Dark Matter from a vector field in the fundamental representation of $SU(2)_L$

Felipe Rojas Abatte

Universidad Técnica Federico Santa María - Chile
Southampton University - England

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Out line

1. Description and main aspects of the model
2. Theoretical and physical Constraints
3. Description of the parameter space
4. Dark Matter signatures at LHC
5. Conclusions

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Bastian Díaz Sáes - Alfonso R. Zerwekh - Felipe Rojas-Abatte

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Main aspects of the model

We considered a simplified DM model in which we introduce a new extra vector doublet V_μ transforming with the same quantum numbers as the Higgs field under the gauge symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$V_\mu = \begin{pmatrix} V_\mu^+ \\ V_\mu^o \end{pmatrix} = \begin{pmatrix} V_\mu^+ \\ \frac{V_\mu^1 + iV_\mu^2}{\sqrt{2}} \end{pmatrix} \sim (1,2,1/2)$$

The most general Lagrangian respecting the SM gauge symmetry containing this new vector with operators up to dimension four is

$$\begin{aligned}
\mathcal{L} &= -\frac{1}{2}\left(D_\mu V_\nu - D_\nu V_\mu\right)^\dagger\left(D^\mu V^\nu - D^\nu V^\mu\right) + M_V^2 V_\mu^\dagger V^\mu - \lambda_2(\phi^\dagger\phi)(V_\mu^\dagger V^\mu) \\
&- \lambda_3(\phi^\dagger V_\mu)(V^{\mu\dagger}\phi) - \frac{\lambda_4}{2}\left[(\phi^\dagger V_\mu)(\phi^\dagger V^\mu) + (V^{\mu\dagger}\phi)(V_\mu^\dagger\phi)\right] \\
&- \alpha_1\left[\phi^\dagger(D_\mu V^\mu) + (D_\mu V^\mu)^\dagger\phi\right] - \alpha_2(V_\mu^\dagger V^\mu)(V_\nu^\dagger V^\nu) - \alpha_3(V_\mu^\dagger V^\nu)(V_\nu^\dagger V^\mu) \\
&+ ig\kappa_1 V_\mu^\dagger W^{\mu\nu} V_\nu + i\frac{g'}{2}\kappa_2 V_\mu^\dagger B^{\mu\nu} V_\nu
\end{aligned}$$

where

$$D_\mu V_\nu = \partial_\mu V_\nu + i\frac{g}{2}W_\mu^a\sigma^a V_\nu + \frac{i}{2}B_\mu V_\nu$$

Not possible to couple V to standard fermions without introducing exotic vector-like fermions

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For simplicity $\kappa_1 = \kappa_2 = 1$

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If $\alpha_1 = 0$ appears a Z_2 symmetry

Main aspects of the model

In the limit when $\alpha_1 = 0$ the model acquires an additional Z_2 discrete symmetry allowing the stability of the lightest odd particle (LOP). The Lagrangian is reduce to

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\end{aligned}$$

The model contain 6 free parameters: M_V, λ_2, λ_3, λ_4, α_2 and α_3. After EWSB, the tree level mass spectrum of the new sector is

$$\begin{aligned}
M_{V^\pm}^2 &= \frac{1}{2}\left[2M_V^2 - v^2\lambda_2\right], \\
M_{V_1}^2 &= \frac{1}{2}\left[2M_V^2 - v^2(\lambda_2 + \lambda_3 + \lambda_4)\right], \\
M_{V_2}^2 &= \frac{1}{2}\left[2M_V^2 - v^2(\lambda_2 + \lambda_3 - \lambda_4)\right],
\end{aligned}$$

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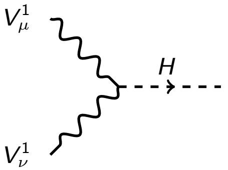
\end{aligned}
$$

$$
\begin{aligned}
M_{V_2}^2 - M_{V_1}^2 > 0 \quad &\Rightarrow \quad \lambda_4 > 0 \\
M_{V^\pm}^2 - M_{V_1}^2 > 0 \quad &\Rightarrow \quad \lambda_3 + \lambda_4 > 0
\end{aligned}
$$

For phenomenological proposes we will work on a different base of free parameters

$$M_{V_1}, \quad M_{V_2}, \quad M_{V^\pm}, \quad \lambda_L, \quad \alpha_2, \quad \alpha_3 \tag{1}$$

where $\lambda_L = \lambda_2 + \lambda_3 + \lambda_4$ play an important role controlling the interaction between the SM Higgs and DM.



