R-parity violation and uses of the rare decay $\tilde{\nu}\to\gamma\gamma$ in hadron and photon colliders

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We consider implications of the loop process $\tilde{\nu}\to\gamma\gamma$ in the minimal supersymmetric standard model with R-parity violation ($\not{R}_P$) for future experiments, where the sneutrino is produced as the only supersymmetric particle. We present a scenario for the $\not{R}_P$ couplings, where this clean decay, although rare with $\mathrm{Br}(\tilde{\nu}\to\gamma\gamma)\sim 10^{-6}$, may be useful for sneutrino detection over a range of sneutrino masses at the CERN Large Hadron Collider. Furthermore, the new $\tilde{\nu}\gamma\gamma$ effective coupling may induce detectable sneutrino resonant production in $\gamma\gamma$ collisions, over a considerably wide mass range. We compare $\tilde{\nu}\to\gamma\gamma,\ gg$ throughout the paper with the analogous yet quantitatively very different, Higgs boson $\to\gamma\gamma,\ gg$ decays and comment on the loop processes $\tilde{\nu}\to WW,\ ZZ$. [S0556-2821(99)06701-6]

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The generalization of the minimal supersymmetric standard model (MSSM) which includes R-parity violating ($\not{R}_P$) processes has been gaining increasing attention in the past few years [1]. The presence of $\not{R}_P$ couplings drastically changes the phenomenology of supersymmetric theories, by opening new experimental strategies in the search for supersymmetry. The sneutrino sector of the MSSM, in which we are interested here, can exhibit new phenomena directly related to the lepton-violating $\not{R}_P$ operators, e.g., sneutrinos can be produced as s-channel resonances [2–4], sneutrinos and anti-sneutrinos can mix [5] and the sneutrino mixing phenomenon can drive large tree-level CP-violating asymmetries [4].

In this paper we study another issue in sneutrino physics unique to the MSSM with $\not{R}_P$, namely the role of rare sneutrino decays in collider experiments. As is well known, rare decays can play a crucial role in collider experiments. An example is the rare Higgs boson decay [6] $h\to\gamma\gamma$, which has a branching ratio of $\mathcal{O}(10^{-3})$ for $m_h\lesssim 2m_W$ [7]. In spite of this small branching ratio, it is now widely believed that this rare decay mode may be the best discovery channel for a Higgs boson with a mass $\lesssim 140$ GeV at the CERN Large Hadron Collider (LHC). It also has implications for Higgs boson production in $\gamma\gamma$ collisions. On the other hand, the effective hgg coupling ($g=$gluon) is unimportant for discovery of h in view of the large QCD background, but is believed to be the main mechanism for Higgs boson production at the LHC.

Here we will concentrate on the decay $\tilde{\nu}^i\to\gamma\gamma$, where $i=e,\mu,\tau$ indicates the sneutrino flavor, and briefly comment on the other rare decay channels $\tilde{\nu}^i\to gg,\ ZZ,\ W^+W^-$. These $\not{R}_P$ sneutrino decays into vector bosons, occur at the one loop-level with an insertion of one $\not{R}_P$ sneutrino coupling to down quarks or leptons. The decay of a sneutrino to a pair of photons, $\tilde{\nu}\to\gamma\gamma$, in the MSSM with $\not{R}_P$, while resembling $h\to\gamma\gamma$, has its own unique characteristics. In fact, as will be shown in this paper, although the branching ratio of $\tilde{\nu}\to\gamma\gamma$ is much smaller than that of $h\to\gamma\gamma$, it may be compensated by a large sneutrino production rate as compared to the Higgs case at the LHC. The basic reaction that we will consider is the inclusive, single $\tilde{\nu}$ production $pp\to\tilde{\nu}+X$ via the parton processes $b\bar{b}\to\tilde{\nu}$, $b(\text{or } \bar{b})\,g\to\tilde{\nu}+b(\text{or } \bar{b})$, $b\bar{b}\to\tilde{\nu}+g$ and $gg\to\tilde{\nu}$, all followed by $\tilde{\nu}\to\gamma\gamma$. At the LHC this $\gamma\gamma$ mode is found to be useful as a sneutrino discovery channel over a sneutrino mass range approximately equal to the corresponding Higgs mass range (i.e., $m_h\lesssim 140$ GeV). In addition, both h and $\tilde{\nu}$ can be produced in $\gamma\gamma$ collisions, though with a smaller rate for $\tilde{\nu}$.

The relevant lepton number violating $\not{R}_P$ Lagrangian is [1]

$$\mathcal{L}_{\not{L}}=\frac{1}{2}\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^c_k+\lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^c_k, \tag{1}$$

where $\hat{L}$ and $\hat{Q}$ are the SU(2)-doublet lepton and quark superfields, respectively and $\hat{E}^c$ and $\hat{D}^c$ are the lepton and quark singlet superfields, respectively. Also, the flavor indices i,j,k are such that, for the pure leptonic operator in Eq. (1), $i\neq j$. Throughout this paper we will neglect another possible lepton-violating $\not{R}_P$ term of the form L_iH_u in the superpotential; the effects of such a term have been considered elsewhere (see [1], and references therein).

In order to calculate the decay rate of $\tilde{\nu}^i\to\gamma\gamma$ it is convenient to define $\tilde{\nu}^i=(\tilde{\nu}^i_+ + i\tilde{\nu}^i_-)/\sqrt{2}$ and work in the $\tilde{\nu}^i_\pm$ mass basis. The relevant $\not{R}_P$ couplings of $\tilde{\nu}^i_\pm$ to down quarks and leptons are then given by

$$\tilde{\nu}^i_+ d_j d_k:\quad i\lambda'_{ijk}/\sqrt{2},\qquad \tilde{\nu}^i_- d_j d_k:\quad -\lambda'_{ijk}\gamma_5/\sqrt{2}, \tag{2}$$

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$$\tilde{\nu}^i_+ \ell_j \ell_k: \quad i\lambda_{ijk}/\sqrt{2}, \quad \tilde{\nu}^i_- \ell_j \ell_k: \quad -\lambda_{ijk}\gamma_5/\sqrt{2}. \quad (3)$$

