Supersymmetry, Baryogenesis and New Fermions at the TeV scale

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Based on following recent works:

M. Carena, A. Megevand, M. Quiros and C.W., hep-ph/0410352

Coral Gables Conference, Miami, December 15, 2004
Celebrating 40 years of quarks, cosmology and CP-violation
The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Anti-matter is only seen in cosmic rays and particle physics accelerators.
- The rate observed in cosmic rays consistent with secondary emission of antiprotons

\[ \frac{n_{\bar{P}}}{n_P} \approx 10^{-4} \]

- All observations consistent with a matter dominated Universe (Cohen, Glashow, de Rujula '97)
Baryon-Antibaryon asymmetry

- Baryon Number abundance is only a tiny fraction of other relativistic species

\[ \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10} \]

- But in early universe baryons, antibaryons and photons were equally abundant. What explains the above ratio?

- Explanation: Baryons and Antibaryons annihilated very efficiently. No net baryon number if B would be conserved at all times.

- What generated the small observed baryon-antibaryon asymmetry?
Baryon Number Generation at the Weak Scale:

Electroweak Baryogenesis
Electroweak Baryogenesis in the Standard Model

- SM fulfills the Sakharov conditions:
  - Baryon number violation: Anomalous Processes
  - CP violation: Quark CKM mixing
  - Non-equilibrium: Possible at the electroweak phase transition.
Baryon Number Violation at finite $T$

- At zero $T$, baryon number violating processes highly suppressed.

- At finite $T$, only Boltzmann suppression.

$$
\Gamma(\Delta B \neq 0) \propto A T \exp \left( - \frac{E_{\text{sph}}}{T} \right) \quad E_{\text{sph}} \propto \frac{8\pi v}{g}
$$

- Baryon Number violating processes unsuppressed at high temperatures, but suppressed at temperatures below the electroweak phase transition.

- Anomalous processes violate both baryon and lepton number, but preserve $B - L$. Relevant for the explanation of the Universe baryon asymmetry.
Baryon Number Generation

- From weak scale mass particle decay: Difficult, since non-equilibrium condition is satisfied for small couplings, for which CP-violating effects become small (example: resonant leptogenesis).

- Baryon number violating processes out of equilibrium in the broken phase if phase transition is sufficiently strongly first order: Baryon asymmetry generation at the electroweak phase transition (Electroweak Baryogenesis).

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

If Baryon number generated at the electroweak phase transition,

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

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:

\[
\frac{v(T_c)}{T_c} > 1
\]
Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order Phase Transition
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

\[ \Delta V_1(\phi, T) = \sum_{i=b,f} \left[ \frac{n_i m_i^2(\phi) T^2}{48} - \frac{\eta_i m_i^4(\phi)}{64\pi^2} \log \left( \frac{m_i^2(\phi)}{T^2} \right) \right] 
- \sum_b \frac{m_b^3(\phi) T}{12\pi} \]

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.

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

\[ \frac{\nu(T_c)}{T_c} \sim \frac{E_B}{\lambda(T_c)} \]
Finite Temperature Higgs Potential

\[ V(T) = D(T^2 - T^2_0)\phi^2 - E_B T \phi^3 + \frac{\lambda(T)}{2} \phi^4 \]

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,

\[ \frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40 \text{GeV}. \]
If the Higgs Boson is created, it will decay rapidly into other particles.

At LEP energies mainly into pairs of $b$ quarks.

One detects the decay products of the Higgs and the $Z$ bosons.

LEP Run is over:

- No Higgs seen with a mass below 114 GeV.
- But, tantalizing hint of a Higgs with mass about 115 -- 116 GeV (just at the edge of LEP reach).

**Electroweak Baryogenesis in the SM is ruled out.**
Electroweak Baryogenesis

and

New Physics at the Weak Scale
Supersymmetry

**fermions**

- Electron
- Quark

**bosons**

- Photon
- Gluon
- W
- Z
- Higgs

**Known Particles**

- Quark
- Electron

**Theoretical Plane Dividing Two Realms**

- Squark
- Selectron

**Their “Sparticle” Partners**

- Photino
- Zino
- Neutral Higgsino

- Charged Wino
- Charged Higgsino

*Photino, Zino and Neutral Higgsino: Neutralinos*

*Charged Wino, charged Higgsino: Charginos*

Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling).
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.

