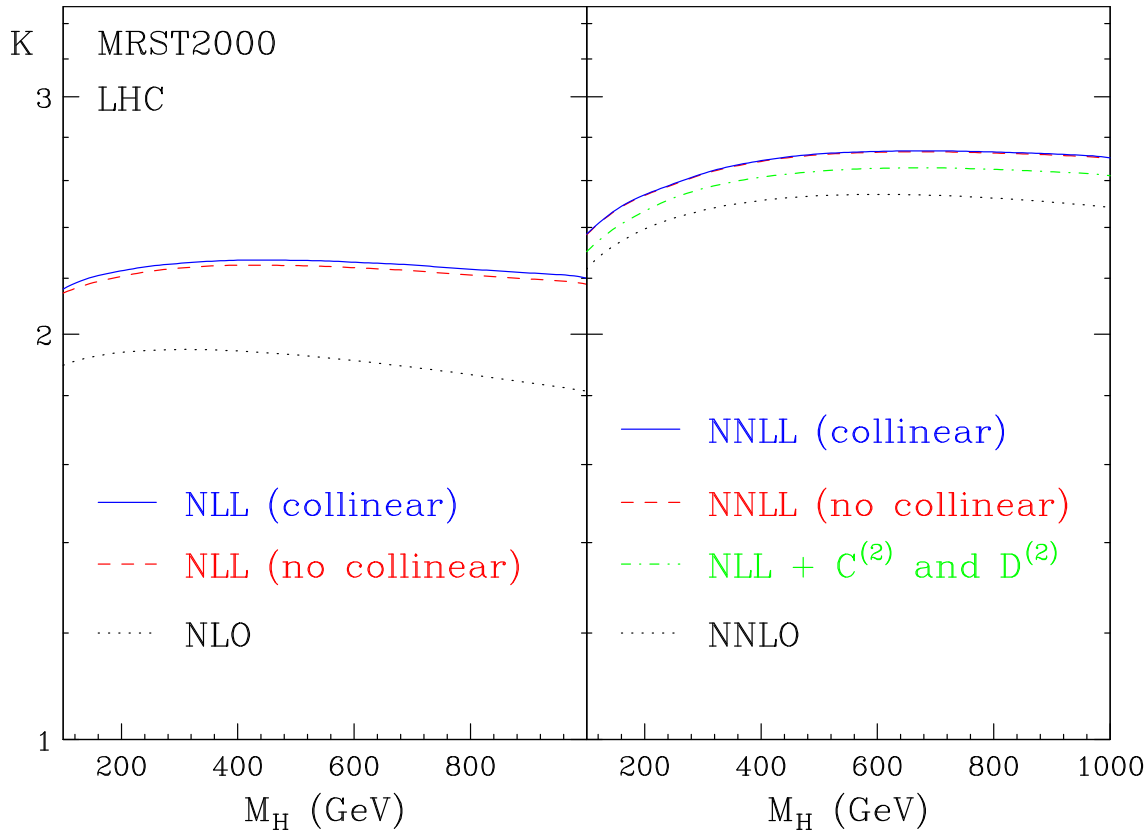
- W/Z fusion: $pp \to W^*W^*/Z^*Z^* \to h/H$



QCD corrections: $\sim 10\%$ Han, Valencia, Willenbrock

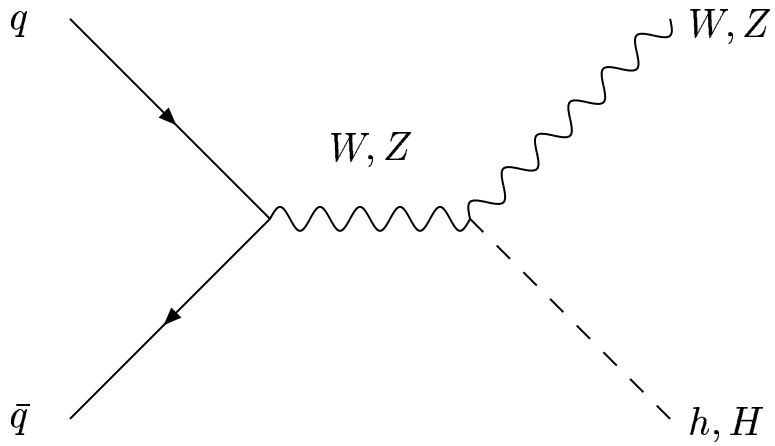
Harlander, Kilgore





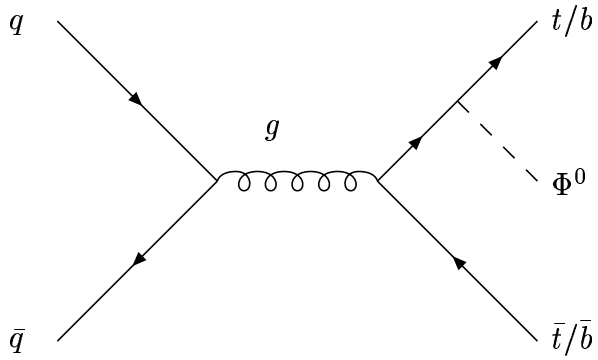
Catani, de Florian, Grazzini, Nason

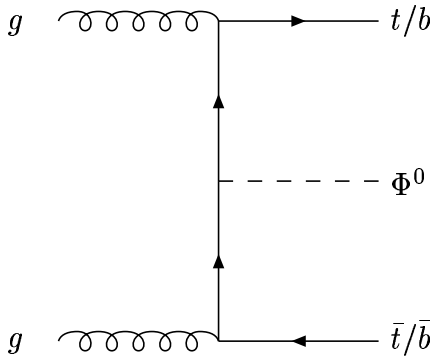
- Higgs–strahlung: $pp \to W^*/Z^* \to W/Z + h/H$



QCD corrections: $\sim 30\%$ Han, Willenbrock

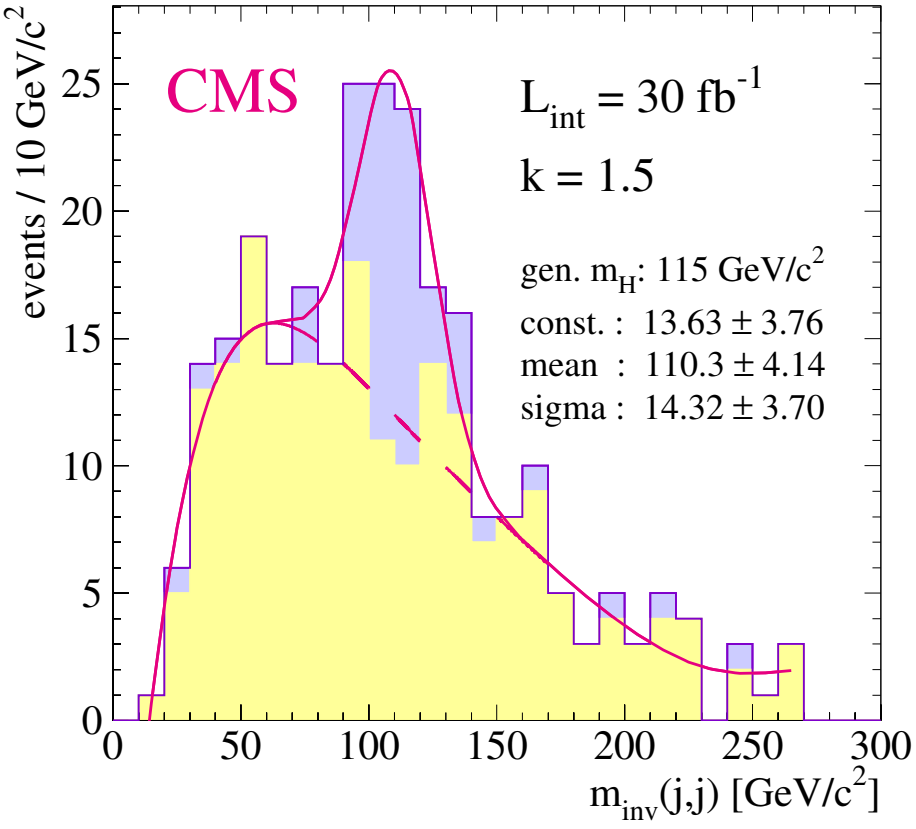
- Bremsstrahlung: $pp \to t\bar{t}/b\bar{b} + h/H/A$



