Dark Sector of a Higgs Portal with $Q4$ Symmetric Matter*

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Cátedra Conacyt – IFUNAM

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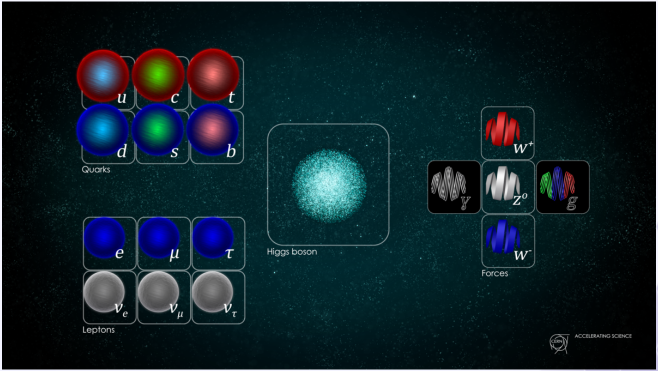
*A. E. Cárcamo-Hernández, C. E., J.C. Gómez-Izquierdo and M. Mondragón, Eur. Phys. J. Plus 137 (2022) 11, 1224

Outline

MOTIVATION

Motivation

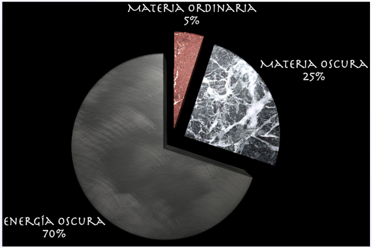
The Standard Model of Particle Physics can be regarded as one of the most important achievements of fundamental science.

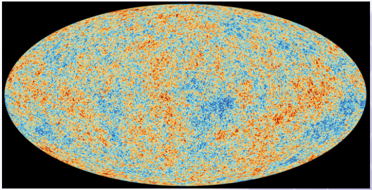


Motivation

Despite the Standard Model's outstanding successes, by now it is clear that **a more fundamental theory** is required to tackle several shortcomings and unexplained evidences such as (e.g. J. Ellis, hep-th/9812235):

- Dark matter and dark energy





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- Why aren't the particle masses much closer to the Planck mass (10^{19} GeV)?
- Why some particle masses are so small (m_ν) and others relatively much larger (m_t)?
- Can all the particle interactions be unified in a simple gauge group?
- What is the origin of the 6 flavours each of quarks and leptons?
- Baryon asymmetry, mixing patterns, quantization of gravity, ...

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In this talk I will describe one model built with the aim of:

- Provide one (particle) dark matter (DM) candidate.
- Generate the mass hierarchy of quarks and leptons through a discrete symmetry.

In particular, this Beyond the SM (BSM) theory has the following characteristics:

- An extended scalar sector.
- DM sector coupled through a **Higgs portal**.

However I will focus only in the description of the scalar sector phenomenology and its correlations with the DM sector.

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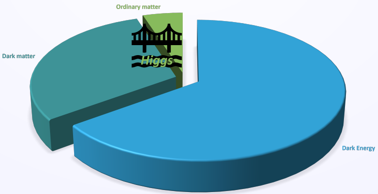
HIGGS PORTALS

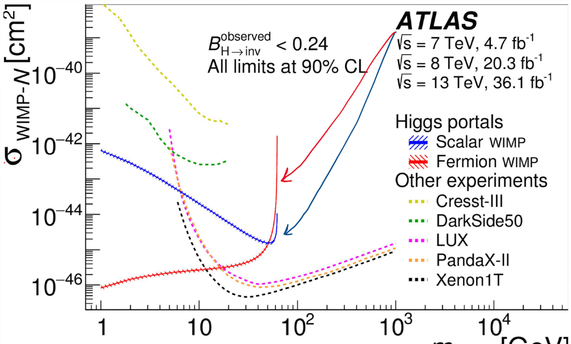
Higgs portals

- In a Higgs portal model the DM fields couple only to the scalar fields of the visible sector.
- An immediate consequence of these couplings is that an effective coupling between dark matter particles and quarks is induced, leading to the possibility of **dark matter - nucleon scattering.**



Higgs portals

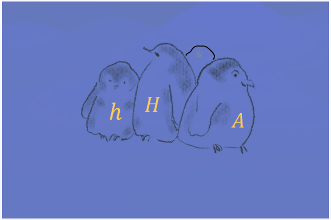
- **LHC constraints** from SM invisible Higgs decays nicely complement Direct Detection limits.



