Vector Doublet Dark Matter

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UTFSM/CCTVal

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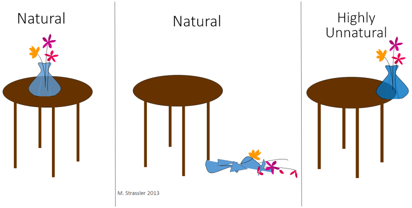
Outline

- Motivations
- Model
- Theoretical and experimental constraints
- Relic density
- Conclusions

NATURALNESS PROBLEM

The Higgs boson:

- related to the mass generation of the rest of the (elementary) particles.
- the "last"piece in particle physics.
- its mass is explained in a miracoulous way if we trust in the model up to M_{Planck} (10^{19} GeV).



DARK MATTER

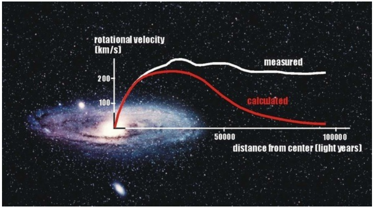


Figura: Above: Rotational curves. Left: Galaxy collisions. Right: Gravitational lensing.

Motivations: Models proposal

From particle physics, there have been a plethora of models trying to account for the elusive DM particle:

- **Scalars**: scalar singlets, I2HDM, triplets, Axions, etc.
- **Fermions**: Sterile neutrinos, Vector-like fermions, etc.
- **Vectors**: $U(1)$ and $SU(2)$ gauge bosons.

Model

Taking into account the SM gauge symmetry,

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

we introduce a set of vectors which enter in the same representation than the Higgs doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \frac{v+h+iZ}{\sqrt{2}} \end{pmatrix} \qquad V_\mu = \begin{pmatrix} V_\mu^+ \\ \frac{V_\mu^1 + iV_\mu^2}{\sqrt{2}} \end{pmatrix} \quad \sim \quad (\mathbf{1}, \mathbf{2}, 1/2)$$

These kind of objects have been motivated by different approaches:

- PNGBs, Extra-dimensions, Twin-Higgs (Dvali, Chizhov; 2011).
- Gauge-Higgs Unification (Maru, et. al.; 2018).

Model

The most general Lagrangian up to dimension-4 is

$$
\begin{aligned}
\mathcal{L}^{EFT} &= \mathcal{L}^{SM} - \frac{1}{2}\left(D_\mu V_\nu - D_\nu V_\mu\right)^\dagger \left(D^\mu V^\nu - D^\nu V^\mu\right) + M_V^2 V_\mu^\dagger V^\mu \\
&+ \lambda_2(\phi^\dagger\phi)(V_\mu^\dagger V^\mu) + \lambda_3(\phi^\dagger V_\mu)(V_\mu^\dagger \phi) + \frac{\lambda_4}{2}\left[(\phi^\dagger V_\mu)(\phi^\dagger V^\mu) + h.c.\right] \\
&+ \alpha_1 \phi^\dagger D_\mu V^\mu + \alpha_1^*(D_\mu V^\mu)^\dagger \phi \\
&+ \alpha_2(V_\mu^\dagger V^\mu)(V_\nu^\dagger V^\nu) + \alpha_3(V_\mu^\dagger V^\nu)(V_\nu^\dagger V^\mu) \\
&+ \beta_w V^{\mu\dagger} W_{\mu\nu} V^\nu + \beta_b V^{\mu\dagger} B_{\mu\nu} V^\nu
\end{aligned}
$$

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

- **Nine free parameters**: $M_V, \lambda_2, \lambda_3, \lambda_4, \alpha_1, \alpha_2, \alpha_3, \beta_w, \beta_b$.
- **No Yukawa-like SM fermions-vectors couplings**.

Model

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&+ \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) + h.c.\right] \\
&+ \cancelto{0}{\alpha_1 \phi^\dagger D_\mu V^\mu} + \cancelto{0}{\alpha_1^* (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) \\
&+ \beta_w V^{\mu\dagger} W_{\mu\nu} V^\nu + \beta_b V^{\mu\dagger} B_{\mu\nu} V^\nu
\end{aligned}
$$

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

- **Seven free parameters**: $M_V, \lambda_2, \lambda_3, \lambda_4, \alpha_1, \alpha_2, \alpha_3$.
- **No Yukawa-like SM fermions-vectors couplings**.
- If $\boldsymbol{\alpha_1} = 0$ the Lagrangian manifiest a $\boldsymbol{Z_2}$ symmetry.

