

Single sneutrino production at hadron colliders

Masud Chaichian^{a,b}, Anindya Datta^{b,1}, Katri Huitu^{a,b}, Sourov Roy^{b,c,2}, and
Zenghui Yu^{a,b}

^aDivision of High Energy Physics, Department of Physical Sciences, and
^bHelsinki Institute of Physics,
P.O.Box 64, FIN-00014 University of Helsinki, Finland

^cDepartment of Physics, Technion - Israel Institute of Technology
Haifa 32000, Israel

Abstract

We study the production of a single sneutrino in association with one or two b -quarks at hadron colliders, in the framework of an R-parity violating supersymmetric model. We find that at the Large Hadron Collider (LHC) four b final states are promising with efficient b -tagging. $l^+l'^-$ decay modes of the sneutrino can also be viable for detection at the LHC. However, the branching ratio for rare $\gamma\gamma$ decay channel is too small to be seen.

Detection of supersymmetric (SUSY) particles will be one of the major goals at the LHC. The common strategy for the detection is to study the production and cascade decays of strongly interacting superparticles like squarks and gluinos. The production cross-sections for sleptons or sneutrinos are small as they are weakly interacting. At the same time, pair production of these weakly interacting superpartners may not be favoured by kinematics even at the LHC. Single production of these particles might be useful to consider in such situations.

The supersymmetric partners can be produced singly, if the R-parity [1] is broken ($R_p = (-1)^{3B+L+2S}$, where B , L and S denote the baryon number, lepton number and spin, respectively). Another important consequence of the R_p -violation (\mathcal{R}_p) is that it may explain the experimental results on neutrino masses from atmospheric [2], solar neutrinos

¹Present Address : INFN, Sezione di Roma, Universita La-Sapienza, P.le A. Moro 2, I-00185, Rome, Italy

²Present address: Helsinki Institute of Physics

[3, 4] and reactor [5] experiments. In the sneutrino sector, sneutrinos and antisneutrinos can mix, which can give rise to CP violation [6]. Detection of weakly interacting, neutral sneutrinos at hadron colliders may not be straightforward, but since they may be among the lightest supersymmetric particles with interesting properties, it is important to explore all possibilities for their detection.

We will consider here the L -violating trilinear terms [7]:

$$W_{\mathcal{R}_p'} = \frac{1}{2} \lambda_{[ij]k} L_i \cdot L_j \bar{E}_k + \lambda'_{ijk} L_i \cdot Q_j \bar{D}_k, \quad (1)$$

where L_i and Q_i are the SU(2) doublets containing lepton and quark superfields, respectively, \bar{E}_j (\bar{D}_j , \bar{U}_j) are the singlets of lepton (down-quark and up-quark), and i, j, k are generation indices and square brackets on them denote antisymmetry in the bracketed indices.

The single sneutrino production at hadron colliders has been studied in Refs. [8, 9, 10, 11]. The resonant sneutrino produced in the Drell-Yan process via first generation λ' type couplings could also decay via the same couplings, but its detection seems problematic due to the large QCD background [8] especially at LHC. Therefore, other decay channels following the resonant production have been studied, *e.g.* decays to a lepton pair [9] and decays via gauge interactions [10], including cascade decay to three leptons [11]. In all these cases the detection seems viable for some part of the parameter space. In Ref. [12] the rare decay mode to two photons was considered. It was found that taking into account single sneutrino production from several different two parton processes, the accumulated events may provide a sufficient signal at the LHC, at least for relatively light sneutrino mass and large \mathcal{R}_p coupling. The single production of sneutrinos in lepton colliders has been considered in [13].

We will assume here that the \mathcal{R}_p couplings have a family hierarchy and only the third generation fermions couple significantly to the sneutrinos. Thus the valence quark contribution to the parton level Drell-Yan process is small. Here we will concentrate on the single production of sneutrinos in proton proton (anti-proton) process in association with two jets, of which at least one is a b -quark. Efficient b -tagging helps to find out the signal events. Some of the Feynman graphs are depicted in Fig. 1. There are two classes of sub-processes (quark initiated and gluon initiated) contributing to the total cross-section. At the LHC, gluon fluxes are larger than quark fluxes. In addition, in the quark initiated sub-processes one of the initial partons is an anti-quark, and thus is excited from the sea. Eventually from a proton-proton collision, effective $q\bar{q}$ luminosity is negligible compared to the gluon-gluon luminosity at the LHC. At the Tevatron, which is a proton anti-proton collider, both the initial quark and anti-quark can be valence partons. Although the gluon initiated contribution is dominant also here, the quark initiated subprocesses are not negligible. We can easily see this by calculating the ratio of the cross section for quark initiated

