R-parity violating supersymmetric contributions to the neutron beta decay

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Abstract. We investigate the contribution to the angular correlation coefficients of the neutron beta decay within the R-parity violating (RPV) minimal supersymmetric standard model (MSSM). The RPV effects contribute to the scalar interaction at the tree level. The coefficient of the effective scalar interaction of the nucleon is determined in terms of the nucleon mass difference. On the basis of the recent update of the analyses of the superallowed Fermi transitions and the recent measurement of transverse polarization of the emitted electrons at PSI, we deduce new upper limits on the RPV couplings and compare them with those obtained through pion decay and atomic electric dipole moment (EDM). We also give a comprehensive analysis of angular correlations sensitive to the RPV interactions.

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1. Introduction

In recent years, the search for new physics “Beyond the Standard Model” has been performed in many ways. A particular attention is paid to the low energy approach, which consists of observing small discrepancies between low energy phenomena and the Standard Model (SM) [1, 2, 3, 4, 5]. Among several others, neutron decay experiments are expected to be very promising for new physics search and are actively planned or under operation by many groups at PSI, LANSCE, ILL, J-PARC and so forth.

On the theoretical side, the Minimal Supersymmetric Standard Model (MSSM) [6] is known to be the leading candidate of the new physics beyond the SM. We must impose on the MSSM a new parity called R-parity \( R_p = (-1)^{3B+L+2s} \) to conserve the baryon and lepton numbers, in contrast to the SM in which these quantum numbers are automatically conserved due to the gauge invariance. The violation of the R-parity causes many exotic phenomena such as the proton decay. Although its conservation is generally assumed, this assumption is completely ad hoc. The RPV interactions may exist which could be unveiled by upcoming high-precision experiments. Until now, many allowed regions and upper bounds have been established for single and combined parameters of the RPV interactions by means of the weak processes [7, 8, 9, 10].

Herczeg [1] analyzed the \( d \to u e^- \bar{\nu}_e \) transition by including the RPV interactions and pointed out that they generate two types of new interactions. One is the usual V-A interactions and the other is of the scalar and pseudoscalar type. It was shown that rather severe upper bounds on the RPV interactions [11] were obtained from the contribution of the pseudoscalar interaction of the pion decay \( \Gamma(\pi \to e\nu_e)/\Gamma(\pi \to \mu\nu_\mu) \) [12]. The bound on the scalar interaction was also derived by the use of electroweak radiative corrections [13] and the atomic EDM data [11].

Recently, new data sensitive to the scalar interaction have been reported. Hardy and Towner [14] updated their analysis on the superallowed Fermi transitions and gave an improved limit on the real part of the scalar interaction between the hadron and lepton currents. Meanwhile, the experiment at PSI [15] has measured the transverse polarization of electrons emitted in the neutron beta decay, and has given observables sensitive to both the real and imaginary parts of the scalar interaction.

As the scalar interaction is sensitive to the RPVMSSM contributions at the tree level [1], the present analysis of neutron beta decay will provide useful constraints on RPV interactions complementary to those obtained from the pseudoscalar interaction of the pion decay and the atomic EDM via one-loop corrections.

The purpose of the present paper is to perform the quantitative analysis of the RPV contributions to the neutron beta decay in the light of [14] and [15]. In order to explore a possibility to investigate the scalar interaction from the neutron beta decay, we use the formula of angular correlation coefficients given in literatures [16, 17]. We notice here assumptions we made in this paper, which are the followings: (a) The R-parity conserving sfermion sector of the MSSM is assumed to be flavour diagonal and with no CP phases. (b) The RPV sector of the MSSM does not contain any soft SUSY breaking
terms.

This paper is structured as follows. In sec. 2 we first construct the effective interaction of the neutron beta decay within RPVMSSM. In sec. 3 we explore the angular correlation coefficients by including neutrino momentum in the electron polarization term. In sec. 4 we obtain new constraints on the RPV couplings from the recent data of nuclear beta decay. Sec. 5 is devoted to summary.

