Quartic Coupling Unification in the MS-2HDM

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Outline

- The Two Higgs Doublet Model type-II (2HDM type-II); SM Alignment limit
- Maximally Symmetric 2HDM (MS-2HDM)
- The unification of the running quartic couplings
- Predictions of MS-2HDM
- The electroweak vacuum lifetime
- Summary and conclusion

2HDM Type-II

- 2HDM consists of two SU(2) scalar doublets ϕ_1 and ϕ_2.

$$Z_2 \text{ transformation}: \;\; \phi_1 \to \phi_1, \quad \phi_2 \to -\phi_2$$

- Potential for 2HDM

$$\begin{aligned} V &= -\mu_1^2(\Phi_1^\dagger\Phi_1) - \mu_2^2(\Phi_2^\dagger\Phi_2) - \left[m_{12}^2(\Phi_1^\dagger\Phi_2) + h.c.\right] \\ &+ \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+ \left[\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_2) + h.c.\right] \end{aligned}$$

- 2HDM type-II for Yukawa interaction

$$\langle\Phi_1^0\rangle = \frac{v_1}{\sqrt{2}} \neq 0, \; \langle\Phi_2^0\rangle = \frac{v_2}{\sqrt{2}} \neq 0, \quad v \equiv \sqrt{v_1^2 + v_2^2} = 246\,\text{GeV}, \;\; \tan\beta = v_2/v_1$$

$$\text{d-type quarks} \to \phi_1, \;\; \text{u-type quarks} \to \phi_2$$

2HDM Type-II

- There are 5 physical Higgs particle with these masses: $M_h, M_H, M_a, M_{h^\pm}$

$$M_{h^\pm}^2 = \frac{m_{12}^2}{s_\beta c_\beta} - \frac{v^2}{2}(\lambda_4+\lambda_5) + \frac{v^2}{2 s_\beta c_\beta}(\lambda_6 c_\beta^2 + \lambda_7 s_\beta^2)$$

$$M_a^2 = M_{h^\pm}^2 + \frac{v^2}{2}(\lambda_4-\lambda_5) \quad \rightarrow \quad \text{CP-odd scalar}$$

$$M_{h,H}^2 = \begin{pmatrix} \widehat{A} & \widehat{C} \\ \widehat{C} & \widehat{B} \end{pmatrix} \quad \rightarrow \quad \text{CP-even scalars}$$

In the Higgs basis:

$$\widehat{A} = 2v^2 \left[c_\beta^4 \lambda_1 + s_\beta^2 c_\beta^2 \lambda_{345} + s_\beta^4 \lambda_2 + 2 s_\beta c_\beta \left(c_\beta^2 \lambda_6 + s_\beta^2 \lambda_7 \right) \right],$$

$$\widehat{B} = M_a^2 + \lambda_5 v^2 + 2v^2 \left[s_\beta^2 c_\beta^2 (\lambda_1 + \lambda_2 - \lambda_{345}) - s_\beta c_\beta \left(c_\beta^2 - s_\beta^2 \right) (\lambda_6 - \lambda_7) \right],$$

$$\widehat{C} = v^2 \left[s_\beta^3 c_\beta (2\lambda_2 - \lambda_{345}) - c_\beta^3 s_\beta (2\lambda_1 - \lambda_{345}) + c_\beta^2 \left(1 - 4 s_\beta^2\right) \lambda_6 + s_\beta^2 \left(4 c_\beta^2 - 1\right) \lambda_7 \right].$$

SM Alignment in The 2HDM

- The SM Higgs field is identified as:

$$H_{\rm SM} = H \quad \cos(\beta-\alpha) + h \quad \sin(\beta-\alpha)$$

- The couplings of h and H to the gauge bosons $(V = W^{\pm}, Z)$:

$$g_{HVV} = \cos(\beta-\alpha) \quad g_{hVV} = \sin(\beta-\alpha)$$

- The SM alignment limit can be realized in two different scenarios:
  - $M_H = 125$ GeV (SM-like H scenario) $\quad \cos(\beta-\alpha) \sim 1 \quad g_{hVV} \sim 0$
  - $M_h = 125$ GeV (SM-like h scenario) $\quad \sin(\beta-\alpha) \sim 1 \quad g_{HVV} \sim 0$

