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Explaining a CMS *eejj* excess with $\mathcal{R}$-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 2.8σ excess around $m_{eejj} \sim 2$ TeV. In this work, we explain the reported CMS excess with $\mathcal{R}$-parity violating supersymmetry. We consider resonant selectron and sneutrino production, followed by the three body decays of the neutralino and chargino via an $\mathcal{R}$-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 LHC and a center-of-mass energy of 8 TeV and 19.7 fb^{-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 2.8σ [1]. In the $1.8\text{ TeV} < m_{eejj} < 2.2$ 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. [2]. The W_R excess was interpreted in grand unified theory models in Refs. [3,4]. In Ref. [5], pair production of vectorlike leptons was proposed via W'/Z' vector bosons. Reference [6] 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 $\mathcal{R}$-parity violating (RPV) minimal supersymmetric model (MSSM). $\mathcal{R}$-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 particular, we show that RPV with a nonzero λ'_{111} coupling can fit the CMS excess [1,7] 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 $\mathcal{R}$-parity violating decays of charginos, as shown in Fig. 2.

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

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

This induces the following Lagrangian terms:

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

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

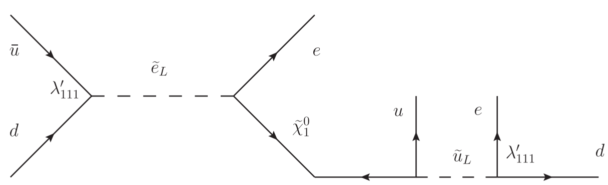

FIG. 1. Feynman diagram for single selectron production leading to the $eejj$ signal at the LHC.

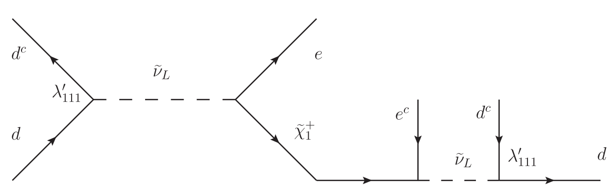

FIG. 2. Feynman diagram for single sneutrino production leading to the $eejj$ signal at the LHC.

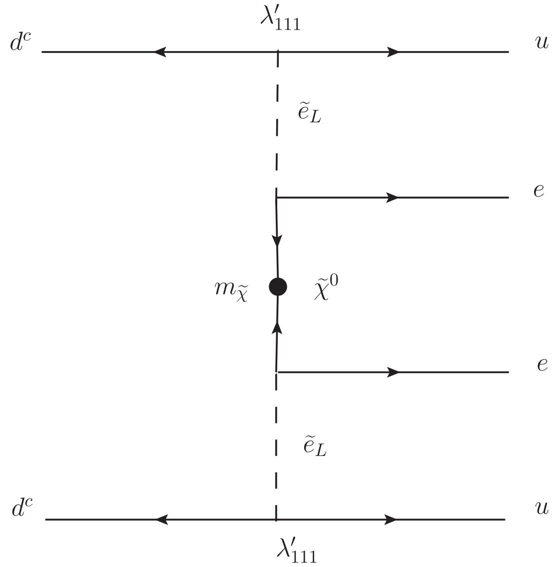

FIG. 3. Sample Feynman diagram for $0\nu\beta\beta$, corresponding to the selectron and neutralino contribution. There are several other diagrams from gluino and squark mediation, that contribute to the half-life $T^{0\nu}_{1/2}$ [14]. In our analysis of $0\nu\beta\beta$, we consider all possible contributions via the λ'_{111} coupling [10,14].

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 Standard Model (SM) because of lepton number conservation. The present bound on the half-life of the ^{76}Ge isotope is $T^{0\nu}_{1/2} > 2.1 \times 10^{25}$ yrs at 90% C.L. from GERDA [12], while the 90% C.L. combined bound on the half-life from previous experiments is $T^{0\nu}_{1/2} > 3.0 \times 10^{25}$ 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 $T^{0\nu}_{1/2} \sim 2 \times 10^{26}$ 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 supersymmetry.

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 Ref. [16]

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

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

and subsequently in Refs. [14,17–23]. 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. [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 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 is $pp \to \tilde{\nu}_e/\tilde{\nu}^*_e \to e^-\chi^+_1/e^+\chi^-_1 \to e^+e^-jj$. It is our aim to see if resonant selectron and sneutrino production can fit the CMS W_R excess while evading other experimental constraints.

