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Lars Fromme, Bielefeld University

Electroweak baryogenesis with dimension-6 Higgs interactions

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Dietrich Bödeker, L. F., Stephan J. Huber and Michael Seniuch

Outline

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- Numerical Results
- Summary / Conclusions

INTRODUCTION

BAU: $\eta_B \equiv \frac{n_B}{s} = (8.9 \pm 0.4) \times 10^{-11}$

Sakharov's conditions

- B violation
- C and CP violation
- Deviation from thermal equilibrium

Nonlocal baryogenesis

1st order PT (two energetically degenerate phases)

$\Rightarrow$ Formation of bubbles which start to nucleate, expand and percolate.

Higgs field changes rapidly as bubble wall passes through space.

The CP violating interactions with bubble wall create locally an excess of left-handed quarks over the corresponding anti-quarks.

This asymmetry is converted in the symmetric phase by sphaleron induced $(B+L)$-violating reactions into an asymmetry in B.

Within the bubbles these transitions have to be suppressed.

$\Rightarrow$ 'washout criterion' $\xi = v_c/T_c \gtrsim 1$

The moving wall sweeps over that region where $\Delta B \neq 0$.

$\Rightarrow$ A net baryon asymmetry will be generated!

But: BAU cannot be explained within the SM!

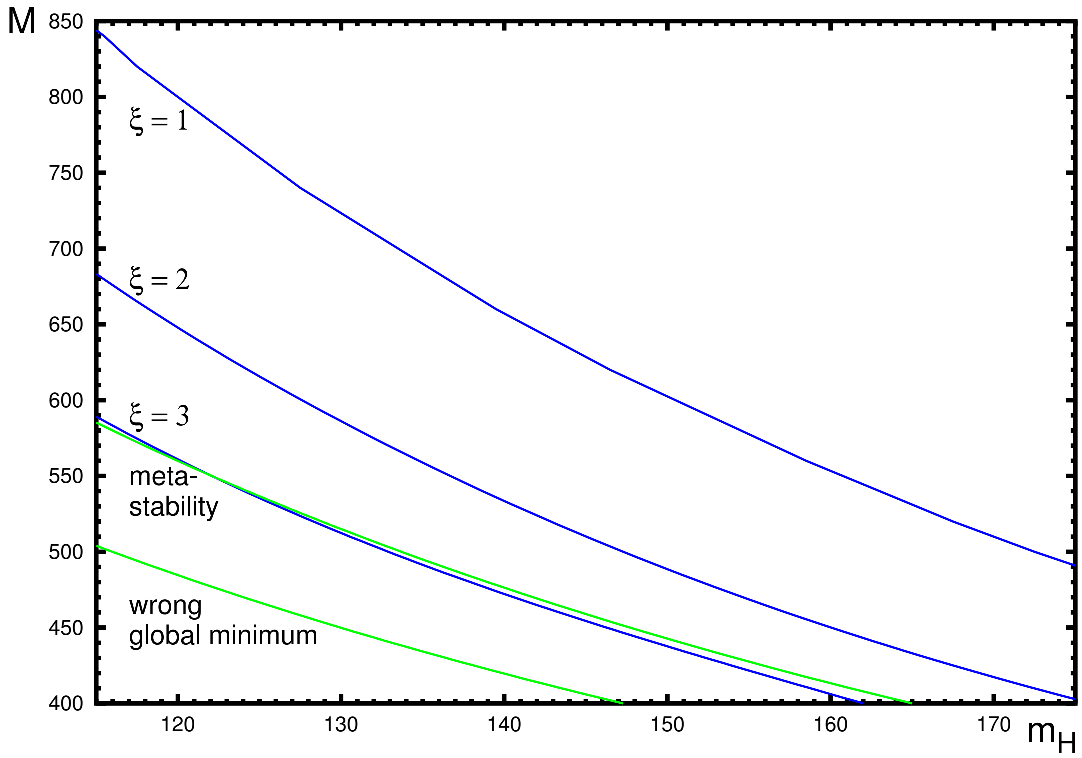
Idea: Add a non-renormalizable ϕ^6 operator

$$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{1}{8M^2}\phi^6,$$

where $\phi^2 \equiv 2\Phi^\dagger\Phi$ with the SM Higgs doublet Φ.

