Non-Invertible Peccei-Quinn Symmetry, Natural 2HDM Aligment, and the Visible Axion

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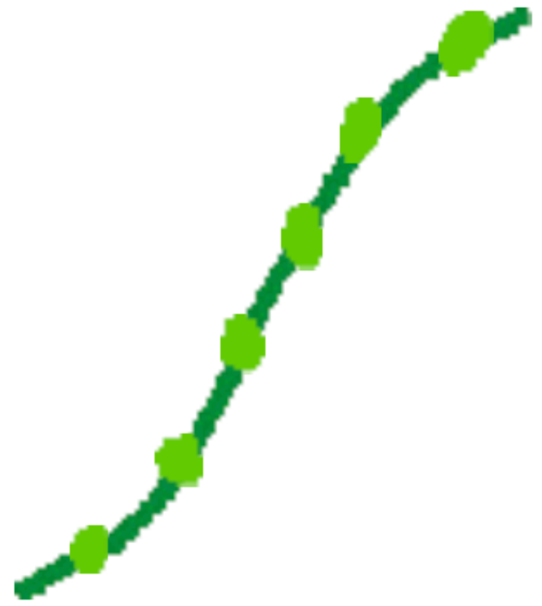
Introduction

- During the last forty years there has been a lot of activity in trying to understand the flavour structure of Yukawa matrices:
  - Doing a spurion analysis to understand the hierarchy of masses (Froggat-Nielsen)
  - Using textures to understand the CKM and the PMNS matrices.
  - Botton-tau unification
  - Extra dimensional models.
  - Gauging CP
  - …..

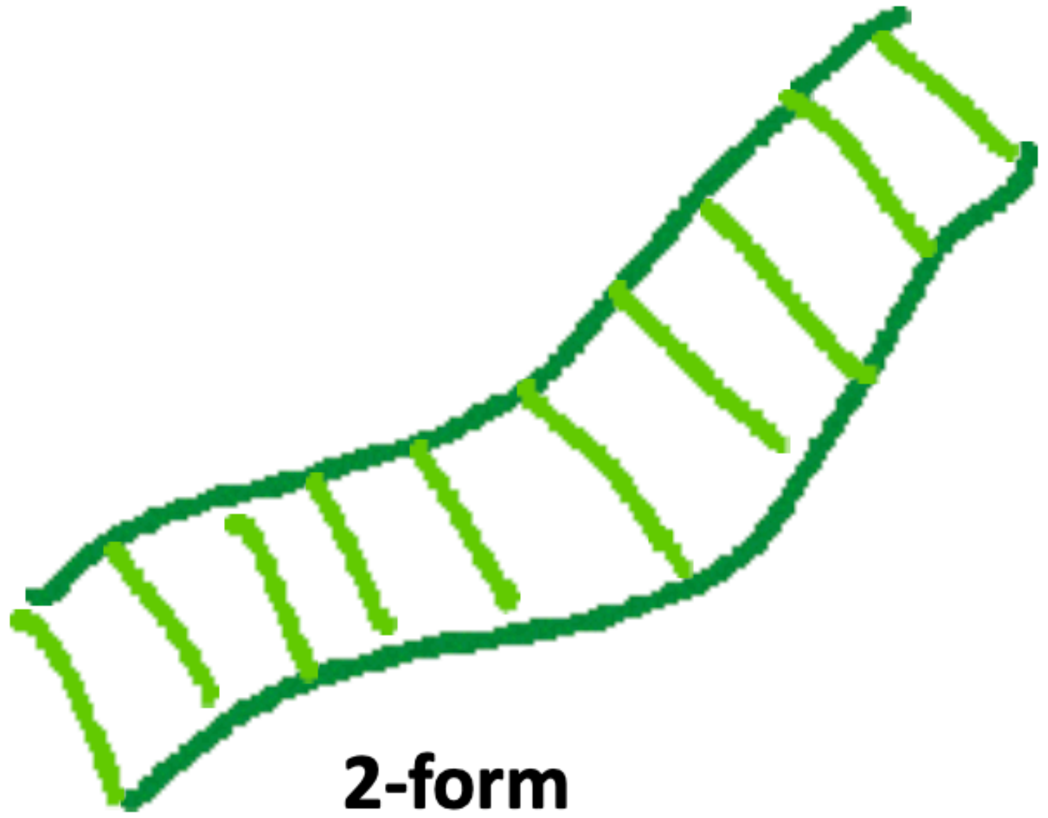
- Recently there has been a lot of activity on Generalized symmetries.
- They extend the usual concept of transformations of point like particles to extended objects like Wilson loops.
- In this talk I will embed the usual PQ symmetry of a 2HDM into a continuous flavour group that upon breaking realizes in a natural way an scenario where one gets the alignment limit. (A light Higgs with SM like properties).
- One extra feature of this model is the realization of the Weinberg-Wilczek visible axion.

