R-PARITY VIOLATING CONTRIBUTIONS TO FLAVOR CHANGING AND CP VIOLATION EFFECTS IN FERMION AND SFERMION PAIR PRODUCTION

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We examine the contributions from the R-parity odd interactions, \( \lambda_{ijk} L_i L_j E^c_k \) and \( \lambda'_{ijk} L_i Q_j D^c_k \), to the total rates and the CP asymmetry rates in the production of fermion-antifermion (lepton, down and up quark) pairs and slepton-antislepton pairs of different flavors at leptonic colliders. For the top-charm associated production case, we evaluate dynamical distributions for the semileptonic top decay events and estimate the sensitivity reach on the relevant parameters.

1 Introduction

The flavor non-diagonal and/or CP violating effects induced through the R parity violating (RPV) interactions may become observably accessible at the high energy leptonic colliders. For the two-body reactions of fermion-antifermion pair production, \( l^- + l^+ \to f_J + \bar{f}_{J'} \), where the produced fermions are charged leptons, down-quarks or up-quarks of different flavors, \( J \neq J' \), the RPV interactions contribute at the tree level to the rates, \( \sigma_{JJ'} \). Furthermore, the differences of rates for the pairs of CP-conjugate processes, \( M_{JJ'} = l^- + l^+ \to f_J + \bar{f}_{J'} \), and \( \bar{M}_{JJ'} = l^- + l^+ \to f_J + \bar{f}_{J'} \), as described by the asymmetry, \( A_{JJ'} = (|M_{JJ'}|^2 - |M_{J'J'}|^2)/(|M_{JJ'}|^2 + |M_{J'J'}|^2) \), provide simple CP-odd observables involving interference terms of tree and one-loop level amplitudes. The particular mechanism we study uses the possibility where a complex CP-odd phase is embodied in the RPV coupling constants, as is allowed thanks to the non trivial structure of the RPV coupling constants in the quarks and leptons generation spaces. One may, of course, think of other RPV induced mechanisms in which the CP-odd complex phase arises from the regular interactions in the minimal supersymmetric standard model (MSSM). It is worth recalling here that the standard model contributions to the flavor changing rates and/or CP asymmetries for fermion pair production arise first at the one-loop order and are found to be exceedingly small. By contrast, the prospects are on the optimistic side in most physics extensions beyond the standard model, including the MSSM, where the contributions may be bounded by postulating either a degeneracy of the soft supersymmetry breaking scalars masses or an alignment of the fermion and scalar superpartners mass matrices.

If the initial energy at linear colliders is sufficient for the production of a pair of sfermions, the analogous two-body reactions involving the production of slepton pairs, \( l^- + l^+ \to \tilde{e}_{HJ} + \tilde{e}_{H'J'} \), \( H,H' = (L,R) \), could also be observed. Flavor non-diagonal sfermion pair production can proceed in the MSSM via a flavor oscillation mechanism.

In this report, we present a summary of results for the rates \( \sigma_{JJ'} \) and the CP
Table 1: RPV coupling constants products entering the t- and u-channel exchange amplitudes for fermion-antifermion pair production. The column entries refer to the final states with charged lepton, down-quark and up-quark pairs, respectively, and the two line entries to the tree and one-loop level contributions.

| e_i e_j | d_i d_j | u_i u_j |
|---------|---------|---------|
| $\lambda_{iJ1} \bar{\nu}_i \nu_i^*$, $\bar{\nu}_i L$ | $\lambda_{iJ1} \bar{\nu}_i \nu_i^*$, $\bar{\nu}_i L$ | $\lambda_{iJ1} \bar{\nu}_i \nu_i^*$, $\bar{\nu}_i L$ |

2 Fermion pair production

The flavor non-diagonal fermion pair production process, $l^- + l^+ \rightarrow f_f + \bar{f}_f$, proceeds at the tree level through sfermion exchange diagrams (t-channel for lepton and down-quark, u-channel for up-quark and s-channel for lepton and down-quark) controlled by pairs of distinct RPV interactions coupling constants. Restricted sets of chirality configurations for the initial and final state fermions are generally selected. The vertex and box diagrams arising at the one-loop level are controlled by different pairs of RPV coupling constants. We shall restrict consideration to the vertex corrections in the $\gamma -$ and $Z -$ boson exchange. The quadratic products of the relevant RPV coupling constants, along with the intermediate fermion and scalar particles, present in the tree and one-loop amplitudes are displayed in Table 1. This clearly demonstrates that a large number of the RPV coupling constants can be probed through the study of these reactions.

