Uplifted supersymmetric Higgs region

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work with Paddy Fox and Adam Martin

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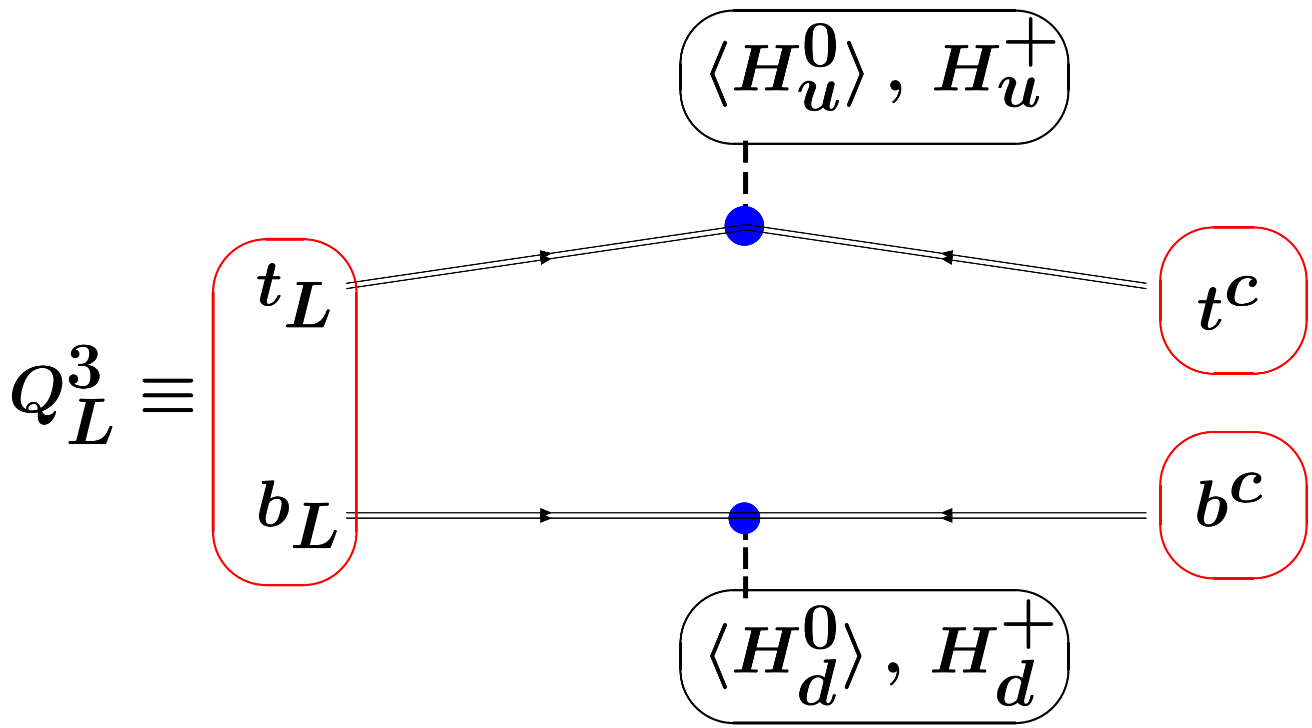
Minimal Supersymmetric Standard Model

The supersymmetric Higgs sector is a Two-Higgs-Doublet model of type-II *(only up-type quarks get masses from H_u).*

This is imposed by holomorphy, i.e., the superpotential is a function of fields and not their Hermitian conjugates.

Superpotential: $$W = y_u\,\hat{u}^c\hat{H}_u\hat{Q} - y_d\,\hat{d}^c\hat{H}_d\hat{Q} - y_\ell\,\hat{e}^c\hat{H}_d\hat{L} + \mu\,\hat{H}_u\hat{H}_d$$



Lagrangian $\mathcal{L} \supset -y_b \bar{b}_R Q_L^3 H_d - y_\tau \bar{\tau}_R L_L^3 H_d$ (due to the superpotential)

The MSSM allows $y_b = O(1)$ if $\tan\beta \equiv \frac{v_u}{v_d} \approx 50$.

$\tan\beta$ is determined by the minimization of the potential:

$$\left(|\mu|^2 + m_{H_u}^2\right)|H_u|^2 + \left(|\mu|^2 + m_{H_d}^2\right)|H_d|^2 + b\, H_u H_d$$

$$+\frac{1}{8}\left(g^2 + g'^2\right)\left(|H_u|^2 - |H_d|^2\right)^2$$

$m_{H_u}^2$, $m_{H_d}^2$ and b ($\equiv B\mu$) are soft susy-breaking parameters.

Note: $y_\tau/y_b = m_\tau/m_b$ in the MSSM is independent of $\tan\beta$, so that

$$\frac{B(A^0 \to \tau^+\tau^-)}{B(A^0 \to b\bar{b})} \approx \frac{y_\tau^2}{3y_b^2} = \frac{m_\tau^2}{3m_b^2} \approx 10\%$$

Uplifted region of the MSSM

Dobrescu, Fox, 1001.3147

Let us assign R-charges such that the susy-breaking term $b\,H_u H_d$ is forbidden, *e.g.*, $R[\hat{H}_d, \hat{Q}, \hat{u}^c, \hat{e}^c] = 0$ **and** $R[\hat{H}_u, \hat{d}^c, \hat{L}] = 2$.

We impose that

$$|\mu|^2 + m_{H_u}^2 < 0$$
$$|\mu|^2 + m_{H_d}^2 > 0$$

and, in order for the potential to be bounded from below, that

$$2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2 > 0 \ .$$

$\Rightarrow$ **only** H_u **acquires a VEV ...** *ooops*

H_d **has no VEV** $\Rightarrow$ **down-type quarks and leptons do not acquire masses from the Yukawa couplings given in the superpotential.**

Should one dismiss this region of parameter space?

not so fast ...

