Explaining a CMS eejj Excess With $R$–parity Violating Supersymmetry and Implications for Neutrinoless Double Beta Decay

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A recent CMS search for the right handed gauge boson $W_R$ reports an interesting deviation from the Standard Model. The search has been conducted in the $eejj$ channel and has shown a 2.8$\sigma$ excess around $m_{eejj} \sim 2$ TeV. In this work, we explain the reported CMS excess with $R$-parity violating supersymmetry (SUSY). We consider resonant selectron and sneutrino production, followed by the three-body decays of the neutralino and chargino via an $R$–parity violating coupling. We fit the excess for slepton masses around 2 TeV. The scenario can further be tested in neutrinoless double beta decay ($0\nu\beta\beta$) experiments. GERDA Phase-II will probe a significant portion of the good-fit parameter space.

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The recent CMS search for a hypothetical $W_R$ gauge boson in the Left-Right model reports an intriguing deviation from the Standard Model in the $eejj$ channel. The CMS search uses $pp$ collision data at the Large Hadron Collider (LHC) and a centre of mass energy of 8 TeV and 19.7fb$^{-1}$ of integrated luminosity. The invariant mass distribution $M_{eejj}$ shows an excess around $M_{eejj} \sim 2$ TeV, with a local CERN CL$_s$ significance of 2.8$\sigma$ [1]. In the 1.8 TeV $< m_{eejj} < 2.2$ TeV bin, CMS reported 14 events on an expected background of 4.0±1.0. However, no significant deviation was observed in the $\mu\mu jj$ channel. This excess is not significant enough to claim a discovery. However, it is timely before the next LHC run (Run II) to explain it with a concrete model of new physics such that further tests can be applied and analysis strategies can be set for Run II.

There have been a few attempts to explain the CMS excess with different models. Coloron-assisted leptoquarks were proposed in Ref. [3], the $W_R$ excess was interpreted in GUT models in Refs. [4, 5]. In Ref. [6], pair production of vector-like leptons was proposed via $W'/Z'$ vector bosons. Ref. [7] performed a detailed analysis (including a general flavor structure) of $W'/Z'$ interpretations of the $W_R$ search data.

In this letter, we propose a different hypothesis for a new physics explanation of the $W_R$ search excess in terms of the $R$-parity violating (RPV) minimal supersymmetric model (MSSM). $R$-parity is a multiplicative discrete symmetry defined as $R = (-1)^{3(B-L)+2S}$, where $B$ and $L$ correspond to baryon and lepton number, and $S$ is spin. In particular, we show that RPV with a non-zero $\lambda_{111}$ coupling can fit the CMS excess [1, 2] via resonant slepton production (with a slepton mass of around 2 TeV) in $pp$ collisions. The slepton then subsequently decays to a charged lepton and neutralino, followed by the RPV decay modes of the neutralino via the $\lambda'_{111}$ coupling, producing an excess of events in the $eejj$ channel, as depicted in Fig. 1. The same signature in the $eejj$ channel can also be obtained from the resonant production of a sneutrino, followed by the $R$-parity violating decays of charginos, as shown in Fig. 2.

![FIG. 1: Feynman diagram for single selectron production leading to $eejj$ signal at the LHC.](image1)

![FIG. 2: Feynman diagram for single sneutrino production leading to $eejj$ signal at the LHC.](image2)

