SUSY–QCD CORRECTIONS TO $t\bar{t}/b\bar{b}$ *+ HIGGS PRODUCTION*

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I Introduction

II SUSY–QCD Corrections

III Conclusions

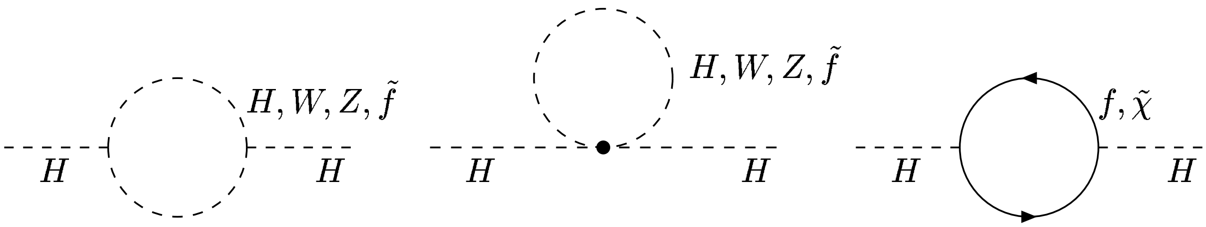
in collaboration with Petra Häfliger

I *INTRODUCTION*

MSSM

- SUSY: fermions $\leftrightarrow$ bosons

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



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

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

- minimal model: 2 Higgs doubletts ϕ_1, ϕ_2

$$\begin{aligned} V_\phi &= m_1^2|\phi_1|^2 + m_2^2|\phi_2|^2 - m_{12}^2\left[\phi_1^+\phi_2 + h.c.\right] \\ &+ \frac{g^2+g'^2}{8}\left[|\phi_1|^2 - |\phi_2|^2\right]^2 + \frac{g^2}{2}|\phi_1^+\phi_2|^2 \end{aligned}$$

ESB $\to$ 5 Higgs bosons:

$$\begin{array}{rl} h, H & \text{neutral, } \mathcal{CP} \text{ even} \\ A & \text{neutral, } \mathcal{CP} \text{ odd} \\ H^\pm & \text{charged} \end{array}$$

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

$$\begin{aligned} M_h^2 &= \frac{1}{2}\{M_A^2 + M_Z^2 + \epsilon \\ &- \sqrt{(M_A^2 + M_Z^2 + \epsilon)^2 - 4M_A^2 M_Z^2 c_{2\beta}^2 - 4\epsilon(M_A^2 s_\beta^2 + M_Z^2 c_\beta^2)}\Big\} \end{aligned}$$

- large radiative corrections:

$$\epsilon = \frac{3G_F}{\sqrt{2}\pi^2} \frac{m_t^4}{s_\beta^2} \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

$$M_h < M_Z \to \boxed{M_h \lesssim 135 \text{ GeV}}$$

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

- 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	ctgβ	tgβ	0

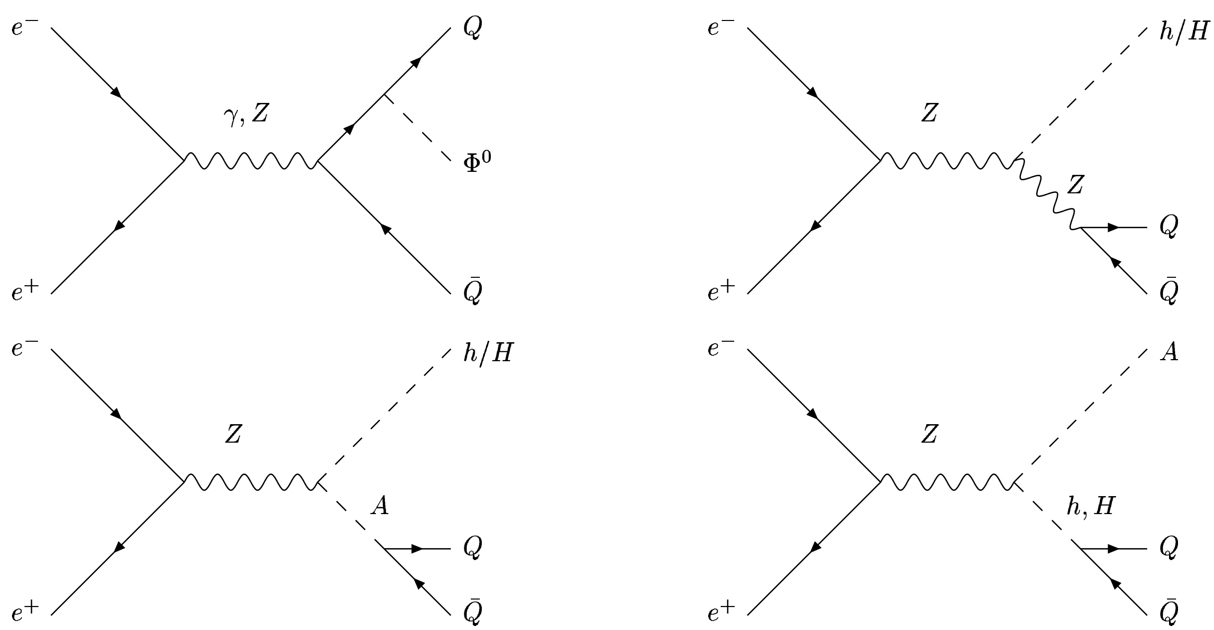
- mixing: $\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$

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

• SM: $g_{ttH} = m_t/v$ largest Yukawa coupling

• MSSM: large tg$\beta \to b$ couplings enhanced
$\leftarrow$ measurable in $e^+e^- \to b\bar{b} + \phi$

• LO:



