QCD corrections in two-Higgs-doublet extensions of the Standard Model

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Based on: *G.Degrassi and P.S., arXiv:1002.1071, to appear in PRD*

Higgs-quark interactions in an extended Higgs sector

The SM with its SU(2)-doublet Higgs is just the *minimal* realization of the Higgs mechanism

$$-\mathcal{L}_Y \;=\; \bar{q}_L\,\widetilde{\Phi}\,Y^U u_R \;+\; \bar{q}_L\,\Phi\,Y^D d_R\;, \qquad M^{U,D} = Y^{U,D}\,\langle\Phi^0\rangle$$

In principle, more than one Higgs doublet might participate in EWSB and couple to quarks

$$-\mathcal{L}_Y \;=\; \sum_i \bar{q}_L\,\widetilde{\Phi}_i\,y_i^U u_R \;+\; \sum_i \bar{q}_L\,\Phi_i\,y_i^D d_R\;, \qquad M^{U,D} = \sum_i y_i^{U,D}\,\langle\Phi_i^0\rangle$$

Rotating the fields to a basis where one Higgs ($\Phi_{\rm SM}$) gets the vev and the others (Φ_i) don't

$$-\mathcal{L}_Y \;=\; \bar{q}_L\,\widetilde{\Phi}_{\rm SM}\,Y^U u_R \;+\; \bar{q}_L\,\Phi_{\rm SM}\,Y^D d_R \;+\; \sum_i \bar{q}_L\,\widetilde{\Phi}_i\,y_i^U u_R \;+\; \sum_i \bar{q}_L\,\Phi_i\,y_i^D d_R$$

In general, the matrices $y_i^{U,D}$ are not diagonal in the basis where $Y^{U,D}$ are diagonal

→ Flavor-Changing Neutral Currents!!!

Avoiding FCNC in many-Higgs extensions of the SM

Natural Flavor Conservation:
(Glashow & Weinberg, 1977)

FCNC in Higgs-quark interactions are *absent* when only one doublet couples to each species of quarks

e.g., in models with two doublets:

$$-\mathcal{L}_Y = \bar{q}_L \, \widetilde{\Phi}_1 \, Y^U u_R + \bar{q}_L \, \Phi_1 \, Y^D d_R \qquad \text{(type I)}$$

$$-\mathcal{L}_Y = \bar{q}_L \, \widetilde{\Phi}_2 \, Y^U u_R + \bar{q}_L \, \Phi_1 \, Y^D d_R \qquad \text{(type II)}$$

Minimal Flavor Violation:
(strict interpretation)

FCNC are *absent* when all the matrices of non-SM Higgs couplings are proportional to Y^U and Y^D

$$y_i^U = A_u^i \, Y^U \, , \qquad y_i^D = A_d^i \, Y^D$$

Minimal Flavor Violation:
(loose interpretation)

FCNC are *suppressed* when the matrices of non-SM Higgs couplings are made up of combinations of Y^U and Y^D with the right properties under rotations in flavor space

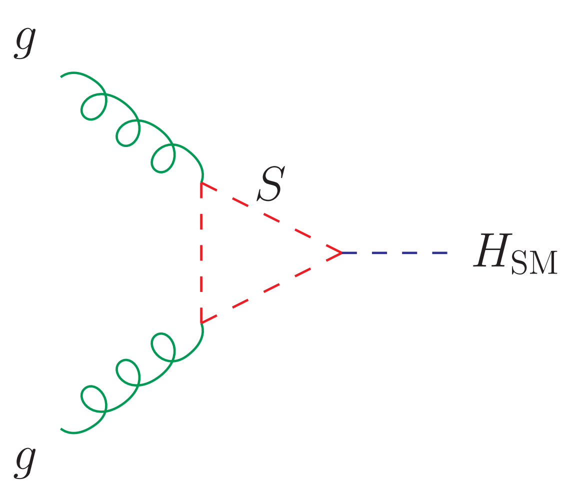
$$y_i^U = A_u^i \, \left(1 + \epsilon_u \, Y^U Y^{U\,\dagger} + \ldots\right) \, Y^U \, , \qquad y_i^D = A_d^i \, \left(1 + \epsilon_d \, Y^U Y^{U\,\dagger} + \ldots\right) \, Y^D$$

