Electroweak Baryogenesis in the nMSSM

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SUSY 06

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Why is the nMSSM interesting?

Panagiotakopoulos, Pilaftsis ('02)
The nearly Minimal Supersymmetric Standard Model has the following effective superpotential

$$W_{nMSSM} = \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 - \frac{m_{12}^2}{\lambda} \hat{S} + W_{MSSM},$$

and has the virtues to solve the μ-problem of the MSSM by introducing a dynamical μ-term

$$\mu = -\lambda \langle S \rangle .$$

In this model singlet self-couplings are forbidden by a R'-symmetry. The resulting model has neither problems with the stability of the hierarchy nor with domain walls.

Higgs potential of the nMSSM

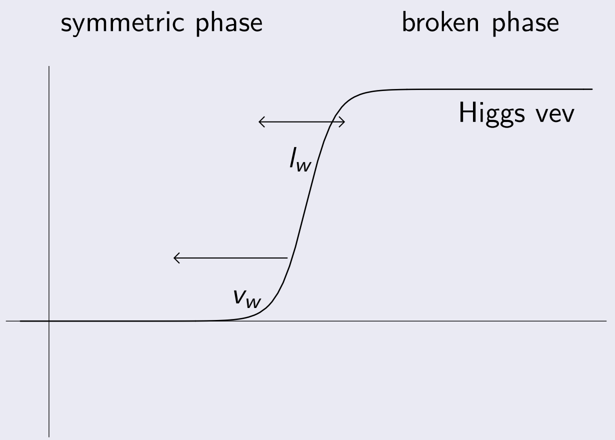
Including soft SUSY breaking terms, the Higgs potential reads

$$\begin{aligned} V_0 &= m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + m_s^2 |S|^2 + \lambda^2 |H_1 \cdot H_2|^2 \\ &+ \lambda^2 |S|^2 (H_1^\dagger H_1 + H_2^\dagger H_2) + \frac{\bar{g}^2}{8} (H_2^\dagger H_2 - H_1^\dagger H_1)^2 + \frac{g^2}{2} |H_1^\dagger H_2|^2 \\ &+ t_s (S + \ h.c.) + (a_\lambda S H_1 \cdot H_2 + \ h.c.) - m_{12}^2 (H_1 \cdot H_2 + \ h.c.). \end{aligned}$$

Compared to the MSSM, the new singlet terms help to strengthen the EWPT and introduce additional sources of CP violation.

Picture of Electroweak Baryogenesis

Kuzmin, Rubakov, Shaposhnikov ('87)



Picture of Electroweak Baryogenesis

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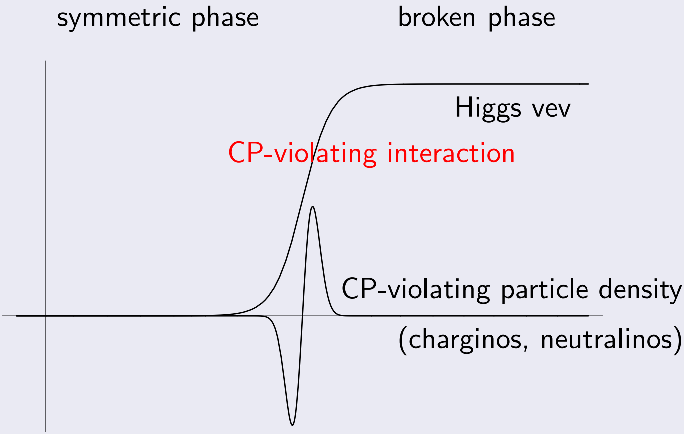

