A Strongly First Order Electroweak Phase Transition in Explicitly $\mathcal{CP}$ Violating Two-Higgs-Doublet Models

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Overview

The Baryon Asymmetry of the Universe (BAU)

The present Universe: Baryons vastly more numerous than antibaryons

Before proposing mechanisms, what is needed to generate the BAU (so-called baryogenesis)?

$\longrightarrow$ **Sakharov conditions** (necessary, not sufficient):

1. Baryon number violation (obvious)
2. $\mathcal{C}$ and $\mathcal{CP}$ violation (differentiates between particle and anti-particle)
3. Thermal inequilibrium (to avoid baryon wash-out)

Electroweak Baryogenesis:

- Electroweak scale $T \sim 100$ GeV
- Electroweak Phase Transition (EWPT):

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$$

- Symmetry broken when scalar fields acquire non-zero VEVs (Higgs mechanism) and asymmetry is generated

The BAU – Electroweak Baryogenesis (EWBG)

EWPT: Needs to be strongly first order ($\zeta = v_C / T_C \gtrsim 1$, rule of thumb)

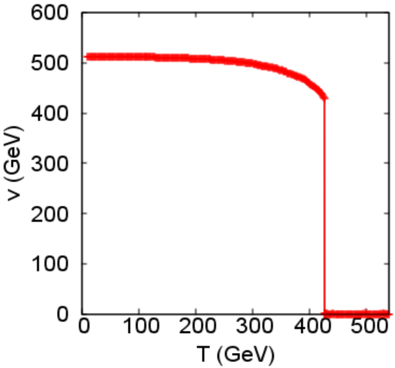


Figure 1: A strongly first order phase transition

Standard Model (SM): Not enough $\mathcal{CP}$ violation + if EWPT first order, then $m_h \lesssim 70$ GeV $\implies$ BSM physics needed!

Motivation: Minimal extension of the SM – e.g., more sources for $\mathcal{CP}$ violation

Define $SU(2)_L$ doublets $\Phi_i(x) = \left(\Phi_i^+(x),\, \Phi_i^0(x)\right)^T$ for $i \in \{1,\, 2\}$ with hypercharge $+1/2$

$$\Longrightarrow \qquad V_{\text{tree}}\left(\Phi_1, \Phi_2\right) = $$
$$m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{H.C.}\right) + \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 +$$
$$+\frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) +$$
$$+\left(\frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1\right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2\right)\right]\left(\Phi_1^\dagger \Phi_2\right) + \text{H.C.}\right)$$

where $m_{11}^2,\, m_{22}^2,\, \lambda_1,\, \lambda_2,\, \lambda_3,\, \lambda_4 \in \mathbb{R}$ and $\lambda_5,\, \lambda_6,\, \lambda_7,\, m_{12}^2 \in \mathbb{C}$
$\Longrightarrow$ New sources for $\mathcal{CP}$ violation (explicit)!
Note: Many new parameters $\Longrightarrow$ Parameter space scans

Two-Higgs-Doublet Models – Vacuum Expectation Values (VEVs)

In EWPT, the two scalar fields acquire VEVs:

$$\langle \Phi_1 \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ e^{i\xi_1} \cos\beta \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ e^{i\xi_2} \sin\beta \end{pmatrix}$$

where $v = 1/(\sqrt{2}G_F)^2 \approx 246$ GeV and $\beta \in [0, \pi/2]$. Non-zero phases $e^{i\xi_j} \implies$ yet another source for $\mathcal{CP}$ violation (spontaneous)! However, assume $\xi_j = 0$

Define new parameter: $\tan\beta = \frac{v_2}{v_1}$

Two-Higgs-Doublet Models – Particles

Particles: Note 8 d. o. f. in $\Phi_{1,2}$

- $G^{\pm}$ and G^0 Goldstone modes: give mass to $W^{\pm}$ and Z $(8 - 3 = 5)$
- h_1, h_2, h_3, and $H^{\pm}$ physical Higgs states with $m_{h_1} \leq m_{h_2} \leq m_{h_3}$ $(5 - 5 = 0)$

One of h_i must have $m_{h_i} = 125$ GeV!