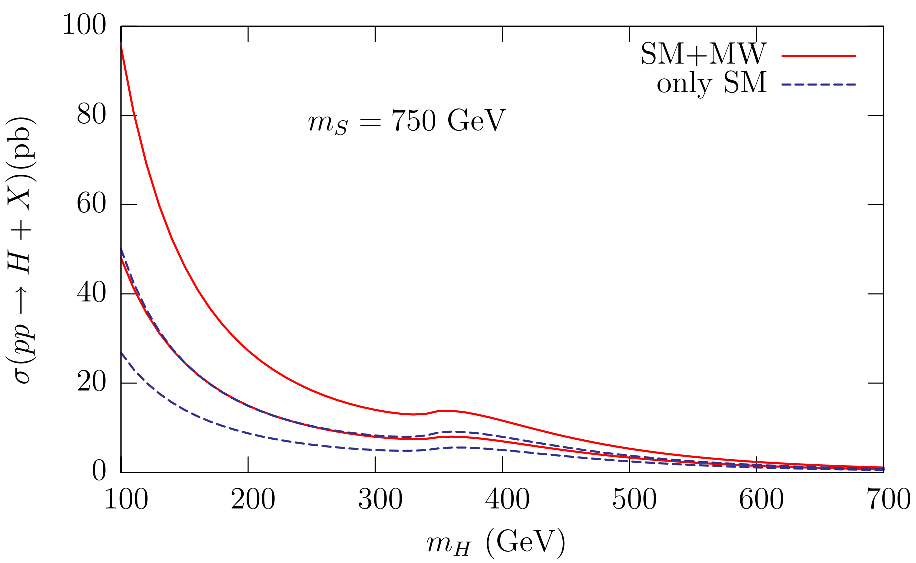
Only *two* sets of *SU(3)xSU(2)xU(1)* quantum numbers are allowed for an additional scalar whose Yukawa couplings transform like Y^U and Y^D under rotations in flavor space

(1,2)$_{1/2}$ Like the usual THDMs, but independent couplings y^U and y^D *(aka Type III)*

(8,2)$_{1/2}$ The additional scalar is a color octet *(Manohar & Wise, hep-ph/0606172)*

In the MW model, the colored scalars contribute to the production of the SM-like Higgs:





Bonciani et al., 0709.4227

The contribution of the extra scalars to several electroweak and flavor observables is also enhanced by color factors w.r.t. the case of the usual THDMs

Charged-Higgs contributions to precision observables

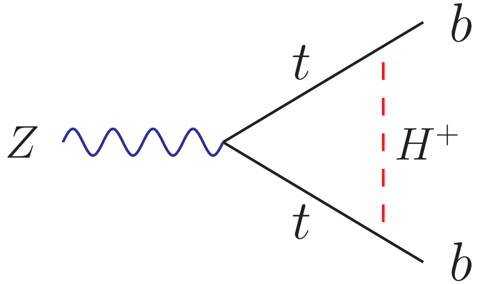
The scalar sector of a THDM contains five physical states: $h,\ H,\ A,\ H^{\pm}$

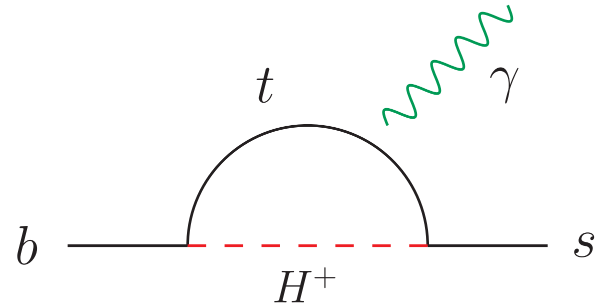
Electroweak and flavor observables involving the b quark receive sizable contributions from loops with a charged Higgs and a top quark. The relevant interaction is:

$$\mathcal{L}_{H^+ t d_j} = -\frac{g}{\sqrt{2}\, m_W} \sum_{j=1}^{3} \bar{t}\, T_R^{(a)} \left(A_u\, m_t\, P_L - A_d\, m_{d_j}\, P_R \right) V_{3j}\, d_j\, H^+_{(a)} \; + \; \text{h.c.}$$

(e.g., in the type-II THDM $A_u = -1/A_d = 1/\tan\beta$. Now we treat them as independent)

The processes $Z \to b\bar{b}$ and $B \to X_s \gamma$ allow us to constrain the couplings A_u and A_d





$$\propto \left[\left(\frac{A_u m_t}{\sqrt{2} m_W} \right)^2 + \left(\frac{A_d m_b}{\sqrt{2} m_W} \right)^2 \right] F\left(\frac{m_t}{m_{H^+}} \right)$$

$$\propto\ A_u^2\, F_1\left(\frac{m_t}{m_{H^+}} \right) \ + \ A_u\, A_d\, F_2\left(\frac{m_t}{m_{H^+}} \right)$$

The computation of $Z \to b\bar{b}$ and $B \to X_s\gamma$ in the THDMs is not as advanced as in the SM

Status of $Z \to b\bar{b}$:

- SM: one loop + two- and three-loop QCD
- THDM: one loop
- MW: one loop

Status of $B \to X_s\gamma$:

- SM: NNLO in QCD
- THDM: NLO
- MW: LO (partial)

In *arXiv:1002.1071* we computed the two-loop QCD corrections to the charged-Higgs contributions to $Z \to b\bar{b}$ and $B \to X_s\gamma$ in both the usual THDM and the MW model

- The results for $Z \to b\bar{b}$ will be implemented in Gfitter and CKMfitter
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- MW: one loop + two-loop QCD

