Collider Feasibility of the Dynamical Scotogenic Model

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Prepared for submission to **P.R.D.**, 2024

Particle content and symmetries of the model

	q_L	u_R	d_R	ℓ_L	e_R	N	η	σ	H
$\mathrm{SU}(3)_C$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{SU}(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$
$\mathrm{U}(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$\frac{-1}{3}$	$\frac{-1}{2}$	-1	0	$\frac{1}{2}$	0	$\frac{1}{2}$
$\mathrm{U}(1)_L$	0	0	0	1	1	1	0	-2	0
$\mathbb{Z}_2$	$+$	$+$	$+$	$+$	$+$	-	-	$+$	$+$

Model Description

- The SM leptons only couple to the dark sector through the Yukawa couplings (y_{ij}).
- The new fermion sector includes the following terms in the Lagrangian:

$$\mathcal{L}_F = y_{ij}\bar{\ell}_i\tilde{\eta}N_j + \kappa_{ij}\overline{N_i}^c\sigma N_j + \text{h.c.} \tag{1}$$

- The σ VEV allows the Majorana fermions (N_i) to acquire mass. In this case, κ_{ij} is a 3×3 matrix, that we will consider diagonal for our study without any loss of generality.
- The potential reads:

$$\begin{aligned}\mathcal{V} =& m_H^2 H^\dagger H + m_\eta^2\eta^\dagger\eta + m_\sigma^2\sigma^\dagger\sigma + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\eta^\dagger\eta)^2 + \frac{\lambda_\sigma}{2}(\sigma^\dagger\sigma)^2 \\ &+ \lambda_3(H^\dagger H)(\eta^\dagger\eta) + \lambda_3^{H\sigma}(H^\dagger H)(\sigma^\dagger\sigma) + \lambda_3^{\eta\sigma}(\eta^\dagger\eta)(\sigma^\dagger\sigma) + \lambda_4(H^\dagger\eta)(\eta^\dagger H) \\ &+ \frac{\lambda_5}{2}[(H^\dagger\eta)^2 + (\eta^\dagger H)^2]\end{aligned}$$

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- After the Kibble parametrization

$$H = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v + S_H + iP_H) \end{pmatrix}; \quad \sigma = \frac{1}{\sqrt{2}}(v_\sigma + S_\sigma + iP_\sigma); \quad \eta = \begin{pmatrix} \eta^+ \\ \frac{1}{\sqrt{2}}(\eta_R + i\eta_I) \end{pmatrix}, \tag{2}$$

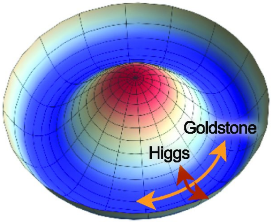


Figure: Representation of the Kibble parametrization of a scalar around the VEV topology.

one finds that the quadratic parts of the coupling potential between H^0 and σ take the form

$$\mathcal{V}_{H^0\sigma} = \frac{1}{2}\,\mathrm{Re}\{\varphi_i\}(\mathcal{M}_R^2)_{ij}\,\mathrm{Re}\{\varphi_j\} + \frac{1}{2}\,\mathrm{Im}\{\varphi_i\}(\mathcal{M}_I^2)_{ij}\,\mathrm{Im}\{\varphi_j\}; \quad \varphi = (H^0, \sigma) \tag{3}$$

- The mass matrices, $\mathcal{M}_R$ and $\mathcal{M}_I$ are given by

$$\mathcal{M}_R^2 = \begin{pmatrix} m_H^2 + \frac{3}{2}\lambda_1 v^2 + \frac{\lambda_3^{H\sigma}}{2} v_\sigma^2 & \lambda_3^{H\sigma} v v_\sigma \\ \lambda_3^{H\sigma} v v_\sigma & m_\sigma^2 + \frac{3}{2}\lambda_\sigma v_\sigma^2 + \frac{\lambda_3^{H\sigma}}{2} v^2 \end{pmatrix} \tag{4}$$

$$\mathcal{M}_I^2 = \begin{pmatrix} m_H^2 + \frac{\lambda_1}{2} v^2 + \frac{\lambda_3^{H\sigma}}{2} v_\sigma^2 & 0 \\ 0 & m_\sigma^2 + \frac{\lambda_\sigma}{2} v_\sigma^2 + \frac{\lambda_3^{H\sigma}}{2} v^2 \end{pmatrix} \tag{5}$$

