# $\Phi \to gg$ : QCD CORRECTIONS TO SQUARK LOOPS

Michael Spira (PSI)

I Introduction

II $\Phi \to gg$

III Conclusions

in collaboration with Margarete Mühlleitner

# I *INTRODUCTION*

- MSSM: 2 Higgs doublets $\overset{\text{ESB}}{\rightarrow}$ 5 Higgs bosons: $h, H, A, H^{\pm}$
- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \rightarrow \boxed{M_h \lesssim 140 \text{ GeV}}$

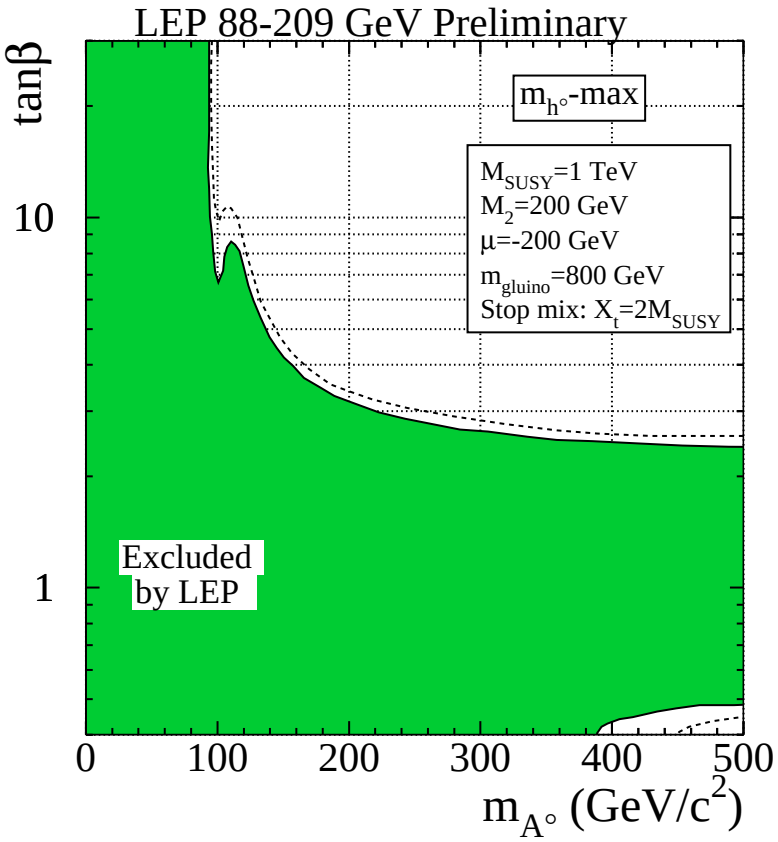
Haber,. . .
Carena,. . .
Heinemeyer,. . .
Zhang
etc.

- LO: 2 input parameters: $M_A, \text{tg}\beta = \frac{v_2}{v_1}$
- mixing: $\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$
- modified couplings:

| $\phi$ | $g_u^\phi$ | $g_d^\phi$ | $g_V^\phi$ |
|---|---|---|---|
| $h$ | $c_\alpha/s_\beta$ | $-s_\alpha/c_\beta$ | $s_{\beta-\alpha}$ |
| $H$ | $s_\alpha/s_\beta$ | $c_\alpha/c_\beta$ | $c_{\beta-\alpha}$ |
| $A$ | $\text{ctg}\beta$ | $\text{tg}\beta$ | 0 |

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

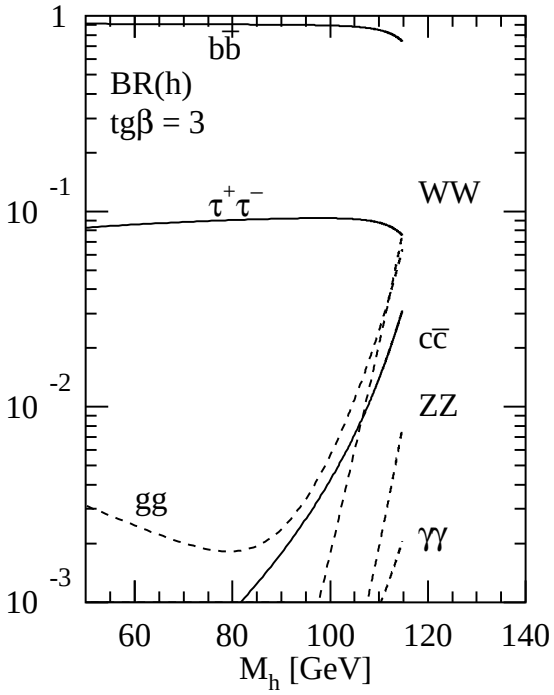
- direct search at LEP2: $e^+e^- \to Z + h/H, A + h/H, \nu_e\bar{\nu}_e + h/H$