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Charged-Higgs contribution to R_b including QCD corrections

$$R_b \;\equiv\; \frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to \text{hadrons})} \;=\; \left(1+\frac{\sum_{(q\neq b)}\left[(\bar{g}_L^q)^2+(\bar{g}_R^q)^2\right]K_q}{\left[(\bar{g}_L^b)^2+(\bar{g}_R^b)^2\right]K_b}\right)^{-1}$$

where:

$$\mathcal{L}_{Zq\bar{q}} \;=\; -\frac{e}{s_W c_W}\, Z_\mu\, \bar{q}\,\gamma^\mu \left(\bar{g}_L^q\, P_L \;+\; \bar{g}_R^q\, P_R\right) q$$

$$\bar{g}_{L,R}^q \;=\; (g_{L,R}^q)_{\rm SM} \;+\; \delta g_{L,R}^q$$

The SM prediction for R_b is roughly one standard deviation below the measured value

$$R_b^{\rm SM} \;=\; 0.21580 \pm 0.00006\;, \qquad R_b^{\rm exp} \;=\; 0.21629 \pm 0.00066$$

→ Strong constraints on New-Physics contributions that further reduce R_b

Up to terms of $\mathcal{O}(m_Z^2/m_t^2)$, the charged-Higgs contributions to the *Zbb* couplings read

$$\delta g_b^L = \frac{g^2}{32\pi^2}\, C_R^1 \left(\frac{A_u\, m_t}{\sqrt{2}\, m_W}\right)^2 f_1(m_t^2/m_{H^+}^2)$$

$$\delta g_b^R = -\frac{g^2}{32\pi^2}\, C_R^1 \left(\frac{A_d\, m_b}{\sqrt{2}\, m_W}\right)^2 f_1(m_t^2/m_{H^+}^2)$$

$$f_1(x) = \frac{x}{x-1} - \frac{x \ln x}{(x-1)^2}$$

The inclusion of the QCD corrections amounts to a simple replacement:

$$f_1(x) \longrightarrow f_1(x) + \frac{\alpha_s}{4\pi}\left[C_F\, f_2^{u,d}(x) + C_R^2\, f_3(x)\right]$$

The color factors depend on the model

THDM: $C_R^1 = 1\,, \quad C_R^2 = 0$

MW: $C_R^1 = C_F\,, \quad C_R^2 = N_c$

- The two-loop corrections can amount to 10-20% of the one-loop contribution
- Their inclusion reduces the uncertainty associated with the choice of scheme for m_t

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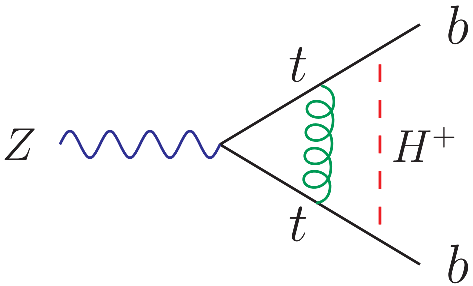

