HIGGS PHYSICS @ FUTURE COLLIDERS

Michael Spira (PSI)

I Introduction

II Higgs Boson Production @ LHC

III Higgs Boson Production @ ILC

IV Conclusions

I *INTRODUCTION*

(i) 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 $\quad [\Lambda \sim M_{GUT}]$

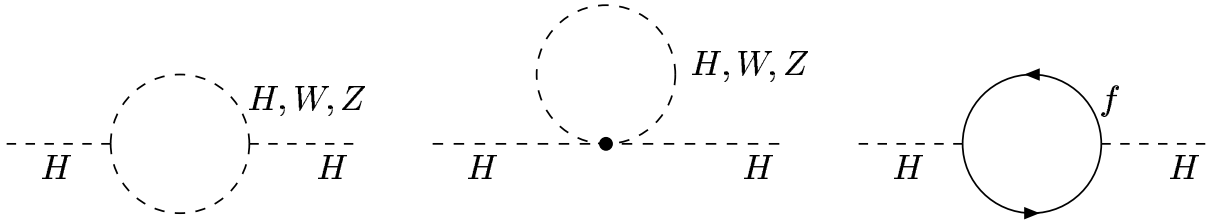
Sher
Lindner
Lüscher, Weisz
Hasenfratz,. . .
etc.

- electroweak fits: $M_H \lesssim 260$ GeV (95% CL)

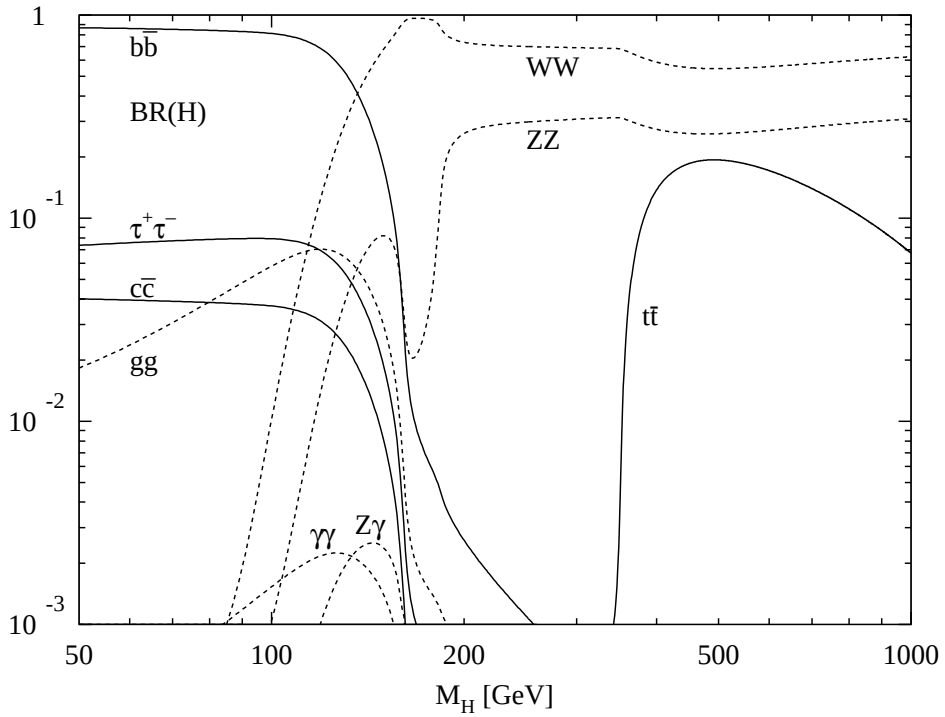
LEP/SLC

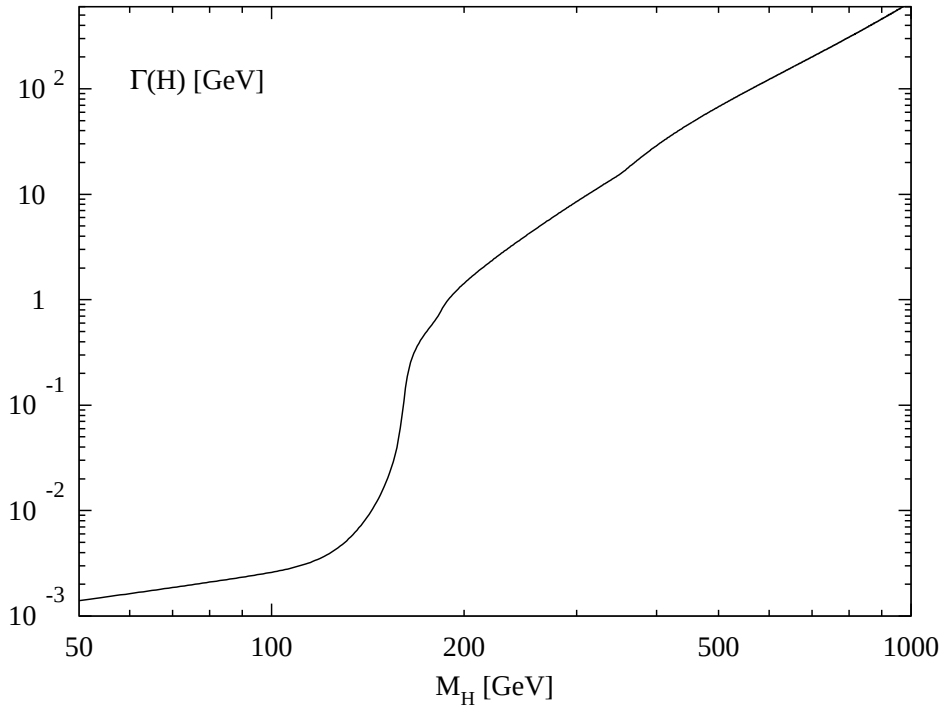
$\Rightarrow$ light Higgs boson

- GUT: hierarchy problem



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


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

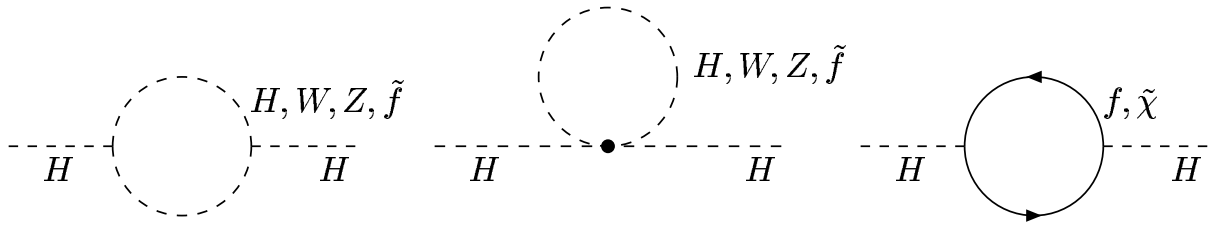

10 2
10
1
10 -1
10 -2
10 -3
Γ(H) [GeV]
50
100
200
500
1000
M_H [GeV]

HDECAY

(ii) MSSM

- SUSY: fermions $\leftrightarrow$ bosons

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



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

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

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

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

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

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

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

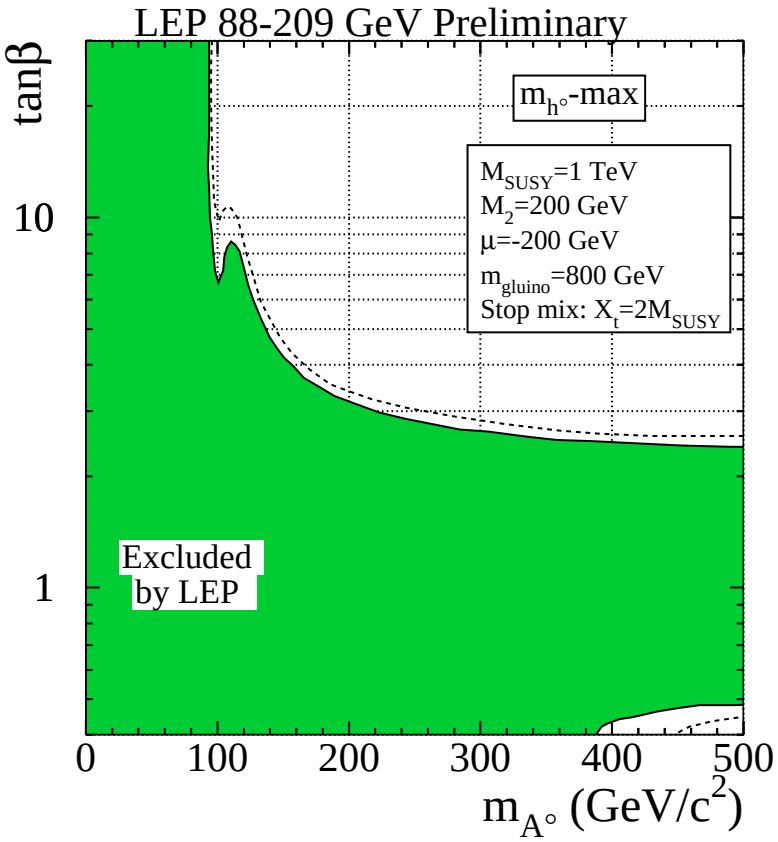
- mixing: $\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$

- modified couplings:

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	$\text{ctg}\beta$	$\text{tg}\beta$	0

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

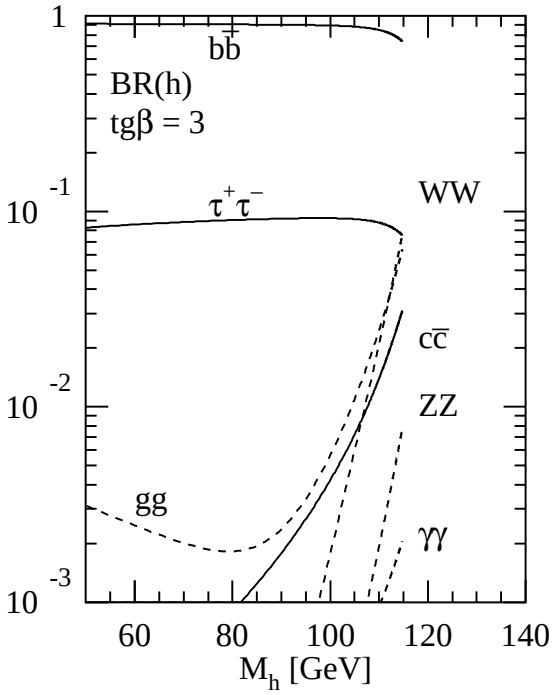
- direct search at LEP2: $e^+e^- \to Z + h/H, A + h/H, \nu_e\bar{\nu}_e + h/H$