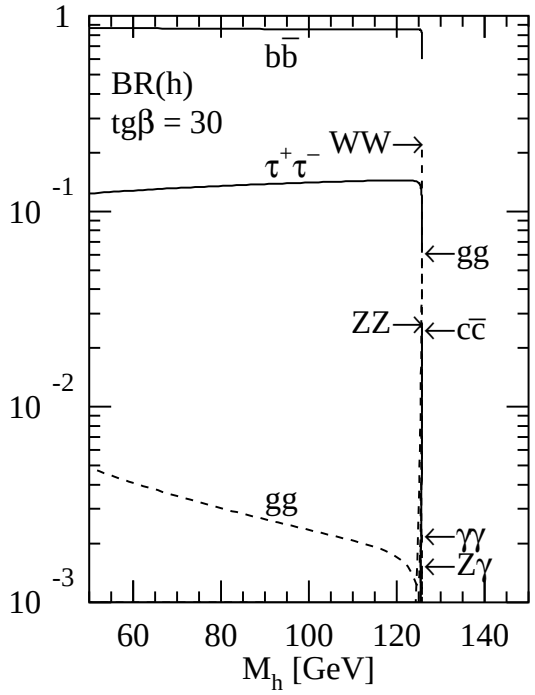


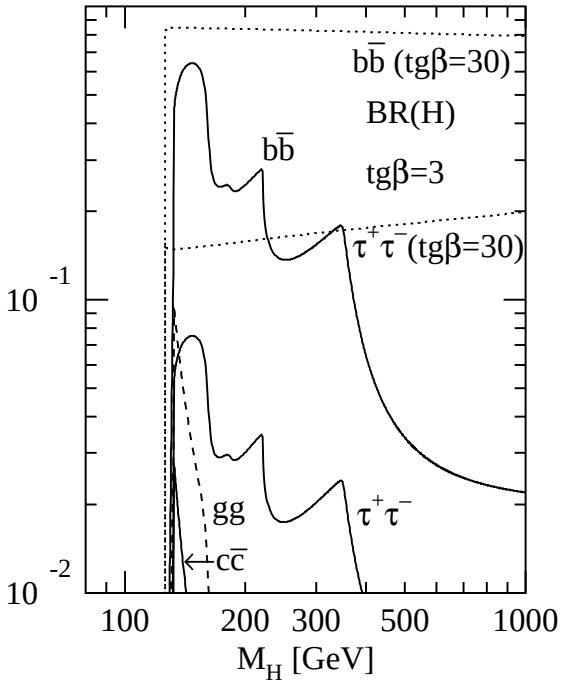

$M_{h/H} > 91$ GeV, $M_A \gtrsim 91.9$ GeV, $M_{H^\pm} > 78.6$ GeV

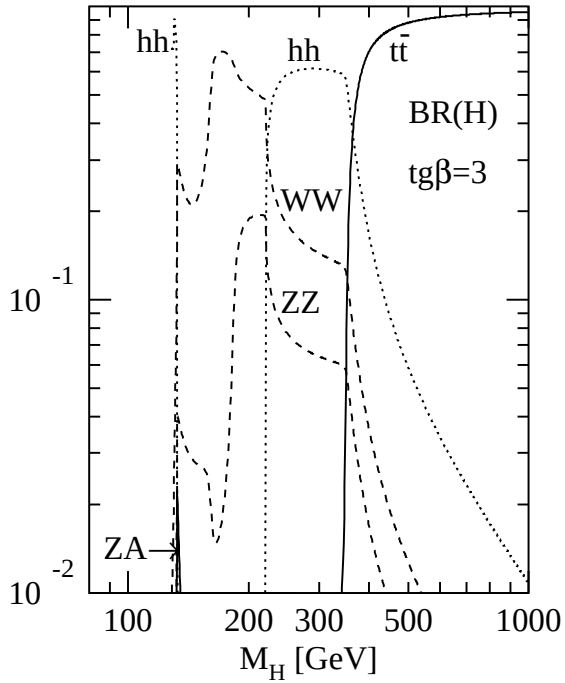
$0.5 < \mathrm{tg}\beta < 2.4$ excluded

[only for $m_t = 174.3$ GeV]

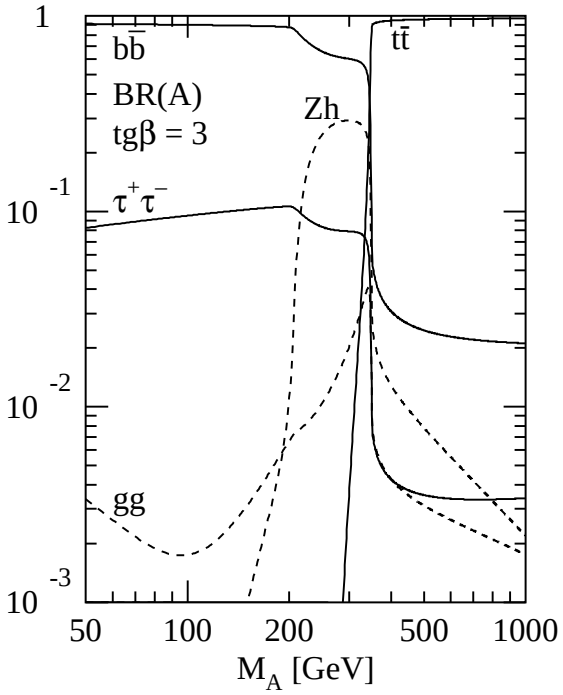

BR(h)
tgβ = 3
bb̄
τ⁺τ⁻
WW
cc̄
ZZ
gg
γγ
M_h [GeV]

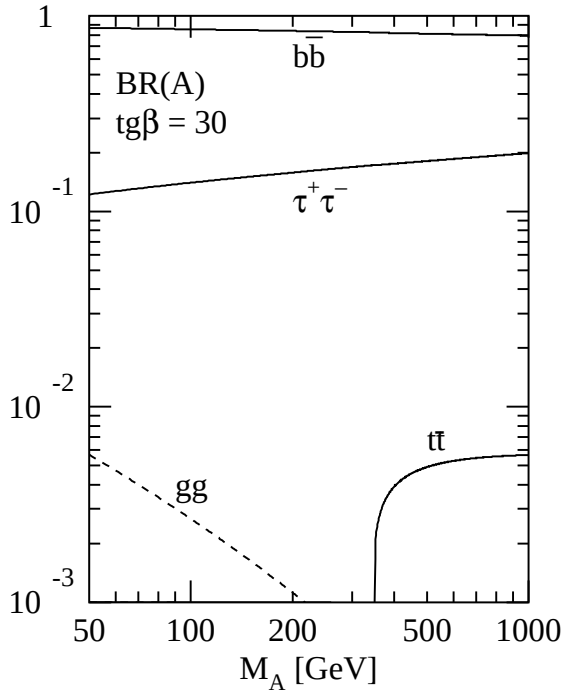

BR(h)
tgβ = 30
bb̄
τ⁺τ⁻
WW
gg
ZZ
cc̄
gg
γγ
Zγ
M_h [GeV]

