A stable Higgs portal with vector dark matter

Mateusz Duch
Institute of Theoretical Physics, University of Warsaw

55. Cracow School of Theoretical Physics
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In collaboration with Bohdan Grzadkowski and Moritz McGarrie

Outline

1. Introduction to the model
2. Perturbativity and stability conditions
3. Experimental bounds
4. Dark matter - relic density
5. Dark matter - direct detection constraints

The Higgs portal with vector dark matter

Additional complex scalar field S

- singlet of $U(1)_Y \times SU(2)_L \times SU(3)_c$
- charged under $U(1)_X$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + (D_\mu S)^* D^\mu S + \tilde{V}(H, S) \tag{1}$$

$$V(H, S) = -\mu_H^2 |H|^2 + \lambda_H |H|^4 - \mu_S^2 |S|^2 + \lambda_S |S|^4 + \kappa |S|^2 |H|^2 \tag{2}$$

Vacuum expectation values:

$$\langle H \rangle = \frac{v_{SM}}{\sqrt{2}}, \qquad \langle S \rangle = \frac{v_x}{\sqrt{2}} \tag{3}$$

$U(1)_X$ vector gauge boson V_μ

- $D_\mu = \partial_\mu + i g_x V_\mu$
- Stability condition - no mixing of $U(1)_X$ with $U(1)_Y$ $\quad$ ~~$B_{\mu\nu} V^{\mu\nu}$~~
  $\mathcal{Z}_2 : V_\mu \to -V_\mu, \qquad S \to S^*, \qquad S = \phi e^{i\sigma}: \ \phi \to \phi, \ \sigma \to -\sigma$
- V_μ acquires mass due to the Higgs mechanism in the hidden sector

$$M_{Z'} = g_x v_x \tag{4}$$

The Higgs portal with vector dark matter

Positivity of the potential

$$V(H,S) = -\mu_H^2|H|^2 + \lambda_H|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2 \quad (5)$$

$$\lambda_H > 0, \quad \lambda_S > 0, \quad \kappa > -2\sqrt{\lambda_H\lambda_S} \quad (6)$$

Scalar mixing

$$S = \frac{1}{\sqrt{2}}(v_x+\phi_S+i\sigma_S)\ , \ \ H^0 = \frac{1}{\sqrt{2}}(v+\phi_H+i\sigma_H), \ \text{ where } \ H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \quad (7)$$

$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_H v^2 & \kappa v v_x \\ \kappa v v_x & 2\lambda_S v_x^2 \end{pmatrix}, \ \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_H \\ \phi_S \end{pmatrix} \quad (8)$$

$M_{h_1} = 125$ GeV - observed Higgs particle

Higgs couplings

$$\mathcal{L} \supset \frac{h_1\cos\alpha + h_2\sin\alpha}{v}\left(2M_W W_\mu^+ W^{\mu-} + M_Z^2 Z_\mu Z^\mu - \sum_f m_f \bar{f} f\right) \quad (9)$$

One-loop beta functions $\beta_\lambda = 16\pi^2 \frac{d}{dt}\lambda$

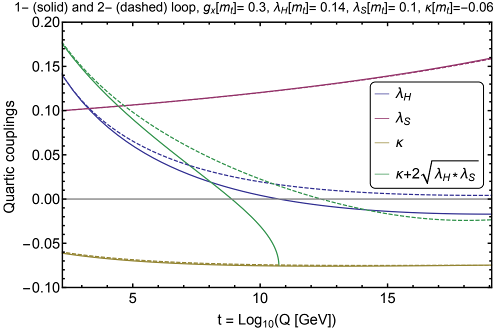
$$\beta^{(1)}_{\lambda_H} = \frac{27}{200} g_1^4 + \frac{9}{20} g_1^2 g_2^2 + \frac{9}{8} g_2^4 - \frac{9}{5} g_1^2 \lambda_H - 9 g_2^2 \lambda_H + 24 \lambda_H^2 + \kappa^2 - 6 y_t^4 + 12 \lambda_H y_t^2$$

$$\beta^{(1)}_{\lambda_S} = \frac{1}{2}\Big(40\lambda_S^2 - 36 g_x^2 \lambda_S + 27 g_x^4 + 4\kappa^2\Big) > 0$$

$$\beta^{(1)}_{\kappa} = \frac{\kappa}{10}\Big[-9 g_1^2 - 90 g_x^2 - 45 g_2^2 + 120\lambda_H + 80\lambda_S + 40\kappa + 60 y_t^2\Big]$$

