LIGHT NEUTRALINOS IN B-DECAYS

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ABSTRACT

We consider the decays of a $B_s$-meson into a pair of lightest supersymmetric particles (LSP) in the minimal supersymmetric standard model. It is found that the parameter space for light LSP’s in the range of 1 GeV can be appreciably constrained by looking for such decays.

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The study of B-mesons is hoped to be a rather fruitful adventure in the years to come [1, 2]. B-factories working at the $\Upsilon(4s)$ -resonance can produce upto $10^{7-8}$ $B\bar{B}$ -pairs which are mixtures of $B^0_{\text{d}} \bar{B}^0_{\text{d}}$ and $B^+ B^-$. In addition, if the beams are tuned just above the $B_s$ -threshold, then $B^{0}_{s} \bar{B}^{0}_{s}$ - pairs can be also present copiously among the products. In addition to giving insights into the hadronization of heavy quarks, the various things that B-factories can probe include CP-violation in B-decays, precise determination of the quark mixing matrix and indirect evidence of physics beyond the standard model through loop-induced B-decays.

In this note we want to point out that it is also possible to explore direct signals of non-standard physics through B-decay experiments at least in a certain area of the parameter space. In this context we focus our attention on the supersymmetric (SUSY) extension of the standard model [3]. As we all know, lower limits on the masses of superparticles already exist in the literature. The limits on the squark and the gluino masses as inferred from experiments at the Fermilab Tevatron are especially stringent, ranging upto the 150-200 GeV range [4]. However, because of the necessity to eliminate backgrounds, events with very soft final states as well as those with little missing transverse energy $\not{E}$ have to be left out. Thus a light gluino ($\approx 5$ GeV or less) can still escape detection in such experiments. In such a case, the squarks can directly decay into gluinos whose decay products may be degraded enough to be lost among the backgrounds, thereby relaxing the squark mass limits as well. Thus a window [5], although controversial [6], still exists with the gluino in the 2.5-5 GeV range and the squarks with masses around 70 GeV or above. If the gluino is so light, then according to most viable models the lightest supersymmetric particle (LSP) will have to be even lighter. Various efforts to close this window in direct or indirect ways have gone on in recent times [7]. Side by side, a light gluino has been claimed to be instrumental in causing better agreement between theory and experiment in the evolution of the strong coupling $\alpha_s$ [8]. Together with other attempts to theoretically justify such a scenario (for example, by postulating radiative gaugino masses [9]), the option of light sparticles still remains a matter
of lively interest.

Here we address the following question: in a light sparticle scenario, can a neutral B-meson decay invisibly into a pair of LSP’s? If that indeed be the case, then, provided that a substantial number of such decays in a B-factory is predicted, it will be possible to constrain the SUSY parameter space from the viewpoint of light LSP’s. Since in most models the light LSP is the lightest neutralino, we also limit ourselves to that choice here. Furthermore, such a light LSP is predominantly a photino state, as can be seen, for example, by taking recourse to a SUSY theory motivated by Grand Unified Theories (GUT) \[10\]. In such a case the range in the parameter space that is allowed by LEP experiments and is simultaneously compatible with a light gluino corresponds to $\mu \approx -50$ to $-100$ GeV and $\tan \beta \approx 1.0-1.8$, $\mu$ and $\tan \beta$ being respectively the Higgsino mass parameter and the ratio of the scalar vacuum expectation values. On diagonalisation of the neutralino mass matrix containing parameters in the above range, the LSP turns out to be almost entirely the photino state.

The process of our concern is the decay $B_s \rightarrow \chi_1^0 \chi_1^0$ where $\chi_1^0$ is the LSP. Such an invisible final state has no standard model backgound, since the only candidates for an invisible final state can be the neutrinos whose near-masslessness suppresses the decay from helicity considerations. At the quark level, the SUSY process corresponds to $b \rightarrow s \chi_1^0 \chi_1^0$. Interestingly, such a flavour-changing neutral current (FCNC) process can be allowed at the tree-level \[11\]. This is because the left squark mass matrices are not simultaneously diagonal with the quark mass matrices. For example, in a basis where the charge-1/3 quark mass matrix is diagonal, the charge -1/3 left squark mass matrix is given by

$$M_{Ld}^2 = (m_L^2 \mathbf{1} + m_{\tilde{d}}^2 + c_0 K m_{\tilde{u}}^2 K^\dagger)$$  \hspace{1cm} (1)

where $m_{\tilde{d}}, m_{\tilde{u}}$ are the diagonal down-and up-quark mass matrix respectively, and $K$ is the
Kobayashi-Maskawa matrix. $m_L$ is a flavour-blind SUSY breaking parameter that sets the scale of squark masses. We neglect here left-right mixing among squarks which can potentially contribute to the off-diagonal blocks. The term proportional to $m_u^2$ arises out of quantum corrections to the left-squark masses induced by up-type Yukawa couplings. In a scenario where the SUSY is embedded in a higher structure [12], the evolution of the soft SUSY-breaking terms from the higher scale to the scale of the electroweak symmetry makes such quantum corrections particularly important. Consequently, $M^2_{\tilde{d}}$ is not diagonal in this basis, thereby entailing the occurrence of flavour violation in squark-quark-neutralino (or gluino) interactions. Tree-level graphs (fig. 1) contributing to $B \rightarrow \chi^0_1 \chi^0_1$ originate from this kind of an interaction. The corresponding term in the lagrangian is

$$\mathcal{L}_{\tilde{q}\tilde{q}\chi_i^0} = -\sqrt{2} g \sum_{ij} \bar{q}_j \chi_i^0 \left[ \tan \theta_w e J_{ij2} N_{ij2} \Gamma_{jk} \frac{1 - \gamma_5}{2} \right] q_k + \text{h.c.} \quad (2)$$

where $\Gamma_{jk}$ is the $(jk)$-th element of the unitary matrix that diagonalises $M^2_{\tilde{d}}$ in equation(1). $N$ is the neutralino mixing matrix.