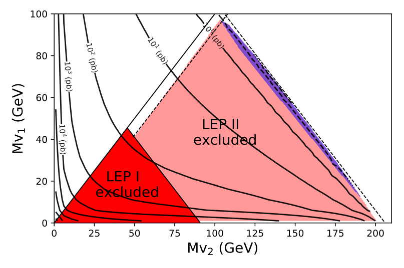
$$: \qquad 2\frac{M_W \sin\theta_W}{e} g^{\mu\nu}\lambda_L$$

It is convenient to write the quartic coupling and the mass parameter as a function of the new free parameters

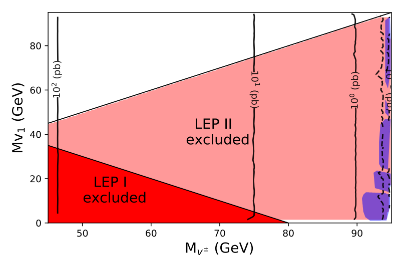
$$\lambda_2 = \lambda_L + 2\frac{\left(M^2_{V_1} - M^2_{V^\pm}\right)}{v^2}, \qquad \lambda_3 = \frac{2M^2_{V^\pm} - M^2_{V_1} - M^2_{V_2}}{v^2},$$

$$\lambda_4 = \frac{M^2_{V_2} - M^2_{V_1}}{v^2}, \qquad M^2_V = M^2_{V_1} + \frac{v^2\lambda_L}{2}. \tag{2}$$

Constraints from LEP data



Allowed mass region for neutral vectors.



Allowed mass region for charged and neutral vectors.

Excluded by LEP I

$M_{V_1} + M_{V\pm} < M_{W\pm}$ $\qquad$ $M_{V_1} + M_{V_2} < M_Z$

$M_{V_2} + M_{V\pm} < M_{W\pm}$ $\qquad$ $2M_{V\pm} < M_Z$

Excluded by LEP II

$M_{V_1} < 100$ GeV & $M_{V_2} < 200$ GeV & $M_{V_2} - M_{V_1} > 8$ GeV & $M_{V_1} + M_{V_2} < \sqrt{s}_{LEP}$

$M_{V\pm} \lesssim 93$ GeV

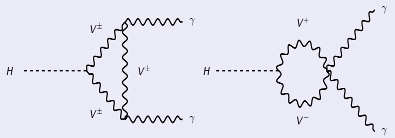
Constraints from LHC Higgs data

- **Invisible Higgs Decay:** The decay channel $H \to V_1 V_1$ is kinematically open when $M_{V_1} < M_H/2$ and it can affect the total width decay of H.

Excluded by Higgs data

$$Br(H \to \text{invisible}) > 24\%$$

- **Diphoton signal strength $\mu^{\gamma\gamma}$:**



The $\mu^{\gamma\gamma}$ in the DVDM normalized to the SM value can be written as

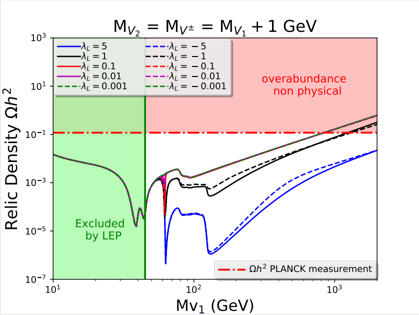
Diphoton signal limit

$$\frac{Br^{BSM}(H \to \gamma\gamma)}{Br^{SM}(H \to \gamma\gamma)} = \mu^{\gamma\gamma} = 0.99 \pm 0.14$$

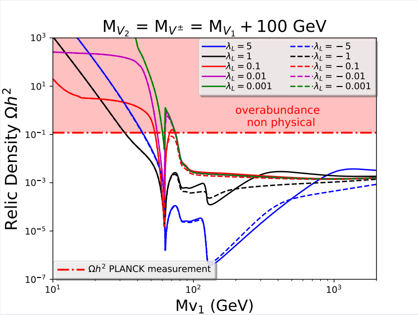
Relic Density Plots

Relic Density limit

$$\Omega_\chi h^2 = 0.1184 \pm 0.0012$$



Quasi-degenerate case.



