PAUL SCHERRER INSTITUT

THEORY BSM

Michael Spira (PSI)

I Introduction

II Higgs [Boson] Decays

III Higgs Boson Production @ Hadron Colliders

IV Summary

I *INTRODUCTION*

MSSM

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

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

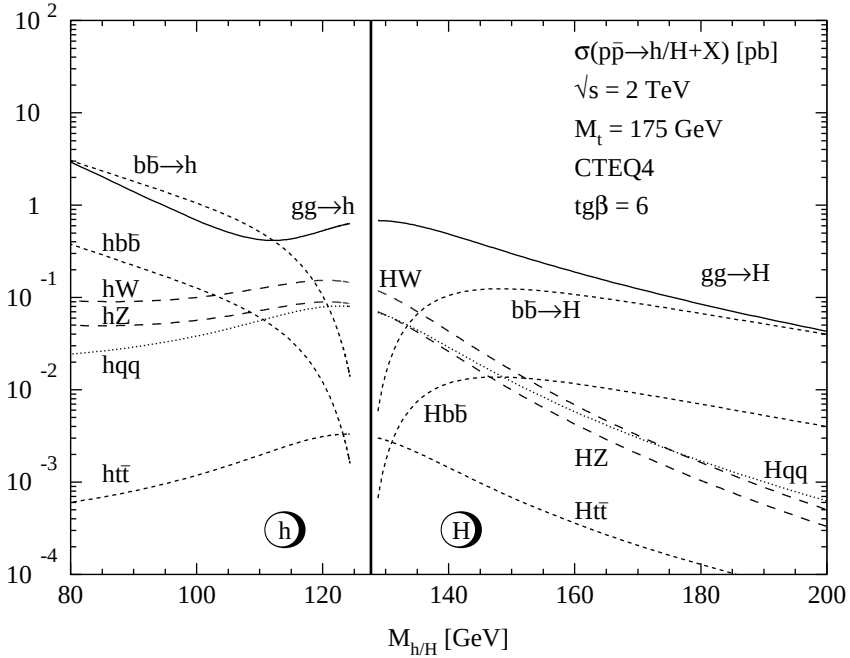
- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\rightarrow$ $\boxed{M_h \lesssim 135 \text{ GeV}}$ Haber, Carena,..., Heinemeyer,..., Zhang, Slavich,..., ...

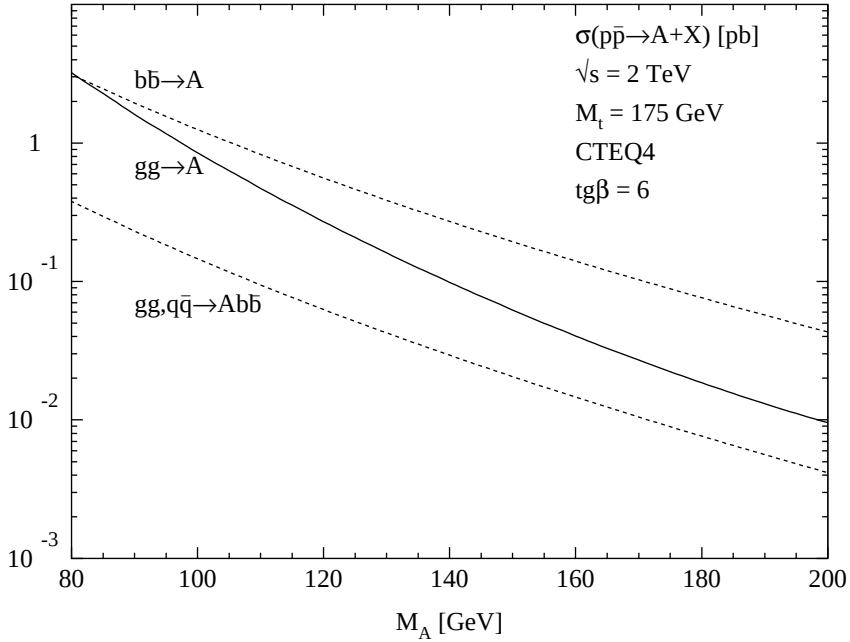
- Yukawa couplings: $\text{tg}\beta\uparrow$ $\Rightarrow$ $g_u^{\phi}\downarrow$ $g_d^{\phi}\uparrow$ $g_V^{\phi}\downarrow$

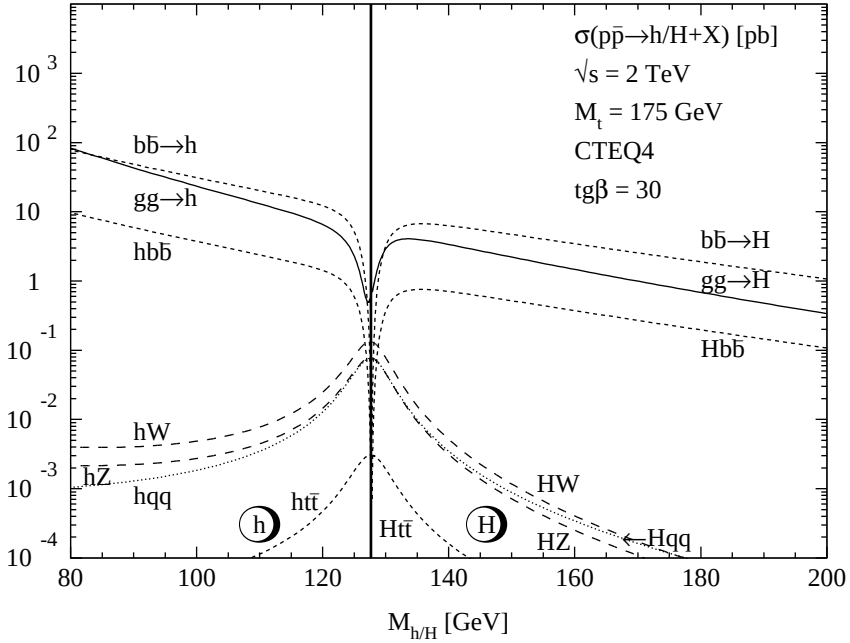
- Tevatron: $gg \rightarrow \phi$ dominant [$\phi b\bar{b}$ for large $\text{tg}\beta$]
  $q\bar{q}' \rightarrow \phi W$ most important

- LHC: $gg \rightarrow \phi$ dominant for $\text{tg}\beta \lesssim 10$
  $gg \rightarrow \phi b\bar{b}$ dominant for $\text{tg}\beta \gtrsim 10$

Tevatron


σ(pp̄→h/H+X) [pb]
√s = 2 TeV
M_t = 175 GeV
CTEQ4
tgβ = 6
bb̄→h
gg→h
hbb̄
hW
hZ
hqq
htt̄
HW
gg→H
bb̄→H
Hbb̄
HZ
Hqq
Htt̄
h
H
M_h/H [GeV]


σ(pp̄→A+X) [pb]
√s = 2 TeV
M_t = 175 GeV
CTEQ4
tgβ = 6
bb̄→A
gg→A
gg,qq̄→Abb̄
M_A [GeV]


σ(pp̄→h/H+X) [pb]
√s = 2 TeV
M_t = 175 GeV
CTEQ4
tgβ = 30
bb̄→h
gg→h
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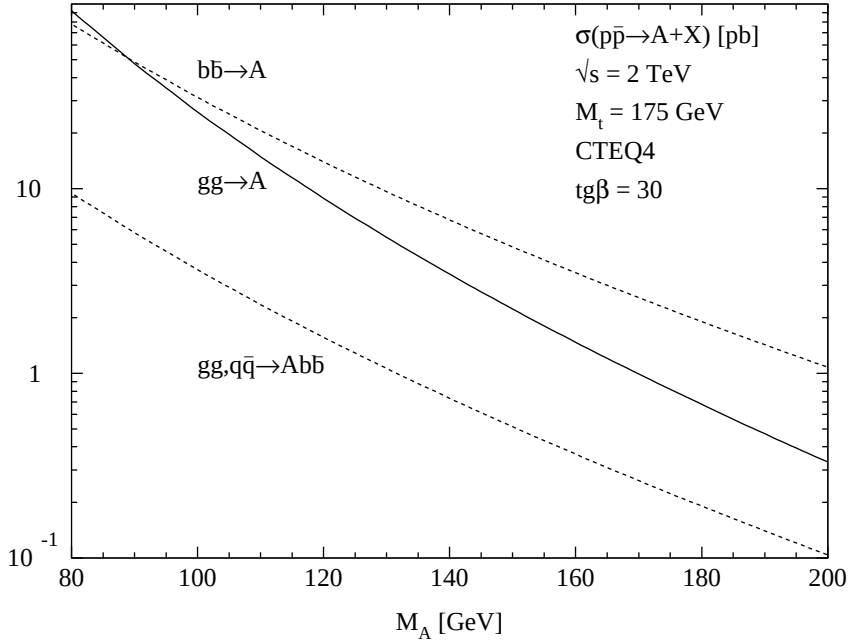
hW
hZ
hqq
htt̄
bb̄→H
gg→H
Hbb̄
HW
HZ
Hqq
Htt̄
h
H
M_h/H [GeV]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tgβ = 30
bb̄→A
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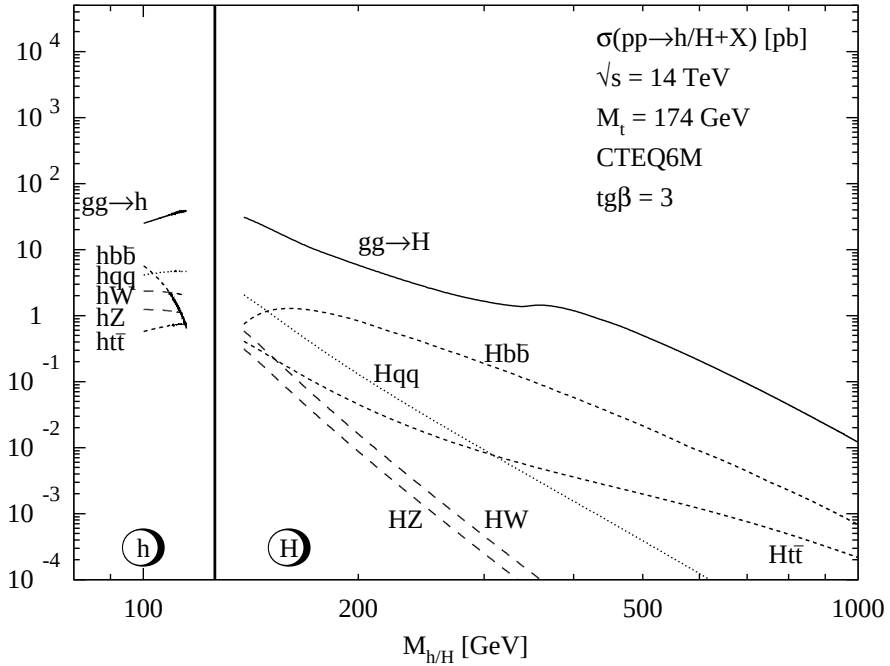
M_A [GeV]

LHC


σ(pp→h/H+X) [pb]
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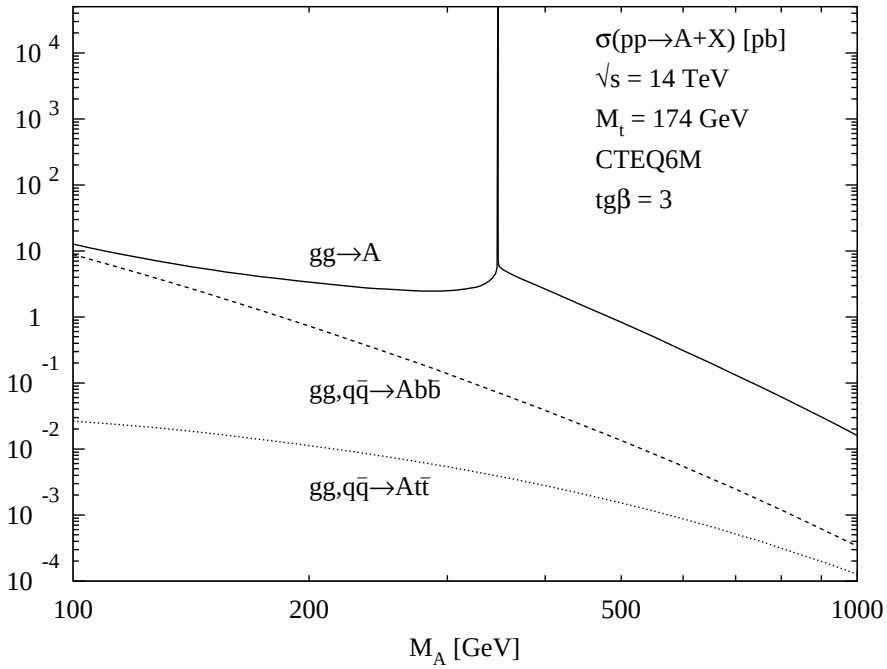
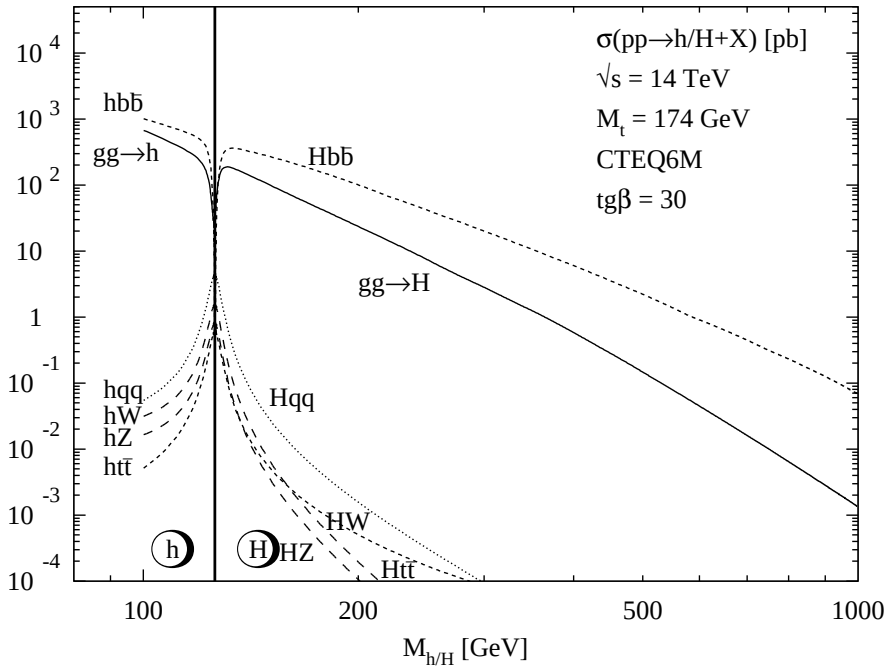
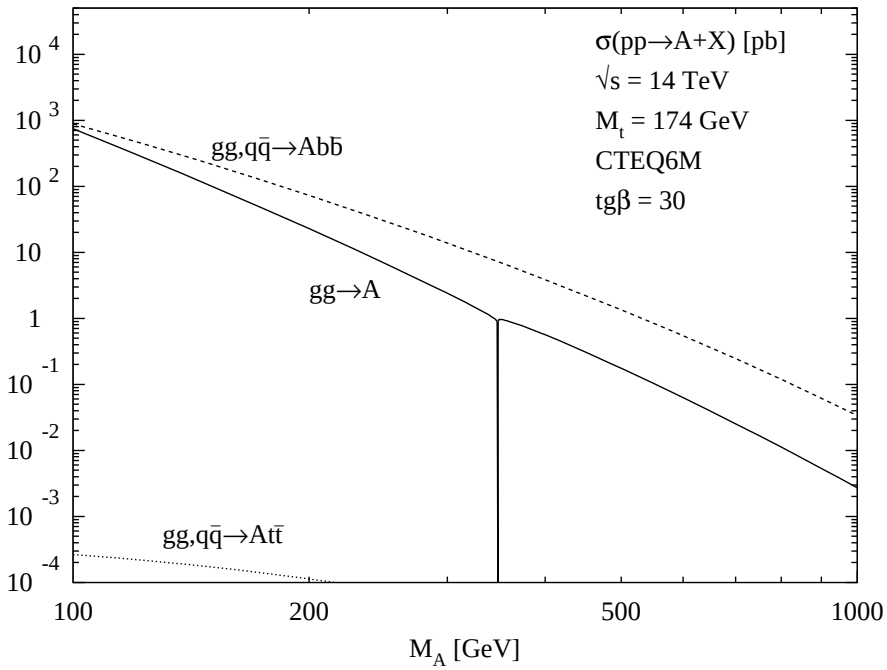
M_t = 174 GeV
CTEQ6M
tgβ = 3
gg→h
hbb̄
hqq
hW
hZ
htt̄
gg→H
Hbb̄
Hqq
HZ
HW
Htt̄
h
H
M_h/H [GeV]