$\leftarrow$ measurement of Yukawa couplings and tgβ

NLO needed

$\to$ reduction of theoretical uncertainties

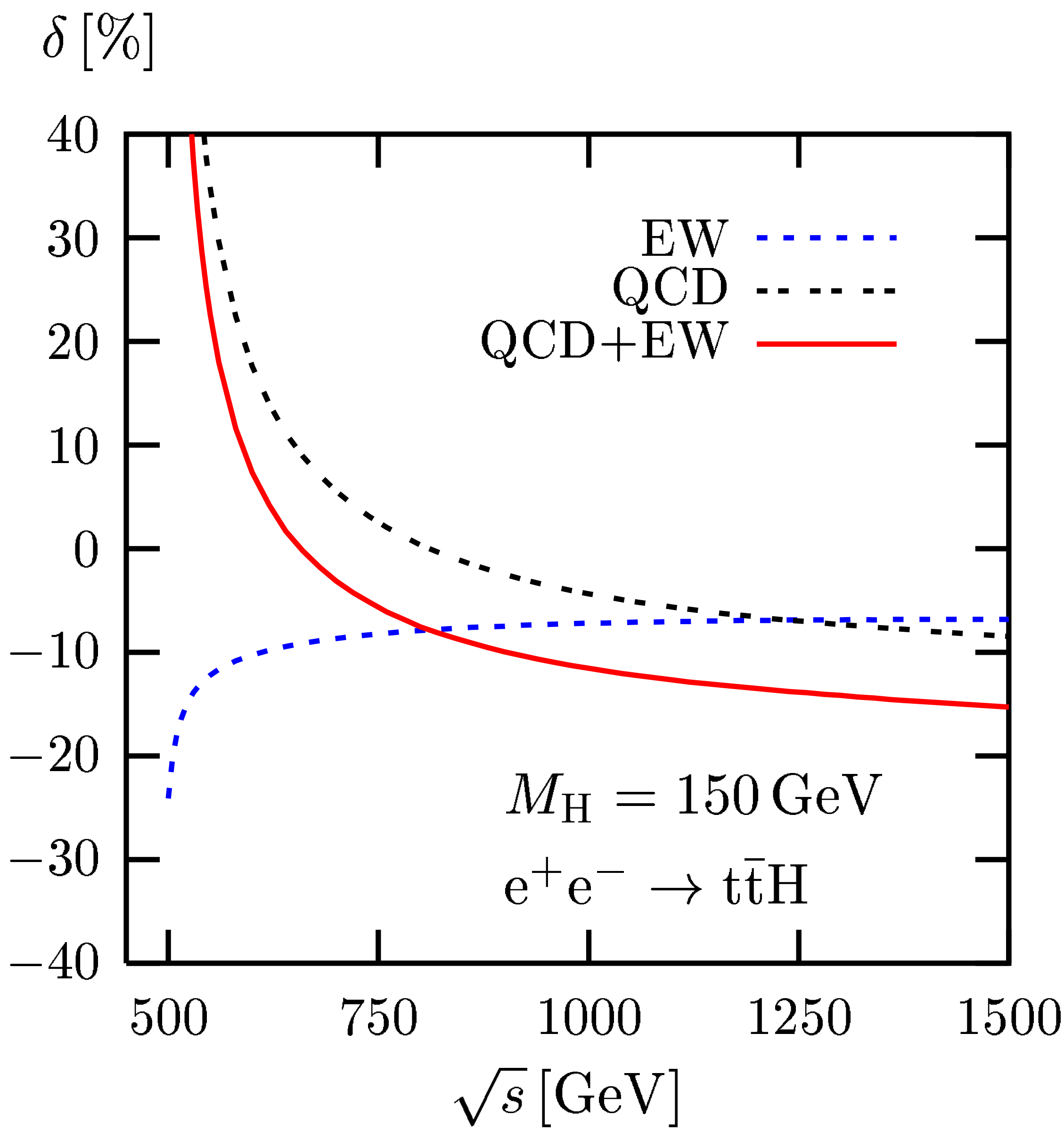
$\to$ sizeable contributions

- QCD corrections: $-10\% \ldots + 40\%$ (threshold)

Dittmaier,...
Dawson, Reina

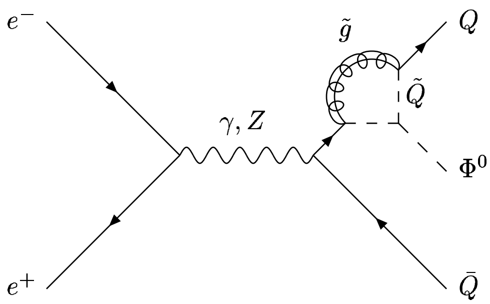
- SM: elw. to $t\bar{t}H \sim -10\% \ldots -20\%$

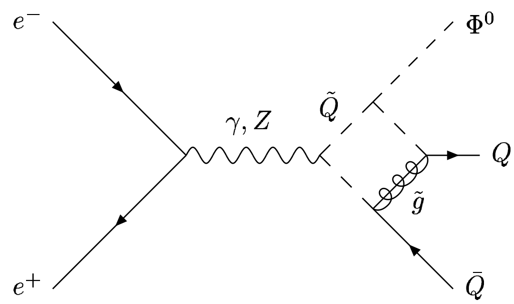
Denner, Dittmaier, Roth, Weber
Belanger,...
Yu,...



Denner, Dittmaier, Roth, Weber

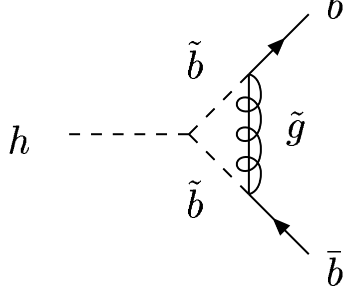
II *SUSY–QCD CORRECTIONS*





- only virtual corrections [massive particles]
- $n = 4 - 2\epsilon$ dimensions
- naive γ_5 [checked]
- m_Q on-shell
- $g_{tt\phi}$ on-shell, $g_{bb\phi}$ running $\overline{\text{MS}}$ at $\mu = Q_\phi$

• large SUSY–QCD corrections to $g_{b\bar{b}\phi}$



$+\cdots \qquad \propto \frac{m_{\tilde{g}}\mu \mathsf{tg}\beta}{m_{\tilde{b}}^2}$

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

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

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

• resummation:

$$\tilde{g}_b^h = \frac{g_b^h}{1+\Delta_b}\left(1 - \frac{\Delta_b}{\mathsf{tg}\alpha\ \mathsf{tg}\beta}\right)$$

$$\tilde{g}_b^H = \frac{g_b^H}{1+\Delta_b}\left(1 + \Delta_b\frac{\mathsf{tg}\alpha}{\mathsf{tg}\beta}\right)$$

$$\tilde{g}_b^A = \frac{g_b^A}{1+\Delta_b}\left(1 - \frac{\Delta_b}{\mathsf{tg}^2\beta}\right)$$