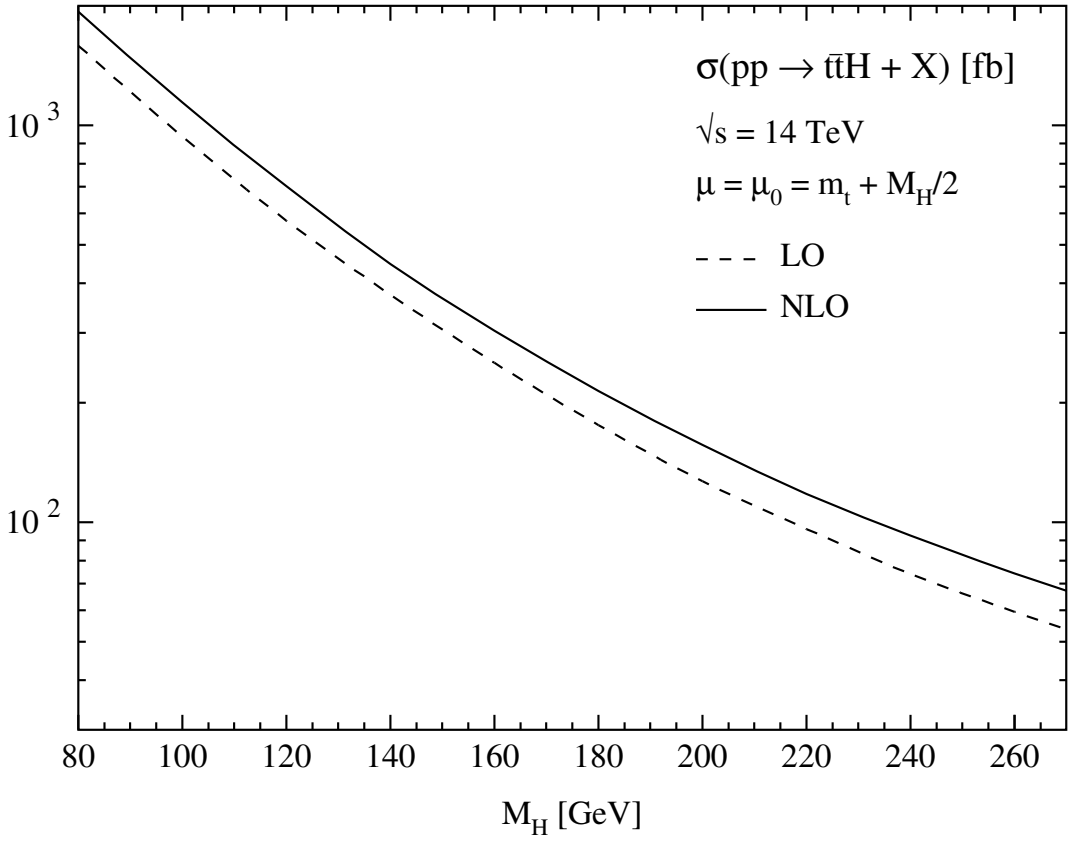


QCD corrections: $t\bar{t}\phi$: $\sim +20\%$ Beenakker,. . .
Dawson, . . .

$b\bar{b}\phi$: $\sim +(50 - 100)\%$ Dittmaier, Krämer, S.



