NEW DEVELOPMENTS IN MSSM HIGGS PRODUCTION & DECAY

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I Introduction

II Higgs Decays into Quarks

III $gg \to A$

IV Conclusions

I INTRODUCTION

MSSM

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

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

- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\rightarrow$ $\boxed{M_h \lesssim 135 \text{ GeV}}$

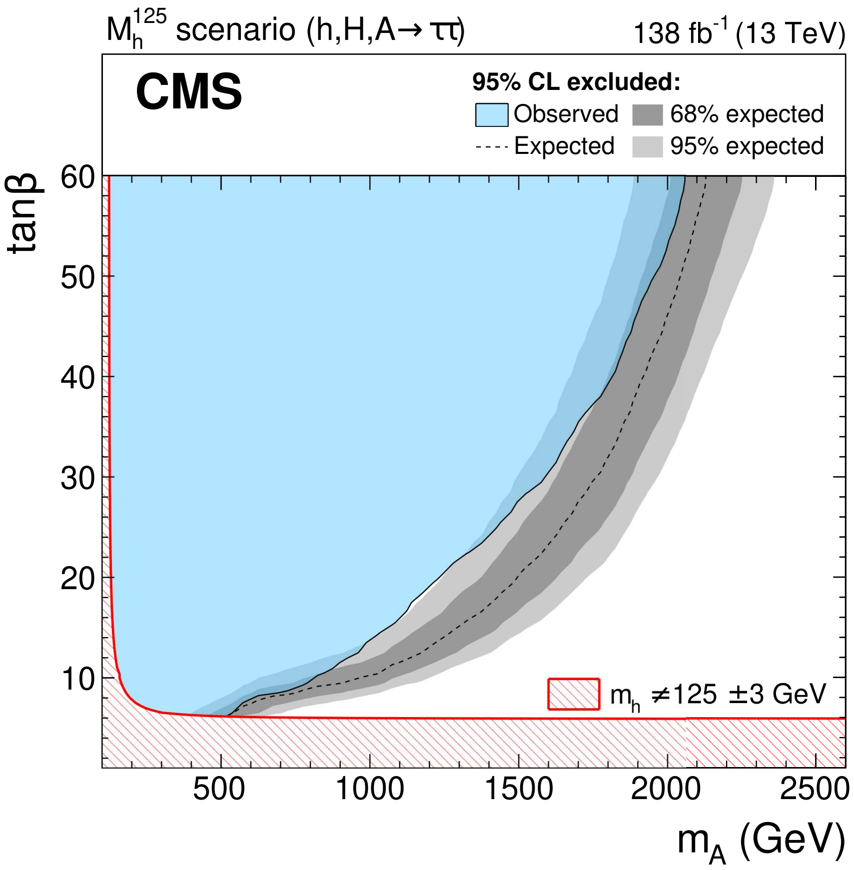
Haber
Carena,. . .
Heinemeyer,. . .
Zhang
Slavich,. . .
. . .

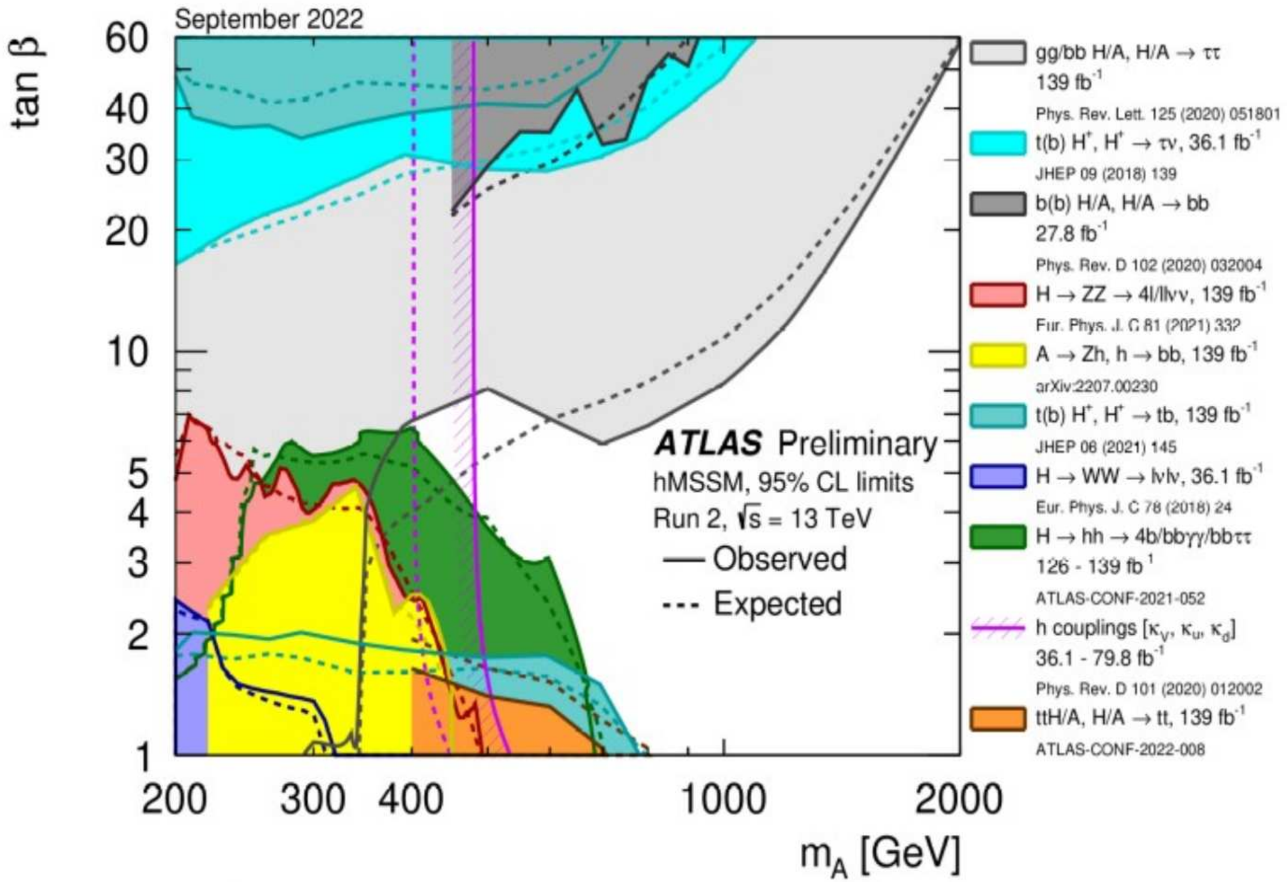
- Yukawa couplings: $\text{tg}\beta\uparrow$ $\Rightarrow$ $g_u^\phi\downarrow$ $g_d^\phi\uparrow$ $g_V^\phi\downarrow$

