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

Herki K. Dreiner,1 Kilian Nickel,1 and Florian Staub2
1Bethe Center for Theoretical Physics & Physikalisches Institut der Universität Bonn, 53115 Bonn, Germany
2Theory Division, CERN, 1211 Geneva 23, Switzerland

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 ($m \sim 1\text{ TeV}$) and couplings close to the unitarity bound we find positive corrections up to a few GeV in the Higgs mass.

I. 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] 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 [7]. 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 SUSY the mass of the Higgs boson is restricted at tree–level to be less than the mass of the MSSM [23–27]. However, the quantum corrections to the mass can be large [28, 29]. The observed mass of the Higgs boson, $m_h^{\text{phys}} \approx 125.7$ GeV [30–32], is well within the previous predicted allowed range for SUSY models [33]. 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 [34, 35].

When extending the MSSM these conclusions can be modified, e.g. in the NMSSM [36–38]. Here we consider the Higgs mass in supersymmetric models with RpV. The additional operators contribute to the Higgs mass at the two–loop level [2]. This effect is expected to be large especially when involving third generation squarks. We study the impact of large LQD and UDD operators involving stops and sbottoms on the lightest CP–even Higgs boson mass. (The effects of LLE 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 [40–44] and SPheno [15–16], as recently presented in [17].

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 sec. III. The numerical results are presented in sec. IV before we conclude in sec. V.

II. 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, 48]

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

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

$$W_R = Y_{ij}^d L_i E_j H_d + Y_{ij}^u Q_i D_j H_u + Y_{ij}^d Q_i U_j H_d + Y_{ij}^u Q_i D_j H_u + \mu H_u H_d,$$

and extend it by trilinear RpV operators [47, 48]

$$W_R = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k.$$

We assume the bi–linear term has been rotated away [51]. Here $i, j, k = 1, 2, 3$ are generation indices, while $SU(3)$
colour and $SU(2)$ isospin indices are suppressed. Above $L_i$, $E_j$, $Q_i$, $U_i$, $D_i$, $H_d$, $H_u$ denote the left chiral superfields of the MSSM in the standard notation. We thus have for the total superpotential

$$W_{\text{tot}} = W_R + W_R.$$  

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.

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

$$\mathcal{L}_{\text{SB},R} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + \sum_i \phi_i \bar{m}_{\phi_i}^2 \phi_i$$

$$+ \frac{1}{2} \left( M_1 \tilde{B} \tilde{B} + M_2 \tilde{W}_a \tilde{W}_a + M_3 \tilde{g} \tilde{g} + \text{h.c.} \right)$$

$$+ \left( \tilde{Q}_i^\dagger \tilde{U}^\dagger H_u + \tilde{Q}_i \tilde{D}^\dagger H_d + \tilde{L}_i \tilde{E}^\dagger H_d \right)$$

$$+ B_\mu H_u H_d + \text{h.c.}$$

$$\mathcal{L}_{\text{SB},R} = \frac{1}{2} T_{\lambda,ijk} \tilde{L}_i \tilde{L}_j \tilde{E}_k + T_{\lambda,ijk} \tilde{L}_j \tilde{Q}_i \tilde{D}_k + B_\mu H_u H_d + \text{h.c.}$$

$$= \frac{1}{2} T_{\lambda,ijk} \tilde{L}_i \tilde{L}_j \tilde{E}_k + T_{\lambda,ijk} \tilde{L}_j \tilde{Q}_i \tilde{D}_k + B_\mu H_u H_d + \text{h.c.}.$$  

with $\phi_i \in \{ \tilde{Q}_i, \tilde{D}_i, \tilde{U}_i, \tilde{E}_i, \tilde{L}_i \}$. We have suppressed all generation indices in Eq. (5). The $m_{\phi_i}^2$ are $3 \times 3$ matrices and denote the squared soft masses of the scalar components $\phi_i$ of the corresponding chiral superfields $\Phi$. The $T_{u,d,e}$ are $3 \times 3$ matrices of mass–dimension one. They can be written in terms of the standard $A$–terms if no flavour violation is assumed, $T_{\lambda,ijk} = A_{\lambda}^{ij} Y_{\lambda}^{j3}$, $f = e, u, d$, $i = 1, 2, 3$, and no summation over repeated indices. Similarly, for the baryon number violating term we have $T_{\lambda,ijk}^{\prime \prime} = A_{\lambda}^{ij} Y_{\lambda}^{j3}$.

### III. 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. 56 in the 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, by using the results of Refs. 57. 61. For more general information about the calculation of two–loop Higgs mass extensions in the MSSM with SARAH and SPheno we refer to Ref. 67.