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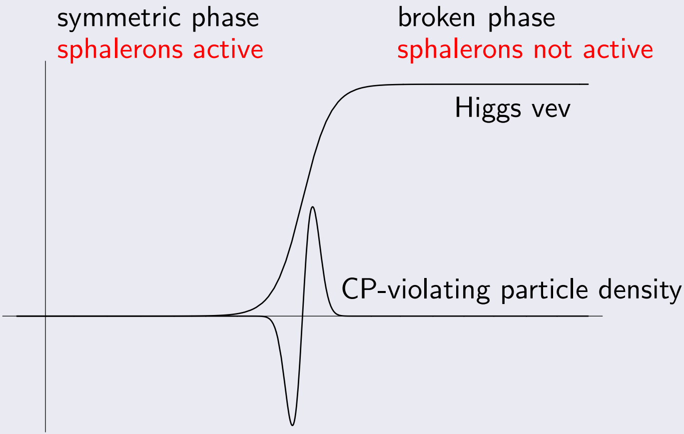
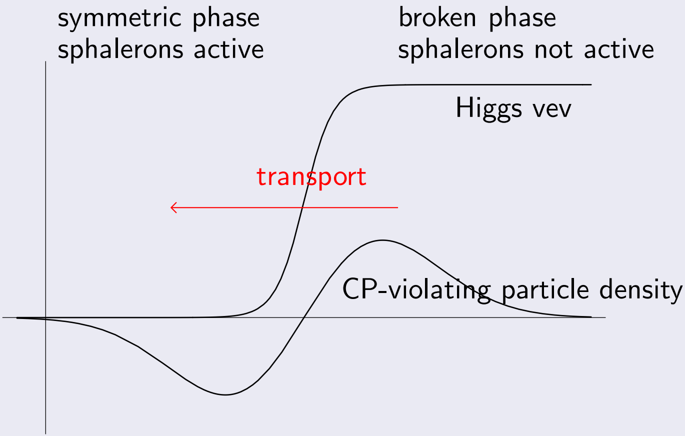


Picture of Electroweak Baryogenesis

Cohen, Kaplan, Nelson ('94)



First Principle Transport Equations: A Simple Example

Kainulainen, Prokopec, Schmidt, Weinstock ('01)

Kadanoff-Baym equations (bosonic, without interactions):

$$e^{-i\diamondsuit}\{(k^2 - m^2(z)), S^<(k^\mu, z)\} = 0$$

with $2\diamondsuit\{A, B\} := \partial_{X^\mu} A \, \partial_{k_\mu} B - \partial_{k_\mu} A \, \partial_{X^\mu} B$.

Free bosonic theory with one flavour and a constant mass in equilibrium:

- The hermitian/antihermitian parts are the so called constraint/kinetic equations:

$$(k^2 - m^2)S^< = 0, \quad k^\mu \partial_{X_\mu} S^< = 0$$

- Using the KMS condition and the correct normalization

$$iS^< = 2\pi \,\mathrm{sign}(k_0)\, \delta(k^2 - m^2)\; n(k_0), \qquad n(k_0) = \frac{1}{\exp(\beta k_0) - 1}$$

Gradient Expansion

If the background in the MSSM is weakly varying ($l_w \, T_c \gg 1$) the Moyal star product can be simplified by the semi-classical approximation

$$\partial_k \partial_X \approx \frac{1}{T_c l_w} \ll 1 \quad \rightarrow \quad e^{-i\Diamond} \approx 1 - i\Diamond + \cdots$$

The simplest example for an transport equation in a varying background is for one bosonic flavour with real mass

$$\begin{aligned} (k^2 - m^2) S^< &= 0 \\ (k^\mu \partial_\mu - \frac{1}{2} (\partial_z m^2) \, \partial_{k_z}) S^< &= 0. \end{aligned}$$

Fermionic Systems

Kainulainen, Prokopec, Schmidt, Weinstock ('01)
T.K., Prokopec, Schmidt ('04)

