The Dark Phases of the N2HDM

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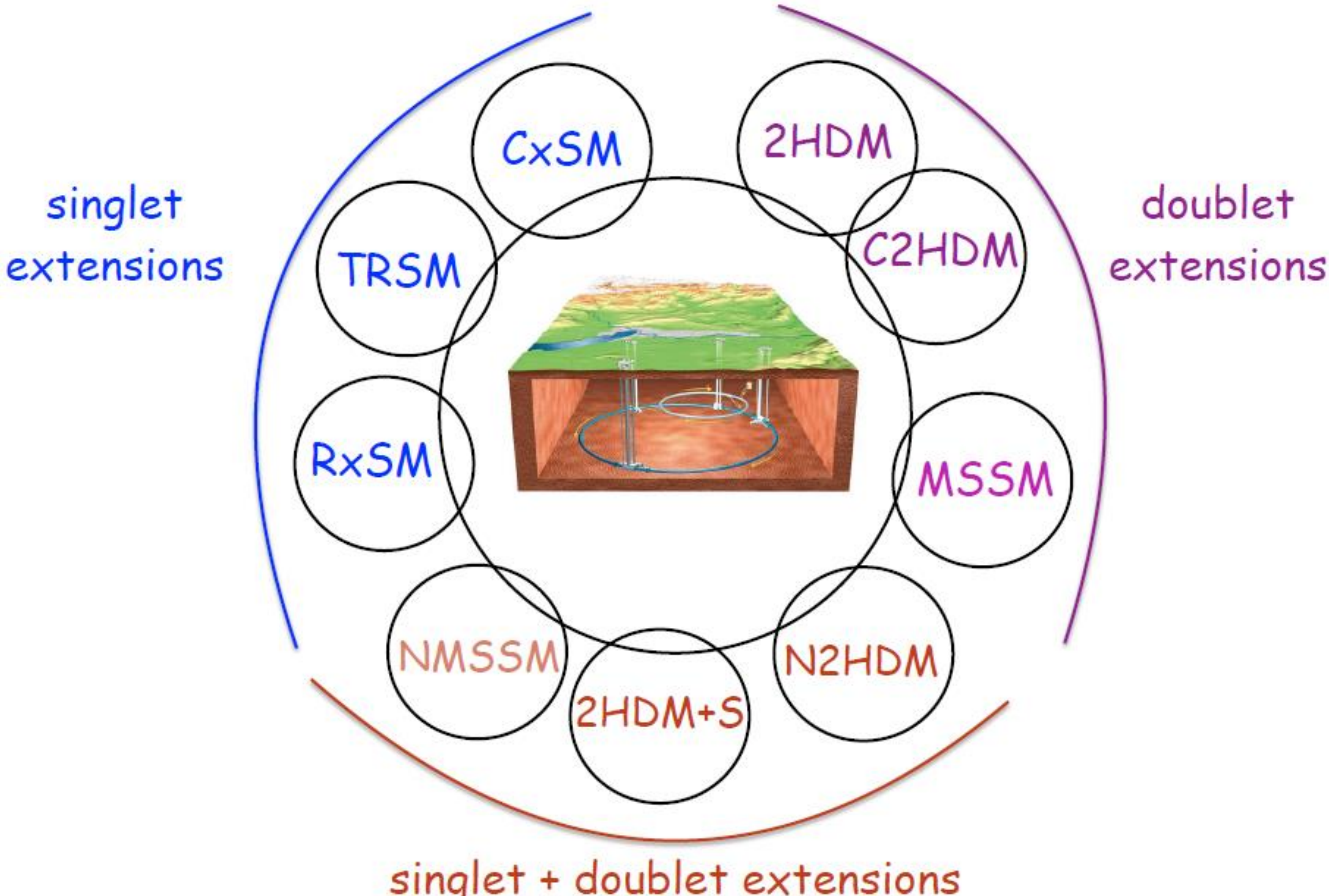
Examples of Extended Higgs Sectors



The Next-to-Two Higgs Doublet Model (N2HDM)

