PAUL SCHERRER INSTITUT

NEUTRAL HIGGS PRODUCTION

Michael Spira (PSI)

I Introduction

II Higgs Boson Production @ LHC: Gluon Fusion

III Summary

I INTRODUCTION

(i) Standard Model

- LEP2: $M_H > 114.4$ GeV

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

- triviality and vacuum stability:

$\Rightarrow M_H \lesssim 700$ GeV [$\Lambda \sim 1$ TeV]
130 GeV $\lesssim M_H \lesssim$ 190 GeV [$\Lambda \sim M_{GUT}$]

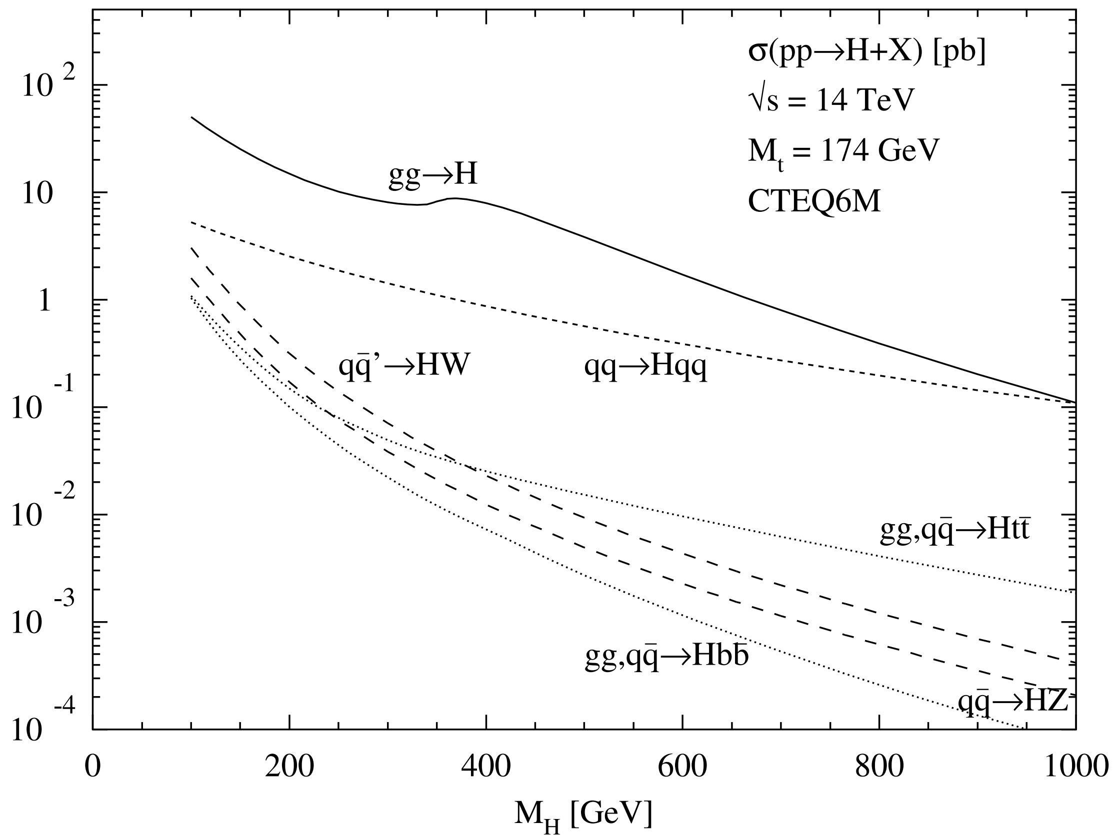
- elw. fits: $M_H \lesssim$ 193 GeV (95% CL) LEP/SLC

- LHC: $gg \to H$ dominant F

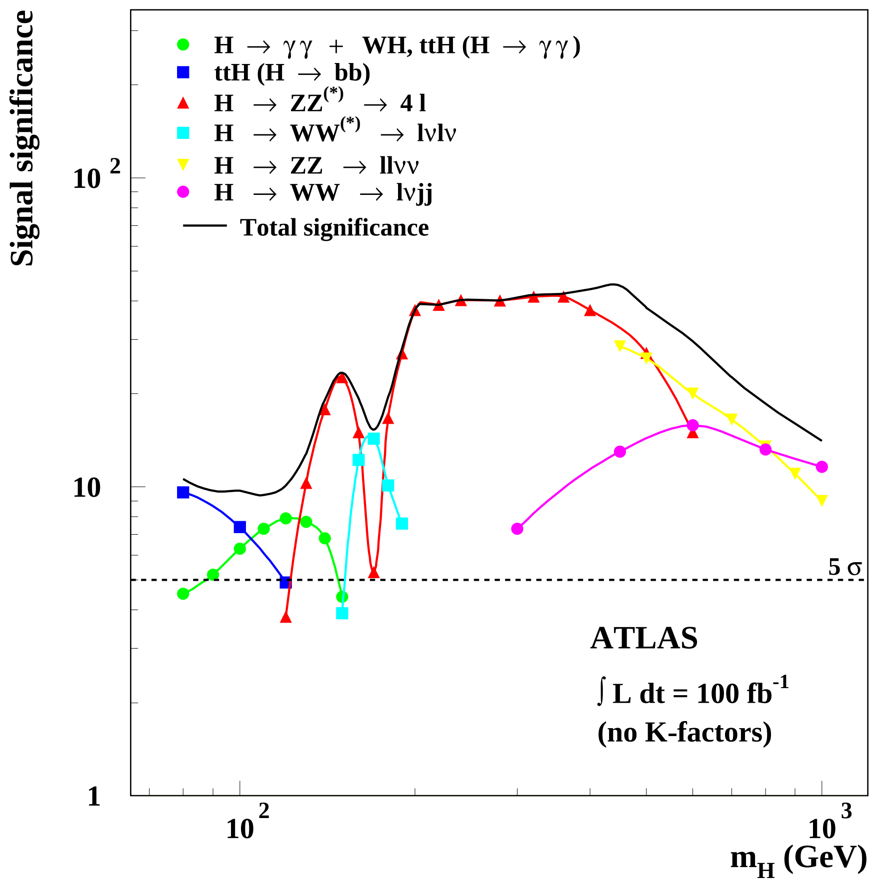
$M_H \lesssim$ 140 GeV: $H \to \gamma\gamma, (b\bar{b})$ F

140 GeV $\lesssim M_H \lesssim$ 1 TeV: $H \to ZZ^{(*)} \to 4\ell^{\pm}$
$H \to WW, ZZ \to \ell' s, jets$

120 GeV $\lesssim M_H \lesssim$ 200 GeV: $H \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$ [ang. corr.]
Dittmar, Dreiner



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]



Signal significance
H → γγ + WH, ttH (H → γγ)
ttH (H → bb)
H → ZZ(*) → 4 l
H → WW(*) → lνlν
H → ZZ → llνν
H → WW → lνjj
Total significance
10^2
10
1
5 σ
ATLAS
∫L dt = 100 fb^-1
(no K-factors)
10^2
10^3
m_H (GeV)

(ii) MSSM

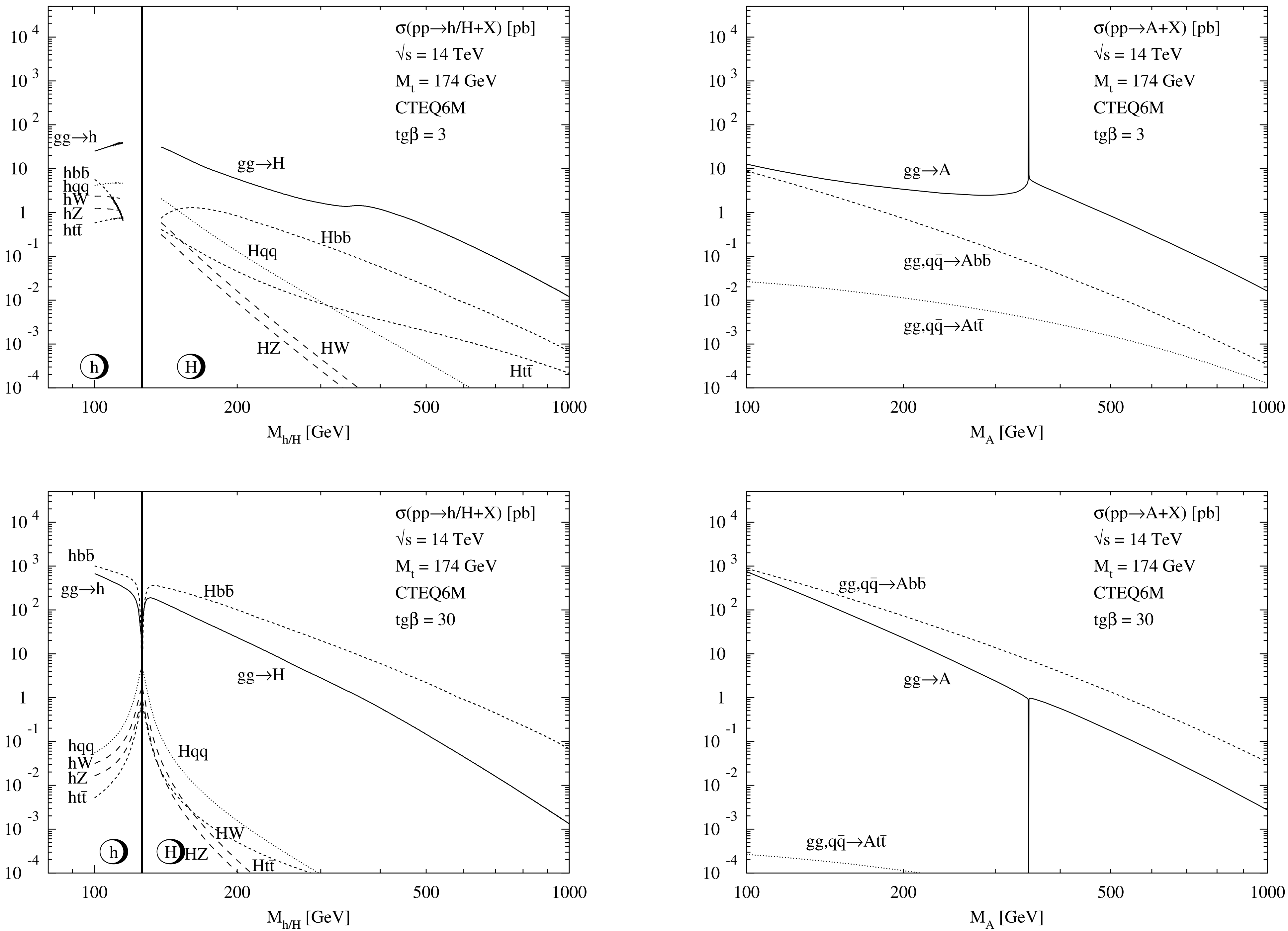
- 2 Higgs doubletts $\xrightarrow{\text{ESB}}$ 5 Higgs bosons: $h, H, A, H^\pm$
- LO: 2 input parameters: $M_A, \text{tg}\beta = \frac{v_2}{v_1}$
- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\rightarrow$ $\boxed{M_h \lesssim 135 \text{ GeV}}$

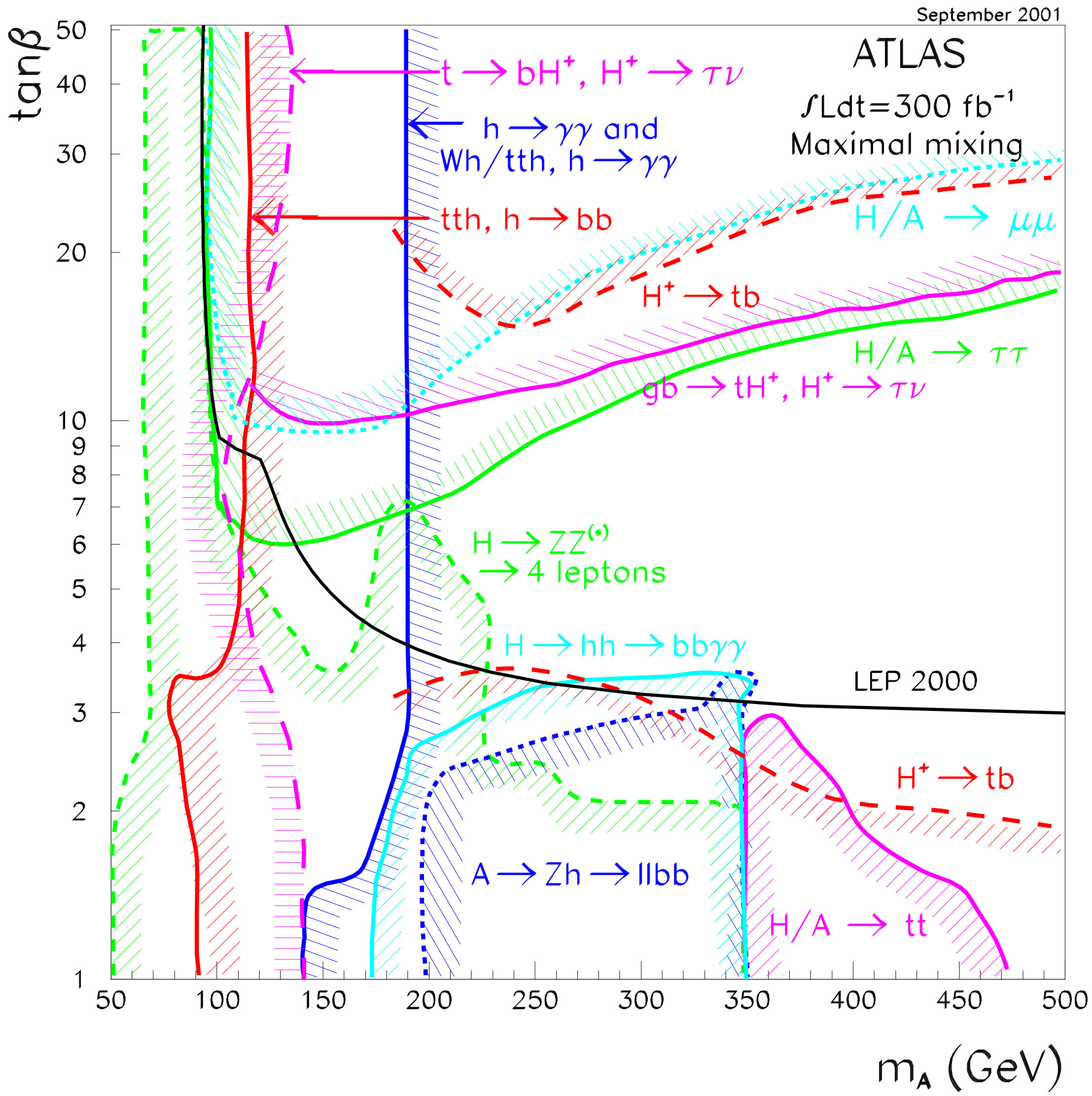
Haber
Carena, . . .
Heinemeyer, . . .
Zhang
Slavich, . . .
. . .