After spin projection the fermionic system of equations reads

$$
\begin{aligned}
\left(2i\tilde{k}_0 - \frac{k_0\partial_t + \vec{k}_\| \cdot \nabla_\|}{\tilde{k}_0}\right) S_0^s - (2isk_z + s\partial_z)\, S_3^s - 2im_h e^{\frac{i}{2}\overleftarrow{\partial_z}\overrightarrow{\partial_{k_z}}} S_1^s - 2im_a e^{\frac{i}{2}\overleftarrow{\partial_z}\overrightarrow{\partial_{k_z}}} S_2^s &= 0 \\
\left(2i\tilde{k}_0 - \frac{k_0\partial_t + \vec{k}_\| \cdot \nabla_\|}{\tilde{k}_0}\right) S_1^s - (2sk_z - is\partial_z)\, S_2^s - 2im_h e^{\frac{i}{2}\overleftarrow{\partial_z}\overrightarrow{\partial_{k_z}}} S_0^s + 2m_a e^{\frac{i}{2}\overleftarrow{\partial_z}\overrightarrow{\partial_{k_z}}} S_3^s &= 0 \\
\left(2i\tilde{k}_0 - \frac{k_0\partial_t + \vec{k}_\| \cdot \nabla_\|}{\tilde{k}_0}\right) S_2^s + (2sk_z - is\partial_z)\, S_1^s - 2m_h e^{\frac{i}{2}\overleftarrow{\partial_z}\overrightarrow{\partial_{k_z}}} S_3^s - 2im_a e^{\frac{i}{2}\overleftarrow{\partial_z}\overrightarrow{\partial_{k_z}}} S_0^s &= 0 \\
\left(2i\tilde{k}_0 - \frac{k_0\partial_t + \vec{k}_\| \cdot \nabla_\|}{\tilde{k}_0}\right) S_3^s - (2isk_z + s\partial_z)\, S_0^s + 2m_h e^{\frac{i}{2}\overleftarrow{\partial_z}\overrightarrow{\partial_{k_z}}} S_2^s - 2m_a e^{\frac{i}{2}\overleftarrow{\partial_z}\overrightarrow{\partial_{k_z}}} S_1^s &= 0\,,
\end{aligned}
$$

where $S_0 \ldots S_3$ are 2×2 matrices in flavour space and s denotes the spin.

CP violation: Chargino masses in the nMSSM

T.K., Prokopec, Schmidt, Seco ('05)

The chargino transport equations for the left/right handed deviations from equilibrium ($\delta S^< = S^< - S^<_{eq}$) are of the form

$$k^\mu \partial_\mu \delta S^< + \frac{i}{2}\left[m^2, \delta S^<\right] + \Gamma\, k_0\, \delta S^< = Sources(S^<_{eq})$$

with the following properties

- full 2x2 flavour structure (flavor basis, CP violation explicit)
- sources are without ambiguities from the gradient expansion
- the second term induces flavor oscillations $\omega = \Delta m^2 / k$

Sources for EWBG

This approach resembles two mechanisms of EWBG from former approaches

Joyce, Prokopec, Turok ('96)

Cline, Joyce, Kainulainen ('97,'00)

Fromme, Huber ('06)

The dispersion shift source from the WKB approach:

$$\mathcal{S}^{(2)} \sim \left\{ m^{\dagger\prime\prime} m - m^{\dagger} m^{\prime\prime}, \partial_{k_z} S^{<} \right\}.$$

Carena, Moreno, Quiros, Seco, Wagner ('00)

Carena, Quiros, Seco, Wagner ('02)

Cirigliano, Profumo, Ramsey-Musolf ('06)

Cirigliano, Ramsey-Musolf, Tulin, Lee ('06)

Sources from flavor mixing effects, e.g.

