Singlets and the Electroweak Phase Transition

S. J. Huber

Institut für Theoretische Physik, Universität Heidelberg,
69120 Heidelberg, Germany
E-mail: huber@thphys.uni-heidelberg.de

Singlet extensions of the Standard Model (SM) allow for a strongly first order electroweak phase transition, because of trilinear terms in the tree-level potential. We present a systematic procedure to study the parameter space of the Next-to-Minimal Supersymmetric SM (NMSSM). We find that this model is consistent with electroweak baryogenesis for a wide range of parameters, allowing Higgs masses up to at least 115 GeV.

1 Introduction

The order and strength of the electroweak phase transition are central questions in electroweak baryogenesis. Only in case of a first order phase transition (PT) the associated departure from equilibrium is sufficient to induce a relevant baryon number production. At the critical temperature $T_c$ of a first order phase transition there exist two energetically degenerate phases which are separated by an energy barrier. In case of the electroweak phase transition (EWPT) these phases differ in the vacuum expectation value (vev) of the Higgs field $\langle h \rangle$ and are referred to as “symmetric” ($\langle h \rangle = 0$) and “Higgs” phase ($\langle h \rangle \neq 0$). In the effective potential description this behavior is translated into two degenerate minima which are separated by a bump.

At a particular temperature below $T_c$ Higgs phase bubbles, just large enough to grow (“critical bubbles”), nucleate and expand. After the completion of the phase transition they fill all of space. As a bubble wall passes a point in space, the Higgs field changes rapidly which leads to a significant departure from equilibrium making it possible to satisfy Sakharov’s criteria.

A further condition has to be satisfied: The anomalous baryon number violating processes which are essential for the baryon production during the phase transition may wash out the baryon asymmetry afterwards if they are too weakly suppressed in the emerging Higgs phase at $T_c$. Since their rate is determined by the sphaleron energy which is proportional to the Higgs vev, the washout criterion can be translated into $\frac{\langle h \rangle(T_c)}{T_c} \gtrsim 1$.

Intensive studies of the electroweak phase transition in the past few years however showed that in case of the Standard Model (SM) this necessary condition cannot be fulfilled. (For Higgs masses compatible with experimental...
bounds there is no phase transition at all.) Successful electroweak baryogenesis therefore requires extensions of the minimal particle content in order to enlarge the cubic term in the effective potential that triggers the first order phase transition. Very promising in this respect are models with additional scalar gauge singlet fields. Trilinear terms in the tree-level potential which arise due to singlet-Higgs couplings should significantly strengthen the electroweak phase transition\cite{1}, as long as the singlet and the Higgs are on the same (electroweak) scale.

We have investigated the supersymmetric Standard Model with an additional gauge singlet superfield $S$ (NMSSM). Its Higgs sector is characterized by the superpotential

$$W = \mu H_1 H_2 + \lambda S H_1 H_2 - \frac{k}{3} S^3 - r S$$

(1)

and the soft SUSY breaking terms

$$V_{soft} = (BH_1 H_2 + \lambda A_\lambda S H_1 H_2 - \frac{k}{3} A_k S^3 + h.c.)$$

$$+ m_{H_1}^2 |H_1|^2 + m_{H_2}^2 |H_2|^2 + m_S^2 |S|^2 .$$

(2)

Most interesting with respect to the strength of the phase transition are the trilinear couplings $A_\lambda$ and $A_k$ since they contribute to the energy barrier that separates the symmetric and the Higgs phase.

The well known domain wall problem is avoided by including the mass parameters $\mu, r, B$ that explicitly break the dangerous $Z_3$-symmetry. Furthermore, it was shown that in the $Z_3$-symmetric limit a viable phenomenology requires couplings $\lambda, k \ll 1$ and a singlet vev $< S >$ much larger than the Higgs vev. In such a scenario the electroweak phase transition is basically not modified by the presence of the singlet and proceeds in the SM (MSSM) way. Therefore, strengthening the phase transition compared to the SM case requires violation of the $Z_3$-symmetry. Unfortunately, the general superpotential (1) leaves the $\mu$-problem, it was originally designed for, unsolved and there remains the question of destabilizing singlet tadpole divergences.

\section{Renormalization Group Analysis}

We require the model to remain perturbative up to the GUT scale $M_{\text{GUT}}$, where the soft parameters are assumed to be characterized by a common gaugino mass $M_0$, a universal trilinear coupling $A_0$ and a universal scalar mass squared $m_0^2$. The parameters at different scales are related via the renormalization group equations (RGEs), which we approximate to 1-loop order.
Figure 1: (a): Sketch of our procedure to determine the weak scale as function of the GUT scale parameters. (b): Constrained parameter range in the $M_0$-$A_0$ plane, while the remaining parameters are fixed.