The calculation can now be simply performed in analogy with the CP-even (h) and CP-odd (A) neutral Higgs decays to a pair of photons in the MSSM [8] (and similarly for a pair of gluons):

$$\Gamma(\tilde{\nu}^i_\pm \to \gamma\gamma) = \frac{\alpha^2 m^3_{\tilde{\nu}^i_\pm}}{512\pi^3} \sum_{j=1}^{3} \left| \frac{N_c}{m_{d_j}} e^2_{d_j} \lambda'_{ijj} F^\pm_{1/2}(\tau_{d_j}) + \frac{1}{m_{\ell_j}} \lambda_{ijj} F^\pm_{1/2}(\tau_{\ell_j})(1-\delta_{ij}) \right|^2, \quad (4)$$

$$\Gamma(\tilde{\nu}^i_\pm \to gg) = \frac{\alpha_s^2 m^3_{\tilde{\nu}^i_\pm}}{256\pi^3} \sum_{j=1}^{3} \left| \frac{1}{m_{d_j}} \lambda'_{ijj} F^\pm_{1/2}(\tau_{d_j}) \right|^2, \quad (5)$$

where in Eq. (4) the sum runs over all down fermions, while in Eq. (5) only down quarks are included. Furthermore, $N_c = 3$ is the number of colors, $e_{d_j} = -1/3$ is the charge of quark d_j. The functions $F^\pm_{1/2}(\tau)$, where $\tau = 4m^2/m^2_{\tilde{\nu}}$, are defined as follows [9]:

$$F^+_{1/2} = -2\tau[1+(1-\tau)f(\tau)], \quad F^-_{1/2} = -2\tau f(\tau), \quad (6)$$

where

$$f(\tau) = \begin{cases} [\sin^{-1}(\sqrt{1/\tau})]^2, & \text{if } \tau \geq 1, \\ -\frac{1}{4}[\ln(\eta_+/\eta_-) - i\pi]^2, & \text{if } \tau < 1 \end{cases} \quad (7)$$

and

$$\eta_\pm \equiv 1 \pm \sqrt{1-\tau}. \quad (8)$$

Note that $F^\pm_{1/2}(m)/m \to 0$ for $m \to 0$.

From the above equations we observe that, unlike the Higgs case, W bosons, charged Higgs particles (present in some extensions of the SM), 2/3 charged quarks and neutrinos do not appear in the loop. This results from the absence of the relevant terms in the $R\!\!\!/_P$ Lagrangian. In addition, sfermion loops resulting from a $\tilde{\nu}\tilde{f}_L\tilde{f}_R$ coupling are excluded. This is similar to $A \to \gamma\gamma$, gg but, unlike the corresponding decays of h in the MSSM [8], is due to the chirality conserving γ (and g) coupling to sfermions [10]. Finally, sneutrino couplings to a pair of left-handed or right-handed sfermions, i.e., $\tilde{\nu}\tilde{f}_L\tilde{f}_L$ and $\tilde{\nu}\tilde{f}_R\tilde{f}_R$, are generated by the superpotential and therefore suppressed by the corresponding (light) fermion masses. Since $m_f/m_{\tilde{\nu}} \ll 1$, for $f = b$ or τ, these type of sfermion loops were neglected.

We now describe two possible scenarios, each one of which has distinct phenomenological implications for collider experiments.

Scenario 1: Only $\lambda'_{i33} \neq 0$ *and* $\lambda_{i33} \neq 0$.

Within this scenario, which may be theoretically motivated by imposing a mass hierarchy on the $R\!\!\!/_P$ couplings in Eq. (1) (i.e., only the heavier third generation fermions have a non-negligible $R\!\!\!/_P$ coupling to sneutrinos), the sneutrinos can be produced as a single supersymmetric particle at the LHC and in a future $\gamma\gamma$ linear collider [Photon Linear Collider (PLC) [11]], but not in e^+e^- and $\mu^+\mu^-$ colliders.

As will be shown below, due to the high production rate of $\tilde{\nu}^i_\pm$, predominantly through the $b\bar{b}$ and bg fusion processes, the decay $\tilde{\nu}^i_\pm \to \gamma\gamma$ may prove to be a useful detection mechanism (*à la* $h \to \gamma\gamma$) at the LHC. At the Tevatron, due to the low b-quark and gluon content of the beams, the $\gamma\gamma$ decays of sneutrinos cannot be used to detect them; as we comment later, it appears difficult to ''save'' this detection mode at the Tevatron even in a modified scenario.

Scenario 2: All $\lambda'_{ijk} = 0$ *and only* $\lambda_{i33} \neq 0$.

In this scenario the only $R\!\!\!/_P$ interactions present couple $\tilde{\nu}^i$ with $i = e, \mu$ to a pair of τ leptons. In this case sneutrinos will not be produced singly in either $e^+e^-, \mu^+\mu^-$ colliders or in hadron colliders [13]. Therefore $\gamma\gamma \to \tilde{\nu}^i_\pm$ in a future PLC, remains as the sole process for production of a sneutrino as the only supersymmetric particle within $R\!\!\!/_P$ MSSM.

Within the above scenarios, for $\tilde{\nu} \to \gamma\gamma$, gg, we can assume without loss of generality, that only flavor diagonal $\tilde{\nu}$ couplings are present. Furthermore, for definiteness, in both scenarios we will only consider couplings of the μ-sneutrino, i.e., $i = 2$, although our results hold for the e-sneutrino as well; for $i = 3$ the results for $\tilde{\nu}^\tau$ decay to $\gamma\gamma$ will have only quarks in the loop, as the $\tilde{\nu}^\tau\tau\tau$ coupling λ_{333} is forbidden.

Before presenting the results of our study we remark that, just as in the case of Higgs reactions, higher-order corrections (mainly QCD), may be substantial [14] for both decay widths and production cross sections. Since such corrections have not been calculated for sneutrinos, and since the discussion here is exploratory, all higher-order corrections will be ignored. The values of the parameters used here are: $m_\tau = 1.8$ GeV, $m_b = 4.5$ GeV, $\alpha = 1/128$ and $\alpha_s = 0.118$.