Nierste, Carena, Garcia, Wagner

$\longrightarrow$ absorption of large terms @ large $\mathsf{tg}\beta$

• refinement: $\Delta_b \rightarrow \dfrac{\Delta_b}{1+\Delta_{A_b}}$

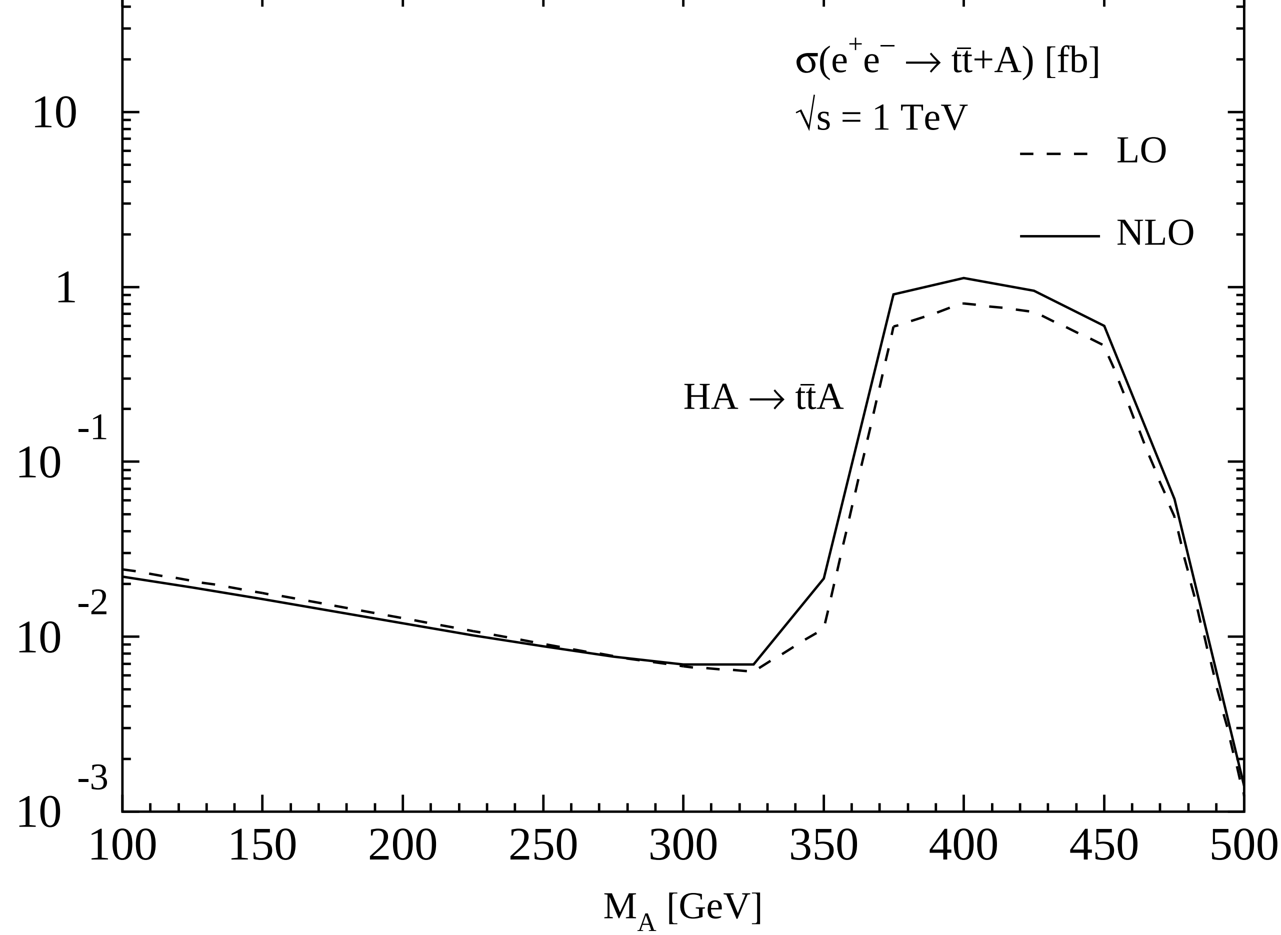
$$\Delta_{A_b} = -\frac{C_F}{2}\,\frac{\alpha_s}{\pi}\, m_{\tilde{g}}\ A_b\ I(m^2_{\tilde{q}_1}, m^2_{\tilde{q}_2}, m^2_{\tilde{g}})$$

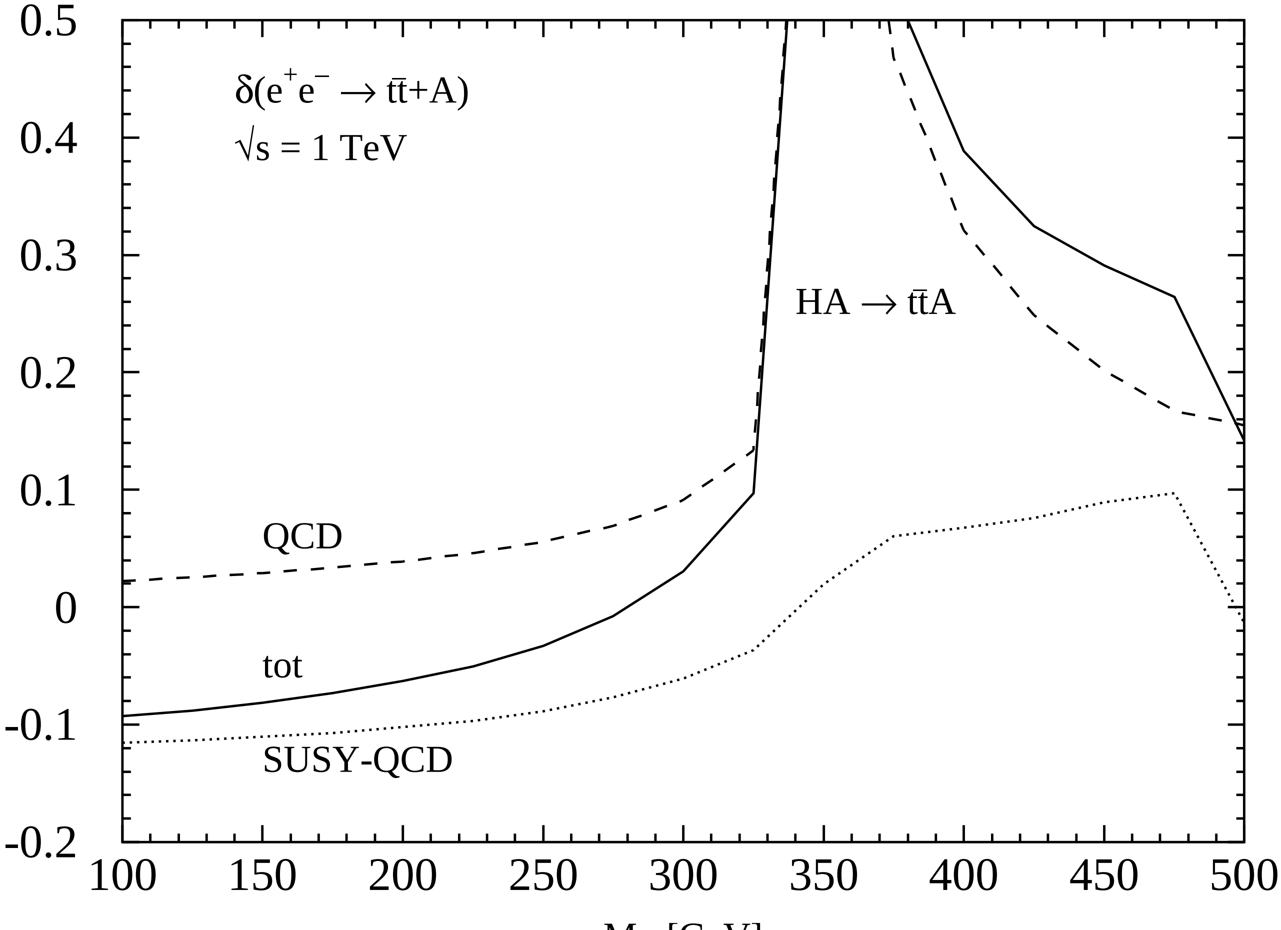
Guasch, Häfliger, S.

