The νDFSZ Axion model dubbed 2hdSMASH

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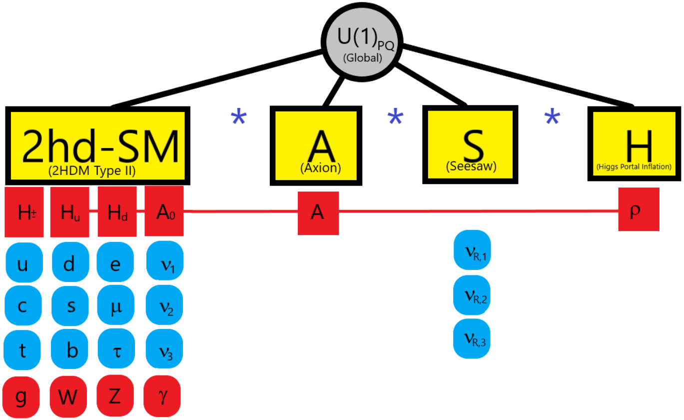
Overview

Introduction and Motivation



> Extension of SMASH [1610.01639] G.Ballesteros, J.Redondo, A.Ringwald, C.Tamarit

> Yukawa-Sector:

$$\mathcal{L}_Y^{\text{2HDM-II}} - y_\nu \overline{l_L} \tilde{H}_d \nu_R - \frac{1}{2} y_N \overline{(\nu_R)^c} \sigma \nu_R + \text{h.c.}$$

> Explains:

- Neutrino masses
- Baryon Asymmetry
- Strong CP-Problem
- Dark Matter
- Inflation

> Describes Universe from Inflation to today

2hdSMASH Scalar Sector

- 2hdSMASH Scalar Potential:

$$V(\Phi_1,\Phi_2,\sigma) = m_{11}^2\,|\Phi_1|^2 + m_{22}^2\,|\Phi_2|^2 + m_{\sigma\sigma}^2\,|\sigma|^2 + \frac{1}{2}\lambda_1\,|\Phi_1|^4 + \frac{1}{2}\lambda_2\,|\Phi_2|^4 + \lambda_3\,|\Phi_1|^2\,|\Phi_2|^2 + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$
$$+\frac{1}{2}\lambda_\sigma\,|\sigma|^4 + \lambda_{1\sigma}\,|\Phi_1|^2\,|\sigma|^2 + \lambda_{2\sigma}\,|\Phi_2|^2\,|\sigma|^2 - \epsilon\left(\Phi_1^\dagger\Phi_2\sigma^2 + \Phi_2^\dagger\Phi_1\sigma^{*2}\right)$$

with complex fields: $\Phi_{1,2} = \begin{pmatrix} h^+_{1,2} \\ \frac{v_{1,2}+h_{1,2}+ia_{1,2}}{\sqrt{2}} \end{pmatrix}$, $\sigma = \frac{\rho+v_\sigma+ia_\sigma}{\sqrt{2}}$

- Theoretical constraints (Boundedness-from-Below, Perturbative unitarity):

$$\lambda_{1,2,\sigma} > 0 \ , \ \lambda_{34} > -\sqrt{\lambda_1\lambda_2}$$
$$\sqrt{\lambda_{1,2}\lambda_\sigma} > \lambda_{1\sigma,2\sigma} > -\sqrt{\lambda_{1,2}\lambda_\sigma}$$
$$\lambda_\sigma\lambda_{34} - \lambda_{1\sigma}\lambda_{2\sigma} + \sqrt{(\lambda_1\lambda_\sigma - \lambda_{1\sigma}^2)(\lambda_2\lambda_\sigma - \lambda_{2\sigma}^2)} > 0$$
$$\lambda_{1\sigma} + \lambda_{2\sigma} > 0 \ , \ \lambda_{1\sigma}\lambda_{2\sigma} - \epsilon^2 > 0$$

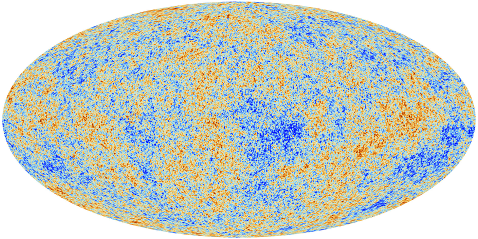
$$|\lambda_{1,2,3,1\sigma,2\sigma}| < 8\pi$$
$$|\lambda_3 - \lambda_4| < 8\pi$$
$$\frac{1}{2}\left|\lambda_1 + \lambda_2 + \sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_3^2}\right| < 8\pi$$
$$\frac{1}{2}\left|\lambda_{1\sigma} + \lambda_{2\sigma} + \sqrt{16\epsilon^2 + (\lambda_{1\sigma}-\lambda_{2\sigma})^2}\right| < 8\pi$$
$$\frac{1}{2}\left|\lambda_3 + 2\lambda_4 + \lambda_\sigma + \sqrt{16\epsilon^2 + (\lambda_3+2\lambda_4-\lambda_\sigma)^2}\right| < 8\pi$$

