HIGGS DECAYS & HDECAY

Michael Spira (PSI)

I Introduction

II Higgs Boson Decays

III Summary

HDECAY: Djouadi, Kalinowski, Mühlleitner, Spira

I *INTRODUCTION*

Standard Model

- LEP2: $M_H > 114.4$ GeV $[e^+e^- \to ZH, \nu_e\bar{\nu}_e H]$

- triviality and vacuum stability

$\Rightarrow M_H \lesssim 700$ GeV $\quad [\Lambda \sim 1$ TeV$]$

130 GeV $\lesssim M_H \lesssim 190$ GeV $\quad [\Lambda \sim M_{GUT}]$

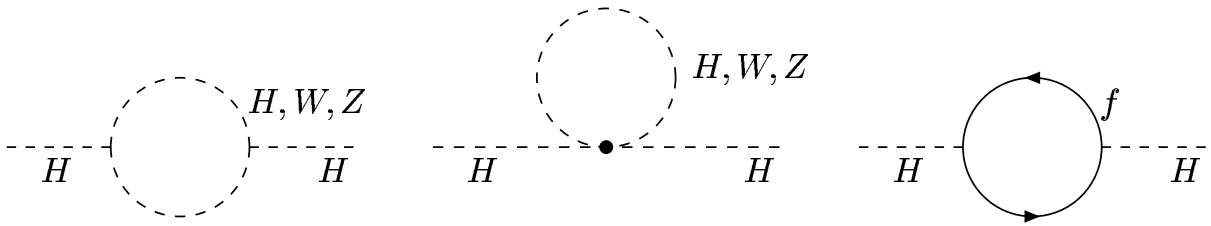
Sher
Lindner
Lüscher, Weisz
Hasenfratz,. . .
etc.

- electroweak fits: $M_H \lesssim 158$ GeV (95% CL)

LEP/SLC/Tevatron

$\Rightarrow$ light Higgs boson

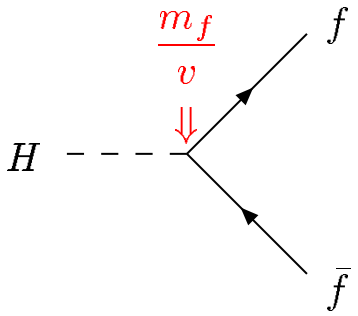
- GUT: hierarchy problem



$\delta M_H^2 \sim \Lambda^2$ [quadratic divergence]

II *HIGGS BOSON DECAYS*

Standard Model



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

- $H \to b\bar{b}$ dominant for $M_H \lesssim 140$ GeV

- elw. corr.: moderate in interm. mass range

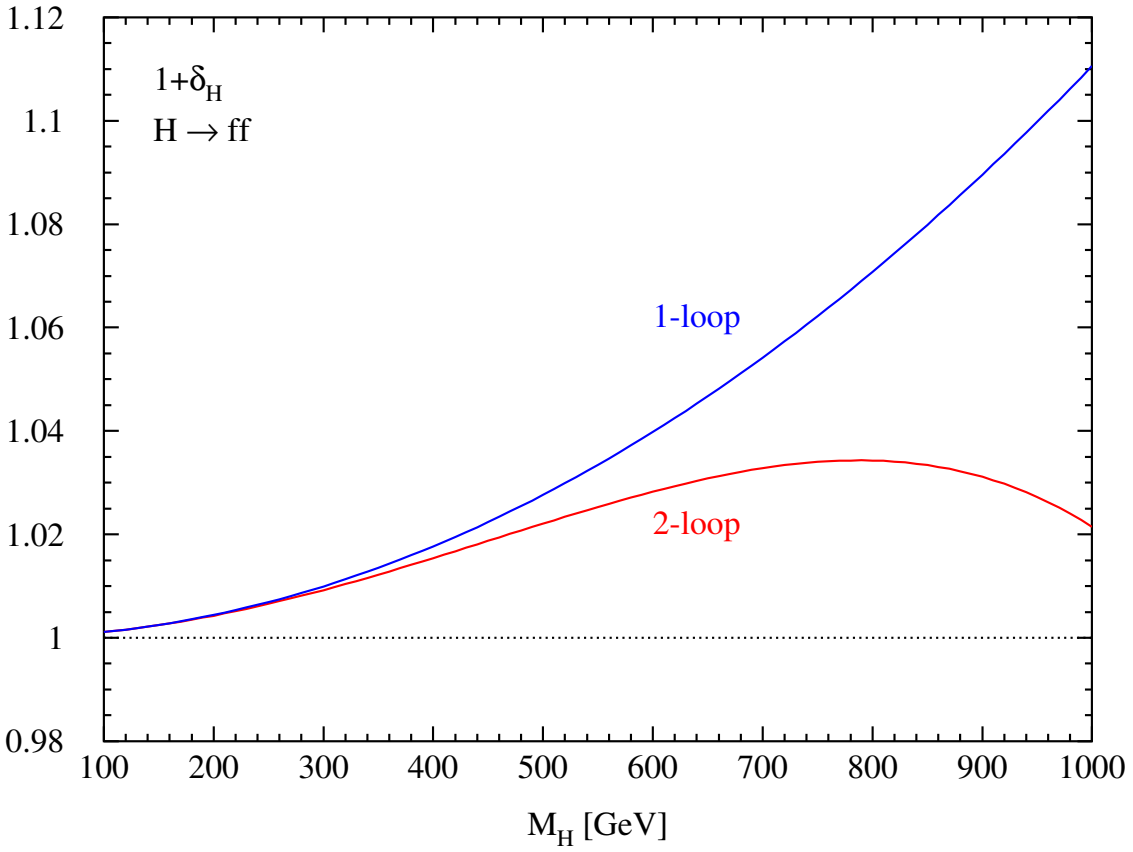
  Fleischer, Jegerlehner
  Bardin,...
  Dabelstein, Hollik
  Kniehl

  sizable for large Higgs masses F

  Ghinculov
  Durand, Riesselmann, Kniehl

- HDECAY: approx. NLO elw. interm. + large Higgs mass @ 2 loops

$H \to f\bar{f}$



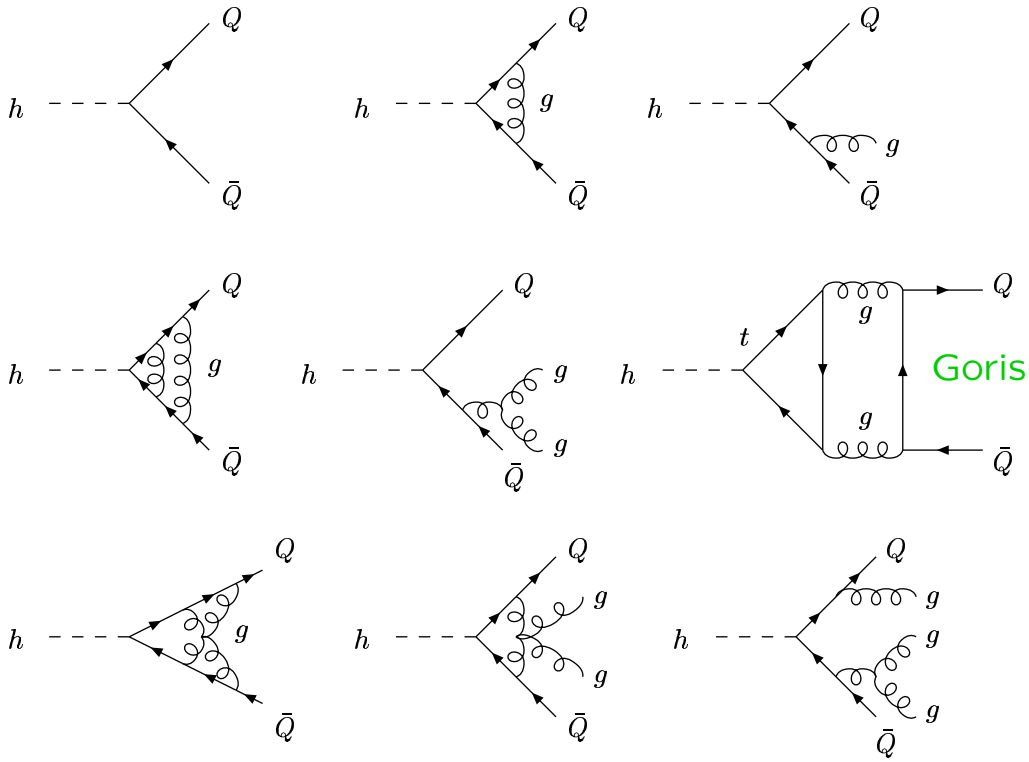
Ghinculov

Durand, Riesselmann, Kniehl

- moderate QCD corrections to $H \to t\bar{t}$

Braaten, Leveille
Drees, Hikasa

- large QCD corrections to $H \to b\bar{b}, c\bar{c}$: $\sim -50 \ldots -80\%$



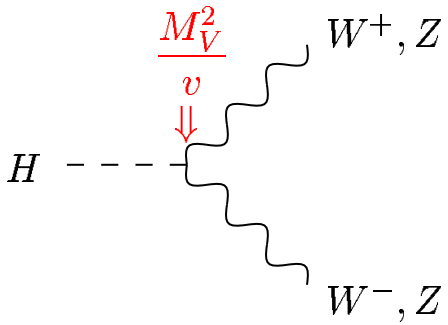
Gorishnii, Kataev, Larin, Surguladze

Chetyrkin

- dominant effect: $m_b \to \overline{m}_b(M_h)$

- HDECAY: massive NLO QCD corr. interpol. to 4-loop for large Higgs masses

Baikov, Chetyrkin, Kühn



$$BR(H \to W^{+(*)}W^{-(*)}) \lesssim 60 - 95\%$$
$$BR(H \to Z^{(*)}Z^{(*)}) \lesssim 30\%$$

below threshold: $H \to V^{(*)}V^*$ important for $M_H \gtrsim M_V$ Rizzo, Keung, Marciano, Cahn

