Vacuum stability of an extended Higgs sector with multi-scalars under $U(1)$ global symmetries

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The model: explains neutrino mass, BAU, & dark matter

⋆ The scalar potential [Phys.Rev.D 106 9 (2022) 095017]

$$\begin{aligned}V_{\rm BSM} = {}& \mu_1^2(\eta^\dagger\eta) - \mu_2^2 H^\dagger H + \frac{1}{2}\mu_3^2\Phi^2 + \frac{1}{3}\mu_4\Phi^3 - \mu_5^2(\Phi'^\dagger\Phi') + \frac{\mu_6}{\sqrt{2}}\Phi(H^\dagger H) \\ & + \frac{\mu_7}{\sqrt{2}}\Phi(\Phi'^\dagger\Phi') + \lambda_1(\eta^\dagger\eta)^2 + \lambda_2(\eta^\dagger\eta)(H^\dagger H) + [\lambda_3(\eta^\dagger H)^2 + \text{H.c.}] \\ & + \lambda_4(H^\dagger H)^2 + \frac{1}{4}\lambda_5\Phi^4 + \lambda_6(\Phi'^\dagger\Phi')^2 + \frac{\lambda_7}{2}H^\dagger H\Phi^2 + \lambda_8 H^\dagger H(\Phi'^\dagger\Phi') \\ & + \frac{\lambda_9}{2}\Phi^2(\Phi'^\dagger\Phi') \underbrace{+\lambda_{10}(\eta^\dagger H)(H^\dagger\eta) + \lambda_{11}(\eta^\dagger\eta)(\Phi'^\dagger\Phi') + \lambda_{12}\eta^\dagger\eta\Phi^2}_{\text{our modification}}\end{aligned}$$

Under $\overbrace{SU(3)_c \times SU(2)_L \times U(1)_Y}^{\text{Standard Model}} \times \underbrace{U(1)_D \times \overbrace{U(1)_{B-L}}^{\text{only governs fermions}}}_{\text{global symmetries}}$,

$$\eta : \left(1, 2, 1, \frac{1}{2}, 0\right), \quad H : \left(1, 2, \frac{1}{2}, 0, 0\right), \quad \Phi' : (1, 1, 0, 1, 0), \quad \Phi : (1, 1, 0, 0, 0).$$

⇓ *parameterized as*

$$\eta = \begin{pmatrix} \eta^+ \\ \frac{1}{\sqrt{2}}(v_4 + h_4 + i\phi_4) \end{pmatrix}, \quad H = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v_2 + h_2 + i\phi_2) \end{pmatrix}, \quad \Phi = v_3 + h_3, \quad \Phi' = \frac{1}{\sqrt{2}}(v_1 + h_1 + i\phi_1).$$

$v_4 \simeq 0$ *to preserve remnant* Z_2

⋆ Scalar mass spectrum

$$\bar{m}_{h_4}^2 = \mu_1^2 + \frac{1}{2}(\lambda_2 + 2\lambda_3 + \lambda_{10})v_2^2 + \frac{1}{2}\lambda_{11}v_1^2 + \lambda_{12}v_3^2,$$

$$m_{H^\pm}^2 = -\frac{1}{2}(2\lambda_3 + \lambda_{10})v_2^2, \qquad m_{A_3}^2 = -2\lambda_3 v_2^2,$$