2. Effective interaction from R-parity violation

2.1. R-parity violating Lagrangian

The first step of the estimation is to construct the tree level amplitude of the quark beta decay. The relevant interactions can be obtained from the RPV part of the superpotential which can be written as follows:

\[ W_R = \frac{1}{2} \lambda_{ijk} \epsilon_{ab} L^a_i L^b_j (E^c)_k + \lambda'_{ijk} \epsilon_{ab} L^a_i Q^b_j (D^c)_k + \frac{1}{2} \lambda''_{ijk} \epsilon_{lmn} (U^c)^l_i (D^c)^m_j (D^c)^n_k , \] (1)

with \( i, j, k = 1, 2, 3 \) indicating the generation, \( a, b = 1, 2 \) the \( SU(2) \) indices, \( l, m, n = 1, 2, 3 \) the colour indices. \( L \) and \( E^c \) denote the lepton doublet and singlet left-chiral superfields. \( Q, U^c \) and \( D^c \) denote the quark doublet, up quark singlet and down quark singlet left-chiral superfields, respectively. The third term in (1) is baryon number violating, so is not relevant to our subsequent discussions. We therefore disregard it hereafter. By taking the F-terms of \( W_R \), we obtain lepton number violating Yukawa interactions and also scalar four-point interactions. In our discussion, the scalar four-point interactions are irrelevant since we cannot construct diagrams which involve them at the tree level. The RPV interactions contributing to the neutron beta decay is as follows:

\[ \mathcal{L} = -\frac{1}{2} \sum_{ijk} \lambda_{ijk} \left\{ \bar{e}_i^c \tilde{\nu}_i^c P_L e_j + \bar{e}_j^c \tilde{\nu}_j^c P_L e_i + \bar{\nu}_j^c \tilde{\nu}_j^c P_L e_i \right\} - \frac{1}{2} \sum_{ijk} \lambda'_{ijk} \left\{ \bar{d}_i^c \tilde{\nu}_i^c P_L d_j + \bar{d}_j^c \tilde{\nu}_j^c P_L d_i + \bar{\nu}_i^c \tilde{\nu}_i^c P_L d_j \right\} - \frac{1}{2} \sum_{ijk} \lambda''_{ijk} \left\{ \bar{d}_i^c \tilde{\nu}_i^c P_L e_j - \bar{\nu}_i^c \tilde{\nu}_i^c P_L e_j \right\} + \text{h.c.} , \] (2)

with \( P_L = \frac{1}{2} (1 - \gamma_5) \).

2.2. Feynman diagrams

We can now build the amplitude of the quark beta decay within RPVMSSM at the tree level. The Feynman diagrams are shown in Fig. 1.

Fig. 1 (a) is the SM contribution at the lowest order. Its expression is as follows:

\[ \mathcal{M}_{SM} = \frac{G_F}{\sqrt{2}} V_{ud} \bar{u} \gamma^\mu (1 - \gamma_5) d \cdot \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e , \] (3)
where $G_F = (1.16637 \pm 0.00001) \times 10^{-5}\text{GeV}^{-2}$ [18] is the Fermi constant and $V_{ud} = 0.97418 \pm 0.00027$ [19] is the CKM matrix element.

In the tree approximation, the RPV contributions to the $d \to u + e^- + \bar{\nu}_e$ process are the selectron($\tilde{e}_L$) (Fig. 1 (b)) and the squark($\tilde{d}_R$) (Fig. 1 (c)) exchange mechanisms [1]. The amplitude of the selectron exchange between the quark and lepton in Fig. 1 (b) can be written as

$$M_{\tilde{e}_L} = \sum_{i=2,3} \frac{(\lambda_{i11} - \lambda_{i1i1})\lambda_{i11}^\ast}{8m_{\tilde{e}_Li}^2} \bar{u} (1 + \gamma_5) d \cdot \bar{e} (1 - \gamma_5) \nu_e$$

where we have used the antisymmetry of the couplings $\lambda_{ijk}$ under the interchange of the first and second index ($\lambda_{ijk} = -\lambda_{jik}$). It is interesting to note that $M_{\tilde{e}_L}$ is of the type of the scalar interaction.

