LOW-ENERGY ASPECTS OF THE PHENOMENOLOGY OF THE NMSSM

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The Next-to-Minimal Supersymmetric Standard Model is a well-motivated singlet extension of the MSSM, liable, e.g., to solve the "μ-problem". A remarkable feature of this NMSSM lies in the possibility of very light CP-odd Higgs states (below the $B-\bar{B}$ threshold). While most of the aspects of the phenomenology of the NMSSM at low energy remain similar to the effects expected in the MSSM, such light particles may lead to significant new contributions. We shall here review a few aspects of the low energy phenomenology of the NMSSM, focussing on rare B decays, muon $(g-2)$ and bottomonium spectroscopy and decays. Special emphasis shall be given to the NMSSM specific effects, associated with a light CP-odd Higgs.

1 Introduction

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) is a singlet-extention of the MSSM [1]. Without spoiling the usual advantages of softly-broken supersymmetric models (with respect to the Hierarchy Problem, Dark Matter or the convergence of gauge couplings), this very simple kind of extension is liable to answer the μ-problem of the MSSM [2]. The so-called μ parameter is a supersymmetric mass term of the MSSM lagrangian. Its natural order of magnitude should thus be that of some very high energy scale, such as the Planck scale, or 0. Both these possibilities are however phenomenologically excluded (requirement for Electroweak Symmetry Breaking / bounds on chargino masses). The necessary requirement $\mu \sim O(1\text{ TeV})$ leads then to a naturalness problem. The basic idea behind singlet-extensions [3] of the MSSM consists thus in generating μ in a similar way as the fermion masses of the Standard Model (SM), that is through the vacuum expectation value of a new (super-)field, a gauge-singlet S: $\mu_{\text{eff}} = \lambda < S >$. The simplest version of this model, known as the NMSSM, has a scale invariant superpotential (imposed through a $\mathbb{Z}^3$ symmetry), so that the only scale involved in the Higgs potential is the supersymmetry-breaking scale [1]. Moreover, several mechanisms may also be used in the Higgs sector to alleviate the Little Fine-Tuning problem:

- The theoretical upper bound on the lightest CP-even Higgs mass receives a specific NMSSM contribution and can be increased with respect to the MSSM limit [4].
- LEP bounds do not apply straightforwardly on the lightest CP-even Higgs state and two mechanisms have been proposed to ensure a phenomenologically realistic "light" CP-even Higgs state. The first possibility consists in a singlet-dominated CP-even state [5] (with reduced couplings to Z-bosons and thus reduced production cross-sections); the second one involves a possibly doublet-like Higgs decaying unconventionally to two light CP-odd Higgs A_1 below the $B-\bar{B}$ threshold, so that these states decay essentially into $\tau^+\tau^-$

(and/or $c\bar{c}$) [6]. This last scenario is however further constrained by a new analysis of ALEPH data [7]. Moreover, in both these cases, a CP-even Higgs around ~ 100 GeV could lead to a succesful interpretation of the $2.3\,\sigma$ excess observed at LEP in $e^+e^- \to Z + b\bar{b}$ [6].

Therefore, one of the interesting feature of the NMSSM phenomenology lies in the possibility of very light CP-odd Higgs states A_1 (possibly lighter than $2\,M_B$). CP-odd particles are indeed difficult to constrain from direct observation, since they have vanishing couplings to gauge bosons. Note that what constraints forbid a light CP-odd Higgs in the MSSM are essentially indirect and originate from relations among the parameters of the MSSM Higgs sector. In the NMSSM however, the CP-odd Higgs sector contains two degrees of freedom, once the Goldstone boson has been removed. At tree-level:

$$\mathcal{M}^2_{\text{CP odd}} = \begin{pmatrix} \frac{2\lambda s(A_\lambda+\kappa s)}{\sin 2\beta} & \lambda v(A_\lambda - 2\kappa s) \\ \lambda v(A_\lambda - 2\kappa s) & -3\kappa s A_\kappa + \frac{\lambda v^2 \sin 2\beta}{2s}(A_\lambda + 4\kappa s) \end{pmatrix} \begin{array}{l} \leftarrow \;\; \text{Doublet} \\ \leftarrow \;\; \text{Singlet} \end{array} \qquad (1)$$