- Yukawa couplings: $\text{tg}\beta\uparrow \quad \Rightarrow \quad g_u^\phi\downarrow \quad g_d^\phi\uparrow \quad g_V^\phi\downarrow$
- LHC: $gg \to \phi$ dominant for $\text{tg}\beta \lesssim 10$
  $gg \to \phi b\bar{b}$ dominant for $\text{tg}\beta \gtrsim 10$ F

$h \to \gamma\gamma, b\bar{b}$
$H, A \to \tau^+\tau^-, \mu^+\mu^-$
$H^\pm \to \tau\nu_\tau$ F
and $VV \to h, H \to \tau^+\tau^-$ Kauer, . . .

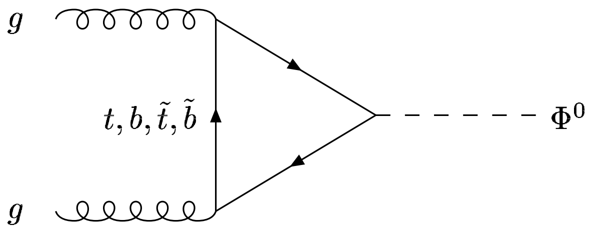
- $h \to b\bar{b}$ in SUSY production Paige, . . .


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


September 2001
ATLAS
∫Ldt=300 fb⁻¹
Maximal mixing
t → bH⁺, H⁺ → τν
h → γγ and
Wh/tth, h → γγ
tth, h → bb
H/A → μμ
H⁺ → tb
H/A → ττ
gb → tH⁺, H⁺ → τν
H → ZZ(*)
→ 4 leptons
H → hh → bbγγ
LEP 2000
H⁺ → tb
A → Zh → llbb
H/A → tt
tanβ
m_A (GeV)

II *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]
- two-loop QCD corrections: $\sim 10 \ldots 100\%$
  [moderate for large tg$\beta \leftarrow b$-loop]

SDGZ
Dawson, Kauffman

- NNLO calculated for $m_t \gg M_\phi \Rightarrow +$ 20–30%

Harlander, Kilgore
Anastasiou, Melnikov
Ravindran,. . .

- NNNLO estimated $m_t \gg M_\phi \quad \Rightarrow$ scale stabilization
scale dependence: $\Delta \lesssim 10 - 15\%$

Moch, Vogt
Ravindran

- NNLL resummation: +10%

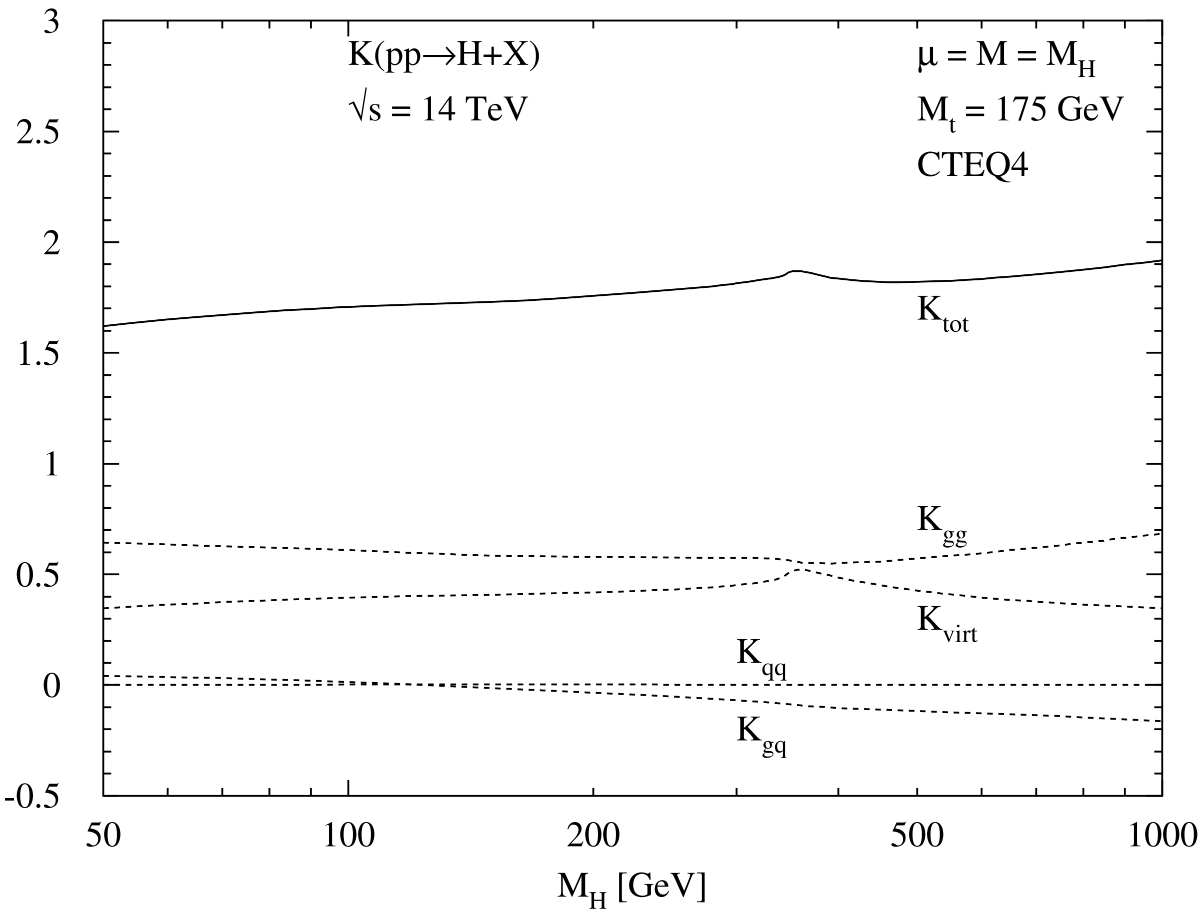
Catani, De Florian, Grazzini, Nason

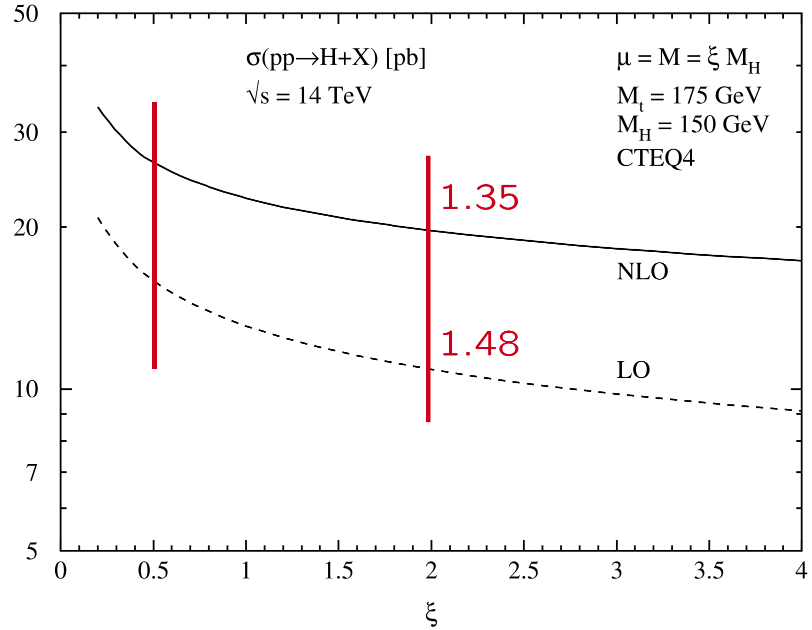
- NNLO mass effects calculated
for $M_H \lesssim$ 300 GeV $\Rightarrow \mathcal{O}(0.5\%)$

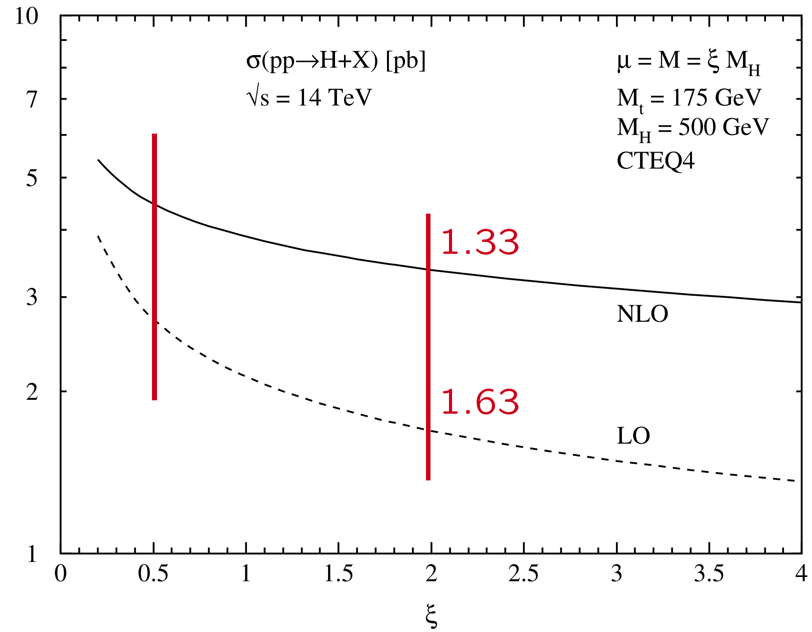
Harlander, Ozeren
Pak, Rogal, Steinhauser
Marzani, Ball, Del Duca, Forte, Vicini

- NLO electroweak corrections: -4% – 6%

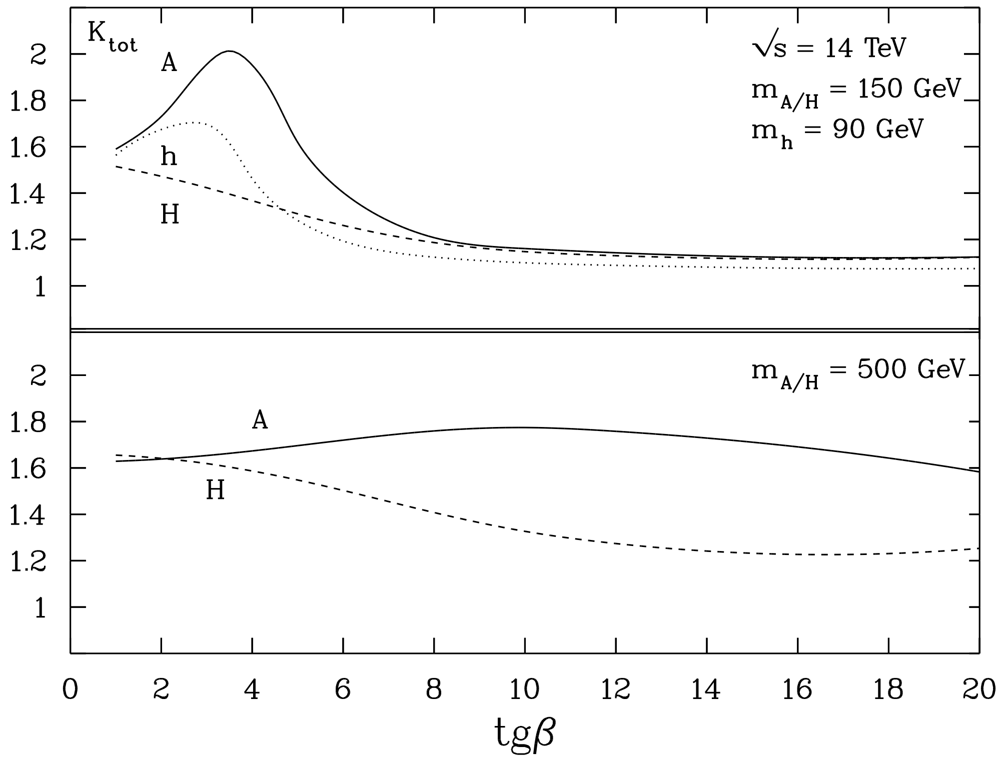
Aglietti,. . .
Degrassi, Maltoni
Actis,. . .