Instead of simply studying the phenomenology of a randomly chosen GUT scale parameter set ("random shooting"), which is a rather inefficient method because there usually appear some light unobserved SUSY particles in the spectrum, we use the more elaborated procedure sketched in fig. 1a. Our method determining the parameters at the weak scale which combines RGEs and extremal conditions for the effective potential $V(H_1, H_2, S)$ is based on the decoupling of $\mu, r, B$ from the RGEs of the other parameters. Therefore, after fixing the values of $\lambda_0, k_0, M_0, A_0, m_0^2$ we can calculate all parameters in $V(H_1, H_2, S)$ with exception of $\mu, B, r$. These we determine via the extremal condition $\nabla V(H_1, H_2, S) = 0$ postulated at some minimum characterized by $(M_Z, \tan \beta, <S>)$. For the elimination of $\mu, r, B$ we use the 1-loop Higgs potential $V(H_1, H_2, S)$ at zero temperature where the contributions of tops, stops and gauge bosons are taken into account. Our procedure allows for an efficient and systematic study of the remaining seven dimensional parameter space

$$\tan \beta, <S>, \lambda_0, k_0, M_0, A_0, m_0^2.$$

In the following we perform cuts in the $M_0$-$A_0$ plane since these parameters determine the trilinear couplings $A_\lambda, A_k$ which regulate the strength of the electroweak phase transition in this model. The phenomenologically viable parameter space is characterized by the following conditions:

- The extremum used in the elimination procedure discussed above has to be the global minimum of the Higgs potential which results in the lower bound on $A_0$ in fig. 1b.

- There should exist no light unobserved particles, especially the mass of
the lightest chargino has to obey $M_{\tilde{\chi}^\pm} > 80$ GeV corresponding to the lower bound on $M_0 > 100$ GeV in fig. 1b.

Of particular interest are the properties of the lightest neutral CP-even 'Higgs' boson mass eigenstate $H$, which is a mixing of the Higgses and the singlet. Its mass $M_H$ is maximized for low values of $A_0$. From fig. 1b one can also read off the parameter region where the lightest 'Higgs' is predominantly a singlet. In this case the experimental bound on $M_H$ is certainly lower than the 95 GeV for Standard Model like Higgses, therefore we also kept smaller Higgs masses down to 65 GeV.

3 The Electroweak Phase Transition

In order to examine the strength of the phase transition, one has to take into account thermal corrections to the effective Higgs potential $V(H_1, H_2, S)$. We include the 1-loop contributions of tops, stops, gauge bosons, Higgs bosons, neutralinos and charginos. Since we can rely on the tree-level cubic terms, the most important effect of finite temperature is the appearance of effective thermal masses:

$$ m^2 \rightarrow m^2 + \text{const} \cdot T^2 $$

From the thermal effective potential $V_T(H_1, H_2, S)$ we determine the critical temperature $T_c$ where there exist two degenerate minima, a symmetric one with $<H_i>=0$ and a broken minimum with $<H_i>\equiv v_{1,c} \neq 0$. With this information we can check the washout criterion for electroweak baryogenesis:

$$ \frac{\sqrt{v_{1,c}^2 + v_{2,c}^2}}{T_c} \gtrsim 1. $$

Our choice of $m^2_0$ prevents the appearance of any light sfermions.
Fig. 2a displays the strength of the EWPT for the parameter set already presented in fig. 1b. We find that in a large part of the parameter space the washout condition is satisfied ("strong PT"), while Higgs masses up to 90 GeV are accessible. In fig. 2b we have increased $<S>, \tan \beta$ in order to obtain larger values of $M_H \lesssim 115$ GeV. We observe that the parameter region compatible with electroweak baryogenesis (3) becomes smaller in this case. Notice, that both parameter sets used in fig. 2 satisfy $<S> \sim O(M_Z)$, otherwise we would just obtain the SM phase transition.

4 Summary and Outlook

We presented a method to systematically study the NMSSM parameter space, avoiding random shooting. Our investigation of the EWPT shows that a considerable range of parameters exhibits a phase transition strong enough for electroweak baryogenesis, where Higgs masses up to at least 115 GeV are allowed.

Having found a parameter set with a strongly first order EWPT, one can start calculating the arising baryon asymmetry. To tackle this problem one has to address the questions of CP-violation (talk of A. Davies, this conference) and the dynamics of the nucleating bubbles (poster of P. John, this conference).

Acknowledgments

I would like to thank M. G. Schmidt for enjoyable collaboration and also P. John for a lot of useful discussions. This work was supported in part by the TMR network *Finite Temperature Phase Transitions in Particle Physics*, EU contract no. ERBFMRXCT97-0122.

References

1. M. Pietroni, *Nucl. Phys.* B402 (1993) 27
2. J. Gunion, H. E. Haber, G. L. Gordon, S. Dawson, *The Higgs Hunter’s Guide*, Addison-Wesley, Reading MA, 1990
3. A. T. Davies, C. D. Froggatt, R. G. Moorhouse *Phys. Lett.* B372 (1996) 88
4. S. A. Abel, S. Sarkar, P. L. White, *Nucl. Phys.* B454 (1995) 663
5. U. Ellwanger, M. Rausch de Traubenberg, C. Savoy, *Z. Phys.* C67 (1995) 665
6. S. J. Huber, M. G. Schmidt, [hep-ph/9809506](http://arxiv.org/abs/hep-ph/9809506) to appear in *Eur. J. C