$t\bar{t}\phi^0$: SPS 5

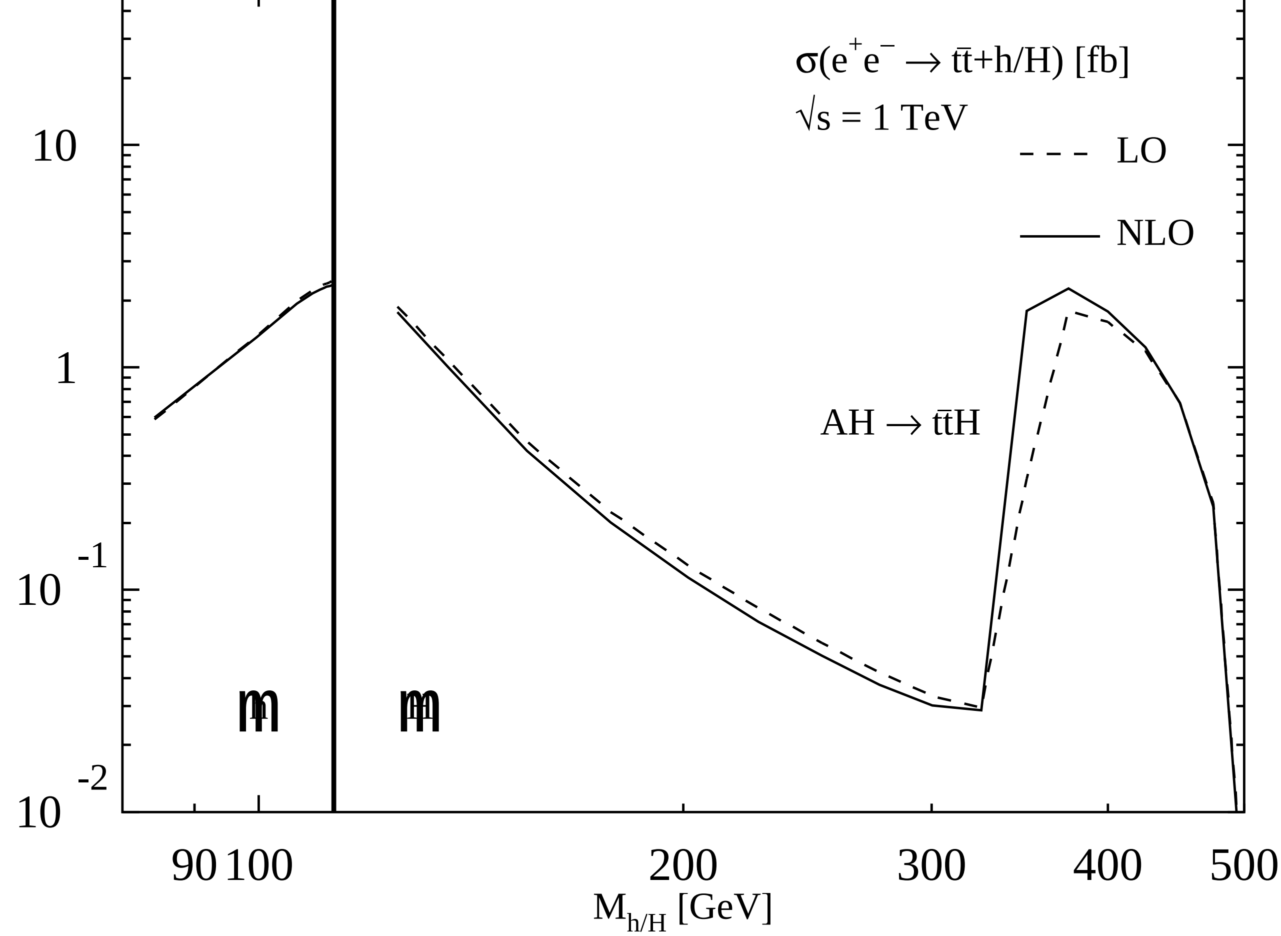
$$
\begin{aligned}
\mathrm{tg}\beta &= 5 \\
\mu &= 639.8\ \mathrm{GeV} \\
A_t &= -1671.4\ \mathrm{GeV} \\
A_b &= -905.6\ \mathrm{GeV} \\
m_{\tilde{g}} &= 710.3\ \mathrm{GeV} \\
m_{\tilde{q}_L} &= 535.2\ \mathrm{GeV} \\
m_{\tilde{b}_R} &= 620.5\ \mathrm{GeV} \\
m_{\tilde{t}_R} &= 360.5\ \mathrm{GeV}
\end{aligned}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