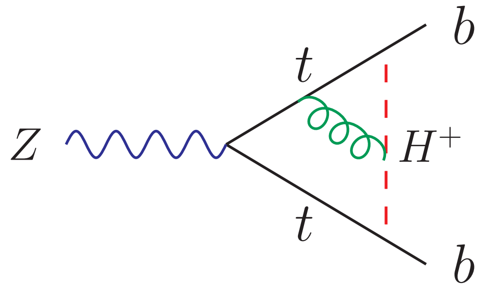

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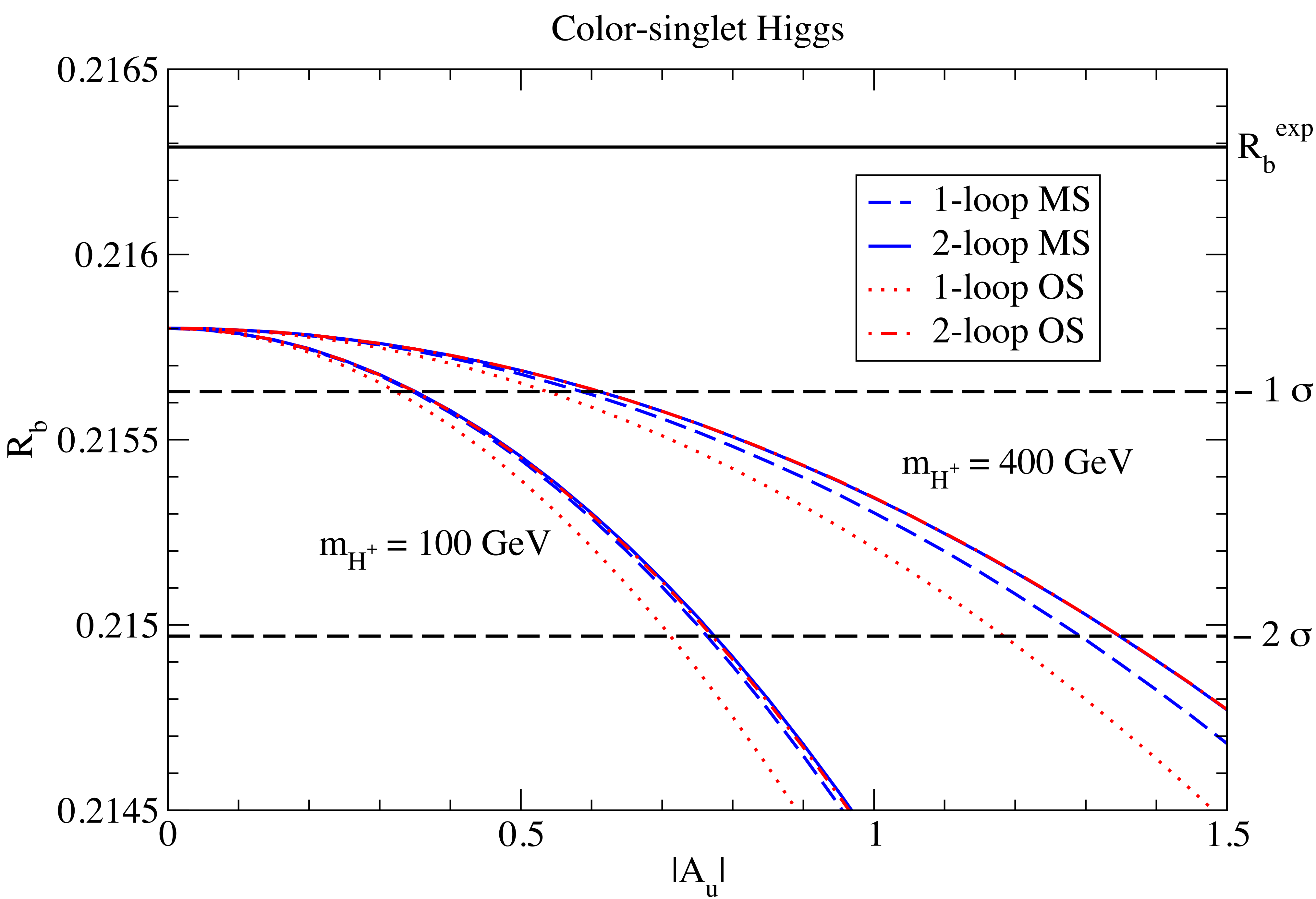
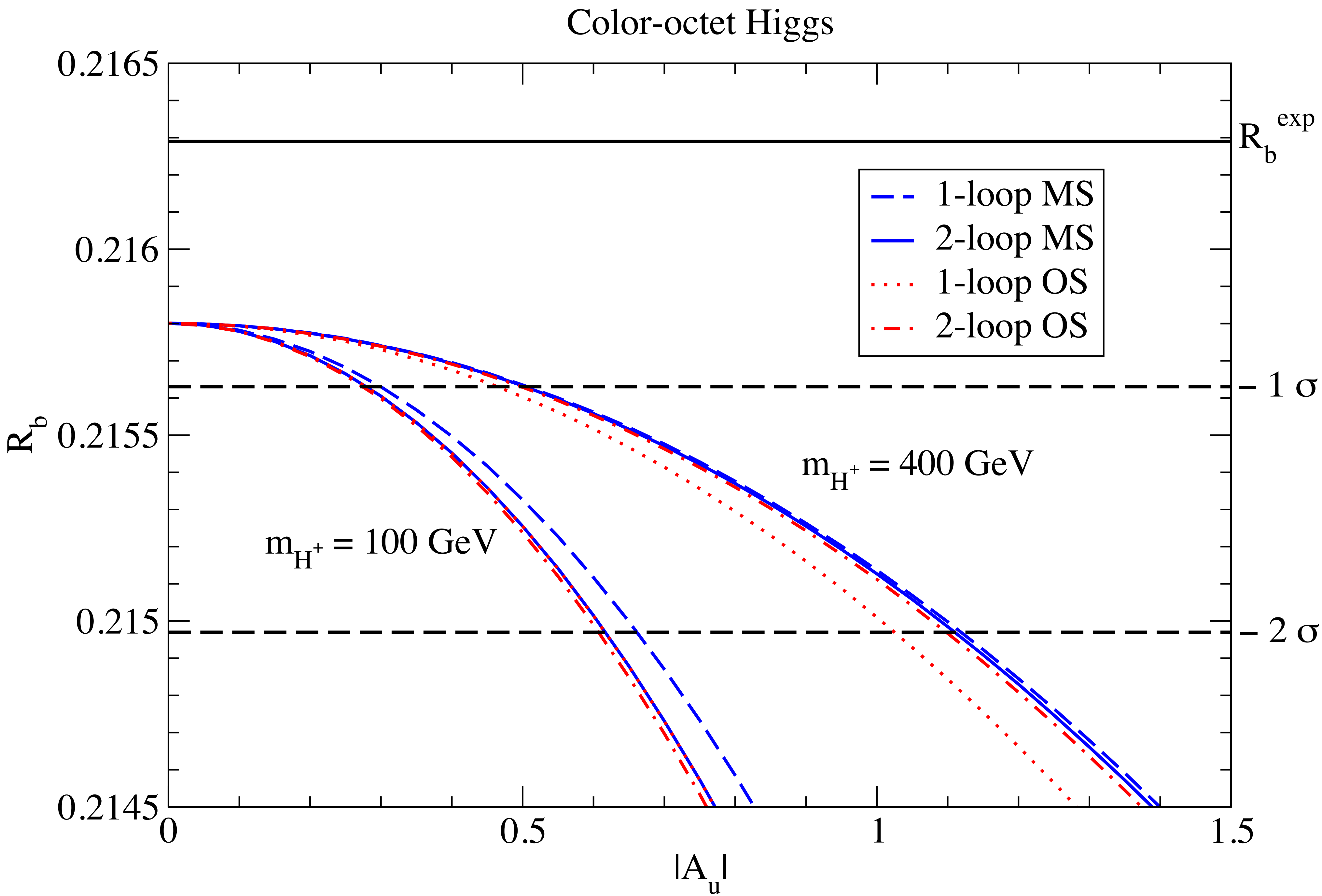