We note that bounds on the sneutrino masses can be obtained without reference to a specific $R\!\!\!/_P$ scenario using sneutrino pair production at, for example, the CERN e^+e^- collider LEP2. This can be done, for instance, through R_P-conserving MSSM interactions (see, e.g., [15]), and the subsequent decays into four fermion states, i.e., $\tilde{\nu}\tilde{\nu} \to \tau\tau\tau\tau$, $bbbb$, $bb\tau\tau$ in scenario 1, or $\tilde{\nu}\tilde{\nu} \to \tau\tau\tau\tau$ in scenario 2. However, the pair production cross section strongly depends on the values of the R_P-conserving MSSM parameters. Thus, one cannot exclude light sneutrinos with masses $\gtrsim 50$ GeV from current LEP2 data (see, e.g., [16]). Recently resonant sneutrino production has been searched for in [17]; note however that none of their scenarios is the same as ours.

There are also bounds for the $R\!\!\!/_P$ couplings relevant to the above scenarios for $i = 2$, i.e., on λ'_{233} and λ_{233}. These bounds are usually given at the 1σ or 2σ level and are deduced by using some simplifying assumptions, e.g., only one coupling at a time is assumed to be nonzero (see [1], and references therein). Furthermore, the bounds are usually presented for $m_{\tilde{f}} = 100$ GeV, where $\tilde{f} \neq \tilde{\nu}$ is the sfermion in-

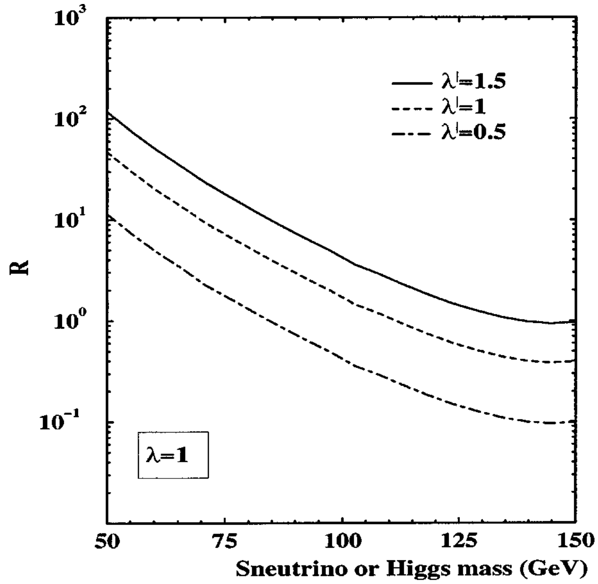

FIG. 1. The ratio R of the production cross sections × branching ratios for decays to $\gamma\gamma$, between sneutrinos and Higgs boson [R is defined in Eq. (9)], at the LHC with $\sqrt{s}=14$ TeV, as a function of the mass $m_h = m_{\tilde{\nu}_+^{\mu}} = m_{\tilde{\nu}_-^{\mu}}$, in scenario 1 (see text) with $\lambda=1$ and $\lambda'=0.5$ (dash-dot), 1 (dashed), or 1.5 (solid). Only leading-order terms are kept in R, also no cuts are imposed.

volved in the process employed to obtain the bounds, and such constraints become weaker as $m_{\tilde{f}}$ increases.

The 1σ upper limit on λ'_{233} is about 0.4 for $m_{\tilde{b}}=100$ GeV; it is derived (see [18] and its update in [1]), from the data for the ratio $\Gamma(Z\to\text{hadrons})/\Gamma(Z\to\mu^+\mu^-)$. The upper limit rises (practically linearly) with $m_{\tilde{b}}$, reaching $\mathcal{O}(1)$ for $m_{\tilde{b}}$ around 500 GeV [18]. We can therefore take $0.5<\lambda'_{233}<1.5$, without violating any existing bound; this will be the range investigated within scenario 1.

The 1σ upper limit on λ_{233} was extracted (see [2] and its update by Dreiner in [1]) from the ratio $R_\tau \equiv \Gamma(\tau\to e\nu\bar{\nu})/\Gamma(\tau\to\mu\nu\bar{\nu})$ and it scales with the stau mass as $\lambda_{233}<0.06(m_{\tilde{\tau}}/100\ \text{GeV})$. Both λ_{133} and λ_{233} contribute to R_τ where their contributions may appear with a relative minus sign [2]. Therefore, either by assuming that $m_{\tilde{\tau}}\gtrsim 500$ GeV and requiring an effect larger than 1σ, or assuming that there is a (possibly partial) cancellation between the contributions of λ_{133} and λ_{233} to R_τ, $\lambda_{233}=1$ is not ruled out. Hereafter, we fix the value of λ_{233} to unity, for both scenarios.

We now consider the prospects of discovering sneutrinos at the LHC via their decay to a pair of photons within scenario 1, then briefly comment on the corresponding effects at the Tevatron. Within the present scenario, the $\tilde{\nu}bb$ coupling is much larger than the hbb one, and the effective $\tilde{\nu}gg$ coupling is smaller than the hgg one. Therefore, at the LHC, single sneutrinos are expected to be produced mainly from the parton processes listed below, which result from the $\tilde{\nu}bb$ coupling, while the Higgs boson is considered to be dominantly produced through gg fusion. The leading processes contributing to the inclusive single sneutrino production, $pp\to\tilde{\nu}_\pm + X$ at the LHC, are

(1) *s*-channel resonant sneutrino production: $b\bar{b}\to\tilde{\nu}_\pm$.

(2) Associated production of sneutrino and a *b*-jet: $bg\to b\tilde{\nu}_\pm$, where the $\tilde{\nu}$ is obviously either emitted from the outgoing b (an *s*-channel process), or from the incoming b (a *t*-channel process). In both cases one needs to add the corresponding cross sections with $b\to\bar{b}$, which is equivalent to multiplying the *b*-quark result by 2. This is the analog to the process $e\gamma\to\tilde{\nu}e$, discussed in [19].

(3) Associated production of sneutrino and a *g*-jet: $b\bar{b}\to\tilde{\nu}_\pm g$, again where the sneutrino is emitted either from the b or from $\bar{b}$.

