Attempts at explaining the NuTeV observation of dimuon events

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The NuTeV Collaboration has observed an excess in their dimuon channel, possibly corresponding to a long-lived neutral particle with only weak interactions and which decays to muon pairs. We show that this cannot be explained by pair production of neutralinos in the target followed by their decay far downstream in the detector via a LLE R-parity violating operator, as suggested in the literature. In the parameter region allowed by the CERN e^+e^- collider LEP the event rate is far too small. We propose instead a new neutralino production method via B mesons, which can fully explain the observation. This is analogous to neutrino production via π mesons. This model can be completely tested and thus also possibly excluded with NOMAD data. If it is excluded, the NuTeV observation is most likely not due to physics beyond the standard model. Our model can also be tested at the current and future B factories. This opens up a new way of testing for a long-lived neutralino lightest supersymmetric particle at fixed-target experiments and thus the possibility of closing the gap between collider and cosmological tests of R-parity violation. We also discuss a possible explanation in terms of a neutral heavy lepton mixing with the standard model neutrinos. The flavor structure of the observation can be accounted for but the production rate is far too low.

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I. INTRODUCTION

In supersymmetry [1] with broken R parity [2,3] the minimal supersymmetric standard model (MSSM) superpotential is extended by

$$W_{\not R_p}=\lambda_{ijk}\epsilon_{ab}L_i^aL_j^b\overline{E}_k+\lambda'_{ijk}\epsilon_{ab}L_i^aQ_j^b\overline{D}_k+\lambda''_{ijk}\epsilon_{\alpha\beta\gamma}\overline{U}_i^\alpha\overline{D}_j^\beta\overline{D}_k^\gamma + \kappa_i\epsilon_{ab}L_i^aH_u^b. \tag{1}$$

Here L,Q ($\overline{E},\overline{U},\overline{D}$) are the lepton and quark doublet (singlet) left-handed chiral superfields, respectively. $\lambda,\lambda',\lambda''$ are dimensionless coupling constants and $i,j,k=1,2,3$ are generation indices. $a,b=1,2$ and $\alpha,\beta,\gamma=1,2,3$ are $SU(2)_L$ and $SU(3)_c$ gauge indices, respectively. The main phenomenological changes to the MSSM are that the lightest supersymmetric particle (LSP) is no longer stable and supersymmetric particles can be produced singly at colliders. Through resonance production the couplings ($\lambda,\lambda',\lambda''$) can be probed down to about 10^{-3} before the production cross section becomes too small [4–8]. If we consider MSSM supersymmetric pair production with a neutralino LSP then we can typically probe couplings down to 10^{-5} or 10^{-6} [9–12]. For smaller couplings the LSP decays outside the detector and we retrieve the MSSM signatures at colliders. Cosmologically one can exclude lifetimes for the LSP in the range 1 s $<\tau_{\chi_1^0}<10^{17}$ yr [13], which corresponds to couplings $10^{-22}<(\lambda,\lambda',\lambda'')<10^{-10}$. This leaves a gap in experimental sensitivity to the R-parity violating couplings[1] $10^{-10}<(\lambda,\lambda',\lambda'')<10^{-6}$ [2]. Fixed-target experiments with remote detectors can probe significantly longer lifetimes than collider experiments and are thus an ideal environment for closing this gap in sensitivity [14].

The NuTeV Collaboration has searched for long-lived neutral particles (N^0) with mass $M_{N^0}\geqslant 2.2$ GeV and small interaction rates with ordinary matter [15–17]. They look for the decay of the neutral particles in a detector that is 1.4 km downstream from the production point. They observe three $\mu\mu$ events where they expect to see only a background of 0.069 ± 0.010 events. The probability that this is a fluctuation of this specific channel is about 8×10^{-5}, which corresponds to about 4.6σ. The probability for a fluctuation of this magnitude into any of the dilepton channels is about 3σ.

The NuTeV experiment considered in detail the possibility that this discrepancy is due to a N^0 that decays into a three-body final state. In Ref. [16] several kinematic distributions of the dimuon events were checked against the hypothesis of a N^0 with mass 5 GeV: the transverse mass, invariant dimuon mass, and missing p_T distributions all agree well with the N^0 hypothesis. The distribution in the energy asymmetry $A_E\equiv|E_1-E_2|/(E_1+E_2)$ of the three events (E_1 and E_2 are the two observed muon energies in each event) shows a low probability for the N^0 hypothesis. Thus three out of four distributions work very well and, as does the NuTeV Collaboration, we consider it worthwhile to investigate whether this observation could be due to new physics. It is the purpose of this article to consider two possible models which could explain the observation: (i) a light neutralino that decays via R-parity violation and (ii) a neutral heavy lepton (NHL) mixing with the standard model neutrinos.

A search for R-parity violating neutralino decays at NuTeV was proposed in Ref. [14] and the couplings λ_{122} and λ_{133} were discussed. In Refs. [16,17] the NuTeV Collabora-

[1]These coupling values have been determined for a photino LSP of $M_{\chi_1^0}=\mathcal{O}(50)$ GeV and scalar fermion masses of $M_{\tilde f}=\mathcal{O}(100\ \text{GeV})$.

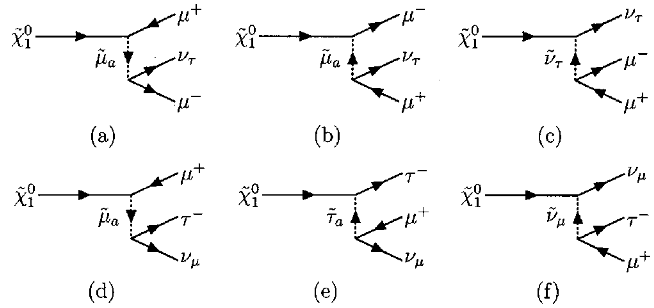

FIG. 1. Neutralino decays through the *R*-parity violating coupling λ_{232}. Diagrams (a)–(c) give rise to dimuon events and diagrams (d)–(f) to tau-muon ones. The index $a=1,2$ denotes the mass eigenstate of the slepton.

tion themselves mention the possibility of *R*-parity violating neutralino decays as a solution to the observed discrepancy, without looking at any specific couplings. In Ref. [15], the NuTeV experiment searched for the neutralino of a very specific model [18]. This neutralino was very light and decayed via $L_1L_2\overline{E}_1$ or $L_1L_3\overline{E}_1$ to an ee final state. Certain supersymmetric parameter ranges were excluded assuming neutralino pair production.

