Constraining the Charged Higgs Mass in the MSSM

A Low-Energy Approach

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Based on arXiv:0901.3337 [hep-ph]
by B. Dudley and CK

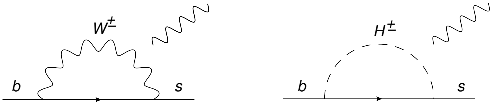
Some similar studies in the literature:

- Domingo and U. Ellwanger, JHEP 0712, 090 (2007) [arXiv:0710.3714 [hep-ph]]
- G. Barenboim, P. Paradisi, O. Vives, E. Lunghi and W. Porod, JHEP 0804, 079 (2008) [arXiv:0712.3559 [hep-ph]]
- D. Eriksson, F. Mahmoudi and O. Stal, JHEP 0811, 035 (2008), [arXiv:0808.3551 [hep-ph]]
- N. Chen, D. Feldman, Z. Liu, P. Nath, Phys. Lett. B685: 174 (2010), [arXiv:0911.0217 [hep-ph]]

Can the charged Higgs of the MSSM be "light"?

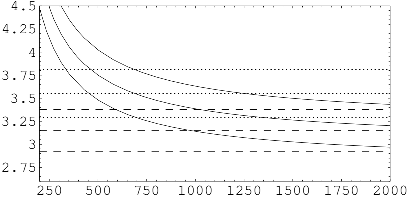
Two major issues inform this question:

- $b \to s\gamma$: The $H^\pm$ contribution adds to $W^\pm$ piece, yielding large correction unless $H^\pm$ is heavy.



In minimal 2-Higgs model, $m_{H^\pm} > 315\,\text{GeV}$ at 99%CL

Gambino et al. '06



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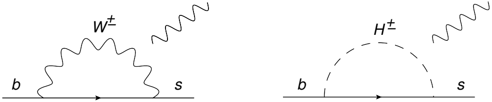

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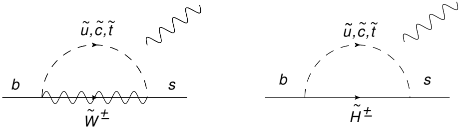
- SUSY Cancellation: SUSY brings other contributions which tend to interfere destructively with above diagrams.



In SUSY limit, magnetic moment transitions cancel completely!

But that's not the whole story . . .

From LEP ($e^+e^- \to H^+H^-$): $m_{H^\pm} > 79\,\mathrm{GeV}$.

Many other constraints on $H^\pm$, including:

- Correlations with SM-like neutral Higgs (h^0)
- $B \to \tau\nu$ and $B \to D\tau\nu$
- $B_s \to \mu\mu$

There are also constraints on the cancellation, through constraints on masses of squarks, winos and higgsinos.

Most of these highly model-dependent, *like the cancellation of the* $b \to s\gamma$ *contributions!*

The goals for this analysis:

- Examine parameters space of minimal SUSY to find regions in which significant cancellation of $b \to s\gamma$ occurs.
- Find a lower bound on $H^{\pm}$ mass consistent with all constraints.
- Correlate the existence of a light $H^{\pm}$ with other SUSY observables.
- Do this analysis without embedding into mSUGRA, CMSSM or any other model for ultraviolet physics $\longrightarrow$ work from the bottom up!

Begin by examining the constraints . . .

Light Higgs Mass Bound

In Standard Model, LEP obtained $m_{h^0} > 114\,\text{GeV}$ from $e^+e^- \to Z^0 h^0$.

In MSSM, bound applies to lightest Higgs when it is SM-like.

