Constraining BSM Discrete Flavor Symmetries with Heavy Scalar Searches at Colliders

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Cátedra Conacyt – IFUNAM

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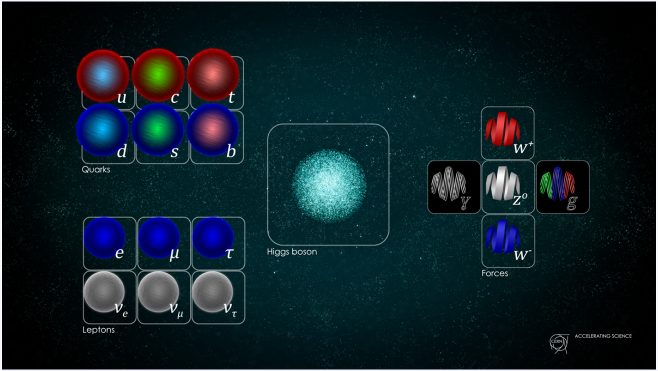
Outline

MOTIVATION

Motivation

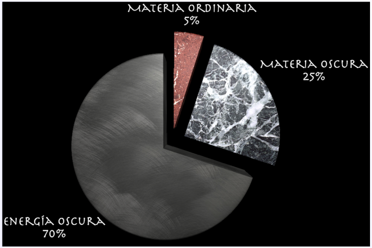
The Standard Model of Particle Physics can be regarded as one of the most important achievements of fundamental science.

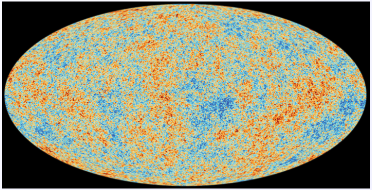


Motivation

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





Motivation

- 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 models built with the aim of:

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

In particular I will give examples of Beyond the SM (BSM) theories with the following characteristics:

- Extended scalar sector.
- One or more discrete symmetries.
- DM sector coupled through **Higgs portals**.

However I will focus only in the description of the scalar sector phenomenology and its correlations with the DM sector and how current collider constraints limit the parameter space of these models.

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BSM Extended Scalar Sectors

What is the intuition behind **multi-scalar** sectors?

- One of the simplest recipes to generalize the SM is to include additional scalars (singlets, doublets or even higher $SU(2)$ multiplets).
- As opposed to the SM, multi-higgs models have additional sources of CP violation that might solve the baryon asymmetry problem.
- Extended scalar sectors are necessary in well studied BSM models such as SUSY to ensure the absence of anomalies.

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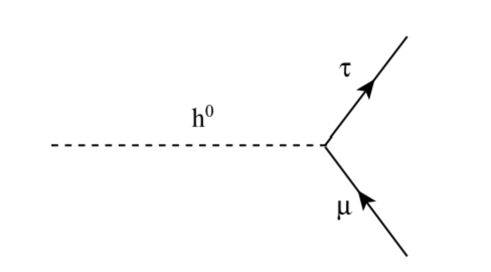
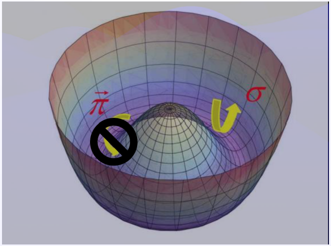
Nevertheless, in models with a multi-higgs sector flavour changing neutral currents (FCNC) are often predicted. This is one of the motivations for the introduction of additional discrete symmetries.



Discrete Symmetries

Among the different type of symmetries, **discrete non-abelian** ones have interesting characteristics:

- When spontaneously broken, no Goldstone bosons surge – In contrast to continuous global symmetries.



Discrete Symmetries

- Their non-abelian nature can lead to the generation of **nontrivial mixing patterns** for quarks and neutrinos.

$$U_{\text{tribi}} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix},$$

$$M_\nu = U^*_{\text{tribi}} \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} U^\dagger_{\text{tribi}}$$

Discrete Symmetries and multi-higgs sectors

When postulating a discrete symmetry ...

- If one has an extended scalar sector it is also natural to assume that all or some of the scalars **transform non-trivially** under it.
- The assignment of non-trivial charges to the scalars **will dictate** the analytical form of the scalar potential and the Yukawa terms.
- In particular, the phenomenology of the scalar sector will reflect the underlying symmetry.
- This means that **collider constraints** from scalar searches can be used to probe such symmetries.
- This constraints are actually complementary to those in the matter sector from e.g. FCNC.

