STABILIZED $NMSSM$ WITHOUT DOMAIN WALLS.

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ABSTRACT: We reconsider the next to minimal supersymmetric Standard Model (NMSSM) as a natural solution to the μ-problem and show that both the stability and the cosmological domain walls problems are eliminated if we impose a discrete $\mathcal{Z}_2$ R-symmetry on the non-renormalizable operators of the theory. The content of this talk is based on work done in collaboration with C.Panagiotakopoulos.

The $N = 1$ supersymmetric extension of the Standard Model provides a well defined framework for the study of new physics beyond it[1]. The low energy data support the unification of gauge couplings in the supersymmetric case in contrast to the standard case. The minimal supersymmetric extension of the Standard Model (MSSM) is defined by promoting each standard field into a superfield, doubling the Higgses and imposing R-parity conservation. The most viable scenario for the breaking of supersymmetry at some low scale m_s , no larger than the TeV range, is the one based on spontaneously broken Supergravity. Although this scenario does not employ purely gravitational forces but could require the appearance of gaugino condensates of some hidden sector, it is usually refered to as gravitationally induced supersymmetry breaking. The resulting broken theory, independently of the details of the underlying high energy theory, contains a number of *soft* supersymmetry breaking terms proportional to powers of the scale m_s . Probably the most atractive feature of the MSSM is that it realises a version of "dimensional transmutation" where radiative corrections generate a new scale, namely the electroweak breaking scale M_W . This is a highly desirable, but also non-trivial, property that is equivalent to deriving M_W from the supersymmetry breaking scale as opposed to putting it by hand as an extra arbitrary parameter. Unfortunately a realistic utilization of radiative symmetry breaking[2] in MSSM requires the presence of the so called μ-term, namely $\mu H_1 H_2$, with values of the theoretically arbitrary parameter μ close to m_s or M_W . This nulifies all merits of radiative symmetry breaking since it reintroduces an extra arbitrary scale from the back door. Of course, there exist explanations for the values of the μ-term, alas, all in extended settings[3].

At first glance, the most natural solution to the μ-problem would be to introduce a massless gauge singlet field S , coupled as $\lambda S H_1 H_2$, whose v.e.v., after minimization would turn out to be of the order of the other scales floating around, namely m_s and M_W . The simplest extension of the MSSM is the so called "Next to Minimal" SSM or NMSSM[4] with a cubic superpotential(renormalizable part)

$$\mathcal{W}_{ren} = \lambda S H_1 H_2 + \frac{f}{3!} S^3$$

$$+Y^{(d)} Q D^c H_1 + Y^{(u)} Q U^c H_1 + Y^{(e)} L E^c H_1 \quad (1)$$

Unfortunately, this scenario runs into difficulties. As can be readily seen the NMSSM at the renormalizable level has a (non-anomalous) $\mathcal{Z}_3$ global discrete symmetry under which all superfields are multiplied by $e^{2\pi i/3}$. This symmetry is broken during the phase transition associated with the electroweak symmetry breaking in the early universe and cosmologically dangerous domain walls are produced. These walls would be harmless provided they disappear effectivelly before nucleosynthesis. This would, roughly, require the presence in the effective potential of $\mathcal{Z}_3$-breaking terms of magnitude

$$\delta V \geq (MeV)^4 \sim 10^{-12} GeV^4$$

This estimate is not very different from the more elaborate one of Abel, Sarkar and White[5]

$$\delta V \geq 10^{-7} v^3 M_W^2 / M_P$$

where v is the scale of spontaneous breaking of the discrete symmetry and M_P is the Planck mass. The above magnitude of $\mathcal{Z}_3$-breaking seems to correspond to the presence in the superpotential or the Käler potential of $\mathcal{Z}_3$- breaking operators suppressed by one inverse power of the Planck mass.

Non-renormalizable terms involving the singlet S can induce quadratically divergent corrections[1] which give rise to quadratically divergent tadpoles for the singlet[6]. Their generic form, cut-off at the Planck mass, is

$$\xi m_s^2 M_P (S + S^*) \qquad (2)$$

where m_s is the scale of susy breaking in the visible sector. The value of ξ depends on the loop order of the associated graph (two or three in this case), which, in turn, depends on the particular non-renormalizable term that gives rise to the tadpole. Such terms lead to vevs for the light singlet S much larger than the electroweak scale. Thus it seems that the non-renormalizable terms that are able to make the walls disappear before nucleosynthesis are the ones that destabilize the hierarchy.

The purpose of the present article is to address the two poblems of domain walls and destabilization that arise in the NMSSM and show that, despite the impass that the previous arguments seem to indicate, there is a simple way out rendering the model a viable solution to the μ-problem. The crucial observation is that due to the divergent tadpoles a $\mathcal{Z}_3$-breaking operator could have a much larger effect on the vacuum than its dimension naively indicates. Thus, it is conceivable that non-renormalizable terms suppressed by more than one power of M_P are able to generate linear terms in the effective potential which are strong enough to eliminate the domain wall problem, although, at the same time, they are too small to upset the gauge hierarchy. Clearly, a better understanding of the symmetries that could be imposed on the model and of the magnitude of destabilization that the various non-renormalizable operators generate is needed.

[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.

