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ELECTROWEAK PHASE CHANGES IN TWO HIGGS MODELS

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INTRODUCTION

As reviewed by Espinosa¹ in his contribution, a strongly first order electroweak phase transition is required in order that the baryon asymmetry, however generated, be not washed out by sphaleron transitions. In the standard one Higgs doublet model, perturbatively treated, this implies an unacceptably low Higgs mass of < 35 GeV. There are indications that non-perturbative calculations can push the bound up to around the current experimental lower limit of 60 GeV, but in view of the possibility that this may be only a temporary remission we investigate the extent to which it may be evaded in a general two doublet model. This has the advantage compared with other extensions of the standard model of allowing CP violation in the Higgs sector, a desideratum of several baryogenesis scenarios.

Our work differs from earlier studies of this model^{2,3} by including the CP violating term, by working in the Landau gauge rather than a suspect unitary gauge, by incorporating Debye suppression of longitudinal gauge boson modes (which weakens the first order transition), and incorporating a heavy top.

We find that a two doublet model can coexist with the preservation of baryon asymmetry, perhaps not surprisingly in view of the many experimentally ill-determined parameters in the potential. The baryogenesis constraint rules out about 95% of otherwise acceptable sets of coupling constants. The lightest physical scalar corresponding to potentials fulfilling all our criteria is in the range 50-200 GeV. The presence of a CP violating term in the potential makes it easier to satisfy the required conditions.

Finally, as baryogenesis places non-trivial constraints on the potential, we inquire whether the acceptable sets include the special case of the Minimal Supersymmetric Standard Model.

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TWO HIGGS DOUBLET EFFECTIVE POTENTIAL

To suppress flavour changing neutral currents we adopt the usual tree-level scalar potential with a softly broken discrete symmetry $\Phi_2 \rightarrow -\Phi_2$ with Φ_2 having a Yukawa coupling g_t only to the t quark, and Φ_1 to the b quark and τ lepton. Couplings to lighter particles are neglected. In the notation of Sher ⁴ this is

$$V_0 = -\mu_1^2 \Phi_1^* \Phi_1 - \mu_2^2 \Phi_2^* \Phi_2 - \mu_3^2 \Phi_1^* \Phi_2 - \mu_3^{*2} \Phi_2^* \Phi_1 + \lambda_1 (\Phi_1^* \Phi_1)^2 + \lambda_2^2 (\Phi_2^* \Phi_2)^2 + \lambda_3 (\Phi_1^* \Phi_1)(\Phi_2^* \Phi_2) + \lambda_4 |\Phi_1^* \Phi_2|^2 + \frac{1}{2} \left[\lambda_5 (\Phi_1^* \Phi_2)^2 + \lambda_5^* (\Phi_2^* \Phi_1)^2 \right] \quad (1)$$

where μ_1^2 , μ_2^2 and the dimensionless λ_{1-4} are real. The relative phase of the Φ can be adjusted to make λ_5 real, and then a complex μ_3^2 implies CP violation. (In the MSSM case, $\lambda_5 = 0$ and then μ_3^2 can always be made real.) Φ_1 and Φ_2 contain a total of 8 real fields ϕ_i .

The one loop effective potential in the high temperature approximation is

$$V(\phi, T) = V_0(\phi) - \frac{N_{eff} \pi^2 T^4}{90} + \frac{T^2}{24} \text{Tr} M_0^2 - \frac{T}{12\pi} \text{Tr} M_T^3 \quad (2)$$

where

$$\begin{aligned} \text{Tr} M_0^2 = & -4(\mu_1^2 + \mu_1'^2) + (6\lambda_1 + 2\lambda_3 + \lambda_4 + 3g_b^2 + g_\tau^2 + \frac{9}{4}g^2 + \frac{3}{4}g'^2) \sum_1^4 \phi_i^2 \\ & + (6\lambda_2 + 2\lambda_3 + \lambda_4 + 3g_t^2 + \frac{9}{4}g^2 + \frac{3}{4}g'^2) \sum_5^8 \phi_i^2 \end{aligned} \quad (3)$$

and

$$\text{Tr} M_T^3 = \sum_1^8 m_i^3(\phi, T) + 4 \left[\frac{g^2}{4} \sum_1^8 \phi_i^2 \right]^{\frac{3}{2}} + 2 \left[\frac{g^2 + g'^2}{4} \sum_1^8 \phi_i^2 \right]^{\frac{3}{2}}. \quad (4)$$

The scalar masses used in $\text{Tr} M_0^2$ are the eigenvalues of the mass matrix derived from V_0 . This T^2 term provides thermal mass corrections, which are included in the $\text{Tr} M_T^3$ term where they are needed to keep V real near its minimum. This term has to be evaluated numerically, as the mass matrix consists of 4x4, not 2x2, blocks, due to the complex μ_3^2 terms.