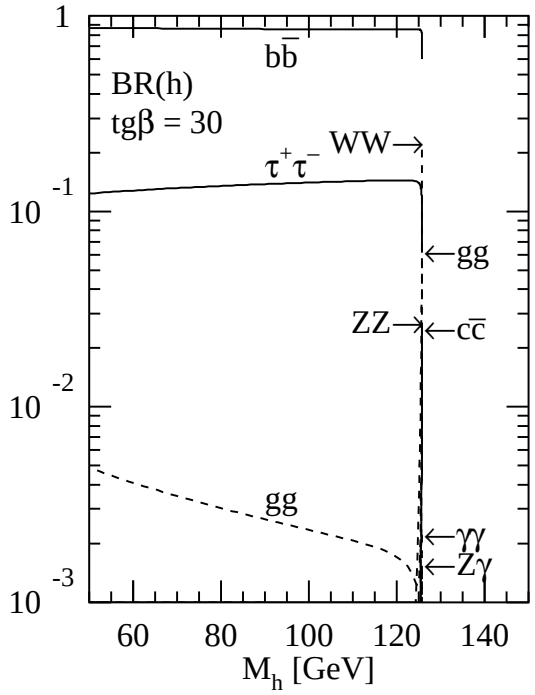


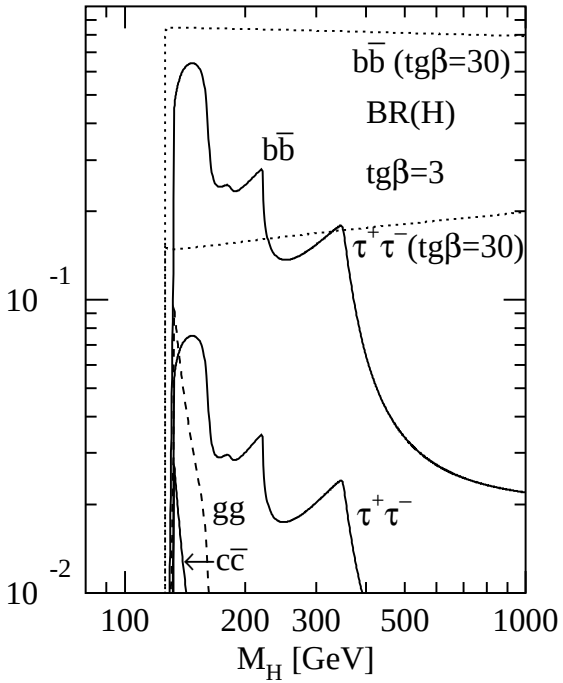
$M_{h/H} > 91$ GeV, $M_A \gtrsim 91.9$ GeV, $M_{H^\pm} > 78.6$ GeV

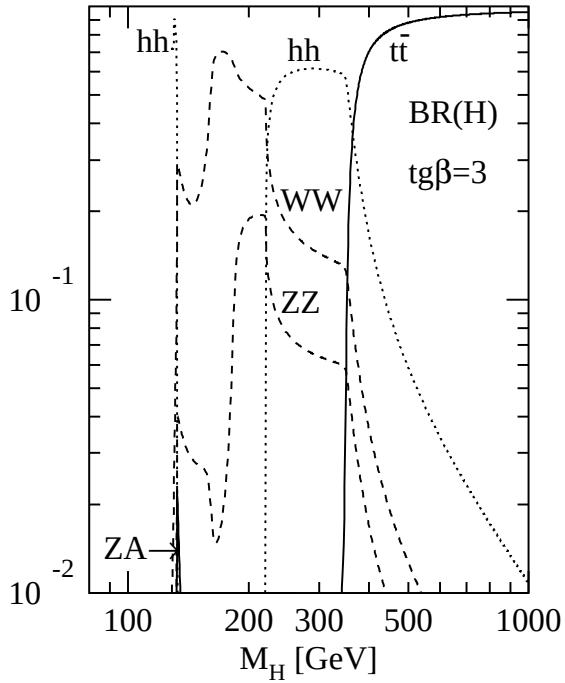
$0.5 < \mathrm{tg}\beta < 2.4$ excluded

[only for $m_t = 174.3$ GeV]

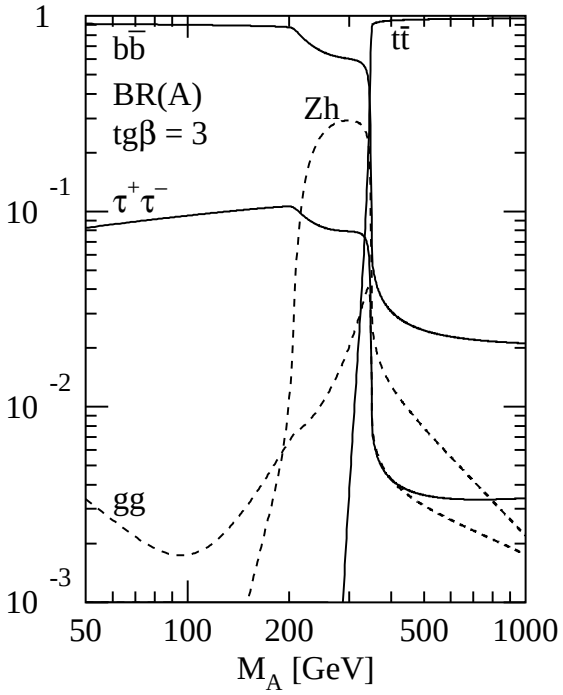

BR(h)
tgβ = 3
bb̄
τ⁺τ⁻
WW
cc̄
ZZ
gg
γγ
M_h [GeV]

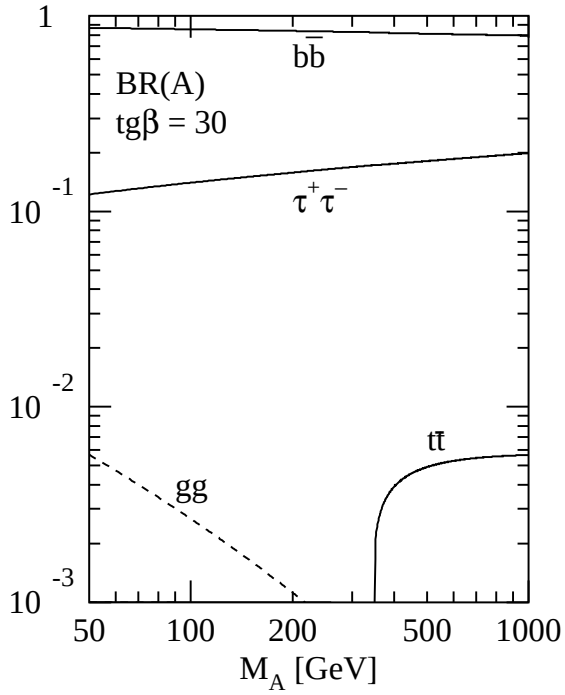

BR(h)
tgβ = 30
bb̄
τ⁺τ⁻
WW
gg
ZZ
cc̄
gg
γγ
Zγ
M_h [GeV]

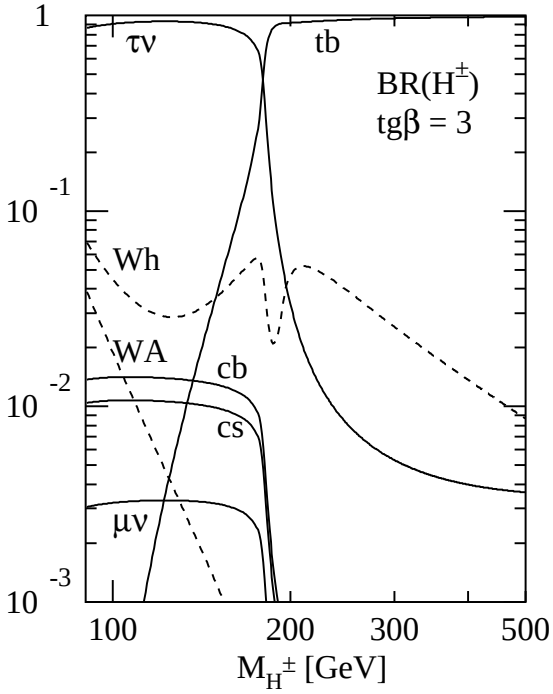

bb̄ (tgβ=30)
BR(H)
tgβ=3
bb̄
τ⁺τ⁻(tgβ=30)
gg
cc̄
τ⁺τ⁻
M_H [GeV]

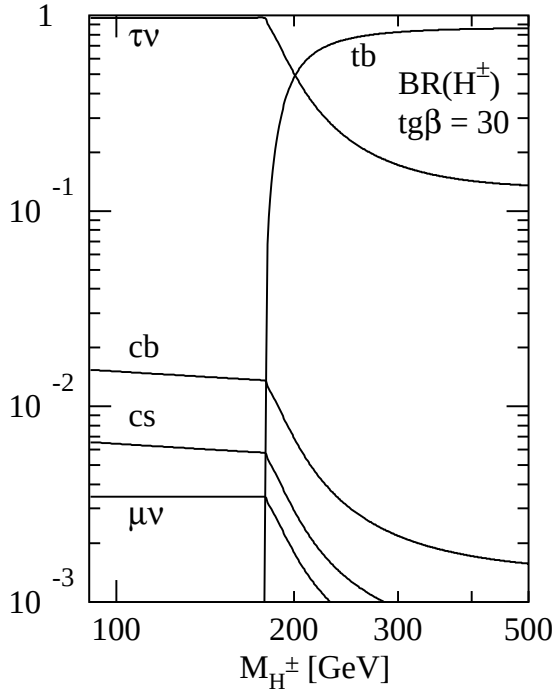

hh
hh
tt̄
BR(H)
tgβ=3
WW
ZZ
ZA
M_H [GeV]

