The CP properties of the 2HDM

Talk given at *Scalars 2011*

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The 2HDM potential

$$
\begin{aligned}
V(\Phi_1, \Phi_2) \quad = \quad & -\frac{1}{2}\left\{m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right]\right\} \\
& +\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
& +\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right] \\
& +\left\{\left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right](\Phi_1^\dagger\Phi_2) + \text{h.c.}\right\}
\end{aligned}
$$

EWSB

- Vacuum expectation values – most general form that preserves $U(1)_{em}$:

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 e^{i\theta} \end{pmatrix}$$

Change of basis

- Initial expression of potential is defined with respect to fields Φ_1 and Φ_2 - this defines our initial basis.
- We can change to a new basis by the following transformation

$$\bar{\Phi}_i = U_{ij}\Phi_j$$

where *U* is a U(2) matrix.

CP-properties

- Higgs-sector is CP-conserving if a basis exists in which all the parameters of the potential AND the vevs are simultaneously real.
- If CP is broken, it can be broken either *explicitly* or *spontaneously.*
  - – *<u>Explicit breaking:</u> No basis exists in which the parameters of the potential are all real.*
  - – *<u>Spontaneous breaking:</u> A basis exists in which all the parameters of the potential are real, but the vevs cannot be made real simultaneously.*

Motivation

- Will it be possible in experiments to measure if CP is broken *explicitly* or *spontaneously*?
- Will the type of CP-violation (explicit vs spontaneous) have any important physical consequences?

CP conservation

- To determine if CP is conserved or broken, we study the three weak-basis invariants J_1, J_2, J_3.
- If J_1, J_2, J_3 are all real, CP is conserved.
- If at least one of J_1, J_2, J_3 is complex, CP is broken.

CP breaking

- If CP is not conserved, we can determine if it is broken spontaneously or explicitly by studying another set of invariants: I_{Y3Z} , I_{2Y2Z} , I_{6Z} , I_{3Y3Z} .
- If CP is not conserved, and at the same time I_{Y3Z} , I_{2Y2Z} , I_{6Z} , I_{3Y3Z} are all zero, then CP is spontaneously broken.
- If CP is not conserved, and at the same time at least one of I_{Y3Z} , I_{2Y2Z} , I_{6Z} , I_{3Y3Z} is non-zero, then CP is broken explicitly.

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Assumptions

- Z_2 symmetry only softly broken:

$$\lambda_6 = \lambda_7 = 0$$

- Real ”vacuum”

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

with $v_1^2 + v_2^2 = v^2 = (246 \text{ GeV})^2$

The invariants J_i

$$
\begin{aligned}
\mathrm{Im}J_1 &= -\frac{v_1^2 v_2^2}{v^4}(\lambda_1 - \lambda_2)\mathrm{Im}\lambda_5 \\
\mathrm{Im}J_2 &= -\frac{v_1^2 v_2^2}{v^8}\left[\left((\lambda_1 - \lambda_3 - \lambda_4)^2 - |\lambda_5|^2\right) v_1^4 + 2(\lambda_1 - \lambda_2)\mathrm{Re}\lambda_5 v_1^2 v_2^2 \right. \\
&\qquad \left. - \left((\lambda_2 - \lambda_3 - \lambda_4)^2 - |\lambda_5|^2\right) v_2^4\right] \mathrm{Im}\lambda_5 \\
\mathrm{Im}J_3 &= \frac{v_1^2 v_2^2}{v^4}(\lambda_1 - \lambda_2)(\lambda_1 + \lambda_2 + 2\lambda_4)\mathrm{Im}\lambda_5
\end{aligned}
$$

The invariants I_{Y3Z} , I_{2Y2Z} , I_{6Z} , I_{3Y3Z}

$$
\begin{aligned}
I_{Y3Z} &= 0, \\
I_{2Y2Z} &= \frac{1}{4}(\lambda_1 - \lambda_2)\mathrm{Im}\left[(m_{12}^2)^2\lambda_5^*\right] \\
I_{3Y3Z} &= -\frac{1}{8}(m_{11}^2 - m_{22}^2)\left[(\lambda_1 - \lambda_3 - \lambda_4)(\lambda_2 - \lambda_3 - \lambda_4) - |\lambda_5|^2\right] \\
&\quad \times \mathrm{Im}\left[(m_{12}^2)^2\lambda_5^*\right] \\
I_{6Z} &= 0.
\end{aligned}
$$