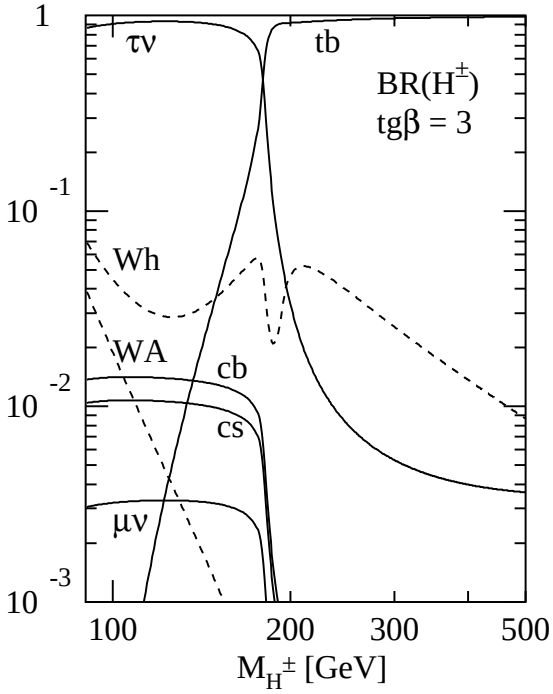

bb̄ (tgβ=30)
BR(H)
tgβ=3
bb̄
τ⁺τ⁻(tgβ=30)
gg
cc̄
τ⁺τ⁻
M_H [GeV]

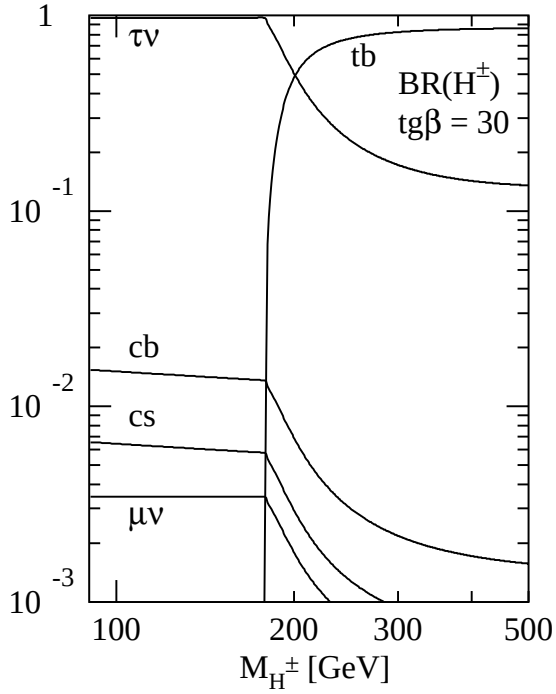

hh
hh
tt̄
BR(H)
tgβ=3
WW
ZZ
ZA
M_H [GeV]

HDECAY


1
10^-1
10^-2
10^-3
bb̄
tt̄
BR(A)
tgβ = 3
Zh
τ⁺τ⁻
gg
50
100
200
500
1000
M_A [GeV]

