Weak Scale Baryogenesis in the MSSM and in an SU(2) extended model

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Under natural assumptions, there are three conditions, enunciated by Sakharov, that need to be fulfilled for baryogenesis. The SM fulfills them:

- **Baryon number violation**: Anomalous Processes
- **C and CP violation**: Quark CKM mixing
- **Non-equilibrium**: Possible at the electroweak phase transition.
If Baryon number generated at the electroweak phase transition,

\[ \frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp \left( - \frac{10^{16}}{T_c \text{(GeV)}} \exp \left( - \frac{E_{\text{sph}}(T_c)}{T_c} \right) \right) \]

Kuzmin, Rubakov and Shaposhnikov, ’85—’87

Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase. Therefore, to preserve the baryon asymmetry, a strongly first order phase transition is necessary:

\[ E_{\text{sph}} \propto \frac{8\pi v}{g} \quad \frac{v(T_c)}{T_c} > 1 \]
Finite Temperature Higgs Potential

\[ V(T) = D(T^2 - T_0^2) \phi^2 - E_B T \phi^3 + \frac{\lambda(T)}{2} \phi^4 \]

\( D \) receives contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, and is responsible for the phenomenon of symmetry restoration.

\( E \) receives contributions proportional to the sum of the cube of all light boson particle couplings.

\[ \frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2} \]

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass,

\[ \frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40 \text{ GeV}. \]

Electroweak Baryogenesis in the SM is ruled out.
CP-Violation sources

Another problem for the realization of the SM electroweak baryogenesis scenario:

Absence of sufficiently strong CP-violating sources

Even assuming preservation of baryon asymmetry, baryon number generation several order of magnitudes lower than required

\[ \Delta_{CP}^{\text{max}} = \left[ \sqrt{\frac{3\pi}{2}} \frac{\alpha_W T}{32 \sqrt{\alpha_s}} \right]^3 J \frac{(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)}{M_W^6} \frac{(m_b^2 - m_s^2)(m_s^2 - m_d^2)(m_b^2 - m_d^2)}{(2\gamma)^9} \]

\[ J \equiv \pm \text{Im}[K_{ij}K^*_{ij}K_{ij}K^*_{ij}] = c_1 c_2 c_3 s_1 s_2 s_3 s_4 s_5 \]

\( \gamma \) : Quark Damping rate

Gavela, Hernandez, Orloff, Pene and Quimbay'94
Electroweak Baryogenesis

and

New Physics at the Weak Scale
Preservation of the Baryon Asymmetry

- EW Baryogenesis requires new boson degrees of freedom with strong couplings to the Higgs.

- Supersymmetry provides a natural framework for this scenario. Huet, Nelson ’91; Giudice ’91, Espinosa, Quiros, Zwirner ’93.

- Relevant SUSY particle: Superpartner of the top

- Each stop has six degrees of freedom (3 of color, two of charge) and coupling of order one to the Higgs

\[ E_{\text{SUSY}} = \frac{g_w^3}{4\pi} + \frac{h_t^3}{2\pi} \approx 8 E_{\text{SM}} \]

\[ \frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2} \]

- Since

Higgs masses up to 120 GeV may be accommodated
Upper Bound on the Higgs Mass. Largest values of $\tilde{m}$

M. Carena, G. Nardini, M. Quiros, C.W. ’08

$m_Q = m_{\tilde{q}} = m_A = m_{\tilde{l}} = \tilde{m}$

Both the Higgs and the lightest stop must be lighter than about 125 GeV for the mechanism to work. Values of the Higgs mass above 120 GeV may only be obtained for very large values of $\tilde{m}$. 
Experimental Tests of Electroweak Baryogenesis in the MSSM
Experimental Tests of Electroweak Baryogenesis and Dark Matter

- Higgs searches beyond LEP:

1. **Tevatron** collider may test this possibility: close to 3 sigma evidence with $f_{b}^{-1}$ about 10

   Discovery quite challenging, detecting a signal will mean that the Higgs has relevant strong (SM-like) couplings to W and Z

2. A **definitive test** of this scenario will come at the **LHC** with the first 30 $f_{b}^{-1}$ of data

   $$qq \rightarrow qqV^{*}V^{*} \rightarrow qqh$$

   with $h \rightarrow \tau^{+}\tau^{-}$
Prospects for Higgs Searches at the Tevatron in the SM and in the MSSM

T. Liu, P. Draper and C.W.’09

Each Tevatron experiment is expected to obtain about 10 fb\(^{-1}\) of good quality data. Improvements in efficiencies in all channels are expected.