Drollinger

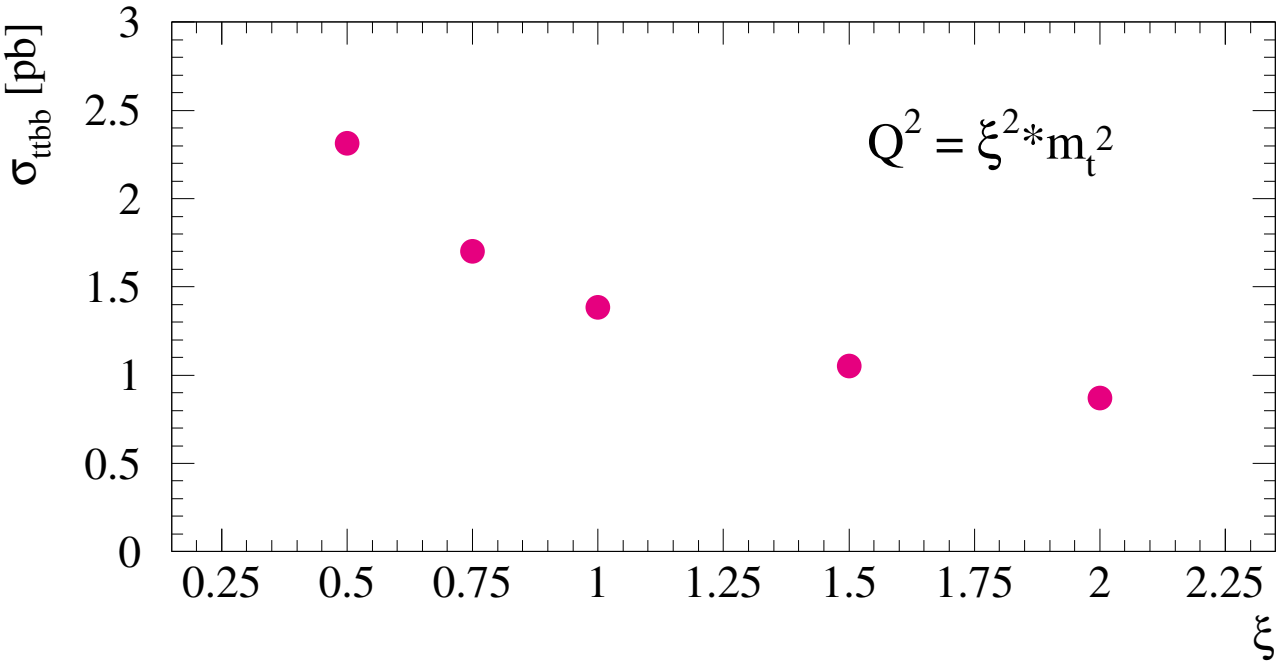


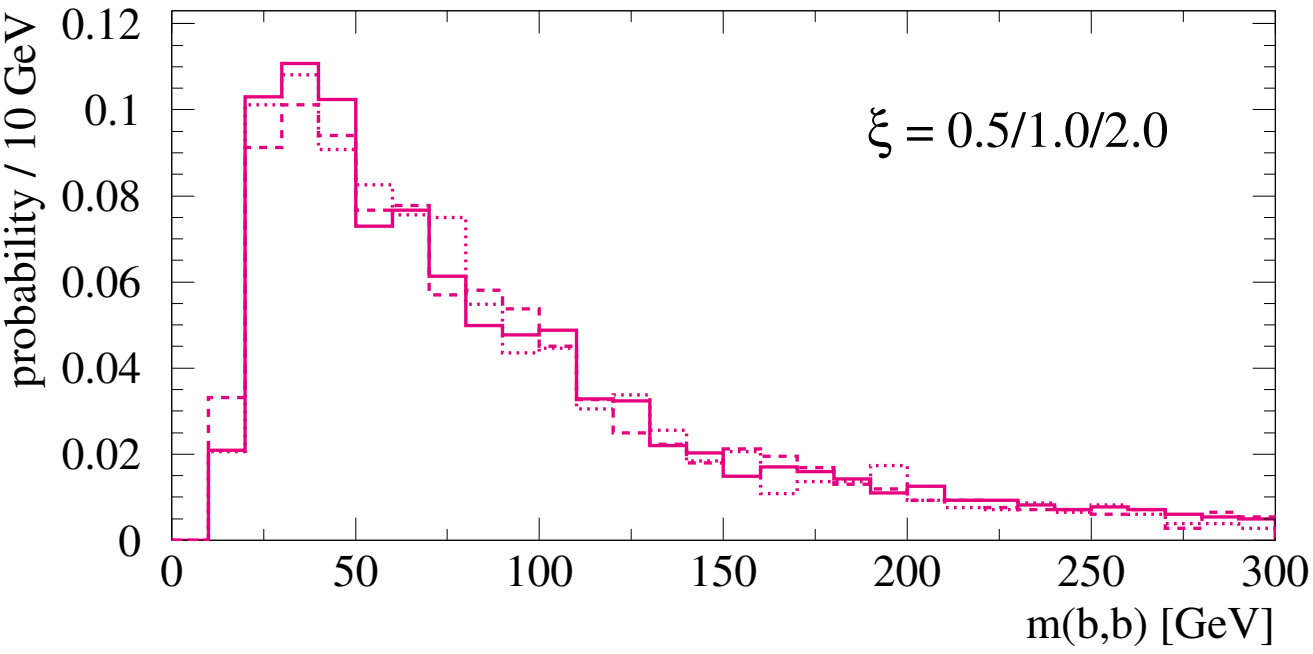
~ 1.2

Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas

$t\bar{t}b\bar{b}$ $[t\bar{t}H \rightarrow t\bar{t}b\bar{b}]$

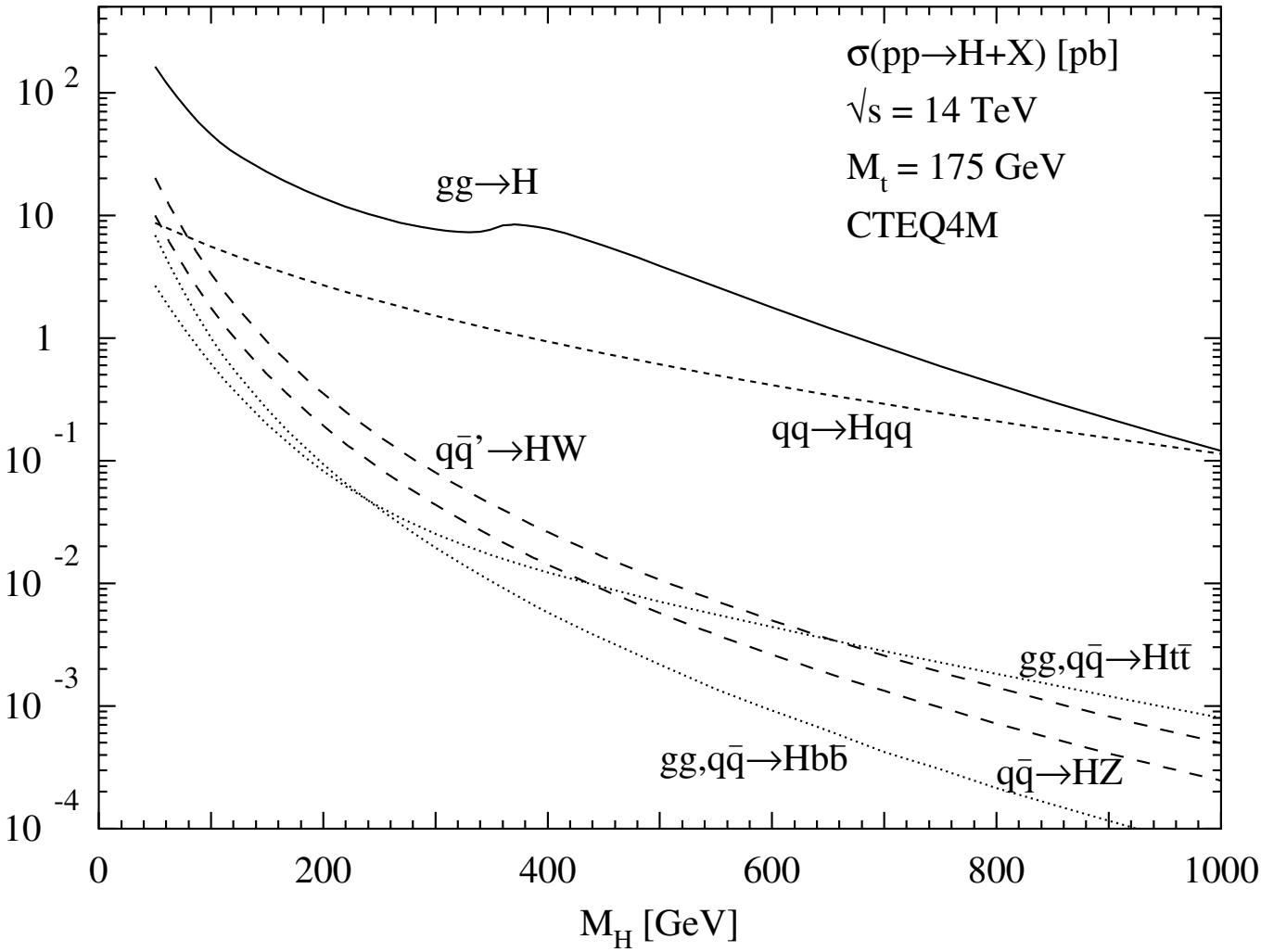
$Q^2 = m_t^2$, CTEQ5L , $p_T(b) > 25$ GeV , $|\eta| < 2.4$, $\Delta R(b,b) < 0.4$