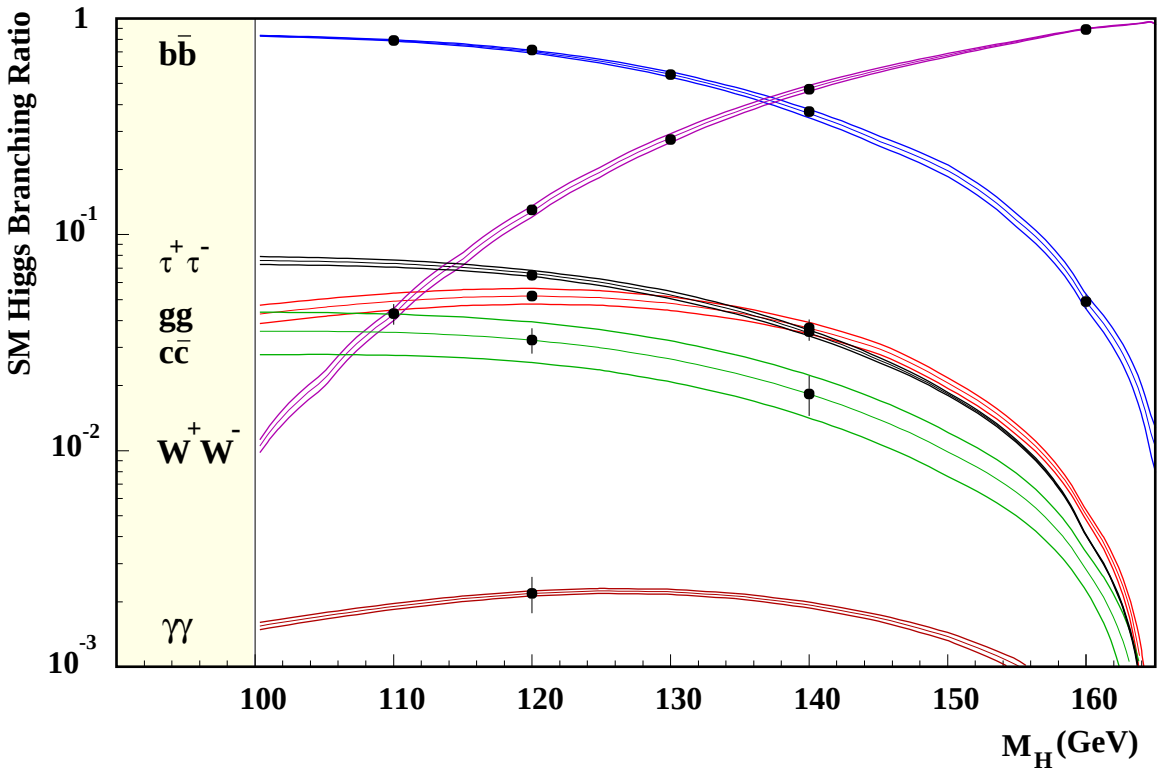

1
10^-1
10^-2
10^-3
bb̄
BR(A)
tgβ = 30
τ⁺τ⁻
tt̄
gg
50
100
200
500
1000
M_A [GeV]


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


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

HDECAY

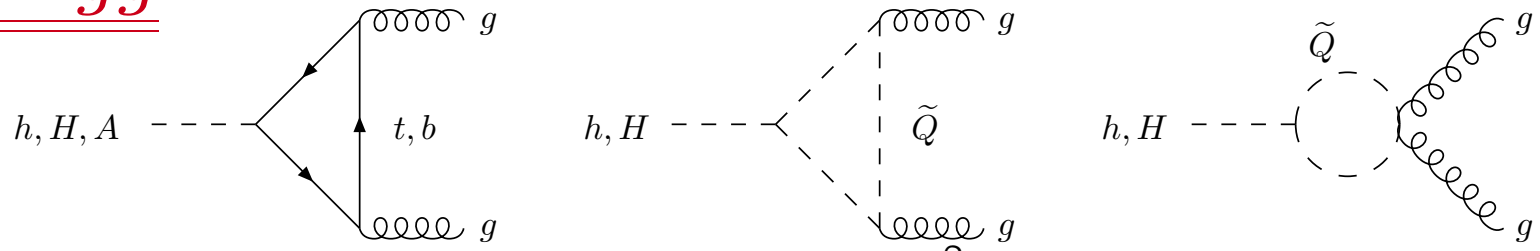
- branching ratios:




Battaglia

$\Rightarrow \delta BR/BR \sim$ few %

# II $\Phi \longrightarrow gg$




$$\Gamma_{LO}(A \to gg) = \frac{G_F \alpha_s^2 M_A^3}{16\sqrt{2}\pi^3} \left| \sum_Q g_Q^A A_Q^A(\tau_Q) \right|^2$$

$$\Gamma_{LO}(h/H \to gg) = \frac{G_F \alpha_s^2 M_{h/H}^3}{36\sqrt{2}\pi^3} \left| \sum_Q g_Q^{h/H} A_Q^{h/H}(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^{h/H} A_{\tilde{Q}}^{h/H}(\tau_{\tilde{Q}}) \right|^2$$

$$A_Q^A(\tau) = \tau f(\tau) \longrightarrow 1$$

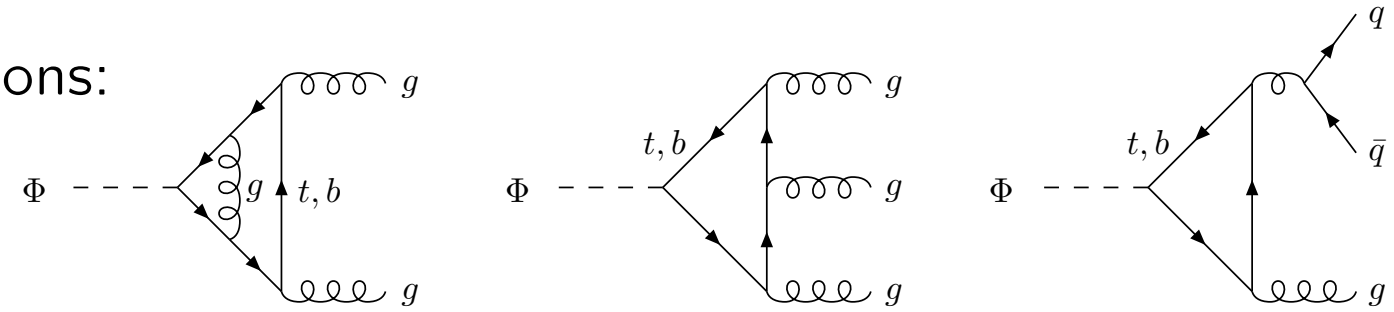
$$A_Q^{h/H}(\tau) = \frac{3}{2}\tau[1 + (1-\tau) f(\tau)] \longrightarrow 1$$

$$A_{\tilde{Q}}^{h/H}(\tau) = -\frac{3}{4}\tau[1 - \tau f(\tau)] \longrightarrow \frac{1}{4}$$

$$f(\tau) = \begin{cases} \arcsin^2 \dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\dfrac{1}{4}\left[\log \dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

$$g_{\tilde{Q}}^{h/H} = \frac{m_Q^2}{m_{\tilde{Q}}^2} g_Q^{h/H} + \text{mixing terms} + D\text{-terms}$$

- third generation dominant $\Rightarrow t, b, \tilde{t}, \tilde{b}$
- tg$\beta$ $\uparrow$ $\quad\Rightarrow\quad$ $t, \tilde{t}$ $\downarrow$ $\quad b, \tilde{b}$ $\uparrow$
- $\tilde{Q}$ sizeable for $m_{\tilde{Q}} \lesssim 400$ GeV
- QCD corrections:




$$\Gamma^{\Phi} = \Gamma^{\Phi}_{LO}\left\{1 + E_{\Phi}\frac{\alpha_s}{\pi}\right\}$$

$$E_{h/H} = \frac{95}{4} - \frac{7}{6}N_F + \Delta E_{h/H}$$ Inami, Kubota, Okada

$$E_A = \frac{97}{4} - \frac{7}{6}N_F + \Delta E_A$$

full massive result: $\delta \sim 70\%$ S., Djouadi, Graudenz, Zerwas

- NNLO corrections: $M^2_{\Phi} \ll 4m^2_Q \quad\Rightarrow\quad \sim 20\%$ Chetyrkin, Kniehl, Steinhauser

