

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

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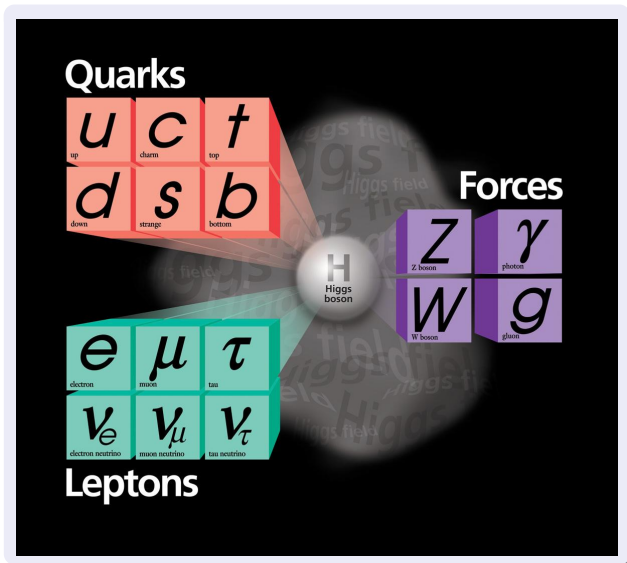
Decoding new physics from data: connecting theory and signatures



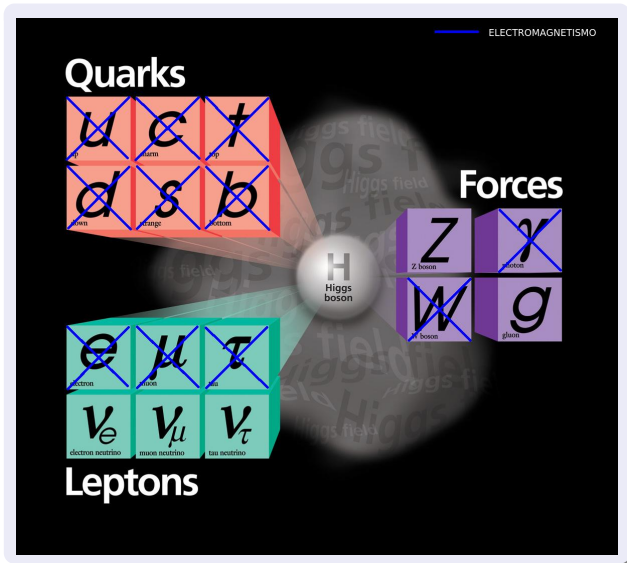
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Southampton

