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Inert Model and evolution of the Universe

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We consider evolution of the Universe after EWSB leading to the present inert phase, containing a SM-like Higgs boson and scalar dark particles, among them a Dark Matter candidate. We address the question, if there is a possibility to have a sequence of the phase transitions instead of a single one leading directly from EW symmetric phase to the inert one.

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PoS(ICHEP 2010)457

We consider the 2HDM Lagrangian for two $SU(2)$ scalar doublets φ_S, φ_D with Yukawa interaction set to Model I and the potential V:

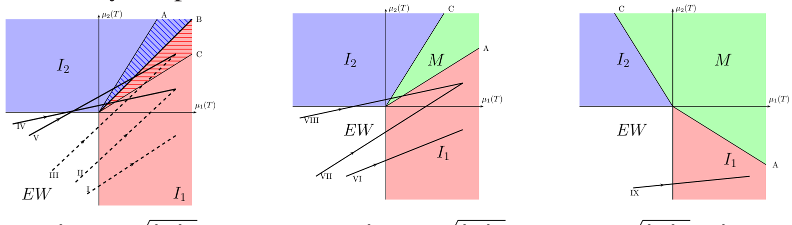
$$V = -\frac{m_{11}^2}{2}|\varphi_S|^2 - \frac{m_{22}^2}{2}|\varphi_D|^2 + \frac{\lambda_1}{2}|\varphi_S|^4 + \frac{\lambda_2}{2}|\varphi_D|^4 + \lambda_3|\varphi_S|^2|\varphi_D|^2 + \lambda_4|\varphi_S^\dagger\varphi_D|^2 + \frac{1}{2}\left(\lambda_5(\varphi_S^\dagger\varphi_D)^2 + h.c\right).$$

V is invariant under a Z_2 transformation: $\varphi_S \to \varphi_S$, $\varphi_D \to -\varphi_D$. In the Inert Model also vacuum state is Z_2-symmetric and the Dark Matter candidate, from the Z_2-odd doublet φ_D, appears.

The most general EWSB solution $\langle\varphi_S\rangle^T = \frac{1}{\sqrt{2}}(0, v_S), \langle\varphi_D\rangle^T = \frac{1}{\sqrt{2}}(u, v_D)$ gives three neutral extrema ($u = 0$): ***inert*** ($I_1; v_D = 0, v_S^2 = v^2$) with SM-like Higgs h from φ_S and DM candidate from φ_D (eg. H); ***inert-like*** ($I_2; v_S = 0, v_D^2 = v^2$) with massless fermions (Model I: only φ_S couples to fermions) and no candidate for DM; ***mixed*** ($M; v_D, v_S \neq 0, v^2 = v_S^2 + v_D^2$) – a standard 2HDM extremum. The lowest energy extremum, fulfilling positivity constraints, is the vacuum.

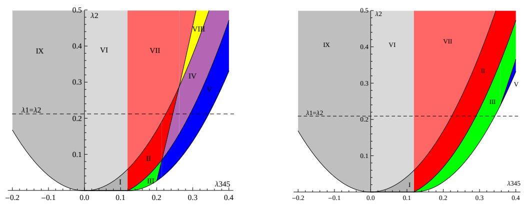
The one-loop thermal corrections to V are $m_{ii}^2(T) = m_{ii}^2 - c_i T^2$ ($i = 1,2$) where $c_i = c_i(\lambda_{1-4}; g, g'; g_t^2 + g_b^2$ for $i = 1$), with fixed λ_i (g, g' – EW gauge couplings, g_t, g_b – SM Yukawa couplings).

The possible sequences of phase transitions between different vacua are shown as rays in plots (1a-1c), for (μ_1, μ_2) plane ($\mu_i(T) = m_{ii}^2(T)/\sqrt{\lambda_i}, i = 1,2$). For $EW \to I_1$, I_1 is the only vacuum that existed after EWSB. For **rays I, VI, IX** I_2 is not an extremum, for **rays II, VII** I_2 is an extremum, but not a local minimum; for **ray III** I_2 is a local minimum. The sequence: $EW \to I_2 \to I_1$, with transition between I_2 and I_1 vacuum, is possible for **ray IV**, where I_2 is not a local minimum and for **ray V**, where I_2 is a local minimum, that coexists with the global minimum I_1. For **ray VIII** there is a possibility of going through the mixed vacuum $EW \to I_2 \to M \to I_1$. In this case there is only one minimum at any temperature.



(a) $\lambda_{345} > \sqrt{\lambda_1\lambda_2}$ (b) $0 < \lambda_{345} < \sqrt{\lambda_1\lambda_2}$ (c) $-\sqrt{\lambda_1\lambda_2} < \lambda_{345} < 0$

Figure 1: Possible rays from EW symmetric phase to the inert phase I_1; $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$.



(a) with fermions (b) without fermions

Figure 2: Example of rays for $M_h = 120$ GeV$, M_H = 60$ GeV$, M_A = 68$ GeV$, M_{H^\pm} = 110$ GeV.

Plots 2a,2b show the different vacua sequences (rays I-IX) leading to I_1 in (λ_2,λ_{345}) plane. For $\lambda_2 \leq \lambda_1$ different types of vacua in the past are possible only if the fermionic part of c_1 is included.

References

[1] *Evolution of Universe to the present inert phase*, I.F. Ginzburg, K.A. Kanishev, M. Krawczyk, D. Sokołowska [arXiv:1009.4593]

PoS(ICHEP 2010)457