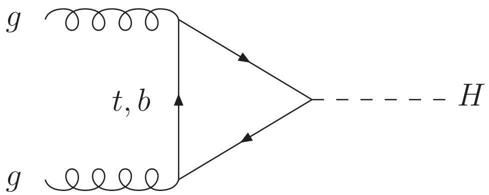
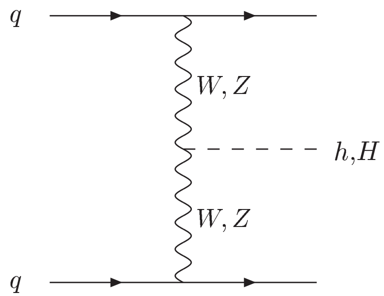
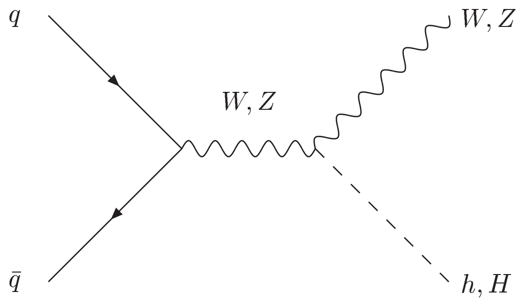
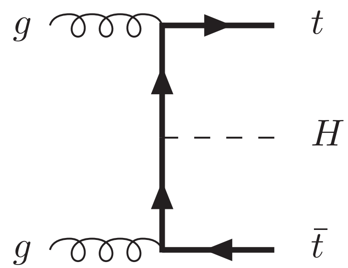
I INTRODUCTION