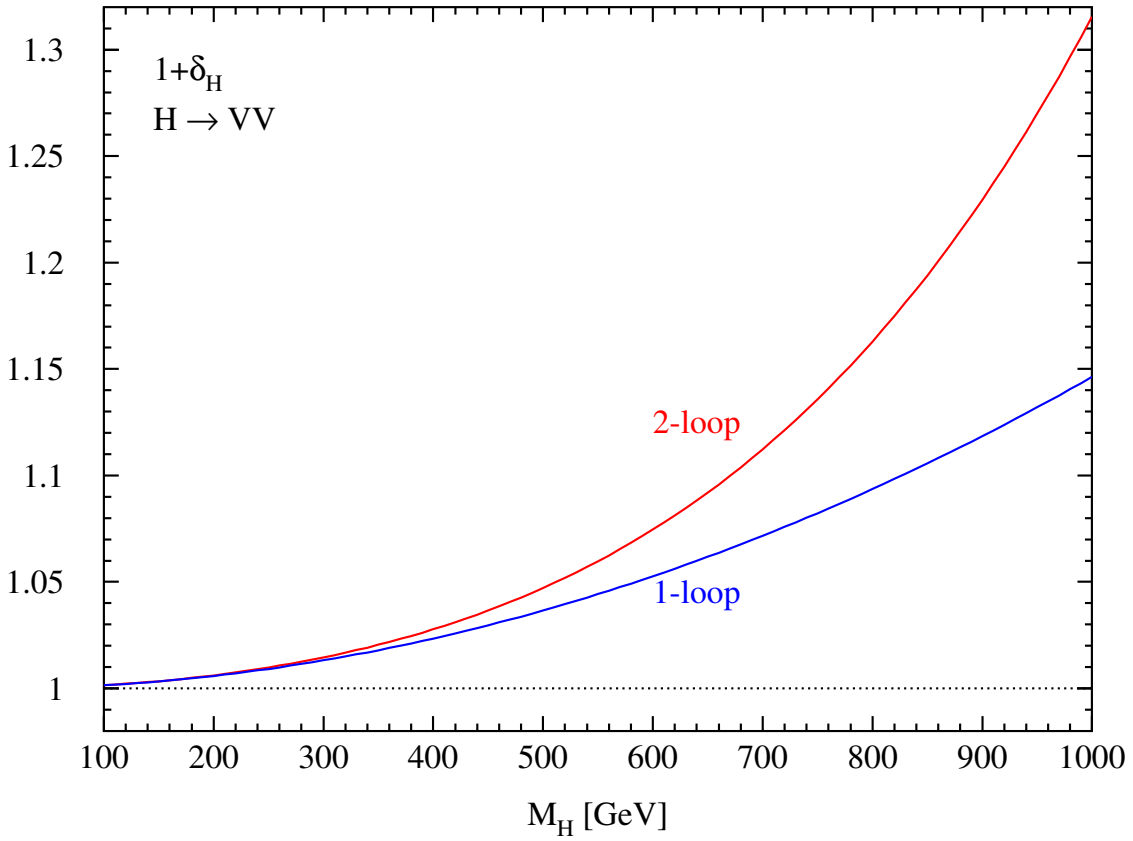
$H \to W^{+*}W^{-*}$ dominant for $M_H \gtrsim 140$ GeV

- elw. corr.: $\sim 5 \ldots 20\%$ interm. Fleischer, Jegerlehner, Bardin,..., Kniehl, Bredenstein, Denner, Dittmaier, Weber

sizable for large Higgs masses F Ghinculov, Frink, Kniehl, Kreimer, Riesselmann

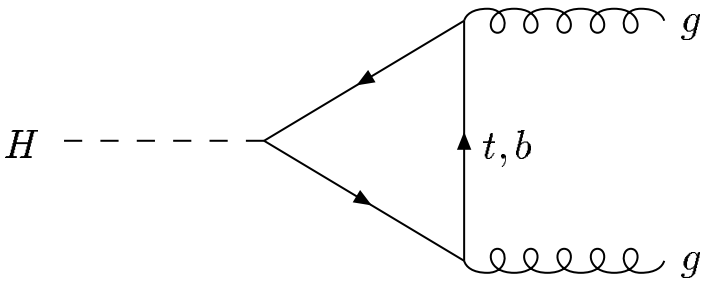
- HDECAY: approx. NLO elw. + large Higgs mass @ 2 loops
  $\to$ Prophecy4f Bredenstein, Denner, Dittmaier, Weber

$H \to VV$



Ghinculov

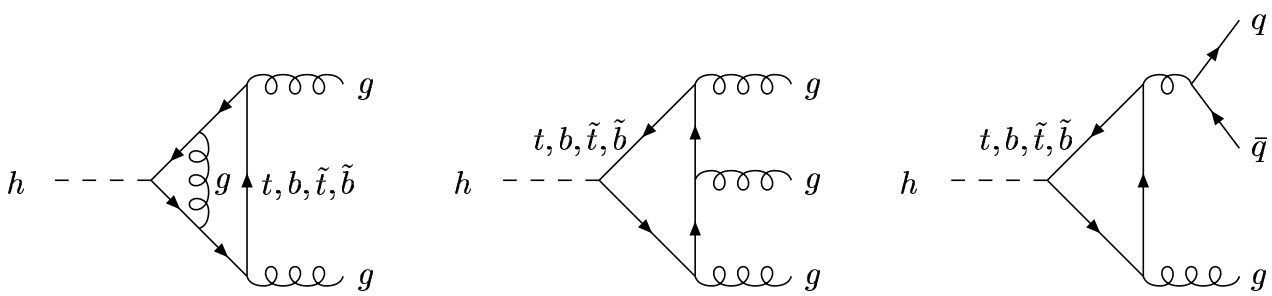
Frink, Kniehl, Kreimer, Riesselmann



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

large QCD corrections: $\sim +90\%$

Inami, Kubota, Okada
S., Djouadi, Graudenz, Zerwas



3/4-loop corrections ($M_H \ll 4m_t$): $\mathcal{O}(20\%) \Rightarrow$ perturbatively stable

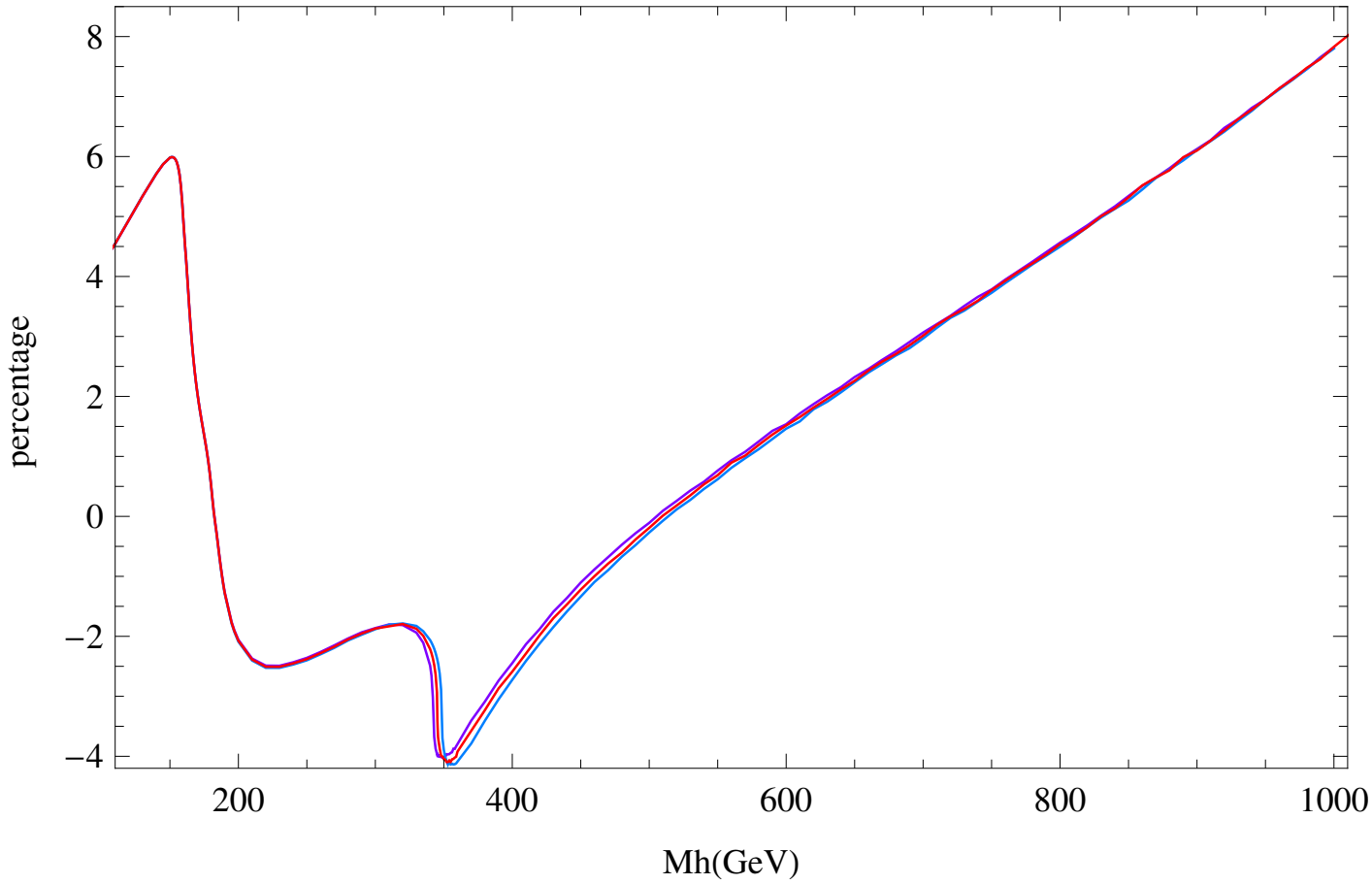
Chetyrkin, Kniehl, Steinhauser
Baikov, Chetyrkin

small elw. corrections: $\mathcal{O}(5\%)$ F

Aglietti, Bonciani, Degrassi, Vicini
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati

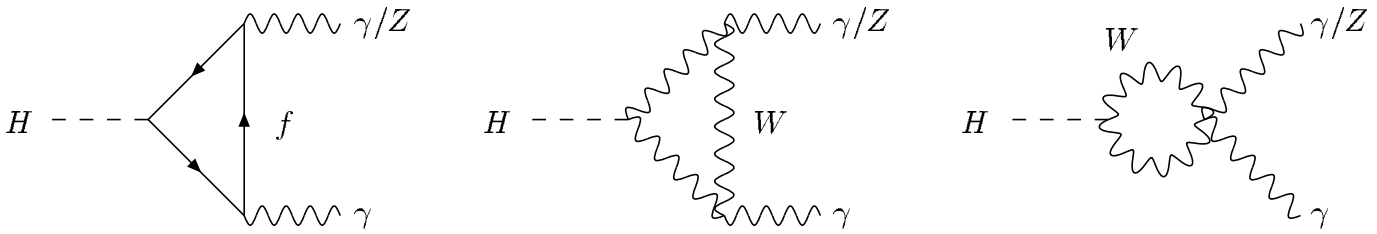
- HDECAY: 4-loop QCD corrections + NLO elw. corrections