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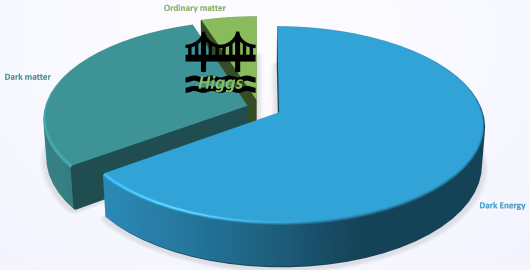
HIGGS PORTALS

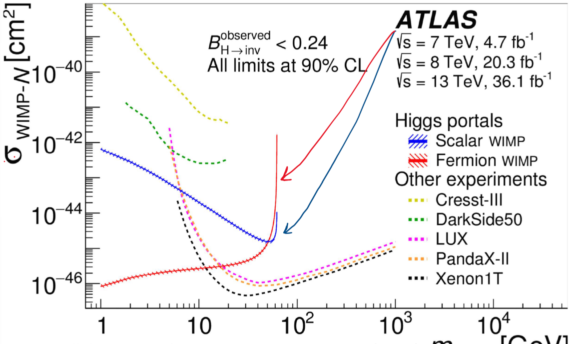
Higgs portals

In the particular case of a DM sector coupled through Higgs portals:



Higgs portals

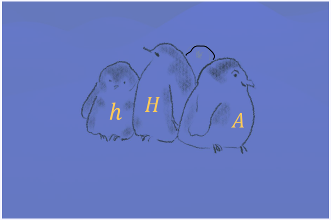
- **LHC constraints** from SM invisible Higgs decays nicely complement Direct Detection limits.



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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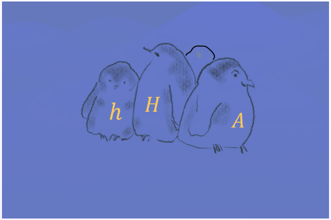


Higgs portals

- The couplings and mass spectrum of such scalars are constrained thanks to decades of collider searches.

Higgs portals

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

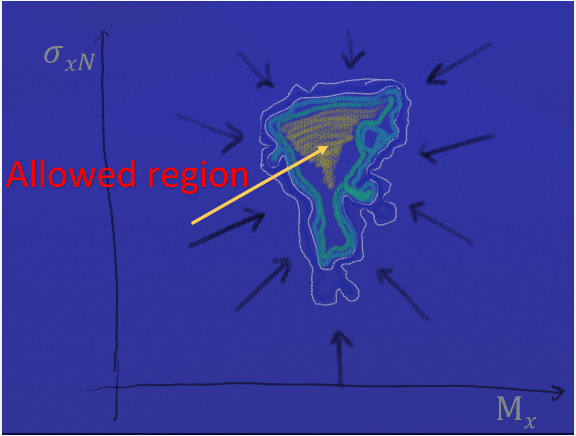
$$L_{\text{eff}} = \sum_k \overline{\Psi_R^C} c_\Psi^k \Psi_R \, h_k + \sum_{k,q} \overline{q} c_q^k q \, h_k$$

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

$$\mathcal{M}_k = \frac{4 M_\Psi m_N}{q^2 + m_{h_k}^2} c_\Psi^k c_N^k \; \delta_{ss'} \delta_{rr'}$$

Higgs portals

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



S4 MODEL

S4 Model

We propose[1] a BSM model with a multi-higgs sector:

- Three Higgs doublets H_1, H_2 and H_3 plus one scalar singlet DM candidate ϕ.
- Contains a proposed **non-abelian discrete S4 Symmetry**, the symmetry of all possible permutations of 4 objects.
- In the scalar sector only 2 Higgs doublets transform **non-trivially** with respect to S4:

$$H_I \equiv (H_1, H_2) \sim \mathbf{2}$$

[1] A. E. Cárcamo-Hernández, C. E., J. C. Gómez-Izquierdo, J. Marchant, M. Mondragón. In preparation.

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Dark Sector

- The third doublet and the dark scalar are invariant with respect to S4:

$$H_3 \sim \mathbf{1}, \ \phi \sim \mathbf{1}$$

- We minimally couple the dark scalar to the Higgs doublets:

$$V \supset (\lambda_a H_1^\dagger H_1 + \lambda_b H_2^\dagger H_2 + \lambda_c H_3^\dagger H_3)\phi^2$$

- In addition, the dark scalar ϕ is charged under an additional $\mathbf{Z}_2$ to ensure its stability.