Dark Matter Model: Z_2 symmetry

Fields transforming under Z_2:

$$\begin{aligned} \textbf{SM particles} &: \quad \phi \to \phi \\ \textbf{New particles} &: \quad V_\mu \to -V_\mu \end{aligned}$$

Implications:

- The new particles can only appear in **pairs** in their interaction vertices.
- It allows the **stability of the lightest odd particle**, generating a good

DARK MATTER CANDIDATE!

Dark Matter Model

What do we have after all? An extension to the content of the SM. Four new particles:

- V^1: **Dark Matter** candidate (neutral, massive, no color)
- V^2: Another state with mass at least as massive the DM candidate.
- $V^{\pm}$: Charged massive vectors.

Their masses are unkown: they depend on the free parameters of the model.

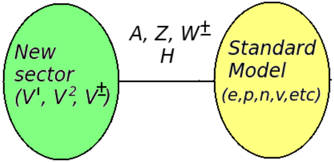

Figura: Boson portal between the new sector and the SM fields.

Model Constraints

- Perturbativity
- LEP limits
- Higgs to two photons
- Perturbative unitarity
- Electroweak precision tests

Perturbativity + LEP limits + Higgs to two photons

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to \gamma\gamma)_{BSM}}{\sigma(pp \to \gamma\gamma)_{SM}} \cong \frac{Br(H \to \gamma\gamma)_{BSM}}{Br(H \to \gamma\gamma)_{SM}}$$

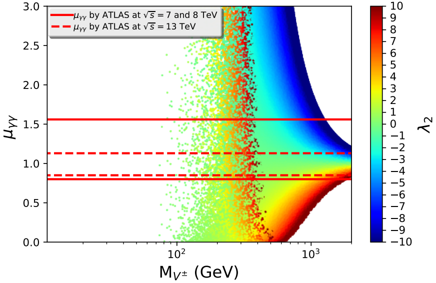

Figura: Ratio between Higgs Branching decay to two photons in our model and the SM. In between the red curves is the allowed region by experimental searches (ATLAS).

DM relic density

Dark Matter relic density: $\Omega h^2 = 0.1190 \pm 0.0010$ (Planck).
MicrOMEGAs:

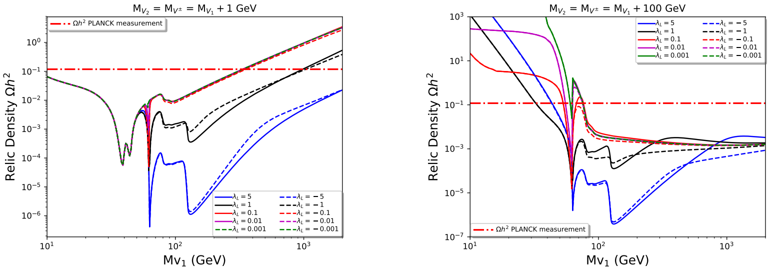

Figura: DM relic density for the model as a function of the DM mass and the other parameters. Quasi (left) and non mass degenerate (right) cases.

Conclusions

- The SM of particle physics has been very successfull in accuracy and predictions, but there are some issues that we do not understand totally: **Naturalness problem**.
- The astrophysical data give us evidence of something new that we call: **Dark Matter**.
- We are studying a new simple extension to the SM including a set of vectors, in which one of them can be a:

Dark Matter particle candidate

- We are **constraining the model** through out numerous theoretical and experimental constraints.
- Future: to study **vector DM signatures** at the LHC.

Aknownledgments

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- Thanks to ICTP/SAIFR/UNESP.

Appendix A: Masses and couplings

After **ElectroWeak Symmetry Breaking** (EWSB) , the mass spectrum at tree level is

$$
\begin{aligned}
M^2_{V^\pm} &= M^2_V - \frac{v^2}{2}\lambda_2 \\
M^2_{V^1} &= M^2_V - \frac{v^2}{2}(\lambda_2 + \lambda_3 + \lambda_4) \equiv M^2_V - \frac{v^2}{2}\lambda_L \\
M^2_{V^2} &= M^2_V - \frac{v^2}{2}(\lambda_2 + \lambda_3 - \lambda_4) \equiv M^2_V - \frac{v^2}{2}\lambda_R
\end{aligned}
$$

- Mass shift between the neutral states given by λ_4.
- A lot of new vertices resembling **Higgs-portal** Dark Matter:

$$HAA, \quad HV^1V^1, \quad HV^2V^2$$

and others between the new sector and the SM gauge bosons

$$ZV^1V^2, \quad W^+V^-V^1, \quad W^+W^-V^+V^-$$

Appendix B: Custodial Symmetry

- In the limit $g' = 0$ ands $y_i = 0$, the SM has $SU(2)_L \times SU(2)_R$ symmetry. After SSB there is a residual $SU(2)_V$ global symmetry.
- In the SM there is a **very well measured parameter**:

$$\rho = \frac{M_W}{M_Z \cos\theta_w} \cong 1 \tag{1}$$

which custodial symmetry forbids large deviations from the unity.

