Status Report on Electroweak Baryogenesis

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hep-ph/0410135, hep-ph/0505103, hep-ph/0606298

Outline

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1. Introduction
   - Electroweak Baryogenesis
   - Approaches to Transport
2. Models
   - SM
   - MSSM
   - nMSSM
   - SM with dim-6 operators
3. Conclusions

Sakharov conditions

Baryogenesis is one of the cornerstones of the Cosmological Standard Model.

The celebrated Sakharov conditions state the necessary ingredients for baryogenesis:

Sakharov conditions

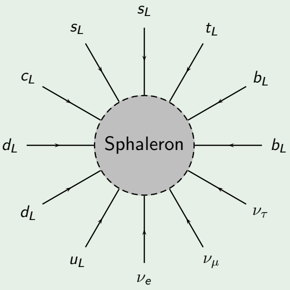
- B violation
- non-equilibrium
- C and CP violation

Electroweak baryogenesis: Generate the BAU as late as possible.

B violation: The sphaleron process

In the hot universe B and C violation is present in the SM and its extensions due to sphaleron precesses.

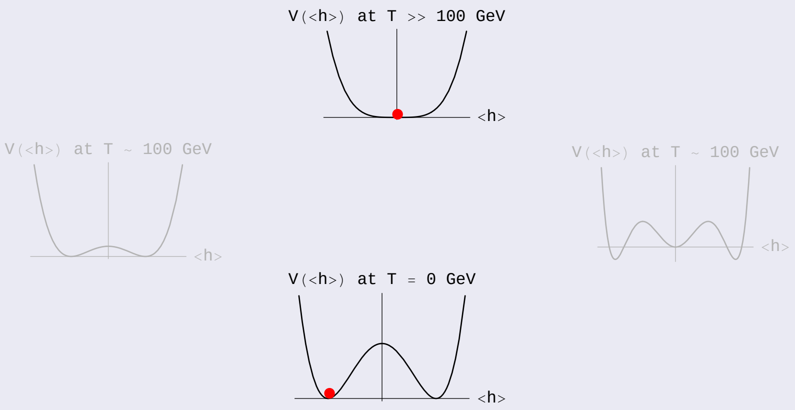
The effective sphaleron vertex



- $\Delta B = 3,\ \Delta L = 3,\ \Delta N_{CS} = 1$
- $B - L$ conserving
- $B + L$ violating
- Exponentially suppressed by the W mass
- Topological effect of the SU(2) gauge sector

Non-equilibrium: The electroweak phase transition

Cross-over *versus* first-order electroweak phase transition:



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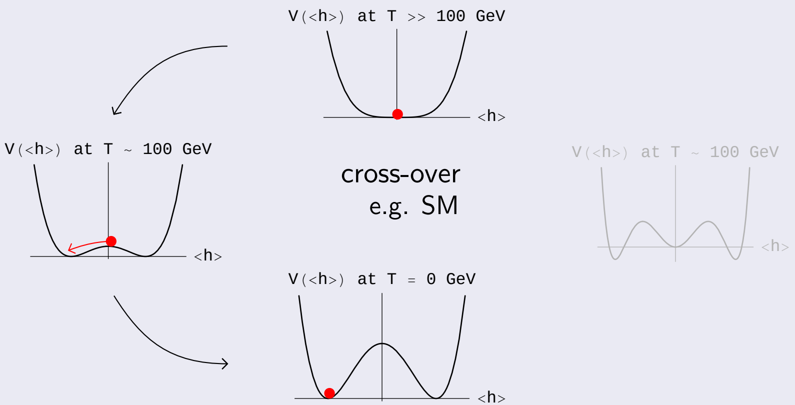

