Impact of B Physics on the NMSSM.[1]

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[1] F. Domingo and U. Ellwanger, JHEP12(2007)090, arXiv:0710.3714 [hep-ph].

Outline

1. **Present Status of B Observables**
2. What is the NMSSM?
3. Computation of B observables
4. Remarks on the Behaviour of $BR(\bar{B} \to X_s\gamma)$
5. B constraints on the Parameter Space of the NMSSM

Recent Experimental and SM Achievements on B Physics Observables

$BR(B \to X_s\gamma)$

- Status until 2005:

$$BR(B \to X_s\gamma)|^{exp.}_{E_\gamma>1.6\,GeV} = (3.23 \pm 0.42)\,.10^{-4} \quad \text{Exp. World Average, 2001}$$
$$BR(B \to X_s\gamma)|^{NLO}_{E_\gamma>1.6\,GeV} = (3.61 \pm 0.5)\,.10^{-4} \quad \text{SM NLO prediction, [\textit{Hurth et al.}, 2005]}$$

- Present situation:

$$BR(B \to X_s\gamma)|^{exp.}_{E_\gamma>1.6\,GeV} = \left(3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03\right).10^{-4} \quad \text{Exp. World Average, 2005}$$
$$BR(B \to X_s\gamma)|^{NNLO}_{E_\gamma>1.6\,GeV} = (3.15 \pm 0.23)\,.10^{-4} \quad \text{SM NNLO, [\textit{Misiak et al.}, 2006]}$$
$$BR(B \to X_s\gamma)|^{NNLO}_{E_\gamma>1.6\,GeV} = (2.98 \pm 0.26)\,.10^{-4} \quad \text{SM NNLO, [\textit{Becher, Neubert}, 2006]}$$

(using an improved treatment of the photon energy cutoff)

$\Delta M_d = M_{B_d} - M_{\bar{B}_d}$, $\Delta M_s = M_{B_s} - M_{\bar{B}_s}$

- ΔM_d:

$$\begin{array}{ll} \Delta M_d^{exp} = (0.507 \pm 0.004)\,.ps^{-1} & \text{HFAG, 2005} \\ \Delta M_d^{SM} = (0.59 \pm 0.19)\,.ps^{-1} & \text{SM prediction} \end{array}$$

- ΔM_s:

$$\begin{array}{ll} \Delta M_s^{exp} = (17.77 \pm 0.12)\,.ps^{-1} & \text{CDF, 2006} \\ \Delta M_s^{SM} = (20.5 \pm 3.1)\,.ps^{-1} & \text{SM prediction} \end{array}$$

$BR(\bar{B}_s \to \mu^+\mu^-)$

$$\begin{array}{ll} BR(\bar{B}_s \to \mu^+\mu^-)\big|_{exp} < 5.8 \times 10^{-8}\ \ (95\%C.L.) & \text{CDF, 2007} \\ BR(\bar{B}_s \to \mu^+\mu^-)\big|_{SM} = (3.8 \pm 0.1) \times 10^{-9} & [\textit{Dedes et al.}, 2002] \end{array}$$

$BR(\bar{B}^+ \to \tau^+\nu_\tau)$

$$\begin{array}{llll} BR(\bar{B}^+ \to \tau^+\nu_\tau)\big|_{exp.} = (1.32 \pm 0.49)\,.10^{-4} & \text{HFAG, 2005} & & \\ BR(\bar{B}^+ \to \tau^+\nu_\tau)\big|_{SM} \ \text{from}\ \ (0.85 \pm 0.13)\,.10^{-4} & [\textit{Carena et al.}, 2007] & |V_{ub}|_{excl.} \sim 3.7 \times 10^{-3} \\ \qquad\qquad\qquad\qquad \text{to}\ \ (1.59 \pm 0.40)\,.10^{-4} & [\textit{Isidori, Paradisi}, 2006] & |V_{ub}|_{incl.} \sim 4.4 \times 10^{-3} \end{array}$$

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Supersymmetry (SUSY) at Low Energy (TeV Scale)

Supersymmetry Relates Fermions and Bosons (N=1)

- Chiral superfields (matter) → 1 Complex Scalar Field (A) + 1 Weyl Spinor (ψ):

$$\hat{\Phi} \supset \begin{pmatrix} A \\ \psi \end{pmatrix} \quad ; \quad \hat{\Phi}^+ \supset \begin{pmatrix} A^+ \\ \bar{\psi} \end{pmatrix}$$

- Vector Superfields (gauge) → 1 Weyl spinor (λ) + 1 Vector Field (A^μ): $\hat{V} \supset \begin{pmatrix} \lambda \\ A^\mu \end{pmatrix}$

Physics Beyond the Standard Model (SM) at the TeV Scale

- Hierarchy Problem
- Unification of Gauge Couplings
- Dark Matter
- …

⇒

Low Energy SUSY answers many of these questions.