$H \to gg$



Actis, Passarino, Sturm, Uccirati

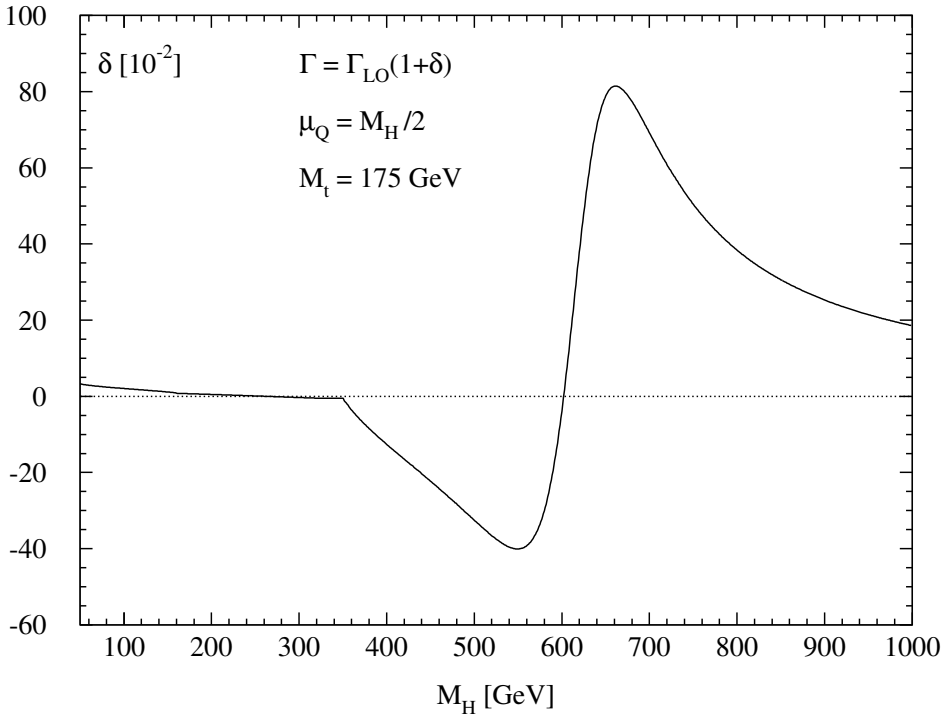
NLO elw.: full mass dependence → HDECAY



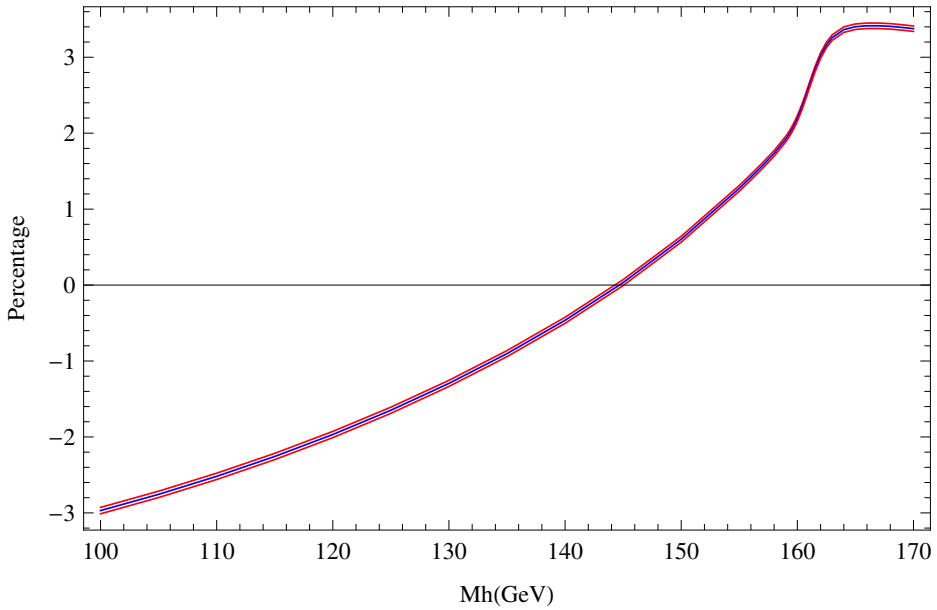
$$BR(H \to \gamma\gamma, Z\gamma) \lesssim 2 \times 10^{-3}$$

- W–loop dominant
- QCD corrections: $\lesssim$ 3% in intermediate mass range — F Zheng, Wu; Djouadi, S., Zerwas; Melnikov, Yakovlev; Inoue,. . .
- elw. corr.: $\lesssim \mathcal{O}(10\%)$ [large for $M_H \sim 600 - 700$ GeV] — F Aglietti, Bonciani, Degrassi, Vicini; Degrassi, Maltoni; Actis, Passarino, Sturm, Uccirati
- $H \to \gamma\gamma$ extremely important decay channel @ LHC
- HDECAY: NLO QCD + elw. corrections

$H \to \gamma\gamma$



S., Djoaudi, Zerwas



Actis, Passarino, Sturm, Uccirati

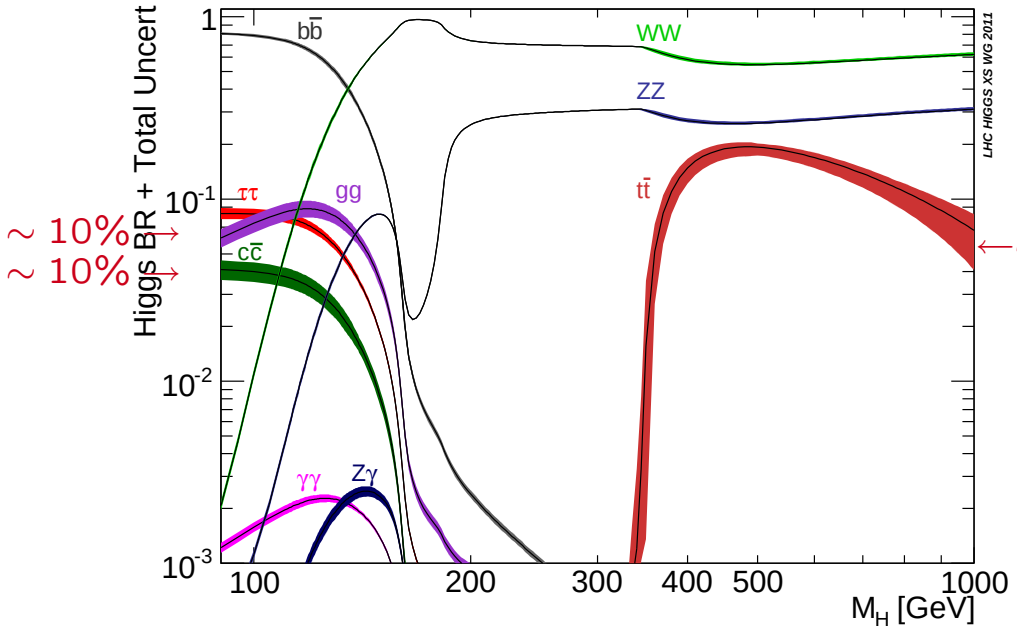
NLO QCD + elw.: full mass dependence → HDECAY

Partial Width	QCD	Electroweak	Total	
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	$\sim$ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NNNNLO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim$ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NLO
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim$ 2–5% for $M_H < 500$GeV	$\sim 5\%$	(NNN)NLO / LO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	$\sim$ 5–10%	
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$GeV	$\sim 0.5\%$	(N)NLO
		$\sim 0.17(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	$\sim$ 0.5–15%	

- QCD: variation of Higgs widths for scale by factor 2 and 1/2
  elw: missing HO estimated from known structure at NLO
  $M_H \gtrsim 500$ GeV: Higgs self-interactions dominate error
  different uncertainties added linearly for each channel

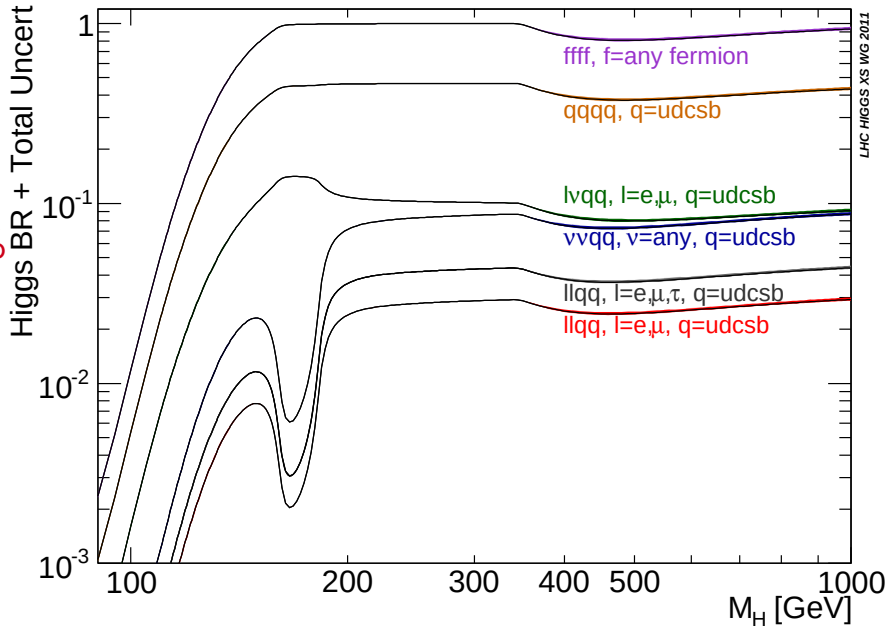
- parametric uncertainties:
  $m_t = 172.5 \pm 2.5$ GeV $\qquad \alpha_s(M_Z) = 0.119 \pm 0.002$
  $m_b(m_b) = 4.16 \pm 0.06$ GeV $\qquad m_c(m_c) = 1.28 \pm 0.03$ GeV
  different uncertainties added quadratically for each channel

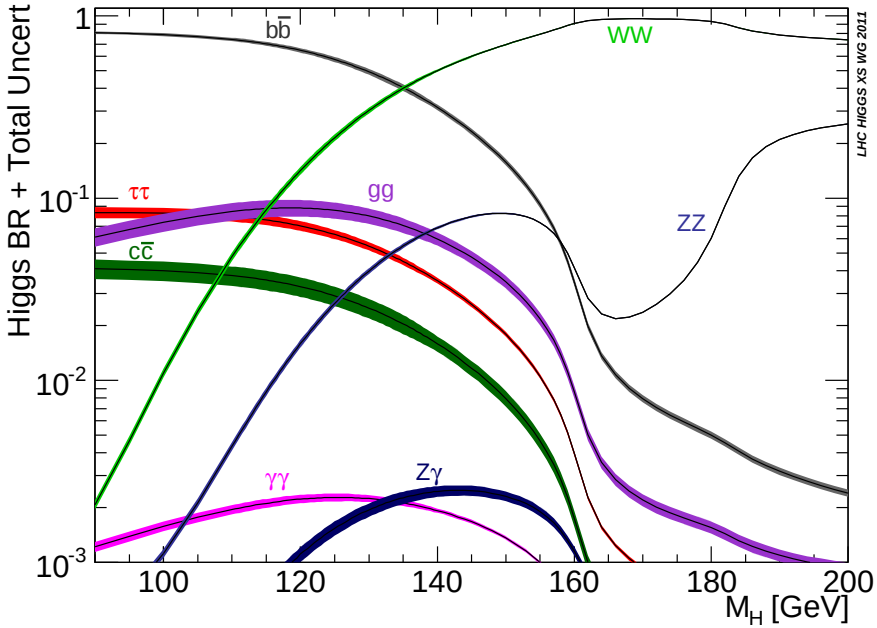
- total uncertainties: parametric & theor. uncertainties added linearly