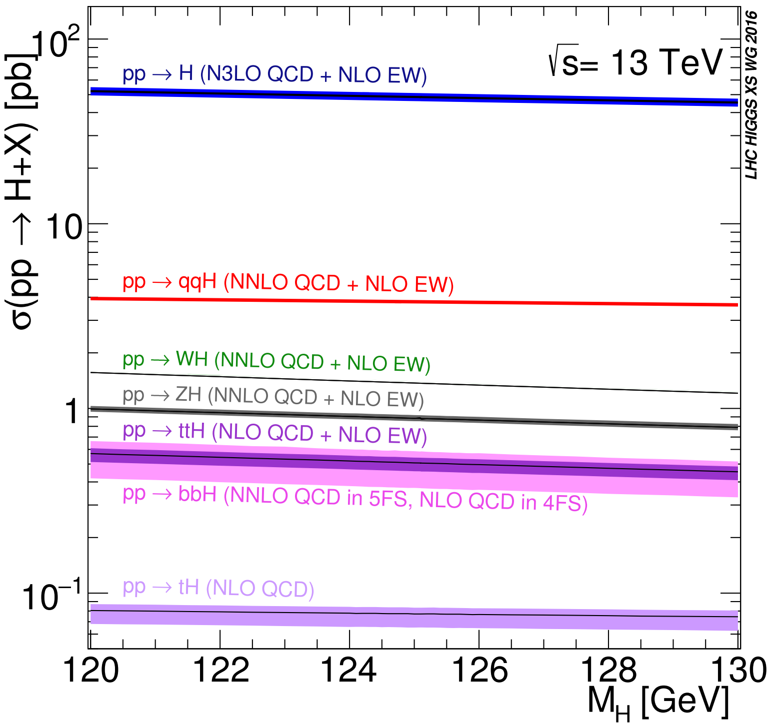
- Higgs Boson Production

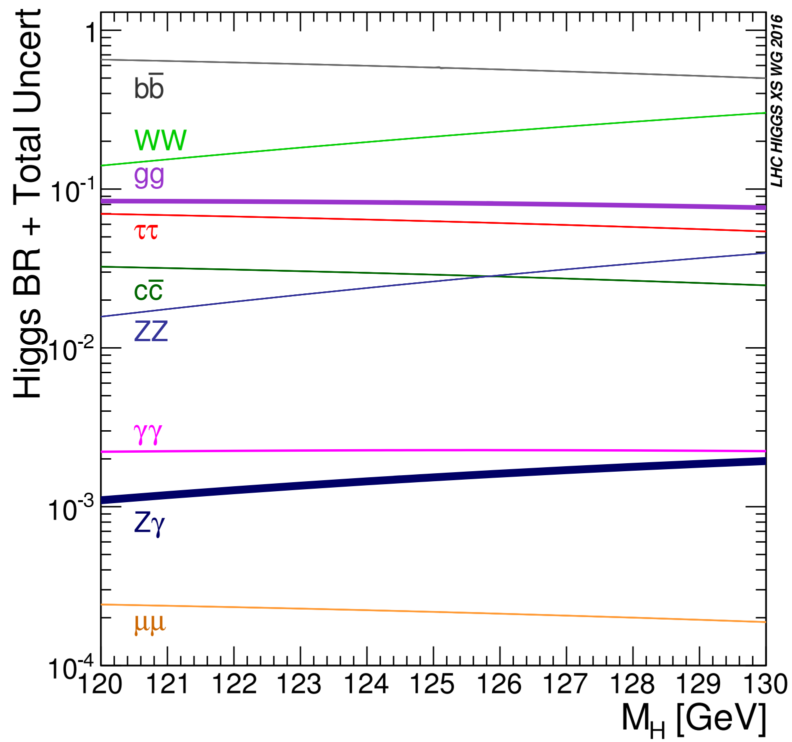




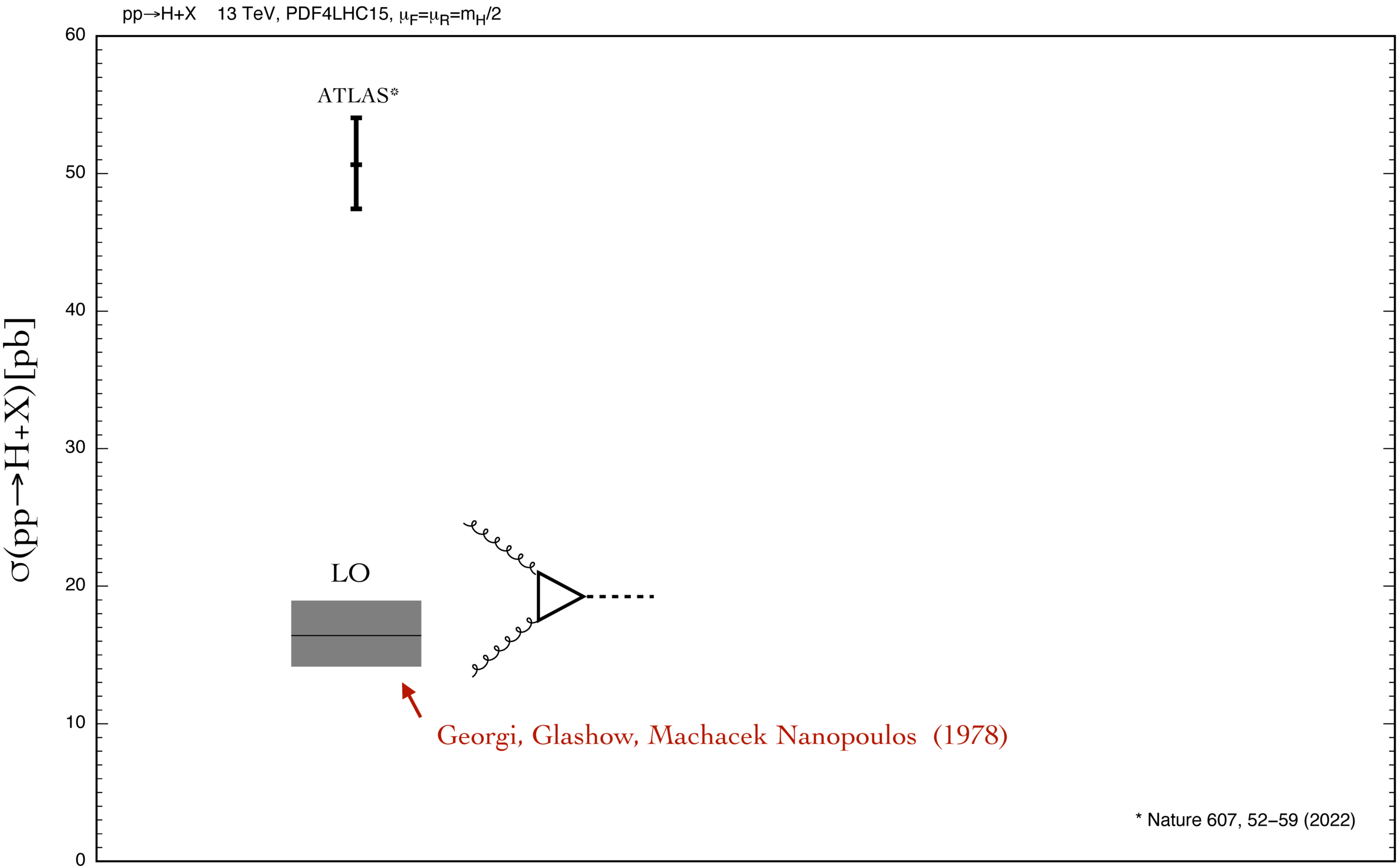




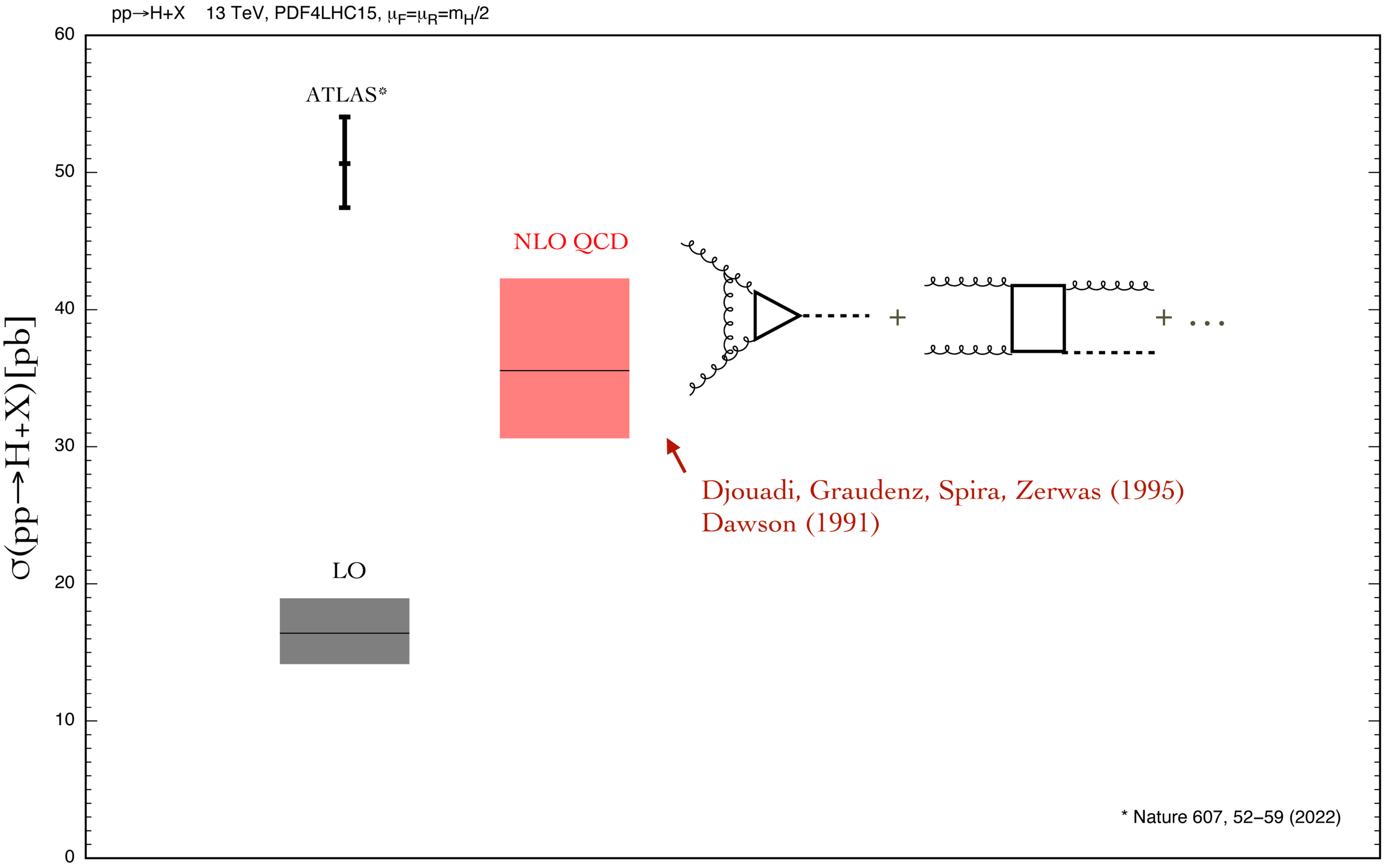




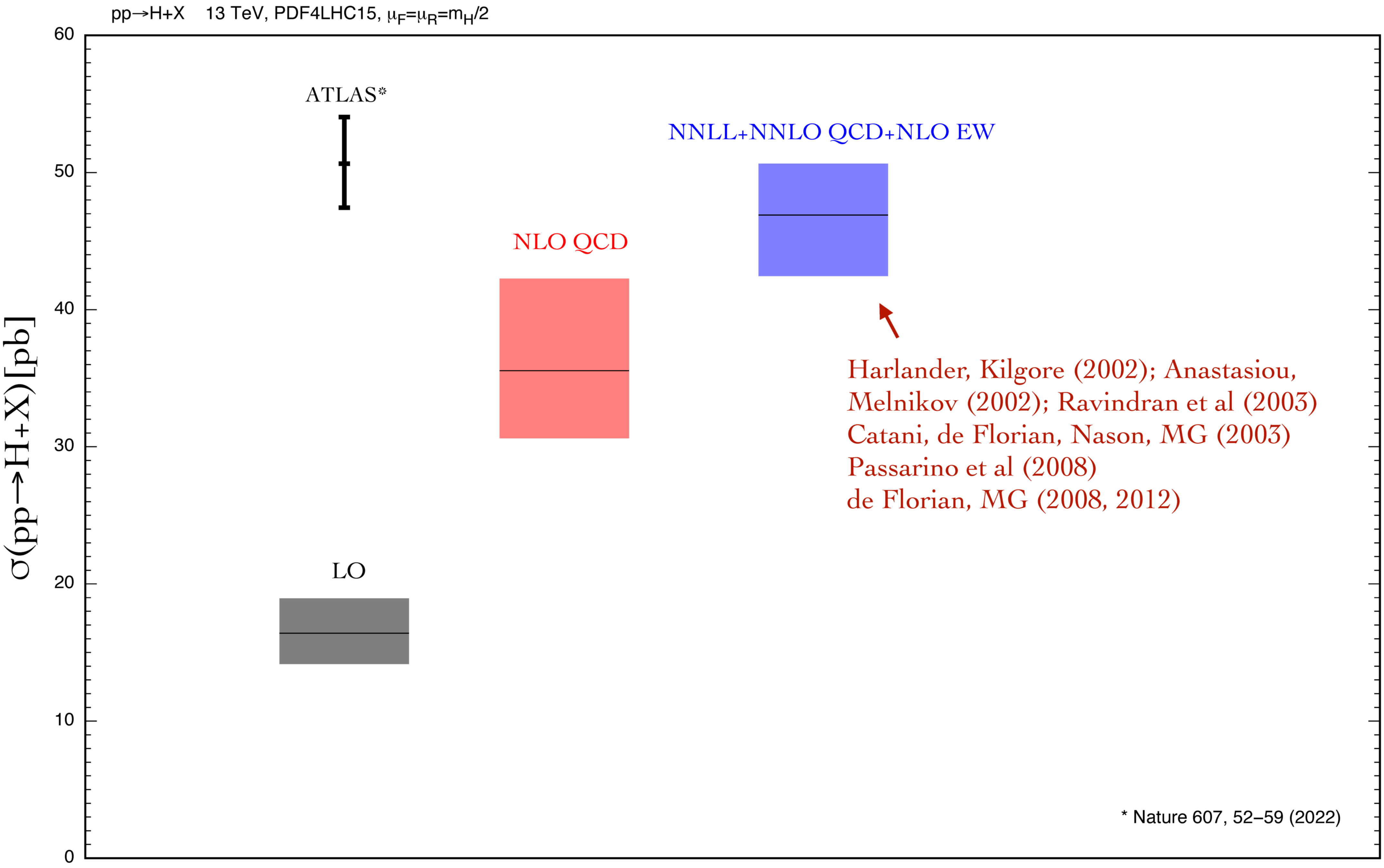
LHC Higgs XS WG



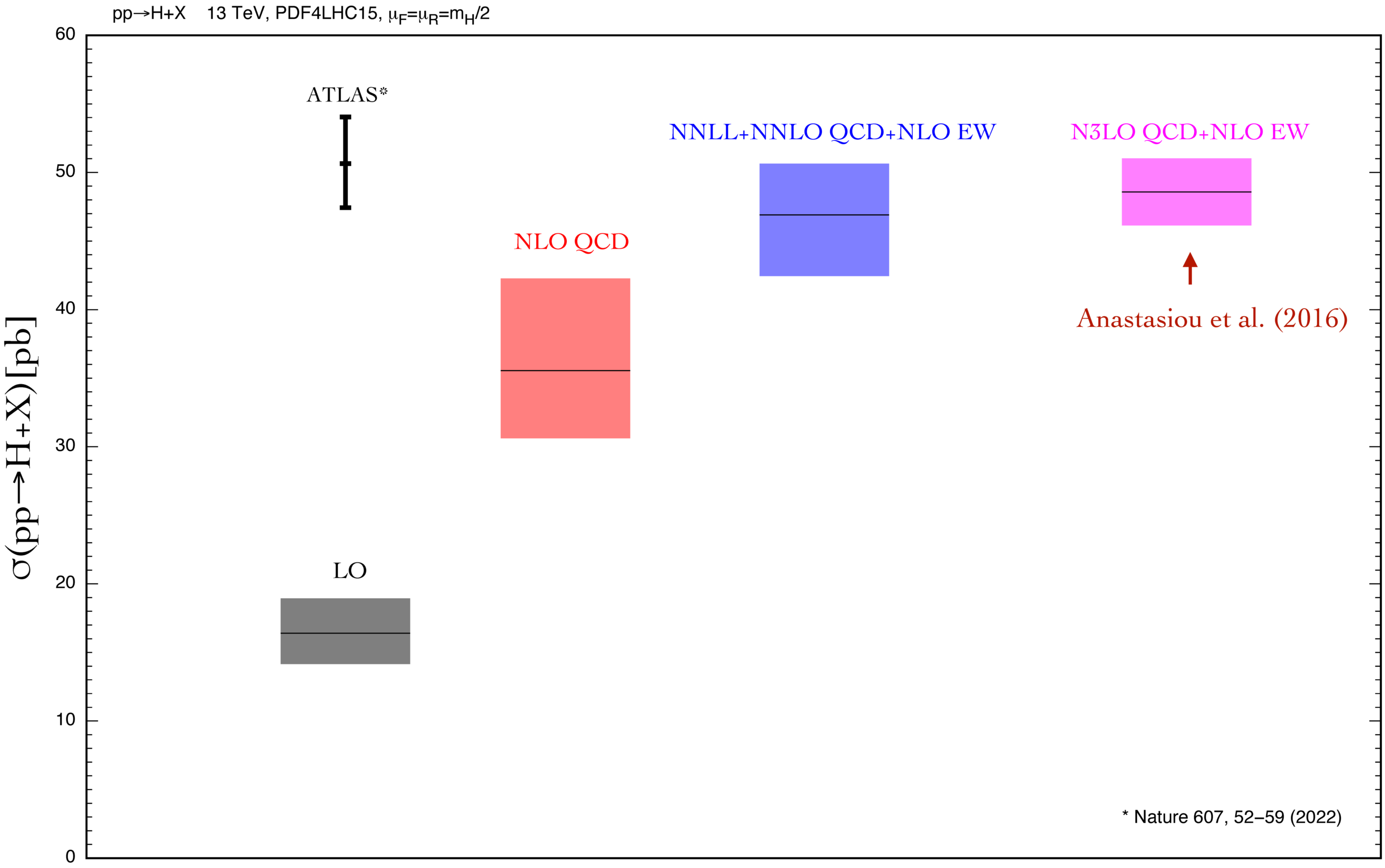
stolen from M. Grazzini@Higgs10



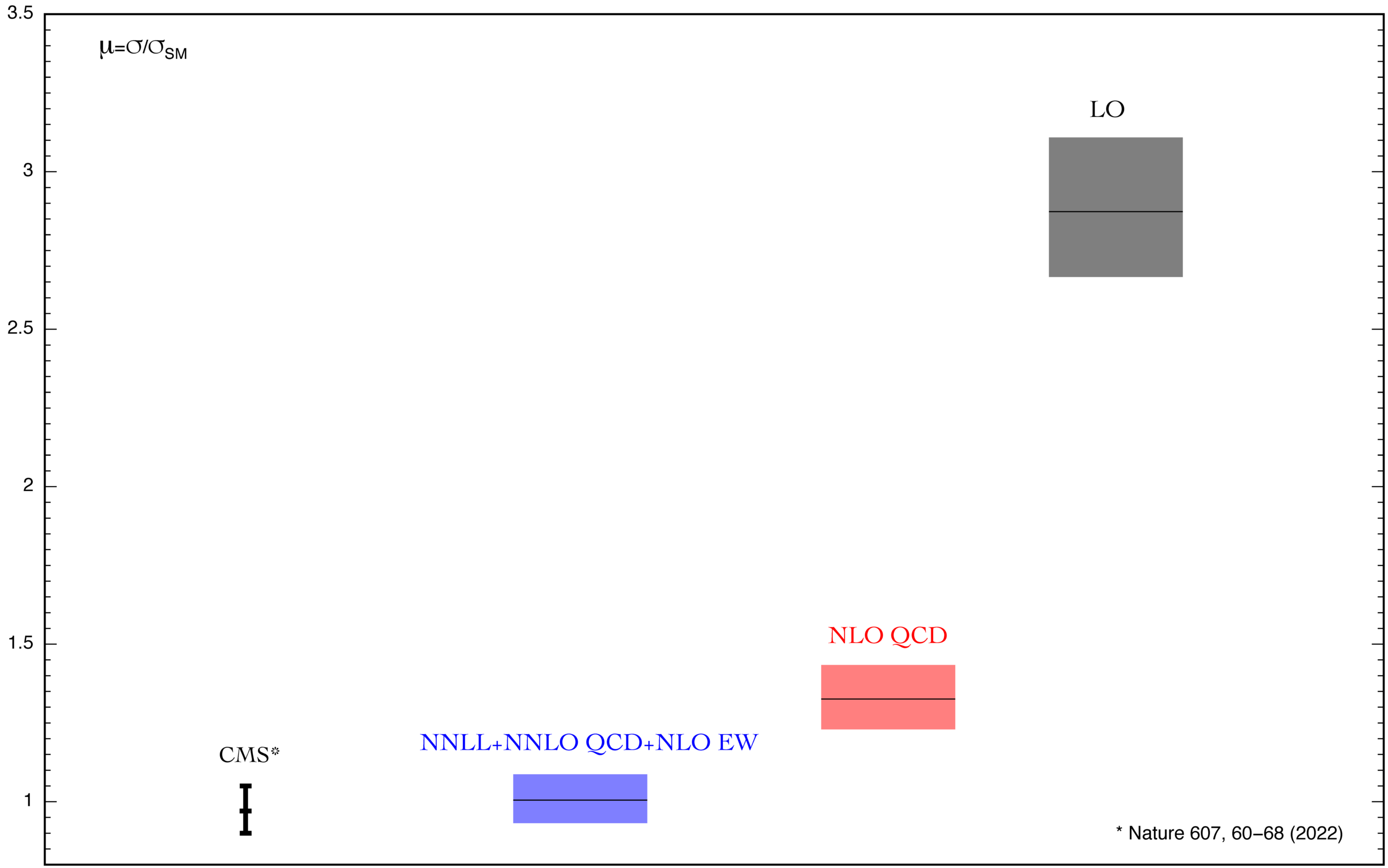
stolen from M. Grazzini@Higgs10



stolen from M. Grazzini@Higgs10

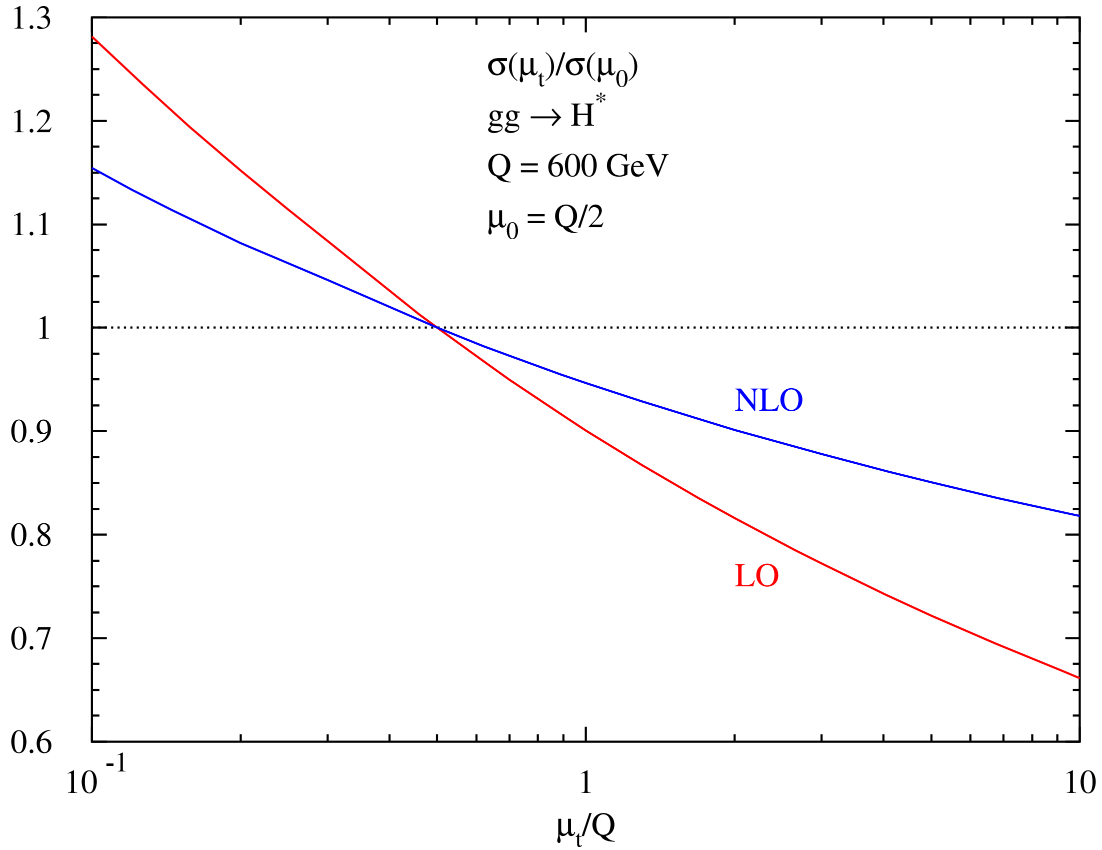


stolen from M. Grazzini@Higgs10



stolen from M. Grazzini@Higgs10

$$\sigma(gg \to H)_{LO} = 18.43^{+0.8\%}_{-1.1\%}\ \text{pb} \qquad \sigma(gg \to H)^{QCD}_{NLO} = 42.17^{+0.4\%}_{-0.5\%}\ \text{pb}$$



Jones, S.

$$\sigma(gg \to H_{SM^*}) \equiv \sigma(gg \to H_{BSM})\Big|_{M_{H_{BSM}}=Q}$$

- m_t scheme/scale uncertainties only:

- LO:

$$\sigma(gg \to H^*)|_{Q=125\ \text{GeV}} = 18.43^{+0.8\%}_{-1.1\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=300\ \text{GeV}} = 4.88^{+23.1\%}_{-1.1\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=400\ \text{GeV}} = 4.94^{+1.2\%}_{-1.8\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=600\ \text{GeV}} = 1.13^{+0.0\%}_{-26.2\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=900\ \text{GeV}} = 0.139^{+0.0\%}_{-36.0\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=1200\ \text{GeV}} = 0.0249^{+0.0\%}_{-41.1\%}\ \text{pb}$$