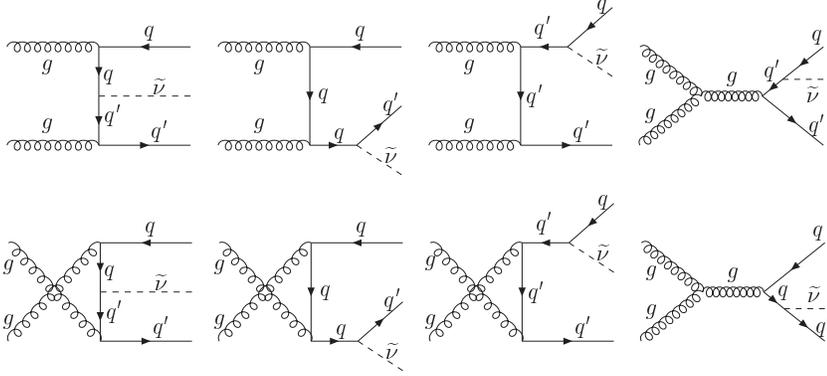


Figure 1: Some of the parton level Feynman diagrams contributing to the process $pp \rightarrow \tilde{\nu}qq'$.

contributions to the cross section, in which both quark and gluon initiated contributions are included. At the LHC for a sneutrino of mass 180 GeV (with $\lambda' = 1$), the ratio is nearly 1/135 (1.35 pb) compared to 1/5 (3.5 fb) at the Tevatron.

The production of single sneutrinos depends only on two unknown parameters, namely the sneutrino mass and the value of the relevant coupling λ'_{ijk} .

The constraints on R_p -violation coming from the low energy experiments have been widely discussed [14]. Here we will consider those third generation couplings which are relevant for us. We will first discuss the bounds other than those due to the neutrino mass. The best bound on λ'_{33k} comes from the ratio $R_l = \Gamma(Z \rightarrow had)/\Gamma(Z \rightarrow l\bar{l})$. Assuming that the \tilde{q} masses in the loop are above 200 GeV, the upper bound becomes $\lambda'_{33k} \lesssim 0.55$ [15]. For us the other relevant experimental limits on the couplings are (from Allanach et al. in [14])

$$\lambda_{32k} \lesssim 0.070 \times \frac{m_{\tilde{e}_{kR}}}{100 \text{ GeV}}, \quad \lambda'_{323} \lesssim 0.52 \times \frac{m_{\tilde{b}_R}}{100 \text{ GeV}}. \quad (2)$$

The bounds in (2) are found [16] from the measurements of $R_\tau = \Gamma(\tau \rightarrow e\nu\bar{\nu})/\Gamma(\tau \rightarrow \mu\nu\bar{\nu})$ and $R_{\tau\mu} = \Gamma(\tau \rightarrow \mu\nu\bar{\nu})/\Gamma(\mu \rightarrow e\nu\bar{\nu})$ for λ_{32k} , and from [17] $R_{D_s} = \Gamma(D_s \rightarrow \tau\nu_\tau)/\Gamma(D_s \rightarrow \mu\nu_\mu)$ for λ'_{323} .

It has been shown that phenomenologically acceptable neutrino masses can be generated by using only R -parity violation, see e.g. [18]. The fit results in R -parity violating couplings, which are quite small in size. We will not insist in generation of the neutrino mass matrix, but instead take a more conservative viewpoint, and take into account only the limits in the previous paragraph, and consider the possibilities to detect a sneutrino at LHC.