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Scalar Potential

The S4 symmetry **dictates the analytical form** of the scalar potential:

$$
\begin{aligned}
V \quad = \quad & -\mu_1^2\left(H_1^\dagger H_1\right) - \mu_2^2\left(H_2^\dagger H_2\right) - \mu_3^2 H_3^\dagger H_3 + \lambda_1\left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 + \lambda_2\left(H_2^\dagger H_1 - H_1^\dagger H_2\right)^2 \\
& +\lambda_3\left[\left(H_1^\dagger H_2 + H_2^\dagger H_1\right)^2 + \left(H_1^\dagger H_1 - H_2^\dagger H_2\right)^2\right] \\
& +\lambda_4\left[\left(H_1^\dagger H_2 + H_2^\dagger H_1\right)\left(H_1^\dagger H_3 + H_3^\dagger H_1\right) + \left(H_1^\dagger H_1 - H_2^\dagger H_2\right)\left(H_2^\dagger H_3 + H_3^\dagger H_2\right)\right] \\
& +\lambda_5\left(H_3^\dagger H_3\right)\left(H_1^\dagger H_1 + H_2^\dagger H_2\right) + \lambda_6\left[\left(H_3^\dagger H_1\right)\left(H_1^\dagger H_3\right) + \left(H_3^\dagger H_2\right)\left(H_2^\dagger H_3\right)\right] \\
& +\lambda_7\left[\left(H_3^\dagger H_1\right)^2 + \left(H_3^\dagger H_2\right)^2 + \left(H_1^\dagger H_3\right)^2 + \left(H_2^\dagger H_3\right)^2\right] + \lambda_8\left(H_3^\dagger H_3\right)^2
\end{aligned}
$$

We have 8 quartic couplings plus 3 couplings from the scalar portals to the DM sector, 1 mass parameter of the dark scalar and the quotient of the Higgs independent vevs make a total of 13 free parameters.

Electroweak symmetry breaking

With EWSB the Higgs doublets acquire non-zero vacuum expectation values:

- For simplicity we assume the alignment of two of these vevs (those of H_1 and H_2): $v_1 = v_2$
- The mass spectra is obtained by diagonalizing the mass matrices, for example for the **CP-even physical scalars** (h, H and H_3):

$$diag\left(m_h^2, m_H^2, m_{H3}^2\right) = Z^H \, M_s^2 \, Z^{HT}$$

- We denote by **h** the SM Higgs-like scalar.

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CP-even scalars

- The mass matrix of the CP-even scalars has the form:

$$M_s^2 = \begin{pmatrix} a & d & f \\ d & b & e \\ f & e & c \end{pmatrix}$$

  where each matrix element is a function of the quartic couplings in the scalar potential.

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CP-even scalars

We obtain:

$$
\begin{aligned}
m_h^2 &= \frac{1}{3}(a+b+c-2\sqrt{x_1}\cos[\Xi_s/3]) \\
m_H^2 &= \frac{1}{3}(a+b+c+2\sqrt{x_1}\cos[(\Xi_s-\pi)/3]) \\
m_{H3}^2 &= \frac{1}{3}(a+b+c+2\sqrt{x_1}\cos[(\Xi_s+\pi)/3])
\end{aligned}
$$

where

$$x_1 = a^2+b^2+c^2-ab-ac-bc+3(d^2+f^2+e^2)$$

CP-even scalars

And:

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

with

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

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.

Sub-TeV heavy scalars

The point of showing you this is that we can focus the analysis to a region of parameter space where **all the scalars have masses sub-TeV**.

- This is achieved by imposing the condition:

$$x_2 = 0$$

- This is a quadratic equation in one of the quartic couplings (λ_5). We can always choose this parameter such that the condition is fulfilled.

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The symmetric gap region

In this region of parameter space defined by the slice $x_2 = 0$, the expressions for the masses simplify:

$$
\begin{aligned}
m_h^2 &= \frac{1}{3}(a + b + c - 2\sqrt{x_1}) \\
m_H^2 &= \frac{1}{3}(a + b + c + 2\sqrt{x_1}) \\
m_{H3}^2 &= \frac{1}{3}(a + b + c)
\end{aligned}
$$

We call this slice **"the symmetric gap" region**, since the square of the scalar masses are separated by the same amount:

$$\Delta \equiv 2\sqrt{x_1}/3 = m_H^2 - m_{H3}^2 = m_{H3}^2 - m_h^2$$

The symmetric gap region

Thanks to the simplification of the equations:

- Control over the values of the masses is achieved by eliminating three quartic couplings in favor of them.
- This allows us to make a scan of parameter space in which we fix the mass of h at around 125 GeV and take $m_{H3} < 1000$ GeV.
- 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.