Generalized symmetries

0-form symmetry
charged local
operators
e.g. particles



1-form
line operators
e.g. Wilson line



2-form
surface operators
e.g. cosmic string

3-form
volume operators
e.g. domain wall

$\partial_\mu J^\mu = 0$

$\partial_\mu J^{\mu\nu} = 0$

Generally $\partial_\mu J^{\mu_1\mu_2\cdots\mu_{p+1}} = 0$ antisymmetric

- Extended objects (d-dimensions) can couple to d+1 currents.

- In a UV theory with non-trivial dynamics leading to magnetic phases those extended objects can lead to IR theories where symmetries are realized not by standard unitary operators but as non-invertible objects.

- One example are QCD instantons and how the baryon number anomaly leads to a discreet subgroup to be conserved in the SM Z_3

- From the IR one understand the symmetry as the transformation of a extended object that then in the UV is realized in the standard way of invertible symmetries.

- These generalized symmetries have already been used to explain neutrinos mass or as a solution to the strong CP problem. (Koren et al. 2022-2024)

2HDM

- The 2HDM is a minimal extension to the SM with one extra Higgs doublet.

$$
\begin{aligned}
V(\Phi_1, \Phi_2) = {} & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{ h.c.} \right] \\
& + \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) \\
& + \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2 \right)^2 + \left[\lambda_6 \left(\Phi_1^\dagger \Phi_1 \right) + \lambda_7 \left(\Phi_2^\dagger \Phi_2 \right) \right] \left(\Phi_1^\dagger \Phi_2 \right) + \text{ h.c.} \right\} .
\end{aligned} \tag{2.1}
$$

- Depending on the different Yukawa structures you can have different models. We are going to work with a type II 2HDM.
- LHC data forces us to have a Higgs which SM-like. ‘alignment limit’
- One possibility to realise it is to try to implement a PQ symmetry

$$\mathcal{L} \supset (y_t)^i_j \Phi_1 Q_i \bar{u}^j + (y_b)^i_j \tilde{\Phi}_2 Q_i \bar{d}^j$$

$$m^2_{12}, \lambda_5, \lambda_6, \lambda_7 = 0 \text{ all vanish.}$$

- We are going to embed this model in a UV $SU(3)_H$ symmetry.

	$SU(3)_C$	$SU(3)_H$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\rm PQ}$
Q	3	3	2	$+1$	0
$\bar{u}$	$\bar{3}$	$\bar{3}$	–	-4	1
$\bar{d}$	$\bar{3}$	$\bar{3}$	–	$+2$	1
Φ_1	–	–	2	-3	-1
Φ_2	–	–	2	-3	1

Anomalous!!!!!!!!!