CP conservation:

CP is conserved if one or more of the following conditions are satisfied:

- $v_1 = 0$
- $v_2 = 0$
- $\mathrm{Im}\,\lambda_5 = 0$
- $\lambda_1 = \lambda_2$ and $v_1 = v_2$
- $\lambda_1 = \lambda_2$ and $(\lambda_1 - \lambda_3 - \lambda_4)^2 = |\lambda_5|^2$

CP is broken spontaneously when:

- CP is not conserved

  AND in addition one (or both) of the following conditions are satisfied

- $\mathrm{Im}\left[(m_{12}^2)^2\lambda_5^*\right] = 0$

- $\lambda_1 = \lambda_2$ and $m_{11}^2 = m_{22}^2$

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CP is broken explicitly when:

- CP is not conserved or broken spontaneously

Strategy

- Start out with a physical spectrum, mixing angles and ”vacuum expectation values”. (Pick M_1 , M_2 , M , $\tan\beta = v_2 / v_1$, μ^2 , α_i)
- From this, calculate the parameters of the potential, (λ_i and m_{ij}) and $(M_3)^2$
- Apply theoretical (and experimental) constraints
- Determine the CP properties

Theoretical constraints

- Positivity (potential must be bounded from below)
- Globality (the starting ”vacuum” should be the global minimum of the potential)
- Unitarity (unitarity at tree level)

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Two cases

Case A

- M_1 = 100 GeV
- M_2 = 300 GeV
- $M^{\pm}$ = 500 GeV
- μ^2 = $(200\ \text{GeV})^2$
- tan β = 2
- $\alpha_1 = -\pi/6$

  Explore the CP properties in α_2-α_3 space

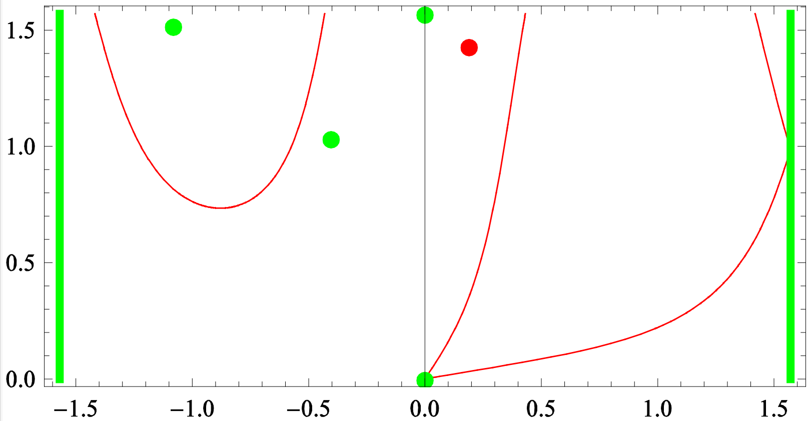
Case B

- M_1 = 100 GeV
- M_2 = 300 GeV
- $M^{\pm}$ = 500 GeV
- μ^2 = $(200\ \text{GeV})^2$
- tan β = 2
- $\alpha_1 = \pi/6$

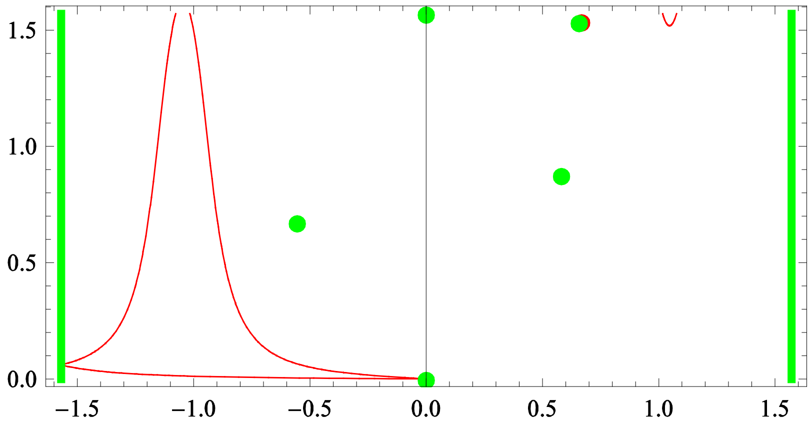
  Explore the CP properties in α_2-α_3 space