We consider: $\quad g_{HVV} = \cos(\beta-\alpha) \sim 1$

SM Alignment in The 2HDM

$$\widehat{A} = 2v^2 \left[c_\beta^4 \lambda_1 + s_\beta^2 c_\beta^2 \lambda_{345} + s_\beta^4 \lambda_2 + 2 s_\beta c_\beta \left(c_\beta^2 \lambda_6 + s_\beta^2 \lambda_7\right)\right],$$
$$\widehat{B} = M_a^2 + \lambda_5 v^2 + 2v^2 \left[s_\beta^2 c_\beta^2 \left(\lambda_1 + \lambda_2 - \lambda_{345}\right) - s_\beta c_\beta \left(c_\beta^2 - s_\beta^2\right)\left(\lambda_6 - \lambda_7\right)\right],$$
$$\widehat{C} = v^2 \left[s_\beta^3 c_\beta \left(2\lambda_2 - \lambda_{345}\right) - c_\beta^3 s_\beta \left(2\lambda_1 - \lambda_{345}\right) + c_\beta^2 \left(1 - 4 s_\beta^2\right)\lambda_6 + s_\beta^2 \left(4 c_\beta^2 - 1\right)\lambda_7\right].$$

1. $\widehat{C} \to 0$ [Krawczyk et al, '99; Carena, '13]

$$\lambda_7 t_\beta^4 - \left(2\lambda_2 - \lambda_{345}\right) t_\beta^3 + 3\left(\lambda_6 - \lambda_7\right) t_\beta^2 + \left(2\lambda_1 - \lambda_{345}\right) t_\beta - \lambda_6 = 0$$

[Bhupal, Pilaftsis, '14]

$\lambda_1 = \lambda_2 = \dfrac{\lambda_{345}}{2}, \quad \lambda_6 = \lambda_7 = 0$ are applicable for any values of $\tan\beta$

$$M_H^2 = 2v^2 \left(\lambda_1 c_\beta^4 + \lambda_{345} s_\beta^2 c_\beta^2 + \lambda_2 s_\beta^4\right) \equiv 2\lambda_{\rm SM} v^2,$$
$$M_h^2 = M_a^2 + \lambda_5 v^2 + 2v^2 s_\beta^2 c_\beta^2 \left(\lambda_1 + \lambda_2 - \lambda_{345}\right).$$

$\to$requires a fine-tuning among the quartic couplings

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SM Alignment in The 2HDM

$$\widehat{A} = 2v^2 \left[c_\beta^4 \lambda_1 + s_\beta^2 c_\beta^2 \lambda_{345} + s_\beta^4 \lambda_2 + 2 s_\beta c_\beta \left(c_\beta^2 \lambda_6 + s_\beta^2 \lambda_7\right)\right],$$
$$\widehat{B} = M_a^2 + \lambda_5 v^2 + 2v^2 \left[s_\beta^2 c_\beta^2 \left(\lambda_1 + \lambda_2 - \lambda_{345}\right) - s_\beta c_\beta \left(c_\beta^2 - s_\beta^2\right)\left(\lambda_6 - \lambda_7\right)\right],$$
$$\widehat{C} = v^2 \left[s_\beta^3 c_\beta \left(2\lambda_2 - \lambda_{345}\right) - c_\beta^3 s_\beta \left(2\lambda_1 - \lambda_{345}\right) + c_\beta^2 \left(1 - 4 s_\beta^2\right)\lambda_6 + s_\beta^2 \left(4 c_\beta^2 - 1\right)\lambda_7\right].$$

