Physics Letters B 737 (2014) 156–161

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

# Constraining the Natural MSSM through tunneling to color-breaking vacua at zero and non-zero temperature

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ARTICLE INFO

*Article history:*
Received 5 June 2014
Received in revised form 13 August 2014
Accepted 14 August 2014
Available online 19 August 2014
Editor: A. Ringwald

*Keywords:*
Supersymmetry
Vacuum stability

ABSTRACT

We re-evaluate the constraints on the parameter space of the minimal supersymmetric standard model from tunneling to charge- and/or color-breaking minima, taking into account thermal corrections. We pay particular attention to the region known as the Natural MSSM, where the masses of the scalar partners of the top quarks are within an order of magnitude or so of the electroweak scale. These constraints arise from the interaction between these scalar tops and the Higgs fields, which allows the possibility of parameter points having deep charge- and color-breaking true vacua. In addition to requiring that our electroweak-symmetry-breaking, yet QCD- and electromagnetism-preserving vacuum has a sufficiently long lifetime at zero temperature, also demanding stability against thermal tunneling further restricts the allowed parameter space.



## 1. Introduction

The mechanism of spontaneous symmetry breaking by the vacuum expectation value for a scalar field is an essential component of the standard model of particle physics (SM) [1–3], which has proven itself to be an accurate description of Nature all the way to the tera-electronvolt scale. The discovery of the bosonic resonance at 125 GeV at the Large Hadron Collider (LHC) [4,5] is consistent with the Higgs boson of the spontaneous symmetry breaking of the SM, leading one to take the issue of minimizing the scalar potential seriously.

The minimal supersymmetric extension of the SM (the MSSM) has a much more complex scalar potential by merit of there being many more scalar fields (partners for each SM fermion as well as a second Higgs $SU(2)_L$ doublet) which interact with the Higgs fields. The large effect of the extra loops on the mass of the Higgs boson along with the non-observation of supersymmetric partners thus far has led to the pragmatic region of the MSSM parameter space known as the Natural MSSM [6–8]. This is the region where the masses of all the partners are very large but for those with the largest contributions to the Higgs mass [9–14], which should have masses not very far above the electroweak scale so that there is little finely tuned cancellation between loop contributions to the minimization conditions, and thus is in some sense natural [15–18]. Thus the *stops* $\tilde{t}$ (scalar partners of the top quarks) should have TeV-scale soft supersymmetry-breaking parameters while all others are assumed to have very large masses. The partners of the bottom quarks and tau leptons could also be in the TeV-scale, but in this letter we consider only stops, noting that our algorithm is trivially generalizable and is already implemented in the public code `Vevacious` [19].

While the interaction between stops and the Higgs fields allow the mass of the Higgs boson to reach 125 GeV in the MSSM, it also leads to the possibility of the scalar potential having undesired minima apart from the desired symmetry-breaking (DSB) vacuum, where only the neutral components of the Higgs doublets get non-zero VEVs. Even though a parameter point may be chosen where the scalar potential has a minimum where the stops do not have non-zero VEVs, there is no guarantee that this is the global minimum: there may be deeper charge- and color-breaking (CCB) minima to which the Universe may tunnel [20–30]. However, even if the DSB vacuum is only metastable, the parameter point is still acceptable if the expected tunneling time is of the order of the age of the known Universe [31–33]. Also, given the convincing success of the Big Bang theory, acceptable parameter points with metastable DSB vacua should also have a high probability of surviving tunneling to the true CCB vacua through thermal fluctuations.

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http://dx.doi.org/10.1016/j.physletb.2014.08.036
0370-2693/

In Section 2 we lay out the algorithm by which we compute whether a parameter point is excluded by the DSB vacuum having a very low probability of surviving to the present day either by a high probability of critical bubbles of true vacuum forming through quantum fluctuations in our past light-cone at zero temperature, or by such bubbles forming through thermal fluctuations during the period when the Universe was at sufficiently high temperature. In Section 3, we show how much of the parameter space is excluded by such conditions, and compare this to previous work. Finally we conclude in Section 4.

## 2. Parameter point selection and stability evaluation

We categorize the stability or metastability of a parameter point by a multi-stage process. First, a consistent set of Lagrangian parameters at a fixed renormalization scale is generated by SPheno [34,35], such that the MSSM physics at the DSB vacuum is consistent with the SM inputs ($m_Z$, $G_F$, *etc.*), and these parameters are stored in a file in the SLHA format which is passed to Vevacious, using a model file automatically generated by SARAH [36–40]; for consistency of input, the version of SPheno was also generated by SARAH. Vevacious is a publicly-available code [19] that then prepares the minimization conditions for the tree-level potential as input for the publicly-available binary HOM4PS2 [41] that finds all possible solutions to the particular minimization conditions of the parameter point. These are then used by Vevacious as starting points for gradient-based minimization by MINUIT [42] through HOM4PS2 [43] to minimize the full one-loop potential with thermal corrections at a given temperature. If a minimum deeper than the DSB vacuum is found, the probability of tunneling out of the false DSB vacuum is then calculated through CosmoTransitions [44]. For a full discussion of the calculation of the bounce action and its conversion to a tunneling time from a false vacuum to a true vacuum, we refer the reader to the Vevacious manual [19], the CosmoTransitions manual [44], and the seminal papers on tunneling out of false vacua [45,46].