- Both matrices can be reduced after inserting the tadpole equations of the potential

$$\frac{\partial \mathcal{V}_{H^0\sigma}}{\partial H^0}\Big|_{H^0=\langle H^0\rangle} = m_H^2 \frac{v}{\sqrt{2}} + \frac{\lambda_1}{2\sqrt{2}} v^3 \lambda_1 + \frac{\lambda_3^{H\sigma}}{2\sqrt{2}} v v_\sigma^2 = 0 \tag{6}$$

$$\frac{\partial \mathcal{V}_{H^0\sigma}}{\partial \sigma}\Big|_{\sigma=\langle\sigma\rangle} = \frac{v_\sigma}{\sqrt{2}} m_\sigma^2 + \frac{\lambda_\sigma}{2\sqrt{2}} v_\sigma^3 + \frac{\lambda_3^{H\sigma}}{2\sqrt{2}} v_\sigma v^2 = 0. \tag{7}$$

- $\mathcal{M}_I^2$ becomes exactly zero, allowing us to identify P_H as the SM neutral Goldstone boson from the parametrization

$$H = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v + S_H + iP_H) \end{pmatrix}; \quad \sigma = \frac{1}{\sqrt{2}}(v_\sigma + S_\sigma + iP_\sigma);$$

- $P_\sigma = J$ remains a physical state of the theory, the Majoron.
- $\mathcal{M}_R^2$ reduces to

$$\mathcal{M}_R^2 = \begin{pmatrix} \lambda_1 v^2 & \lambda_3^{H\sigma} v v_\sigma \\ \lambda_3^{H\sigma} v v_\sigma & \lambda_\sigma v_\sigma^2 \end{pmatrix}, \tag{8}$$

which is still non diagonal. To find the mass eigenstates, and the mass values, we must diagonalize.

- Eigenvalues are given by

$$m^2_{h_2/h_1} = \frac{\lambda_1}{2} v^2 + \frac{\lambda_\sigma}{2} v_\sigma^2 \pm \frac{1}{2}\sqrt{(2\lambda_3^{H\sigma} v v_\sigma)^2 + (\lambda_1 v^2 - \lambda_\sigma v_\sigma^2)^2}, \tag{9}$$

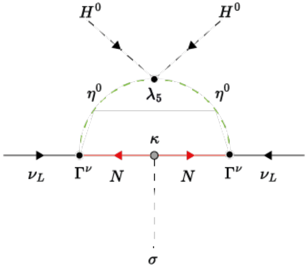
- Additionally, the eigenstates can be obtained via change of basis

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R \cdot \begin{pmatrix} S_H \\ S_\sigma \end{pmatrix}, \tag{10}$$

where R is obtained from

$$\begin{pmatrix} m^2_{h_1} & 0 \\ 0 & m^2_{h_2} \end{pmatrix} = R \mathcal{M}^2_R R^T; \quad R = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \in \mathrm{SO}(2).$$

- Now, neutrino masses can be generated via the Yukawa term $-\mathcal{L} \supset y_{ij}\bar{\ell}_i\tilde{\eta}N_j + \kappa_{ij}\bar{N}_i^c\sigma N_j$. Which induces the 1-loop correction



$$(\mathcal{M}_\nu)_{ij} = \sum_{k=1}^{3} \frac{y_{ki}y_{kj}}{32\pi^2} M_{N_k^0}\left[\frac{m_{\eta_R^2}}{m_{\eta_R}^2 - M_{N_k^0}^2} \ln\left(\frac{m_{\eta_R}^2}{M_{N_k^0}^2}\right) - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - M_{N_k^0}^2} \ln\left(\frac{m_{\eta_I}^2}{M_{N_k^0}^2}\right)\right], \quad (11)$$

$$\text{where } M_{N_i^0} = \sqrt{2}\kappa_{ii}v_\sigma$$

Constraints

- The following discussion considers both scalar and fermionic DM scenarios.
- Neutrino oscillation data can be implemented via a modified Casas-Ibarra parametrization