In this paper, we follow a bottom-up phenomenological approach. We fix any sparticles which are not relevant for our hypothesized 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 λ'_{111}.

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

(i) *S1:* $M_1 < M_2 = M_1 + 200 < \mu$, i.e., the lightest supersymmetric particle (LSP) is mostly binolike 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.

(ii) *S2:* $M_1 < \mu < M_2$; the LSP is still dominated by the bino component, with a heavy intermediate

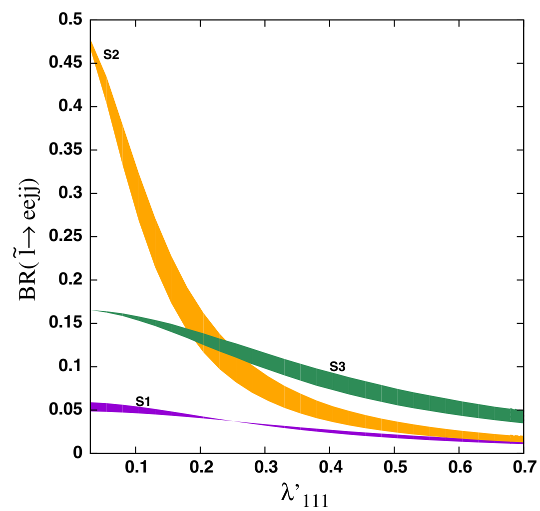

FIG. 4 (color online). The effective branching ratio of the decay $\tilde{\ell} \to eejj$ in S1–S3 for possible choices of λ'_{111} coupling. The small color bands indicate the variation of the branching ratio with $m_{\tilde{\chi}^0_1}$(400 GeV–1.0 TeV) for a given λ'_{111}.

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 $m_{\tilde{\chi}_1^0} = 532$ GeV. The data and SM backgrounds are taken from Ref. [1].

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 $< M_{eejj} <$ 22 TeV	10	4.0 ± 1.0	14

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.

(iii) *S3:* $M_2 \ll M_1 \simeq \mu$, i.e., the LSP is dominantly winolike. In this case, the slepton also decays to a lighter chargino and a neutrino with a substantial branching fraction. In this scenario, both the lighter chargino and lightest neutralino decay via λ'_{111}. Hence, the lepton and jet multiplicities in the final state are enhanced compared to S1 and S2.

Depending on the nature of the lightest neutralino and the value of the λ'_{111} coupling, the branching ratio changes considerably [22]. We show the effective branching fraction $\text{Br}(\tilde{l} \to eejj)$ for our various scenarios in Fig. 4. We note that a higher value of λ'_{111} leads to stringent limits from dijet resonance searches. We take into account the constraint from CMS dijet resonance search [24]. The limit on the cross section for a dijet resonance around 2.1 TeV is

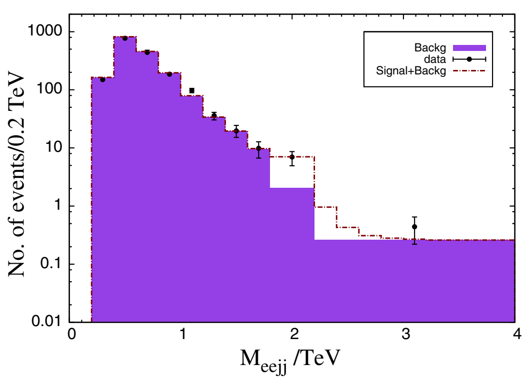

FIG. 5 (color online). A comparison of the data, signal and background M_{eejj} distributions after imposing cuts as done in the analysis of the W_R search. The signal point corresponds to $\lambda'_{111} = 0.105$ and $m_{\tilde{\chi}_1^0} = 532$ GeV (S3). The data and SM backgrounds are taken from Ref. [1].