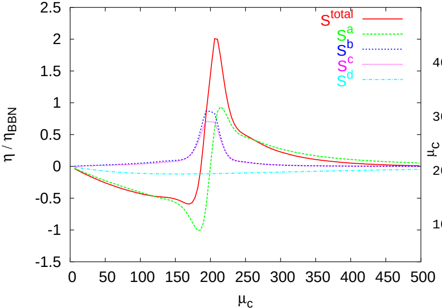
$$\mathcal{S}^{(1)} \sim \left[m^{\dagger\prime} m - m^{\dagger} m^{\prime}, \partial_{k_z} S^{<} \right].$$

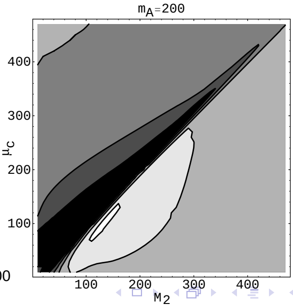
Situation in the MSSM

In the MSSM case the higgsino/wino mass matrix is:

$$m = \begin{pmatrix} M_2 & g\langle H_2\rangle \\ g\langle H_1\rangle & \mu \end{pmatrix}$$

In the MSSM the second order source is two weak to explain the observed BAU. The first order sources show resonant behavior due to flavor oscillations. ($M_2 = 200$ GeV in the left plot)





CP violation: Chargino masses in the nMSSM

Huber, Konstandin, Prokopec, Schmidt (in preparation)

In the nMSSM the μ term contains a z-dependent complex phase

$$\mu(z) = -\lambda \langle S \rangle = -\lambda \phi_s(z)\, e^{i q_s(z)}$$

In the nMSSM second order sources dominate

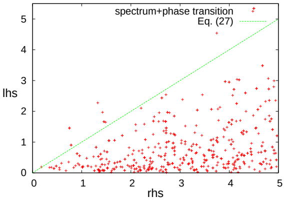
- The dynamical parameter $\mu = \lambda \langle S \rangle$ leads to novel and dominating sources
- Charginos are generically non-degenerate ($M_2 \gtrsim \mu$)
- Thin wall profiles

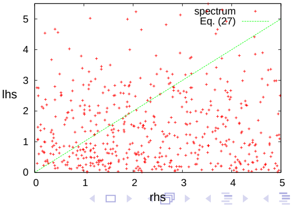
Phase Transition due to Tree–Level Dynamics

In the MSSM, a first order phase transition requires a light stop.
Menon, Morrissey, Wagner ('04)
In a simplified model without CP violation and the thermal effective potential $\Delta V^T = \alpha T^2 \phi^2$, the criterion for a first order phase transition is

$$m_s^2 < \frac{1}{\tilde{\lambda}} \left| \frac{\lambda^2 t_s}{m_s} - m_s \tilde{a} \right| .$$

This criterion seems to be decisive, even if one-loop effects and CP violation is taken into account

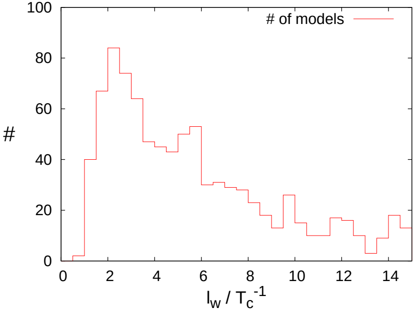




Thin Bubble Walls

In the MSSM, the bubble wall is rather thick $l_w T_c \sim 20 - 30$ (Moreno, Quiros, Seco ('98)).

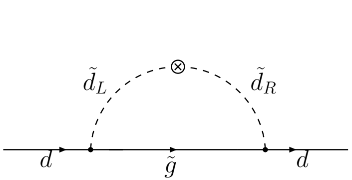
In the nMSSM, bubble walls are comparably thin, what enhances the second order sources in the gradient expansion

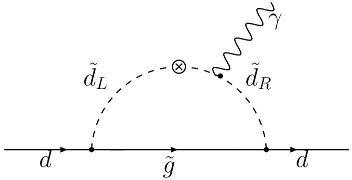


For numerical methods of multi dimensional phase transitions see Konstandin, Huber ('06).