σ(pp→A+X) [pb]
√s = 14 TeV
M_t = 174 GeV
CTEQ6M
tgβ = 3
gg→A
gg,qq̄→Abb̄
gg,qq̄→Att̄
M_A [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
M_h/H [GeV]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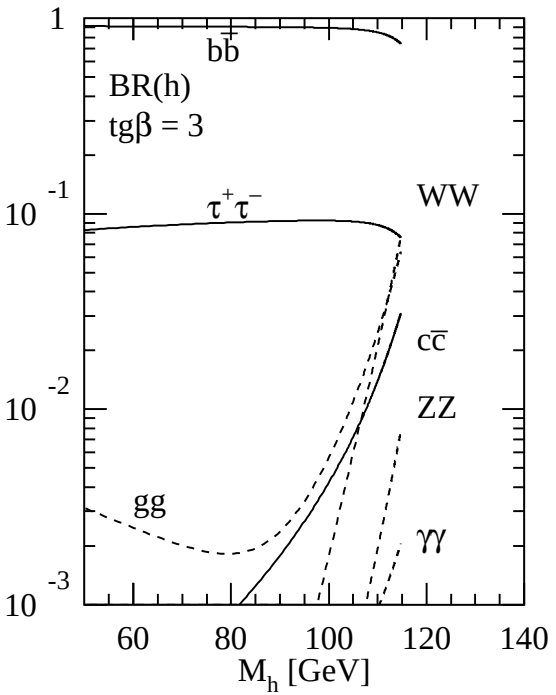
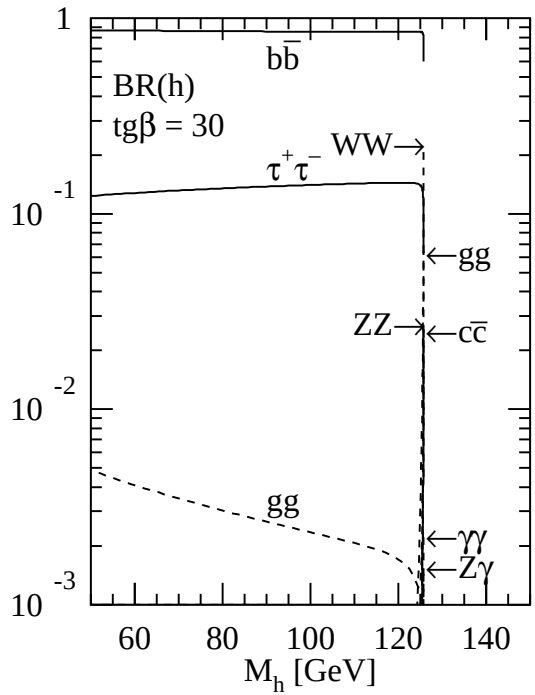
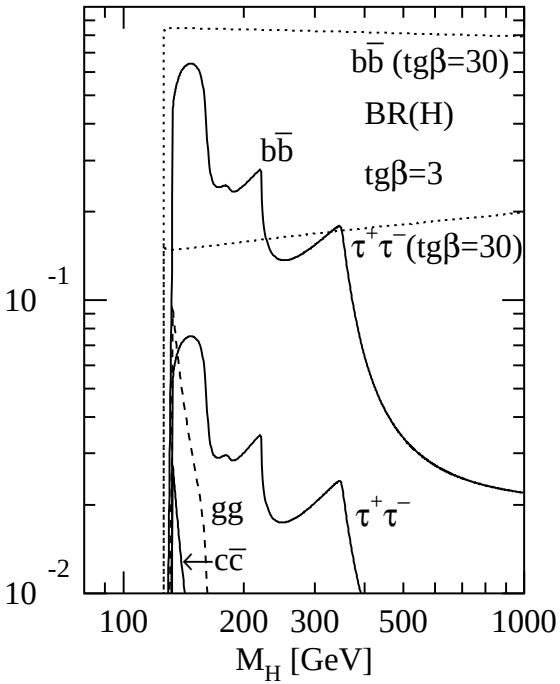
CTEQ6M
tgβ = 30
gg,qq̄→Abb̄
gg→A
gg,qq̄→Att̄
M_A [GeV]

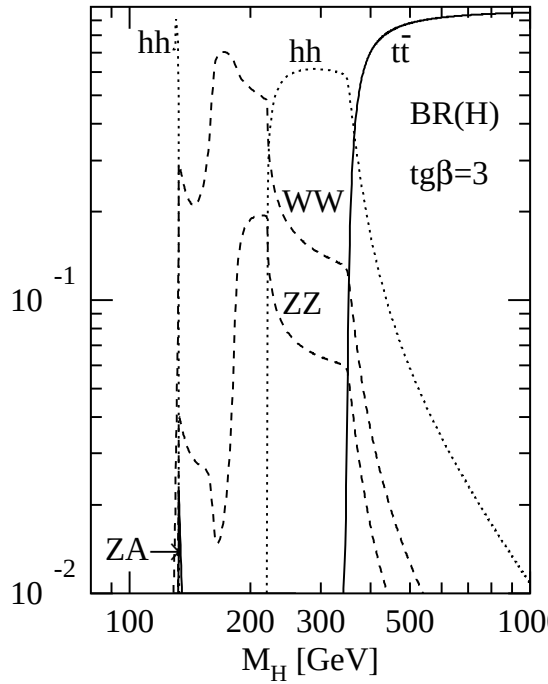
II HIGGS DECAYS

MSSM

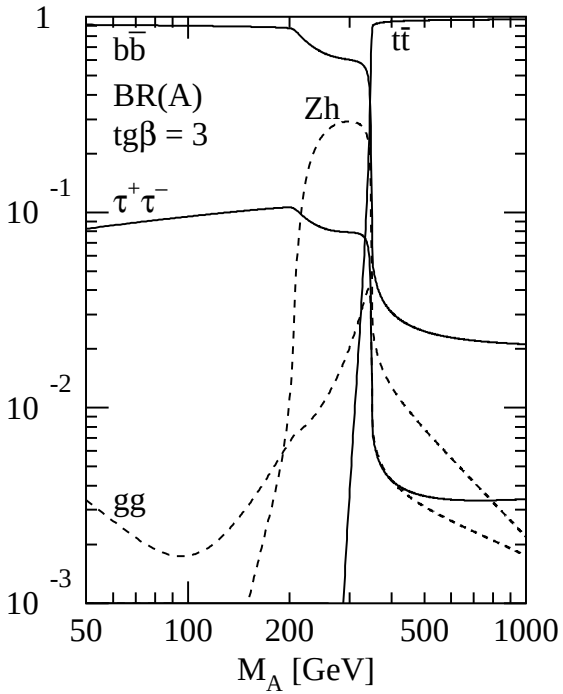


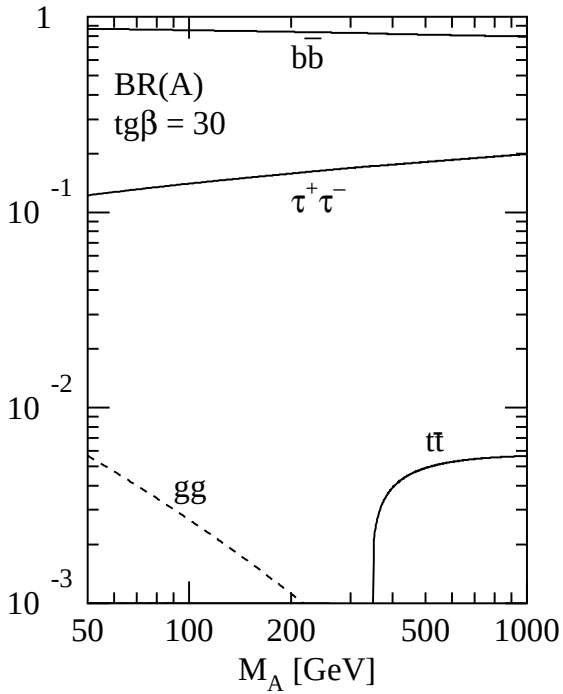


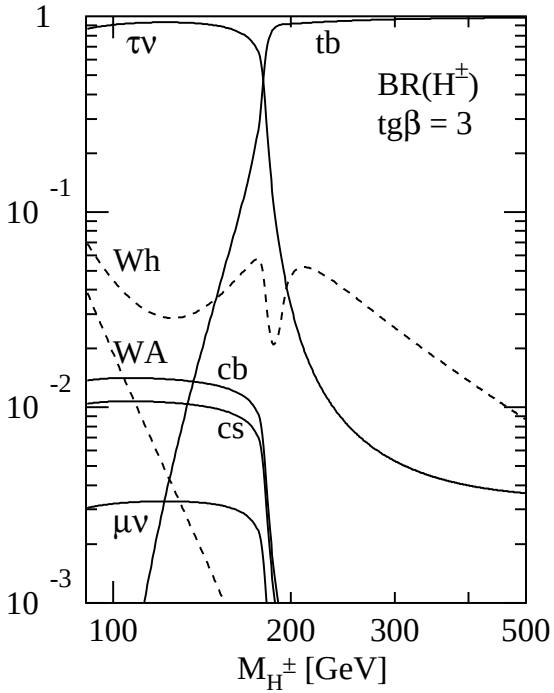


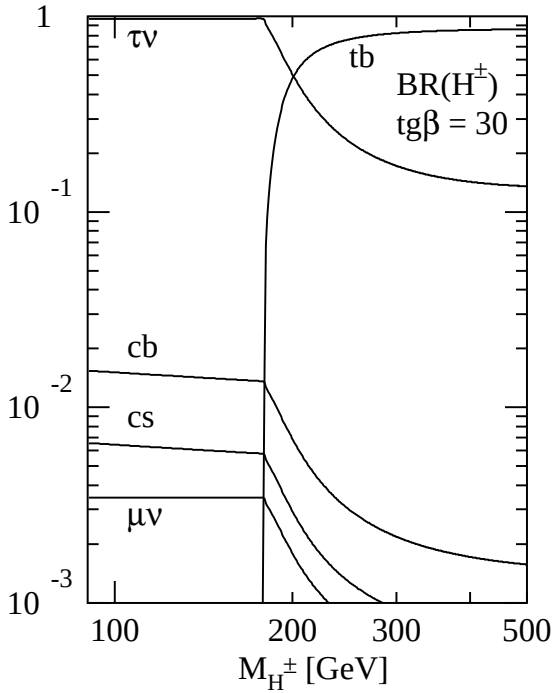


HDECAY


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]