- 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

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

- Since

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

\textit{Higgs masses up to 120 GeV may be accommodated}
MSSM: Limits on the Stop and Higgs Masses to preserve the baryon asymmetry

Sufficiently strong first order phase transition to preserve generated baryon asymmetry:

- Higgs masses up to 120 GeV
- The lightest stop must have a mass below the top quark mass.

M. Carena, M. Quiros, C.W. ‘98

![Graph showing the limits on stop and Higgs masses with moderate values of tan β, tan β ≥ 5, preferred in order to raise the Higgs boson mass.](image)
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: 3 sigma evidence with about 4 $fb^{-1}$
   
   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 $fb^{-1}$ of data

   $$qq \rightarrow qqV^*V^* \rightarrow qqh$$
   
   with h $\rightarrow \tau^+\tau^-$
Main signature:

2 or more jets plus missing energy

2 or more Jets with $E_T > 15$ GeV
Missing $E_T > 35$ GeV

Demina, Lykken, Matchev, Nomerotsky ‘99
Stop-Neutralino Mass Difference: Information from the Cosmos

M. Carena, C. Balazs, C.W., PRD70:015007, 2004

- If the neutralino provides the observed dark matter relic density, then it must be stable and lighter than the light stop.

- Relic density is inversely proportional to the neutralino annihilation cross section.

If only stops, charginos and neutralinos are light, there are three main annihilation channels:

1. Coannihilation of neutralino with light stop or charginos: Small mass differences.
2. s-channel annihilation via Z or light CP-even Higgs boson
3. s-channel annihilation via heavy CP-even Higgs boson and CP-odd Higgs boson
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. Searches become easier at a Linear Collider!
Baryon Asymmetry

- Here the Wino mass has been fixed to 200 GeV, while the phase of the parameter mu has been set to its maximal value. Necessary phase given by the inverse of the displayed ratio. Baryon asymmetry linearly decreases for large $\tan \beta$

Balazs, Carena, Menon, Morrissey, C.W. ’04

\begin{equation}
\tan \beta = 7
\end{equation}
**Electron electric dipole moment**

- Assuming that sfermions are sufficiently heavy, dominant contribution comes from two-loop effects, which depend on the same phases necessary to generate the baryon asymmetry.

- Chargino mass parameters scanned over their allowed values. The electric dipole moment is constrained to be smaller than

  \[ d_e < 1.6 \times 10^{-27} \text{ e cm} \]

Balazs, Carena, Menon, Morrissey, C.W.’04
Allowed region of parameters

- After constrains from the electric dipole moment, the baryon asymmetry and the dark matter constraints are included, there is a limited region of $\tan \beta$ consistent with electroweak baryogenesis.

Balazs, Carena, Menon, Morrissey, C.W.'04
Direct Dark Matter Detection

- Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei
Electroweak Baryogenesis and New Fermions at the TeV scale

M. Carena, A. Megevand and M. Quiros, hep-ph/0410352
Fermions Strongly Coupled to the Higgs Boson

- The finite T corrections to the effective potential presented before were computed in high temperature expansion, valid for masses smaller than T.

- When finite T expansion not valid, one should keep the whole contribution:

\[
\mathcal{F}(\phi, T) = \mathcal{F}_{\text{SM}}(\phi, T) \pm \sum_i g_i V_i(m_i(\phi)) + T^4 \sum_i g_i I_{\mp}[m_i(\phi)/T]/2\pi^2
\]

with

\[
I_{\mp}(x) = \pm \int_0^{\infty} dy y^2 \log \left( 1 \mp e^{-\sqrt{y^2+x^2}} \right)
\]

+ : Fermions, - : Bosons

for \( m^2(\phi) = h^2 \phi^2 + \mu^2 \),

\[
V_i(m_i(\phi)) = \frac{1}{64\pi^2} \left[ m_i^4(\phi) \log \left( \frac{m_i^2(\phi)}{m_i^2(\nu)} \right) - 1.5 m_i^4(\phi) + 2 m_i^2(\phi) m_i^2(\nu) \right]
\]

- Particles with masses much larger than the temperature give no finite T contribution to the free energy, while for \( m = 0 \),

\[
I_{\pm}(0) = - \frac{7\pi^4}{360}, \quad I_{-}(0) = - \frac{\pi^4}{45}
\]
Potential Stability

- Just like in the case of the top quark in the Standard Model, heavy fermions, strongly coupled to the Higgs induce instabilities (Higgs dependent quartic coupling becomes negative).