	$U(1)_{\rm PQ}$
m_{12}^2	-2
λ_5	-4
λ_6	-2
λ_7	-2

- With this assignments one recreates one of the exceptional regions of the 2HDM (Ferreira, Haber, Silva 2009) imposing and extra Z_2

- The LHC data suggests that one of the two Higgses has to have SM properties, i.e., alignment limit.
- In the 2HDM one can achieve the alignment w/o decoupling with a far richer phenomenology.
- Haber and Silva have analyzed the different scenarios for such a result:
  - Generalized CP, Peccei-Quinn, Higgs family,…
- Our goal is to try to see if we can embed the PQ symmetry in a UV model making use of some non-invertible symmetry.

- The PQ charges we assigned are anomalous with respect to SU(3).
- QCD instantons will therefore break the symmetry to Z_6
- We are going to asume that there is an UV theory where colour and flavour are unified and embed the left over PQ global symmetry in this way:

$$U(1)_{\mathrm{PQ}} \to \mathbb{Z}_2 \ (\text{invertible}) \times \mathbb{Z}_3 \ (\text{non-invertible}).$$

Colour-Flavour model SU(9) Cordova, Hong, Koren '24

	$SU(9)$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathrm{PQ}}$
Q	9	2	$+1$	0
$\bar{u}$	$\bar{9}$	$-$	-4	1
$\bar{d}$	$\bar{9}$	$-$	$+2$	1
Φ_1	$-$	2	-3	-1
Φ_2	$-$	2	-3	1
Ξ	165	$-$	0	0

Higgs breaking of SU(9)

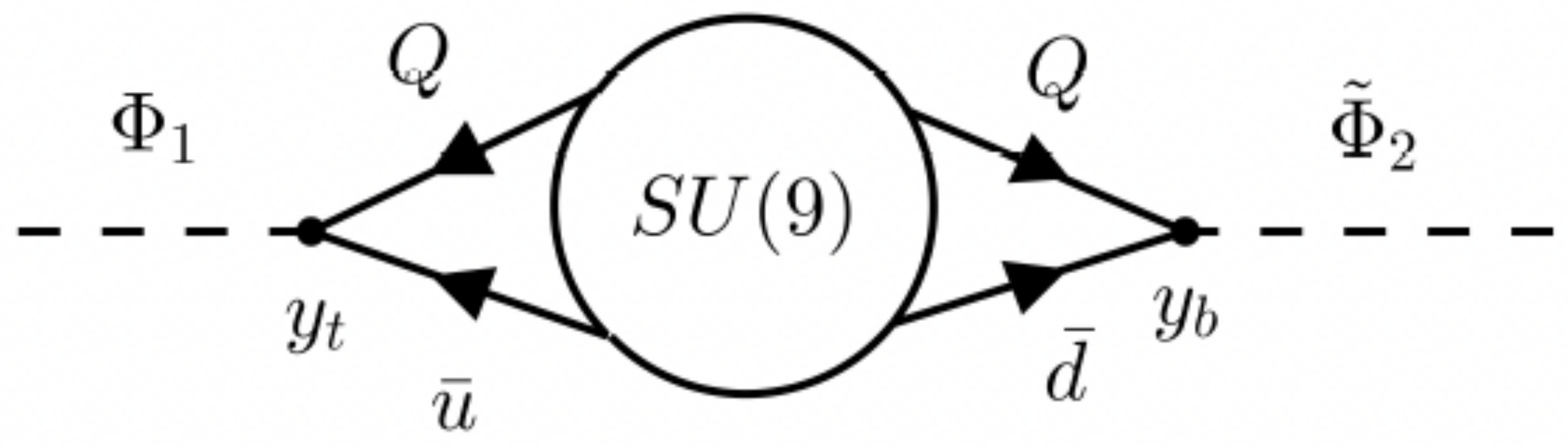
- This model provides an unified set up for colour and flavour as an attempt to explain both the Yukawas and maybe the CP-violaton sector but those details are not important for this talk.

- SU(9) instantons break the non-invertible Z_3 and generates a contribution to m_{12}^2.