We have also studied the $2\to3$ subprocess $gg\to\tilde{\nu}_\pm b\bar{b}$. Naively, this process is a source for large logarithms. However, to avoid double counting, since the logs are already included in the definition of the *b*-quark parton distributions

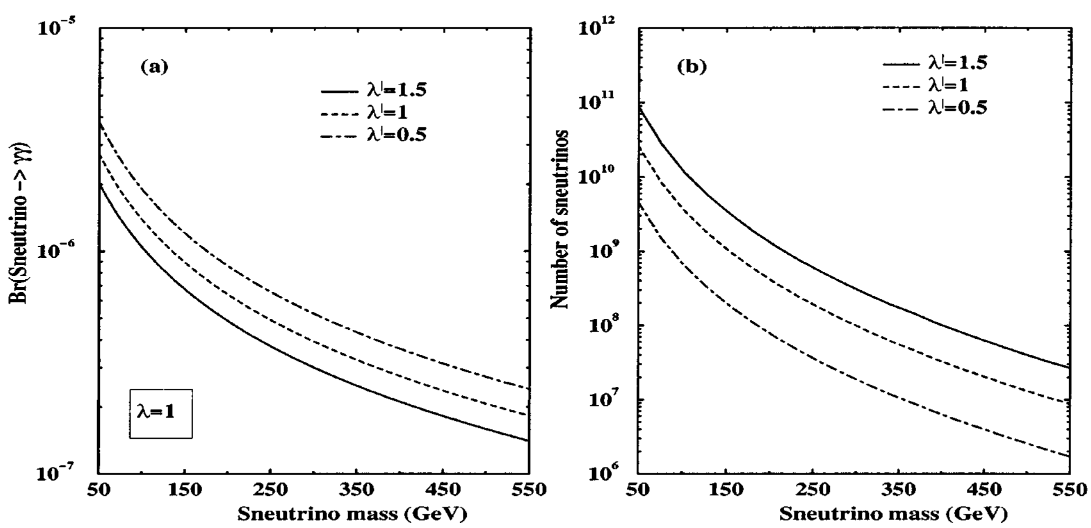

FIG. 2. (a) The branching ratio $\text{Br}(\tilde{\nu}_+^{\mu}\to\gamma\gamma)$; the numbers for $\tilde{\nu}_-^{\mu}$ are very similar. (b) The number of μ sneutrinos with $CP=+$, plus the number of μ sneutrinos with $CP=-$, at the LHC with $L=100$ fb^{-1}. Both figures are in scenario 1 (see text). See also caption to Fig. 1.

[20], we have done a rough estimate of the rates for the $2\to3$ subprocess without including these logs. The remaining contributions for the $2\to3$ subprocess are estimated to be much smaller than the $2\to1$ and $2\to2$ processes mentioned above and therefore is not being included in our calculations.

The cross sections for $\tilde{\nu}^{\mu}_{\pm}$ production in a hadron collider are then obtained [21] by folding the parton-level cross sections with the relevant parton distribution functions in the beams, neglecting all higher-order corrections, as mentioned above. We follow this procedure, employing the CTEQ4M parametrization [22] and find that the cross sections for the first and second processes above are approximately equal to each other and larger than the third process by about an order of magnitude; nevertheless, for completeness, the latter is also included [23].

Since sneutrino and Higgs production rates and decays are expected to have similar higher-order corrections and are expected to be subjected to comparable experimental cuts, and since the expected statistical significance of the $h\to\gamma\gamma$ signal at the LHC is known [24], the ratio

$$R=\frac{\sum_{s=+,-}\sigma(pp\to\tilde{\nu}^{\mu}_{s}+X)\mathrm{Br}(\tilde{\nu}^{\mu}_{s}\to\gamma\gamma)}{\sigma(pp\to h+X)\mathrm{Br}(h\to\gamma\gamma)}, \qquad (9)$$

will provide a simple guide for the possibility of using $\tilde{\nu}\to\gamma\gamma$ as a detection channel for sneutrinos at the LHC. The plot of R as a function of $m_{\tilde{\nu}}=m_h$ for $\sqrt{s}=14$ TeV (corresponding to the LHC) is presented in Fig. 1 where, as throughout this paper, we take $m_{\tilde{\nu}}\equiv m_{\tilde{\nu}^{\mu}_{+}}=m_{\tilde{\nu}^{\mu}_{-}}$. We note that the branching ratios $\Gamma(\tilde{\nu}^{\mu}_{+}\to\gamma\gamma)\approx\Gamma(\tilde{\nu}^{\mu}_{-}\to\gamma\gamma)$ within $\sim10\%$ and the production cross sections for $\tilde{\nu}^{\mu}_{\pm}$ are equal up to $\sim50\%$. Cross sections and branching ratios were calculated to lowest order in EW and QCD, as mentioned before, and without cuts. Results for three values of $\lambda'\equiv\lambda'_{233}$, all with $\lambda\equiv\lambda_{233}=1$ are displayed; note that we assume that both couplings appear with the same sign.

We approximate the branching ratio of $\tilde{\nu}^{\mu}_{\pm}\to\gamma\gamma$ by

$$\mathrm{Br}(\tilde{\nu}^{\mu}_{\pm}\to\gamma\gamma)=\frac{\Gamma(\tilde{\nu}^{\mu}_{\pm}\to\gamma\gamma)}{\Gamma(\tilde{\nu}^{\mu}_{\pm}\to b\bar{b})+\Gamma(\tilde{\nu}^{\mu}_{\pm}\to\tau^{+}\tau^{-})+\Gamma(\tilde{\nu}^{\mu}_{\pm}\to\tilde{\chi}^{+}\ell)+\Gamma(\tilde{\nu}^{\mu}_{\pm}\to\tilde{\chi}^{0}\nu)}, \qquad (10)$$

where (see Barger *et al.* in [2]):

$$\Gamma(\tilde{\nu}^{\mu}_{\pm}\to\tilde{\chi}^{+}\ell)\sim\mathcal{O}[10^{-2}m_{\tilde{\nu}^{\mu}_{\pm}}\times(1-m^2_{\tilde{\chi}^{+}}/m^2_{\tilde{\nu}^{\mu}_{\pm}})^2], \qquad (11)$$

$$\Gamma(\tilde{\nu}^{\mu}_{\pm}\to\tilde{\chi}^{0}\nu)\sim\mathcal{O}[10^{-2}m_{\tilde{\nu}^{\mu}_{\pm}}\times(1-m^2_{\tilde{\chi}^{0}}/m^2_{\tilde{\nu}^{\mu}_{\pm}})^2]. \qquad (12)$$