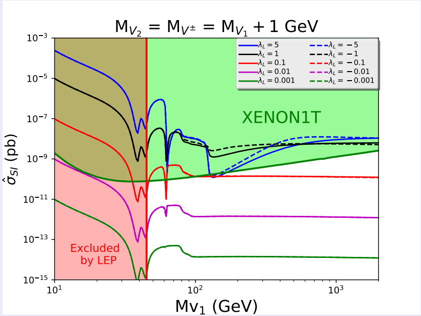
Non-negligible mass split.

Two scenarios of large and small ΔM qualitatively covers the whole parameter space.

Direct Detection

Rescaled SI cross section

$$\hat{\sigma}_{\rm SI} = \frac{\Omega_{DM}}{\Omega_{\rm Planck}} \times \sigma_{\rm SI}(V_1 p \to V_1 p)$$



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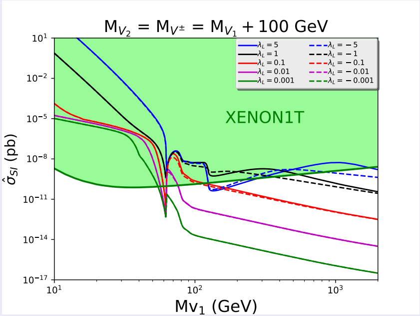
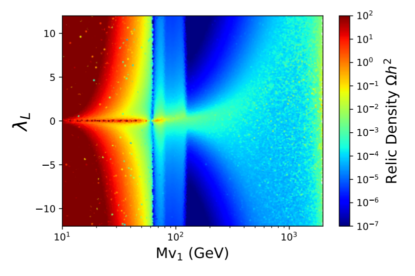
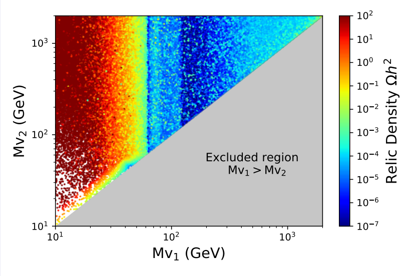


Non-negligible mass split.

Constraints on the Parameter space

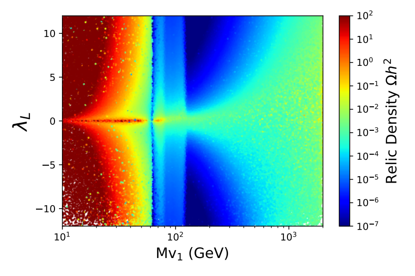


Colour map of relic density in the M_{V_1}, λ_L plane



Colour map of relic density in the M_{V_1}, M_{V_2} plane

Constraints on the Parameter space



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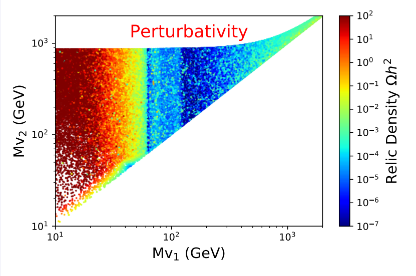

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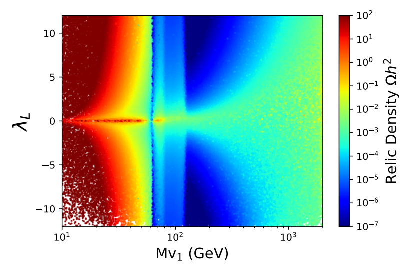

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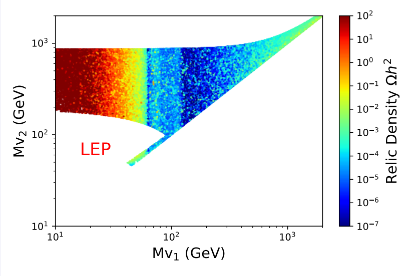

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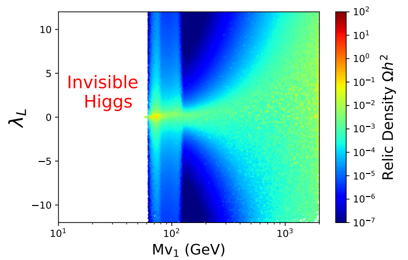

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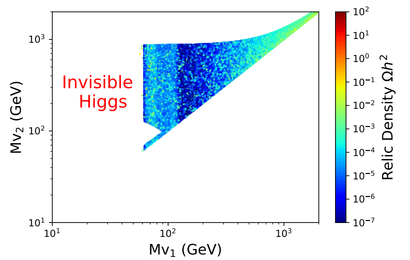