One of them is the usual doublet component whereas the other one is the singlet imaginary part. Singlet fields being mainly unconstrained, this additionnal degree of freedom is sufficient to reach, without specific difficulty, low values for the masses. This scenario is particularly natural in two limits of the Higgs parameter-space of the NMSSM, the R-symmetry [8] (with vanishing trilinear soft terms) and Peccei-Quinn symmetry [9] (with vanishing singlet self-couplings) limits, where the light CP-odd Higgs can be interpreted as the pseudo-Goldstone boson resulting from the spontaneous breaking of these (approximate) symmetries by the Higgs vacuum expectation values. Furthermore, as mentioned before, this light CP-odd state can be associated with a CP-even Higgs below 114 GeV to alleviate the little fine-tuning problem and/or interpret the $2.3\,\sigma$ excess in $e^+e^- \to Z + b\bar{b}$. We stress however that the new ALEPH [7] constraints on $e^+e^- \to Z + (H \to 2A_1 \to 4\tau)$ now restrict this possibility: CP-even doublet masses below 105 GeV can be reached only for reduced branching ratios $A_1 \to \tau^+\tau^-$ (with *e.g.* significant $A_1 \to c\bar{c}$) [6].

Although the consequences of this scenario for the Higgs phenomenology could be significant, the light CP-odd Higgs would yet remain difficult to probe in high-energy collisions. It is therefore particularly interesting to investigate its effects on low-energy observables. There, indeed, the couplings to b-quarks or leptons are related to the quantity $X_d \equiv \cos\theta_A \times \tan\beta$, where $\cos\theta_A$ corresponds to the amount of doublet component in A_1 and $\tan\beta$, to the usual ratio of the doublet vacuum expectation values. Let us stress that this quantity is not necessarily large. However, it can be enhanced for significant values of $\tan\beta$, provided $\cos\theta_A$ does not vanish. In such a case, the couplings to down-type quarks and leptons could lead to observable effects in low-energy observables. In the following sections, we will discuss the NMSSM contributions to B-physics processes [10], $(g-2)_\mu$ [11] and finally bottomonium spectroscopy and decays [12,13], distinguishing between MSSM-like effects and specific NMSSM contributions. Special emphasis will be dedicated to the light CP-odd Higgs scenario.

2 B-Physics in the NMSSM

Rare B decays and mixing are known to be sensitive probes of new-physics. In the following we will consider constraints from $BR(\bar{B} \to X_s\gamma)$, $BR(\bar{B}_s \to \mu^+\mu^-)$, $BR(\bar{B} \to X_s l^+l^-)$, $\Delta M_{d,s}$ and $BR(B^+ \to \tau^+\nu_\tau)$ [10]. All these quantities show a good agreement between SM predictions and experimental measurements (or limits). They dictate thus that the possible new-physics contributions remain comparatively small. Effects from explicit flavour violation by neutral currents in the NMSSM sfermion sector (through soft masses and trilinear couplings) should be comparable to what is expected in the MSSM and strongly constrained by such flavour-changing observables. We will therefore neglect all possibilities for neutral flavour-changing vertices at tree-level, assuming minimal flavour violation, and focus on flavour-changing charged currents.

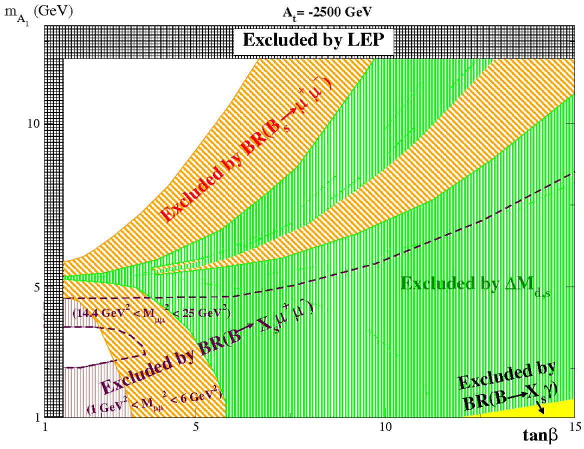

Figure 1: B-physics constraints in the light CP-odd Higgs scenario.

2.1 MSSM-like effects

In softly-broken supersymmetric models, the leading new-physics contributions to $\bar{B} \to X_s\gamma$ originate from charged Higgs/top and chargino/squark loops. The charged Higgs contribution has a positive sign and tends to become large when this particle becomes light. On the other hand, the contribution from supersymmetric particles is enhanced for large values of $\tan\beta$ and of the trilinear soft coupling A_t. It can have both signs and thus interfere constructively or destructively with the charged Higgs effect. All such effects are very similar to what is expected in the MSSM. The main specific effects from the NMSSM intervene either at higher order (additionnal neutralino state, neutral Higgs sector) and are thus small, or have indirect causes (possibility of a slightly displaced charged Higgs mass, accessibility of the low $\tan\beta$ region).

