PHYSICAL REVIEW D VOLUME 52, NUMBER 5 1 SEPTEMBER 1995

Light neutralinos in B decays

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(Received 28 November 1994; revised manuscript received 17 February 1995)

We consider the decays of a B_s meson into a pair of lightest supersymmetric particles (LSP's) 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.

PACS number(s): 14.80.Ly, 12.15.Mm, 12.60.Jv, 14.40.Nd

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 up to 10^7–$10^8 B\bar{B}$ pairs which are mixtures of $B_d^0\overline{B_d^0}$ and B^+B^-. In addition, if the beams are tuned just above the B_s threshold, then $B_s^0\overline{B_s^0}$ pairs also can be present copiously among the products. In addition to giving insight into the hadronization of heavy quarks, the various things that B factories can probe include CP violation in B decays, the precise determination of the quark mixing matrix, and indirect evidence of physics beyond the standard model through loop-induced B decays.

In this Brief Report we want to point out that it is also possible to explore *direct* signals of nonstandard 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 up to the order of 150–200 GeV [4]. However, because of the necessity to eliminate backgrounds, events with very soft final states as well as those with little missing transverse energy $\not{E}_T$ 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 background, 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 effects 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 α_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 this 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. This should be an independent laboratory constraint, in addition to those obtainable from, say, decays of light charginos which often occur in the light LSP scenario. 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's) [10]. In such a case the range in the parameter space that is allowed by experiments at the CERN e^+e^- collider LEP and is simultaneously compatible with a light gluino corresponds to $\mu = -50$ to -100 GeV and $\tan\beta \approx 1.0 - 1.8$, μ and $\tan\beta$ being, respectively, the Higgsino mass parameter and the ratio of the scalar vacuum expectation values. On diagonalization 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 $B_s \to \chi_1^0\chi_1^0$ where χ_1^0 is the LSP. Such an invisible final state has no standard model background, 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 $b \to s\chi_1^0\chi_1^0$. Interestingly, such a flavor-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-$\frac{1}{3}$ quark mass matrix is diagonal, the charge-$\frac{1}{3}$ left squark mass matrix is given by

$$M_{L_d}^2 = (m_L^2 1 + m_d^2 + c_0 K m_{\bar{u}}^2 K^\dagger) , \quad (1)$$

where m_d and $m_{\bar{u}}$ are the diagonal down- and up-quark mass matrices, respectively, and K is the Kobayashi-Maskawa matrix. m_L is a flavor-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 $m_{\bar{u}}^2$ arises out of quantum corrections to the left-squark masses induced by up-type Yukawa cou-

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plings. 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, $M_{L_d}^2$ is not diagonal in this basis, thereby entailing the occurrence of flavor violation in squark-quark-neutralino (or gluino) interactions. Tree-level graphs (Fig. 1) contributing to $B \to \chi_1^0 \chi_1^0$ originate from this kind of an interaction. The corresponding term in the Lagrangian is

$$\mathcal{L}_{q\tilde{q}\chi_i^0} = -\sqrt{2}g \sum_{ij} \tilde{q}_j^\dagger \bar{\chi}_i^0 \left[\tan\theta_w e_j N_{i1} \Gamma_{jk} \frac{1-\gamma_5}{2}\right] q_k + \text{H.c.} , \quad (2)$$

where Γ_{jk} is the (jk)th element of the unitary matrix that diagonalizes $M_{\tilde{d}}^2$ in Eq. (1). N is the neutralino mixing matrix.

For $b \to s$, the element Γ_{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 dependent; 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 $(\Delta m_{\tilde{q}}^2/m_{\tilde{q}}^2)\Gamma_{23} = cK_{23}$, where c is a function of c_0, K is the Kobayashi-Maskawa matrix, and $\Delta m_{\tilde{q}}^2$ is the squark mass square splitting. From rare decays such as $b \to s\gamma$ [14], a value of $|c_0| \approx 0.05$ is allowed for $m_t \approx 175$ GeV and $m_{\tilde{q}} \approx 60$ GeV. For higher $m_{\tilde{q}}$ this constraint gets more relaxed. In such cases Γ_{23} is of the same order of magnitude as K_{23}. Thus for about 1% splitting in squark masses, $c \approx 0.01$ is easily possible. In the present discussion, we have treated c as a free parameter.