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

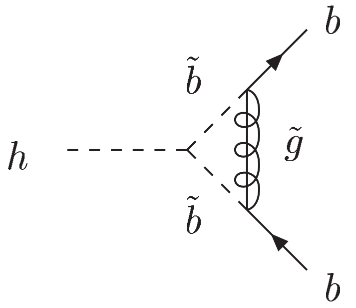
$$gg \to b\bar{b}\phi^0,\ \ gg \to \phi^0 \qquad \phi^0 \to \tau^+\tau^-$$

↓ ↓



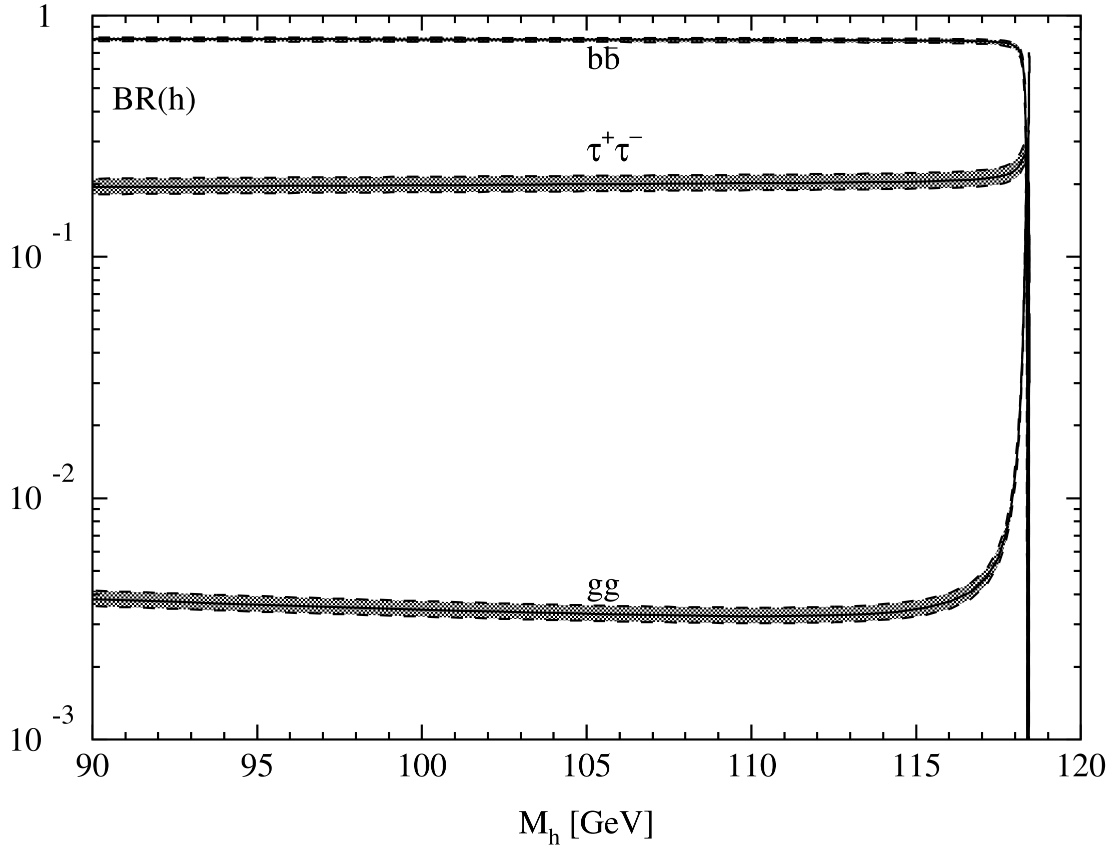


• large SUSY–QCD corrections to $\phi^0 \to b\bar{b}$



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

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



Guasch, Häfliger, S.

II Higgs Decays into Quarks

SUSY-QCD Corrections to $b\bar{b}\phi^0$

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

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

$$\Delta_b = \Delta_b^{QCD(1)} + \Delta_b^{elw(1)} \qquad \to \text{NNLO}$$

Noth, S. & Mihaila, Reisser

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

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

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

$\Rightarrow$ resummed Yukawa couplings $\tilde{g}_b^\Phi$

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

- extension to A_b terms:

$$\mathcal{L}_{eff} = -\lambda_b^0 \overline{b_R} \left[(1+\Delta_{b,1})\phi_1^0 + \frac{\Delta_{b,2}}{\mathrm{tg}\beta}\phi_2^{0*} \right] b_L + h.c.$$

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

$$\Rightarrow \qquad \Delta_b = \frac{\Delta_{b,2}}{1+\Delta_{b,1}}$$

Guasch, Häfliger, S.
Ghezzi, Glaus, Müller, Schmidt, S.

$$\Delta_{b,1} = -\frac{2}{3}\frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}} \, A_b \, I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, M^2_{\tilde{g}}) \qquad \rightarrow \text{NNLO}$$

- strange Yukawa couplings:

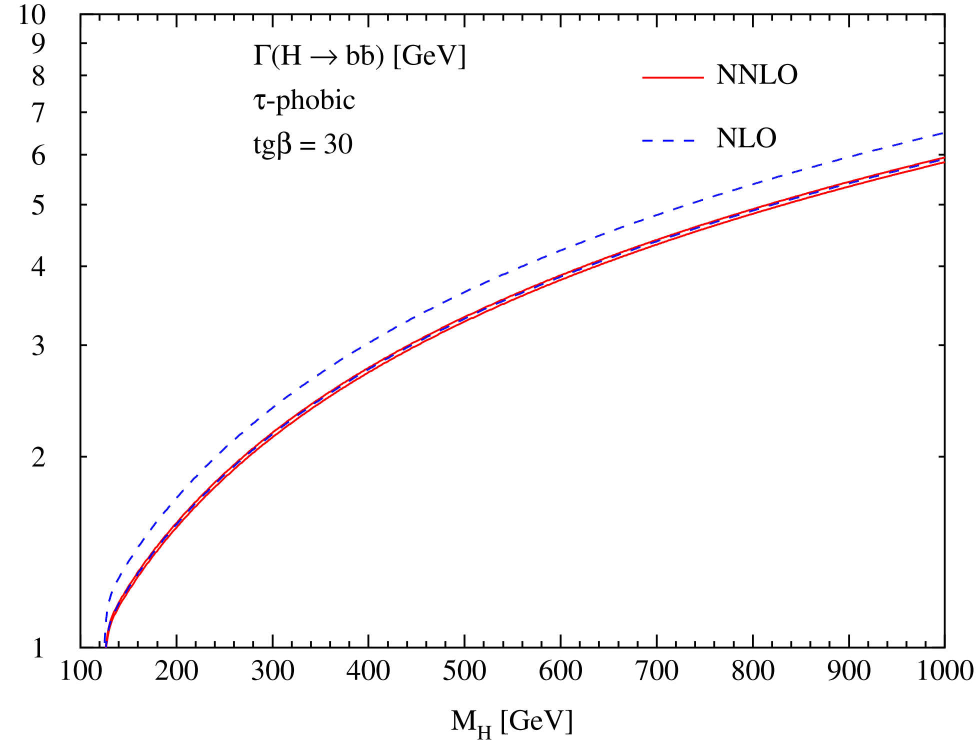
$$\Delta_{s,1} = -\frac{2}{3}\frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}} \, A_s \, I(m^2_{\tilde{s}_1}, m^2_{\tilde{s}_2}, M^2_{\tilde{g}})$$

