Phase transitions in 2HDM

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Motivation

Minimal SM

- One Higgs doublet – charge and CP conserving vacuum.
- Early universe – high temperatures T.
- Vacuum expectations are given by minimisation of Gibbs potential
  $$\Phi = V(\phi) + aT^2\phi^2$$
- Cooling $\langle\phi\rangle = 0 \to \langle\phi\rangle \neq 0$ – EWSB phase transition.

Two Higgs doublet model (2HDM)

- Vacua with different properties can exist.
- It is possible to have a sequence of phase transitions (between different vacua) during cooling of the Universe. [Ginzburg,Kanishev,2007]

2HDM Potential

- Two scalar doublets: $\phi_1 = \begin{pmatrix} \phi_{11} \\ \phi_{12} \end{pmatrix} \qquad \phi_2 = \begin{pmatrix} \phi_{21} \\ \phi_{22} \end{pmatrix}$
- Scalar combinations: $x_1 = \phi_1^\dagger \phi_1, \quad x_2 = \phi_2^\dagger \phi_2, \quad x_3 = \phi_1^\dagger \phi_2 \,.$

Most general form of potential

$$V = \tfrac{1}{2}\lambda_1 x_1^2 + \tfrac{1}{2}\lambda_2 x_2^2 + \lambda_3 x_1 x_3 + \lambda_4 x_3^\dagger x_3 + \left[\tfrac{1}{2}\lambda_5 x_3^2 + (\lambda_6 x_1 + \lambda_7 x_2)\, x_3 + h.c.\right]$$
$$-\tfrac{1}{2}\left[m_{11}^2 x_1 + m_{22}^2 x_2 + \left(m_{12}^2 x_3 + h.c.\right)\right]$$

- Most general case: λ_{1-4}, m_{11}^2, m_{22}^2 - real, λ_{5-7}, m_{12}^2 - complex. Positivity constraints: $V > 0$ at large values of ϕ_i
- Explicitly CP conserving potential – all λ_i and m_{ij}^2 are real.
- Soft Z_2 violation: $\lambda_6 = \lambda_7 = 0$ (Z_2 is violated only by quadratic term)

Extremum, minimum, vacuum

Usual definitions

Extremum : point with $\left.\frac{\partial V}{\partial \phi_i}\right|_{\langle \phi_j \rangle} = \left.\frac{\partial V}{\partial \phi_i^\dagger}\right|_{\langle \phi_j \rangle} = 0$ (extremum conditions)

Minimum : local minimum $\left.\frac{\partial^2 V}{\partial \phi_i \partial \phi_j^\dagger}\right|_{\langle \phi_j \rangle} \geq 0 \quad \Leftrightarrow \quad$ masses $M^2 > 0$

Vacuum or global minimum: local minimum with lowest E.

- We use the fact that extremum with least energy is the global minimum due to positivity of potential.
  1. Find all extrema.
  2. Find extremum with least energy.
  3. This extremum is the global minimum.

Classification of extrema in 2HDM

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle\phi_2\rangle = \begin{pmatrix} u \\ v_2 e^{-i\xi} \end{pmatrix}, \quad u, v_1, v_2 > 0$$

$$v^2 = v_1^2 + v_2^2 + u^2, \quad \tan\beta = v_2/v_1$$

Electroweak conserving point (EW): $u = v_1 = v_2 = 0$

Electroweak symmetry is not broken.
Gauge bosons and fermions are massless.

Neutral extremum: $u = 0$

Electric charge is conserved, 5 physical Higgs particles (h_1, h_2, h_3, and $H^{\pm}$)

Spontaneous CP violating (sCPv) $\xi \neq 0$ – two degenerate extrema

CP conserving (CPc) $\xi = 0$ – up to 4 such extrema [A.Barroso, R.Santos]

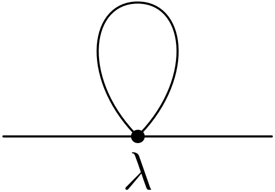
Charged extremum: $u \neq 0$

Electric charge is not conserved, photon is massive

Temperature dependence

Gibbs potential

- $V_G = \dfrac{Tr\left\{V\, e^{-H/T}\right\}}{Tr\left\{e^{-H/T}\right\}} = V + \Delta V$



- Matsubara diagram technique
- First corrections are $\sim T^2$

$$\Delta m_{11}^2 = g(3\lambda_1 + 2\lambda_3 + \lambda_4)\,T^2$$
$$\Delta m_{22}^2 = g(3\lambda_2 + 2\lambda_3 + \lambda_4)\,T^2$$
$$\Delta m_{12}^2 = 2g(\lambda_6 + \lambda_7)\,T^2$$

Evolution of parameters with T^2 leads to evolution of vacuum states during cooling of Universe.