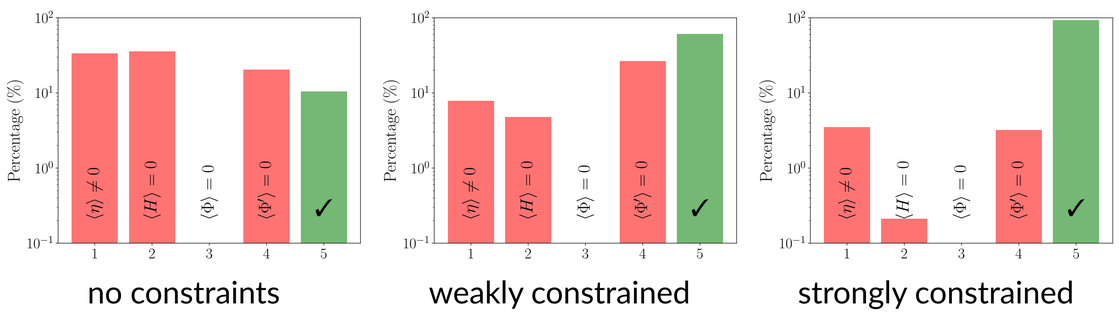
$$\mathcal{M}_{\rm even}^2 = \begin{pmatrix} 2\lambda_6 v_1^2 & \lambda_8 v_1 v_2 & \frac{\mu_7}{\sqrt{2}}v_1 + \lambda_9 v_1 v_3 \\ \lambda_8 v_1 v_2 & 2\lambda_4 v_2^2 & \frac{\mu_6}{\sqrt{2}}v_2 + \lambda_7 v_3 v_2 \\ \frac{\mu_7}{\sqrt{2}}v_1 + \lambda_9 v_1 v_3 & \frac{\mu_6}{\sqrt{2}}v_2 + \lambda_7 v_3 v_2 & 2\lambda_5 v_3^2 + \mu_4 v_3 - \frac{1}{2\sqrt{2}v_3}(\mu_6 v_2^2 + \mu_7 v_1^2) \end{pmatrix}.$$

Numerical analysis

⋆ Vacua distribution of the potential [JHEP 02 (2019) 154]

Good vacuum := satisfy $\langle\eta\rangle = 0,\ \langle H\rangle \neq 0,\ \langle\Phi\rangle \neq 0,$ and $\langle\Phi'\rangle \neq 0$

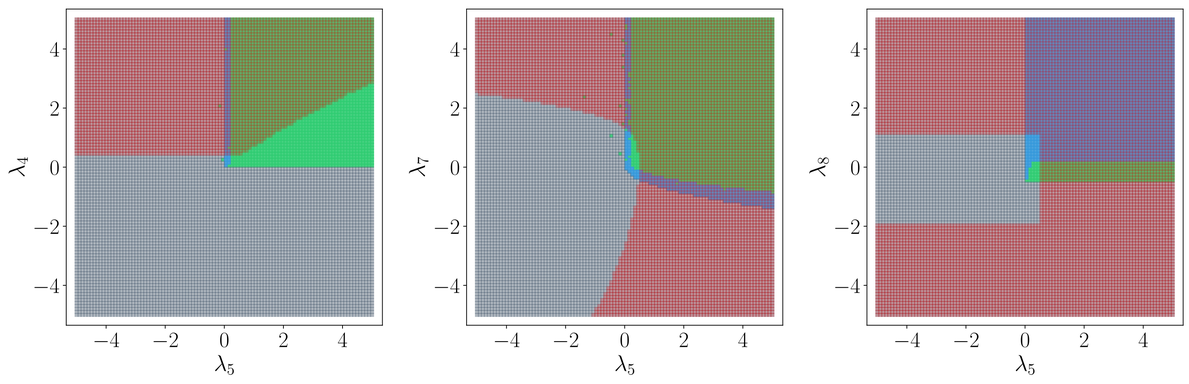
Random Sampling ⇒ BfB Filtering ⇒ Minimization ⇒ Classification



no constraints | weakly constrained | strongly constrained

⋆ Globally minimized vacua and perturbative constraint

Grid Sampling ⇒ BfB Check ⇒ Minimization ⇒ Classification ⇒ Perturbativity Check



∵ red points: exceeding the perturbative limit 4π ∵ green points: good vacua

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Theoretical & experimental constraints