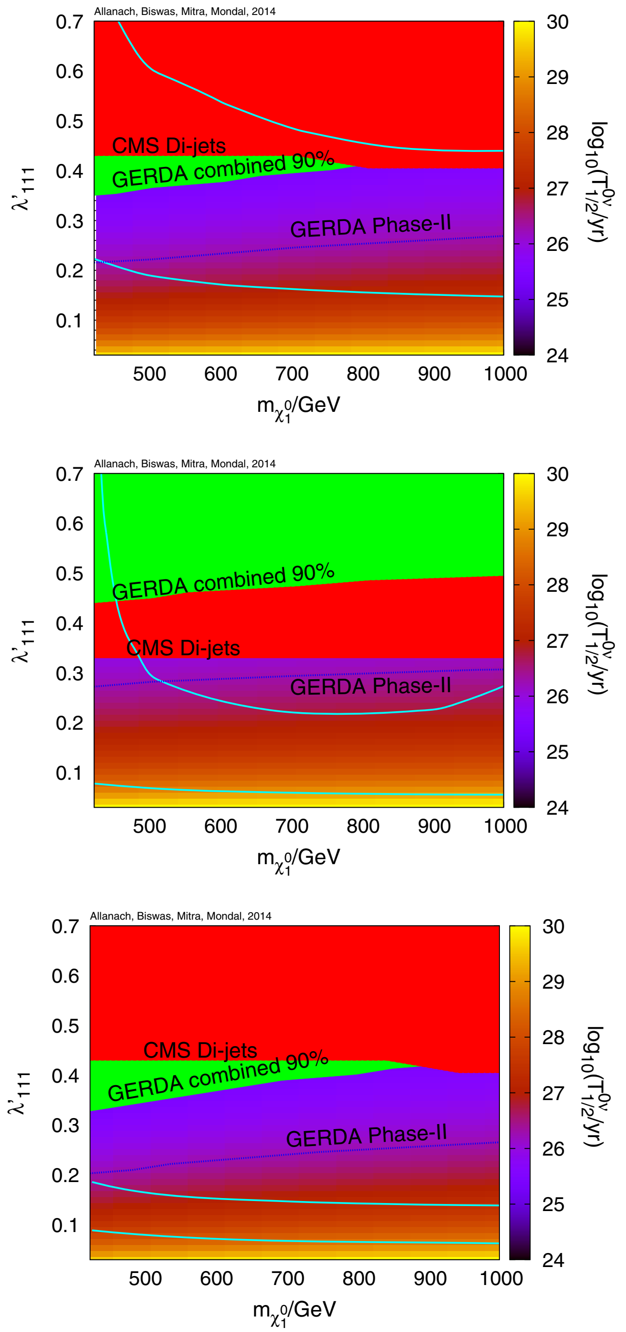

FIG. 6 (color online). A scan in the λ'_{111} coupling and the neutralino mass plane assuming 2.1 TeV slepton mass and scenario (top) S1, (middle) S2 and (bottom) S3. The color gradient represents the half-life $T^{0\nu}_{1/2}$ of the $0\nu\beta\beta$ process, where the nuclear matrix uncertainty has been adopted from Ref. [14]. The region between the light curves fit data from the bin 1.8 TeV $< m_{eejj} < 2.2$ at the 95% C.L. level. We show regions excluded at 95% C.L. by the CMS dijet resonance search [24] and the 90% C.L. current combined constraints coming from $0\nu\beta\beta$ half-life limits [12]. The expected 90% C.L. exclusion reach from GERDA Phase-II [13] is also shown.

< 45 fb. This in turn gives a bound on the product ${\lambda'_{111}}^2 \times \mathrm{Br}(\tilde{e}/\tilde{\nu} \to jj)$ [22].

We simulate first-generation resonant slepton production in pp collisions at a center-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 [22]. 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 parametrized as in Ref. [30] for the final state objects.

The final state studied in Ref. [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 Ref. [1], have been imposed:

(i) Invariant mass of the lepton pair, $M_{\ell\ell} > 200$ GeV.
(ii) 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 of $\bar{b} \pm \sigma_b$ background events,

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

where B is a normalization factor that makes the distribution integrate to 1. We marginalize the Poissonian probability of measuring n events over b in order to obtain confidence limits,

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

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

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_{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. Figure 6 shows the $\lambda'_{111} - m_{\tilde{\chi}_1^0}$ plane for S1–S3, 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 dijet 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 dileptons (R) is predicted to be independent of λ'_{111} and $m_{\tilde{\chi}_1^0}$ 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 vs 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% C.L. 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 $m_{\tilde{\chi}_1^0} < 550$ 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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[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.