- NLO QCD:

$$\sigma(gg \to H^*)|_{Q=125\ \text{GeV}} = 42.17^{+0.4\%}_{-0.5\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=300\ \text{GeV}} = 9.85^{+7.5\%}_{-0.3\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=400\ \text{GeV}} = 9.43^{+0.1\%}_{-0.9\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=600\ \text{GeV}} = 1.97^{+0.0\%}_{-15.9\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=900\ \text{GeV}} = 0.230^{+0.0\%}_{-22.3\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=1200\ \text{GeV}} = 0.0402^{+0.0\%}_{-26.0\%}\ \text{pb}$$

$\Rightarrow$ limited sensitivity to interference effects!

$$\sigma = \sigma_{H_1} + \Delta\sigma_{int} + \sigma_{H_2}$$

[BTW: very difficult to determine charm Yukawa coupl. from charm loops in p_{TH} distribution ($H + j$)] Bishara, Haisch, Monni, Re

• different radiative corrections to top and bottom loops [pole masses]:

$$\begin{aligned} \sigma(gg \to H) &= \sigma_{tt} + \sigma_{tb} + \sigma_{bb} \\ K_{tt} &\sim 1.68 \\ K_{tb} &\sim 0.97 \\ K_{bb} &\sim 1.20 \end{aligned}$$

$\Rightarrow$ up to 20 – 30% differences in NLO cxn [m_b: scheme/scale dep.?]
$\Rightarrow$ not possible to use SM-like cxns in many BSM cases
for different weighting of top and bottom loops
[enhancement of bottom loops (e.g. 2HDM type II, MSSM,. . .)]

