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On the two-loop corrections to the Higgs mass in trilinear R-parity violation

Herbi K. Dreiner [a], Kilian Nickel [a,*], Florian Staub [b]

[a] Bethe Center for Theoretical Physics & Physikalisches Institut der Universität Bonn, 53115 Bonn, Germany
[b] Theory Division, CERN, 1211 Geneva 23, Switzerland

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ABSTRACT

We study the impact of large trilinear R-parity violating couplings on the lightest CP-even Higgs boson mass in supersymmetric models. We use the publicly available computer codes SARAH and SPheno to compute the leading two-loop corrections. We use the effective potential approach. For not too heavy third generation squarks ($\tilde{m} \lesssim 1$ TeV) and couplings close to the unitarity bound we find positive corrections up to a few GeV in the Higgs mass.

1. Introduction

On July 4th, 2012 the discovery of the Higgs boson was announced at CERN [1,2]. It is not yet established whether this is the Standard Model (SM) Higgs boson [3–5]. However, in the SM the Higgs sector suffers from the hierarchy problem [6], to which supersymmetry (SUSY) [7,8] is the most obvious solution. It predicts a wide range of observables at the Large Hadron Collider (LHC), for which the first run has finished; Run II is expected to start in the Spring, 2015.

There is no convincing experimental indication of any physics beyond the Standard Model (SM) at the LHC.[1] This puts pressure on many proposed scenarios for beyond the standard model (BSM) physics, in particular also SUSY. The simplest SUSY scenario, the constrained minimal supersymmetric Standard Model (CMSSM) [7], is now excluded [9], see also [10–13]. However, the MSSM extended for example by R-parity violation (RpV) operators [14–18] can significantly weaken the collider mass limits [19–22] and provide an even richer phenomenology than the MSSM [23–27].

Within the MSSM the mass of the Higgs boson is restricted at tree-level to be less than the mass of the Z^0-boson. However the quantum corrections to the mass can be large [28–31]. The observed mass of the Higgs boson, $m_h^{\mathrm{exp}} \approx 125.7$ GeV [32–34], is well within the allowed range for SUSY models, previously predicted by [35]. Such large corrections however typically require very large mixing in the stop sector and/or a very heavy stop squark. This in turn is disfavoured by fine-tuning arguments [36,37].

When extending the MSSM these conclusions can be modified, *e.g.* in the NMSSM [38–40]. Here we consider the Higgs mass in supersymmetric models with RpV. The additional operators contribute to the Higgs pole mass at the two-loop level.[2] This effect might be large, especially when involving third generation squarks, and deserves to be investigated. We study the impact of large $\mathbf{LQ\bar{D}}$ and $\mathbf{\bar{U}\bar{D}\bar{D}}$ operators involving stops and sbottoms on the lightest CP-even Higgs boson mass. (The effects of $\mathbf{LL\bar{E}}$ are here completely negligible.) For this purpose we calculate two-loop Higgs masses in models beyond the MSSM, but with MSSM precision, with the public computer tools SARAH [42–46] and SPheno [47,48], as recently presented in [49].

This letter is organized as follows: we present in the next section our conventions for the models we consider, before we give details about the two-loop calculation in Section 3. The numerical results are presented in Section 4, before we conclude in Section 5.

2. The MSSM extended by trilinear R-parity violation

R-parity is a discrete multiplicative Z_2 symmetry of the MSSM, defined as [14–16,18,50]

$$R_P = (-1)^{3(B-L)+2s}, \tag{1}$$

* Corresponding author.
E-mail addresses: dreiner@th.physik.uni-bonn.de (H.K. Dreiner), nickel@th.physik.uni-bonn.de (K. Nickel), florian.staub@cern.ch (F. Staub).

[1] See for example the talk given by O. Buchmüller at the EPS 2013 conference in Stockholm https://indico.cern.ch/event/218030/session/28/contribution/869/material/slides/.

[2] See also the two-loop RpV renormalization group equations, which modify the running of the $\overline{\mathrm{DR}}'$ tree-level Higgs mass [41].