Proceeding to the numerical results, we find that the predicted flavor non-diagonal rates slowly decrease with the center of mass energy and scale with the the exchanged superpartner mass parameter, $\tilde{m}$, approximately as, $
sigma_{f_f} \approx (\Lambda^2 / \tilde{m})^{1/2} (10^{10} GeV^{-1})^{1/2} (1 - 10) fbarns$, where, $\Lambda = \lambda$ or $\lambda'$, as the case may be. The exponent controlling the superpartner mass dependence lies in the range, $p \approx (2 - 3)$, and decreases with increasing center of mass energy. For realistic experimental conditions corresponding to a maximum of signal events around, $N_S = \sigma L = 10$, and an integrated luminosity around, $L = 100 fb^{-1}$, the sensitivity on the relevant RPV coupling constants products, as quoted in Table 1, reads: $\Lambda < 3 \times 10^{-3} (m / 100 GeV)^{-p/2} (N_S^{1/2} (100 fb^{-1} / L)^{1/2}$. The majority of the current indirect bounds on the relevant products, $\lambda \lambda$, $\lambda' \lambda'$, lie close to the above quoted value, while the strongest bounds on quadratic products, such as those arising
from $\mu \rightarrow 3l$, $K \rightarrow \pi \nu \bar{\nu}$, $\cdots$ can be evaded thanks to the existence of several different contributions to the fermion pair production amplitudes. An analysis of the current single coupling constants bounds yields the following list of least constrained products of couplings and the corresponding preferred fermion pair production: $e\bar{\tau} : \lambda_{211}\lambda_{321,213} < O(10^{-3})$, $\lambda_{311}\lambda_{313} < O(10^{-3})$; $\mu\bar{\tau} : \lambda_{121}\lambda_{131} < O(10^{-3})$, $\lambda_{212}\lambda_{213} < O(10^{-3})$, $\lambda_{312}\lambda_{313} < O(10^{-3})$, $\lambda_{311}\lambda_{323} < O(10^{-3})$, $\lambda_{211}\lambda_{232} < O(10^{-3})$; $d\bar{b} : \lambda_{121}\lambda_{123} < O(10^{-3})$; $s\bar{b} : \lambda_{122}\lambda_{123} < O(10^{-2})$; $c\bar{t} : \lambda_{122}\lambda_{132} < O(10^{-2})$, $\lambda_{121}\lambda_{131} < O(10^{-3})$.

We choose to assign the CP-odd phase in such a way that the RPV coupling constants product in the tree amplitude is real while that of the loop amplitude has a non-vanishing complex phase, $e^{i\psi}$. Assuming that all the relevant RPV coupling constants are set at equal values, we find asymmetries of order, $A_{\ell \nu} \approx (10^{-2} - 10^{-3}) \sin \psi$. The rational dependence of the CP asymmetries on the coupling constants, $\text{Im}((\lambda^{\star})_{\text{loop}}((\lambda^{\star})_{\text{tree}})/(\lambda^{\star})_{\text{tree}})$, may lead to strong enhancement or suppression factors on the CP rate asymmetries to the extent that the quarks or leptons generation dependence of the RPV coupling constants presents a hierarchical structure. Setting tentatively the RPV coupling constants at their current bounds, one predicts for $e\bar{\tau}$, $\text{Im}((\lambda^{\star})_{132}(\lambda^{\star}_{332}/\lambda_{311}\lambda_{321})/O(10)$, and for, $t\bar{c}$ : $\text{Im}((\lambda^{\star}_{122}(\lambda^{\star}_{123}/\lambda_{12k}\lambda_{13k})/O(1)$. We also obtain predictions for the $Z$-boson flavor non diagonal decay rates, $B_{\ell \nu} = B(Z \rightarrow \ell_{\nu} + \ell_{\nu}^{\star}) \approx (\frac{\lambda^{\star}}{\sqrt{m}})^{2}(\frac{100 GeV^{2}}{m}) 10^{-9}$. The corresponding CP-odd asymmetries, $A_{\ell \nu} = \frac{B_{\ell \nu} - B_{\ell \nu}^{\star}}{B_{\ell \nu} + B_{\ell \nu}^{\star}}$, as induced through interference terms between contributions to the loop amplitudes in different flavor configurations, vary inside the range, $(10^{-1} - 10^{-3}) \sin \psi$.