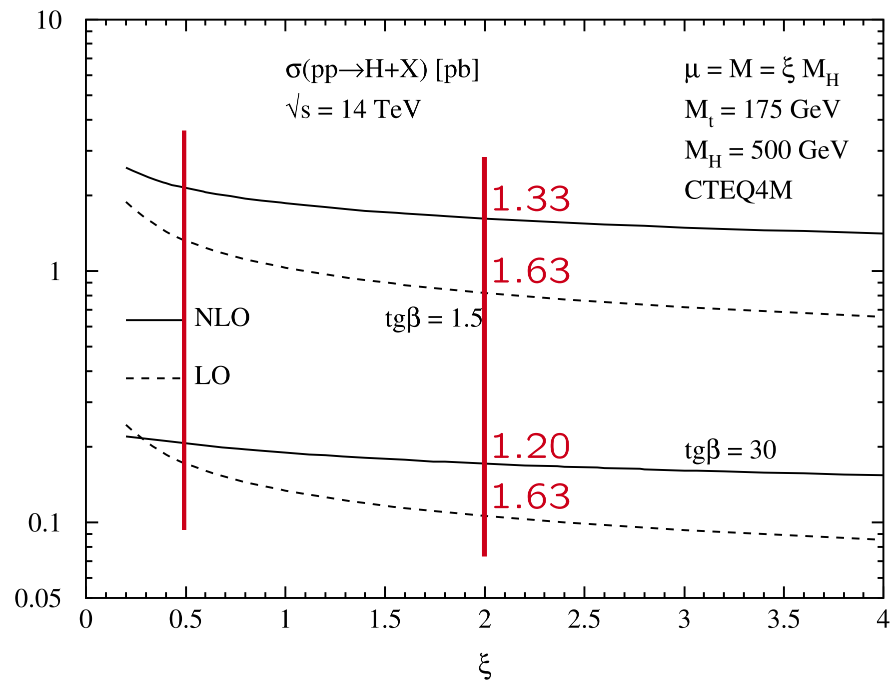


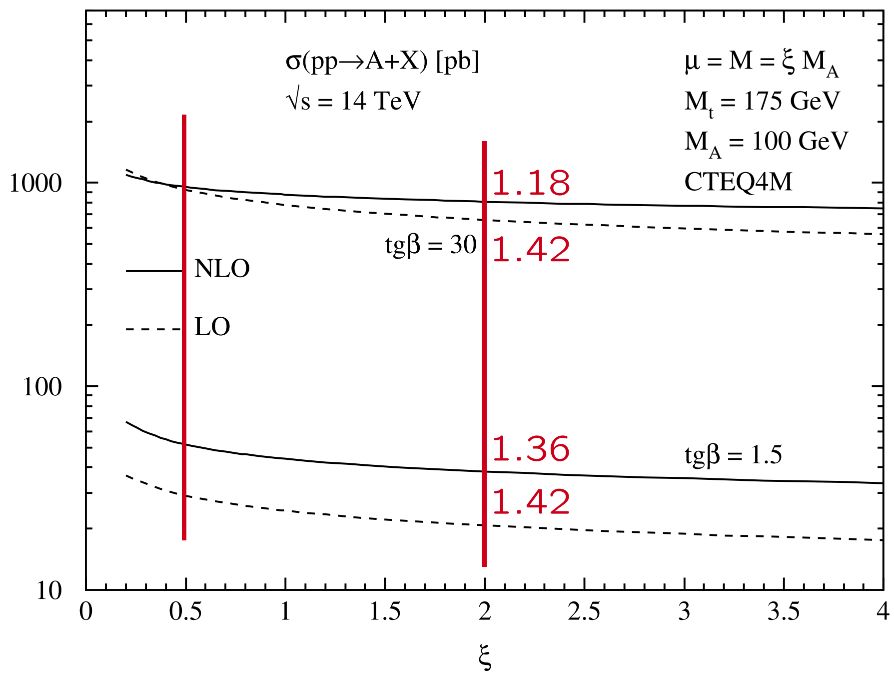




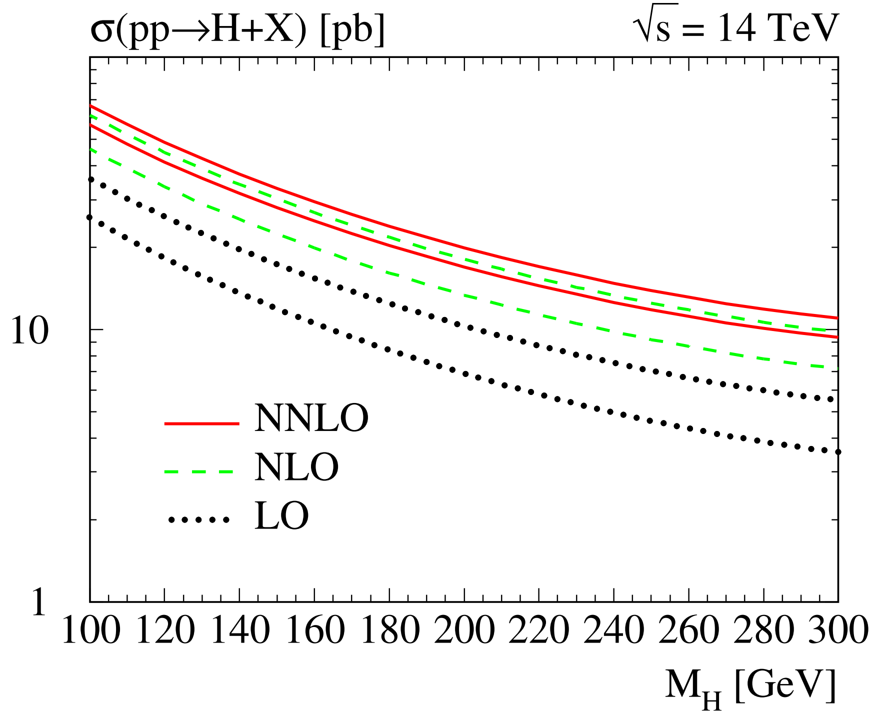
S., Djouadi, Graudenz, Zerwas



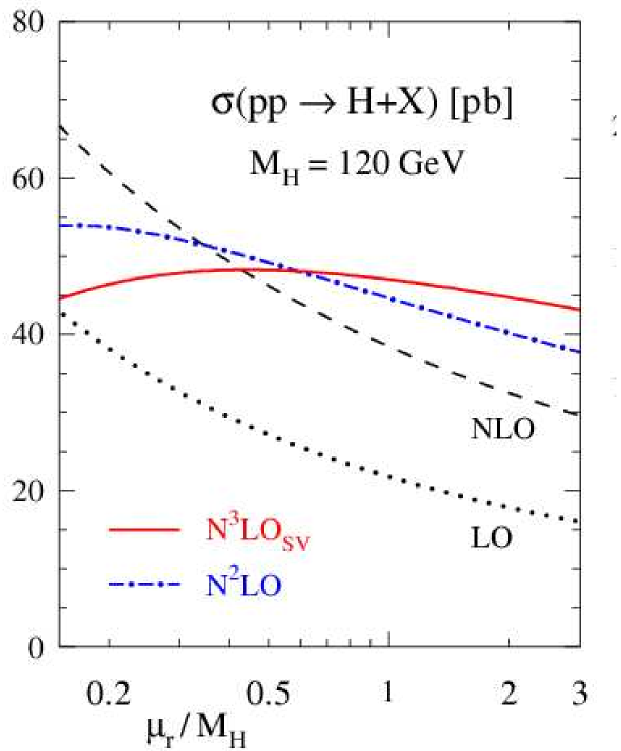




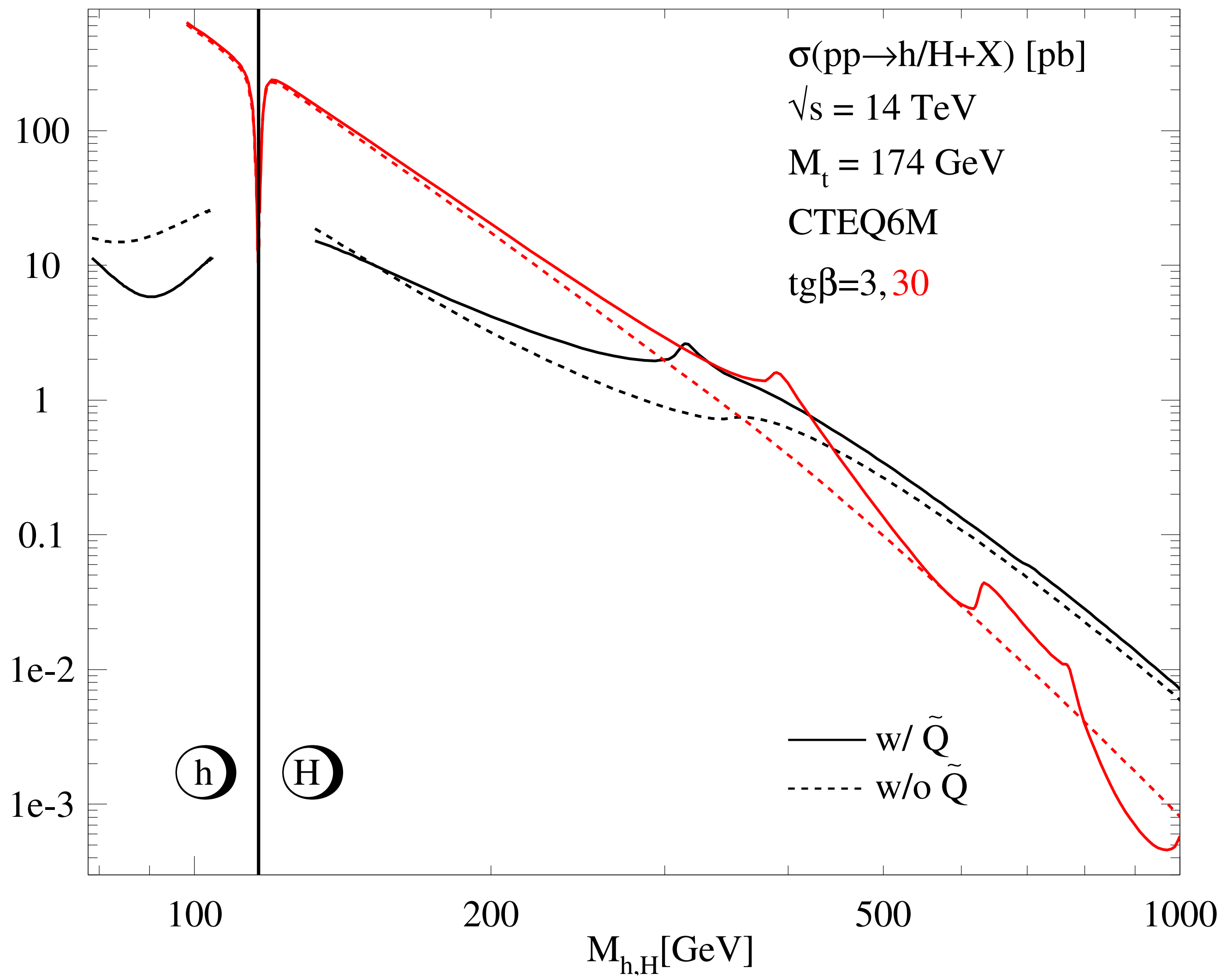
S., Djouadi, Graudenz, Zerwas



Harlander, Kilgore



Moch, Vogt



Mühlleitner, S.

gluophobic scenario

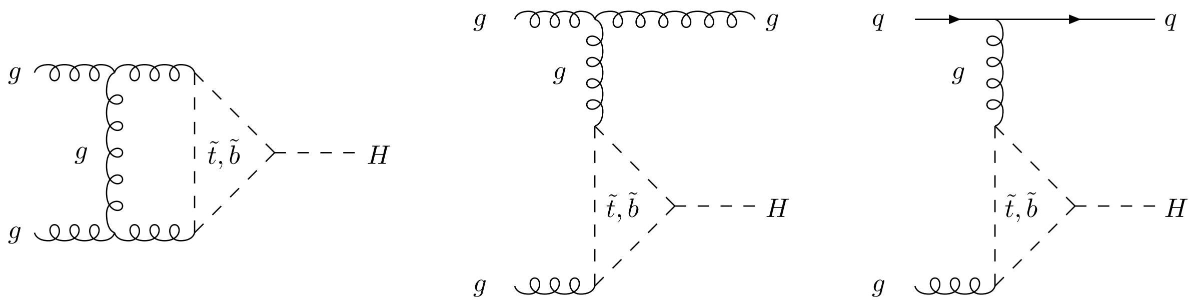
tgβ=3: $m_{\tilde{t}_1}$=156 GeV, $m_{\tilde{t}_2}$=516 GeV, $m_{\tilde{b}_1}$=346 GeV, $m_{\tilde{b}_2}$=358 GeV

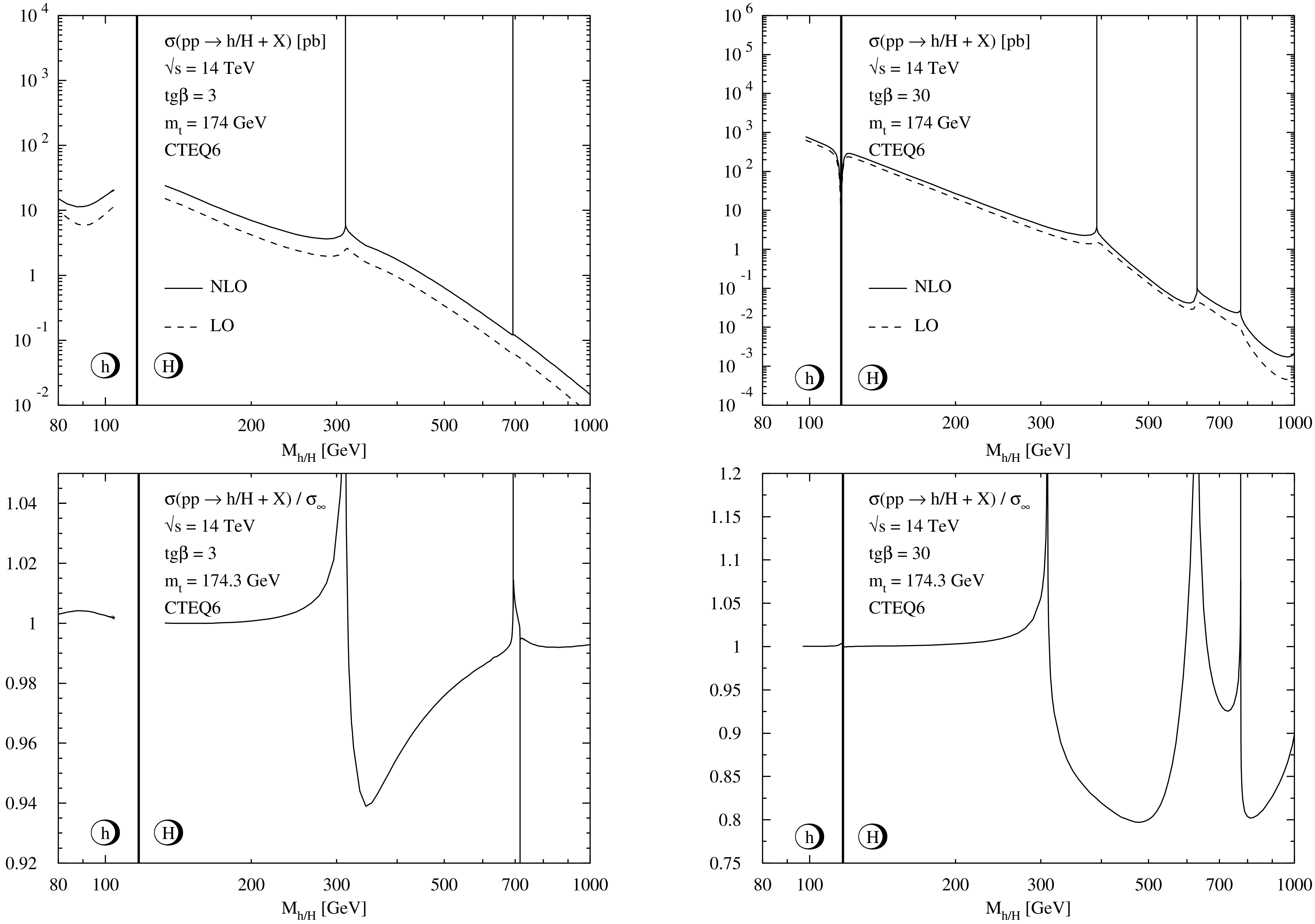
tgβ=30: $m_{\tilde{t}_1}$=195 GeV, $m_{\tilde{t}_2}$=502 GeV, $m_{\tilde{b}_1}$=315 GeV, $m_{\tilde{b}_2}$=387 GeV