HDECAY

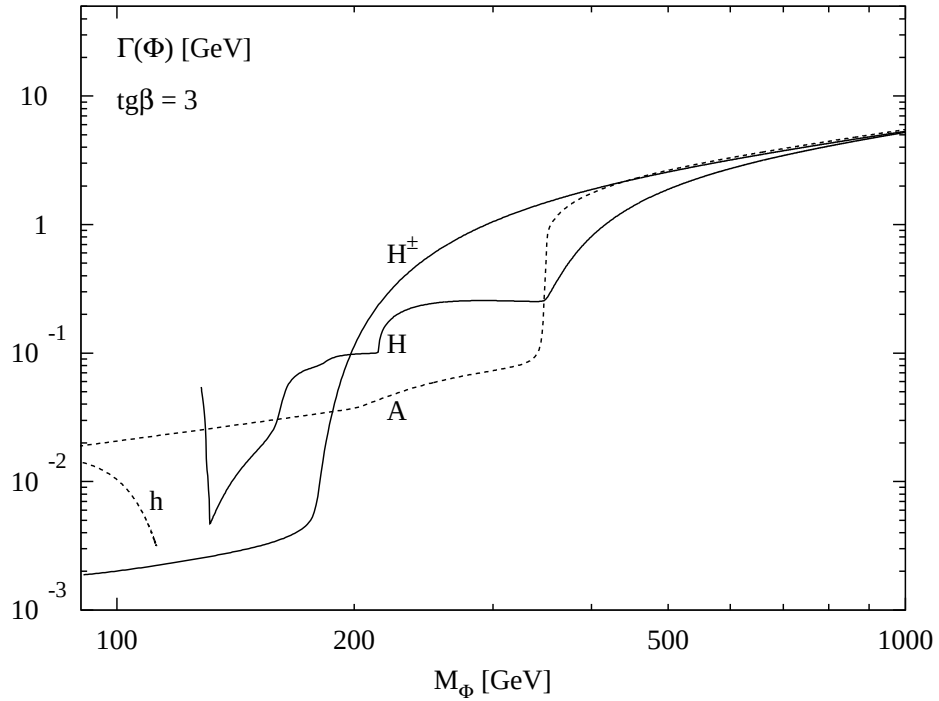

1
10^-1
10^-2
10^-3
bb̄
tt̄
BR(A)
tgβ = 3
Zh
τ⁺τ⁻
gg
50
100
200
500
1000
M_A [GeV]

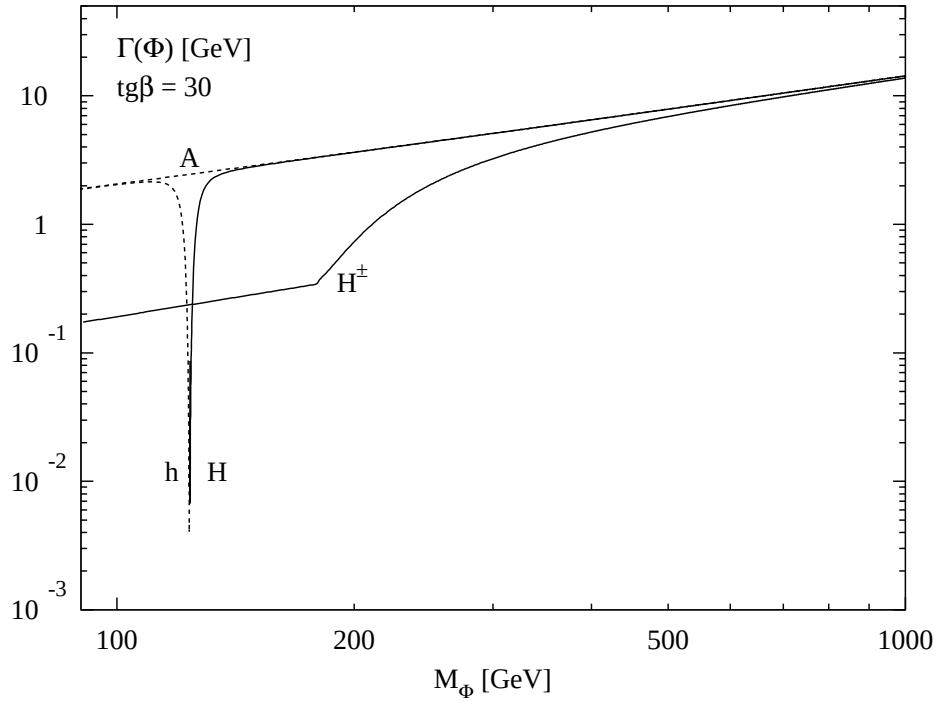

1
10^-1
10^-2
10^-3
bb̄
BR(A)
tgβ = 30
τ⁺τ⁻
tt̄
gg
50
100
200
500
1000
M_A [GeV]


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]

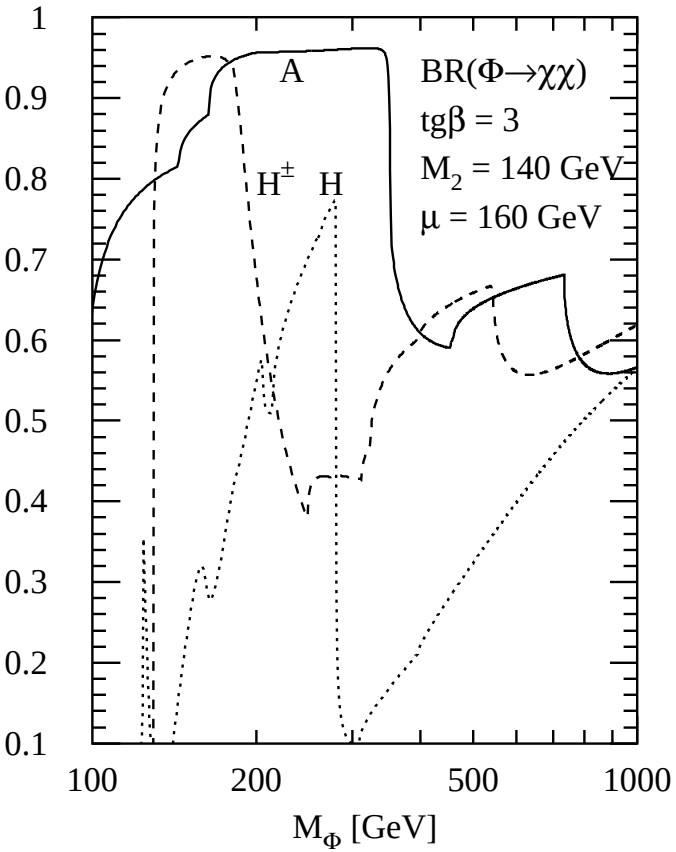
HDECAY

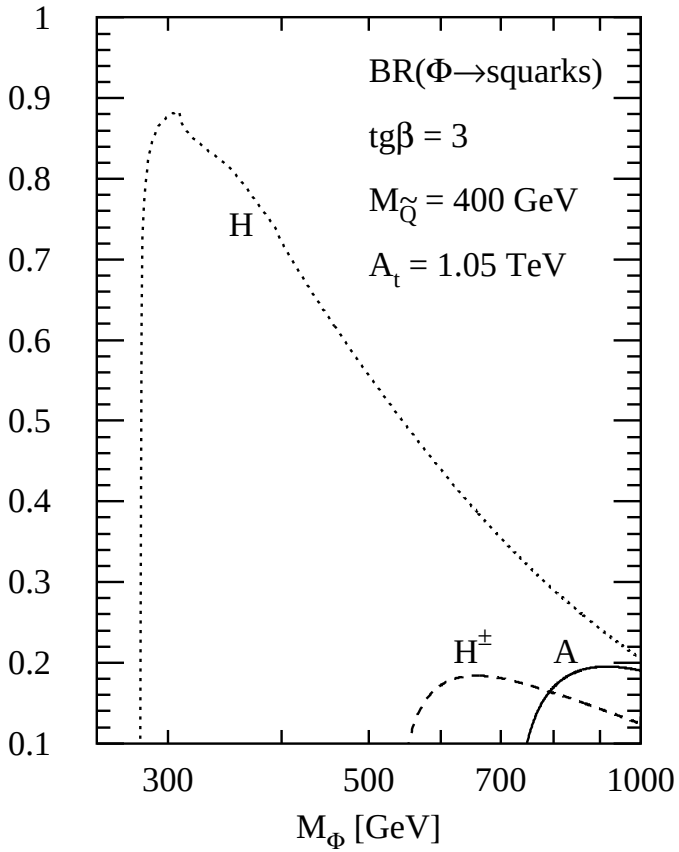

Γ(Φ) [GeV]
tgβ = 3
10
1
10^-1
10^-2
10^-3
H±
H
A
h
100
200
500
1000
M_Φ [GeV]


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



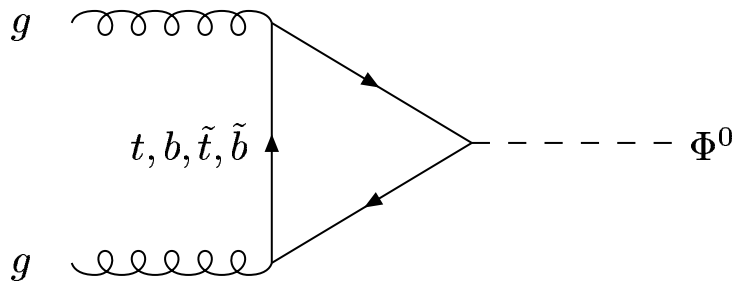


HDECAY

- if kinematically possible → important

II *HIGGS BOSON PRODUCTION*

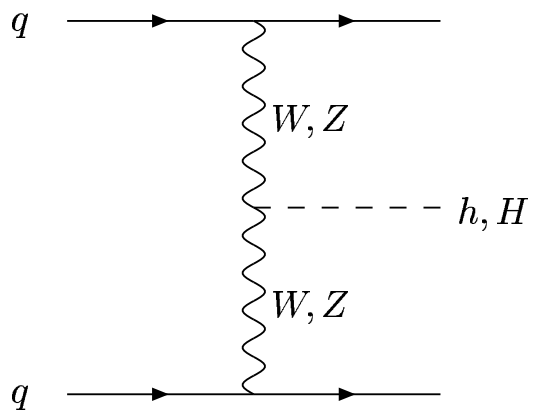
- Gluon fusion: $pp \to gg \to h/H/A$



QCD corrections: $\sim 10 \ldots 100\%$
elw. corrections: small

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman
Harlander, Kilgore
Anastasiou, Melnikov
Ravindran, Smith, van Neerven
Catani, de Florian, Grazzini, Nason

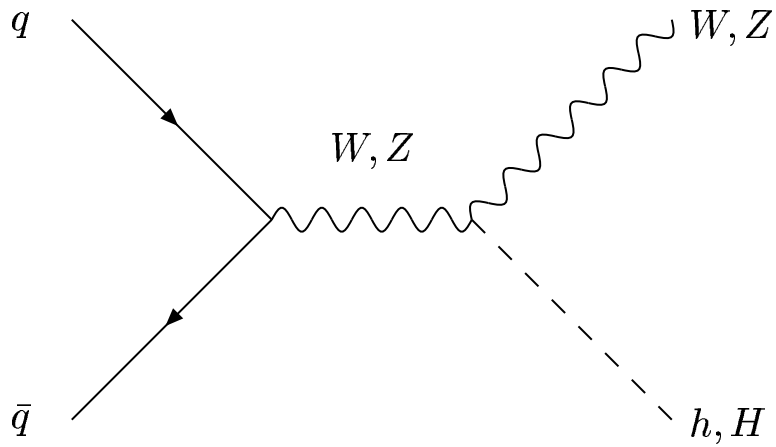
- W/Z fusion: $pp \to W^*W^*/Z^*Z^* \to h/H$