Color-singlet Higgs
0.2165
0.216
0.2155
0.215
0.2145
R_b
0
0.5
1
1.5
$|A_u|$
R_b^{exp}
1 σ
2 σ
1-loop MS
2-loop MS
1-loop OS
2-loop OS
m_{H^+} = 400 GeV
m_{H^+} = 100 GeV



Color-octet Higgs
0.2165
0.216
0.2155
0.215
0.2145
R_b
R_b^{exp}
1-loop MS
2-loop MS
1-loop OS
2-loop OS
1 σ
2 σ
m_{H^+} = 400 GeV
m_{H^+} = 100 GeV
0
0.5
1
1.5
$|A_u|$

Charged-Higgs contributions to $B \to X_s \gamma$

The basis of effective operators relevant to the $b \to s$ transition:

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_\mu}{\sqrt{2}}\,V_{ts}^* V_{tb}\sum_i C_i(\mu)\,Q_i(\mu)$$

$$Q_{1,2} = (\bar{s}\,\Gamma_i\,c)\,(\bar{c}\,\Gamma_i\,b)\,, \qquad Q_{3,4,5,6} = (\bar{s}\,\Gamma_i\,b)\,(\bar{q}\,\Gamma_i\,q)$$

$$Q_7 = \frac{e}{16\pi^2}\,m_b\,\bar{s}_L\,\sigma^{\mu\nu}\,b_R\,F_{\mu\nu}\,, \qquad Q_8 = \frac{g_s}{16\pi^2}\,m_b\,\bar{s}_L\,\sigma^{\mu\nu}\,T^a\,b_R\,G_{\mu\nu}$$

The Wilson coefficients can be decomposed in a SM part and a New-Physics part

$$C_i(\mu_W) = C_i^{(0)}(\mu_W) + \delta C_i^{(0)}(\mu_W) + \frac{\alpha_s(\mu_W)}{4\pi}\left[C_i^{(1)}(\mu_W) + \delta C_i^{(1)}(\mu_W)\right]$$

Loops with charged Higgs and top contribute to $\delta C_7^{(0)},\ \delta C_8^{(0)},\ \delta C_7^{(1)},\ \delta C_8^{(1)}$ and $\delta C_4^{(1)}$

$$\delta C_{7,8} \approx A_u^2\,F_{7,8}^1\left(\frac{m_t}{m_{H^+}}\right) + A_u\,A_d\,F_{7,8}^2\left(\frac{m_t}{m_{H^+}}\right)$$

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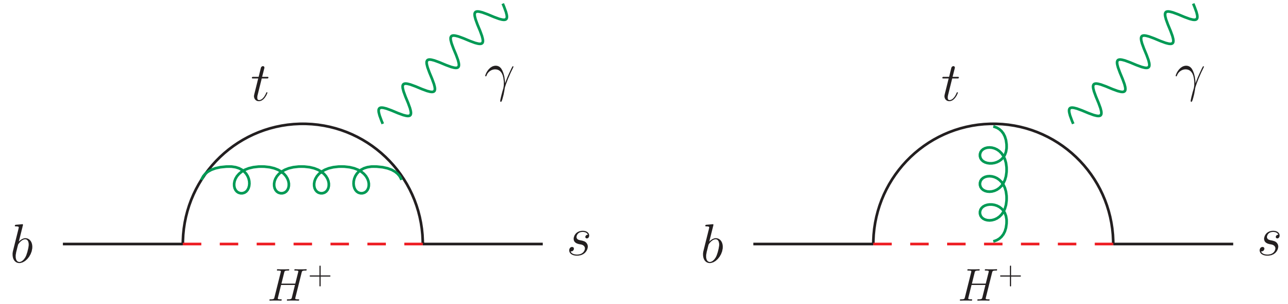

