Resonant Slepton Production Yields CMS $eejj$ and $e\nu jj$ Excesses

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Recent CMS searches for di-leptoquark production report local excesses of 2.4σ in the $eejj$ channel and 2.6σ in a $e\nu jj$ channel. Here, we simultaneously explain both excesses with resonant slepton production in $R-$parity violating supersymmetry (SUSY). We consider resonant slepton production, which decays to a lepton and a chargino/neutralino, followed by three-body decays of the neutralino/chargino via an $R-$parity violating coupling. There are regions of parameter space which are also compatible at the 95% confidence level (CL) with a 2.8σ $eejj$ excess in a recent CMS $W_R$ search, while being compatible with other direct search constraints. Phase-II of the GERDA neutrinoless double beta decay ($0\nu\beta\beta$) experiment will probe a sizeable portion of the good-fit region.

The recent CMS search for di-leptoquark production found, with a certain set of cuts, a 2.4σ local excess in the $eejj$ channel and a 2.6σ local excess in a $e\nu jj$ channel\(^{[1]}\) in comparison to Standard Model (SM) expectations. The CMS searches use pp collision data at the Large Hadron Collider (LHC) and a centre of mass energy of 8 TeV and 19.6 fb\(^{-1}\) of integrated luminosity. Requiring a certain set of cuts (called ‘$M_{LQ} = 650$ GeV’ cuts), CMS reported 36 events on a background\(^{[2]}\) of 20.5 ± 3.5 in the $eejj$ channel, and 18 events on a background of 7.5 ± 1.6 in the $e\nu jj$ channel\(^{[1]}\). Taken simultaneously and ignoring correlations between the systematics, these excesses amount to a 3.5σ effect. In addition, a $W_R$ search (with different cuts to the di-leptoquark search) reported a 2.8σ excess in the $eejj$ channel at 1.8 TeV < $M_{eejj} <$ 2.2 TeV\(^{[2]}\). These excesses are not significant enough to claim a discovery, or even evidence. They are similar enough to attempt a unified explanation of all three, and a timely explanation before the next LHC run (Run II) in terms 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 excesses with different models. Coloron-assisted leptoquarks were proposed in Ref.\(^{[3]}\). The $W_R$ excess was interpreted in GUT models in Refs.\(^{[4]–[6]}\). 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 ref.\(^{[8]}\), it was supposed that leptoquarks consistent with the di-leptoquark excess decay into dark matter particles with a significant branching ratio. Ref.\(^{[9]}\) explains the di-leptoquark excesses with di-sbottom production, followed by $R-$parity violating (RPV) decay. In a previous letter\(^{[10]}\), we proposed that resonant slepton production was responsible for the $W_R$ search excess in RPV supersymmetry. One of us showed that this explanation is also consistent with recent deviations from SM prediction measured by LHCb in $B^+ \rightarrow K^+\ell\ell$ decays\(^{[11]}\).

In the present letter, we shall show that RPV resonant slepton production can simultaneously fit the two excesses in the di-leptoquark search while remaining consistent with other direct searches, including the $W_R$ search data. $R$-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 the spin. In particular, we show that RPV with a non-zero $\lambda'_{111}$ coupling can fit the CMS excesses\(^{[11]}\) via resonant slepton production (with a left-handed slepton mass of around $m_\tilde{l}_1 \sim 2$ TeV) in pp collisions. The slepton (either a selectron or an electron sneutrino) then decays, as shown in Fig. 1, either into $eejj$ or $e\nu jj$. For sleptons much

\(^{[1]}\) CMS refers to this channel as $eejj$, and we shall from here use the same nomenclature.

\(^{2}\) We have added systematic and statistical errors in quadrature.

FIG. 1. Feynman diagrams for single slepton production leading to a $eejj$($e\nu jj$) signal at the LHC. Other diagrams, where the $\chi^0_1$ is replaced by $\chi^\pm_1$ (among other replacements) also contribute.
heavier than $M_Z$, one automatically gets cross-sections of the same order of magnitude for the $eejj$ and the $e\nu jj$ channels because their masses are at tree-level related by $12$

$$m_{\tilde{e}_L}^2 = m_{\tilde{\nu}_L}^2 + M_W^2 \cos 2\beta,$$  

(1)

where $\cos 2\beta < 0$, $\tan \beta$ is the ratio of the two MSSM Higgs doublet vacuum expectation values, and we have neglected small terms proportional to powers of lepton masses. For $m_{\tilde{e}_L}$ around 2 TeV (which we shall be interested in), $m_{\tilde{\nu}_L} \approx m_{\tilde{e}_L}$ is a good approximation. In addition, the parton distribution functions for anti-up quarks $u^c$ and anti-down quarks $d^c$ are similar within the proton, resulting in cross-sections for the two processes shown in Fig. 1 of a similar order of magnitude.