For $b \rightarrow s$, the element $\Gamma_{23}$ is important. Its value depends on $m_t$ and $c_0$. In view of the recent results from the Fermilab Tevatron, we have chosen $m_t = 170$ GeV here. The value of $c_0$ is model independent; however, as recent estimates indicate, a value around 0.01 or slightly above is likely even from a rather conservative point of view [13]. Here we write $\Gamma_{23} = cK_{23}$, where $c$ is a function of $c_0$. Explicit diagonalisation of the squark mass matrix reveals that $c$ lies in the range $\approx 0.5-0.9$ for $c_0 \approx 0.01 - 0.001$. Thus the mixing elements relevant for our purpose are quite close in magnitude to those of the Kobayashi-Maskawa matrix.

Using equation (2) in the limit neutralino $\approx$ photino, the Fierz-transformed quark level matrix element for $b(p_0) \rightarrow s(p_3) \chi^0_1(p_2) \chi^0_1(p_1)$ is given by
\[ M = -\frac{c^2 c V_{23}^2}{18 m_q^2} \left[ \bar{s}(p_3) \gamma^\mu (1 - \gamma_5) b(p_0) \bar{u}(p_1) \gamma_\mu (1 + \gamma_5) v(p_2) - \right. \\
\left. \bar{s}(p_3) \gamma^\mu (1 - \gamma_5) b(p_0) \bar{u}(p_2) \gamma_\mu (1 + \gamma_5) v(p_1) \right] \]  

where \( m_q \) is the common squark mass.

Next, one has to use

\[ \langle 0 | \bar{s} ( \gamma^\mu (1 - \gamma_5) b) | B_s^0 \rangle = f_{B_s} q_\mu \]  

where \( q \) is the four-momentum of the decaying \( B_s \), and \( f_{B_s} \) is the \( B_s \)-decay constant.

The two-body decay-width is given by

\[ \Gamma = \frac{g^4 \sin^4 \theta_w |V_{23}|^2 \left( c^2 f_{B_s}^2 \right)}{216 \pi m_q^4} m^2 \left( m_B^2 - 4 m^2 \right)^{1/2} \]  

\( m \) being the mass of the LSP.

In figure 2 we show the dependence of the branching ratio for \( B \to \chi_1^0 \chi_1^0 \) on the LSP mass. Here we have taken \( m_q = 80 \text{ GeV} \), which is within the allowed region of the parameter space in this scenario. The branching ratio is presented in units of \( c^2 f_{B_s}^2 \).

If one adheres to a scenario inspired by GUT’s, then, provided that the light gluino window is in the 2.5-5 GeV range, one might expect the corresponding window for the light LSP in the range 0.4-1 GeV. If one looks at the graph, then this range corresponds to a branching ratio of \( (10^{-4} - 10^{-5}) c^2 f_{B_s}^2 \text{ GeV}^{-2} \). As we have already remarked, with a heavy top quark the value of \( c \) turns out to be quite close to 1. As for the parameter \( f_{B_s} \), its value, although not completely known yet, can be expected to lie in the range 0.2-0.3 GeV [14]. Depending on this, a branching ratio of \( O(10^{-5} - 10^{-7}) \) can be expected for the invisible
channel. If an accumulation of $10^8$ events takes place in a B-factory, then the number of such decays could be sizable. Moreover, if one wants to free oneself from the shackles of GUT’s and restrict light LSP’s from a phenomenological point of view, then it is possible to put limits in the range of 1-2 GeV as well, since the branching ratio is even higher in that range.

It may be noted here that $B_s$-mesons and not $B_d$’s are going to be useful for the above purpose. This is because for the latter to decay invisibly, contributions have to come at the quark level from $b \rightarrow d \chi_1^0 \chi_1^0$. This decay width would thus be suppressed compared to the $B_s$-decay case by a factor $(K_{td}/K_{ts})^2$.

The experimental problems that one can foresee are perhaps the difficulty of obtaining an accurate estimate of the proportion of the $B_s$-mesons in the admixture of $B^\pm$ and $B^0_d$. For the kinds of decay discussed here, one has to identify one $B_s$ through decay channels such as $D_s \pi$ or $J/\psi \phi$ [15], and look for those cases when the other one in the pair becomes invisible. There again, the question to address is that of separating those events where tagging of one $B_s$ is simply unsuccessful.

In summary, we have considered the contributions to the decay width of a $B_s$-meson from a pair of LSP’s, which can make the $B_s$ invisible. The estimate is model-independent, apart from the introduction of a phenomenological parameter to quantify the extent of neutral flavour violation. The prediction shows the feasibility of imposing independent constraints on the parameter space of light LSP’s. Looking for such invisible decays may thus be an interesting challenge in B-factory experiments.
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Figure Captions

Figure 1:
The tree-level contributions to $b \rightarrow s\chi^0_1\chi^0_1$. In addition there will be crossed diagrams where the four-momenta of the LSP’s are interchanged.

Figure 2:
The branching ratio for invisible $B_s$-decay (in units of $c^2 f_{B_s}^2$) plotted against the LSP mass.

$m_{\tilde{q}} = 80$ GeV.
\[ b \rightarrow \chi_1^0 \]

FIG. 1
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