Search for R-parity violation from J-PARC and LHC

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We consider the case that $\mu$-$e$ conversion signal is discovered but other charged lepton flavor violating (cLFV) processes will never be found. In such a case, we need other approaches to confirm the $\mu$-$e$ conversion and its underlying physics without conventional cLFV searches. We study R-parity violating (RPV) SUSY models as a benchmark. We briefly review that our interesting case is realized in RPV SUSY models with reasonable settings according to current theoretical/experimental status. We focus on the exotic collider signatures at the LHC ($pp \rightarrow \mu^- e^+$ and $pp \rightarrow jj$) as the other approaches. We show the correlations between the branching ratio of $\mu$-$e$ conversion process and cross sections of these processes. It is first time that the correlations are graphically shown. We exhibit the RPV parameter dependence of the branching ratio and the cross sections, and discuss the feasibility to determine the parameters. This paper is based on Ref. [1].

KEYWORDS: $\mu$-$e$ conversion, charged lepton flavor violation, R-parity violating SUSY models, J-PARC, LHC

1. Introduction

Lepton flavor violation (LFV) is the clearest signal for physics beyond the Standard Model (SM) [2], and extensive searches for LFV have been made since the muon was found [3–6]. Though a lot of efforts have been made, we have not found any LFV signals with charged leptons. LFV had, however, been found in neutrino oscillation [7, 8] and it indeed requires us to extend the SM so that physics beyond the SM must include LFV. This fact also gives us a strong motivation to search for charged lepton flavor violation (cLFV).

Along this line new experiments to search for cLFV will start soon. COMET [9, 10] and DeeMe [11] will launch within a few years and search $\mu$-$e$ conversion. In these experiments, first, muons are trapped by target nucleus, then, if cLFV exists, it converts into an electron. If COMET/DeeMe observe the $\mu$-$e$ conversion, then with what kind of new physics should we interpret it? Now it is worth considering since we are in-between two kinds of cLFV experiments with muon.

For these several decades, theories with supersymmetric extension have been most studied. These theories include a source of LFV. It is realized by the fact that the scalar partner of charged leptons have a different flavor basis from that of charged leptons. In addition, R-parity is often imposed on this class of the theory [12, 13]. With it, $\mu \rightarrow e\gamma$ process has the largest branching ratio among the three cLFV processes. This occurs through the dipole process depicted and the other two, $\mu - e$ conversion and $\mu \rightarrow 3e$, are realized by attaching a quark line and an electron line at the end of the photon line respectively, giving an $O(\alpha)$ suppression. Those branching ratios must be smaller than that of $\mu \rightarrow e\gamma$. At this moment, however, the upper bounds for those branching ratios are almost same each other. It means if COMET/DeeMe observe the $\mu - e$ conversion, we have to discard this scenario.

It is, however, possible to find a theory easily in which COMET/DeeMe find cLFV first. To see this we first note that the $\mu \rightarrow e\gamma$ process occurs only at loop level due to the gauge invariance, while other two can occur as a tree process. Therefore in this case we have to consider a theory in which the $\mu - e$ conversion process occurs as tree process. In other words we have to assume a particle which
violate muon and electron number. Since \( \mu - e \) conversion occurs in a nucleus, it also couples with quarks with flavor conservation. Furthermore it is better to assume that it does not couple with two electrons as we have not observed \( \mu \rightarrow 3e \).

In this paper we consider the case that COMET/DecMe indeed observe the cLFV process, while all the other experiments will not observe anything new at that time. With this situation, we need to understand how to confirm the cLFV in other experiments. Unfortunately in this case other new physics signals are expected to be quite few, since the magnitude of the cLFV interaction is so small due to its tiny branching ratio. Therefore it is very important to simulate now how to confirm the COMET signal and the new physics. As a benchmark case we study supersymmetric models without R parity [14]. In this kind of theory the scalar lepton mediates \( \mu \leftrightarrow e \) flavor violation.

2. RPV interaction and our scenario

In general the supersymmetric gauge invariant superpotential contains the R-parity violating terms [15–17],

\[
W_{\text{RPV}} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c,
\]

where \( E_i^c, U_i^c \) and \( D_i^c \) are \( SU(2)_L \) singlet superfields, and \( L_i \) and \( Q_j \) are \( SU(2)_L \) doublet superfields. Indices \( i, j, \) and \( k \) represent the generations. We take \( \lambda_{ijk} = -\lambda'_{ijk} \) and \( \lambda''_{ijk} = -\lambda'_{ijk} \). First two terms include lepton number violation, and the last term includes baryon number violation. Since some combinations of them accelerate proton decay, we omit the last term.