With modest increases in efficiencies, most of the Higgs range consistent with precision measurements can be probed. Similarly, the minimal mixing scenario of the MSSM may be probed. Other benchmark scenarios, and impact of non-SM Higgs searches also studied.
Higgs Boson Production via $gg \to h^0$

- $\sigma(gg \to h^0) \propto \Gamma(h^0 \to gg)$.
- Stop loops interfere constructively with tops.

MSSM EWBG Region: $m_{\tilde{t}_1}, m_{h^0} \lesssim 125 \text{ GeV}$.

[Carena, Nardini, Quirós, Wagner ’08]
Tevatron Stop Reach when two body decay channel is dominant
Tevatron stop searches and dark matter constraints

Carena, Balazs and C.W. ‘04

Green: Relic density consistent with WMAP measurements.

Searches for light stops difficult in stop-neutralino coannihilarion region.

LHC will have equal difficulties.

But, LHC can search for stops from gluino decays into stops and tops. Stops may be discovered for gluino masses lower than 900 GeV, even if the stop-neutralino mass difference is as low as 10 GeV! Stop bound states, decaying to photons, may also provide a test.

Kraml, Raklev ‘06, Martin’08
Alternative Channel at the LHC

- When the stops and neutralino mass difference is small, the jets will be soft.
- One can look for the production of stops in association with jets or photons. **Signature: Jets plus missing energy**

Excellent reach until masses of the order of 220 GeV and larger.

Full region consistent with EWBG will be probed by combining the LHC with the Tevatron searches.

M. Carena, A. Freitas, C.W. ‘08
Baryon Number Generation

- Baryon number violating processes out of equilibrium in the broken phase if phase transition is sufficiently strongly first order.

Konstantin, Huber, Schmidt,Prokopec’00--’06
Cirigliano, Profumo, Ramsey-Musolf’05--06

Baryon number is generated by reactions in and around the bubble walls.

Talks by M. Carena and B. Garbrecht
Baryogenesis in Gauge Extensions of the MSSM
Solution to the SUSY Hierarchy Problem

An SU(2) Gauge Extension

- One solution to this problem is to increase the Higgs mass by having it participate in new strong gauge interactions.
- Consistent with data, $m_H$ may increase as high as 350 GeV – radically affecting MSSM Higgs phenomenology.
- We invoke a new SU(2) interaction under which the Higgses and third family are charged.
  \[ SU(2)_1 \times SU(2)_2 \times U(1)_Y \]
- This model has been called “Topflavor”: a separate weak interaction for the 3rd family.
- Because $SU(2)_1$ is asymptotically free, it has no problems with strong coupling at high energies.
- The extra W’s are a hallmark of the model, and can be observed in single top at the LHC.


Z. Sullivan, hep-ph/0306266
How does this work in practice?

If SUSY breaking scale is smaller than gauge symmetry breaking scale, decoupling occurs. Low energy D-terms are just the standard ones.

Therefore, supersymmetry breaking terms larger than the vev that breaks the gauge symmetry should be present. Calling \( < \Sigma > \equiv u I \), to this vev

\[
V = m_\Sigma^2 \Sigma^\dagger \Sigma + \frac{\lambda_1^2}{4} |\Sigma \Sigma|^2 - \frac{B}{2} (\Sigma \Sigma + h.c.) + \ldots
\]

\[
u^2 = (B - m_\Sigma^2)/\lambda_1^2.
\]

\[
\Delta V = \frac{g_1^2}{8} \left( \text{Tr} [\Sigma^\dagger \tau^a \Sigma] + H_u^\dagger \tau^a H_u + H_d^\dagger \tau^a H_d + L^\dagger \tau^a L + Q^\dagger \tau^a Q \right)^2 + \frac{g_2^2}{8} (\text{Tr} [\Sigma^\dagger \tau^a \Sigma] + \ldots)^2
\]

Integrating out the sigma field, we obtain a modification of the low energy D-term

\[
\Delta V_D = \frac{g_2^2}{2} \Delta \sum_a \left( H_u^\dagger \tau^a H_u + H_d^\dagger \tau^a H_d + L_3^\dagger \tau^a L_3 + Q_3^\dagger \tau^a Q_3 \right)^2
\]

\[
\Delta = \frac{1 + \frac{2m_\Sigma^2}{g_2^2 u^2}}{1 + \frac{2m_\Sigma^2}{(g_2^2 + g_1^2) u^2}}.
\]

As mentioned before, if the supersymmetry breaking scale is small, \( \Delta \to 1 \).