2. $M_{h^\pm} \sim M_a \gg v$ [Georgi, Nanopoulos '79; Gunion, Haber, '02; Ginzburg, Krawczyk, '05]

$$M_H^2 \simeq 2\lambda_{\rm SM} v^2 - \frac{v^4 s_\beta^2 c_\beta^2}{M_a^2 + \lambda_5 v^2}\left[s_\beta^2 \left(2\lambda_2 - \lambda_{345}\right) - c_\beta^2 \left(2\lambda_1 - \lambda_{345}\right)\right]^2,$$
$$M_h^2 \simeq M_a^2 + \lambda_5 v^2 \gg v^2 .$$

$\rightarrow$requires a very heavy M_a

SM Alignment in The 2HDM

$$\begin{aligned}
\widehat{A} &= 2v^2\left[c_\beta^4\lambda_1 + s_\beta^2 c_\beta^2\lambda_{345} + s_\beta^4\lambda_2 + 2s_\beta c_\beta\left(c_\beta^2\lambda_6 + s_\beta^2\lambda_7\right)\right],\\
\widehat{B} &= M_a^2 + \lambda_5 v^2 + 2v^2\left[s_\beta^2 c_\beta^2\left(\lambda_1 + \lambda_2 - \lambda_{345}\right) - s_\beta c_\beta\left(c_\beta^2 - s_\beta^2\right)\left(\lambda_6 - \lambda_7\right)\right],\\
\widehat{C} &= v^2\left[s_\beta^3 c_\beta\left(2\lambda_2 - \lambda_{345}\right) - c_\beta^3 s_\beta\left(2\lambda_1 - \lambda_{345}\right) + c_\beta^2\left(1 - 4s_\beta^2\right)\lambda_6 + s_\beta^2\left(4c_\beta^2 - 1\right)\lambda_7\right].
\end{aligned}$$

1. $\widehat{C} \to 0$

$\rightarrow$requires a fine-tuning among the quartic couplings

2. $M_{h^\pm} \sim M_a \gg v$

$\rightarrow$requires a very heavy M_a

• Our interest: **Natural SM alignment limit** without decoupling and also without an unpleasant degree of fine-tuning among the quartic couplings. [Bhupal, Pilaftsis, '14]

This can be achieved in the Maximal Symmetry-2HDM

The Maximal Symmetry-2HDM

- The SU(2) scalar doublets of 2HDM $\rightarrow$ The 8-dimentional multiplet-$\mathbf{\Phi}$

[Battye, Brawn, Pilaftsis, '11]

$$\mathbf{\Phi} = \begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \widetilde{\Phi}_1 \\ \widetilde{\Phi}_2 \end{pmatrix}$$

- An $SU(2)_L$ gauge-kinetic terms of $\mathbf{\Phi}$ should remain canonical : $Sp(4)/Z_2 \cong SO(5)$
- The SO(5) puts some restrictions on the parameters of the model

$$\mu_1^2 = \mu_2^2, \quad m_{12}^2 = 0, \quad \lambda_1 = \lambda_2 = \frac{\lambda_3}{2}, \quad \lambda_4 = \lambda_5 = \lambda_6 = \lambda_7 = 0.$$

$\rightarrow$ MS-2HDM leads to Natural SM alignment limit

Symmetry Breaking: RG Effect and Soft SO(5)-Breaking Mass

- Two loops RGEs effects:

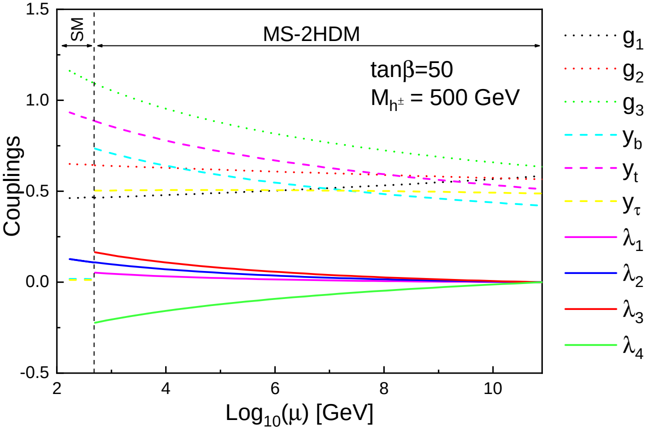
$$
\begin{aligned}
\mathrm{SO}(5) \otimes \mathrm{SU}(2)_L \quad & \xrightarrow{g' \neq 0} \quad \mathrm{O}(3) \otimes \mathrm{O}(2) \otimes \mathrm{SU}(2)_L \sim \mathrm{O}(3) \otimes \mathrm{U}(1)_Y \otimes \mathrm{SU}(2)_L \\
& \xrightarrow{\text{Yukawa}} \quad \mathrm{O}(2) \otimes \mathrm{U}(1)_Y \otimes \mathrm{SU}(2)_L \sim \mathrm{U}(1)_{\mathrm{PQ}} \otimes \mathrm{U}(1)_Y \otimes \mathrm{SU}(2)_L \\
& \xrightarrow{\langle \Phi_{1,2} \rangle \neq 0} \quad \mathrm{U}(1)_{\mathrm{em}}
\end{aligned}
$$

- Including non-zero value for soft term $\mathrm{Re}(m_{12}^2)$, lifts the masses

$$
M_H^2 = 2\lambda_2 v^2, \quad M_h^2 = M_a^2 = M_{h^\pm}^2 = \frac{\mathrm{Re}(m_{12}^2)}{s_\beta c_\beta}.
$$

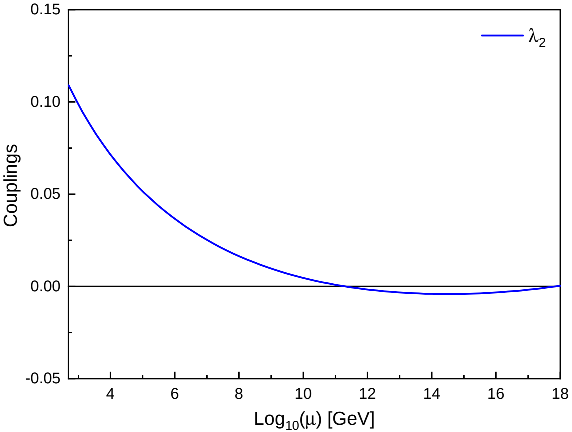
The Unification of Quartic Couplings

- The SO(5) symmetry is realized at high scale 10^{11} GeV
- At the threshold scale SM is realized
- y_b and y_τ are jumping significantly at the threshold scale



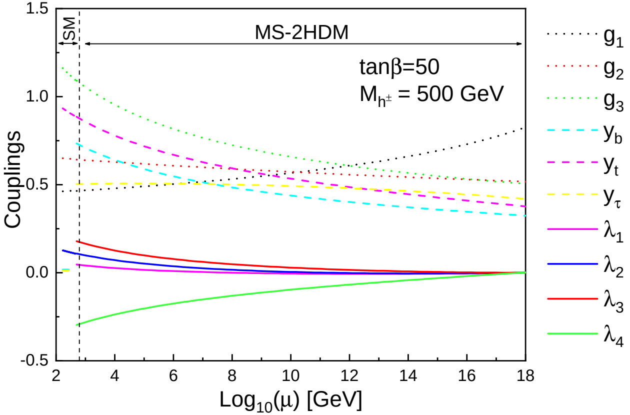
The Unification of Quartic Couplings

- A closer look at the trajectory of λ_2.