The $\lambda'_{111}$ term in the RPV superpotential is $3$.

$$W_R = \lambda'_{111} L Q d^c,$$  

(2)

This induces the following Lagrangian terms,

$$\mathcal{L} = \lambda'_{111} \left( -\bar{e} u d^c - \bar{\nu} e d^c + \bar{\nu} e d^c + \ldots \right)$$  

(3)

The $\lambda'_{111}$ coupling in Eq. 3 can lead to single slepton production at hadron colliders, as first studied in 18 and subsequently in 19–25. For an example slepton mass of $m_{\tilde{\tau}_1} = 2.1$ TeV and $0.03 < \lambda'_{111} < 0.5$ the production cross-section varies from less than 1 fb to as high as 130 fb 22.

The coupling $\lambda'_{111}$ responsible for single slepton production in Fig. 1 induces $0\nu\beta\beta$ 13–15, which is not permitted in the SM because of its prediction of lepton number conservation. The present bound on the $0\nu\beta\beta$ half-life of $^{76}$Ge is $T_{0\nu}^{1/2} > 2.1 \times 10^{25}$ yrs at 90%CL from GERDA 16, 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 16. 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 17.

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. There are several contributing diagrams including slepton, neutralino, squark and/or gluino exchange, but for high squark and gluino masses, the dominant one often involves internal sleptons and lightest neutralinos $\chi^0_1$ 10. As pointed out in Ref. 25, one can then marry resonant slepton search data from the LHC with the predicted $0\nu\beta\beta$ rate in order to provide further tests and interpretations. We shall here neglect contributions to $0\nu\beta\beta$ coming from neutrino masses, assuming the one due to RPV is dominant.

It is our aim to see if resonant slepton production and decay can fit the CMS di-leptoquark excesses while evading other experimental constraints, and to examine the compatibility with our previous resonant slepton explanation of the $W_R$ excess. Then, we wish to explore the $0\nu\beta\beta$ decay experiments’ prospects within any good-fit region. In fact, the strongest indirect bound that is relevant to our analysis is that from $0\nu\beta\beta$. Other indirect bounds on the $\lambda'_{111}$ coupling can be found in Ref. 26–27. For example, the RPV violating contribution to the anomalous magnetic moment of the electron $g_\mu^e$ is $5$.

$$\delta g_\mu^e - \frac{2}{2} \sim \frac{|\lambda'_{111}|^2 m^2}{32 \pi^2 m^2},$$  

(4)

where $\tilde{m}$ is the size of supersymmetric particle masses appearing in the one-loop diagram. Putting $\lambda'_{111} = 1$ and $\tilde{m} = 1$ TeV, we obtain a contribution of $< 10^{-15}$, far below current bounds: the difference between the experimental value and the Standard Model prediction is $24$ ($-1.06 \pm 0.82) \times 10^{-12}$.

We shall follow a bottom-up phenomenological approach. We decouple sparticles which are not relevant for our hypothesised signals. Otherwise, we fix the first generation lightest neutralino mass $M_{\chi_1^0}$ to be 1 TeV (although we have checked that there are only small deviations in our predictions and constraints if we reduce this to 0.8 TeV) the slepton mass varies from 1.8 TeV up to 2.2 TeV and all other sparticles are above the TeV scale. The squark and gluino masses are fixed at 2.5 TeV. We set other RPV couplings to zero, allowing us to focus purely on the effects of $\lambda'_{111}$.

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 decays to the second lightest neutralino or lightest chargino $\chi^\pm_2$. **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 increases the branching ratio of slepton decays into the lightest neutralino and a lepton compared to S1. **S3:** $M_2 \ll M_1 \approx \mu$, i.e. the LSP is dominantly wino-like. In this case, slepton decay to $\chi^0_1$ and $\chi^0_2$ with a substantial branching fraction, which then subsequently decay via $\lambda'_{111}$. Depending on the nature of the lightest neutralino and the value of the $\lambda'_{111}$ coupling, the branching

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3. Charged slepton production is larger because it couples to $u$ in the proton rather than the $d$.