- Instead of doing a naïve NDA to calculate the size of that breaking

- The contribution can be calculated using the technique by Csaki et al.

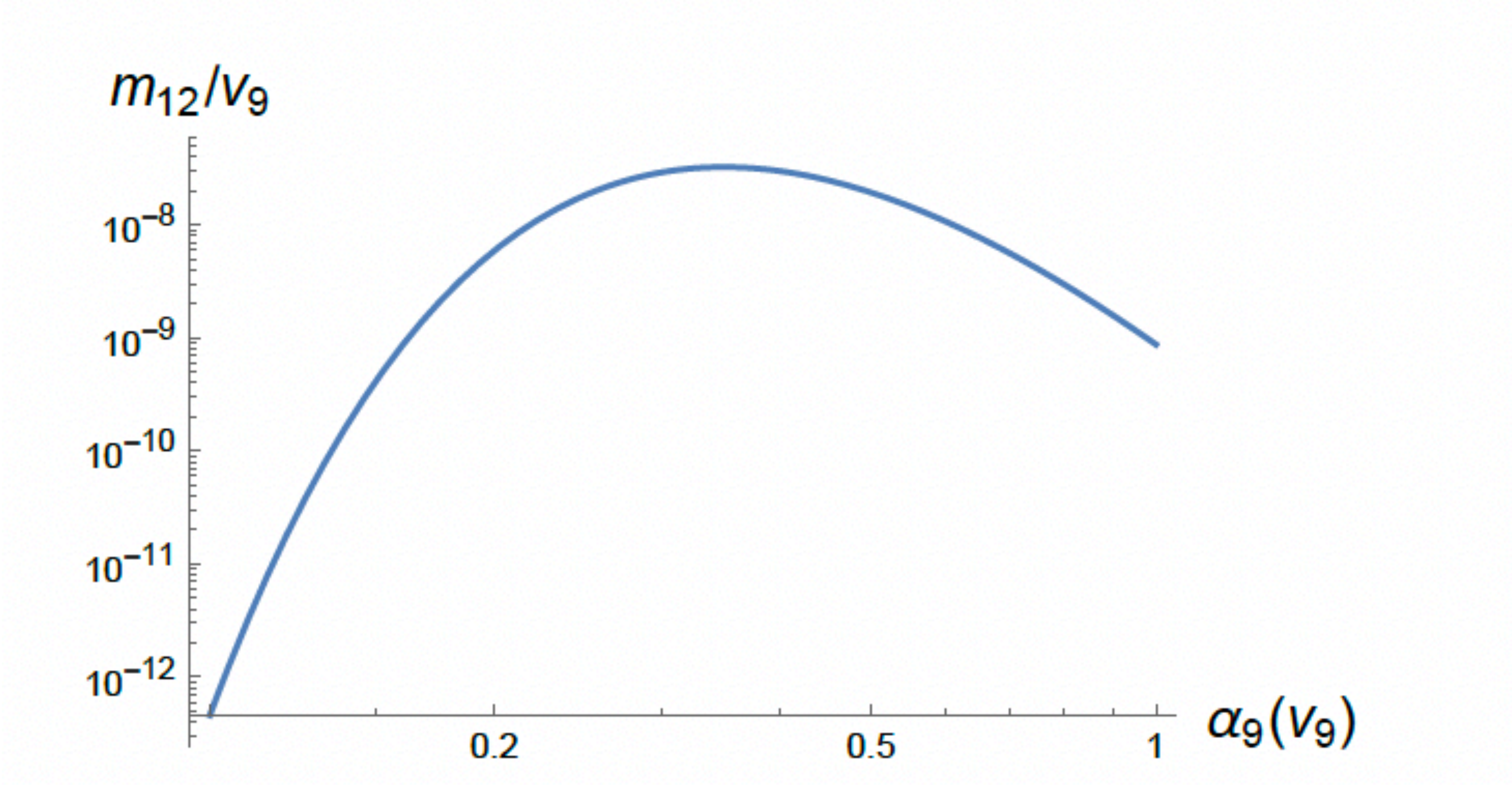
Λ_9 is the b.c.
v_9 is the vev
b_0 the beta function coef.
C_9 the instanton density factor