The RPV couplings are constrained by extensive analyses on current experimental data. The upper limits of the RPV couplings used in (4) are given by the first four entries in Table I. The upper limits of $\lambda_{i1i1}, \lambda'_{i1i1}$ for $i = 2, 3$ are obtained from charged current (CC) universality and decay ratios $\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu}), \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ and $\Gamma(\tau \to \pi\nu_e)/\Gamma(\pi \to \mu\nu)$ [7, 8, 9]. As we see, the magnitude of $M_{\tilde{e}_L}$ is small compared with that of $M_{\text{SM}}$. This scalar interaction is, however, potentially important since it could give rise to observables in neutron beta decay to which $V - A$ interactions do not contribute.

The squark exchange amplitude in Fig. 1 (c) can be written as

$$M_{\tilde{d}_R} = \sum_{i=1,2,3} \frac{|\lambda'_{1i1i}|^2}{8m_{\tilde{d}_Ri}^2} \bar{u} \gamma^\mu (1 - \gamma_5) d \cdot \bar{e} \gamma_\mu (1 + \gamma_5) e^\nu$$

To obtain the final result in (5), we have used the Fierz transformation. [5] has the
Table 1. Current upper limits of (the magnitude of) RPV couplings [6, 20]. Expressions with square brackets correspond to their masses in unit of 100 GeV. $\tilde{q}$ and $\tilde{g}$ refer to the squark and gluino, respectively.

| Coupling constants | Upper bounds |
|--------------------|--------------|
| $|\lambda_{121}|$  | $< 0.049 [m_{\tilde{e}_R}]$ |
| $|\lambda_{131}|$  | $< 0.062 [m_{\tilde{e}_R}]$ |
| $|\lambda_{211}|$  | $< 0.059 [m_{\tilde{d}_R}]$ |
| $|\lambda_{311}|$  | $< 0.11 [m_{\tilde{d}_R}]$ |
| $|\lambda_{111}|$  | $< 1.3 \times 10^{-4} \cdot [m_{\tilde{q}}]^2 [m_{\tilde{g}}]^{1/2}$ |
| $|\lambda_{112}|$  | $< 0.021 [m_{\tilde{e}_R}]$ |
| $|\lambda_{113}|$  | $< 0.021 [m_{\tilde{b}_R}]$ |

2.3. Effective interaction

The next step is to build the effective interaction of the neutron beta decay process. To obtain it, we must construct the nucleon matrix elements from the quark beta decay amplitudes. The effective interaction can be written as

$$H_\beta = H_{SM} + H_R,$$

where the first term is the SM contribution and the second term the contribution from Fig. 1(b). The nucleon matrix elements are described by form factors as follows:

$$\langle p|\bar{u}\gamma^\mu d|n\rangle = g_V(q^2)\bar{p}\gamma^\mu n,$$

$$\langle p|\bar{u}\gamma^\mu \gamma_5 d|n\rangle = g_A(q^2)\bar{p}\gamma^\mu \gamma_5 n,$$

$$\langle p|\bar{u}d|n\rangle = g_S(q^2)\bar{p}n,$$

where we have explicitly written the nucleon fields as $n$ and $p$, and $q$ is the momentum transfer. The form factor of the pseudoscalar interaction need not be introduced since its contribution vanishes in the non-relativistic limit. The induced form factors were also neglected. In this paper, we use the constants $g_V = g_V(0)$, $g_A = g_A(0)$, $g_S = g_S(0)$ since $q^2$ is much smaller than the nucleon mass. Here recall that $g_V = 1$ from the CVC and $g_A = 1.2739 \pm 0.0019$ from [21].