Observe that for \( g_1^2 \gg g_2^2 \) and large values of \( m_\Sigma \), \( \Delta \gg 1 \).
Tree-level Higgs Mass modification and Sparticle Spectrum

A. Medina, N. Shah, C.W.‘09

The low energy D-terms control the tree-level Higgs mass

\[ m_h^2 = \frac{1}{2} \left( g^2 \Delta + g_Y^2 \right) v^2 \cos^2 2\beta + \text{loop corrections} \]

So, large values of the Higgs mass may be obtained.

Same D-terms, however, modify the rest of the third generation spectrum:

\[ m_{\tilde{\tau}_L}^2 - m_{\tilde{\nu}_\tau}^2 = \Delta_D \]
\[ m_{\tilde{b}_L}^2 - m_{\tilde{t}_L}^2 = \Delta_D - m_t^2 \]
\[ \Delta_D = \frac{g^2 v^2}{2} \Delta |\cos 2\beta| \]

As well as the non-standard Higgs mass splittings

\[ m_{H^\pm}^2 - m_A^2 = \frac{g^2 \Delta}{2} v^2. \]

Large values of \( \Delta \) can induce large values of the Higgs mass, up to 250 GeV, but also produce large modifications of the spectrum.
Modified spectrum and precision measurements

Large values of the Higgs mass tend to induce large corrections to the T and S parameters

\[
\Delta T = -\frac{3}{8\pi c_W^2} \ln \frac{m_h}{m_{h_{\text{ref}}}}
\]

\[
\Delta S = \frac{1}{6\pi} \ln \frac{m_h}{m_{h_{\text{ref}}}},
\]

It is known, however, that if an extra positive contribution to the T parameter is present, agreement may be restored. The split sparticle spectrum provides such a contribution in a natural way. Calling \( \Delta m_{ud} \) the mass difference between the upper and lower doublet component, each doublet contributes by

\[
\Delta T = \frac{N_c}{12\pi s_W^2 m_W^2} (\Delta m_{ud})^2
\]

\[
= \frac{N_c}{12\pi s_W^2 m_W^2} \frac{(\Delta m_{ud}^2)^2}{(m_u + m_d)^2},
\]
Sparticle Spectrum Consistent with Precision Measurements

Assuming, for instance, that the sleptons are the lightest sfermions in the spectrum, we obtain

Sleptons acquire values that are of the order of the weak scale. Particle physics phenomenology depends on characteristics of SUSY spectrum. Different possibilities were studied in above reference. Observe that when the Higgs is at the current reach of the Tevatron, sneutrinos may be light.
Very recent news:

Tevatron sets the first significant bounds on a heavy Higgs boson

Higgs with SM properties, in mass range 160–170 GeV is excluded at 95% C.L.
Light sneutrinos and Higgs searches

Presence of light sneutrinos may affect Higgs searches, in particular due to their enhanced couplings to Higgs bosons:

\[ \Gamma(h \rightarrow \tilde{\nu}_\tau \tilde{\nu}_\tau) \simeq \frac{(g^2 \Delta + g_Y^2)^2 v^2}{128 \pi m_h} \left( 1 - \frac{4m^2_{\tilde{\nu}_\tau}}{m^2_h} \right)^{1/2} \]

This should be compared with the width into gauge bosons

\[ \Gamma(h \rightarrow VV) \simeq \frac{G_F(|Q_V| + 1)}{\sqrt{2} \ 16 \ \pi} \frac{m^3_h}{1 - \frac{4m^2_V}{m^2_h} + \frac{12m^4_V}{m^4_h}} \left( 1 - \frac{4m^2_V}{m^2_h} \right)^{1/2} \]

For instance, for a light sneutrino of order 70 GeV, and a Higgs mass of about 170 GeV, the gauge boson width is reduced by half.

The Tevatron bounds can be therefore avoided.
Baryon Number Violation

In the SM, baryon and lepton number violation processes are present, induced by the anomalous currents.