$$m_{12}^2 \sim y_t y_b C_9 \left(\frac{8\pi^2}{g(v_9)^2}\right)^{2\cdot 9} \int \frac{d\rho}{\rho^5} (\Lambda_9 \rho)^{b_0} e^{-2\pi^2 \rho^2 v_9^2} \rho^2$$

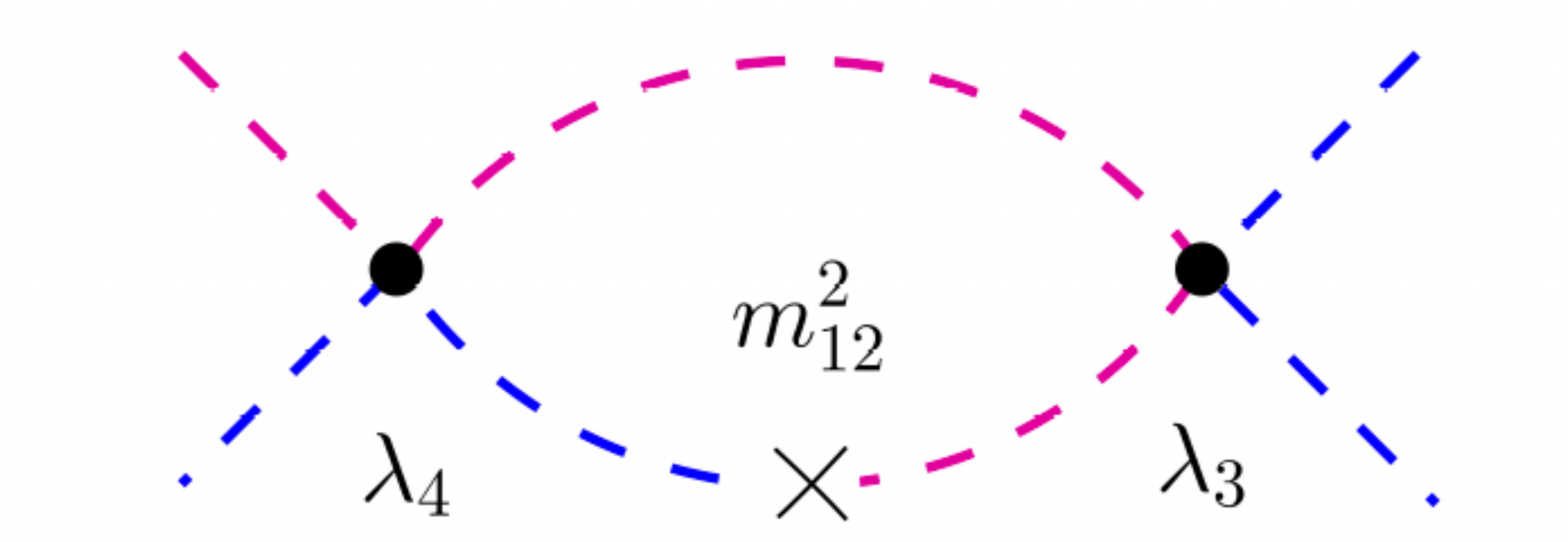
Instanton size

$$m_{12}^2 \sim y_t y_b v_9^2 \frac{C_9 \pi^2}{(\sqrt{2}\pi)^{b_0}} \left(\frac{8\pi^2}{g(v_9)^2}\right)^{18} e^{-\frac{8\pi^2}{g(v_9)^2}} \Gamma\left(\frac{b_0}{2} - 1\right)$$