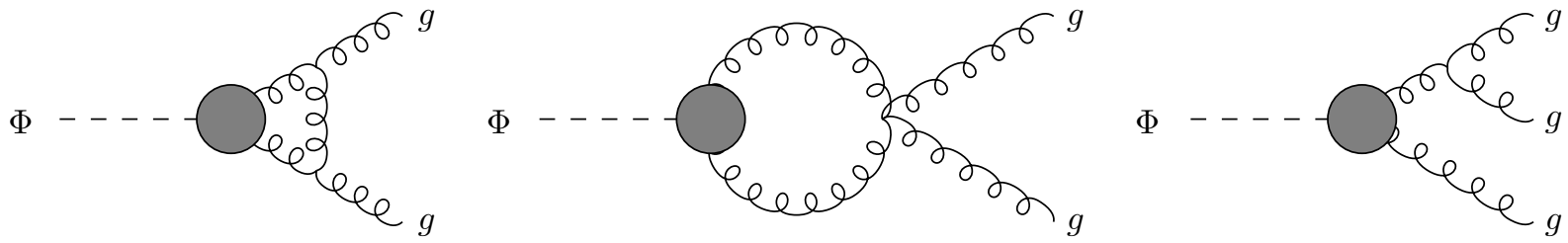
$\leftarrow$ only valid for small tg$\beta$

- LET:

$$\mathcal{L}_{eff}^{H} = g_Q^H \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{H}{v} \left\{ 1 + \frac{11}{4} \frac{\alpha_s}{\pi} \right\}$$

$$\mathcal{L}_{eff}^{A} = g_Q^A \frac{\alpha_s}{8\pi} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} \frac{A}{v}$$

Dawson
S., Djouadi, Graudenz, Zerwas
Kauffman, Schaffer




- extension to heavy squarks:

$$\Delta\mathcal{L}_{eff}^{H} = g_{\tilde{Q}}^H \frac{\alpha_s}{48\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{H}{v} \left\{ 1 + \frac{9}{2} \frac{\alpha_s}{\pi} \right\} \qquad \text{[heavy gluinos]}$$

Dawson, Djouadi, S.
Mühlleitner, S.

$\Rightarrow \delta_{\tilde{Q}} \sim 70\%$

- gluino corrections $\lesssim 5\%$ $\qquad [M_\Phi^2 \ll m^2_{\tilde{g},\tilde{Q}}]$

Harlander, Steinhauser

$\Rightarrow$ full massive SUSY–QCD corrections missing

- first step: QCD corrections to squark loops [scalar Higgs: $h/H \to H$]

$$\begin{aligned}
\mathcal{L} &= -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} + \frac{1}{2}\left[(\partial_\mu H)^2 - M_H^2 H^2\right] \\
&+ \sum_Q \left[\bar{Q}(i\not{D} - m_Q)Q - g_Q^H \frac{m_Q}{v}\bar{Q}QH\right] \\
&+ \sum_{\tilde{Q}} \left[|D_\mu \tilde{Q}|^2 - m_{\tilde{Q}}^2|\tilde{Q}|^2 - g_{\tilde{Q}}^H \frac{m_{\tilde{Q}}^2}{v}|\tilde{Q}|^2 H\right] \\
iD_\mu &= i\partial_\mu - g_s G_\mu^a T^a
\end{aligned}$$

- renormalization:

  $m_{Q,\tilde{Q}}$: on-shell

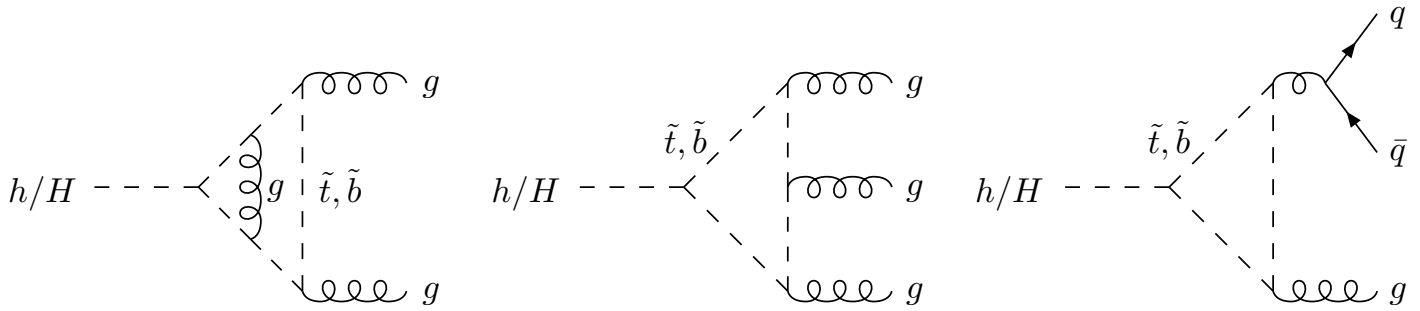
  $\alpha_s$: $\overline{\text{MS}}$ (5 active flavors)

  $HQ\bar{Q}$ vertex: $\mathcal{L}_{int} = -g_Q^H \frac{m_{Q0}}{v}\bar{Q}_0 Q_0 H = -g_Q^H \frac{m_Q}{v}\bar{Q}QH\left[Z_2^Q - \frac{\delta m_Q}{m_Q}\right]$