As in the MSSM, $BR(B^+ \to \tau^+\nu_\tau)$ can be mediated at tree-level by a charged Higgs exchange. Note that the large uncertainties on the CKM element V_{ub}, the hadronic decay parameters and the experimental value for this branching ratio limit the impact of this constraint.

2.2 Specific NMSSM effects

The light CP-odd Higgs scenario offers the possibility of enhanced Higgs-penguin diagrams which is the main specific effect: the contribution to 4-fermion operators can be significantly enhanced in regions where the light CP-odd Higgs is exchanged close to its mass shell. Moreover, the effective $b-s-A_1$ vertex, mediated by loops of supersymmetric particles, receives significant enhancement at large $\tan\beta$. The A_1 contribution could then exceed the experimental bounds on $BR(\bar{B}_s \to \mu^+\mu^-)$, $BR(\bar{B} \to X_s l^+ l^-)$ or $\Delta M_{d,s}$, which translates into constraints on the (m_{A_1}, X_d) plane: see Fig. 1. Note however that the $\tan\beta$ enhancement can be reduced when the $b-s-A_1$ vertex is small, *e.g.* for small trilinear soft couplings. Nevertheless, the "pole" regions where the CP-odd Higgs would be exchanged on its mass shell are always excluded, which leaves most of the region $m_{A_1} \lesssim m_B$ severely constrained by $\bar{B} \to X_s l^+ l^-$ and $\bar{B}_s \to \mu^+\mu^-$.

3 Muon Anomalous Magnetic Moment

In this section, we analyse constraints from the muon $(g-2)$ on the NMSSM parameter space [11]. Let us first summarize briefly the current status of this observable. Depending on the experimental source chosen to compute the hadronic contribution to $(g-2)_\mu$ (vacuum polarization diagram), one finds a discrepancy of about $1.9\,\sigma$ (using data from τ-decays to hadrons), $2.4\,\sigma$ (BABAR e^+e^- ISR data), $3.2\,\sigma$ (combined e^+e^- data) or up to $3.7\,\sigma$ (e^+e^- data without BABAR)

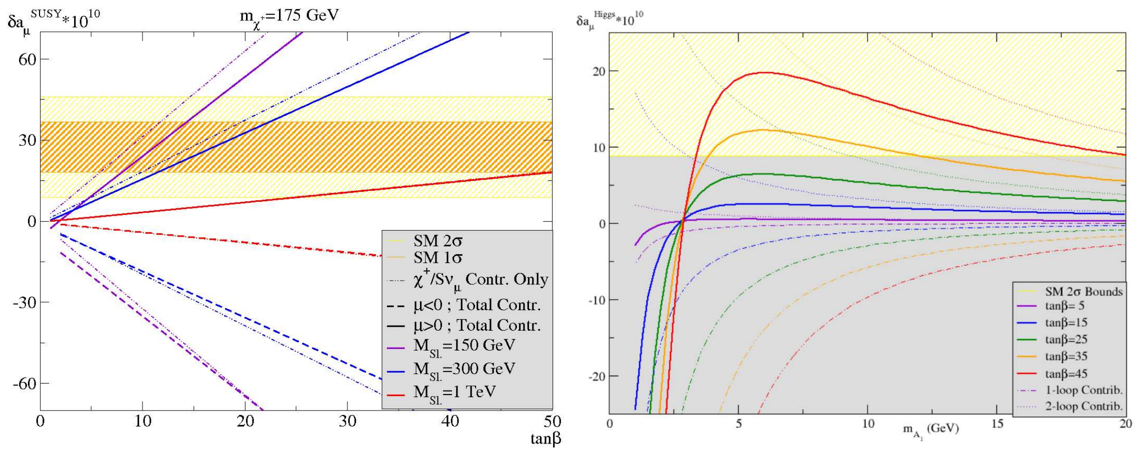

Figure 2: MSSM-like (left) and light CP-odd Higgs (right) contributions to $(g-2)_\mu$.