QCD corrections: $\sim 10 - 30\%$

Han, Valencia, Willenbrock
Figy, Oleari, Zeppenfeld
Berger, Campbell

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



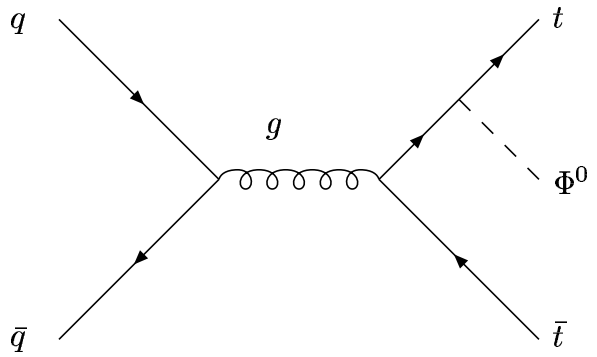
QCD corrections: $\sim 30\%$

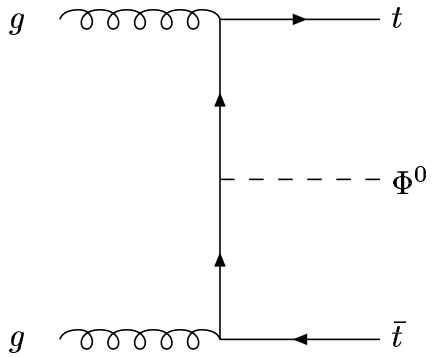
Han, Willenbrock
Brein, Djouadi, Harlander

elw. corrections: $\sim 10\%$

Ciccolini, Dittmaier, Krämer

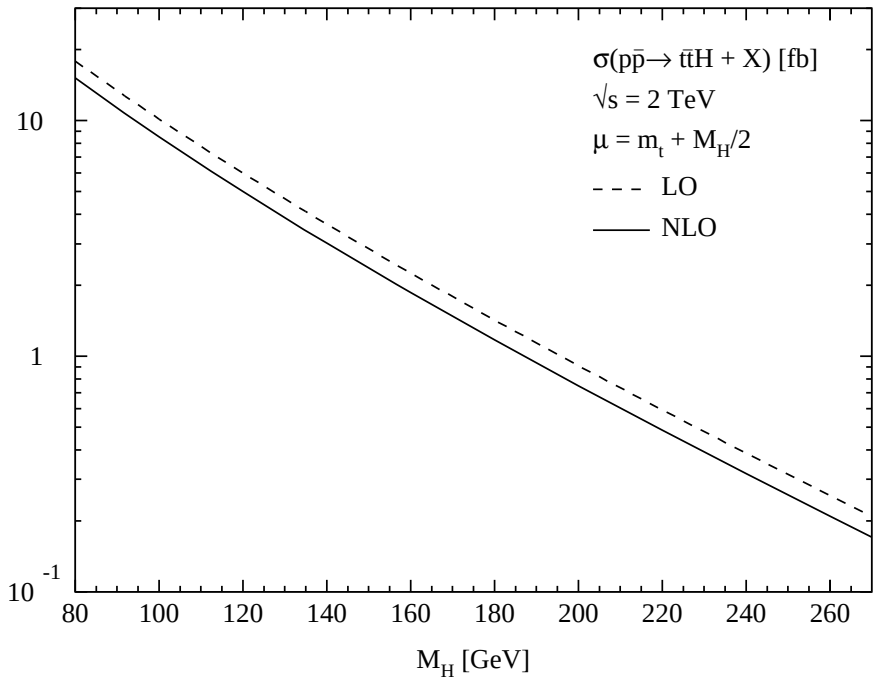
- Bremsstrahlung: $pp \to t\bar{t} + \phi^0$

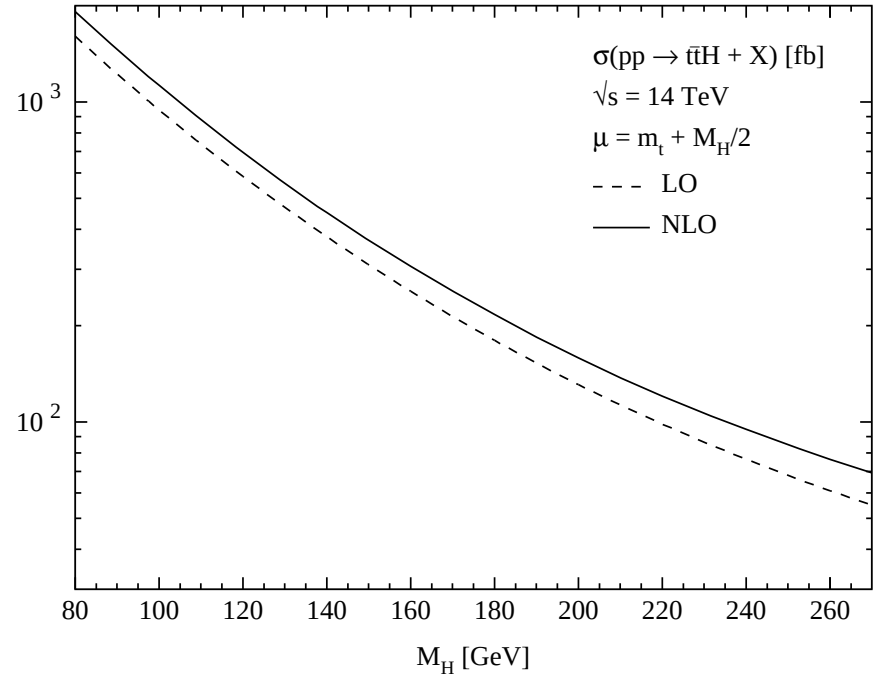




QCD corrections: $\sim \pm 20\%$

Beenakker,. . .
Dawson, . . .



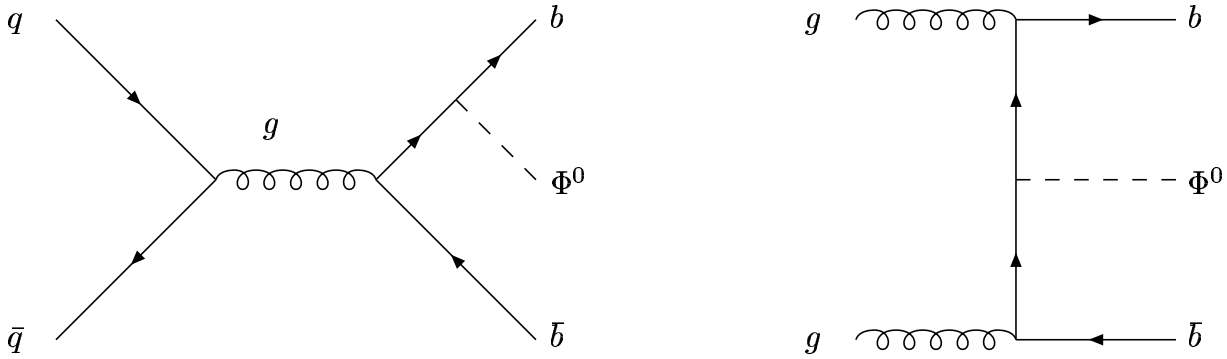


Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas

- Bremsstrahlung: $pp \to b\bar{b} + \phi^0$

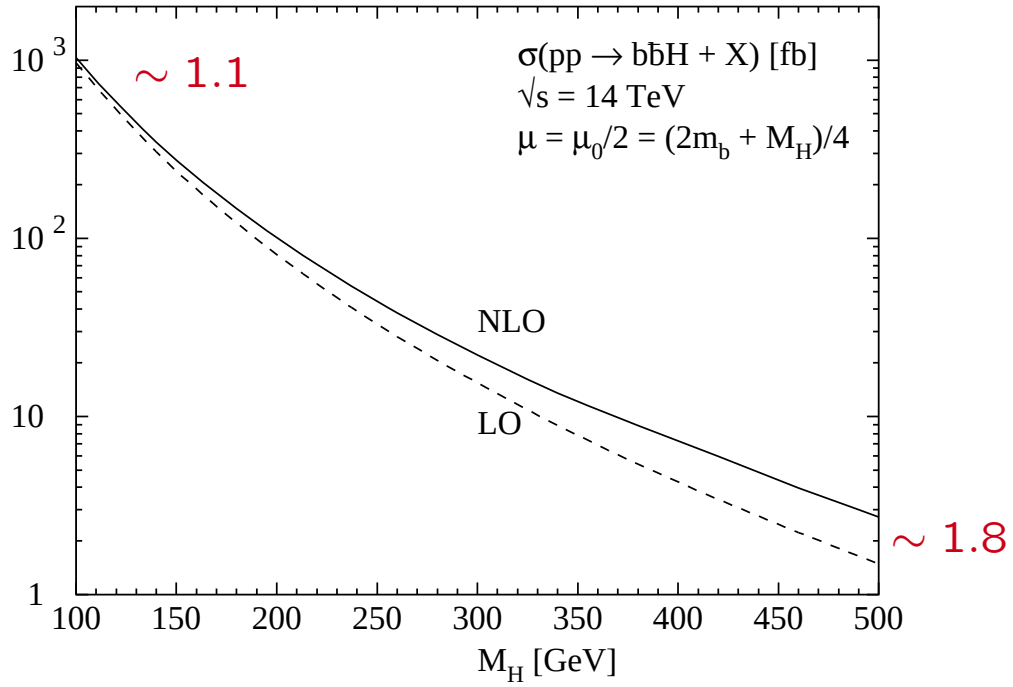
  $b\bar{b} + H/A$ dominant for large tgβ