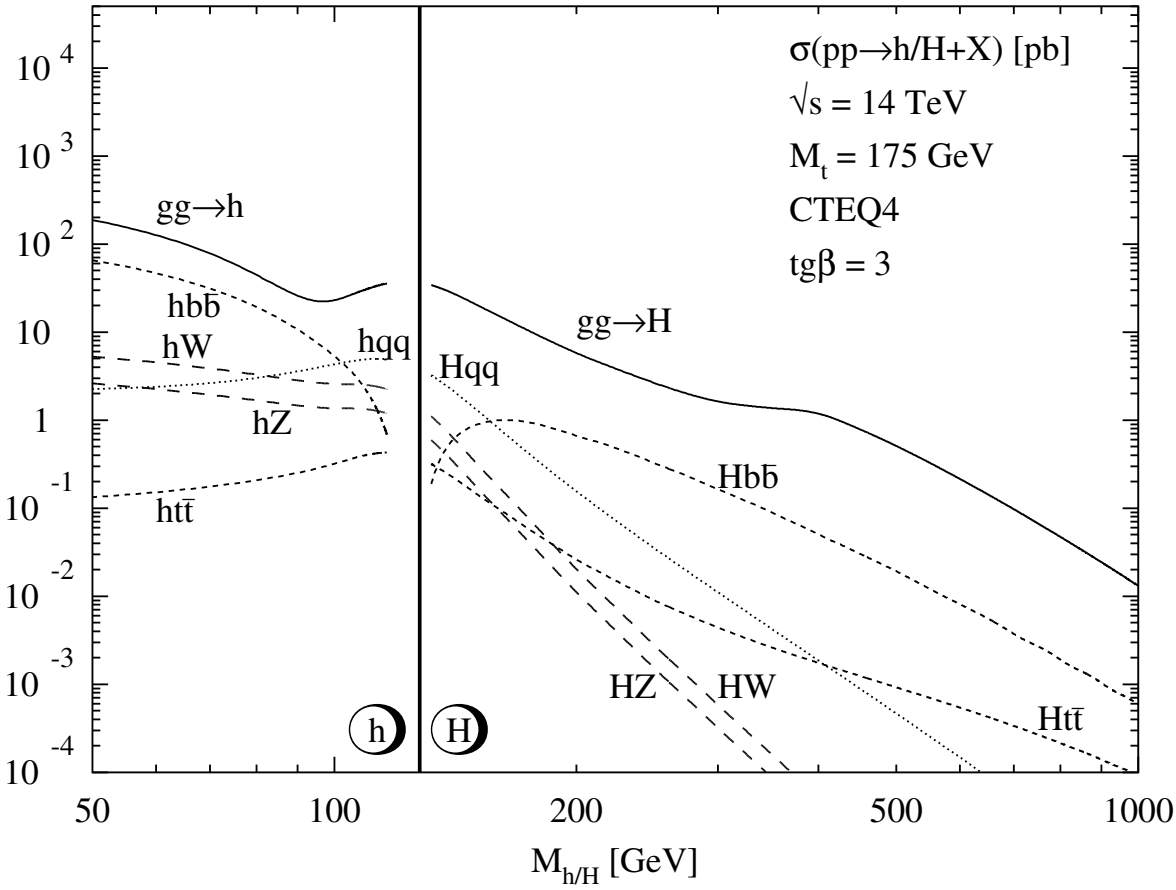


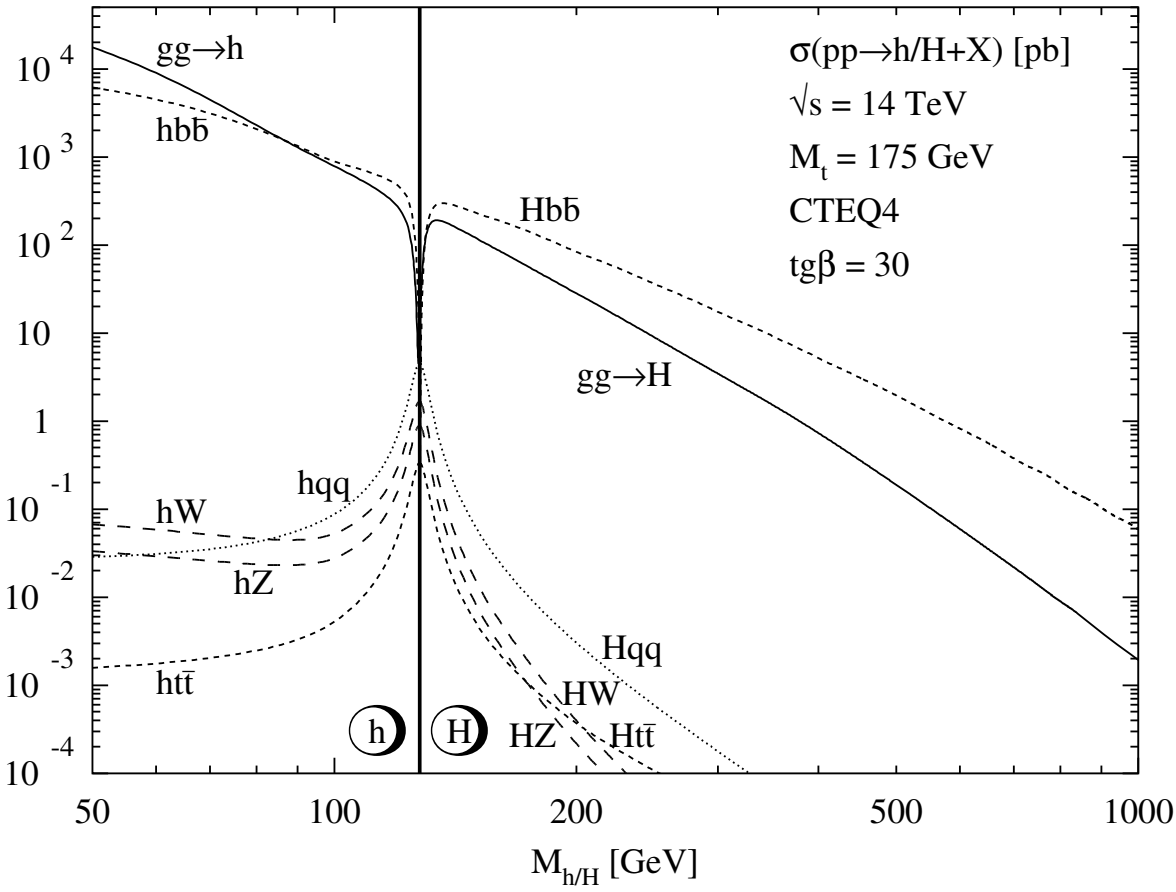
Drollinger

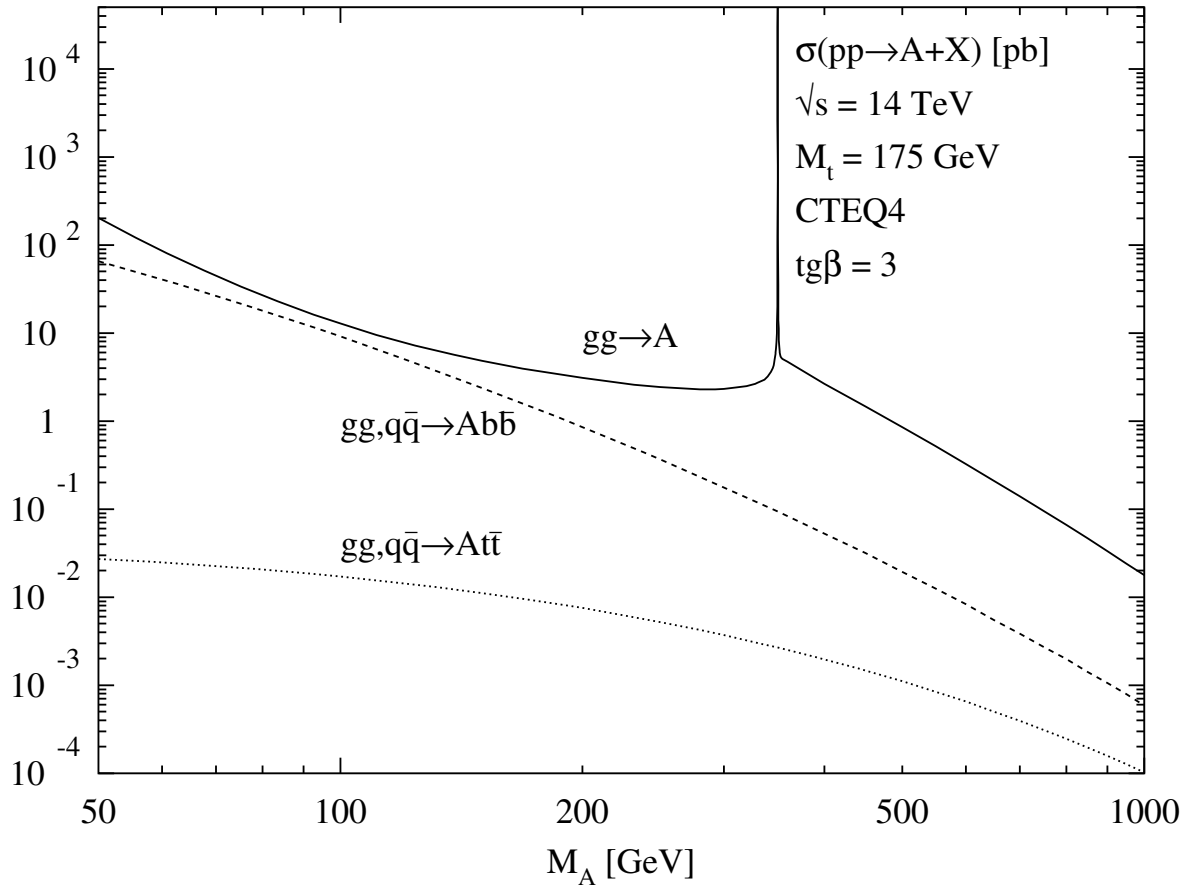
Standard Model

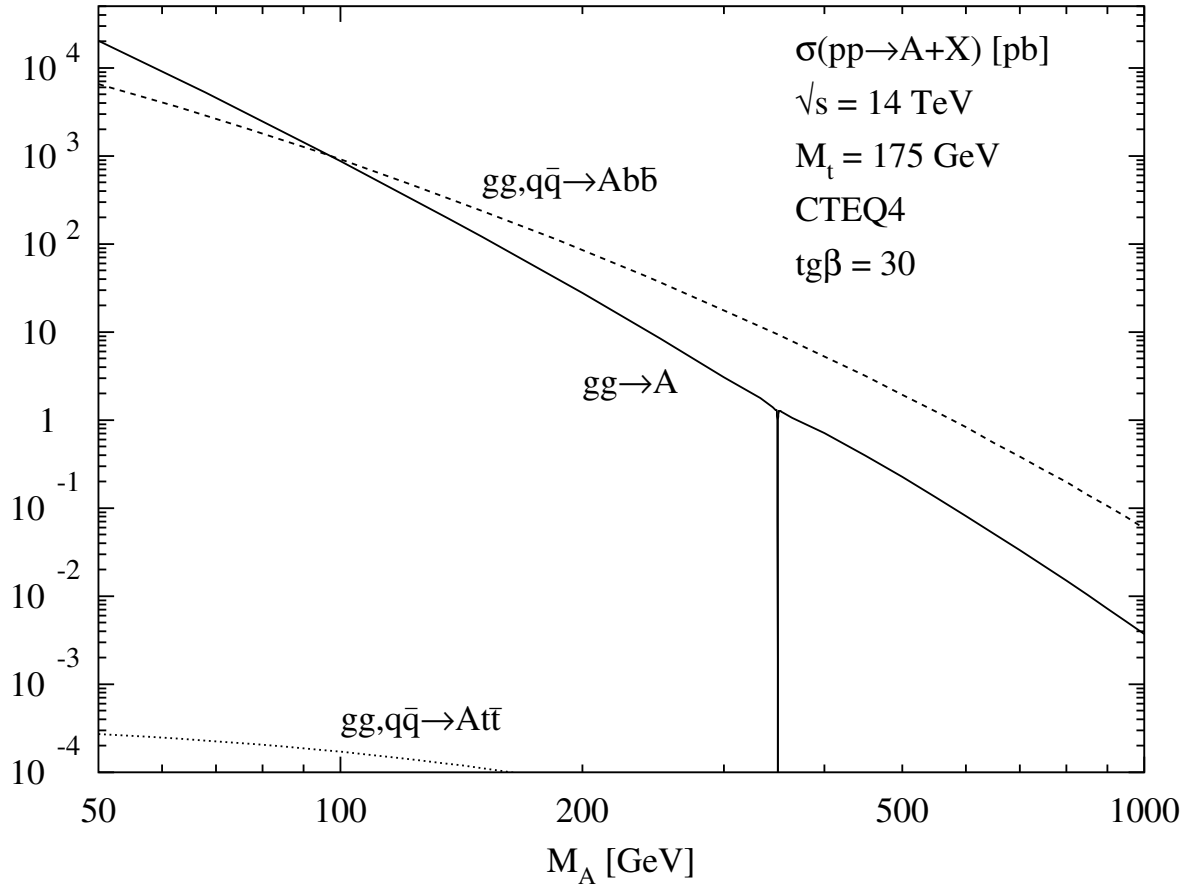


MSSM


σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 3
gg→h
hbb̄
hW
hqq
hZ
htt̄
gg→H
Hqq
Hbb̄
HZ
HW
Htt̄
h
H
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
50
100
200
500
1000
M_h/H [GeV]


σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 30
gg→h
hbb̄
hqq
hW
hZ
htt̄
Hbb̄
gg→H
Hqq
HW
HZ
Htt̄
h
H
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
50
100
200
500
1000
M_h/H [GeV]


σ(pp→A+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 3
gg→A
gg,qq̄→Abb̄
gg,qq̄→Att̄