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

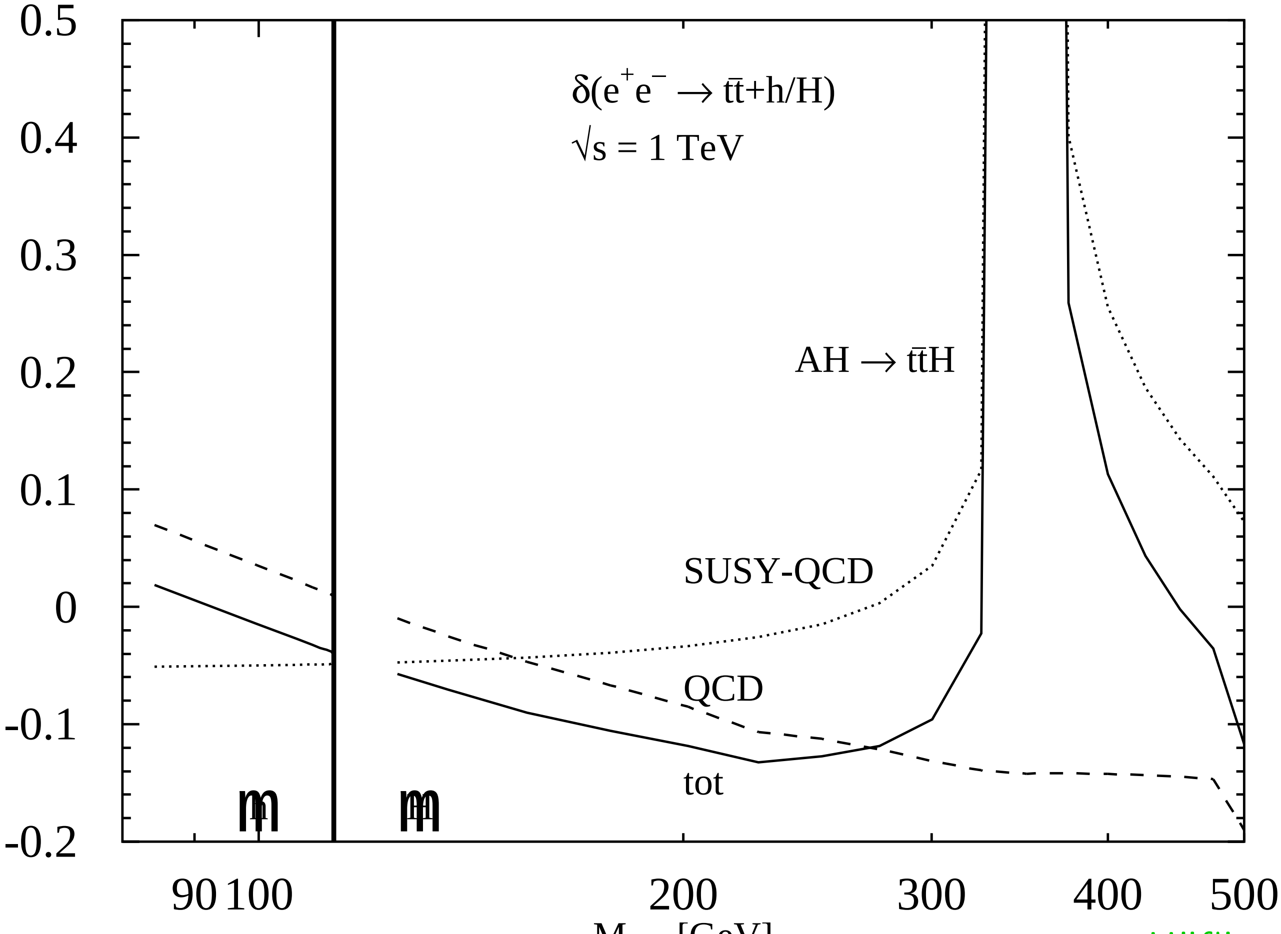

σ(e+e− → tt̄+A) [fb]
√s = 1 TeV
LO
NLO
HA → tt̄A
10
1
10 -1
10 -2
10 -3
100 150 200 250 300 350 400 450 500
M_A [GeV]


δ(e+e− → tt̄+A)
√s = 1 TeV
HA → tt̄A
QCD
tot
SUSY-QCD
0.5 0.4 0.3 0.2 0.1 0 -0.1 -0.2
100 150 200 250 300 350 400 450 500
M_A [GeV]

Häfliger, S.



σ(e+e− → tt̄+h/H) [fb]
√s = 1 TeV
LO
NLO
AH → tt̄H
10
1
10-1
10-2
m h
m H
90 100
200
300
400
500
M_h/H [GeV]



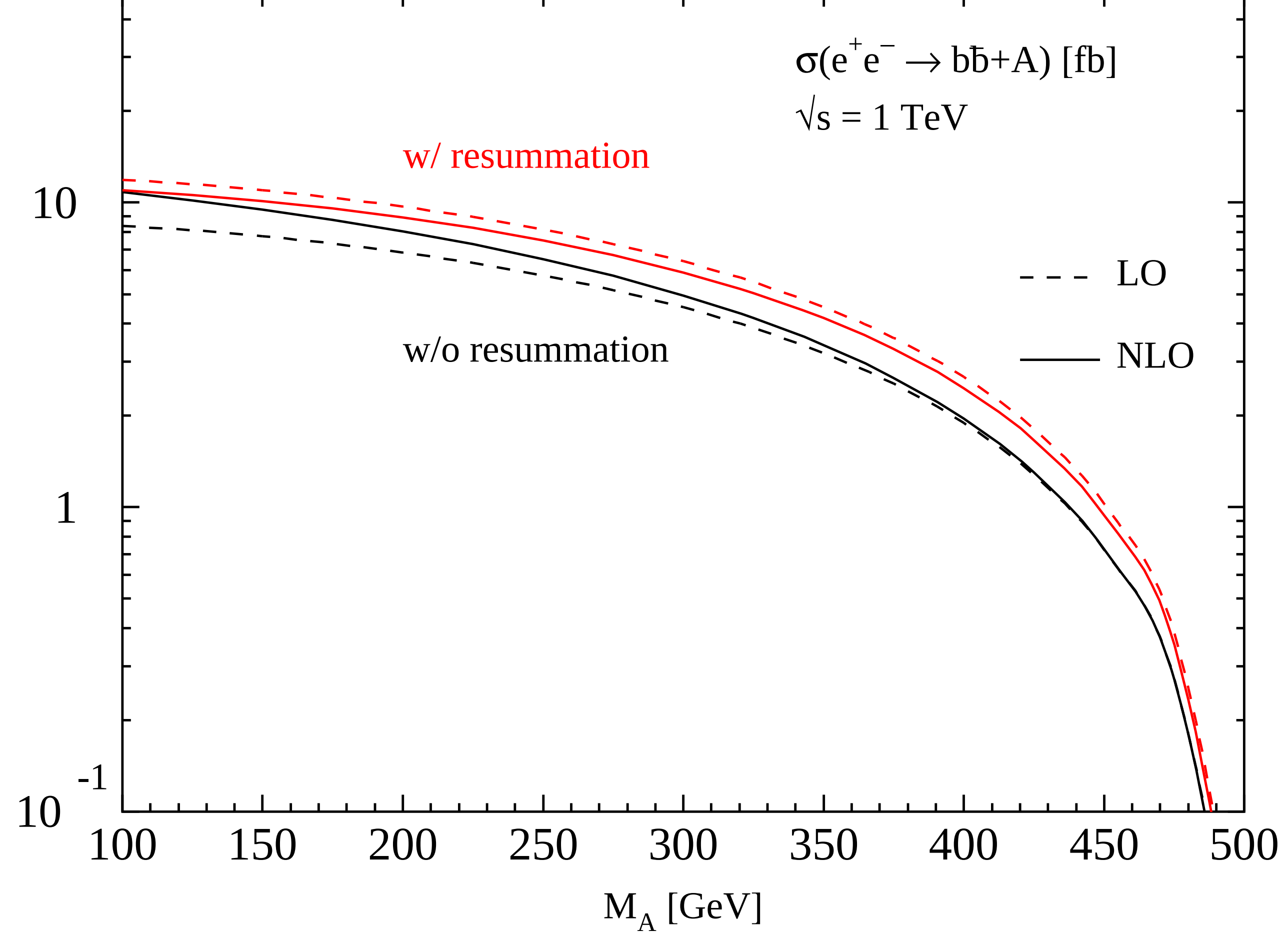
δ(e+e− → tt̄+h/H)
√s = 1 TeV
AH → tt̄H
SUSY-QCD
QCD
tot
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
m h
m H
90 100
200
300
400
500
M_h/H [GeV]