ATLAS Collaboration, Phys. Rev. Lett. 122, 231801 (2019)

Higgs portals

- For DM masses above 100 GeV up to several TeV, collider constraints from heavy scalar searches “propagate” to the DM sector.
- For example, in multi-higgs models several **additional heavy scalars** are predicted.



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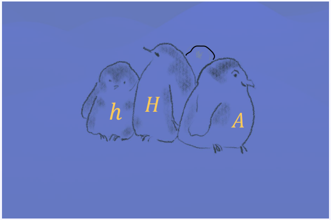


Higgs portals

- The couplings and mass spectrum of such scalars are constrained thanks to decades of collider searches (**Tevatron, LEP and LHC**).

Higgs portals

- This has immediate repercussions in the DM sector since the scalars mediate e.g. the scattering DM - nucleon cross section.

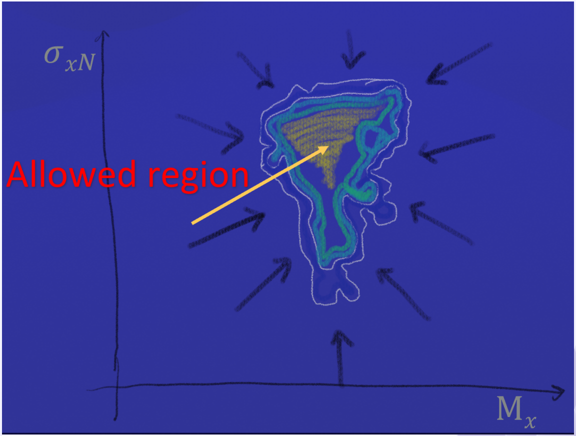
$$L_{\text{eff}} = \sum_k \overline{\Psi^C_R} c^k_\Psi \Psi_R \; h_k + \sum_{k,q} \overline{q} c^k_q q \; h_k$$

- The scattering amplitude will depend directly on the scalar masses which are directly constrained from collider searches.

$$\mathcal{M}_k = \frac{4 M_\Psi m_N}{q^2 + m^2_{h_k}} c^k_\Psi c^k_N \; \delta_{ss'} \delta_{rr'}$$

Higgs portals

- This effectively helps to limit the parameter space of the DM sector.



Q4 MODEL

Q4 Model

We made an analysis for a BSM model with **non-abelian Q4 discrete symmetry**:

- The discrete D_N symmetry is that of a regular polygon of N sides, and occurs in nature e.g. in poly-atomic molecules.
- The discrete non-abelian group Q_4 (or binary dihedral group with $N = 4$) can be seen as the group cover of D_4, and **has pseudo-real representations** which is advantageous for chiral theories.
- In this model the Q4 symmetry is imprinted in **the fermionic sector in order to predict** the mass and mixing patterns of quarks and neutrinos.
- We propose a scalar sector with **2 Higgs doublets** H_1, H_2 and **1 real scalar singlet** ϕ that **mixes with the CP-even scalars**.
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Q4: Scalar potential

- The scalar potential is given by the expression $V = V_1 + V_2$ with:

$$V_1 = m_{11}^2 H_1^\dagger H_1 + m_{22}^2 H_2^\dagger H_2 - m_{12}^2 \left(H_1^\dagger H_2 + H_2^\dagger H_1\right) + \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \left(H_2^\dagger H_1\right)^2\right], \quad (1)$$

$$V_2 = \mu_\varphi^2 \varphi^2 + \frac{\lambda_\varphi}{2}\varphi^4 + \lambda_7 \varphi^2 H_1^\dagger H_1 + \lambda_9 \varphi^2 H_2^\dagger H_2 + h.c., \quad (2)$$

with all parameters real.

Q4: Particle masses

- From the scalar potential we obtain the mass matrices for the different scalar particles. The physical particles A and $H^{\pm}$ have masses given by:

$$M_A^2 = m_{12}^2 \csc\beta \sec\beta - v^2\lambda_5 \tag{3}$$

$$M_{H^{\pm}}^2 = m_{12}^2 \csc\beta \sec\beta - \frac{1}{2}v^2(\lambda_4 + \lambda_5) \tag{4}$$

where $\tan\beta = v_{H_2}/v_{H_1}$. For the CP-even neutral scalars we can write the mass matrix as:

$$M^2_{\mathrm{scalar}} = \begin{pmatrix} a & d & f \\ d & b & e \\ f & e & c \end{pmatrix}, \tag{5}$$