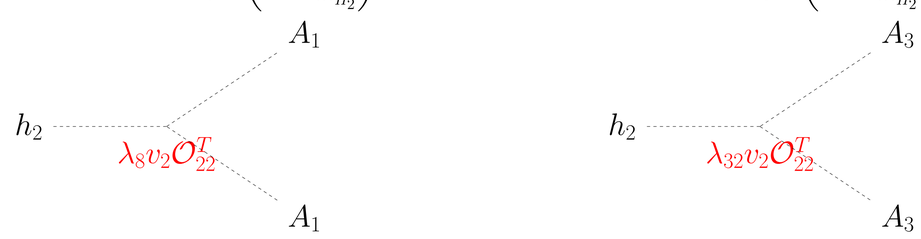
⋆ BFB conditions from copositivity [Eur.Phys.J.C 72 (2012) 2093]

$$\Lambda = \begin{pmatrix} \lambda_1 & \lambda_{231} & \lambda_{11} & \lambda_{12} \\ \lambda_{231} & \lambda_4 & \lambda_8 & \frac{1}{2}\lambda_7 \\ \lambda_{11} & \lambda_8 & \lambda_6 & \frac{1}{2}\lambda_9 \\ \lambda_{12} & \frac{1}{2}\lambda_7 & \frac{1}{2}\lambda_9 & \lambda_5 \end{pmatrix} \geq 0 \quad \Rightarrow \quad \begin{cases} \lambda_1 \geq 0, \quad \lambda_4 \geq 0, \quad \lambda_5 \geq 0, \quad \lambda_6 \geq 0 \\ \qquad \text{(the obvious ones)} \\ \text{etc.} \end{cases}$$

where $\lambda_{231} = \lambda_2 + \lambda_3 + \lambda_{10}$.

⋆ Higgs invisible decay

$$\Gamma_{H_2\to\chi\bar{\chi}} = \lambda_D^2(\mathcal{O}_{32}^T)^2\frac{m_{H_2}}{8\pi}\left(1 - \frac{4m_\chi^2}{m_{H_2}^2}\right)^{\frac{3}{2}} \qquad \Gamma_{H_2\to H_3H_3} = g^2\frac{m_{H_2}}{8\pi}\left(1 - \frac{4m_{H_3}^2}{m_{H_2}^2}\right)^{\frac{3}{2}}$$



$$\Gamma_{H_2\to A_1A_1} = \lambda_8^2 v_2^2(\mathcal{O}_{22}^T)^2\frac{m_{H_2}}{32\pi}\left(1 - \frac{4m_{A_1}^2}{m_{H_2}^2}\right)^{\frac{3}{2}} \qquad \Gamma_{H_2\to A_3A_3} = \lambda_{32}^2 v_2^2(\mathcal{O}_{22}^T)^2\frac{m_{H_2}}{8\pi}\left(1 - \frac{4m_{A_3}^2}{m_{H_2}^2}\right)^{\frac{3}{2}}$$

Experimental bounds: $\text{BR}_{h\to\text{inv}} < 0.18\,(\textbf{CMS})$ and $\text{BR}_{h\to\text{inv}} < 0.145\,(\textbf{ATLAS})$
[Phys.Rev.D 105 9 (2022) 092007; JHEP 08 (2022) 104]