• QCD corrections to squark loops:

decouple gluino contributions as first step $\longleftarrow$ adjust renormalization
[gluino contribution: $\mathcal{O}(10\%)$]

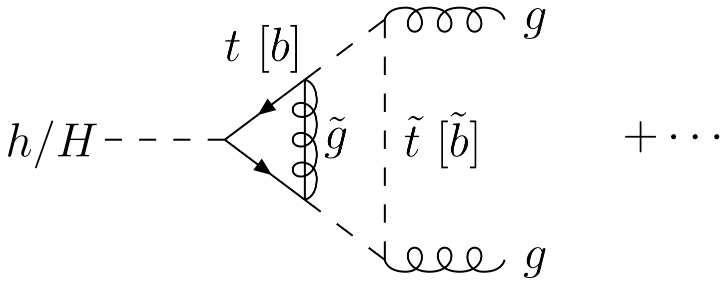
Harlander, Steinhauser, Hofmann
Degrassi, Slavich





Mühlleitner, S.

genuine SUSY–QCD corrections:



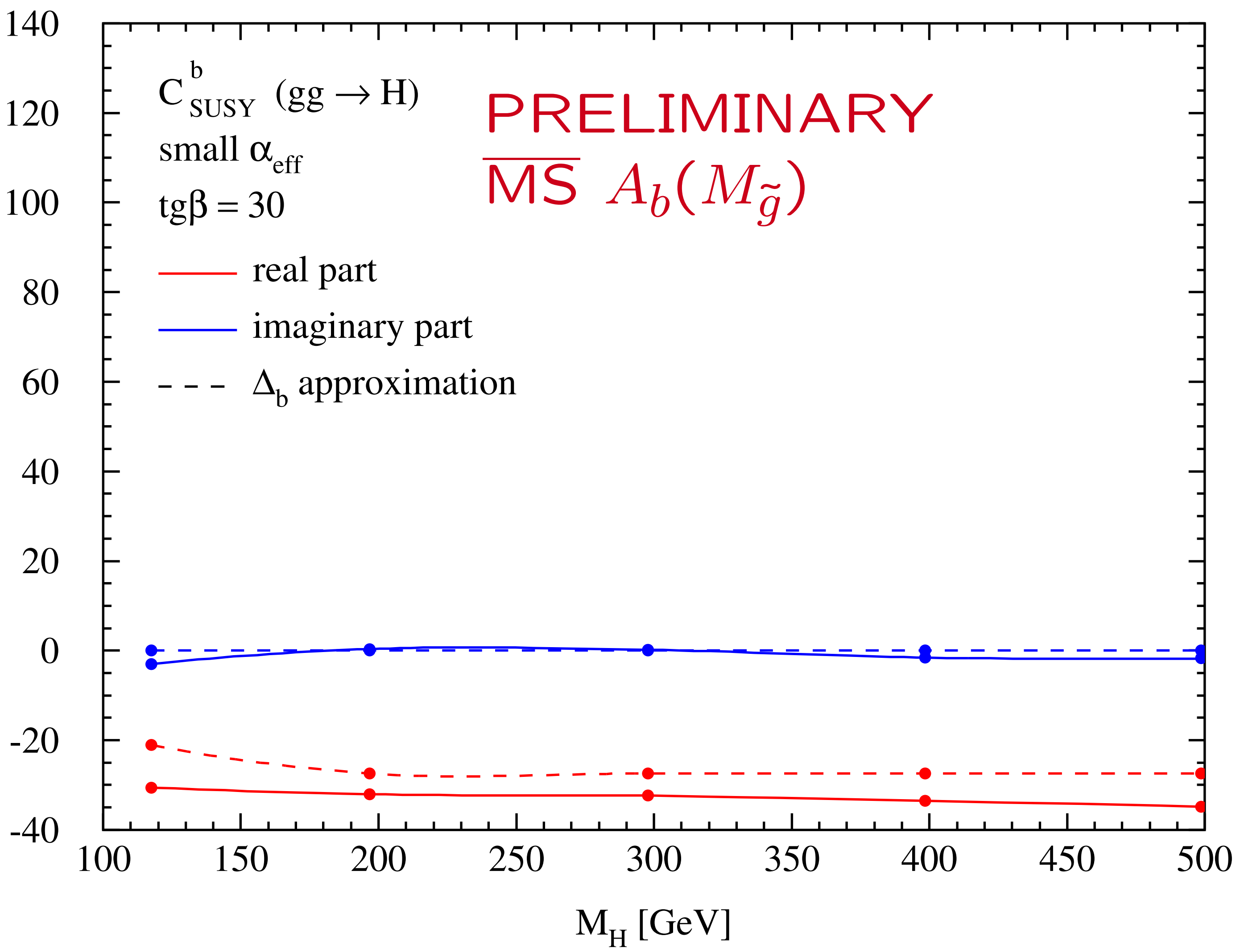
Anastasiou, Beerli, Daleo
Mühlleitner, Rzehak, S.

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

$$\sigma_0^{h/H} = \frac{G_F \alpha_s^2}{288\sqrt{2}\pi} \left| \sum_Q g_Q^{h/H} A_Q^{h/H}(\tau_Q) + \sum_{\tilde{Q}} g_{\tilde{Q}}^{h/H} A_{\tilde{Q}}^{h/H}(\tau_{\tilde{Q}}) \right|^2 \qquad \sigma_0^A = \frac{G_F \alpha_s^2}{128\sqrt{2}\pi} \left| \sum_Q g_Q^A A_Q^A(\tau_Q) \right|^2$$

- numerical analysis: $A_Q^{h/H}(\tau_Q) \to A_Q^{h/H}(\tau_Q)\left[1 + C_{SUSY}^Q \frac{\alpha_s}{\pi}\right]$

  $\longrightarrow$ M. Mühlleitner



Mühlleitner, Rzehak, S.

SUSY-QCD Corrections to $b\bar{b}\phi^0$ $[\Delta \lesssim 1\%]$

$$\mathcal{L}_{eff} = -\lambda_b \overline{b_R}\left[\phi_1^0 + \frac{\Delta_b}{\mathrm{tg}\beta}\phi_2^{0*}\right] b_L + h.c. \quad \text{valid to all orders in } \Delta_b$$

$$= -m_b \bar{b}\left[1 + i\gamma_5 \frac{G^0}{v}\right] b - \frac{m_b/v}{1+\Delta_b}\bar{b}\left[g_b^h\left(1 - \frac{\Delta_b}{\mathrm{tg}\alpha\ \mathrm{tg}\beta}\right) h + g_b^H\left(1 + \Delta_b \frac{\mathrm{tg}\alpha}{\mathrm{tg}\beta}\right) H - g_b^A\left(1 - \frac{\Delta_b}{\mathrm{tg}^2\beta}\right) i\gamma_5 A\right] b$$

$$\Delta_b = \Delta_b^{QCD(1)} + \Delta_b^{elw(1)}$$

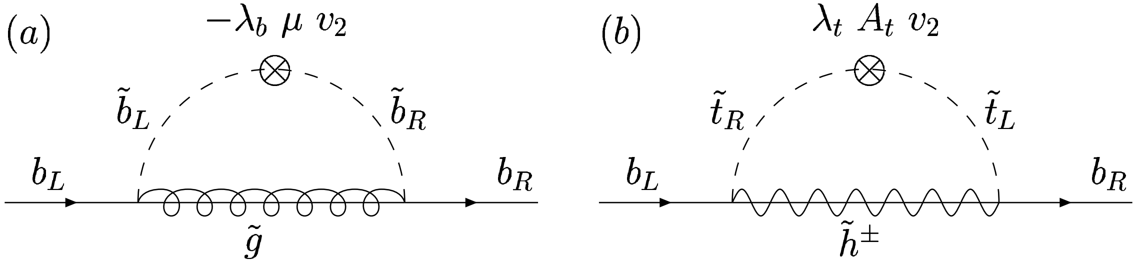
$$\Delta_b^{QCD(1)} = \frac{2}{3}\frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}}\ \mu\ \mathrm{tg}\beta\ I(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2, M_{\tilde{g}}^2)$$

$$\Delta_b^{elw(1)} = \frac{\lambda_t^2(\mu_R)}{(4\pi)^2}\ \mu\ A_t\ \mathrm{tg}\beta\ I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2)$$

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

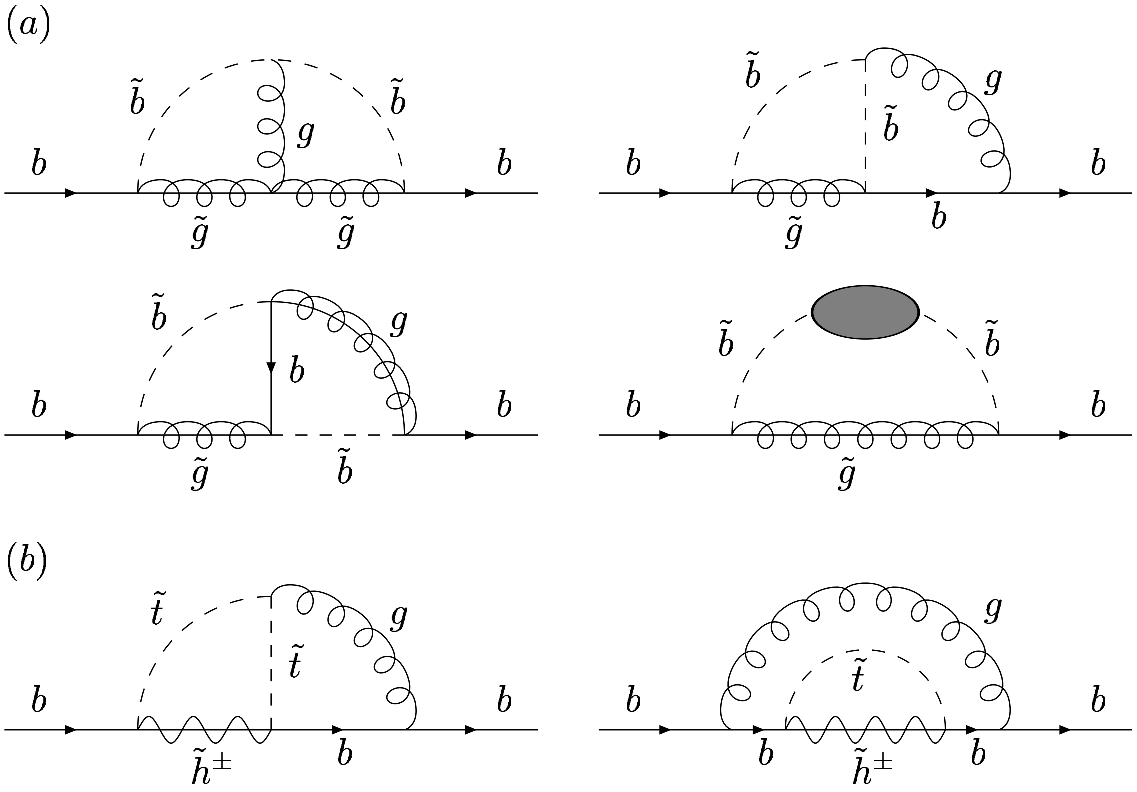
$\Rightarrow$ resummed Yukawa couplings

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



- LET: $v_2 \to \sqrt{2}\phi_2^{0*}$

Ellis,. . .
Shifman,. . .