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Theoretical predictions

Using also public tools, for points not filtered by the hard cuts, **predicted observables** are calculated with respect to:

- Couplings of the 125 GeV SM Higgs-like scalar (SPheno, Comput. Phys. Commun. **183** (2012), 2458-2469 ,SARAH, Adv. High Energy Phys. **2015** (2015), 840780)
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- DM-nucleon scattering cross sections. (MicrOmegas, Comput. Phys. Commun. **231** (2018), 173-186)
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Likelihood function

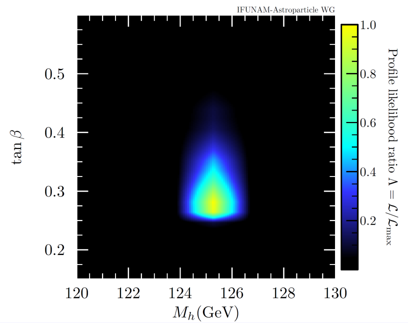
The comparison is done through a **composite likelihood function:**

- $$\log\,\mathcal{L} = \log\,\mathcal{L}_{DD} + \log\,\mathcal{L}_{\Omega h^2} + \log\,\mathcal{L}_{m_h} + \log\,\mathcal{L}_{ATLAS}$$

- We scan the parameter space of the model to construct the **likelihood profile** and find the best fit point (BFP) that maximizes the likelihood function (Diver, Eur. Phys. J. C **77** (2017) no.11, 761 , P. Scott, Eur. Phys. J. Plus **127** (2012), 138)

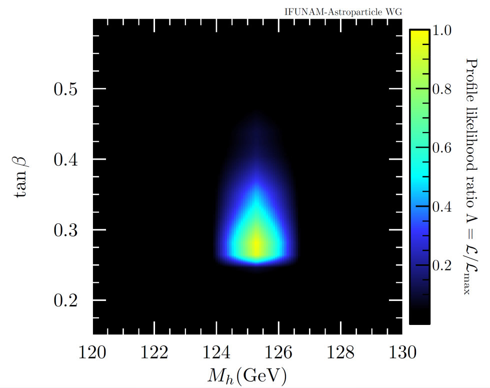
Phenomenology

- This "control" plot shows the mass of the SM Higgs-like scalar as a function of $\tan\beta \propto v_1/v_3$.
- **Dark regions** of the parameter space **are highly disfavored**, they correspond to small values of the likelihood function away from the maximum.



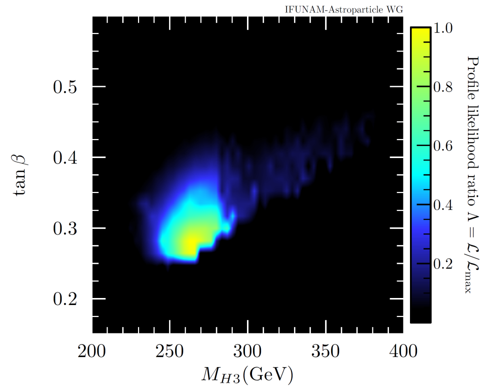
Phenomenology

- As expected the bright region stands around 125 GeV.
- The first result inferred from the analysis is that the model is congruent with experimental observations only for small values of tan β.



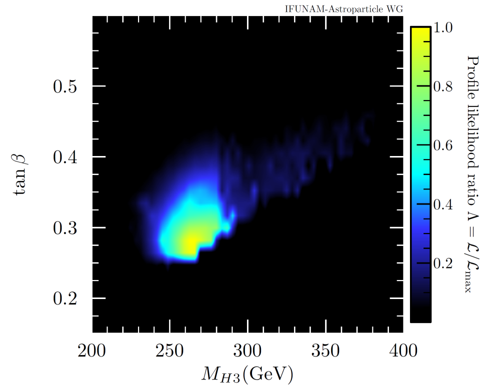
Heavy scalars

- This is the likelihood profile corresponding to **the H_3 CP-even scalar** as a function of $\tan\beta$.
- The mass value of this scalar that best fits the likelihood function stands **around 265 GeV.**