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where s is the spin of the field and B, L are its baryon and lepton numbers. We consider the R-parity conserving superpotential of the MSSM

$$W_R = Y_e^{ij}\mathbf{L}_i\mathbf{H}_d\bar{\mathbf{E}}_j + Y_d^{ij}\mathbf{Q}_i\mathbf{H}_d\bar{\mathbf{D}}_j + Y_u^{ij}\mathbf{Q}_i\mathbf{H}_u\bar{\mathbf{U}}_j + \mu\mathbf{H}_u\mathbf{H}_d, \tag{2}$$

and extend it by trilinear RpV operators [51,52]

$$W_{\not R} = \frac{1}{2}\lambda_{ijk}\mathbf{L}_i\mathbf{L}_j\bar{\mathbf{E}}_k + \lambda'_{ijk}\mathbf{L}_i\mathbf{Q}_j\bar{\mathbf{D}}_k + \frac{1}{2}\lambda''_{ijk}\bar{\mathbf{U}}_i\bar{\mathbf{D}}_j\bar{\mathbf{D}}_k. \tag{3}$$

We assume the bi-linear term has been rotated away [53]. The superfields **L**, **Q**, **D** are taken to be the gauge eigenstates before electroweak symmetry breaking. Here $i, j, k = 1, 2, 3$ are generation indices, while $SU(3)$ colour and $SU(2)$ isospin indices are suppressed. Above $\mathbf{L}_i$, $\bar{\mathbf{E}}_j$, $\mathbf{Q}_i$, $\bar{\mathbf{U}}_i$, $\bar{\mathbf{D}}_i$, $\mathbf{H}_d$, $\mathbf{H}_u$ denote the left chiral superfields of the MSSM in the standard notation [18]. We thus have for the total superpotential

$$W_{\text{tot}} = W_R + W_{\not R}. \tag{4}$$

In the following we consider only the presence of one RpV operator at a time, including the anti-symmetric counter part, if it exists. This ensures the stability of the proton and avoids many constraints from flavour changing neutral currents and lepton flavour violation [53–55].

The corresponding standard soft supersymmetry breaking terms for the scalar fields $\widetilde{L}$, $\widetilde{E}$, $\widetilde{Q}$, $\widetilde{U}$, $\widetilde{D}$, H_d, H_u and the gauginos $\widetilde{B}$, $\widetilde{W}$, $\widetilde{g}$ read

$$\begin{aligned}-\mathcal{L}_{\text{SB},R} &= m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + \sum_\ell \widetilde{\phi}_\ell^\dagger m_{\widetilde{\phi}_\ell}^2\widetilde{\phi}_\ell \\ &\quad + \frac{1}{2}\left(M_1\widetilde{B}\widetilde{B} + M_2\widetilde{W}_a\widetilde{W}^a + M_3\widetilde{g}_\alpha\widetilde{g}^\alpha + \text{h.c.}\right) \\ &\quad + \left(\widetilde{Q}T_u\widetilde{U}^\dagger H_u + \widetilde{Q}T_d\widetilde{D}^\dagger H_d + \widetilde{L}T_e\widetilde{E}^\dagger H_d \right.\\ &\quad \left. + B_\mu H_u H_d + \text{h.c.}\right)\end{aligned} \tag{5}$$

$$\begin{aligned}-\mathcal{L}_{\text{SB},\not R} &= \frac{1}{2}T_{\lambda,ijk}\widetilde{L}_i\widetilde{L}_j\widetilde{E}_k + T'_{\lambda,ijk}\widetilde{L}_i\widetilde{Q}_j\widetilde{D}_k \\ &\quad + \frac{1}{2}T''_{\lambda,ijk}\widetilde{U}_i\widetilde{D}_j\widetilde{D}_k + \text{h.c.}\end{aligned} \tag{6}$$

with $\tilde{\phi}_\ell \in \{\widetilde{Q}, \widetilde{D}, \widetilde{U}, \widetilde{E}, \widetilde{L}\}$. The gaugino fields are two component fermions [56]. We have suppressed all generation indices in Eq. (5). The $m_{\tilde{\phi}}^2$ are 3×3 matrices and denote the squared soft masses of the scalar components $\tilde{\phi}$ of the corresponding chiral superfields Φ. The $T_{u,d,e}$ are 3×3 matrices of mass-dimension one. They can be written in terms of the standard A-terms [57], if no flavour violation is assumed, $T_{ii}^f = A_i^f Y_f^{ii}$, $f = e, u, d$, $i = 1, 2, 3$, and no summation over repeated indices. Similarly, for the baryon number violating term we have $T''_{\lambda,ijk} = A''_{ijk}\lambda''_{ijk}$.