The determination of $g_S$ needs more involved discussion. Within approximate isospin symmetry, the matrix element $\langle p|\bar{u}d|n\rangle = \langle p|\bar{u}u-\bar{d}d|p\rangle$. According to Gasser and Leutwyler [22], the isospin asymmetric part of the nucleon form factor can be written as

$$\delta = \frac{m_d - m_u}{2M_N} \langle p|\bar{u}u-\bar{d}d|p\rangle,$$

$$V-A$$ type interaction like the SM. Here the constraints on the RPV couplings appearing in (5) are given by the last three entries in Table 1. The couplings $\lambda'_{i11}$ ($i = 1, 2, 3$) are constrained from the analysis of the double beta decay [20] and CC universality [7, 8, 9]. In our analysis, we use the empirical value of $V_{ud}$ and axial vector coupling constant $g_A$, therefore the effect of (5) is absorbed into those coupling constants.
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where \( M_N \) indicates the nucleon mass. To the lowest order expansion in up and down quark mass difference, the neutron and proton mass difference equals \( \delta \):

\[
\delta = M_n - M_p = (2.05 \pm 0.30) \text{ MeV},
\]

where the mass difference \( M_n - M_p \) are of pure QCD origin, i.e., without electromagnetic contribution. From (9), (10) and (11) we obtain

\[
g_S = \frac{M_n - M_p}{m_d - m_u} = 0.49 \pm 0.17,
\]

where we have used \( m_d = 9.3 \pm 0.9 \text{ MeV}, \frac{m_u}{m_d} = 0.553 \pm 0.043 \)\(^\text{[23]}\). The error in (12) is mostly due to the ambiguities of the current quark mass. Note that the values of \( g_S \) obtained previously by Adler \textit{et al.} \(^\text{[24]}\), and by Wakamatsu \(^\text{[25]}\) are consistent with (12).

We can now construct the effective interaction of the neutron beta decay within RPVMSSM at the tree level, which is given by

\[
H_{SM} = \frac{G_F}{\sqrt{2}} V_{ud} \bar{p}_n \gamma^\mu (g_V - g_A \gamma_5) n \cdot \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e
\]

and

\[
H_R = C_S \bar{p}_n \cdot \bar{e} (1 - \gamma_5) \nu_e + \text{h.c.}
\]

where

\[
C_S = g_S \sum_{i=2,3} \frac{\lambda_{1i}^e \lambda_{i1}^\nu}{4 m_e^2 E_i^2}
\]

3. Angular correlations of the neutron beta decay

The formula for the angular correlation coefficients of the beta decay by taking into account of the polarized neutron and electron is given by Jackson, Treiman and Wyld (JTW) \(^\text{[16]}\), and extended by Ebel and Feldman \(^\text{[17]}\) as follows:

\[
\omega(E_e, \Omega_e, \Omega_\nu) \propto 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \bar{\sigma}_n \cdot \left\{ A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right\} + \bar{\sigma}_e \cdot \left\{ G \frac{\vec{p}_e}{E_e} + H \frac{\vec{p}_\nu}{E_\nu} + K \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e + m_e} + L \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right\} + \bar{\sigma}_n \cdot \left\{ N \frac{\vec{p}_e}{E_e} + Q \frac{\vec{p}_\nu}{E_\nu} + R \frac{\vec{p}_n \cdot \vec{p}_e}{E_e E_\nu} + S \frac{\vec{p}_n \times \vec{p}_e}{E_e E_\nu} \right\} + \bar{\sigma}_e \cdot \left\{ T \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + U \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + V \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} + W \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} \right\}.
\]

Here \( \vec{p}_e \) and \( \vec{p}_\nu \) are respectively the momenta of the electron and the neutrino, \( \bar{\sigma}_n \) the neutron spin polarization and \( \bar{\sigma}_e \) the final state electron polarization. The angular
correlations of the last line (terms with $S$, $T$, $U$, $V$ and $W$ coefficients) are correlations with momentum of emitted anti-neutrino, polarizations of initial neutron and emitted electron, given by Ebel and Feldman [17].