Our interesting situation is that only \( \mu-e \) conversion is discovered, and other cLFV processes will never be observed. The situation is realized under the following 3 setting on the RPV interaction:

1. only the third generation slepton contributes to the RPV interactions
2. for quarks, flavor diagonal components are much larger than that of off-diagonal components, i.e., CKM-like matrix, \( \lambda'_{ijk} \gg \lambda''_{ijk}(j \neq k) \)
3. the generation between left-handed and right-handed leptons are different, \( \lambda_{ijk}(i \neq k \text{ and } j \neq k) \).

The setting-1 is naturally realized by the RG evolved SUSY spectrum with universal soft masses at the GUT scale. For the simplicity, we decouple SUSY particles except for the third generation sleptons. The setting-2 is also realized in most cases unless we introduce additional sources of flavor violations. The setting-3 is artificially introduced to realize the interesting situation (see Introduction).

Under the settings, the Lagrangian from the superpotential (1) is reduced as follows,

\[
\mathcal{L}_{\text{RPV}} = \mathcal{L}_4 + \mathcal{L}'_4,
\]

\[
\mathcal{L}_4 = 2[\lambda_{12} \bar{\nu}_{1L} \bar{P}_1 \nu L + \lambda_{321} \bar{\nu}_{1L} \bar{P}_1 \mu + \lambda_{132} \bar{\tau}_L \bar{P}_1 \nu e + \lambda_{231} \bar{\tau}_L \bar{P}_1 \nu e] + \text{h.c.},
\]

\[
\mathcal{L}'_4 = [\lambda'_{311}(\bar{\nu}_{1L} \bar{P}_1 \mu - \bar{\tau}_L \bar{P}_1 \nu e) + \lambda'_{322}(\bar{\nu}_{1L} \bar{P}_1 \nu e - \bar{\tau}_L \bar{P}_1 \nu e)] + \text{h.c.}.
\]

Some kind of processes described by the Lagrangian (2) strongly depend on the values of \( \lambda'_{311} \) and \( \lambda'_{322} \). In order to clarify the dependence and to discuss the discrimination of each other, we study following three cases in our paper [1]: [case-I] \( \lambda'_{311} \neq 0 \) and \( \lambda'_{322} = 0 \), [case-II] \( \lambda'_{311} = 0 \) and \( \lambda'_{322} \neq 0 \), and [case-III] \( \lambda'_{311} \neq 0 \) and \( \lambda'_{322} \neq 0 \). In this talk, we focus on the case-I.

3. Exotic processes in our scenario

In the scenario we have five types of exotic processes:

1. \( \mu-e \) conversion in a nucleus (\( \mu^-N \rightarrow e^-N \))
Table 1. Current and future experimental limits on the $\mu$-$e$ conversion branching ratio and the upper limits on $\lambda'$ corresponding to each experimental limit.

| Experiment | BR limit | Limit on $\lambda'_{311}$ (case-I) | Limit on $\lambda'_{322}$ (case-II) | Limit on $\lambda'$ (case-III) |
|------------|----------|-----------------------------------|-----------------------------------|-------------------------------|
| SINDRUM    | $7 \times 10^{-13}$ [5] | $1.633 \times 10^{-7} \frac{m_\nu_e}{1\text{TeV}}^2$ | $3.170 \times 10^{-7} \frac{m_\nu_e}{1\text{TeV}}^2$ | $1.072 \times 10^{-7} \frac{m_\nu_e}{1\text{TeV}}^2$ |
| DeeMe      | $5 \times 10^{-15}$ [11] | $1.550 \times 10^{-8} \frac{m_\nu_e}{1\text{TeV}}^2$ | $2.915 \times 10^{-8} \frac{m_\nu_e}{1\text{TeV}}^2$ | $1.012 \times 10^{-8} \frac{m_\nu_e}{1\text{TeV}}^2$ |
| COMET-I    | $7 \times 10^{-15}$ [10] | $1.830 \times 10^{-8} \frac{m_\nu_e}{1\text{TeV}}^2$ | $3.504 \times 10^{-8} \frac{m_\nu_e}{1\text{TeV}}^2$ | $1.196 \times 10^{-8} \frac{m_\nu_e}{1\text{TeV}}^2$ |
| COMET-II   | $3 \times 10^{-17}$ [10] | $1.198 \times 10^{-9} \frac{m_\nu_e}{1\text{TeV}}^2$ | $2.294 \times 10^{-9} \frac{m_\nu_e}{1\text{TeV}}^2$ | $7.827 \times 10^{-10} \frac{m_\nu_e}{1\text{TeV}}^2$ |
| PRISM      | $7 \times 10^{-19}$ [10] | $1.830 \times 10^{-10} \frac{m_\nu_e}{1\text{TeV}}^2$ | $3.504 \times 10^{-10} \frac{m_\nu_e}{1\text{TeV}}^2$ | $1.196 \times 10^{-10} \frac{m_\nu_e}{1\text{TeV}}^2$ |