4. $e^c$ denotes the charge conjugate.
TABLE I. 95% upper bound on cross-section times branching ratio times acceptance for resonantly produced sleptons decaying to di-jets [30].

| Channel | Cuts ($M_{LQ} = 650$ GeV) |
|---------|--------------------------|
| $eejj$  | $S_T > 850$ GeV, $m_{ee} > 155$ GeV, $m_{ej}^{min} > 360$ GeV, $m_{ej} > 555$ GeV, $m_T(eejj) > 270$ GeV |
| $evjj$  | $S_T > 1040$ GeV, $E_T > 145$ GeV, $m_{ee} > 160$ GeV, $m_{ej}^{min} > 390$ GeV, $m_{ej} > 600$ GeV, $m_T(evjj) > 280$ GeV |

FIG. 2. A comparison of the measured (‘Data’), background (‘B’) and example signal plus background (‘S+B’) distributions for $m_{ej}^{min}(eejj)$, $m_{ej}(evjj)$ and the scalar sum of the $p_T$ of visible objects for (lower left) $eejj$ and (lower right) $evjj$. $m_{ej}^{min}$ is the invariant mass of the electron-jet pairing combination for which the difference between the $m_{ej}$ for each pair is smallest. The vertical axis measures the number of events falling in a bin after imposing cuts. The signal point corresponds to $\chi_{111} = 0.175, m_T = 2$ TeV and $M_{\chi^{\prime}_1} = 0.9$ TeV (S2). Data and SM backgrounds are taken from [1].

TABLE II. Cuts in each channel, from Refs. [1, 2]. $S_T = \sum |p_T|$ is the scalar sum of transverse momenta of all visible objects, $m_{ee}$ is the invariant mass of the lepton pair and $m_{ej}^{min}$ is the invariant mass of the electron-jet pairing combination for which the difference between the $m_{ej}$ for each pair is smallest. $m_T(ejj)$ is the electron-neutrino transverse mass, and $m_{ej}$ is the electron-jet invariant mass where the lepton is paired with the jet that results in the most smallest difference between $m_{ej}$ and $m_T(ejj)$.

| Channel | Cuts ($M_{LQ} = 700$ GeV) |
|---------|--------------------------|
| $eejj$  | $S_T > 1120$ GeV, $m_{ee} > 160$ GeV, $m_{ej}^{min} > 390$ GeV, $m_{ej} > 600$ GeV, $m_T(eejj) > 280$ GeV |
| $evjj$  | $S_T > 1120$ GeV, $E_T > 155$ GeV, $m_{ee} > 160$ GeV, $m_{ej}^{min} > 390$ GeV, $m_{ej} > 600$ GeV, $m_T(evjj) > 280$ GeV |

Together with final selection cuts, as outlined in [1], have been imposed as shown in Table I. In their analysis, CMS defined many signal regions, each with its own set of cuts. We pick one of them (designed for 700 GeV di-leptoquark sensitivity) which only shows a small excess, to check that our model is not ruled out by it.

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

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

(5)

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:

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

(6)

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 $evjj$ excess is a 2.9$\sigma$ effect, and the $eejj$ excess is a 2.6$\sigma$ effect, making the two combined 3.9$\sigma$. With a two-tailed 95% CL, the number of signal events in the $eejj$ channel is $s_{eejj} \in [19.4, 58.4]$, whereas in the $evjj$ channel it is $s_{evjj} \in [7.8, 34.3]$. For the $W_R$ search, we combine the statistics from the bins $M_{eejj}/$TeV $\in [1.6-1.8, 1.8-2.2, 2.2-4]$ (bin $i = 1, 2, 3$, respectively). CMS only observed a large excess in the 1.8-2.2 TeV bin, there was no large excess in the adjacent bins and so these help constrain parameter space. Bin $i$ has a $\chi^2$ statistic $\chi^2 = -2 \ln P(n^{(i)}|n_{exp}^{(i)}, b^{(i)}, \sigma_b^{(i)})$, where $P$ is obtained from Eq. 6. When considering $W_R$ search constraints, we therefore form a total $\chi^2 = \chi^2_1 + \chi^2_2 + \chi^2_3$. Imposing a 95%CL limit is equivalent to limiting the total $\chi^2 < 3.84$. 

ratio changes considerably [23]. At large values of $\lambda'_{111}$, the branching ratio of a lepton into two jets becomes larger. Thus, resonant slepton production then becomes constrained by di-jet resonance searches [23]. We take into account the constraint from the CMS di-jet resonance search [30]: the upper limits are displayed in Table I.