[14] between the SM prediction and the experimental measurement from BNL laboratory. In the following, we choose to take this signal for new physics seriously by assuming a deviation of about $\sim 3\,\sigma$ and considering whether the NMSSM is able to generate it.

3.1 MSSM-like contributions

As in the MSSM, $(g-2)_\mu$ receives significant contributions from chargino/sneutrino and neutralino/smuon loops. The leading two-loop effects are also taken into account. The chargino diagram depends linearly on $\tan\beta$ and tends to dominate the new-physics contribution. The sign of the deviation between SM and experiment dictates that the $\mu_{(\mathrm{eff})}$ parameter be chosen positive. Then, reaching the experimentally favoured region requires sufficient $\tan\beta$ enhancement or sufficiently light supersymmetric particles, as can be observed in Fig. 2. Light binos can also generate relevant contributions independent on $\tan\beta$. All such effects are however identical in the MSSM and NMSSM, since the decoupling singlino contribution remains small in the NMSSM.

3.2 Light CP-odd Higgs region

Higgs contributions to $(g-2)_\mu$ can be safely neglected in the SM or the MSSM, due to the constraints on masses in this sector. This assumption is yet no longer valid in the light CP-odd Higgs region of the NMSSM: there, both one- and two-loop diagrams must be considered. The resulting contribution depends quadratically on $\tan\beta$ (or, more precisely, on X_d). Below ~ 3 GeV, its sign is opposite to that of the experimental/SM deviation, leading to significant constraints on this region. However, a deviation of the appropriate sign is generated for CP-odd masses beyond ~ 3 GeV, the effect being maximal for $m_{A_1} = 5-7$ GeV. With sufficient $\tan\beta$ enhancement, this contribution can reach the favoured region by itself. It is therefore significant and must be considered along with the MSSM-like effects.

4 Bottomonium physics

Bottomonium states are of particular interest to study the light CP-odd Higgs region, especially in the case of significant $A_1 - b - \bar{b}$ (X_d) coupling.

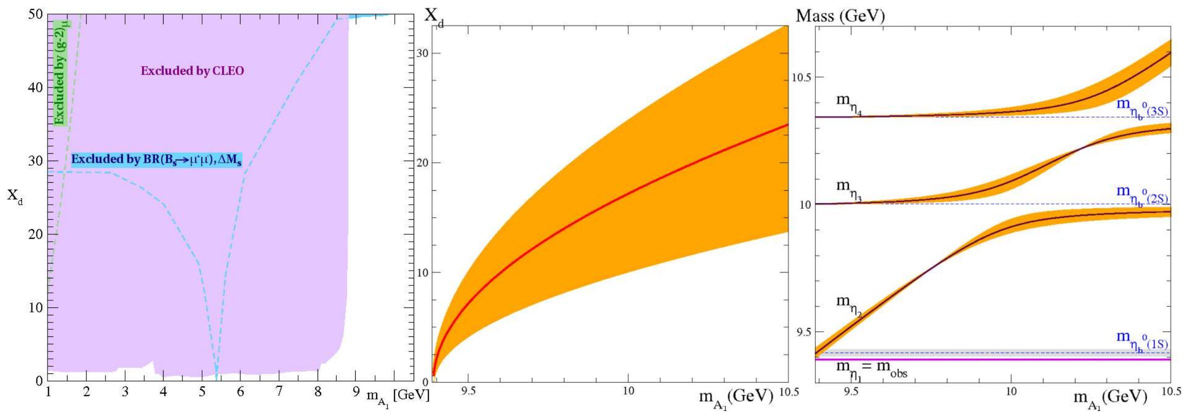

Figure 3: a) Constraints from $\Upsilon \to X_s\gamma$; b) Region favoured by $m_{\eta_b(1S)}$; c) η_b spectrum in this favoured region.

4.1 Bounds from radiative Υ decays

First, the absence of signal for $\Upsilon \to \gamma(A_1 \to \tau^+\tau^-/\mu^+\mu^-)$ at CLEO [15] or BABAR [16] sets constraints on the mass and coupling of the A_1: see Fig. 3a. Essentially all the region below $m_{A_1} \sim 8.8$ GeV is excluded by such bounds, except for $X_d \lesssim 1$[a]. Beyond ~ 8.8 GeV, little can be said however, since the theoretical estimate becomes unreliable (and is expected to vanish for soft photons).