BUT, $h^0 \simeq h^0_{SM}$ when m_{A^0} is large:

$$\sigma^{hZ}_{\text{SUSY}} = \sin^2(\beta - \alpha) \times \sigma^{hZ}_{\text{SM}}$$

where

$$\sin^2(\beta - \alpha) = 1 - \frac{m^2_{h^0}\left(m^2_{Z^0} - m^2_{h^0}\right)}{m^2_{A^0}\left(m^2_{H^0} - m^2_{h^0}\right)}.$$

When A^0 is heavy, so is $H^\pm$:

$$m^2_{H^\pm} = m^2_{A^0} + m^2_{W^\pm}$$

Since we want a light $H^\pm$, we want a light A^0 and a (potentially) non-SM-like $h^0 \Longrightarrow$ We must allow for h^0 below LEP bound.

Light Higgs Mass Bound

But one of strongest bounds on $m_{H^\pm}$ will still come from bound on m_{h^0}. Due to sensitivity, we must examine multiple cases:

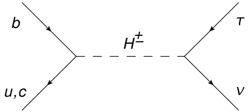
$$
\begin{aligned}
m_h^2 &= m_Z^2 \cos^2 2\beta \left(1 - \frac{3m_t^2}{8v^2\pi^2} \log \frac{M_{\rm SUSY}^2}{m_t^2}\right) \\
&\quad + \frac{3m_t^4}{4v^2\pi^2}\left[\frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right) + \log \frac{M_{\rm SUSY}^2}{m_t^2}\right],
\end{aligned}
$$

with $X_t = A_t - \mu \cot\beta$.

- No-Mixing scenario: Take $X_t = 0$. Minimizes 1-loop contributions to m_{h^0}. Requires heavy stops to lift Higgs mass.
- Max-Mixing scenario: take $X_t = \sqrt{6}M_{\rm SUSY}$. Usually means large A-terms are present.
- "Wee bit o' mixing" scenario: take $A_t = m_{\tilde{t}}/10$ independent of X_t.

Rare B-Decays

The rare decays $B^{\pm} \to \tau\nu$ and $B^{\pm} \to D^0\tau\nu$ can be mediated by $H^{\pm}$ exchange:



For $B^{\pm} \to \tau\nu$:

$$\Gamma(B^{\pm} \to \tau\nu) = \frac{G_F^2 m_B m_\tau^2 f_B^2}{8\pi} |V_{ub}|^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \times r_H$$

where r_H contains the $m_{H^{\pm}}$ dependence:

$$r_H = \left(1 - \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta} \frac{m_B^2}{m_{H^{\pm}}^2}\right)^2 .$$

$B \to \tau\nu$:

Experimental limit expressed as *(HFAG '08)*

$$R_{B\to\tau\nu} = \frac{\mathrm{Br}(B\to\tau\nu)_{\mathrm{exp}}}{\mathrm{Br}(B\to\tau\nu)_{\mathrm{SM}}} = 1.28 \pm 0.38$$

We use 2σ confidence interval on $R_{B\to\tau\nu}$:

$$0.52 < R_{B\to\tau\nu} < 2.04.$$

BUT, f_B and V_{ub} have very large uncertainties at present.

$\Longrightarrow$ This constraint is most important for No-Mixing case.

$B \to D\tau\nu$:

$B \to D\tau\nu$ depends on better known V_{cb}, but detection is experimental challenge thanks to difficult final state. One predicts: *(Kamenik & Mescia '08, Nierste et al '08)*

$$\frac{\mathrm{Br}(B \to D\tau\nu)}{\mathrm{Br}(B \to De\nu)} = (0.28 \pm 0.02) \times \left(1 + 1.38\, Re(C_{NP}) + 0.88\, |C_{NP}|^2\right)$$

where

$$C_{NP} = -\frac{m_b m_\tau}{m_{H^\pm}^2} \frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta}.$$

We compare to BaBar measurement: *(BaBar '07)*

$$\frac{\mathrm{Br}(B \to D\tau\nu)}{\mathrm{Br}(B \to De\nu)} = 0.416 \pm 0.117 \pm 0.052,$$

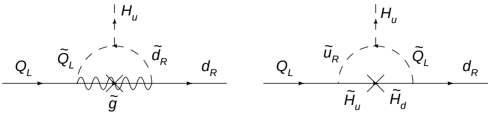
which means, at 2σ:

$$0.151 < \frac{\mathrm{Br}(B \to D\tau\nu)}{\mathrm{Br}(B \to De\nu)} < 0.681.$$

$\Rightarrow$ Plays minor role in constraining these models, *if* we trust $B \to \tau\nu$ calculation.