3. Two-loop corrections from *R*-parity violating operators

In the presence of trilinear RpV there are new contributions to the Higgs mass at the two-loop level. We use the public codes SARAH and SPheno to compute them. These codes perform an effective potential calculation based on the generic results in Ref. [58] in the $\overline{\text{DR}}'$ scheme. The precision of this calculation using SARAH and SPheno is the same for models beyond the MSSM as in many public computer tools for the MSSM, which use results of Refs. [59–63]. For more general information about the calculation of two-loop Higgs masses in extensions of the MSSM with SARAH and SPheno we refer to Ref. [49]. Note that this calculation is done in the gaugeless limit, *i.e.* $g_1 = g_2 = 0$, where all loop corrections from massive vector bosons and their corresponding ghosts and Goldstone bosons vanish.

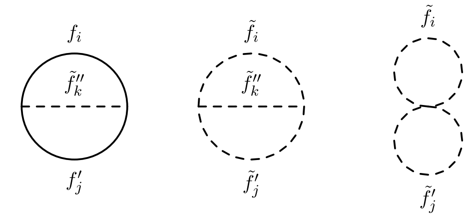

Fig. 1. Two-loop corrections to the effective potential involving trilinear RpV couplings. f are SM fermions and $\tilde{f}$ are SUSY sfermions. The graph on the left involves superpotential couplings, Eq. (3), the middle graph involves soft supersymmetry breaking terms, Eq. (6), and the graph on the right, RpV terms in the F-term scalar potential.

The corrections to the effective potential at the two-loop level involving trilinear RpV couplings come from the diagrams shown in Fig. 1. From these, the tadpole contributions and self-energies are calculated by taking the first and second derivatives of the two-loop effective potential $V_{\text{eff}}^{(2)}$

$$\delta t_i^{(2)} = \frac{\partial V_{\text{eff}}^{(2)}}{\partial v_i}, \tag{7}$$

$$\Pi_{h_i h_j}^{(2)}(0) = \frac{\partial^2 V_{\text{eff}}^{(2)}}{\partial v_i \partial v_j}, \tag{8}$$

with $i = u, d$. Here, h_i are the real parts of the neutral Higgs scalar fields, $H_{u,d}^0$, with $H_i^0 = (v_i + h_i + i\sigma_i)/\sqrt{2}$. There are two possibilites to take the derivatives in the SARAH/SPheno code: either calculate numerically the derivative of the entire potential as done in Ref. [64] for the MSSM, or take analytically the derivative of the potential with respect to the masses and numerically the derivative of the masses and couplings with respect to the VEVs (semi-analytical approach). A third way would be a purely analytical differentiation. This however also needs an analytical diagonalization of all mass matrices that can't be done in general. The combination SARAH/SPheno has implemented the first two methods and we checked their numerical agreement. Throughout we neglect the possibility of sneutrino vacuum expectation values for the $\mathbf{LQ\bar{D}}$ operators. These effects are very small since the bounds on neutrino masses restrict the sneutrino VEVs to be of order 10 MeV or smaller [18].

We use the results of Eqs. (7) and (8) together with the tree-level minimization conditions, T_i, and the one-loop corrections to find the minimum of the effective potential by demanding

$$T_i + \delta t_i^{(1)} + \delta t_i^{(2)} = 0 \tag{9}$$

and to calculate the loop corrected Higgs mass matrix squared

$$M_h^2(p^2) = \left[M_h^{(T)}\right]^2 - \Pi_{h_i h_j}^{(1)}(p^2) - \Pi_{h_i h_j}^{(2)}(0). \tag{10}$$

$[M_h^{(T)}]^2$ is the Higgs mass matrix squared at tree-level at the minimum of the effective potential. The two eigenvalues $m_{h_i}^2$ of $M_h^2(p^2 = m_{h_i}^2)$, $i = 1, 2$, are the pole masses of the corresponding scalar fields. For the parameter points discussed below, the smaller eigenvalue, $m_h \equiv m_{h_1}$, is the mass of the SM-like Higgs boson, which we are mainly interested in.