Evidently, with $\lambda'=1$, for example, the R_P-conserving decay channels of the sneutrino, if open, are always smaller than the $\not{R}_P$ decays to a pair of b quarks:

$$\Gamma(\tilde{\nu}^{\mu}_{\pm}\to b\bar{b})=(\lambda'_{233})^2\frac{3}{16\pi}m_{\tilde{\nu}^{\mu}_{\pm}}. \qquad (13)$$

Therefore, for simplicity, we take (conservatively), $\Gamma(\tilde{\nu}^{\mu}_{\pm}\to\tilde{\chi}^{+}\ell)+\Gamma(\tilde{\nu}^{\mu}_{\pm}\to\tilde{\chi}^{0}\nu)=10^{-2}m_{\tilde{\nu}^{\mu}_{\pm}}$, ignoring the phase-space factors in Eqs. (11) and (12).

As can be seen from Fig. 1, the ratio R in Eq. (9), obeys $R\gtrsim1$ for $m_{\tilde{\nu}}\lesssim85,110,140$ GeV, when $\lambda'\gtrsim0.5,1,1.5$, respectively. Moreover, it is interesting to note that $R\gtrsim10$ with $\lambda'\gtrsim0.5,1,1.5$ for $m_{\tilde{\nu}}\lesssim50,70,85$ GeV, respectively. Now, for $pp\to h+X$ followed by $h\to\gamma\gamma$ the values for $S/\sqrt{B}$ range between 2.3 and 7.1 for m_h between 80 and 140 GeV [24], where S is the signal for single Higgs boson production and its subsequent decay into two photons at the LHC with higher-order corrections included, and B is the QCD background. Since the higher-order corrections are expected to be similar for the numerator and denominator in R, the results in Fig. 1 are encouraging and a further study of the two photon decay modes of sneutrinos produced singly in $\not{R}_P$ MSSM is warranted. Later we will consider the QCD background to $pp\to\tilde{\nu}^{\mu}_{\pm}+X\to\gamma\gamma+X$. The conclusions are similar to the ones above, though they should be verified by including radiative corrections.

In Fig. 2(a) we plot $\mathrm{Br}(\tilde{\nu}^{\mu}_{+}\to\gamma\gamma)$, which is approximately equal to $\mathrm{Br}(\tilde{\nu}^{\mu}_{-}\to\gamma\gamma)$, as a function of the sneutrino mass, in scenario 1. It is interesting to note that while $\mathrm{Br}(h\to\gamma\gamma)$ sharply falls once $m_h\gtrsim2m_W$, from $\approx10^{-3}$ around 150 GeV, to $\approx10^{-7}$ at 550 GeV, $\mathrm{Br}(\tilde{\nu}^{\mu}_{\pm}\to\gamma\gamma)$ smoothly drops only by about an order of magnitude as one goes from $m_{\tilde{\nu}}=50$ to 550 GeV, where it is $\approx10^{-7}$.

In Fig. 2(b) we show, again for scenario 1, the total number of μ sneutrinos, both $\tilde{\nu}^{\mu}_{+}$ and $\tilde{\nu}^{\mu}_{-}$, produced at the LHC with a high luminosity of 100 fb^{-1}. Taking $\lambda'=1$, and comparing the expected number of sneutrinos produced singly at the LHC (mainly through the $b\bar{b}$ and bg fusion mechanisms), with the expected number of Higgs boson produced (predominantly through $gg\to h$ [7]), we find that for $m_{\tilde{\nu}}=m_h=100$ GeV the number of sneutrinos is more than two orders of magnitude larger, while for 500 GeV it is about an order of magnitude larger.

In order to better estimate the feasibility of detecting the sneutrino through its decay to a pair of photons, one has to study the signal to background ratio, i.e., $pp\to\tilde{\nu}^{\mu}_{\pm}+X\to\gamma\gamma+X$ versus $pp\to\gamma\gamma+X$ from the continuum. At the LHC, as a result of the high gg luminosity, the box graph

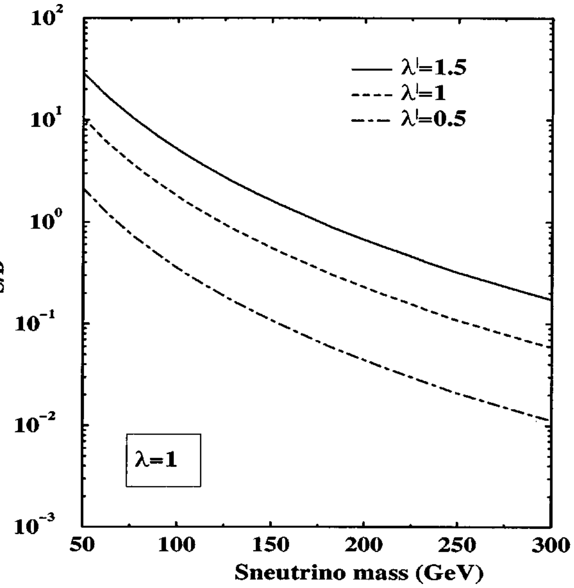

FIG. 3. The statistical significance $S/\sqrt{B}$, for a signal from $pp \to \tilde{\nu}^\mu + X \to \gamma\gamma + X$, as a function of the $\tilde{\nu}^\mu$ mass at the LHC with $L=100\ \text{fb}^{-1}$, in scenario 1 (see text). A cut on the photon scattering angle $|\cos\theta|<0.5$ is imposed. The signal is defined in Eq. (15) and the background is given in Eq. (14). See also caption to Fig. 1.

