A stable Higgs portal with vector dark matter

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Matter To The Deepest
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MD, Bohdan Grzadkowski, Moritz McGarrie, "A stable Higgs portal with vector dark matter", arXiv:1506.08805 (to appear in JHEP)

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 $U(1)_X$

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

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

Vacuum expectation values:

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v_{SM}}{\sqrt{2}} \end{pmatrix}, \qquad \langle S \rangle = \frac{v_x}{\sqrt{2}}$$

$U(1)_X$ vector gauge boson V_μ

- $D_\mu = \partial_\mu + i g_x V_\mu$
- Stability condition - no mixing of $U(1)_X$ with $U(1)_Y$ ~~$B_{\mu\nu} V^{\mu\nu}$~~

  $\mathcal{Z}_2 : V_\mu \to -V_\mu$, $S \to S^*$, $S = \phi e^{i\sigma}$: $\phi \to \phi$, $\sigma \to -\sigma$
- V_μ acquires mass due to the Higgs mechanism in the hidden sector

$$M_{Z'} = g_x v_x$$

The Higgs portal with vector dark matter

Positivity of the potential

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

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

Scalar mixing

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

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

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

Higgs couplings

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

Perturbativity and stability conditions - RGEs

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

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

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

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

Positivity - vacuum stability

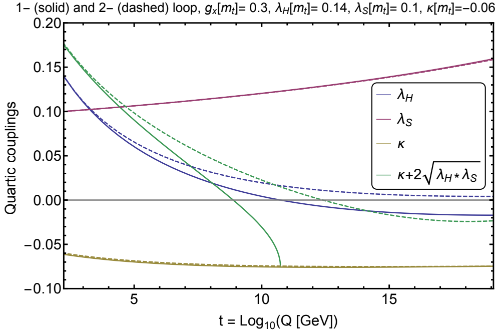
$\lambda_H(Q) > 0$

$\lambda_S(Q) > 0$

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

2-loop analysis

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



Perturbativity and stability conditions

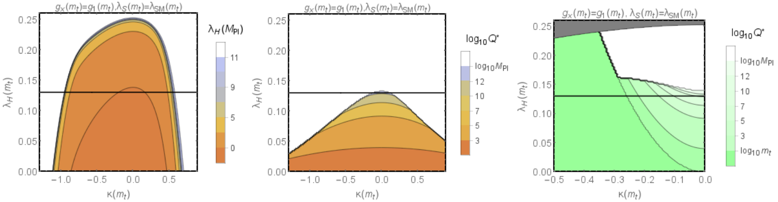
$$V(H,S) = -\mu_H^2|H|^2 + \lambda_H|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2$$

Perturbativity

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

Positivity - vacuum stability

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



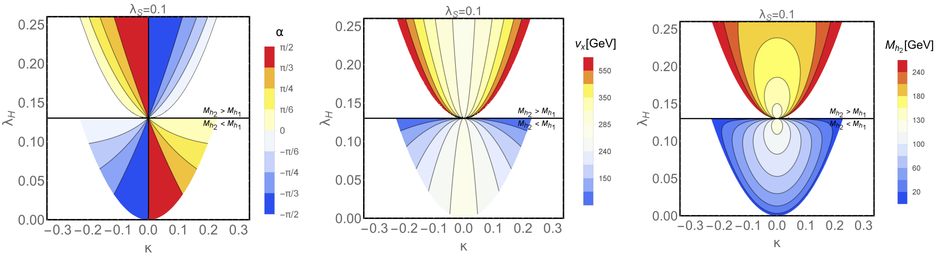
$\lambda_S(m_t) \in [0, 0.28]$

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

$\lambda_H(m_t) \approx 0.14$

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

Theoretical and experimental bounds



Experimental constraints

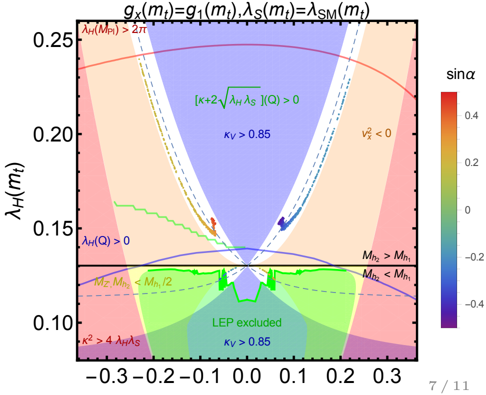
- Higgs couplings

$$\kappa_V = \frac{g_{h_1 VV}}{g^{SM}_{h_1 VV}} = \cos\alpha, \quad 0.85 < \kappa_V < 1,$$