BUT:

It must be broken near the EW Scale.

Minimal Supersymmetric Models: MSSM and NMSSM

Minimal SuperSymmetric Model (MSSM)

- Global SUSY (N=1) + R-Parity + Gauge Group $SU(3)_c \times SU(2)_L \times U(1)_Y$;
- Minimal Supersymmetric matter content for SM particles:
  1. Three Families of Lepton/Quark Superfields:

$$\hat{L}_L = \begin{pmatrix} \hat{\nu}_L \\ \hat{E}_L \end{pmatrix}, \hat{E}^c_R \, , \; \hat{Q}_L = \begin{pmatrix} \hat{U}_L \\ \hat{D}_L \end{pmatrix}, \hat{U}^c_R \, , \; \hat{D}^c_R .$$

  2. Two Higgs Doublets (Superfields): $\hat{H}_u \, , \; \hat{H}_d$
     coupling respectively to u-like fields and d-like fields;
     Electroweak Symmetry Breaking ⇒ v.e.v.'s v_u, v_d → parameter $\tan\beta \equiv \frac{v_u}{v_d}$.
  3. Vector Superfields for all the gauge groups: $\hat{B} \, , \; \hat{W}^a \, , \; \hat{A}^c$.
- Superpotential: $W = \mu \hat{H}_u . \hat{H}_d + Y_u \hat{Q}_L . \hat{H}_u \hat{U}^c_R - Y_d \hat{Q}_L . \hat{H}_d \hat{D}^c_R - Y_e \hat{L}_L . \hat{H}_d \hat{E}^c_R$
- Soft SUSY Breaking terms…

μ-problem: a Naturalness Problem of the MSSM

- μ : SUSY parameter → Natural Scale: $O(M_{\text{Planck, GUT,}\ldots})$…or Zero!
- LEP Constraints on Chargino masses: $\mu \gtrsim 100\,\text{GeV}$
- Electroweak Symmetry Breaking needs: $\mu \lesssim M_{\text{SUSY}}$

Next-to-Minimal SuperSymmetric Model (NMSSM)

- Additionnal Gauge-Singlet superfield $\hat{S}$
- Superpotential ($\mathbb{Z}_3$ symmetry):
  $$W = \frac{\kappa}{3}\hat{S}^3 + \lambda\hat{S}\hat{H}_u.\hat{H}_d + Y_u\hat{Q}_L.\hat{H}_u\hat{U}_R^c - Y_d\hat{Q}_L.\hat{H}_d\hat{D}_R^c - Y_e\hat{L}_L.\hat{H}_d\hat{E}_R^c$$
- v.e.v. $\langle S \rangle = s \quad \Rightarrow \quad \mu_{eff} = \lambda s$
- + Soft terms…

Particle Content of the NMSSM:

- SM particles: quarks, leptons, gauge bosons;
- Extended Higgs Sector:
  1. 3 neutral scalars: h_1, h_2, h_3;
  2. 2 neutral pseudoscalars: A_1, A_2;
  3. 1 charged scalar: $H^\pm$;
- SUSY particles:
  1. Sfermions: supersymmetric partners (scalar fields) of quarks and leptons;
  2. Charginos (charged fermions): $\chi^\pm_{1,2}$
  3. Neutralinos (neutral fermions): $\chi^o_{1,\ldots,5}$
  4. Gluinos: supersymmetric partners of the gluons.

Phenomenological Advantages of the NMSSM…

The Decoupling Limit

$\lambda \sim \kappa \to 0$: the singlet sector decouples

$\Rightarrow$ Effective MSSM with:

$$\mu_{eff} = \lambda s \sim M_{SUSY} \quad ; \quad B_{eff} = A_\lambda + \kappa s \sim M_{SUSY}$$

Higgs Physics

- **Tree Level Upper Bound on the Lightest Higgs Mass:**

  $$m_{h_1}^2 \leq M_Z^2 \left[\left(\frac{1 - \tan^2\beta}{1 + \tan^2\beta} \right)^2 + \frac{2\lambda^2}{g_1^2 + g_2^2} \frac{4\tan^2\beta}{(1 + \tan^2\beta)^2} \right] \quad ; \quad \lambda(M_{GUT}) < \infty \Rightarrow \lambda(M_Z) \leq 0.7$$

  NMSSM upper bound on the lightest Higgs mass: $m_{h_1} \lesssim 140\,GeV$ (reached at low $\tan\beta$)
- **Light Singlet Higgs Scalar:** very weak coupling to SM particles $\Rightarrow$ INVISIBLE!
  LHC: Lightest Doublet-like Higgs → can be 20 GeV heavier than above.
- **Light Pseudoscalars A_1:** Decay $h_1 \to A_1 A_1$ can be dominant

  $m_{h_1} \lesssim 90\,GeV$ can be consistent with LEP constraints!