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

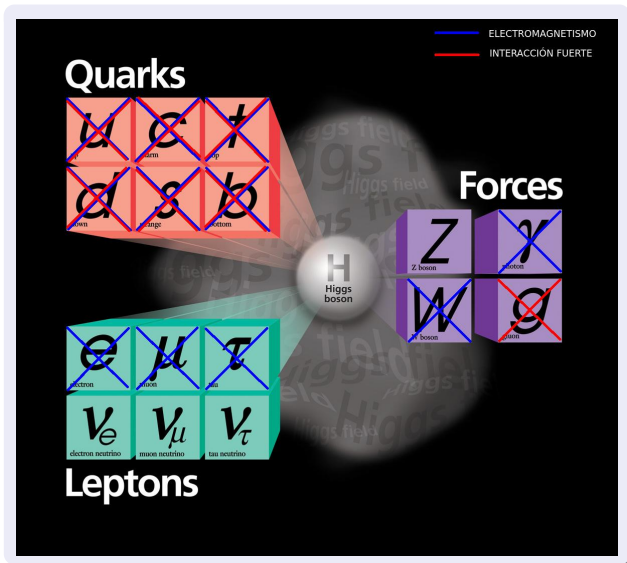
Dark Matter in the Standard Model



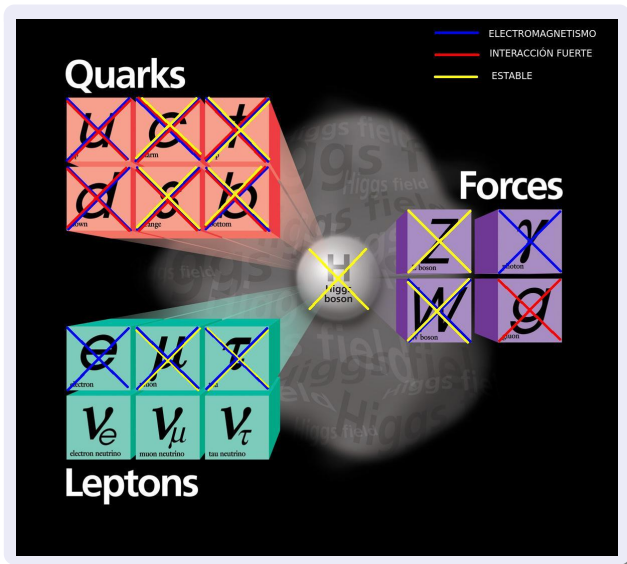
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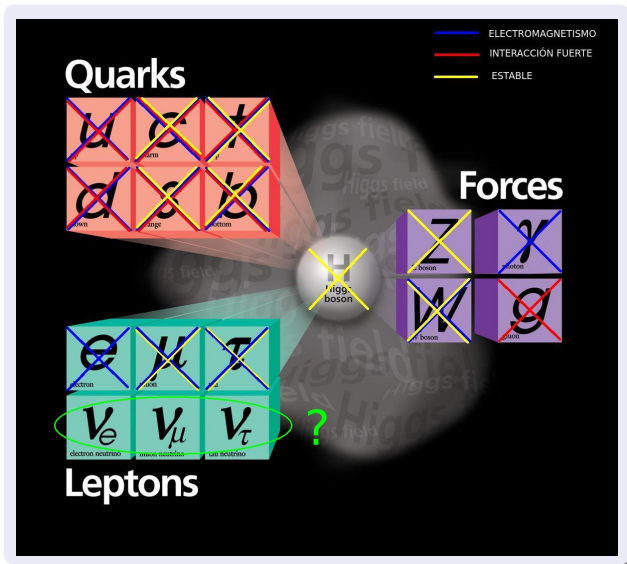
Dark Matter in the Standard Model



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

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



- Phys.Rev. D99 (2019) no.7, 075026 , arXiv:1810.06375 [hep-ph]

Main aspects of the model

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

$$V_\mu = \begin{pmatrix} V_\mu^+ \\ V_\mu^0 \\ V_\mu^- \end{pmatrix} = \begin{pmatrix} V_\mu^+ \\ \frac{V_\mu^1 + iV_\mu^2}{\sqrt{2}} \\ V_\mu^- \end{pmatrix} \sim (1, 2, 1/2)$$

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

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

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

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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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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

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

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$$M_{V_2}^2 = \frac{1}{2} [2M_V^2 - v^2 (\lambda_2 + \lambda_3 - \lambda_4)],$$

$$M_{V_2}^2 - M_{V_1}^2 > 0 \Rightarrow \lambda_4 > 0$$

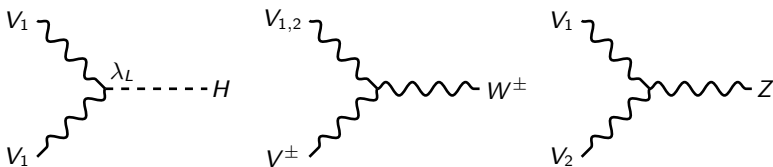
$$M_{V^\pm}^2 - M_{V_1}^2 > 0 \Rightarrow \lambda_3 + \lambda_4 > 0$$

Main aspects of the model

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

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

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



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

$$\lambda_2 = \lambda_L + 2 \frac{(M_{V_1}^2 - M_{V^\pm}^2)}{v^2},$$

$$\lambda_4 = \frac{M_{V_2}^2 - M_{V_1}^2}{v^2},$$

$$\lambda_3 = \frac{2M_{V^\pm}^2 - M_{V_1}^2 - M_{V_2}^2}{v^2},$$

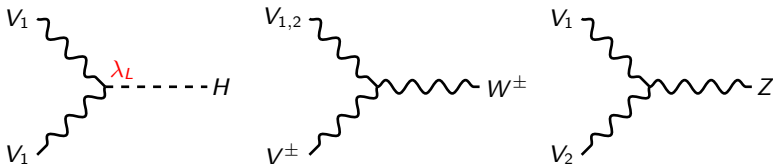
$$M_V^2 = M_{V_1}^2 + \frac{v^2 \lambda_L}{2}$$