Häfliger, S.

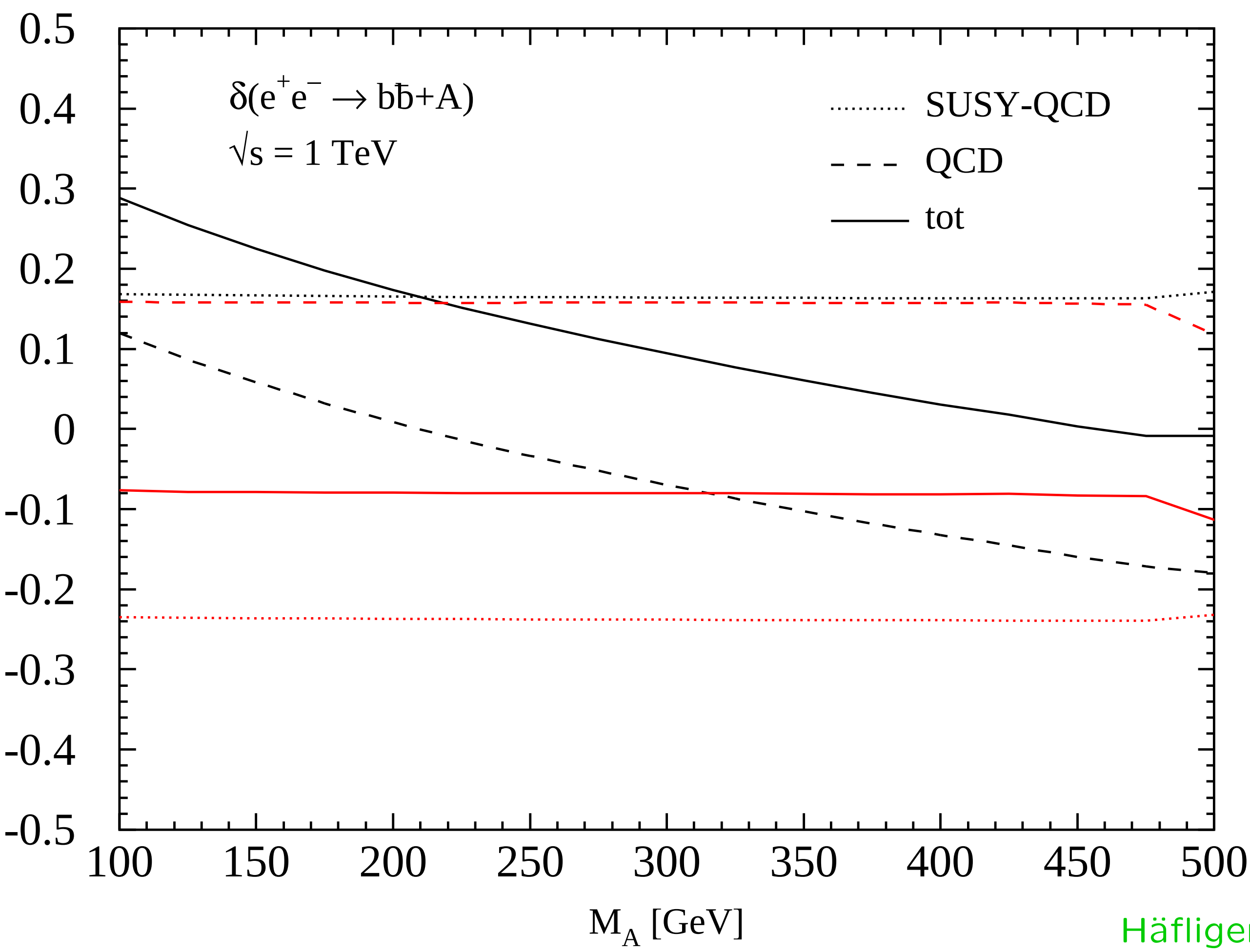
$b\bar{b}\phi^0$: SPS 1b

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

$$\longrightarrow m_{\tilde{b}_1} = 745.7 \text{ GeV}, m_{\tilde{b}_2} = 799.0 \text{ GeV}$$