- **The Next-to-2HDM (N2HDM) contains two hypercharge Y = 1 scalar doublets, Φ_1 and Φ_2, and a real scalar gauge singlet, Φ_S.**

- **There are several versions of this model, depending on the extra symmetries imposed.**

- **We consider two discrete Z_2 symmetries, of the form**

$$\mathbb{Z}_2^{(1)} : \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad \Phi_S \to \Phi_S$$

and

$$\mathbb{Z}_2^{(2)} : \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to \Phi_2, \quad \Phi_S \to -\Phi_S \, .$$

- **Vacua which preserve one or both of these symmetries may yield viable Dark Matter candidates.**

Scalar potential and spontaneous symmetry breaking

- **With the two Z_2 symmetries chosen, the scalar potential becomes**

$$V_{\text{Scalar}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right]$$
$$+ \frac{1}{2} m_s^2 \Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}\Phi_1^\dagger \Phi_1 \Phi_S^2 + \frac{\lambda_8}{2}\Phi_2^\dagger \Phi_2 \Phi_S^2 \,,$$

with all parameters taken, without loss of generality, real.

- **The most general neutral vacuum has vevs v_1, v_2 for the doublets and v_S for the singlet,**

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\,\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\,\eta_2) \end{pmatrix}, \quad \Phi_S = v_s + \rho_s$$

- **Spontaneous CP breaking is not possible in this model (unless one introduces soft breaking terms), so all these vevs are *real*.**

(ASIDE:

If the field content was the same but the discrete symmetry was different,

$$\Phi_1 \to \Phi_1 \quad , \quad \Phi_2 \to -\Phi_2 \quad , \quad \Phi_S \to -\Phi_S$$

the scalar potential would become quite different,

$$\begin{aligned} V = & \; m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{1}{2}m_S^2\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + h.c.\right) \\ & + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] \\ & + \frac{1}{4}\lambda_6\Phi_S^4 + \frac{1}{2}\lambda_7|\Phi_1|^2\Phi_S^2 + \frac{1}{2}\lambda_8|\Phi_2|^2\Phi_S^2 \,, \end{aligned}$$

CUBIC TERM!

where, with the exception of *A*, all the parameters are *REAL*.

This model would have the possibility of explicit CP violation and a much different phenomenology.

D. Azevedo, P.M. Ferreira, M.M. Muhleitner , S. Patel, R. Santos, JHEP 1811 (2018) 091

END OF ASIDE)

Possible neutral vacua/phases

Depending which vevs are non-zero, there are several possible vacua which preserve or break different symmetries and thus describe different phases of the model, with different phenomenology. In all cases electroweak symmetry breaking occurs.

The Broken Phase (BP)

Both the doublets and the singlet aquire vevs:

$$\langle \Phi_1 \rangle_{BP} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle \Phi_2 \rangle_{BP} = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \qquad \langle \Phi_S \rangle_{BP} = v_s$$

$$(v_1)^2 + (v_2)^2 = (246\ GeV)^2$$

No discrete symmetry is left unbroken by the vacuum and *there are no dark matter candidates*.

This phase includes three CP-even neutral scalars, a pseudoscalar and a charged scalar.

The Dark Doublet Phase (DDP)

Only one of the doublets, and the singlet, aquire vevs:

$$\langle\Phi_1\rangle_{DDP} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \qquad \langle\Phi_2\rangle_{DDP} = \begin{pmatrix}0\\ 0\end{pmatrix}, \qquad \langle\Phi_S\rangle_{DDP} = v_s$$

v = 246 GeV

The discrete symmetry $Z_2^{(1)}$ is left unbroken by the vacuum, and *the lightest neutral scalar from the second doublet will be a dark matter candidates*.

This phase is the equivalent, within the N2HDM, of the Inert Doublet model, but it has a larger parameter space and is not as constrained by current Dark Matter searches.

The scalar spectrum includes four "dark" scalars which do not couple to fermions (two neutral scalars, a charged one); the singlet neutral field mixes with the neutral component of the first doublet and yields two CP-even scalars.