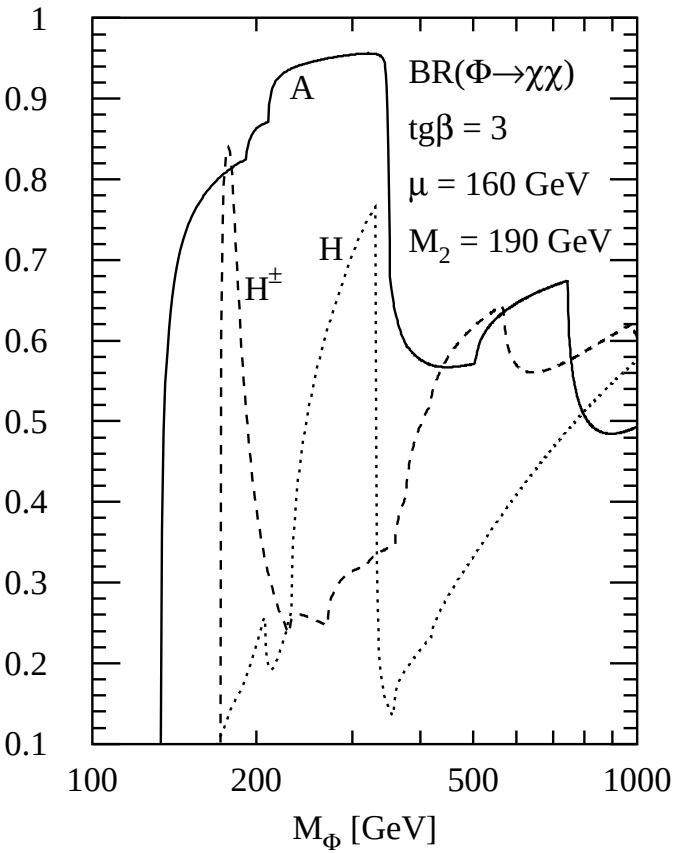

1
10 -1
10 -2
10 -3
τν
tb
BR(H±)
tgβ = 3
Wh
WA
cb
cs
μν
100
200
300
500
M_H± [GeV]

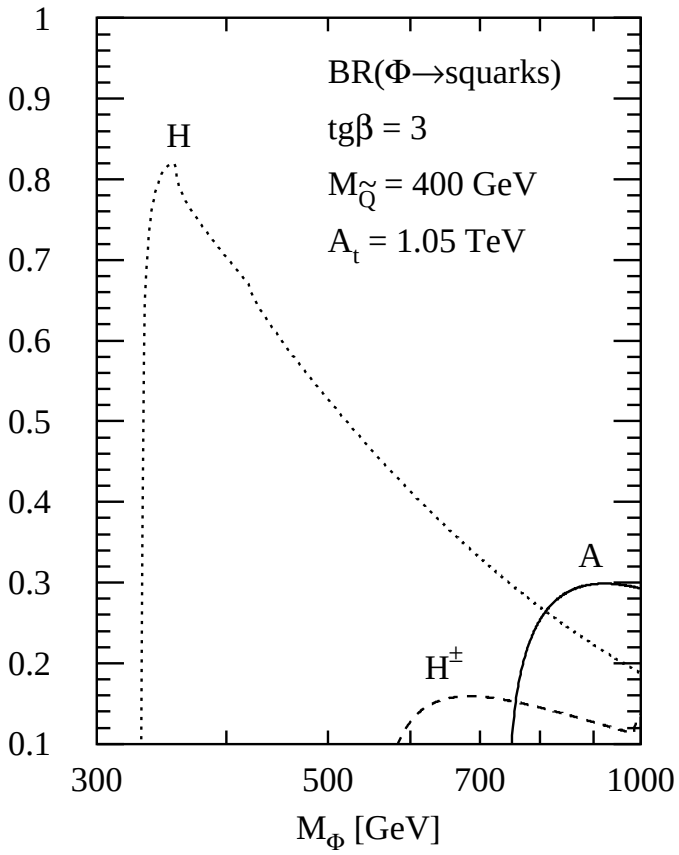

1
10 -1
10 -2
10 -3
τν
tb
BR(H±)
tgβ = 30
cb
cs
μν
100
200
300
500
M_H± [GeV]

HDECAY

SUSY Decays

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



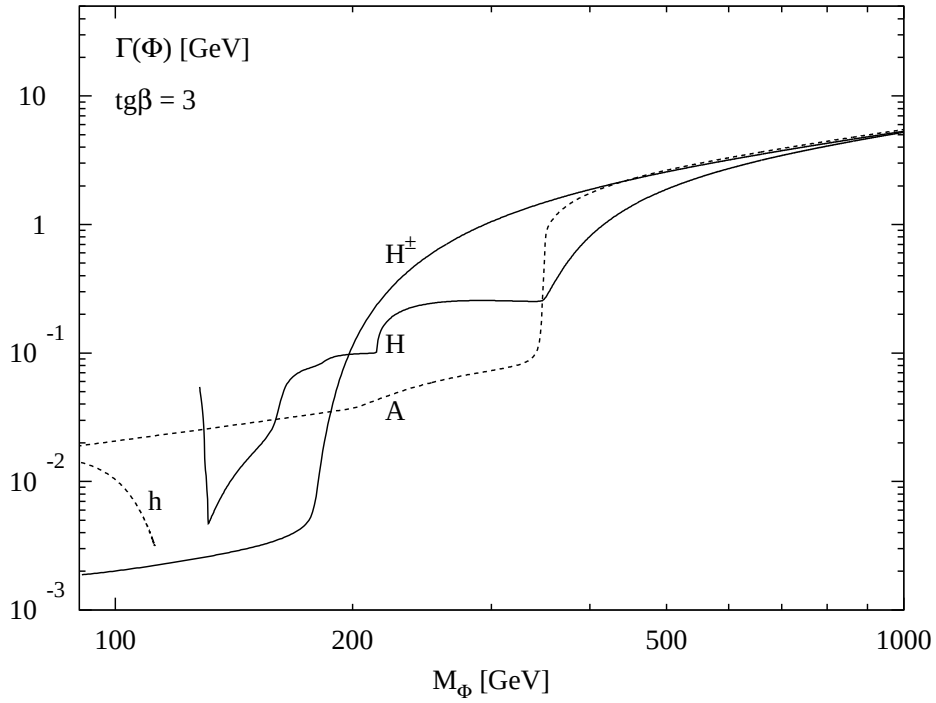


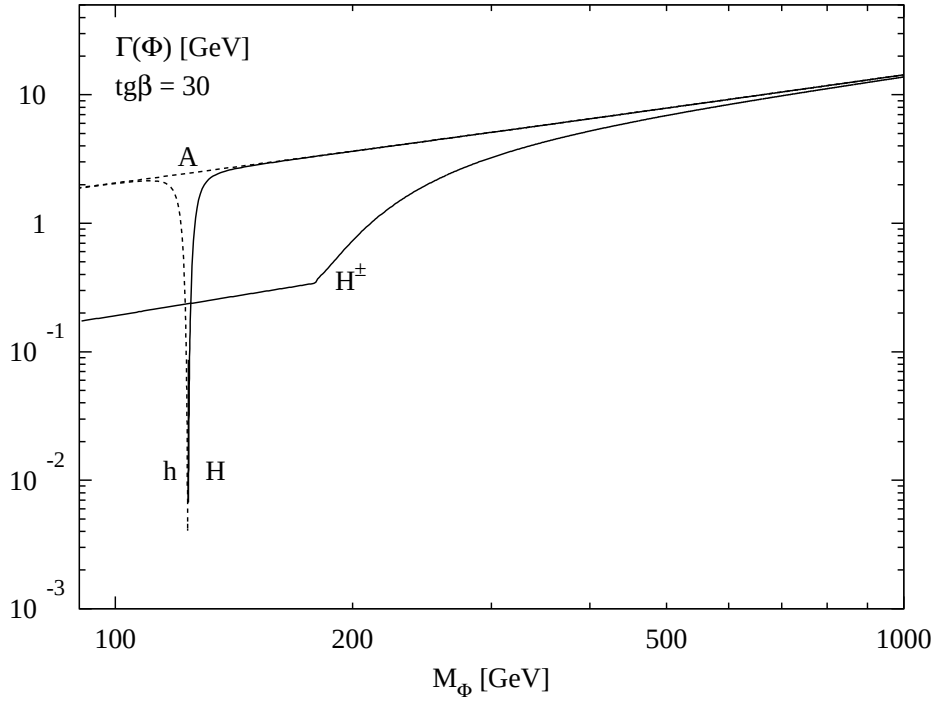
HDECAY

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

Arhrib,. . .
Eberl,. . .

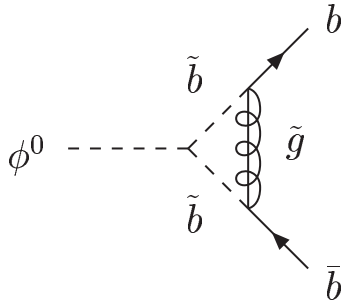
$\Rightarrow$ more work required


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

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



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

Hall,. . .
Carena,. . .
Nierste,. . .
Guasch,. . .
etc.

$$\mathcal{L}_{eff} = -\frac{m_b/v}{1+\Delta_b}\bar{b}\left[g_b^h\left(1-\frac{\Delta_b}{\mathrm{tg}\alpha\ \mathrm{tg}\beta}\right)h + g_b^H\left(1+\Delta_b\frac{\mathrm{tg}\alpha}{\mathrm{tg}\beta}\right)H - g_b^A\left(1-\frac{\Delta_b}{\mathrm{tg}^2\beta}\right)i\gamma_5 A\right]b$$

$$\Delta_b = \frac{2}{3}\,\frac{\alpha_s}{\pi}\,m_{\tilde{g}}\ \mu\ \mathrm{tg}\beta\ I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}})$$

$$I(a,b,c) = -\frac{ab\log\frac{a}{b}+bc\log\frac{b}{c}+ca\log\frac{c}{a}}{(a-b)(b-c)(c-a)}$$

Carena, Garcia, Nierste, Wagner
Guasch, Häfliger, S.

$\Rightarrow$ resummed Yukawa couplings

- NNLO: $\mathcal{O}(10\%)$, $\mu = M_{SUSY}$

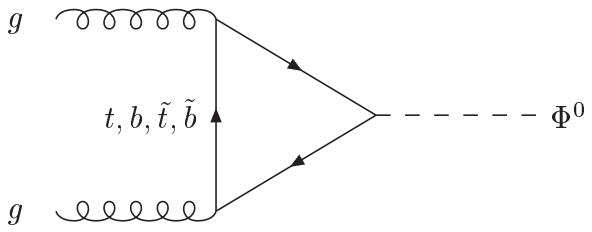
Noth, S.
Mihaila, Reißer

- approximation of NLO SUSY-QCD corrections within $< 1\%$

Guasch, Häfliger, S.

III HIGGS BOSON PRODUCTION @ LHC

(i) Gluon fusion: $pp \to gg \to h/H/A$



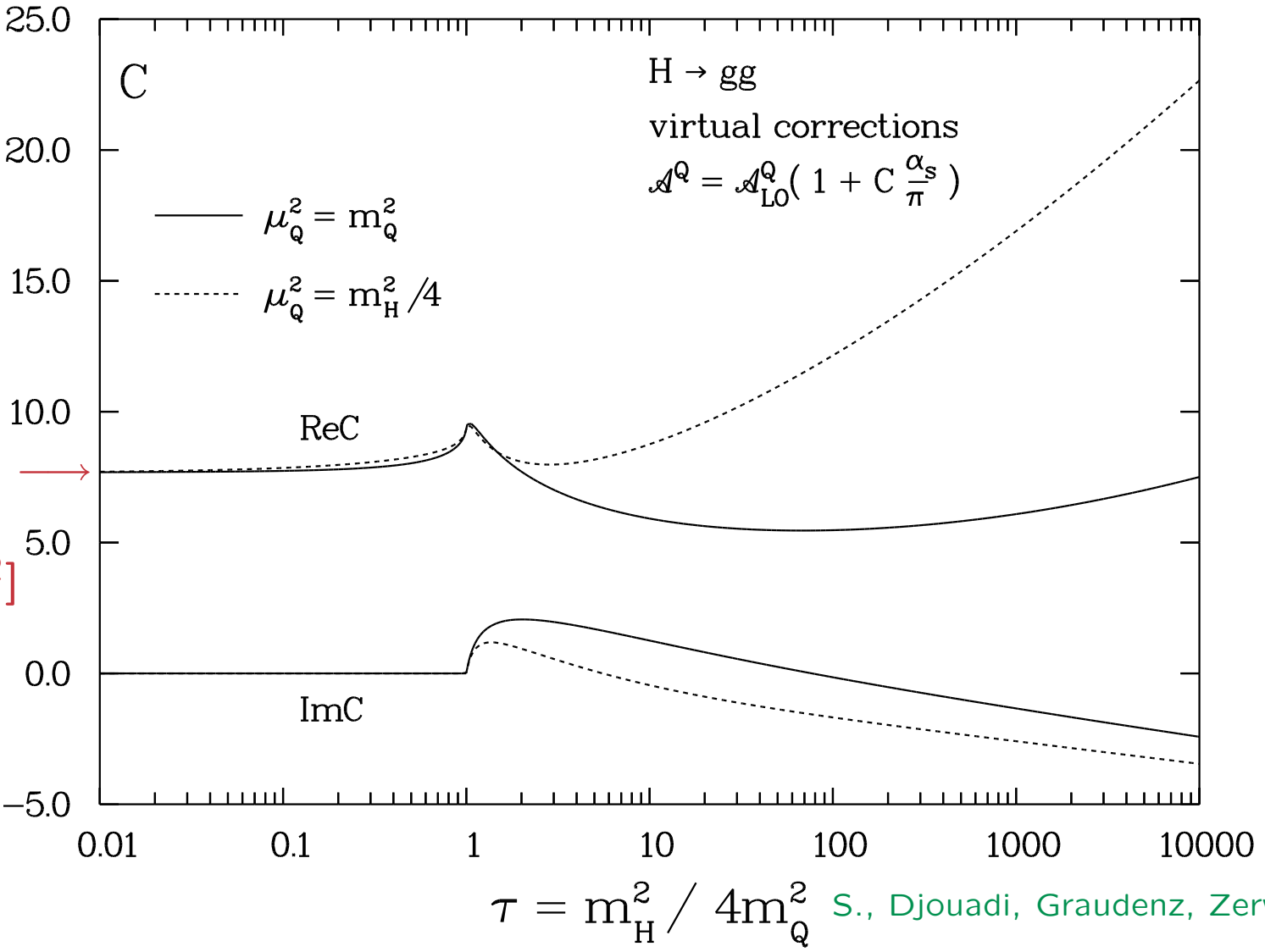
Georgi,. . .

Gamberini,. . .