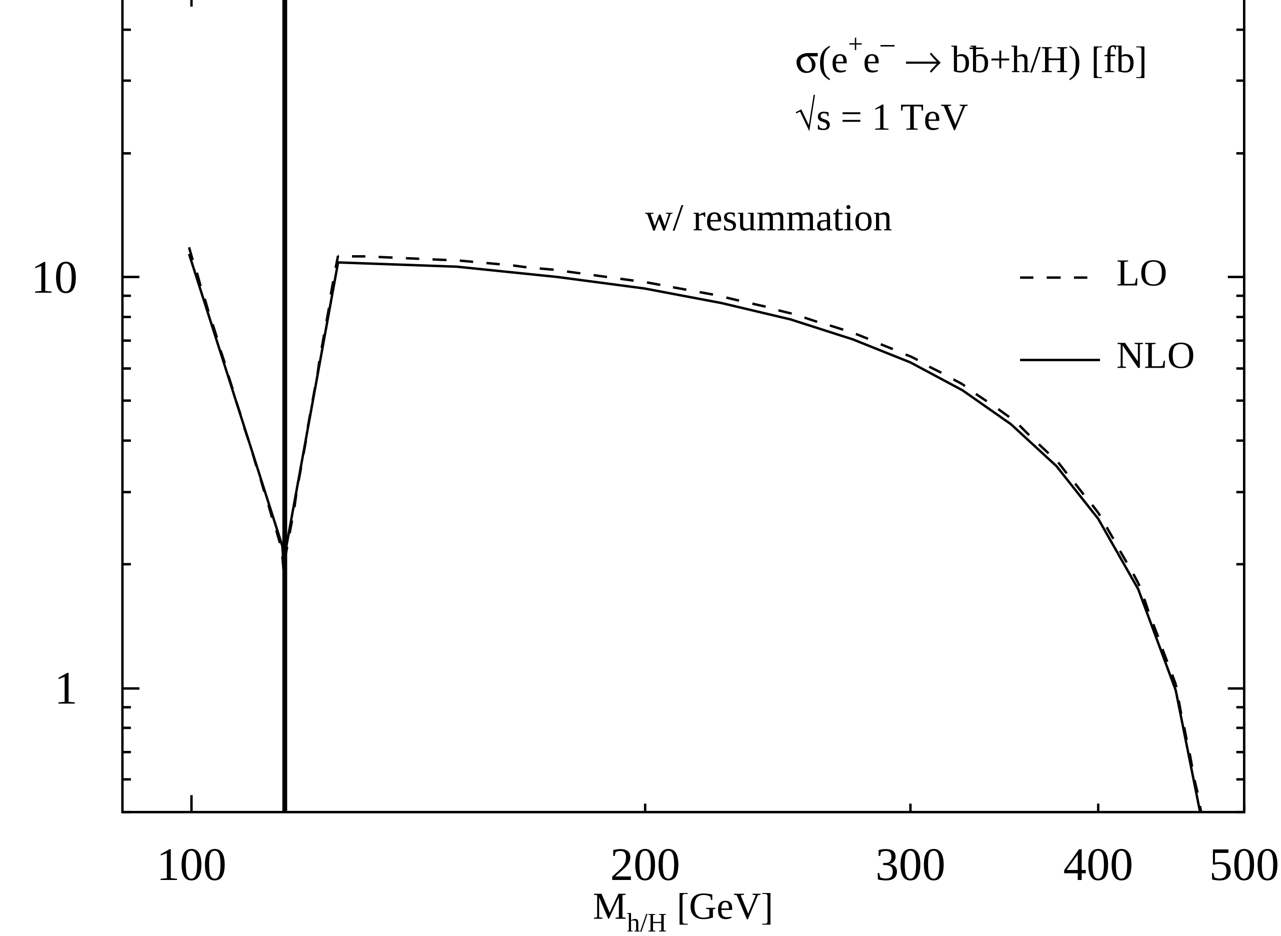


σ(e+e− → bb̄+A) [fb]
√s = 1 TeV
w/ resummation
w/o resummation
LO
NLO
10
1
10^-1
100
150
200
250
300
350
400
450
500
M_A [GeV]

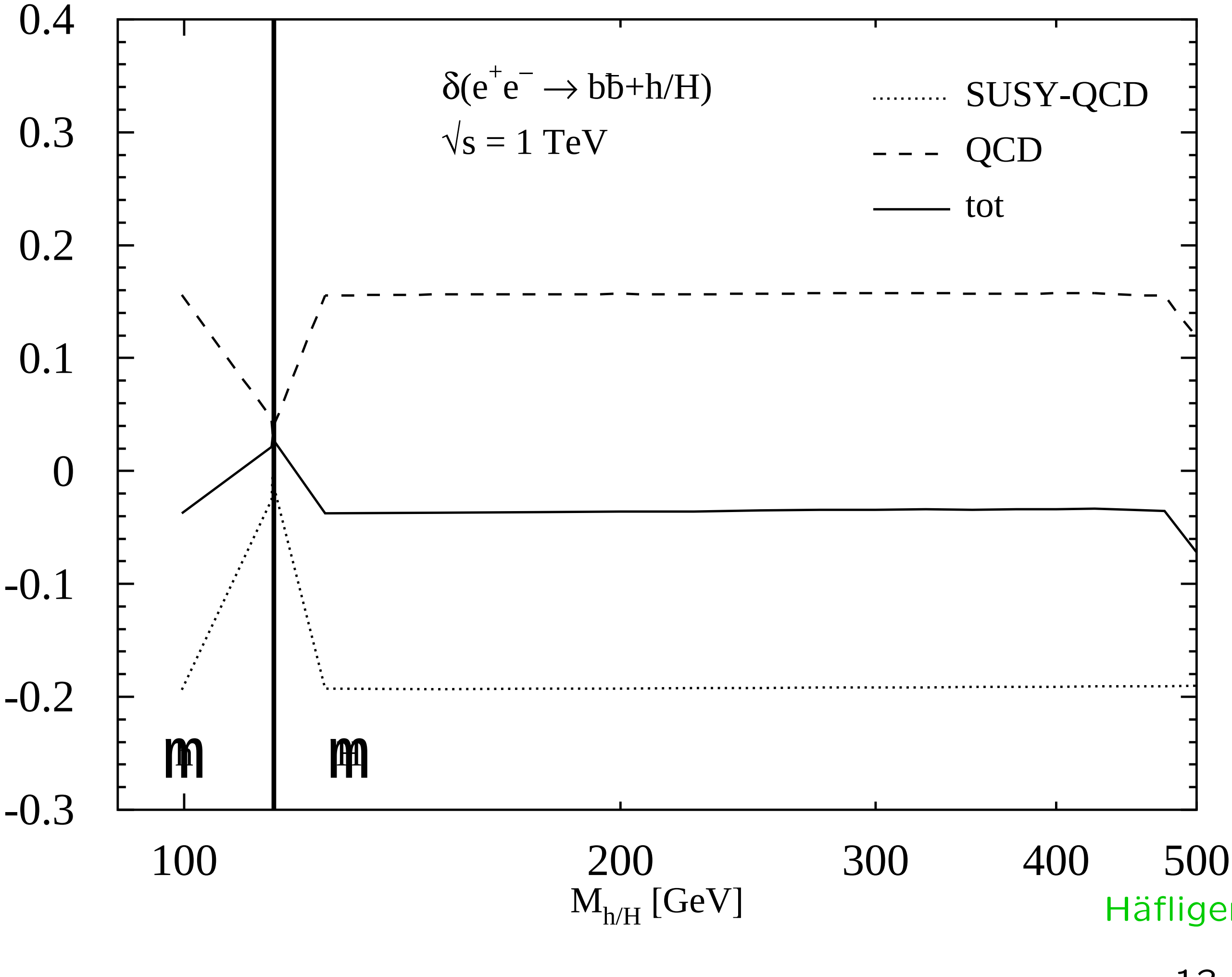


δ(e+e− → bb̄+A)
√s = 1 TeV
SUSY-QCD
QCD
tot
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
100
150
200
250
300
350
400
450
500
M_A [GeV]

Häfliger, S.