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
50
100
200
500
1000
M_A [GeV]


σ(pp→A+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4
tgβ = 30
gg,qq̄→Abb̄
gg→A
gg,qq̄→Att̄
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
50
100
200
500
1000
M_A [GeV]

(i) Standard Model

- search strategy:

$$M_H \lesssim 140 \text{ GeV}: H \to \gamma\gamma$$
$$t\bar{t}H \to t\bar{t}b\bar{b}$$
$$120 \text{ GeV} \lesssim M_H \lesssim 200 \text{ GeV}: H \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$$

[angular correlations]

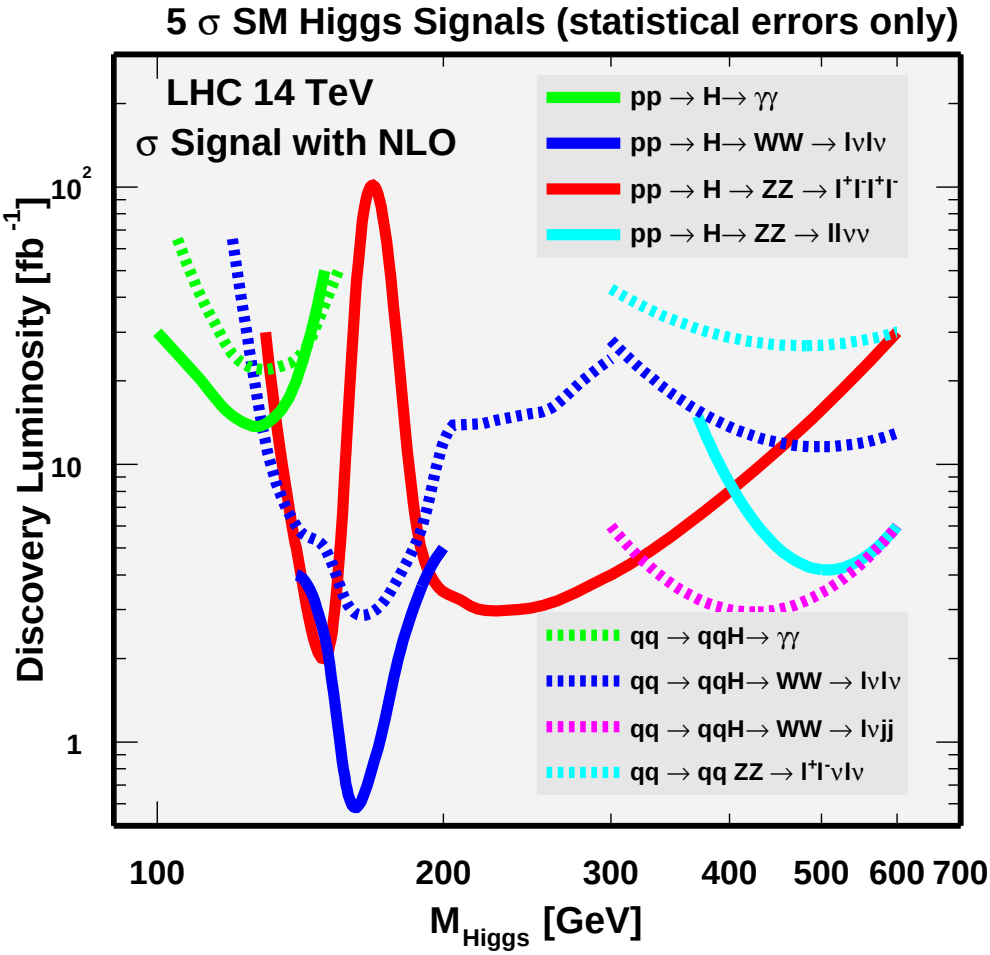
Dittmar, Dreiner

$$140 \text{ GeV} \lesssim M_H \lesssim 1 \text{ TeV}: H \to ZZ^{(*)} \to 4\ell^{\pm}$$

[gold − plated]