- third generation dominant [$\tilde{t}, \tilde{b}$: $m_{\tilde{q}} \lesssim 400$ GeV] — F
- two-loop QCD corrections: $\sim 10 \ldots 100\%$ [moderate for large tg$\beta \leftarrow b$-loop] — SDGZ, Dawson, Kauffman
- tg$\beta \lesssim 5$: limit $m_t \gg M_\phi$ approximation for K-factor [$\Delta \lesssim 25\%$] — Harlander, Kilgore, Anastasiou, Melnikov, Ravindran,. . .
- NNLO calculated for $m_t \gg M_\phi \Rightarrow +$ 20–30% — Moch, Vogt, Ravindran
- NNNLO estimated $m_t \gg M_\phi \quad \Rightarrow$ scale stabilization scale dependence: $\Delta \lesssim 10 - 15\%$ — Catani, De Florian, Grazzini, Nason
- NNLL resummation: +10%
- NNLO mass effects calculated [t-loops] for $M_H \lesssim 300$ GeV $\Rightarrow \mathcal{O}(0.5\%)$ — Harlander, Ozeren, Pak, Rogal, Steinhauser, Marzani, Ball, Del Duca, Forte, Vicini, Aglietti,. . .
- NLO electroweak corrections: -4% – 6% [SM] — Degrassi, Maltoni, Actis,. . .

$$\sigma_{LO}(pp \to \phi^0) = \sigma_0^{\phi} \tau_{\phi} \frac{d\mathcal{L}^{gg}}{d\tau_{\phi}}$$

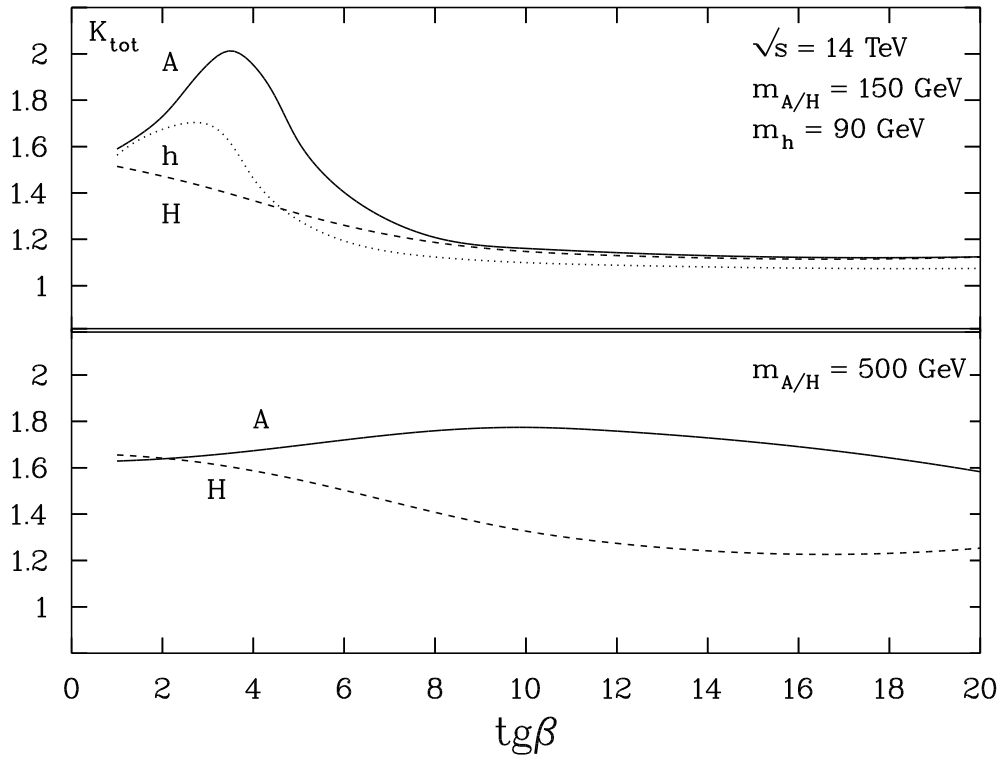
$$\sigma_0^{h/H} = \frac{G_F \alpha_s^2}{288\sqrt{2}\pi} \left| \sum_Q g_Q^{h/H} A_Q^{h/H}(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^{h/H} A_{\tilde{Q}}^{h/H}(\tau_{\tilde{Q}}) \right|^2$$

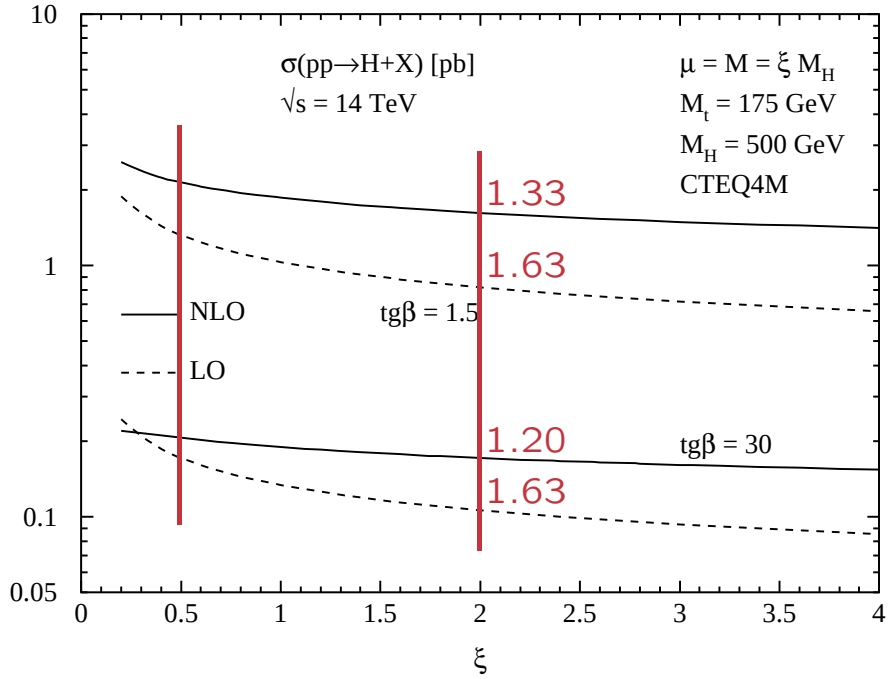


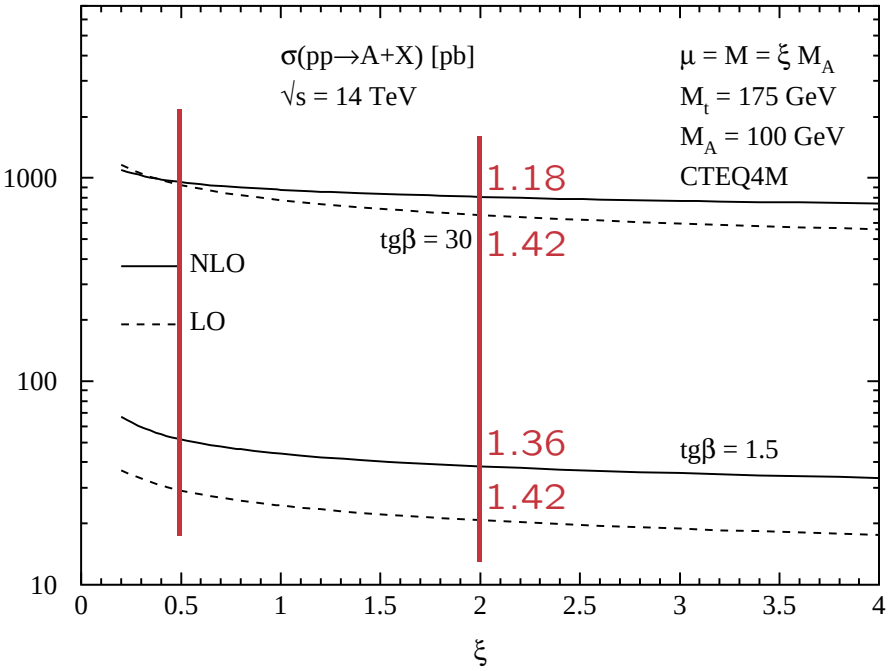
$\frac{1}{2}\left(\pi^2 + \frac{11}{2}\right) \longrightarrow$

$[M_H^2 \ll 4m_t^2]$

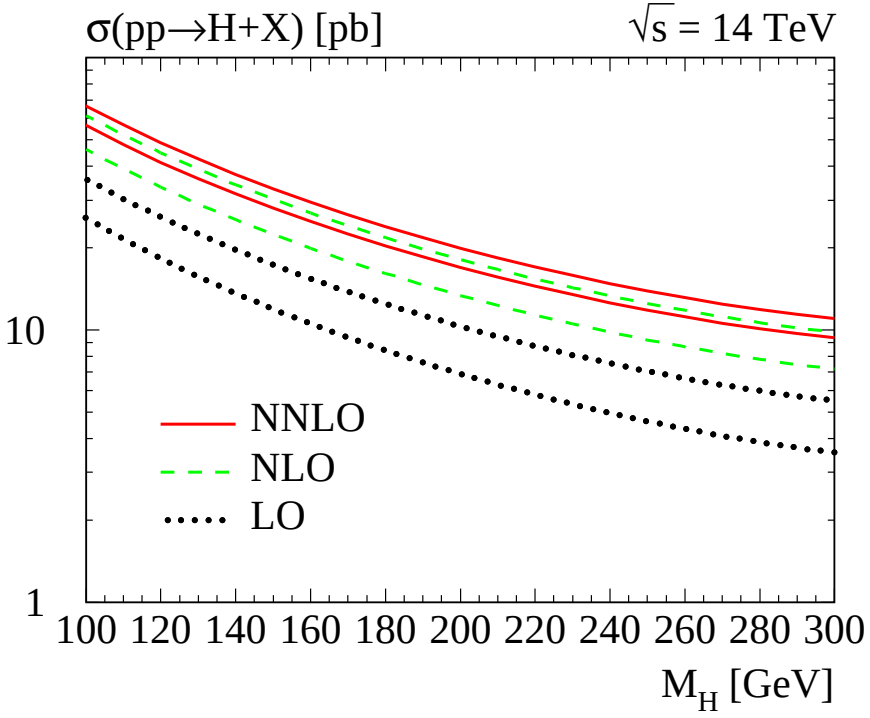
S., Djouadi, Graudenz, Zerwas



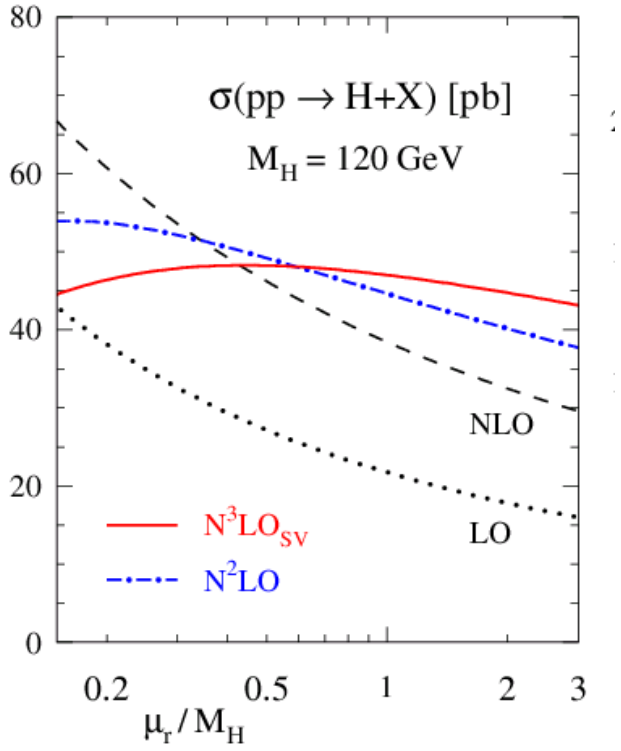




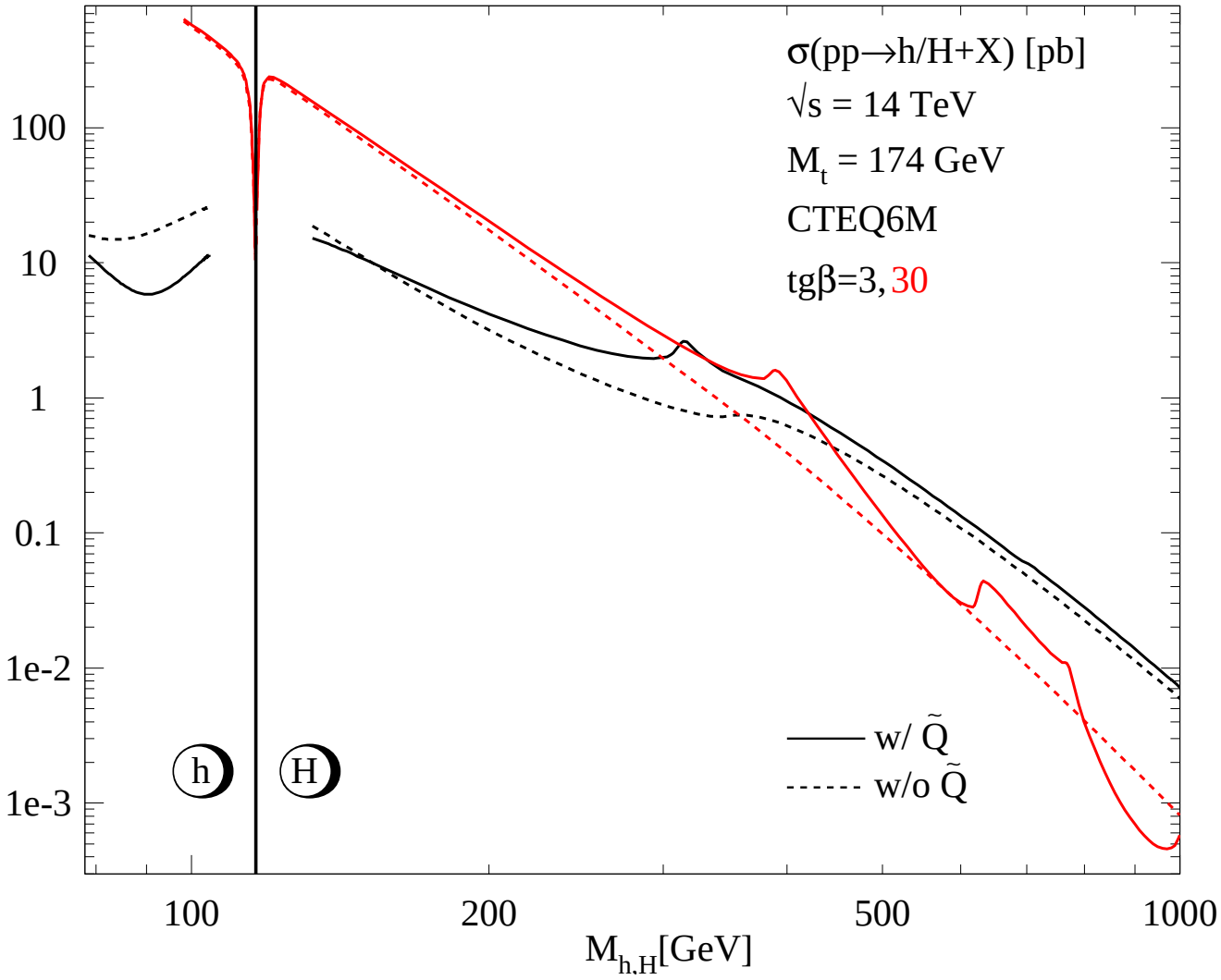
S., Djouadi, Graudenz, Zerwas



Harlander, Kilgore



Moch, Vogt



Mühlleitner, S.