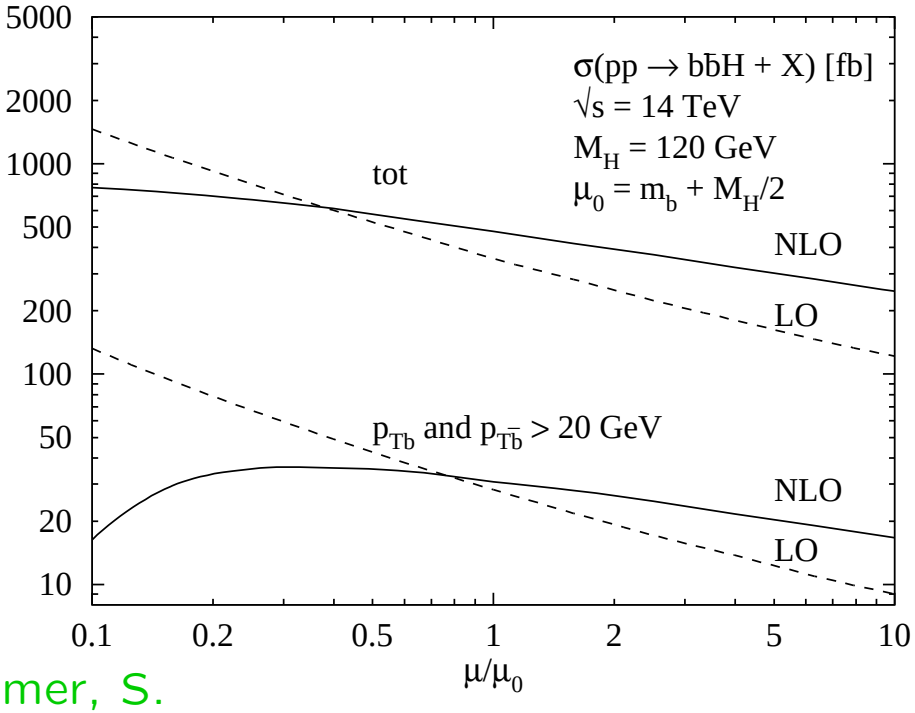
  measurement of tgβ



QCD corrections: $\sim 10 - 80\%$

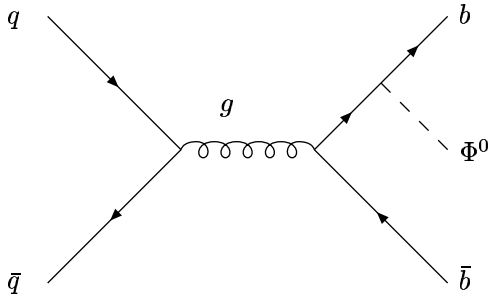
Dittmaier,Krämer, S. Dawson, . . .

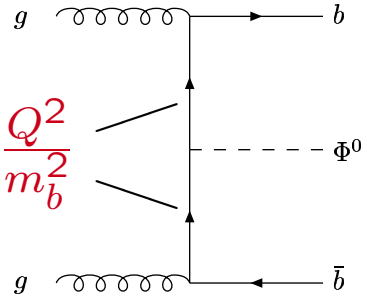




Dittmaier, Krämer, S.

b densities





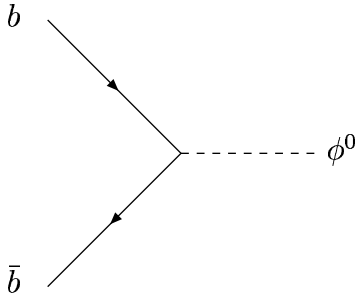
$\log \frac{Q^2}{m_b^2}$

dominant

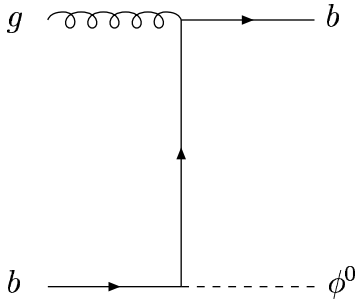
large logs from phase space integration $\longrightarrow$ absorbed in bottom PDF

resummation $\equiv$ DGLAP evolution

- new processes:



NNLO



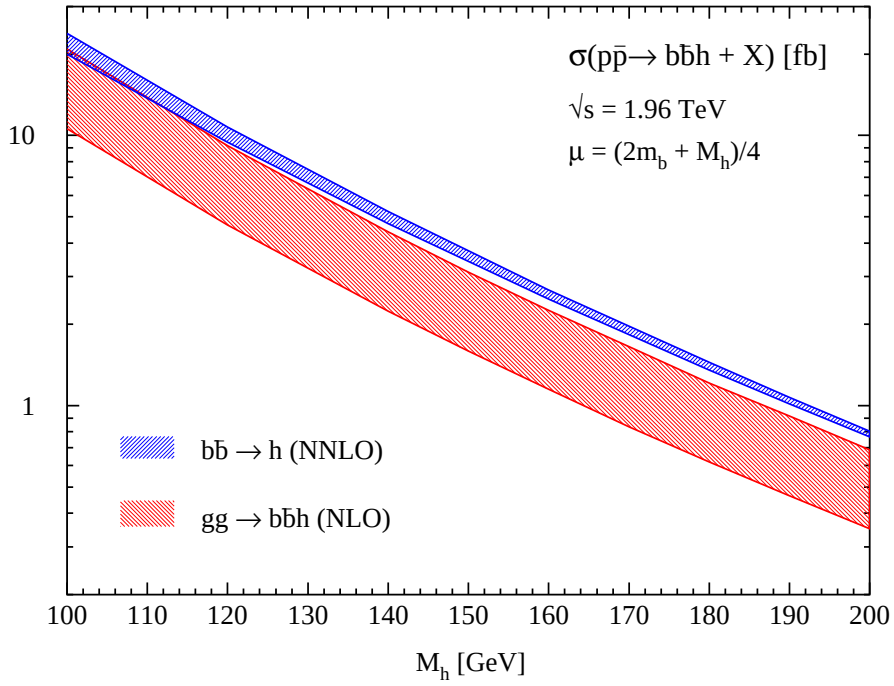
NLO

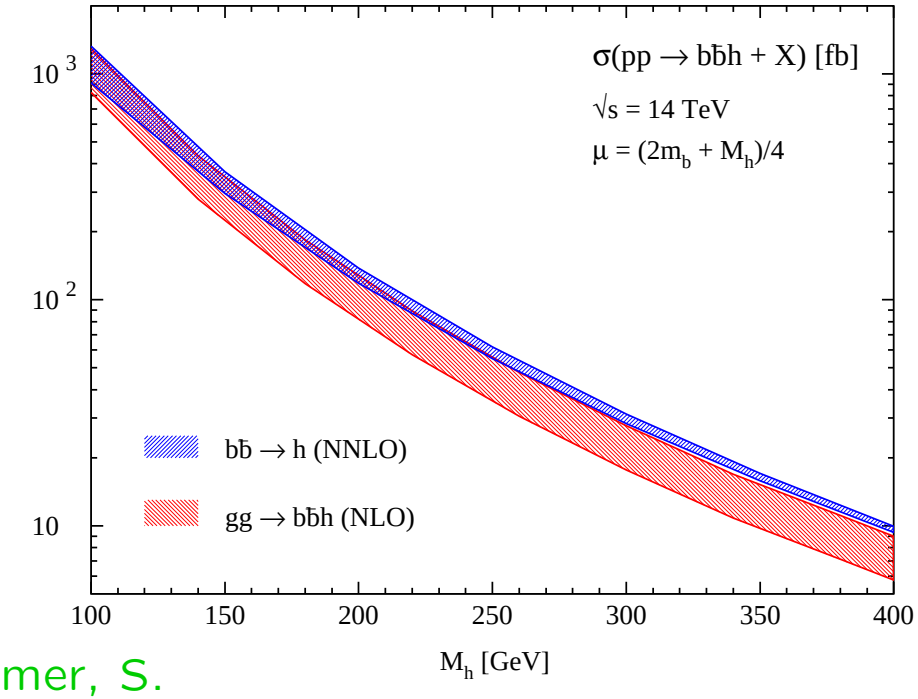
Dicus,Willenbrock
Stelzer, . . .
Balazs,. . .
Campbell,. . .

Harlander, Kilgore

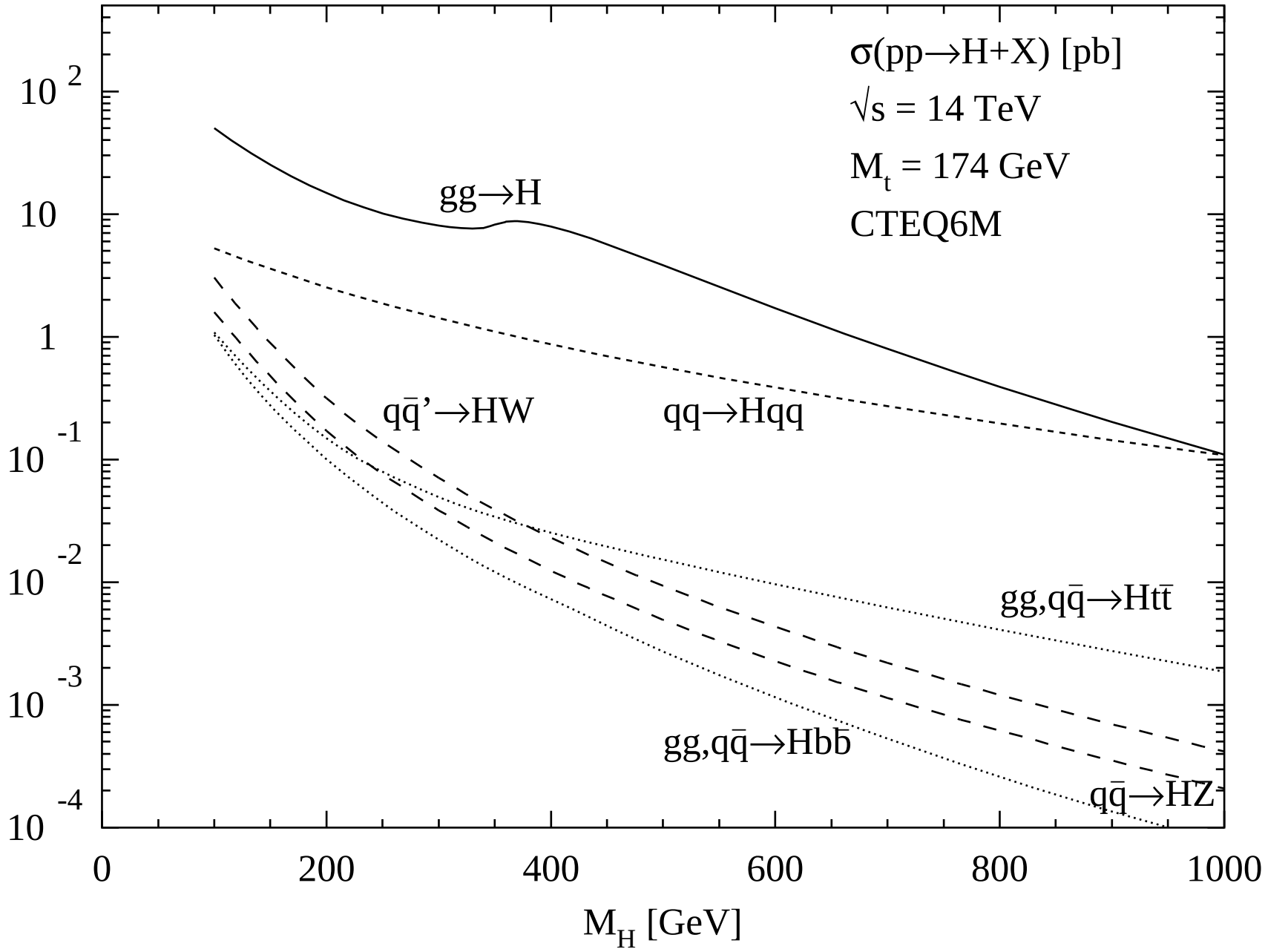
$$b(x,\mu^2) \longrightarrow b(x,\mu^2) - \frac{\alpha_s}{2\pi} P_{qg} \otimes g(x,\mu^2) \log \frac{\mu^2}{m_b^2}$$