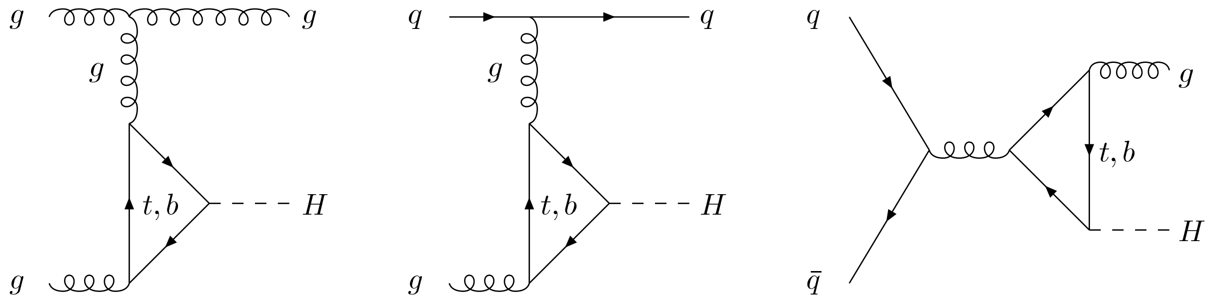
• bottom-loop dominance: full NLO 20% uncertainties $\leftarrow$ double logs

• can only use N^{3}LO results for σ_{tt}
$\Rightarrow$ individual grids [(pseudo)scalar] for $\sigma_{tt}, \sigma_{tb}, \sigma_{bb}$ [$\leftarrow \sigma_{BSM}$?]

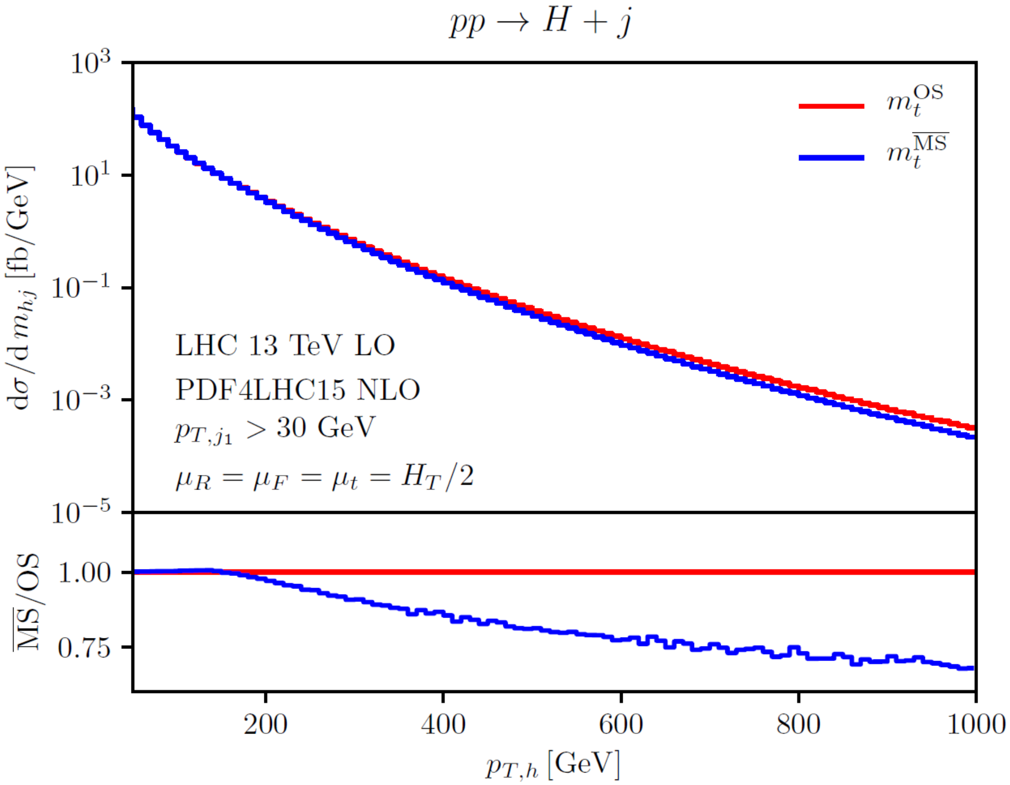
• BSM heavy: eff. ggH coupl. $c_g \to$ interf. with full top/bottom loops!

$$\sigma(gg \to H) = \underbrace{\sigma_{c_g c_g} + \sigma_{tt}}_{\sim N^3LO} \underbrace{+ \sigma_{tb} + \sigma_{bb}}_{NLO} \underbrace{+ \sigma_{c_g t}}_{\sim N^3LO} \underbrace{+ \sigma_{c_g b}}_{NLO} \qquad \left[\mathcal{L}_{BSM} = c_g \, G^{a\mu\nu} G^a_{\mu\nu} H \right]$$

- Higgs + jet production: $gg \to H + j$

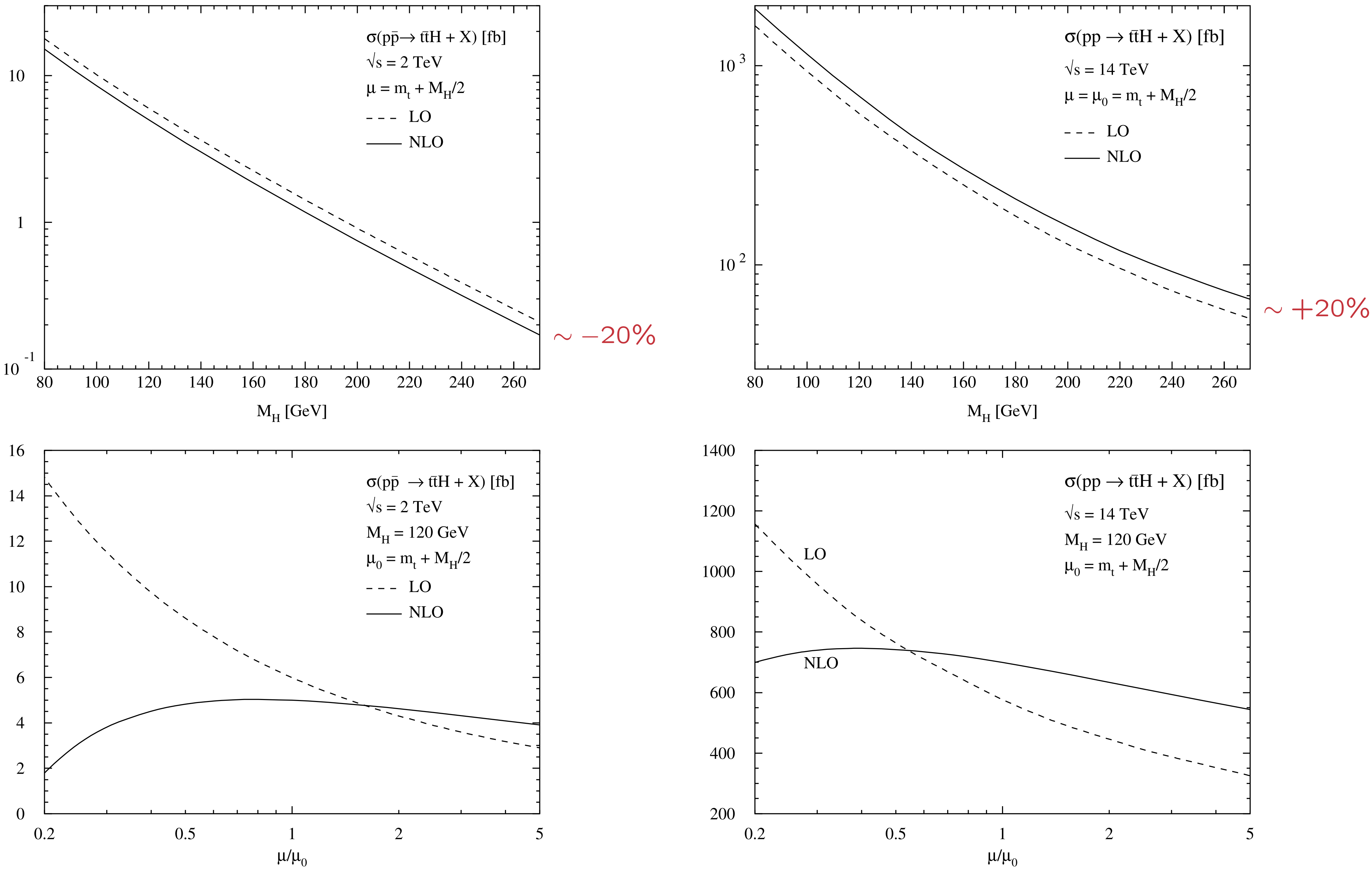


LO: $\mu_t = H_T/2 = (\sqrt{M_H^2 + p_T^2} + p_{Tj})/2$



Jones, S.