Lagrangian $\mathcal{L} \supset -y_b\, b^c H_d Q^3 - y_\tau\, \tau^c H_d L^3$ *(due to the superpotential)*

These Yukawa couplings explicitly break the chiral symmetries from $U(3)^5$ to $U(1)_B \times U(1)_L$:

$\Rightarrow$ *loops will generate masses for the down-type quarks and leptons.*

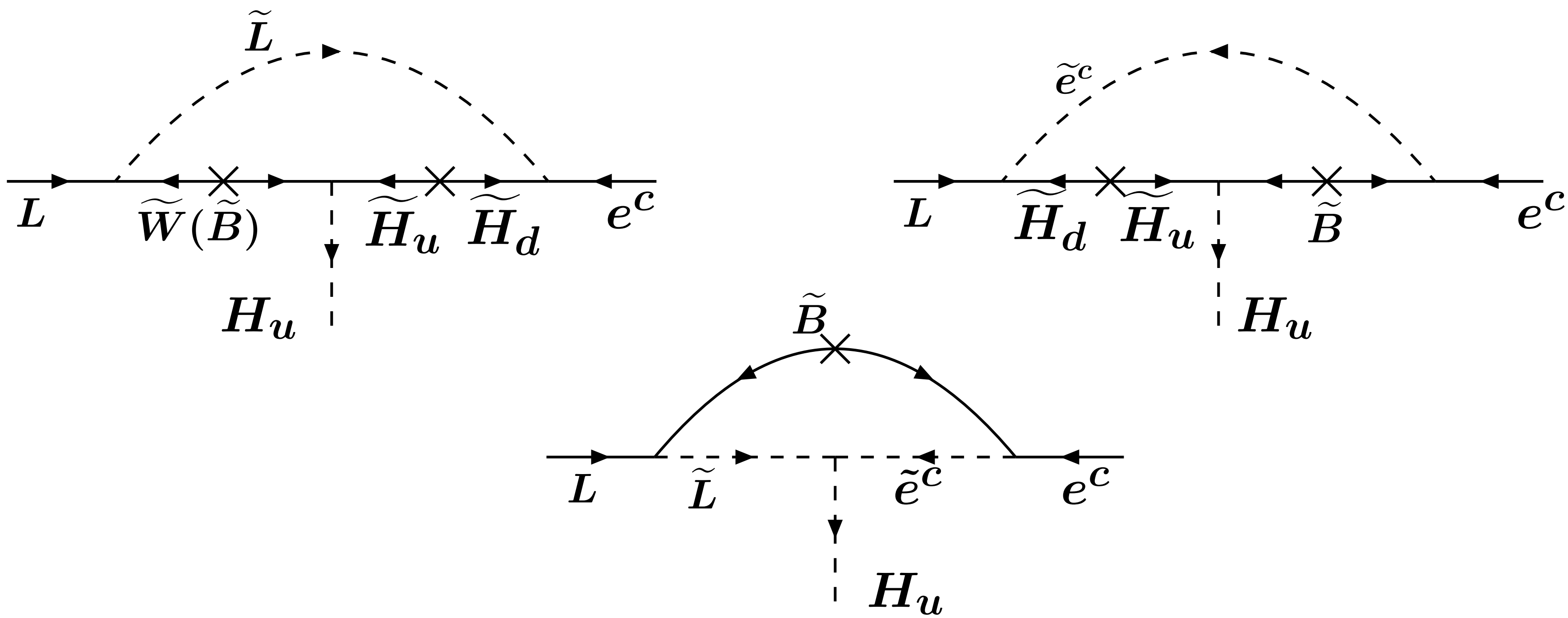
Once supersymmetry is broken, holomorphy does not restrict anymore the Higgs couplings to fermions

$\rightarrow$ **all gauge invariant operators may be present in the low-energy effective Lagrangian. These include:**

$$-y'_b\, b^c H_u^\dagger Q^3 - y'_\tau\, \tau^c H_u^\dagger L^3$$

"Wrong-Higgs couplings" - *Hall, Rattazzi, Sarid, hep-ph/9306309*
Haber, Mason, 0711.2890
...

Loop-induced Yukawa couplings of the leptons to $H_u^\dagger$:



The F term for H_d which follows from the superpotential is

$$F^\dagger_{H_d} = y_d\, \tilde{d}^c \widetilde{Q} + y_\ell\, \tilde{e}^c \widetilde{L} - \mu H_u \quad .$$

This F term generates the following trilinear scalar interactions in the Lagrangian:

$$\mu^* H_u^\dagger \left(y_d \tilde{d}^c \widetilde{Q} + y_\ell \tilde{e}^c \widetilde{L} \right) + \mathrm{H.c.}$$

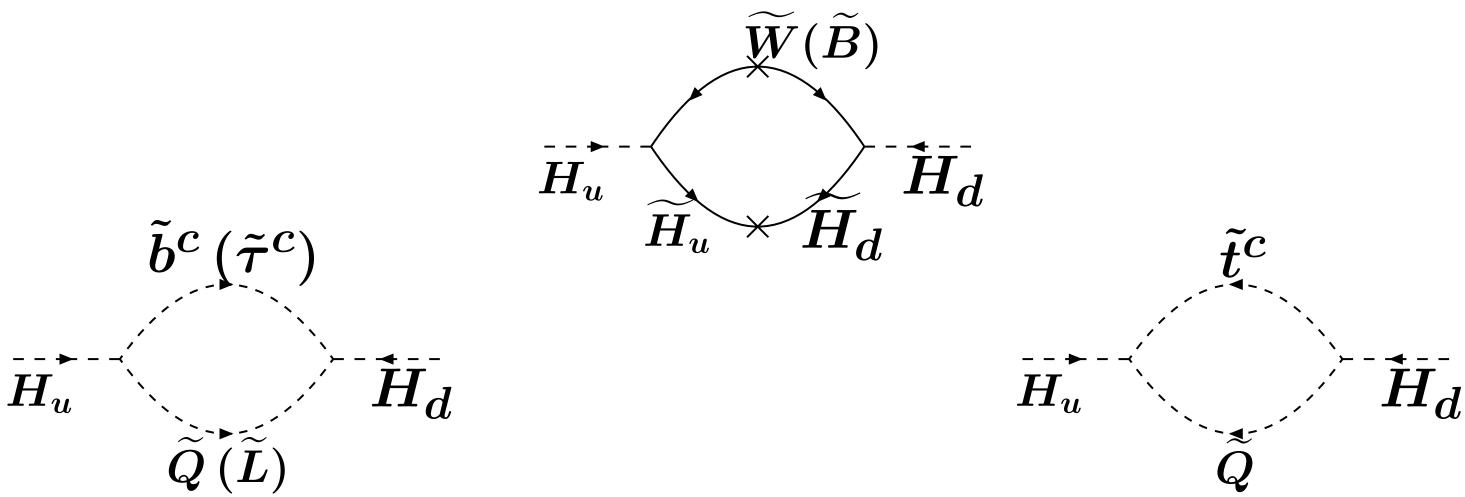
These 1-loop diagrams are finite, and give rise to uplifted-Higgs lepton couplings:

$$y'_\ell = \frac{y_\ell\, \alpha}{8\pi} \left\{ \frac{3}{s_W^2} F\left(\frac{M_{\tilde W}}{M_{\tilde L}}, \frac{|\mu|}{M_{\tilde L}}\right) + \frac{1}{c_W^2} \left[-F\left(\frac{M_{\tilde B}}{M_{\tilde L}}, \frac{|\mu|}{M_{\tilde L}}\right) + 2F\left(\frac{M_{\tilde B}}{M_{\tilde e}}, \frac{|\mu|}{M_{\tilde e}}\right) - \frac{2|\mu|}{M_{\tilde e}} F\left(\frac{M_{\tilde B}}{M_{\tilde L}}, \frac{M_{\tilde e}}{M_{\tilde L}}\right) \right] \right\}$$

$$F(x, y) = \frac{2xy}{x^2 - y^2} \left(\frac{y^2 \ln y}{1 - y^2} - \frac{x^2 \ln x}{1 - x^2} \right)$$

$$0 < F(x, y) < 1$$

The bH_uH_d soft term is generated at one loop:



$$b \;=\; -\frac{\alpha\mu}{2\pi}\left[\frac{3}{s_W^2}M_{\tilde{W}}G(|\mu|,M_{\tilde{W}})e^{-2i\theta_W}+\frac{1}{c_W^2}M_{\tilde{B}}G(|\mu|,M_{\tilde{B}})e^{-2i\theta_B}\right]$$
$$-\;\frac{\mu}{8\pi^2}\left[3y_b^*A_bG(M_{\tilde{Q}},M_{\tilde{b}})+y_\tau^*A_\tau G(M_{\tilde{L}},M_{\tilde{\tau}})+3y_t^*A_tG(M_{\tilde{Q}},M_{\tilde{t}})\right]$$

$$G(m_1,m_2)=\frac{1}{m_2^2-m_1^2}\left(m_2^2\ln\frac{\Lambda}{m_2}-m_1^2\ln\frac{\Lambda}{m_1}\right)$$

So H_d gets a small VEV at 1 loop:

$$\frac{v_u}{v_d} \equiv \tan\beta \approx \frac{1}{|b|} M^2_{A^0}\left[1 + O(1/\tan^2\beta)\right] \gg 1$$

For $M_{\tilde{B}} = 100$ GeV, $M_{A^0} = 700$ GeV and $\mu = 100 - 300$ GeV:

$\tan\beta$ varies from 240 to 90.

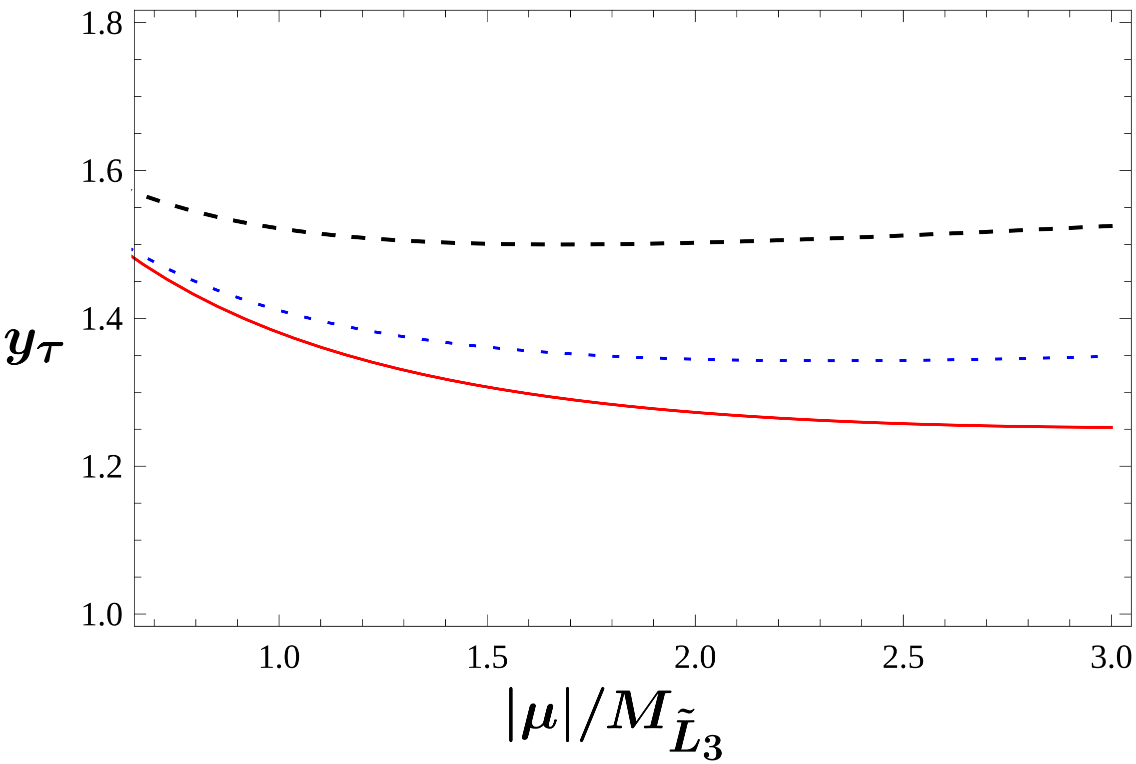
The tau mass is given by $m_\tau = y_\tau v_d + y'_\tau v_u$

y_τ is large but perturbative.

