Spontaneous CP-violation in 2HD models and the MSSM

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1. **Motivation**
2. **The parameter space for spontaneous CP-violation within the 3d 2HD model**
3. **Comparison with the parameter space allowed by finite temperature MSSM**
4. **Conclusions**

Electroweak baryogenesis requires:

Sakharov 1967

1. Thermodynamical non-equilibrium during the transition, and sufficient switch-off afterwards.

$\Rightarrow$ Need a strong first order transition.

The region: right-handed stops are light, $m_{\tilde{t}_R} < m_{\text{top}}$.
($\Rightarrow$ The Higgs mass is $m_H =$ 90...110 GeV.)

Bödeker et al;
Carena et al;
Cline and Moore;
Losada;...

2. Microscopic B-violation.

The (non-perturbative) anomalous rate in the symmetric phase is by now well understood, and fast enough.

Arnold et al;
Bödeker;
Moore et al;...

3. Microscopic C, CP-violation.

Problematic, since experimentally very small $\Rightarrow$
Could it be enhanced around the EW transition? $\Rightarrow$
Spontaneous CP-violation in the MSSM at finite T?
(At the phase boundary? In the broken phase?)

Comelli et al 1993;
Espinosa et al 1993

SU(2) two Higgs doublet model in 3d ($\lambda_i \in \mathbf{R}$):

$$
\begin{aligned}
\mathcal{L}_{\text{3d}} &= \frac{1}{4}F^a_{ij}F^a_{ij} + (D_iH_1)^\dagger(D_iH_1) + (D_iH_2)^\dagger(D_iH_2) \\
&+m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 + [m_{12}^2 H_1^\dagger H_2 + \text{H.c.}] \\
&+\lambda_1(H_1^\dagger H_1)^2 + \lambda_2(H_2^\dagger H_2)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 \\
&+[\lambda_5(H_1^\dagger H_2)^2 + \lambda_6 H_1^\dagger H_1 H_1^\dagger H_2 + \lambda_7 H_2^\dagger H_2 H_1^\dagger H_2 + \text{H.c.}].
\end{aligned}
$$

Parametrize the scalar part as

$$
H_1 = \frac{v_1}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad H_2 = \frac{v_2}{\sqrt{2}}\begin{pmatrix} e^{i\phi} \\ 0 \end{pmatrix}.
$$

The part of the potential depending on ϕ:

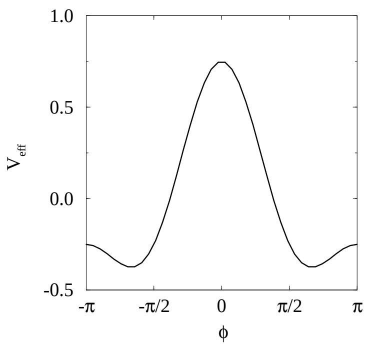
$$
\left[m_{12}^2 + \frac{1}{2}(\lambda_6 v_1^2 + \lambda_7 v_2^2)\right] v_1 v_2 \cos\phi + \frac{1}{2}\lambda_5 v_1^2 v_2^2 (2\cos^2\phi - 1).
$$

Symmetric in $\phi \to -\phi \Leftrightarrow$ C-invariance (& CP).

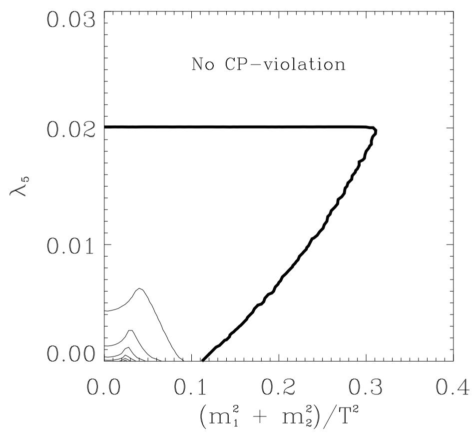
However, a non-trivial minimum exists if

$$
\left|\frac{m_{12}^2 + (1/2)(\lambda_6 v_1^2 + \lambda_7 v_2^2)}{2\lambda_5 v_1 v_2}\right| < 1.
$$

Lee 1973



The region of spontaneous CP-violation can be mapped out perturbatively at 1-loop level. A typical projection:



Note, in particular, that $m_1^2 + m_2^2 \lesssim 0.3T^2$.