The RPV superpotential with the $\lambda'_{111}$ term is

$$W_R = \lambda'_{111} LQd^c.$$

This induces the following Lagrangian terms,

$$\mathcal{L} = -\lambda'_{111} \tilde{e} u d^c - \lambda'_{111} \tilde{u} e d^c + \lambda'_{111} \tilde{d} \nu e d^c + \tilde{\nu} e d d^c + \ldots$$
The MSSM with $\chi'_{111}$ is constrained by empirical data on charge current universality, $e-\mu-\tau$ universality, atomic parity violation etc [8]. In addition, the model contributes to lepton number violating neutrinoless double beta decay (0$\nu\beta\beta$) [9–11], as shown in Fig. 3. 0$\nu\beta\beta$ is not permitted in the SM because of lepton number conservation. The present bound on the half-life of $^{76}$Ge isotope is $T_{1/2}^{0\nu} > 2.1 \times 10^{25}$ yrs at 90% confidence level (CL) from GERDA [12], while the 90% CL combined bound on the half-life from previous experiments is $T_{1/2}^{0\nu} > 3.0 \times 10^{25}$ yrs [12]. The future 0$\nu\beta\beta$ experiment GERDA Phase-II will be commissioned soon and is expected to improve the half-life sensitivity to $T_{1/2}^{0\nu} \sim 2 \times 10^{26}$ yrs [13]. A positive signal in 0$\nu\beta\beta$ experiments is likely to be interpreted in terms of a Majorana nature of the light neutrinos, but instead it could be in part, or dominantly, due to RPV SUSY.

The most stringent bounds on the $\chi'_{111}$ coupling can be found in Ref. [14] and are shown in Table I. While the bounds in the table are for 100 GeV sparticles, they become greatly weakened for the heavier sparticles that we shall consider.

The $\chi'_{111}$ coupling in Eq. 2 can lead to single slepton production at hadron colliders, as first studied in [15] and subsequently in [16–23]. For a slepton of mass around the CMS excess (2.1 TeV) and $0.03 < \lambda_{111}^\prime < 0.5$ the production cross-section varies from less than 1 fb to as high as 130 fb [19]. As pointed out in Ref. [23], one can marry resonant slepton search data from the LHC with the predicted 0$\nu\beta\beta$ rate in order to provide further tests and interpretations. The $\chi'_{111}$ coupling also leads to the resonant production of sneutrinos, as shown in Fig. 2. The decay mode of the sneutrino leading to the $eejj$ signal is: $pp \rightarrow \tilde{\nu}_e/\tilde{\nu}_e^\ast \rightarrow e^-\chi_1^+/e^+\chi_1^- \rightarrow e^+e^-jj$. It is our aim to see if resonant selectron and sneutrino production can fit the CMS $W_R$ excess while evading other experimental constraints.

![Feynman diagram](image)

**Fig. 3:** Sample Feynman diagram for 0$\nu\beta\beta$, corresponding to selectron and neutralino contribution. There are several other diagrams from gluino and squark mediation, that contribute to the half-life $T_{1/2}^{0\nu}$ [22]. In our analysis of 0$\nu\beta\beta$, we consider all possible contributions via the $\chi'_{111}$ coupling [10, 22].

| Bound          | Origin                                      |
|----------------|---------------------------------------------|
| 0.05$^\ast$    | Lepton flavour universality of $\pi^\pm$ decay |
| 0.02           | Charge current universality $0\nu\beta\beta$ |
| $7.7 \times 10^{-6}$ |                                |

**Table I:** Upper bounds on the $\chi'_{111}$ coupling, assuming all sparticle masses to be 100 GeV. The bounds are at 95% confidence level (CL), except for that marked $^\ast$, which is at the 68% CL.

In this letter, we follow a bottom-up phenomenological approach. We fix any sparticles which are not relevant for our hypothesised signals to be heavy enough not to be produced at the LHC. Otherwise, we fix the first generation left-handed slepton mass to be 2.1 TeV, the lightest neutralino mass varies from 400 GeV up to 1 TeV and all other sparticles are above the TeV scale. The squarks are fixed at 2 TeV masses (the 0$\nu\beta\beta$ rate we predict below depends somewhat on this assumption due to additional diagrams to Fig. 3 involving squarks). In addition, we set other RPV couplings to zero, allowing us to focus purely on the effects of $\chi'_{111}$.

The phenomenology is model dependent. We have considered the following representative scenarios:

- **S1:** $M_1 < M_2 = M_1 + 200 < \mu$, i.e., the LSP is mostly bino-like with a small wino-component. In this case the slepton has a substantial branching ratio of decaying to the second lightest neutralino or lightest chargino.