CONCLUSION: the NMSSM can escape the Little Hierarchy Problem!

Dark Matter (Neutralino LSP)

New Possibilities compared to the MSSM…

NMSSM specific effects relative to B constraints with respect to the MSSM…

Peculiarities concerning B processes

- Extended Unconstrained Parameter Space: in the NMSSM, low values of $\tan\beta$ (~ 1.5) are not excluded by LEP;
- Charged Higgs Mass: the NMSSM parameter λ gives a negative contribution to $M_{H^\pm}$, which allows for slight modulations on $\bar{B} \to X_s\gamma$;
- The effect of the extended neutralino sector is negligibly small;
- Light pseudoscalars (below 10 GeV) escape LEP constraints, but they are significantly constrained by ΔM_q and $BR(\bar{B}_s \to \mu^+\mu^-)$.

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An Additional Assumption…

Minimal Flavour Violation

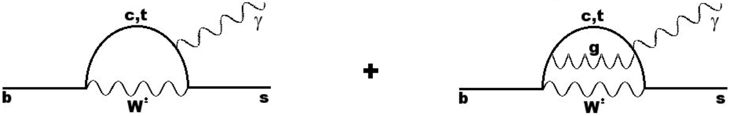
- We assume the only source of Flavor Violation is the Cabibbo–Kobayashi–Maskawa (CKM) matrix.
- Therefore: Quark and Squark mass matrices are simultaneously diagonalized.
- No Flavor Changing Gluino Couplings at Tree Level…

Squark mass matrices in the (SQ_R, SQ_L) base after CKM rotation:

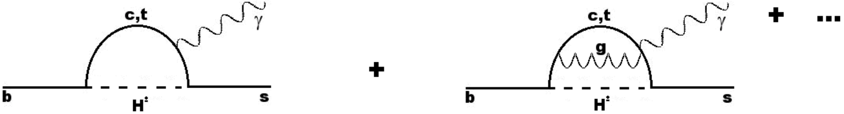
$$M^2_{SQ} = \begin{pmatrix} * & 0 & 0 & 0 & 0 & 0 \\ 0 & * & 0 & 0 & 0 & 0 \\ 0 & 0 & * & 0 & 0 & * \\ 0 & 0 & 0 & * & 0 & 0 \\ 0 & 0 & 0 & 0 & * & 0 \\ 0 & 0 & * & 0 & 0 & * \end{pmatrix}$$

Contributions to $BR(b \to s\gamma)$

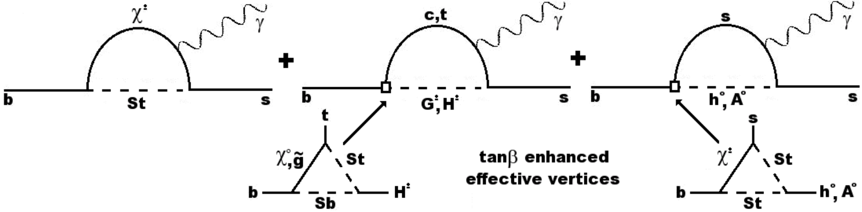
- SM:



- Charged Higgs:



- SUSY particles:



tanβ enhanced effective vertices

$BR(\bar{B} \to X_s\gamma)$: Formalism [*Gambino, Misiak*, 2001]; [*Hurth, Lunghi, Porod*, 2005]

Formula derived in a low-energy Effective Theory (matching scale $\mu_o \equiv m_t$):

$$\begin{aligned} BR(\bar{B} \to X_s\gamma)\Big|_{E_\gamma > E_o} &= \frac{6\alpha_{em}}{\pi C}\left|\frac{V_{ts}^* V_{tb}}{V_{cb}}\right|^2 BR(\bar{B} \to X_c e\bar{\nu}) \\ &\quad \times \left[\left|K_c + \frac{m_b(m_t)}{m_b^{1S}}\,(K_t + K_{BSM}) + \epsilon_{ew}\right|^2 + B(E_o) + N\right] \end{aligned}$$