[Grojean, Servant, Wells (2004)], [Ham, Oh (2004)]

The Strength of the Phase Transition



The PT becomes weaker for increasing Higgs mass,
but in contrast to SM 1st order PT even for $m_H > 150$ GeV!

Requirements of the electroweak baryogenesis are fulfilled for a large part of the parameter space!

The bubble wall profile:

The solution of the field equation can be fitted by a kink

$$\phi(z) = \frac{v_c}{2}\left(1 - \tanh\frac{z}{L_{\rm w}}\right).$$

CP Violation

We introduce a dimension-six operator for the fermions:

$$\mathcal{L} = \bar{\Psi}_R\left(y\Phi + \frac{x}{M^2}\left(\Phi^\dagger\Phi\right)\Phi\right)\Psi_L + h.c.$$

In general the couplings x contain complex phases.

Concentrate on the top quark and choose maximal CP violation

$$\Rightarrow \qquad \mathcal{L} = \bar{t}_R m_{top} t_L + \bar{t}_L m^*_{top} t_R$$

$$\text{where} \qquad m_{top} = y_t\frac{\phi(z)}{\sqrt{2}} + i|x_t|\frac{\phi(z)^3}{2\sqrt{2}M^2} = m(z)e^{i\theta(z)}$$

$$\text{with} \qquad \theta(z) = \arctan\left(\frac{|x_t|\phi(z)^2}{2y_t M^2}\right).$$

This is $\mathcal{C}$ conserving but $\mathcal{P}$ violating!

$\Rightarrow$ Different dispersion relations for particles and anti-particles

$$E_\pm = E_0 \pm \Delta E = \sqrt{p^2+m^2} \pm \mathrm{sign}(p_z)\theta'\frac{m^2}{2(p^2+m^2)}$$

which induce different force terms in the transport equations.

TRANSPORT EQUATIONS

We describe the evolution of the particle distributions $f_i(\vec{x}, \vec{p}, t)$ by classical Boltzmann equations.

We use a fluid-type ansatz in the rest frame of the plasma

$$f_i(t, \vec{x}, \vec{p}) = \frac{1}{e^{\beta(E_i - v_i p_z - \mu_i)} \pm 1},$$

with velocity perturbations v_i and chemical potentials μ_i for each particle type.

- expand the Boltzmann eqs. in derivatives of the fermion mass
- weight the Boltzmann eqs. with 1 and p_z
- average over momentum

To first order in derivatives:

$$\begin{aligned} \kappa_i v_\mathrm{w} \mu'_{i,1} - K_{1,i} v'_{i,1} - \langle \mathcal{C}_i \rangle &= K_{3,i} v_\mathrm{w} (m_i^2)' \\ -K_{1,i} \mu'_{i,1} + K_{2,i} v_\mathrm{w} v'_{i,1} - \langle p_z \mathcal{C}_i \rangle &= 0 \end{aligned}$$

(no difference between particles and anti-particles)

To second order in derivatives:

$$\begin{aligned} \kappa_i v_\mathrm{w} \mu'_{i,2} - K_{1,i} v'_{i,2} - \langle \mathcal{C}_i \rangle &= -K_{6,i} \theta'_i m_i^2 \mu'_{i,1} \\ -K_{1,i} \mu'_{i,2} + K_{2,i} v_\mathrm{w} v'_{i,2} - \langle p_z \mathcal{C}_i \rangle &= K_{4,i} v_\mathrm{w} m_i^2 \theta''_i + K_{5,i} v_\mathrm{w} (m_i^2)' \theta'_i \\ &\quad - K_{7,i} m_i^2 \theta'_i v'_{i,1} \end{aligned}$$

(after subtracting eqs. for particles and anti-particles)

[Joyce, Prokopec, Turok (1995)], [Prokopec, Schmidt, Weinstock (2004)]

We have to solve this set of coupled differential equations to compute the asymmetry in the left-handed quark density.

