Relaxion in symmetric 2HDM

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Based on Z. Lalak, AM, Dynamical relaxation in 2HDM models [arXiv:1612.09128].

Outline

1. Quick overview of dynamical relaxation
2. CHAIN and the final vev
3. Extension to 2HDM

Dynamical relaxation

Idea

Graham, Kaplan, Rajendran, Phys. Rev. Lett. **115** 221801 (2015) [arXiv:1504.07551]

Cancel quantum corrections to the Higgs mass (and the EW scale) with a large value of another field.

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$$V = g\phi\Lambda - \Lambda^2\left(\alpha - \frac{g\phi}{\Lambda}\right)|H|^2 + \lambda|H|^4 + \Lambda_c^3 v \cos\left(\frac{\phi}{f}\right)$$

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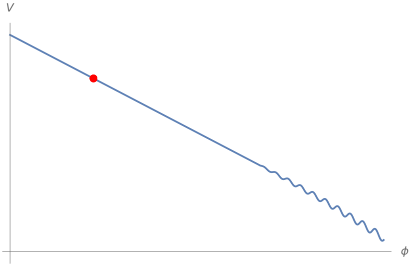

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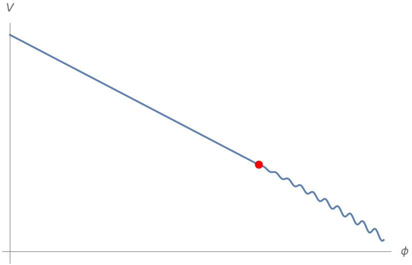

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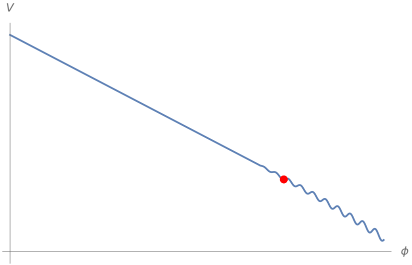
2. At $\phi = \alpha\ \Lambda/g\ \ m^2$ changes sign and EWSB occurs.
3. Amplitude of the periodic term increases until ϕ stops in one of the minima produced, stabilizing the EW scale at a small value.



Double scanner mechanism (CHAIN)

Espinosa et al, Phys. Rev. Lett. **115** 251803 (2015) [arXiv:1506.09217]

Motivation

- Terms generated at loop level ($\epsilon\Lambda_c^4 \cos(\phi/f)$, $\epsilon\Lambda_c^3\phi \cos(\phi/f)$) will stop relaxation to early unless $\Lambda_c < v$.
- Extra scalar field σ can be used to cancel those corrections.

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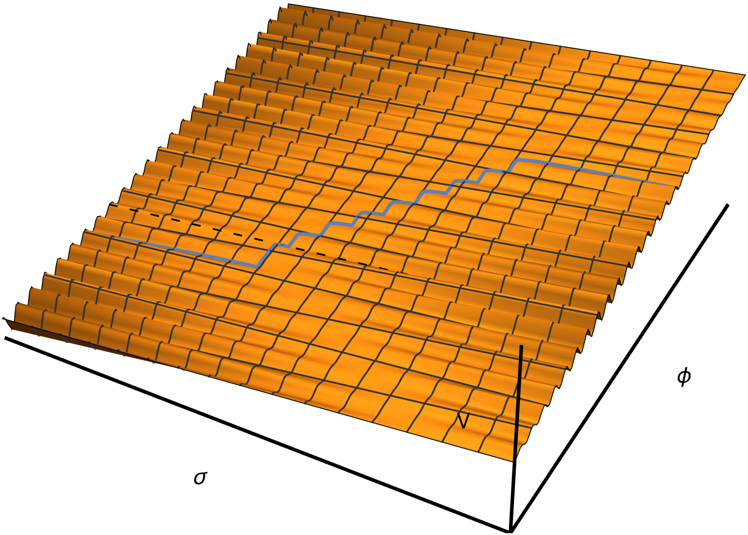
- Extra scalar field σ can be used to cancel those corrections.