$$y = \sqrt{\Lambda^{-1}} O \sqrt{\hat{M}_\nu} U^\dagger, \tag{12}$$

where O is a 3×3 orthogonal matrix, U is the PMNS matrix containing all the experimental oscillation data, and $\Lambda =$Diag(Λ_i) is the matrix containing loop functions:

$$\Lambda_i = \frac{M_{N_i^0}}{32\pi^2}\left[\frac{m_{\eta_R}^2}{m_{\eta_R}^2 - M_{N_i^0}^2}\ln\left(\frac{m_{\eta_R}^2}{M_{N_i^0}^2}\right) - \frac{m_{\eta_I}^2}{m_{\eta_I}^2 - M_{N_i^0}^2}\ln\left(\frac{m_{\eta_I}^2}{M_{N_i^0}^2}\right)\right] \tag{13}$$

Observable	Constraint
m_H	125.25 ± 3.0 GeV
$\mathrm{BR}(\mu^- \to e^-\gamma)$	$< 4.2 \times 10^{-13}$
$\mathrm{BR}(\tau^- \to e^-\gamma)$	$< 3.3 \times 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-\gamma)$	$< 4.2 \times 10^{-8}$
$\mathrm{BR}(\mu^- \to e^-e^+e^-)$	$< 1.0 \times 10^{-12}$
$\mathrm{BR}(\tau^- \to e^-e^+e^-)$	$< 2.7 \times 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-\mu^+\mu^-)$	$< 2.1 \times 10^{-8}$
$\mathrm{BR}(\tau^- \to e^-\mu^+\mu^-)$	$< 2.7 \times 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-e^+e^-)$	$< 1.8 \times 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-e^+\mu^-)$	$< 1.7 \times 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^+e^-e^-)$	$< 1.5 \times 10^{-8}$
$\mathrm{BR}(\tau^- \to e^-\pi)$	$< 8.0 \times 10^{-8}$

Observable	Constraint
$\mathrm{BR}(\tau^- \to e^-\eta)$	$< 9.2 \times 10^{-8}$
$\mathrm{BR}(\tau^- \to e^-\eta')$	$< 1.6 \times 10^{-7}$
$\mathrm{BR}(\tau^- \to \mu^-\pi)$	$< 1.1 \times 10^{-7}$
$\mathrm{BR}(\tau^- \to \mu^-\eta)$	$< 6.5 \times 10^{-8}$
$\mathrm{BR}(\tau^- \to \mu^-\eta')$	$< 1.3 \times 10^{-7}$
$\mathrm{CR}_{\mu\to e}(\mathrm{Ti})$	$< 4.3 \times 10^{-12}$
$\mathrm{CR}_{\mu\to e}(\mathrm{Pb})$	$< 4.3 \times 10^{-11}$
$\mathrm{CR}_{\mu\to e}(\mathrm{Au})$	$< 7.0 \times 10^{-13}$
$\mathrm{BR}(Z^0 \to e^\pm\mu^\mp)$	$< 7.5 \times 10^{-7}$
$\mathrm{BR}(Z^0 \to e^\pm\tau^\mp)$	$< 5.0 \times 10^{-6}$
$\mathrm{BR}(Z^0 \to \mu^\pm\tau^\mp)$	$< 6.5 \times 10^{-6}$
$\mathrm{BR}(h \to \text{invisible})$	$< 0.19 \times \cos(\alpha)^{-2}$

- The DM candidate particle must comply with the current relic density value measured by PLANCK:

$$\Omega_\chi h^2 = 0.120 \pm 0.0036$$

- To analyze the parameter space that complies with all the constraints we used a **Markov Chain Monte Carlo** scan.
- Two different m_{h_2} were considered$\sim$ 246 GeV, and 500 GeV

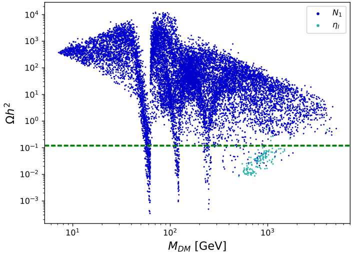


Figure: Projection of the relic density on the dark matter mass, for the two different candidates for dark matter.

- We first analyze the behavior of the DM relic density for the three different v_σ cases, independent of the compressed mass spectrum.