The CP properties

Case A: $\alpha_1 = -\pi/6$



Case B: $\alpha_1 = \pi/6$



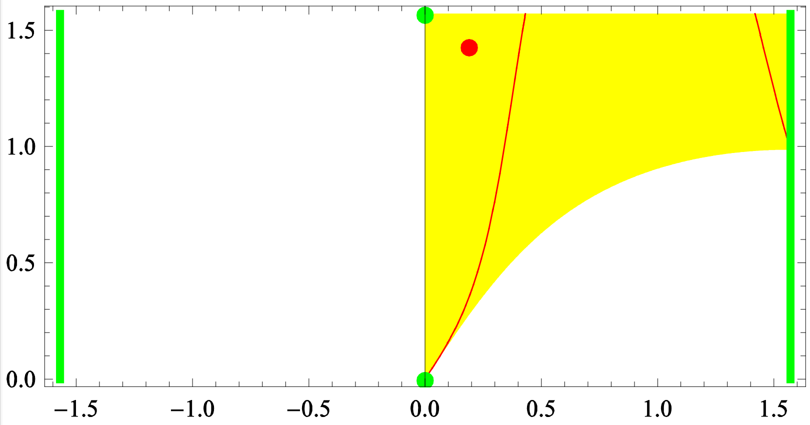
Green: CPC

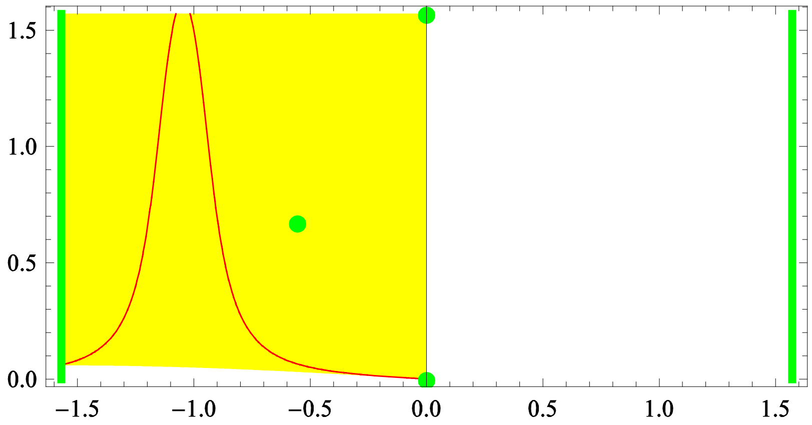
Red: Spontaneous CPV

Region with $(M_3)^2 > (M_2)^2$

Case A: $\alpha_1 = -\pi/6$

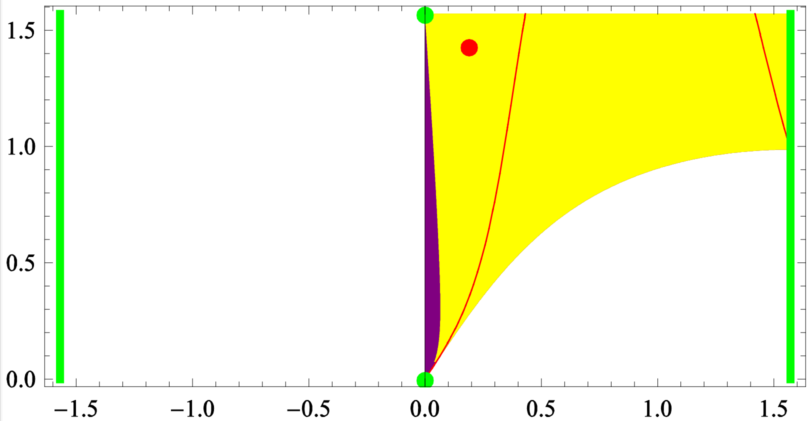
Case B: $\alpha_1 = \pi/6$