- 2-loop self-energies @ vanishing momentum

- dimensional regularization in $n = 4 - 2\epsilon$ dimensions

- integration by parts: reduction to 1-point functions

$$A_0(m) = \int \frac{d^n k}{(2\pi)^n} \frac{1}{k^2 - m^2}$$

and one 2-loop master integral

$$T_{134}(m_1, m_3, m_4) = \int \frac{d^n k}{(2\pi)^n} \frac{d^n q}{(2\pi)^n} \frac{1}{(k^2 - m_1^2)[(k-q)^2 - m_3^2](q^2 - m4^2)}$$

- α_s, λ_t: $\overline{\text{MS}}$ scheme [5 flavours]
  masses, A_t: on-shell

- dim. reg. violates SUSY: anomalous counter terms

$$\begin{aligned} \hat{g}_s &= g_s \left[1 + \left(\frac{C_A}{6} - \frac{C_F}{8} \right) \frac{\alpha_s}{\pi} \right] \\ \lambda_{Hbb} &= \lambda_{H\tilde{b}\tilde{b}} \left[1 + \frac{C_F}{4} \frac{\alpha_s}{\pi} \right] = \lambda_{\tilde{H}\tilde{b}b} \left[1 + \frac{3}{8} C_F \frac{\alpha_s}{\pi} \right] \end{aligned}$$

Martin, Vaughn

Limits

- $m_t^2 \ll m_{\tilde{g}}^2 = m_{\tilde{b}_i}^2 = \mu^2 = m_{\tilde{t}_i}^2 \equiv M^2$:

$$\Delta_b^{QCD\,(1)} = \frac{C_F}{4}\frac{\alpha_s(\mu_R)}{\pi}\mathrm{tg}\beta$$

$$\Delta_b^{QCD\,(2)} = \frac{\alpha_s}{\pi}\left\{\frac{C_A}{3} + C_F + \frac{N_F+1}{4} + \underbrace{\frac{1}{6}\log\frac{M^2}{m_t^2}}_{\to\ \alpha_s^{(6)}} + \beta_0^L \log\frac{\mu_R^2}{M^2}\right\}\Delta_b^{QCD\,(1)}$$

$$\Delta_b^{elw\,(1)} = \frac{1}{2}\frac{\lambda_t^2(\mu_R)}{(4\pi)^2}\frac{A_t \mathrm{tg}\beta}{M}$$

$$\Delta_b^{elw\,(2)} = C_F\frac{\alpha_s}{\pi}\left\{\frac{7}{4} + \underbrace{\frac{3}{2}\log\frac{\mu_R^2}{m_t M}}_{\lambda_{t/b}\ \to\ \lambda_{t/b,MO}^{\tilde{h}^\pm}}\right\}\Delta_b^{elw\,(1)}$$

Noth, S.

$$\lambda_{t/b}(\mu_R) = \lambda_{t/b,MO}^{\tilde{h}^\pm}(\mu_R)\left\{1 - C_F\frac{\alpha_s}{\pi}\left[\frac{3}{8}\log\frac{\mu_R^2}{m_{\tilde{g}}^2} + \frac{9}{16}\right]\right\} \qquad [\mu_R \ll m_{\tilde{g}}]$$

- $m_t^2, m_{\tilde{b}_i}^2, \mu^2, m_{\tilde{t}_i}^2 \ll m_{\tilde{g}}^2$:

$$\Delta_b^{QCD\,(1)} = \frac{C_F}{2}\frac{\alpha_s(\mu_R)}{\pi}\frac{\mu \mathrm{tg}\beta}{m_{\tilde{g}}} \left\{ -\log\frac{m_{\tilde{g}}^2}{m_{\tilde{b}_2}^2} + \frac{m_{\tilde{b}_1}^2}{m_{\tilde{b}_2}^2 - m_{\tilde{b}_1}^2}\log\frac{m_{\tilde{b}_2}^2}{m_{\tilde{b}_1}^2} \right\}$$

$$\Delta_b^{QCD\,(2)} = \frac{\alpha_s}{\pi}\left\{ \frac{4}{3}C_A + C_F\left[\log\frac{m_{\tilde{g}}^2}{m_{\tilde{b}_2}^2} - \frac{m_{\tilde{b}_1}^2}{m_{\tilde{b}_2}^2 - m_{\tilde{b}_1}^2}\log\frac{m_{\tilde{b}_2}^2}{m_{\tilde{b}_1}^2} + \frac{5}{2}\right] - \frac{N_F+1}{2} + \underbrace{\frac{1}{6}\log\frac{m_{\tilde{g}}^2}{m_t^2} + \frac{1}{24}\sum_{\tilde{q}}\log\frac{m_{\tilde{g}}^2}{m_{\tilde{q}}^2}}_{\to\ \alpha_s^{(SUSY)}} + \beta_0^L\log\frac{\mu_R^2}{m_{\tilde{g}}^2} \right\}\Delta_b^{QCD\,(1)}$$

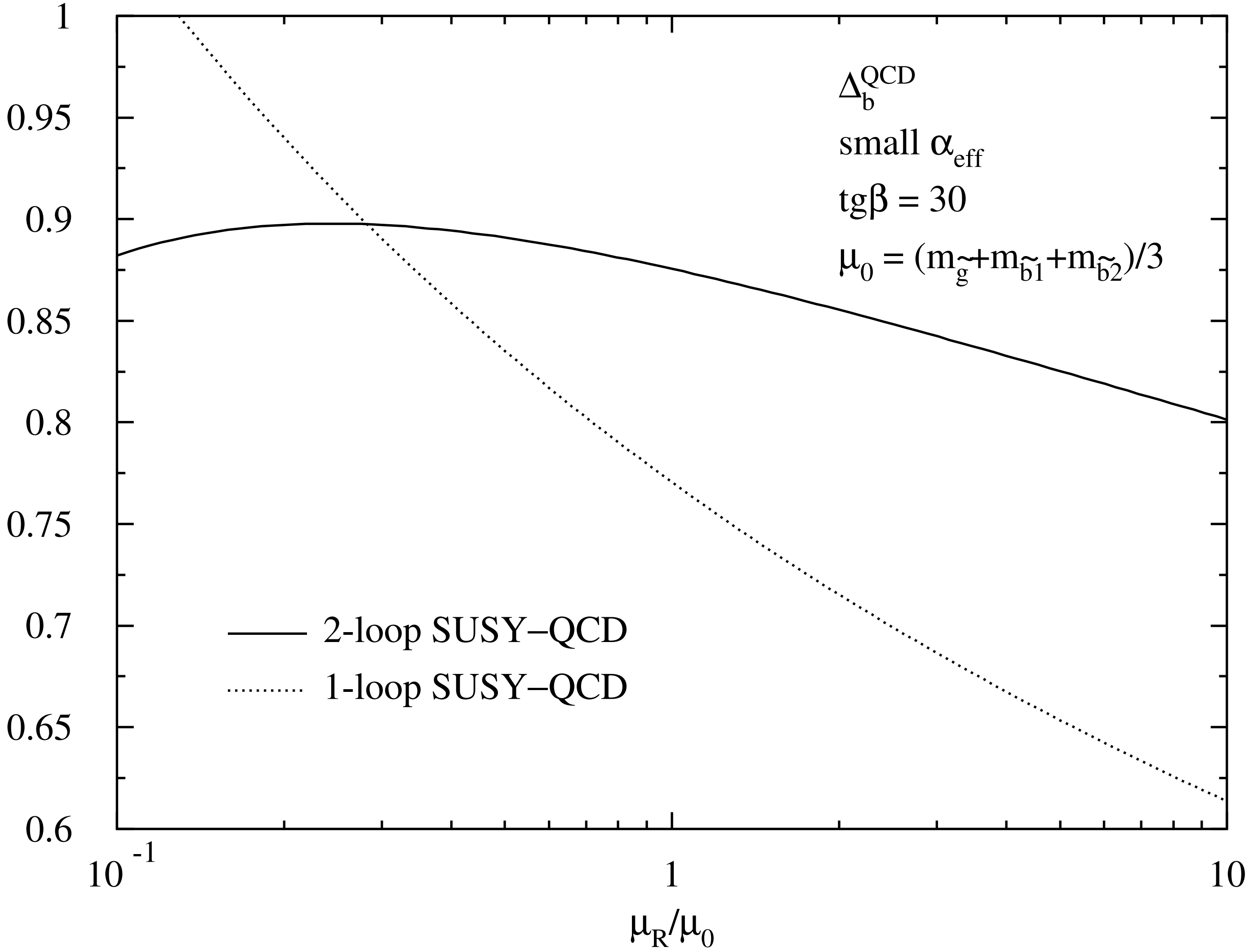
$$\Delta_b^{elw\,(2)} = C_F\frac{\alpha_s}{\pi}\left\{ \frac{23}{8} + \underbrace{\frac{3}{2}\log\frac{\mu_R^2}{m_t m_{\tilde{g}}}}_{\lambda_{t/b}\ \to\ \lambda_{t/b,MO}^{\tilde{h}^\pm}} \right\}\Delta_b^{elw\,(1)}$$

Noth, S.

small α_{eff} scenario [modified]

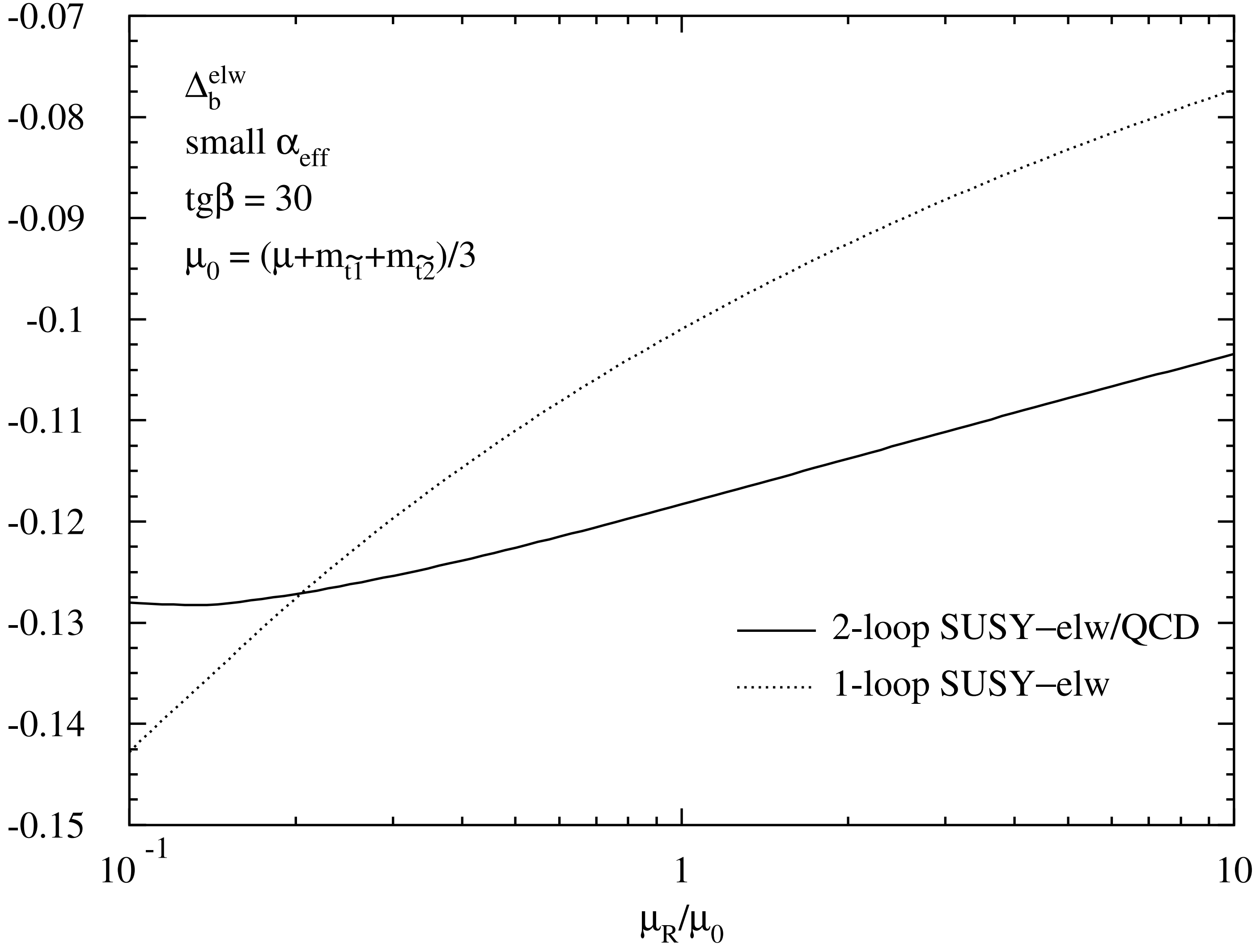
$$
\begin{aligned}
\mathrm{tg}\beta &= 30 \\
M_{\tilde{Q}} &= 800 \text{ GeV} \\
M_{\tilde{g}} &= 1000 \text{ GeV} \qquad \longleftarrow \\
M_2 &= 500 \text{ GeV} \\
A_b = A_t &= -1.133 \text{ TeV} \\
\mu &= 2 \text{ TeV}
\end{aligned}
$$

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



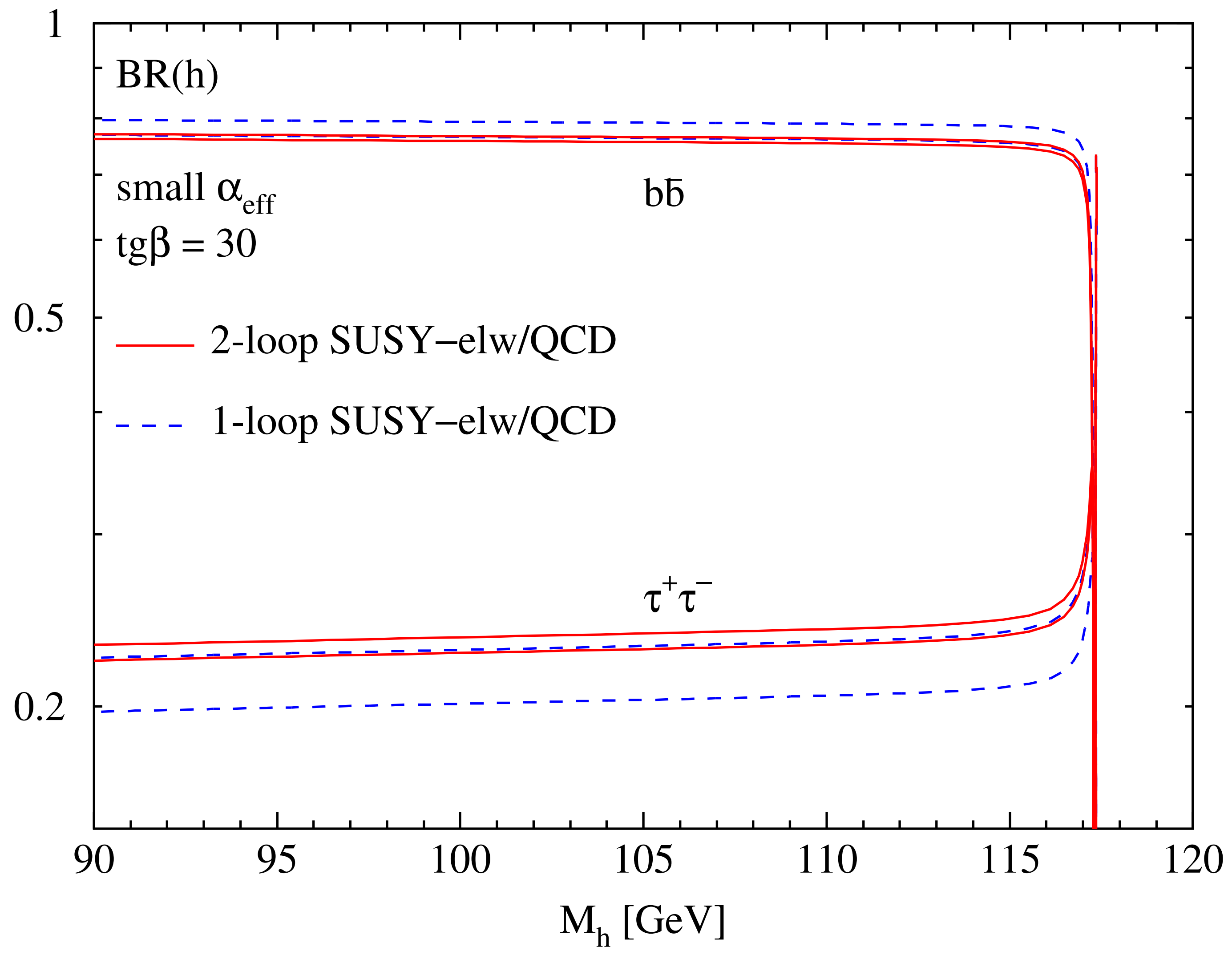
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Δ_b^{QCD}
small α_{eff}
tgβ = 30
$\mu_0 = (m_{\tilde{g}}+m_{\tilde{b}1}+m_{\tilde{b}2})/3$
2-loop SUSY−QCD
1-loop SUSY−QCD
10^{-1}
1
10
μ_R/μ_0

Noth, S.