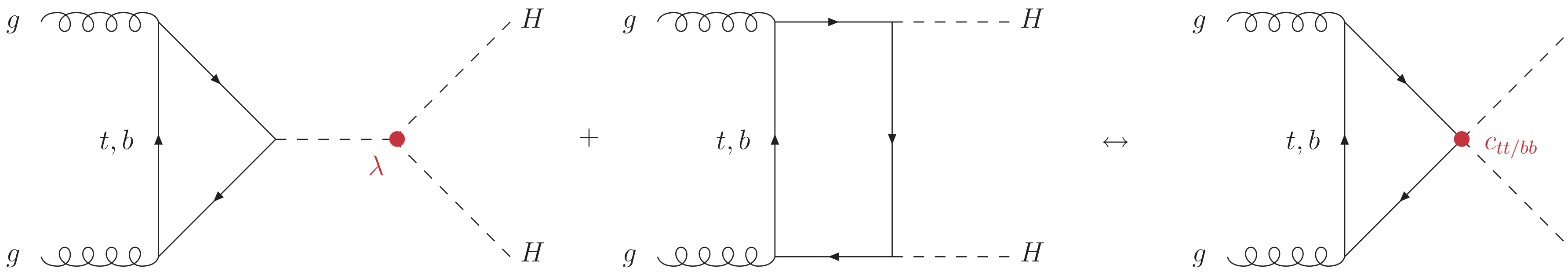
$\to$ NLO? Jones, Kerner, Luisoni



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

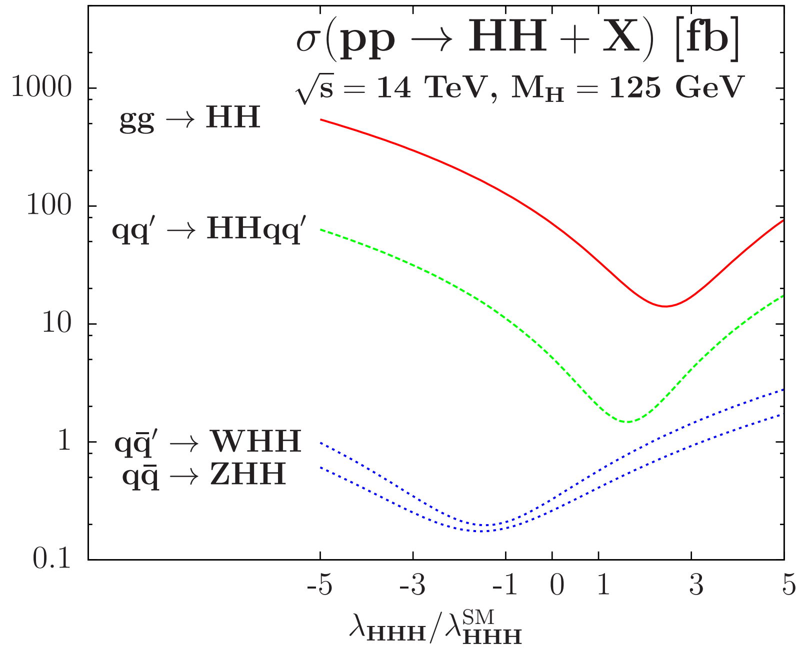
- full agreement with Dawson, Orr, Reina, Wackeroth

(v) $gg \to HH$



- threshold region: sensitive to λ

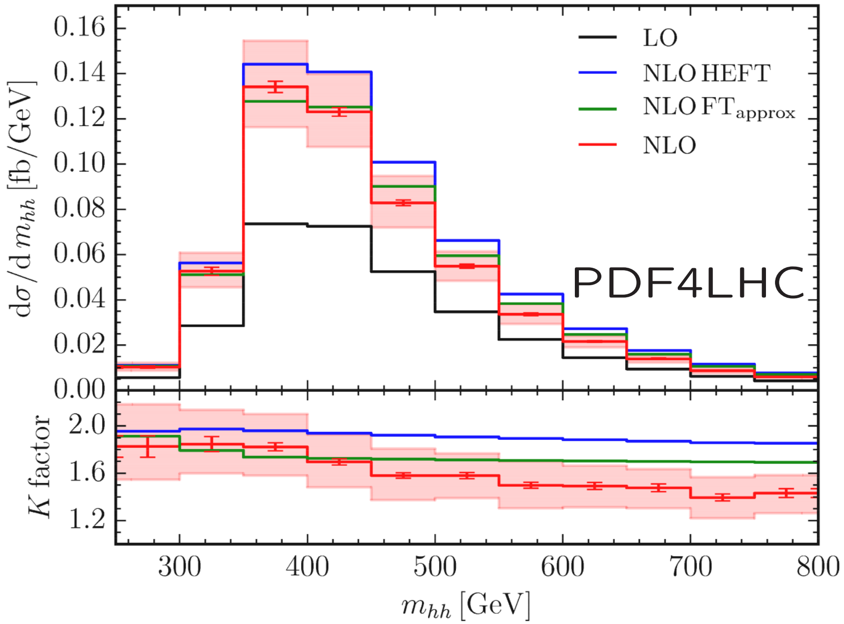
  large M_{HH}: sensitive to $c_{tt/bb}$ [e.g. boosted Higgs pairs]



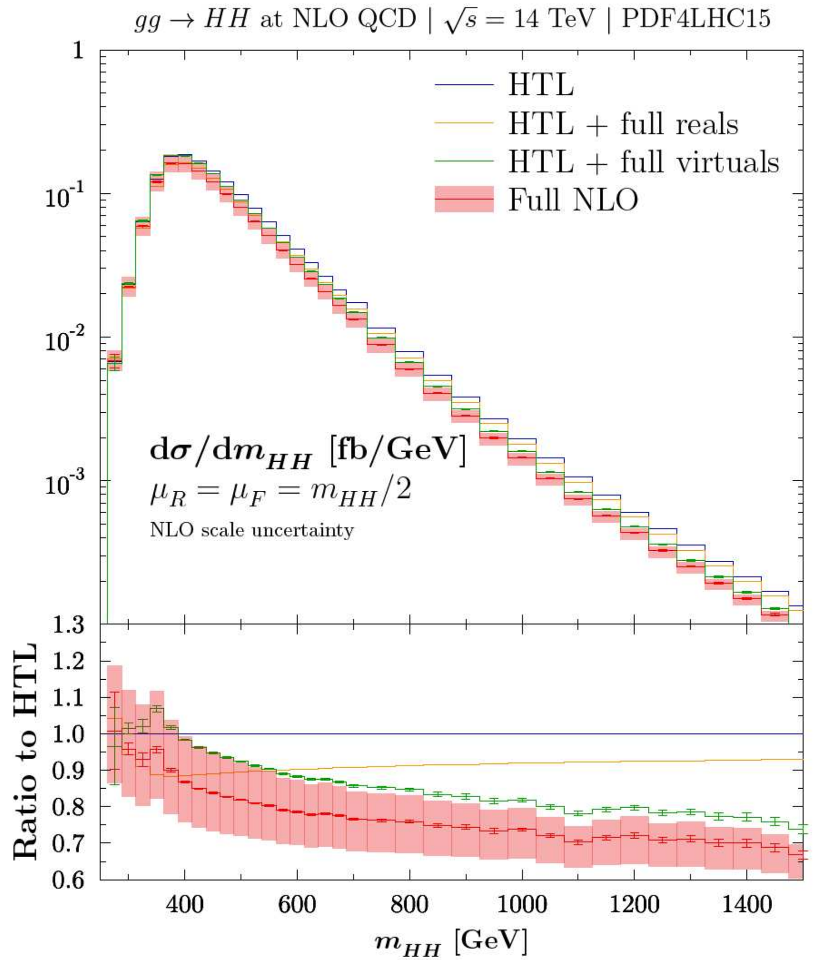
$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M_{HH}^2]

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.



Borowka, Greiner, Heinrich, Jones, Kerner
Schlenk, Schubert, Zirke



Baglio, Campanario, Glaus,
Mühlleitner, Ronca, S., Streicher

$\sigma_{NLO} =$	$32.91(10)^{+13.8\%}_{-12.8\%}\ fb$	$32.81(7)^{+13.5\%}_{-12.5\%}\ fb$
$\sigma^{HTL}_{NLO} =$	$38.75^{+18\%}_{-15\%}\ fb$	$38.66^{+18\%}_{-15\%}\ fb$
$m_t =$	173 GeV	172.5 GeV

$\Rightarrow$ -15% mass effects on top of LO

- renormalization/factorization scale uncertainties @ NLO:

$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 27.73(7)^{+13.8\%}_{-12.8\%} \text{ fb}$$
$$\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} = 32.81(7)^{+13.5\%}_{-12.5\%} \text{ fb}$$
$$\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} = 127.0(2)^{+11.7\%}_{-10.7\%} \text{ fb}$$
$$\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} = 1140(2)^{+10.7\%}_{-10.0\%} \text{ fb}$$

- m_t scale/scheme uncertainties @ NLO:

$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%} \text{ fb}$$
$$\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} = 32.81(7)^{+4\%}_{-18\%} \text{ fb}$$
$$\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} = 127.8(2)^{+4\%}_{-18\%} \text{ fb}$$
$$\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} = 1140(2)^{+3\%}_{-18\%} \text{ fb}$$

- how to combine them? $\rightarrow$ envelope $\sim$ linear sum (rel. err.)

final combined ren./fac. scale and m_t scale/scheme unc. @ NNLO$_{FTapprox}$:

$$\sqrt{s} = 13\ \text{TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}\ \text{fb}$$

$$\sqrt{s} = 14\ \text{TeV}: \quad \sigma_{tot} = 36.69^{+6\%}_{-23\%}\ \text{fb}$$

$$\sqrt{s} = 27\ \text{TeV}: \quad \sigma_{tot} = 139.9^{+5\%}_{-22\%}\ \text{fb}$$

$$\sqrt{s} = 100\ \text{TeV}: \quad \sigma_{tot} = 1224^{+4\%}_{-21\%}\ \text{fb}$$

final combined ren./fac. scale and m_t scale/scheme unc. @ NNLO$_{FTapprox}$:

$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%} \text{ fb}$$

$$\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} = 36.69^{+6\%}_{-23\%} \text{ fb}$$

• similar uncertainties for other Higgs masses expected

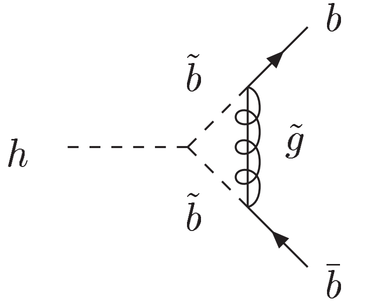
$$\begin{aligned} \sigma(gg \to HH) &= \sigma_{tt} + \sigma_{tb} + \sigma_{bb} \\ K_{tt} &\sim 1.7 \text{ (incl. } m_t \text{ effects, } \mu = Q/2) \\ K_{tb} &\sim ??? \\ K_{bb} &\sim ??? \end{aligned}$$

[grid in M_H?]