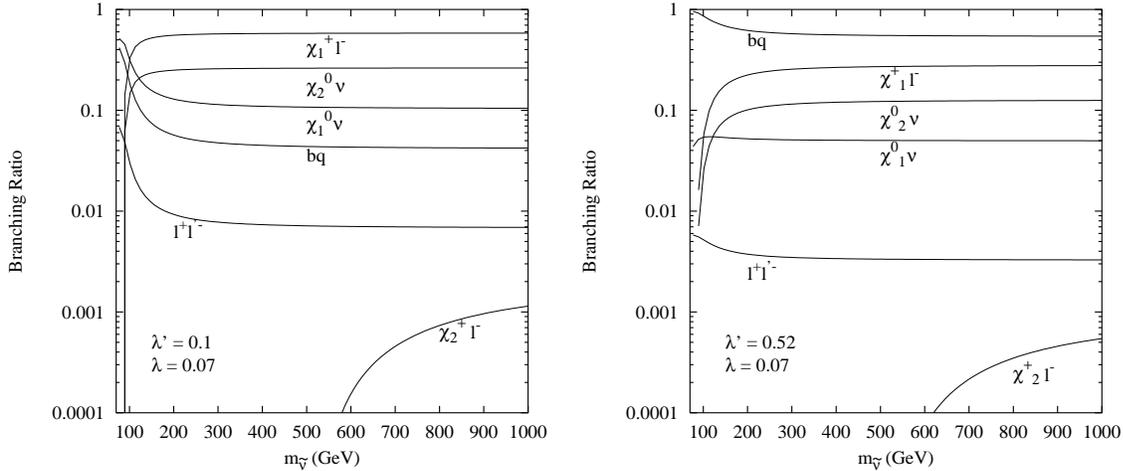


Figure 2: The branching ratio of a sneutrino, when $\lambda' = 0.1$ or 0.52 , and $\lambda = 0.07$. In both the cases $\mu = 500$ GeV and $\tan \beta = 10$.

The mass bounds for the sneutrinos and other supersymmetric particles in R -parity violating models have been studied in the LEP and Tevatron experiments [19, 20]. In [20] it was found that if the λ'_{3jk} coupling dominates, the lower limit on the tau sneutrino mass varies between 79 GeV and 92 GeV, depending on the lightest neutralino mass. If the lightest neutralino is heavier than around 80 GeV, the lower bound on the sneutrino mass drops to slightly above 40 GeV.

The $\tilde{\nu}$ decay modes are essential for the detection. These depend on the SUSY parameters. Here we will consider the sneutrino decay modes to at least one b -jet, leptons and photons, *i.e.*

$$\tilde{\nu} \rightarrow bq, l^+ l'^-, \gamma\gamma. \quad (3)$$

In our example of the branching ratios for the sneutrino in Fig. 2, the lightest neutralino mass is 41 GeV, the second lightest neutralino and the lightest chargino ~ 80 GeV and the heavy chargino ~ 500 GeV. The value of μ is taken to be 500 GeV and $\tan \beta = 10$. With the coupling $\lambda' = 0.52$, the decay channel to two quarks is the dominant one. A heavier neutralino or chargino mass would significantly increase the R -parity violating branching ratio of the sneutrino. This in turn implies a higher rate of the sneutrino decay signal we are interested in. The decays via λ' interactions do not require any new information of the model, since the decay can occur via the same coupling as the production. The

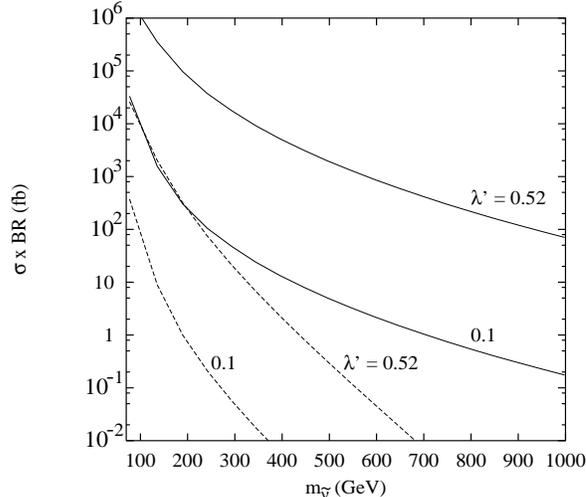


Figure 3: The cross section for the process $pp \rightarrow bq\tilde{\nu} \rightarrow bq\bar{b}q$ as a function of the sneutrino mass with $\lambda' = 0.52, 0.1$, as indicated in the figure. The solid lines correspond to LHC and the dashed ones to Tevatron.

other relevant decay modes are the gauge decays, which are dominant, if the \mathcal{R}_p couplings are small. The decays via gauge interactions lead typically to complicated cascade decays [10]. The branching ratio to two photons is $\mathcal{O}(10^{-6})$. In Fig. 2, we have also assumed that $\lambda = 0.07$, and consequently the sneutrino decays to two leptons as well.