Here we show that the simple scenarios discussed in the literature cannot lead to an excess at NuTeV, since the decisive supersymmetric parameter range to get a significant neutralino production cross section has been excluded by the CERN e^+e^- collider LEP. We propose instead the production of light neutralinos via B mesons, which could give a measurable excess. We briefly present the two possible models and then discuss them quantitatively.

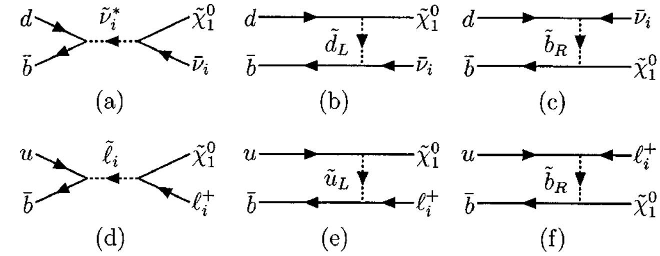

FIG. 2. Neutralino production in B-meson decays: (a)–(c) $B_d^0 \to \overline{\nu_i}\tilde{\chi}_1^0$, and (d)–(f) $B^+ \to l_i^+ \tilde{\chi}_1^0$.

In Sec. V we show that the production rate for neutral heavy leptons is also too low and does not lead to a viable explanation.

II. THE R_p VIOLATING MODEL

The heavy neutral particle we consider is the lightest neutralino $\tilde{\chi}_1^0$, which we also assume to be the LSP. In the no-

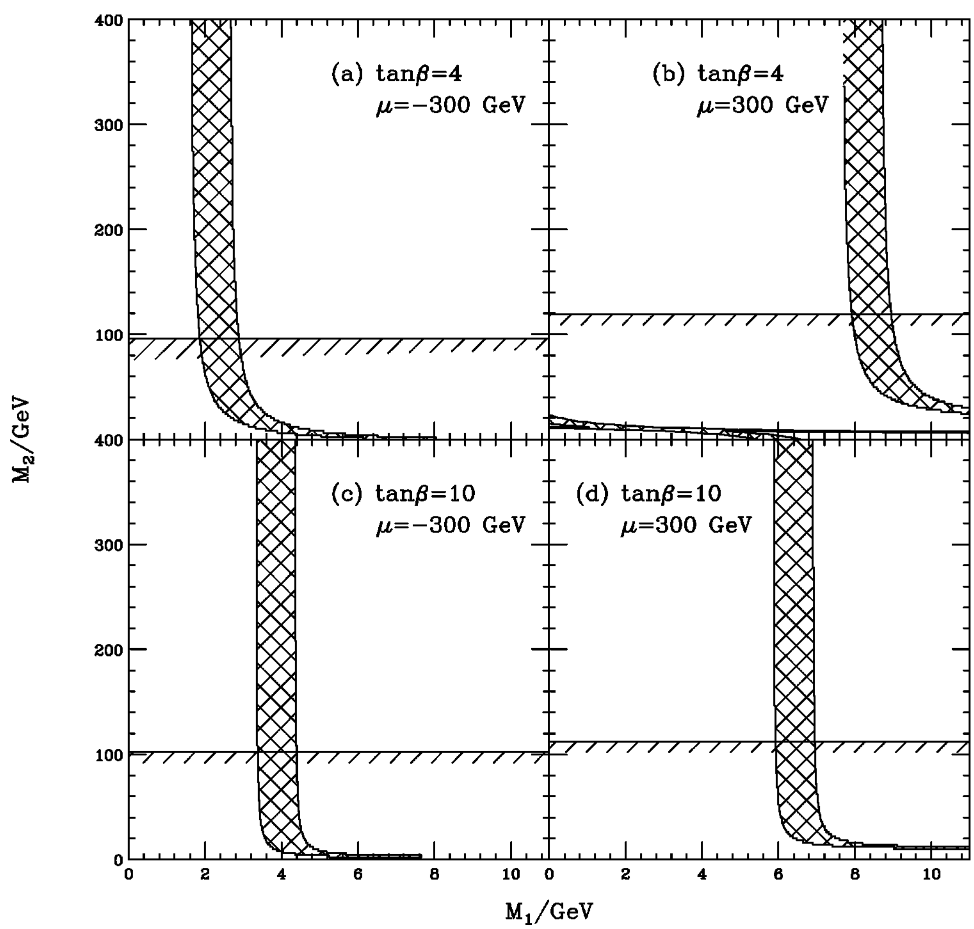

FIG. 3. Solutions in (M_1, M_2, μ, $\tan\beta$) giving 4.5 GeV $\leq M_{\tilde{\chi}_1^0} \leq$ 5.5 GeV in the cross-hatched region. Points below the horizontal hatched line are excluded by the requirement that $M_{\tilde{\chi}_1^+} > 100$ GeV.

tation of [9], the neutralino decays as $\tilde{\chi}_1^0 \to \mathcal{O}_{R_p}$, where $\mathcal{O}_{R_p}$ is the dominant R-parity violating operator. Only two operators give a dimuon signature: $\lambda_{2i2}\epsilon_{ab}L_2^a L_i^b \overline{E}_2$, $i=1,3$. For $i=1$ the neutralino will decay with equal probability to $e\mu\nu$ and $\mu\mu\nu$. No $e\mu$ events are observed; we therefore propose one dominant R-parity violating operator:

$$\mathcal{O}_{R_p} = \epsilon_{ab}\lambda_{232}L_\mu^a L_\tau^b \overline{E}_\mu . \tag{2}$$

For later reference we quote the experimental bound on this operator [19]:

$$\lambda_{232} < 0.070\left(\frac{m_{\tilde{\mu}_R}}{100\ \text{GeV}}\right), \quad (2\sigma). \tag{3}$$

The operator in Eq. (2) corresponds to the two neutralino decay modes (Fig. 1)

$$\tilde{\chi}_1^0 \to \begin{cases} \mu_L^- \mu_R^+ \nu_\tau , \\ \tau_L^- \mu_R^+ \nu_\mu , \end{cases} \tag{4}$$

as well as their complex conjugate, since the neutralino is a Majorana spinor. We shall show below that for a light neutralino the $\tau\mu$ decays are sufficiently phase space suppressed to give an expectation below one event. For the light neutralino production we shall consider two possibilities.