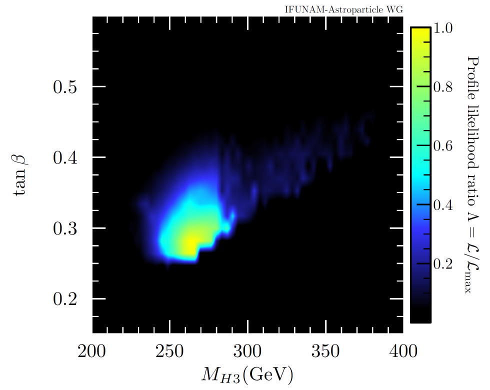
Heavy scalars

- **The frontier between the two blue tones** approximately corresponds to **68%** of confidence level (C.L.), while the frontier with the black region corresponds to approximately **95% C.L.**



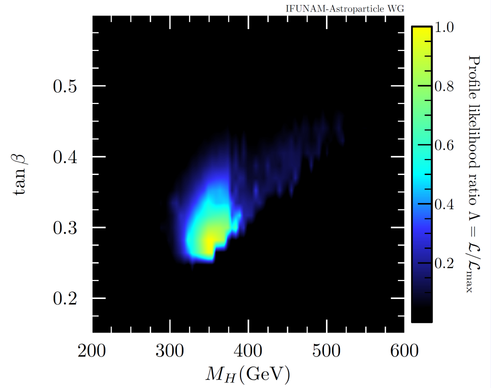
Heavy scalars

- The analysis allow us to constrain the mass of this scalar **in between 240 and 300 GeV** with a C.L. of 68%.



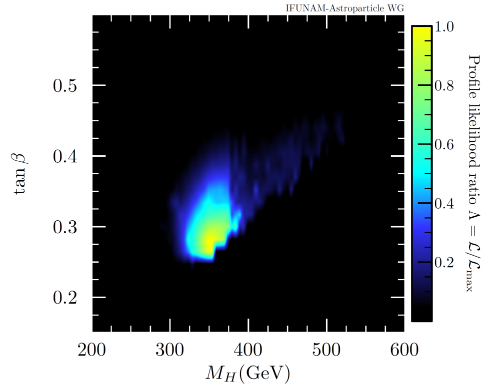
Heavy scalars

- This is the corresponding likelihood profile of **the heaviest** H **CP-even scalar** as a function of $\tan\beta$.
- For this case the mass value that best fits the likelihood function stands around **350 GeV.**



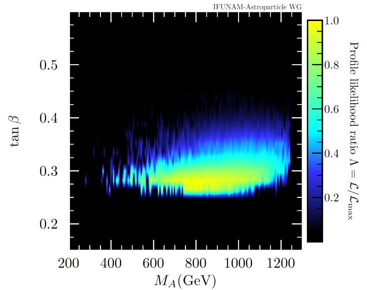
Heavy scalars

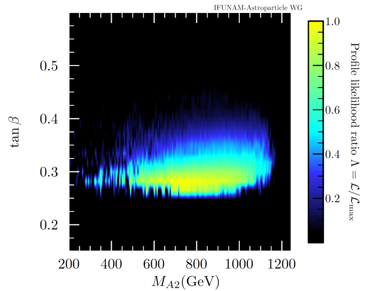
- With the analysis we can limit the mass of this scalar to the range **325 - 400 GeV** at 68% of C.L.



CP-odd scalars

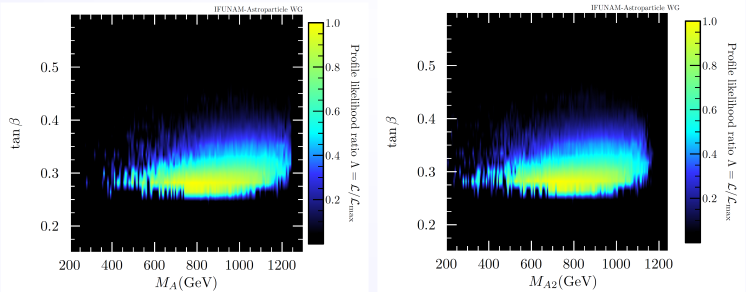
- These are the likelihood profiles associated with the **pseudo-scalars** denoted A and $A2$.