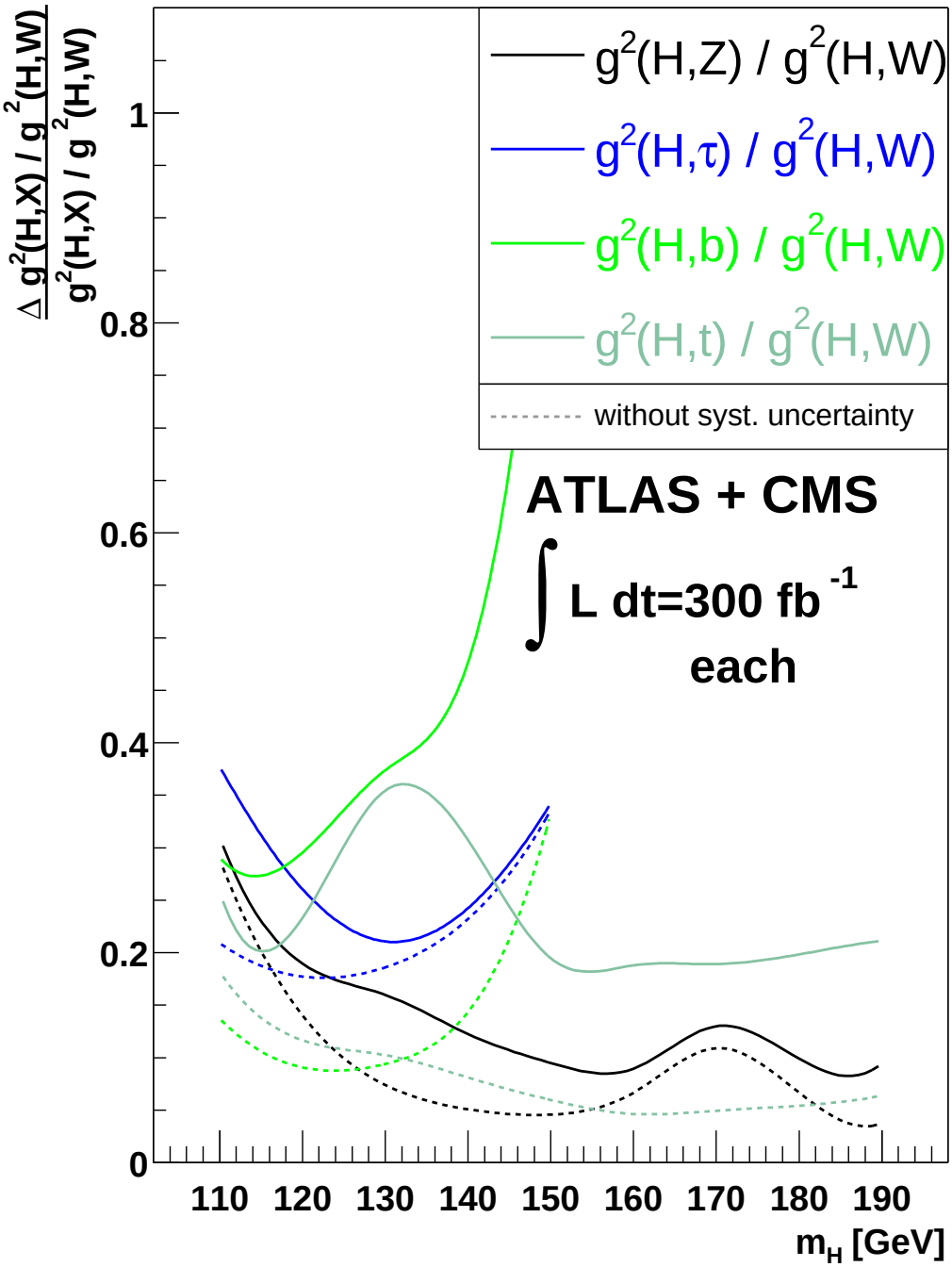
$$H \to WW \to \ell\nu jj$$
$$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$$

$\Rightarrow$ coverage of full mass range



Dittmar

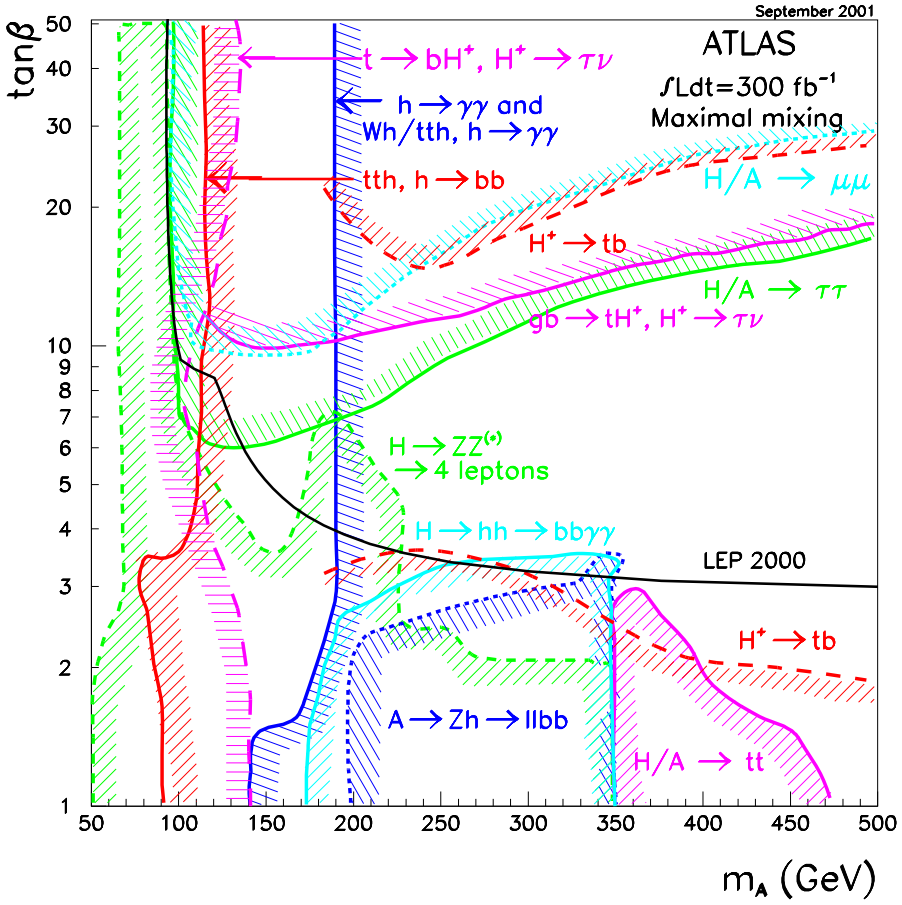
• accuracies: $\delta M_H/M_H \sim 10^{-3}$, $\delta\Gamma/\Gamma \sim 10\%$, ratios of couplings: $\gtrsim 10\%$



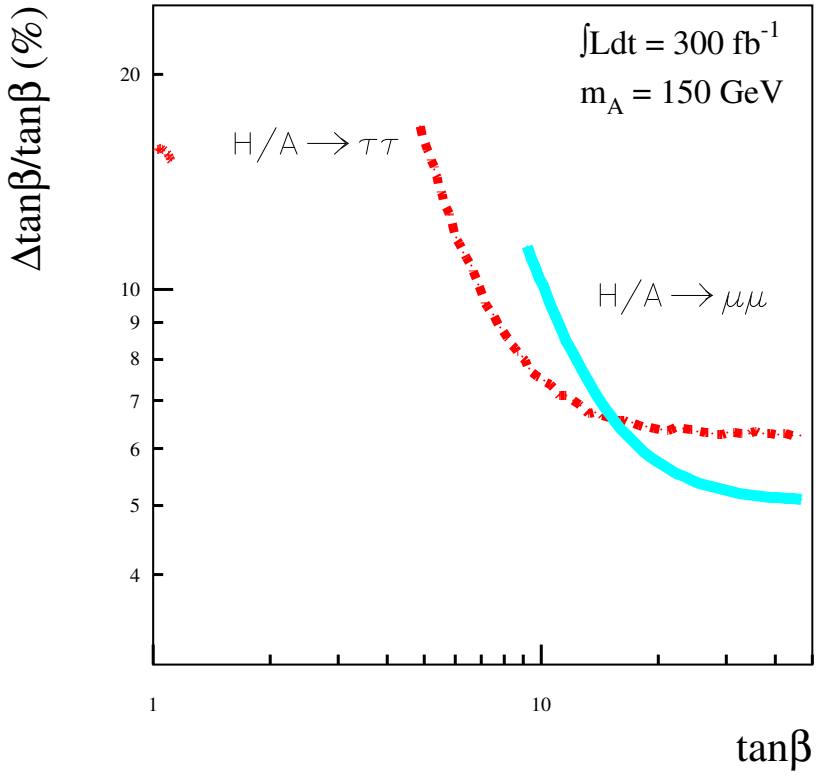
Dührssen

(ii) MSSM

- coverage of full MSSM parameter plane



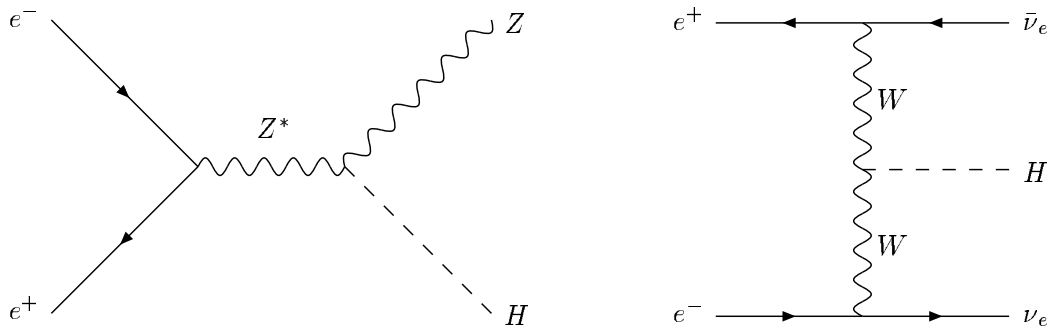
- $\delta M_H/M_H \sim 10^{-3}$, $\delta \mathrm{tg}\beta/\mathrm{tg}\beta \sim (5-10)\%$