eEDM: One Loop Contributions

One-loop contributions to the EDMs are of the following form





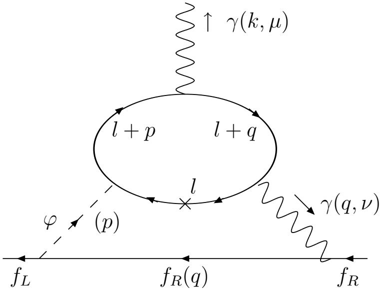
As in the MSSM, these contributions have to be suppressed by large sfermion masses in the first two generations. This restriction can be relaxed, since in the nMSSM CP violation could be small in the broken phase.

$$\begin{aligned} \text{BAU} &\propto \Delta Arg(\mu) \text{ in the nMSSM}, \\ &\propto Arg(M_2\mu) \text{ in the MSSM}, \\ \text{EDM} &\propto Arg(M_2\mu). \end{aligned}$$

eEDM: Two Loop Contributions

Chang, Chang, Keung ('02), Pilaftsis ('02)

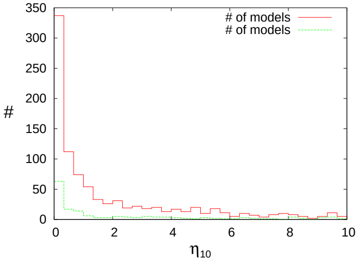
Potentially dangerous diagrams are of the following form with a chargino in the loop

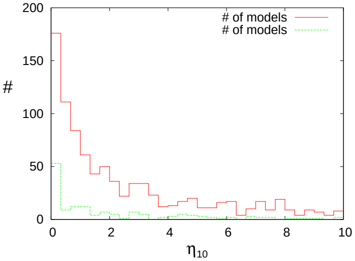


However in the nMSSM, these contributions are not as severe as in the MSSM, since usually $tan(\beta) \sim O(1)$.

Numerical Results

A numerical analysis of the BAU leads to the following result (sets passed LEP constraints and have a first order phase transition)

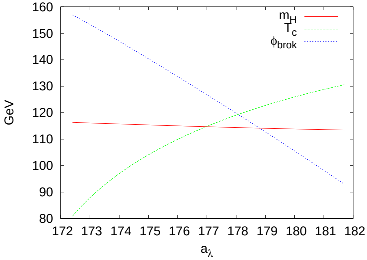




The left (right) plot shows the generated BAU for $M_2 = 1$ TeV ($M_2 = 200$ GeV). 50% (63%) of the models are in accordance with observation. The lower models fulfill the the EDM bounds with 1 TeV sfermion masses, 4.8 % (6.2 %).

The Landau Pole in λ

Constructing nMSSM models without Landau pole in the parameter λ requires some tuning. Choosing $\langle S \rangle = 250$ GeV, $\lambda = 0.55$, $m_A = 500$ GeV, $\tan(\beta) = 2.0$, $Arg(t_s) = 0.3$ and $t_s^{1/3} = 70$ GeV one obtains the following result



The produced BAU is in this case $\eta_{10} \approx 2.7$.

Conclusions

EWBG in the MSSM possible if ...

- Strong first order phase transition in the light stop scenario
- $\eta_{10} \gtrsim 1$ only for almost mass degenerate charginos ($\pm$20 GeV) with masses $\chi^+_{1/2} \lesssim 400$ GeV
- Additional argument needed to suppress two loop EDMs

EWBG in the nMSSM is very promising

- Strong first order phase transition due to tree-level dynamics
- $\eta_{10} \gtrsim 1$ for most of the parameter space
- two loop EDMs small due to $tan(\beta) \sim O(1)$

Open questions

Landau pole in λ

- "Fat Higgs"
- $0.7 < \lambda < 0.8$

One-loop EDMs

- Heavy sfermions (split SUSY)
- Suppressed CP violation in broken phase