  $H\tilde{Q}\bar{\tilde{Q}}$ vertex: $\mathcal{L}_{int} = -g_{\tilde{Q}}^H \frac{m_{\tilde{Q}0}^2}{v}|\tilde{Q}_0|^2 H = -g_{\tilde{Q}}^H \frac{m_{\tilde{Q}}^2}{v}|\tilde{Q}|^2 H\left[Z_2^{\tilde{Q}} - \frac{\delta m_{\tilde{Q}}^2}{m_{\tilde{Q}}^2}\right]$

$\leftarrow$ renormalization of $g_{\tilde{Q}}^H$ disregarded [$\rightarrow$ gluino loops]

- results:



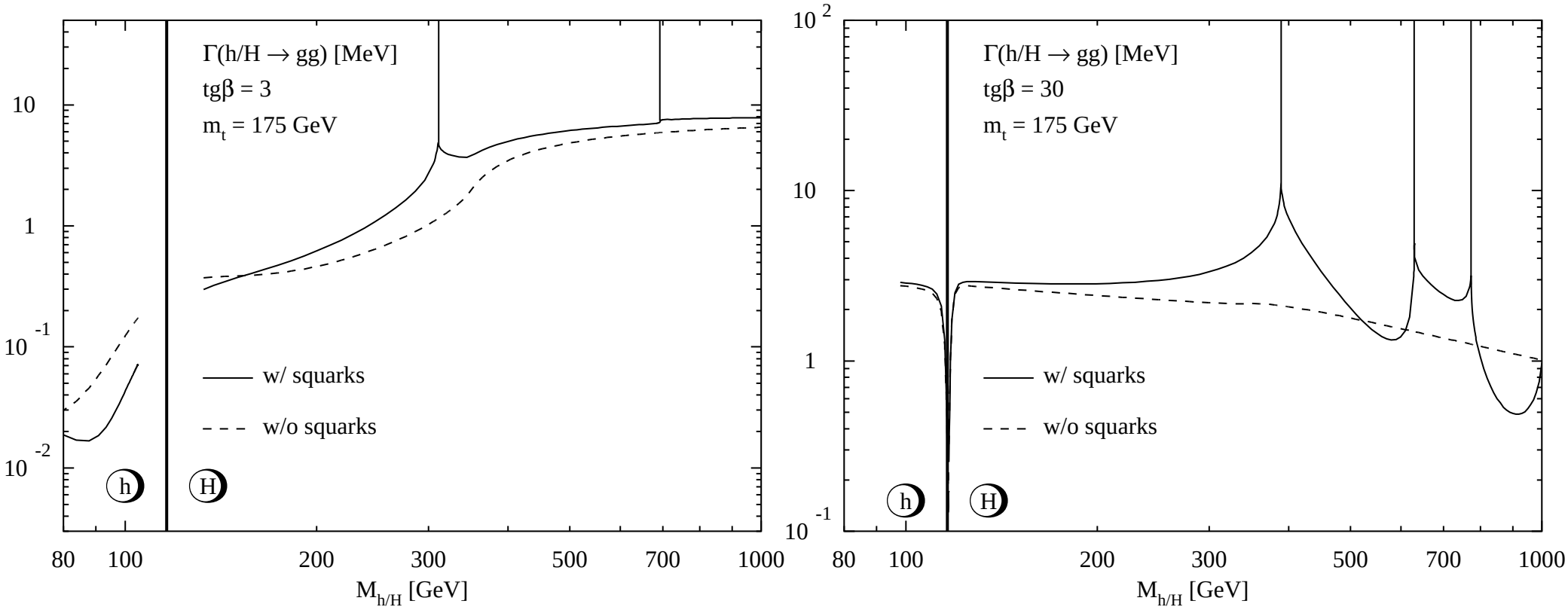

$$\Gamma^{h/H} = \Gamma^{h/H}_{LO}\left\{1 + E_{h/H}\frac{\alpha_s}{\pi}\right\}$$

$$E_{h/H} = \frac{95}{4} - \frac{7}{6}N_F + \frac{7}{2}\Re e\left\{\frac{\sum_{\tilde{Q}} g^{h/H}_{\tilde{Q}} A^{h/H}_{\tilde{Q}}(\tau_{\tilde{Q}})}{\sum_Q g^{h/H}_Q A^{h/H}_Q(\tau_Q) + \sum_{\tilde{Q}} g^{h/H}_{\tilde{Q}} A^{h/H}_{\tilde{Q}}(\tau_{\tilde{Q}})}\right\} + \Delta E_{h/H}$$