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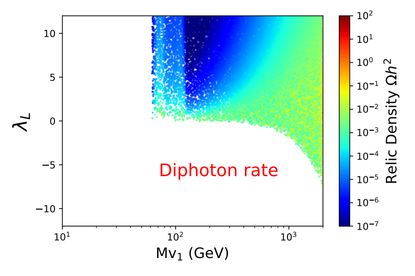
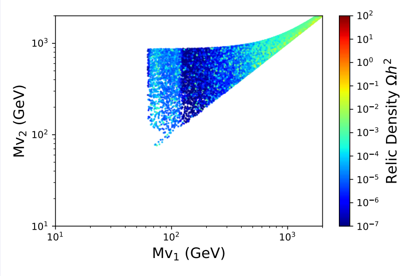


Colour map of relic density in the M_{V_1} , λ_L plane



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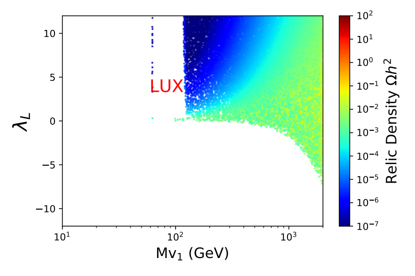

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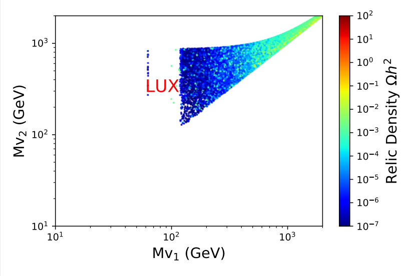

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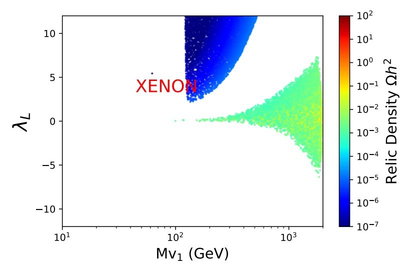

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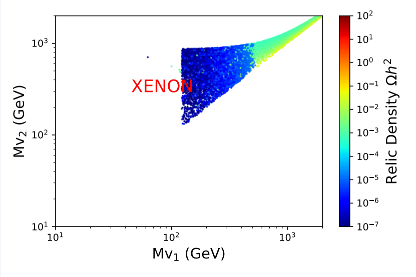
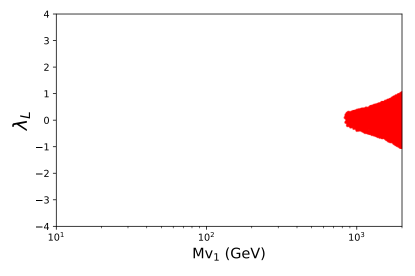
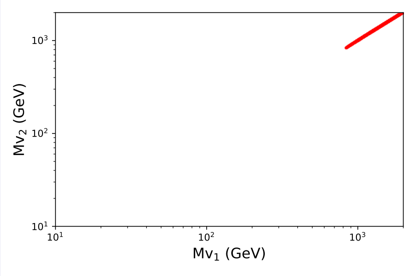


Colour map of relic density in the M_{V_1} , M_{V_2} plane

Vector Dark Matter as the only source



Scatter plot of the Relic Density in the plane M_{V_1}, λ_L after all constraints.

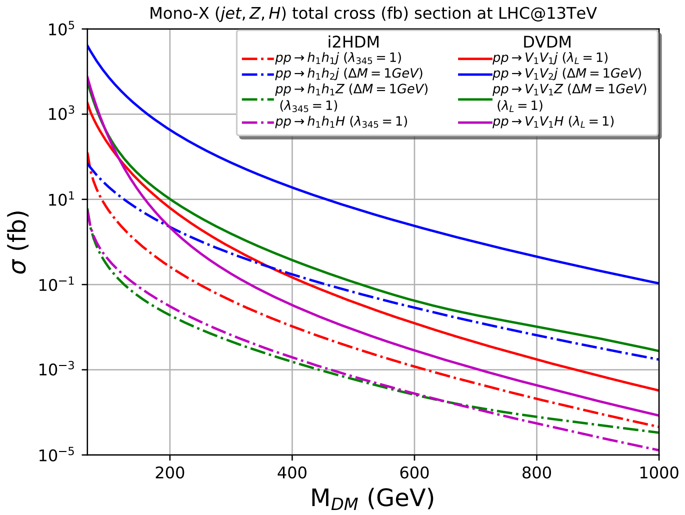


Scatter plot of the Relic Density in the plane M_{V_1}, M_{V_2} after all constraints.

