Electroweak baryogenesis in the two Higgs doublet model

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Outline

- Introduction
- 2 Higgs doublet model
- Phase transition – CP conserving case
- Phase transition – CP violating case
- Baryon asymmetry – Preliminary results
- Summary and Outlook

INTRODUCTION

Aim: Explaining the BAU $\eta = \frac{n_B}{s} = (8.9 \pm 0.4)\, 10^{-11}$.

[Spergel et al. (2003)]

SAKHAROV CONDITIONS

i) B violation.

ii) C and CP violation.

iii) Deviation from thermal equilibrium.

ELECTROWEAK BARYOGENESIS

Formation of bubbles of the Higgs field condensate at the electroweak phase transition (EWPT).

Strong first order EWPT to avoid washout in the broken phase:

$$\xi \equiv v_c/T_c \gtrsim 1$$

2 Higgs doublet model

Zero-temperature potential:

$$\begin{aligned} V_0(\Phi_1,\Phi_2) &= -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \mu_3^2\Phi_1^\dagger\Phi_2 - \mu_3^{2*}\Phi_2^\dagger\Phi_1 \\ &\quad + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ &\quad + h_1(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + h_2(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &\quad + h_3[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2] \end{aligned}$$

For the VEVs we choose: $\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\binom{0}{v_1}$ and $\langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\binom{0}{v_2}$
with the ratio $v_2/v_1 \equiv \tan\beta = 1$ and $v = \sqrt{v_1^2+v_2^2} = 246$ GeV.

For simplification: $\mu_1^2 = \mu_2^2$, $\lambda_1 = \lambda_2$, and $\mu_3^{2*} = \mu_3^2 \geq 0$
(CP violation for complex μ_3^2.)

Particle spectrum:

3 Goldstone bosons:	G^+, G^-, G^0
4 heavy physical Higgs bosons:	H^+, H^-, A^0, H^0
1 light physical Higgs boson:	h^0

Parameters of the potential: $\mu_1^2, \mu_3^2, h_1, h_2, h_3, \lambda_1$

Translation into physical parameters: $m_{H^\pm}, m_{A^0}, m_{H^0}, m_{h^0}, v_1, \mu_3^2$

via minimum condition $\left.\frac{\partial V_0}{\partial\phi_i}\right|_{\mathrm{VEV}} = 0$

and mass matrix $M^2 = \left.\frac{\partial^2 V_0}{\partial\phi_i\partial\phi_j}\right|_{\mathrm{VEV}}$.

EFFECTIVE POTENTIAL

1-loop finite temperature contribution:

$$\begin{aligned}\Delta V_{\text{eff,T}} = &\quad T^4 f_B(m_B/T) + T^4 f_F(m_F/T) \\ = &\quad T^4 \sum_B \frac{1}{2\pi^2} \int_0^\infty dx\, x^2 \ln\left(1 - \exp(-\sqrt{x^2 + m_B^2/T^2})\right) \\ - &\quad T^4 \sum_F \frac{1}{2\pi^2} \int_0^\infty dx\, x^2 \ln\left(1 + \exp(-\sqrt{x^2 + m_F^2/T^2})\right)\end{aligned}$$

Approximation of these integrals by high and low temperature expansion and a smooth interpolation in between.

$\Rightarrow$ Effective potential:

$$V_{\text{eff}}(\phi_1, \phi_2) = V_0 + \Delta V_{\text{eff,T}}$$

PHASE TRANSITION – CP CONSERVING CASE

We explore the parameter region:

$$0 \le \mu_3^2 \le 60000 \text{ GeV}^2$$

$$100 \text{ GeV} \le m_{\text{light}} \equiv m_{h^0} \le 150 \text{ GeV}$$

$$300 \text{ GeV} \le m_{\text{heavy}} \equiv m_{H^0} = m_{A^0} = m_{H^\pm} \le 800 \text{ GeV}$$