2 $\mu^-e^+$ production at LHC ($pp \rightarrow \mu^-e^+$)  
3 dijet production at LHC ($pp \rightarrow jj$)  
4 non-standard interaction (NSI) of neutrinos  
5 muonium conversion ($\mu^+e^- \rightarrow \mu^-e^+$)

In the situation that the $\mu$-$e$ conversion is discovered while other cLFV signals will never be found, we discuss the possibility whether we can confirm the $\mu$-$e$ conversion signal with the five types processes or not. Details of each process and the formulation of their reaction rates are given in our paper [1].

Note that in our scenario other muon cLFV processes ($\mu \rightarrow e\gamma, \mu \rightarrow 3e, \mu^-e^- \rightarrow e^-e^-$ in muonic atom [18], and so on) occur at two-loop level. At one glance the tau sneutrino can connect with the photon via d-quark loop. The contribution of the loop of the diagram is

$$\lambda'\left(-\frac{1}{3}e\frac{m_{d\ell}\mu}{8\pi^2}\int_0^1 dx(1-2x)\log(m_{d\ell}^2-(x-x^2)q^2)\right)\propto q^2q'^4,$$

where $q$ is the momentum of the photon. The contribution to cLFV is, therefore vanish with on-shell photon ($q^2 = 0$) for $\mu \rightarrow e\gamma$ and with $\bar{e}\nu_\mu e$ attached for $\mu \rightarrow 3e$ due to gauge symmetry($q'^2\bar{e}\nu_\mu e = 0$). Thus these processes occur at two-loop level. Furthermore these processes are extremely suppressed by higher order couplings, gauge invariance, and so on. Therefore we do not study these processes.

4. Numerical result

We are now in a position to show numerical results. Table I shows the current experimental limit and the future single event sensitivity for $\mu$-$e$ conversion process, and shows the upper limits on the combination of the RPV couplings, $\lambda'\lambda$, corresponding to the limit and the sensitivities in each experiment. In the calculation of the upper limits, we take Au, Si, and Al for target nucleus of SINDRUM-II, DeeMe, and other experiments, respectively.

$\mu$-$e$ conversion search is a reliable probe to both the RPV couplings and tau sneutrino mass. The current experimental limit puts strict limit on the RPV couplings, $\lambda'\lambda \lesssim 10^{-7}$ for $m_{\tilde{\nu}_e} = 1\text{TeV}$ and $\lambda'\lambda \lesssim 10^{-5}$ for $m_{\tilde{\nu}_e} = 3\text{TeV}$, respectively. In near future, the accessible RPV couplings will be extended by more than 3 orders of current limits, $\lambda'\lambda \approx 10^{-10}$ for $m_{\tilde{\nu}_e} = 1\text{TeV}$ and $\lambda'\lambda \approx 10^{-8}$ for $m_{\tilde{\nu}_e} = 3\text{TeV}$, respectively.

The $\mu$-$e$ conversion process is one of the clear signatures for the RPV scenario, but it is not the sufficient evidence of the scenario. We must check the correlations among the reaction rates of $\mu$-$e$ conversion process, the cross sections of $pp \rightarrow \mu^-e^+$ and $pp \rightarrow jj$, and so on in order to discriminate the case-I, -II, and -III each other and to confirm the RPV scenario.