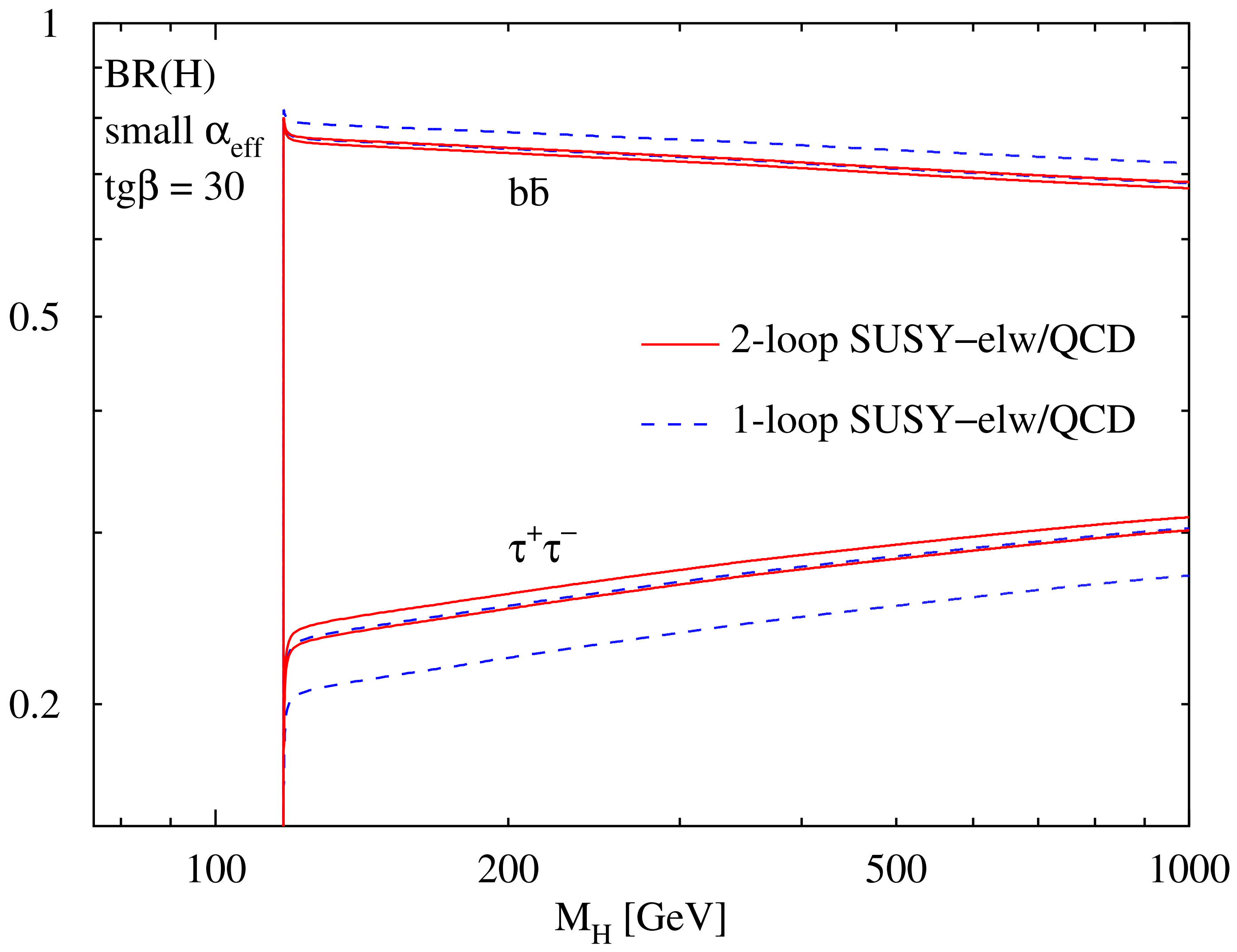
-0.07
-0.08
-0.09
-0.1
-0.11
-0.12
-0.13
-0.14
-0.15
Δ_b^{elw}
small α_{eff}
tgβ = 30
$\mu_0 = (\mu + m_{\tilde{t}1} + m_{\tilde{t}2})/3$
2-loop SUSY−elw/QCD
1-loop SUSY−elw
10^{-1}
1
10
μ_R/μ_0

Noth, S.



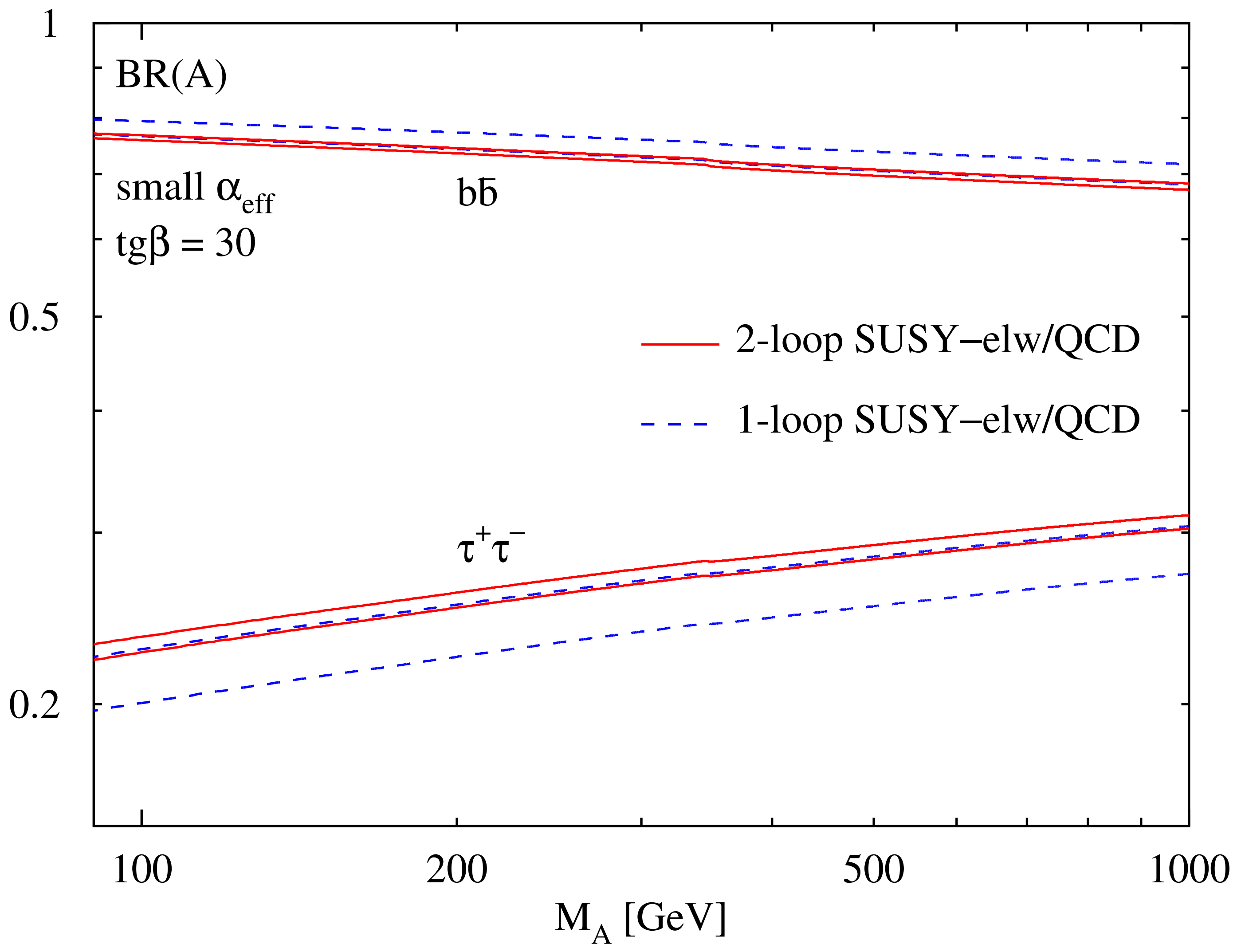
BR(h)
small α_{eff}
tgβ = 30
$b\bar{b}$
$\tau^+\tau^-$
2-loop SUSY−elw/QCD
1-loop SUSY−elw/QCD
1
0.5
0.2
90
95
100
105
110
115
120
M_h [GeV]

Noth, S.



BR(H)
small α_{eff}
tgβ = 30
$b\bar{b}$
$\tau^+\tau^-$
2-loop SUSY−elw/QCD
1-loop SUSY−elw/QCD
1
0.5
0.2
100
200
500
1000
M_H [GeV]

Noth, S.



BR(A)
small α_{eff}
tgβ = 30
$b\bar{b}$
$\tau^+\tau^-$
2-loop SUSY−elw/QCD
1-loop SUSY−elw/QCD
1
0.5
0.2
100
200
500
1000
M_A [GeV]

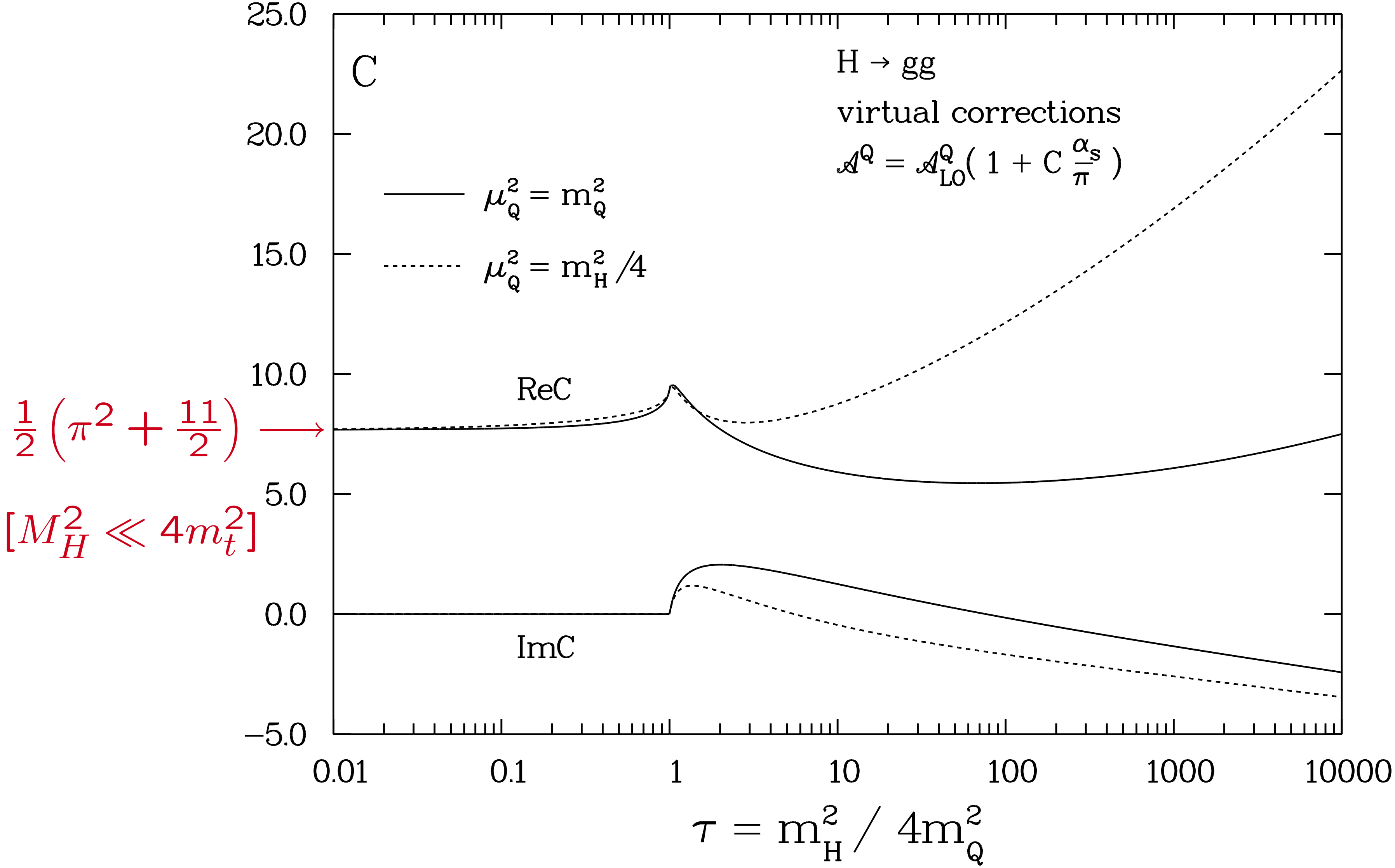
Noth, S.