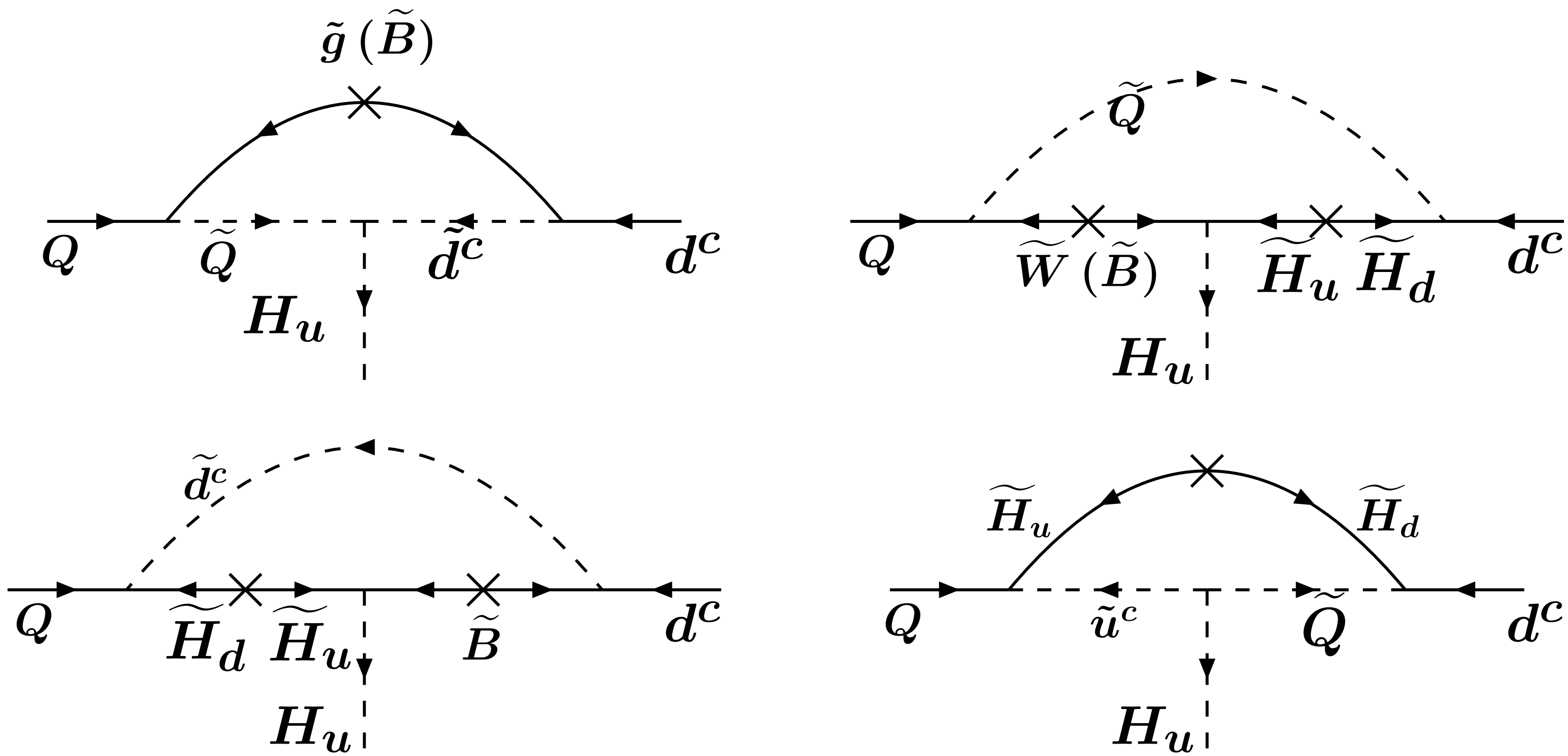
E.g., $M_{\tilde{\tau}^c} = M_{\tilde{B}}$, $\tan\beta = 200$,

$$M_{\tilde{W}} \approx \frac{3\,c_W^2}{5\,s_W^2} M_{\tilde{B}} \ ,$$

$M_{\tilde{B}}/M_{\tilde{L}_3}$: 0.3 (dashed line),
0.6 (dotted line),
1 (solid line).



Contributions to the y'_d Yukawa coupling of the down-type quarks:



The F-term interaction for quarks appears in a loop that involves either a bino (as in the case of leptons) or a gluino.

$$(y'_d)_F = \frac{2y_d}{3\pi}\frac{|\mu|}{M_{\tilde{d}}}\left[\alpha_s e^{i\theta_g} F\left(\frac{M_{\tilde{g}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}}\right) + \frac{\alpha}{24c_W^2} F\left(\frac{M_{\tilde{B}}}{M_{\tilde{Q}}}, \frac{M_{\tilde{d}}}{M_{\tilde{Q}}}\right)\right]$$

The gaugino interactions induce the same contributions as in the lepton sector except for the replacement of sleptons by squarks:

$$(y'_d)_{\tilde{H}} = \frac{y_d \alpha}{8\pi} \left\{ \frac{3}{s_W^2} F\left(\frac{M_{\tilde{W}}}{M_{\tilde{Q}}}, \frac{|\mu|}{M_{\tilde{Q}}}\right) \right.$$

$$\left. + \frac{e^{i(\theta_B - \theta_W)}}{3c_W^2} \left[F\left(\frac{M_{\tilde{B}}}{M_{\tilde{Q}}}, \frac{|\mu|}{M_{\tilde{Q}}}\right) + 2F\left(\frac{M_{\tilde{B}}}{M_{\tilde{d}}}, \frac{|\mu|}{M_{\tilde{d}}}\right) \right] \right\}$$

There is also a novel type of contribution to y'_d coming from the susy-breaking trilinear term:

$$(y'_d)_A = -\frac{y_u y_d}{8\pi^2} \frac{A_u^*}{M_{\tilde{u}}} F\left(\frac{M_{\tilde{u}}}{M_{\tilde{Q}}}, \frac{|\mu|}{M_{\tilde{Q}}}\right)$$