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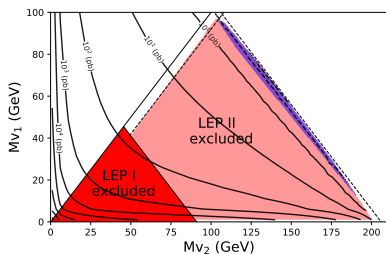
$$\lambda_2 = \lambda_L + 2 \frac{(M_{V_1}^2 - M_{V^\pm}^2)}{v^2},$$

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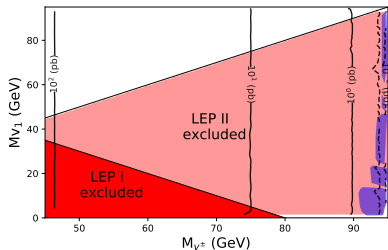
$$\lambda_3 = \frac{2M_{V^\pm}^2 - M_{V_1}^2 - M_{V_2}^2}{v^2},$$

$$M_V^2 = M_{V_1}^2 + \frac{v^2 \lambda_L}{2}$$

Constraints from LEP data



Allowed mass region for neutral vectors.



Allowed mass region for charged and neutral vectors.

Excluded by LEP I

$$M_{V_1} + M_{V_{\pm}} < M_{W_{\pm}}$$

$$M_{V_1} + M_{V_2} < M_Z$$

$$M_{V_2} + M_{V_{\pm}} < M_{W_{\pm}}$$

$$2M_{V_{\pm}} < M_Z$$

Excluded by LEP II

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

$$M_{V_{\pm}} \lesssim 93 \text{ GeV}$$

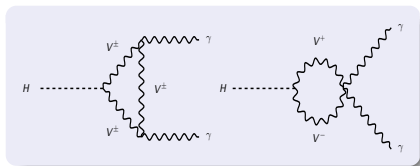
Constraints from LHC Higgs data

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

Excluded by Higgs data

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

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



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

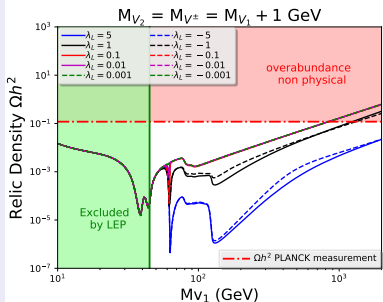
Diphoton signal limit

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

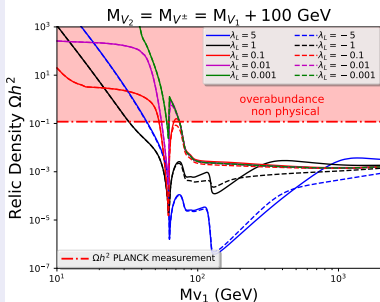
Relic Density Plots

Relic Density limit

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



Quasi-degenerate case.

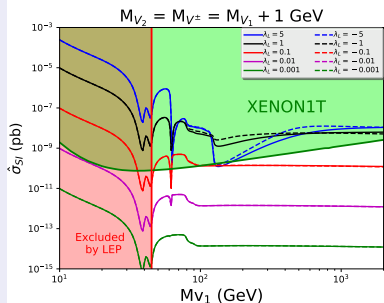


Non-negligible mass split.

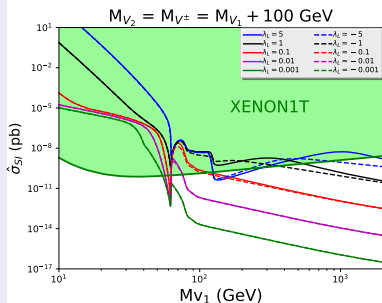
Two scenarios of large and small ΔM qualitatively covers the whole parameter space.

Rescaled SI cross section

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

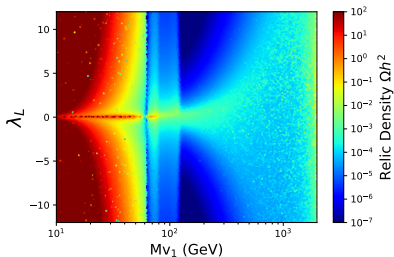


Quasi-degenerate case.