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) [31], and the subsequent decay, showering and hadronization effects have been performed by PYTHIA (v6.4) [32]. We use SARAH-v4.0.1 [33] and SPheno-v3.2.4 [34] 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 [23]. We use CTEQ6L parton distribution functions [35] with factorization and renormalization scales set at $m_{\tilde{t}}$. To take the detector resolution into account, we use various resolution functions parameterized as in [30] for the final state objects.

The final states studied in [1], contain either exactly two isolated $e_s$ and at least two jets ($eejj$), or one isolated $e_s$ jet and missing transverse momentum ($lvjj$). Basic object definitions for the leptons and jets
FIG. 3. Constraints in the $m_l - \lambda_{111}$ plane assuming $M_{\chi_1^0} = 0.9$ TeV in scenario (top) S1, (middle) S2 and (bottom) S3, where the nuclear matrix elements have been adopted from [24]. The parameter space fitting the $eejj$, $evjj$ di-leptoquark search excesses and the $W_R eejj$ excess to 95%CL is shown in the key. The region above the lines (except for the one labelled ‘GERDA Phase-II Search’) is excluded, labeled near the edge of exclusion: either the 90%CL constraint from current combined neutrinoless double beta decay bounds ($0\nu\beta\beta$) or at the 95%CL from the CMS di-jets shape analysis. The expected 90% CL exclusion reach from GERDA Phase-II [17] is shown as the region above the solid black line. The cross in the middle panel shows the location of our example point.

We present the predicted event numbers in Table III and Fig. 2 for an example point in our parameter space and an integrated luminosity of 19.6 fb$^{-1}$. In Fig. 2 the distributions $m_{eejj}$, $m_{e\nu}$ and the scalar sum of $p_T$ for the visible objects are shown for data [1], background and an example signal model point prediction[6]. The figure shows that the distributions are reproduced to a reasonably good level by our model point, although the model point is perhaps slightly broader and of higher energy, compared to the measurements. One must bear in mind though that the statistical power of the kinematical distributions is very limited because of the small statistics.

In Fig. 3 shows the $\lambda_{111}' - m_{l_1}$ plane for S1-S3. It is evident that the largest values of $\lambda_{111}'$ that we take are ruled out by the CMS di-jets search [30]. In S1 and S2, there is a small region where all constraints are respected and the three excesses are within their 95%CL constraints. In S1, the whole of this region around $\lambda_{111}' = 0.175$, $m_l = 2$ TeV and $M_{\chi_1^0} = 0.9$ TeV. The data and SM backgrounds are taken from Ref. [1] and Ref. [2].

| Channel                  | $s + b$ | $b \pm \sigma_b$ | Data |
|--------------------------|---------|------------------|------|
| $eejj (M_{LQ} = 650$ GeV) | 41.5    | 20.5$\pm$3.3    | 36   |
| $evjj (M_{LQ} = 650$ GeV) | 33.9    | 7.5$\pm$1.6     | 18   |
| $eejj (M_{LQ} = 700$ GeV) | 32.7    | 12.7$\pm$2.7    | 17   |
| $W_R (1.6 < M_{eejj}/TeV < 1.8)$ | 12.4    | 9.6$\pm$3.8     | 10   |
| $W_R (1.8 < M_{eejj}/TeV < 2.2)$ | 26.0    | 4.0$\pm$1.0     | 14   |
| $W_R (M_{eejj}/TeV > 2.2)$ | 2.6     | 2.2$\pm$1.8     | 4    |

TABLE III. Number of events from signal plus central background $s + b$, background $b$, background uncertainty $\sigma_b$ and reconstructed data after application of the selection cuts for 19.6 fb$^{-1}$ integrated luminosity and 8 TeV center of mass energy. The signal model is scenario S2 with $\lambda_{111}' = 0.175$, $m_l = 2$ TeV and $M_{\chi_1^0} = 0.9$ TeV. The data and SM backgrounds are taken from Ref. [1] and Ref. [2].
is precluded by the fact that the $W_R$ search and the $eejj$ channels contain common background events, and we do not have access to the correlations between them. For the current paper, we content ourselves with a depiction of where the preferred regions for each measurement lie.

To summarize, the CMS di-leptoquark search excesses are well described by the hypothesis of resonant slepton production. Both the $eejj$ channels and the $e\nujj$ channel event rates can fit the excess well, and the most important kinematic distributions appear by eye to be reasonable. We have found regions parameter space that are consistent with the 95%CL regions for the di-leptoquark channels and the $W_R$ search.

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