$B_s \to \mu\mu$: (Babu, CK '99)

At large $\tan\beta$ a powerful probe of SUSY is $B_s \to \mu\mu$, mediated by *neutral* Higgs penguins, through non-holomorphic couplings $\bar{Q}_L d_R H_u^*$



After SUSY-breaking, these generate effective $H_u \bar{d}_R \Delta_u q_L$ coupling:

$$(\Delta_u)_{ij} = y_{d_i} \left(\epsilon_0 \delta_{ij} + \epsilon_Y y_t^2 V_{3i}^* V_{3j} \right)$$

where

$$\epsilon_0 = -\frac{2\alpha_s}{3\pi} \frac{\mu}{m_{\tilde{g}}} H_2(x_{Q/\tilde{g}}, x_{D/\tilde{g}}), \quad \epsilon_Y = \frac{1}{16\pi^2} \frac{A_t}{\mu} H_2(x_{Q/\mu}, x_{U/\mu}),$$

$$x_{Q/\mu} = m_Q^2/\mu^2, \qquad H_2(x,y) = \frac{x \ln x}{(1-x)(x-y)} + \frac{y \ln y}{(1-y)(y-x)}.$$

$B_s \to \mu\mu$:

At large $\tan\beta$:

$$\mathrm{Br}(B_s \to \mu\mu) \simeq 3.5 \times 10^{-5} \left[\frac{\tan\beta}{50}\right]^6 \left[\frac{m_{top}}{m_{A^0}}\right]^4 (16\pi^2\epsilon_Y)^2$$

where

$$16\pi^2\epsilon_Y \approx (A_t/\mu) \times O(1).$$

SM prediction is Cabibbo- *and* helicity-suppressed:

$$\mathrm{Br}(B_s \to \mu\mu)_{\mathrm{SM}} = (3.2 \pm 0.5) \times 10^{-9}.$$

This leaves lots of room for SUSY discovery if $\tan\beta$ is large. Present analysis was done with 2007 CDF limit:

$$\mathrm{Br}(B_s \to \mu\mu)_{\mathrm{exp}} < 5.8 \times 10^{-8}.$$

$B \to X_s\gamma$:

Calculation of $b \to s\gamma$ is well known – won't repeat most details here.

Key points:

- Contributions of $W^\pm$ and $H^\pm$ interfere *constructively,* would push $m_{H^\pm}$ above 300 GeV by themselves.
- Contributions of charginos ($\chi^\pm = \widetilde{W}^\pm, \widetilde{H}^\pm_{u,d}$) can have either sign, but have tendency to cancel against $W^\pm, H^\pm$.
- Contributions of gluinos and neutralinos are generally negligible in minimally flavor-violating models.
- We include contributions due to non-holomorphic interactions $\bar{Q}_L d^R H_u^*$. At leading order these alter relation $m_b = y_b \cos\beta$.

$B \to X_s \gamma$:

Calculation of $b \to s\gamma$ is well known – won't repeat most details here.

Key points:

- We follow NLO calculation of Hurth *et al.* ('03) and Misiak *et al.* ('06) for incorporating long-range effects and calculating $\mathrm{Br}(B \to X_s \gamma)$ from Wilson coefficients.
- Largest source of error is m_c/m_b. We tune this ratio to reproduce the NNLO calculation of $\mathrm{Br}(B \to X_s \gamma) = 3.15 \times 10^{-4}$ in the SM.