- **S2:** $M_1 < \mu < M_2$, the LSP is still dominated by the bino-component, with a heavy intermediate higgsino mass and an even heavier wino mass (> 1 TeV). This case is interesting because it increases the branching ratio of slepton decaying into the lightest neutralino and a lepton.

- **S3:** $M_2 << M_1 \approx \mu$, i.e., the LSP is dominantly wino-like. In this case, the slepton also decay to lighter chargino and a neutrino with a substantial branching fraction. In this scenario, both the lighter chargino and lightest neutralino decay via $\chi'_{111}$. Hence, the lepton and jet multiplicities in the final state are enhanced compared to S1, S2.

Depending on the nature of the lightest neutralino and the value of the $\chi'_{111}$ coupling, the branching ratio changes considerably [21]. We show the effective branching fraction $\text{Br}(l \rightarrow eejj)$ for our various scenarios in Fig. 4. We note that a higher value of $\chi'_{111}$ leads to stringent limits from di-eejj searches. We take into account the constraint from CMS di-eejj resonance searches [24]. The limit on the cross-section for a di-eejj resonance around 2.1 TeV is $< 45$ fb. This in turn gives a bound on the product $\chi'_{111}^\ast \times \text{Br}(\tilde{\nu}/\tilde{\nu} \rightarrow jj)$ [21].
We simulate first generation resonant slepton production in $pp$ collisions at a centre of mass energy $\sqrt{s} = 8$ TeV using CalcHEP (v3.4.2) [25], and the subsequent decay, showering and hadronization effects have been performed by PYTHIA (v6.4) [26]. We use SARAH-v4.0.1 [27] and SPheno-v3.2.4 [28] for the model implementation and to compute branching ratios. We approximate the next-to-leading order QCD corrections by multiplying the tree-level production cross section with a $K$-factor of 1.34 [21]. We use CTEQ6L parton distribution functions [29] with factorization and renormalization scales set at the slepton mass $\tilde{m}_L$. To take into account detector resolution effects, we also use various resolution functions parameterized as in [30] for the final state objects.

The final state studied in [1], contains exactly two isolated leptons and at least two jets (2$\ell$+ ≥ 2j). Basic object definitions for the leptons and jets together with the following final selection cuts, as outlined in [1], have been imposed:

- Invariant mass of the lepton pair, $M_{\ell\ell} > 200$ GeV.
- Invariant mass of the leptons and two hardest jets, $M_{\ell\ell jj} > 600$ GeV.

We assume a truncated Gaussian for the prior probability density function (PDF) of $b\pm\sigma_b$ background events:

$$p(b|\bar{b}, \sigma_b) = \begin{cases} Be^{-\frac{(b-\bar{b})^2}{2\sigma_b^2}} & \forall b > 0 \\ 0 & \forall b \leq 0 \end{cases}$$

where $B$ is a normalisation factor that makes the distribution integrate to 1. We marginalise the Poissonian probability of measuring $n$ events over $b$ in order to obtain confidence limits:

$$P(n|n_{exp}, \bar{b}, \sigma_b) = \int_0^{\infty} db \ p(b|\bar{b}, \sigma_b) \frac{e^{-n_{exp}n_{exp}^b}}{n!}$$

where $n_{exp}$ is the number of expected events. The CL of $n_{obs}$ observed events is then $P(n \leq n_{obs})$. Calculated in this way, the local significance of the 1.8 < $M_{\ell\ell jj}$/TeV < 2.2 bin is 3.6σ[1]. The two-sided 95%CL bound on the number of signal events in this bin is $s \in [4.1 - 19.7]$.

We present our results in Table II and in Fig. 5 for a typical S3 scenario. In Table II, we show the event rate assuming an integrated luminosity of 19.7 fb$^{-1}$ and the corresponding experimental data and SM backgrounds.