$\xrightarrow{I}$ First order phase transition: discontinuity in $v(T^2)$ and $\tan\beta(T^2)$.

$\xrightarrow{II}$ Second order phase transition: $v(T^2)$, $\tan\beta(T^2)$ change continuously.

Toy model

Parameters

$$\lambda_1 = \lambda\,, \quad \lambda_2 = k^4\lambda\,, \quad m_{11}^2 = m^2(1-\delta) \quad m_{22}^2 = k^2m^2(1+\delta)$$

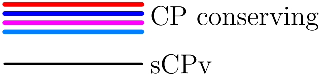
$$\lambda_6 = \lambda_7 = 0\,, \qquad \lambda_3, \lambda_4, \lambda_5, m_{12}^2 \in \mathbb{R}$$

- At $\delta = 0$ potential is symmetric under $\phi_1 \to k\phi_2$, $\phi_2 \to \frac{\phi_1}{k}$, $k > 1$

$$V = \lambda(\phi_1^\dagger\phi_1)^2 + k^4\lambda(\phi_2^\dagger\phi_2)^2 + ... + m^2\phi_1^\dagger\phi_1 + k^2m^2\phi_2^\dagger\phi_2 + ...$$

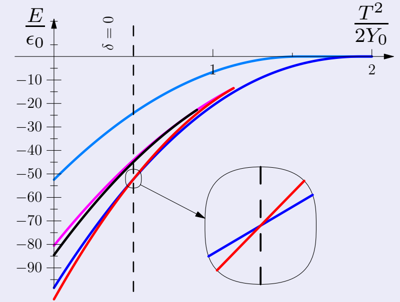
- During evolution potential passes through $\delta = 0$. At this moment two global minima could coexist.
- Useful quantities $Y = m^2/(2\lambda)$, $\epsilon = m^4/(8\lambda)$

EW $\xrightarrow{II}$ CPc $\xrightarrow{I}$ CPc

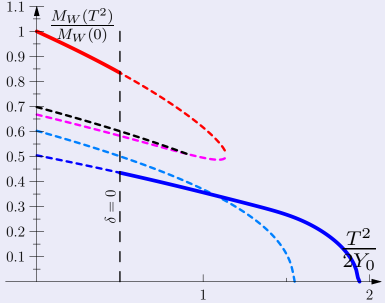


- First order phase transition at $\delta = 0$

Energies of extrema



M_W evolution



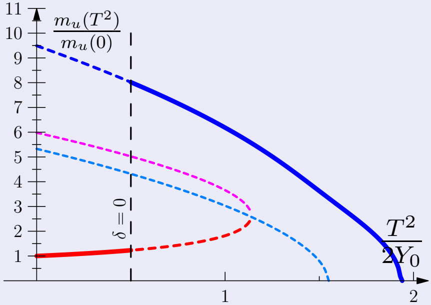
$$\lambda_1 = \lambda,\ \lambda_2 = 16\lambda\,(k = 2),\ \lambda_3 = 7\lambda,\ \lambda_4 = 0.9\lambda,\ \lambda_5 = -0.1\lambda,$$

$$m_{11}^2 = 28m^2,\ m_{22}^2 = 110m^2,\ m_{12}^2 = 6m^2$$

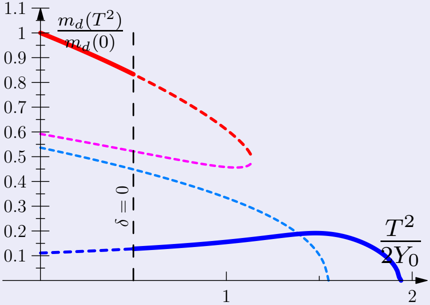
EW $\xrightarrow{II}$ CPc $\xrightarrow{I}$ CPc (...continuation.)