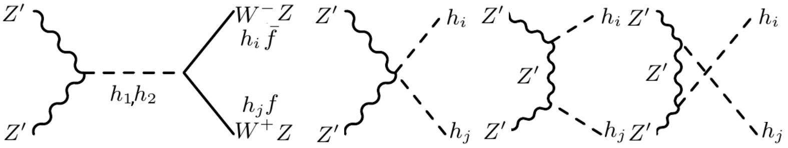
Atlas and CMS combined: $\cos\alpha > 0.94$

$$\mu = \frac{\sigma \times BR}{\sigma_{SM} \times BR_{SM}} = \cos^2\alpha$$

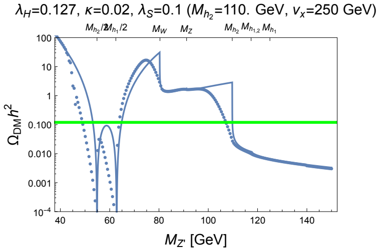
- LEP bounds from $e^+e^- \to Zh_2$
- no invisible Higgs decays
  $h_1 \to Z'Z', \quad h_1 \to h_2 h_2$
- electroweak precision data (S,T)
- dark matter relic density



Annihilation channels:



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



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

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

Planck result:

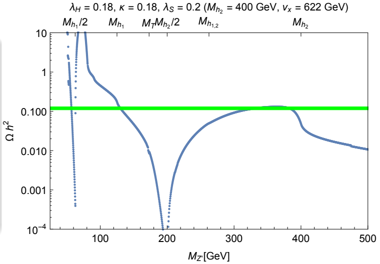
$$\Omega h^2 = 0.1199 \pm 0.0022$$

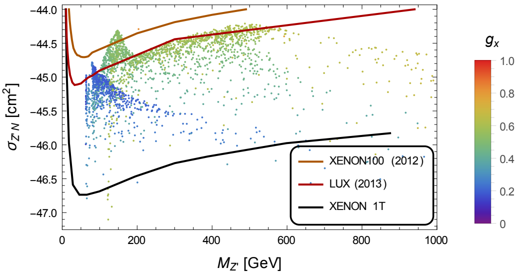
Direct detection $M_{h_2} > 125$ GeV

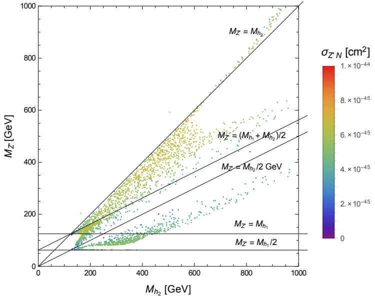
$$\sigma_{Z'N} = \frac{\mu^2}{4\pi} g_x^2 g_{hNN}^2 \sin^2 2\alpha \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2} \right)^2$$

$\mu = \frac{M_{Z'} M_N}{M_N + M_{Z'}}$

g_{hNN} – effective nucleon-Higgs coupling







Direct detection $M_{h_2} < 125$ GeV

$$\sigma_{Z'N} = \frac{\mu^2}{4\pi} g_x^2 g_{hNN}^2 \sin^2 2\alpha \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2} \right)^2$$

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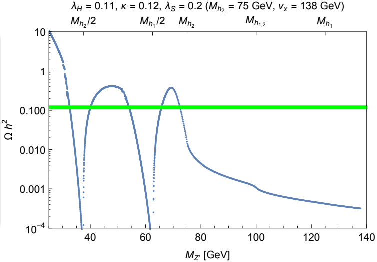

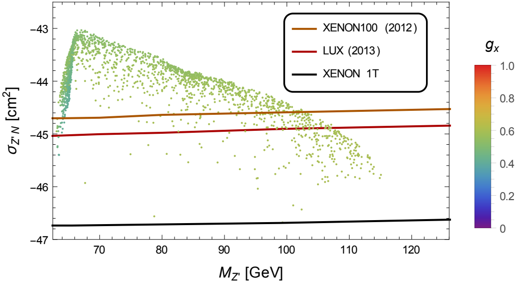

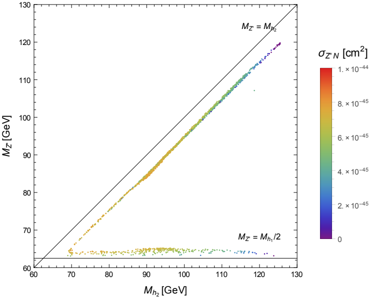

Conclusions

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 the absolute stability of the electroweak vacuum.

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