Electroweak Baryogenesis in the MSSM

C.E.M. Wagner

Argonne National Laboratory

– Research* done in collaboration with M. Carena#, J. Ellis, H. Haber, S. Heinemeyer, W. Hollik, S. Mrenna, J. Moreno#, A. Pilaftsis, M. Quiros#, M. Seco# and G. Weiglein

Outline:

1. Introduction
2. Higgs Boson and Stop Masses and Electroweak Baryogenesis
3. Higgs Physics and CP-Violation
4. CP-violating currents and the Baryon Asymmetry
5. Conclusions

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I. Introduction

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

$$N_B \gg N_{\bar{B}}$$

- Cosmic Rays:

$$N_{\bar{P}} \simeq 10^{-4} \, N_P$$

- Consistent with secondary emmision of $\bar{P}$
- No γ-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 Temperaure, instead,
  $\Gamma \simeq \beta_0 \, T \, \exp(-E_{sph}(T)/T)$
  with
  $E_{sph} \simeq 8\pi v(T)/g$,
  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

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

- 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

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

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.

$$\begin{aligned}V(T) &= D(T^2 - T_0^2)\phi^2 - E_B T\phi^3 + \frac{\lambda(T)}{2}\phi^4 \\ \frac{v(T_c)}{T_c} &\simeq E_B/\lambda(T_c)\end{aligned}$$

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

$$\frac{v(T_c)}{T_c} \geq 1 \qquad \text{implies} \qquad m_H \leq 40\text{GeV},$$

- 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 accomodated 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

$$\mathcal{M}_{\tilde{t}}^2 = \begin{bmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t^* & m_U^2 + m_t^2 + D_R \end{bmatrix}$$

  where $m_t = h_t H_2$, $X_t = A_t - \mu^* / \tan\beta$ 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

$$
\begin{aligned}
m_h^2 &\simeq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{8\pi^2 v^2}\left[\log\left(\frac{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}{m_t^4}\right)\right. \\
&+ \left. 2\frac{|X_t|^2}{m_Q^2}\log\left(\frac{m_{\tilde{t}_1}^2}{m_{\tilde{t}_2}^2}\right) + \mathcal{O}\left(\frac{|X_t|^4}{m_Q^4}\right)\right]
\end{aligned}
$$

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

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

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

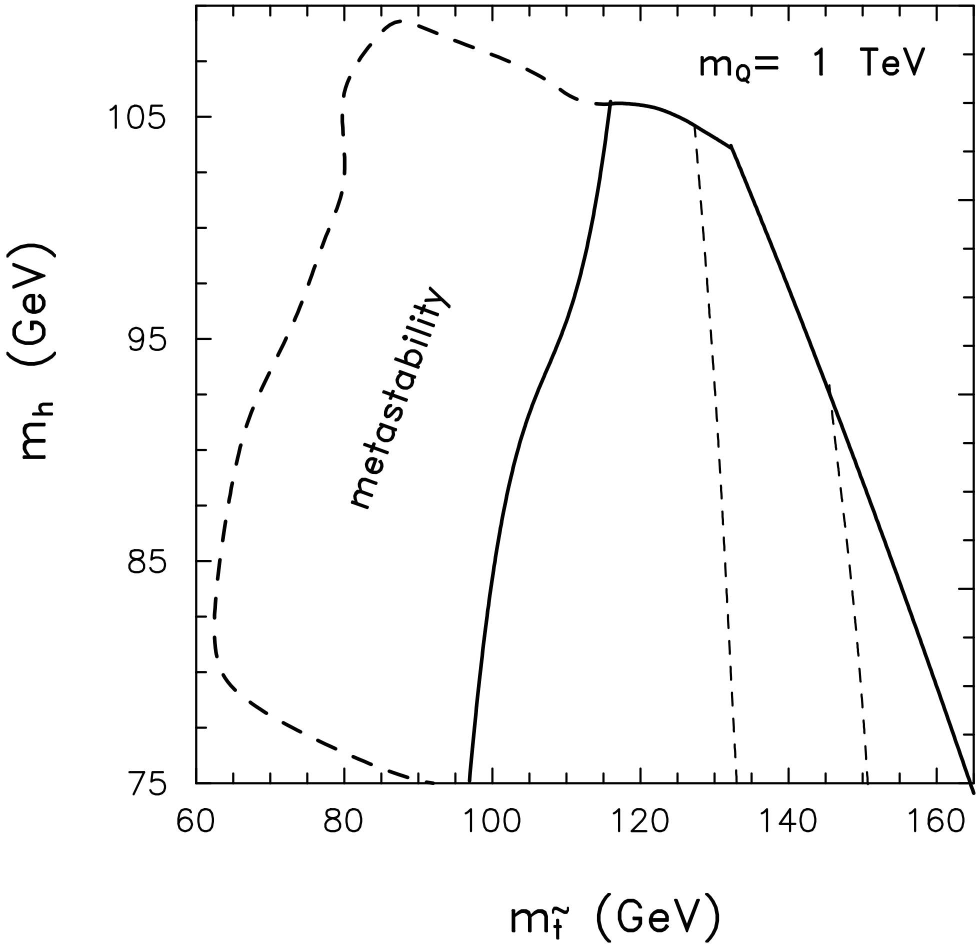
  In order to make a precise analysis, we should take into account