Model II: $\mathcal{L}_Y = -\Gamma_1^{ij} Q_L^i \phi_1 \, d_R^j - \Delta_2^{ij} Q_L^i \tilde{\phi}_2 \, u_R^j + h.c. \qquad Q_L^i = \begin{pmatrix} \bar{u}_L^i \\ \bar{d}_L^i \end{pmatrix}$

Fermion masses, Model II



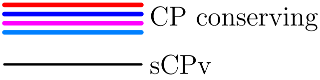
$m_{u,c,t}(T) \sim v(T) \cos\beta(T)$



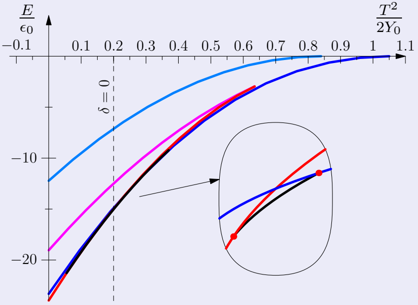
$m_{b,s,b}(T) \sim v(T) \sin\beta(T)$

EW $\overset{II}{\rightarrow}$ CPc $\overset{II}{\rightarrow}$ sCPv $\overset{II}{\rightarrow}$ CPc

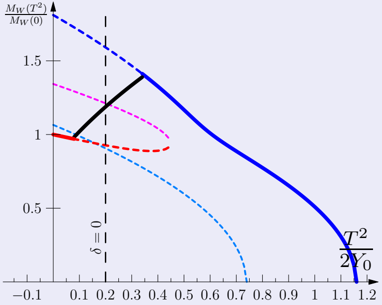
- Transition through spontaneously CP violating vacuum



Energies of extrema



M_W evolution



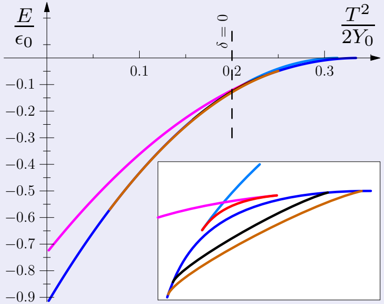
$$\lambda_1 = \lambda,\ \lambda_2 = 16\lambda\,(k=2),\ \lambda_3 = 5\lambda,\ \lambda_4 = 0.95\lambda,\ \lambda_5 = 2\lambda$$

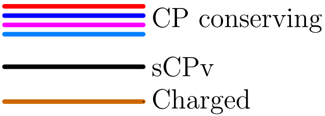
$$m_{11}^2 = 13.5m^2,\ m_{22}^2 = 55m^2,\ m_{12}^2 = 6m^2$$

EW $\xrightarrow{//}$ CPc $\xrightarrow{//}$ Charged $\xrightarrow{//}$ CPc

Transition through charged vacuum $< \phi_2 >= \begin{pmatrix} u \\ v_2 e^{-i\xi} \end{pmatrix}$

Energies of extrema





- Electric charge is not conserved
- Four massive Higgs bosons and four massive gauge bosons without definite electric charges.
- Up and down fermions can mix.

List of all possible sequences of phase transitions in soft Z_2 violating 2HDM

- EW $\xrightarrow{II}$ CPc $\xrightarrow{I}$ CPc
- EW $\xrightarrow{II}$ CPc $\xrightarrow{II}$ sCPv $\xrightarrow{II}$ CPc
- EW $\xrightarrow{II}$ CPc $\xrightarrow{II}$ sCPv
- EW $\xrightarrow{II}$ CPc $\xrightarrow{II}$ Charged $\xrightarrow{II}$ CPc
- EW $\xrightarrow{II}$ CPc $\xrightarrow{II}$ Charged
- EW $\xrightarrow{II}$ CPc

Based on geometrical approach by I.P. Ivanov
Sequences with most number of steps was presented.

Summary

- Different types of vacua can exist in 2HDM.
- It is possible to have phase transitions between these vacua during cooling of our Universe.
- Examples for first order phase transition, transition though CP violating and charged vacuum were presented.
- This set of sequences of phase transitions is exaustive for soft Z_2 violating potential.