Using Eq. (2) in the limit neutralino ≈ photino, the Fierz-transformed quark level matrix element for $b(p_0) \to s(p_3)\chi_1^0(p_2)\chi_1^0(p_1)$ is given by

$$\mathcal{M} = -\frac{e^2 c K_{23}}{18 m_{\tilde{q}}^2} \times [\bar{s}(p_3)\gamma^\mu(1-\gamma_5)b(p_0)\bar{u}(p_1)\gamma_\mu(1+\gamma_5)v(p_2) - \bar{s}(p_3)\gamma^\mu(1-\gamma_5)b(p_0)\bar{u}(p_2)\gamma_\mu(1+\gamma_5)v(p_1)] , \quad (3)$$

where $m_{\tilde{q}}$ is the common squark mass.

Next, one has to use

$$\langle 0|\bar{s}[\gamma^\mu(1-\gamma_5)b]|B_s^0\rangle = f_{B_s} q_\mu \quad (4)$$

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

$$\Gamma = \frac{g^4 \sin^4\theta_w |V_{23}|^2 (c^2 f_{B_s}^2)}{216\pi m_{\tilde{q}}^4} m^2 (m_B^2 - 4m^2)^{1/2} , \quad (5)$$

m being the mass of the LSP.

In Fig. 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 $m_{\tilde{q}} = 80$ GeV, which is within the allowed region of the parameter space in this scenario. The branching ratio corresponding to other values of $m_{\tilde{q}}$ can be obtained from the same graph using Eq. (5) and with appropriate scaling. 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 $(10^{-2}$–$10^{-3})c^2 f_{B_s}^2$ GeV^{-2}. The values of the parameter f_{B_s}, although not completely known yet, can be expected to lie in the range of 0.3 GeV [15]. Depending on this, a branching ratio of $\sim 10^{-3}$–$10^{-4}c^2$ can be expected for the invisible channel. If an accumulation of 10^8 $B\bar{B}$ pairs takes place in a B factory, then the observation (or absence) of such decays could be employed to set limits in the m-c parameter space. Moreover, if one wants to free oneself from the shackles of GUT's and restrict light LSP's from a purely 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.

The large branching ratio of the invisible decay (as compared to other rare decays) makes the question of its experimental observability a rather important issue. For such a decay, one has to reconstruct one B_s in the pair. The reconstruction has to depend upon channels such as $D_s X$, leading to charged particles in the final state. The overall efficiency of such reconstruction, according to current facilities, is $\sim 10^{-3}$ [16]. However, this efficiency can be increased by extending the search techniques to decays such as $B_s \to D_s^{*\pm} X$ [17], taking into account both $\pi^\pm$ and $\rho^\pm$ as products, and also using semileptonic

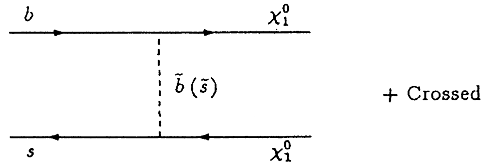

FIG. 1. The tree-level contributions to $b \to s\chi_1^0\chi_1^0$. In addition there will be crossed diagrams where the four-momenta of the LSP's are interchanged.

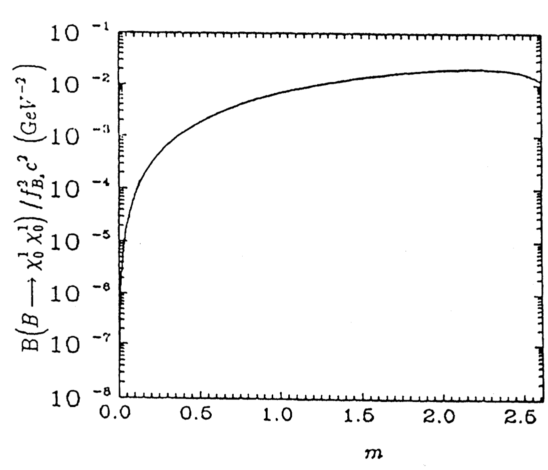

FIG. 2. The branching ratio for invisible B_s decay (in units of $c^2 f_{B_s}^2$) plotted against the LSP mass. $m_{\tilde{q}} = 80$ GeV.

tags. Thus it is possible to envisage an ultimate efficiency of about 10^{-2} [18]. Of course, one has to consider also the possibility of failures in B_s identification, mostly due to disappearance along the beam pipe. Nevertheless, the branching ratio for $B_s \to \chi\chi$ still remains large enough to enable us to constrain the parameter space. It should be reiterated that such constraints are model independent (and not necessarily confined to minimal SUSY). Since $\Upsilon(5S)$ is a copious source of B_s mesons, the above discussion may serve as a pointer to the importance of running B factories at this resonance over a substantial length of time.