In addition to the two-loop corrections to the Higgs potential due to trilinear RpV parameters, there are also one-loop corrections to the SM Yukawa couplings due to the trilinear RpV parameters, see for example [41]. In particular there are one-loop RpV contributions to the up and down quark self-energy matrices: Σ_L^q, Σ_R^q, Σ_S^q, $q = u, d$. These self-energies in turn contribute at one-loop to the Higgs potential, leading to an overall two-loop effect on the

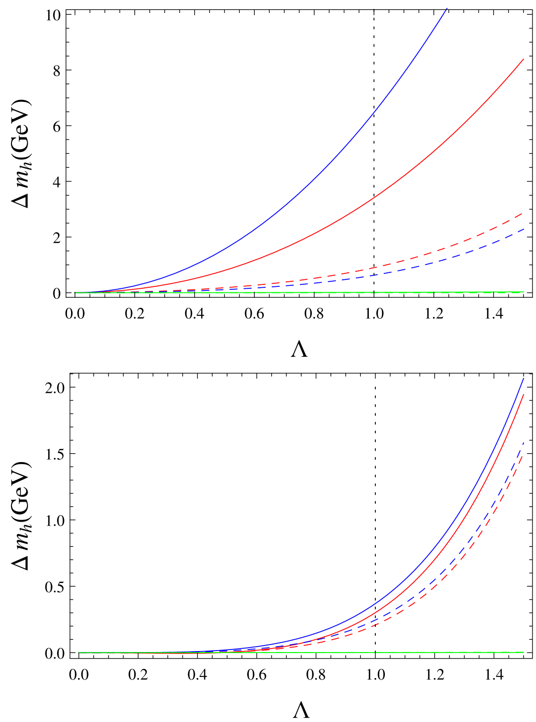

Fig. 2. Δm_h for the two mass hierarchies given at the beginning of Section 4, hierarchy (i) [top plot], and (ii) [bottom plot]. The shift is shown as a function of $\Lambda = \lambda'_{ijk}, \lambda''_{ijk}$, with the colour code: λ''_{313} (full red), λ''_{312} (full blue), λ''_{213} (full green), λ'_{333} (dashed red), λ'_{331} (dashed blue), λ'_{313} (dashed green). The dashed, vertical line indicates the perturbativity limit. The two green lines are degenerate in both plots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Higgs mass, *i.e.* of the same order as we are investigating. These self-energies enter the calculation of the Yukawa couplings as [65]

$$\frac{v_q}{\sqrt{2}} Y^q = U_L^T m^{q,\text{pole}} U_R + \Sigma_S^q + \Sigma_L^{q,T} \left(\frac{v_q}{\sqrt{2}} Y^q \right) + \left(\frac{v_q}{\sqrt{2}} Y^q \right) \Sigma_R^q + \dots, \tag{11}$$

which has to be solved iteratively. The dots stand for two-loop corrections important for the top quark, U_L, U_R are the matrices that diagonalize the Yukawa matrix Y^q. $m^{q,\text{pole}}$ is a diagonal matrix with the pole masses as entries.

4. Results

We now discuss the numerical impact of the RpV operators on the Higgs mass at the two-loop level. To be specific, we consider the supersymmetric parameter point fixed by $\tan\beta = 10$, $M_1 = M_2 = \frac{1}{2} M_3 = 1$ TeV, $\mu = 0.5$ TeV, and $M_A = 1$ TeV. All slepton soft masses as well as all squark soft masses of the first two generations are set to 1.5 TeV. For the third generation squark soft masses we distinguish two exemplary mass hierarchies

(i) $m_{\tilde{Q},33} = 1.5$ TeV, $m_{\tilde{U},33} = m_{\tilde{D},33} = 0.5$ TeV,
(ii) $m_{\tilde{Q},33} = m_{\tilde{U},33} = m_{\tilde{D},33} = 2.5$ TeV.