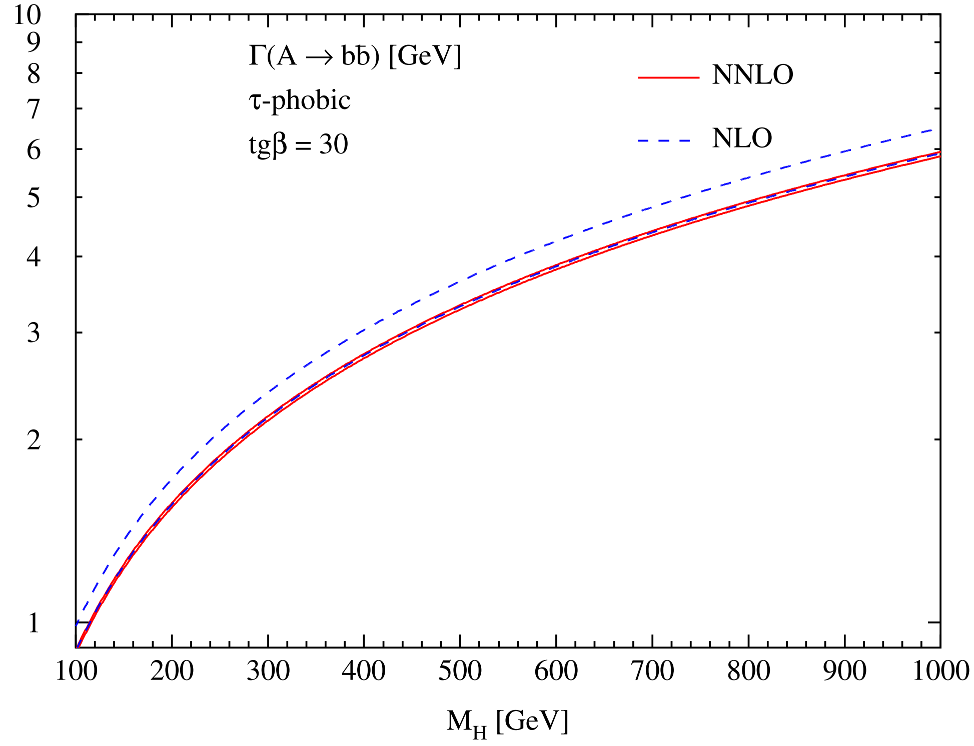
$$\Delta_{s,2} = \frac{2}{3}\frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}} \, \mu \mathrm{tg}\beta \, I(m^2_{\tilde{s}_1}, m^2_{\tilde{s}_2}, M^2_{\tilde{g}})$$

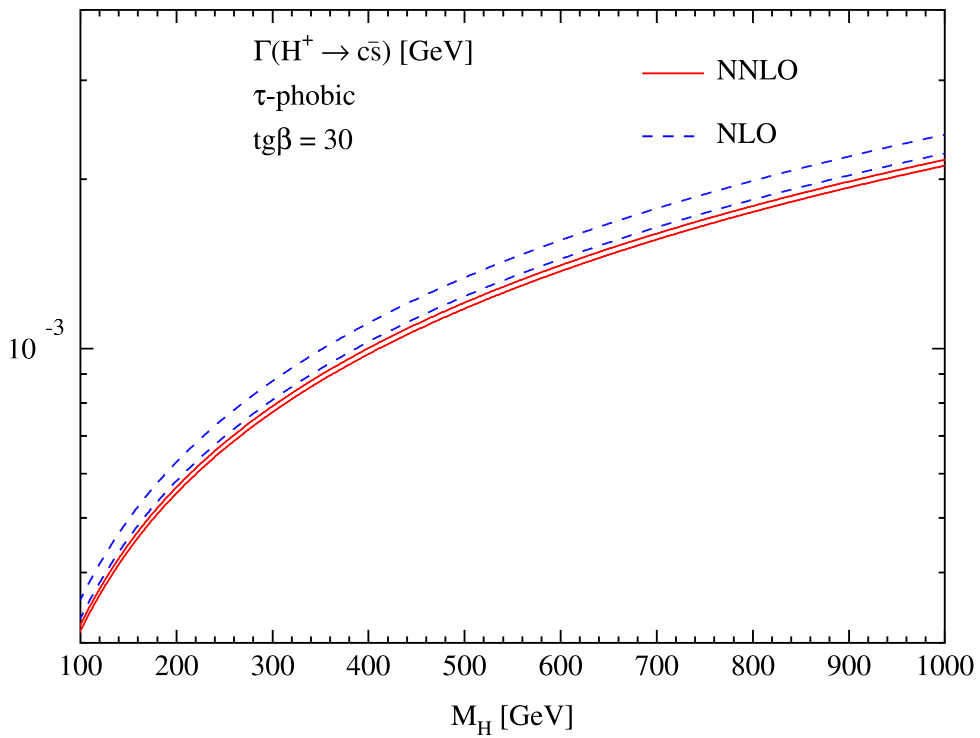
$$\Delta_s = \frac{\Delta_{s,2}}{1+\Delta_{s,1}} \qquad \rightarrow \text{NNLO}$$

Ghezzi, Glaus, Müller, Schmidt, S.

- identify charged Higgs-Yukawas with pseudoscalar: $g_{t,b}^{H^\pm} = g_{t,b}^A$







Ghezzi, Glaus, Müller, Schmidt, S.

- extension to Δ_t: $\quad (g_t^A = 1/\text{tg}\beta)$ Chang, Kirk, Mühlleitner, S.

$$\mathcal{L}_{eff} = -\lambda_t \overline{t_R} \left[\phi_1^0 + \frac{\Delta_t}{\text{tg}\beta} \phi_2^{0*} \right] t_L + h.c.$$

$$= -m_t \bar{t} \left[1 - i\gamma_5 \frac{G^0}{v} \right] t - \frac{m_t/v}{1+\Delta_t} \bar{t} \left[g_t^h \left(1 - \Delta_t \text{tg}\alpha\ \text{tg}\beta\right) h + g_t^H \left(1 + \Delta_t \frac{\text{tg}\beta}{\text{tg}\alpha}\right) H - g_t^A \left(1 - \Delta_t \text{tg}^2\beta\right) i\gamma_5 A \right] t$$

$$\Delta_t^{QCD(1)} = \frac{2}{3} \frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}} \frac{\mu}{\text{tg}\beta} I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, M_{\tilde{g}}^2) \qquad \to \text{NNLO}$$