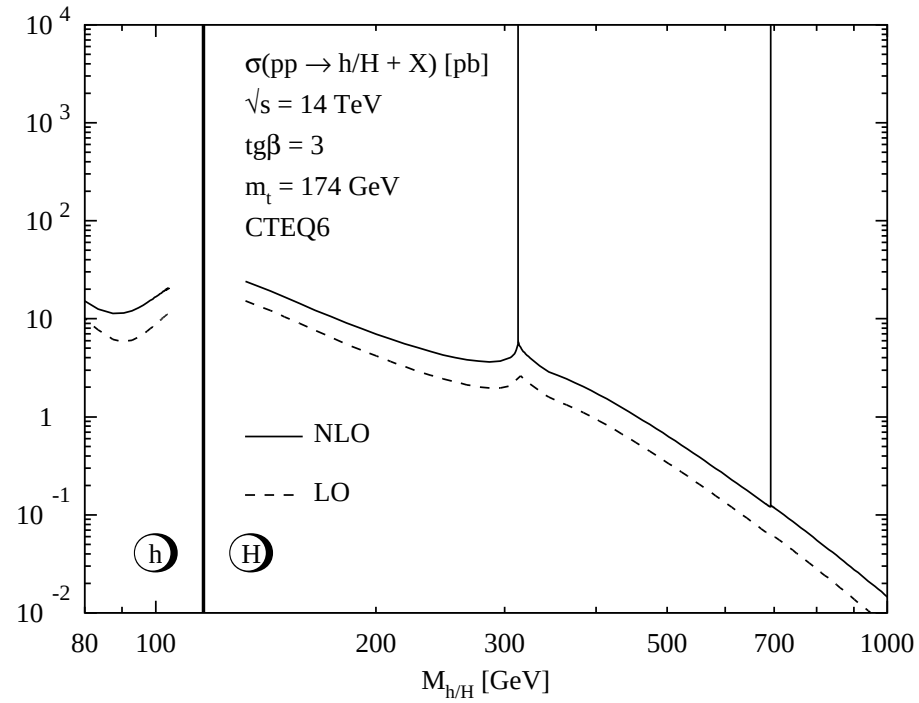
gluophobic Higgs scenario:

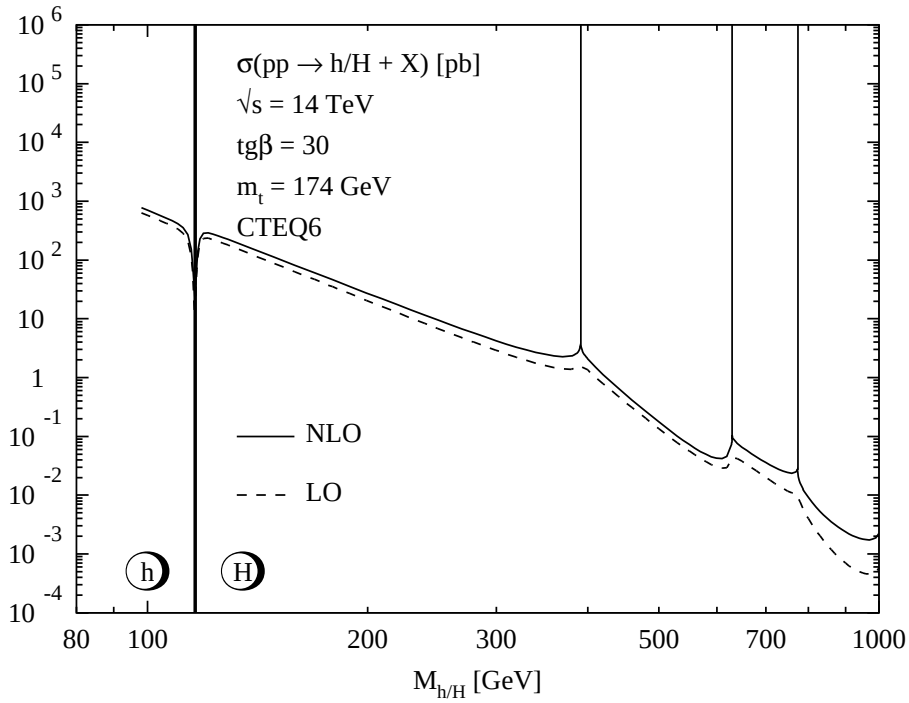
tgβ=3: $m_{\tilde{t}_1}$=156 GeV, $m_{\tilde{t}_2}$=516 GeV, $m_{\tilde{b}_1}$=346 GeV, $m_{\tilde{b}_2}$=358 GeV

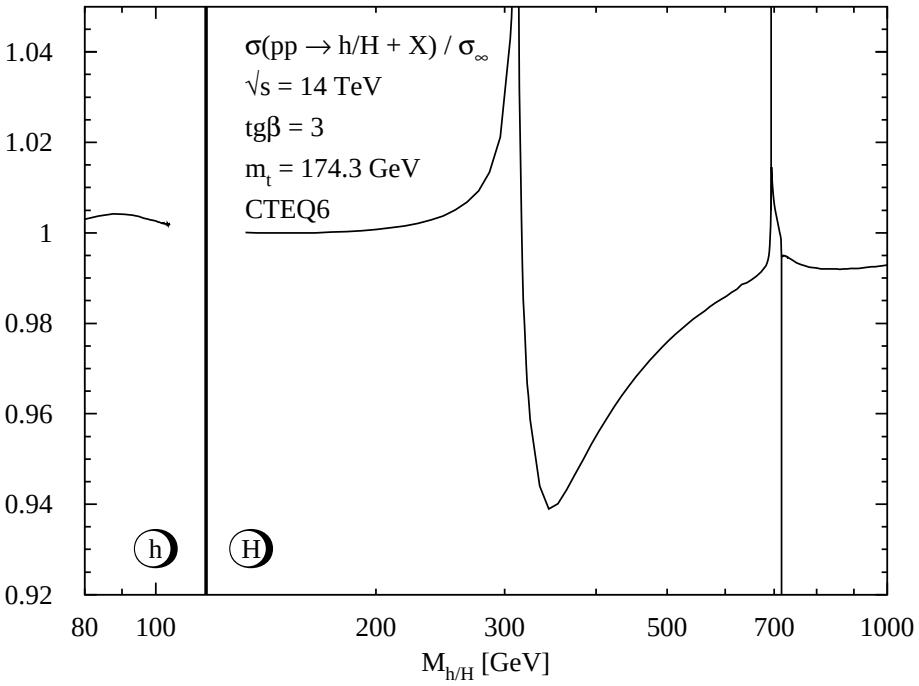
tgβ=30: $m_{\tilde{t}_1}$=195 GeV, $m_{\tilde{t}_2}$=502 GeV, $m_{\tilde{b}_1}$=315 GeV, $m_{\tilde{b}_2}$=387 GeV

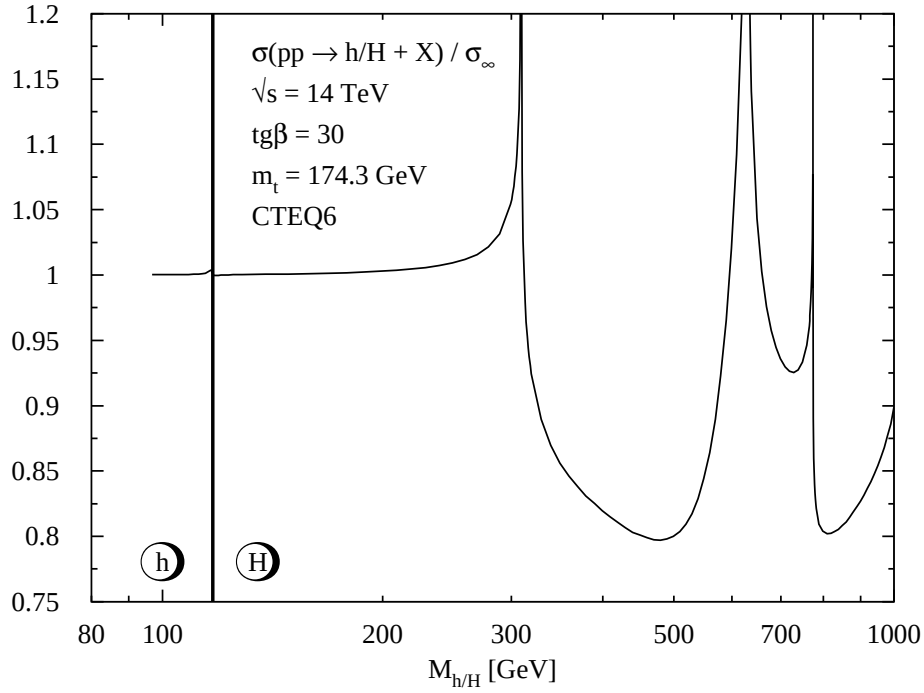
pure QCD corrections to squark loops:

Mühlleitner, S.



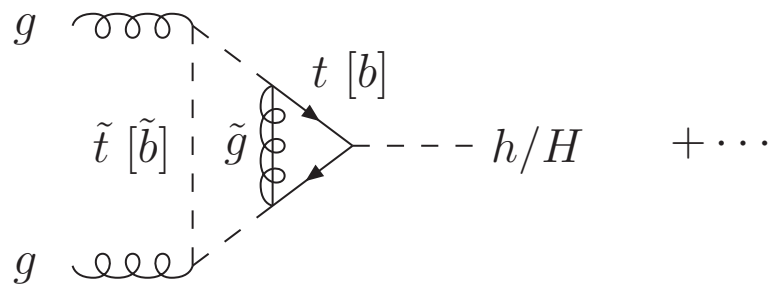




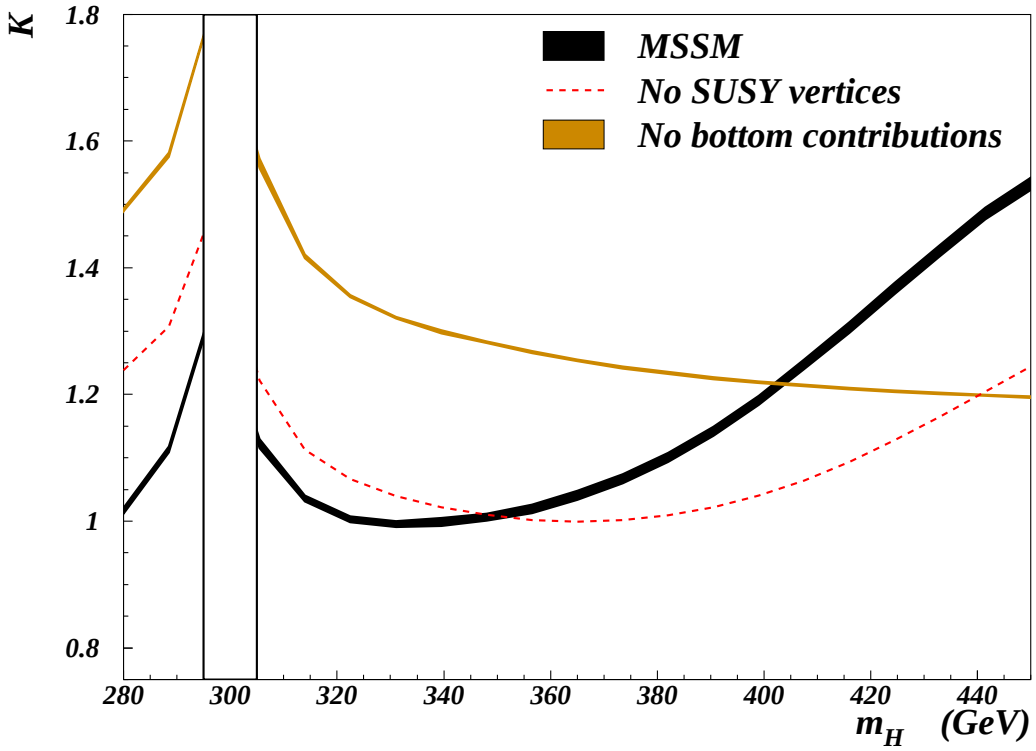


genuine SUSY–QCD corrections: O(10%) for $M_\Phi \ll M_{SUSY}$

Harlander, Steinhauser
Hofmann



Anastasiou, Beerli, Daleo
Mühlleitner, Rzehak, S.