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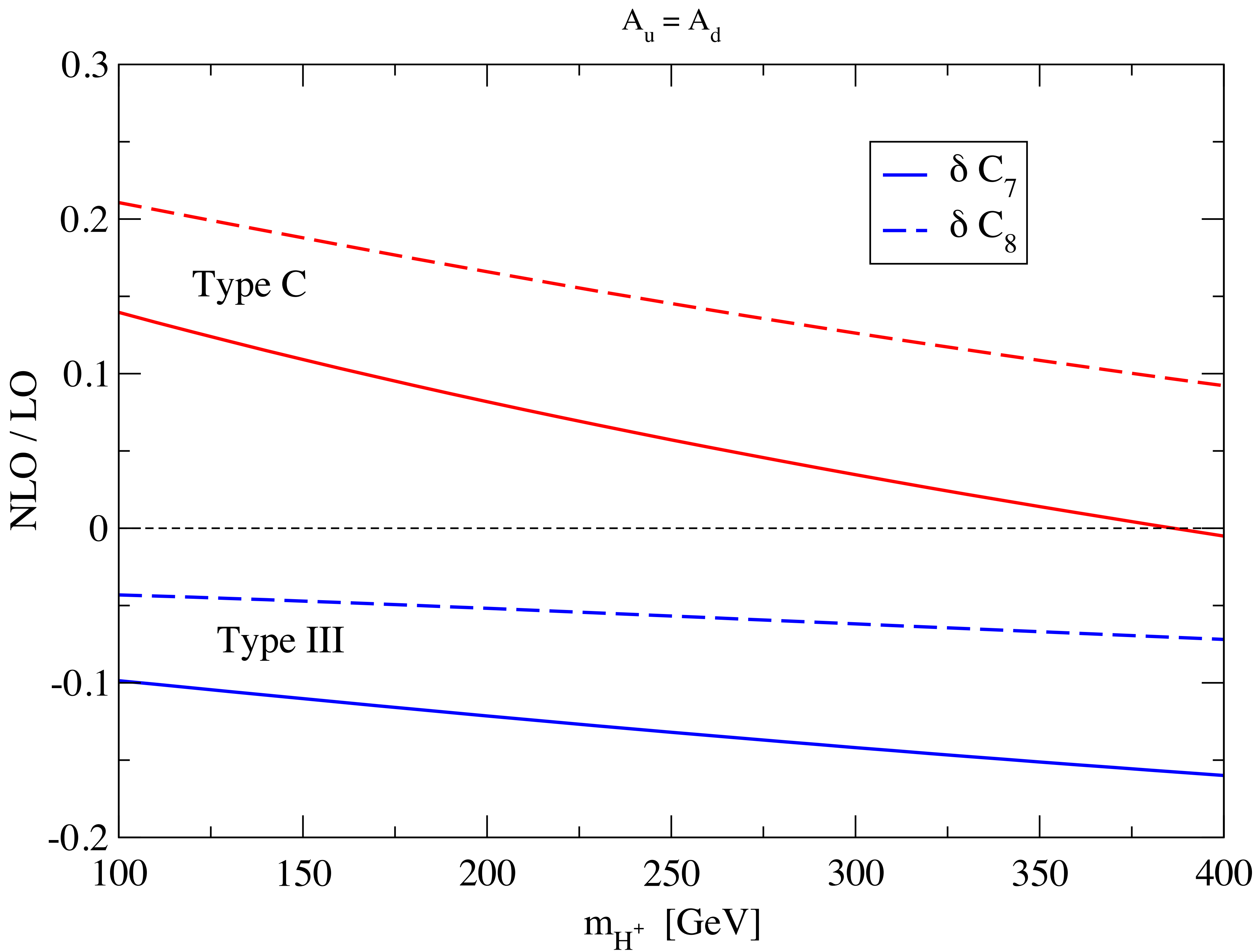
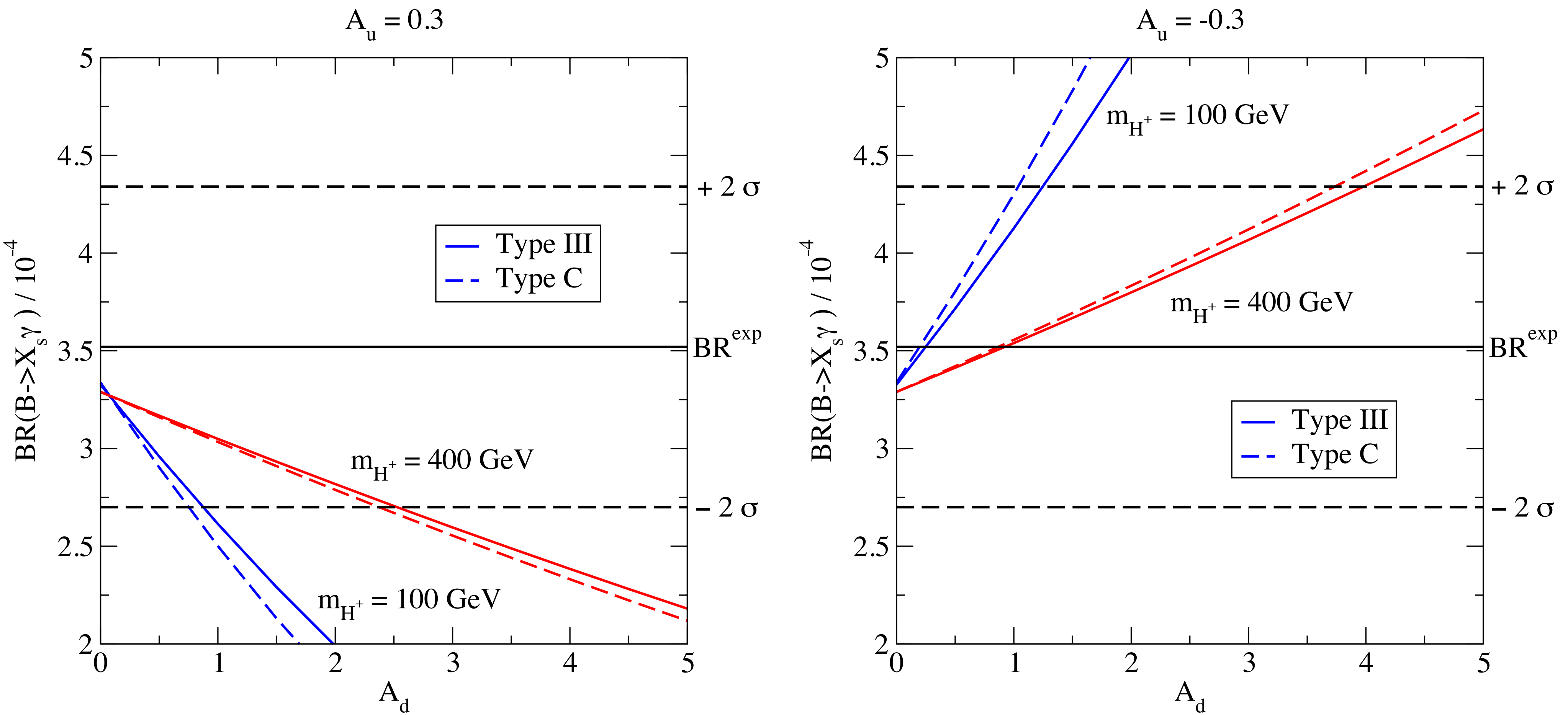