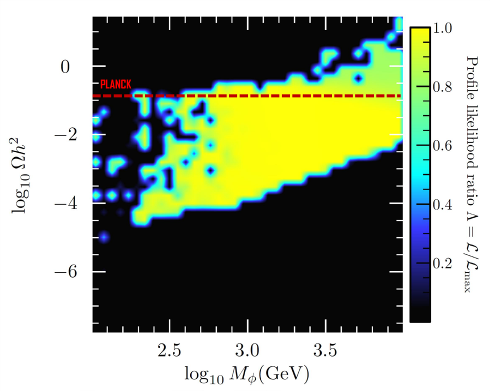
CP-odd scalars

- In these cases the analysis is not deep enough to significantly constrain the masses of these scalars.



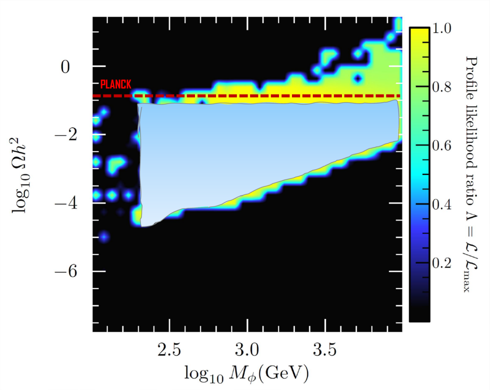
Dark sector: relic density

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



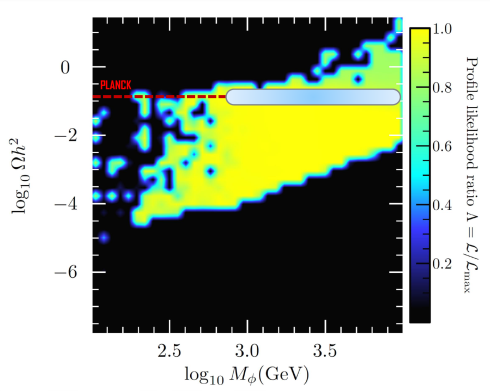
Dark sector: relic density

- We can see that in most of the explored parameter space the dark scalar contribute only in a **sub-optimal way to the observed abundance.**



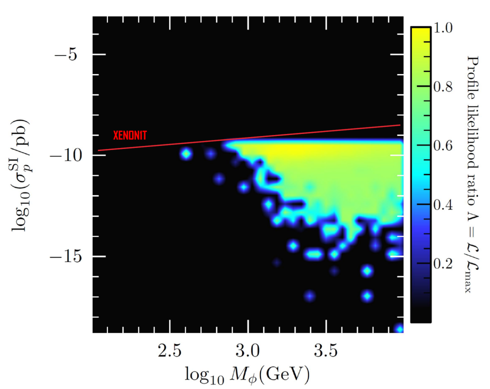
Dark sector: relic density

- However, close to **5% of the explored parameter space** comprising a mass interval in-between 800 GeV and 10 TeV can explain **the observed DM abundance.**



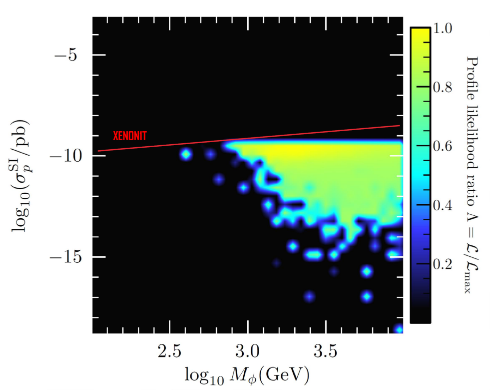
Dark sector: Elastic cross section

- This likelihood profile corresponds to **the elastic DM - nucleon cross section** as a function of the mass of the dark scalar.



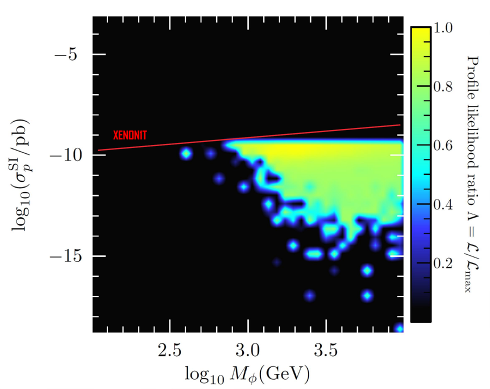
Dark sector: Elastic cross section

- The red curve shows the **XENON 1T** experiment exclusion curve.



Dark sector: Elastic cross section

- For this observable, the mass of the dark scalar that best fits the likelihood function (not shown) stands around **1.6 TeV**.