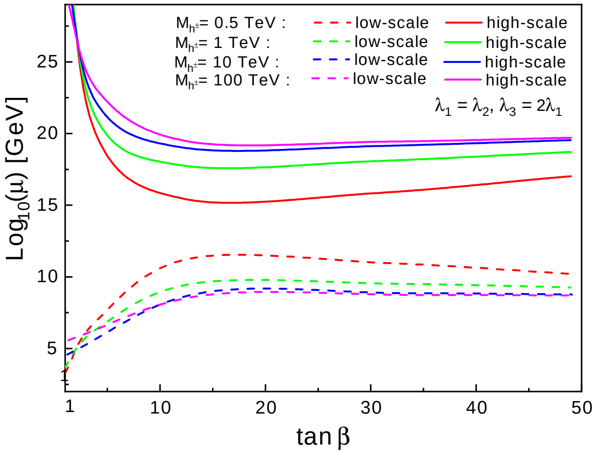


The Unification of Quartic Couplings

- Looking at the scale above $\mu_X \sim 10^{11}$ GeV
- At the scale $\mu_X \sim 10^{11}$ GeV, λ_2 turns to negative
- At the scale $\mu_X \sim 10^{18}$ GeV, the SO(5) symmetry is realized
- λ_2 turns to negative $\to$ vacuum stability



The Unification of Quartic Couplings

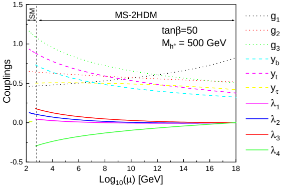


Only three parameters are required to define the structure of the MS-2HDM:

- the unification scale μ_X
- the charged Higgs mass $M_{h^\pm}$ (or m_{12}^2)
- $\tan\beta$

Misalignment

Misalignment in gauge bosons coupling



$$g_{HVV} \simeq 1 - \frac{\widehat{C}^2}{2\widehat{B}^2}\,,$$

$$g_{hVV} \simeq -\frac{\widehat{C}}{\widehat{B}} = \frac{v^2 s_\beta c_\beta}{M_a^2 + \lambda_5 v^2}\left[c_\beta^2\left(2\lambda_1 - \lambda_{345}\right) - s_\beta^2\left(2\lambda_2 - \lambda_{345}\right)\right].$$

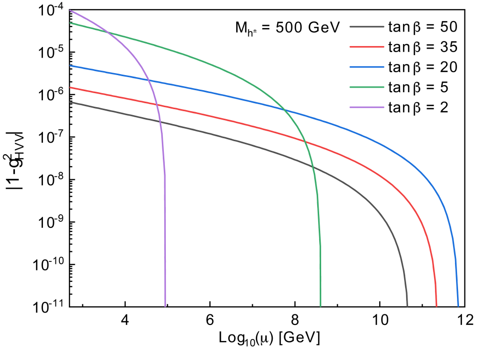
Misalignment in the fermions coupling

$$g_{huu} \simeq -\frac{\widehat{C}}{\widehat{B}} + \frac{1}{\tan\beta}\,, \qquad g_{hdd} \simeq -\frac{\widehat{C}}{\widehat{B}} - \tan\beta\,,$$

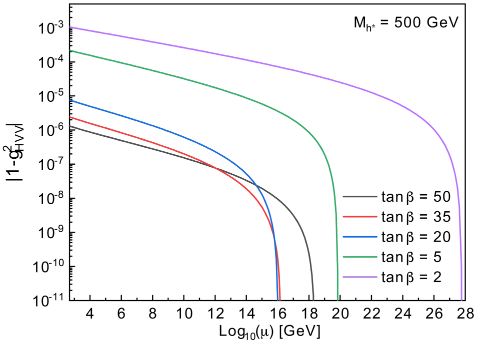
$$g_{Huu} \simeq 1 + \frac{1}{\tan\beta}\frac{\widehat{C}}{\widehat{B}}\,, \qquad g_{Hdd} \simeq 1 - \frac{\widehat{C}}{\widehat{B}}\tan\beta\,.$$