Satisfy PLANCK limits

$M_{V_1} > 840$ GeV

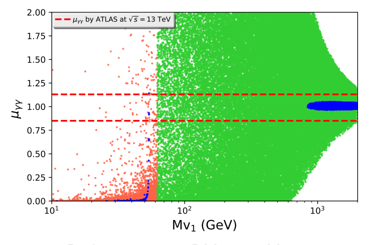
Production at LHC



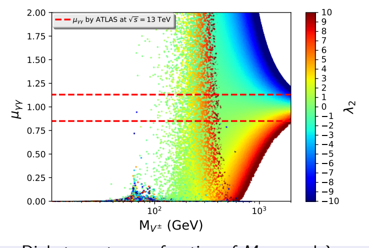
Conclusions

- We studied a simple extension to the SM including a new vector doublet.
- The model acquires a Z_2 symmetry when the only nonstandard dimension 3 operator is eliminated, allowing the neutral V_1 component to be a good Dark Matter candidate.
- The model is consistent with experimental constraints and it is capable to fulfill the DM budget with masses over 840 GeV
- The model is strongly challenged by experimental data and by unitarity constraints.

$H \to \gamma\gamma$ constraints from LHC data



Diphoton rate vs DM mass M_{V_1}.



Diphoton rate as a function of $M_{V^\pm}$ and λ_2.

The $\mu^{\gamma\gamma}$ in the DVDM normalized to the SM value can be written as

Diphoton signal limit

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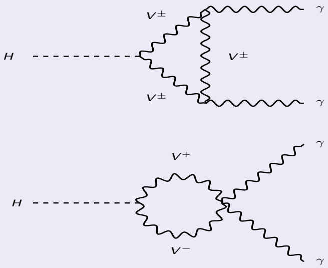
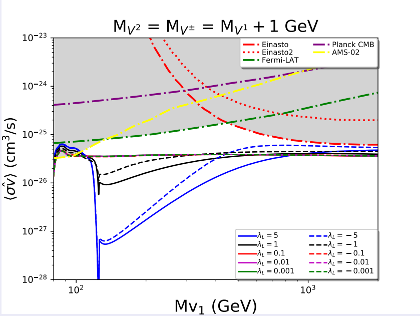


Contribution of the DVDM on the Higgs decay into two photons.

Rescaled average annihilation σ

$$\langle \hat{\sigma v} \rangle = \frac{\Omega_{DM}}{\Omega_{\text{Planck}}} \times \langle \sigma v \rangle$$



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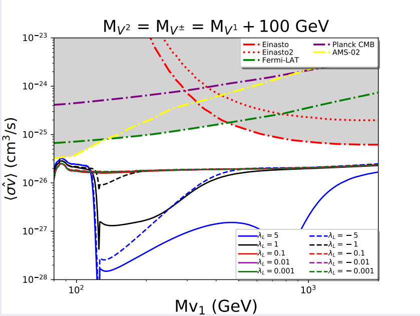
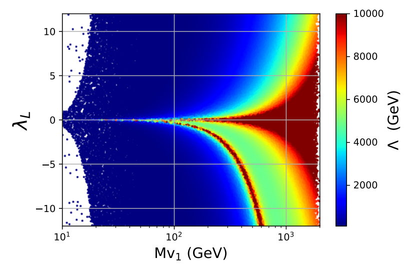


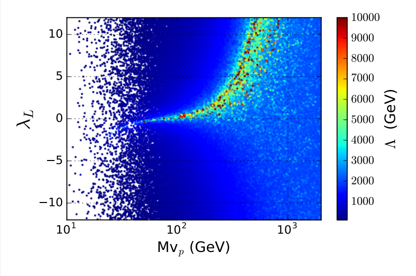
Non-negligible mass split.

Perturbative Unitarity

The main theoretical challenge faced by our construction is the eventual violation of perturbative unitarity introduced by the new massive vectors. We studied the process $V^1 h \to V^1 h$ and $ZV^{\pm} \to ZV^{\pm}$



Maximum energy scale Λ until the process $V^1 h \to V^1 h$ start to violate perturbative unitarity.



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