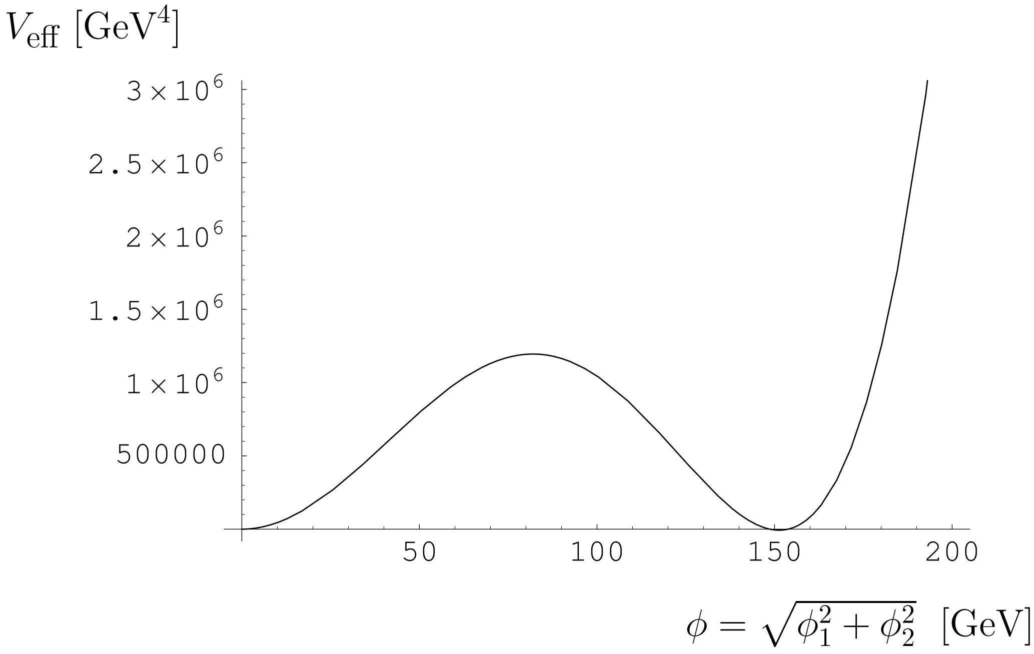
[Turok, Zadrozny (1992)], [Davies, Froggatt, Jenkins, Moorhouse (1994)]
[Cline, Lemieux (1997)]

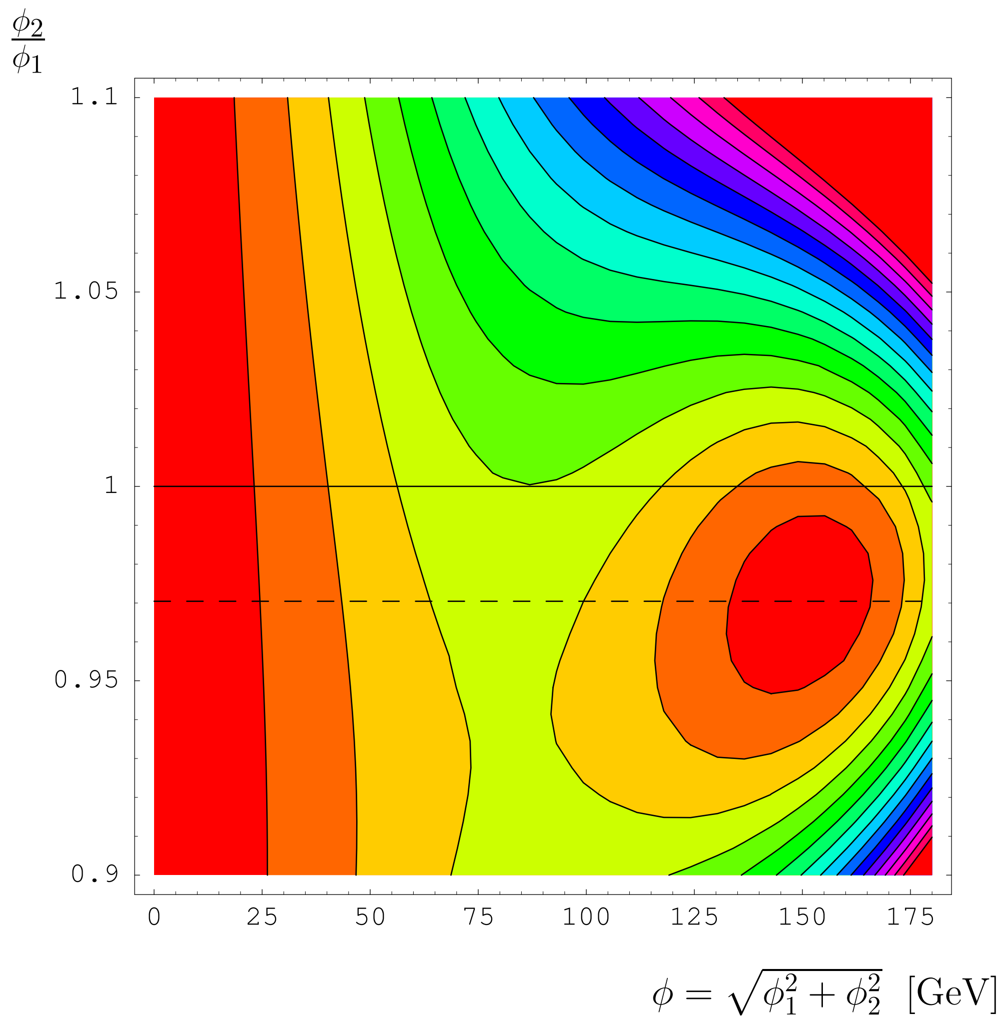
EXAMPLE:

$\mu_3^2 = 30000 \text{ GeV}^2, m_{\text{light}} = 120 \text{ GeV}, m_{\text{heavy}} = 600 \text{ GeV}$

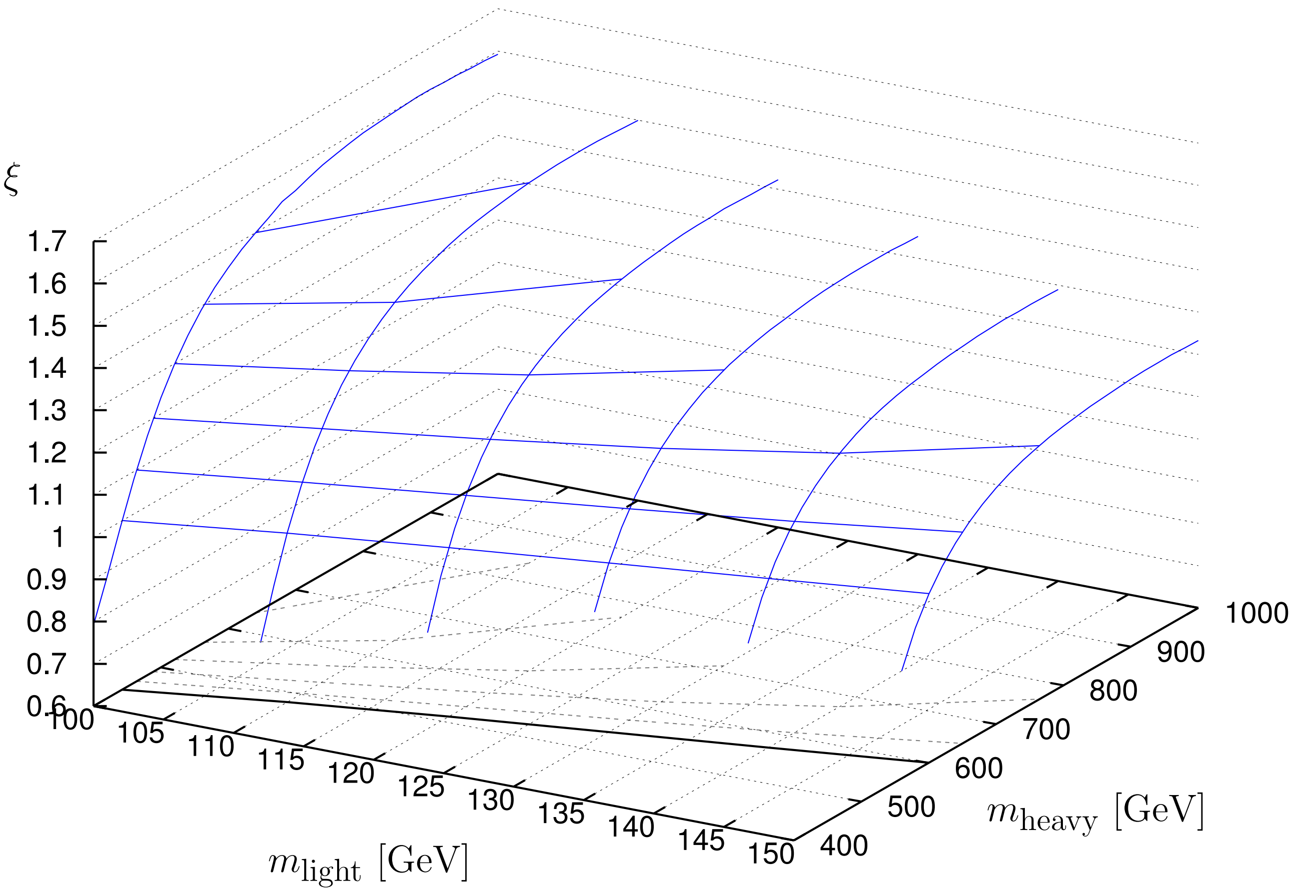
$T_c = 120.5 \text{ GeV},\ v_c = \sqrt{{v_{c_1}}^2 + {v_{c_2}}^2} = 151.3 \text{ GeV} \quad \Rightarrow \quad \xi = 1.3$