In (i) the third generation is lighter than the other sfermions, in (ii) it is heavier. The two hierarchies are assumed in the two plots shown in Fig. 2. We choose the R-parity conserving trilinear parameters as $T_t = -2.5$ TeV, resulting in large mixing in the stop sector; all other R-parity conserving trilinear parameters vanish. In the RpV sector we choose

$$T_{\Lambda_{ijk}} = A_0 \Lambda_{ijk}, \qquad \Lambda = \lambda', \lambda'', \tag{12}$$

with $A_0 = -2.5$ TeV. The renormalization scale is always set to $Q = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, where $m_{\tilde{t}_i}$ are the $\overline{\text{DR}}'$ stop masses. For the SM parameters we use $m_t = 173.1$ GeV, $m_b = 4.18$ GeV, $m_\tau = 1.777$ GeV, and $\alpha_S = 0.1184$. The impact on the light Higgs mass as a function of the RpV trilinear couplings Λ is defined as

$$\Delta m_h \equiv m_h(\Lambda) - m_h(0), \tag{13}$$

where the Higgs mass in the R-parity conserving case, $m_h(0)$, for the two hierarchies is given by

(i) $m_h(0) = 110.0$ GeV,
(ii) $m_h(0) = 124.3$ GeV.

Since we just wish to demonstrate an effect, we have not attempted to tune our parameters to get the correct Higgs mass in all scenarios. We restrict ourselves to the couplings λ''_{313}, λ''_{312}, λ''_{213}, λ'_{313}, λ'_{331}, and λ'_{333}. However, through the rotation to the mass eigenbasis we generate further couplings. As mentioned, since the operators corresponding to λ_{ijk} do not couple to squarks, the associated corrections to the Higgs mass are negligible. For the green line in the two plots of Fig. 2, this is also the case, corresponding to squark contributions not involving stops: λ''_{213}, λ'_{313}.

In general, we find that for light third generation squarks, hierarchy (i), shown in the top plot in Fig. 2, there can be large positive contributions of several GeV to the Higgs mass, if stops are involved in the RpV operator. If the third generation squarks are heavier (hierarchy (ii)) shown in the bottom plot in Fig. 2, the effects are significantly smaller.

To get large effects, the RpV couplings have to be very large. An enhancement of several GeV is only found for couplings which are close to or even above the perturbativity limit, which is approximately 1 at the weak scale [66,67].[3] In order to avoid the Landau pole the large coupling scenarios must have a low cut-off similar to the λ-SUSY setup [68].

The couplings involving stops are hardly constrained by flavor physics, especially if the non-stop masses are in the TeV range [69]. Furthermore, we have checked that the shift in the Higgs mass changes by less than 5% in the λ''_{312} case, if we choose $\tan\beta = 25$ instead. We have to note that very small soft masses together with large trilinear couplings often suffer from an unstable electroweak vacuum and have to be considered carefully [70–72]. We used the public code `Vevacious` [73] to check that hierarchy (i) is metastable with a life-time longer than the age of the universe.

We show in Fig. 3 the change in the top-Yukawa coupling

$$\Delta Y_t(\Lambda) \equiv Y_t(\Lambda) - Y_t(0), \tag{14}$$

from including the RpV loop corrections to all quarks. Here $Y_t(0) \simeq 0.85$, for $\tan\beta = 10$. The effect is very small. The dependence of the Higgs mass on the mass of the involved squarks is depicted in Fig. 4, where we kept $\lambda''_{313} = 1$, respectively $\lambda'_{333} = 1$, fixed and varied $m_{\tilde{Q},33}$, $m_{\tilde{U},33}$, and $m_{\tilde{D},33}$, separately. The soft masses not being varied are fixed at 1.5 TeV.

The largest corrections appear in the case of light right-handed squarks together with large $\bar{\mathbf{U}}\bar{\mathbf{D}}\bar{\mathbf{D}}$ operators. For $\mathbf{L}\mathbf{Q}\bar{\mathbf{D}}$ operators the strongest dependence is on the left-squark soft mass. The value of $m_{\tilde{D},33}$ plays always a subdominant role.

[3] The authors required perturbativity, or lack of a Landau pole, up to the unification scale $M_X \approx 10^{16}$ GeV. The bounds are given at the weak scale.

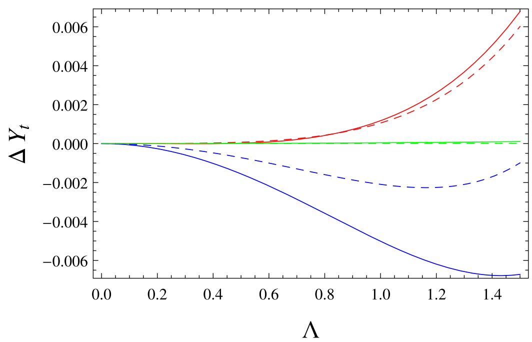

Fig. 3. The change in the top Yukawa coupling, $\Delta Y_t(\Lambda)$, for the first mass hierarchy given at the beginning of Section 4. The colour code is the same as for Fig. 2.