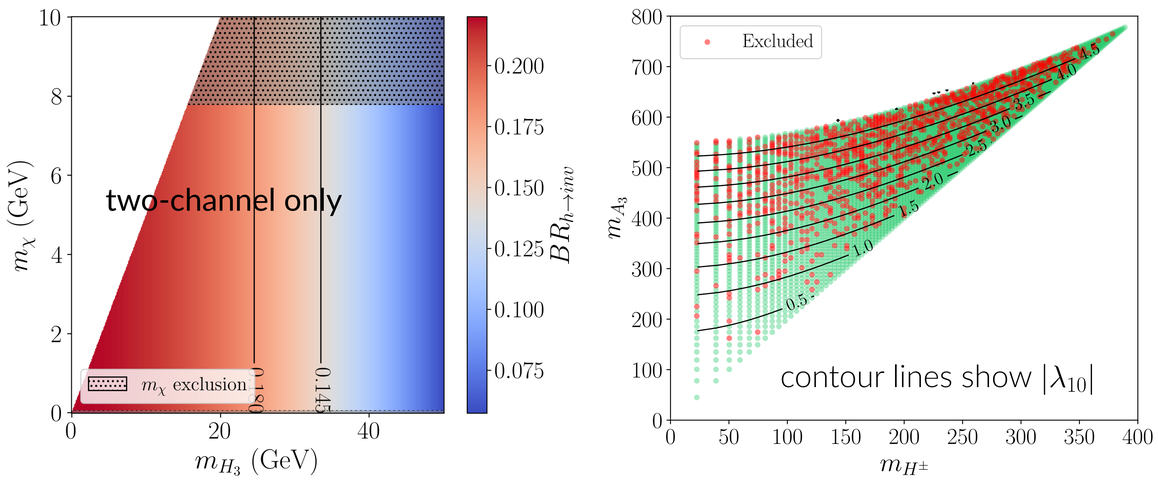
⋆ DM relic density

$\Omega_{DM} \approx 5\Omega_B$ $(\textbf{WMAP}\ \&\ \textbf{Planck})$ ⇒ $m_\chi = 1.3 - 7.76\,\text{GeV}$

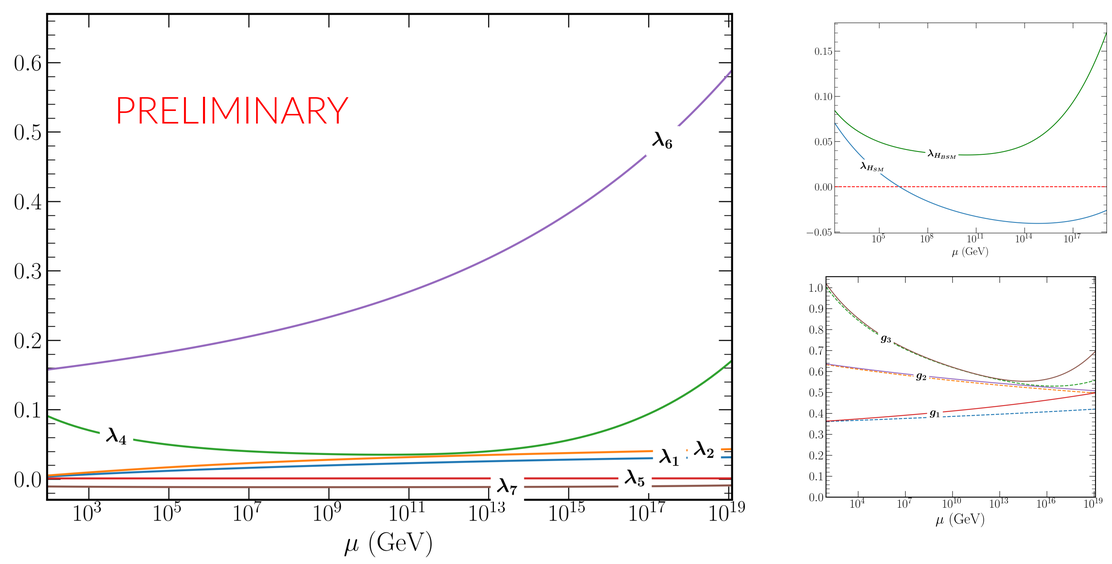
[Astrophys.J.Suppl. 208 (2013) 19; Astron.Astrophys. 641 (2020) A1]

Constrained mass parameter space

$m_{H_2} = 125.09\,\text{GeV},\ \ v_2 = 246\,\text{GeV},\ \ \lambda_4 \equiv \lambda_{SM} = 0.129$



Constrained running couplings



Summary: a stable vacuum is obtained while satisfying both theoretical and experimental requirements for a small part of the parameter space.

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