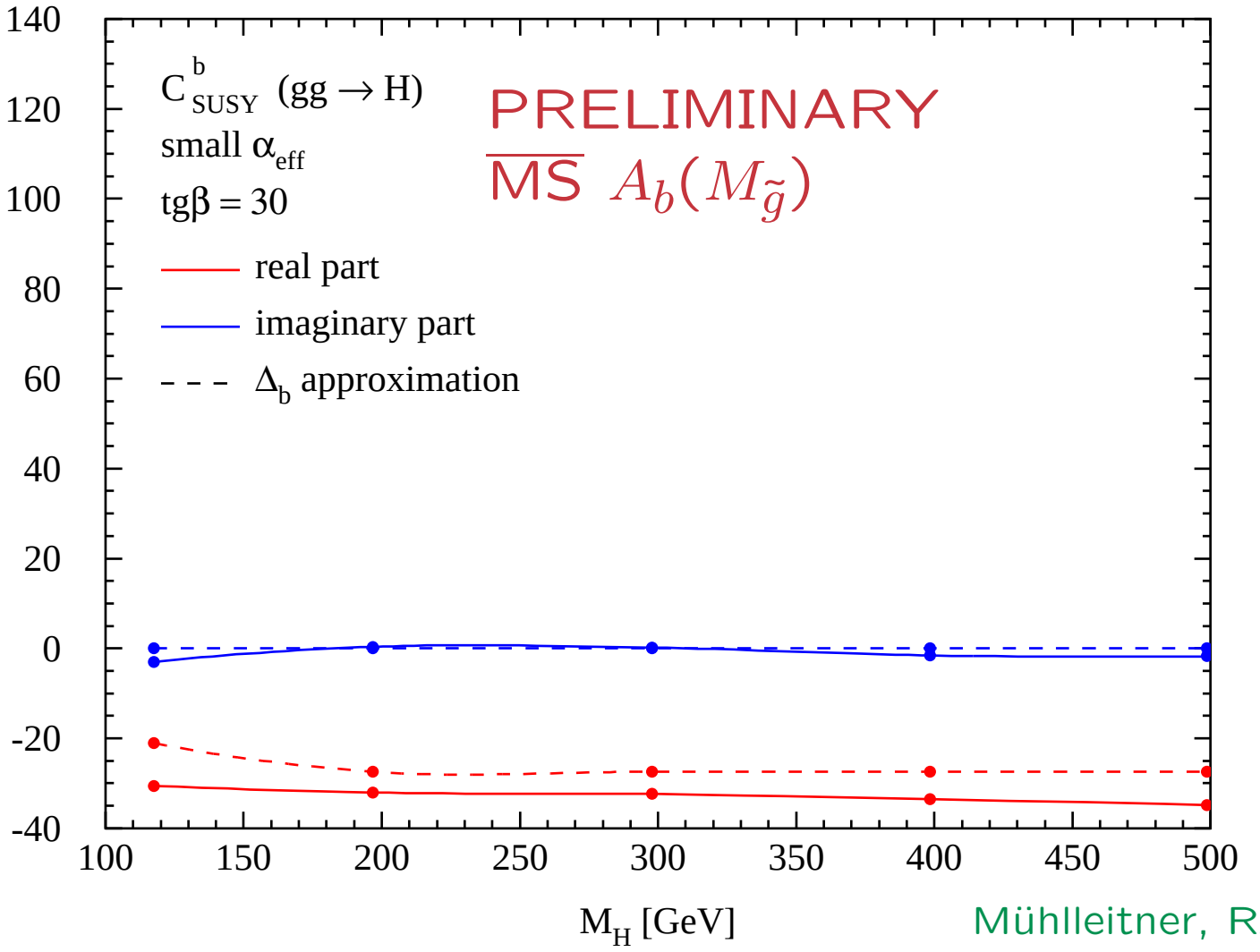
Anastasiou, Beerli, Daleo

$$\text{tg}\beta = 20 \quad \mu = 300\ GeV \quad \alpha = 3^o \quad \theta_t = \theta_b = 40^o$$

$$m_{\tilde{t}_1} = 150\ GeV \quad m_{\tilde{t}_2} = 350\ GeV \quad m_{\tilde{b}_1} = 350\ GeV \quad m_{\tilde{b}_2} = 370\ GeV$$

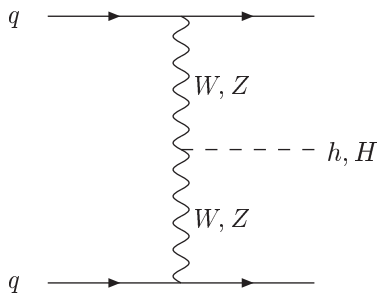
$$\sigma_{LO}(pp \to \phi^0) = \sigma_0^\phi \tau_\phi \frac{d\mathcal{L}^{gg}}{d\tau_\phi}$$

$$\sigma_0^{h/H} = \frac{G_F \alpha_s^2}{288\sqrt{2}\pi} \left| \sum_Q g_Q^{h/H} A_Q^{h/H}(\tau_Q) \left[1 + C_{SUSY}^Q \frac{\alpha_s}{\pi} \right] + \sum_{\tilde{Q}} g_{\tilde{Q}}^{h/H} A_{\tilde{Q}}^{h/H}(\tau_{\tilde{Q}}) \right|^2$$



Mühlleitner, Rzehak, S.

(ii) W/Z fusion: $pp \to W^*W^*/Z^*Z^* \to h/H$



Cahn, Dawson
Hikasa
Atarelli, Mele, Pitolli

- NLO QCD corrections ← DIS: $\sim 10\%$ for σ
  $\lesssim 20\%$ for $d\sigma$

  Han, Valencia, Willenbrock

  Figy, Oleari, Zeppenfeld
  Berger, Campbell
  Ciccolini, Denner, Dittmaier

- NNLO QCD corrections ← DIS: $< 1\%$ for σ

  Bolzoni, Maltoni, Moch, Zaro

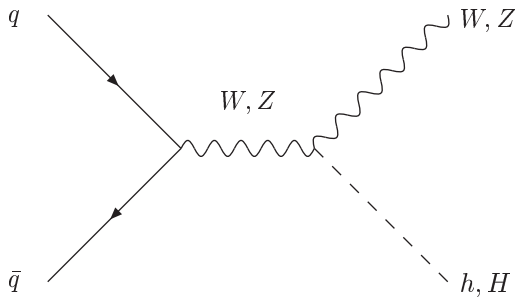
- elw. corrections: $\sim -(5-20)\%$

  Ciccolini, Denner, Dittmaier

- SUSY-QCD and -elw. corrections: $\lesssim$ few per cent

  Djouadi, Spira
  Hollik, Plehn, Rauch, Rzehak

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

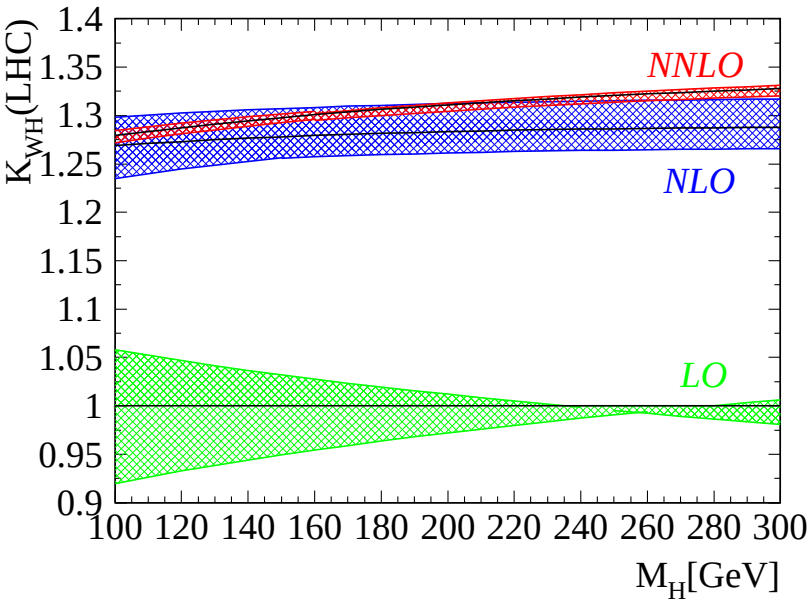


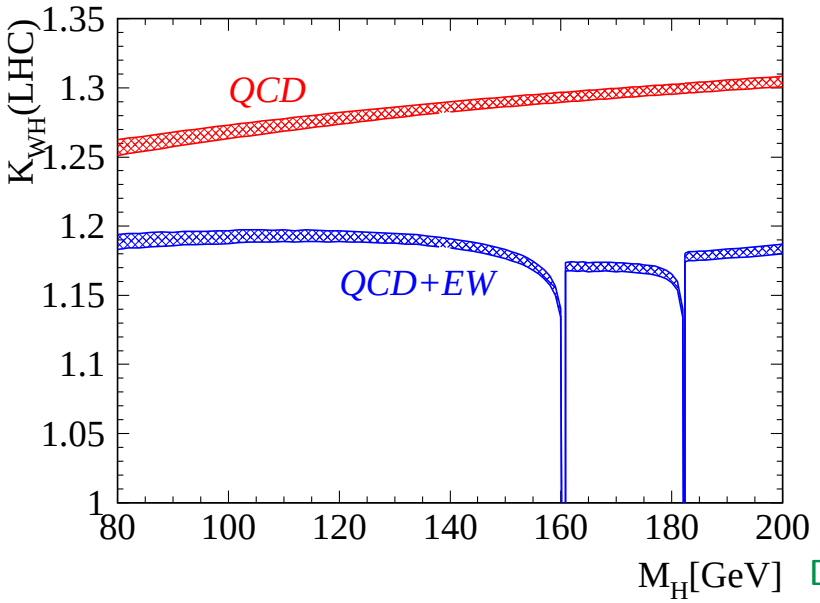
Glashow,. . .
Kunszt,. . .

- QCD corrections ← DY: $\sim 30\%$
  2–loop: $\lesssim 5\%$

Han, Willenbrock

Brein, Djouadi, Harlander



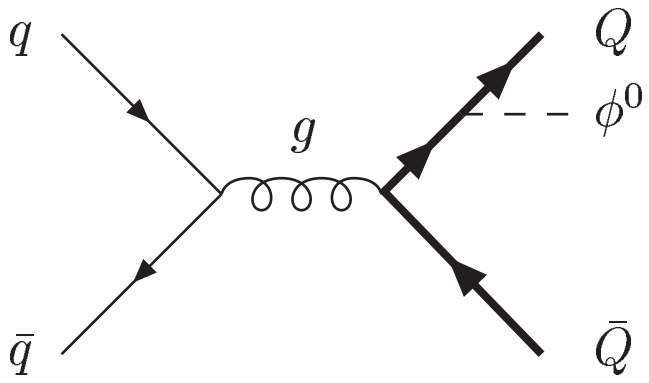


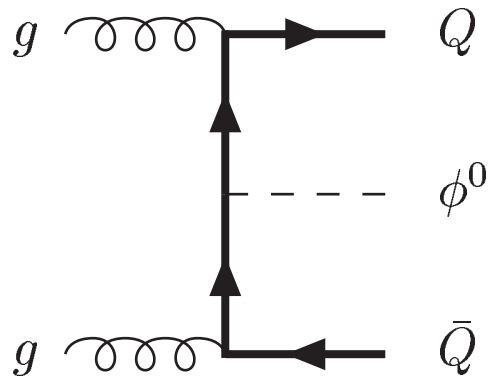
Brein, Ciccolini, Dittmaier, Djouadi, Harlander, Krämer