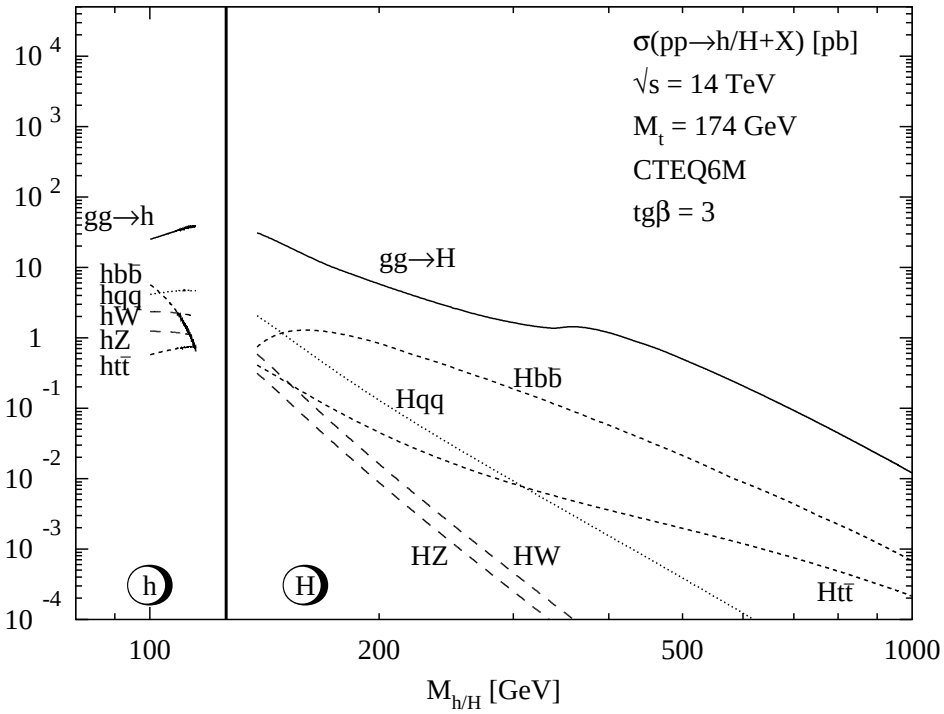
$$\mu \sim Q \sim M_\phi/4 \Rightarrow \sigma_{tot}$$

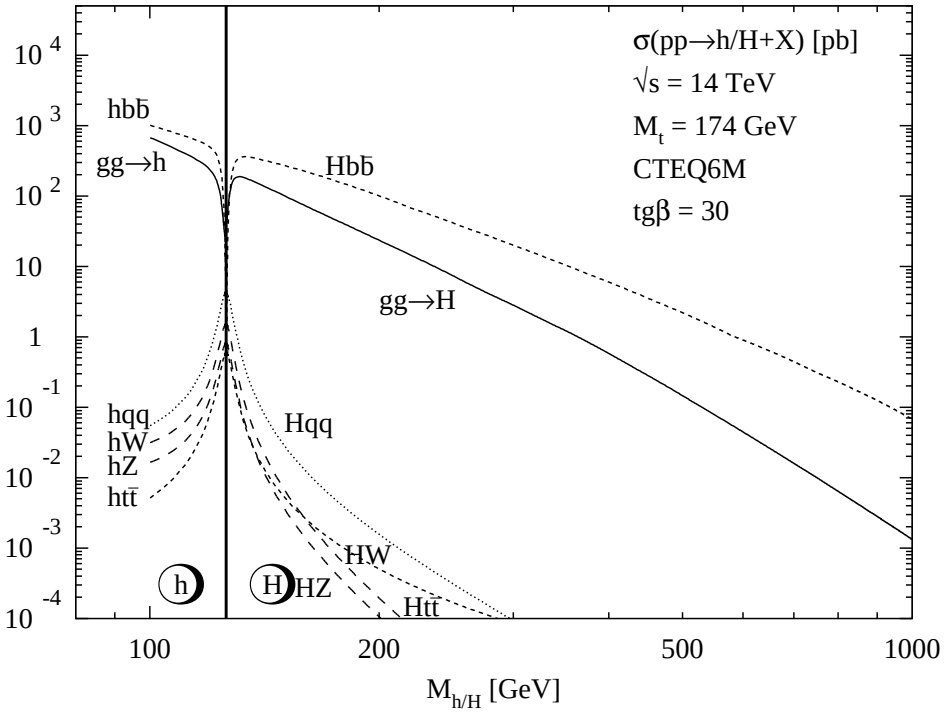


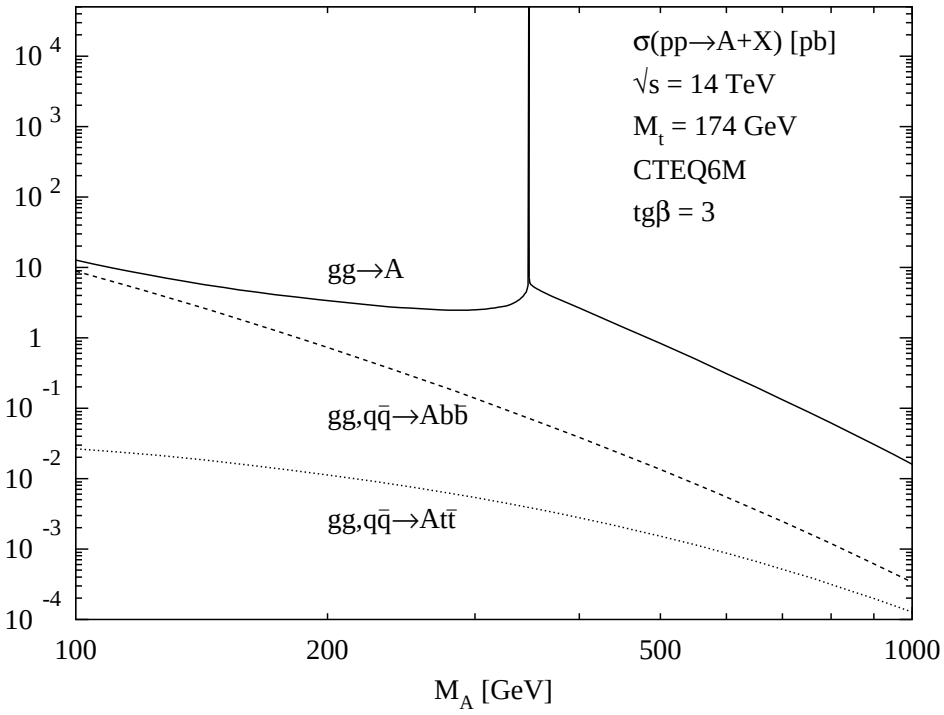


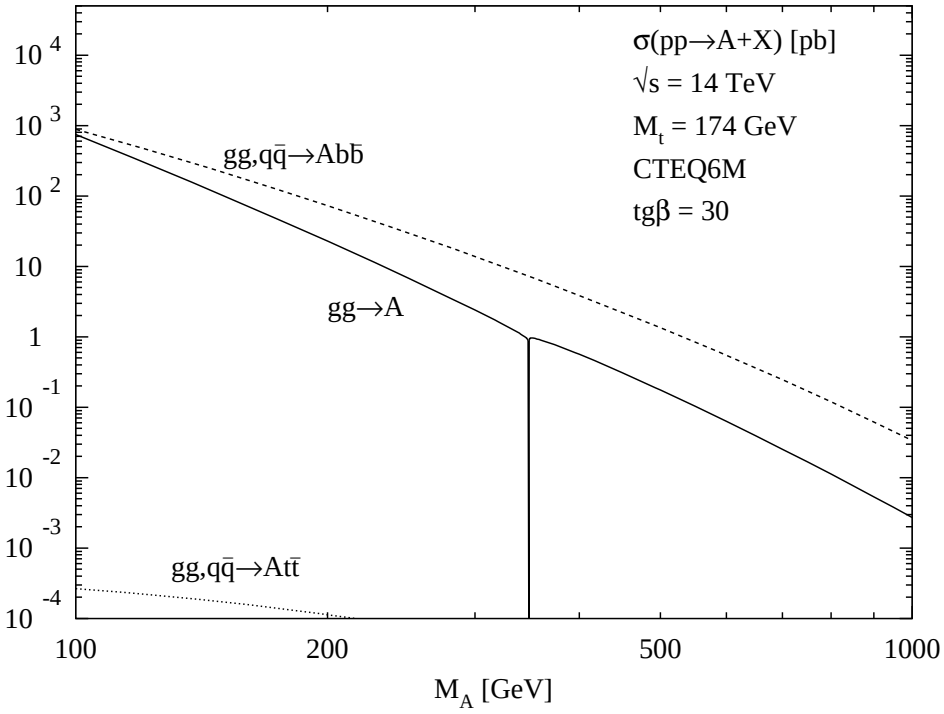
Dittmaier, Krämer, S.
Harlander, Kilgore