  - Two loop corrections at zero and finite T. Finite two-loop corrections, ingnored 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.

Stop and Higgs Mass Predictions



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 $m_H \gtrsim 112$ GeV at 95 % C.L. A 2.6 σ 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 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

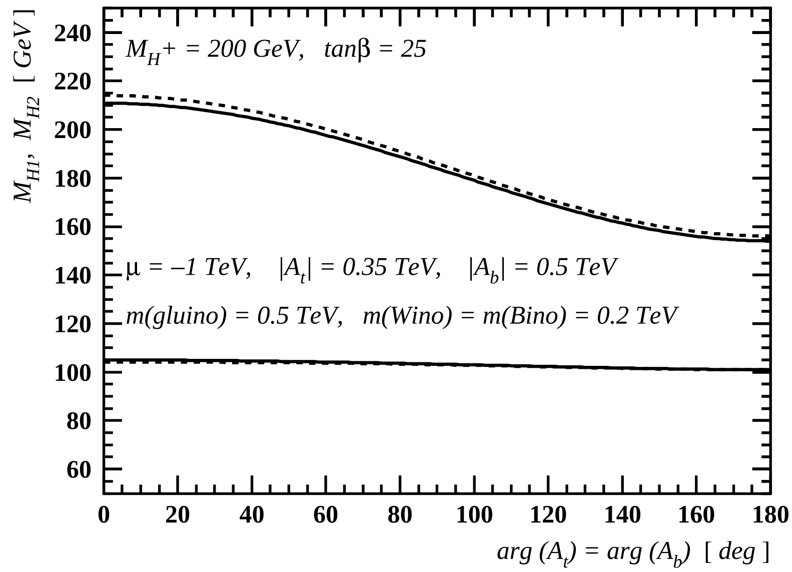
In the presence of CP-violating phases of the SUSY parameters, the three neutral Higgs boson mix and their couplings to the Z-boson fulfill

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

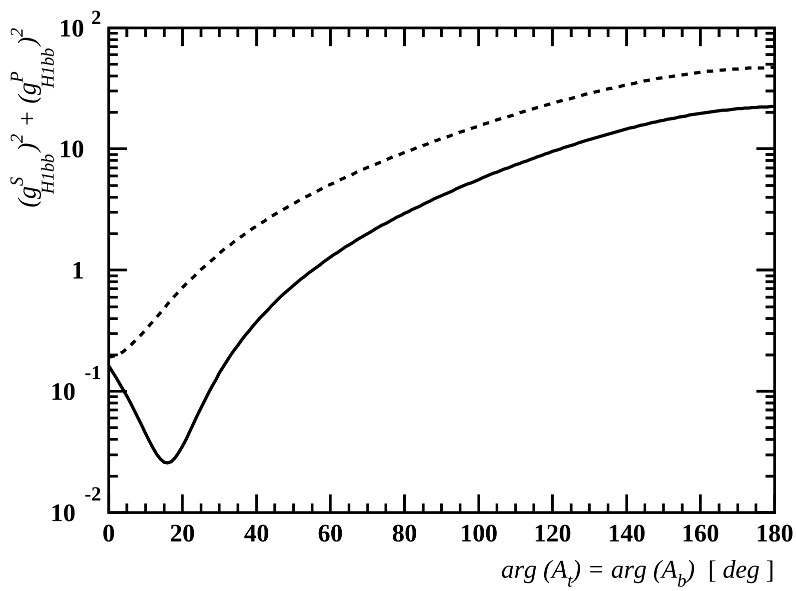
M. Carena, J.Ellis, A.Pilaftsis and C. Wagner '99, '00

