New Minimal Extension of MSSM

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Abstract

We construct a new minimal extension of the Minimal Supersymmetric Standard Model (MSSM) by promoting the μ-parameter to a singlet superfield. The resulting renormalizable superpotential is enforced by a $\mathcal{Z}_5$ R-symmetry which is imposed on the non-renormalizable operators as well. The proposed model provides a natural solution to the μ-problem and is free from phenomenological and cosmological problems.

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The Minimal Supersymmetric extension of the Standard Model (MSSM) [1], defined by promoting each standard field to a superfield, doubling the higgs fields and imposing R-parity conservation, seems to be preferred by the low energy data which support unification of the gauge couplings in the supersymmetric case. The most viable scenario for the breaking of supersymmetry at some low scale m_s, no larger than $\sim 1\ TeV$, is the one based on spontaneously broken supergravity. The breaking of supergravity takes place in some hidden sector and is communicated to the visible sector through gravitational interactions. The resulting theory with broken supersymmetry contains, independently of the details of the underlying high energy theory, a number of *soft* supersymmetry (susy) breaking terms proportional to powers of the scale m_s. Probably the most attractive feature of the MSSM is that it realizes a version of "dimensional transmutation" where radiative corrections generate the electroweak scale M_W from the susy-breaking scale m_s. Unfortunately, a realistic implementation of radiative symmetry breaking [2] in MSSM requires the presence of a coupling $\mu H_1 H_2$ involving the higgs fields H_1 and H_2, the so called μ term, with values of the theoretically arbitrary parameter μ close to $m_s \sim M_W$. This nullifies all merits of radiative symmetry breaking since it amounts to introducing the electroweak scale by hand. Of course, there exist scenarios to account for the origin of the μ term, alas, all in extended settings [3].

A straightforward solution to the μ-problem would be to enlarge the field content of MSSM by adding a massless gauge singlet field S that couples to the higgs fields as $\lambda S H_1 H_2$ and acquires a vacuum expectation value (vev) of the order of $m_s \sim M_W$. Such a model with a purely cubic renormalizable superpotential containing a self-coupling of S as well became known as the "Next to Minimal" SSM or NMSSM [4]. At the renormalizable level the model possesses a $\mathcal{Z}_3$ symmetry under which all superfields are multiplied by $e^{2\pi i/3}$ whose spontaneous breaking leads to the formation of cosmologically catastrophic domain walls unless the discrete symmetry is not respected by higher order (non-renormalizable) operators. The existence of higher order operators [1] violating the $\mathcal{Z}_3$ symmetry, however, was shown [5] to be intimately related to the generation of quadratically divergent tadpoles for the singlet [6]. Their generic contribution to the effective potential, cut-off at the Planck scale M_P, is

$$\delta V \sim \xi M_P m_s^2 S + h.c., \tag{1}$$

where ξ is a factor depending on the loop order in which the tadpole is generated. Such terms tend to destabilize the gauge hierarchy through a vev for the light singlet S much larger than the electroweak scale.

Recently we have found [7] a simple resolution to the above problems of NMSSM by imposing a $\mathcal{Z}_2$ R-symmetry on the non-renormalizable operators under which all superfields as well as the superpotential flip sign. Thus, the potentially harmful to the gauge hierarchy operators [8] are forbidden but a harmless tadpole

$$\delta V \sim \xi m_s^3 S + h.c. \tag{2}$$

breaking the $\mathcal{Z}_3$ symmetry and making the walls disappear can still be generated.

[1]These non-renormalizable terms appear either as D-terms in the Kähler potential or as F-terms in the superpotential. The natural setting for these interactions is $N = 1$ Supergravity spontaneously broken by a set of hidden sector fields.

Our purpose in the present note is to get rid of the cubic superpotential self-coupling of the singlet S thereby constructing the simplest extension of the MSSM. To accomplish our goal we should, of course, find substitutes for the twofold role played by the S^3 coupling, as this trilinear coupling contributes to the mechanism generating the vev of S through the soft susy-breaking terms and explicitly breaks the unwanted Peccei-Quinn symmetry present in its absence.

The renormalizable superpotential of the proposed model

$$\mathcal{W}_{ren} = \lambda S H_1 H_2 + Y^{(u)} Q U^c H_1 + Y^{(d)} Q D^c H_2 + Y^{(e)} L E^c H_2 \tag{3}$$

possesses the global symmetries

$$U(1)_B : Q(\frac{1}{3}),\ U^c(-\frac{1}{3}),\ D^c(-\frac{1}{3}),\ L(0),\ E^c(0),\ H_1(0),\ H_2(0),\ S(0);$$

$$U(1)_L :\ Q(0),\ U^c(0),\ D^c(0),\ L(1),\ E^c(-1),\ H_1(0),\ H_2(0),\ S(0);$$

$$U(1)_{PQ} :\ Q(-1),\ U^c(0),\ D^c(0),\ L(-1),\ E^c(0),\ H_1(1),\ H_2(1),\ S(-2);$$