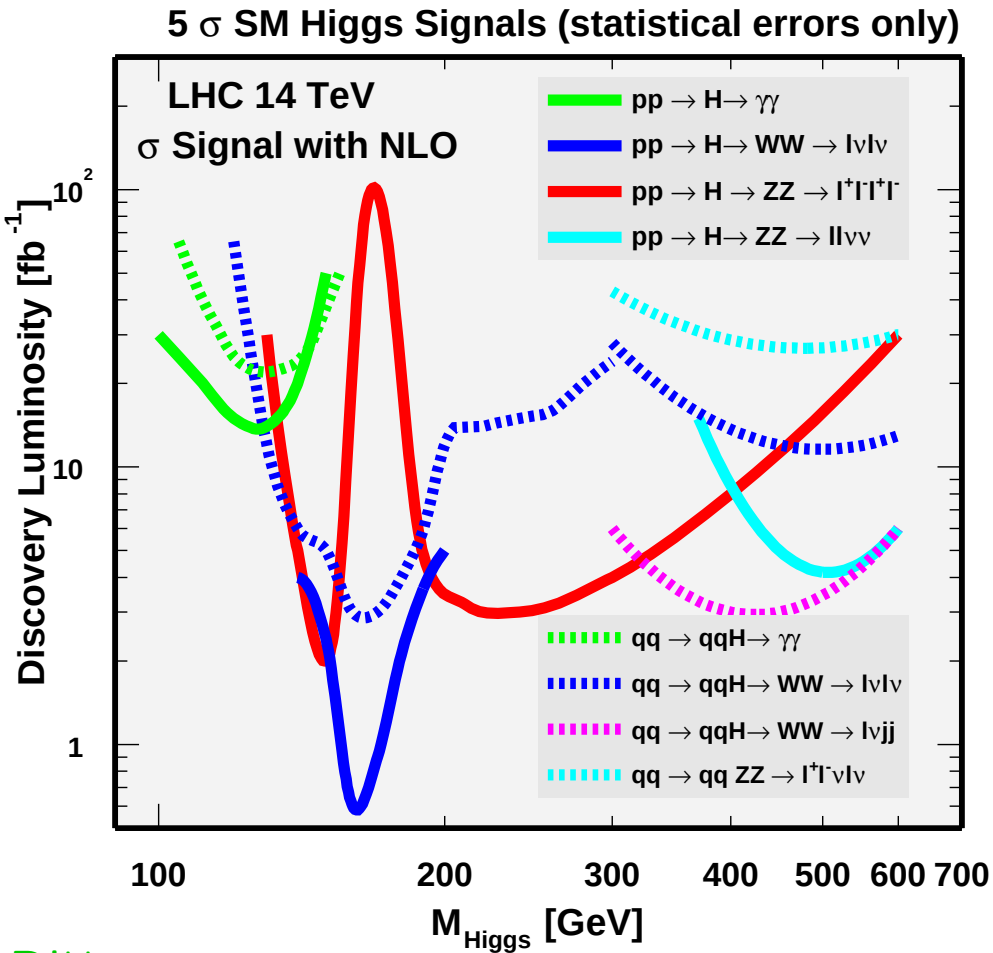

σ(pp→H+X) [pb]
√s = 14 TeV
M_t = 174 GeV
CTEQ6M
gg→H
qq̄'→HW
qq→Hqq
gg,qq̄→Htt̄
gg,qq̄→Hbb̄
qq̄→HZ
10 2
10
1
10 -1
10 -2
10 -3
10 -4
0
200
400
600
800
1000
M_H [GeV]


σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 174 GeV
CTEQ6M
tgβ = 3
gg→h
hbb̄
hqq
hW
hZ
htt̄
gg→H
Hbb̄
Hqq
HZ
HW
Htt̄
h
H
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
100
200
500
1000
M_h/H [GeV]

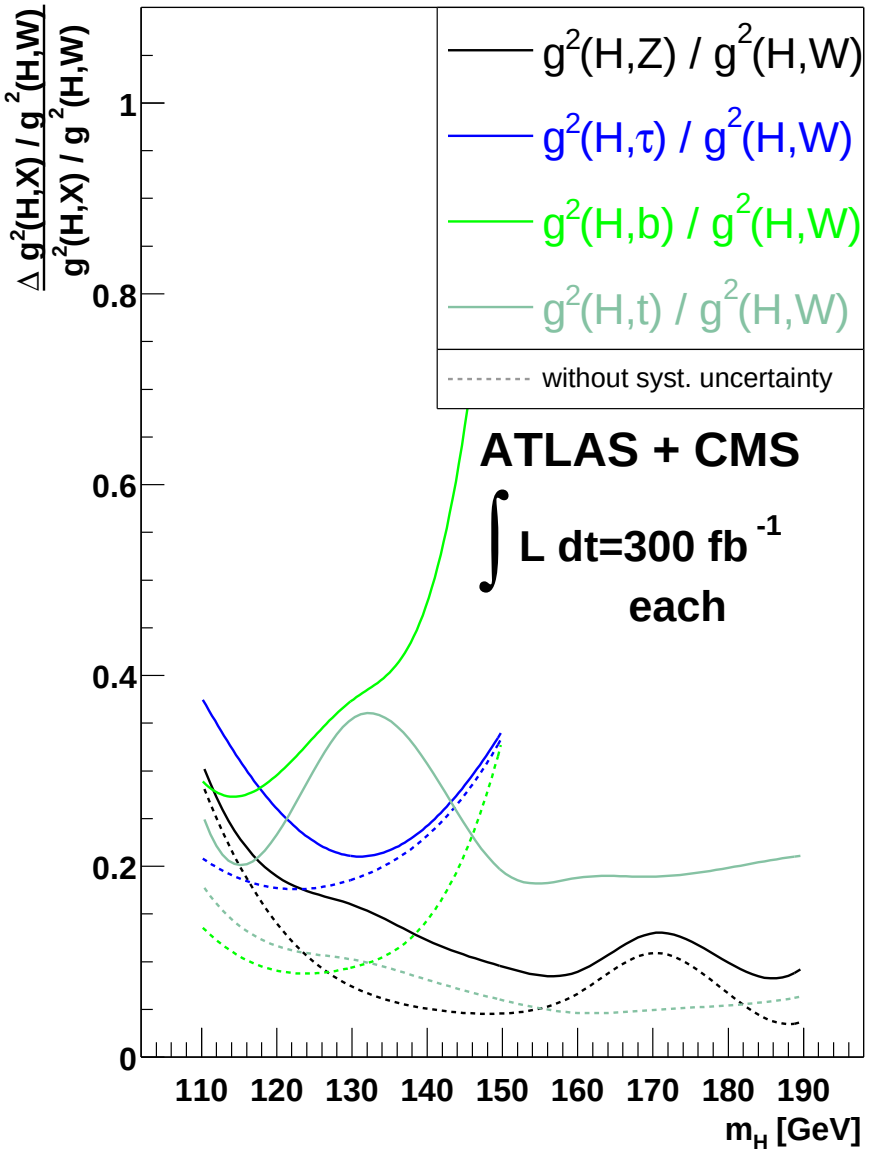

σ(pp→h/H+X) [pb]
√s = 14 TeV
M_t = 174 GeV
CTEQ6M
tgβ = 30
hbb̄
gg→h
Hbb̄
gg→H
hqq
hW
hZ
htt̄
Hqq
HW
HZ
Htt̄
h
H
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
100
200
500
1000
M_h/H [GeV]


σ(pp→A+X) [pb]
√s = 14 TeV
M_t = 174 GeV
CTEQ6M
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
100
200
500
1000
M_A [GeV]


σ(pp→A+X) [pb]
√s = 14 TeV
M_t = 174 GeV
CTEQ6M
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
100
200
500
1000
M_A [GeV]



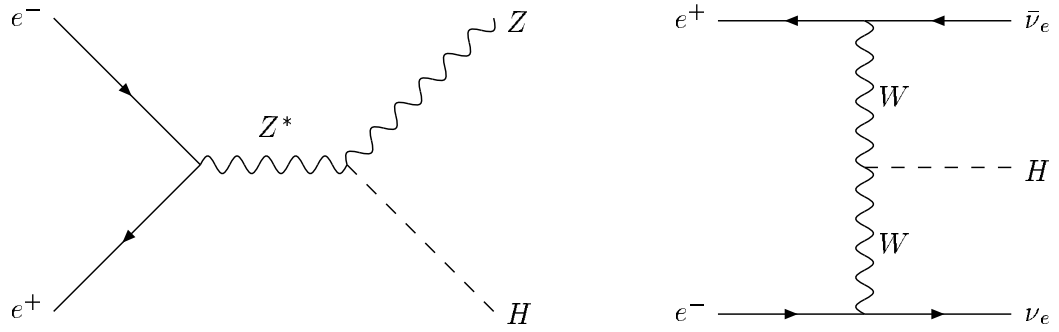
Dittmar



Dührssen,. . .