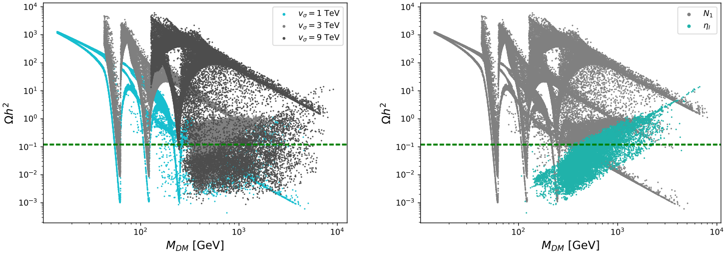


Figure: DM relic density as function of the DM mass. Left: Distribution with the different VEV values. Right:Distribution for the two possible DM candidate . Green band: PLANCK results.

- Without imposing any conditions on the $\Delta m = \left| m_{N_1} - m_{\eta^0} \right| \rightarrow$ 89% of all points are N_1

- We now impose $\Delta m = \left| m_{N_1} - m_{\eta^0} \right| < 50$ GeV to check the impact of the Δm in the relic density distribution.

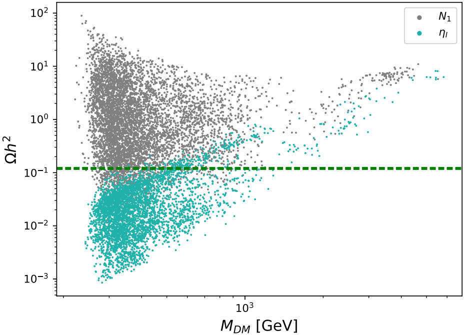


Figure: DM relic density as a function of the DM candidate mass. Red dots are solution to DM relic density and green band: PLANCK results. Results are given for $v_\sigma = 9$ TeV

- De Romeri, et. al: Considering $\Delta m(N_1, \eta_R)$ very close in mass values (Compressed Mass Spectrum) inside the coannihililation region implies that DM could be produced via DY processes at the LHC!
- Idea: Produce the η as shown in the diagram and let them decay after considering each DM possibility

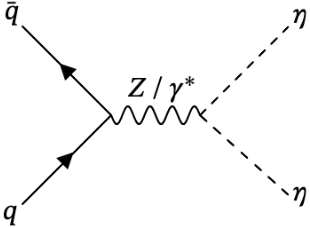


Figure: Drell-Yan production of a pair of η scalars.

- In the case of Fermion DM production, as it does not couple directly to the SM gauge bosons, we consider $p + p \to \eta^+ + \eta^-$ and allow the $\eta^\pm \to N + \ell$ decay.
- We considered the cases $m_{h_2} = 246$ GeV, 500 GeV and $v_\sigma = 1$ TeV, 2, TeV, 3 TeV, 4 TeV, 5 TeV, 6 TeV, and 9 TeV. Additionally, we considered different compressed mass spectra $\sim \Delta m < 20$ GeV, 50 GeV.
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- Dominant intermediate topologies for each scenario:
  1. Scalar DM: $p + p \rightarrow \eta_I + \eta_R$
  2. Fermion DM: $p + p \rightarrow \eta^+ + \eta^-$

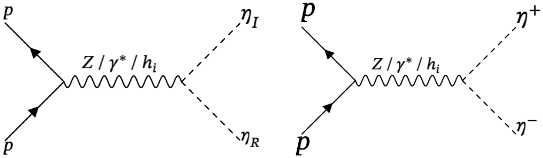

Figure: Feynman diagram corresponding to the Drell-Yan production of the components of the η doublet for each DM case before decay. Left: Production of $\eta_I + \eta_R$ for Scalar DM. Right: Production of of $\eta^+ + \eta^-$ for fermion DM.