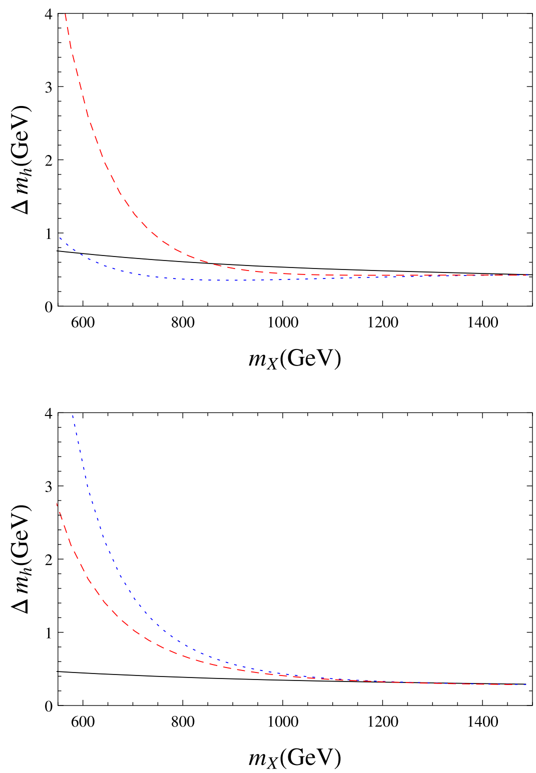

Fig. 4. Two-loop RpV contributions to the light Higgs mass as a function of the soft squark masses. We set all soft masses to be 1.5 TeV and then vary $m_{\tilde{Q}}$ (dotted blue), $m_{\tilde{U}}$ (dashed red), and $m_{\tilde{D}}$ (solid black), independently, while keeping the other masses fixed. In the first plot, $\lambda''_{313} = 1$ and $T_{\lambda''_{313}} = -2.5$ TeV, in the second $\lambda'_{333} = 1$ and $T_{\lambda'_{333}} = -2.5$ TeV.

We finally consider the dependence on A_0. For this purpose we show in Fig. 5 the light Higgs mass as function of A_0 with and without RpV operators. Here, we have chosen light right-handed stops, $m_{\tilde{U},33} = 0.5$ TeV, while all other scalar soft masses are set to 1.5 TeV. Once again the RpV couplings can easily shift the light Higgs mass by a few GeV. In the case of λ''_{313} the shift shows a clear dependence on A_0 while it is rather insensitive to A_0 if λ' couplings are considered. That is consistent with our choice of small $m_{\tilde{U},33}$. For small $m_{\tilde{Q},33}$ the λ' would show a stronger dependence on A_0.

5. Conclusion

We have discussed the impact of large trilinear RpV couplings on the light CP-even Higgs mass at the two-loop level. We have shown that in particular for light stops these corrections can be

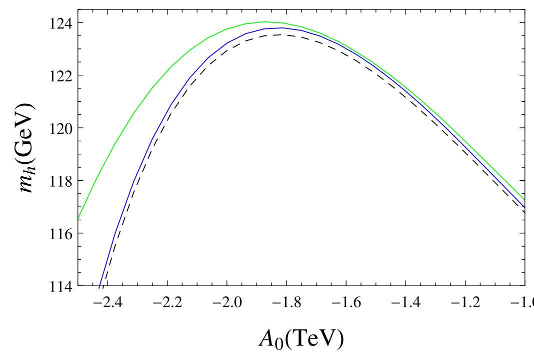

Fig. 5. The CP-even Higgs mass m_h as a function of A_0. The dashed line is the calculation without RpV contributions, while the blue line is for $\lambda'_{333} = 1$, $T_{\lambda'_{333}} = A_0$ and the green one for $\lambda''_{313} = 1$, $T_{\lambda''_{313}} = A_0$. All sfermion soft masses but $m_{\tilde{U},33}$ are fixed to 1.5 TeV. We set $m_{\tilde{U},33}$ to 0.5 TeV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

very important, increasing the Higgs mass by several GeV, if the couplings are $\mathcal{O}(1)$.

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