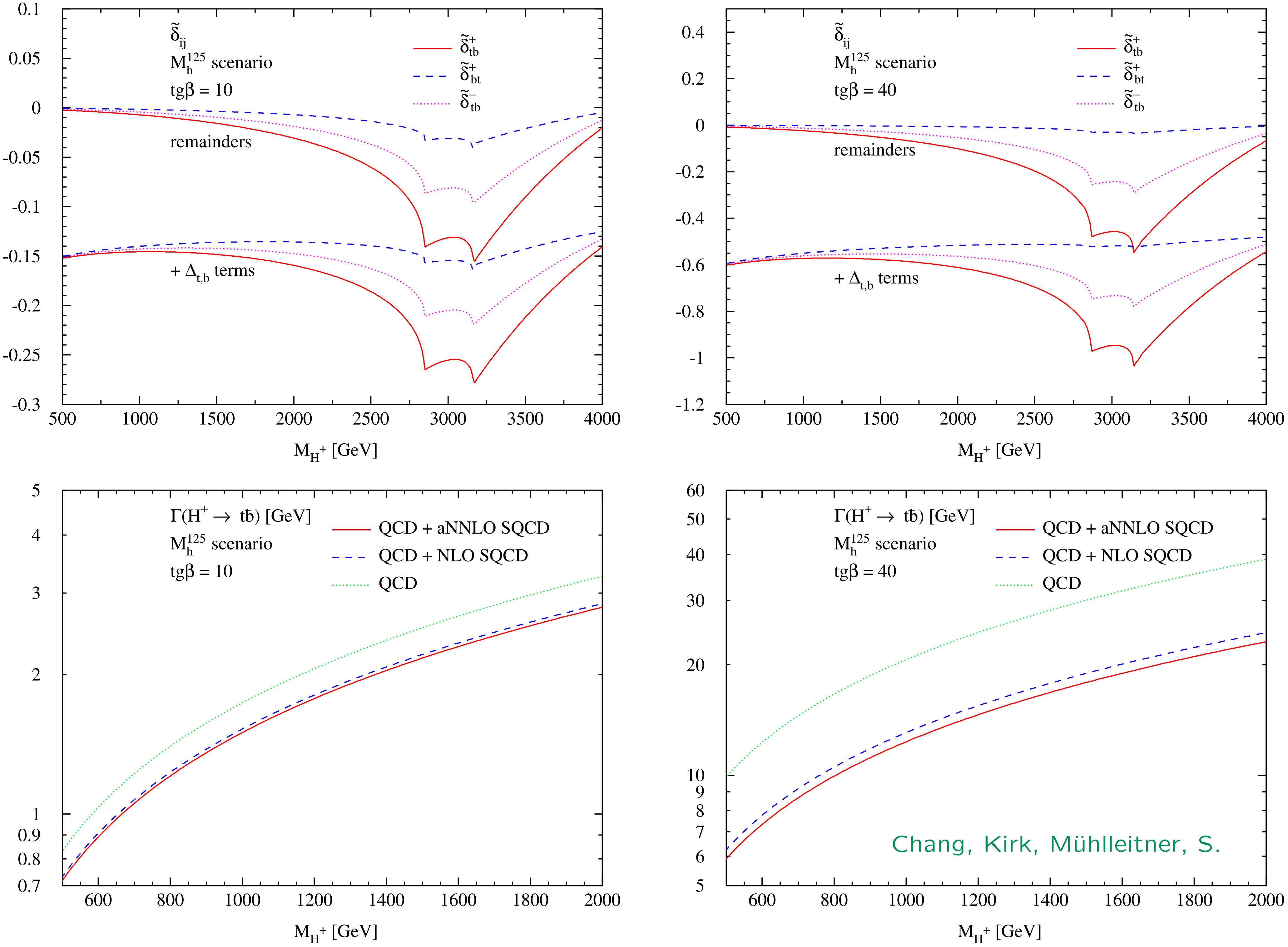
$M_{H^\pm} \gg m_{U,D}$:

$$\Gamma(H^+ \to U\overline{D}) = \frac{3G_F M_{H^\pm}}{4\sqrt{2}\pi} |V_{UD}|^2 \left[\overline{m}_U^2 \tilde{g}_U^A \left(\tilde{g}_U^A + g_U^A \tilde{\delta}^+_{UD,rem}\right) + \overline{m}_D^2 \tilde{g}_D^A \left(\tilde{g}_D^A + g_D^A \tilde{\delta}^+_{DU,rem}\right) \right] (1 + \delta_{\text{QCD}})$$

- δ_{QCD}: N^{4}LO $\qquad \delta_{ij}, \tilde{\delta}_{ij}$: NLO

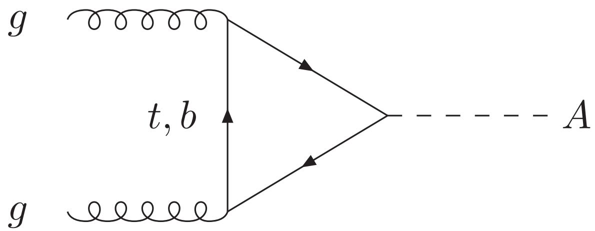
- $\tilde{\delta}_{ij}$ small up to $M_{H^\pm} \approx 2$ TeV $\Rightarrow$ aNNLO

- translated to $H^\pm \to cb, cs$



δ̃ij
Mh125 scenario
tgβ = 10
δ̃+tb
δ̃+bt
δ̃−tb
remainders
+ Δt,b terms
MH+ [GeV]
δ̃ij
Mh125 scenario
tgβ = 40
δ̃+tb
δ̃+bt
δ̃−tb
remainders
+ Δt,b terms
MH+ [GeV]
Γ(H+ → tb̄) [GeV]
Mh125 scenario
tgβ = 10
QCD + aNNLO SQCD
QCD + NLO SQCD
QCD
MH+ [GeV]
Γ(H+ → tb̄) [GeV]
Mh125 scenario
tgβ = 40
QCD + aNNLO SQCD
QCD + NLO SQCD
QCD
Chang, Kirk, Mühlleitner, S.
MH+ [GeV]

III $\underline{\underline{gg \to A}}$



Georgi,. . .

Gamberini,. . .

- NLO QCD corrections: $\sim 10 \ldots 100\%$

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman

- NNLO calculated for $m_t \gg M_\phi \Rightarrow$ further increase by 20–30%

Harlander, Kilgore
Anastasiou, Melnikov
Ravindran, Smith, van Neerven

- impl. of $gg \to \phi$ in POWHEG including mass effects @ NLO QCD

Bagnaschi, Degrassi, Slavich, Vicini

- SUSY-elw. corrections unknown

- genuine SUSY–QCD corrections: 10–100% [$\leftarrow \Delta_{t,b}$]