In our numerical calculations we use for the gluon distribution functions the PDFLIB package [21] and the GRV distribution [22] from there.

When one of the couplings λ'_{323} , λ'_{332} , or λ'_{333} does not vanish, we shall have two or four b -jets in the final state. If only one of the couplings λ'_{323} and λ'_{332} is different from zero, in the final state one observes two b -jets and two s -jets with a pair of a b -jet and an s -jet forming the sneutrino, while if also $\lambda'_{333} \neq 0$, one can have final states with three or four b -jets. In Fig. 3 we have plotted the production cross section times the branching ratio for LHC (solid) and Tevatron (dashed) using two values for the coupling, $\lambda' = 0.52$ and 0.1 . For LHC the cross sections remain above 1 fb up to $m_{\tilde{\nu}} \sim 700$ GeV, while for Tevatron the cross sections are considerably lower.

The signal that we are interested in, is not free from the Standard Model (SM) backgrounds. In fact, the cross-section of the SM processes contributing to the four jet final state is huge. A large number of diagrams contribute to this final state. We have estimated

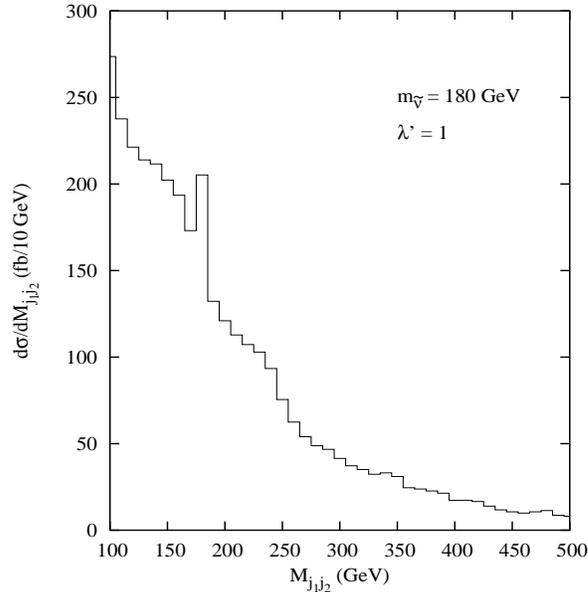


Figure 4: Invariant mass distribution of two highest p_T jets, of sneutrino events superimposed on SM QCD background. We have used bin sizes of 10 GeV. For the sneutrino signal a sneutrino mass of 180 GeV and $\lambda' = 1$ have been used.

this SM background using the package MADGRAPH [23] and HELAS [24]. The SM QCD background is populated mostly at the low transverse momentum and high rapidity of the jets. We have demanded that the final state is comprised of exactly four jets with rapidity $|\eta| < 2.5$ and transverse momentum $p_T > 25$ GeV. We also demand that the angular separation in between any two of the jets is substantial, $\Delta R (= \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}) > 0.7$. Using only these cuts does not help us to reduce the SM background much. We notice that the jets coming from sneutrino decay have larger transverse energy/momentum. This is demonstrated in Fig. 4, where we have plotted the invariant mass distribution of two highest p_T -jets for signal and background for a 180 GeV sneutrino mass. For the signal, invariant mass distribution of two highest p_T -jets peaks sharply (modulo the detector smearing and decay width of the sneutrino) around the sneutrino mass compared to the monotonically decreasing distribution from SM QCD processes. We have taken into account the finite detector resolution effects by gaussian smearing of the p_T of the jets, as $\Delta p_T^j/p_T^j = 0.6/\sqrt{p_T^j} + 0.03$. Thus we compare the number of signal and background events in the bin (of width 10 GeV) corresponding to the sneutrino mass.