On the other hand, this same 3d theory can be derived from the finite temperature MSSM by dimensional reduction! Then,

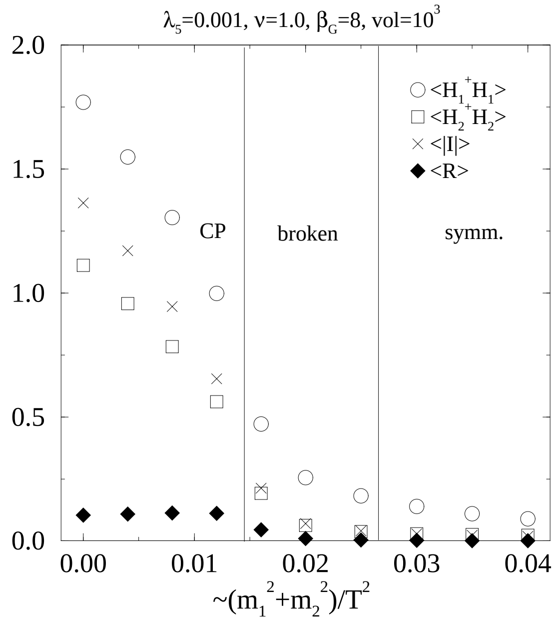
$$m_1^2 + m_2^2 \approx m_A^2 + 0.53T^2 + \ldots \gtrsim 0.9T^2$$

for all temperatures below 100 GeV, i.e., also in the broken electroweak Higgs phase. (The experimental lower limit on the CP-odd Higgs mass is $m_A \gtrsim 63$ GeV).

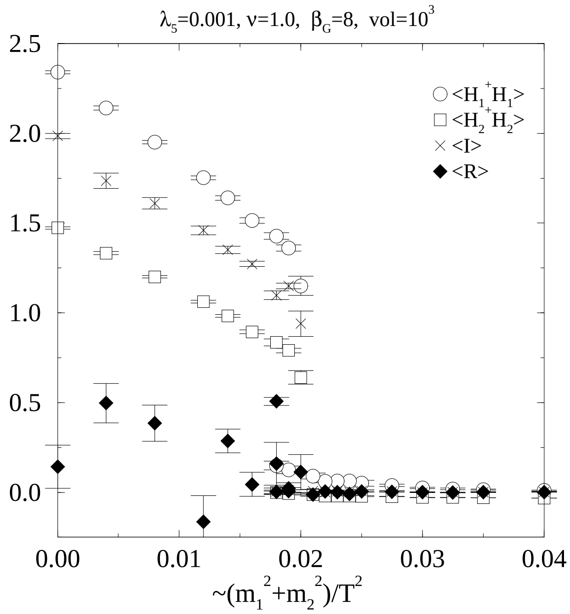
$\Rightarrow$ No spontaneous CP-violation in the MSSM!
(At least without a very light stop.)

Could the pattern change when non-perturbative effects are taken into account? Study with lattice: $I = \mathrm{Im}\, H_1^\dagger H_2$.

Perturbation theory:



Lattice:



$\Rightarrow$ The properties of the phase transition can change a lot. However, $\Delta(m_1^2 + m_2^2)/T^2$ does not change enough.

Conclusions

The parameter space of the 3d two Higgs doublet model contains a macroscopic region where CP is spontaneously violated. We have verified this statement non-perturbatively.

For the parameter values of the finite temperature MSSM studied (no 'dynamically light' stop), one does not end up in this region of the 3d theory with dimensional reduction.

Outlook

A light stop could improve the prospects of spontaneous CP-violation. More generally, spontaneous CP-violation can take place in general 4d two Higgs doublet models.

One could also study explicit CP-violation non-perturbatively, as well as effects restricted to the phase boundaries.