- We shall assume the presence of stabilizing bosonic fields, and we shall take for them the largest explicit mass consistent with vacuum stability (finite T effects of bosons minimized).

- We shall further assume no CP-violating sources associated with the stabilizing fields.
- What if a particle, strongly coupled to the Higgs has a mass much larger than $T$ in the broken phase?

- Its contribution to the effective potential for Higgs fields close to the minimum would vanish, while in the symmetric phase it still would give a contribution to the free-energy.

- The critical temperature would then be modified by the presence of this particle. If the dispersion relation is linear in Higgs field,

$$V_{\text{SM}}(\phi(T_c, T_c) = -\frac{\pi^2}{90} \Delta g_s T_c^4$$

- This happens at a lower temperature and larger values of the Higgs v.e.v. The condition of baryon asymmetry preservation is given by

$$\left(\frac{m_H}{v}\right)^2 < 4E + 4\pi^2 \Delta g_s / 45.$$  

- Only a few degrees of freedom need to satisfy this condition for Higgs boson masses above the experimental bound.
Decoupling of particles only possible for large Yukawa couplings.

In general, number of degrees of freedom necessary to make the phase transition strongly first order would depend on dispersion relation. For fermions with

$$m^2(\phi) = h^2 \phi^2 + \mu^2, \quad \langle \phi(T = 0) \rangle = 246 \text{ GeV}$$
Interesting Example: Model with Charginos and Neutralinos

\[
\mathcal{L} = H^\dagger \left( h_2 \sigma_a \tilde{W}^a + h'_2 \tilde{B} \right) \tilde{H}_2 + H^T \epsilon \left( -h_1 \sigma_a \tilde{W}^a + h'_1 \tilde{B} \right) \tilde{H}_1 \\
+ \frac{M_2}{2} \tilde{W}^a \tilde{W}^a + \frac{M_1}{2} \tilde{B} \tilde{B} + \mu \tilde{H}_2^T \epsilon \tilde{H}_1 + h.c.
\]

- The same low energy Lagrangian as for gauginos and Higgsinos as in the supersymmetric case, but with arbitrary Yukawa couplings. In the particular case of the MSSM, \( h_2 = g \sin \beta / \sqrt{2}, h_1 = g \cos \beta / \sqrt{2} \).

- In the MSSM, the couplings are too weak to influence the electroweak phase transition. Larger values of these couplings necessary. Let’s call

\[
h_+ = \frac{h_1 + h_2}{2} \quad \quad h_- = \frac{h_1 - h_2}{2}
\]
Phase Transition strength

- Particular case, \( h' = 0 \), 12 degrees of freedom (two Dirac particles and two Majorana, with similar masses coupled to the Higgs)

\[
\mu = - M_2, \quad M_2 = M, \quad h_+ = 2, \quad h_- = 0
\]

\[ m_H = 120 \text{ GeV} \]
Preservation of Baryon Number

- Phase transition strength diminishes for large values of the Higgs mass. Here both Yukawas take values equal to $h$, and $M$ is as before.

\[ \mu = -M_2, \quad M_2 = M \]
Dark Matter

- In the limit under analysis, the Bino decoupled and one of the neutralinos decouple from the Higgs boson. It is a pure Higgsino state with mass $|\mu|$.

- Relevant cross section is induced by s-channel Z diagram. Relevant coupling vanish for equal values of the Yukawa couplings:

$$\tilde{\chi} \approx \frac{h_1}{\sqrt{h^2_1 + h^2_2}} \tilde{H}_2 + \frac{h_2}{\sqrt{h^2_1 + h^2_2}} \tilde{H}_1$$

$$g_{\tilde{\chi}Z} \propto \frac{h^2_1 - h^2_2}{h^2_1 + h^2_2}$$

Dark matter imposes an interesting correlation between its mass and the difference of Yukawa couplings.