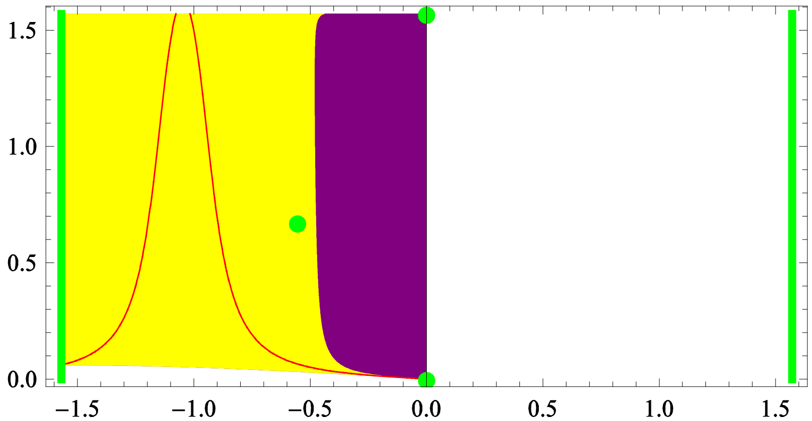


Positivity constraint imposed

Case A: $\alpha_1 = -\pi/6$



Case B: $\alpha_1 = \pi/6$



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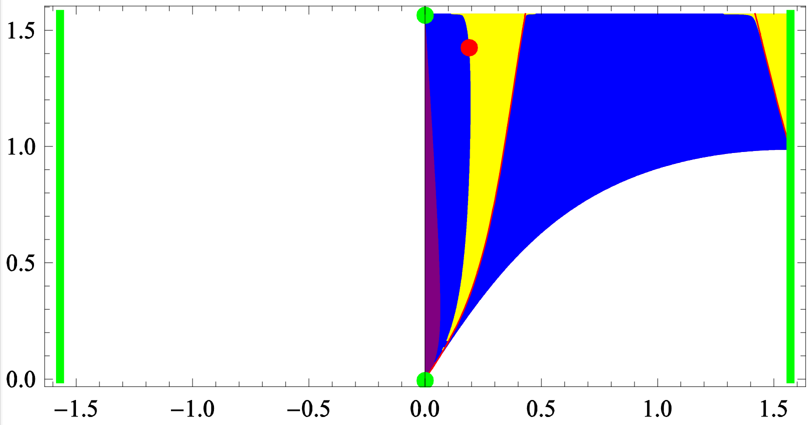
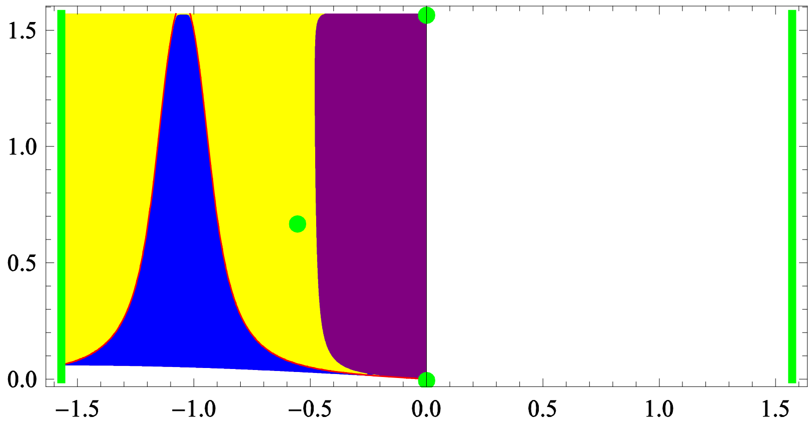
Globality constraint imposed

