Electroweak Baryogenesis in the MSSM

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* [hep-ph/0003180,/0001002,/9912516,/9907422]; # to appear
I. Introduction

- Observable Universe presents a clear asymmetry between Matter and Anti-Matter

\[ N_B \gg N_{\bar{B}} \]

- Cosmic Rays:

\[ N_{\bar{P}} \sim 10^{-4} N_P \]

- Consistent with secondary emission of \( \bar{P} \)

- No \( \gamma \)-ray sources in cluster of galaxies

- What is the origin of the baryon asymmetry?

- Sakharov Requirements
  - Baryon Number Violation
    Any Baryon Number conserving process
    \[ N_B = N_{\bar{B}} \]
  - C and CP Violation \( (N_B)_{L,R} \neq (N_{\bar{B}})_{L,R} \)
  - Departure from Thermal Equilibrium. In thermal equilibrium \( N_B = N_{\bar{B}} \)
• In S.M. Baryon Number violation mediated by Non-Trivial Topological Configurations (Instantons)
\[ \Delta B = \Delta L \]

• Rate exponentially suppressed at \( T = 0 \)
\[ \Gamma(T = 0) \simeq \exp(-2\pi/\alpha_W) \simeq 10^{-173} \]

• At finite Temperature, instead,
\[ \Gamma \simeq \beta_0 \cdot T \cdot \exp(-E_{sp}(T)/T) \]
with
\[ E_{sp} \simeq 8\pi v(T)/g, \]
and \( v(T) \) being the v.e.v. of the Higgs field.

• If \( n_B = 0 \) for \( T > T_c \), independently of the source of baryon asymmetry
\[
\frac{n_B}{s} = \left( \frac{n_B}{s} \right)_{T_c} \exp \left[ -\frac{10^{16}}{T_c[GeV]} \exp \left( -\frac{E_{sp}(T_c)}{T_c} \right) \right]
\]

• Therefore, for the preservation of the generated \( n_B \),
\[
\frac{v(T_c)}{T_c} \geq 1
\]
Finite Temperature Effective Potential

\[ V(\phi, T) = V_0(\phi) + V_1(\phi, 0) + \Delta V_1(\phi, T) \]

where the finite \( T \) contribution is given by

\[ \Delta V_1(\phi, T) = \sum_{i=b,f} \left[ \frac{n_i m_i^2(\phi) T^2}{48} - \frac{\eta_i m_i^4(\phi)}{64 \pi^2} \log \left( \frac{m_i^2(\phi)}{T^2} \right) \right] \]

\[ - \sum_b m_b^3(\phi) T \]

where \( \eta_i = n_i (-1)^{2S} \) and \( m_i(\phi) \leq 2T \). For large values of the particle masses, \( m(\phi) \gg 2T \), the finite \( T \)-contributions are exponentially suppressed.

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

\[ \frac{v(T_c)}{T_c} \simeq \frac{E_B}{\lambda(T_c)} \]

- In the SM, \( E_B \simeq \sqrt{2}(2 M_W^3 + M_Z^3)/(3 \pi v^3) \), while \( m_H^2 \simeq 2 \lambda v^2 \). The condition of preservation of the generated baryon number

\[ \frac{v(T_c)}{T_c} \geq 1 \quad \text{implies} \quad m_H \leq 40 \text{GeV}, \]

- Electroweak Baryogenesis in the SM is ruled out.
EW Baryogenesis implies presence of new light boson
degrees of freedom, with relevant couplings to the Higgs
field. The Higgs boson should remain light.

\[ \frac{\phi(T_c)}{T_c} \simeq \frac{E_B}{\lambda(T_c)} \simeq \sum_b n_b g_{bH}^3 \frac{v^2}{m_H^2} \]

- Supersymmetry provides a natural framework for
  this scenario. Relevant Light Bosons:
  Supersymmetric Partners of the top quark (stops).
  Espinosa, Quiros, Zwirner ’93; Carena, Quiros, Wagner ’96

- Each stop has six degrees of freedom, and
couplings of order one to the Higgs field.

\[ E_B \simeq \frac{g_W^3}{4\pi} + \frac{h_t^3}{2\pi} \simeq 8 \, E_{SM} \]

and hence, Higgs masses up to 110–115 GeV can
be accommodated within the SUSY framework.