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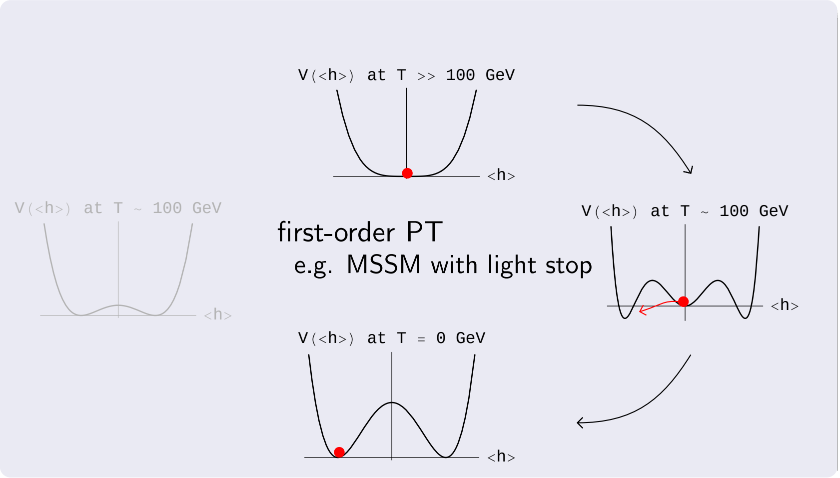
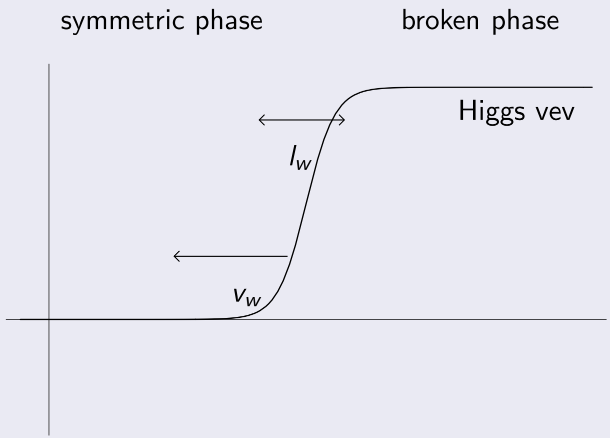


Picture of Electroweak Baryogenesis

Shaposhnikov ('87)

local EWBG



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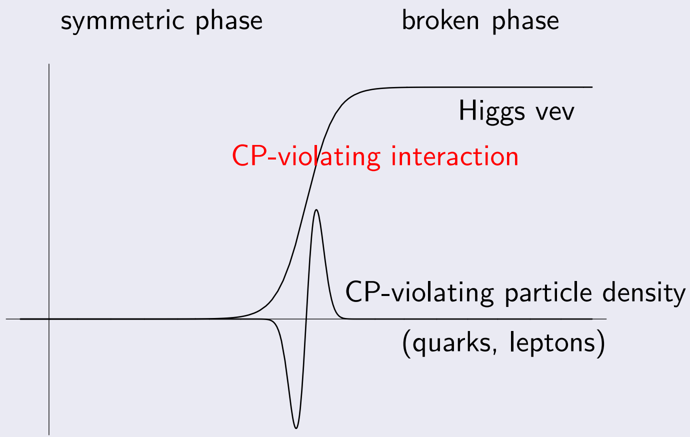

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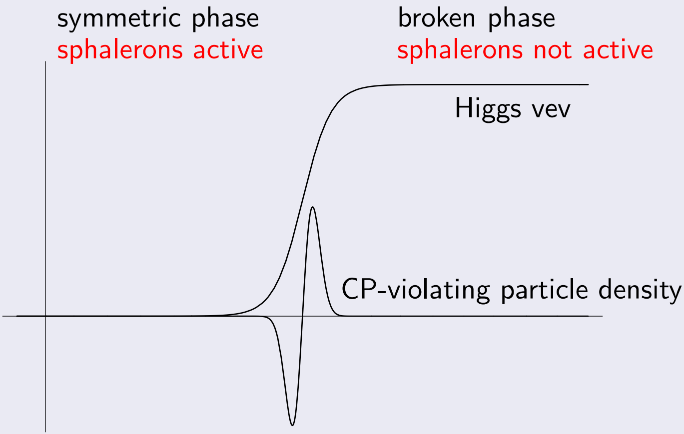
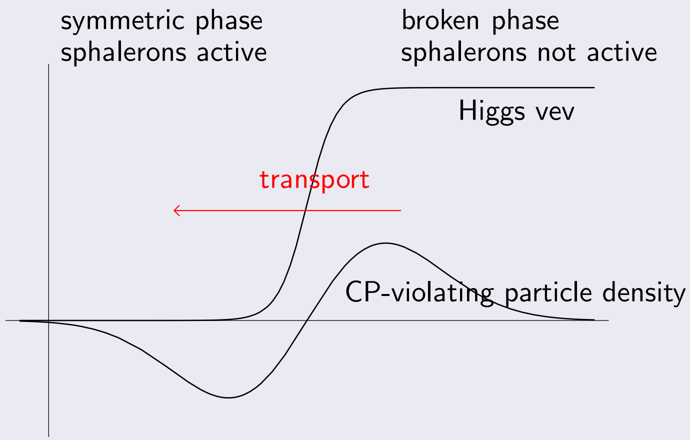