contribution to $gg \to \gamma\gamma$ is comparable to the tree-level $q\bar{q} \to \gamma\gamma$ one and also has to be considered. Comprehensive background analysis is beyond the scope of this work (this can be found, for example, in [24] for $h \to \gamma\gamma$ at the LHC). For the purposes of this paper it suffices to calculate $d\sigma/dM_{\gamma\gamma}(q\bar{q} \to \gamma\gamma)$, where $M_{\gamma\gamma}$ is the invariant mass of the photon pair, and multiply it by a factor of 2 to account for the box-mediated subprocess $gg \to \gamma\gamma$ [25]. The number of background $\gamma\gamma$ events is therefore taken here as

$$B = 2 \times \frac{d\sigma}{dM_{\gamma\gamma}}(q\bar{q} \to \gamma\gamma) \times \Delta M_{\gamma\gamma}, \tag{14}$$

where $\Delta M_{\gamma\gamma}$ is the mass resolution bin for the reconstruction of the $\gamma\gamma$ invariant mass which we take to be $\Delta M_{\gamma\gamma} = 10^{-2} M_{\gamma\gamma}$, i.e., 1% accuracy in measuring $M_{\gamma\gamma}$ is assumed.

The signal for $m_{\tilde{\nu}^\mu_+} \approx m_{\tilde{\nu}^\mu_-}$, is given by

$$S = \left[\sum_{s=+,-} \sigma(pp \to \tilde{\nu}^\mu{}_s + X) \times L \times \text{Br}(\tilde{\nu}^\mu_s \to \gamma\gamma) \right] \times (1-t). \tag{15}$$

We have included the factor $(1-t)$ in Eq. (15) to take into account the reduction in signal within one bin since the sneutrino width is larger than 1% of its mass. Specifically, we choose $t=1/2$ thus decreasing the signal by half.

In Fig. 3 we show the statistical significance $S/\sqrt{B}$ for the process $pp \to \tilde{\nu}^\mu_\pm + X \to \gamma\gamma + X$ as a function of the sneutrino mass. In calculating both S and B we employ a cut on the photon scattering angle $|\cos\theta|<0.5$ and again we take a high yearly luminosity at the LHC ($L=100\ \text{fb}^{-1}$). We find that, with $\lambda'=0.5$, $S/\sqrt{B}>1$ only if $m_{\tilde{\nu}^\tau_\pm} \lesssim 70$ GeV, thus in this case the outlook is not that optimistic. We therefore discuss the numerical results only for $\lambda'=1,1.5$. We observe from Fig. 3 that, for $\lambda'=1$, a 1σ signal is possible at the LHC for $m_{\tilde{\nu}^\mu_\pm} \lesssim 125$ GeV. If $\lambda'=1.5$, then a 1σ sneutrino signal through $\tilde{\nu}^\mu_\pm \to \gamma\gamma$ may be possible for $m_{\tilde{\nu}^\mu_\pm} \lesssim 180$ GeV. Furthermore, the 3σ discovery sensitivity seems attainable for $m_{\tilde{\nu}^\mu_\pm} \lesssim 85,120$ GeV when $\lambda'=1,1.5$, respectively. It is interesting to note that the discovery ranges for both the SM Higgs boson and the sneutrino through their $\gamma\gamma$ decay modes at the LHC, are about the same.

We close this discussion of single sneutrino production in hadron colliders within scenario 1, with a comment about single sneutrino production at the Fermilab Tevatron. As mentioned before, due to the small probability of finding a b quark or gluon in a proton (or antiproton) at $\sqrt{s}=2$ TeV, the $b\bar{b}$ and bg luminosities at the Tevatron, are too small to allow detection of sneutrinos through their two photons decay mode. We can, of course, envisage a modified scenario in which the sneutrino, which for definiteness is again taken as $\tilde{\nu}^\mu$, is produced from the valence $d\bar{d}$ annihilation. However, it is unlikely that λ'_{211} is of $\mathcal{O}(1)$, as required in order to render the production rate large enough. This is due to a gauge hierarchy argument, and to the fact that, in this case, there is no possibility of a cancellation between the contributions of two λ' couplings [2].

Finally, let us investigate scenario 2 and its implications for e-sneutrino and μ-sneutrino production in a future PLC. As mentioned earlier, if only $\lambda_{i33} \neq 0$, for $i=1,2$ then the only production mechanism of an s-channel sneutrino is via $\gamma\gamma$ fusion, $\gamma\gamma \to \tilde{\nu}^i_\pm$. Following [26], we find that the number of $\tilde{\nu}^i_\pm$ produced in a polarized PLC is (see also [27]):

$$\begin{aligned} N_{\tilde{\nu}^i_\pm} &= \left.\frac{dL_{\gamma\gamma}}{dW_{\gamma\gamma}}\right|_{W_{\gamma\gamma}=m_{\tilde{\nu}^i_\pm}} \times \frac{4\pi^2 \Gamma(\tilde{\nu}^i_\pm \to \gamma\gamma)}{m^2_{\tilde{\nu}^i_\pm}} \times (1+h_1h_2) \\ &\simeq 1.54 \times 10^4 \times \left(\frac{L_{ee}}{\text{fb}^{-1}}\right)\left(\frac{E_{ee}}{\text{TeV}}\right)^{-1}\left(\frac{\Gamma(\tilde{\nu}^i_\pm \to \gamma\gamma)}{\text{keV}}\right) \\ &\quad \times \left(\frac{m_{\tilde{\nu}^i_\pm}}{\text{GeV}}\right)^{-2} F(m_{\tilde{\nu}^i_\pm}) \times (1+h_1h_2), \end{aligned} \tag{16}$$

where h_1,h_2 are the helicities of the initial photons and E_{ee} and L_{ee} are the e^+e^- machine energy and yearly integrated luminosity, respectively. $F(W_{\gamma\gamma}) = (E_{ee}/L_{ee}) dL_{\gamma\gamma}/dW_{\gamma\gamma}$ depends on the machine parameters and is of $\mathcal{O}(1)$ [26]; for simplicity we take $F(W)=1$ [27]. Note again that for $m_{\tilde{\nu}^i_+} = m_{\tilde{\nu}^i_-}$ we have $\Gamma(\tilde{\nu}^i_+ \to \gamma\gamma) \simeq \Gamma(\tilde{\nu}^i_- \to \gamma\gamma)$, so that the number of $(\tilde{\nu}^i_+ + \tilde{\nu}^i_-)$ produced is $N_{(\tilde{\nu}^i_+ + \tilde{\nu}^i_-)} \simeq 2N_{\tilde{\nu}^i_\pm}$. In what follows we consider $\tilde{\nu}^\mu_\pm$ production with the relevant coupling $\lambda_{233} \neq 0$; the analysis for $\tilde{\nu}^e_\pm$ production is similar.