4.2 $A_1 - \eta_b$ mixing

Nevertheless, the region with CP-odd masses around $\sim 9 - 10$ GeV is phenomenologically attractive because significant mixing of the A_1 with the η_b states could take place there [13]. This effect can be taken into account through an effective mass matrix, whose eigenstates are thus admixtures of the pure Higgs and the pure bottomonium CP-odd particles.

A remarkable feature lies in the possibility to use this mechanism to interpret the slight tension between the QCD-predicted [17] and experimentally measured [18] $\eta_b(1S)$ masses[b]. The mixing with the A_1 can indeed generate a mass shift of the appropriate sign, provided the pure A_1 mass is slightly larger than the QCD-predicted η_b mass. A "favoured region", showed in Fig. 3b, can then be determined in the (m_{A_1}, X_d) plane, where the appropriate shift is generated. Along this line, the effect of the (yet unobserved) heavier η_b states must be taken into account, which could lead to significant perturbations of the η_b spectrum (Fig. 3c), with displaced masses and possibly large branching ratios of the heavier states into $\tau^+\tau^-$. Note that the branching ratio of the observed state into $\tau^+\tau^-$ can be calculated exactly and remains safely below the experimental bounds. A future observation of displaced $\eta_b(2S, 3S, \ldots)$ masses or decays into $\tau^+\tau^-$ could then be used as a reliable spectroscopic hint for the light CP-odd Higgs.

4.3 Breakdown of Lepton Universality

Another interesting signal in the bottomonium sector would be a breakdown of lepton universality [12] in inclusive leptonic decays of Υ hadrons. The presence of the CP-odd Higgs could lead to an excess in the tauonic branching fraction, due to the radiative Υ decay mediated by the A_1 (the photon remaining undetected/unlooked for). This signal used to reach the $2\,\sigma$ level but is now further constrained [19]. Moreover, from the theoretical side, $BR(\Upsilon \to \gamma A_1)$ is poorly

[a] Note, however, that $X_d \lesssim 1$ is a natural but difficult-to-test possibility.

[b] The exact discrepancy of the predicted $\eta_b(1S)$ mass (or rather, the hyperfine splitting, $m_{\Upsilon(1S)} - m_{\eta_b(1S)}$) depends on the specific choice of the hadronic model, though most of them predict a heavier mass than the observed one. As a guideline, the perturbative-QCD result is off by about $\sim 2\,\sigma$.

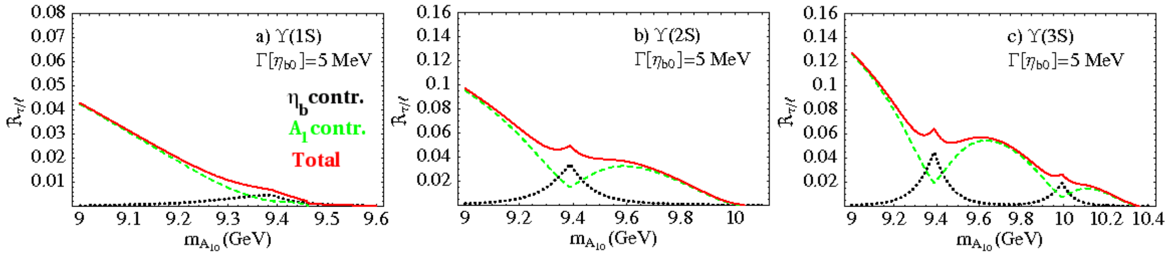

Figure 4: Estimates of the breakdown of lepton universality generated by the A_1.

controlled in the interesting region ($m_{A_1} \sim 9 - 10$ GeV). Under crude assumptions, some estimates for the breakdown of lepton universality due to a CP-odd Higgs are shown in Fig. 4: the corresponding signal could reach up to a few percent.

5 Conclusion

As a solution to the μ-problem and given the new mechanisms at our disposal in the Higgs sector, the NMSSM is a well-motivated extension of the MSSM, leading to several phenomenological improvements. Concerning low-energy observables, the results follow essentially those of the MSSM, except when a light CP-odd Higgs is present. The corresponding specific effects are usually enhanced with large $\tan\beta$ and receive constraints from B-physics bounds on Higgs-penguin contributions. The effect on $(g-2)_\mu$ is also relevant and may alleviate the requirements on the MSSM sector. Finally, this light-A_1 scenario is further constrained and may be probed in bottomonium physics. Note in particular the possible contribution to the $\eta_b(1S)$ mass.

Acknowledgments

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