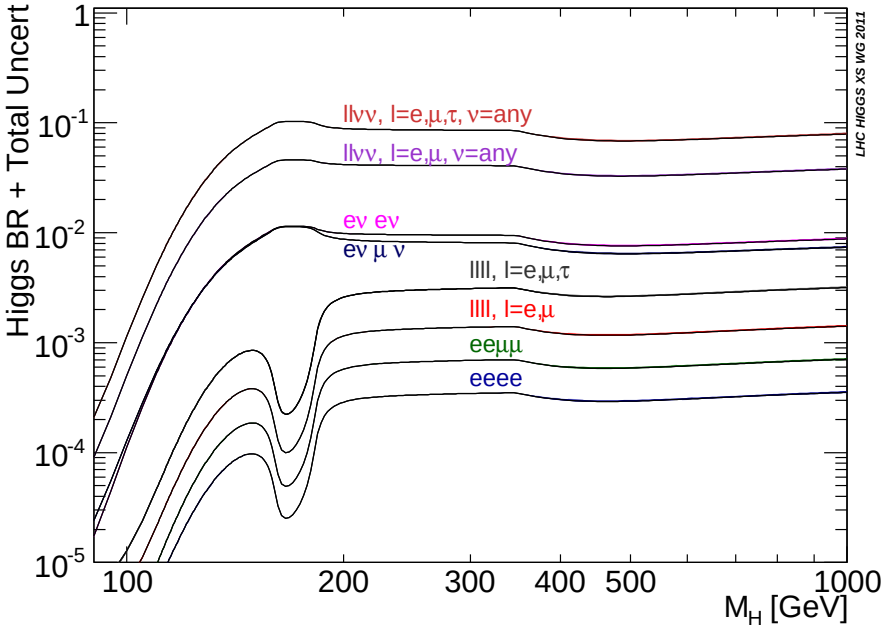


~ 10%
~ 10%

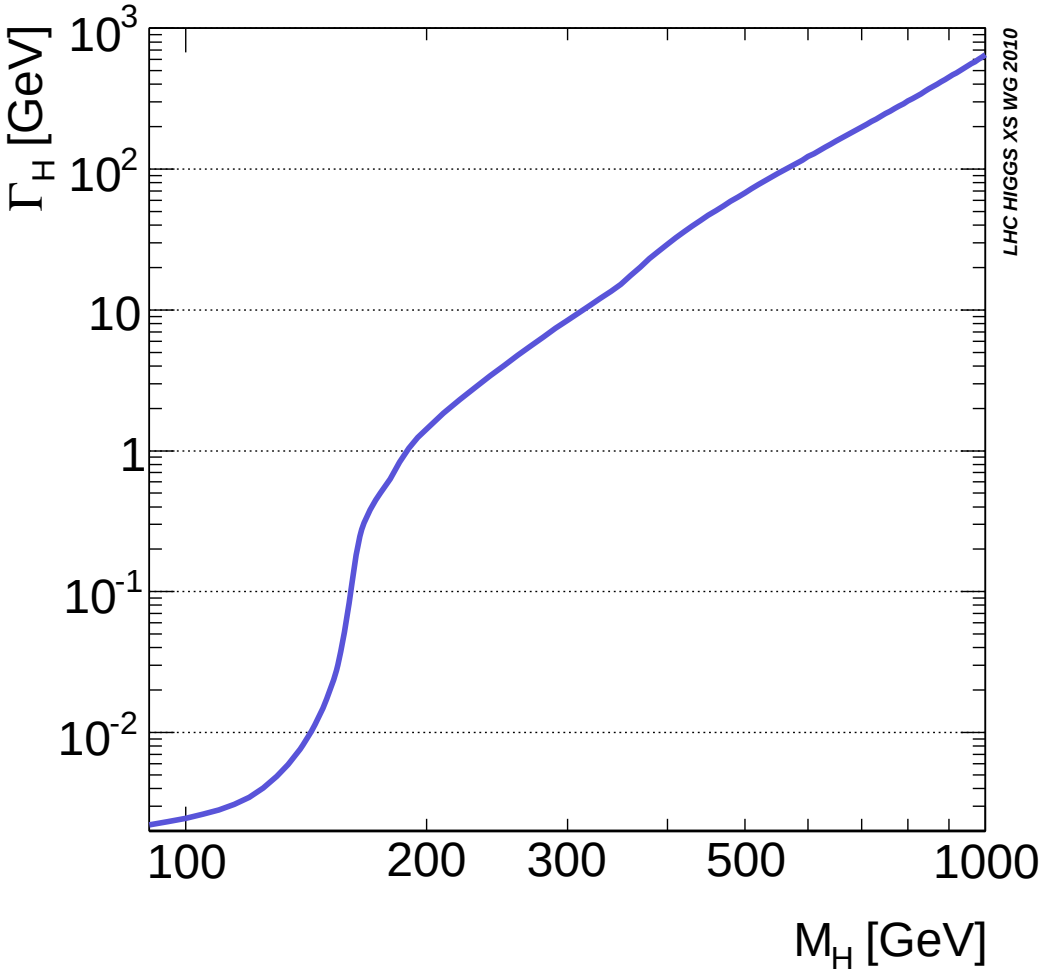
~ 30%







Denner, Heinemeyer, Puljak, Rebuzzi, S.



Denner, Heinemeyer,
Puljak, Rebuzzi, S.

SM4

- left-handed isodublets/right-handed isosinglets added
- vacuum stability: $m_{f'} \lesssim 500 \ldots 600$ GeV
- escape elw. precision constraints:

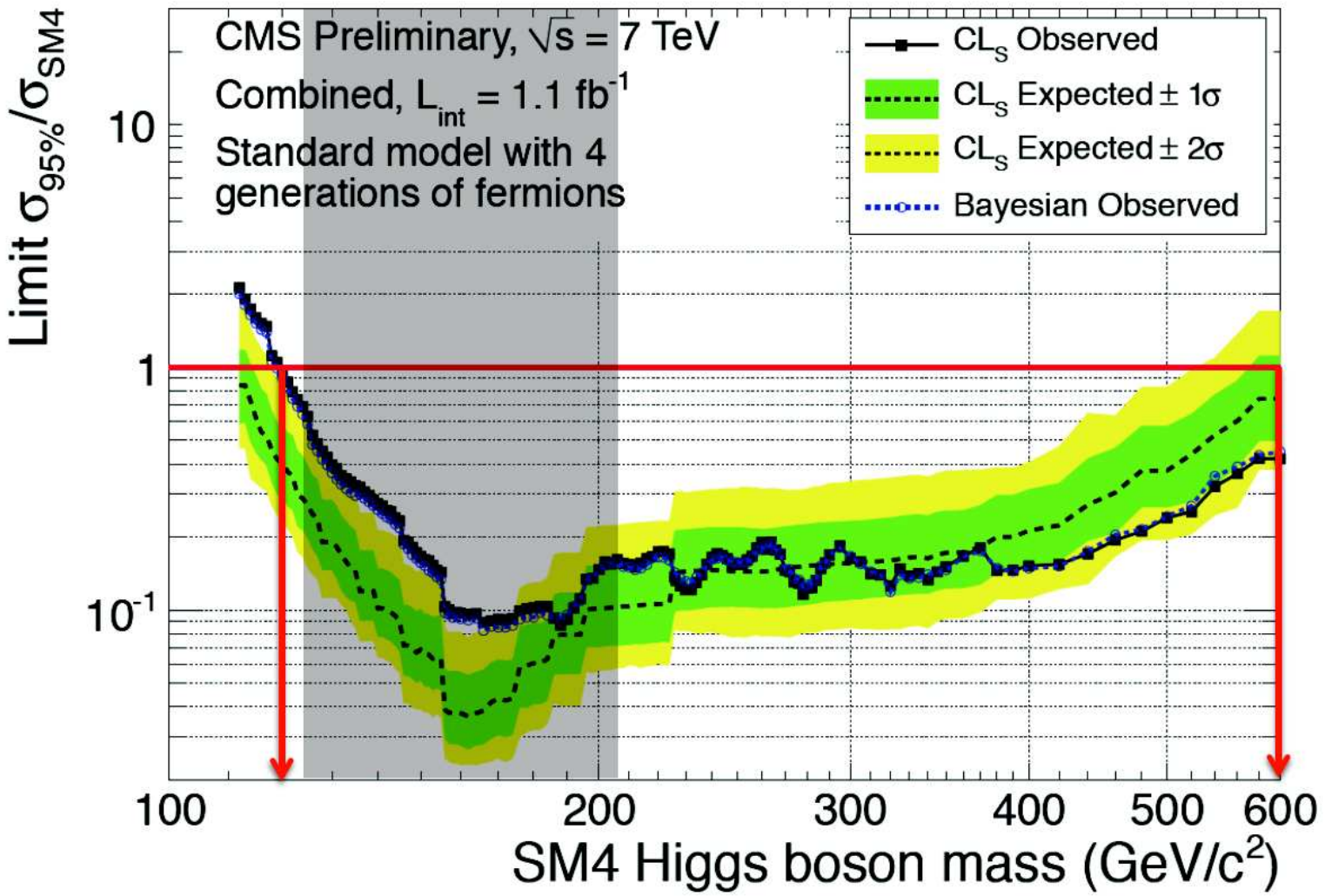
scenario A

$$\begin{aligned} m_{b'} &= m_{\ell'} = 450 \text{ GeV} \\ m_{t'} &= 500 \text{ GeV} \\ m_{\nu'} &= 375 \text{ GeV} \end{aligned}$$

scenario B

$$\begin{aligned} m_{b'} &= m_{\ell'} = m_{\nu'} = 600 \text{ GeV} \\ m_{t'} &= m_{b'} + \left[1 + \frac{1}{5} \log\left(\frac{M_H}{115 \text{ GeV}}\right)\right] 50 \text{ GeV} \end{aligned}$$

- neglect mixing with first 3 generations



- 120 GeV $< M_H <$ 600 GeV excluded ?