In Table I we give, for $m_{\tilde{\nu}^\mu_+} = m_{\tilde{\nu}^\mu_-} = 50-300$ GeV, the scaled partial width $\Gamma(\tilde{\nu}^\mu_\pm \to \gamma\gamma)/\lambda^2_{233}$ and the expected num-

TABLE I. The $\tilde{\nu}_+^\mu \to \gamma\gamma$ width in keV (the widths for $\tilde{\nu}_-^\mu \to \gamma\gamma$ are larger by $\sim 10\%$) and the approximate number of $\tilde{\nu}_\pm^\mu$ produced in a future $\gamma\gamma$ collider, scaled by λ_{233}^2, for $E_{ee}=0.5$ TeV. We take $L_{ee}=20$ fb^{-1} and $L_{ee}=100$ fb^{-1}, with $m_{\tilde{\nu}_\pm^\mu}=50-300$ GeV. All entries are within scenario 2 (see text).

$m_{\tilde{\nu}_\pm^\mu}$, GeV⇒	50	100	150	200	250	300
$\Gamma(\tilde{\nu}_+^\mu \to \gamma\gamma)/\lambda_{233}^2$, keV	2.8	2.7	2.5	2.4	2.2	2.1
$N_{(\tilde{\nu}_+^\mu+\tilde{\nu}_-^\mu)}/\lambda_{233}^2$ ($L_{ee}=20$ fb^{-1})	2700	650	270	150	90	60
$N_{(\tilde{\nu}_+^\mu+\tilde{\nu}_-^\mu)}/\lambda_{233}^2$ ($L_{ee}=100$ fb^{-1})	14000	3300	1400	730	440	290

ber of $\tilde{\nu}_+^\mu + \tilde{\nu}_-^\mu$ also scaled by λ_{233}^2. [Recall that $\Gamma(\tilde{\nu}_\pm^\mu \to \gamma\gamma) \propto \lambda_{233}^2$; see Eq. (4) and assume scenario 2 with $i=2$.] In the table, $N_{(\tilde{\nu}_+^\mu+\tilde{\nu}_-^\mu)}/\lambda_{233}^2$ is given for a polarized PLC with initial photon helicities [28] $h_1 h_2 = 1$ and for two e^+e^- luminosity values of $L_{ee}=20$ fb^{-1} and a high luminosity PLC with $L_{ee}=100$ fb^{-1}, both for $E_{ee}=0.5$ TeV. Evidently, for $\lambda_{233}=1$, from thousands to hundreds of sneutrinos with masses 50–300 GeV, respectively, may be produced in a PLC with an integrated luminosity of $L_{ee}=100$ fb^{-1}. Similarly, hundreds to tens of sneutrinos may be produced if $L_{ee}=20$ fb^{-1} within the same $\tilde{\nu}_\pm^\tau$ mass range.

Given the event rates in Table I, one can estimate the statistical significance of the sneutrino signal in a PLC. Within scenario 2 with $\lambda_{233} \neq 0$, the μ-sneutrino will decay predominantly to $\tau^+\tau^-$, if we assume, for simplicity, that its R_P-conserving decays are either suppressed by phase-space factors in Eqs. (11) and (12), or are kinematically inaccessible. With these assumptions, $\mathrm{Br}(\tilde{\nu}_\pm^\mu \to \tau^+\tau^-) \sim 1$ with effectively no dependence on λ_{233}. The main background to $\gamma\gamma \to \tilde{\nu}_\pm^\mu \to \tau^+\tau^-$ is therefore from the continuum t-channel tree-level process $\gamma\gamma \to \tau^+\tau^-$. However, a significant reduction of this background is achieved if the $\tau^+\tau^-$ pair are restricted to be in a $J_z=0$ state by using polarized photon beams [26,27].

In [26] the number of tree-level t-channel exchange continuum $\gamma\gamma \to c\bar{c}$, $b\bar{b}$ events, as a function of the $q\bar{q}$ ($q = c$, b) invariant mass and in 10 GeV mass bins, was calculated in order to estimate the background to $\gamma\gamma \to h \to c\bar{c}$, $b\bar{b}$. A cut on the scattering angle $|\cos\theta| < 0.7$ was imposed, and only $q\bar{q}$, $J_z=0$ states were taken into account. We will use these results to estimate our $\gamma\gamma \to \tau^+\tau^-$ background. Note that since $\Gamma_{\tilde{\nu}_\pm^\mu} < 10$ GeV, we will assume that all the sneutrino events fall in one bin.