Mass matrix for neutral scalars: 3×3, diagonalized by angles α, α_b and α_c ($\beta - \alpha$, α_b and α_c physically interesting)

Two-Higgs-Doublet Models – Yukawa Sector

$$-\mathcal{L}_{\rm Yuk} \;=\; \bar{Q}_L\left(\eta_1^D\Phi_1+\eta_2^D\Phi_2\right)d_R+\bar{Q}_L\left(\eta_1^U\tilde{\Phi}_1+\eta_2^U\tilde{\Phi}_2\right)u_R+\text{H.C.}$$

Yukawa matrices $\eta_i^F \in \mathbb{C}^{3\times 3}$, the scalar field $\tilde{\Phi}_j = -i\sigma_2\,\Phi_j^*$

Remark: Theorem by Glashow and Weinberg – No FCNCs if given fermion only couples to one Higgs doublet $\implies$ Symmetry $\mathbb{Z}_2 : \Phi_i \mapsto (-1)^{i+1}\Phi_i$ and $f_R \mapsto (\pm 1)\,f_R$. Note that $\mathbb{Z}_2 : \mathcal{L} \mapsto \mathcal{L}$ requires $m_{12}^2, \lambda_6, \lambda_7 = 0 \implies$ Different types (I and II)

Two-Higgs-Doublet Models – Effective Potential

The full potential can be written at $T = 0$, with ith loop correction given by $V_{(i)}(\Phi_1, \Phi_2)$,

$$V(\Phi_1, \Phi_2) = V_{\text{tree}}(\Phi_1, \Phi_2) + \sum_{i=1}^{\infty} V_{(i)}(\Phi_1, \Phi_2)$$

Want temperature dependent potential (1-loop at least). Use 1-loop thermally corrected effective potential

$$\begin{aligned} V(\Phi_1, \Phi_2, T) \; &= \; V_{\text{tree}}(\Phi_1, \Phi_2) + V_{(1)}(\Phi_1, \Phi_2) + V_{CT}(\Phi_1, \Phi_2) \\ & \quad V_T(\Phi_1, \Phi_2, T) \end{aligned}$$

where $V_{CT}(\Phi_1, \Phi_2)$ are counterterms and

$$V_{(1)}(\Phi_1, \Phi_2) = \sum_i \pm \frac{n_i}{64\pi^2} m_i^4(\Phi_1, \Phi_2) \left[\ln \frac{m_i^2(\Phi_1, \Phi_2)}{Q^2} - \frac{3}{2} \right]$$

$$V_T(\Phi_1, \Phi_2, T) = T^4 \sum_i \pm \frac{n_i}{2\pi} \int_0^{\infty} dx\, x^2 \ln\left(1 \mp e^{-\sqrt{x^2 + m_i^2(\Phi_1, \Phi_2)/T^2}}\right)$$

Constraints – Theoretical and Experimental

A "good" point in parameter space:
EWPT:

- $\zeta = v_C / T_C \gtrsim 1$

Theoretical constraints:

- Positivity, unitarity and perturbativity at tree level
- Global minimum at tree level

Experimental constraints:

- Higgs physics (from searches and discovery): `HiggsBounds` and `HiggsSignals`
- Electroweak physics (Oblique parameters S, T and U define how "SM like" a model is, with $(S, T, U) = (0, 0, 0)$ for the SM. Ellipse of 90% CL)
- Electric dipole moment searches for electron

Results

Parameter space scans:

- Phenomenological basis:
  $\left\{ m_{h_i},\ m_{H^\pm},\ \alpha,\ \alpha_b,\ \alpha_c,\ \tan\beta,\ \nu = \frac{\Re\left(m_{12}^2\right)}{2v_1 v_2},\ \lambda_6,\ \lambda_7 \right\}$
- $m_{h_1} = 125$ GeV
- $m_{h_2} \in (125,\ 900)$ (GeV)
- $\left| m^2_{h_3,H^\pm} - m^2_{h_2} \right| < v^2$ (motivated by oblique parameters)
- $\nu \in (-5,\ 5)$
- $\tan\beta \in (1/2,\ 10)$
- Explicitly $\mathcal{CP}$ violating
- Broken $\mathbb{Z}_2$:
  - $\lambda_6, \lambda_7 = 0$ (soft) and $m_{12}^2 \neq 0$, or $\lambda_6, \lambda_7, m_{12}^2 \neq 0$ (hard)

Results – Soft $\mathbb{Z}_2$ breaking

- $\lambda_6, \lambda_7 = 0$
- α not independent parameter

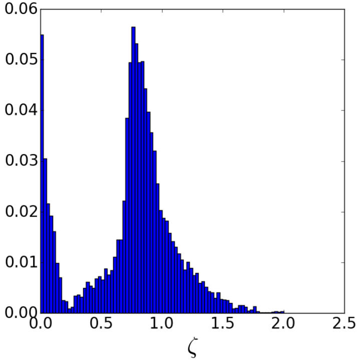


Figure 2: The distribution of ζ

Type I:

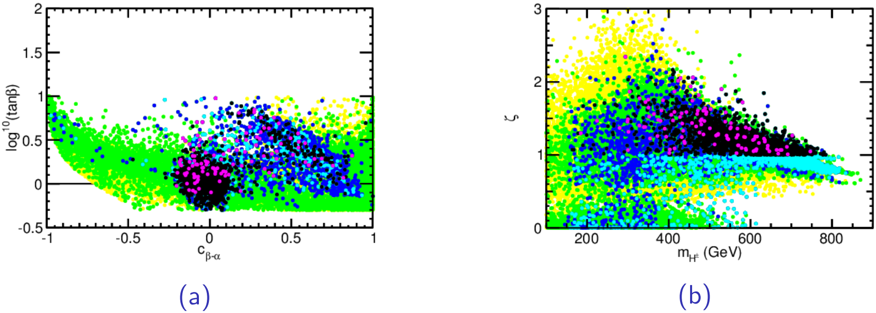
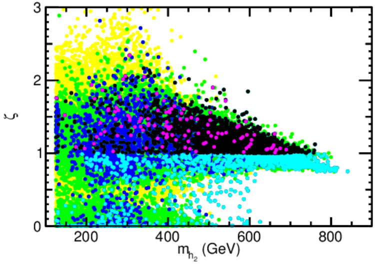
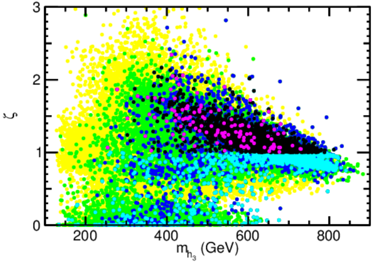


Figure 3: (a) $\tan\beta$ as a function of $\cos(\beta-\alpha)$, and (b) The strength of the EWPT, ζ, as a function of $m_{H^\pm}$

Results – Soft $\mathbb{Z}_2$ breaking



(a)



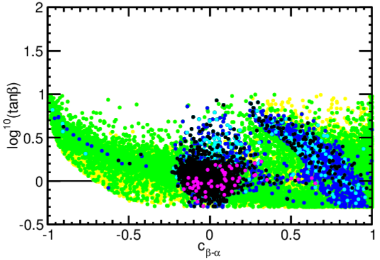
(b)

Figure 4: The strength of the EWPT, ζ, as a function of (a) m_2 and (b) m_{h_3}.

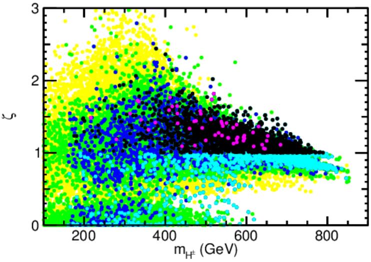
$\Longrightarrow$ Prediction: $m_{h_{2,3}}$ and $m_{H^\pm}$ must be $\gtrsim$ 400 GeV. Consistent with flavour physics constraints

No clear correlation between ζ and other parameters

Type II:



(a)



(b)

Figure 5: (a) $\tan\beta$ as a function of $\cos(\beta-\alpha)$, and (b) The strength of the EWPT, ζ, as a function of $m_{H^\pm}$

Low $\tan\beta$ good, consistent with baryon asymmetry. Here lower than for Type I.

Conclusions and Outlook

- Distribution of ζ shows that 2HDMs indeed can support strongly first order EWPT
- Exist regions in parameter space with points having strongly first order EWPT and satisfying the other imposed constraints

$\Longrightarrow$ There seems to be hope for 2HDMs to explain the BAU through EWBG!

Other interesting things to do:

- Lowest neutral scalar mass $\leq$ 125 GeV
- Include thermally corrected masses
- Cosmological implications of several minima of potential
- Study the exact dynamics during generation of baryon asymmetry to see whether or not 2HDMs actually can produce the BAU

Thank you for listening!

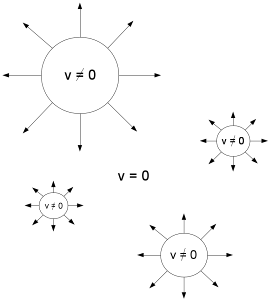


Figure 6: Bubbles of broken phase nucleate and start expanding.