Case A: α_1 = -π/6



Case B: α_1 = π/6



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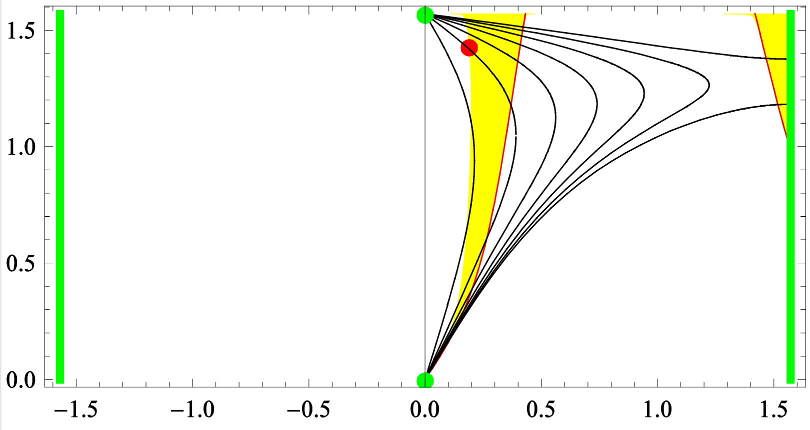
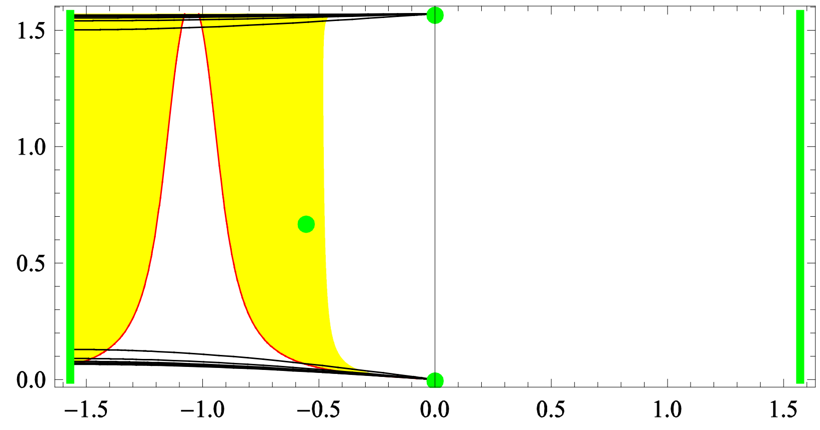
Mass contours for M_3

Case A: $\alpha_1 = -\pi/6$

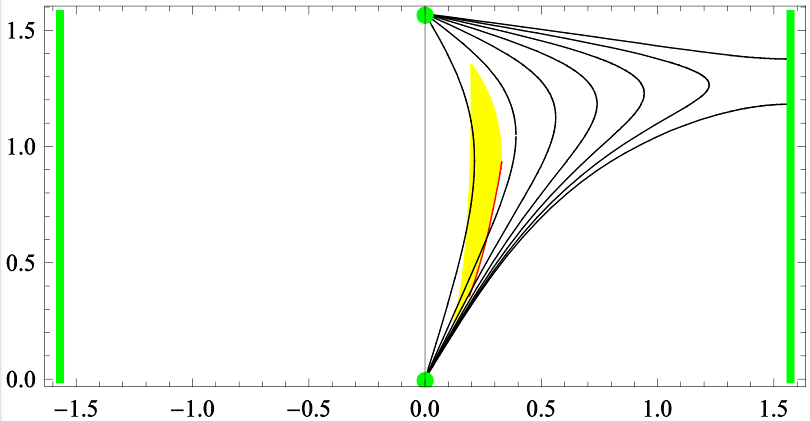


Case B: $\alpha_1 = \pi/6$

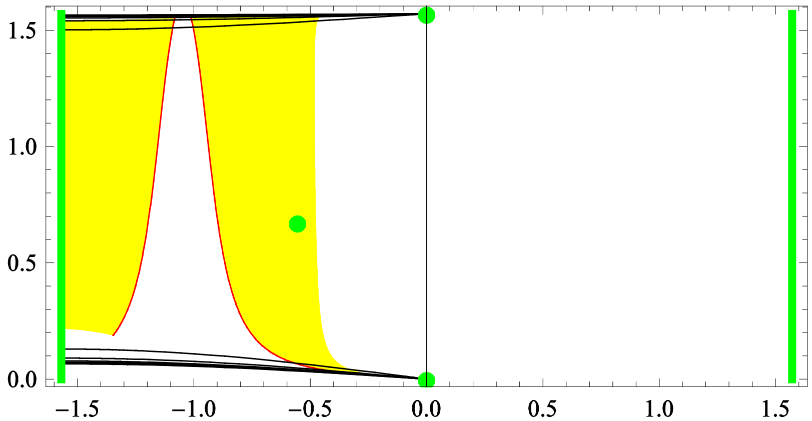


Unitarity constraint imposed

Case A: $\alpha_1 = -\pi/6$



Case B: $\alpha_1 = \pi/6$



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Summary

- SCPV only appears along the boundary between the explicitly CP-violating region and the region forbidden because our ”vacuum” is not the global minimum.
- When we have SCPV the potential has two minima of exactly the same depth, meaning that the global minimum is not unique.

Open questions

- What are the physical implications of two minima of the same depth?
- Will the universe choose one of these minima, or exist in a mixed state?
- Could the early universe have rested in a ”false vacuum” before tunneling into the proper vacuum?
- Is our universe today in a state of a ”false vacuum” so that it at a later stage may tunnel into the proper vacuum?