- The considered decay chains for the η components were:
  1. Scalar DM: $\eta_R \to W^{\pm} + N_i + \ell$ via decay of a $\eta^{\pm}$.
  2. Fermion DM: $\eta^{\pm} \to N_i \ell$

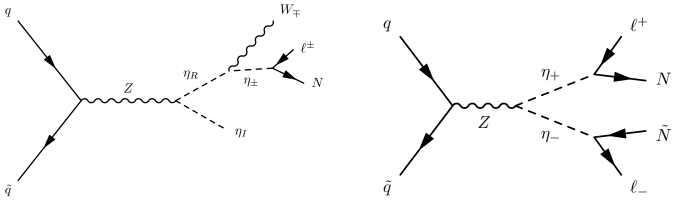

Figure: Example topology for the decay chain considered for cross section calculation. Left: Example topology for scalar DM production via Drell-Yan. Right: Example topology for fermion DM production via Drell-Yan.

- Spectrum points considered for the cross section calculation $\rightarrow$ compatible with the DM relic density for each candidate scenario.
- Cross section exhibits some randomness whihc arises when including Y_N, λ_i, $\cos\alpha$, etc $\rightarrow$ Random from the MCMC.
- We define a new parameter that contains all the, BRs and interference terms:

$$\beta = \frac{\sigma(p+p \rightarrow N + W^{\pm} + \ell + \eta_I)}{\sigma(p+p \rightarrow \eta_R + \eta_I)} \quad \text{(Scalar DM)}$$

$$\beta = \frac{\sigma(p+p \rightarrow N + \ell + N + \ell)}{\sigma(p+p \rightarrow \eta^+ + \eta^-)} \quad \text{(Fermion DM)}$$

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- We calculated the cross section values @ 1.69 significance for $\mathcal{L} = \{137, 300, 3000\}\text{fb}^{-1}$ in an optimistic scenario with 20% background, 20% systematic uncertainties and 10% acceptance.

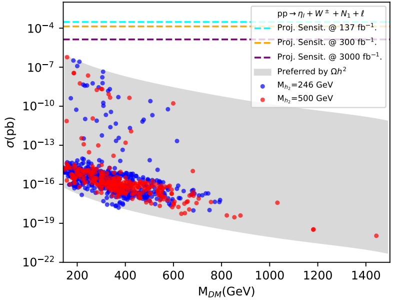


Figure: Behavior of the $p + p \to \eta_I + W^{\pm} + N_i + \ell$ cross section as a function of the DM candidate particle mass, in the scalar sector, for $\Delta m < 30$ GeV and both m_{h_2} scenarios.

- As the final states considered in our analysis are similar to those shown in `arXiv:1911.12606v2[hep-ex]` (SUSY), we interpreted their results and applied them to estimate sensitivity for our analysis in scenarios with $\mathcal{L} = \{300, 3000\}\text{fb}^{-1}$.
- The maximum and minimum β values were used to estimate a region where all plausible points of our scan would fall when considering larger statistics.

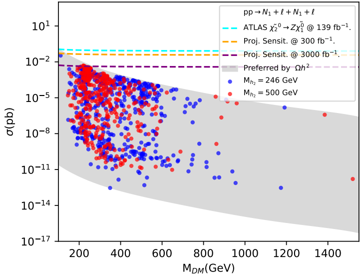
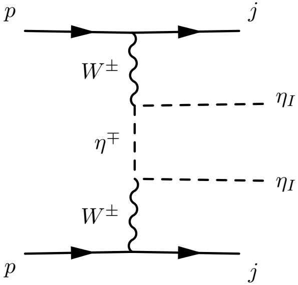


Figure: Behavior of the $p + p \to N_i + \ell + N_i + \ell$ cross section as a function of the fermionic DM mass, for $\Delta m < 30$ GeV and both m_{h_2} scenarios. Dashed lines denote the experimental limits taken from ATLAS SUSY studies in compressed mass spectra models.

- One way to probe the purely neutral production of the DM candidates is via Vector Boson Fusion (VBF) or VBF-like processes.



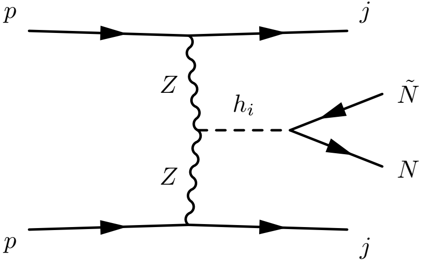


Figure: Feynman diagrams illustrating the production of DM via vector boson fusion (VBF) processes. The scalar DM channel is depicted on the left, while the fermionic channel is shown on the right

- Scenarios with $\Delta m < 50$ GeV were considered to compare results with CMS SUSY results (see `arXiv:1905.13059[hep-ex]`).
- CMS results were also used to estimate sensitivity in $\mathcal{L} = \{300, 3000\}\text{fb}^{-1}$ scenarios.