The parameter dependence of $\sigma(pp \rightarrow \mu^-e^+), \sigma(pp \rightarrow jj)$, and $\text{BR}(\mu^-N \rightarrow e^-N)$ in the case-I
we take the couplings universally in leptonic RPV sector: (see Table I). Light shaded region is excluded by the dark shaded band is excluded region by the excluded region by the 

![Fig. 1.](image)

\[\lambda \equiv \lambda_{312} = \lambda_{321} = -\lambda_{132} = -\lambda_{231}.\]

Figure 1 displays the strong potential of \(\mu-e\) conversion search to explore the RPV scenarios. The PRISM experiment will cover almost parameter space wherein the LHC experiment can survey. In the parameter range between the SINDRUM-II limit and the PRISM reach, combining the measurement results of \(\sigma(pp \rightarrow \mu^- e^+), \sigma(pp \rightarrow jj),\) and \(BR(\mu^- Al \rightarrow e^- Al),\) the RPV couplings and the tau sneutrino mass will be precisely determined.

Figure 2 shows \(\sigma(pp \rightarrow \mu\bar{e})\) as a function of \(BR(\mu + N \rightarrow e + N)\) in the case-I. Candidate materials for the target of \(\mu-e\) conversion search are silicon (Si) at the DeeMe, and are aluminum (Al) at the COMET, Mu2e, and PRISM. Vertical dotted lines show the experimental reach of DeeMe 1-year running (DeeMe(1yr)), DeeMe 4-years running (DeeMe(4yrs)), COMET phase-I (COMET-I), COMET phase-II (COMET-II), and PRISM (PRISM). Shaded regions are the excluded region by
the SINDRUM-II [5], which are translated into the limit for each nucleus from that for Au. Each line corresponds to the dijet production cross section at the LHC, $\sigma(pp \rightarrow jj)$, at $\sqrt{s} = 14\text{TeV}$ (left panels) and at $\sqrt{s} = 100\text{TeV}$ (right panels), respectively. For simplicity, we take universal RPV coupling, $\lambda \equiv \lambda_{312} = \lambda_{321} = -\lambda_{132} = -\lambda_{231}$.

Figure 2 shows the clear correlations among $\sigma(pp \rightarrow \mu^- e^+)$, $\sigma(pp \rightarrow jj)$, and $\text{BR}(\mu^- N \rightarrow e^- N)$. Checking the correlations makes possible to distinguish the RPV scenario and other new physics scenarios.

5. Summary and discussion

We have studied a supersymmetric standard model without R parity as a benchmark case that COMET/DeeMe observe $\mu - e$ conversion prior to all the other experiments observing new physics.

In this case with the assumption that only the third generation sleptons contribute to such a process, we need to assume that $|\lambda'_{311} |$ and/or $|\lambda'_{322} | \times |\lambda_{312} |$ and/or $|\lambda_{321} |$ must be sufficiently large. Though other combinations of coupling constants can lead a significant $\mu - e$ conversion process, only those are considered here. This is because in most of scenarios in the supersymmetric theory,
the third generation of the scalar lepton has the lightest mass.

With these assumptions, we calculated the effects on future experiments. First we considered the sensitivity of the future $\mu - e$ conversion experiments on the couplings and the masses.

Then with the sensitivity kept into mind we estimated the reach to the couplings by calculating the cross section of $pp \rightarrow \mu^-e^+$ as a function of the slepton masses and the couplings. To have a signal of $\mu^-e^+$ both the coupling $\lambda'$ and $\lambda$ must be large and hence there are lower bounds for them while to observe dijet event via the slepton only the coupling $\lambda'$ must be large and hence there is a lower bound on it. In all cases we have a chance to get confirmation of $\mu - e$ conversion in LHC indirectly. In addition, we put a bound on the couplings by comparing both modes.

Finally we considered muonium conversion. If $\lambda'$ is very small we cannot expect a signal from LHC. In this case at least one of $\lambda_{312}$ and $\lambda_{321}$ must be very large and if it is lucky, that is both of them are very large we can expect muonium conversion.

There are other opportunities to check the result on $\mu - e$ conversion. For example we can distinguish $\lambda_{312}$ and $\lambda_{321}$ in linear collider with polarized beam. We can also expect the signal $pe^- \rightarrow p\mu^-$ in LHeC. It is however beyond the scope of this paper to estimate their sensitivities and we leave them in future work [20].

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