Q4 MODEL

Q4 Model

We made[2] a similar 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 we propose a scalar sector with 2 Higgs doublets and 1 real scalar singlet that **mixes with the CP-even scalars**.
- The scalar singlet is further coupled to a **right handed heavy neutrino DM candidate**.

[2] A. E. Cárcamo-Hernández, C. E., J. C. Gómez-Izquierdo, M. Mondragón. To appear in EPJ Plus.

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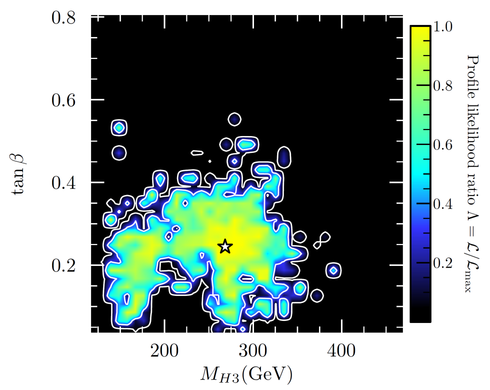
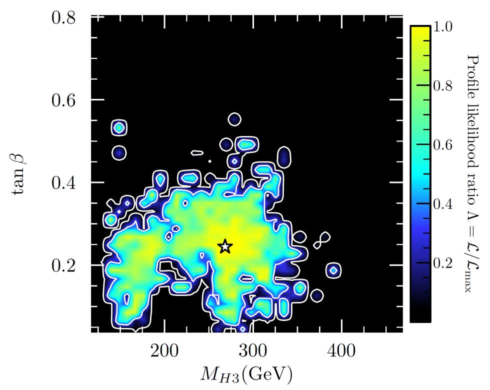
Q4: Mass spectra of the scalar sector

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



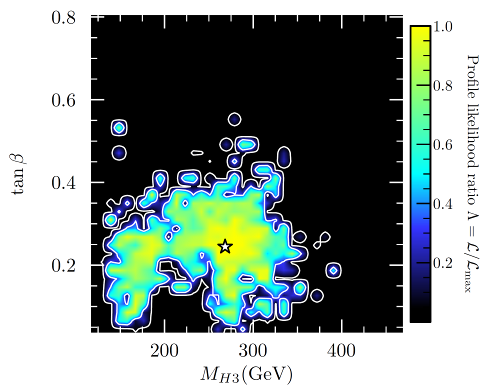
Q4: Mass spectra of the scalar sector

- 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.



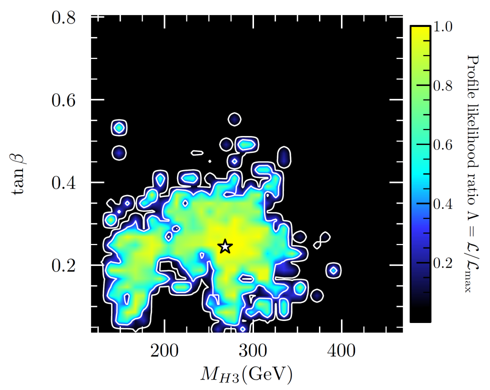
Q4: Mass spectra of the scalar sector

- **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.



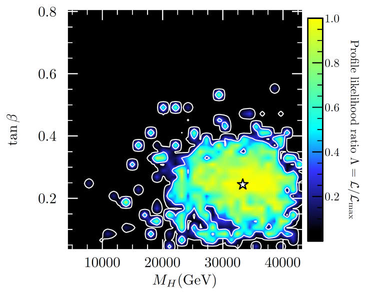
Q4: Mass spectra of the scalar sector

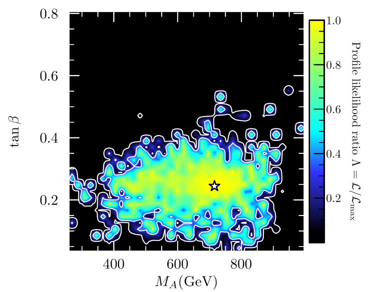
- For this model the mass of the H_3 scalar that maximizes the composite likelihood is found to be around **260 GeV** and contained in an interval **in-between 150 - 350 GeV** at 68% of C.L.