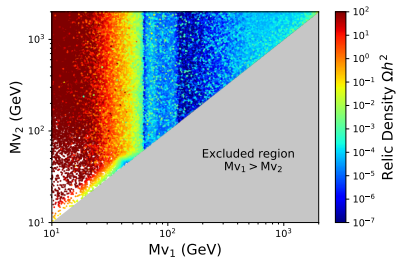


Non-negligible mass split.

Constraints on the Parameter space



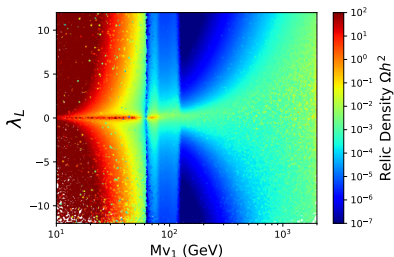
Colour map of relic density in the M_{V_1}, λ_L plane



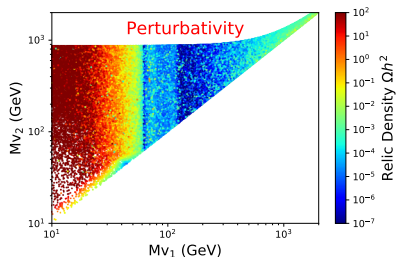
Colour map of relic density in the M_{V_1}, M_{V_2} plane

Constraints on the Parameter space: Perturbativity

$$|\lambda_i| < 4\pi \quad \& \quad |\alpha_j| < 4\pi$$

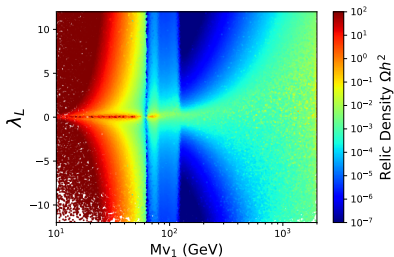


Colour map of relic density in the M_{V_1}, λ_L plane

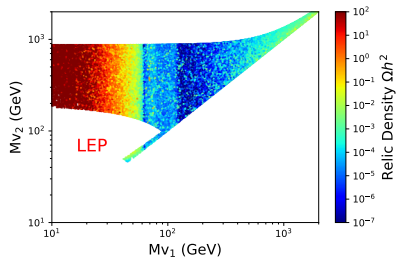


Colour map of relic density in the M_{V_1}, M_{V_2} plane

Constraints on the Parameter space: LEP



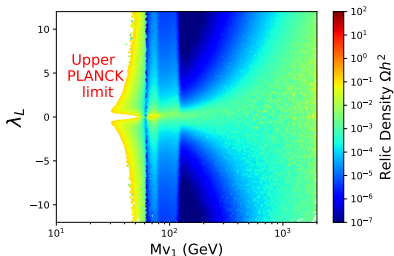
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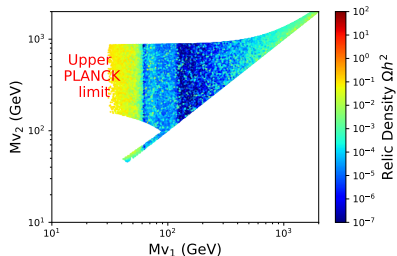
Colour map of relic density in the M_{V_1}, M_{V_2} plane

Constraints on the Parameter space: Upper PLANCK limit

$$\Omega_\chi h^2 < 0.1184 + 0.0012$$



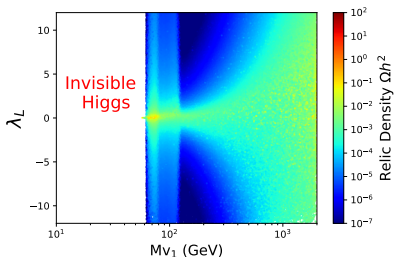
Colour map of relic density in the M_{V_1}, λ_L plane



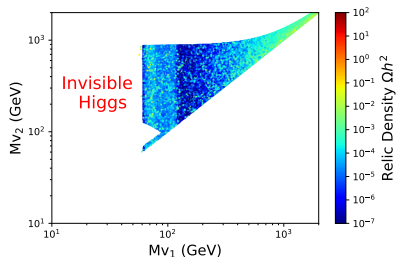
Colour map of relic density in the M_{V_1}, M_{V_2} plane