Misalignment: Gauge Bosons Couplings

- Low-scale unification

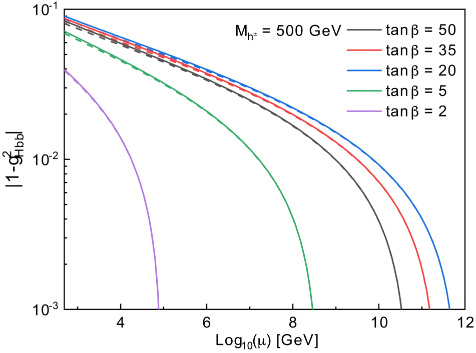


- High-scale unification

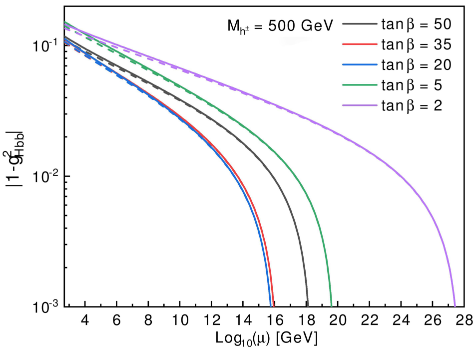


Misalignment: b-quark Couplings

- Low-scale unification



- High-scale unification



Predictions of MS-2HDM

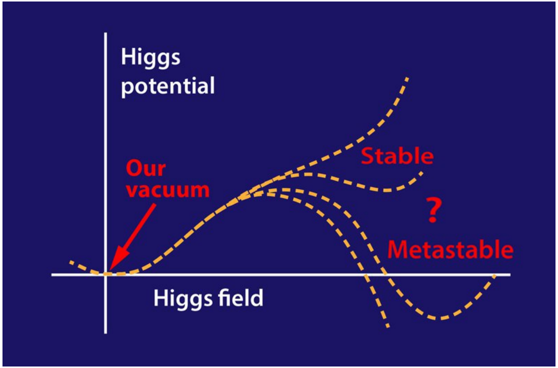
Couplings	ATLAS	CMS	$\tan\beta = 2$	$\tan\beta = 20$	$\tan\beta = 50$
$\lvert g_{HZZ}^{\text{low-scale}} \rvert$	[0.86, 1.00]	[0.90, 1.00]	0.9999	0.9999	0.9999
$\lvert g_{HZZ}^{\text{high-scale}} \rvert$			0.9981	0.9999	0.9999
$\lvert g_{Htt}^{\text{low-scale}} \rvert$	$1.31^{+0.35}_{-0.33}$	$1.45^{+0.42}_{-0.32}$	1.0049	1.0001	1.0000
$\lvert g_{Htt}^{\text{high-scale}} \rvert$			1.0987	1.0003	1.0001
$\lvert g_{Hbb}^{\text{low-scale}} \rvert$	$0.49^{+0.26}_{-0.19}$	$0.57^{+0.16}_{-0.16}$	0.9803	0.9560	0.9590
$\lvert g_{Hbb}^{\text{high-scale}} \rvert$			0.8810	0.9449	0.9427

Table: *Predicted values of the SM-like Higgs boson couplings to the Z boson and to top- and bottom-quarks in the MS-2HDM for both scenarios with low- and high-scale quartic coupling unification, assuming $M_{h^\pm} = 500\ GeV$.*

- Misalignment predictions are consistent with experimental constraints

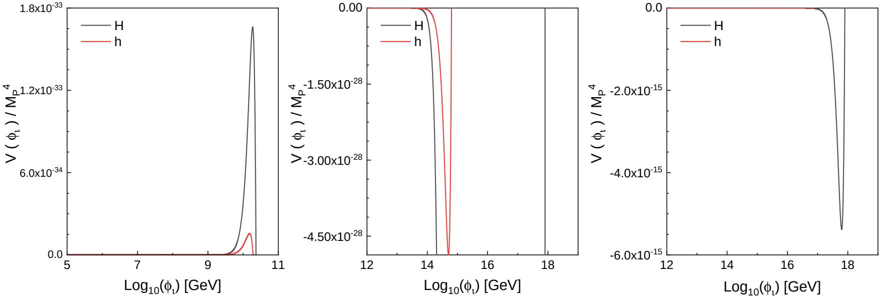
Vacuum Stability

- If at some point $\lambda < 0$, there can be a minimum, which is much deeper than our vacuum, so stability of the latter should be questioned
- a local minimum of potential can tunnel to a true vacuum
- The EW vacuum is metastable if its lifetime is extremely long, much larger than the age of the Universe.