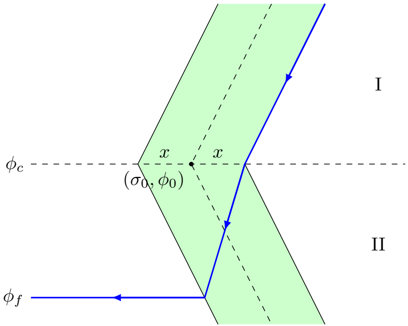
$$V = \Lambda^4\left(\frac{g\phi}{\Lambda} + \frac{g_\sigma\sigma}{\Lambda}\right) + \Lambda^2\left(\alpha - \frac{g\phi}{\Lambda}\right)|H|^2 + \lambda|H|^4$$
$$+\epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\sigma}{\Lambda} + \frac{|H^2|}{\Lambda^2}\right)\cos\left(\frac{\phi}{f}\right)$$

CHAIN potential



Final electroweak scale

- Can we go beyond order-of-magnitude qualitative study?



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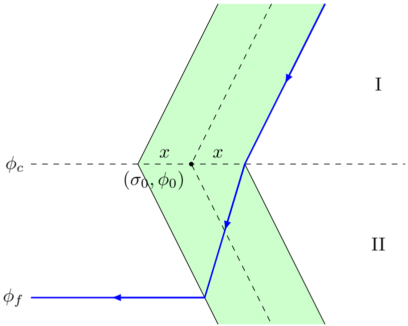

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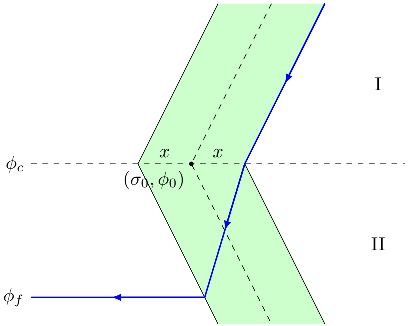
$$v^2 = -\frac{\Lambda^2}{\lambda}\left(\alpha - \frac{g\phi}{\Lambda}\right)$$
$$= \frac{4g^3\Lambda f}{\epsilon\lambda\left(c_\sigma g_\sigma^2 - c_\phi g^2 + \frac{g^2}{2\lambda}\right)}$$



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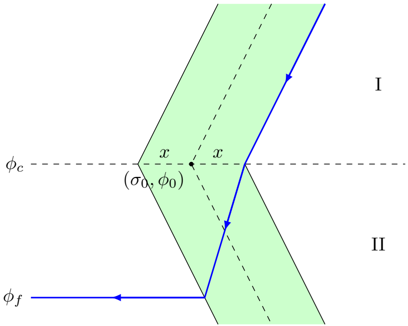

Two Higgs doublet model

$$
\begin{aligned}
V_{2HDM} = {} & 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{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{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{\lambda_5}{2} \left(\Phi_1^\dagger \Phi_2 \right)^2 + \lambda_6 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_1^\dagger \Phi_2 \right) \right. \\
& \left. + \lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \left(\Phi_1^\dagger \Phi_2 \right) + \text{h.c.} \right]
\end{aligned}
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General potential for 2HDM relaxation

$$V_{2HDM} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$
$$+ \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \lambda_6\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_1^\dagger\Phi_2\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + \text{h.c.}\right]$$

How we can include dynamical relaxation in it?

$$m_{ab}^2 = -\Lambda^2\left(\alpha_{ab} - \gamma_{ab}\frac{g\phi}{\Lambda}\right)$$