Harlander, Steinhauser, Hofmann
Degrassi, Di Vita, Slavich

$\leftarrow$ numerical integration of full 2-loop diagrams

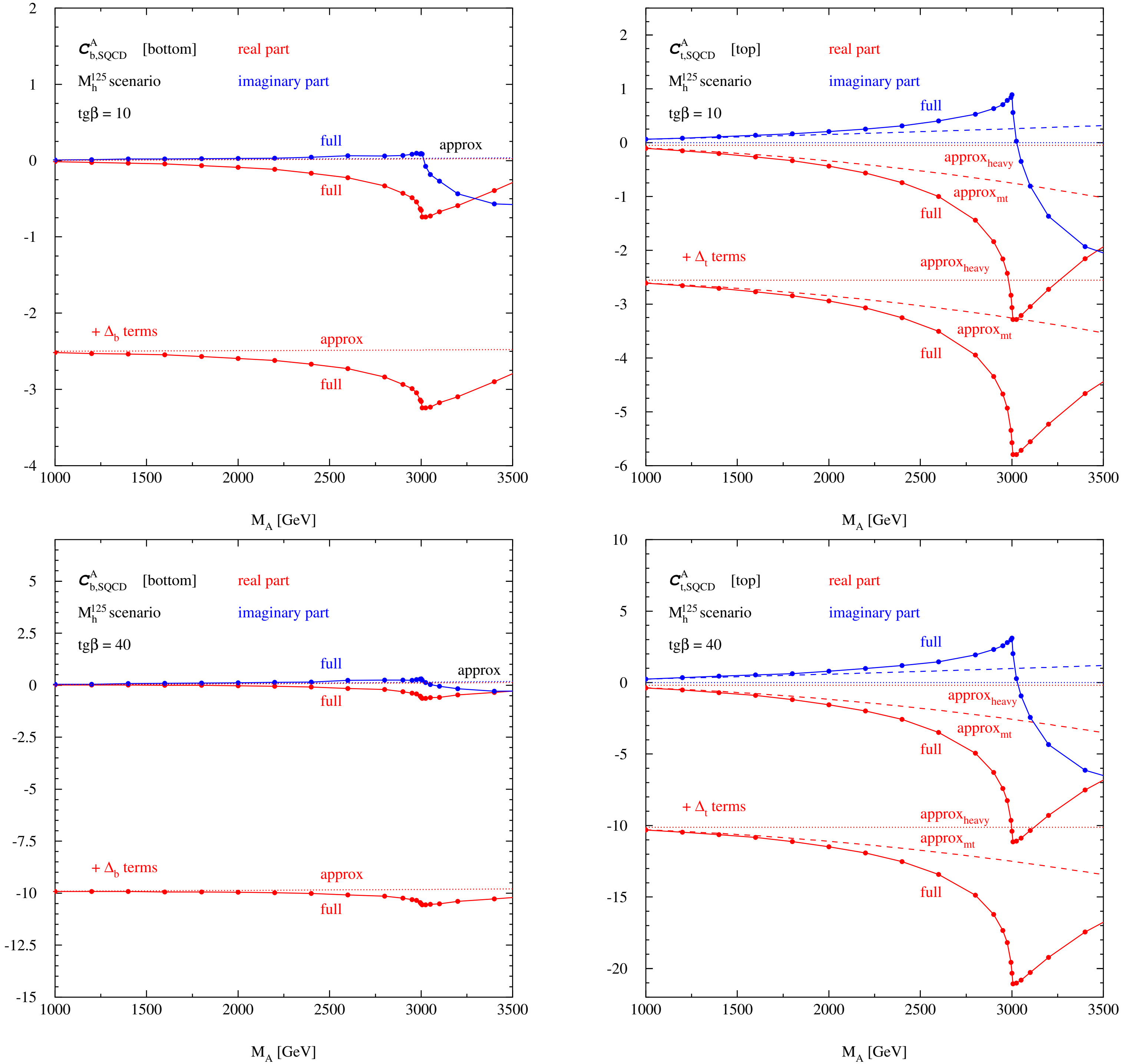
Bagnaschi, . . .

$$\sigma_{LO}(pp \to A) = \sigma_0^A \tau_A \frac{d\mathcal{L}^{gg}}{d\tau_A} \qquad \frac{d\mathcal{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x}\, g(x,\mu_F^2) g(\tau/x,\mu_F^2)$$

$$\hat{\sigma}_{LO}^A(gg \to A) = \sigma_0^A \delta(1-z) \qquad \sigma_0^A = \frac{G_F \alpha_s^2(\mu_R)}{128\sqrt{2}\pi} \left| \sum_Q g_Q^A A_Q^A(\tau_Q) \right|^2$$

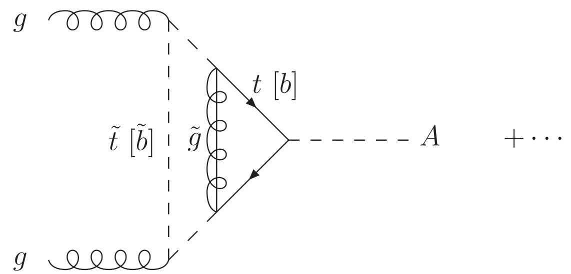
$$A_Q^A(\tau) = \tau f(\tau) \qquad f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

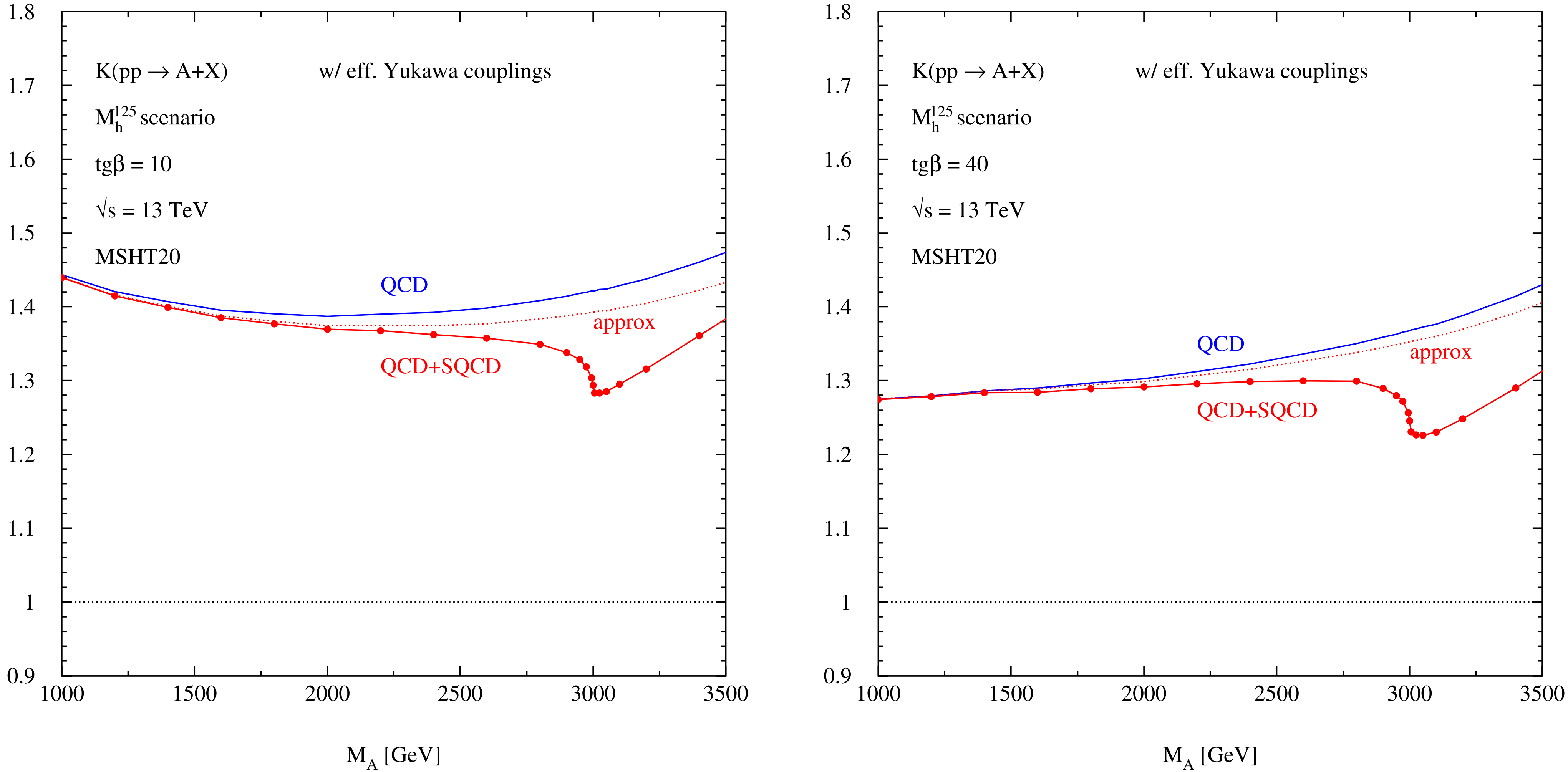
$$A_Q(\tau_Q) \to A_Q(\tau_Q)\left[1 + C_{Q,SQCD}^A \frac{\alpha_s}{\pi}\right]$$