Weak sphalerons convert μ_{B_L} into a baryon asymmetry

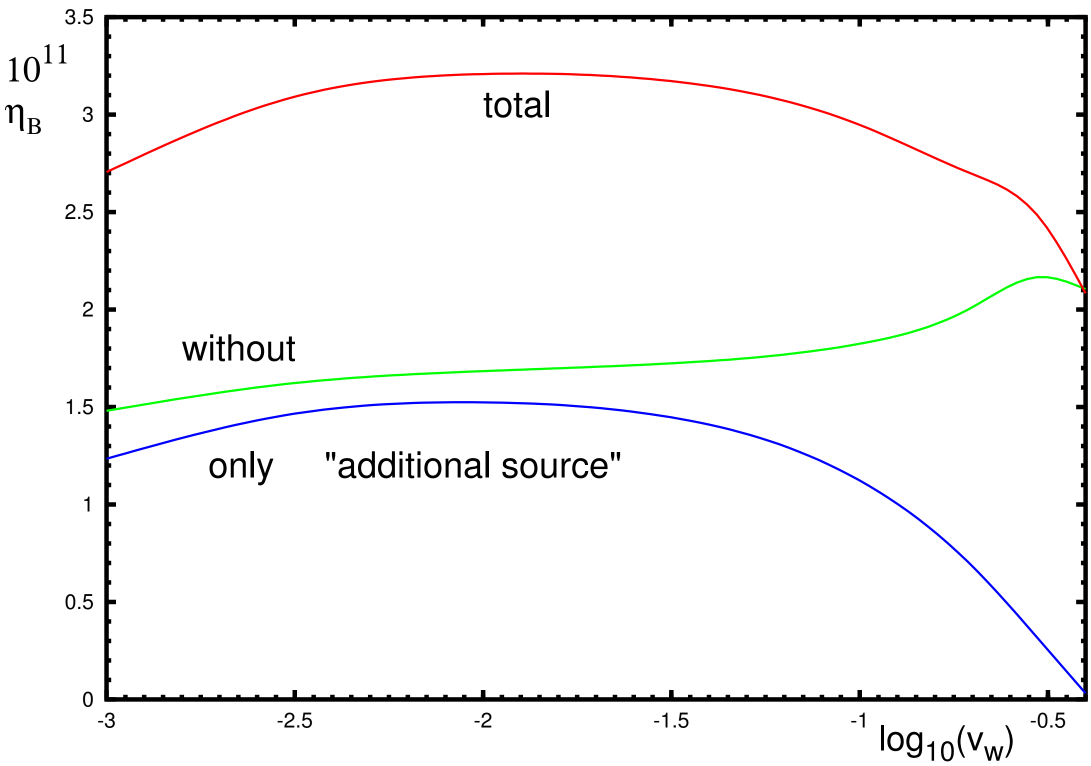
$$\eta_B = \frac{n_B}{s} = \frac{405\bar{\Gamma}_{ws}}{4\pi^2 v_{\rm w} g_* T^4} \int_0^\infty d\bar{z}\mu_{B_L}(\bar{z})e^{-\nu\bar{z}}$$

where $g_* = 106.75$, $\bar{\Gamma}_{ws}$ is the weak sphaleron rate and $\nu = 45\bar{\Gamma}_{ws}/(4v_{\rm w}T^3)$.