Quantities Involved:

- $K_c + \frac{m_b(m_t)}{m_b^{1S}}\,(K_t + K_{BSM})$: NLO QCD partonic amplitude for $b \to s\gamma$. Ambiguous dependence at NLO on $\frac{m_c}{m_b} = 0.23\,^{+0.08}_{-0.05}$: SM NNLO results reproduced for $\frac{m_c}{m_b} \simeq 0.307$;
- $BR(\bar{B} \to X_c e\bar{\nu})$: measured experimentally, $\simeq 0.1061$;
- $C = \left|\frac{V_{ub}}{V_{cb}}\right|^2 \frac{\Gamma(\bar{B}\to X_c e\bar{\nu})}{\Gamma(\bar{B}\to X_u e\bar{\nu})}$, calculable $\simeq 0.580$;
- N: Non-Perturbartive corrections (Heavy Quark Effective Theory) $\sim \frac{\Lambda_{QCD}^2}{m_c^2}$ (+ higher orders);
- $B(E_o)$: (gluon) Bremsstrahlung corrections, depends on the lower limit E_o on the photonic energy E_γ. Here: $E_o = 1.6\,GeV$;
- ϵ_{ew}: electroweak radiative corrections;

Calculation of ΔM_q, $q = d, s$

Formula for the Mass difference, [*Buras et al.*, 2003]

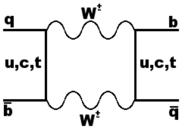
$$\Delta M_q = \frac{G_F^2 M_W^2}{6\pi^2} M_{B_q} \eta_B f_{B_q}^2 \hat{B}_{B_q} \left|V_{tq}^* V_{tb}\right|^2 \left|F_{tt}^q\right|$$

with: $$F_{tt}^q = S_0(x_t) + \frac{1}{4r} C_{new}^{VLL} + \bar{P}_1^{SLL}\left(C_1^{SLL} + C_1^{SRR}\right) + \bar{P}_2^{LR} C_2^{LR} + \ldots$$

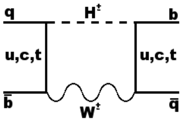
Parameters

- Hadronic parameters (lattice QCD):
  $f_{B_s}\sqrt{\hat{B}_{B_s}} = (0.281 \pm 0.021)\,\mathrm{GeV}$ [*Dalgic et al.*, 2007]
  $f_{B_s}\sqrt{\hat{B}_{B_s}}/f_{B_d}\sqrt{\hat{B}_{B_d}} = 1.216 \pm 0.041$ [*Okamoto*, 2006]
- CKM, from Tree Level measurements [*Ball,Fleisher*, 2006]:
  $|V_{td}^* V_{tb}| = (8.6 \pm 1.4).10^{-3}$
  $|V_{ts}^* V_{tb}| = (41.3 \pm 0.7).10^{-3}$

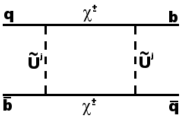
- SM



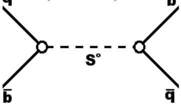
- Charged Higgs



- SUSY



-Neutral Higgs
(effective)



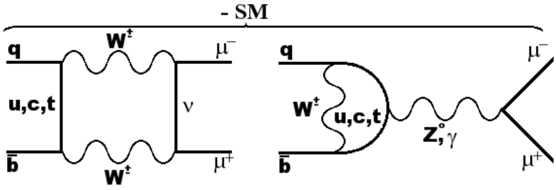
Branching Ratio $\bar B_s \to \mu^+\mu^-$

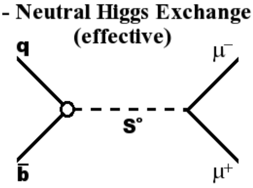
Formula [*Bobeth et al.*, 2002]

$$BR(\bar B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2 M_{B_s}^5 f_{B_s}^2 \tau_{B_s}}{64\pi^3 \sin^4\theta_W}\left|V_{tb}V_{ts}^*\right|^2 \sqrt{1-4\frac{m_\mu^2}{m_{B_s}^2}}\left[\frac{1-4\frac{m_\mu^2}{M_{B_s}^2}}{\left(1+\frac{m_s}{m_b}\right)^2}|c_S|^2 + \left|\frac{c_P}{1+\frac{m_s}{m_b}} + \frac{2m_\mu}{M_{B_s}^2}c_A\right|^2\right]$$

Effective coefficients

- SM contribution in c_A: 1 order of magnitude below the sensitivity of experiments;
- Effective Neutral Higgs contributions in c_S, c_P: enhanced for light scalars/large $\tan\beta$.