- $H \to WW/ZZ \to 4f$: Prophecy4f — Denner, Dittmaier, Mück, Weber

  NLO elw.: −60% . . . −85% !!! [$\delta_{elw} \approx N_c X_A \left(\frac{-5}{3}(1+x) + \frac{2x}{1-x}\log x\right)$ $x = m_B^2/m_A^2$ $X_A = \frac{G_F m_A^2}{8\sqrt{2}\pi^2}$]

  NNLO elw.+QCD: +5% . . . +15% — Djouadi, Gambino, Kniehl

  uncertainty $\sim 20 - 50\%$

  HDECAY: approx. NLO elw.

- $H \to f\bar{f}$:

  (NNN)NLO QCD: +20% (quarks) as usual

  NLO elw.: +20% . . . +40% !!! [$\delta_{elw} \approx N_c X_A \left(\frac{7}{3}(1+x) + \frac{2x}{1-x}\log x\right)$]

  NNLO elw.+QCD: +5% . . . +20% — Djouadi, Gambino, Kniehl

  uncertainty $\sim 5 - 10\%$

  HDECAY: approx. NLO elw.

- $H \to gg$:

  NNNLO QCD: +90% (mismatch @ NNLO) — Anastasiou, Boughezal, Furlan

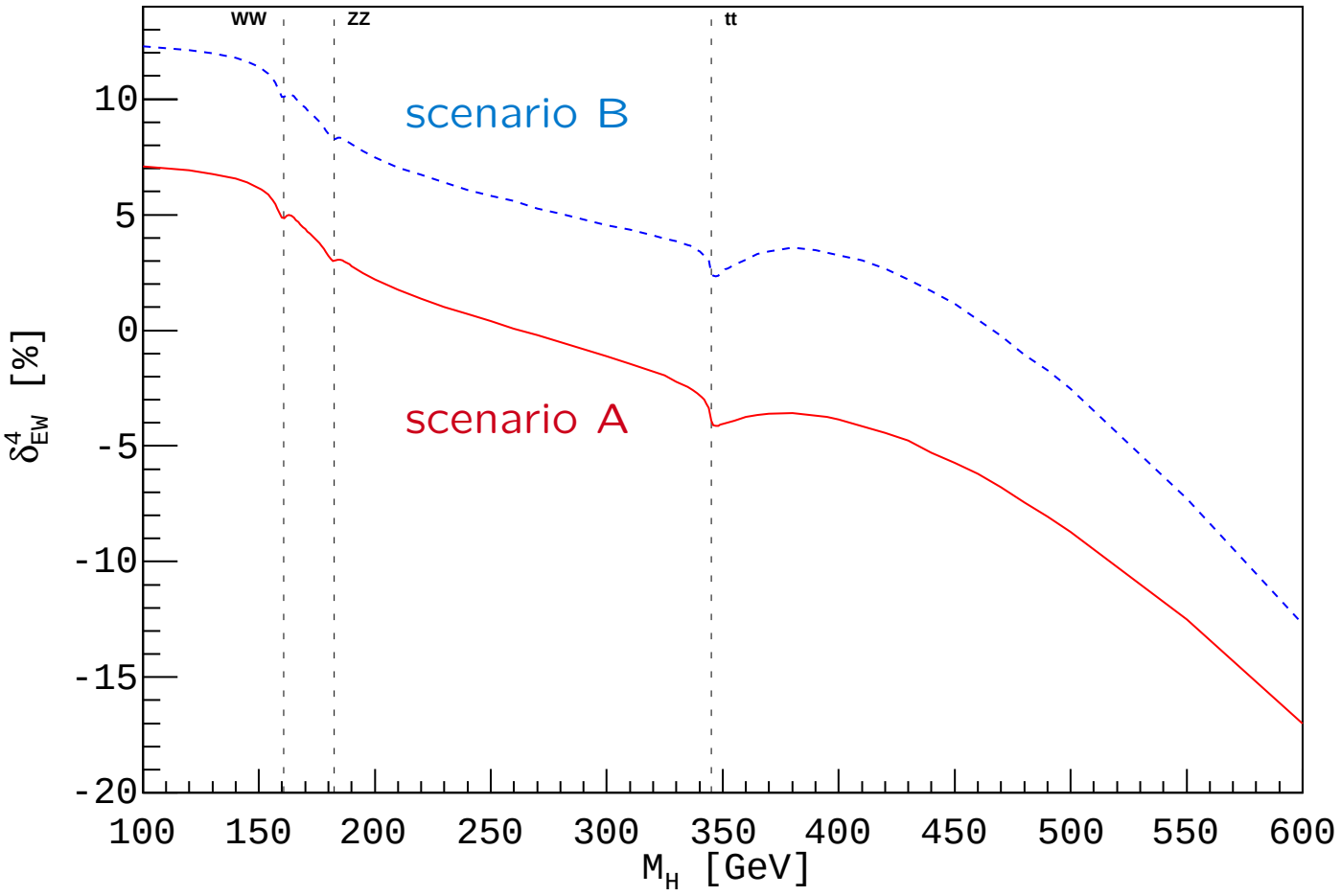
  NLO elw.: +10% . . . −60% [num. int.] — Passarino, Sturm, Uccirati

  uncertainty $\sim 2\%$

  HDECAY: approx. NNNLO QCD + NLO elw. [grids]

- large novel Yukawa couplings → perturbative???

$H \longrightarrow gg$



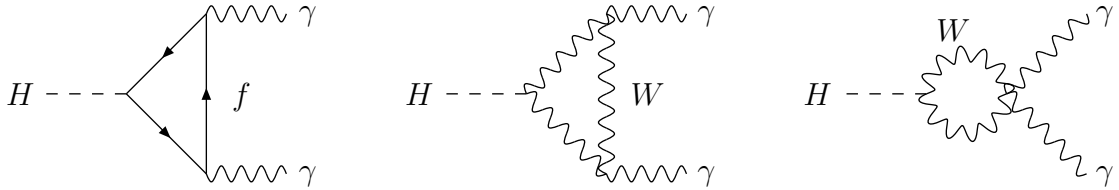
Passarino, Sturm, Uccirati

- $\underline{H \to \gamma\gamma}$: Passarino, Sturm, Uccirati

  NLO elw.: −320% @ $M_H = 100$ GeV !!!

  large cancellations between W, f-loops at LO $\to$ square amplitude

  $\Rightarrow$ NLO elw.: −65% @ $M_H = 100$ GeV



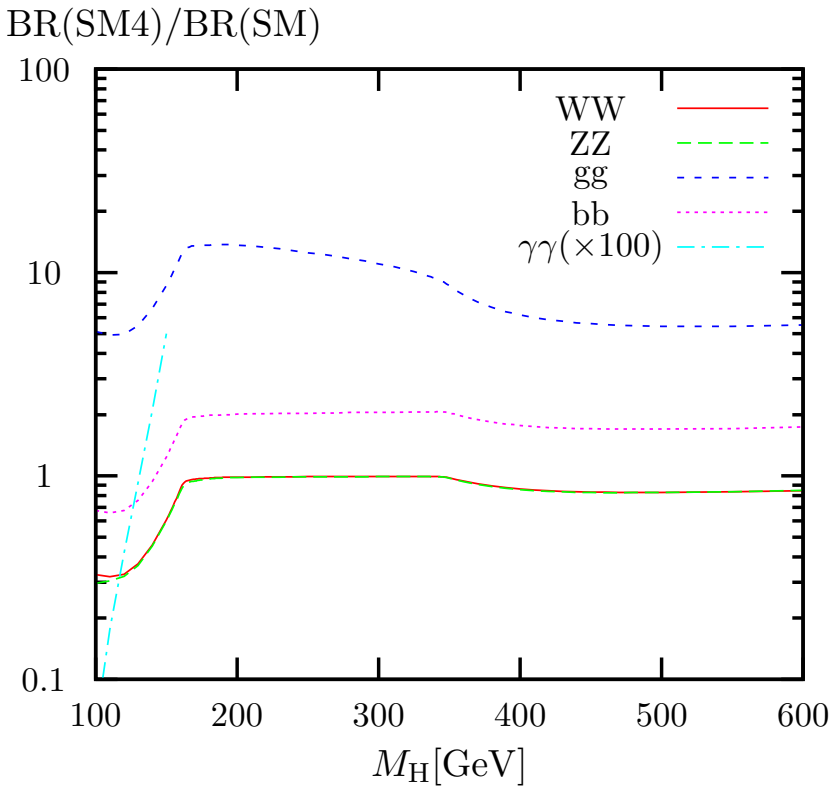
M_H [GeV]	A: δ [%]	δ_{THU} [%]	B: δ [%]	δ_{THU} [%]
100	−99.4	68.3	−64.5	25.4
110	−98.2	37.1	−74.4	28.2
120	−96.3	23.8	−83.3	32.5
130	−93.4	16.4	−90.8	40.4
140	−89.2	11.6	−96.6	59.7
150	−83.1	8.3	−99.7	> 100

approach breaks down for $M_H \gtrsim 150$ GeV
$\Leftarrow$ reliable predictions ???

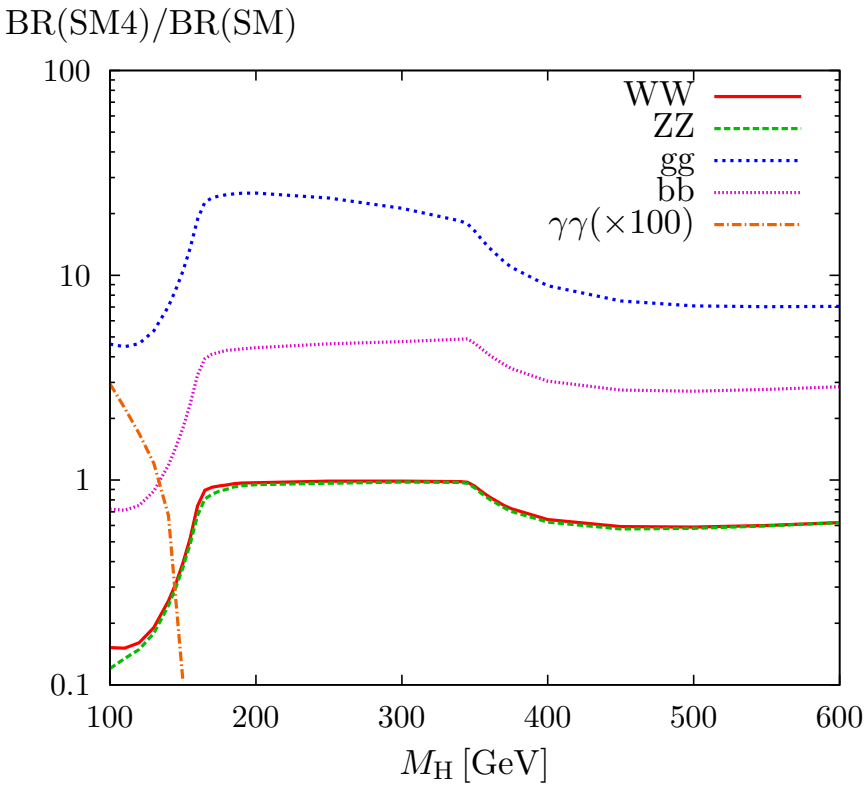
HDECAY: NLO QCD + approx. NLO elw.