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$$m_{ab}^2 = -\Lambda^2 \left(\alpha_{ab} - \gamma_{ab} \frac{g\phi}{\Lambda} \right)$$

$$A(\phi, \sigma, \Phi_1, \Phi_2) = \Lambda^4 \epsilon \left(\beta + c_\phi \frac{g\phi}{\Lambda} - c_\sigma \frac{g_\sigma \sigma}{\Lambda} + \frac{\rho_{ab}}{\Lambda^2} |\Phi_a||\Phi_b| \right)$$

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\begin{aligned}
V(\phi,\sigma,H_1,H_2) = {} & \Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right) \\
& -\Lambda^2\left(\alpha_1-\frac{g\phi}{\Lambda}\right)|H_1|^2+\lambda_1|H_1|^4 \\
& -\Lambda^2\left(\alpha_2-\frac{g\phi}{\Lambda}\right)|H_2|^2+\lambda_2|H_2|^4 \\
& +\lambda_3|H_1|^2|H_2|^2 \\
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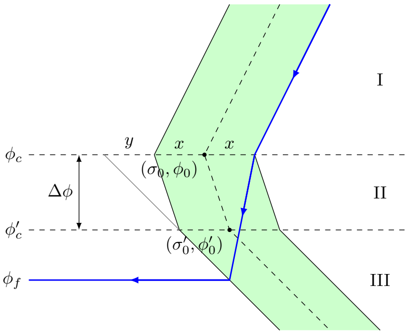
Not physical (spectrum contains a massless scalar), but can provide insight into 2HDM relaxation.

Final vevs in 2HDM

- Both doublets significant if $\Delta\alpha = \alpha_1 - \alpha_2 \lesssim g/\epsilon$.



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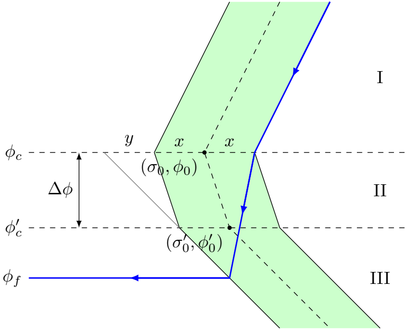

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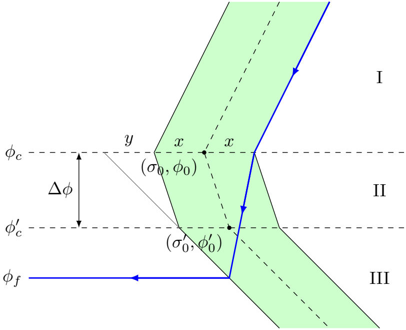
- Exactly the Higgs alignment limit.



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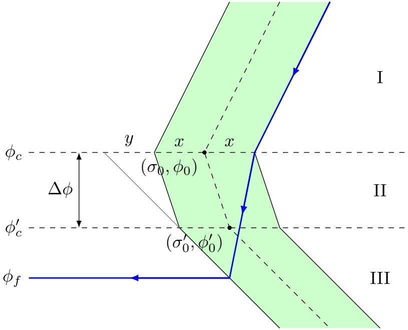

$$v_1^2 = \frac{\Lambda^2}{\lambda_1}\left(1 - \frac{\lambda_3^2}{4\lambda_1\lambda_2}\right)^{-1}\left[\frac{\lambda_3}{2\lambda_2}\Delta\alpha + \left(1 - \frac{\lambda_3}{2\lambda_2}\right)\frac{\frac{2g^3 f}{\epsilon\Lambda} - c_2 g^2 \frac{2\lambda_1}{4\lambda_1\lambda_2 - \lambda_3^2}\Delta\alpha}{c_\sigma g_\sigma^2 - c_\phi^{III} g^2}\right]$$

$$v_2^2 = \frac{\Lambda^2}{\lambda_2}\left(1 - \frac{\lambda_3^2}{4\lambda_1\lambda_2}\right)^{-1}\left[-\Delta\alpha + \left(1 - \frac{\lambda_3}{2\lambda_1}\right)\frac{\frac{2g^3 f}{\epsilon\Lambda} - c_2 g^2 \frac{2\lambda_1}{4\lambda_1\lambda_2 - \lambda_3^2}\Delta\alpha}{c_\sigma g_\sigma^2 - c_\phi^{III} g^2}\right]$$

