IPPP/14/78, DCPT/14/156

Explaining the CMS $eejj$ Excess With $\mathcal{R}-$parity Violating Supersymmetry and Implications for Neutrinoless Double Beta Decay

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The recent CMS searches 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 an excess around $m_{eejj} \sim 2$ TeV. In this work, we explain the reported CMS excess with R-parity violating supersymmetry (SUSY). We consider the resonant slepton and sneutrino production, followed by the three body decays of neutralino and chargino via R-parity violating coupling. These fit the excess for slepton and sneutrino masses around 2 TeV. This scenario can further be tested in neutrinoless double beta decay experiment ($0\nu\beta\beta$). GERDA Phase-II will probe a significant portion of the good-fit parameter space.

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 2 TeV, with a local CERN CL$_s$ significance of 2.8σ [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. In addition, CMS searches for first generation di-leptoquark production have also reported excesses over Standard Model (SM) background expectations in two different channels. This search was conducted with 19.6fb^{-1} of integrated luminosity and a 8 TeV LHC run, that reports a deviation in the $eejj$ and $e\not{p}_{\rm T}$jj channels, with a local significance of 2.4 σ and 2.6 σ, respectively [2]. None of these excesses are significant enough to claim a discovery. However, it is timely before the next LHC run (Run II) to explain such excesses 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 recent CMS excesses with different models. Coloron-assisted leptoquarks were proposed in Ref. [3] in order to explain all three excesses. The W_R excess was interpreted in GUT models in Refs. [4, 5]. In Ref. [6], resonant pair production of vector-like leptons was proposed via W'/Z' vector bosons. Ref. [7] performed closer analysis (including a general flavor structure) of W'/Z' interpretations of the W_R search data. Ref. [8] explains the di-leptoquark excess with sbottom LSP decay processes via $\mathcal{R}$-parity violation (RPV). $\mathcal{R}$-parity is a multiplicative discrete symmetry defined as $\mathcal{R} = (-1)^{3(B-L)+2S}$, where B and L correspond to baryon and lepton number, and S is spin.

In this letter, we propose a new hypothesis for a new physics explanation of the W_R search excess in terms of the RPV minimal supersymmetric model (MSSM). In particular, we show that RPV with a non-zero λ'_{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 λ'_{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.

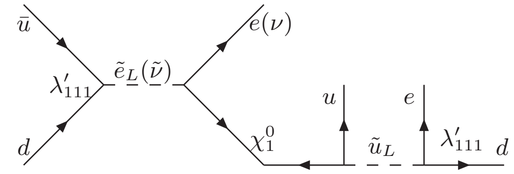

FIG. 1. Feynman diagram for single selectron production leading to $eejj$ signal at the LHC.

The RPV superpotential with the λ'_{111} term is

$$W_{\not{R}} = \lambda'_{111} L Q d^c. \tag{1}$$

This induces the following Lagrangian terms,

$$\mathcal{L} = -\lambda'_{111}\tilde{e}ud^c - \lambda'_{111}\tilde{u}ed^c + \lambda'_{111}\tilde{d}\nu_e d^c + \tilde{\nu}_e d d^c + \ldots \tag{2}$$

The MSSM with λ'_{111} is constrained by empirical data on charge current universality, e–μ–τ universality, atomic

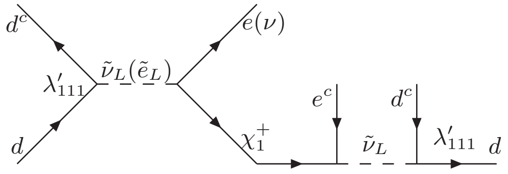

FIG. 2. Feynman diagram for single sneutrino production leading to $eejj$ signal at the LHC.

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

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

parity violation etc [9]. In addition, the model contributes to lepton number violating neutrinoless double beta decay ($0\nu\beta\beta$) [10–12], as shown in Fig. 3. The process is not permitted in the SM because of lepton number conservation. The present bound on the half-life of ^{76}Ge isotope is $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yrs at 90% confidence level (CL) from GERDA [13], while the 90% CL combined bound on the half-life from previous experiments is $T^{0\nu}_{1/2} > 3.0 \times 10^{25}$ yrs [13]. The future $0\nu\beta\beta$ experiment GERDA Phase-II will be commissioned soon and is expected to improve the half-life sensitivity to $T^{0\nu}_{1/2} \sim 2 \times 10^{26}$ yrs [14]. 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 λ'_{111} coupling can be found in Ref. [15] 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 λ'_{111} coupling in Eq. 2 can lead to single slepton production at hadron colliders, as first studied in [16] and subsequently in [17–24]. For a slepton of mass around the CMS excess (2.1 TeV) and $0.03 < \lambda'_{111} < 0.5$ the production cross-section varies from less than 1 fb to as high as 130 fb [20]. As pointed out in Ref. [24], 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 λ'_{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: $pp \to \tilde{\nu}_e/\tilde{\nu}_e^* \to e^-\chi_1^+/e^+\chi_1^- \to e^+e^-jj$. It is our aim to see if resonant selectron and sneutrino production can fit the CMS W_R excess while evading other experimental constraints.