Constraints on the Parameter space: Invisible Higgs Decay

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



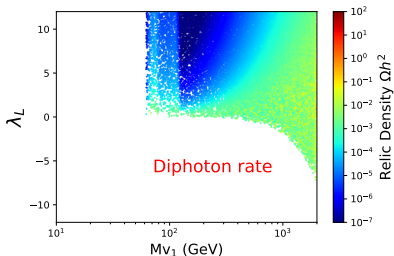
Colour map of relic density in the M_{V_1}, λ_L plane



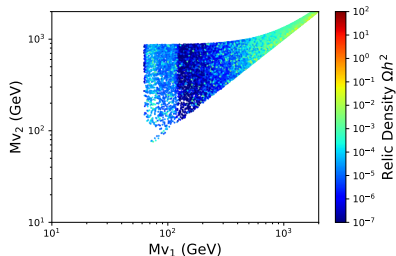
Colour map of relic density in the M_{V_1}, M_{V_2} plane

Constraints on the Parameter space: Diphoton rate

$$\mu^{\gamma\gamma} = 0.99 \pm 0.14$$

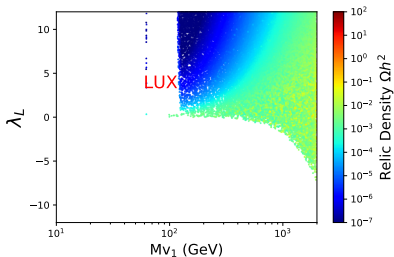


Colour map of relic density in the M_{V_1}, λ_L plane

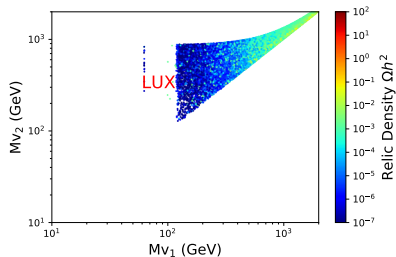


Colour map of relic density in the M_{V_1}, M_{V_2} plane

Constraints on the Parameter space: DD LUX

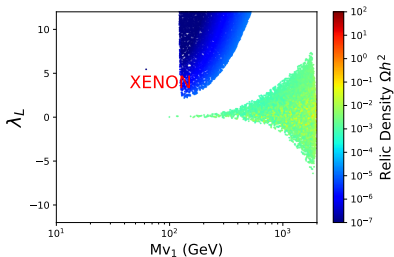


Colour map of relic density in the M_{V_1}, λ_L plane

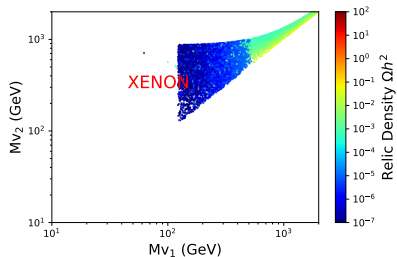


Colour map of relic density in the M_{V_1}, M_{V_2} plane

Constraints on the Parameter space: DD XENON1T



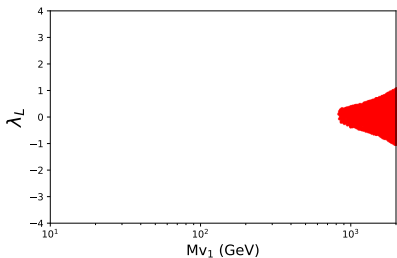
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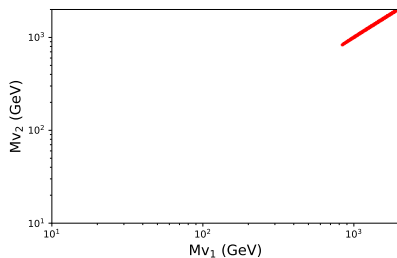
Colour map of relic density in the M_{V_1}, M_{V_2} plane