Picture of Electroweak Baryogenesis

Cohen, Kaplan, Nelson ('94)

non-local EWBG



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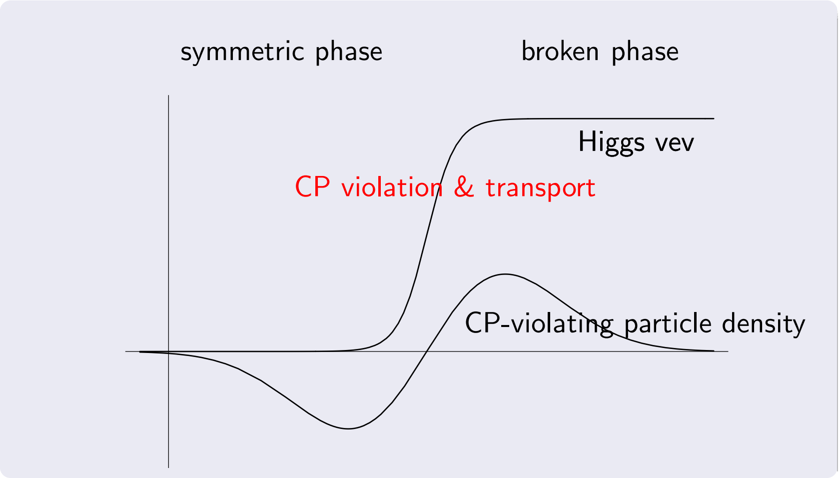

Summary of Approaches to Transport

Semi-classical force approach

Joyce, Prokopec, Turok, hep-ph/9401352, hep-ph/9408339
Joyce, Cline, Kainulainen, hep-ph/9708393
Huber, Schmidt, hep-ph/0003122

Perturbative mixing approach

Carena, Quiros, Riotto, Vilja, Wagner, hep-ph/9702409
Carena, Moreno, Quiros, Seco, Wagner, hep-ph/0011055
Carena, Quiros, Seco, Wagner, hep-ph/0208043
Cirigliano, Profumo, Ramsey-Musolf, hep-ph/0603246

Kadanoff-Baym approach

Kainulainen, Prokopec, Schmidt, Weinstock, hep-ph/0105295
Konstandin, Prokopec, Schmidt, hep-ph/0410135
Konstandin, Prokopec, Schmidt, Seco, hep-ph/0505103

Semi-classical force in WKB approximation

Consider a single fermion with a complex, z-dependent mass term

$$m(z) = |m(z)| \times e^{i\theta(z)} \propto \langle H \rangle$$

In this case the particle distribution function $n_s(k^\mu, x^\mu)$ for the particles with spin s fulfills the CP-violating equation (WKB approximation)

$$\begin{aligned} \left(k^2 - m^2 + s\frac{m^2\theta'}{2k_0}\right) n_s &= 0, \\ \left(k^\mu \partial_\mu - \frac{1}{2}(m^2)'\,\partial_{k_z} + s\frac{(m^2\theta')'}{2k_0}\,\partial_{k_z}\right) n_s &= 0. \end{aligned}$$

Notice that CP violation arises not from interaction but from **kinematics**.

Kadanoff-Baym Approach

Our approach is based on the Kadanoff-Baym equations, which are the analog of the Schwinger-Dyson equations in thermal field theory.

Wigner space: $G(x_1^\mu, x_2^\mu) \to \tilde{G}(k^\mu, X^\mu)$ with

$$X = (x_1 + x_2)/2, \quad k = \text{ FT w.r.t. } (x_2 - x_1)$$

- **Quantum transport** equations and 'forces' are derived in a uniform approach
- The Wightman function is a matrix in flavor space and contains the classical particle numbers as well as quantum correlations
- The equations reproduce flavor ($\sim$ neutrino) oscillations
- More technical advantages

Fermionic Systems

After spin projection the fermionic system of equations reads

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

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

In the one-flavor case these equations can be decoupled and reproduce the equations from the semi-classical force approach (to first order in gradients).

EWBG check list

Check list

- Choose your favorite model!
- Strongly first-order phase transition?
- Sufficient CP violation?
- Particle physics constraints? (particle spectrum, EDMs, dark matter, ...)
- Efficient transport and produced BAU?

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EWBG in the Standard Model

Phase transition

A strongly first-order phase transition would be possible in the SM for light Higgs, $m_H \lesssim 70$ GeV, what is excluded by LEP data.