The angular correlation coefficients are evaluated using the main term of vector and axial vector current of the SM in (13) and the scalar interaction in (14). Here we take static approximation of nucleon current and keep only the leading order contributions. The results are summarized in Table 2 where we used

$$\lambda = \frac{g_A}{g_V},$$ (17)

$$\alpha_R = \frac{2Re(C_S)}{\sqrt{2} V_{ud} g_V (1 + 3\lambda^2)},$$ (18)

$$\alpha_I = \frac{2Im(C_S)}{\sqrt{2} V_{ud} g_V (1 + 3\lambda^2)}.$$ (19)

There are quite a few terms which are sensitive to the scalar interaction (see Table 2). The coefficients $b$, $S$, $U$ and $R$, $L$, $V$, $W$ probe respectively the real and the imaginary part of the scalar interaction. Among them, $S$, $T$, $V$ and $W$, in addition to the $b$, $R$ and $L$ which already studied by JTW, are particularly interesting observables. Since the main term of the SM (or $V - A$) does not contribute to those observables, there is a possibility to probe new physics through the scalar interaction. The effects of the final state interaction (FSI) have been in [16, 26, 27].

It is also noticed that the $B$ correlation can be used to investigate the scalar interaction. Though $V - A$ interactions contribute to $B$, one may be able to extract a small effect of the scalar interaction by using the extra energy dependence $\frac{m_{ee}}{E_e}$ in the scalar contribution [4].

4. Analyses

As we have seen, the RPV interaction of (2) generates (4) which turns out to be scalar interactions of the neutron beta decay (14). Combining the current upper limits of Table 1 we have the following bounds for each combination of RPV couplings in (15):

$$|\lambda_{121} \lambda_{211}^*| < 0.0029 [m_{\tilde{e}_R}][m_{\tilde{d}_R}],$$ (20)

$$|\lambda_{131} \lambda_{311}^*| < 0.0068 [m_{\tilde{e}_R}][m_{\tilde{d}_R}],$$ (21)

where $[m_{\text{SUSY}}] = m_{\text{SUSY}}/(100 \text{ GeV})$. (20) and (21) will be compared with the analysis confronted with [14] and [15].

From the recent update of the analysis on 20 superallowed Fermi transitions, Hardy and Towner [14] have given a new bound on the Fierz interference term $b_F$ which corresponds to $b$ term in (16). This one is a probe of the real part of the scalar interaction. By fitting $F_t$ values of the superallowed Fermi transitions, they obtained

$$\frac{b_F}{2} = \frac{Re(C_S)}{C_V} = +0.0011 \pm 0.0013,$$ (22)
Table 2. Angular correlation coefficients of the neutron beta decay

| Coefficients | SM                  | RPV                  |
|--------------|---------------------|----------------------|
| $a$          | $(1 - \lambda^2)/(1 + 3\lambda^2)$ | 0                    |
| $b$          | 0                   | $\alpha_R$           |
| $A$          | $2\lambda(1 - \lambda)/(1 + 3\lambda^2)$ | 0                    |
| $B$          | $2\lambda(1 + \lambda)/(1 + 3\lambda^2)$ | $\lambda\alpha_R (m_e/E_e)$ |
| $D$          | 0                   | 0                    |
| $G$          | $-1$                | 0                    |
| $H$          | $(m_e/E_e)(\lambda^2 - 1)/(1 + 3\lambda^2)$ | $-\alpha_R$          |
| $K$          | $(\lambda^2 - 1)/(1 + 3\lambda^2)$ | $\alpha_R$           |
| $L$          | 0                   | $\alpha_I$           |
| $N$          | $-(m_e/E_e)2\lambda(1 - \lambda)/(1 + 3\lambda^2)$ | $-\lambda\alpha_R$ |
| $Q$          | $-2\lambda(1 - \lambda)/(1 + 3\lambda^2)$ | $\lambda\alpha_R$ |
| $R$          | 0                   | $-\lambda\alpha_I$  |
| $S$          | 0                   | $\lambda\alpha_R$   |
| $T$          | $-2\lambda(1 + \lambda)/(1 + 3\lambda^2)$ | 0                    |
| $U$          | 0                   | $-\lambda\alpha_R$  |
| $V$          | 0                   | $-\lambda\alpha_I$  |
| $W$          | 0                   | $\lambda\alpha_I$   |

where $C_V = V_{ud} \frac{G_F}{\sqrt{2}} g_V$. From this, we obtain the following limit on the combined RPV couplings:

$$Re\left(\sum_{i=2,3} \lambda_{1i1} \lambda_{11}^{*}\right) = (7.2 \pm 8.5) \times 10^{-4} \frac{[m_{\tilde{e}_L}]^2}{[g_s]} ,$$

(23)

where $[g_s] \equiv \frac{g_s}{0.49}$.