The effective Yukawa coupling of $H_u^\dagger$ to down-type quarks is then the sum of the three contributions:

$$y'_d = (y'_d)_F + (y'_d)_{\tilde{H}} + (y'_d)_A$$

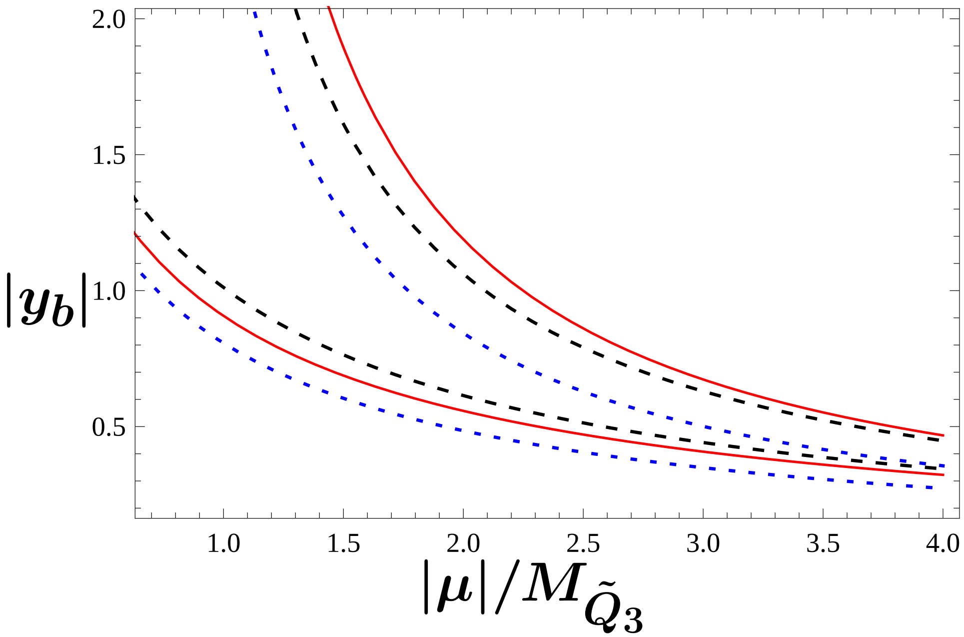
y_b is also perturbative.

E.g., $M_{\tilde{b}^c} = M_{\tilde{Q}}$, $\tan\beta = 200$, $A_t = 0$

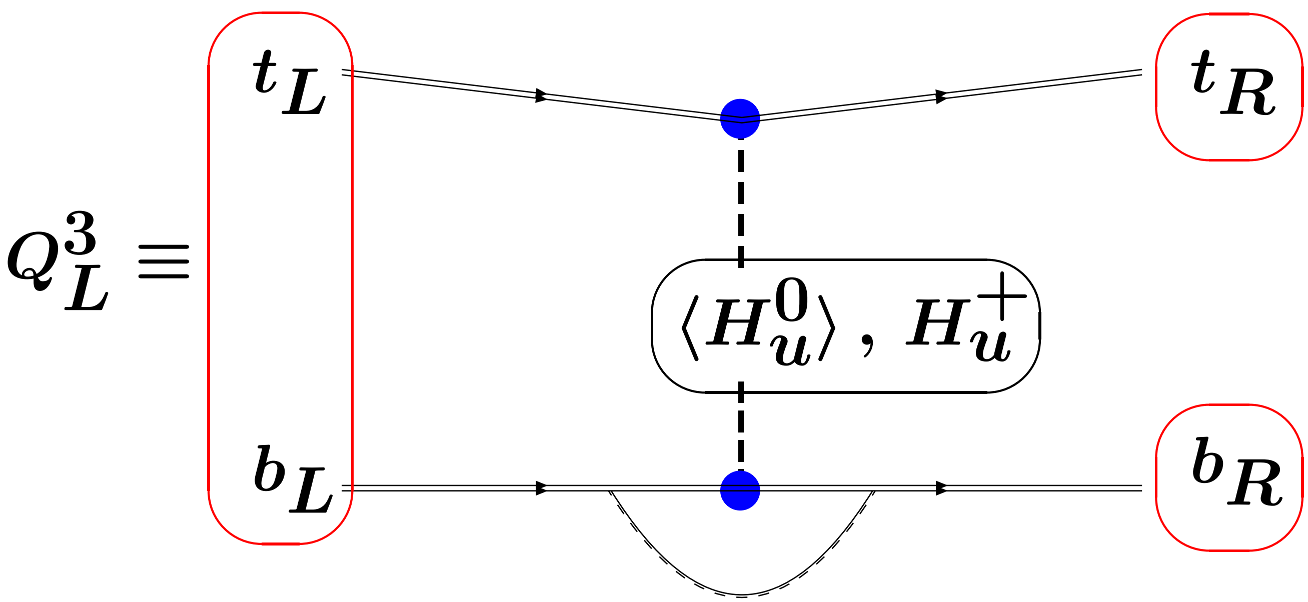
$$M_{\tilde{W}} \approx \frac{3\,c_W^2}{5\,s_W^2} M_{\tilde{B}} \quad , \quad M_{\tilde{g}} = M_{\tilde{W}} \frac{\alpha_s}{\alpha} s_W^2$$

$\theta_g = 0$ - lower set of curves
$\theta_g = \pi$ - upper set

$M_{\tilde{B}}/M_{\tilde{Q}_3}$: 0.1 (dashed line),
0.5 (dotted line),
1 (solid line).



Uplifted SUSY region: t and b masses are generated as in the SM, but with loop-induced b Yukawa coupling.



The Higgs boson h^0 that couples to WW is at tree level entirely part of the H_u doublet.