Experimental input from HFAG ('08):

$$\mathrm{Br}(B \to X_s \gamma)_{exp} = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$$

We impose 2σ limits:

$$3.03 \times 10^{-4} < \mathrm{Br}(B \to X_s \gamma)_{E_\gamma > 1.6\,\mathrm{GeV}} < 4.06 \times 10^{-4}$$

Other Constraints

We also impose:

- $m_{\chi_1^\pm} > 103\,\text{GeV}$
- $m_{\tilde{t}_1} > 95\,\text{GeV}$
- Tevatron searches for $m_{\tilde{t}_1}$ below $\sim 300\,\text{GeV}$
- Bounds on $\tilde{b}$ and χ^0 have little effect

We do *not* impose constraints on slepton masses, rare lepton decays, dark matter abundances, or anything which requires additional assumptions or parameters.

This is a bottom-up analysis of the MSSM, not the CMSSM or some other UV model. All parameters are treated as parameters in an effective theory.

Other Constraints

Three exceptions:

- Dark matter candidate: We require only that χ_1^0 is the LSP
  $\Rightarrow$ we set M_1 small (60 GeV)
- Minimal Flavor Violation (MFV): We assume that the SUSY flavor problem is solved in a minimal way, such as through degeneracy of the first two squark generations. Then their contributions to all our observables are small
  $\Rightarrow$ set $m_{\tilde{Q}_{1,2}}$ heavy (1 TeV)
- Anomalous magnetic moment of muon: A light SUSY spectrum which cancels against $b \to s\gamma$ will tend to contribute to a_μ unless sleptons very heavy. Currently:

  $$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29.5 \pm 8.8) \times 10^{-10}$$

  Sign of contribution to a_μ determined (almost) entirely by sgn μ. Current discrepancy prefers $\mu > 0$, which we will assume.

Scan over parameter space

Vary $\tan\beta$ over entire perturbative regime.

$\tan\beta$	$1 - 70$
$m_{H^\pm}$	$79 - 315$ GeV
μ	$0 - 1000$ GeV
M_1	60 GeV
M_2	$100 - 500$ GeV
M_3	1000 GeV
$m_{\tilde{q}_3}$	$300 - 1000$ GeV
$m_{\tilde{q}_{1,2}}$	1 TeV
$m_{\tilde{\ell}}$	10 TeV

Scan over parameter space

$m_{H^\pm}$ is *input* parameter.
Allow it down to LEP bound, up to $b \to s\gamma$ "lower bound".

$\tan\beta$	$1 - 70$
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Scan over parameter space

Take $\mu > 0$. Vary up to 1 TeV. Values below $\sim 100\,\text{GeV}$ result in $\chi^{\pm}$ below LEP bound.

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Scan over parameter space

Bino and wino masses not coupled.

Bino kept light to ensure χ^0 is LSP, but plays little role in any other constraint.

Wino mass is important in $b \to s\gamma$, so must be varied.

$\tan\beta$	1 – 70
$m_{H^\pm}$	79 – 315 GeV
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Scan over parameter space

Gluino mass relevant for 2-loop contributions to light Higgs mass. But dependence is weak if gluino heavy, so push it to 1 TeV.

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$m_{H^\pm}$	79 – 315 GeV
μ	0 – 1000 GeV
M_1	60 GeV
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$m_{\tilde{\ell}}$	10 TeV

Scan over parameter space

Three soft masses for 3rd generation ($m^2_{\tilde{Q}}, m^2_{\tilde{u}}, m^2_{\tilde{d}}$) are varied independently down to 300 GeV.

But *very* few points survive for $m_{\tilde{q}} < 500$ GeV.

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Scan over parameter space

Remaining sparticles are pushed up and out of way.

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$m_{\tilde{\ell}}$	10 TeV

Scan over parameter space

All A-terms set to zero except A_t.