$$U(1)_R :\ Q(1),\ U^c(1),\ D^c(1),\ L(1),\ E^c(1),\ H_1(0),\ H_2(0),\ S(2),$$

where the charge of the superfield under the corresponding symmetry is given in parenthesis. $U(1)_B$ and $U(1)_L$ are the usual baryon and lepton number symmetries, $U(1)_{PQ}$ is an anomalous Peccei-Quinn symmetry whereas $U(1)_R$ is a non-anomalous R-symmetry under which the renormalizable superpotential $\mathcal{W}_{ren}$ has charge 2. The soft trilinear susy-breaking terms break the continuous R-symmetry $U(1)_R$ down to its maximal non-R $\mathcal{Z}_2$ subgroup which is the usual matter-parity. The $U(1)_{PQ}$, which remains unbroken by the soft susy-breaking terms, could be broken by a linear effective potential term of the type given by Eq. (2) with $\xi \sim 1$ arising from non-divergent tadpoles. It is, however, quite difficult to achieve such an unsuppressed value of ξ. Thus, we rather have to resort to divergent tadpole contributions cut-off at M_P which occur at very high order such that $\xi M_P \sim m_s$. Finally, $U(1)_B$ and $U(1)_L$ remain unbroken by both the susy-breaking terms and the tadpole but might be violated by some non-renormalizable operators hopefully of sufficiently high order. Consequently, it is sufficient to find a symmetry which ensures the renormalizable superpotential of Eq. (3) and allows the generation of an adequately suppressed tadpole. All unwanted symmetries will then be broken and a vev $< S > \sim m_s$ will readily be generated by combining the soft susy-breaking mass-squared term $\sim m_s^2 S S^*$ with the above linear in S contribution to the effective potential.

A continuous symmetry enforcing the form of $\mathcal{W}_{ren}$ in Eq. (3) is the $U(1)$ R-symmetry obtained as the linear combination $R' = 3R + PQ$ of $U(1)_R$ and $U(1)_{PQ}$:

$$U(1)_{R'} :\ Q(2),\ U^c(3),\ D^c(3),\ L(2),\ E^c(3),\ H_1(1),\ H_2(1),\ S(4)$$

under which the superpotential $\mathcal{W}$ has charge 6. $U(1)_{R'}$ is broken by the trilinear soft susy-breaking terms down to its maximal non-R subgroup $\mathcal{Z}_6$ which is the product of a $\mathcal{Z}_2$ and a $\mathcal{Z}_3$ subgroup. The $\mathcal{Z}_2$ is essentially the usual matter parity (up to a $SU(2)_L$ element reversing the sign of all doublets) which leaves the tadpole invariant. Under the $\mathcal{Z}_3$

(which is a subgroup of $U(1)_{PQ}$) instead, S transforms non-trivially and the tadpole does not remain invariant. Thus, we should avoid imposing the whole $U(1)_{R'}$ symmetry or one of its subgroups which contains the aforementioned $\mathcal{Z}_3$ if we want a tadpole to be generated.

A subgroup of $U(1)_{R'}$ which is completely broken by the trilinear soft susy-breaking terms and is sufficiently large to enforce $\mathcal{W}_{ren}$ of Eq. (3) but sufficiently small to allow the generation of a sizeable tadpole is the $\mathcal{Z}_5$ subgroup $\mathcal{Z}_5^r$ of $U(1)_{R'}$ generated by

$$\mathcal{Z}_5^r \, : \, (H_1, H_2) \to \alpha(H_1, H_2), \quad (Q, L) \to \alpha^2(Q, L), \quad (U^c, D^c, E^c) \to \alpha^3(U^c, D^c, E^c),$$
$$S \to \alpha^4 S, \quad \mathcal{W} \to \alpha \mathcal{W}$$

with $\alpha = e^{2\pi i/5}$. To examine the generation of the tadpole we bear in mind that the potentially harmful non-renormalizable terms are either even superpotential terms or odd Kähler potential ones. Moreover, a tadpole diagram is divergent if an odd number of such “dangerous” non-renormalizable terms is combined with any number of renormalizable ones. Respecting the above rules [8] and the $\mathcal{Z}_5^r$ R-symmetry we were able to show, not without some effort, that divergent tadpoles first appear at six loops. One example of such a divergent six-loop tadpole diagram is obtained by combining the non-renormalizable Kähler potential terms $\lambda_1 S^2 H_1 H_2 / M_P^2 + h.c.$ and $\lambda_2 S (H_1 H_2)^3 / M_P^5 + h.c.$ with the renormalizable superpotential term $\lambda S H_1 H_2$ (four times). The so generated linear effective potential term

$$\delta V \sim (16\pi^2)^{-6} \lambda_1 \lambda_2 \lambda^4 M_P m_s^2 S + h.c.$$

is of the desired order of magnitude.

Notice that the $\mathcal{Z}_5$ R-symmetry $\mathcal{Z}_5^r$, although it does not contain the usual matter parity, still manages to adequately stabilize the proton since, in addition to all $d = 4$ baryon and lepton number violating operators, it also forbids the dangerous $QQQL$ and $U^c U^c D^c E^c$ $d = 5$ ones.

It is very interesting that non-zero light neutrino masses are readily incorporated in the model by simply introducing gauge singlet states ν^c transforming like E^c under all global symmetries. The allowed large majorana mass terms for these states break $U(1)_L$ down to its $\mathcal{Z}_2$ subgroup and generate small ordinary neutrino masses through the standard see-saw mechanism.

In conclusion, we have shown that the μ term of MSSM can be generated by promoting the parameter μ to a singlet superfield and imposing a $\mathcal{Z}_5$ R-symmetry. The resulting model is a truly minimal extension of MSSM.

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