[e.g. Branchina et al, '13]

The Electroweak Vacuum Lifetime



	$\phi_i(0)/M_p$	λ_1	λ_2	λ_3	λ_4	τ/T_U
H	$1.73 \cdot 10^{-5}$	$4.2 \cdot 10^{-4}$	$-2.05 \cdot 10^{-3}$	$-9.86 \cdot 10^{-3}$	$2.818 \cdot 10^{-2}$	10^{5400}
h	$5.06 \cdot 10^{-7}$	$-1.6 \cdot 10^{-4}$	$-1.11 \cdot 10^{-3}$	$-4.42 \cdot 10^{-3}$	$1.162 \cdot 10^{-2}$	10^{114180}

- The electroweak vacuum lifetimes is extremely larger than the age of Universe.

Summary and Conclusion

- In the MS-2HDM the SM alignment limit can be achieved naturally.
- The quartic couplings can be unified at some high scale near Planck scale.
- The misalignment predictions are consistent with experimental constraints.
- We have shown that the EW vacuum lifetime τ is extremely long, larger than the age of the universe, therefore our universe is metastable.
- The MS-2HDM is a minimal extension of the SM governed by only three additional parameters: the unification scale μ_X, the charged Higgs mass $M_{h^\pm}$ (or m_{12}^2) and $\tan\beta$.

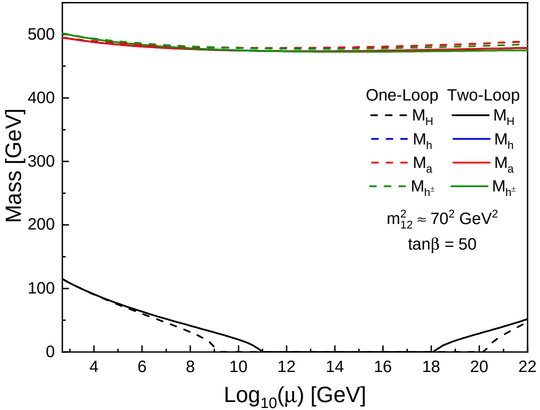
⋆ ⋆ ⋆

N. Darvishi and A. Pilaftsis, Phys. Rev. D 99 (2019) no.11, 115014 [arXiv:1904.06723 [hep-ph]]

THANK YOU!

BACK UP

Mass Spectrum



Lifetime of the Metastable Electroweak Vacuum

- To determine the lifetime of the false vacuum we have to look for the so-called bounce solution

$$\frac{d^2\phi_i}{dr^2} + \frac{3}{r}\frac{d\phi_i}{dr} = \frac{\partial V(\phi_i)}{\partial \phi_i}$$

- The action that is calculated at the bounce solution takes the following form:

$$\Delta S_E^i \equiv S[\phi_{ib}] - S[\phi_i^{fv}] = -\frac{\pi^2}{2}\int_0^\infty dr r^3 \left[\frac{dV(\phi)}{d\phi_i}\phi_i\right]_b .$$

  - we have five second-order equations with boundary conditions at $r = 0$ and another at $r = \infty$
  - The fields begin at $r = 0$ from the bound solution at the center of the bubble and asymptotically approach the false vacuum.
  - The solutions to the bounce equations result in finding the values of the fields at $r = 0$.

Lifetime of the Metastable Electroweak Vacuum

- As the instability of the potential occurs at very large values of ϕ_i, $\phi_i \gg v$ ($\phi_i \sim 10^{10}$), it is a good approximation if we keep only the quartic terms.
- The EW vacuum lifetime is computed by considering the bounce solution to the Euclidean equation of motion for the classical potential

$$V(\mu \gg v) \approx \frac{1}{4}(\lambda_1 h^4 + \lambda_2 H^4 + 2(\lambda_3 + \lambda_4) h^2 H^2)$$

- The effective action: $\Delta S_E^i \simeq -8\pi^2/(3|\lambda_i|)$

$$\tau = \frac{e^{\Delta S_E^i}}{\phi_i(0)^4 T_U^4}$$