To a good approximation, $\sigma(\gamma\gamma \to \tau^+\tau^-)$ can be calculated from $\sigma(\gamma\gamma \to c\bar{c})$ by multiplying the latter by $(Q_c^4 N_c)^{-1} = 27/16$, and disregarding the very mild change due to the replacement $m_c \to m_\tau$ [29]. The significance of the $\tilde{\nu}_\pm^\mu$ signal is given by $S/\sqrt{B}$, where $S = N_{(\tilde{\nu}_+^\mu+\tilde{\nu}_-^\mu)}|_{|\cos\theta|<0.7} \times \mathrm{Br}(\tilde{\nu}_\pm^\mu \to \tau^+\tau^-)$ and $B = N(\gamma\gamma \to \tau^+\tau^-)|_{|\cos\theta|<0.7}$ from the tree-level process. Using the results in [26] we find that for $L_{ee}=20$ fb^{-1} and $m_{\tilde{\nu}_\pm^\mu}=50$, 100, 150, 200 GeV, $S/\sqrt{B} \simeq 46$, 8, 3, 4, respectively. For $L_{ee}=100$ fb^{-1} the corresponding numbers are, $S/\sqrt{B} \simeq 103$, 17, 7, 9, respectively. We also note that with $M_{\gamma\gamma} \gtrsim 200$ GeV the background event rates sharply drop such that there are fewer than ~ 85 background events for $M_{\gamma\gamma} \gtrsim 300$ GeV. Therefore, even with a heavy sneutrino of mass ~ 300 GeV, $S/\sqrt{B} \gtrsim 4$ for $L_{ee}=20$ fb^{-1} and $S/\sqrt{B} \gtrsim 10$ for $L_{ee}=100$ fb^{-1}. This can be compared with the s-channel neutral Higgs case, where the statistical significance of the signal from $\gamma\gamma \to h \to c\bar{c}$, $b\bar{b}$ drops below ~ 3 for $m_h \gtrsim 160$ GeV (when $L_{ee}=20$ fb^{-1}) [26] due to the opening of the decay channel $h \to VV, V=W$ or Z, and even before that to VV^*. For a heavier Higgs, $h \to t\bar{t}$ becomes important. Higgs bosons can then be detected in a PLC through these new decay modes [30], which have their own backgrounds and are not available for sneutrino decays at tree level (having neglected mass mixings in the superpotential). Therefore, both $\tilde{\nu}$ and h may be resonantly produced at a future photon-photon collider, then observed through their decays.

To summarize, we have demonstrated that within certain scenarios in $\not{R}_P$ MSSM, the loop-induced decay $\tilde{\nu} \to \gamma\gamma$ may be used as a tool for detecting singly produced sneutrinos at a high luminosity LHC over a significant $\tilde{\nu}$ mass range, if the relevant $\not{R}_P$ couplings are large enough, yet still within their experimentally allowed bounds. In addition we have discussed, at some length, resonant sneutrino production in a $\gamma\gamma$ collider.

At the LHC the main single sneutrino production mechanisms would be $b\bar{b}$ and bg fusion, while the Higgs boson will be produced via gg fusion. At the Tevatron, sneutrino production through $d\bar{d}$ fusion (irrelevant for resonant Higgs boson production) and its decay, via the two-photon mode, appears too small. Resonant sneutrino production in a hadron collider through $q\bar{q}$ fusion, has already been discussed in the literature [1–4]. Here we add two processes, where one of them, namely $bg \to \tilde{\nu} b$ is as significant as $b\bar{b} \to \tilde{\nu}$ at the LHC, and suggest $\tilde{\nu} \to \gamma\gamma$ as a relatively clean decay mode of sneutrinos as a signal for their detection. Though sneutrinos may be more abundantly produced than Higgs bosons in hadron colliders, their branching ratio to $\gamma\gamma$ are usually smaller (except for very high masses). These two effects thus compensate each other. The relatively clean $\gamma\gamma$ mode remains a promising prospect for detection, at least for masses $\lesssim 125-180$ GeV for $\lambda' = 1-1.5$, as can be seen from Figs. 1 and 3.

Sneutrinos can also be produced in future $\gamma\gamma$ colliders with a statistically significant signal, over a wide $m_{\tilde{\nu}}$ range. In particular, we have investigated a scenario in which all the couplings of the λ' type vanish and only $\lambda_{i33}\neq 0$. In this case, $\gamma\gamma$ colliders will be the only venue to produce resonant *s*-channel sneutrinos. In fact, the effect of a new $R\!\!\!/_P$ one-loop $\tilde{\nu}\gamma\gamma$ coupling is much more pronounced in a $\gamma\gamma$ collider than at the LHC. The reason is that $\tilde{\nu}$ production via $\gamma\gamma$ fusion is proportional to $\Gamma(\tilde{\nu}\rightarrow\gamma\gamma)$ which is only about one order of magnitude smaller then $\Gamma(h\rightarrow\gamma\gamma)$, whereas $pp\rightarrow\tilde{\nu}+X\rightarrow\gamma\gamma+X$ is proportional to $\mathrm{Br}(\tilde{\nu}\rightarrow\gamma\gamma)$ which is about three orders of magnitude smaller then $\mathrm{Br}(h\rightarrow\gamma\gamma)$ in the interesting mass range, $m_{\tilde{\nu}}$ or $m_h \lesssim 140$ GeV.

The situation is less optimistic with regards to uses of $\tilde{\nu}\rightarrow gg$: for sneutrino detection it will be (as in the Higgs case) swamped by the QCD background, while as far as production at the LHC goes, $gg\rightarrow\tilde{\nu}$ will be overshadowed by $b\bar{b}\rightarrow\tilde{\nu}$ and $bg\rightarrow\tilde{\nu}+b$, unlike the Higgs case where it will be mainly produced through gg fusion.

Loop-induced sneutrino decays to WW and ZZ, are expected at the same order as the decays to $\gamma\gamma$ (disregarding L_iH_u terms). These decays may also be useful for $\tilde{\nu}$ production (e.g., through WW fusion), or detection (e.g., in $\tilde{\nu}\rightarrow ZZ$).

A few directions for future research are listed below:

(1) EW and QCD corrections to the lowest-order processes presented here may need to be calculated.

(2) More realistic background estimates have to be performed, including signal to background ratios for the competing processes $pp\rightarrow\tilde{\nu}+X\rightarrow b\bar{b}$, $\tau^+\tau^-+X$. Similarly, the interesting triple-fermionic final states in $pp\rightarrow\tilde{\nu}b+X\rightarrow bb\bar{b}$, $b\tau^+\tau^-+X$ in which the single sneutrino from $bg\rightarrow\tilde{\nu}+b$ decays to $b\bar{b}$ or $\tau^+\tau^-$, should be studied.

(3) Can one gain much by requiring that a b jet accompany the two photons, thus enhancing the sensitivity to the processes $bg\rightarrow\tilde{\nu}+b$?

(4) The importance of the loop processes $\tilde{\nu}\rightarrow WW$, ZZ remains to be assessed.

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