ATLAS

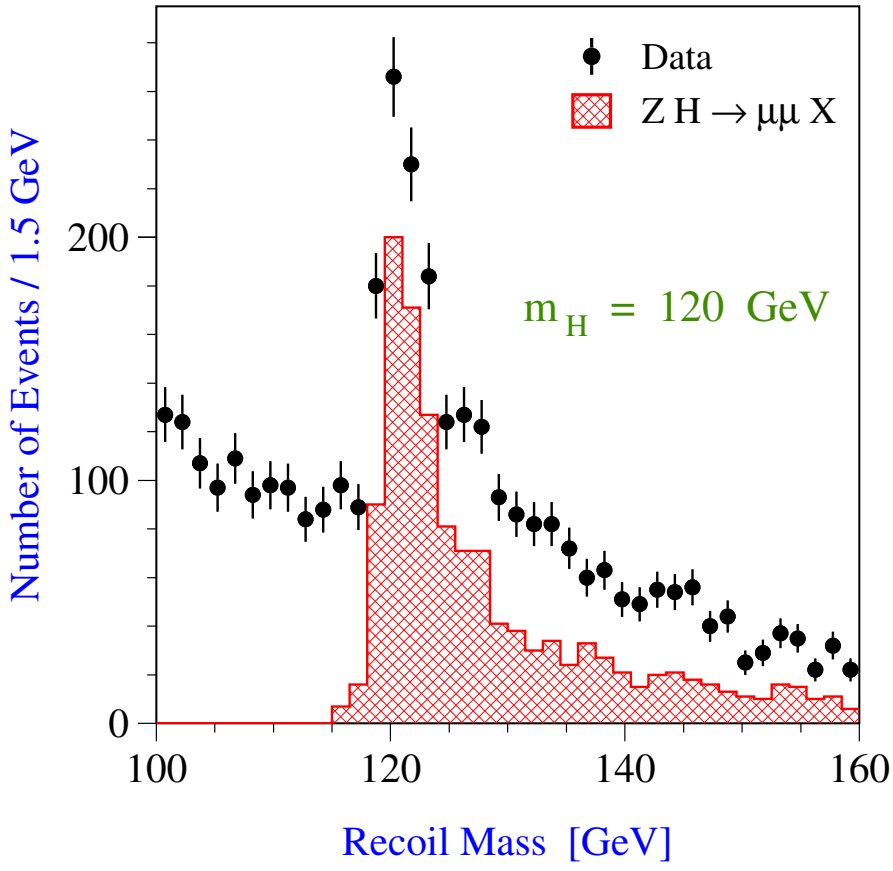
IV HIGGS SEARCH @ LC

- Higgs boson production analogous to LEP2



- discovery of Higgs bosons up to $M_H \lesssim 0.7\sqrt{s}$

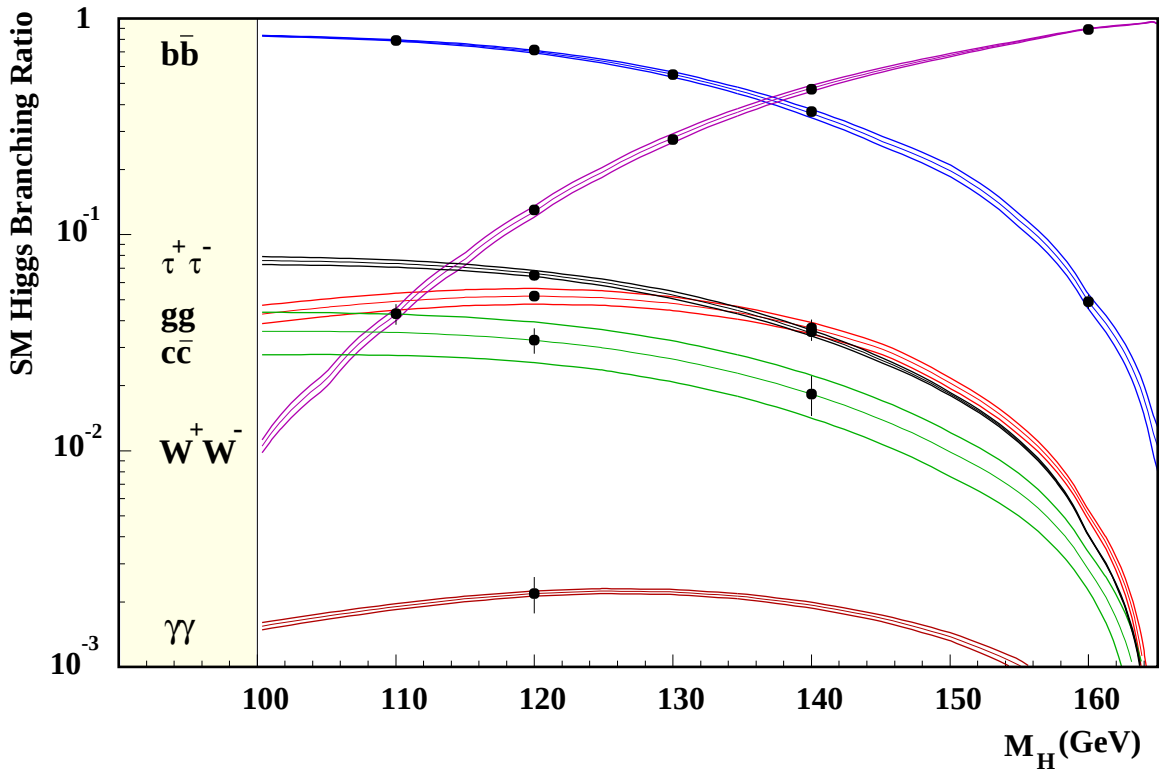
- Higgs-strahlung $e^+e^- \to ZH$: Z monoenergetic
  $\Rightarrow M_H^2 = s - 2\sqrt{s}E_Z + M_Z^2$
  $\Rightarrow$ reconstruction from recoil mass