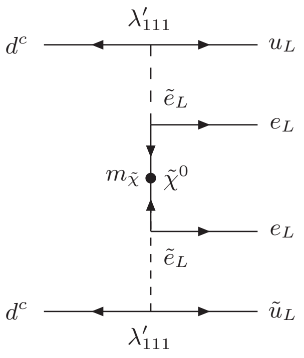

FIG. 3. Sample Feynman diagram for $0\nu\beta\beta$, corresponding to selectron and neutralino contribution. There are several other diagrams from gluino and squark mediation, that contribute to the half-life $T^{0\nu}_{1/2}$ [23]. In our analysis of $0\nu\beta\beta$, we consider all possible contributions via λ'_{111} coupling [11, 23].

In this letter, we follow a bottom-up phenomenological approach. We consider the sparticles which are not relevant for our hypothesised signals to be heavy enough not to be produced at the LHC. In particular, 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 particles are above the TeV scale. In particular, 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 also set other RPV couplings to zero, allowing us to focus purely on the effects of λ'_{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:** $M_1 << M_2 \simeq \mu$, i.e., the LSP is purely bino-like, the other neutralinos and charginos are much heavy so that the decays $\tilde{e}^\pm \to \nu\chi^\pm_{1,2}$ or $\tilde{e} \to e\chi^0_i$ ($i = 2, 3, 4$) are suppressed.

- **S4:** $M_2 << M_1 \simeq \mu$, i.e., the LSP is purely 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 RPV coupling. Hence, the lepton and jet multiplicity get enhanced in the final state compared to

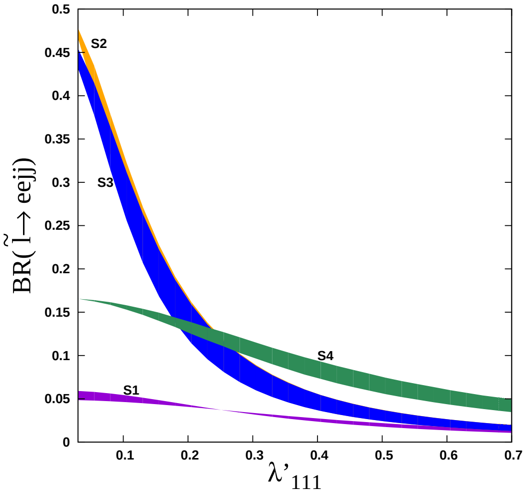

FIG. 4. The effective branching ratio of the decay $\tilde{\ell} \rightarrow eejj$ in four benchmark scenarios for possible choices of λ'_{111} coupling. The small color bands indicate the slight variation of the branching ratio with $m_{\tilde{\chi}^0_1}(400\text{ GeV} - 1.0\text{ TeV})$ for a given λ'_{111}.

the above three. This possibility is therefore particularly interesting for the small λ'_{111} coupling.

The other scenarios, for example where the LSP is purely Higgsino-like, are not interesting for this study. Depending on the nature of the lightest neutralino and the value of the λ'_{111} coupling, the branching ratio changes considerably [22]. For example, assuming the neutralino to be purely bino-like and $0.03 < \lambda'_{111} < 0.5$ the branching ratio $\text{Br}(\tilde{e} \rightarrow e\chi^0_1)$ varies from 90% to 5%. We show the effective branching fraction $\text{Br}(\tilde{l} \rightarrow eejj)$ for our four scenarios in Fig. 4. On the other hand, a higher value of λ'_{111} leads to stringent limits from di-jet resonance searches. In this work, we take into account the constraint from CMS di-jet resonance search [25]. The model independent limit on the cross-section for a resonance around 2.1 TeV is < 45 fb. This in turn gives a bound on the product ${\lambda'_{111}}^2 \times Br(\tilde{e}/\tilde{\nu} \rightarrow jj)$ [22].

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) [26], and the subsequent decay, showering and hadronization effects have been performed by PYTHIA (v6.4) [27]. We use SARAH-v4.0.1 [28] and SPheno-v3.2.4 [29] 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 [22]. We use CTEQ6L parton distributions function [30] with factorization and renormalization scales set at the slepton mass $\mu_F = \mu_R = \tilde{m}_L$. To take into account the finite detector resolution effects, we also use various resolution functions parameterized as in [31] for the final state objects.