If a parameter point is found to have a deeper CCB minimum, we label it as metastable, otherwise we label it stable.[1] We then divide the metastable points into short-lived points which would tunnel out of the false DSB vacuum in three giga-years or less (corresponding to a survival probability of lasting 13.8 Gy of one per-cent or less), and the rest as long-lived. Finally, we divide the long-lived points into thermally excluded, by having a probability of the DSB vacuum surviving thermal fluctuations of one per-cent or less, or allowed, by having a survival probability of greater than one per-cent, as described in more detail in the following subsection.

### 2.1. Thermal corrections

Since the temperature of the Universe has been negligible for most of its existence, it is quite reasonable to calculate the tunneling time assuming that the four-dimensional bounce action $S_4$ is the dominant contribution to the decay width of the false vacuum. However, for sufficiently high temperatures, the dominant contribution may come from solitons that are $O(3)$ cylindrical in Euclidean space rather than $O(4)$ spherical [47].

[1] It may be that a parameter point is actually metastable if other scalar fields such as the partners of bottom quarks were allowed non-zero VEVs. However, we restrict ourselves to a region of parameter space where such concerns are negligible as the relevant trilinear interaction is small, but note also that this restriction cannot mistakenly label a stable parameter point as metastable.

If the thermal contribution dominates, the expression for the decay width per unit volume $\Gamma/V$ at a temperature $T$ changes accordingly:

$$\Gamma/V = Ae^{-S_4} \to \Gamma(T)/V(T) = A(T)e^{-S_3(T)/T} \tag{1}$$

where $A$ is a quantity of energy dimension four, which is related to the ratio of eigenfunctions of the determinants of the action's second functional derivative, and $S_3(T)$ is the bounce action integrated over three dimensions rather than four, with the integration over time simply replaced by division by temperature because of the constant value along the Euclidean time direction. The leading thermal corrections to the potential are at one loop, and given by

$$\Delta V(T) = \sum T^4 J_\pm\left(m^2/T^2\right)/\left(2\pi^2\right) \tag{2}$$

where the sum is over degrees of freedom: bosons as sets of real scalars, fermions as sets of Weyl fermions, and

$$J_\pm(r) = \pm\int_0^\infty \mathrm{d}x\, x^2 \ln\left(1 \mp e^{-\sqrt{x^2+r}}\right) \tag{3}$$

with $J_+$ for a real bosonic degree of freedom and $J_-$ for a Weyl fermion (note that we incorporate the negative sign into the definition of $J_-$ in contrast to Ref. [48]). The probability $P(T_i, T_f)$ of not tunneling between the time when the Universe is at temperature $T_i$ and when it is at temperature $T_f < T_i$ becomes

$$P(T_i, T_f) = \exp\left(-\int_{T_i}^{T_f} \frac{\mathrm{d}t}{\mathrm{d}T} V(T)A(T)e^{-S_3(T)/T}\,\mathrm{d}T\right). \tag{4}$$

#### 2.1.1. Evaluating the survival probability

Even the numerical evaluation of the action is computationally intense and while one could attempt to numerically integrate Eq. (4), this is impractical for more than a handful of parameter points. Hence we exclude parameter points based on an upper bound on the survival probability under some approximations, which requires $S_3(T)$ to be evaluated only once.

Firstly, the factor $A(T)$ is taken to be $T^4$, as the evaluation of the eigenfunctions of the determinant is so hard that they are usually estimated on dimensional grounds anyway, which is justified as the exponent of the action is much more important [49]. Any deviation would effectively contribute $\ln(AT^{-4})$ to $S_3(T)/T$, and $S_3(T)/T$ is $\sim 240$ for survival probabilities that are not extremely close to zero or one.

Secondly, we assume that the Universe is radiation dominated during its evolution from $T_i$ to $T_f$ and that entropy is approximately conserved between $T_i$ and today, as it is appropriate for the MSSM. Entropy conservation implies that $V(T_0)/V(T) = s(T)/s(T_0)$, where $s$ is the entropy density and $T_0 = 2.73$ K is the temperature of the Universe today. Using the relation for $\mathrm{d}t/\mathrm{d}T$ during radiation domination, we can replace in Eq. (4)

$$\frac{\mathrm{d}t}{\mathrm{d}T} V(T) = -M_{\text{Planck}}\sqrt{90/\left(\pi^2 g_*(T)\right)}\,T^{-3}V(T_0)\frac{s(T_0)}{s(T)}, \tag{5}$$

where $M_{\text{Planck}}$ is the reduced Planck mass. The volume of the presently observable Universe (defined through the co-moving horizon) with 68.3% Dark Energy and 31.7% non-relativistic matter is $V(T_0) = 141.4(H(T_0))^{-3} = (3.597 \times 10^{42}/\text{GeV})^3$, where $H(T_0) = 0.68 \times 100\ \text{km}\,(\text{s}\,\text{Mpc})^{-1}$, and the ratio $s(T_0)/s(T)$ is taken as $(g_{*s}(T_0)T_0^3)/(g_{*s}(T)T^3)$ and $g_{*s}(T_0) = 43/11$.