[Cline, Joyce, Kainulainen (2000)]

NUMERICAL RESULTS

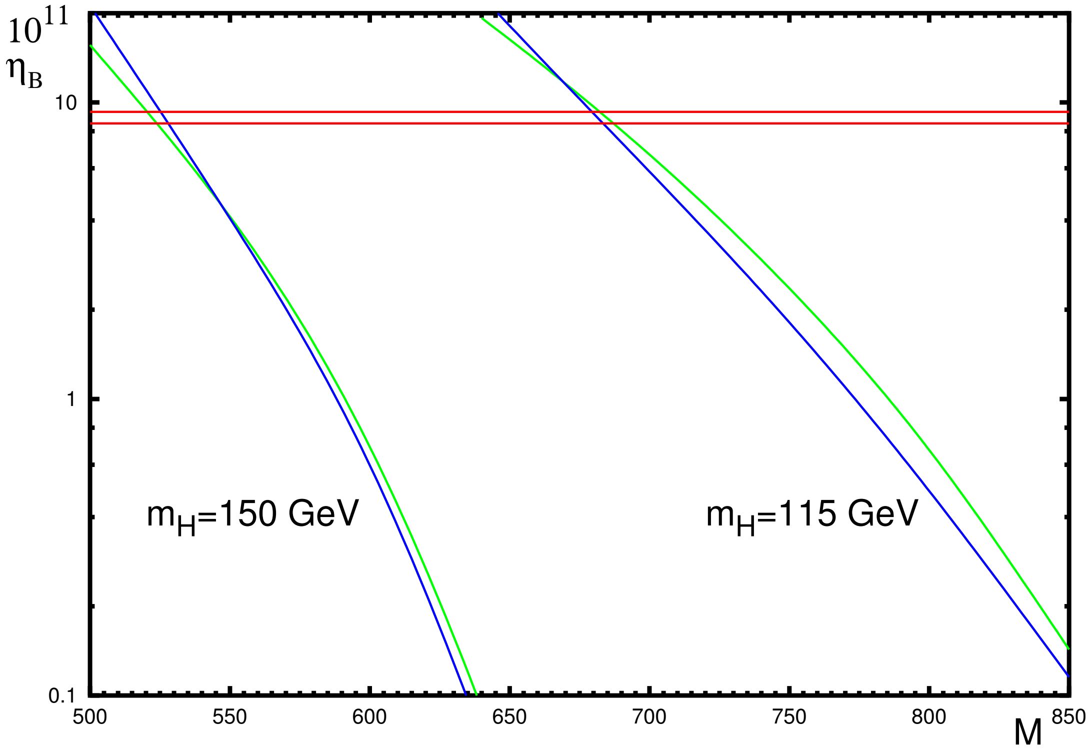
- new source terms proportional to $\mu_{i,1}$ and $v_{i,1}$ are non-negligible
- total baryon asymmetry η_B depends only slightly on $v_{\rm w}$



- η_B increases rapidly for larger values of $\xi = v_c/T_c$
- η_B decreases for larger values of L_w

The model

For every M we compute the strength of the PT ξ and L_w.
(here $|x_t| = 1$)



Two different wall velocities: $v_\text{w} = 0.01$ (green) and $v_\text{w} = 0.3$ (blue).

η_B grows rapidly as we lower M.

The red horizontal lines indicate the errorband of the measured value.

$\Rightarrow$ BAU can be explained for natural values of the parameters!

Summary / Conclusions

- We have investigated the EWPT and baryogenesis in the SM amplified by dimension-six Higgs interactions.
- The EWPT becomes 1st order.
- The PT is strong enough to prevent baryon number washout for Higgs masses up to at least 170 GeV.
- New source of CP violation.
- Novel source terms in the transport equations which enhance the generated baryon asymmetry.
- The observed baryon asymmetry can be explained for natural values of the parameters.
- The CP violating couplings are in agreement with the experimental constraints on the EDM's.
- With a low cut-off the model is expected to lead to non-standard signals in flavor physics, such as EDM's and FCNC's, which can be tested in future experiments.