HIGLU

- LHAPDF $\surd$
- $M_b \leftrightarrow \overline{m}_b(\mu)$ $\surd$
  [$\mu \sim M_H$ disfavoured!]
- distributions: p_T (LO) $\surd$
  y (NLO) takes time. . .
  p_T (NLO) takes more time. . .
- electroweak corrections $\surd$
- NNLO, NNLL corrections takes (much?) more time. . .
- MSSM: $\sigma_{NLO} = g_t^2 \sigma_{tt}^{SM} + g_t g_b \sigma_{tb}^{SM} + g_b^2 \sigma_{bb}^{SM}$

$$\sigma_{(N)NLO} = \sigma_{NLO} + g_t^2 \sigma_{tt}^{LO} \Delta K_{NNLO}$$

- $\tilde{Q}$ loops $\surd$
- SUSY–QCD corrections ???



S., Djouadi, Graudenz, Zerwas

V *SUMMARY*

- Higgs boson searches @ LHC major endeavours

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

- most (SUSY–)QCD and electroweak corrections known
  $\Rightarrow$ large corrections to gluon fusion
  remaining theoretical uncertainties: $\sim 100\% \longrightarrow \; \lesssim 10-15\%$

- HIGLU [upgraded], HggTotal, HNNLO, ggh@NNLO

  Anastasiou,. . .
  De Florian, Grazzini
  Harlander, Kilgore

- close collaboration of experimentalists and theorists necessary

BACKUP SLIDES

SPS 5

$$\begin{aligned} \mathrm{tg}\beta &= 5 \\ \mu &= 639.8\ \mathrm{GeV} \\ A_t &= -1671.4\ \mathrm{GeV} \\ A_b &= -905.6\ \mathrm{GeV} \\ m_{\tilde{g}} &= 710.3\ \mathrm{GeV} \\ m_{\tilde{q}_L} &= 535.2\ \mathrm{GeV} \\ m_{\tilde{b}_R} &= 620.5\ \mathrm{GeV} \\ m_{\tilde{t}_R} &= 360.5\ \mathrm{GeV} \end{aligned}$$

$$\longrightarrow m_{\tilde{t}_1} = 230.4\ \mathrm{GeV}, m_{\tilde{t}_2} = 637.8\ \mathrm{GeV}$$

SPS 1b

$$
\begin{aligned}
\mathrm{tg}\beta &= 30 \\
\mu &= 495.6\ \mathrm{GeV} \\
A_t &= -729.3\ \mathrm{GeV} \\
A_b &= -987.4\ \mathrm{GeV} \\
m_{\tilde{g}} &= 916.1\ \mathrm{GeV} \\
m_{\tilde{q}_L} &= 762.5\ \mathrm{GeV} \\
m_{\tilde{b}_R} &= 780.3\ \mathrm{GeV} \\
m_{\tilde{t}_R} &= 670.7\ \mathrm{GeV}
\end{aligned}
$$

$$\longrightarrow m_{\tilde{b}_1} = 745.8\ \mathrm{GeV}, m_{\tilde{b}_2} = 798.9\ \mathrm{GeV}$$

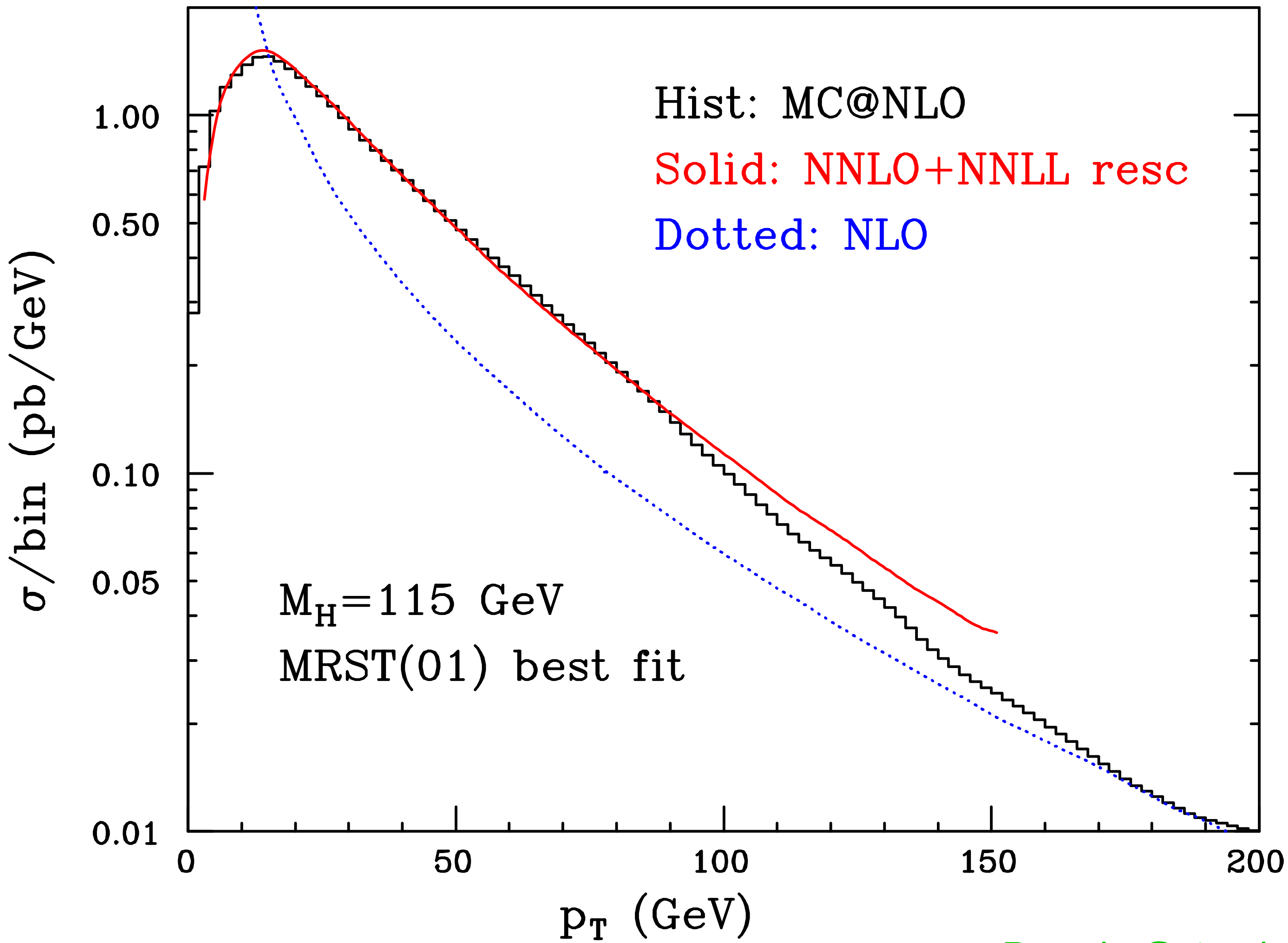
• SUSY decays: $\phi^0 \to \chi_1^0 \chi_1^0$ [LSP] $\Rightarrow$ invisible Higgs $\longrightarrow \not{E}_T$ if $p_{T\phi} > 0$
$\Rightarrow gg \to \phi^0 g$ dominant

Schmidt
de Florian, ...
Ravindran, ...

NLO corrections [$m_t \gg M_\phi$]: 60–80%

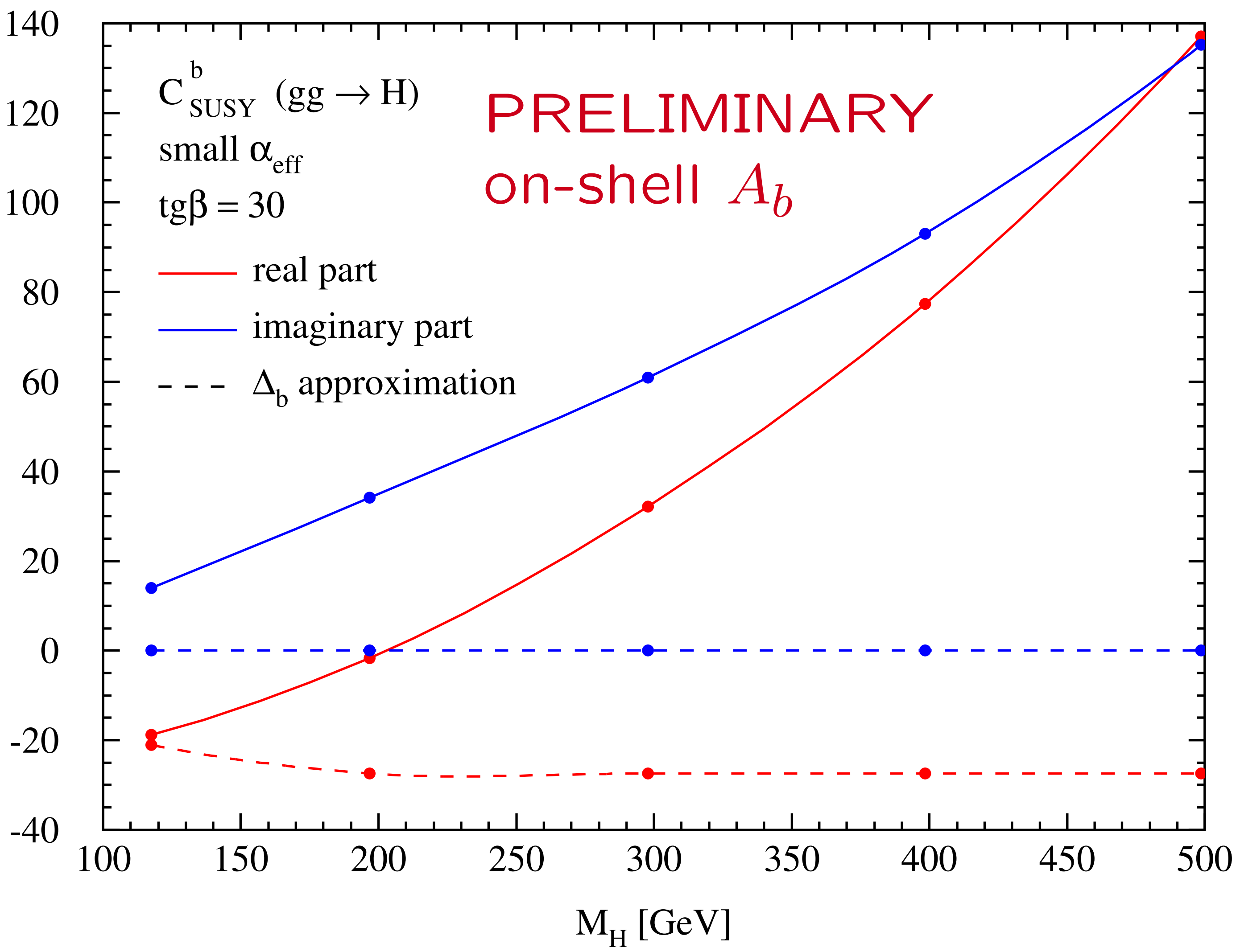
Kauffman
Balazs, Yuan
Bozzi, ...

$\longrightarrow$ resummation: $\Delta \lesssim 15\%$



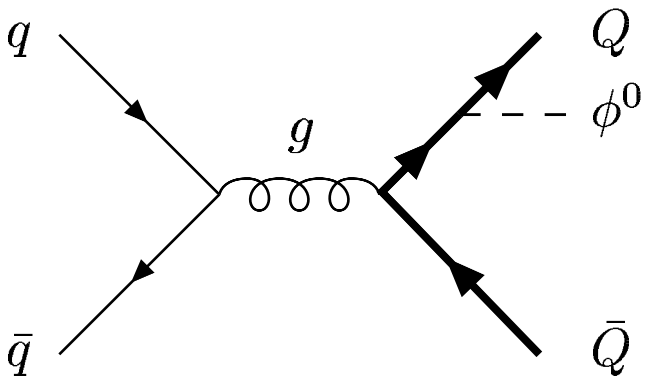
Bozzi, Catani, de Florian, Grazzini

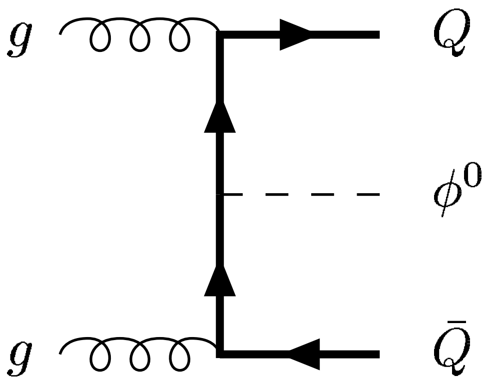
Frixione [MC@NLO]



Mühlleitner, Rzehak, S.