The complementary information on the imaginary part of the RPV couplings can be obtained from the $R$ correlation of the neutron beta decay distribution. The angular correlation $R$, which is the triple product of the polarization and the momentum of emitted electron, and polarization of the initial neutron, has been recently measured at PSI \cite{15} as

$$R = 0.008 \pm 0.011 \pm 0.005 .$$

(24)

The contribution of FSI to $R$ can be estimated as

$$R_{FSI} = 8.57 \times 10^{-4} \times \frac{m_e}{p_e} ,$$

(25)

according to the formula of JTW \cite{16}. Here $m_e$ and $p_e$ are respectively the mass and the magnitude of the spatial momentum of the emitted electron. The effect of FSI is by an order of magnitude smaller than the experimental data (24). Using the experimental value (24) neglecting FSI, we obtained the following constraint on the imaginary part of the coupling constants,

$$Im\left(\sum_{i=2,3} \lambda_{1i1} \lambda_{11}^{*}\right) = (-0.012 \pm 0.017 \pm 0.008) \frac{[m_{\tilde{e}_L}]^2}{[g_s]} .$$

(26)
The obtained limits on the RPV couplings in this analysis are summarized in Fig. 2. Here we have taken all s-particle masses to 100 GeV. As we can see, a strong constraint of the real part of the RPV parameters is obtained from $b$. On the other hand, the constraint of the imaginary part of the RPV parameters might be comparable to (20) and (21). However, the limits obtained in (23) and (26) depend on the mass $m_{\tilde{e}L}$ while the current ones ( (20) and (21)) depends on the masses $m_{\tilde{e}R}$ and $m_{\tilde{d}R}$. Therefore (23) and (26) give a new type of constraint. With the progress of experiment on $R$, one will be able to further constrain the imaginary part of the coupling constant.

It is of interest to compare our constraints, (23) and (26) with those obtained previously. It has been pointed out in [13] that usual electroweak radiative corrections could transform the T-odd, P-even interactions into a T-odd, P-odd ones, and that one could put limits on the T-odd, P-even interactions by using the rich data on the part of T-odd, P-odd interactions. Herczeg [11] considered such radiative corrections in RPV models and confronted the induced interactions with EDM data. The analysis depends on the sparticle masses, but in general more severe constraints can be made available than (26).

It has been pointed out in [12] that the ratio $\Gamma(\pi \to ev)/\Gamma(\pi \to \mu \nu)$ is a sensitive probe to the pseudoscalar type $\tilde{d}u \to ev_e$ interactions. For the case of the RPV contribution (4), The scalar and the pseudoscalar interactions are of the same strength, and one can deduce an upper bound on $C_S/g_S$ by employing the data of the ratio. The upper bound obtained in such a manner is a fraction of the value (23).
5. Summary

To summarize, we have studied the contribution of the RPVMSSM to the angular correlation coefficients and the Fierz interference term in the neutron beta decay. We have deduced new bounds on the real and imaginary parts of the combinations of RPV couplings as in (23) and (26) through the scalar interaction (14) of the beta decay. These are based on the recent data of [14] and [15] respectively. The obtained upper bound for $\text{Re}(\lambda_{121}^* \lambda_{j11}^*)$ is consistent with a stronger constraint obtained from the analysis of pion decay [1, 11, 12]. With the hypothesis of the single coupling dominance, (23) and (26) can be replaced by a constraint for either $\lambda_{121} \lambda_{211}^*$ or $\lambda_{131} \lambda_{311}^*$.

We have also discussed angular correlations $S, T, U, V$ and $W$, which involve emitted electron polarization and neutrino momentum. In addition to the known ones, coefficients $b, S, U$ and $R, L, V, W$ are respectively sensitive to the real and imaginary parts of the scalar interaction. Their precise measurements are therefore of great interest for further limiting the RPV couplings. Regarding the CP violating (imaginary) ones, the precise evaluation of the FSI contribution is also needed, as done in [26] or [27].

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