Q4: Particle masses

- with:

$$\begin{aligned} a &= m_{12}^2 \tan\beta + \lambda_1 v^2 \cos^2\beta \\ b &= m_{12}^2 \cot\beta + \lambda_2 v^2 \sin^2\beta \\ c &= \lambda_\phi v_\phi^2 \\ d &= -m_{12}^2 + \lambda_{345} v^2 \cos\beta \sin\beta \\ e &= \lambda_9 v v_\phi \sin\beta \\ f &= \lambda_7 v v_\phi \cos\beta \end{aligned}$$

where λ_{345} is short for $(\lambda_3 + \lambda_4 + \lambda_5)$. The neutral scalar mass matrix is diagonalized by the mixing matrix Z^H such that

$$\mathrm{Diag}(m_h^2, m_H^2, m_{H3}^2) = Z^H M_{\mathrm{scalar}}^2 Z^{H\mathrm{T}} \tag{6}$$

Q4: Particle masses

- In this model we have **3 physical CP-even scalars** one of which corresponds to a **SM Higgs-like h**, the other two are denoted **H_3 and H**. We find for the masses:

$$
\begin{aligned}
m_h^2 &= \frac{1}{3}\left(a+b+c-2\sqrt{x_1}\cos\left[\Xi_s/3\right]\right) \\
m_H^2 &= \frac{1}{3}\left(a+b+c+2\sqrt{x_1}\cos\left[(\Xi_s-\pi)/3\right]\right) \\
m_{H_3}^2 &= \frac{1}{3}\left(a+b+c+2\sqrt{x_1}\cos\left[(\Xi_s+\pi)/3\right]\right)
\end{aligned} \tag{7}
$$

where

$$
x_1 = a^2+b^2+c^2-ab-ac-bc+3(d^2+f^2+e^2) \tag{8}
$$

Q4: Particle masses

- and:

$$\Xi_s = \begin{cases} \arctan\left(\dfrac{\sqrt{4x_1^3 - x_2^2}}{x_2}\right) & , \quad x_2 > 0 \\ \pi/2 & , \quad x_2 = 0 \\ \arctan\left(\dfrac{\sqrt{4x_1^3 - x_2^2}}{x_2}\right) + \pi & , \quad x_2 < 0 \end{cases} \tag{9}$$

with

$$\begin{aligned} x_2 \quad = \quad & -(2a - b - c)(2b - a - c)(2c - a - b) \\ & +9[(2c - a - b)d^2 + (2b - a - c)f^2 + (2a - b - c)e^2] - 54def \end{aligned} \tag{10}$$

Note that $\Xi_s \in [-\pi/2, 3\pi/2]$ so m_H^2 is always grater than m_h^2 but m_{H3}^2 can be smaller than m_h.

Q4: Likelihood analysis

- We present several numerical results based on a scan of the parameter space of the model where we construct **likelihood profiles** involving observables of interest by comparing predictions with experimental measurements.
- We limit ourselves to include the information from the measured values of the **relic density** $\Omega h^2_{\text{Planck}}$ **and Higgs mass** m_h as basic Gaussian likelihoods $\mathcal{L}_\Omega$, $\mathcal{L}_{m_h}$ respectively.

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Q4: Likelihood analysis

- We also include a likelihood function $\mathcal{L}_{DD}$ based on recent results from the **XENON1T Direct Detection Experiment,** we then maximize over the model's parameter space **the composite log-likelihood**:

$$\log \mathcal{L} = \log \mathcal{L}_{\mathbf{DD}} + \log \mathcal{L}_{\Omega} + \log \mathcal{L}_{m_h} \tag{11}$$

Note that in the high statistic limit, twice the negative of the composite log-likelihood approaches a χ-square function so this procedure is equivalent to minimizing such function.