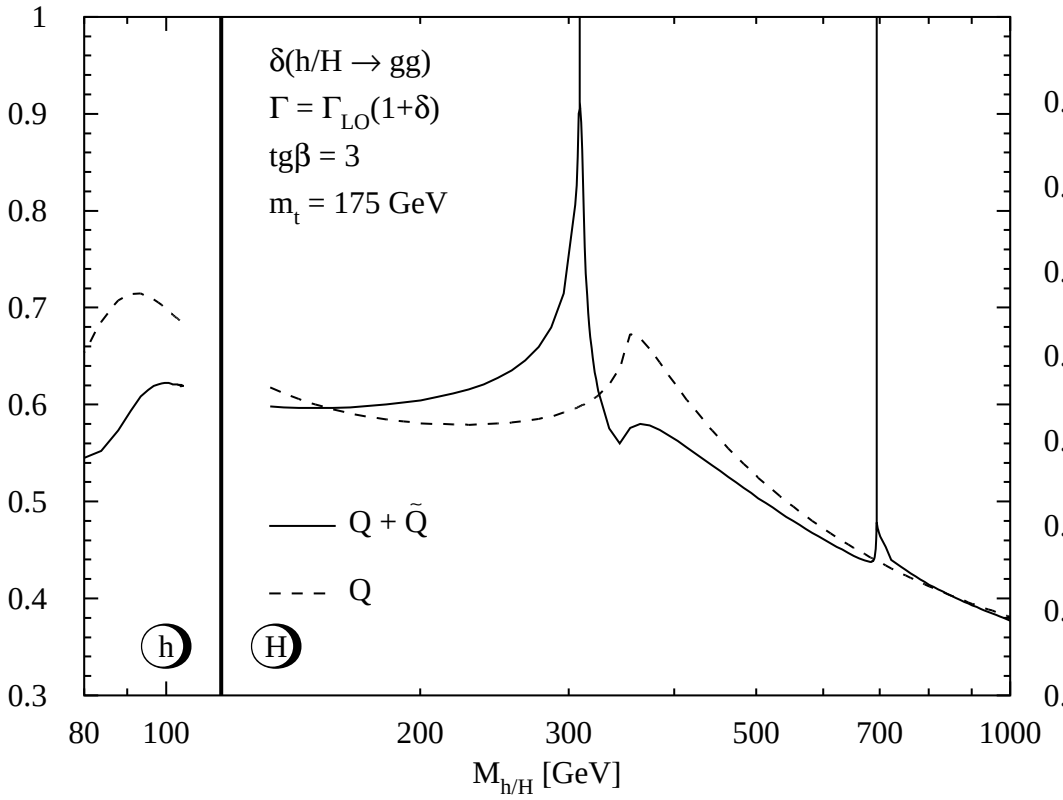
- Gluophobic Higgs scenario: [$m_t = 175$ GeV] Carena, Heinemeyer, Wagner, Weiglein

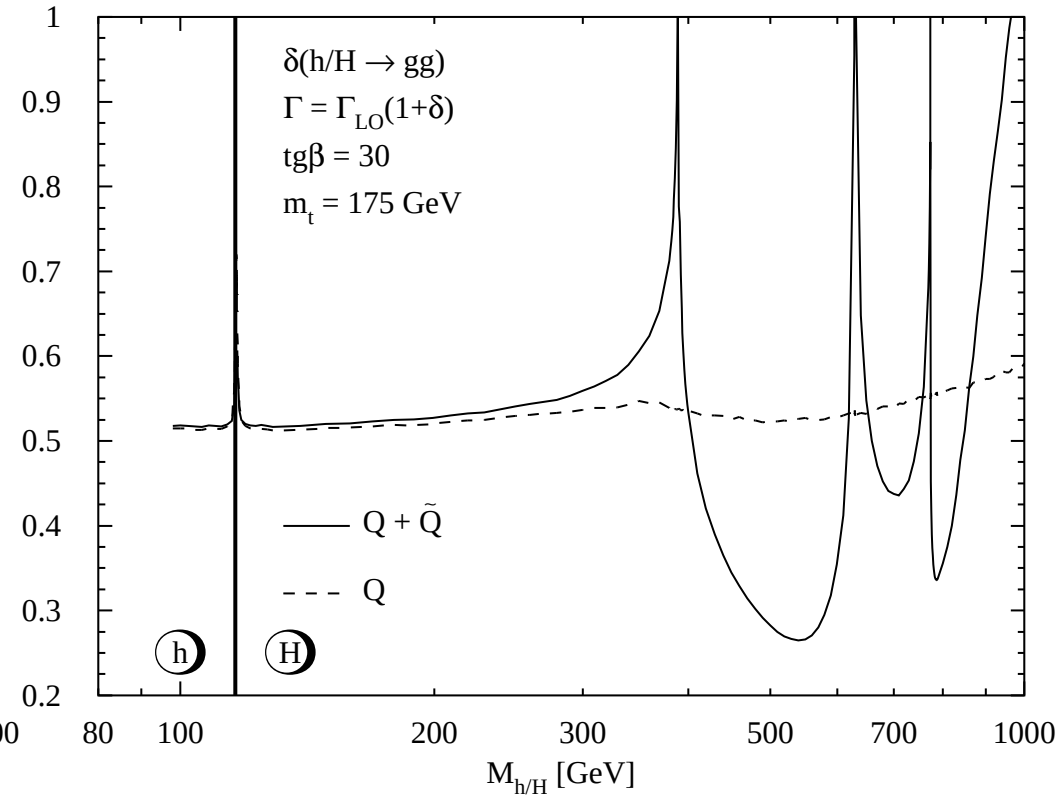
$$M_{SUSY} = 350 \text{ GeV}, \mu = M_2 = 300 \text{ GeV}, A_b = A_t = -670 \text{ GeV}$$

| tg$\beta = 3$ | | tg$\beta = 30$ | |
|---|---|---|---|
| $m_{\tilde{t}_1} = 156$ GeV | $m_{\tilde{t}_2} = 516$ GeV | $m_{\tilde{t}_1} = 195$ GeV | $m_{\tilde{t}_2} = 502$ GeV |
| $m_{\tilde{b}_1} = 346$ GeV | $m_{\tilde{b}_2} = 358$ GeV | $m_{\tilde{b}_1} = 315$ GeV | $m_{\tilde{b}_2} = 387$ GeV |