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)

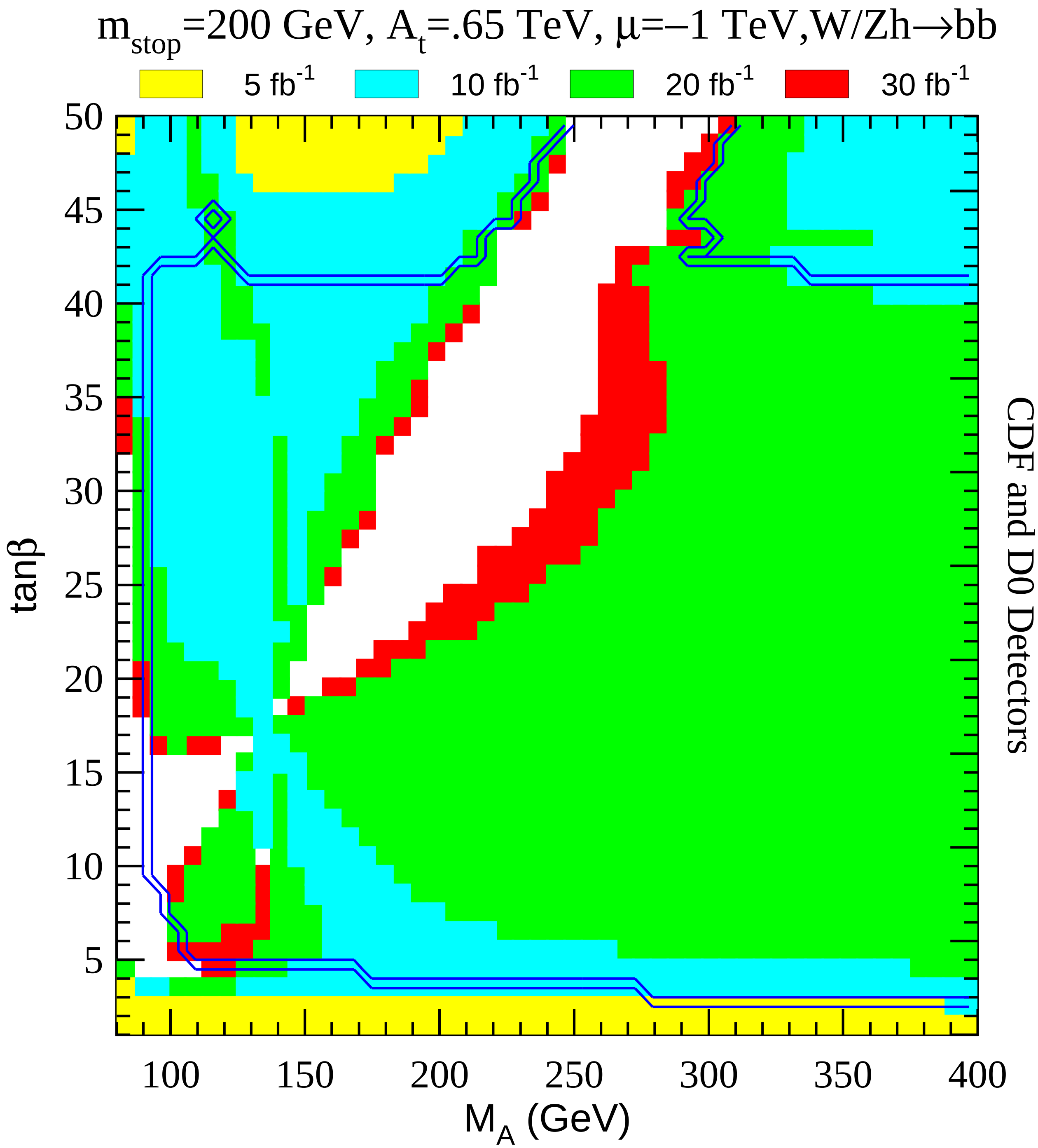


(b)

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 π, respectively.

Suppression of coupling of Higgs to b-quarks and Tevatron Reach



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 difussion 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.