Branching ratio $\bar{B}^+ \to \tau^+\nu_\tau$

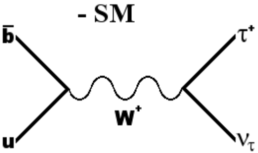
Formula [*Akeroyd, Recksiegel*, 2003]

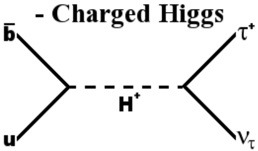
$$BR(\bar{B}^+ \to \tau^+\nu_\tau) = \frac{G_F^2 M_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{M_B^2}\right)^2 f_B^2\, |V_{ub}|^2\, \tau_B\, r_H$$

$$r_H = \left[1 - \left(\frac{M_B}{m_{H^\pm}}\right)^2 \frac{\tan^2\beta}{1+\tilde{\varepsilon}_0 \tan\beta}\right]^2$$

Parameters

- Hadronic parameter: $f_B = (0.216 \pm 0.022)$ GeV, HPQCD, 2005;
- CKM: large uncertainty; we take $|V_{ub}| = (4.0 \pm 0.35).10^{-3}$.





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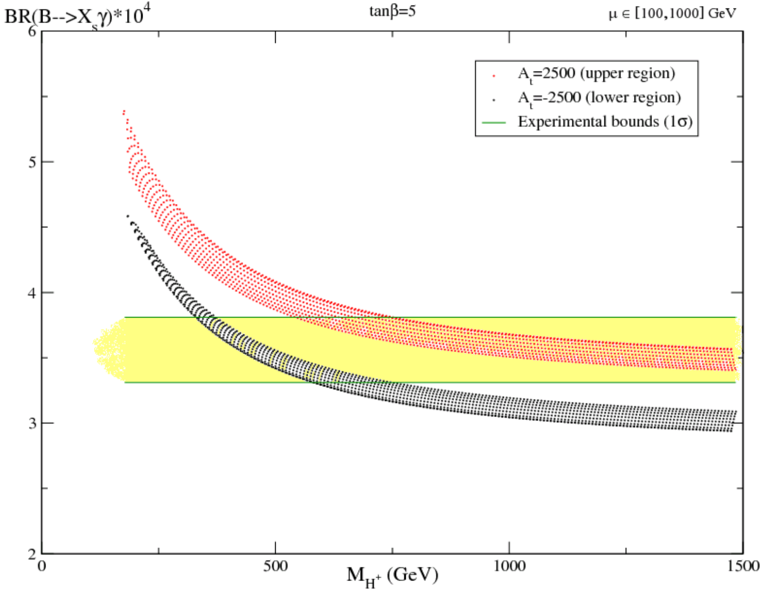
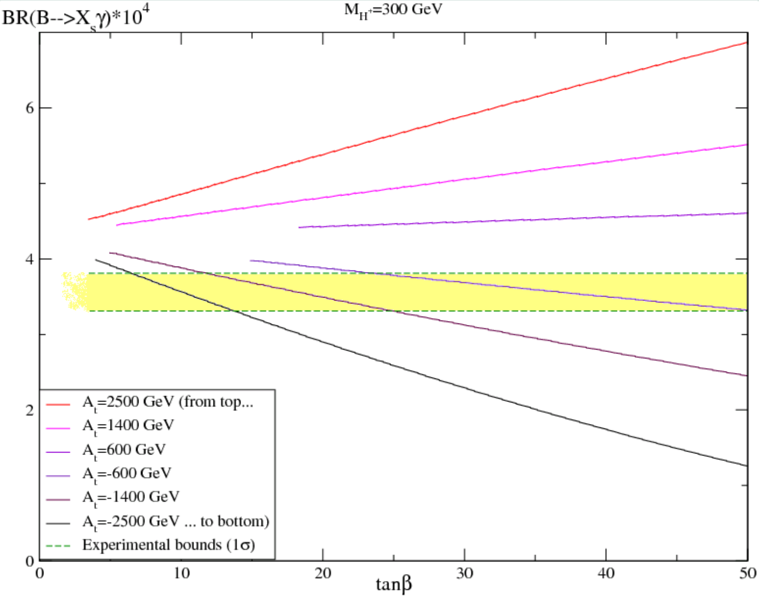
$BR(\bar{B} \to X_s\gamma)$ as a function of $M_{H^\pm}$



$BR(\bar{B} \to X_s\gamma)$ as a function of $\tan\beta$



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Warning!