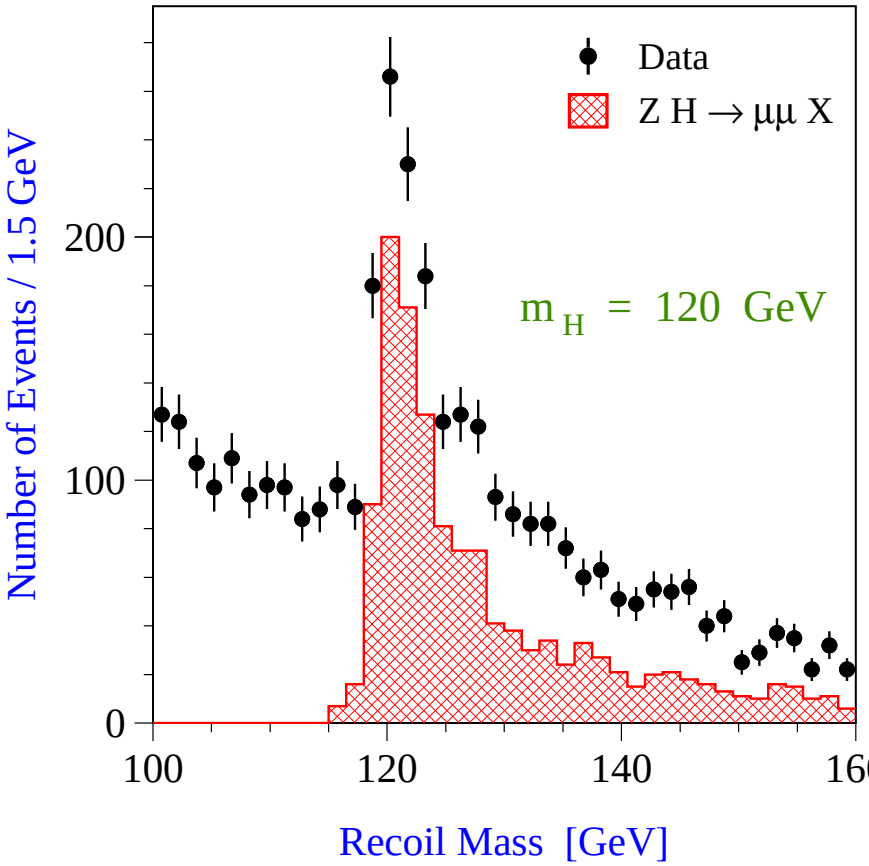
IV HIGGS SEARCH @ LC

- Higgs boson production analogous to LEP2



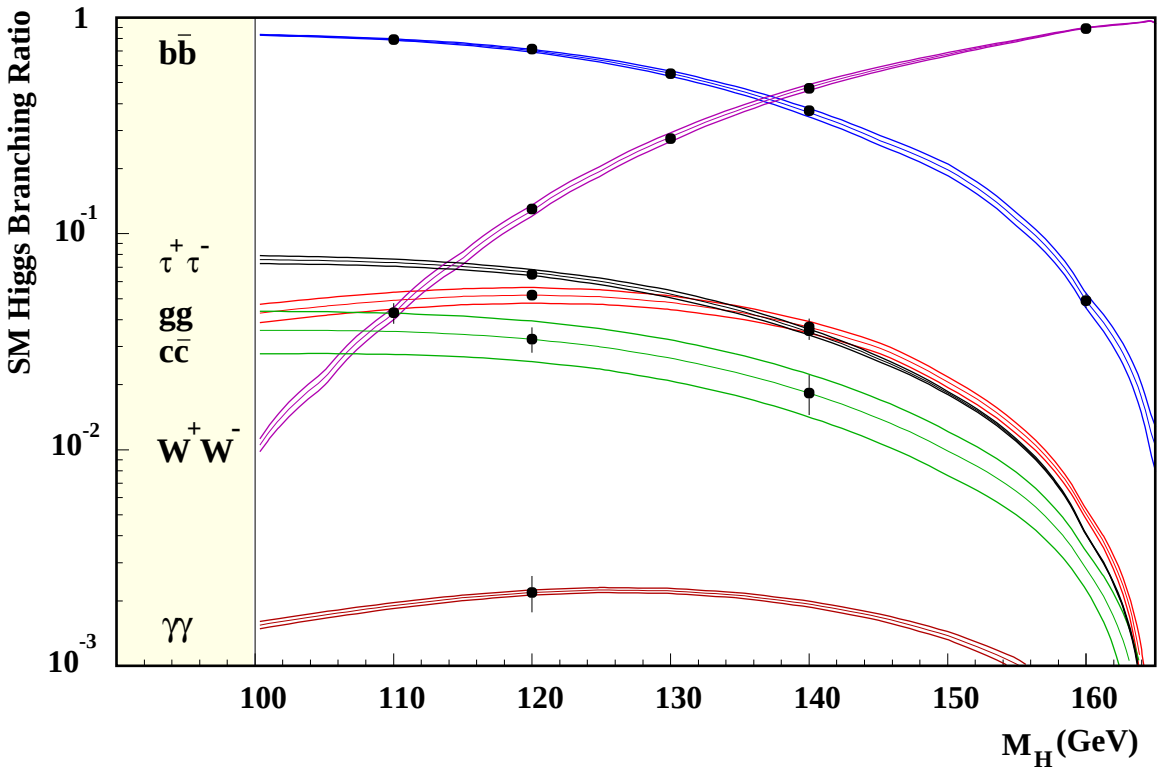
- discovery up to $M_H \lesssim 0.7\sqrt{s}$
- Higgs-strahlung $e^+e^- \to ZH$:
  Z monoenergetic
  $\Rightarrow M_H^2 = s - 2\sqrt{s}E_Z + M_Z^2$
  $\Rightarrow$ reconstruction from recoil mass

TESLA



- mass: $\delta M_H \lesssim 50$ MeV

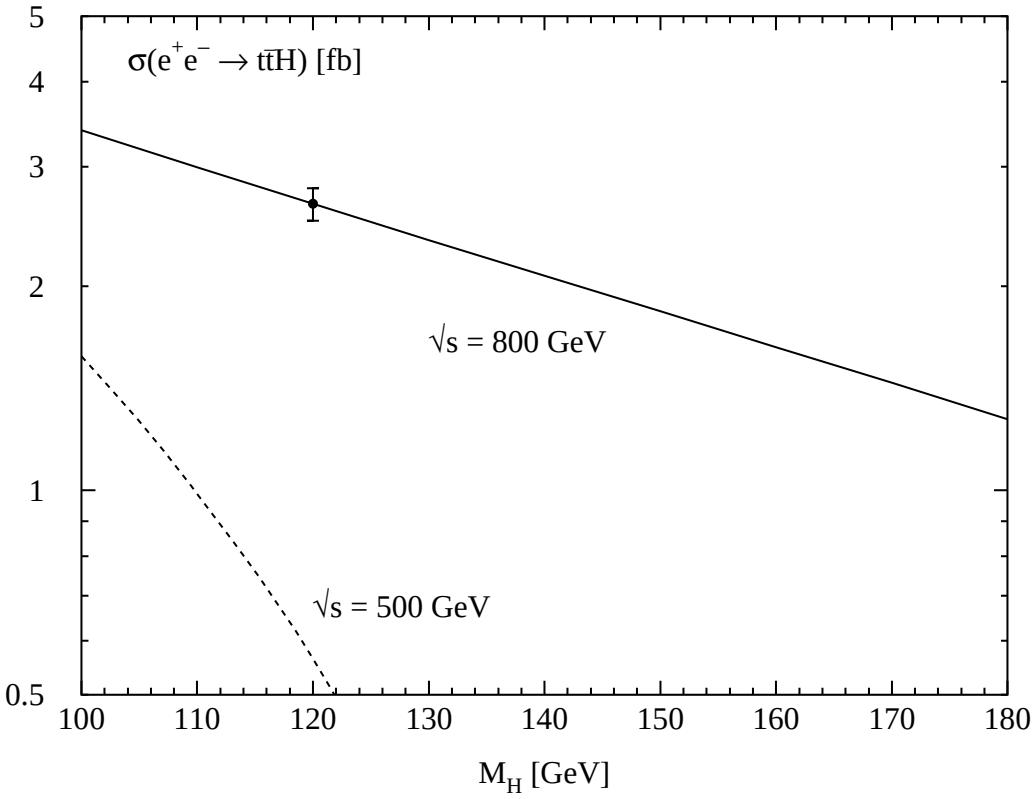
- Yukawa couplings: from branching ratios

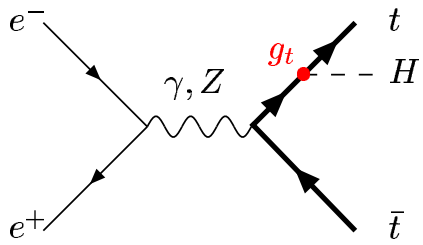


Battaglia

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

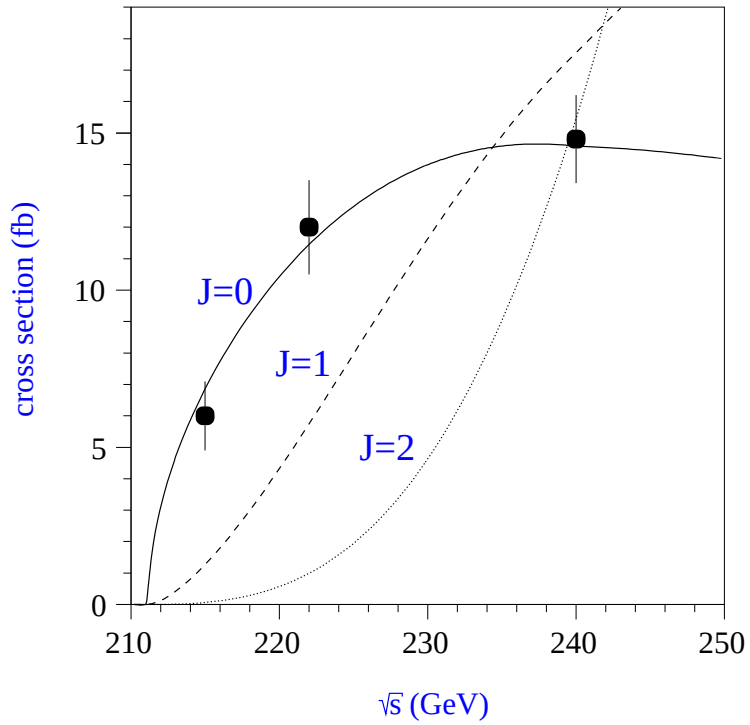
- top Yukawa coupling: $e^+e^- \longrightarrow t\bar{t}H$





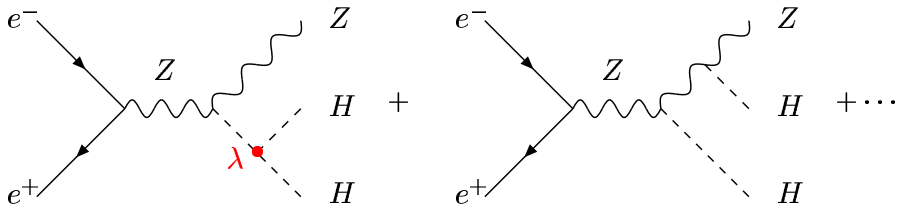
Juste, Merino

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

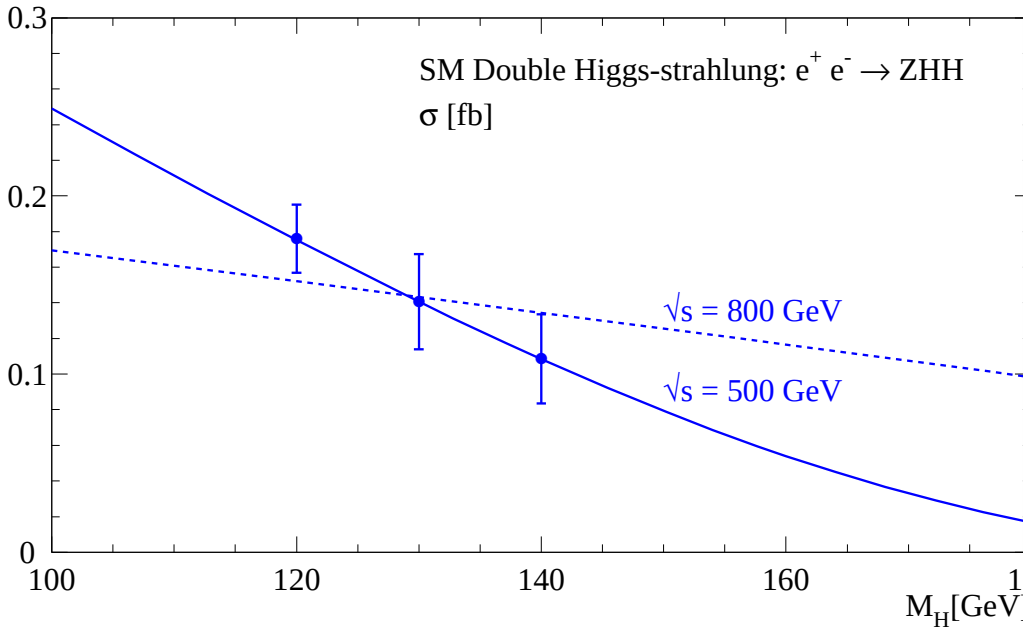


Miller, Choi, Eberle,
Mühlleitner, Zerwas
Dova, Garcia–Abia, Lohmann

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



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



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

III *CONCLUSIONS*

- Higgs searches at the LHC and ILC belong to major endeavours

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

- most QCD and elw. corrections known
  $\Rightarrow$ large corrections in several cases
  remaining theoretical uncertainties:
  $\sim 100\% \longrightarrow \lesssim 15 - 20\%$

- 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