TESLA

- mass: $\delta M_H \lesssim 50$ MeV from Higgs-strahlung

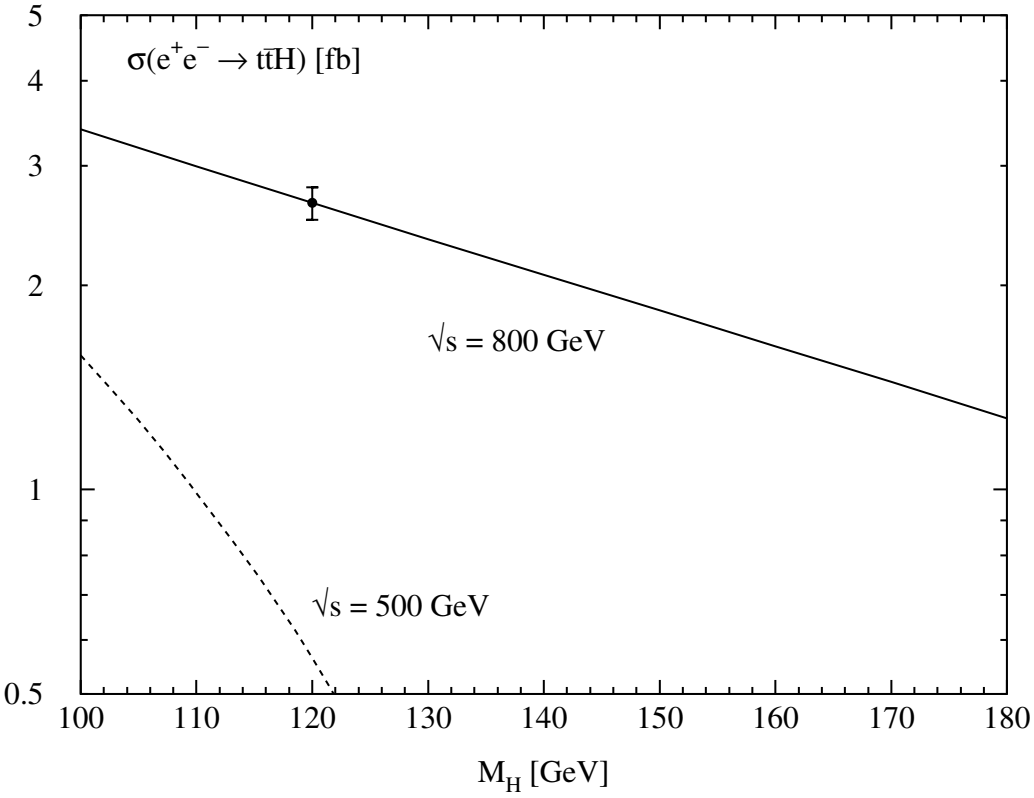
- Yukawa couplings: from branching ratios

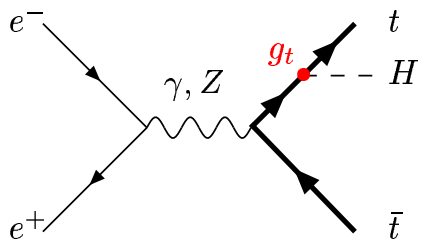


Battaglia

$\Rightarrow \delta BR/BR \sim$ few % $\Rightarrow$ Test $g_f \propto m_f$

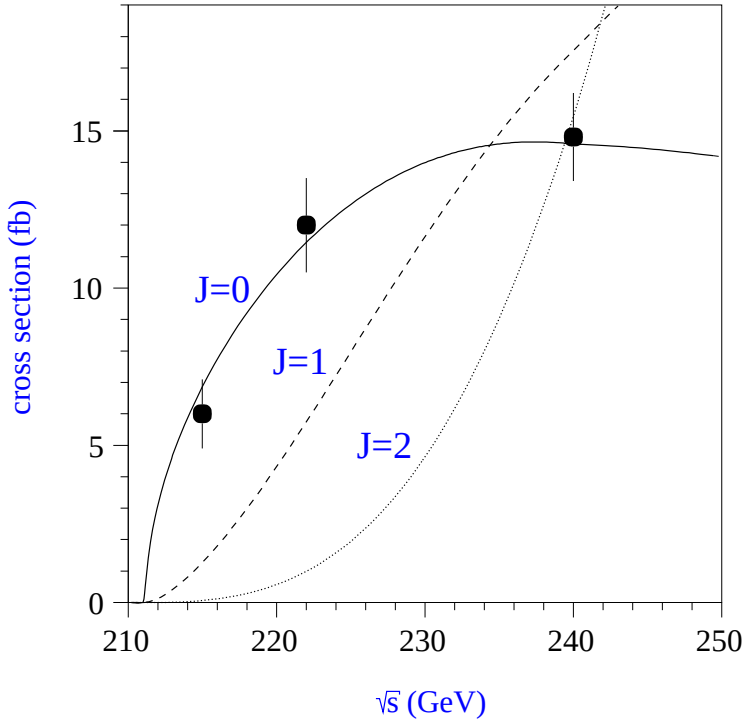
- top Yukawa coupling: $e^+e^- \to t\bar{t}H$





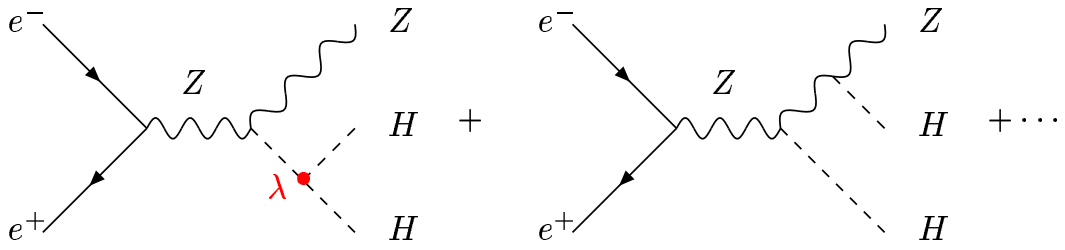
Juste, Merino

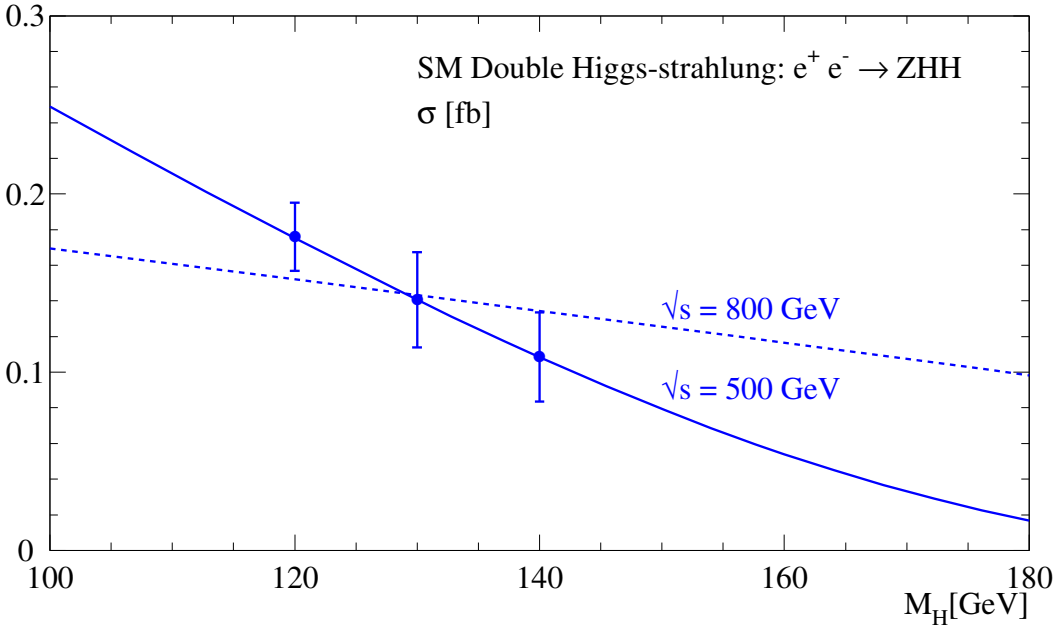
- spin: threshold behaviour $\sigma(e^+e^- \to ZH) \propto \beta^{J+1}$



Miller, Choi, Eberle,
Mühlleitner, Zerwas
Dova, Garcia–Abia, Lohmann

- selfinteraction: $e^+e^- \to ZHH$





Djouadi, Kilian, Mühlleitner, Zerwas
Castanier, Gay, Lutz, Orloff

$\Rightarrow \delta\lambda/\lambda \sim 20\%$

V *SUMMARY*

• Higgs boson crucial ingredient of SM and MSSM
$\Rightarrow$ Higgs boson searches belong to major endeavours at LHC and LC

• LHC will find at least one Higgs boson [light scalar]

• profile of the Higgs bosons can be studied partially @ LHC
$\rightarrow$ completed @ LC with much higher accuracy

• LHC: problematic distinction SM $\leftrightarrow$ MSSM for large $M_A \rightarrow$ can be solved @ LC

$\Rightarrow$ We need both colliders

• close collaboration of experimentalists and theorists necessary