$\Omega h^2 \approx 0.11$

$h_+ = 1$

$h_+ = 2$
Precision Measurements

- In spite of heavy fermions, $S$ parameter remains small
- The $T$ parameter, instead, increases with the value of the difference of the Yukawa couplings.
Allowed values of $S$ and $T$ for different values of the Higgs mass

\[
\Delta S = \frac{1}{12\pi} \log \left( \frac{m_h^2}{m_{h_{\text{ref}}}^2} \right) \quad \Delta T = -\frac{3}{16\pi c_W^2} \log \left( \frac{m_h^2}{m_{h_{\text{ref}}}^2} \right)
\]

- Precision measurement and dark matter are consistent with experimental values, for LSP masses between 45 and 70 GeV and small values of $h$. 
Baryon asymmetry generation

- Ratio of the baryon asymmetry to the one determined by WMAP, for maximal values of the CP-violating phase, for equal values of the Yukawa couplings, for $M = 100$ GeV.

From below, results are shown for the case of no light sfermions, a 500 GeV squark and a light squark.

- Phases of order one necessary to generate baryon asymmetry.
Electron electric dipole moment

- For heavy sfermions, e.d.m. induced at two loops

![Diagram]

\[
\begin{align*}
\sin(\phi) &= 1. \\
h_1 &= h_2 \\
m_H &= 120 \text{ GeV} \\
h_+ &= 2 \\
m_H &= 200 \text{ GeV}
\end{align*}
\]

Present bound, of order 1.6, does not constrain the model. But the expected improvement of bound by three to five orders of magnitude, sufficient to test model, even for \( h = 2 \).
Large Yukawa Couplings in low energy SUSY

- Large Yukawa couplings may be obtained in strongly coupled SUSY theories.
  Batra, Delgado, Kaplan, Tait ’04

- Take the recently proposed theory, based on $SU(3)_C \otimes SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y$

- First and second generations transform under the first $SU(2)$. Third generation and Higgs fields under the second $SU(2)$, which becomes strongly coupled at the weak scale.

- It has a bifundamental, whose v.e.v., which we’ll call $u$, breaks the two $SU(2)$’s to the diagonal one, and a singlet field, with superpotential

$$W = M_{\Sigma \Sigma \Sigma} + \lambda SL H_2 + M_S S^2$$
Supersymmetry Breaking

- Let’s assume that the gaugino masses of the two SU(2) groups fulfill the following relation

\[ M_1, M_\Sigma \gg g_2 u, \quad M_2 \ll g_2 u \]

- Under those conditions, the weakly coupled SU(2) gaugino as well as the bifundamental Higgsino decouple from the low energy theory.

- Low energy Wino is strongly coupled to Higgs and Higgsinos, and acquires a mass

\[ M_2 \simeq M_2 - \frac{g_2^2 u^2}{M_\Sigma} \]
Effective Yukawa Couplings

- More precisely, low energy wino mixes mostly with the bifundamental Higgsino with mixing angle,
  \[
  \sin \theta_{\Sigma} \simeq \frac{g_2 u}{M_\Sigma}.
  \]

- The Yukawa couplings are then given by
  \[
  h_1 \simeq \frac{g_2 \cos \theta_{\Sigma} \cos \beta}{\sqrt{2}}
  \]
  \[
  h_2 \simeq \frac{g_2 \cos \theta_{\Sigma} \sin \beta}{\sqrt{2}}
  \]

- While the Higgs boson mass may be much larger than in the MSSM
  \[
  m_H^2 \simeq \frac{\lambda^2 v^2}{8} \sin^2 2\beta + \text{(loop effects)} + \text{(D-term)}
  \]

- The strong interactions keep \( \lambda \) asymptotically free!
Conclusions

- **Electroweak Baryogenesis in the MSSM** demands a light Higgs, with mass lower than 120 GeV and a stop lighter than the top-quark.

- **Dark Matter**: Even lighter neutralinos. If coannihilation channel relevant, searches for stops at hadron colliders difficult.

- **To be tested** by electron e.d.m. experiments, Tevatron, LHC and LC.

- **nMSSM** provides an attractive phenomenological scenario.

- New Scenario with **TeV fermions, strongly coupled to the Higgs**.

- Model with **charginos and neutralinos**, consistent with baryogenesis, dark matter and precision electroweak data. **To be tested** soon by LHC and e.d.m. experiments.