$\Rightarrow$ sizeable uncerts. that affect extraction of BSM/int. contributions

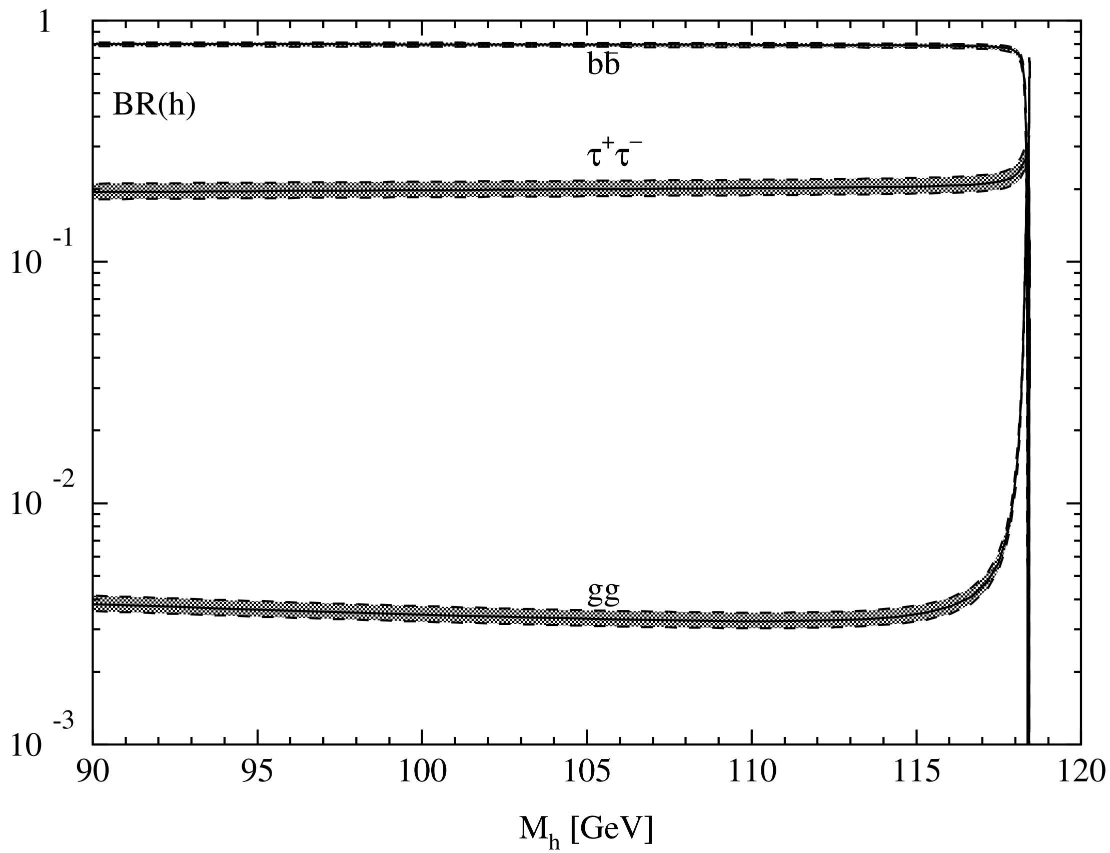
$$\sigma = \sigma_{h^{(*)} \to H_1 H_2} + \Delta\sigma_{int} + \sigma_{H^{(*)} \to H_1 H_2} + \sigma_{\Box\Box} + \sigma_{\triangle\Box} + \cdots$$

• 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 Δ_b CORRECTIONS

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 $\tilde{g}_b^{\Phi}$

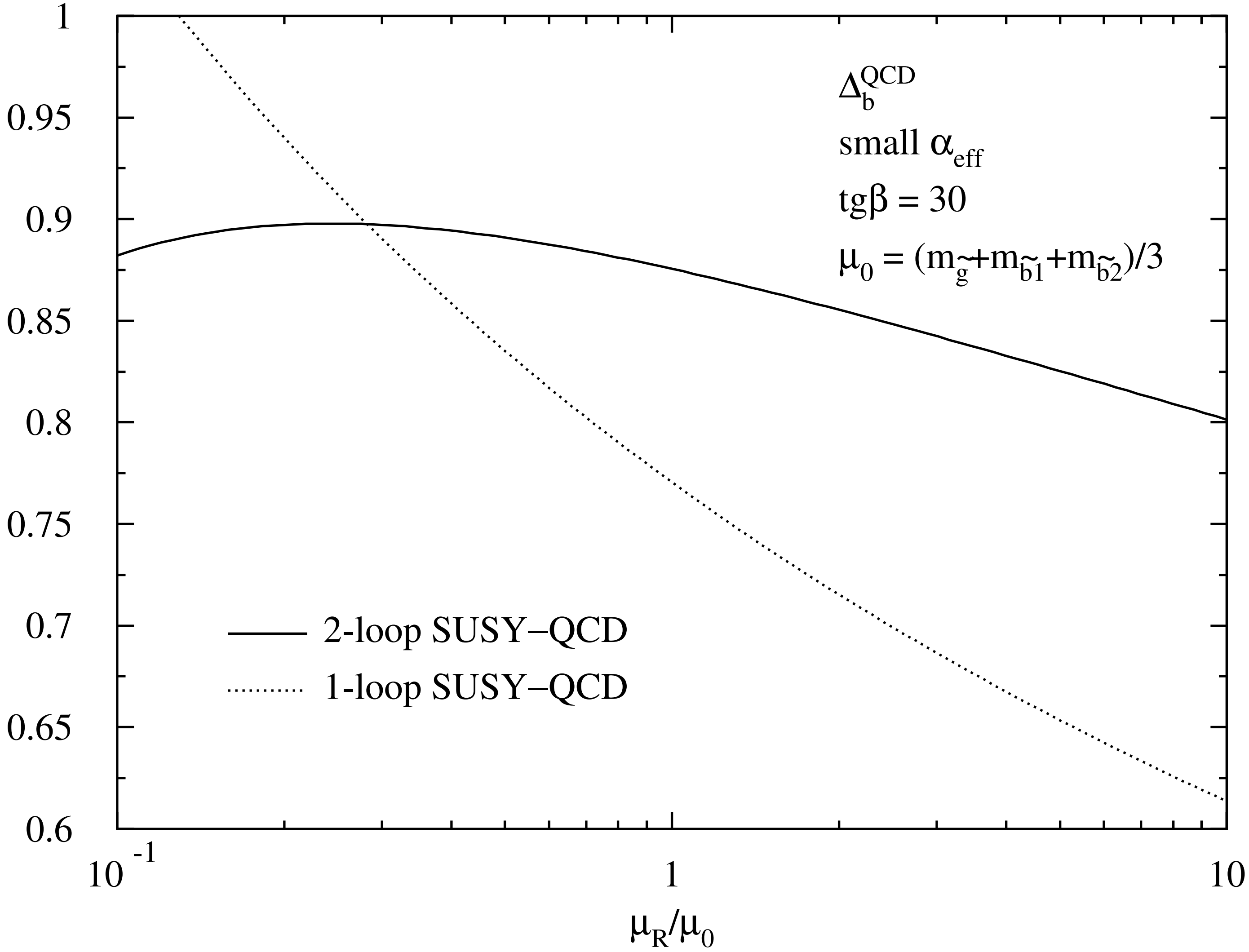
Carena, Garcia, Nierste, Wagner
Guasch, Häfliger, S.

small α_{eff} scenario [modified]

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

$$m_{\tilde{t}_1} = 679\ \mathrm{GeV} \qquad m_{\tilde{t}_2} = 935\ \mathrm{GeV}$$

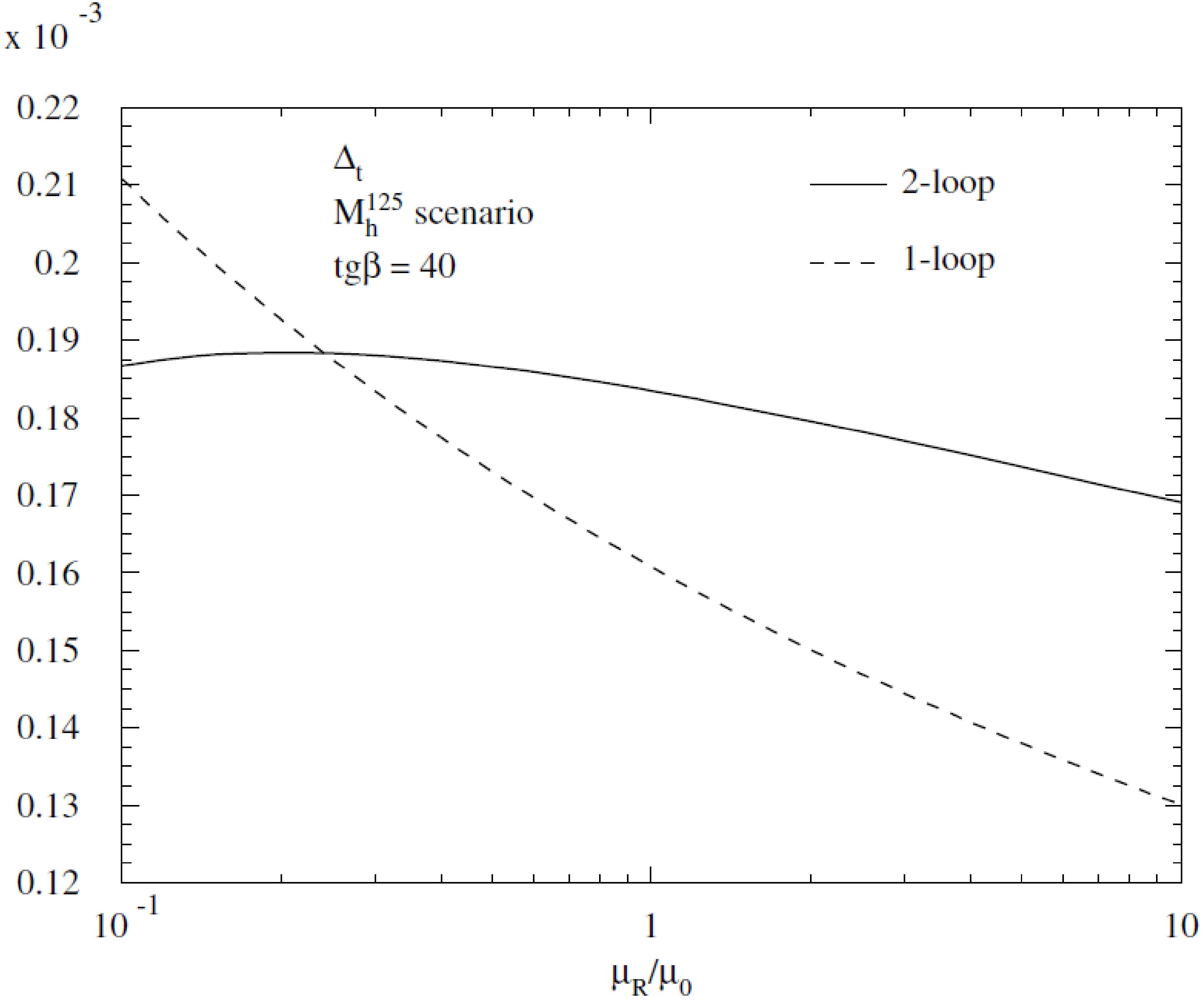
$$m_{\tilde{b}_1} = 601\ \mathrm{GeV} \qquad m_{\tilde{b}_2} = 961\ \mathrm{GeV}$$