A_t set according to Higgs mixing scenario:

No-Mixing:

$$A_t - \mu \cot\beta = 0$$

Max-Mixing:

$$A_t - \mu \cot\beta = \sqrt{6} m_{\tilde{t}}$$

Small A_t:

$$A_t = m_{\tilde{t}}/10$$

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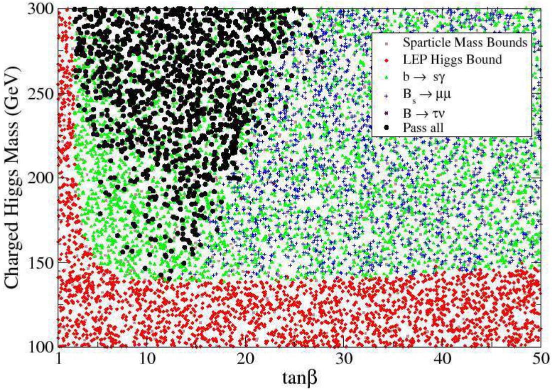
Results: Max Mixing



Low $m_{H^\pm}$ and low $\tan\beta$ excluded by LEP bound on light Higgs

$b \to s\gamma$ excludes points throughout parameter space, but is especially constraining for lighter $H^\pm$

$B \to \mu\mu$ turns on for $\tan\beta > 15 - 20$, killing all points which pass $b \to s\gamma$ constraint

Max-mixing implies larger A_t, which help in cancellation of $b \to s\gamma$ but also generate large $B \to \mu\mu$.

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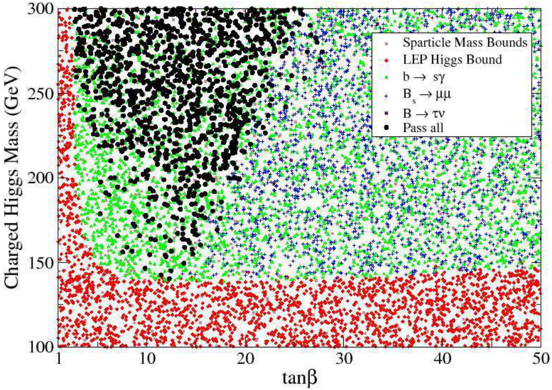

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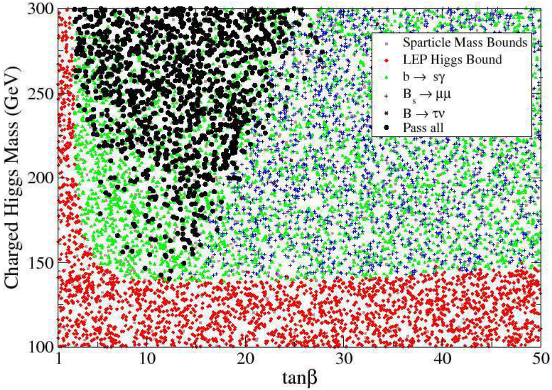

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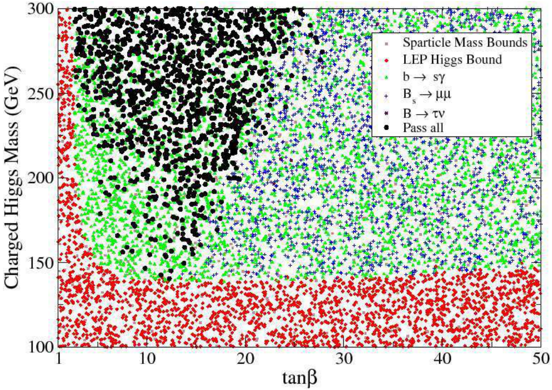