(1) Pair production of the neutralinos [20] which proceeds via (a) s-channel Z^0 boson exchange and (b) t-channel squark exchange.

(2) Single neutralino production in the decay of bottom hadrons. The bottom hadrons are formed following the production of a $b\overline{b}$ pair. These hadrons can then decay via the R-parity violating couplings λ'_{i13} $(i=1,2,3)$. We will consider only the decays of the B_d^0 and B^+ via R-parity violation (Fig. 2):

$$B_d^0 \to \overline{\nu}_i \tilde{\chi}_1^0 , \tag{5}$$

$$B^+ \to l_i^+ \tilde{\chi}_1^0 . \tag{6}$$

This mechanism allows one to produce light neutralinos via a strong interaction process and is analogous to the production of neutrino beams via π's and K's (and D's). A related mechanism was discussed in the context of the Karmen time anomaly [18,21].

For later reference we present the experimental bounds on the λ'_{i13} at 2σ [3,19]:

$$\lambda'_{113} < 0.021\frac{m_{\tilde{b}_R}}{100\ \text{GeV}}, \quad \lambda'_{213} < 0.059\frac{m_{\tilde{b}_R}}{100\ \text{GeV}},$$

$$\lambda'_{313} < 0.11\frac{m_{\tilde{b}_R}}{100\ \text{GeV}} . \tag{7}$$

III. QUANTITATIVE ANALYSIS

As discussed by the NuTeV Collaboration, the mass of the N^0 is roughly 5 GeV. The constraints on a very light neutralino were discussed in detail in Ref. [18]. We expect them to mainly carry over to the present mass region [22]. In order to get an $M_{\tilde{\chi}_1^0} = \mathcal{O}(5\ \text{GeV})$ neutralino and avoid the LEP bounds we must consider the case where the electroweak gaugino masses M_1, M_2 are independent parameters. In Fig. 3 we show the MSSM parameter space that corresponds to $M_{\tilde{\chi}_1^0} = 5 \pm 0.5$ GeV for two values of $\tan\beta$ and sgn μ. The composition of the neutralino is more than 99% B-ino, provided the lightest chargino mass is greater than 100 GeV.

The dominant B-ino nature of the LSP has immediate implications for pair production of neutralinos. The B-ino does not couple to the Z^0 boson and thus the s-channel pair production of the B-ino is negligible. This leaves only the t-channel production, which is proportional to $M_{\tilde{q}}^{-4}$ and thus strongly suppressed. We shall quantify this below.

In both cases neutralino production is followed by the decay. The matrix elements for the decay via R_p were given in [23,11]. As the neutralino in our model will be much lighter than the sleptons ($M_{\tilde{l}} \gtrsim 90$ GeV from LEP) it is sufficient to neglect the momentum flow through the slepton propagators. For a purely B-ino neutralino in this limit the spin averaged matrix element is given by

$$\begin{aligned}
|\overline{\mathcal{M}}|^2(\tilde{\chi}_1^0 \to \overline{\nu}_i l_j^+ l_k^-) &= \frac{g'^2\lambda_{ijk}^2}{4}\left[\frac{Y_{\nu_i}^2}{M_{\tilde{\nu}_i}^4}(m_{l_j l_k}^2 - m_{l_j}^2 - m_{l_k}^2)(M_{\tilde{\chi}_1^0}^2 - m_{l_j l_k}^2) \right. \\
&- 2\frac{Y_{\nu_i}Y_{l_{jL}}}{M_{\tilde{\nu}_i}^2 M_{\tilde{l}_{jL}}^2}(m_{\nu_i l_k}^2 m_{l_j l_k}^2 - M_{\tilde{\chi}_1^0}^2 m_{l_k}^2) \\
&+ \frac{Y_{l_{jL}}^2}{M_{\tilde{l}_{jL}}^4}(m_{\nu_i l_k}^2 - m_{l_k}^2)(M_{\tilde{\chi}_1^0}^2 + m_{l_j}^2 - m_{\nu_i l_k}^2) \\
&+ 2\frac{Y_{\nu_i}Y_{l_{kR}}}{M_{\tilde{\nu}_i}^2 M_{\tilde{l}_{kR}}^2}(m_{\nu_i l_j}^2 m_{l_j l_k}^2 - M_{\tilde{\chi}_1^0}^2 m_{l_j}^2) \\
&+ \frac{Y_{l_{kR}}^2}{M_{\tilde{l}_{kR}}^4}(m_{\nu_i l_j}^2 - m_{l_j}^2)(M_{\tilde{\chi}_1^0}^2 + m_{l_k}^2 - m_{\nu_i l_j}^2) \\
&\left. + 2\frac{Y_{l_{jL}}Y_{l_{kR}}}{M_{\tilde{l}_{jL}}^2 M_{\tilde{l}_{kR}}^2}(m_{\nu_i l_j}^2 m_{\nu_i l_k}^2 - m_{l_j}^2 m_{l_k}^2) \right].
\end{aligned} \tag{8}$$

Here Y_f is the hypercharge of the field f and $m_{f_i f_j} = (f_i + f_j)^2$ is the invariant mass of the f_i, f_j pair of fields. This matrix element can be simplified by assuming a common sfermion mass $M_{\tilde{f}}$ and by putting in explicit values for the couplings:

$$\begin{aligned}
|\overline{\mathcal{M}}|^2(\tilde{\chi}_1^0 \to \overline{\nu}_i l_j^+ l_k^-) &= \frac{9g'^2\lambda_{ijk}^2}{4M_{\tilde{f}}^4}(M_{\tilde{\chi}_1^0}^2 + m_{l_k}^2 - m_{\nu_i l_j}^2) \\
&\times (m_{\nu_i l_j}^2 - m_{l_j}^2).
\end{aligned} \tag{9}$$

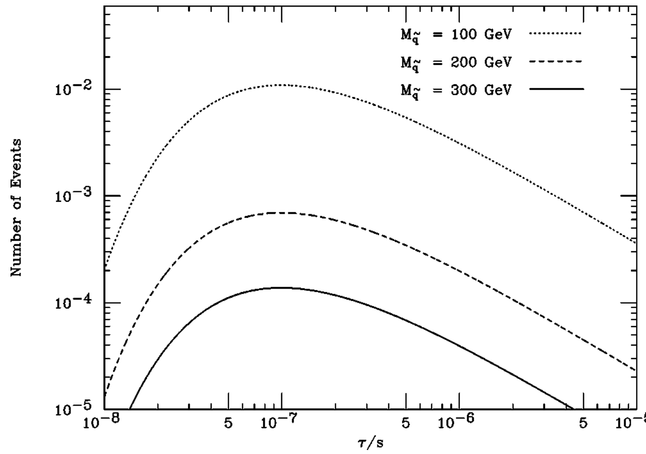

FIG. 4. Number of events in the NuTeV detector for neutralino pair production as a function of the neutralino lifetime.