Noth, S.
(Mihaila, Reisser)

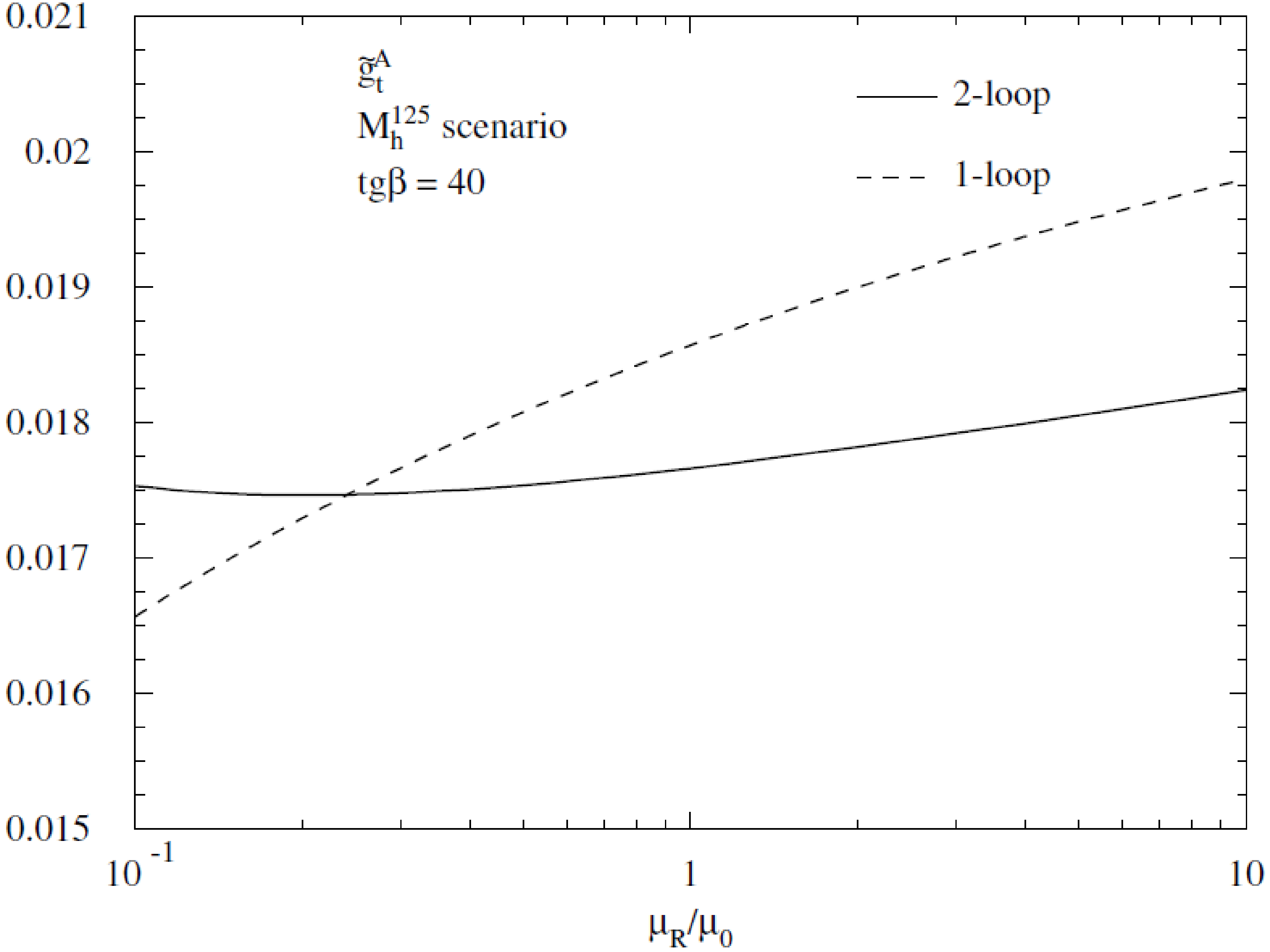
$$\Delta_t = \frac{C_F}{2}\,\frac{\alpha_s}{\pi}\,\frac{m_{\tilde{g}}\;\mu}{\mathrm{tg}\beta}\;I(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, m^2_{\tilde{g}})$$

$$\begin{aligned}
\mathcal{L}_{eff} &= -\lambda_t \overline{t_R}\left[\phi_2^0 + \Delta_t \mathrm{tg}\beta \phi_1^{0*}\right] t_L + h.c. \\
&= -m_t \bar{t}\left[1 - i\gamma_5 \frac{G^0}{v}\right] t - \frac{m_t/v}{1+\Delta_t}\bar{t}\left[g_t^h\left(1 - \Delta_t\ \mathrm{tg}\alpha\ \mathrm{tg}\beta\right) h\right. \\
&\qquad \left. + g_t^H\left(1 + \Delta_t \frac{\mathrm{tg}\beta}{\mathrm{tg}\alpha}\right) H - g_t^A\left(1 - \Delta_t \mathrm{tg}^2\beta\right) i\gamma_5 A\right] t
\end{aligned}$$

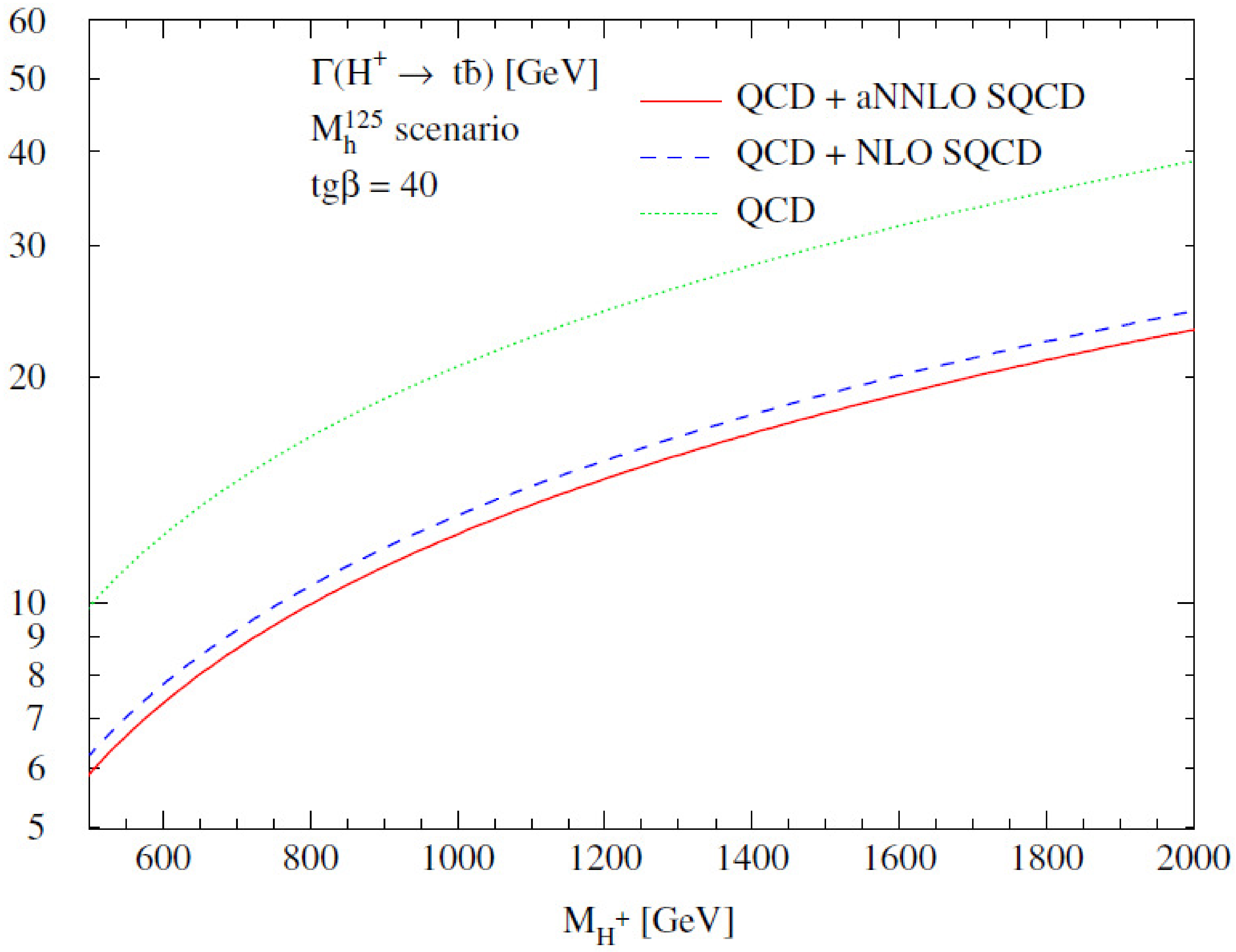


x 10 -3
0.22
0.21
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
Δ_t
M_h^{125} scenario
tgβ = 40
2-loop
1-loop
10 -1
1
10
μ_R/μ_0