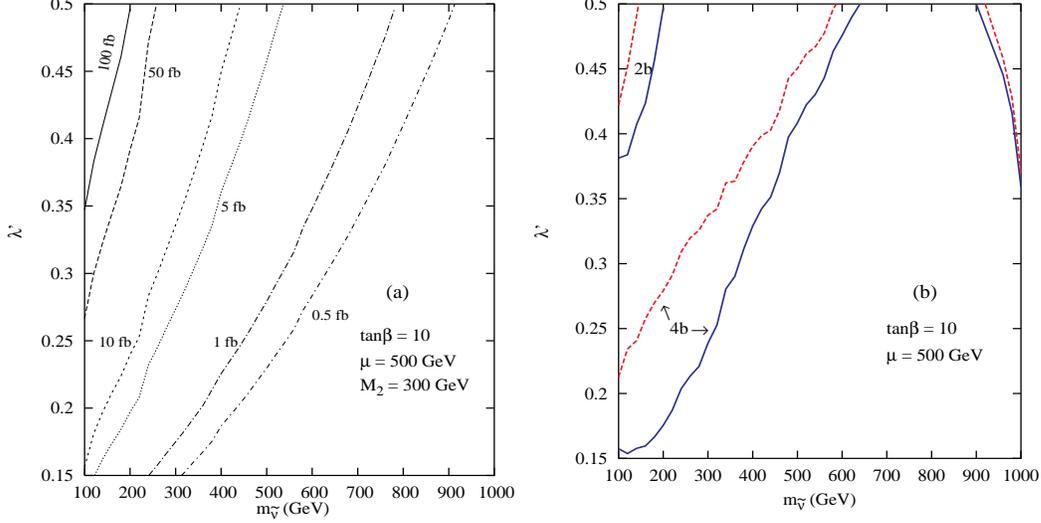


Figure 5: a) Contour levels of $4b$ -cross-section in invariant mass bins (of width 10 GeV, central value of the bin corresponds to sneutrino mass) from sneutrino production and decay via λ' coupling. We have used $\tan\beta = 10$, $\mu = 500$ GeV and $M_2 = 285$ GeV for this plot. b) 5σ discovery regions for LHC (with 100 fb^{-1} integrated luminosity) in $\lambda' - m_{\tilde{\nu}}$ plane for $m_{\tilde{\chi}_1^\pm} = 81$ GeV (dashed) and $m_{\tilde{\chi}_1^\pm} = 272$ GeV (solid). Lines marked with ‘2b’ represent the final states containing two b -jets and lines marked with ‘4b’ represent final states with four b -jets.

There is one caveat regarding the normalisation of the SM background. The background cross-section is proportional to the fourth power of α_s . As we are only using the leading order (in α_s) expression for the background cross-section, the scale dependence of the result is quite strong. To be conservative, we have chosen the scale of α_s (and the factorisation scale of parton distribution function) to be equal to the p_T of the softest jet. While estimating the sneutrino cross-section, the same scale is set to be equal to $\sqrt{\hat{s}}$, center-of-mass energy of the colliding partons. In this way, we have tried to maximise the background and minimise the signal, to make a conservative estimate of signal to background ratio.

In Fig. 5a, the contour levels for four b -quark cross-section in bins (of invariant mass of two highest p_T jets) of 10 GeV have been presented for $\tan\beta = 10$, $\mu = 500$ GeV and $M_2 = 285$ GeV. The central value of the bin corresponds to the sneutrino mass. The nature of the contours can be easily explained. Sneutrino cross-section falls off with mass,

and to make up this decrement one has to have higher values of λ' coupling. The mild 'knees' around $m_{\tilde{\nu}} = 250$ GeV and 550 GeV are due to the opening up of the sneutrino decay channels to the second lightest neutralino, lighter chargino, and heavier chargino.

In Fig. 5b, we have plotted the statistical significance ($\sigma \equiv \text{signal}/\sqrt{\text{background}}$) of the proposed signal over SM background with 100 fb^{-1} luminosity at the LHC. We have considered two different cases of R-parity violating couplings. The lines marked with '4b', assume non-zero values for λ'_{i33} , and represent thus final states with four b -jets. The curves marked with '2b' represent the final states of two b - and two light quark jets (gluons in the case of SM background).