- ratio of SM4/SM3 BRs

scenario A



scenario B



Prophecy4f, HDECAY

III *SUMMARY*

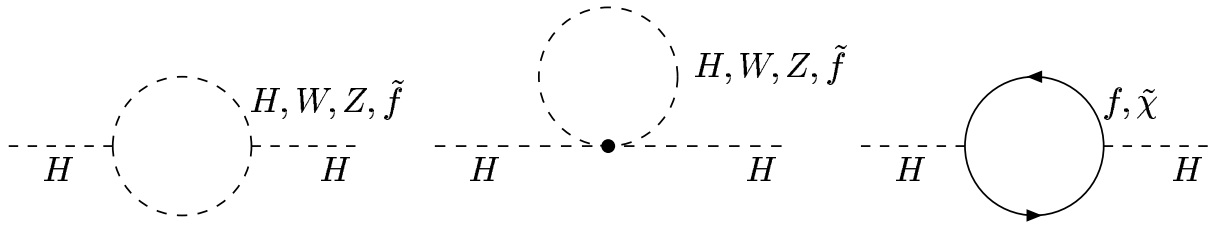
Standard Model

- decay widths and BRs known with sufficient accuracy
- sizeable corrections from QCD and Higgs self-interactions [large M_H]
- consistency/perturbativity for $M_H \gtrsim 600 - 700$ GeV?
- SM4: large Yukawas $\rightarrow$ perturbative reliability?

BACKUP SLIDES

MSSM

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



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

- 2 Higgs doubletts $\overset{\text{ESB}}{\rightarrow}$ 5 Higgs bosons: $h, H, A, H^{\pm}$

- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$

$$\rightarrow \boxed{M_h \lesssim 140 \text{ GeV}}$$

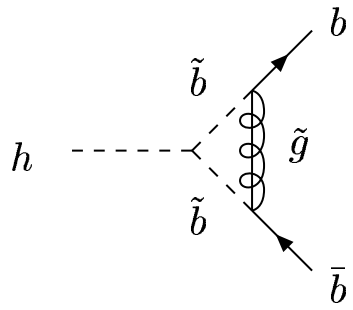
Haber
Carena,. . .
Heinemeyer,. . .
Zhang
etc.

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

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

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

- large SUSY–QCD corrections to $\phi^0 \to b\bar{b}$ ($\Delta\Gamma/\Gamma \sim 10\%$) F

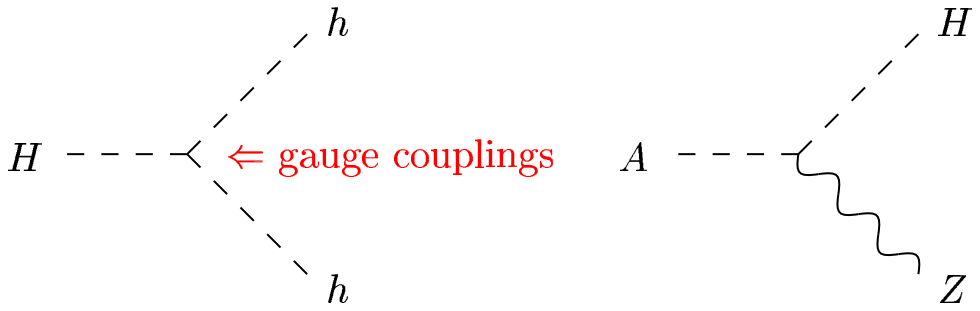


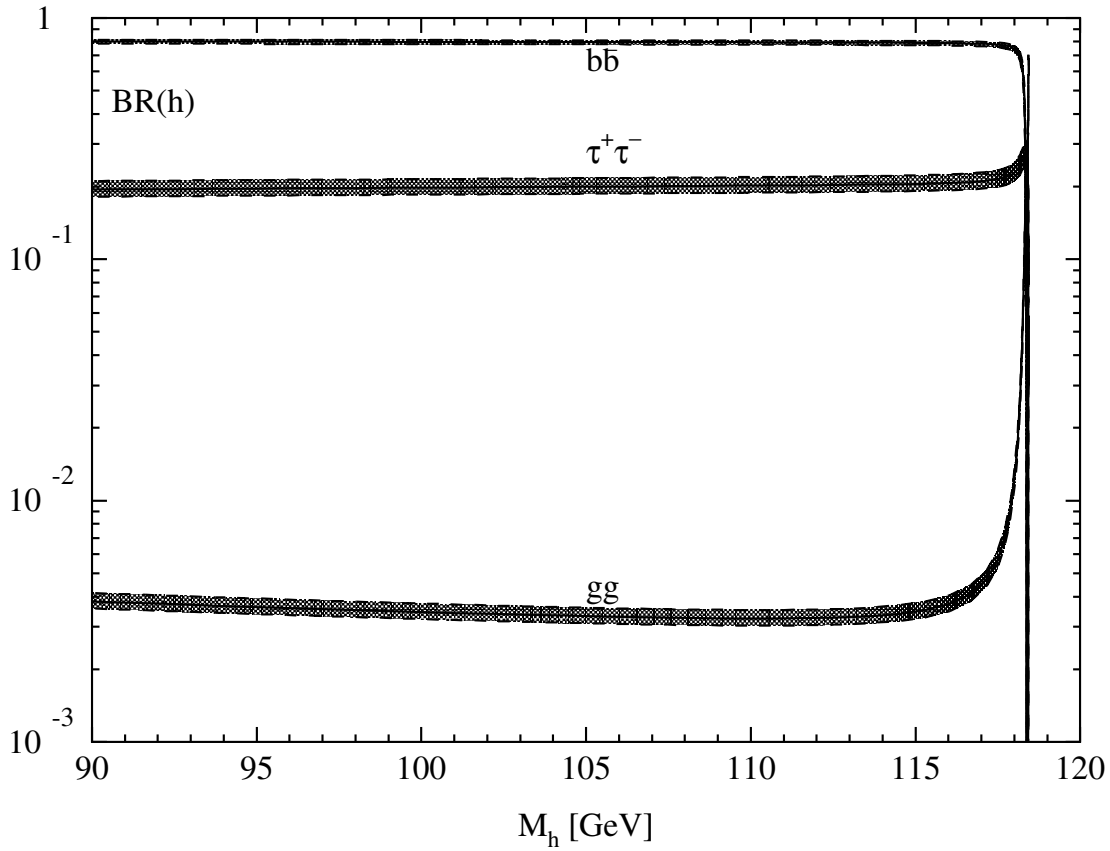
$+ \cdots \qquad \propto \frac{\alpha_s}{\pi} \frac{m_{\tilde{g}} \mu \mathrm{tg}\beta}{m^2_{\tilde{b}}}$

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

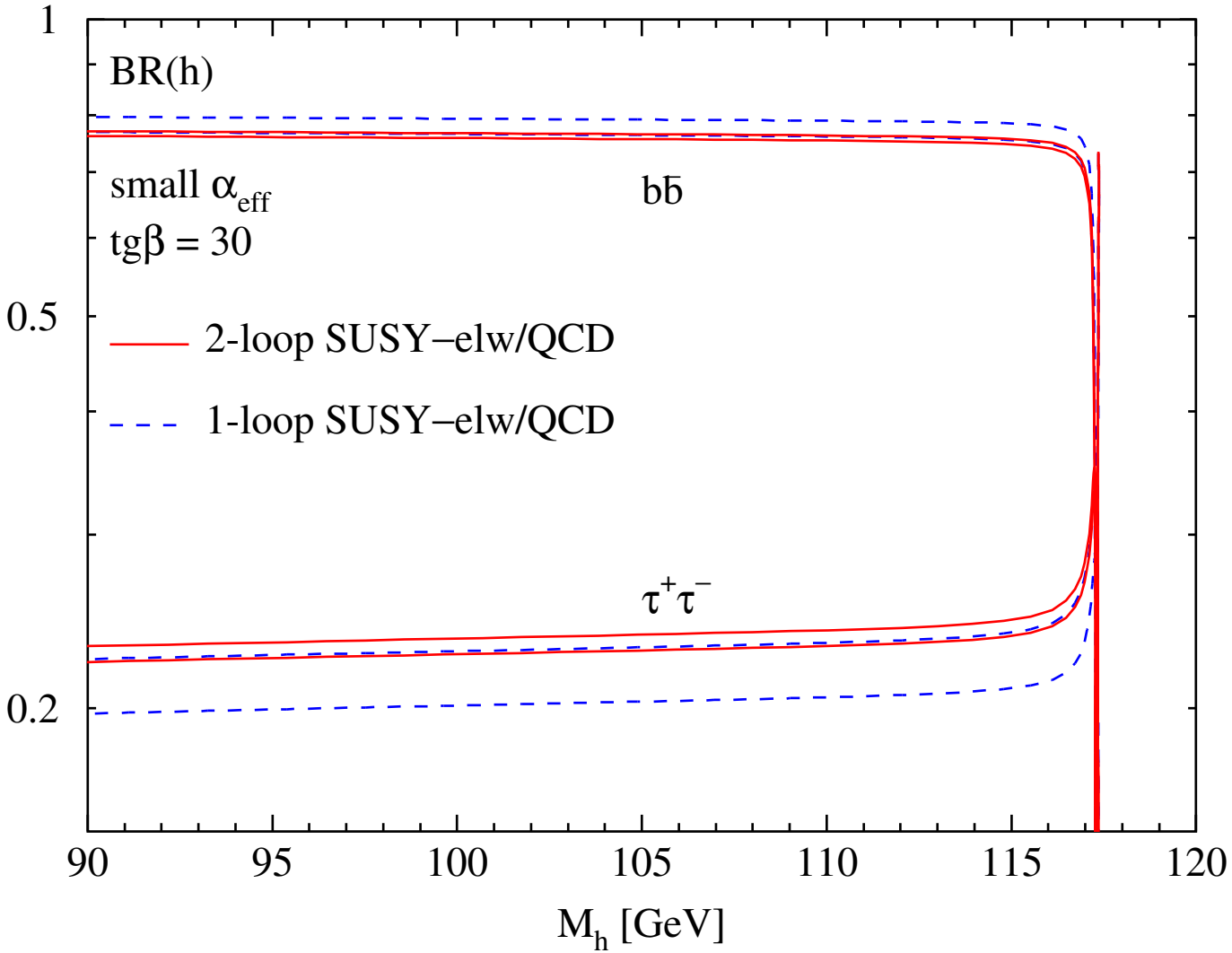
- $\phi^0 \to gg, \gamma\gamma, Z\gamma$: $\tilde{t}, \tilde{b}$ loops [HDECAY: QCD corrections]
  $\gamma\gamma, Z\gamma$: $H^\pm, \tilde{\chi}$ loops