However, they don’t induce proton decay. This is due in great part to the weakness of the gauge couplings.

$$S_{\text{inst}} = \frac{2\pi}{\alpha_{\text{ew}}} \quad \Gamma_{\Delta B \neq 0} \propto \exp(-2S_{\text{inst}})$$

On the other hand, lepton and baryon number change in three units, one per generation.

For strong gauge couplings, the situation may be different. Also, in the model at hand, we have strong “weak-like” interactions coupled strongly to only one generation. Baryon and lepton number are violated by only one unit in instanton processes

This is precisely what is needed for proton decay. However, the relevant generation is the third generation. Does this protect the proton from decaying?
Proton Decay

D. Morrissey, T. Tait and C. W. '05

Actually, the proton will decay due to the standard mixing between generations

One can follow the usual instanton computation developed by t’Hooft, to estimate the rate of proton decay under these considerations

A typical diagram associated with this instanton induced process is:

\[ \mathcal{O}_{\text{eff}} = - \left( \frac{24\pi^2}{3V_g} \right) V_f I_f L_f \varepsilon^{abc} \left[ (u^a_L \cdot s^b_L)(d^c_L \cdot \nu^\tau_L) + (u^a_L \cdot d^b_L)(s^c_L \cdot \nu^\tau_L) \right], \quad V_f = \left( \frac{g}{\sqrt{2}} \right)^4 V_{ts} V_{ub} V_{td} \]

\[ I_f = \frac{C}{g_1^8} e^{-8\pi^2/g_1^2} \left( \frac{\mu}{V} \right)^{b_0} \left( 4\pi^2 \right)^{1-b_0/2} 2^{b_0/2} \Gamma(1 + b_0/2) \frac{1}{V^2}, \quad \nu \simeq \sqrt{2}u \]
For large values of the gauge coupling, sizeable effects on proton lifetime
Bound on the value of the gauge coupling may be obtained.
First low energy bound of this kind I know of.
Higgs mass bound is only slightly affected. Values close to 250 GeV can still
be obtained for the largest values of $g_1$. 
Baryogenesis from a phase transition requires the phase transition be strongly first order. A major obstacle to EW baryogenesis is the fact that in the SM the EW phase transition is predicted to be second order.

- We explore an SU(2) gauge extension of the SM, and use the strongly coupled instantons of the extended interactions to distribute lepton number unevenly through the three families at the time the theory transitions to the SM gauge symmetry.

- We find parameters of the extension leading to a first order phase transition

Reason: Large gauge couplings
**Baryogenesis from an Earlier Phase Transition**

- We solve the coupled differential equations describing the particle number densities near the surface of the bubble.
- An uneven distribution of lepton number is produced in each of the three families, because the SU(2)$_1$ sphalerons only couple to the third family.

We proceeded in a similar way as the computations at the weak phase transition, but at the one leading to

\[
SU(2)_1 \times SU(2)_2 \rightarrow SU(2)_w
\]

Diffusion equations were solved. Main difference: Sphaleron rate large, and these transitions were incorporated into equations.
Diffusion Equations

Following Nelson and Huet,

\[ Q_{1L} = Q_{2L} = -2U_R = -2D_R = -2S_R = -2C_R = -2b. \]

\[ Q \equiv t_L + b_L \]

\[ v_w Q' - D_Q Q'' = -\Gamma_y \left[ \frac{Q}{k_Q} - \frac{h}{k_h} - \frac{t}{k_t} \right] - 6\Gamma_{QCD} \left[ 2 \frac{Q}{k_Q} - \frac{t}{k_t} - 9 \frac{b}{k_b} \right] \]

\[ -6\Gamma_1 \left[ 3 \frac{Q}{k_Q} + \frac{L_3}{k_L} \right], \]

\[ v_w t' - D_Q t'' = -\Gamma_y \left[ -\frac{Q}{k_Q} + \frac{h}{k_h} + \frac{t}{k_t} \right] + 3\Gamma_{QCD} \left[ 2 \frac{Q}{k_Q} - \frac{t}{k_t} - 9 \frac{b}{k_b} \right], \]

\[ v_w h' - D_h h'' = -\Gamma_y \left[ -\frac{Q}{k_Q} + \frac{h}{k_h} + \frac{t}{k_t} \right] + \gamma_h, \]