Large vevs

$$v_1^2 = \frac{\Lambda^2}{\lambda_1}\left(1 - \frac{\lambda_3^2}{4\lambda_1\lambda_2}\right)^{-1}\left[\frac{\lambda_3}{2\lambda_2}\Delta\alpha + \left(1 - \frac{\lambda_3}{2\lambda_2}\right)\frac{\frac{2g^3 f}{\epsilon\Lambda} - c_2 g^2 \frac{2\lambda_1}{4\lambda_1\lambda_2 - \lambda_3^2}\Delta\alpha}{c_\sigma g_\sigma^2 - c_\phi^{III} g^2}\right]$$

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- Terms proportional to $\Delta\alpha$ are not supressed by the small coupling g.
- Impossible to satisfy the SM constraint $v^2 = v_1^2 + v_2^2 \sim 246\,\mathrm{GeV}$.
- Fine-tuning or symmetry required to make $\Delta\alpha$ small.

Constrained 2HDM

symmetry	μ_1^2	μ_2^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	$\mathrm{Re}(\lambda_5)$	$\lambda_6 = \lambda_7$
$Z_2 \times O(2)$	-	-	Real	-	-	-	-	-	Real
$(Z_2)^2 \times SO(2)$	-	-	0	-	-	-	-	-	0
$(Z_2)^3 \times O(2)$	-	μ_1^2	0	-	λ_1	-	-	-	0
$O(2) \times O(2)$	-	-	0	-	-	-	-	0	0
$Z_2 \times [O(2)]^2$	-	μ_1^2	0	-	λ_1	-	-	$2\lambda_1 - \lambda_{34}$	0
$O(3) \times O(2)$	-	μ_1^2	0	-	λ_1	-	$2\lambda_1 - \lambda_3$	0	0
$SO(3)$	-	-	Real	-	-	-	-	λ_4	Real
$Z_2 \times O(3)$	-	μ_1^2	Real	-	λ_1	-	-	λ_4	Real
$(Z_2)^2 \times SO(3)$	-	μ_1^2	0	-	λ_1	-	-	$\pm\lambda_4$	0
$O(2) \times O(3)$	-	μ_1^2	0	-	λ_1	$2\lambda_1$	-	0	0
$SO(4)$	-	-	0	-	-	-	0	0	0
$Z_2 \times O(4)$	-	μ_1^2	0	-	λ_1	-	0	0	0
$SO(5)$	-	μ_1^2	0	-	λ_1	$2\lambda_1$	0	0	0

- Imposing global symmetries can force α_1 and α_2 to be equal.
- Out of 6 symmetry classes 3 result in the requied cancellation.
- Models with weakly broken global symmetries would be particularly interesting.

MS-2HDM

Dev & Pilaftsis, JHEP **1412** 024 (2014) [arXiv:1408.3405]

$$
\begin{aligned}
V &= -\mu^2\left(|\phi_1|^2 + |\phi_2|^2\right) + \lambda\left(|\phi_1|^2 + |\phi_2|^2\right)^2 \\
&= -\frac{\mu^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2
\end{aligned}
$$

- $\mathrm{SO}(5)$ symmetry realized at some high scale.
- Different couplings in the Yukawa sector. RG running leads to a broken symmetry at the EW scale.
- Possibility of satisfying condition of small $\Delta\alpha$.

Conclusions

- Geometrical analysis can be used to find more robust expressions for the relaxed vevs, that takie into account all parameters of the potential.
- In general relaxation in 2HDM requires fine-tuning or symmetries to make sure that corrections to m^2 are almost equal fot both doublets.
- Constrained 2HDMs can be a way out, with weakly broken global symmetries being of particular interest.