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

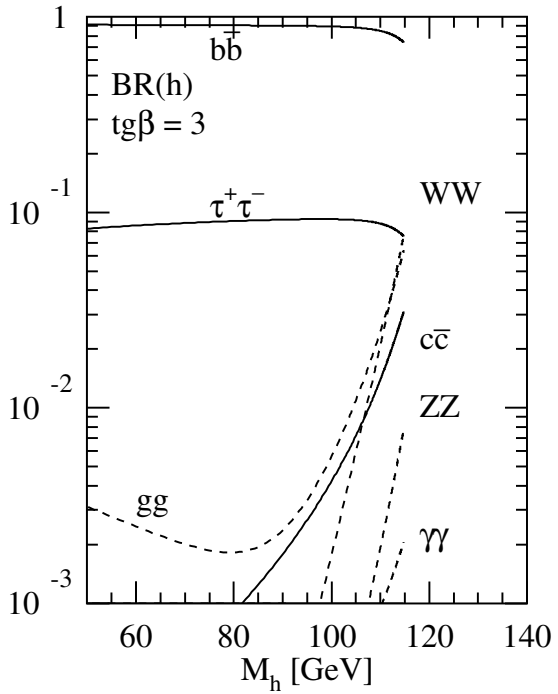


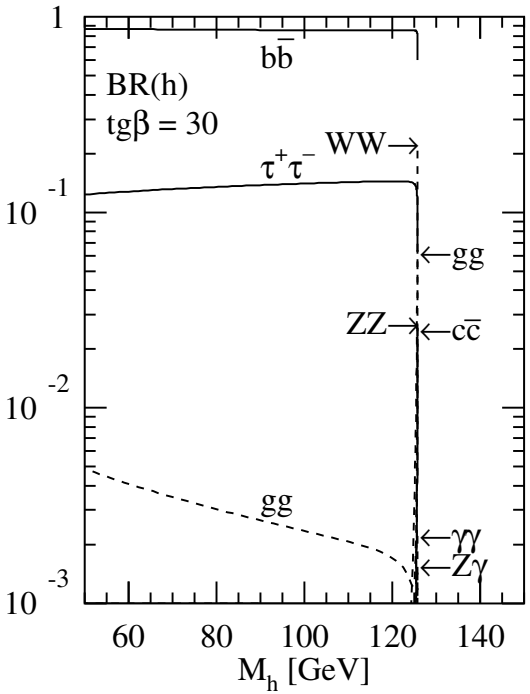


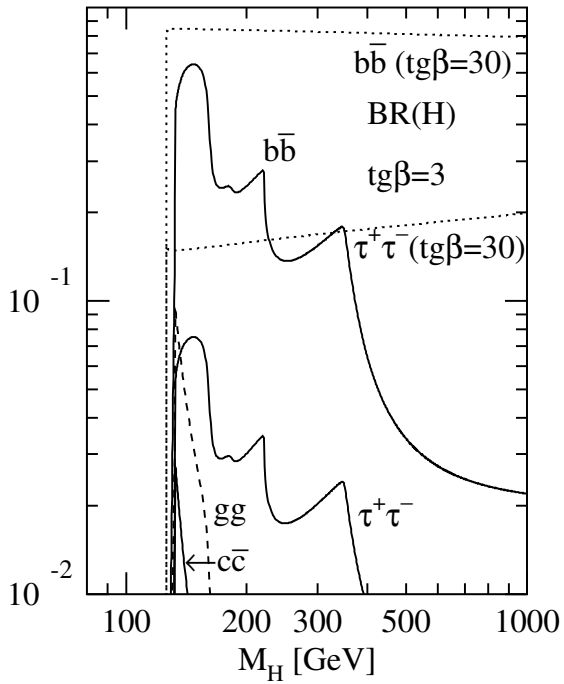
Guasch, Häfliger, S.

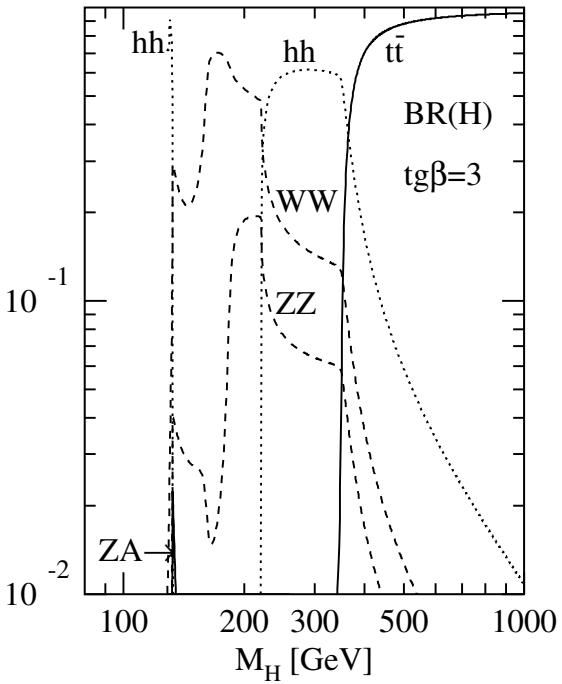


Noth, S. → HDECAY

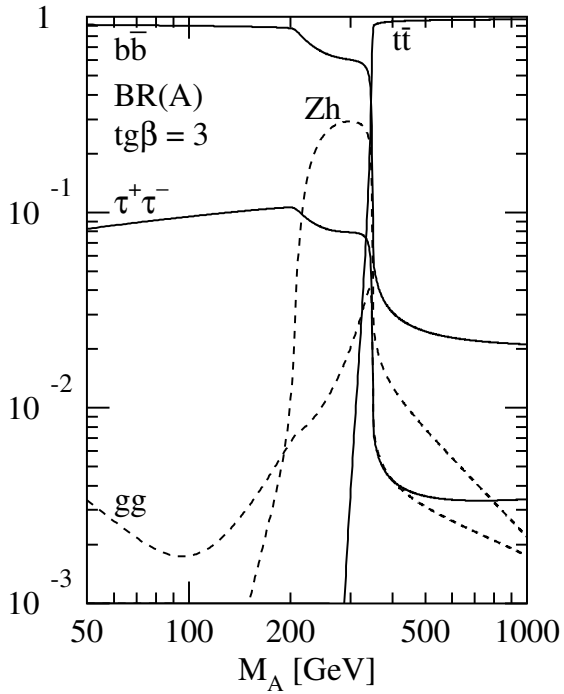

1
10 -1
10 -2
10 -3
bb
BR(h)
tgβ = 3
τ+τ−
WW
cc
ZZ
gg
γγ
60
80
100
120
140
M_h [GeV]

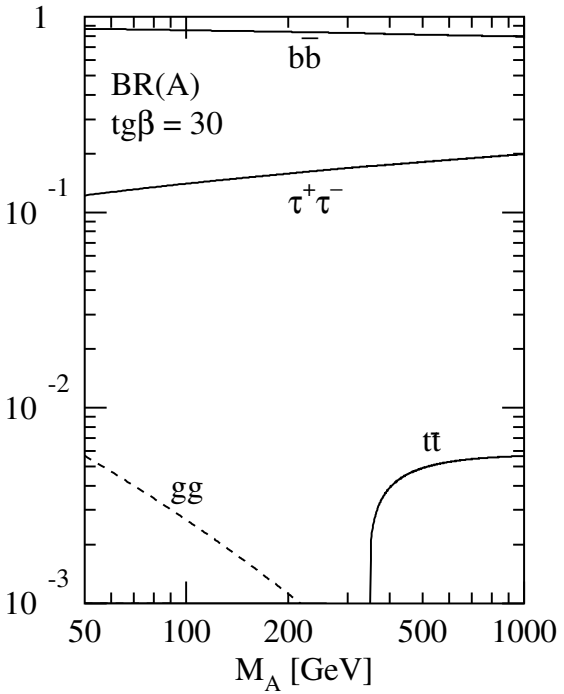

1
10 -1
10 -2
10 -3
bb
BR(h)
tgβ = 30
τ+τ−
WW
gg
ZZ
cc
gg
γγ
Zγ
60
80
100
120
140
M_h [GeV]

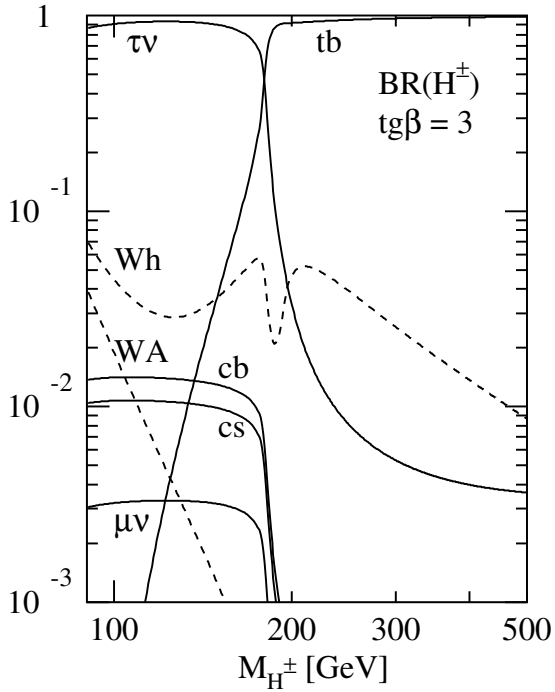

10 -1
10 -2
bb (tgβ=30)
BR(H)
bb
tgβ=3
τ+τ− (tgβ=30)
gg
τ+τ−
cc
100
200
300
500
1000
M_H [GeV]