- SUSY-QCD corrections: $\lesssim$ few per cent

Djouadi, Spira

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





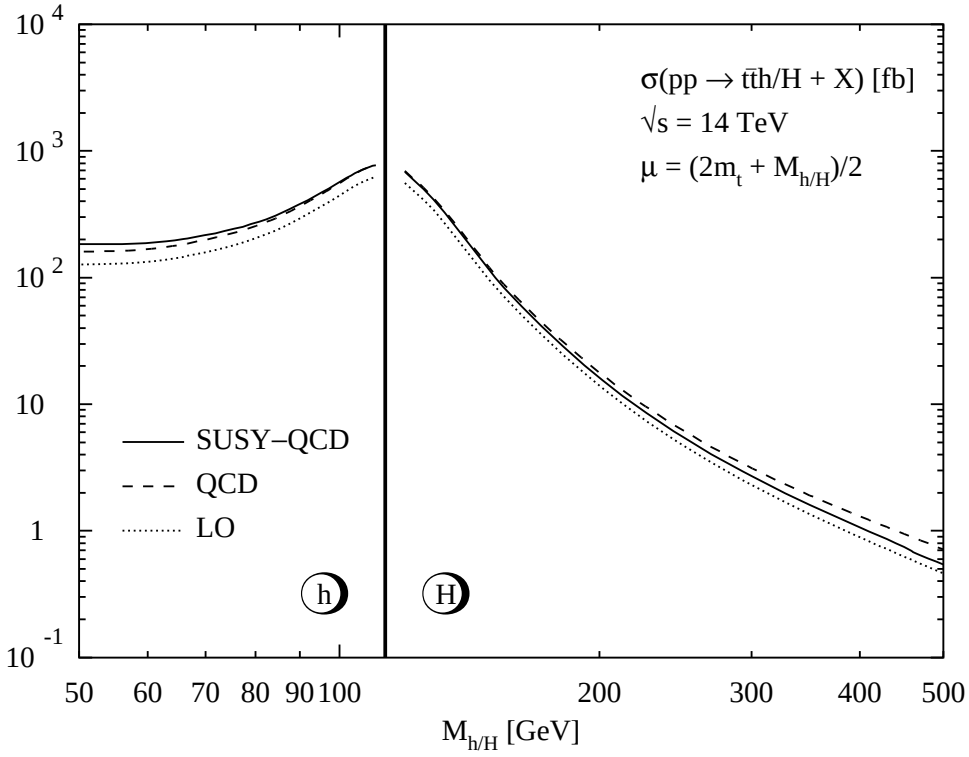
dominant

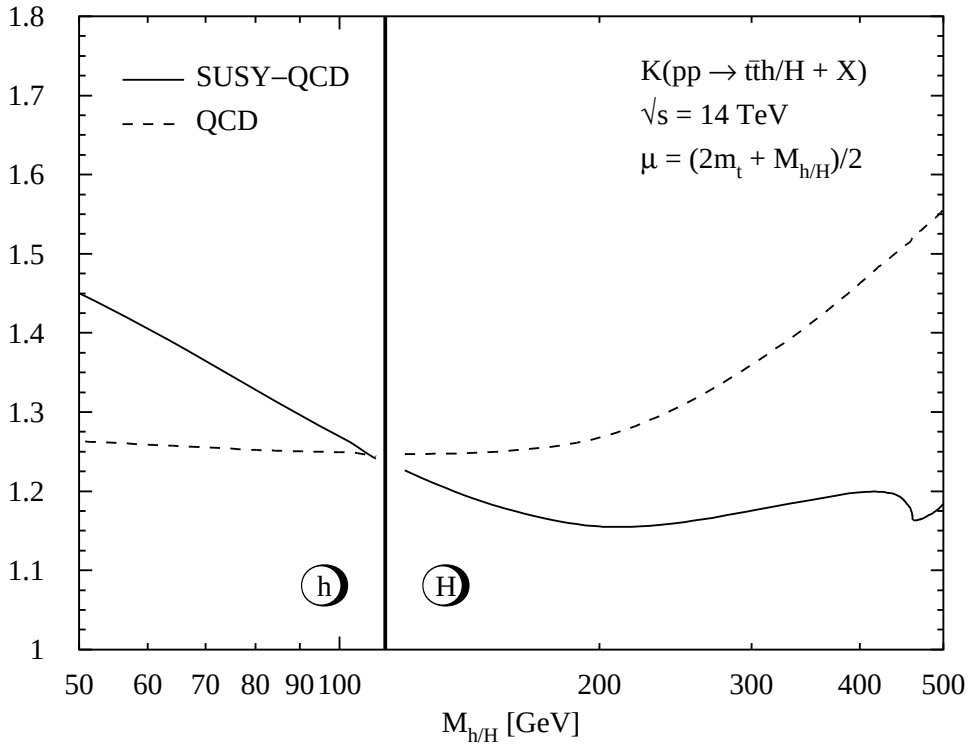
Kunszt
Gunion
Marciano, Paige

- possibility to measure top/bottom Yukawa cplg.
- $b\bar{b} + H/A$ important for large tgβ
- measurement of tgβ
- QCD corrections: -20% for $t\bar{t}\phi$ @ Tevatron
  20% for $t\bar{t}\phi$ @ LHC
  $\mathcal{O}(100\%)$ for $b\bar{b}\phi \Rightarrow$ 4FS $\leftrightarrow$ 5FS

Beenakker,. . .
Dawson,. . .
Dittmaier, Krämer, S.
Dawson, Jackson, Reina, Wackeroth

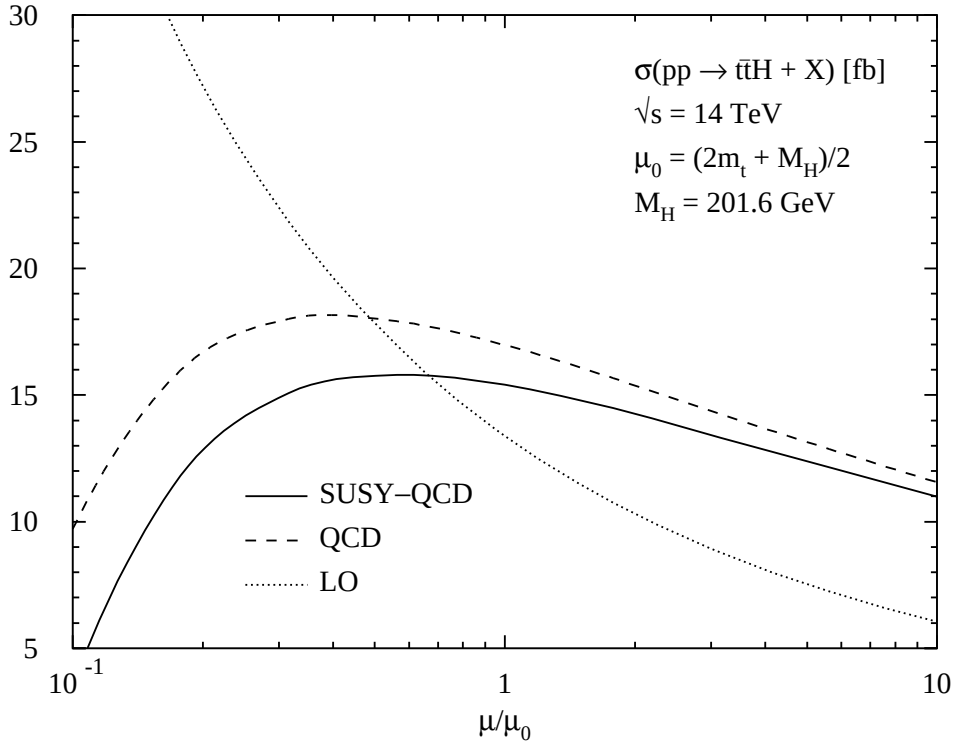
- SUSY-QCD corrections: $\sim \pm(10-30)\%$ for $t\bar{t}\phi$
  Δ_b for $b\bar{b}\phi$ $[\delta < 1\%]$