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 $b \to d\chi_1^0\chi_1^0$. This decay width is expected to be suppressed compared to the B_s-decay case by a factor $(K_{td}/K_{ts})^2$.

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 flavor 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.

We thank Francois Pierre and Sheldon Stone for useful clarifications, and Amitava Raychaudhuri for some important comments on the manuscript.

[1] S. Stone, in *CP Violation*, edited by C. Jarlskog (World Scientific, Singapore, 1989); *B Decays*, edited by S. Stone (World Scientific, Singapore, 1992); P. Kim, Cornell Report No. CLNS 93/1254, 1993 (unpublished); K. Schubert, in *Proceedings of the 1991 EPS Nuclear Physics Conference on Hadronic Structure and Electroweak Interactions,* Amsterdam, The Netherlands, edited by J. J. Engelen, J. H. Koch, and P. K. A. Dewitt [Nucl. Phys. **A546**, 337c (1992)].

[2] R. Eichler, Paul Scherrer Institute Report No. PSI-PR-88-22, 1985 (unpublished); CLEO Collaboration, Cornell Report No. CLNS-91-1047-Rev, 1993 (unpublished); V. Luth, Report No. SLAC-PUB-6669, 1994 (unpublished).

[3] For reviews, see, for example (a) H. P. Nilles, Phys. Rep. **110**, 1 (1984); (b) H. Haber and G. Kane, *ibid.* **117**, 75 (1985).

[4] F. Abe *et al.*, Phys. Rev. Lett. **69**, 3439 (1992); D. Claes, talk presented at the 8th meeting of the Division of Particles and Fields of the American Physical Society, Albuquerque, NM, 1994 (unpublished).

[5] C. Albajar *et al.*, Phys. Lett. B **198**, 261 (1987); see also Particle Data Group, L. Montanet *et al.*, Phys. Rev. D **50**, 1173 (1994), and references therein.

[6] J. Lopez *et al.*, Phys. Lett. B **313**, 241 (1993); M. Diaz, Phys. Rev. Lett. **73**, 2409 (1994).

[7] P. Tuts *et al.*, Phys. Lett. B **186**, 233 (1987); G. Bhattacharyya and A. Raychaudhuri, Phys. Rev. D **49**, R1156 (1994); C. Carlson and M. Sher, Phys. Rev. Lett. **72**, 2686 (1994); R. Adhikari and B. Mukhopadhyaya, Phys. Lett. B (to be published).

[8] L. Clavelli, Phys. Rev. D **46**, 2112 (1992); J. Blümlein and J. Botts, Phys. Lett. B **325**, 190 (1994).

[9] G. Farrar, Phys. Rev. D **51**, 3904 (1995); G. Farrar and A. Masiero, Rutgers University Report No. RU-94-38, 1994 (unpublished).

[10] L. Hall *et al.*, Nucl. Phys. **B221**, 285 (1983); G. Ross and R. Roberts, *ibid.* **B377**, 571 (1992); L. Ibanez and G. Ross, in *Perspectives on Higgs Physics*, edited by G. Kane (World Scientific, Singapore, 1993).

[11] J. Donoghue *et al.*, Phys. Lett. **128B**, 55 (1983); M. Duncan, Nucl. Phys. **B221**, 285 (1993); A. Bouquet *et al.*, Phys. Lett. **148B**, 69 (1984).

[12] R. Barbieri *et al.*, Phys. Lett. **110B**, 343 (1982); P. Nath *et al.*, Phys. Rev. Lett. **49**, 970 (1992); L. Ibanez and C. Lopez, Nucl. Phys. **B233**, 511 (1984).

[13] J. Hagelin *et al.*, Nucl. Phys. **B415**, 293 (1994).

[14] G. Bhattacharyya and A. Raychaudhuri, Phys. Rev. D **51**, 2433 (1995).

[15] See, for example, M. Neubert, Phys. Rep. **245**, 259 (1994), and references therein.

[16] D. Bortoletto *et al.*, Phys. Rev. Lett. **64**, 2117 (1990); H. Albrecht *et al.*, Z. Phys. C **54**, 1 (1992).

[17] D. Bortoletto and S. Stone, Phys. Rev. Lett. **65**, 2951 (1990).

[18] S. Stone (private communication).