In the analysis of Refs. [16,17] the model for the heavy neutral lepton decay studied was based on a weak decay matrix element [24]

$$\mathcal{M}(N^0 \to \nu_i l_j^- l_k^+) = \frac{G_F}{\sqrt{2}} \overline{u}_{N^0} \gamma^\mu (1-\gamma_5) u_{l_j} \overline{v}_{l_i} \gamma_\mu (1-\gamma_5) u_{\nu_i}. \tag{10}$$

If we compute the squared amplitude and average over the spin of the incoming heavy lepton we obtain

$$|\overline{\mathcal{M}}|^2 (N^0 \to \nu_i l_j^- l_k^+) = 16 G_F^2 (m_{N^0}^2 + m_{l_k}^2 - m_{\nu_i l_j}^2)(m_{\nu_i l_j}^2 - m_{l_j}^2). \tag{11}$$

So the distribution of the decay products from the R-parity violating decay will be exactly the same as the weak decay matrix element studied in [16,17] and therefore this model has exactly the same problem with the energy asymmetry A_E as that discussed in [16,17].

A. Neutralino pair production

We simulated neutralino pair production using HERWIG 6.2 [25–27].[2] This allows us to simulate the production cross section with the correct momentum spectrum for the neutralinos and to determine whether they can decay within the NuTeV detector. Those events where the neutralino could decay in the detector were weighted with the probability that the neutralino decayed in the detector, for a given lifetime:

$$\mathcal{P} \approx \exp\left\{ -\frac{l}{\beta\gamma c \tau_{\chi^0}} \right\} \frac{\Delta x}{\beta\gamma c \tau_{\chi^0}}, \tag{12}$$

where $l = 1.4$ km is the distance target-detector, $\Delta x = 28$ m is the length of the detector, βc is the speed of the neutralino, and $\tau_{\tilde{\chi}^0}$ is its lifetime. The neutralino was furthermore decayed with the full R-parity violating (RPV) matrix element [23,29]. We then applied the NuTeV kinematic cuts [17] on the neutralino decay products. We required that the neutralinos decay within the fiducial volume[3] $(2.54 \times 2.54 \times 28)$ m^3 of the NuTeV detector at a distance 1.4 km downstream of the production target. The muons produced in the neutralino decay were required to have energy $E_\mu > 2.2$ GeV and the transverse mass $m_T = |P_T| + \sqrt{P_T^2 + M_V^2} > 2.2$ GeV, as in Refs. [15–17]. Here P_T and M_T are the transverse momentum and mass of the visible decay products, respectively.

As the production of a B-ino occurs only via t-channel squark exchange, the cross section will depend on the (assumed degenerate) squark mass as $\sim 1/M_{\tilde{q}}^4$. The number of events that would be observed in the NuTeV detector is given in Fig. 4 as a function of the lifetime of the neutralino. Given the current limits on the squark mass from both LEP [30–33] and the Tevatron [34,35] it is impossible, for any neutralino lifetime, to get sufficient events to explain the NuTeV results via neutralino pair production. In Ref. [14] the LEP constraints on the MSSM parameter space were not taken into account.

B. Neutralino production in *B*-meson decays

As with the neutralino pair production we used HERWIG to simulate $b\overline{b}$ production. One of the B mesons produced was then forced at random to decay via RPV. The overall normalization was properly taken into account. The partial widths for the decays of the B_0 and B^+ via RPV are given by

$$\begin{aligned}\Gamma(B_d^0 \to \overline{\nu}_i \tilde{\chi}_1^0) &= \frac{\lambda'^2_{i13} f_B^2 m_{B^0}^2 p_{cm}}{16\pi (m_d + m_b)^2} \left[\frac{L_{\nu_i}}{M_{\tilde{\nu}_i}^2} - \frac{L_d}{2M_{\tilde{d}_L}^2} - \frac{R_b^*}{2M_{\tilde{b}_R}^2} \right]^2 \\ &\quad \times (M_{B^0}^2 - M_{\tilde{\chi}_1^0}^2) \\ &= \frac{9\lambda'^2_{i13} g'^2 f_B^2 m_{B^0}^2 p_{cm}}{256\pi (m_d + m_b)^2 M_{\tilde{f}}^4} (M_{B^0}^2 - M_{\tilde{\chi}_1^0}^2),\end{aligned} \tag{13}$$

$$\begin{aligned}\Gamma(B^+ \to l_i^+ \tilde{\chi}_i^0) &= \frac{\lambda'^2_{i13} f_B^2 m_{B^+}^2 p_{cm}}{8\pi (m_u + m_b)^2} \left[\frac{L_{l_i}}{M_{\tilde{l}_i}^2} - \frac{L_u}{2M_{\tilde{u}_L}^2} - \frac{R_b^*}{2M_{\tilde{b}_R}^2} \right]^2 \\ &\quad \times (M_{B^+}^2 - m_{l_i}^2 - M_{\tilde{\chi}_1^0}^2) \\ &= \frac{9\lambda'^2_{i13} g'^2 f_B^2 m_{B^+}^2 p_{cm}}{128\pi (m_u + m_b)^2 M_{\tilde{f}}^4} (M_{B^+}^2 - m_{l_i}^2 - M_{\tilde{\chi}_1^0}^2),\end{aligned} \tag{14}$$

[2]One modification to HERWIG was made in that we used the average of the central and higher gluon parton distribution functions from the leading-order fit of [28]. This will become the default in the next release of HERWIG.

[3]In the original version of our paper this number was smaller as found in [46]. We thank T. Adams for drawing our attention to the corrected value in the published version [17].