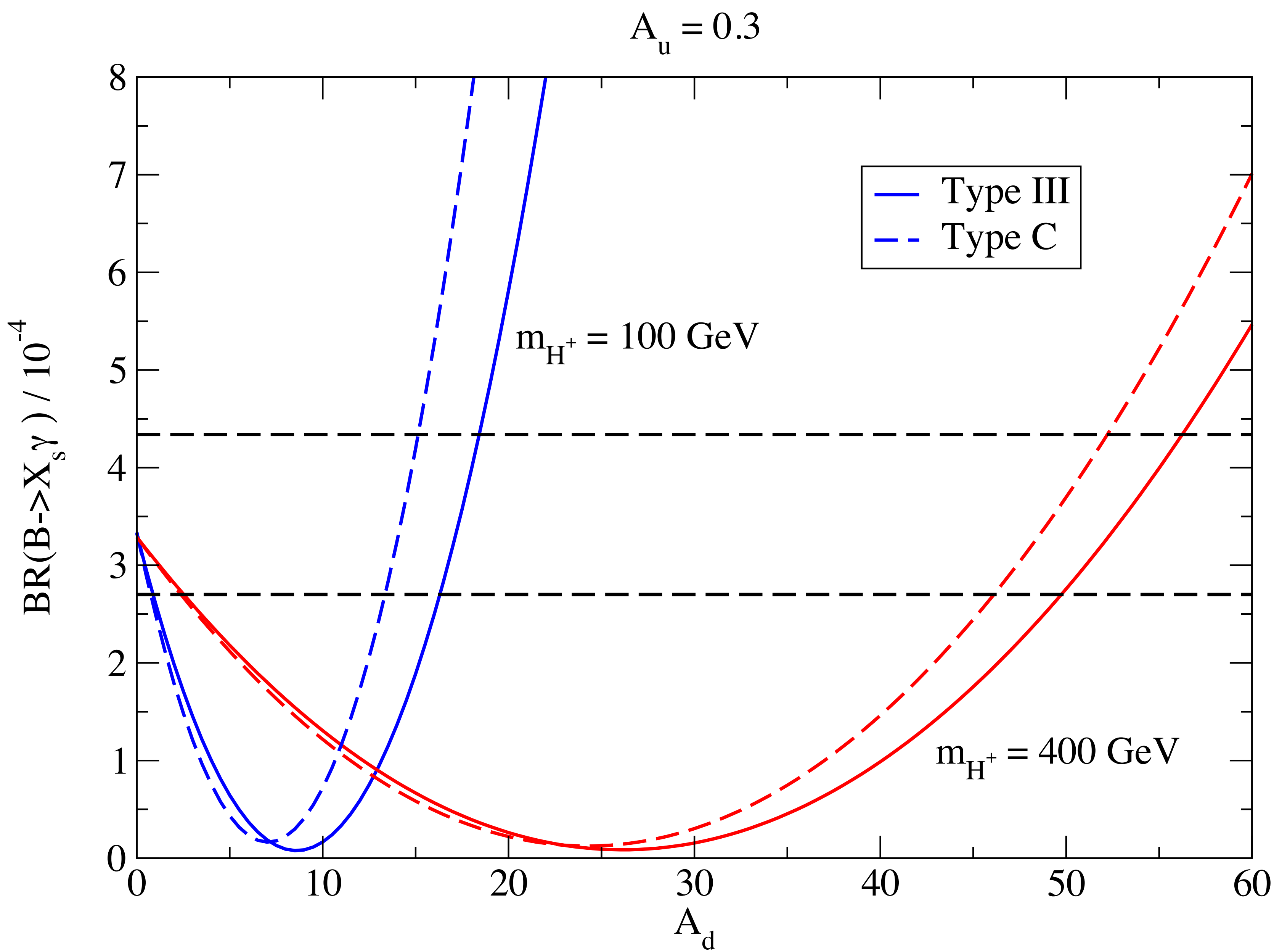
$A_u = A_d$
0.3
0.2
0.1
0
-0.1
-0.2
100
150
200
250
300
350
400
NLO / LO
m_{H^+} [GeV]
δC_7
δC_8
Type C
Type III