Uncertainties

To study the relevance of B constraints on the parameter space of the NMSSM:

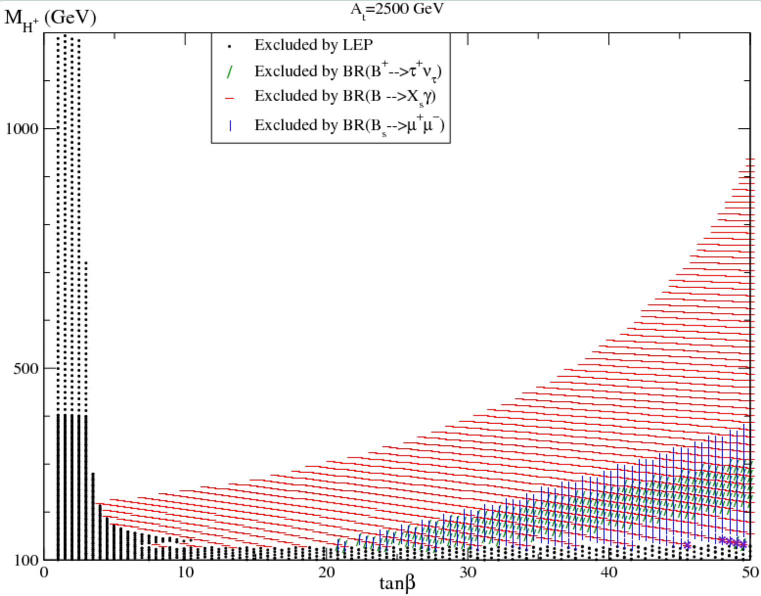
- Experimental error bars have been taken at the 2σ level (Branching Ratios, CKM elements, lattice parameters...);
- Theoretical uncertainties are added linearly.

A Particular Limiting case: Universality

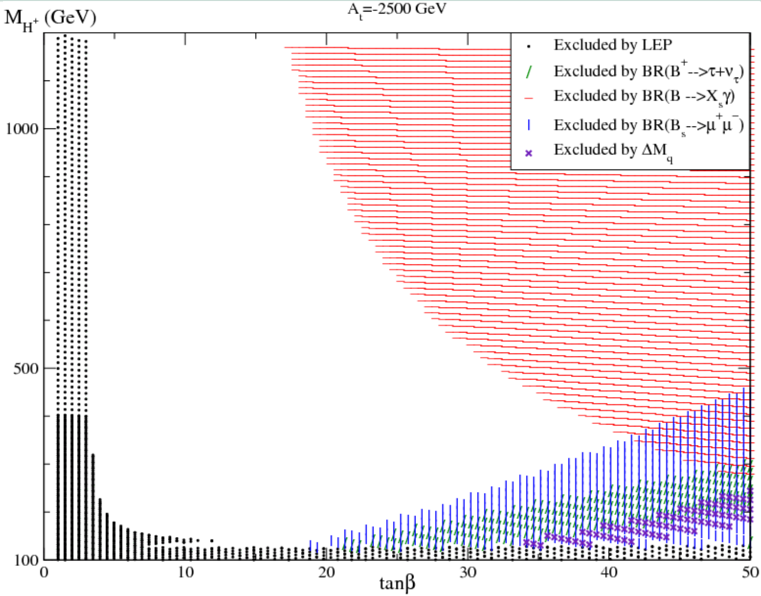
In the following plots, we chose to work with:

- Universal Squark/Slepton soft masses;
- Universal trilinear soft couplings: $A_t = A_b = A_\tau$;
- Hierarchical Gaugino (soft) masses (ratio 1-2-6).

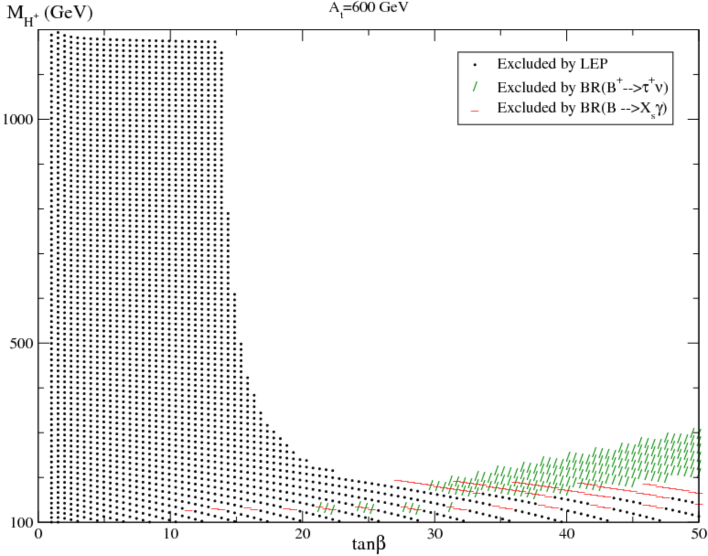
B constraints on the $(M_{H^+}, \tan\beta)$ plane