- In the MSSM, there are two Higgs doublets \( H_1, H_2 \)
  and the left-handed and right-handed stop mix

\[
M_t^2 = \begin{pmatrix}
  m_Q^2 + m_t^2 + D_L & m_t X_t \\
  m_t X_t^* & m_U^2 + m_t^2 + D_R
\end{pmatrix}
\]

where \( m_t = h_t H_2, \quad X_t = A_t - \mu^*/\tan\beta \) and
\( \tan\beta = H_2/H_1. \)
• For $m_Q \gg m_U, |X_t|$, and either for large values of the heavy Higgs doublet mass, $m_A \gg M_Z$, or for large $\tan \beta$, for most values of $m_A$, there is one Higgs boson $h$ with mass

$$m_h^2 \sim M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{8\pi^2 v^2} \left[ \log \left( \frac{m_{t_1}^2 m_{t_2}^2}{m_t^4} \right) \right]$$

$$+ 2 \frac{|X_t|^2}{m_Q^2} \log \left( \frac{m_{t_1}^2}{m_{t_2}^2} \right) + \mathcal{O} \left( \frac{|X_t|^4}{m_Q^4} \right)$$

• For $m_{\tilde{t}_1} \sim m_Q \sim 1$ TeV, $m_{\tilde{t}_2} \sim m_t$ and $|X_t| \leq 0.6 m_Q \quad [g_{tH}^2 = h_t^2 (1 - \frac{|X_t|^2}{m_Q^2})]$,

$$m_h \leq 110 \text{ GeV}$$

The largest values of the Higgs boson mass are obtained for values of $\tan \beta \geq 5$.

In order to make a precise analysis, we should take into account

– Two loop corrections at zero and finite $T$. Finite two-loop corrections, ignored here, can vary $m_h$ by a few GeV

M. Carena, H. Haber, S. Heinemeyer, G. Weiglein and C. Wagner '00

– Study of vacuum stability at zero and finite $T$. 
Carena, Quiros, Wagner '98

- $X_t (\tan \beta)$ grows to the left (top) of figure
- Bound $m_h \lesssim 115$ GeV obtained for $m_Q = 2$–3 TeV.
- Metastability possible if lifetime of metastable vacuum larger than age of the Universe.
The LEP Collider at CERN has reported a bound on the Standard Model Higgs mass of \( m_H \gtrsim 112 \text{ GeV} \) at 95 \% C.L. A 2.6 \( \sigma \) excess of events consistent with a SM-like Higgs boson, with mass of about 113–115 GeV has also been reported. Great news!

What would happen if bound increases to 115 GeV?

- Bound is only valid for a SM-like Higgs. In the MSSM, \( m_h \) behaves as a SM Higgs only for \( m_A \gg M_Z \).
- Low values of \( m_A \) decrease \( v(T_c)/T_c \) for small values of \( \tan \beta \).
- Low values of \( m_A \) decrease \( m_h \) for small values of \( \tan \beta \), without affecting the Higgs couplings in a significant way.
- The scenario of EW Baryogenesis in the MSSM can only survive if
  - Value of \( \tan \beta \) is large, \( \tan \beta \geq 5 \) and either
    * The excess of events observed at LEP correspond to a SM-like Higgs boson of mass in the range 110–115 GeV, or
    * The value of \( m_A \simeq 80–200 \text{ GeV} \).
If all Higgs bosons are light, these particles may escape detection because either

- Their couplings to the gauge bosons are suppressed and/or
- Their couplings to b-quarks are suppressed