Bagnaschi, Fritz, Liebler, Mühlleitner, Nguyen, S.

$$\sigma(gg \to A) = \sigma_{LO}(\tilde{g}_t^A, \tilde{g}_b^A)\left[1 + \delta_{QCD} + \delta_{SQCD}\right]$$





Bagnaschi, Fritz, Liebler, Mühlleitner, Nguyen, S.

IV CONCLUSIONS

- genuine SUSY–QCD corrections large at large tg$\beta \leftarrow \Delta_{t,b}$
- extension to Δ_t new
- small remainders beyond $\Delta_{t,b}$ approximation in most cases
- analogous results for charm and strange Yukawa couplings $\rightarrow \Delta_{c,s}$
- approximate NNLO results for charged Higgs decays into quarks
- full SUSY–QCD corrections to $gg \to A$

BACKUP SLIDES

- 9 triangle diagrams, counterterms: α_s: $\overline{\text{MS}}$ 5FS, m_t: on-shell

- one form factor $\leftarrow$ projector, no tensor reduction

- γ_5: Larin scheme (checked against HVBM, Kreimer)

- UV-singularities: end-point subtractions

$$\int_0^1 dx\, \frac{f(x)}{(1-x)^{1-\epsilon}} \;=\; \int_0^1 dx\, \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx\, \frac{f(x)-f(1)}{(1-x)^{1-\epsilon}} = \frac{f(1)}{\epsilon} + \int_0^1 dx\, \frac{f(x)-f(1)}{1-x} + \mathcal{O}(\epsilon)$$

- thresholds: $M_A^2 \geq 4m_Q^2, 4m_{\tilde{Q}}^2 \rightarrow$ IBP $\rightarrow$ reduction of power of denominator $[m_{Q,\tilde{Q}}^2 \rightarrow m_{Q,\tilde{Q}}^2(1-ih)]$

$$\int_0^1 dx\, \frac{f(x)}{(a+bx)^2} = \frac{f(0)}{ab} - \frac{f(1)}{b(a+b)} + \int_0^1 dx \frac{f'(x)}{b(a+bx)}$$

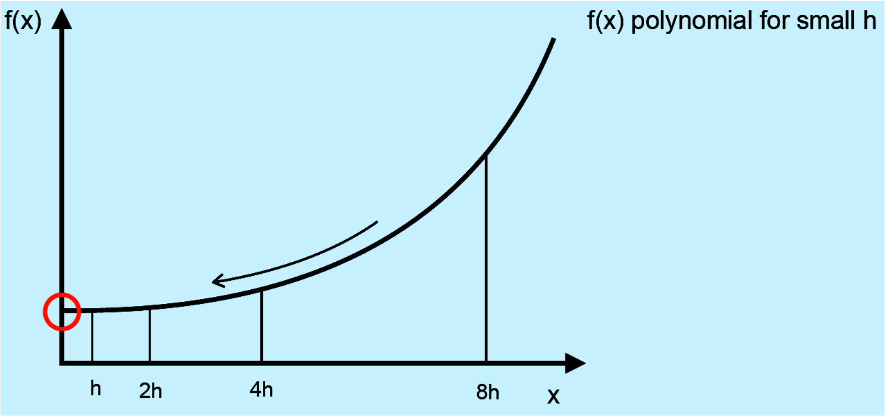
- extrapolation to NWA ($h \to 0$): Richardson extrapolation 1911