EWBG:

(i) Scattering + $\mathcal{CP}$ viol. $\implies$ Asymmetries in number densities
(ii) Biased sphaleron transitions $\implies$ $\Delta_B \neq 0$
(iii) Baryons go inside bubbles + suppressed sphaleron transitions $\implies$ BA

Backup – The Different Types

Type I

$$\begin{cases} \rho^F = \kappa^F \cot\beta, \; \forall F \\ f_R \mapsto f_R, \; \forall f \end{cases}$$

Type II

$$\begin{cases} \rho^D = -\kappa^D \tan\beta \\ \rho^U = \kappa^U \cot\beta \\ u_R \mapsto u_R \\ d_R \mapsto -d_R \end{cases}$$

Backup – Oblique Parameters and Small Mass Squared Differences

$$
\begin{aligned}
T &\propto \sum_{j=1}^{3}\left(1-\tilde{R}_{1j}^2\right)F\left(m_{H^\pm}^2,\, m_{h_j}^2\right)-\tilde{R}_{11}^2F\left(m_{h_2}^2,\, m_{h_3}^2\right)-\tilde{R}_{12}^2F\left(m_{h_3}^2,\, m_{h_1}^2\right)\\
&= \tilde{R}_{11}^2\left[F\left(m_{H^\pm}^2,\, m_{h_2}^2\right)+F\left(m_{H^\pm}^2,\, m_{h_3}^2\right)-F\left(m_{h_2}^2,\, m_{h_3}^2\right)\right]+\\
&\quad \tilde{R}_{12}^2\left[F\left(m_{H^\pm}^2,\, m_{h_1}^2\right)+F\left(m_{H^\pm}^2,\, m_{h_3}^2\right)-F\left(m_{h_1}^2,\, m_{h_3}^2\right)\right]+\\
&\quad \tilde{R}_{13}^2\left[F\left(m_{H^\pm}^2,\, m_{h_1}^2\right)+F\left(m_{H^\pm}^2,\, m_{h_2}^2\right)-F\left(m_{h_1}^2,\, m_{h_2}^2\right)\right]
\end{aligned}
$$

where

$$
\tilde{R}^T = R_3 = \begin{pmatrix} c_1c_2 & s_1c_2 & s_2 \\ -\left(c_1s_2s_3+s_1c_3\right) & c_1c_3-s_1s_2s_3 & c_2s_3 \\ -c_1s_2c_3+s_1s_3 & -\left(c_1s_3+s_1s_2c_3\right) & c_2c_3 \end{pmatrix}
$$

and e.g., $c_i = \cos\alpha_i$ (α_i depends on α, α_b, α_c and β)

$\implies$ Need small mass differences! $\left|m_{h_3,H^\pm}^2 - m_{h_2}^2\right| < v^2$

Backup – eEDM

The electron EDM is given by $\mathcal{T}$ and $\mathcal{P}$ violating low energy effective operators and the corresponding Lagrangian can be written

$$\mathcal{L}_e^{eff} = -i\,\frac{d_e}{2}\,\overline{e}\,\sigma_{\mu\nu}\gamma_5\,e\,F^{\mu\nu}$$

Conventionally a dimensionless EDM $\delta_e = -\frac{v^2 d_e}{2e^2 m_e}$ is defined, which can be calculated from 2-loop Barr-Zee diagrams such that

$$\begin{aligned}\delta_e \;=\; & (\delta_e)^{h\gamma\gamma}_{t/b} + (\delta_e)^{hZ\gamma}_{t/b} + (\delta_e)^{h\gamma\gamma}_{W^\pm} + (\delta_e)^{hZ\gamma}_{W^\pm} + (\delta_e)^{h\gamma\gamma}_{H^\pm} + (\delta_e)^{hZ\gamma}_{H^\pm} + \\ & + (\delta_e)^{H^\pm W^\mp\gamma}_{H^\pm} + (\delta_e)^{H^\pm W^\mp\gamma}_{t/b}\end{aligned}$$

where, e.g., the top contribution in the $h\gamma\gamma$ channel is given by

$$(\delta_e)^{h\gamma\gamma}_t = -N_C Q_e Q_t e^2 \frac{1}{64\pi^2} \sum_{i=1}^{3} \left[f\left(z_t^i\right) c_{t,i}\tilde{c}_{e,i} + g\left(z_t^i\right) \tilde{c}_{t,i} c_{e,i} \right]$$

and $c_{f,i}$ and $\tilde{c}_{f,i}$ are couplings, $z_t^i = m_t^2/m_{h_i}^2$ and f as well as g are loop functions.

Type II:

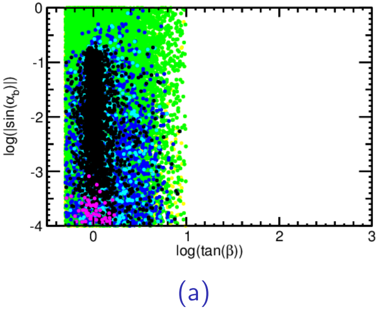


Figure 7: (a) $\log^{10}(\sin \alpha_b)$, and (b) $\log^{10}(\sin \alpha_c)$ plotted against $\log^{10}(\tan \beta)$