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





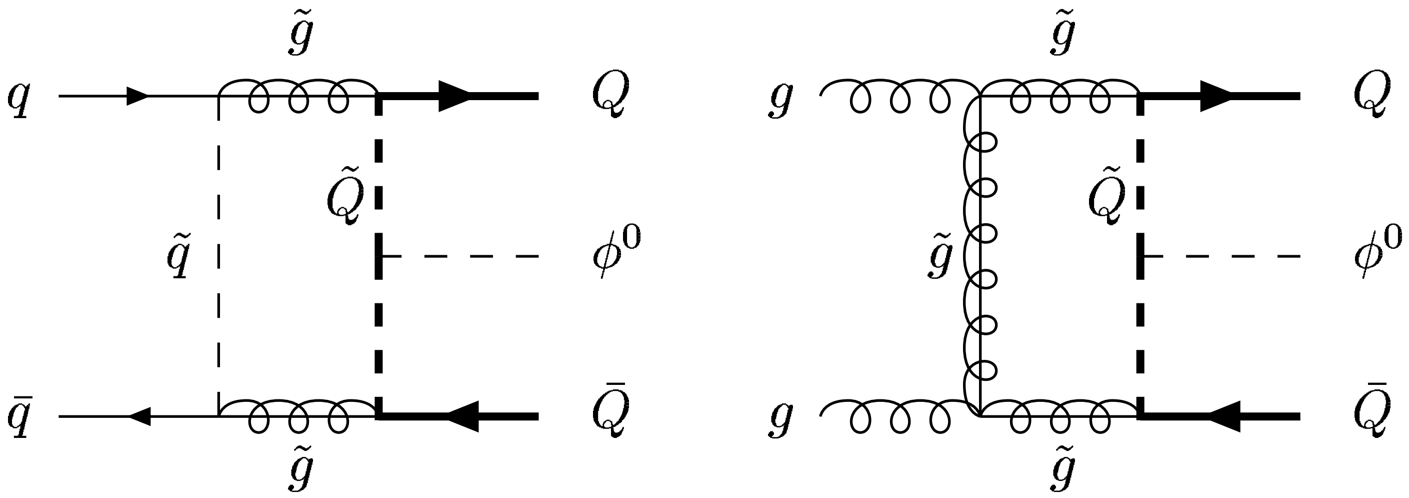
dominant

Kunszt
Gunion
Marciano, Paige

- possibility to measure top Yukawa cplg.
- $b\bar{b} + H/A$ dominant for large tgβ → M. Krämer
- measurement of tgβ
- $t\bar{t}h$: SUSY-QCD corrections computed

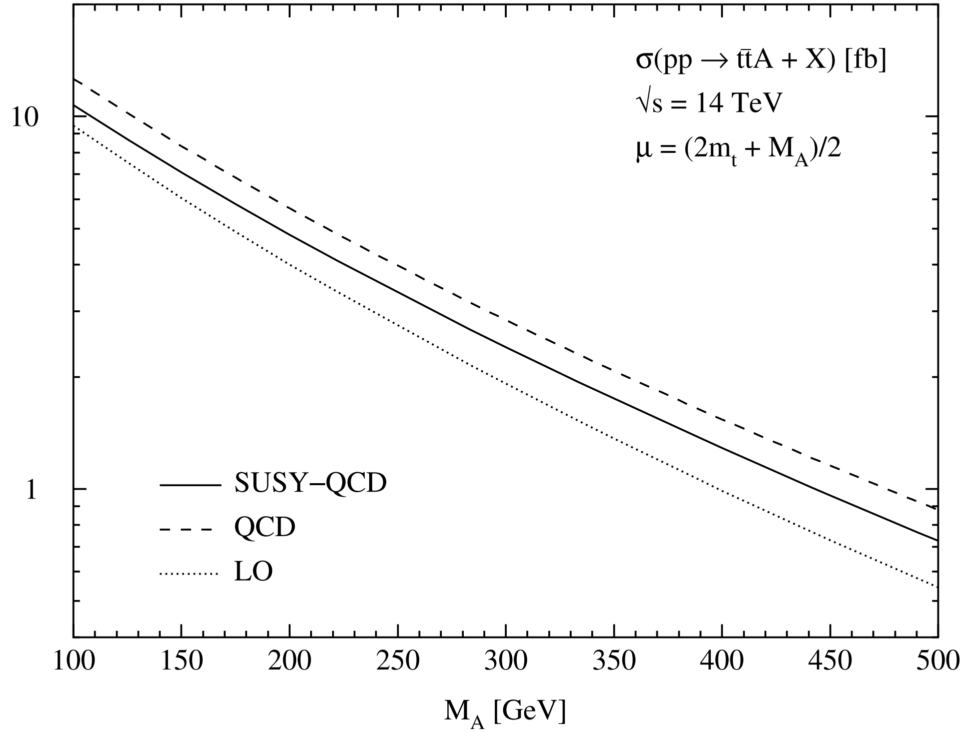
Peng, Wen-Gan, Hong-Shen,
Ren-You, Liang
Rauch, Hollik

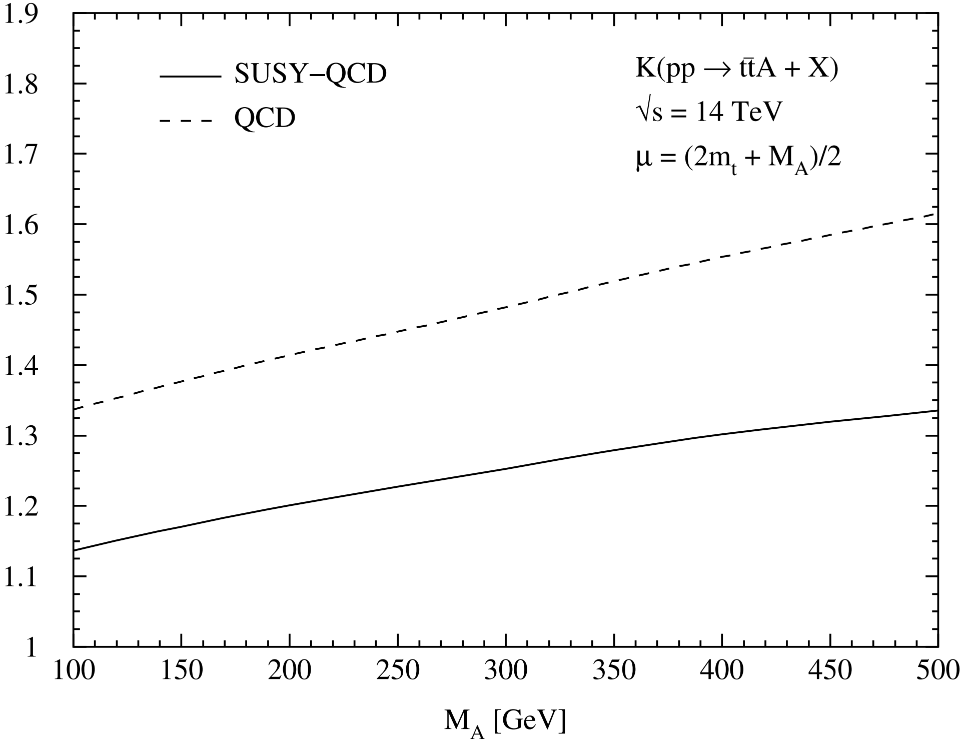
SUSY-QCD Corrections



- no infrared singularities

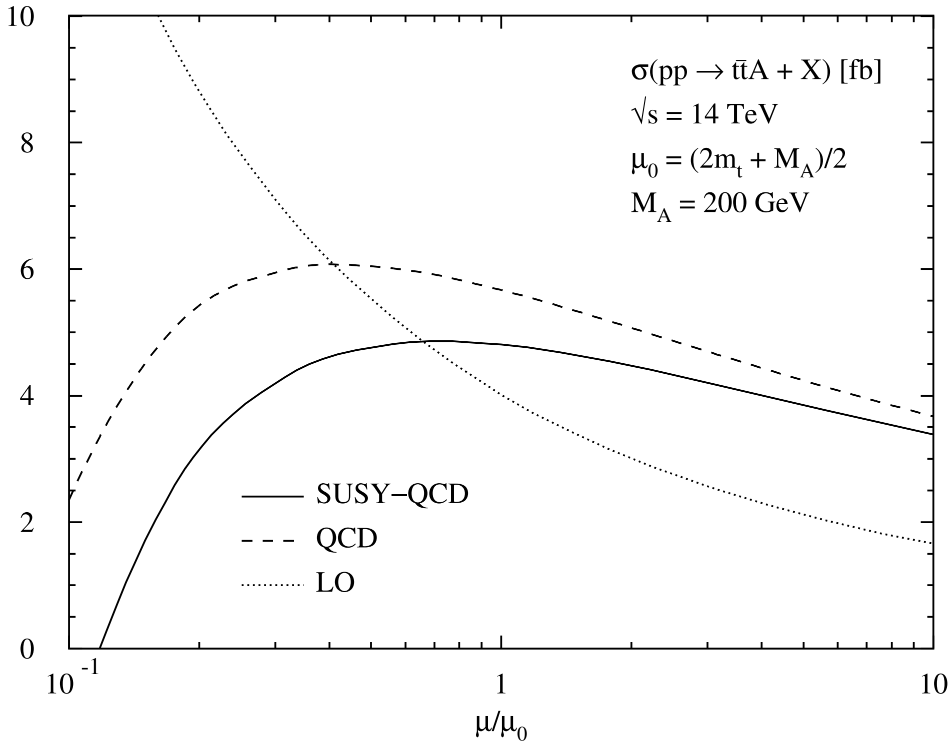
- massive gluinos and squarks decoupled from $\alpha_s \rightarrow 4/5$ active flavours





SPS5

PRELIMINARY

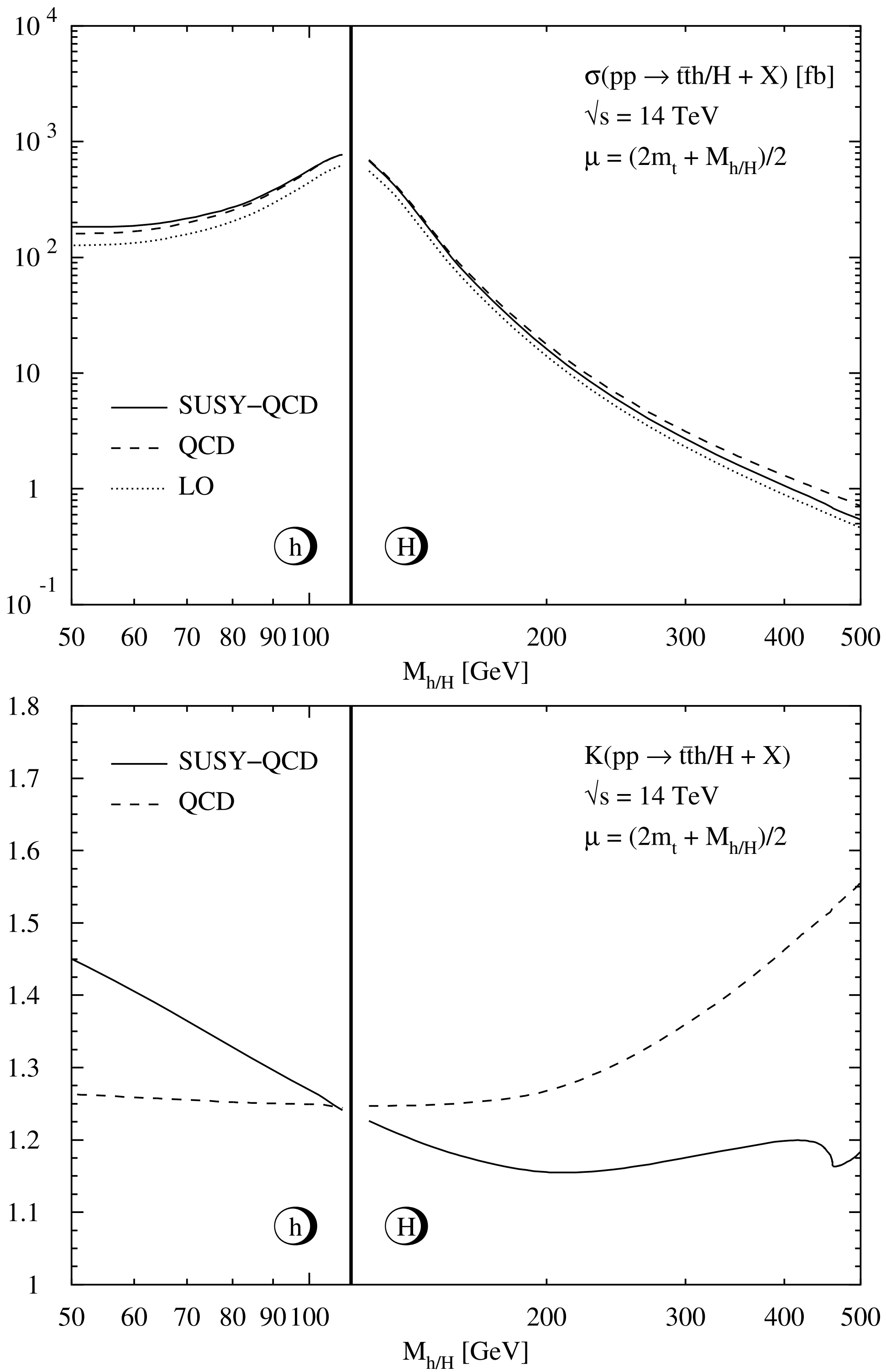


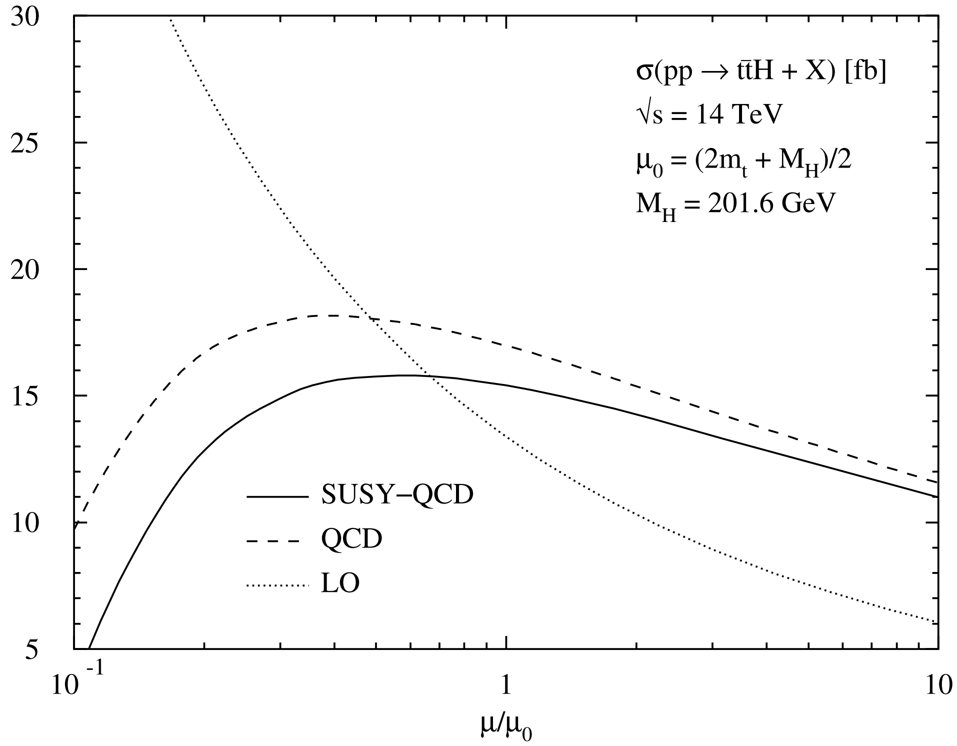
$\Rightarrow \Delta \lesssim 10\%$

Dittmaier, Häfliger,
Krämer, S., Walser

SPS5

PRELIMINARY





$\Rightarrow \Delta \lesssim 10\%$

Dittmaier, Häfliger,
Krämer, S., Walser