2-loop analysis

SARAH 4: A tool for (not only SUSY) model builders, F. Staub; Comput Phys Commun 185 (2014) pp. 1773-1790



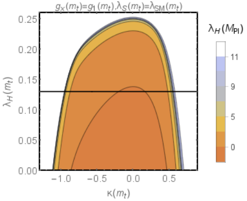
$$V(H,S) = -\mu_H^2|H|^2 + \lambda_H|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2$$

Perturbativity

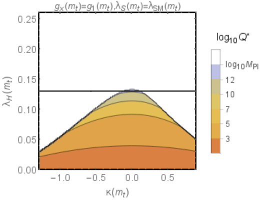
$\lambda_H < 4\pi, \quad \kappa < 4\pi, \quad \lambda_S < 4\pi$

Positivity - vacuum stability

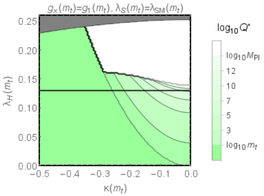
$\lambda_H(Q) > 0, \quad \lambda_S(Q) > 0, \quad \kappa(Q) + 2\sqrt{\lambda_H(Q)\lambda_S(Q)} > 0$



$\lambda_S(m_t) \in [0, 0.28]$
$\lambda_H(m_t) \in [0, 0.25]$

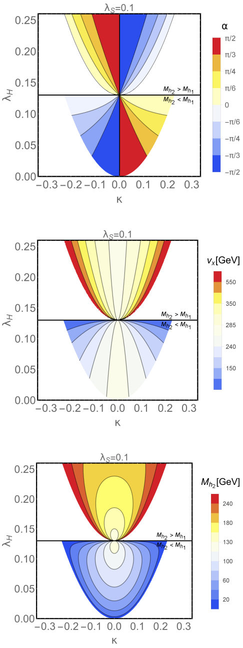


$\lambda_H(m_t) \approx 0.14$



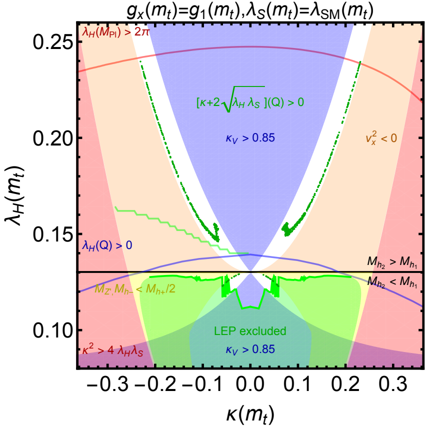
$\kappa(Q) + 2\sqrt{\lambda_H(Q)\lambda_S(Q)} > 0$

Theoretical and experimental bounds



Experimental constraints

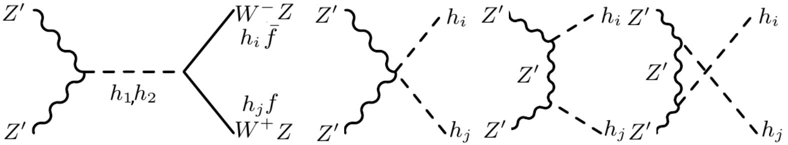
LEP bounds, Higgs couplings, invisible Higgs decays



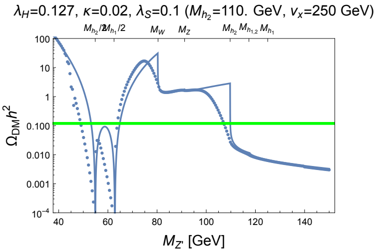
Peskin, Takeuchi S,T,U parameters constraints lie in the non-perturbative/large mixing angle region.