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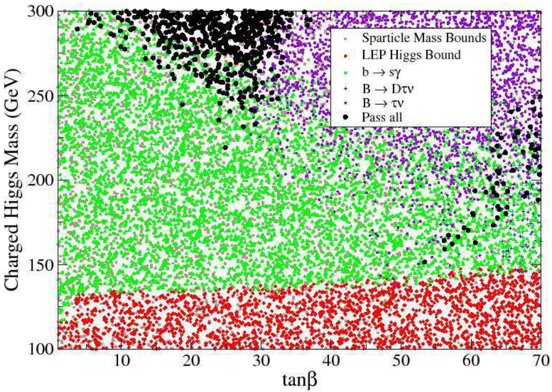
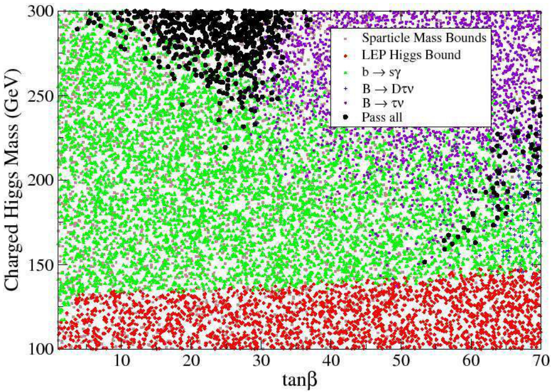


Constraints from light Higgs mass are felt all over parameter space very strongly – we throw out these points except in regions where they completely dominate all other constraints.

Results: No Mixing

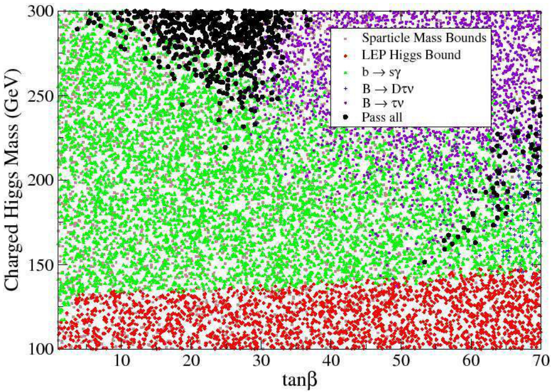


With $A_t \simeq 0$, two effects follow:

Cancellation in $b \to s\gamma$ doesn't work very well. Leading chargino contributions require LR stop mixing.

Br($B \to \mu\mu$) suppressed – not useful constraint for No Mixing case.

Results: No Mixing



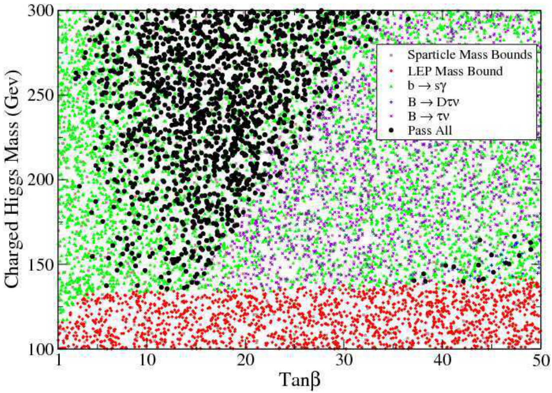
$B \to \tau\nu$ becomes important for moderate to large $\tan\beta$.

To left of excluded region, $H^{\pm}$ contributions are much smaller than usual $W^{\pm}$ pieces.

On the right: $\mathcal{A}(H^{\pm}) \approx -2\mathcal{A}(W^{\pm})$.

No mixing is a very special case, since $A_t \to 0$. What happens for more natural choices?

Results: Small Mixing ($A_t = m_{\tilde{t}}/10$)



Like previous case, light Higgs bound rules out points throughout parameters space, so we only keep it in regions where it is dominant.

But otherwise, picture more similar to Max Mixing case.

$B \to \mu\mu$ not quite as powerful a constraint, but $B \to \tau\nu$ helps to kill off large $\tan\beta$ regime, except for small number of points.