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

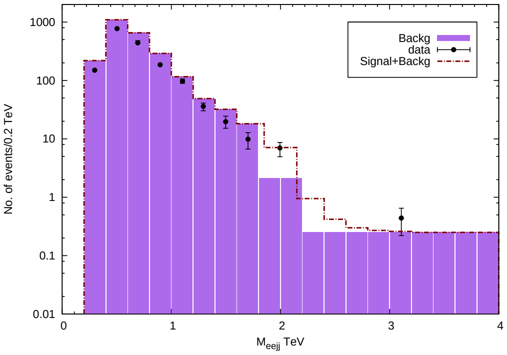

FIG. 5. A comparison of the data, signal and background M_{eejj} distributions after imposing cuts as done in the analysis of the W_R search. The benchmark signal point corresponds to $\lambda'_{111} = 0.105$ and $m_{\tilde{\chi}^0_1} = 532$ GeV (**S4**). The data and SM backgrounds are taken from [1].

- 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 $\bar{b} \pm \sigma_b$ background events:

$$p(b|\bar{b},\ \sigma_b) = \begin{cases} Be^{-(b-\bar{b})^2/(2\sigma_b^2)} & \forall b > 0 \\ 0 & \forall b \leq 0 \end{cases} \tag{3}$$

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:

$$P(n|n_{exp},\ \bar{b},\ \sigma_b) = \int_0^\infty db\ p(b|\bar{b},\ \sigma_b)\frac{e^{-n_{exp}}n^n_{exp}}{n!}, \tag{4}$$

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 $1.8 < M_{eejj}/\text{TeV} < 2.2$ bin is 3.6σ[1]. The two-sided 95%CL bound on the number of putative 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 **S4** scenario. In Table. II, we show the event

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[1] The CL_s 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.

Cut	Signal	Background	Data
$2e+ \geq 2j$	12.7	34154	34506
$M_{ee} > 200$ GeV	12.6	1747	1717
$M_{eejj} > 600$ GeV	12.6	783±51	817
1.8 TeV$< M_{eejj} < 2.2$ 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 **S4** assuming $\lambda'_{111} = 0.105$ and $m_{\tilde{\chi}_1^0} = 532$ GeV. The data and SM backgrounds are taken from Ref. [1].

rate assuming the integrated luminosity of 19.7 fb^{-1} and the corresponding experimental data and SM backgrounds. In Fig. 5, the M_{eejj} 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$< M_{eejj} < 2.2$ TeV bin, because the width of the slepton is very narrow. Figs. 6, 7 show the $\lambda'_{111} - m_{\tilde{\chi}_1^0}$ plane for our four scenarios **S1-S4**, each corresponding to a different hierarchy of mass parameters M_1, M_2 and μ. It is evident that a large λ'_{111} value $\lambda'_{111} \sim 0.4$ is ruled out by the CMS di-jet search [25]. In the 1.8 TeV$< M_{eejj} < 2.2$ TeV bin, CMS measured 1 opposite sign lepton pair and 13 same-sign pairs. For a given scenario, the ratio of the opposite sign to same sign di-leptons (R) is predicted to be independent of λ'_{111} and $m_{\tilde{\chi}_1^0}$ to a good approximation. **S1**, **S2**, **S3** all predict $R = 1$ whereas **S4** predicts $R = 2.98$. 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. For scenarios **S1** and **S4**, the constraint from $0\nu\beta\beta$ can be more stringent than the CMS di-jet bound. 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 [14]. For scenarios **S2** and **S3**, a positive signal in GERDA Phase-II is possible in the good-fit region for lower neutralino masses $m_{\tilde{\chi}_1^0} < 550$ GeV. However, In **S4**, the expected reach of GERDA Phase-II does not probe the good-fit region.

The scenarios that we consider all have first generation slepton masses of 2.1 TeV. As such, they are unlikely *per se* to explain other excesses in the $eejj$ and $ejj\not{p}_T$ channels in the CMS di-leptoquark searches, which occur at lower invariant masses ~ 1.2 TeV. However, we have checked that the CMS di-leptoquark search data are not in contradiction with our model aside from not being able to explain these other excesses.

We note that λ'_{211} will be severely constrained because no excess is observed in the $\mu\mu jj$ channel. The constraints will be less stringent for other λ'_{1jk} couplings that can give rise to resonant first generation slepton production, because of a lower production cross section coming from higher generation suppression in the parton distribution functions.