Constraint from Hidden-Scalar Inflation in 2hdSMASH

- Chaotic Inflation with non-minimal ξ_σ coupling to gravity R: $\frac{-\mathcal{L}}{\sqrt{-g}} \supset \left[\frac{M_{\text{Pl}}^2}{2} + \xi_\sigma\,|\sigma|^2\right] R + V$

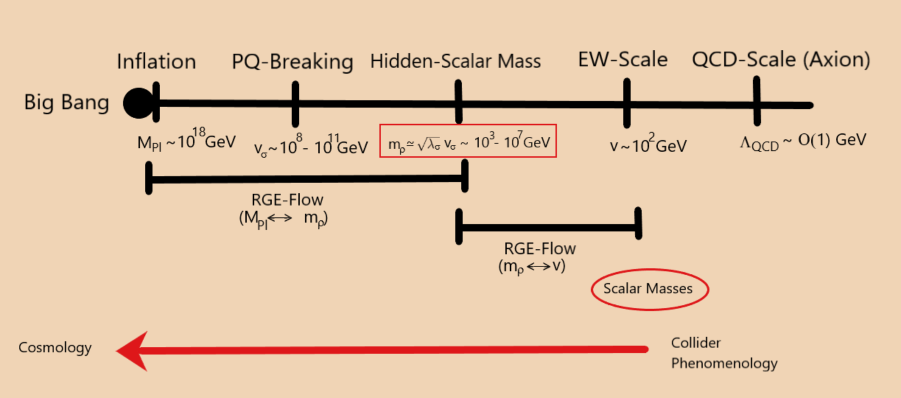
- Temperature fluctuations (anisotropies): $P_\zeta \sim \frac{\lambda_\sigma}{\xi_\sigma^2} \sim 10^{-10}$

- Perturbative unitarity:
  $\xi_\sigma \lesssim 1 \quad \Rightarrow \quad \boxed{\lambda_\sigma \simeq 10^{-10}}$



CREDIT : *ESA*

From Inflation to Collider Phenomenology



> Inflation stabilises the hierarchy $v_\sigma \gg v$

From Inflation to Collider Phenomenology

$$\frac{\lambda_\sigma(\mu)}{\lambda_\sigma(m_\rho)} \approx 1 + \frac{1}{4\pi^2 \lambda_\sigma(m_\rho)} \left[\lambda_{1\sigma}^2 + \lambda_{2\sigma}^2 + 2\epsilon^2 - \frac{1}{2}\,\mathrm{Tr}\left(y_N^\dagger y_N y_N^\dagger y_N \right) \right] \Bigg|_{m_\rho} \ln \frac{\mu}{m_\rho}$$

- Inflation requires:

$$\lambda_\sigma\left(M_{\mathrm{Pl}}\right) \sim \lambda_\sigma\left(m_\rho\right) \sim 10^{-10} \Rightarrow \lambda_{1\sigma,2\sigma}, \epsilon, \sqrt{\mathrm{Tr}\left(y_N^\dagger y_N y_N^\dagger y_N \right)} \ll \sqrt{\lambda_\sigma} \simeq 10^{-5}$$

High-Energy Theory

2hdSMASH

$$V(\Phi_1, \Phi_2, \sigma) = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 + m_{\sigma\sigma}^2 |\sigma|^2 + \frac{1}{2}\lambda_1 |\Phi_1|^4 + \frac{1}{2}\lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{1}{2}\lambda_\sigma |\sigma|^4 + \lambda_{1\sigma} |\Phi_1|^2 |\sigma|^2 + \lambda_{2\sigma} |\Phi_2|^2 |\sigma|^2 - \epsilon \left(\Phi_1^\dagger \Phi_2 \sigma^2 + \Phi_2^\dagger \Phi_1 \sigma^{*2}\right)$$

Integrating
ρ in/out

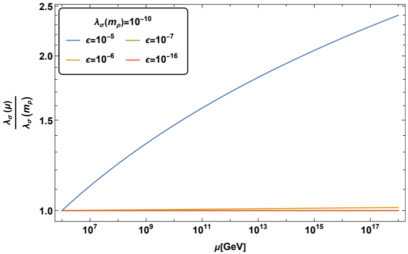
Enhanced Poincarè Symmetry $G_{\mathcal{P}}^{\mathrm{2HDM}}$ x $G_{\mathcal{P}}^{S}$