The Dark Singlet Phase (DSP)

Both doublets have vevs but the singlet does not:

$$\langle \Phi_1 \rangle_{DSP} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle \Phi_2 \rangle_{DSP} = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \qquad \langle \Phi_S \rangle_{DSP} = 0$$

$$(v_1)^2 + (v_2)^2 = (246\ GeV)^2$$

The discrete symmetry $Z_2^{(2)}$ is left unbroken by the vacuum, and *the singlet field is a dark matter candidate*.

This phase is essentially equivalent to *a normal 2HDM* (albeit one without a decoupling limit, because no soft breaking term has been considered) *with an added particle of dark matter*.

The scalar spectrum has the usual *h* and *H* CP-even states, the pseudoscalar *A*, the charged scalar H^+ and a dark scalar, the singlet.

The Fully Dark Phase (FDP)

Only one of the doublets has a vev:

$$\langle\Phi_1\rangle_{FDP} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \qquad \langle\Phi_2\rangle_{FDP} = \begin{pmatrix}0\\ 0\end{pmatrix}, \qquad \langle\Phi_S\rangle_{FDP} = 0$$

v = 246 GeV

Both discrete symmetries are preserved by the vacuum, and *we can have two stable, dark, neutral scalars*. This phase has a single observable scalar, the SM-like Higgs boson, the remainder scalars – neutral and charged – being “dark” and not interacting with fermions. The preservation of two separate quantum numbers means that there is the possibility of two scalars being stable.

The Yukawa Lagrangian

In all phases, the Yukawa lagrangian considered is the analogous of a Type-I 2HDM – only one of the doublets couples to all fermions:

$$\mathcal{L}_{\text{Yukawa}} = -\bar{Q}_L^T Y_U \widetilde{\Phi}_f U_R - \bar{Q}_L^T Y_D \Phi_f D_R - \bar{L}_L^T Y_L \Phi_f E_R + \text{h.c.}$$

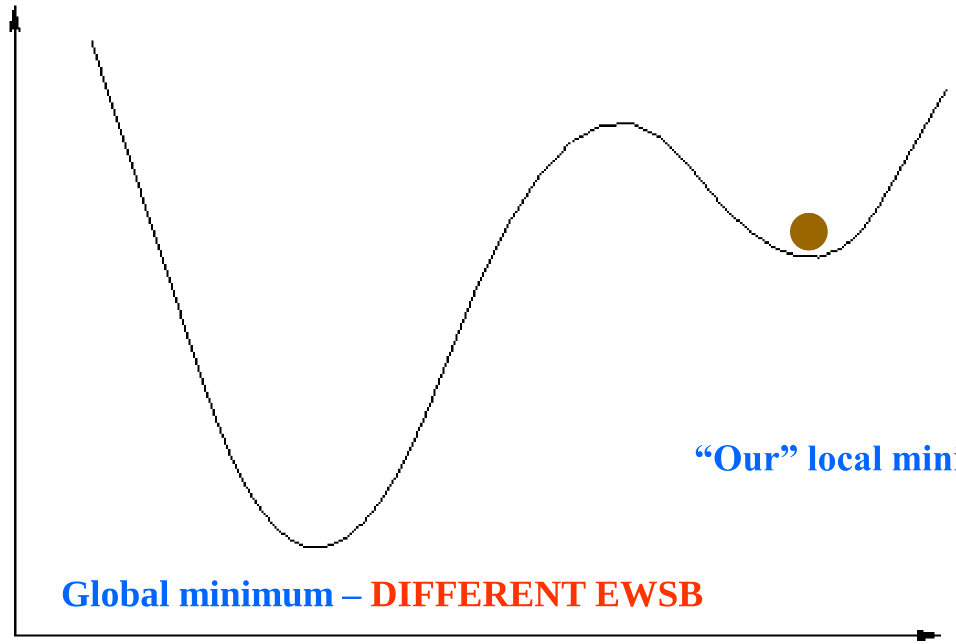
Stability of neutral vacua

- **We therefore have different possible vacua, and unlike the 2HDM case, *in the N2HDM minima which break different symmetries can coexist*.**