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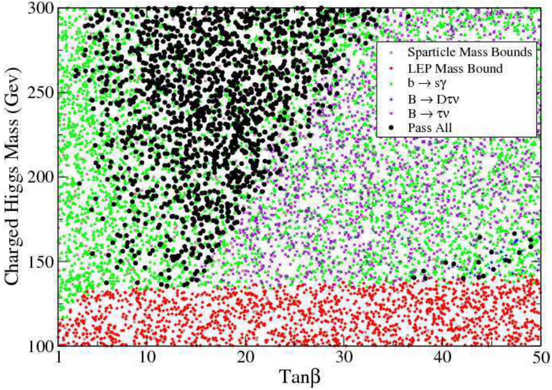

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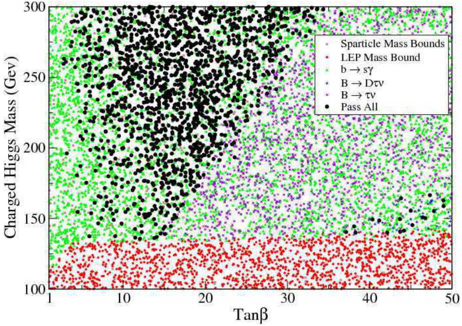
Some General Features



Unless $A_t \simeq 0$, there are two regions in which all constraints are passed:

I. $5 \lesssim \tan\beta \lesssim 30$. In this region one is often on edge of discovery by $B \to \mu\mu$.

II. Scattered points at $\tan\beta \gtrsim 40$, but here the uncertainties in $D \to \tau\nu$ play an important role, and may shift or wipe out allowed points.

Models with $m_{H^\pm}$ down to 140 GeV exist, but are sparse. However, masses above 200 GeV don't seem hard to come by, as some cancellation in $b \to s\gamma$ is fairly generic.

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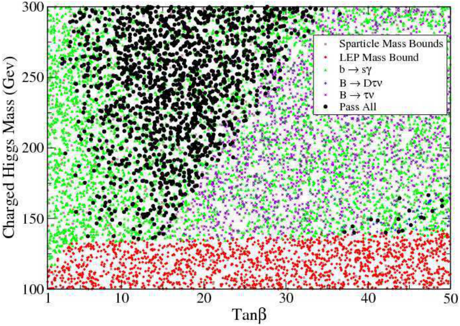

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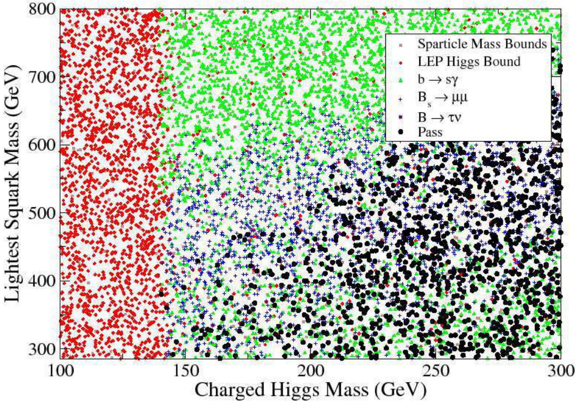
Comments on stop masses

In order to partially cancel $b \to s\gamma$, we need “light” charginos and stops. How light? For Max Mixing scenario:



Stop masses and $H^{\pm}$ masses increase together in lockstep.

Conclusions

A number of analyses have now been completed on parameter space for the charged Higgs in the MSSM, in multiple scenarios (CMSSM/mSUGRA, NUHM, ...). All tend to agree that:

- The charged Higgs can be much lighter than its naive bound from the 2HDM $b \to s\gamma$ calculation.
- Parameter space strongly constrained by flavor observables, and their effects need to be considered when studying specific models (using, *e.g.*, `HiggsBounds` or `SuperIso` packages).
- Parameter space will be strongly limited by any of the following:
  - Increased mass limits on lightest Higgs (no time soon!)
  - Stronger limits on Br($B \to \mu\mu$) (very likely)
  - Better experimental and theoretical understanding of V_{ub}, including smaller error bars on $B \to (D)\tau\nu$. (??)
- If a charged Higgs is found at LHC below 300 GeV we should expect a lot more!