$\tan(\beta_T) = \frac{v_{c2}}{v_{c_1}} = 0.97$


$V_{\rm eff}$ [GeV^4]
3×10^6
2.5×10^6
2×10^6
1.5×10^6
1×10^6
500000
50
100
150
200
$\phi = \sqrt{\phi_1^2+\phi_2^2}$ [GeV]


$\frac{\phi_2}{\phi_1}$
1.1
1.05
1
0.95
0.9
0
25
50
75
100
125
150
175
$\phi = \sqrt{\phi_1^2+\phi_2^2}$ [GeV]

Strength of the phase transition $(\mu_3^2 = 30000\ \mathrm{GeV}^2)$



Phase transition – CP violating case

Complex μ_3^2 in $V_0 = \ldots - \mu_3^2 \Phi_1^\dagger \Phi_2 - \mu_3^{2*} \Phi_2^\dagger \Phi_1 + \ldots$

with $$\mu_3^2 = |\mu_3^2| e^{i\varphi}.$$

VEVs: $$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 e^{i\theta_1} \end{pmatrix} \text{ and } \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 e^{i\theta_2} \end{pmatrix}$$

We treat the CP violation as a small perturbation.

Minimizing the effective Potential $V_{\text{eff}}(\phi_1, \phi_2, \theta \equiv \theta_2 - \theta_1)$.

Symmetric phase: $v_{\text{sym}} = 0, \quad \theta_{\text{sym}} = \varphi$

Broken phase: $v_{\text{brk}} = v_c > 0, \quad \theta_{\text{brk}} \neq \varphi$

$\Delta\theta = \theta_{\text{sym}} - \theta_{\text{brk}} \neq 0$

Bubble wall profile:

$$\phi(z) = \frac{v_c}{2}\left(1 - \tanh\frac{z}{L_W}\right) \qquad \text{with } L_W\text{=thickness of the bubble wall}$$

Restricting to the **top quark**, coupled only to Φ_2,
in the limit $\tan(\beta_T) \approx 1$ we get:

$$\begin{aligned} m_{\text{top}} &= m(z)e^{i\theta_t(z)} \\ \text{with } \; m(z) &= \frac{y_2}{\sqrt{2}}\phi(z) \\ \text{and } \quad \theta_t(z) &= \frac{1}{2}\left(\frac{\Delta\theta}{2}\left(1 + \tanh\frac{z}{L_W}\right)\right) + \theta_{\text{brk}} \end{aligned}$$

[Huber, John, Laine, Schmidt (1999)]

EXAMPLE:

$|\mu_3^2| = 30000 \text{ GeV}^2, \varphi = 0.1, m_{\text{light}} = 120 \text{ GeV}, m_{\text{heavy}} = 600 \text{ GeV}$

$T_c = 117.5$ GeV, $\quad v_c = 145.4$ GeV $\quad \Rightarrow \quad \xi = 1.2$

$\tan(\beta_T) = 0.97$

$\theta_{\text{sym}} = \varphi = 0.1, \quad \theta_{\text{brk}} = 0.036 \quad \Rightarrow \quad \Delta\theta = 0.064$

Results: $\Delta\theta$ becomes larger for

- increasing m_{heavy}
- decreasing m_{light}
- decreasing $|\mu_3^2|$
- increasing φ

Baryon asymmetry – Preliminary results

We describe the evolution of the plasma by
using classical Boltzmann equations with a fluid-type ansatz in the rest frame of the plasma.

Expanding the transport equations in derivatives of the fermion mass.