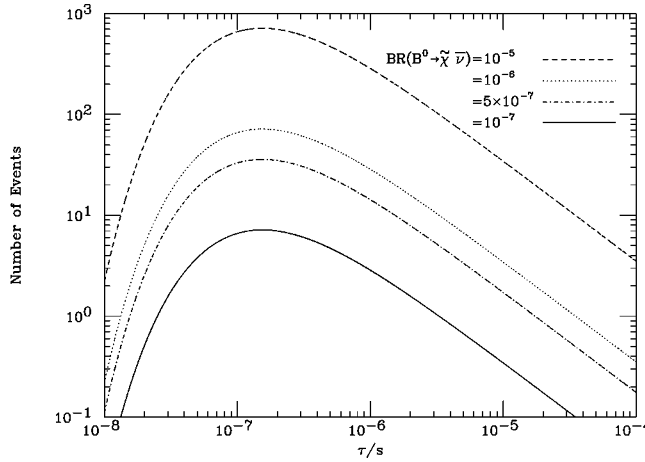

FIG. 5. Number of events in the NuTeV detector for neutralino production in *B*-meson decays as a function of the neutralino lifetime.

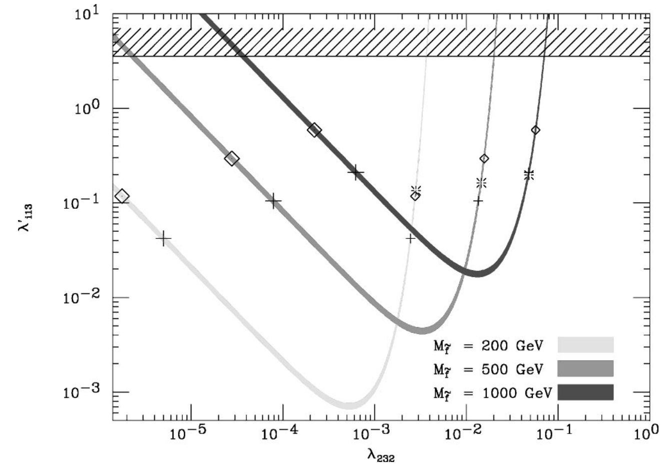

FIG. 6. Regions in $\lambda_{232},\lambda'_{i13}$ parameter space in which we would expect 3 ± 1 events to be observed in the NuTeV detector. The limits from [3,19] on the couplings λ'_{113} (crosses) and λ'_{213} (diamonds) allow solutions between the two points for each of the masses shown. The region above the stars is ruled out for the coupling λ'_{213} by the limit on the product of the couplings $\lambda_{232}\lambda'_{213}$ from the limit on the branching ratio $B^+\to\mu^+\nu$ [36]. The hatched region shows the experimental bound on the coupling λ'_{i13} from perturbativity. The corresponding limits on the coupling λ_{232} from both low-energy experiments [3,19] and perturbativity are not shown as our solutions do not extend into this region.

where p_{cm} is the momentum of the decay products in the rest frame of the decaying meson, $m_{u,d,b}$ are the up, down, and bottom quark masses, respectively, m_{B^0} is the B^0 mass, and m_{B^+} is the B^+ mass. Here $L_f=-g'Y_{f_L}/2$ for the left-handed fermions and $R_f=g'Y_{f_R}/2$ for the right-handed fermions. f_B is the pseudoscalar decay constant for B decays, $M_{\tilde\chi_1^0}$ is the lightest neutralino mass, $M_{\tilde d_L}$ is the left down squark mass, $M_{\tilde u_L}$ is the left up squark mass, and $M_{\tilde b_R}$ is the right bottom squark mass. In Eqs. (13) and (14) we have assumed that the sfermions have a common mass $M_{\tilde f}$. The pseudoscalar decay constant for the B system has not been measured experimentally and must be taken from lattice QCD. We have used the value

$$f_B=204\pm30\ \ \text{MeV} \tag{15}$$

from Ref. [37] where we have added the errors in quadrature. The branching ratio for the decay $B^0\to\tilde\chi_1^0\overline{\nu}$ was taken as an input and the branching ratio for $B^+\to\tilde\chi_1^0 l^+$ calculated from it using the above results. The same cuts were applied as in the previous section. The number of events that would be observed in the detector is shown in Fig. 5. This shows that even for branching ratios below 10^{-7} there is a significant range of neutralino lifetimes for which there are enough events to explain the NuTeV results. The present experimental upper limit on the branching ratio of the purely muonic decay is $\text{BR}(B^\pm\to\mu^\pm\nu_\mu)<2.1\times10^{-5}$ [36].

Using the results for the RPV branching ratios of the B mesons and the neutralino lifetime we can find regions in $(\lambda_{232},\lambda'_{113})$ parameter space, for a given sfermion mass, in which there are 3 ± 1 events inside the NuTeV detector; this is shown in Fig. 6. We have included the low-energy bounds Eq. (7). In the case of the coupling λ'_{213} there is also a bound on the product of the couplings $\lambda_{232}\cdot\lambda'_{213}$ from the limits on the branching ratios for $B^0\to\tau^-\mu^+$ and $B^+\to\mu^+\nu$ [36], the latter giving the stricter bound

$$\frac{\lambda'^2_{213}\lambda^2_{232}f_B^2m^5_{B^+}}{32\pi M^4_{\tilde f}(m_b+m_u)^2\Gamma_{B^+}}\left(1-\frac{m^2_\mu}{m^2_{B^+}}\right)^2\leqslant 2.1\times10^{-5}. \tag{16}$$

Here Γ_{B^+} is the total width for the B^+. This gives

$$\lambda'_{213}\lambda_{232}\leqslant 3.8\times10^{-4}\left(\frac{M_{\tilde f}}{200\ \ \text{GeV}}\right)^2. \tag{17}$$

In Fig. 6 we see that for every value of λ'_{i13} there are two solutions in λ_{232}, except for a minimum value of λ'_{i13}, below which there are no solutions. This can be understood as follows. The maximum fraction of neutralinos decays in the distant detector for a lifetime $\tau=\beta c\gamma/l$, i.e., when the decay length corresponds to the flight length, the distance between the production target and the detector. This optimized lifetime corresponds numerically to

$$\lambda_{232}=5.3\times10^{-4}\left(\frac{M_{\tilde f}}{200\ \ \text{GeV}}\right)^2. \tag{18}$$

This requires the minimum production rate and thus the minimum value of λ'_{i13}, which is the dip in the curves in Fig. 6. For larger values of λ'_{i13} the neutralino production is increased. We can then tune the lifetime of the neutralino such that the decay length is either shorter or longer than the flight length, yielding the two solutions shown in the figure.

C. τ decays

As discussed in Sec. II, in our model the neutralino can decay to $\mu\tau\nu$ as well as $\mu\mu\nu$. Using the calculation of Eq.