[1] V. Khachatryan *et al.* (CMS Collaboration), arXiv:1407.3683.
[2] Y. Bai and J. Berger, arXiv:1407.4466.
[3] F. F. Deppisch, T. E. Gonzalo, S. Patra, N. Sahu, and U. Sarkar, Phys. Rev. D **90**, 053014 (2014).
[4] M. Heikinheimo, M. Raidal, and C. Spethmann, Eur. Phys. J. C **74**, 3107 (2014).
[5] B. A. Dobrescu and A. Martin, arXiv:1408.1082.
[6] J. A. Aguilar-Saavedra and F. R. Joaquim, arXiv:1408.2456.
[7] CMS Collaboration, Report No. CMS-PAS-EXO-12-041.
[8] B. C. Allanach, A. Dedes, and H. K. Dreiner, Phys. Rev. D **60**, 075014 (1999).
[9] R. N. Mohapatra, Phys. Rev. D **34**, 3457 (1986); K. S. Babu and R. N. Mohapatra, Phys. Rev. Lett. **75**, 2276 (1995).
[10] M. Hirsch, H. V. Klapdor-Kleingrothaus, and S. G. Kovalenko, Phys. Lett. B **352**, 1 (1995); Phys. Rev. D **53**, 1329 (1996); **54**, R4207 (1996).
[11] G. Racah, Nuovo Cimento **14**, 322 (1937); W. H. Furry, Phys. Rev. **56**, 1184 (1939).
[12] M. Agostini *et al.* (GERDA Collaboration), Phys. Rev. Lett. **111**, 122503 (2013).
[13] A. A. Smolnikov (GERDA Collaboration), arXiv:0812.4194.
[14] B. C. Allanach, C. H. Kom, and H. Pas, J. High Energy Phys. 10 (2009) 026.
[15] M. Chemtob, Prog. Part. Nucl. Phys. **54**, 71 (2005); R. Barbier *et al.*, Phys. Rep. **420**, 1 (2005); G. Bhattacharyya, arXiv:hep-ph/9709395.
[16] S. Dimopoulos, R. Esmailzadeh, L. J. Hall, J. P. Merlo, and G. D. Starkman, Phys. Rev. D **41**, 2099 (1990).
[17] J. L. Hewett and T. G. Rizzo, arXiv:hep-ph/9809525.
[18] H. K. Dreiner, P. Richardson, and M. H. Seymour, arXiv:hep-ph/9903419.
[19] H. K. Dreiner, P. Richardson, and M. H. Seymour, arXiv:hep-ph/0001224.
[20] H. K. Dreiner, P. Richardson, and M. H. Seymour, Phys. Rev. D **63**, 055008 (2001).
[21] B. C. Allanach, M. Guchait, and K. Sridhar, Phys. Lett. B **586**, 373 (2004).
[22] H. K. Dreiner and T. Stefaniak, Phys. Rev. D **86**, 055010 (2012).
[23] B. C. Allanach, C. H. Kom, and H. Pas, Phys. Rev. Lett. **103**, 091801 (2009).
[24] S. Chatrchyan *et al.* (CMS Collaboration), Phys. Rev. D **87**, 114015 (2013).
[25] A. Belyaev, N. D. Christensen, and A. Pukhov, Comput. Phys. Commun. **184**, 1729 (2013).
[26] T. Sjostrand, S. Mrenna, and P. Z. Skands, J. High Energy Phys. 05 (2006) 026.
[27] F. Staub, arXiv:0806.0538; Comput. Phys. Commun. **181**, 1077 (2010); **182**, 808 (2011).
[28] W. Porod, Comput. Phys. Commun. **153**, 275 (2003); W. Porod and F. Staub, Comput. Phys. Commun. **183**, 2458 (2012).
[29] S. Kretzer, H. L. Lai, F. I. Olness, and W. K. Tung, Phys. Rev. D **69**, 114005 (2004).
[30] S. Khatrchyan *et al.* (CMS Collaboration), JINST **6**, P11002 (2011); CMS Collaboration, Report No. CMS PAS EGM-10-004; CMS Collaboration, Report No. CMS PAS JME-10-014; CMS Collaboration, Report No. CMS PAS MUO-10-004.