Q4: Mass spectra of the scalar sector

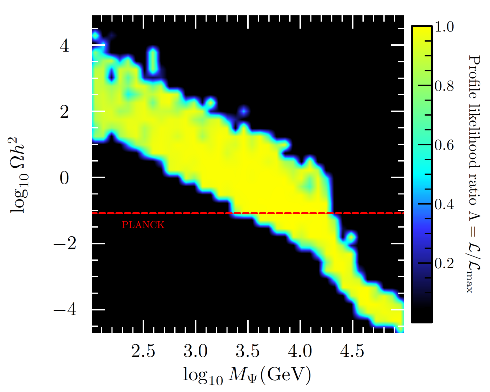
- These are the likelihood profiles for **the scalar H and the pseudo-scalar A**. The mass of A turns out to be around **720 GeV** at the BFP while the scalar H is very heavy around **33 TeV** at the BFP (no symmetric gap present in this model so the analysis is made over the full parameter space).





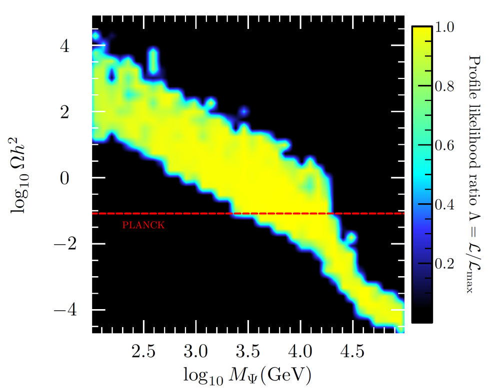
Q4 dark sector: relic density

- Being the dark matter candidate **a spin 1/2 fermion** the phenomenology is somewhat different from the scalar DM case.



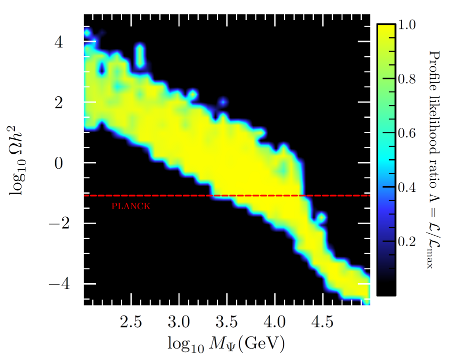
Q4 dark sector: relic density

- 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).



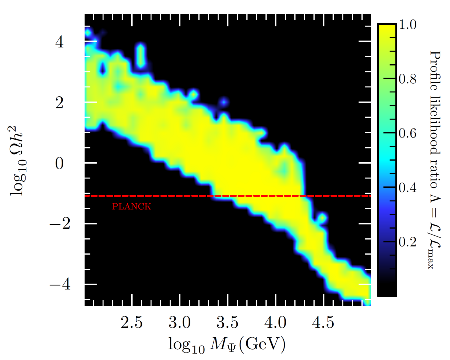
Q4 dark sector: relic density

- 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).



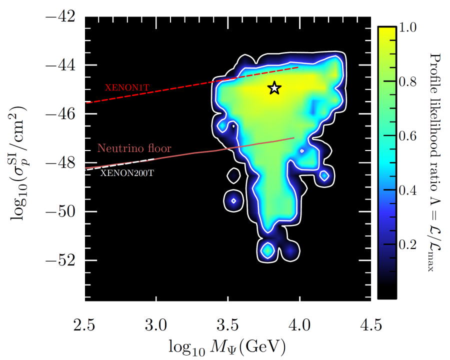
Q4 dark sector: relic density

- 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**.



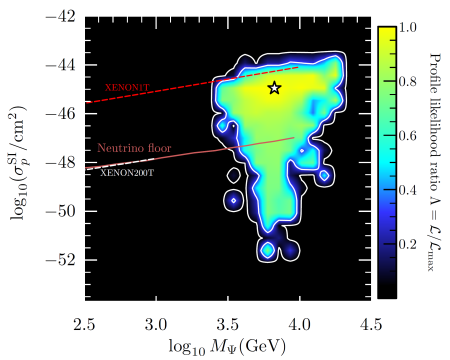
Q4 dark sector: Elastic scattering cross section

- 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 employed the strategy of using the phenomenology of the scalar sector of BSM models to constrain discrete symmetries complementing the usual ones coming from FCNC limits.
- When the BSM model contains Higgs portals to the DM sector the constraints from the scalar sector influence also the phenomenology of the DM candidate.

Conclusions

- We exemplified this strategy analyzing the scalar and DM sectors of two BSM models with respective discrete symmetries S4 and Q4.
- The results of these analysis are complementary and enrich the respective matter sector analysis 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, J. Marchant and M. Mondragón.
- I would like to thank the support of Conacyt – Cátedra No. 341 and IF-UNAM.

Thank you for your attention!