The other physical states, H^0, A^0 and $H^\pm$, are all part of the H_d doublet and have tree-level masses given by :

$$M_{H^0}^2 = M_{A^0}^2 = |\mu|^2 + m_{H_d}^2$$

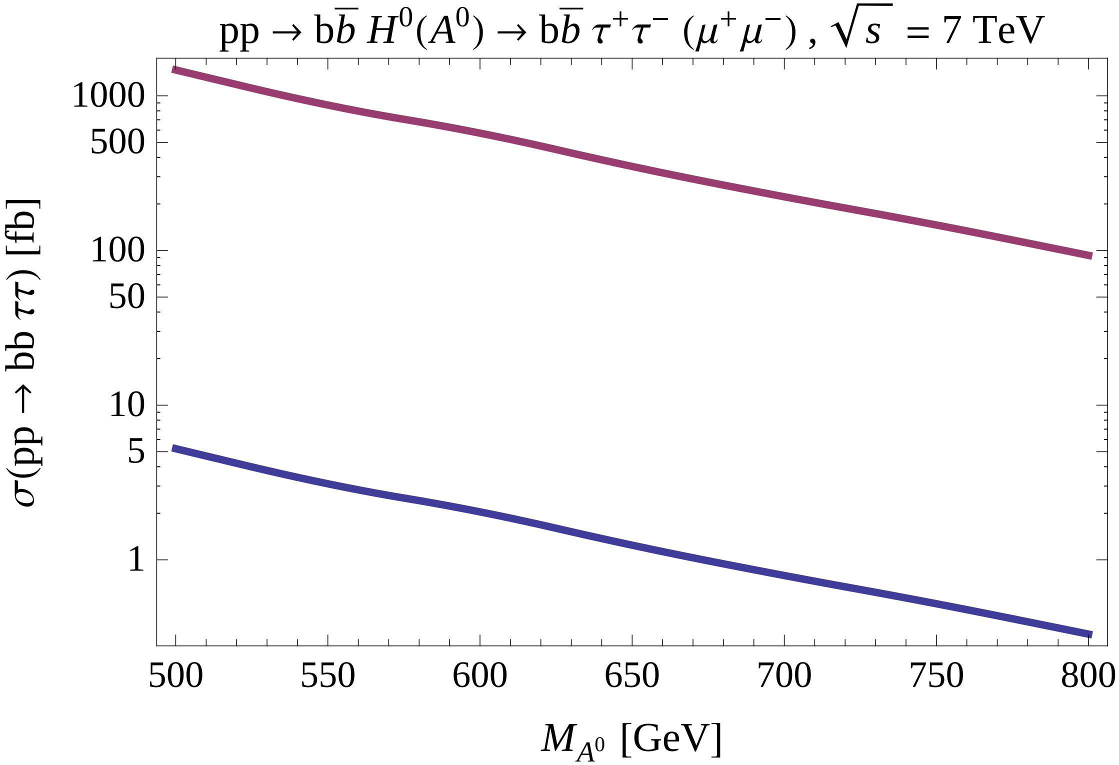
$$M_{H^\pm}^2 = M_{A^0}^2 + M_W^2$$

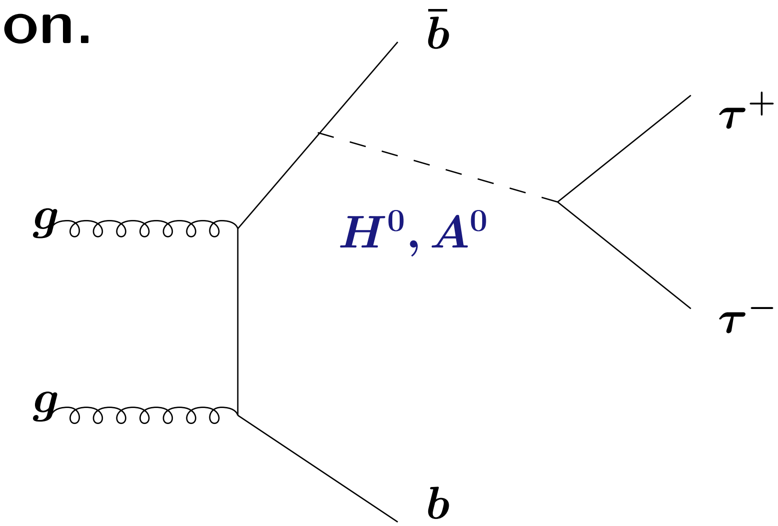
(assumed to be between several hundred GeV and a few TeV).

The heavy "Higgs" bosons $(H^0, A^0, H^\pm)$ have a large Yukawa coupling to the τ, such that the branching fractions for $H^0, A^0 \to \tau^+\tau^-$ and $H^\pm \to \tau^\pm\nu$ are large

$$B(H^0 \to \tau^+\tau^-) \approx \frac{y_\tau^2}{y_\tau^2 + 3y_b^2} \approx 30 - 80\%$$

At the LHC: $b\bar{b}H^0$ associated production.





$y_b = 1,\ y_\tau = 1.5,\ K \approx 2$

Dobrescu, Fox, Martin: 100?.????

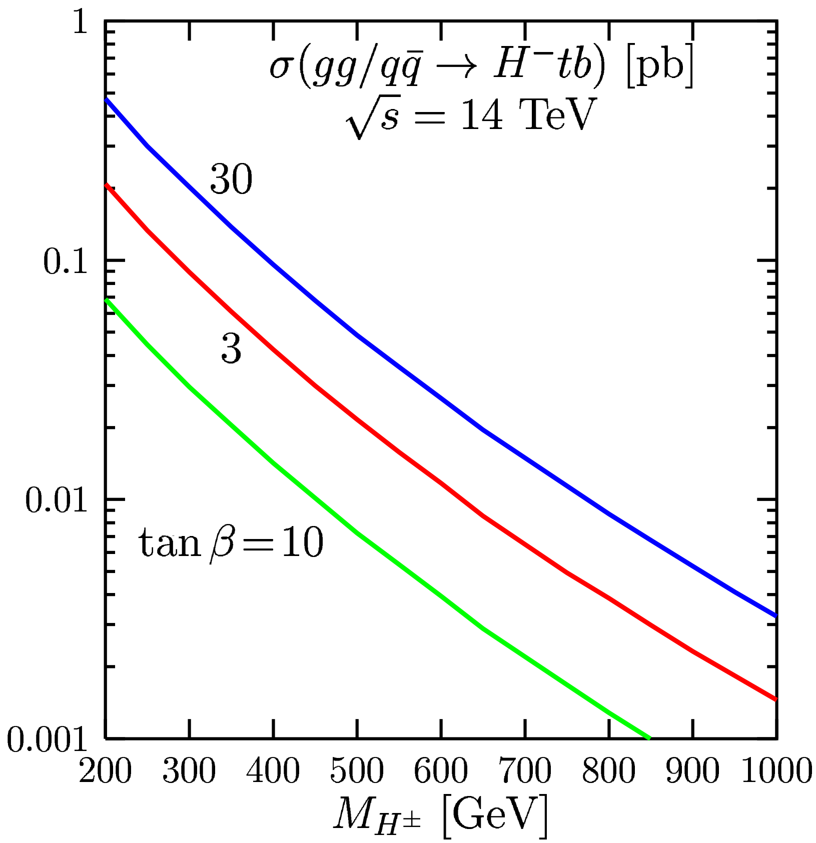
Background to $b\bar{b}\tau^+\tau^-$ from $t\bar{t}$ production.