The renormalizable part of the NMSSM superpotential (1) possesses the following global symmetries

$$U(1)_B \,:\, Q(1/3),\, U^c(-1/3),\, D^c(-1/3),\, L(0),$$
$$E^c(0),\, H_1(0),\, H_2(0),\, S(0)$$
$$U(1)_L \,:\, Q(0),\, U^c(0),\, D^c(0),\, L(1),\, E^c(-1),$$
$$H_1(0),\, H_2(0),\, S(0)$$
$$U(1)_R \,:\, Q(1),\, U^c(1),\, D^c(1),\, L(1),\, E^c(1),$$
$$H_1(1),\, H_2(1),\, S(1)$$

The last $U(1)$ is an anomalous R-symmetry under which the renormalizable superpotential $\mathcal{W}_{ren}$ has a charge $+3$. The soft trilinear susy-breaking terms break the continuous R-symmetry $U(1)_R$ down to its $\mathcal{Z}_3$ subgroup that we mentioned earlier which is not an R-symmetry. We see that the renormalizable part of the model possesses a discrete $\mathcal{Z}_3$ symmetry whose spontaneous breakdown produces domain walls.

Of cource, one does not have to impose all the above continuous symmetries in oredr to obtain $\mathcal{W}_{ren}$ for the NMSSM. The same $\mathcal{W}_{ren}$ can be obtained if we impose a discrete symmetry. There are various choices among which it is useful to consider two interesting possibilities:

a) $\mathcal{Z}_2^{MP} \times \mathcal{Z}_3$

$$\mathcal{Z}_2^{MP} \,:\, (Q, U^c, D^c, L, E^c) \rightarrow -(Q, U^c, D^c, L, E^c)$$
$$(H_1, H_2, S) \rightarrow (H_1, H_2, S)$$

and

$$\mathcal{Z}_3 \,:\, (Q, U^c, D^c, L, E^c, H_1, H_2, S) \rightarrow$$

$$e^{2\pi i/3}(Q, U^c, D^c, L, E^c, H_1, H_2, S)$$

Note that $\mathcal{Z}_3 \subset U(1)_R$ and that the *matter parity* is $\mathcal{Z}_2^{MP} = \mathcal{Z}_2^B \mathcal{Z}_2^L$, with $\mathcal{Z}_2^B \subset U(1)_B$ and $\mathcal{Z}_2^L \subset U(1)_L$. This is not an R-symmetry ($\mathcal{W} \to \mathcal{W}$).

b) $\mathcal{Z}_2^{MP} \times \mathcal{Z}_4^{(R)}$

$$\mathcal{Z}_4^{(R)} \;:\; (Q, U^c, D^c, L, E^c, H_1, H_2, S) \to$$

$$i(Q, U^c, D^c, L, E^c, H_1, H_2, S)$$

$$\mathcal{W} \to -i\mathcal{W}$$

where the matter parity $\mathcal{Z}_2^{MP}$ is as in **a** and the R-symmetry is $\mathcal{Z}_4^{(R)} \subset U(1)_R$.

Although it makes no difference which of the above symmetries are imposed on the renormalizable superpotential, we should make sure that the $\mathcal{Z}_3$ symmetry or any other symmetry containing it is not a symmetry of the non-renormalizable operators. If $\mathcal{Z}_3$ invariance is imposed on the complete theory the domain walls will not disappear. In contrast, the $\mathcal{Z}_4^{(R)}$ symmetry can be imposed on the non-renormalizable operators and no domain walls associated with its breaking will form because the soft susy-breaking terms break $\mathcal{Z}_4^{(R)}$ completely.

Let us now move to another important issue that has to be addressed in the presence of the gauge singlet superfield S , namely the destabilization of the electroweak scale due to quadratically divergent tadpole diagrams involving non-renormalizable operators which generate in the effective action linear terms of the type (2). As mentioned such terms lead to vevs for the light singlet in general much larger than the electroweak scale. Abel[7] has shown that the potentially harmful non-renormalizable terms are either even superpotential terms or odd Kähler potential ones. Such terms are easily avoided if we impose on the full non-renormalizable theory a $\mathcal{Z}_2^{(R)}$ R-symmetry under which all superfields, as well as the superpotential, flip sign. This symmetry is a subgroup of both $U(1)_R$ and $\mathcal{Z}_4^{(R)}$. Therefore, one has the option of imposing on all operators a symmetry $\mathcal{Z}_2^{MP} \times \mathcal{Z}_4^{(R)}$ or $\mathcal{Z}_2^{MP} \times \mathcal{Z}_2^{(R)}$ or just $\mathcal{Z}_2^{(R)}$ assuming in the last two cases that the renormalizable superpotential has *accidentally* a larger symmetry.

Notice that the non-renormalizable terms allowed by $\mathcal{Z}_2^{(R)}$ or $\mathcal{Z}_4^{(R)}$, although not harmful to the gauge hierarchy, are still able to solve the $\mathcal{Z}_3$-domain wall problem since they generate through the n-loop tadpole diagrams linear terms in the effective action of the form

$$\delta V \sim (16\pi^2)^{-n} m_s^3 (S + S^*)$$

These terms are small to upset the gauge hierarchy but large enough to break the $\mathcal{Z}_3$ symmetry and eliminate the domain wall problem. For example, the presence of the term S^7/M_P^4 in the superpotential, allowed by both symmetries $\mathcal{Z}_2^{(R)}$ and $\mathcal{Z}_4^{(R)}$, is able to generate at four loops such a harmless linear term, as shown by Abel.

Combining all the above we see that by adopting the renormalizable superpotential (1) of the NMSSM and imposing on the non-renormalizable operators just a $\mathcal{Z}_2^{(R)}$ R-symmetry we are able to solve both the cosmological and the stability problems of the model . Thus, NMSSM can be finally regarded as a solution to the μ-problem of the MSSM without invoking non-minimal Kähler potentials coupling directly visible and hidden fields.

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