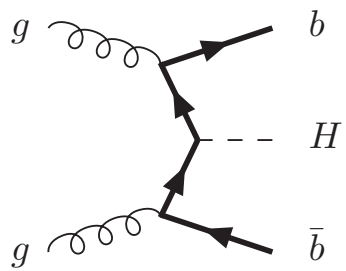
SPS5

PRELIMINARY

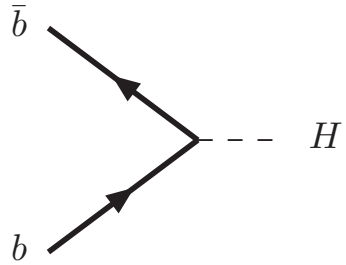


$\Rightarrow \Delta \lesssim 10\%$

Dittmaier, Häfliger,
Krämer, S., Walser



NLO



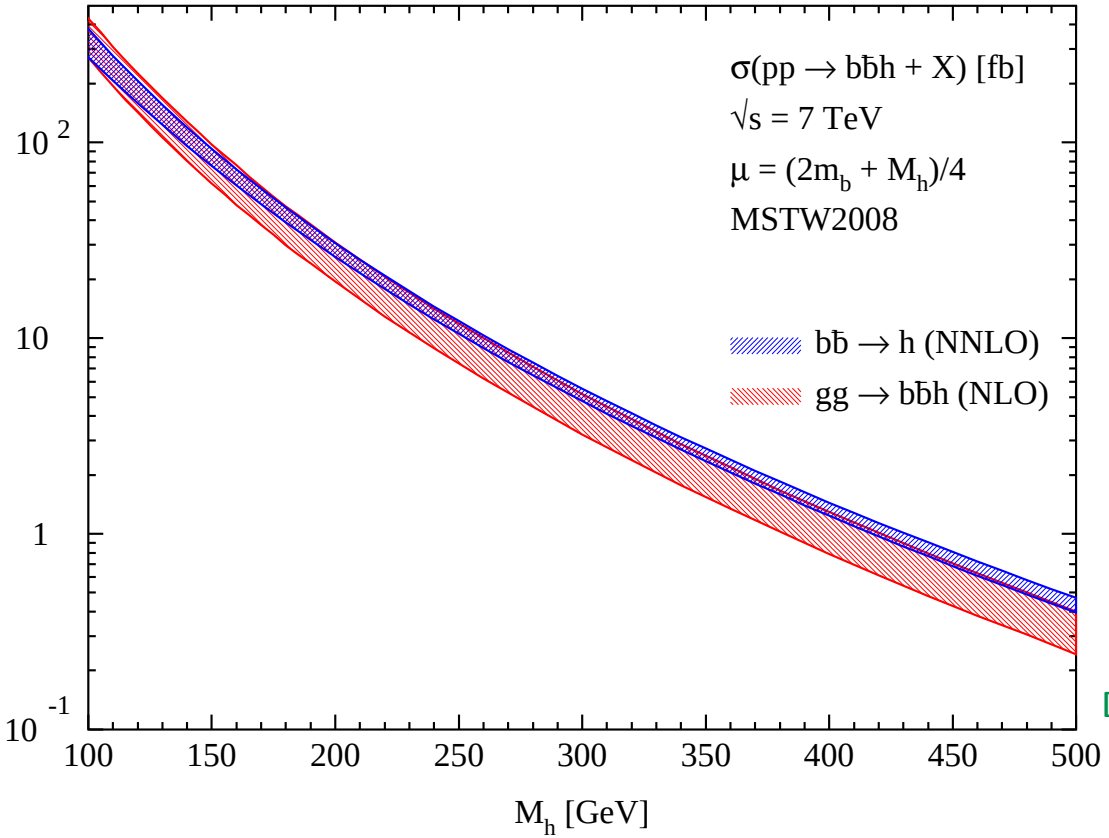
NNLO

exact $g \to b\bar{b}$ splitting & mass/off-shell effects

no resummation of $\log M_H^2/m_b^2$ terms

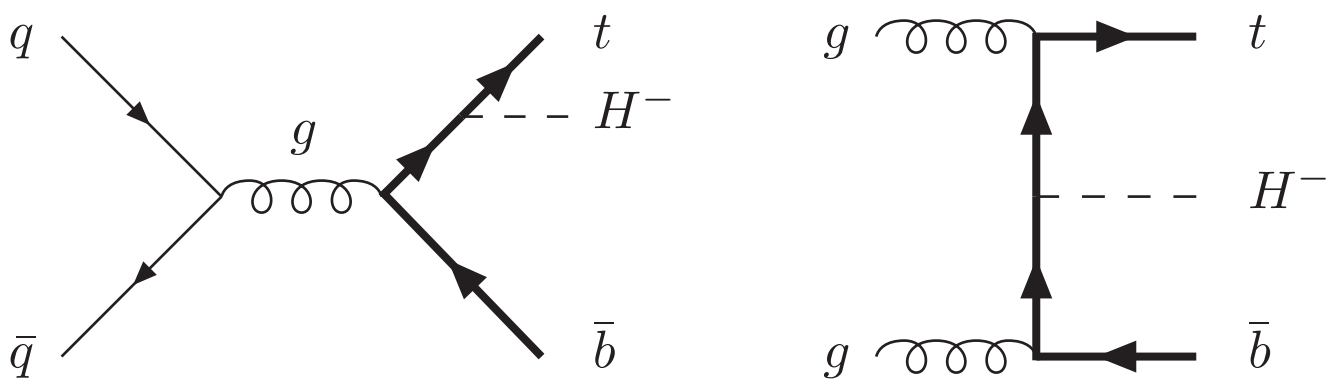
massless/on-shell b's, no p_{Tb}

resummation of $\log M_H^2/m_b^2$ terms



Dittmaier, Krämer, S.
Dawson, Jackson, Reina, Wackeroth
Harlander, Kilgore

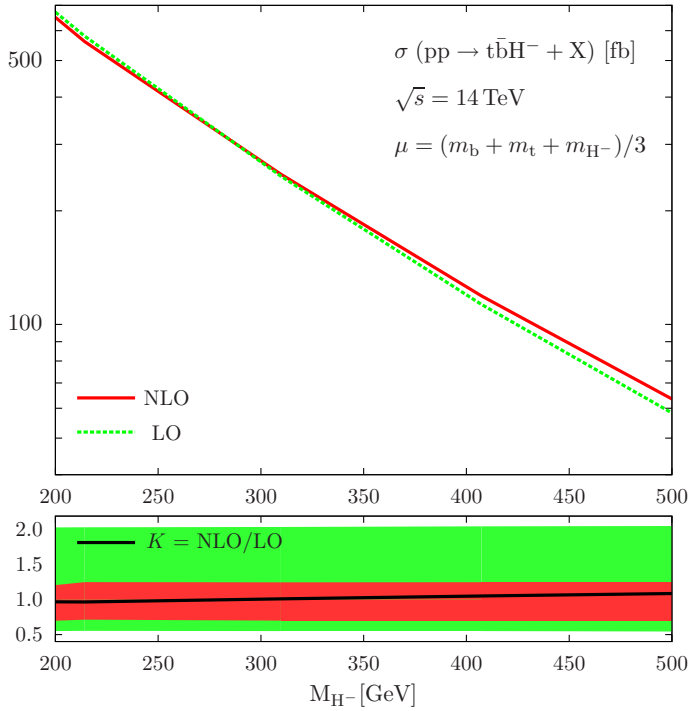
(v) $pp \to t\bar{b}H^- + X$

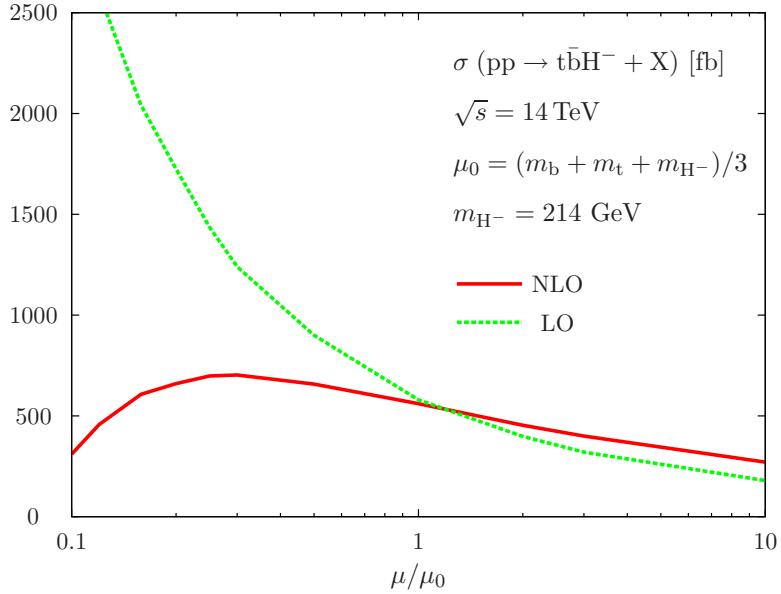


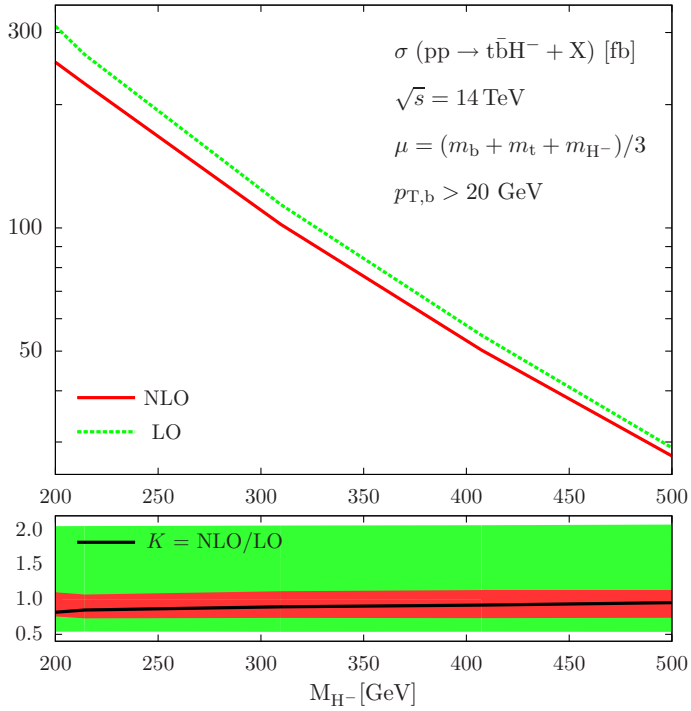
dominant

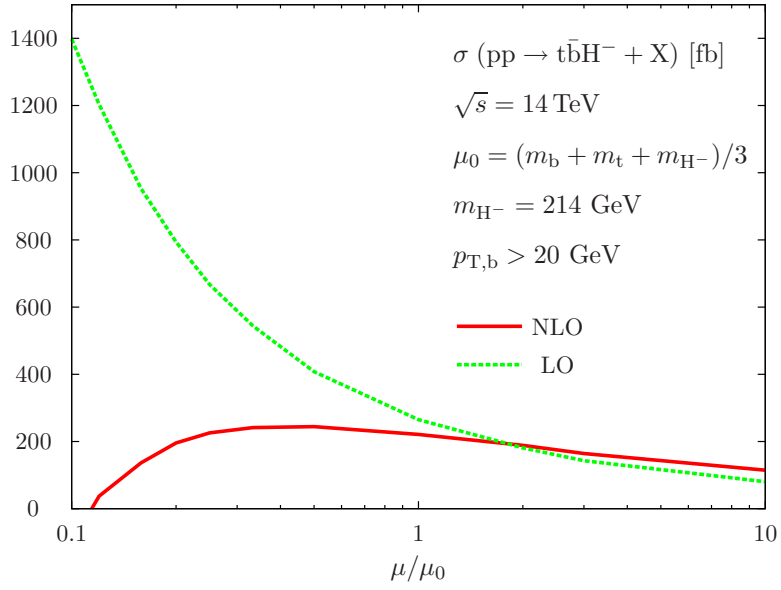
- dominant charged Higgs boson production process
- clear signal of extended Higgs sector
- continuum calculation in 4FS [$M_{H^\pm} > m_t - m_b \quad \Rightarrow \quad \bar{t} \not\to H^-\bar{b}$]
- SUSY-QCD corrections to $bg \to H^-t$ known

Zhu
Gao, Lu, Xiong, Yang
Plehn
Berger, Han, Jiang, Plehn
Kidonakis

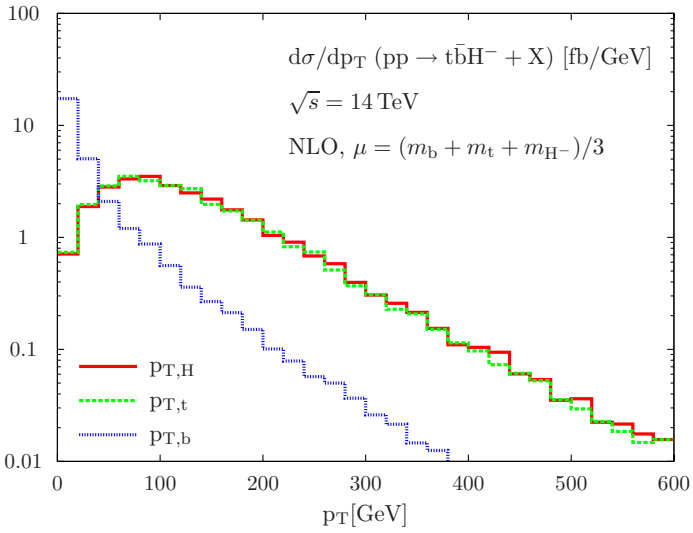


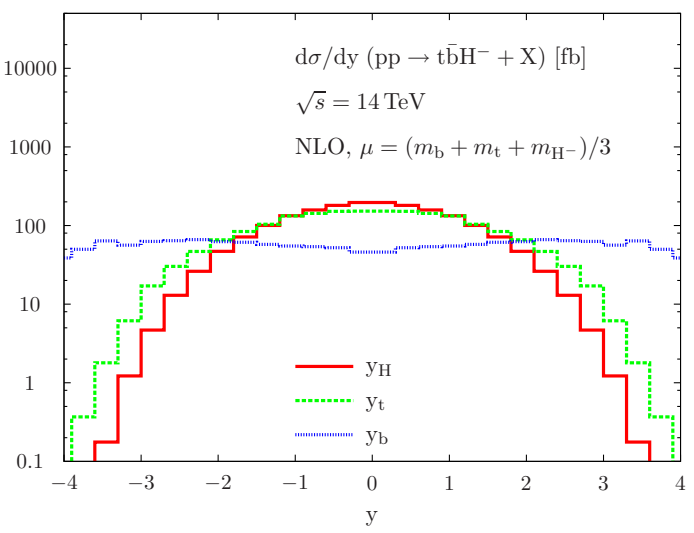


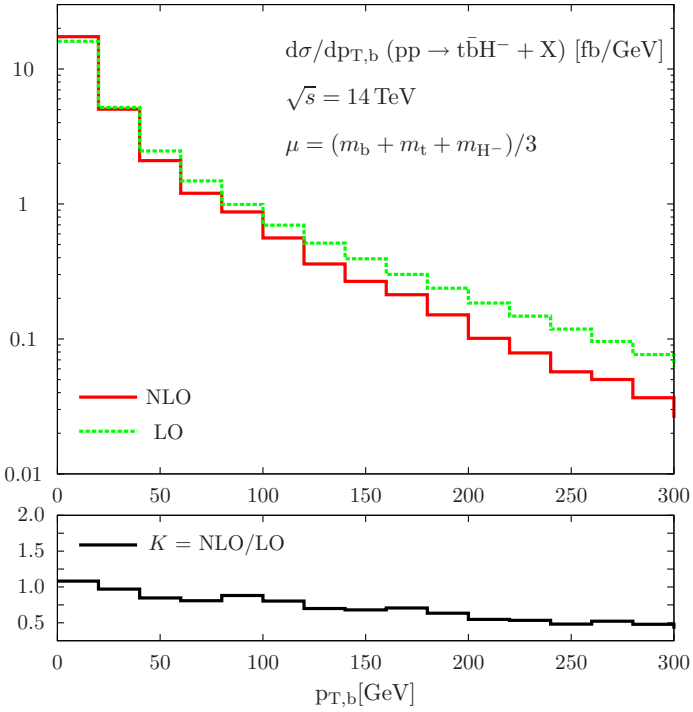


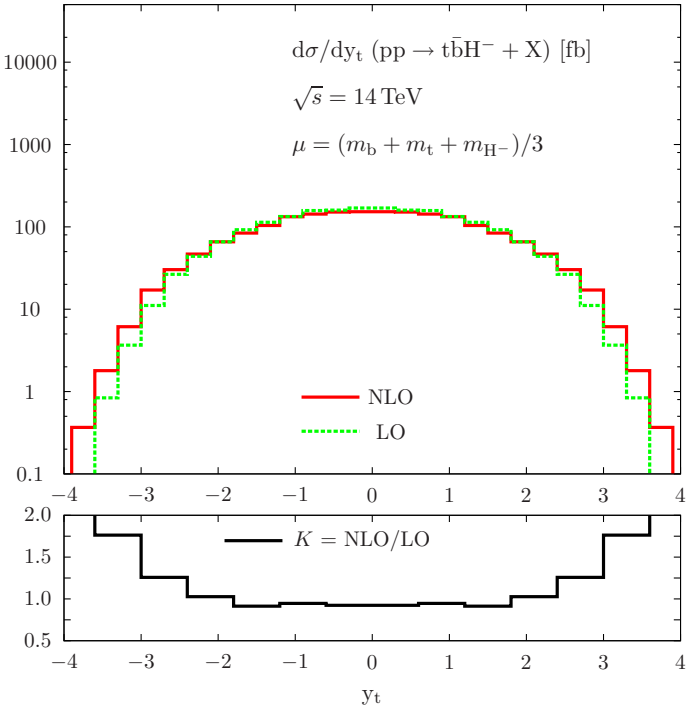


Dittmaier, Krämer, S., Walser

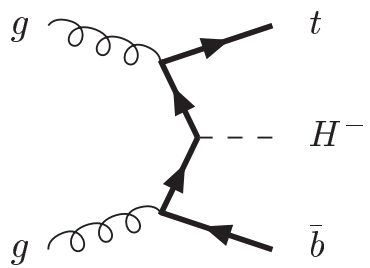








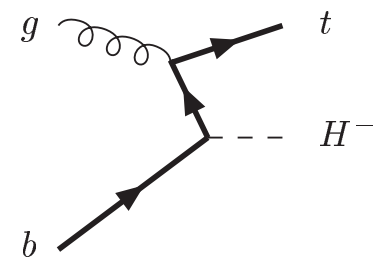
Dittmaier, Krämer, S., Walser



NLO

exact $g \to b\bar{b}$ splitting & mass/off-shell effects

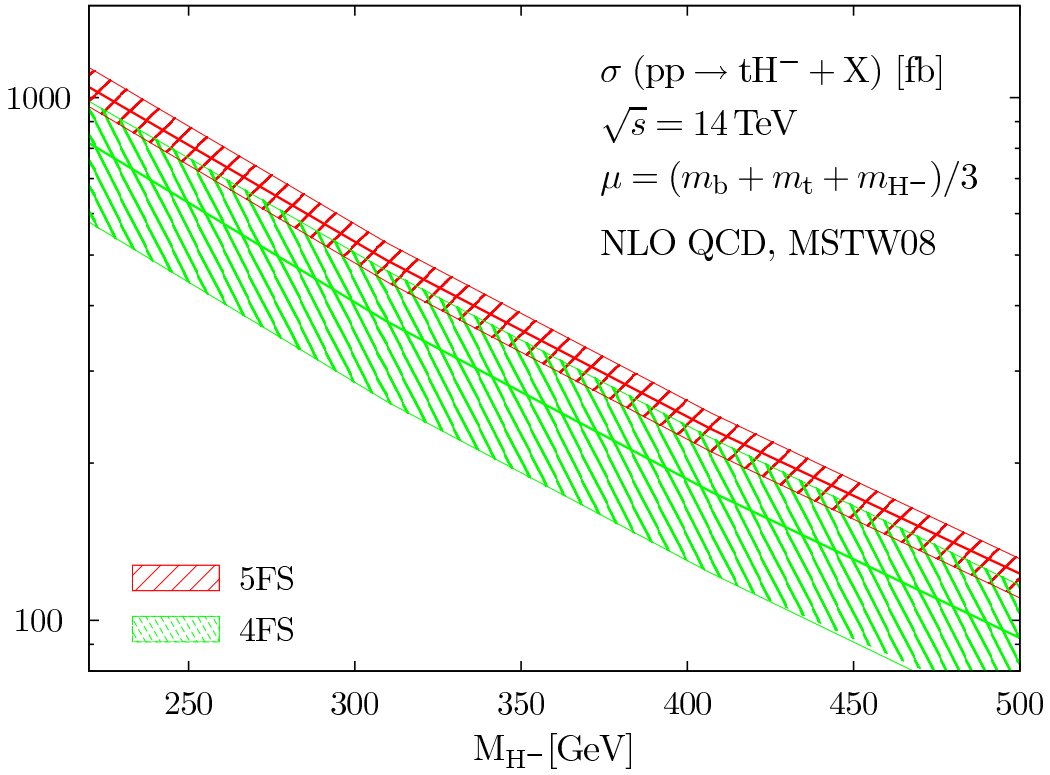
no resummation of $\log M_H^2/m_b^2$ terms



NLO

massless/on-shell b's, no p_{Tb}

resummation of $\log M_H^2/m_b^2$ terms



Dittmaier, Krämer, S., Walser

Plehn

V *SUMMARY*

- Higgs boson searches @ HC major endeavours

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

- most (SUSY–)QCD and electroweak corrections known
  [$\Rightarrow$ large corrections to gluon fusion, $b\bar{b}\phi, t\bar{b}H^-$]
  remaining theoretical uncertainties: $\sim 100\% \longrightarrow \lesssim 15\%$

- close collaboration of experimentalists and theorists:
  LHC Higgs Cross Section WG

BACKUP SLIDES

small α_{eff} scenario [modified]

$$
\begin{aligned}
\mathrm{tg}\beta &= 30 \\
M_{\tilde{Q}} &= 800 \text{ GeV} \\
M_{\tilde{g}} &= 1000 \text{ GeV} \qquad \longleftarrow \\
M_2 &= 500 \text{ GeV} \\
A_b = A_t &= -1.133 \text{ TeV} \\
\mu &= 2 \text{ TeV}
\end{aligned}
$$

$$
\begin{aligned}
m_{\tilde{t}_1} &= 679 \text{ GeV} \qquad & m_{\tilde{t}_2} &= 935 \text{ GeV} \\
m_{\tilde{b}_1} &= 601 \text{ GeV} \qquad & m_{\tilde{b}_2} &= 961 \text{ GeV}
\end{aligned}
$$