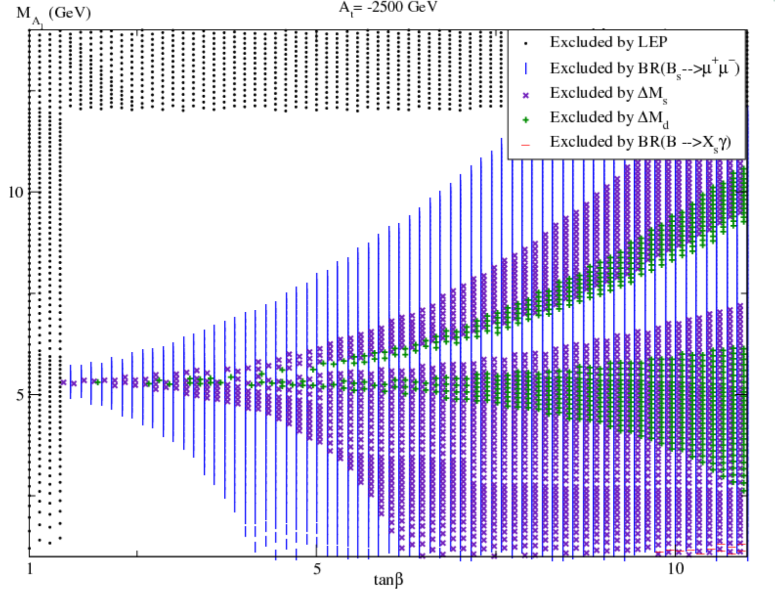
Playing SUSY against Charged Higgs Contribution



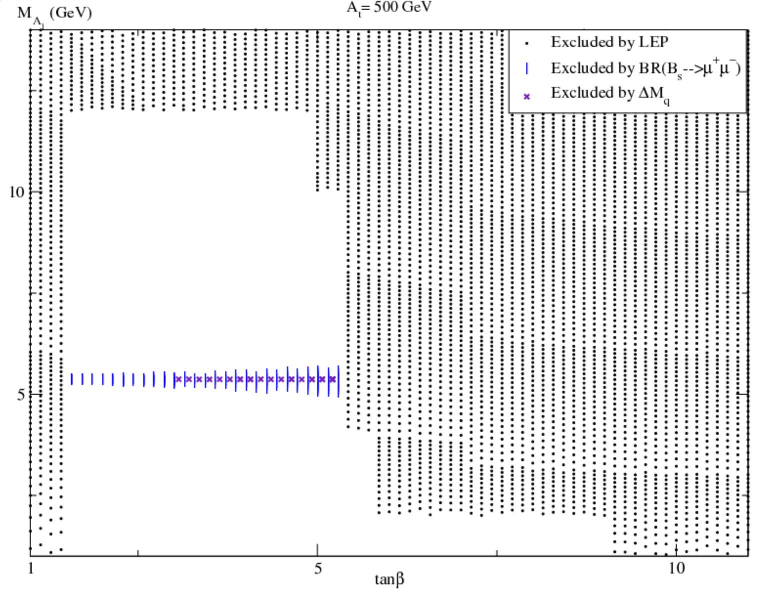
Low values of A_t: weaker B constraints vs enhanced LEP bounds