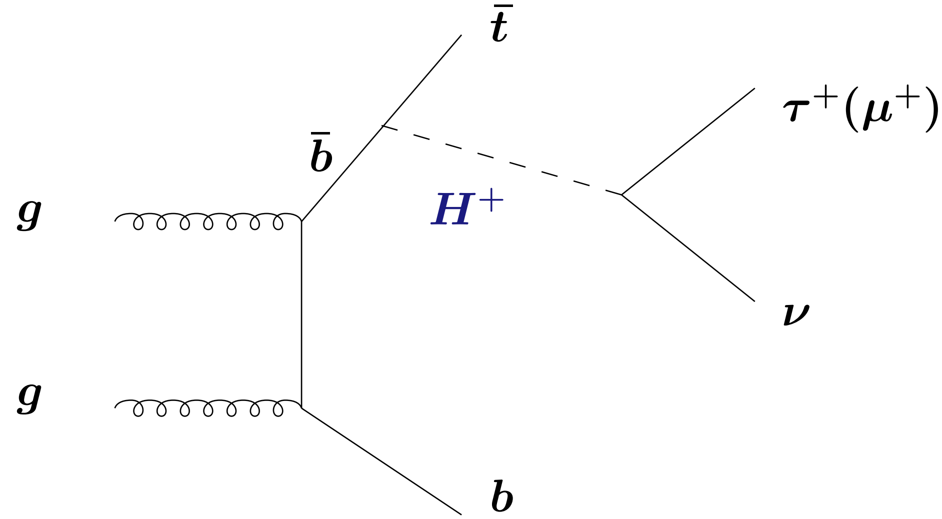
$b\bar{b}\mu^+\mu^-$ channel could be useful:

$$B(A^0 \to \mu^+\mu^-) \approx \frac{m_\mu^2}{m_\tau^2} B(A^0 \to \tau^+\tau^-) \approx 0.1\text{–}0.3\%$$

s-channel H^0, A^0 production via gg fusion (b loop) is also useful.

$H^{\pm}$ couplings to heavy quarks: $\frac{y_b}{\sqrt{2}} H^- \bar{b}_R t_L$





usual MSSM

A. Djouadi, hep-ph/0503173

$$B(H^+ \to \mu\nu) \approx \frac{m_\mu^2}{m_\tau^2} B(H^+ \to \tau\nu)$$

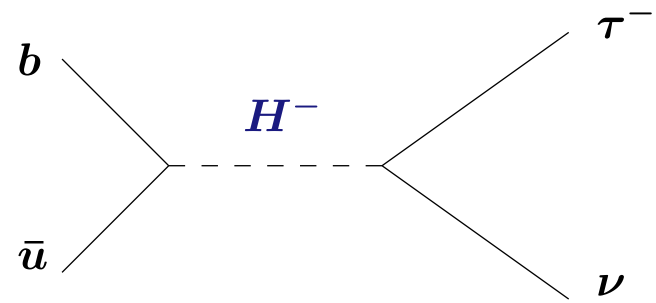
can be larger if slepton masses are generation dependent, or smaller if m_μ is due to something else.

Meson decays

Dobrescu, Fox, Martin: 1005.4238

Charged Higgs couplings in the mass eigenstate basis:

$$H_d^- \left(\frac{m_b V_{ub}\, y_b}{y_b v_d + y_b' v_u} \bar{b}_R u_L + \frac{m_\tau\, y_\tau}{y_\tau v_d + y_\tau' v_u} \bar{\tau}_R \nu_L \right)$$



$$\frac{B(B^- \to \tau\nu)}{B(B^- \to \tau\nu)_{\rm SM}} = \left[1 - \left(\frac{y_b}{y_b v_d + y_b' v_u} \right) \left(\frac{y_\tau}{y_\tau v_d + y_\tau' v_u} \right) \frac{M_B^2}{M_{H^-}^2} \right]^2$$

SM: $B(B^- \to \tau\nu)_{\rm SM} = (0.84 \pm 0.11) \times 10^{-4}$ **(UTfit: 0908.3470)**

Belle + BaBar: $B(B^- \to \tau\nu) = (1.73 \pm 0.34) \times 10^{-4}$

This excess can be "explained" in the uplifted region if there is a gluino phase ($\theta_g = \pi$ **gives** $y_b'/y_b < 0$).

FCNC's in the down-type quark sector

Tree level: $H_d\, d^c \hat{y}_d Q$; **Loop-induced:** $H_u^\dagger\, d^c \hat{y}'_d Q$

RGE's $\Rightarrow$ **different** $\tilde{b}$ **and** $\tilde{s}$ **masses** $\Rightarrow$ $\hat{y}_d$ **and** $\hat{y}'_d$ **are not aligned.**

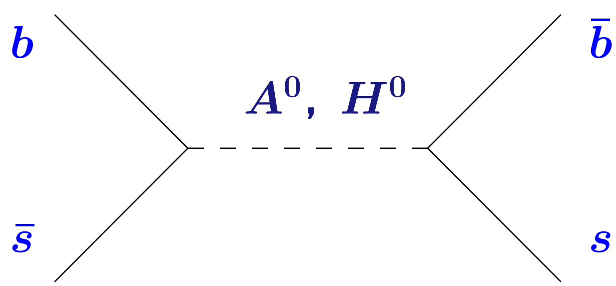
In the mass eigenstate basis: $H_d^0 \left(y_{bs} \bar{b}_R s_L + y_{sb} \bar{s}_R b_L \right)$

$$|y_{bs}| \lesssim V_{cb} \quad , \qquad |y_{sb}| \lesssim V_{cb} \frac{m_s}{m_b}$$