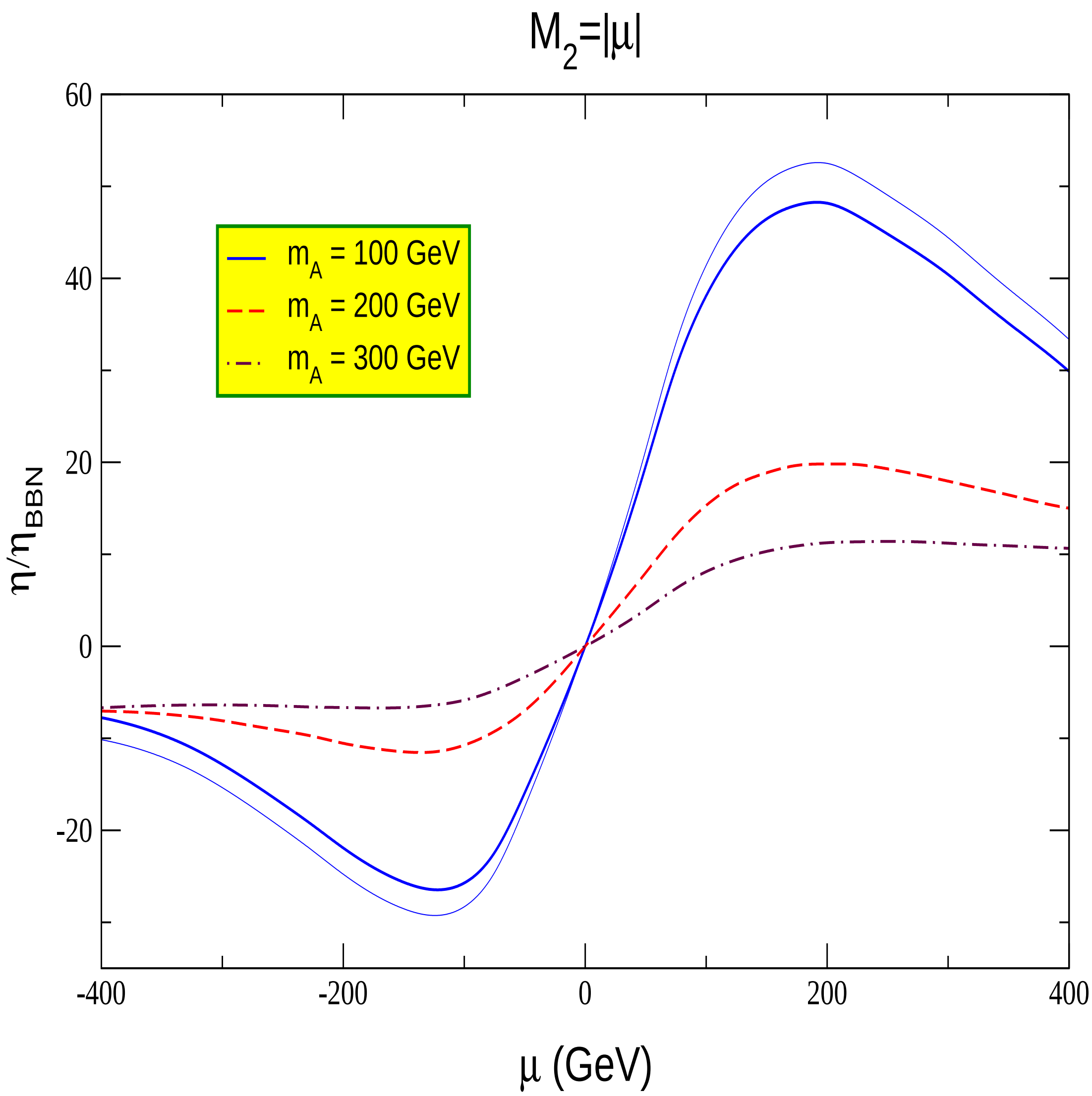
- Sources are dominated by chargino-neutralino contributions, and proportional to $\arg(M_2 \mu)$, where M_2 and μ are the masses of the supersymmetric partners of the gauge and the Higgs boson fields, respectively.

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

- Results generalize the previously found ones

  M. Carena, M. Quiros, A. Riotto, I. Vilja and C.W. '98

Baryon Asymmetry η for $arg(M_2\mu) = \pi/2$



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

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

Conclusions

- The scenario of Electroweak Baryogenesis can be realized in the MSSM if
  $m_h \lesssim$ 110–115 GeV, $m_{\tilde{t}} < m_t$
- Present LEP bounds imply that if this scenario is realized if
  - Large values of $\tan\beta > 5$ and
  - Large values of $m_Q =$ 1–3 TeV .
    Small values of $m_{H^+} < 300$ GeV preferred if no Higgs at LEP.
- Computation of Baryon asymmetry: Acceptable values of η/η_{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.