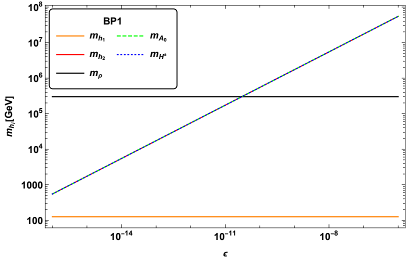
2HDM

$$\tilde{V}(\Phi_1, \Phi_2) = \bar{m}_{11}^2 |\Phi_1|^2 + \bar{m}_{22}^2 |\Phi_2|^2 - \bar{m}_{12}^2 \left(\Phi_1^\dagger \Phi_2 + h.c\right) + \frac{1}{2}\lambda_1 |\Phi_1|^4 + \frac{1}{2}\lambda_2 |\Phi_2|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$

Effective
Low-Energy Theory

Scalar Masses





- Pseudoscalar- and Charged Higgs masses:

$$m_{A_0}^2 = \epsilon \left(\frac{t_\beta v^2}{1+t_\beta^2} + \frac{v_\sigma^2 \left(1+t_\beta^2\right)}{4 t_\beta} \right)$$

$$m_{H^\pm}^2 = \frac{\left(1+t_\beta^2\right)^2 \epsilon v_\sigma^2 - \lambda_4 t_\beta v^2}{2 t_\beta \left(1+t_\beta^2\right)}$$

- For $\lambda_{1\sigma,2\sigma}, \epsilon \ll \sqrt{\lambda_\sigma}$ and $\epsilon \gtrsim \lambda_{1,2,3,4} \left(\frac{v}{v_\sigma}\right)^2$:

$$m_{h_1}^2 \approx \frac{v^2 \left(\lambda_1 + \lambda_2 t_\beta^4 + 2\lambda_{34} t_\beta^2\right)}{\left(1+t_\beta^2\right)^2}$$

$$m_{h_2}^2 \approx \frac{\epsilon v_\sigma^2 \left(1+t_\beta^2\right)}{2 t_\beta} + \frac{v^2 t_\beta^2 \left(\lambda_1 + \lambda_2 - 2\lambda_{34}\right)}{\left(1+t_\beta^2\right)^2}$$

- Numerically acquired Benchmark points satisfying BfB and perturbative unitarity constraints with $\lambda_\sigma = 10^{-10}$ and $v_\sigma = 3 \cdot 10^{10}$GeV:

BPs	m_{h_1}[GeV]	m_{h_2}[GeV]	$m_{H^\pm}$[GeV]	m_{A_0}[GeV]	m_ρ[GeV]	$\lambda_{1\sigma,2\sigma}, \epsilon$	$\lambda_{1,2,3,4}$	t_β
BP1	125.19	864.92	865.23	865.19	$3 \cdot 10^5$	$10^{-15}, 10^{-15}, 2.5 \cdot 10^{-16}$	$1.2, 2.59 \cdot 10^{-1}, 1, -0.1$	6.5
BP2	125.08	1212.86	1212.92	1212.91	$3 \cdot 10^5$	$10^{-15}, 10^{-15}, 2.5 \cdot 10^{-16}$	$1.2, 2.51 \cdot 10^{-1}, 1, -0.1$	13
BP3	125.17	1711.52	1711.53	1711.53	$3 \cdot 10^5$	$10^{-15}, 10^{-15}, 2.5 \cdot 10^{-16}$	$1.2, 2.57 \cdot 10^{-1}, 1, -0.1$	26

Conclusions & Outlook

> Conclusions:

- Inflation requires $\lambda_\sigma \sim 10^{-10} \Rightarrow$ Mass-scale m_ρ drops significantly
- Requiring $\lambda_\sigma\left(M_{\text{Pl}}\right) \sim \lambda_\sigma\left(m_\rho\right) \sim 10^{-10} \Rightarrow$ Higgs-Portal couplings are forced to be very small (stability of RGE β_{λ_σ})
- Scalar Masses are at/near the EW-scale and can be potentially probed by LHC, HL-LHC or future colliders

> Outlook

- Checking whether Benchmark scenarios pass collider constraints (work in progress)
- Acquiring more Benchmark scenarios and evolve parameters to Planck-scale (work in progress)
- Investigating Pre-/Reheating stages of the Universe

Thank you!

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