In Fig. 5, the $M_{\ell\ell jj}$ distribution is compared with data [1] for the background and an example signal model point prediction. We see that the signal is concentrated in the 1.8 TeV < $M_{\ell\ell jj}$ < 2.2 TeV bin, because the width of the slepton is very narrow. Fig. 6 shows the $\lambda'_{111}$ -

| Cut                              | Signal | Background | Data |
|----------------------------------|--------|------------|------|
| $2\ell + \geq 2j$                | 12.7   | 34154      | 34506|
| $M_{ee} > 200$ GeV               | 12.6   | 1747       | 1717 |
| $M_{\ell\ell jj} > 600$ GeV     | 12.6   | 783±51     | 817  |
| $1.8$ TeV < $M_{\ell\ell jj}$ < $2.2$ TeV | 10     | 4.0±1.0    | 14   |

TABLE II: Number of events from signal, backgrounds and reconstructed data after successive application of the selection cuts at 19.7 fb$^{-1}$ integrated luminosity and 8 TeV center of mass energy for scenario S3 assuming $\lambda'_{111} = 0.105$ and $m_{\tilde{\chi}^0_1} = 532$ GeV. The data and SM backgrounds are taken from Ref. [1].

1 The CLs method employed by CMS yields 3.2σ for these assumed statistics. The discrepancy between this number and the quoted 2.8σ comes from separate systematic errors on the different background components, which we do not have access to here.
The expected 90% CL exclusion reach from GERDA Phase-II combined constraints coming from 0νββ light curves fit data from the bin 1.

FIG. 6: A scan in the $\lambda_{111}$ plane assuming 2.1 TeV slepton mass and scenario (top) S1, (middle) S2 and (bottom) S3. The color gradient represents the half-life $T_{1/2}$ of $0\nu\beta\beta$ process, where the nuclear matrix uncertainty has been adopted from [22]. The region between the two light curves fits the 90% CL current combined constraints coming from $0\nu\beta\beta$ half-life limits [12]. The expected 90% CL exclusion reach from GERDA Phase-II [13] is also shown.

$m_{\tilde{\chi}_0}$ plane for S1-S3, each corresponding to a different hierarchy of mass parameters $M_1$, $M_2$ and $\mu$. It is evident that a large $\lambda_{111}$ value $\lambda_{111}^\prime \sim 0.4$ is ruled out by the CMS di-jet search [24]. In the 1.8 TeV $< M_{eejj} < 2.2$ TeV bin, CMS measured 1 same sign lepton pair and 13 opposite-sign pairs. For a given scenario, the ratio $R$ in the signal of the opposite sign to same sign di-leptons ($R$) is predicted to be independent of $\lambda_{111}$ and $m_{\tilde{\chi}_0}$ to a good approximation. S1 and S2 predict $R = 1.0$ whereas S3 predicts $R = 3.0$. It is difficult for us to estimate whether or not this is a good fit because we do not know the background rates for same-sign versus opposite sign leptons. We also show the present bound from combined experiments’ constraints on the $0\nu\beta\beta$ decay rate in the figure. The region between the two light curves fits the CMS excess at the 95% CL level. For scenario S1, most of this ‘good-fit region’ can be covered by GERDA Phase-II [13]. For scenario S2, a positive signal in GERDA Phase-II is possible in the good-fit region for lower neutralino masses $m_{\tilde{\chi}_0} < 550$ GeV. However, In S3, the expected reach of GERDA Phase-II does not probe the good-fit region.

To summarize, our model provides a good fit to the CMS $W_R$ search $eejj$ excess while respecting other empirical constraints. Our model predicts a $0\nu\beta\beta$ rate. Up and coming $0\nu\beta\beta$ experiments such as GERDA Phase-II will probe a significant portion of the good-fit parameter space. We look forward to ATLAS providing a similar analysis of the 8 TeV data, as well as future tests of the excess at LHC Run II. We note that our signal comes from $\tilde{e}_L$ and $\tilde{\nu}$ resonances. With more statistics, it should be possible to resolve these two narrow resonances, providing discrimination between our model and others that explain the $W_R$ search excess.

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