(9) we can compute the branching ratios $\mathrm{BR}_{\mu\mu} \equiv \mathrm{BR}(\tilde{\chi}_1^0 \to \mu^\pm \mu^\mp \nu_\tau)$ and $\mathrm{BR}_{\mu\tau} \equiv \mathrm{BR}(\tilde{\chi}_1^0 \to \tau^\pm \mu^\mp \nu_\mu)$, which are displayed in Fig. 7. For neutralino masses above 10–15 GeV the two decays have practically equal branching ratios. However, when the neutralino mass is close to the τ mass, $\mathrm{BR}_{\mu\tau}$ is phase space suppressed. For $M_{\chi_1^0} = 5$ GeV we have $\mathrm{BR}_{\mu\tau} = 0.287$. In obtaining Fig. 7 the sfermions have been assumed to be degenerate and left/right stau mixing has been neglected.[4] In principle the NuTeV experiment can observe the $(\mu\tau\nu)$ modes through the decays $\tau^\pm \to e^\pm \nu\nu$ and $\tau^\pm \to \pi^\pm (n \cdot \pi^0)\nu$, which would lead to unobserved (e,μ) and (π,μ) events, respectively. Here $(n \cdot \pi^0)$ indicates an additional $n = 0,1,2,3$ emitted neutral pions. Given the three observed (μ,μ) events one would expect the following number of events for $M_{\chi_1^0} = 5$ GeV:

$$N_{(e,\mu)} = 3 \times \frac{\mathrm{BR}_{\mu\tau}}{1 - \mathrm{BR}_{\mu\tau}} \mathrm{BR}(\tau \to e\nu\nu) \approx 0.21, \tag{19}$$

$$N_{(\pi,\mu)} = 3 \times \frac{\mathrm{BR}_{\mu\tau}}{1 - \mathrm{BR}_{\mu\tau}} \mathrm{BR}(\tau \to \pi(n \cdot \pi^0)\nu) \approx 0.56, \tag{20}$$

where we have used the τ branching ratios from Ref. [36]. Thus the nonobservation of (e,μ) and (π,μ) events is consistent. We note that some of the $\tau \to \pi^\pm (n \cdot \pi^0)\nu$ decays would show extra activity in the detector and thus be rejected as pure $\pi^\pm$ events. Therefore the above estimate is conservative [38].

IV. FUTURE TESTS OF THE R_p VIOLATING MODEL

A. NOMAD experiment

The NOMAD experiment [39–41] was a neutrino oscillation experiment at CERN that was dismantled in 1999. The data, however, are still on tape and could be used to test the current proposal. We modified our program to estimate the event rate at NOMAD. For this we used the following numbers [39–41]: distance target-detector $l = 835$ m, fiducial volume of the detector $V = (2.6 \times 2.6 \times 4)$ m^3, target material beryllium, target density $\rho = 1.85$ g/cm^3, target length $d = 1.1$ m, proton beam energy $E = 450$ GeV, integrated number of protons $N_p = 4.1 \times 10^{19}$. Using these numbers we show our prediction for the number of events at NOMAD in Fig. 8. For the same B^0-meson branching ratio we obtain about an order of magnitude more events than at NuTeV. Thus our model can be *completely* tested by the NOMAD data.

[4]In models where the scalar masses are unified at the grand unified theory (GUT) scale the running of the masses to low scales forces the right stau to be lighter than the left stau. For low $\tan\beta$ it is a good approximation to neglect left/right stau mixing. For large values of $\tan\beta$ the right stau becomes much lighter, but this does not contribute to the decay. It is thus a conservative assumption to require degenerate scalar fermion masses.

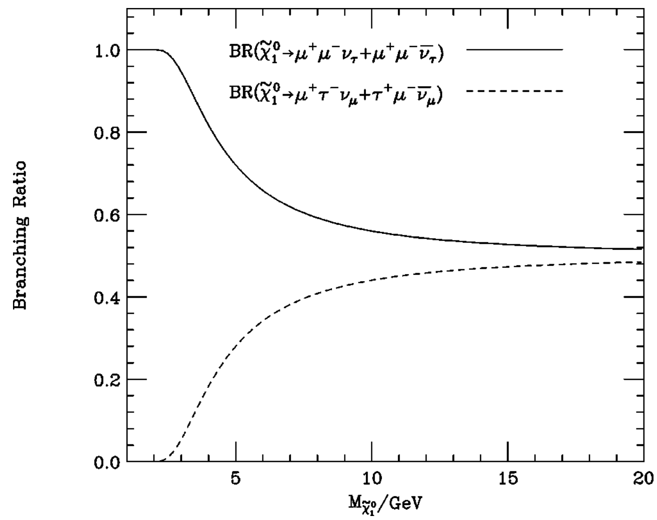

FIG. 7. Branching ratios for the decay of a purely *B*-ino lightest neutralino via the RPV coupling λ_{232}. The sfermions have been assumed to be degenerate and light/right stau mixing has been neglected.

The higher sensitivity at NOMAD can be understood as follows. The total $b\bar{b}$ production cross section for collisions on Be at NOMAD is 4.7 nb, while for collisions on BeO at NuTeV it is 94 nb. The total integrated luminosities are 5.58×10^{11} nb^{-1} (NOMAD) and 6.189×10^9 nb^{-1} (NuTeV). Therefore the number of $b\bar{b}$ events is 2.6×10^{12} (NOMAD) and 5.8×10^{11} (NuTeV), i.e., about 4.5 times more at NOMAD. The NOMAD detector is closer than the NuTeV detector and thus subtends a larger solid angle by about a factor of 3. The required neutralino lifetime is about the same because NOMAD is about half the distance but the energy is also about half. The NOMAD detector is about eight times shorter but the Lorentz boost is only about half the NuTeV boost, so this corresponds to a factor of 4. All in all we would expect about a factor of 3.4 times more events

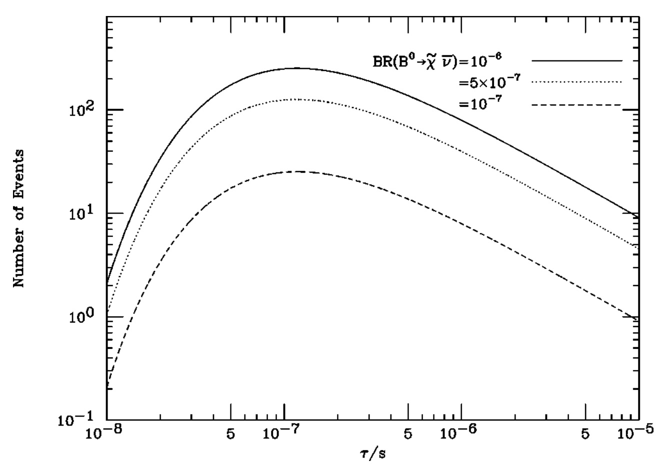

FIG. 8. The predicted number of dimuon events at NOMAD as a function of the neutralino lifetime. We have used our model for neutralino production through *B*-meson decays. We indicate the prediction for three different branching ratios of the neutral *B*-meson decay to neutralinos as in Fig. 5.

at NOMAD than at NuTeV. Comparing Fig. 8 with Fig. 5 we see that this is close to what the full numerical simulation gives.