Custodial symmetric

- The model respects custodial symmetry: It is similar to the 2HDM that we saw in Grinstein Lectures, but with indexes Lorentz.

Appendix B: Custodial Symmetry

In analogy to the SM Higgs matrix notation

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^{0*} & \phi^{+} \\ \phi^{-} & \phi^{0} \end{pmatrix} ; \qquad \mathcal{V}_\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} V^{0*}_{\mu} & V^{+}_{\mu} \\ V^{-}_{\mu} & V^{0}_{\mu} \end{pmatrix} \tag{2}$$

Our Lagrangian can be recast in the new biodoublet notation

$$\begin{aligned} \mathcal{L} \;=\;& -\frac{1}{2}\mathrm{Tr}\left[\left(D_\mu \mathcal{V}_\nu - D_\nu \mathcal{V}_\mu\right)^\dagger \left(D^\mu \mathcal{V}^\nu - D^\nu \mathcal{V}^\mu\right)\right] + M^2 \mathrm{Tr}\left(\mathcal{V}_\mu^\dagger \mathcal{V}^\mu\right) \\ -\;& \lambda_2 \mathrm{Tr}(\Phi^\dagger \Phi)\mathrm{Tr}(\mathcal{V}_\mu^\dagger \mathcal{V}^\mu) - \lambda_3 \mathrm{Tr}\left(\Phi^\dagger \mathcal{V}_\mu\right) \mathrm{Tr}\left(\mathcal{V}^{\mu\dagger} \Phi\right) \\ -\;& \frac{\lambda_4}{2}\left(\left(\mathrm{Tr}\left[\Phi^\dagger \mathcal{V}_\mu\right]\right)^2 + \left(\mathrm{Tr}\left[\mathcal{V}_\mu^\dagger \Phi\right]\right)^2 \right) \\ +\;& \beta_w \mathrm{Tr}\left[\mathcal{V}_\mu^\dagger W^{\mu\nu} \mathcal{V}_\nu\right] + \beta_b \mathrm{Tr}\left[\mathcal{V}_\mu^\dagger B^{\mu\nu} \mathcal{V}_\nu\right] \end{aligned} \tag{3}$$

Appendix B: Custodial symmetry

In order to respect the chiral global symmetry ($g' = 0$), the bidoublets must to transform as the following

$$\Phi \rightarrow L\Phi R^{\dagger} \quad (4)$$

$$D_{\mu}\Phi \rightarrow L\left(D_{\mu}\Phi\right)R^{\dagger} \quad (5)$$

$$\mathcal{V}_{\mu} \rightarrow L\mathcal{V}_{\mu}R^{\dagger} \quad (6)$$

$$D_{\mu}\mathcal{V}_{\nu} \rightarrow L\left(D_{\mu}\mathcal{V}_{\nu}\right)R^{\dagger} \quad (7)$$

It follows that the Lagrangian is symmetric under $SU(2) \times SU(2)$ (using the transformation rules and the cyclic trace property), then the Lagrangian is symmetric under all the subgroups of it.

Custodial symmetric

The small deviations from the unity of the ρ- parameter (T-parameter from EWPT) are guaranteed by the existence of the $SU(2)_V$ global approximate symmetry.

Appendix C: Constraints

- V^1 DM candidate (lightest new state)

$$\lambda_4 > 0, \qquad \lambda_3 + \lambda_4 > 0 \tag{8}$$

- Perturbativity

$$\begin{aligned} |\lambda_i| &< 4\pi; & i = 1, 2, 3. \\ |\alpha_j| &< 4\pi; & j = 1, 2. \end{aligned}$$

- LEP limits

$$\begin{aligned} M_{V^1} + M_{V^\pm} &> M_{W^\pm} \quad , \quad M_{V^2} + M_{V^\pm} > M_{W^\pm} \\ M_{V^1} + M_{V^2} &> M_Z \quad , \quad M_{V^+} + M_{V^-} > M_Z \end{aligned}$$

to make sure that the decay channels are kintematically forbidden, and from SUSY searches:

$$\begin{aligned} M_{V^1} &> 80 \text{ GeV} \quad , \quad M_{V^2} > 100 \text{ GeV} \\ M_{V^2} - M_{V^1} &> 8 \text{ GeV} \quad , \quad M_{V^\pm} > 70 \text{ GeV} \end{aligned}$$