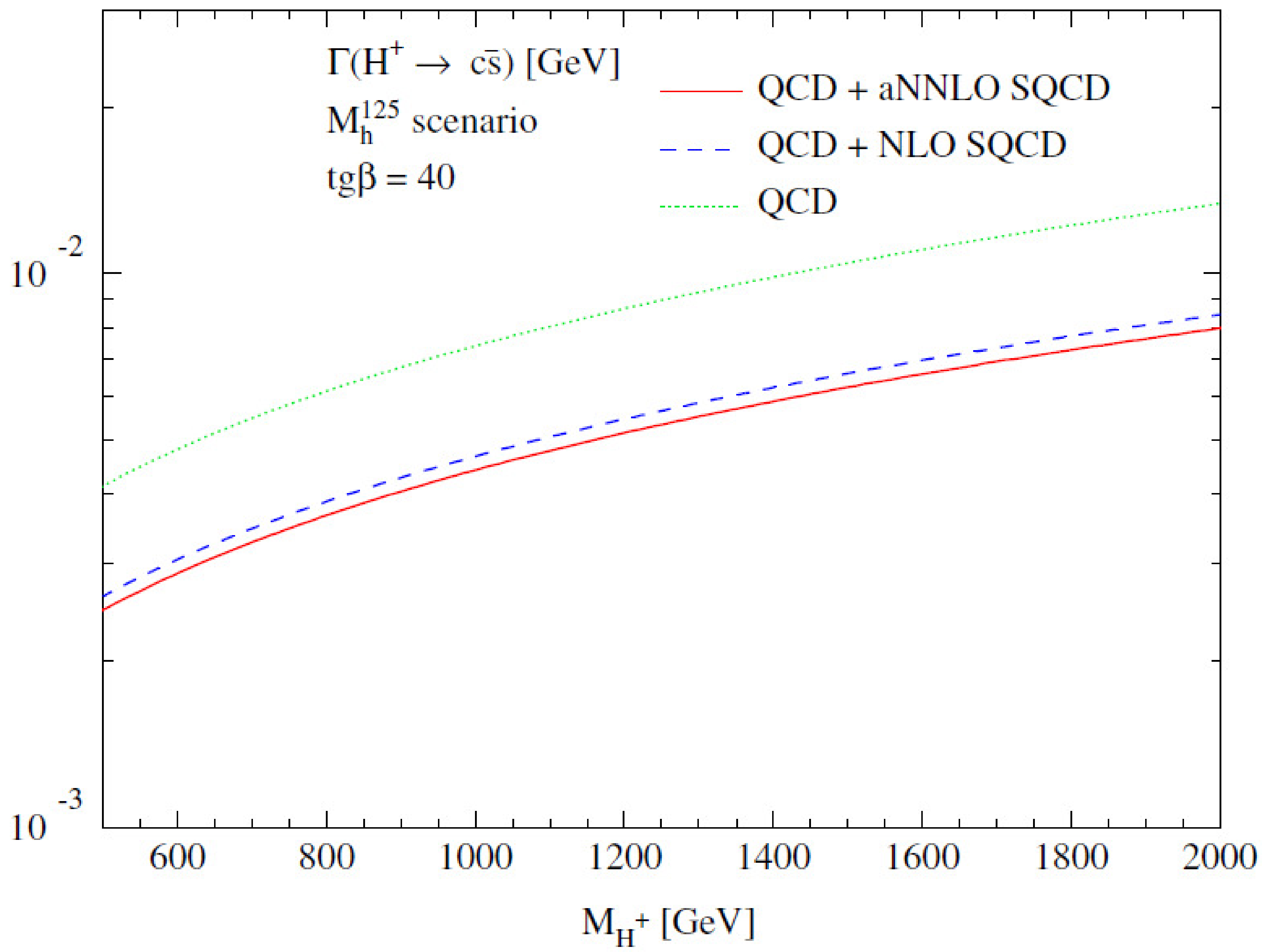
LO = 0.025



0.021
0.02
0.019
0.018
0.017
0.016
0.015
$\tilde{g}_t^A$
M_h^{125} scenario
tgβ = 40
2-loop
1-loop
10^{-1}
1
10
μ_R/μ_0



Γ(H+ → tb̄) [GeV]
M_h^{125} scenario
tgβ = 40
QCD + aNNLO SQCD
QCD + NLO SQCD
QCD
60
50
40
30
20
10
9
8
7
6
5
600
800
1000
1200
1400
1600
1800
2000
M_{H^+} [GeV]



Γ(H⁺ → cs̄) [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]

$$
\begin{aligned}
\mathcal{O}_1 &= |H|^2 G^a_{\mu\nu} G^{a,\mu\nu}\,, \\
\mathcal{O}_2 &= |H|^2 \bar{Q}_L H^c t_R + h.c.\,, \\
\mathcal{O}_3 &= \bar{Q}_L H \sigma^{\mu\nu} T^a t_R G^a_{\mu\nu} + h.c.\,,
\end{aligned}
$$

which, for single-Higgs production, can be expanded as:

$$
\begin{aligned}
\frac{c_1}{\Lambda^2}\,\mathcal{O}_1 &\to \frac{\alpha_s}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu}\,, \\
\frac{c_2}{\Lambda^2}\,\mathcal{O}_2 &\to \frac{m_t}{v}(1-c_t) h\bar{t}t\,, \\
\frac{c_3}{\Lambda^2}\,\mathcal{O}_3 &\to c_{tg}\frac{g_S m_t}{2v^3}(v+h) G^a_{\mu\nu}(\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c)\,,
\end{aligned}
$$

$$
\begin{aligned}
c_t(Q^2) &= c_t(\mu_0^2) + \frac{24}{5}\,\frac{m_t^2(\mu_0^2)}{v^2}\,c_{tg}(\mu_0^2)\,\left\{\left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu_0^2)}\right)^{\frac{5}{6\beta_0}} - 1\right\}, \\
c_{tg}(Q^2) &= c_{tg}(\mu_0^2)\left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu_0^2)}\right)^{-\frac{7}{6\beta_0}}, \\
c_g(Q^2) &= \frac{\beta_0 + \beta_1\alpha_s(Q^2)/\pi}{\beta_0 + \beta_1\alpha_s(\mu_0^2)/\pi}\left\{c_g(\mu_0^2) - \frac{3\pi}{5-6\beta_0}\,\frac{m_t^2(\mu_0^2)}{v^2}\,\frac{c_{tg}(\mu_0^2)}{\alpha_s(\mu_0^2)}\left[\left(\frac{\alpha_s(Q^2)}{\alpha_s(\mu_0^2)}\right)^{\frac{5}{6\beta_0}-1} - 1\right]\right\},
\end{aligned}
\tag{2.4}
$$

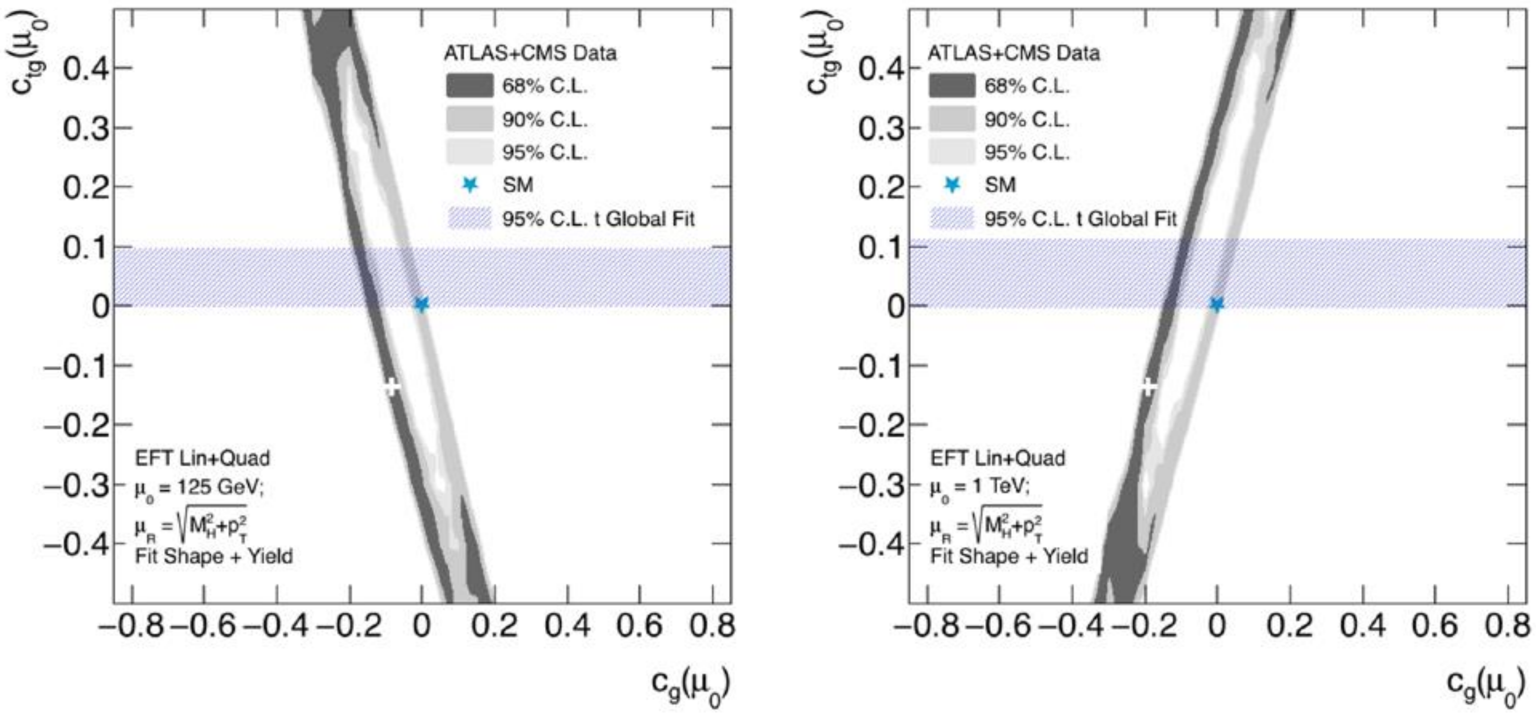


Figure 14. Constraints on the c_g and c_{tg} coefficients at 68% (dark grey), 90% (mid grey) and 95% (light grey) C.L. obtained from the simultaneous fit to ATLAS and CMS data for $\mu_0 = 125\,\text{GeV}$ (left panel) and $\mu_0 = 1\,\text{TeV}$ (right panel). The SM value is indicated by the blue star and the best fit value by the white marker. The shaded horizontal strip indicates the 95% C.L. interval for c_{tg} from the top quark fit of ref. [71] translated to our definition of $c_{tg}(\mu_0)$.