$M_2 = 2f(h) - f(2h) = f(0) + \mathcal{O}(h^2)$

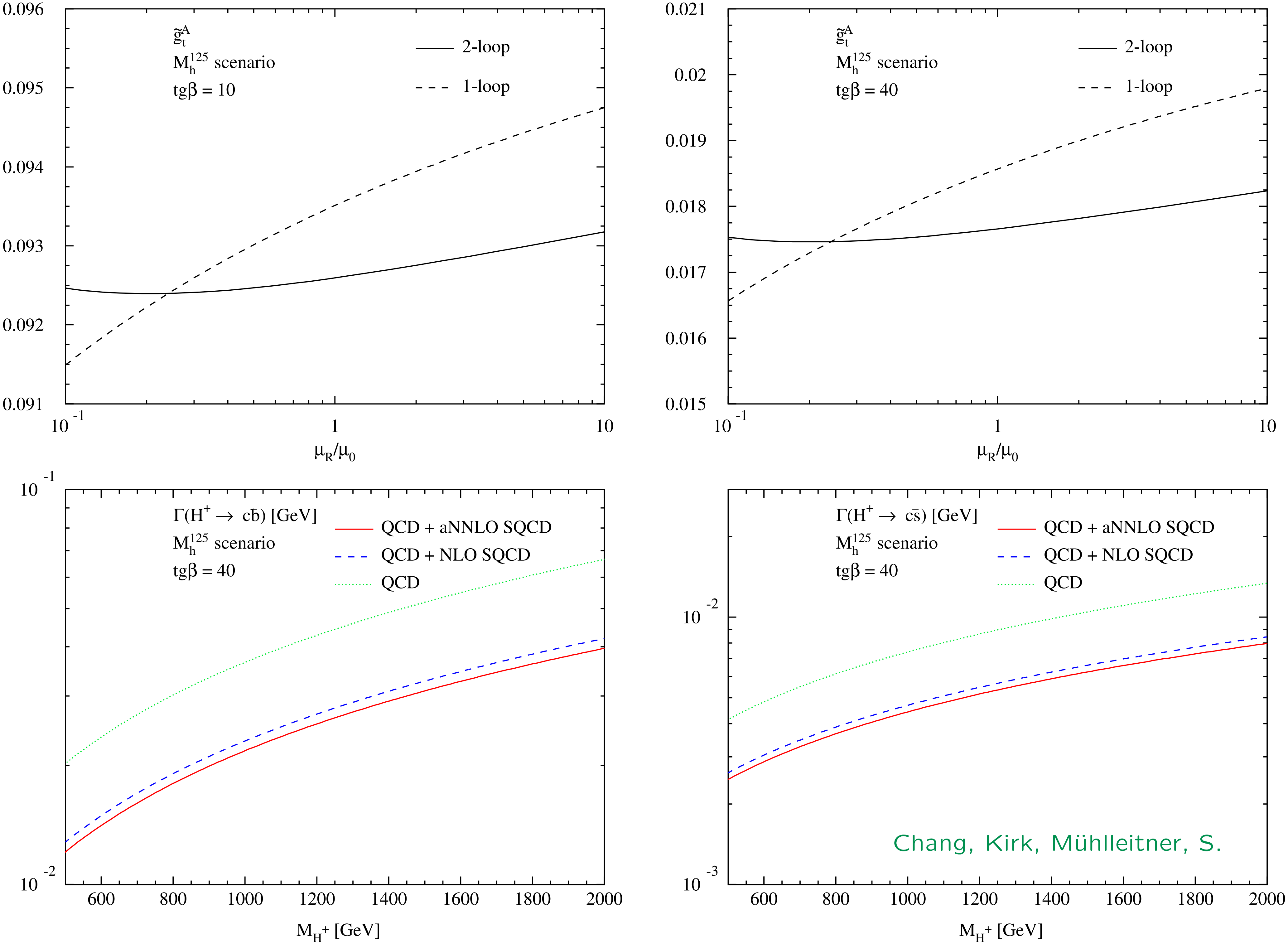
$M_4 = \{8f(h) - 6f(2h) + f(4h)\}/3 = f(0) + \mathcal{O}(h^3)$

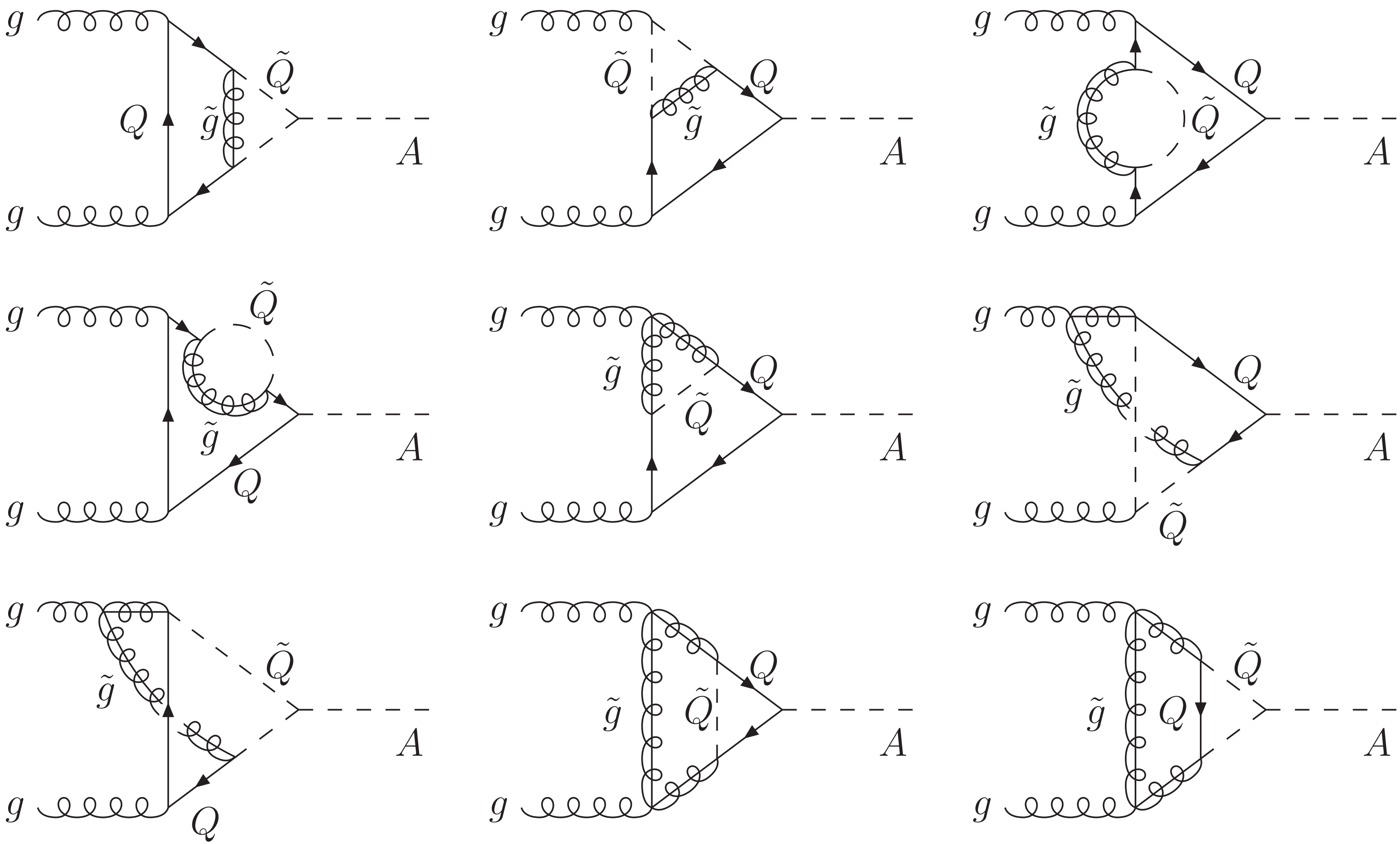
$M_8 = \{64f(h) - 56f(2h) + 14f(4h) - f(8h)\}/21 = f(0) + \mathcal{O}(h^4)$