Vector Dark Matter as the only source

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



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

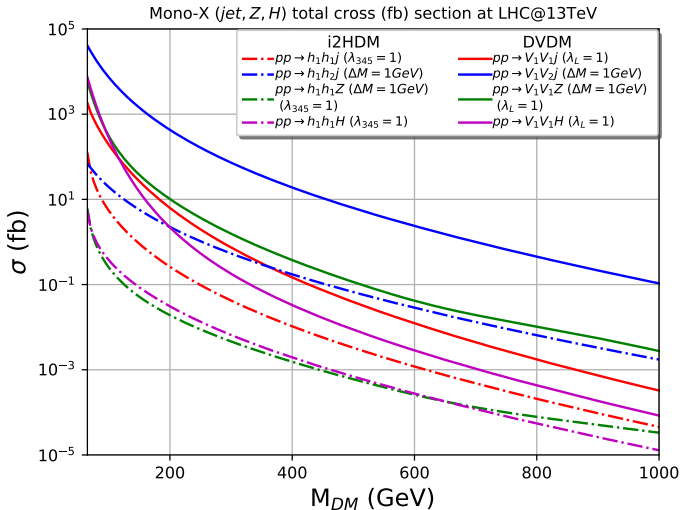


Scatter plot of the Relic Density in the plane M_{V_1}, M_{V_2} after all constraints.

Satisfy PLANCK limits

$$M_{V_1} > 840 \text{ GeV}$$

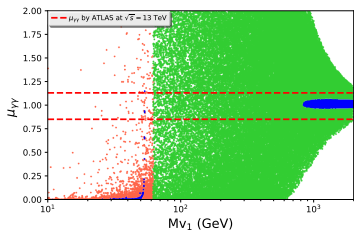
Production at LHC



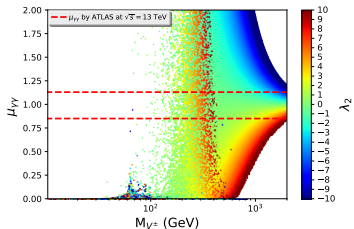
- We studied a simple extension to the SM including a new vector doublet.
- The model acquires a Z_2 symmetry when the only nonstandard dimension 3 operator is eliminated, allowing the neutral V_1 component to be a good Dark Matter candidate.
- The model is consistent with experimental constraints and 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.



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



Diphoton rate vs DM mass M_{V_1} .

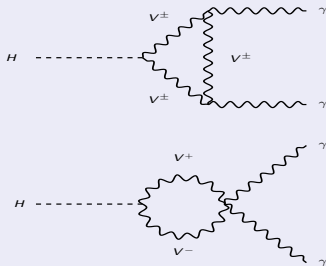


Diphoton rate as a function of $M_{V_{\pm}}$ and λ_2 .

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

Diphoton signal limit

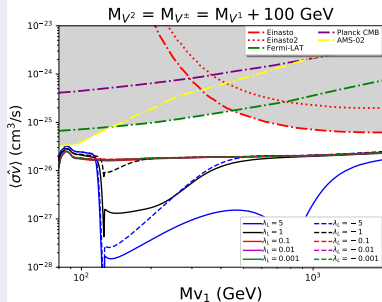
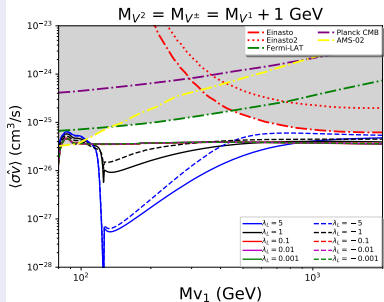
$$\frac{Br^{BSM}(H \rightarrow \gamma\gamma)}{Br^{SM}(H \rightarrow \gamma\gamma)} = \mu^{\gamma\gamma} = 0.99 \pm 0.14$$



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

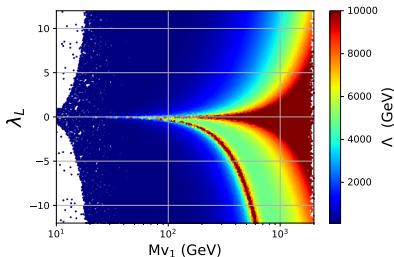
Rescaled average annihilation σ

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

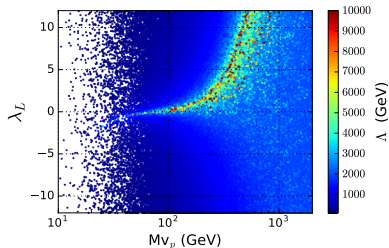


Perturbative Unitarity

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 $V^1 h \rightarrow V^1 h$ and $ZV^\pm \rightarrow ZV^\pm$



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



Maximum energy scale Λ until the process $ZV^\pm \rightarrow ZV^\pm$ start to violate perturbative unitarity.