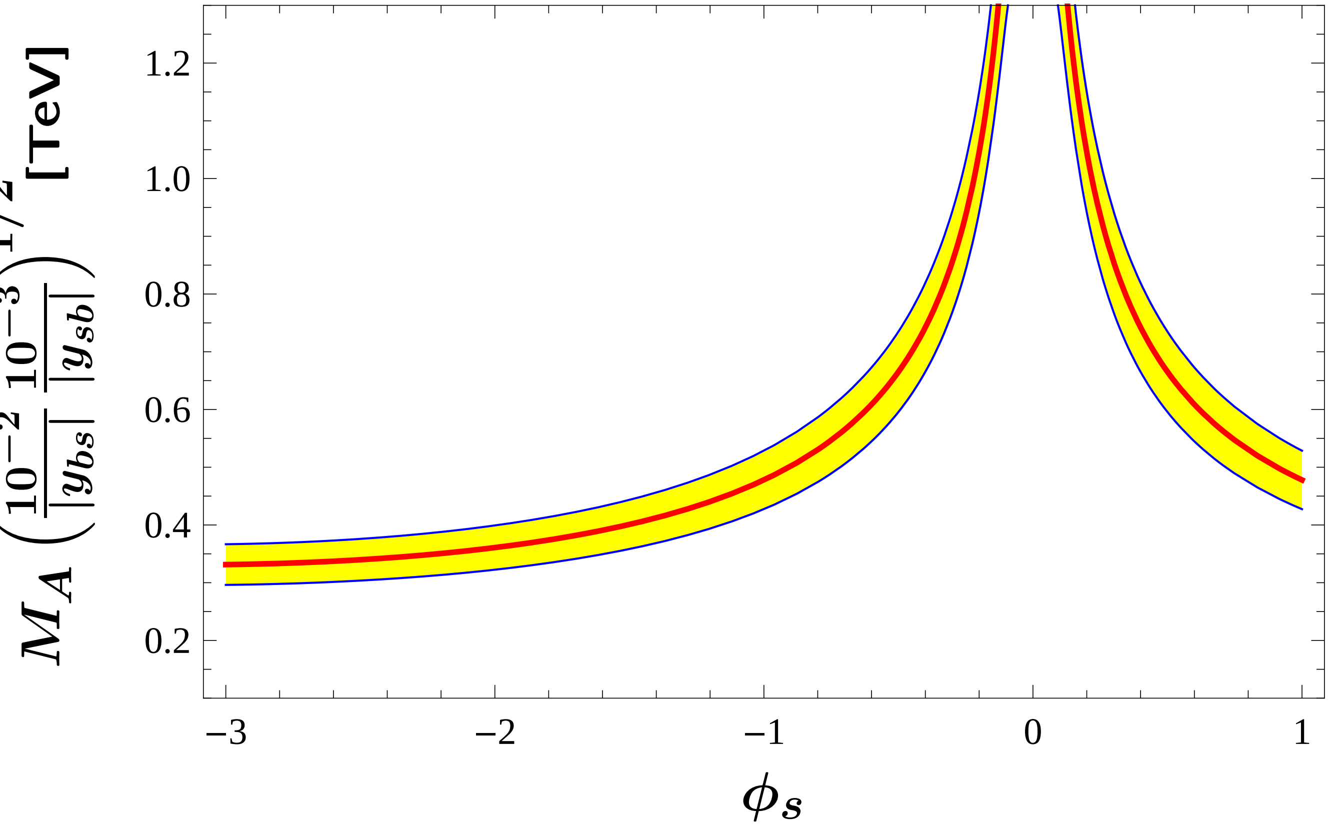
CP violation in $B_s - \bar{B}_s$ mixing due to interference between the SM and the A^0, H^0 contributions:

$$\langle B_s | \mathcal{H}^{\rm NP} | \overline{B}_s \rangle \;\equiv\; \left(C_{B_s} e^{i\phi_s} - 1 \right) 2 M_{B_s} M_{12}^{\rm SM}$$

$$= -\frac{y_{bs} y_{sb}^*}{M_A^2} \frac{M_{B_s}^4 f_{B_s}^2 B_4}{2(m_b + m_s)^2}$$



$C_{B_s} \approx 1$ **fixed by the measured ΔM_s.**



$A^b_{\rm sl}$ dimuon asymmetry: D0 - 3.2σ; combined with CDF $A^b_{\rm sl}$ and D0 $a^s_{\rm sl}$ measurements, the wrong-charge asymmetry in semileptonic B_s decays is: $a^s_{\rm sl} \approx -(12.7 \pm 5.0) \times 10^{-3}$

$$a^s_{\rm sl} = \frac{2|\Gamma_{12}|}{\Delta M_s} \sin\phi_s \;\Rightarrow\; \sin\phi_s = -2.5 \pm 1.3 \;\Rightarrow\; \phi_s = -O(\pi/2)$$

Time-dependent $B_s \to J/\psi\,\phi$ CP asymmetry: D0 -1.5σ; CDF -0.8σ

Conclusions

The MSSM has been hiding (for over 30 years) a large region of parameter space with distinctive phenomenological implications.

In this "Uplifted region" of the MSSM Higgs sector all fermion masses are generated predominantly by their couplings to H_u.
$\tan\beta > 100$ is a confusing parameter.

The Yukawa coupling of H^0 and A^0 to $\tau^+\tau^-$ is larger than 1.
$\rightarrow$ LHC signals: $bbH^0 \rightarrow bb\tau^-\tau^+$, gluon fusion $\rightarrow H^0 \rightarrow \tau^-\tau^+$,
$bbH^0 \rightarrow bb\mu^-\mu^+$, $b\bar{t}H^+ \rightarrow b\bar{t}\tau^+\nu$, $b\bar{t}H^+ \rightarrow b\bar{t}\mu^+\nu$.

"Uplifted susy" (unlike the usual MSSM) allows an increase in $\mathcal{B}(B^- \rightarrow \tau\nu)$ and a large CP asymmetry in $B_s - \bar{B}_s$ mixing.

Enhancement of $B_s \rightarrow \mu^+\mu^-$ depends on the origin of m_μ (*e.g.*, loops involving messengers), and is correlated with $(g-2)_\mu$.