We use SusyBSG to compute $\mathrm{BR}[B \to X_s\gamma]$, and we compare it with the measured value

$$\mathrm{BR}[B \to X_s\gamma]^{\mathrm{exp}} = (3.52 \pm 0.25) \times 10^{-4}$$

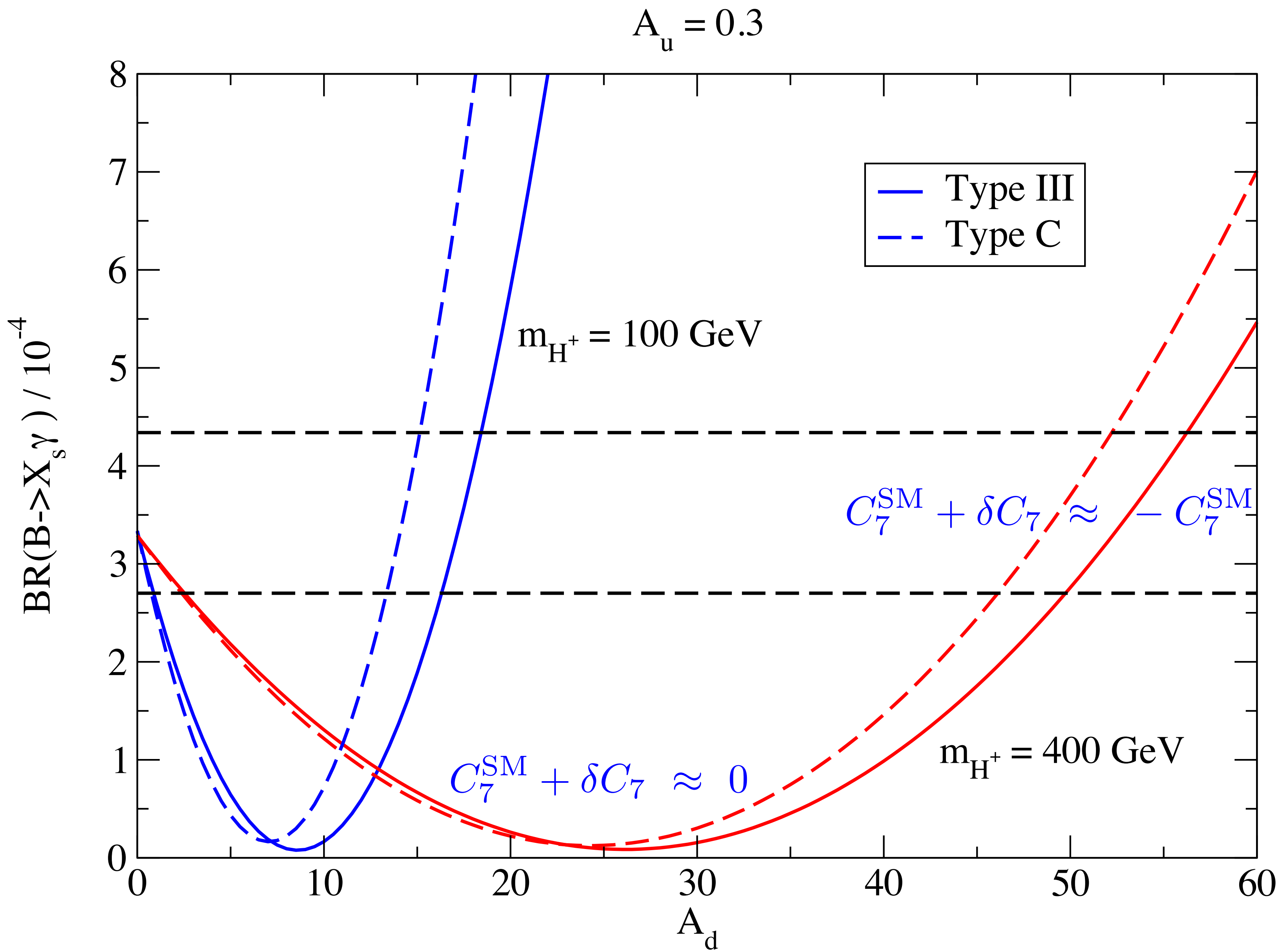
For fixed, smallish values of A_u (compatible with R_b), the comparison sets bounds on A_d





The branching ratio is roughly proportional to $|C_7|^2$, thus it does not constrain the sign of C_7

Other observables (e.g., $\mathrm{BR}[B \to X_s \ell^+ \ell^-]$ and $\Delta[B \to K^* \gamma]$) rule out the case $C_7 \sim -C_7^{SM}$



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Thank you!!!