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 derivative of the two–loop effective potential $V_{\text{eff}}^{(2)}$

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

$$\Pi_{h_i h_i}^{(2)}(0) = \frac{\partial^2 V_{\text{eff}}^{(2)}}{\partial v_i \partial v_j}.$$  

with $i = u, d$. Here, $h_i$ are the real parts of the neutral Higgs scalar fields, $H_0^{h_i d}$, with $H_0 = (v_i + i \sigma_i) / \sqrt{2}$. There are two possibilities to take the derivatives: either calculate numerically the derivative of the entire potential as done in Ref. 62 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). The combination SARAH/SPheno has implemented both methods and we check their numerical agreement. Throughout we neglect the possibility of sneutrino vacuum expectation values for the LQD operators. These effects are very small since the bounds on neutrino masses restrict the sneutrino VEVs to be of order 10 MeV or smaller.

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

$$T_i \cdot \delta_{t_i}^{(1)} + \delta_{t_i}^{(2)} = 0,$$

and to calculate the loop corrected Higgs mass matrix squared

$$M_{\overset{\scriptscriptstyle \scalebox{0.75}{\textsc{i}}}{h}}(p^2) = \left[ M_{\overset{\scriptscriptstyle \scalebox{0.75}{\textsc{i}}}{h}}^{(T)} \right]^2 - \Pi_{h_i h_i}^{(1)}(p^2) - \Pi_{h_i h_i}^{(2)}(0).$$
the corresponding scalar fields. The smaller eigenvalue, \( m_\tilde{h} = m_{h_1} \), 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 [39]. In particular there are one–loop RpV contributions to the up and down quark self–energy matrices: \( \Sigma^q_L, \Sigma^q_R, \Sigma^q_S \), \( q = u, d \). These self–energies in turn contribute at one–loop to the Higgs potential, leading to an overall two–loop effect on the Higgs mass, i.e. of the same order as we are investigating. These self–energies enter the calculation of the Yukawas couplings as [63]

\[
\frac{v_q}{\sqrt{2}} Y^q = U^T_i m^{q,\text{pole}} U_R + \Sigma^q_R + \Sigma^q_L + \left( \frac{v_q}{\sqrt{2}} Y^q \right) + \frac{1}{\Lambda^2} \left( \frac{v_q}{\sqrt{2}} Y^q \right) \Sigma^q_R + \ldots ,
\]

where \( \Sigma^q_S \) is diagonal. These self–energies in turn contribute at one–loop to the Higgs potential, leading to an overall two–loop effect on the Higgs mass, i.e. of the same order as we are investigating. These self–energies enter the calculation of the Yukawas couplings as [63]

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\]

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 which diagonalize the Yukawa matrix \( Y^q \), \( m^{q,\text{pole}} \) is a diagonal matrix with the pole masses as entries.

IV. 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 \( \tan \beta = 10, M_1 = M_2 = \frac{1}{2} M_3 = 1 \text{ TeV}, \mu = 0.5 \text{ TeV}, \) and \( M_A = 1 \text{ TeV} \). All slepton soft masses as well as all squark soft masses of the first two generations are set to 1.5 \( \text{TeV} \). For the third generation squarks soft masses we distinguish two exemplary mass hierarchies

(i) \( m_{\tilde{q},33} = 1.5 \text{ TeV}, \quad m_{\tilde{\ell},33} = m_{\tilde{d},33} = 0.5 \text{ TeV} \),

(ii) \( m_{\tilde{q},33} = m_{\tilde{\ell},33} = m_{\tilde{d},33} = 2.5 \text{ TeV} \).

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 \( T_i = -2.5 \text{ TeV} \), resulting in large mixing in the stop sector; all other \( R \)-parity conserving trilinear parameters vanish. In the RpV sector we choose

\[
T_{\lambda_{ijk}} = A_0 \lambda_{ijk}, \quad \lambda = \lambda', \lambda'', \lambda_{ijk},
\]

with \( A_0 = -2.5 \text{ TeV} \). The renormalization scale is always set to \( Q = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \), where \( m_{\tilde{t}_i} \) are the DR stop masses. For the SM parameters we use \( m_t = 173.1 \text{ GeV}, m_b = 4.18 \text{ GeV}, m_w = 1.777 \text{ GeV}, \) and \( \alpha_S = 0.1184 \). The impact on the light Higgs mass as a function of the RpV trilinear couplings \( \lambda \) is defined as

\[
\Delta m_h = m_h(\lambda) - m_h(0),
\]

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

(i) \( m_h(0) = 110.0 \text{ GeV} \),

(ii) \( m_h(0) = 124.3 \text{ GeV} \).

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 \( \lambda''_{313}, \lambda_{312}, \lambda'_{213}, \lambda_{313}, \lambda''_{313}, \) and \( \lambda_{333} \). However through the radiative corrections we dynamically generate further couplings. As mentioned, since the operators corresponding to \( \lambda_{ijk} \) 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: \( \lambda'_{213}, \lambda''_{313} \).

![Figure 2](image-url)
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. 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 $\lambda_{331} = 1$, $T_{313} = A_0$ and the green one for $\lambda''_{131} = 1$, $T_{313} = A_0$. All sfermion soft masses but $m_{\tilde{G}, 33}$ are fixed to 1.5 TeV. We set $m_{\tilde{G}, 33}$ to 0.5 TeV.

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

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