\[ v_w b' - D_Q b'' = 3\Gamma_{QCD} \left[ 2 \frac{Q}{k_Q} - \frac{t}{k_t} - 9 \frac{b}{k_b} \right], \]

\[ v_w L_3' - D_L L_3'' = -2\Gamma_1 \left[ 3 \frac{Q}{k_Q} + \frac{L_3}{k_L} \right], \]

\[ k_Q = 6; \quad k_L = 2; \quad k_t = k_b = 3; \quad k_h = 8. \]
Sources

The sources here come from CP-Violating couplings in the Higgs sector. The phase of the Higgs vev carries a phase and the fermion number induced is proportional to variations of such a phase. For that purpose, a more general potential than the one introduced before was considered.

\[
V_\Sigma = m^2 |\Sigma|^2 + \lambda |(\Sigma\Sigma)|^2 + \lambda' |\Sigma|^4 + \left( -\frac{1}{2} D(\Sigma\Sigma) + \tilde{\lambda}(\Sigma\Sigma)|\Sigma|^2 + h.c. \right),
\]

\[
u_0^2 = \frac{De^{-2i\theta_0} + D^*e^{-2i\theta_0} - m^2}{\lambda + \lambda' + \tilde{\lambda}e^{2i\theta_0} + \tilde{\lambda}e^{-2i\theta_0}}
\]

\[
\theta_0 = -\frac{1}{4} \text{acos} \text{ Re} \left[ \frac{-2D^* + \tilde{\lambda}^*\nu_0^2}{-2D + \tilde{\lambda}\nu_0^2} \right].
\]

\[
\tilde{\gamma}_{H_d} = \left( \frac{\Delta\theta}{L_w}v_w \right) u^2(x) \left\{ |c_1\mu|^2 - |c_2\mu'|^2 \right\} \mathcal{I}_{H_dH_d'} + \left\{ |A_2|^2 - |A_2'|^2 \right\} \mathcal{I}_{H_dH_u'}
\]

\( \Delta\theta \) is the variation of the phase from inside the bubble of true vacuum to the unbroken phase.
Example: before consider a fast sphaleron transition rate. Is this consistent with the proton lifetime constraints?

![Proton Stability](Shu,Tait,C.W.‘07)
Baryogenesis

At the phase transition, a baryon and lepton number of the third generation is obtained.

For large gauge couplings, this amount can be large. However, it is diluted by low energy weak sphalerons, that tend to dilute the obtained baryon number. But they preserve an asymmetry in the three generation lepton numbers:

\[ \Delta (B/3 - L_i) = 0 \]

Final baryon number is obtained by effects of this asymmetry during the second order electroweak phase transition. This was studied by Dreiner and Ross. They showed that the tau mass effects are enough to induce a final asymmetry in the baryon number. Assuming the sphalerons are in equilibrium during the phase transition,

\[
B = \begin{cases} 
\frac{4}{13} (B - L) & B - L \neq 0 \\
-\frac{4}{13\pi^2} \sum_{i=1}^{N} \Delta_i \frac{m_{i}^2}{T^2} & B - L = 0
\end{cases}
\]

\[ \Delta_i \equiv L_i - \frac{1}{3} B \]
Baryogenesis from an early Phase Transition

- At the early phase transition, an asymmetry of order $10^{-4}$ may be obtained.

- This early result is, however, diluted by standard sphaleron effects.

- For a standard transition temperature of order of 100 GeV, the tau mass effects are approximately equal to $10^{-6}$, leading to a final result for the baryon asymmetry:

$$\frac{n_B}{n_S} \sim 10^{-10}$$

- Consistency with observations therefore may be obtained within this framework.
Conclusions

- Electroweak Baryogenesis provides a very attractive framework for the obtention of the observed baryon asymmetry.
- Supersymmetry provides a natural realization of this scenario, for either light stops or (not discussed) light singlets.
- We explored the alternative possibility of generating the baryon number from an early phase transition, associated with strong interactions in the weak sector.
- This scenario is motivated by a solution to the hierarchy problem and/or to explain the large differences in quark masses of different generations. Splitting between sparticles can compensate the precision electroweak corrections associated with a heavy Higgs.
- Proton decay may be induced in this models, for sufficiently large values of the strong gauge couplings.
- Baryogenesis may occur, in spite of standard sphaleron dilution, and for values of the gauge couplings consistent with proton stability.
Constraints from non-universal bottom coupling

This model