Numerical analysis

- Using public tools* we impose hard cuts discarding points not complying with **positivity and stability of the scalar potential**, and **exclusion limits from scalar searches** at Tevatron, LEP and LHC. * EVADE, JHEP **03** (2019), 109, HiggsBounds, Eur. Phys. J. C **80** (2020) no.12, 1211.
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Experimental information

We compare the predictions of the model with **publicly available data from different experiments** and implemented in diverse public tools:

- XENON 1T for DM direct detection limits (XENON 1T, Phys. Rev. Lett. **121** (2018) no.11, 111302, DDcalc, Eur. Phys. J. C **77** (2017) no.12, 831 , and references therein)
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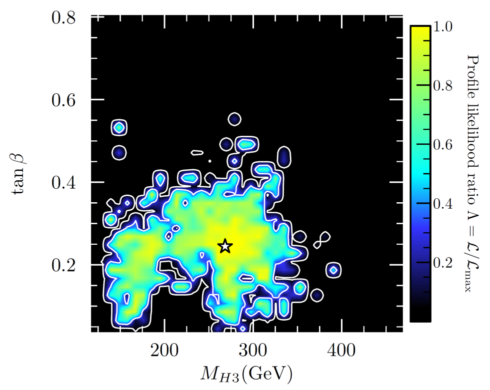
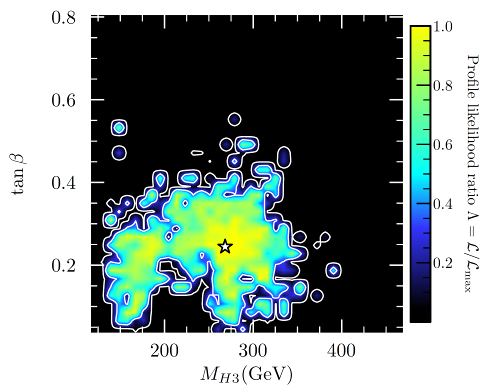
Q4: Mass spectra of the scalar sector

- This is the likelihood profile for **the H_3 scalar** showing the dependence of the quotient of the Higgs vevs ($\tan\beta$) in the mass of H_3.



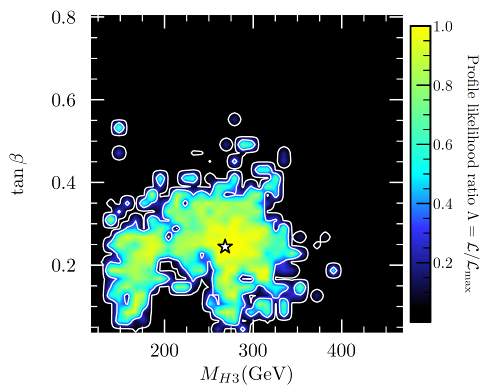
Q4: Mass spectra of the scalar sector

- **Solid lines are contours of 68% and 95% of C.L.** and the star points to the **best fit point (BFP)** or maximum of the composite likelihood function.



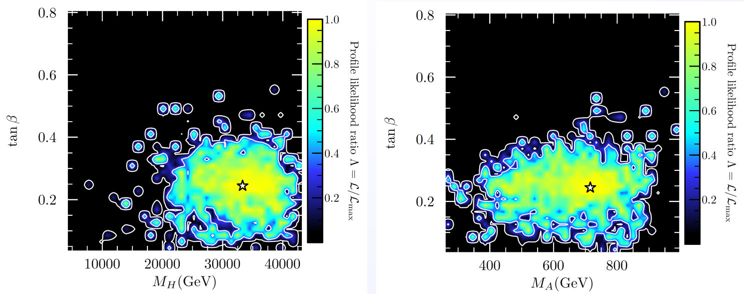
Q4: Mass spectra of the scalar sector

- For this model the mass of the H_3 scalar that maximizes the composite likelihood is found to be around **260 GeV** and contained in an interval **in-between 150 - 350 GeV** at 68% of C.L.



Q4: Mass spectra of the scalar sector

- These are the likelihood profiles for **the scalar** *H* **and the pseudo-scalar** *A*. The mass of *A* turns out to be around **720 GeV** at the BFP while the scalar *H* is very heavy around **33 TeV** at the BFP.



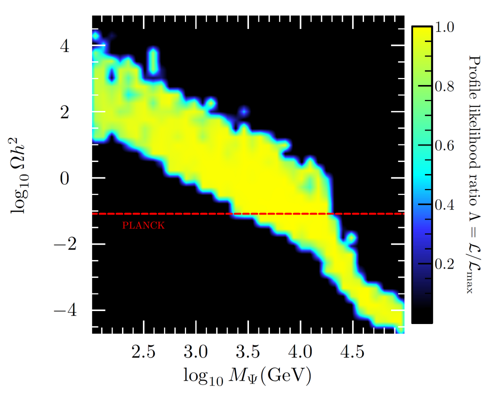
Q4: Dark sector

- The **dark matter candidate is a spin** $1/2$ **fermion** which in general communicates with the visible sector through all the scalar mass eigenstates due to the coupling:

$$L_{\mathrm{yuk}} \supset y_{\Psi} \overline{\Psi_R^C} \Psi_R \varphi$$

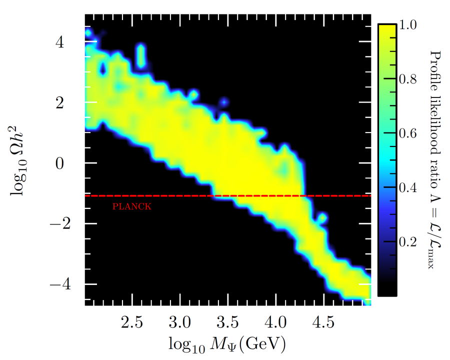
Q4 dark sector: Relic density

- This is the likelihood profile of the **relic density** as a function of the mass of the DM fermion (not including the likelihood function for the relic density).



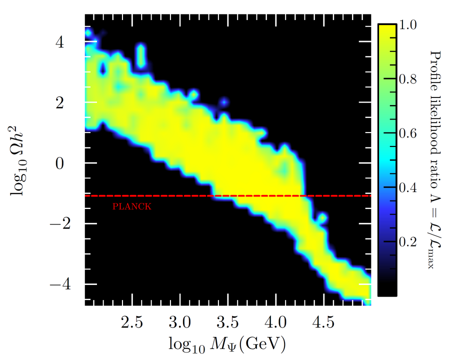
Q4 dark sector: Relic density

- As this plot evidences, **DM fermion masses below around 2.5 TeV would be overproduced** during the freeze-out epoch, so they are excluded despite being consistent with e.g. direct detection constraints (as some regions below 2 TeV have large likelihood function value with respect to the direct detection data).



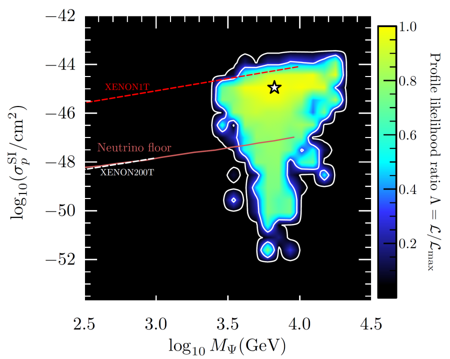
Q4 dark sector: Relic density

- From this analysis we find that this DM candidate can accommodate the observed DM abundance if its mass is **in-between 2.5 and 20 TeV**, we further find the BFP (not shown) corresponds to a **DM mass of 6 TeV**.



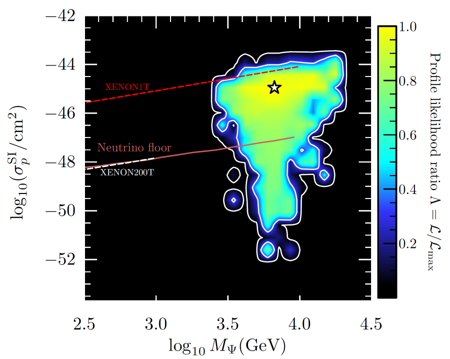
Q4 dark sector: Elastic scattering cross section

- This is the likelihood profile corresponding to **the elastic spin-independent DM-nucleon scattering cross section**. We compare with exclusion limits of the **XENON 1T** experiment and its **projection to 200 tons**.



Q4 dark sector: Elastic scattering cross section

- The analysis shows that **more than half the currently allowed region** will be probed with the high sensitivity of the 200 ton future experiment.



CONCLUSIONS

Conclusions

- We have built a predictive and viable extended 2HDM, where the scalar and fermion sectors are enlarged by the inclusion of a gauge singlet scalar and a right handed Majorana neutrino, respectively.
- The model contains a Higgs portal to the DM sector and the constraints from the scalar sector influence also the phenomenology of the DM candidate.

Conclusions

- The consistency of our model with the constraints arising from collider searches for heavy scalars, stability of the scalar potentials, the dark matter relic density and current and future direct detection experiments sets the mass of the scalar dark matter candidate to be around 6 TeV.
- The results of these analysis are complementary and enrich the respective matter sector analysis (not discussed here) such as those coming from the generation of the fermion masses and mixing patterns.

Acknowledgments

- I would like to thank my collaborators A.E. Cárcamo-Hernández, J.C. Gómez-Izquierdo and M. Mondragón.
- I would like to thank the support of Conacyt – Cátedra No. 341 and IF-UNAM.

Thank you for your attention!