CP violation

CP violation is too small in the SM, what poses a serious problem for every baryogenesis mechanism based on the SM.

EWBG in the MSSM

Phase transition

A strongly first-order phase transition possible for a light stop $m_{\tilde{t}} \approx m_t$ due to **loop** contributions to the Higgs potential.

CP violation in the chargino sector

In the MSSM case the chargino=Higgsino/Wino mass matrix is:

$$m = \begin{pmatrix} M_2 & g\, h_2(z) \\ g\, h_1(z) & \mu \end{pmatrix}$$

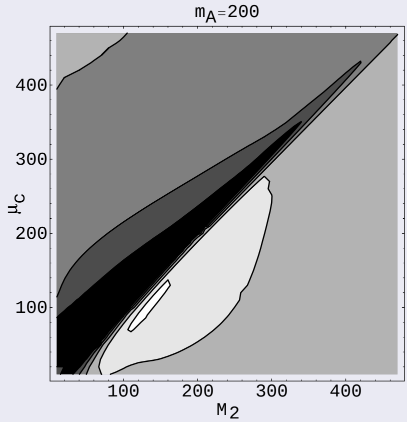
with M_2 and μ containing a CP-violating complex phase.

In the MSSM, the CP-violating sources from mixing dominate over the semi-classical force due to rather thick walls.

Numerical Results for Transport

Konstandin, Prokopec, Schmidt, Seco, hep-ph/0505103

Parameters chosen: $v_w = 0.05$, $l_w = 20/T_c$, CP-phase maximal.



The first principle approach in general predicts a smaller contribution to the BAU by mixing due to flavor oscillation.

Conclusions in the MSSM

MSSM electroweak baryogenesis is a constrained scenario that requires

- A light stop to acquire a strong first order phase transition
- The condition $\mu \approx M_2 \lesssim 400$ GeV of the *a priori* unrelated parameters M_2 and μ
- A large CP-violating phase that is testable by next generation EDM experiments

EWBG in singlet extensions of the MSSM

The nMSSM is a singlet extension of the MSSM with the superpotential

$$W_{\rm nMSSM} = \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 - \frac{m_{12}^2}{\lambda} \hat{S} + y_t \hat{Q} \cdot \hat{H}_2 \hat{U}^c + \cdots ,$$

and solves the μ-problem of the MSSM ($\mu = -\lambda \langle S \rangle$).

Phase transition

A strongly first-order phase transition is possible already on tree-level due to the Higgs coupling to the singlet.

CP violation

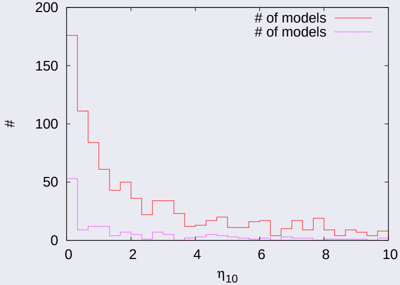
CP violation is present in the chargino sector, as in the MSSM case, but EDM constraints are in general less severe. Nevertheless, EWBG requires rather light charginos in the nMSSM.

Numerical results

Huber, Konstandin, Prokopec, Schmidt, hep-ph/0606298

Strategy:

- Choose seven relevant parameters randomly
- Check LEP constraints ($\longrightarrow$ a few)
- Check phase transition ($\longrightarrow$ 30% to 50%)



The lower represents models that exhibit spontaneous CP violation.

EWBG in the SM with dim-6 operators

BODEKER, FROMME, HUBER, SENIUCH, HEP-PH/0412366

In a minimal framework, electroweak baryogenesis is also viable in the SM enhanced with dimension-six operators at the TeV scale (Techni-color?).

Phase transition

Using a Higgs potential of the form

$$V(H) = \mu H^2 + \lambda H^4 + \frac{1}{M^2} H^6,$$

a strongly first-order phase transition is possible for $\lambda < 0$ and $M \sim 1$ TeV.

CP violation

CP violation is present in the top sector due to additional dimension-six operators of the form $H^2\, H^c\, t\, q_3$.

Outline

Conclusions

Electroweak baryogenesis is still a **viable** but **constrained** scenario that can account for the observed BAU.

Electroweak baryogenesis is a **testable** and **falsifiable** scenario that involves mostly physics that can be probed in the laboratory.

LHC and the next generation of EDM experiments will decide if electroweak baryogenesis could be the main source of the observed baryon asymmetry of the Universe.