σ(e+e− → bb̄+h/H) [fb]
√s = 1 TeV
w/ resummation
LO
NLO
10
1
100
200
300
400
500
M_h/H [GeV]



δ(e+e− → bb̄+h/H)
√s = 1 TeV
SUSY-QCD
QCD
tot
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
100
200
300
400
500
M_h/H [GeV]

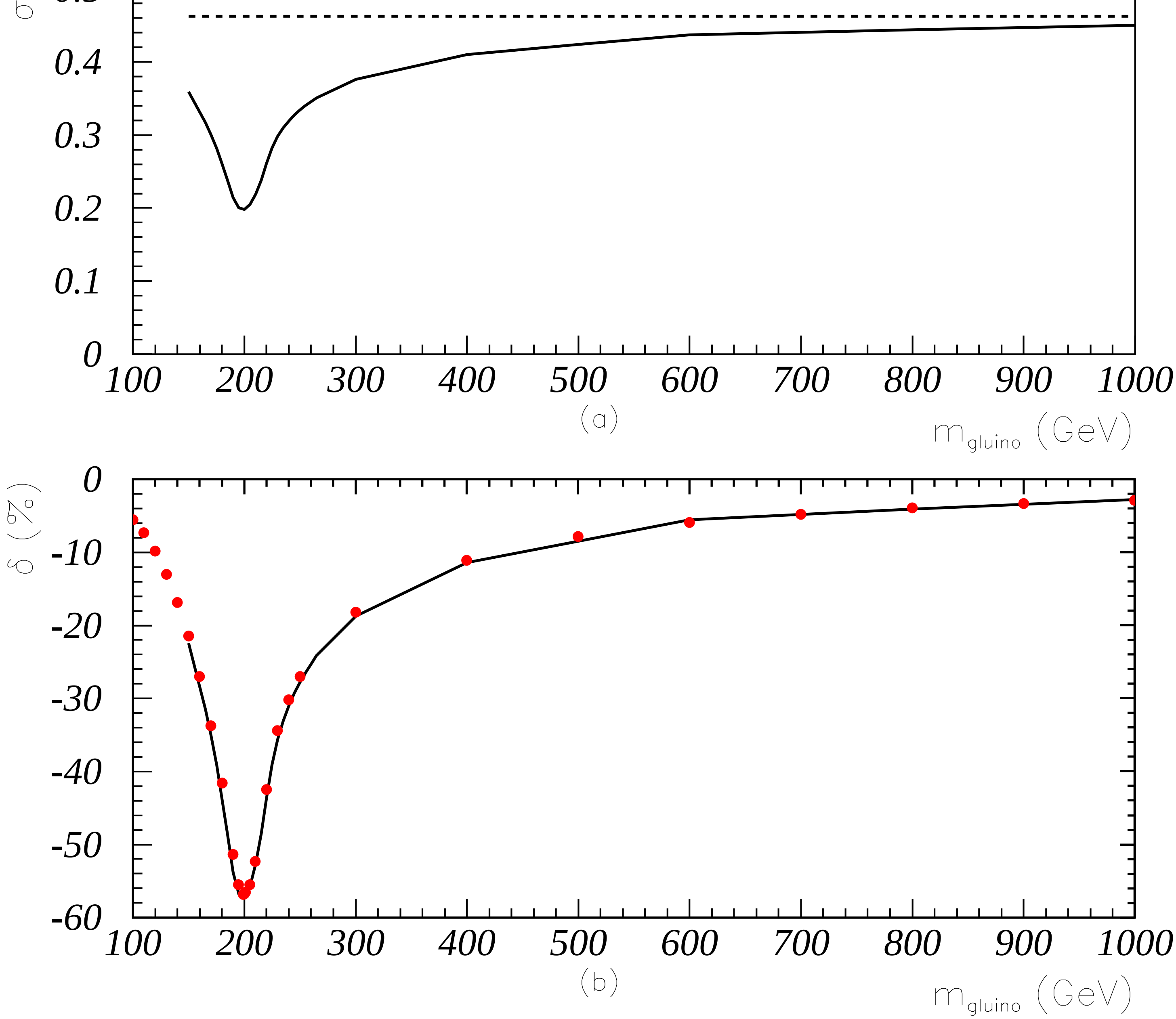
Häfliger, S.

Zhu (hep-ph/0212273):

$$\begin{aligned} M_A &= 300 \text{ GeV} \\ \text{tg}\beta &= 4 \\ \mu &= -100 \text{ GeV} \\ A_t = A_b &= 1 \text{ TeV} \\ m_{\tilde{g}} &= 200 \text{ GeV} \\ m_{\tilde{q}_L} = m_{\tilde{b}_R} = m_{\tilde{t}_R} &= 385(400) \text{ GeV} \end{aligned}$$

$$\longrightarrow m_{\tilde{t}_1} = 100.6 \text{ GeV}, m_{\tilde{t}_2} = 576.1 \text{ GeV}$$

- only approximately reproduced



Zhu
Häfliger, S.

III *CONCLUSIONS*

$t\bar{t}\phi$:

- measurement of top Yukawa coupling
- QCD corrections: $\sim -10\% \ldots +40\%$
- electroweak corrections: $\sim -10\% \ldots -20\%$ ($t\bar{t}H$)
- genuine SUSY–QCD corrections: $\sim -10\% \ldots 10\%$
- agreement with Zhu for $t\bar{t}h$ [$\leftarrow$ very extreme scenario]
- SUSY–electroweak?

$b\bar{b}\phi$:

- important for large tgβ
- determination of tgβ
- QCD corrections: $\sim 5\% - 25\%$
- genuine SUSY–QCD corrections: $\sim -20\% \ldots 20\%$
- dominant effect: $\Delta_b \to$ resummation
- SUSY–electroweak?