NMSSM Light Pseudoscalars

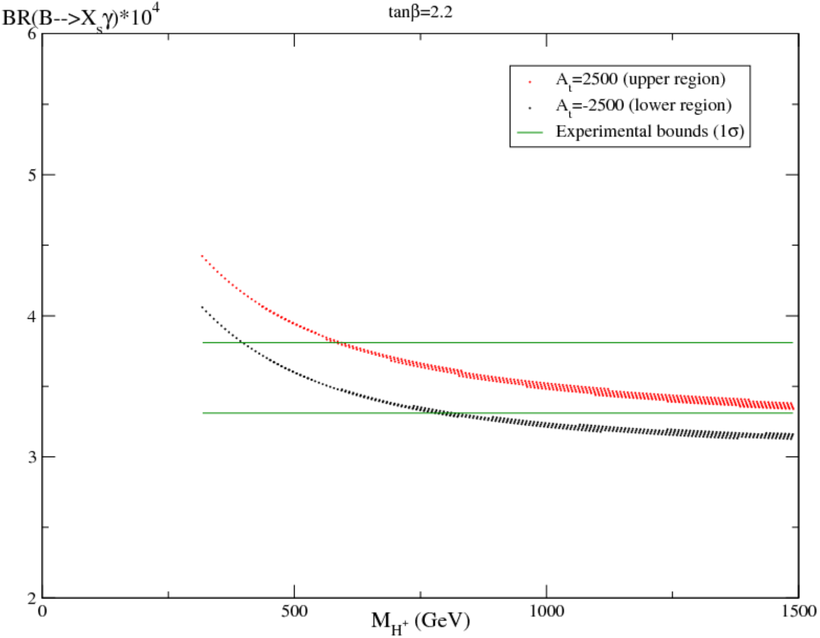


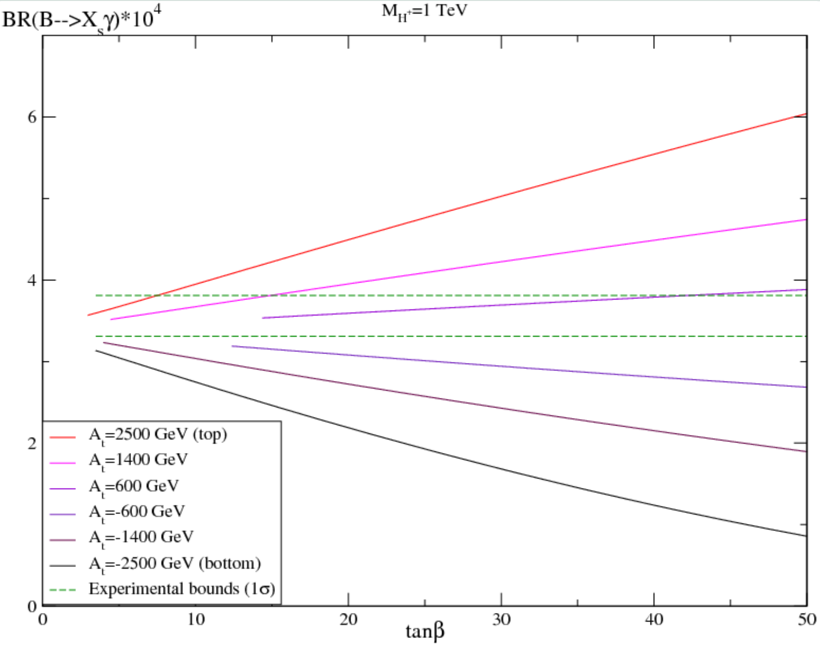
Low A_t


A_t= 500 GeV
M_A1 (GeV)
10
5
1
5
10
tanβ
Excluded by LEP
Excluded by BR(B_s-->μ+μ-)
Excluded by ΔM_q

Conclusions

- Constraints from $\bar{B} \to X_s\gamma$ are weaker than they used to be thanks to the recent improvements on the experimental side and the SM analysis.
- Still, very light ($\leq 200\,GeV$) charged Higgs lead to difficulties for low $\tan\beta$. Domains with both large A_t and large $\tan\beta$ are also strongly constrained.
- $BR(\bar{B}_s \to \mu^+\mu^-)$ is the most sensitive observable depending on neutral Higgs scalar exchanges, provides us with significant constraints especially for light Higgs pseudoscalars.
- The Fortran code is added to the NMSSMTools package (and could also be used for the MSSM…). Such codes for the MSSM: FeynHiggs, Suspect, MicrOmegas, Spheno…


BR(B-->X_sγ)*10^4
tanβ=2.2
A_t=2500 (upper region)
A_t=-2500 (lower region)
Experimental bounds (1σ)
6
5
4
3
2
0
500
1000
1500
M_H+ (GeV)


BR(B-->X_sγ)*10^4
M_H+=1 TeV
6
4
2
0
0
10
20
30
40
50
tanβ
A_t=2500 GeV (top)
A_t=1400 GeV
A_t=600 GeV
A_t=-600 GeV
A_t=-1400 GeV
A_t=-2500 GeV (bottom)
Experimental bounds (1σ)