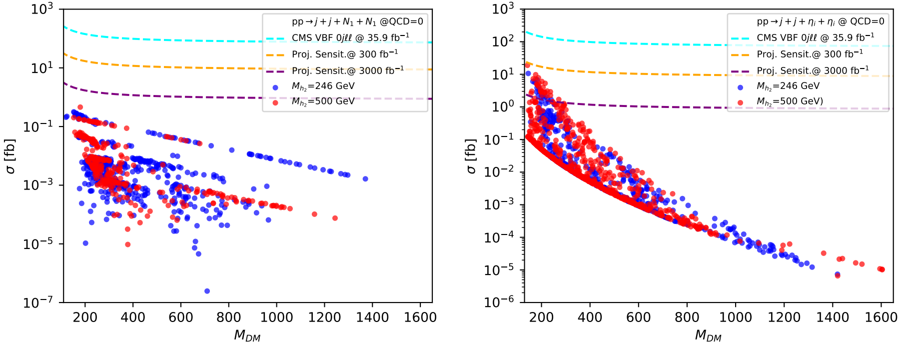
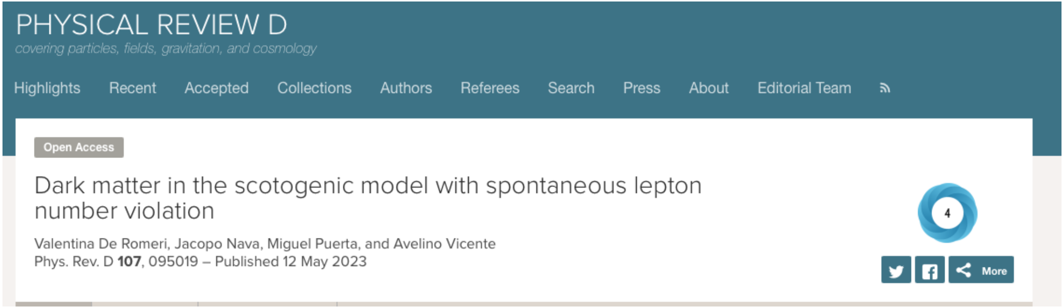


Figure: Left: Analysis performed considering the DM particle as the pseudo-scalar η_I. Right: Analysis performed considering the fermionic DM particle N_1.

- Scalar DM production via DY processes at the LHC can not be performed due to very small σ values.
- σ values obtained for fermionic DM production via DY processes could be probed for M_{DM} between 150 and 220 GeV in future luminosity scenarios at the LHC.
- VBF production of scalar DM could be probed at the LHC for M_{DM} between 150 and 350 GeV in future high luminosity scenarios.
- Fermionic DM production via VBF processes can not be probed at the LHC due to the smallness of the cross section values, showing complementarity between the considered production mechanisms.

¡Muchas gracias!

Our study is based on previous work from Valentina De Romeri and collaborators.



- In this study we fix the masses of the scalars h_1 and h_2, to 125 GeV and 500 GeV respectively, with the following parametrization of the couplings

$$\lambda_1 = (m_{h_1}^2 \cos^2\alpha + m_{h_2}^2 \sin^2\alpha)/v^2$$
$$\lambda_3^{H\sigma} = (m_{h_1}^2 \cos\alpha \sin\alpha - m_{h_2}^2 \cos\alpha \sin\alpha)/v v_\sigma$$
$$\lambda_\sigma = (m_{h_1}^2 \sin^2\alpha + m_{h_2}^2 \cos^2\alpha)/v_\sigma^2$$

- The rest of the free parameters of the model have been varied within the same ranges consider by De Romeri et. al.

Parameter	Range
$\lambda_{2,3,4}$	$[10^{-6},1]$
λ_5	$[10^{-8},1]$
κ_{11}	$[0.01,1]$
m_η^2	$[10^5,10^7]$ GeV^2
v_σ	$[0.5, 10]$ TeV