Since no sfermion mixing is involved here our results are not very sensitive to $\tan\beta$. However, relative strength of μ with respect to M_2 , can alter the compositions of charginos and neutralinos. For presentation we have used $\mu = 500$ GeV with $M_2 = 85$ GeV (correspond to the chargino mass $m_{\tilde{\chi}_1^\pm} = 81$ GeV; dashed line). This configuration essentially results in a wino-like lighter chargino and second lightest neutralino along with a bino-type lightest neutralino. Values of μ comparable with M_2 (285 GeV, solid line) could result in the lightest neutralino and charginos with competing gaugino and higgsino components. This value of M_2 corresponds to $m_{\tilde{\chi}_1^\pm} = 272$ GeV. Larger higgsino components in the lightest neutralino and lighter chargino will diminish the sneutrino decay rates to R-parity conserving channel. This is evident from the nature of the plots presented above. The value of μ (relative to M_2 values) used in our analysis is on the conservative side.

In the regions above the solid and dashed lines, signal strength is higher than a 5σ fluctuation of the SM background. It is evident from the figures that discovery reach for the '4b' channel is better than for the '2b' channel where sneutrino is decaying to a b - and a non- b -quark. This can be accounted for by the size of SM background in these two cases. With an efficient b -tagging (as assumed in our case), '4b' background is more under control compared to the '2b' + '2j' final state. It has been assumed in the calculation that the b -tagging efficiency is 60 %, and mis-tagging probability is 1 % [25]. For Tevatron the 5σ effect can be found in the case of the four b -jets, when the sneutrino mass is around 100 GeV and $\lambda' \sim 0.5$.

Both the signal and background cross-sections decrease monotonically with increasing invariant mass of the two highest p_T jets (equals to sneutrino mass for the signal). However, sneutrino cross-section falls off more rapidly than the QCD background for lower values of the invariant mass. Thus to have a constant value of statistical significance for heavier sneutrino masses we need higher value for λ' . This is evident from the plots in Fig. 5. However, beyond some particular value of this invariant mass, the situation is reversed and QCD cross-section decreases more rapidly than the sneutrino cross-section. This explains the behaviour of the plots (4b-case only) for higher values of invariant mass.

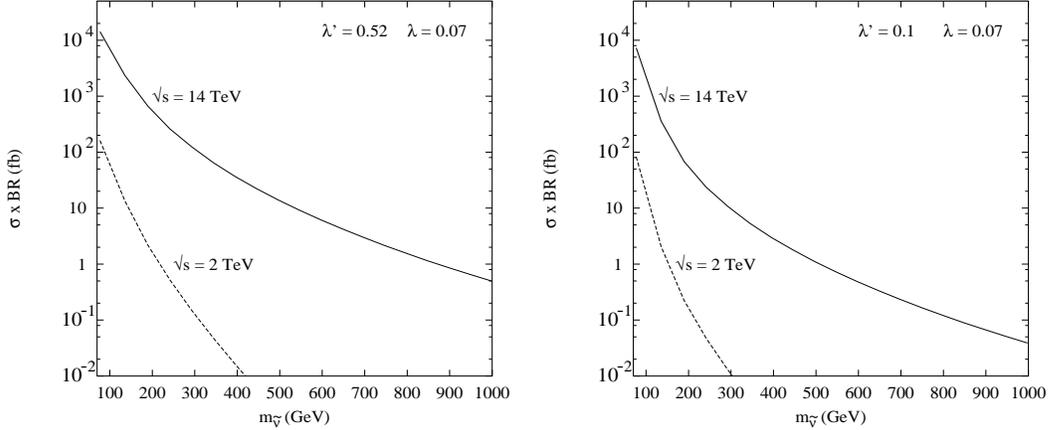


Figure 6: The cross section for the process $pp \rightarrow bq\tilde{\nu} \rightarrow bq\mu e$ as a function of the sneutrino mass with $\lambda' = 0.52$ (left figure) or 0.1 (right figure), and $\lambda = 0.07$. The solid line corresponds to LHC and the dashed one to Tevatron.

We have estimated the prospect of our proposed signal for two different values of the chargino (neutralino) mass. For a higher value of chargino mass (272 GeV in Fig. 5), the R-conserving sneutrino decays are suppressed resulting in an enhancement of our signal coming from R-violating channel. Naturally efficacy of the R-parity violating decay signal for a higher value of chargino (neutralino) mass is better than a lower chargino mass (for illustration we have also presented the result for a chargino mass of 81 GeV).