Annihilation channels:

$\propto \sin 2\alpha$



Comparision of numerical results and non-relativistic approximation.
G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov, micrOMEGAs4.1, Computer Physics Communications, 2015



$$\langle \sigma |v| \rangle = \left[\frac{\hat{\sigma}(s)}{4m_{Z'}^2} + \left(\frac{3}{2}\hat{\sigma}'(s) - \frac{\hat{\sigma}(s)}{4m_{Z'}^4} \right) \frac{T}{M_{Z'}} + \ldots \right]_{s=4m_{Z'}^2},$$

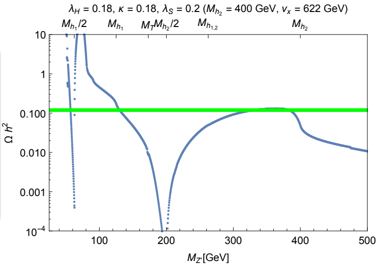
$$\Omega h^2 = \frac{3 \times 10^{-27} cm^3 s^{-1}}{\langle \sigma |v| \rangle}$$

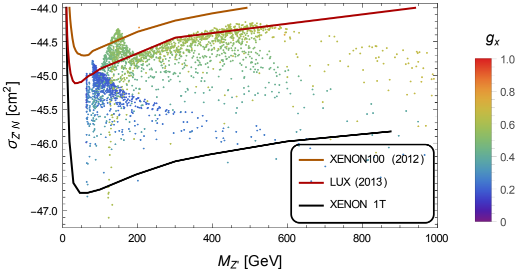
$$\Omega h^2 = 0.1199 \pm 0.0022$$

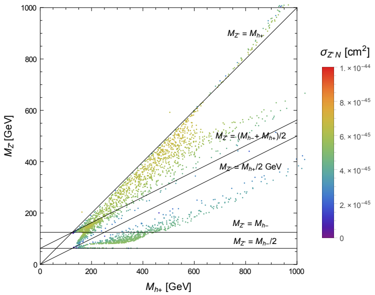
Direct detection $M_{h_2} > 125$ GeV

$$\sigma_{Z'N} = \frac{\mu^2}{16\pi}\frac{M_{Z'}^2}{v_x^2} g_{hNN}^2 \sin^2 2\alpha \left(\frac{1}{m_{h+}^2} - \frac{1}{m_{h-}^2}\right)^2$$

$\mu = M_{Z'} M_N/(M_N + M_{Z'})$,
g_{hNN} is effective nucleon-Higgs coupling







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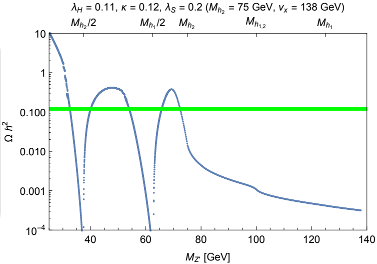

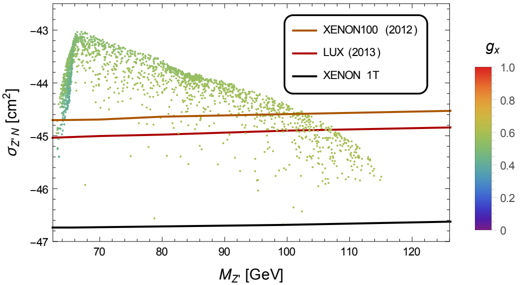

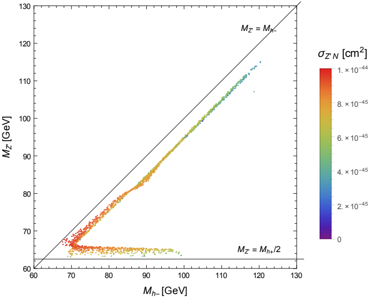

Conclusions

The model fulfils theoretical, collider and cosmological constraints and provides the viable candidate for a dark matter particle.

Parameters of the potential with the second scalar field can be chosen to ensure absolute stability of electroweak vacuum.

The model can be tested by future experiments, especially: precision measurements of Higgs couplings and dark matter direct detection probes at XENON1T.