The flavor tagging for quarks is experimentally difficult except for the case of top production. For the top-charm production reaction, the final state signal associated with the top semileptonic decay, $(b\ell^{+}\nu\bar{c}) + (b\ell^{-}\nu c)$, $[\ell = e, \mu]$, consists of an isolated energetic charged lepton, a pair of $b$ and $c$ quark hadronic jets and missing energy. These events have a clean signature and may easily be distinguished from the standard model background which arises mainly from the $W$-boson pair production reaction, $e^{+}e^{-} \rightarrow W^{+}W^{-}$. We consider a set of characteristic final state kinematical variables. The distributions, as plotted in Fig. show marked differences between signal and background. The numerically evaluated efficiencies found for a suitable set of selective cuts are, $\epsilon_{S} \simeq 0.8$ for the signal and $\epsilon_{B} \simeq 3 \times 10^{-3}$, for the background. For the interval of superpartner masses, $100 < \tilde{m} = m_{\tilde{d}_{k}R} < 1000 GeV$, the sensitivity reach for the relevant RPV coupling constant products is, $\lambda_{12k}\lambda_{13k} < (1.5) \times 10^{-2}(100fb/\mathcal{L})^{\frac{1}{2}}$, where $\mathcal{L}$ is the integrated luminosity.

3 Slepton pair production

The flavor non-diagonal tree level ($\nu_{i}$ exchange) amplitudes for the reactions, $l^{-} + l^{+} \rightarrow \tilde{\nu}_{ij}H + \tilde{\nu}_{ij}^{\star}H$, involve the product of RPV coupling constants, $\lambda_{ij1}\lambda_{11j}$, for L-sleptons and, $\lambda_{ij1}\lambda_{11j}$, for R-sleptons. The loop amplitudes involve a twofold summation over leptons families with a quadratic dependence on the RPV coupling constants involving, $\lambda_{ijk}\lambda_{ijk}^{\star}$, $[d_{k}u_{j}]\lambda_{ijk}\lambda_{ijk}$, $[e_{k}\nu_{j}]$, for L-sleptons, and $\lambda_{ijj}\lambda_{ijj}^{\star}$, $[e_{j}\nu_{j}^{\star}]$ for R-sleptons, where the brackets indicate the fermions circulat-
Dynamical distributions associated with the signal events, \( l^+ l^- \rightarrow (t\bar{t}) + (\bar{t}c) \rightarrow (b^+ \nu c) + (b^- \bar{\nu}c) \) (dashed line) and the background events, \( l^+ l^- \rightarrow W^+ W^- \rightarrow (l^+ \nu qq') + (l^- \bar{\nu}qq') \) (continuous line) at a center of mass energy, \( s^{1/2} = 1 \text{ TeV} \). The kinematical variables are the maximum and minimum energy of the two jets, \( E_{\text{high}} \) and \( E_{\text{low}} \), the dijet invariant mass, \( M_{jj} \), and the charged lepton energy, \( E_l \), and rapidity, \( y_l = \frac{1}{2} \log \frac{E_l + p_l^Z}{E_l - p_l^Z} \).

Summarizing briefly our results, we find that the rates rise sharply at threshold and, with growing center of mass energy, \( s^{1/2} \), settle roughly as, \( \tilde{m}^2 / s \), to constant values of order, \( 20 - 2 \text{ fbarns} \), in units of \( (\lambda' \lambda')^2 \) or \( (\lambda' \lambda')^2 \), as one sweeps through the interval, \( \tilde{m} \in [60, 400] \text{ GeV} \) for the final sleptons mass. The predicted flavor non-diagonal CP asymmetries are of order \( A_{JJ'} = (10^{-2} - 10^{-3}) \sin \psi \), using the same particular prescription as in the above fermion production case where the RPV coupling constants products in the loop and tree amplitudes have the relative phase, \( e^{i\psi} \). Since the same quadratic products of coupling constants enter as in the fermion pair production case, any observable contribution to flavor changing or CP violation effect in fermion pair production would entail a contribution of similar size to sfermion pair production.

References

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