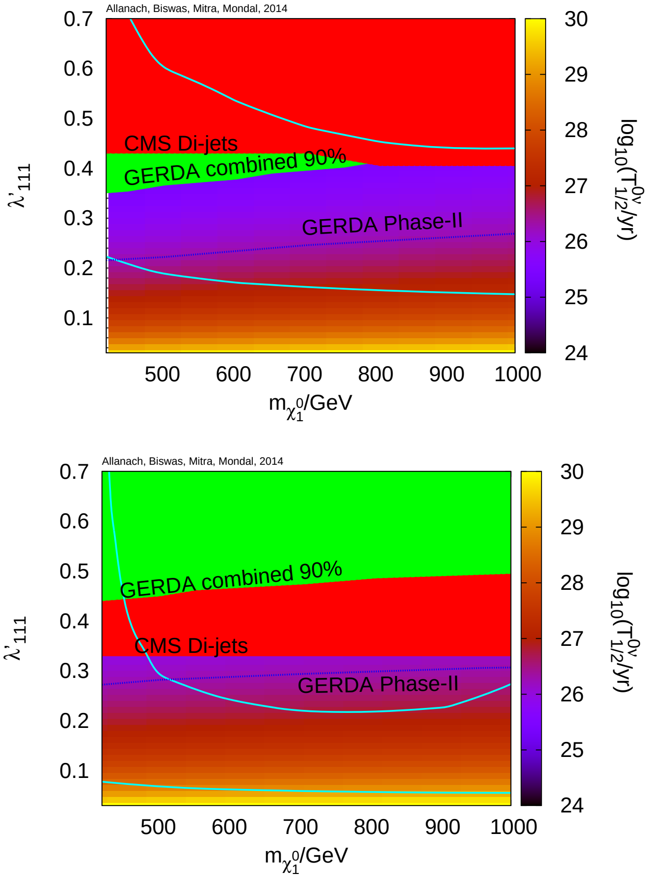

FIG. 6. A scan in the λ'_{111} coupling and the neutralino mass plane assuming 2.1 TeV slepton mass and scenario a) **S1** (top) and b) **S2** (bottom). The color gradient represents the half-life $T^{0\nu}_{1/2}$ of $0\nu\beta\beta$ process, where the nuclear matrix uncertainty has been adopted from [23]. The region between the light curves fit data from the bin 1.8 TeV$< m_{eejj} < 2.2$ at the 95% CL level. We show regions excluded at 95%CL by the CMS di-jet resonance search [25] and the 90% CL current combined constraints coming from $0\nu\beta\beta$ half-life limits [13]. The expected 90% CL exclusion reach from GERDA Phase-II [14] is also shown.

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.

Acknowledgements: This work has been partially supported by STFC. MM and SM would like to thank the organizers of the workshop WHEPP13, Puri, India where part of the work started. MM acknowledges partial

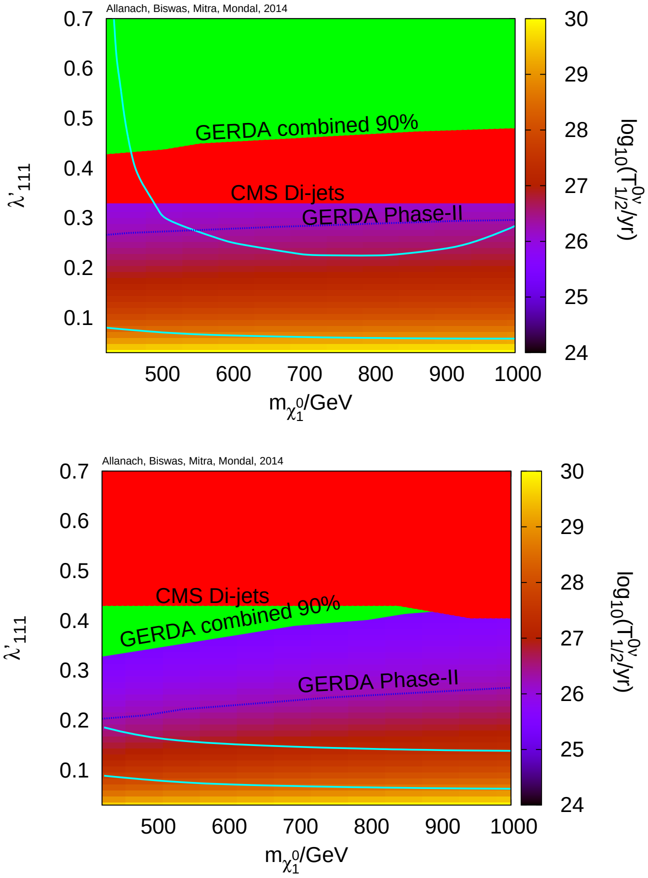

FIG. 7. As in Fig. 6 but for scenario a) **S3** (top) and b) **S4** (bottom).

support of the ITN INVISIBLES (Marie Curie Actions, PITN-GA-2011-289442). MM would like to thank W. Rodejohann for useful correspondence. SB would like to thank Pradipta Ghosh for discussions and help in preparing the draft. We also thank J Chou and J Pastika for helpful communications regarding the CMS W_R analysis.

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