B. *B* factories

As outlined above, for neutralino production we are relying on a rare *B*-meson decay,

$$B^{\pm}\rightarrow\mu^{\pm}+\chi_1^0, \tag{21}$$

$$B^0\rightarrow\nu+\chi_1^0, \tag{22}$$

which can possibly be observed at a present or future *B* factory. In the standard model we have the decay $B^{\pm}\rightarrow\mu^{\pm}+\nu$ with a predicted branching ratio [42] of about 3×10^{-7}. This is probably just below visibility at the BaBar experiment [42].

The decay (21) differs from the standard model decay $B^{\pm}\rightarrow\mu^{\pm}+\nu$ in the energy of the μ, which is now only $E_\mu=(M_{B^\pm}^2+m_\mu^2-M_\chi^2)/(2M_{B^\pm})\approx0.27$ GeV for $M_\chi=5$ GeV. We thus have a monochromatic muon with an order of magnitude less energy than in the standard model decay. This is a distinctive signature which we propose for investigation at BaBar and other *B* factories. We presume this is very difficult due to many sources of soft muons as background. Also the efficiency for such soft muons is typically very low, only about 5% [42].

The decay (22) is invisible, with the neutralino decay far outside the detector at a *B* factory. If we had a B^0-$\overline{B}^0$ system and could tag one of the mesons, via a conventional decay, then we would have an unexpected invisible decay on the opposite side. We propose this as a possible signature for investigation by the experimental collaborations.

V. NEUTRAL HEAVY LEPTONS

In [16,17] the NuTeV Collaboration also considered the possibility of a neutral heavy lepton (NHL) to explain their observation. Here a NHL N_{iL}, $i=1,2,3$, is considered as a primarily isosinglet field under $SU(2)_L$ with a small admixture of the light standard model neutrinos. This is discussed, for example, in Refs. [43,44]. We follow the notation of Ref. [43]. In general such a NHL has charged current (CC) and neutral current (NC) purely leptonic decays proceeding via a virtual $W^{\pm}$ or Z^0 boson, respectively:

$$N_{iL}\rightarrow l_j^-+l_k^++\overline{\nu_k}\quad(\mathrm{CC}), \tag{23}$$

$$N_{iL}\rightarrow\nu_m+l_n^++l_n^-\quad(\mathrm{NC}). \tag{24}$$

For the NC decay the charged leptons are from the same family, whereas for the CC decay they can also be from different families. A given CC leptonic decay is proportional to the mixing element $|U_{jN_i}|^2$. There is a corresponding NC decay proportional to the same mixing element for $m=j$. For a given set of NHL masses and mixings, we typically would expect both NC and CC decays to occur. $k,n=1,2,3$ are free indices which all contribute to the decay rate, independent of the mixings.

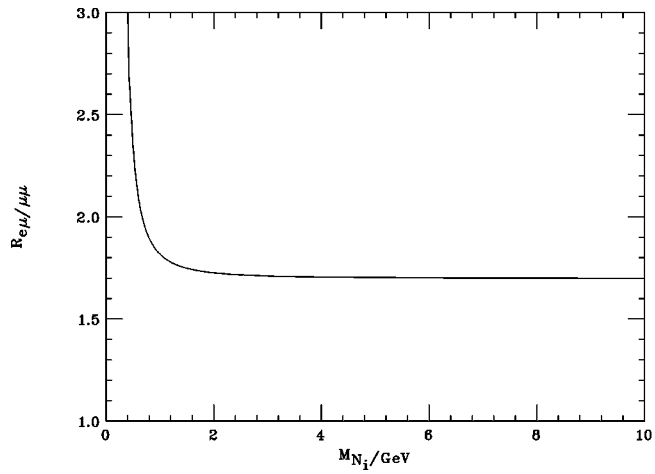

FIG. 9. Ratio of (e,μ) to (μ,μ) events, $R_{e\mu/\mu\mu}\equiv\Gamma(N_2\rightarrow e^+\mu^-\nu_\mu)/\Gamma(N_2\rightarrow\mu^+\mu^-\nu_\mu)$, in the decay of a NHL N_i versus the mass of N_i.

The NuTeV Collaboration observe an excess of dimuon events. Assume we have one NHL N_i with mass $M_{N_i}=5$ GeV, and the other NHL's are unobservably heavy. The dimuon events could occur through CC decays with $j=k=2$ and the mixing element U_{2N_i} or through NC decays with $n=2$ and the mixing elements U_{mN_i}, $m=1,2,3$. For $j=k=n=2$ we obtain dimuon events through both NC and CC decays.

If the CC decays contribute, i.e., $j=2$, we would expect there to be accompanying (e,μ) events with similar probability, from the $k=1$ mode. For example, for a nonvanishing $|U_{2N_i}|^2$, using the decay rates given in [44], we obtain the ratio of (e,μ) to (μ,μ) events given by $R_{e\mu/\mu\mu}\equiv\Gamma(N_2\rightarrow e^+\mu^-\nu_\mu)/\Gamma(N_2\rightarrow\mu^+\mu^-\nu_\mu)$. We plot this as a function of the NHL mass in Fig. 9. From the plot we see that we would expect *more* $(e\mu)$ events than (μ,μ) events. This is excluded by the NuTeV nonobservation of such events.

