Vacuum stability from vector dark matter

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MD, Bohdan Grzadkowski, Moritz McGarrie, “A stable Higgs portal with vector dark matter”, JHEP 1509 (2015) 162

Simplest renormalizable SM extension with a vector dark matter

Hambye (2009), Lebedev et al. (2012, 2015), Baek et al. (2013)

Extra complex scalar field S

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

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

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 - dark matter candidate

- acquires mass due to the Higgs mechanism in the hidden sector

  massive vector boson Z' $\qquad M_{Z'} = g_x v_x$
- stability condition - no mixing of $U(1)_X$ with $U(1)_Y$ $\qquad \cancel{B_{\mu\nu} V^{\mu\nu}}$

  dark charge symmetry $\qquad \mathcal{Z}_2 : Z'_\mu \to -Z'_\mu, \qquad S \to S^*$

The Higgs portal with vector dark matter

Scalar mixing

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

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

$M_{h_1} = 125$ 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

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

One-loop beta functions

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

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

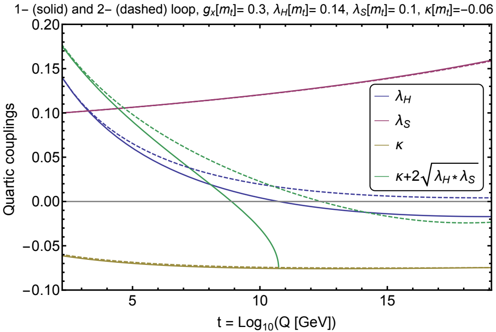
$$\beta^{(1)}_{\kappa} = \frac{\kappa}{10}\left(-9g_1^2 - 90g_x^2 - 45g_2^2 + 120\lambda_H + 80\lambda_S + 40\kappa + 60y_t^2\right)$$

Positivity conditions

$\lambda_H(Q) > 0$

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

$\lambda_S(Q) > 0$



Perturbativity conditions

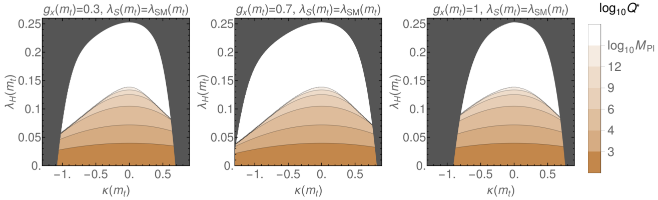
$\lambda_H < 4\pi, \quad \kappa < 4\pi, \quad \lambda_S < 4\pi$

grey regions excluded

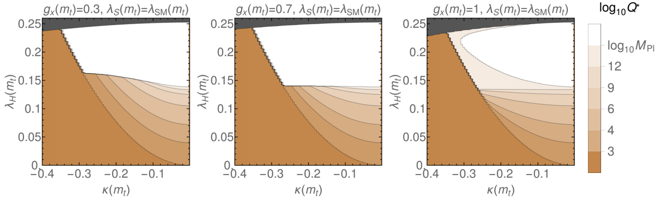
SM limit

$\kappa = 0,\ \lambda_H(m_T) \approx 0.127$

First positivity condition $\lambda_H(Q) > 0$



Second positivity condition $\kappa(Q) > -2\sqrt{\lambda_H(Q)\lambda_S(Q)}$



Experimental bounds

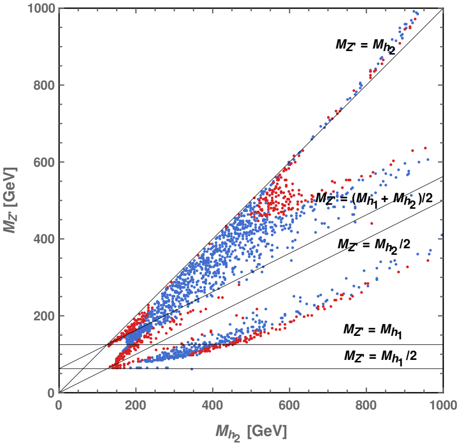
- Higgs couplings

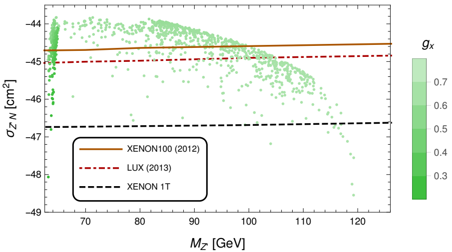
  Atlas and CMS combined data:

  $\mu = \frac{\sigma \times BR}{\sigma_{SM} \times BR_{SM}} = \cos^2\alpha > 0.89$
- LEP bounds from $e^+e^- \to Zh_2$
- no invisible Higgs decays
  $h_1 \to Z'Z', \quad h_1 \to h_2h_2$
- electroweak precision data (S,T)
- dark matter relic density

  Planck data:

  $\Omega h^2 = 0.1199 \pm 0.0022$
- direct detection at LUX and XENON





$M_{h_2} > M_{h_1}$ stable, meta/unstable

$M_{h_2} < M_{h_1}$
stability requires large κ, excluded by bound on invisible Higgs decays

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. Dark $U_X(1)$ gauge coupling affects stability only moderately.

The model can be further tested by experiments:

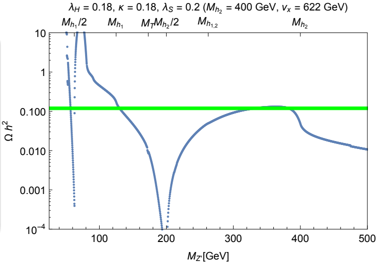
- precision measurements of Higgs couplings,
- searches for new scalar,
- future dark matter direct detection probes.

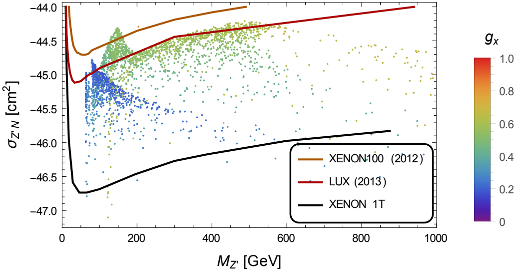
BACKUP SLIDES

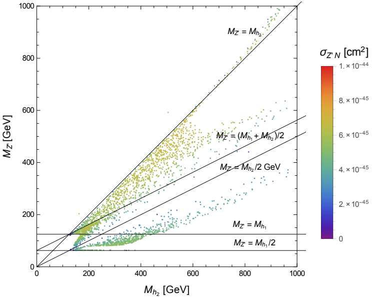
$$\sigma_{Z'N} = \frac{\mu^2}{4\pi} g_x^2 g_{hNN}^2 \sin^2 2\alpha \left(\frac{1}{m_{h_1}^2} - \frac{1}{m_{h_2}^2} \right)^2$$

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

g_{hNN} – effective nucleon-Higgs coupling







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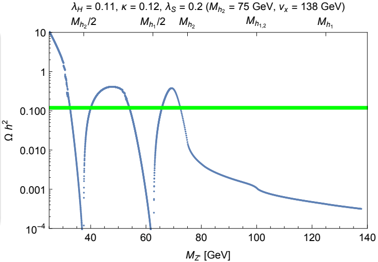

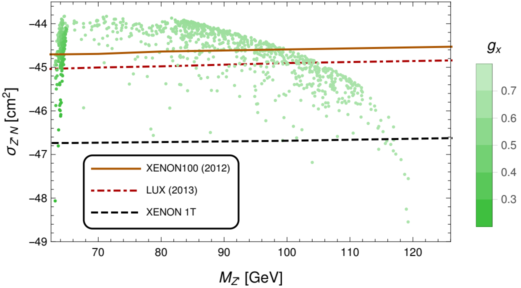

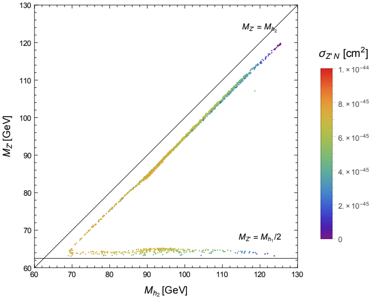

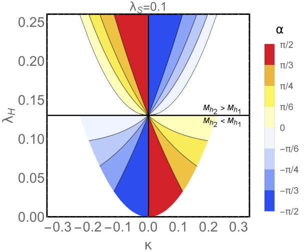

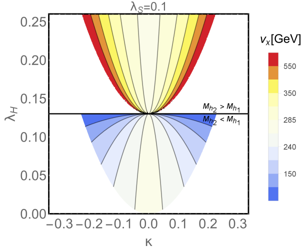

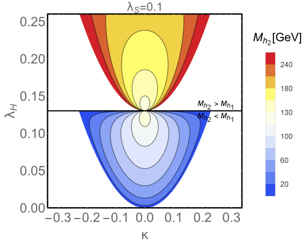

Experimental constraints

- 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)
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