In the presence of CP-violating phases of the SUSY parameters, the three neutral Higgs boson mix and their couplings to the $Z$-boson fulfill

$$\sum_i g_{H_i ZZ}^2 = 1, \quad g_{H_i ZZ} = \epsilon_{ijk} g_{H_j H_k Z}$$

M. Carena, J. Ellis, A. Pilaftsis and C. Wagner '99, '00

Moreover, the couplings of the Higgs bosons to $b$-quarks may be strongly affected by radiative corrections.
Higgs Properties vs. $\arg(A_t \mu)$

(a) $M_{H^+} = 200 \text{ GeV}, \tan \beta = 25$

$\mu = -1 \text{ TeV}, \ |A_t| = 0.35 \text{ TeV}, \ |A_b| = 0.5 \text{ TeV}$

$m(\text{gluino}) = 0.5 \text{ TeV}, \ m(\text{Wino}) = m(\text{Bino}) = 0.2 \text{ TeV}$

(b) $g_{H_1bb}^S + g_{H_1bb}^P$

$\arg (A_t) = \arg (A_b) \ [\deg]$

M. Carena, J. Ellis, A. Pilaftsis and C.W. ’00

- Dashed- and solid-lines correspond to gluino mass phase $\arg(M_{\tilde{g}}) = 0$ and $\pi$, respectively.
Suppression of coupling of Higgs to $b$-quarks and Tevatron Reach

$m_{stop} = 200$ GeV, $A_t = 0.65$ TeV, $\mu = -1$ TeV, W/Zh→bb

M. Carena, S. Mrenna and C.W. '99
Computation of Baryon Asymmetry
M. Carena, M. Quiros, M. Seco and C.W., to appear

- We derived diffusion equations for the chiral charges induced by the passage of the wall of the expanding true-vacuum bubbles.

- We developed a method to compute the CP-Violating sources of baryon asymmetry in a derivative expansion, to all orders in Higgs mass insertions.

- Sources are dominated by chargino-neutralino contributions, and proportional to \( \text{arg} (M_2 \mu) \), where \( M_2 \) and \( \mu \) are the masses of the supersymmetric partners of the gauge and the Higgs boson fields, respectively.

- Results depend slightly on the wall parameters and strongly on \( M_2, |\mu| \) and \( m_A \). The results also depend linearly on \( \text{arg} (M_2 \mu) \).

- Results generalize the previously found ones M. Carena, M. Quiros, A. Riotto, I. Vilja and C.W. '98
Baryon Asymmetry $\eta$ for $\arg(M_2 \mu) = \pi/2$

- We set $v(T_c)/T_c \geq 1; \tan \beta = 5-20, m_h \sim 105-115$ GeV for $m_Q = 1-3$ TeV.

  Gaugino masses of order of the weak scale. Larger $|\mu|$ suppresses $n_B$: $n_B \sim n_B^0 \left| \frac{\mu^0}{\mu} \right|^2$. 

Conclusions

- The scenario of Electroweak Baryogenesis can be realized in the MSSM if
  \[ m_h \lesssim 110\text{–}115\text{ GeV}, \quad m_{\tilde{t}} < m_t \]
- Present LEP bounds imply that if this scenario is realized if
  - Large values of \( \tan \beta > 5 \) and
  - Large values of \( m_Q = 1\text{–}3\text{ TeV} \).
  Small values of \( m_{H^+} < 300\text{ GeV} \) preferred if no Higgs at LEP.
- Computation of Baryon asymmetry: Acceptable values of \( \eta/\eta_{BBN} \) for \( \arg(M_2\mu) \geq 0.01 \).
- Values of the gaugino and Higgsino masses of order of the weak scale are preferred.
- If Higgs bosons are not seen at LEP due to kinematic reasons or a suppression of its coupling to \( b \)-quarks, they should be seen at either a high luminosity Tevatron or at the LHC (\( H \rightarrow \gamma\gamma \)).
- Light stops, and probably light charginos should also be seen at at least one of these colliders.