If the NC decays contribute we can expect further (e,e) and (τ,τ) events. The latter are kinematically suppressed as in the $R\!\!\!/_p$ case above. A search for the (e,e) modes has been presented only for low-energy electrons [15]. However, given a nonvanishing mixing element U_{mN_i} which gives the (μ,μ) events via NC decays, we would expect further CC decays: $N_{iL}\rightarrow l_j^{\pm}+l_k^{\mp}+\nu_k$, $k=1,2,3$. In particular, for $j=1,2$ this leads again to (e,μ) events, which were not observed.

We have thus eliminated all cases except a special model, which we consider in more detail. Assume $j=3$ and U_{3N_i} is the only non-negligible mixing element. Furthermore, as above, assume $M_{N_i}=5$ GeV and the other NHL's are unobservably heavy. We then have the following decay modes:

$$N_i\overset{\mathrm{CC}}{\rightarrow}\{\tau\tau\nu_\tau,\tau\mu\nu_\mu,\tau e\nu_e\}, \tag{25}$$

$$N_i\overset{\mathrm{NC}}{\rightarrow}\{\nu_\tau ee,\nu_\tau\mu\mu,\nu_\tau\tau\tau\}. \tag{26}$$

The τ and $\tau\tau$ decay modes are kinematically suppressed as in the $\not{R}_p$ case discussed above and the observed dimuon events are obtained from the NC decay. This model has been studied by the NOMAD Collaboration for $M_{N_i}=10$–190 MeV [41].

We now estimate the event rate for this model ($j=3$, $U_{3N_i}\neq 0$). The production will go either via the (CC or NC) Drell-Yan mechanism with the tau neutrino mixing with the N_i or via B-meson decays. We have computed the Drell-Yan production cross section to be $\sigma_{DY}=\mathcal{O}(10^{-1}\,\text{pb})\cdot|U_{3N_i}|^2$. The neutral current contribution to the NHL production is more than an order of magnitude smaller. The total integrated luminosity at NuTeV corresponds to $\sim 6.2\times 10^6$ pb^{-1} giving the number of N_i produced as $N_{N_i}^{prod}\sim 4\times 10^6|U_{3N_i}|^2$. Of these only about 1% fly in the direction of the detector [14], leaving us with $N_{N_i}\sim 4\times 10^4|U_{3N_i}|^2$. In order to estimate the total number of events we must combine this with the fraction of N_i that decay in the detector given by Eq. (12). The total event rate is proportional to

$$N_{ev}\approx N_{N_i}\exp\{-a|U_{3N_i}|^2\}\cdot b|U_{3N_i}|^2$$
$$=4\times 10^4 b|U_{3N_i}|^4\exp\{-a|U_{3N_i}|^2\} \qquad (27)$$

where $a=l/(\beta\gamma c\tau_{N_i}|U_{3N_i}|^2)$ and $b=\Delta x/(\beta\gamma c\tau_{N_i}|U_{3N_i}|^2)$ from Eq. (12) are independent of $|U_{3N_i}|$. The event rate is maximal for $|U_{3N_i}|^2=2/a$. We obtain an upper limit on the lifetime if we assume the NC decay is dominant. The latter we determine through the scaled muon lifetime

$$\tau_{N_i}<\tau_\mu\left(\frac{m_\mu}{M_{N_i}}\right)^5|U_{3N_i}|^{-2}=9\times 10^{-15}s|U_{3N_i}|^{-2}. \qquad (28)$$

We then obtain $a=5.2\times 10^8/\gamma$ and $b=1.3\times 10^7/\gamma$. For $\gamma=10$, for example, we obtain the maximal event rate for $|U_{3N_i}|=9\times 10^{-5}$, which is compatible with the independent bound $\Sigma_i|U_{3N_i}|^2<0.016$ [45]. Following Eq. (12), the total fraction decaying in the detector is then roughly 1.1%. Combining this with the previous estimate of the number produced we get a total maximal number of events of about $N_{ev}^{max}=5\times 10^{-7}$, which is of course too small.

The reason this is so much smaller than in the supersymmetric model is that the lifetime of the NHL is typically much shorter. Thus the NHL's typically would decay well before the detector. We get the maximal number of events when the lifetime is approximately the flight time. For this we need a very small $|U_{3N_i}|$. Since we have only one parameter in this model, this feeds into the cross section, resulting in the very low rate. We do not expect the production via B mesons to help. The branching ratio is suppressed compared to the SM decay branching ratio $\text{BR}(B^+\to\tau^+N_i)=|U_{3N_i}|^2\text{BR}(B^+\to\tau^+\nu_\tau)\approx 7\times 10^{-5}|U_{3N_i}|^2$, and thus also too small.

VI. CONCLUSIONS

We have reconsidered the NuTeV dimuon observation in the light of supersymmetry with broken R parity and neutral heavy leptons. We have shown that it is not possible to obtain the observed event rate with pair production of light neutralinos or via the production of neutral heavy leptons. However, we have introduced a new production method of neutralinos via B mesons. Because of the copious production of B mesons in the fixed-target collisions the observed dimuon event rate can be easily obtained for allowed values of the R-parity violating couplings.

The model we have proposed can be completely tested using current NOMAD data. We suspect this is true of any model one might propose. If the NOMAD search is negative our model is ruled out and the NuTeV observation is most likely not due to physics beyond the standard model.

It is worth pointing out that through this mechanism we have opened a new sensitivity range in the R-parity violating couplings. At colliders we can probe the range where the neutralino decays in the detector. For a photino neutralino this corresponds to [2]

$$\lambda>5\times 10^{-7}\sqrt{\gamma}\left(\frac{\tilde{m}}{200\ \text{GeV}}\right)^2\left(\frac{100\ \text{GeV}}{M_{\tilde{\gamma}}}\right)^{5/2}$$
$$=9\times 10^{-4}\sqrt{\gamma}\left(\frac{\tilde{m}}{200\ \text{GeV}}\right)^2\left(\frac{5\ \text{GeV}}{M_{\tilde{\gamma}}}\right)^{5/2}. \qquad (29)$$

Here we have substituted the light neutralino mass we are considering. For significant boost factors we thus can probe couplings at most down to 10^{-3}. From Fig. 6 we see that for a 200 GeV sfermion we can probe couplings down to about 5×10^{-6}, which is more than two orders of magnitude smaller. It is thus worthwhile to study the production of neutralinos via mesons at fixed-target experiments in more detail.

Before concluding we also note that one might worry that the lightest supersymmetric Higgs boson would decay predominantly to the two light neutralinos and thus be invisible. However, as with the Z^0 boson, the Higgs boson does not couple to a B-ino neutralino.

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