Another possibility for producing sneutrinos might be the diffractive production [26] which seems to offer an interesting complementary way for Higgs production at the LHC. We tried to make a naive estimate of this possibility in the case of sneutrino. Unfortunately a chirality flip in the quark loop would essentially suppress the cross-section by the fourth power of the ratio of b and top quark masses, compared to the Higgs production cross section. Even if the R -parity violating coupling were $\lambda' \sim 0.5$, the cross section would be too small for the sneutrinos to be detected. Moreover, all the estimates of the Higgs production via diffractive processes are plagued with huge uncertainties arising from the non-perturbative aspects of QCD involved here. This huge systematic error also affects the sneutrino production cross-section in a very similar way. Considering the above two drawbacks, diffractive sneutrino production at hadronic collision does not seem to be very promising.

Detection of muons at Tevatron and LHC experiments is straightforward. Thus, even if a small λ type coupling leading to a sneutrino decaying to muons exists, the branching

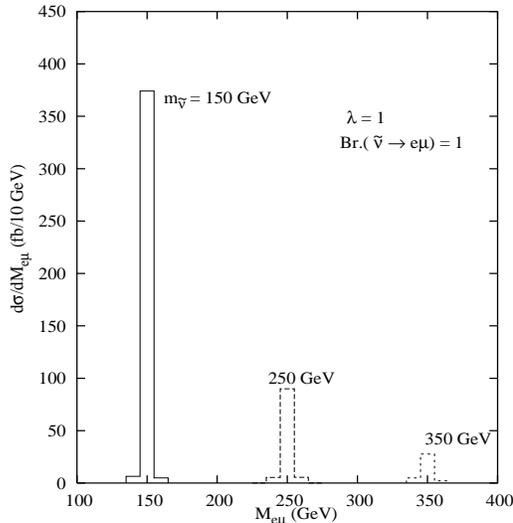


Figure 7: The $e\mu$ -mass distribution in bins of 10 GeV. Here λ_{321} -coupling is assumed nonvanishing.

ratio may be big enough for detecting a peak in the invariant mass. In Fig. 6 we have considered a decay to a muon and an electron, and plotted the $\sigma \times \text{BR}$ for the values of the couplings $\lambda' = 0.52$ and 0.1 and $\lambda_{321} = 0.07$. It is seen that the cross section at the LHC is above 1 fb up to $m_{\tilde{\nu}} \sim 600$ GeV for $\lambda' = 0.52$ and $m_{\tilde{\nu}} \sim 400$ GeV for $\lambda' = 0.1$. Although the number of events at high masses is not large, the narrow sneutrino peak should be easily detected.

In Fig. 7, we present the $e\mu$ -mass distribution in bins of 10 GeV for three representative sneutrino masses. As we are limited by the parton level analysis, we parametrise the finite detector resolution and other effects due to e.m. radiation by gaussian smearing the p_T of the μ and e , according to $\Delta p_T^l / p_T^l = 0.15 / \sqrt{p_T^l} + 0.01$. We assume 100 % μ - and e - detection efficiency. Thus, there is essentially no physics background to this flavour violating decay signal. For purpose of illustration in Fig. 7, we have chosen the λ_{321} -coupling to be non-zero as well as the sneutrino decay branching ratio to $e\mu$ to be equal to 1.

As discussed earlier, in [12] it is proposed that the sneutrino decay to photons could be used for detection. Also, the rare scalar decay mode to two photons is considered to offer the best possibility for detecting the low-mass Higgs at the LHC. In the case of the Higgs, the relatively large branching ratio is due to the large top Yukawa coupling. In our case one might expect large branching ratio, if the third generation λ' coupling is large.

However, the branching ratio is not large because of the chirality structure in the vertex. In Ref. [12], the large production cross section compensates the small branching ratio, and thus the $\gamma\gamma$ decay mode can be observable. In our case, the cross section times branching ratio is less than 0.1 fb for sneutrinos heavier than 120 GeV, and thus we do not consider this a viable search mode here.

As a summary, we conclude that the single production of sneutrino in association with one or two b -jets may be observable at LHC with sneutrino decaying to one or two b 's or to two leptons, if the R_p violating couplings are not very small, but of the order of $\mathcal{O}(10^{-1})$.

Acknowledgements

The authors thank the Academy of Finland (project numbers 48787 and 54023) for financial support. Z.-H. Yu thanks the World Laboratory, Lausanne, for the scholarship. The research of S.R. was partially supported by a Lady Davis postdoctoral fellowship. A.D. acknowledges financial support from I.N.F.N., Sezione di Roma.

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