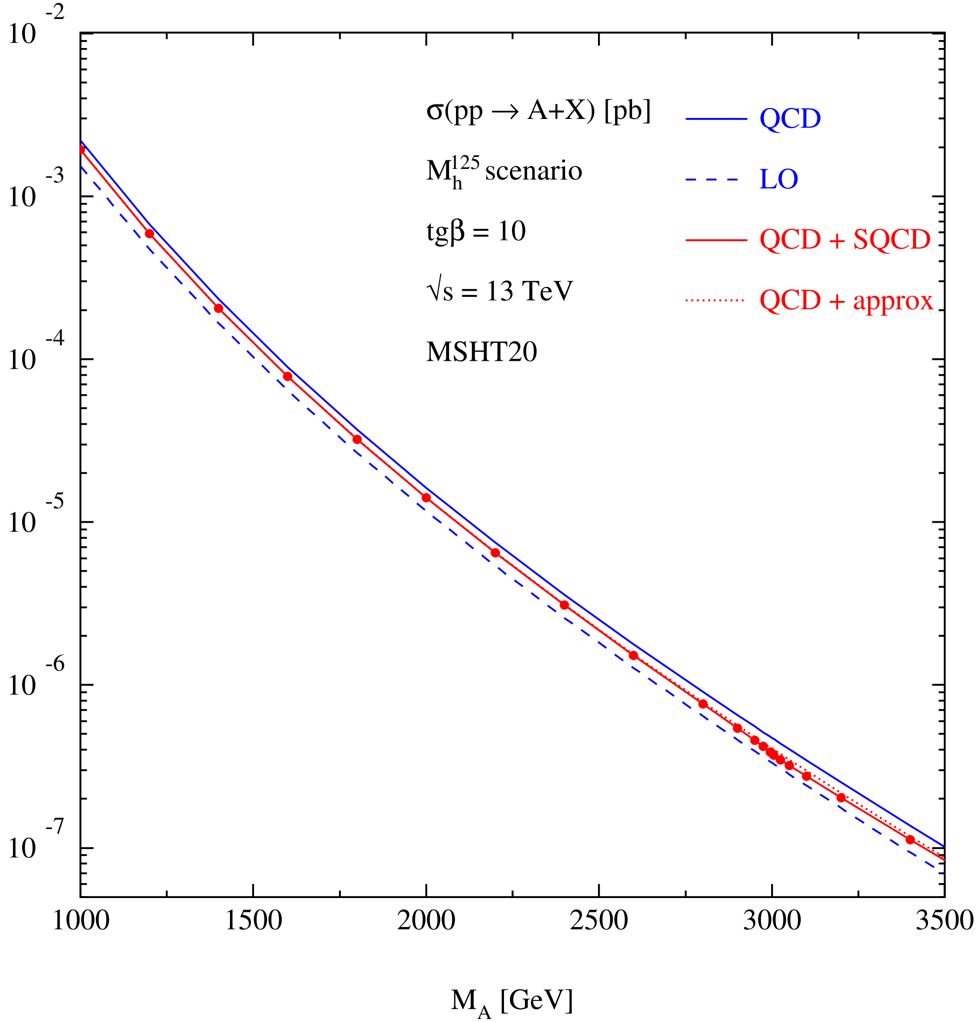
etc.

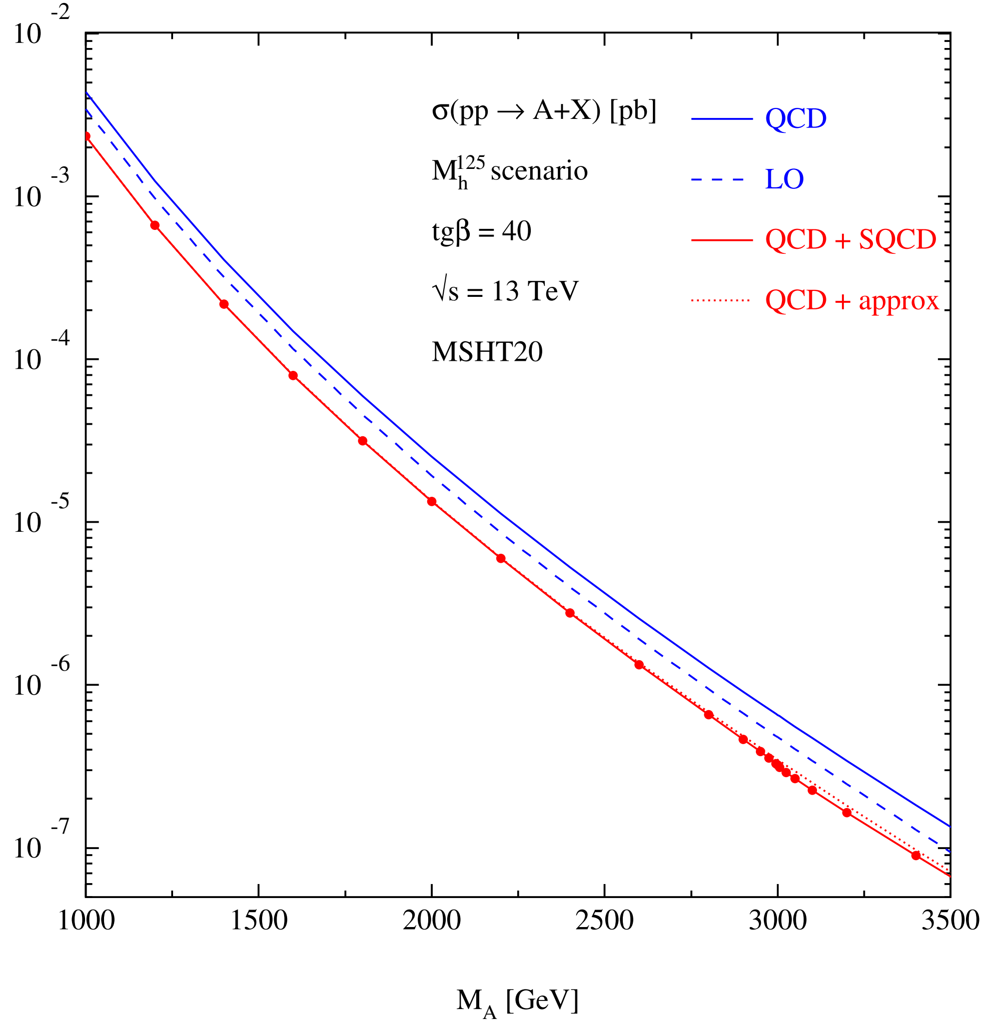


[$h \geq 0.05$]


$\tilde{g}_t^A$
M_h^{125} scenario
tgβ = 10
2-loop
1-loop
0.096
0.095
0.094
0.093
0.092
0.091
10^{-1}
1
10
μ_R/μ_0
$\tilde{g}_t^A$
M_h^{125} scenario
tgβ = 40
2-loop
1-loop
0.021
0.02
0.019
0.018
0.017
0.016
0.015
10^{-1}
1
10
μ_R/μ_0
$\Gamma(H^+ \to c\bar{b})$ [GeV]
M_h^{125} scenario
tgβ = 40
QCD + aNNLO SQCD
QCD + NLO SQCD
QCD
10^{-1}
10^{-2}
600
800
1000
1200
1400
1600
1800
2000
M_{H^+} [GeV]
$\Gamma(H^+ \to c\bar{s})$ [GeV]
M_h^{125} scenario
tgβ = 40
QCD + aNNLO SQCD
QCD + NLO SQCD
QCD
10^{-2}
10^{-3}
600
800
1000
1200
1400
1600
1800
2000
M_{H^+} [GeV]
Chang, Kirk, Mühlleitner, S.


g
g
Q
$\tilde{g}$
$\tilde{Q}$
A





Bagnaschi, Fritz, Liebler, Mühlleitner, Nguyen, S.