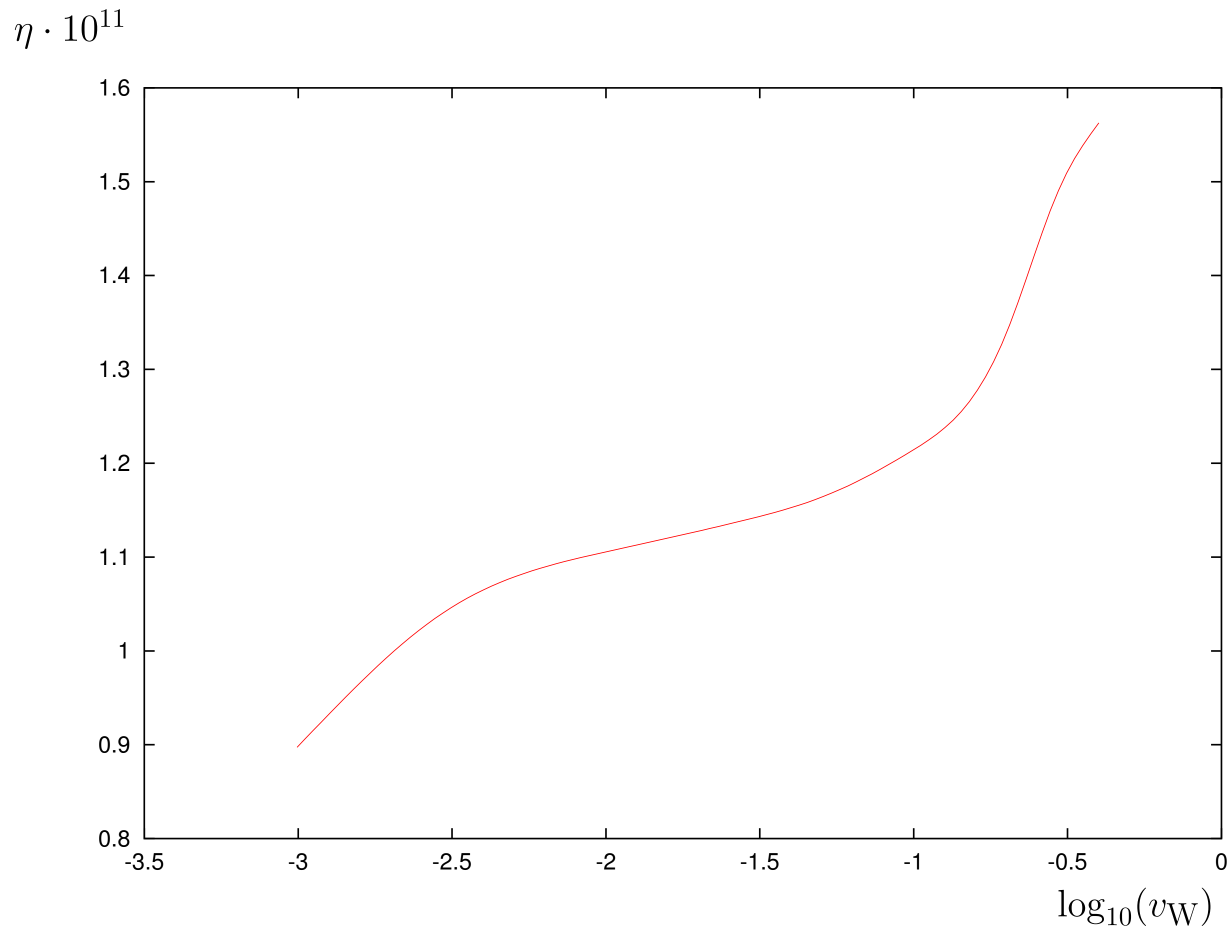
Taking into account source terms proportional to first order perturbations.

Computing the asymmetry in the left-handed quark density.

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

Example:

$|\mu_3^2| = 30000\ \text{GeV}^2, \varphi = 0.1, m_{\text{light}} = 120\ \text{GeV}, m_{\text{heavy}} = 600\ \text{GeV}$



We can reach the right order of magnitude of the BAU.

Summary and Outlook

Summary:

- Investigation of the EWPT in the 2 Higgs doublet model.
- Strong first order phase transition occurs for a wide parameter region.
- Introducing explicit CP violation in the potential.
- Treating the CP violation as a small perturbation.
- Enough CP violation is possible to generate the BAU.
- Parameters are in accord with the experimental electroweak constraints.

Outlook:

- Testing the influence of different Higgs bosons.
- Computing the baryon asymmetry in the 2HDM.
- Analyzing the parameter region with regard to the BAU.