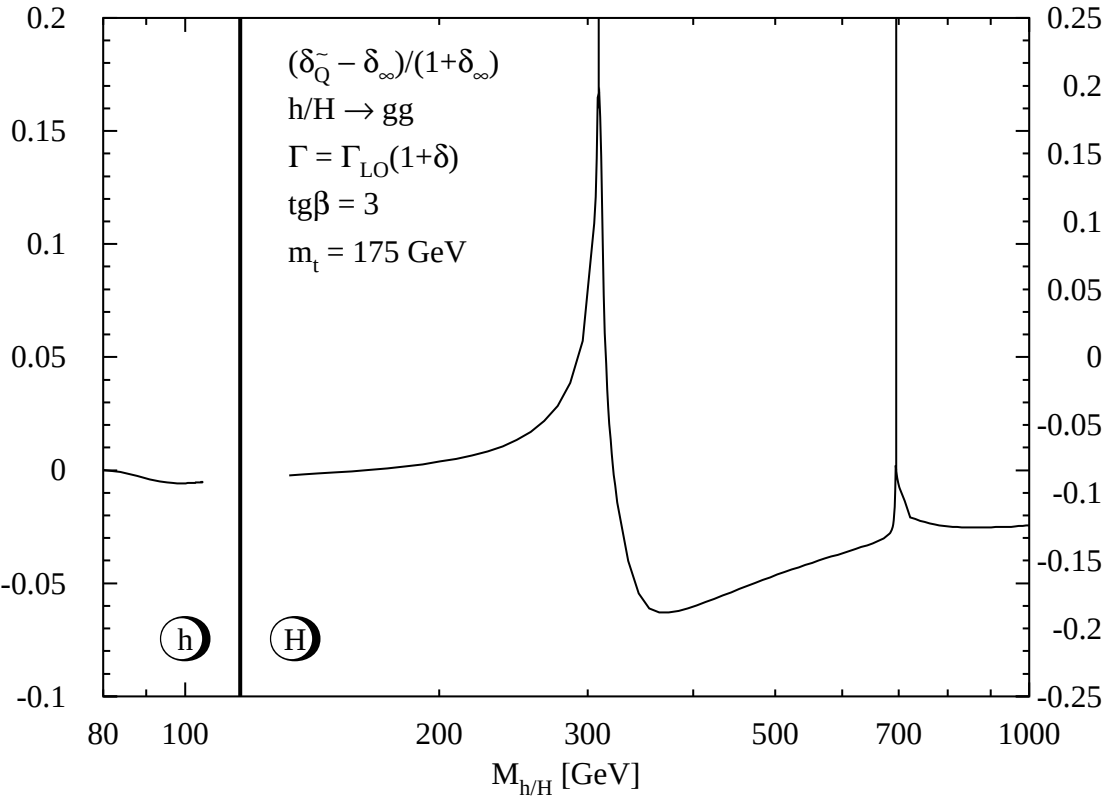


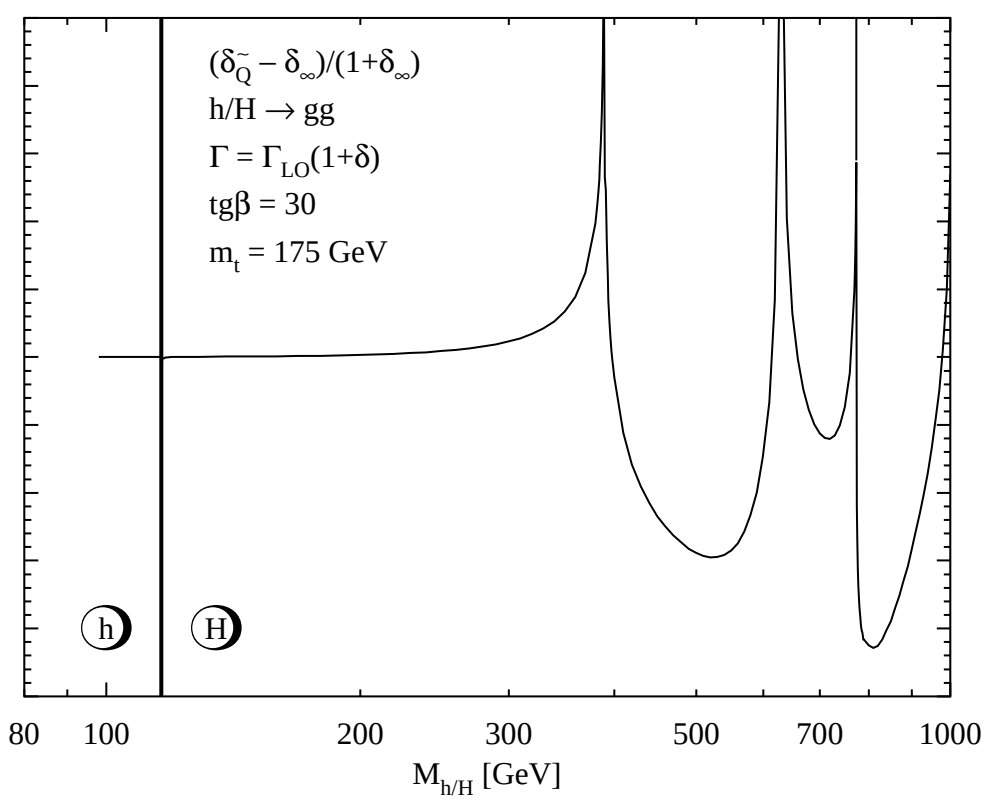

Mühlleitner, S.




Mühlleitner, S.




Mühlleitner, S.

# III *CONCLUSIONS*

- Higgs searches at the LHC and ILC belong to major endeavours
- significant $BR(\Phi \to gg)$
- $\tilde{Q}$ loops important for $m_{\tilde{Q}} \lesssim 400$ GeV
- full massive QCD corrections to quark and squark loops $\lesssim 70\%$
- squark mass effects on relative corrections $\lesssim 20\%$
  $\Rightarrow$ larger than quark mass effects
- outlook: full mass dependence of $\tilde{g}$–$\tilde{Q}$ loops