m_{12} much smaller than v_9

λ_6 generated via loops



Spectrum

- To lowest order our scenario is a softly broken ERPS4 from Haber and Silva

$$m_A^2 = m_{12}^2 \frac{2}{s_{2\beta}}$$

$$m_{H^\pm}^2 = m_A^2 - \frac{1}{2}\lambda_4 v^2$$

$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + \lambda v^2 \pm \sqrt{\left[m_A^2 - \lambda v^2\left(c_{2\beta}^2 + R s_{2\beta}^2\right)\right]^2 + \lambda^2 s_{2\beta}^2 c_{2\beta}^2 (1-R)^2 v^4}\right]$$

$$c_{2\beta} = \frac{m_{22}^2 - m_{11}^2}{m_{22}^2 + m_{11}^2 + \lambda v^2},$$

$$\lambda_1 = \lambda_2 \equiv \lambda \text{ and } R = (\lambda_3 + \lambda_4)/\lambda$$

$$\cos(\beta - \alpha) = \frac{\lambda v^2 s_{2\beta} c_{2\beta} (1-R)}{2\sqrt{(m_H^2 - m_h^2)\left[m_H^2 - \lambda v^2 (1 - \frac{1}{2} s_{2\beta}^2 (1-R))\right]}}$$

- LHC data imposes the m_A to be greater than $m_h/2$ to avoid an invisible decay for the Higgs.
- The current limit on the alignment angle is $\cos(\alpha-\beta)<0.05$
- We are going to require also $\tan\beta>5$
- That implies deviating from the exact Z_2 limit which it is broken by yukawa couplings.
- $m_A>120$ GeV
- $m_H > m_A$
- $\lambda=2\lambda_{SM}$

Visible axion

- The CP odd scalar A could be a realization of the visible axion proposed by Weinberg & Wilczek.
- One can embed this IR model into a complete UV model trying to address both the flavour structure of the SM and also as a possible solution to the strong CP problem.
- The only breaking of the PQ symmetry should only come from the instantons from SU(9).
- The IR PQ symmetry is a non-invertible realization of the UV fundamental PQ symmetry.

Lack of quality problem

$$\mathcal{L} \supset a_6 \left(\Phi_1^\dagger \Phi_2\right)^3 / M_{\rm pl}^2$$

$$V(a) \sim m_{12}^4 \left(1 - \cos(2a)\right) + v_{\rm EW}^4 \left(\frac{v_{\rm EW}}{M_{\rm pl}}\right)^2 \left(1 - \cos(6a + \varphi_6)\right)$$

$$\mathcal{L} \supset a_2 \left(\Phi_1^\dagger \Phi_2\right) |\Xi|^4 / M_{\rm pl}^2$$

$$V(a) \sim m_{12}^4 \left(1 - \cos(2a)\right) + v_{\rm EW}^2 v_9^2 \left(\frac{v_9}{M_{\rm pl}}\right)^2 \left(1 - \cos(2a + \varphi_2)\right)$$

$$v_9^2 / M_{\rm Pl}^2 \lesssim 10^{-10} v_{\rm EW}^2 / v_9^2 \;\; \leftrightarrow \;\; v_9 \lesssim 10^8 \ {\rm GeV}$$

Conclusions

- Symmetries are a fundamental tool to understand Nature.
- Generalized symmetries provide with a extra handle to try to build models to explain the fundamental structure of particle physics.
- In this talk I have introduce the concept of non-invertible symmetries and then I have applied it to the PQ symmetry in a 2HDM.
- One can embed a 2HDM effective model into a UV complete model based on a SU(9) flavour-colour unification model.

- SU(9) instantons break the non-invertible Z_3 and generates a contribution to m_{12}^2.
- The spectrum generated is in the alignment without decoupling limit of the 2HDM providing a very interesting phenomenology.
- It can even serve as an example of a visible axion solving the strong CP problem.
- Lots of possibility in model building and LHC signals.