RESULTS FOR THE GENERAL TWO DOUBLET CASE

We survey the parameter space of the potential.

In the first step we restrict to a basis space of parameters which are acceptable if baryogenesis is not considered. The potential involves 9 real parameters: 4 μ_i and 5 λ_i . We replace μ_1 and μ_2 by one unknown β , where $\tan \beta = v_2/v_1$ at $T=0$ and $v_1^2 + v_2^2 = (246 \text{ GeV})^2$. At each point on an 11x11 grid of $\mu_3^2 = \mu_R^2 + i \mu_I^2$, with $0 \leq \mu_R^2, \mu_I^2 \leq 1.5 \times 10^4 \text{ GeV}^2$, we take random values of the λ_i , restricted to $|\lambda_i| < 0.5$ so that perturbation theory may apply, and of $\tan \beta > 0.9$ so that the top Yukawa coupling is not much greater than unity.

We assume a $T=0$ vacuum structure

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 e^{i\theta} \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \quad (5)$$

which puts further constraints on λ_i , as does the requirement that the potential is bounded below. Many λ_i have also to be discarded to ensure that the masses of the 5 physical scalars are real and compatible with experimental bounds, which, somewhat approximately, we take as > 50 GeV. Acceptable parameters also need the high T minimum at $\phi_i = 0$ to become unstable as T falls below a critical value T_c corresponding to the onset of the electroweak transition. For each set of parameters which passes these tests, we minimize $V(\phi, T_c)$ and determine the vacuum expectation values $v_1(T_c)$, $v_2(T_c)$ and $\theta(T_c)$. At this stage, some points in the basis space have to be discarded because they lead to some $m_i(\phi, T_c)/T_c$ too large for the high T expansion of V to be safe.

Figure 1a. Frequency distribution of baryon number preserving cases in the complex μ_3^2 plane. Each block represents 500 cases. Note that $\mu_3^2 = 0$ is the least favourable case, with a success rate of only 3%

Figure 1b. The average critical temperature $\bar{T}_c$ for the same cases. $\bar{T}_c$ ranges from 90 -160 GeV, being lowest for $\mu_3^2 = 0$.

Figure 2. The scalar masses for the baryon preserving cases, showing that the 35 GeV perturbative bound of the Standard Model can be easily evaded. The high mass cutoff is primarily due to the restriction to small λ_i . The neutral scalars are denoted h_1 , h_2 and h_3 in order of increasing mass.

Now we can assess what fraction of the basis space satisfies the baryon preservation criterion¹ $v(T_c)/T_c > \xi$, as well as having scalar masses > 50 GeV. The successful cases are presented in Figures 1 and 2 for $\xi = 1$, and for $M_{\text{top}} = 170$ GeV. Of 60,000 points in the basis space, overall only about 5% preserve baryon asymmetry.

MINIMAL SUPERSYMMETRIC STANDARD MODEL

The requirement of baryon number preservation thus places significant but not improbable restrictions on the potential. Is the very special case of the MSSM acceptable?

Unbroken SUSY determines all λ_i in terms of g and g' the $SU(2) \times U(1)$ coupling constants,

$$\lambda_1 = \lambda_2 = \frac{g^2 + g'^2}{8}, \quad \lambda_3 = \frac{g^2 - g'^2}{4}, \quad \lambda_4 = \frac{-g^2}{2}, \quad \lambda_5 = 0$$

but SUSY is of course broken at the energy of the EW phase transition.

We link the SUSY and EW scales by making the drastic approximation that SUSY is exact above a certain temperature TS , but that below TS there are only the experimentally established particles (plus top), i.e. we take $M_{\text{stop}} = TS$. We use the two doublet renormalization group equations (RGE) to run g and g' up from their values at the EW scale to those at TS , and hence find the λ_i at TS . The RGE are then used to run the λ_i down to the EW scale. For a particular TS , for which we try several choices in the range 500-2500 GeV, there remain only 2 adjustable parameters, β and the real μ_3 ².

If we adhere to our earlier restriction $\tan \beta > 0.9$ the condition for baryon preservation implies unacceptably low scalar masses. If however we allow smaller β and a high SUSY breaking scale TS , acceptable solutions can be found for a range of μ_3 ²; to quote one example, $TS = 2.5$ TeV, $\tan \beta = 0.67$, $M_{\text{top}} = 150$ GeV and $\mu_3 = 58$ GeV gives a baryon preserving solution with neutral scalars of mass 70, 87 and 156 GeV and charged scalars of mass 113 GeV.

This conclusion is more optimistic for coexistence of the MSSM and baryogenesis than that of Brignole et al.⁵ Supersymmetry breaking has been treated very differently from these authors, but whether this accounts for our different conclusion remains to be investigated. Our solutions do however require $\tan \beta < 1$, which implies a large Yukawa coupling to give a heavy top, thus endangering perturbation theory and also MSSM unification predictions such as b - τ mass unification at high energy.

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