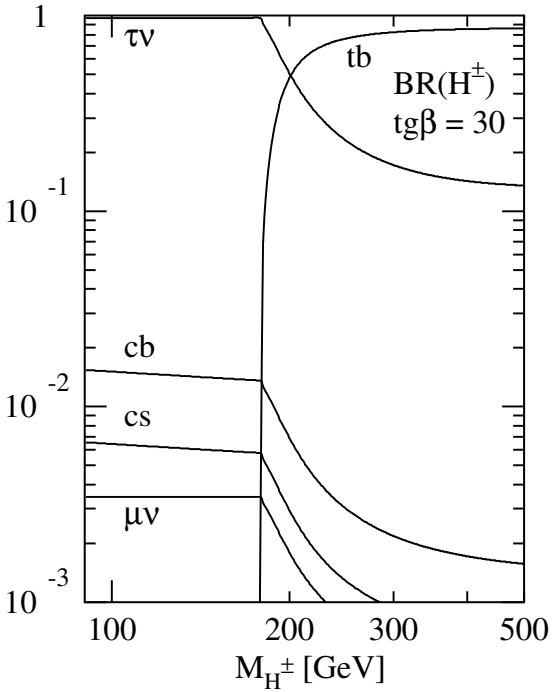

10 -1
10 -2
hh
hh
tt
BR(H)
tgβ=3
WW
ZZ
ZA
100
200
300
500
1000
M_H [GeV]

HDECAY

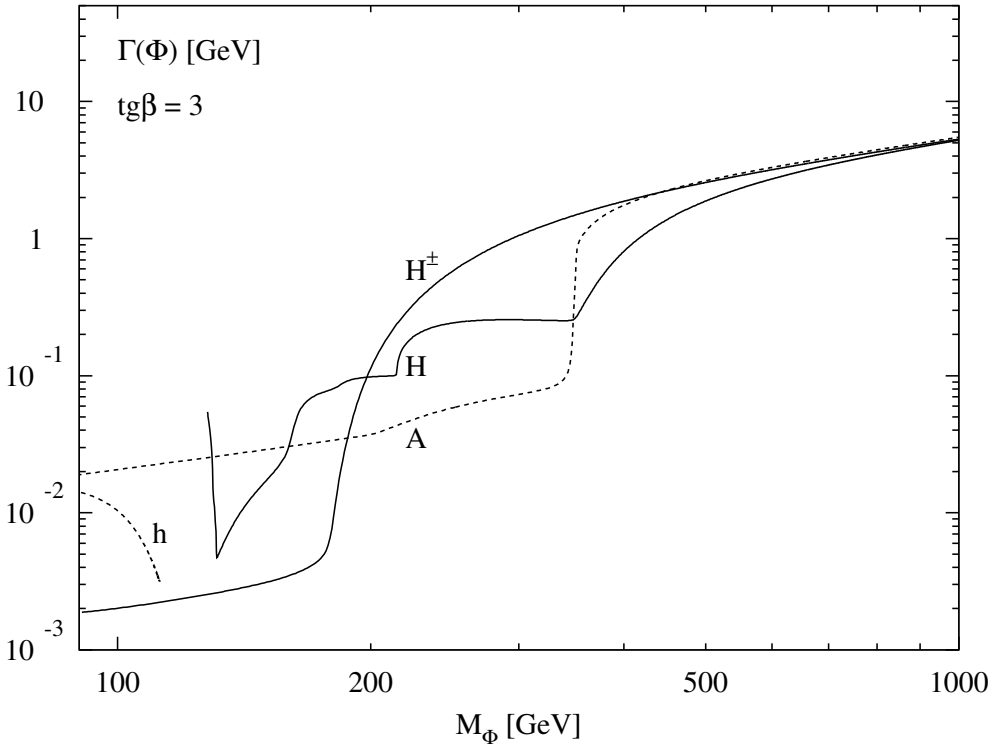

bb̄
tt̄
BR(A)
tgβ = 3
Zh
τ+τ−
gg
1
10 -1
10 -2
10 -3
50
100
200
500
1000
MA [GeV]

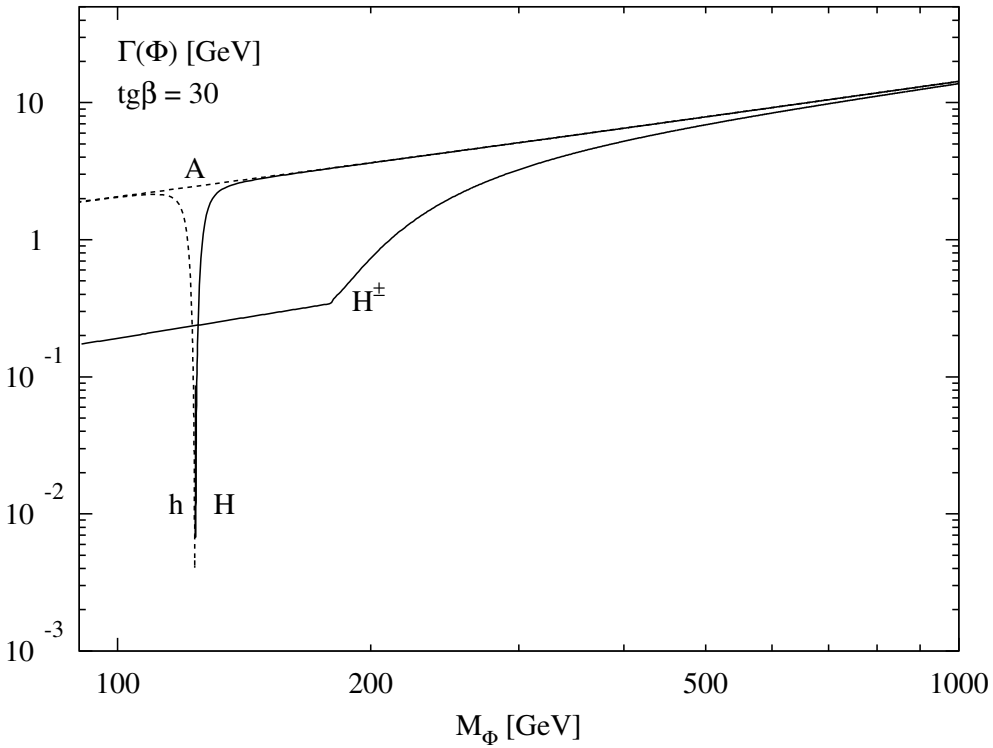

bb̄
BR(A)
tgβ = 30
τ+τ−
tt̄
gg
1
10 -1
10 -2
10 -3
50
100
200
500
1000
MA [GeV]


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


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

HDECAY

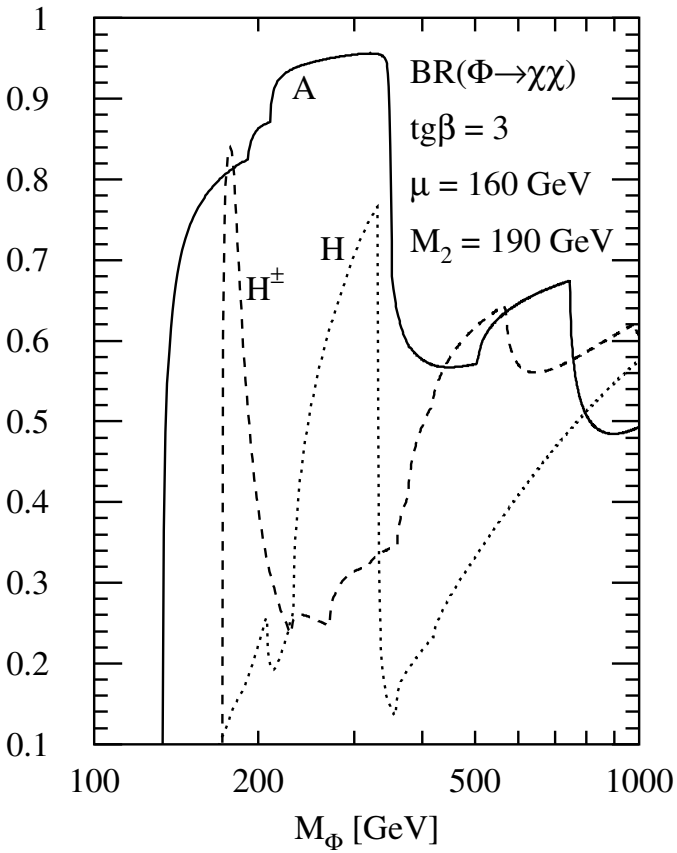

Γ(Φ) [GeV]
tgβ = 3
10
1
10^-1
10^-2
10^-3
H^±
H
A
h
100
200
500
1000
M_Φ [GeV]

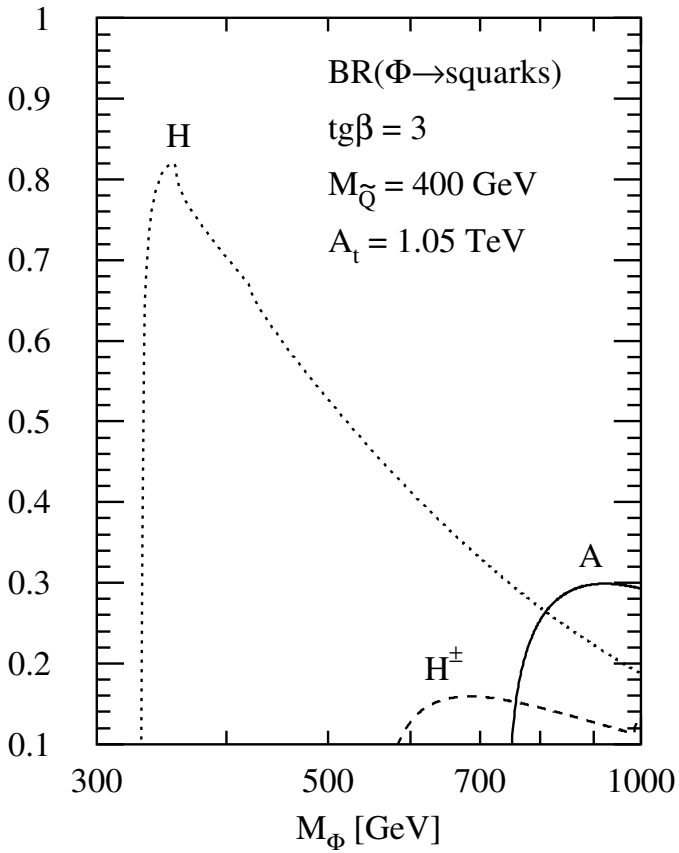

Γ(Φ) [GeV]
tgβ = 30
10
1
10^-1
10^-2
10^-3
A
H^±
h
H
100
200
500
1000
M_Φ [GeV]

HDECAY

SUSY Decays

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





HDECAY

- if kinematically possible → important ($\tilde{q}$: 3rd generation)
- SUSY–QCD corrections to $\phi \to \tilde{q}\bar{\tilde{q}}$ sizeable

$\Rightarrow$ resummation of Δ_b terms

Arhrib,...
Eberl,...
Accomando,...