- **Therefore it is theoretically possible that, for some selection of parameters, a minimum with correct electroweak symmetry breaking is NOT the global minimum of the theory.**

- **Tunelling to a deeper, unacceptable minimum becomes therefore possible – and unlike the SM case, this would already occur at tree-level....**

$$v = 246\, GeV$$
$$m_W = 80\, GeV$$
$$m_t = 173\, GeV$$
$$\ldots$$



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- **It is possible to use a *bilinear formalism* to obtain analytic expressions for the differences in depth of the potential at two stationary points of different natures – this allows one to draw onclusions about the stability, or lack thereof, of certain minima.**

- **This saves considerable time when considering vacuum stability in numerical scans, as we know certain types of minima are absolutely stable.**

- **Given that we will be comparing the value of the potential at different stationary points, it becomes necssary to "tag" the vevs of the doublets and singlet, which will have different values at different extrema:**

Phase	vevs
BP	v_1^B, v_2^B, v_s^B
DDP	v_1^D, v_s^D
DSP	v_1^S, v_2^S
FDP	v_1^F

- **Likewise, we will encounter scalar masses evaluated at different phases, which we also "tag" as: "B" for the Broken Phase; "D" for the Dark Doublet Phase; "S" for the Dark Singlet Phase; and "F" for the Fully Dark Phase.**

To see an example of the bilinear formalism in action, let us assume that a Broken Phase (all fields having vevs) stationary point coexists with a Dark Doublet Phase (one doublet has no vev, other doublet and singlet do) extremum. It can be shown that the difference of the potential at both extrema is given by

$$V_{BP} - V_{DDP} = \frac{1}{4}\,(v_2^B)^2\,(m^2_{H_D})^D$$

Notice how the difference of values of the potential is proportional to the square of a Broken Phase vev, and the squared mass of a scalar in the Dark Doublet Phase.

Therefore, if the Dark Doublet Phase is a minimum, that squared mass will necessarily be positive and we conclude

$$V_{BP} - V_{DDP} > 0 \qquad \text{if DDP is a minimum.}$$

It may also be shown that if the DDP is a minimum, *the Broken Phase will necessarily be a saddle point*, and this expression shows clearly that it lies *above* the DDP minimum.

- **We can perform similar comparisons between the Broken, Dark Singlet and Fully Dark Phases, and we obtain**

$$V_{BP} - V_{DSP} = \frac{1}{4}(v_s^B)^2 \, (m^2_{H_D})^S \, ,$$

$$V_{BP} - V_{FDP} = \frac{1}{4}(v_2^B)^2 \, (m^2_{H^D_D})^F + \frac{1}{4}(v_s^B)^2 \, (m^2_{H^S_D})^F$$

- **Similar conclusions apply: whenever there is a DSP or FDP minimum, any Broken Phase extremum that might occur lie ABOVE them. It can also be shown that it would be a saddle point.**

- **But on the other hand, this analysis also shows that *if the broken phase is a minimum, it is deeper than any other possible neutral extremum in the model* – IT WOULD BE THE GLOBAL MINIMUM OF THE THEORY.**

- **Similar conclusions hold for the Fully Dark Phase: if it is a minimum, *it will be the global minimum of the theory*. We have already compared the FDP potential with the BP one, and if we do the same for the DDP and DSP cases, we obtain**

$$V_{DDP} - V_{FDP} = \frac{1}{4} (v_s^D)^2 \, (m^2_{H^S_D})^F$$

$$V_{DSP} - V_{FDP} = \frac{1}{4} (v_2^S)^2 \, (m^2_{H^D_D})^F$$

Note that the difference in values of the potential is always proportional to a squared scalar mass computed at the Fully Dark Phase – so that, if the FDP is a minimum, *it will necessarily be deeper than the DSP and DDP extrema*.

- **Stability of a Fully Dark Minimum is therefore guaranteed!***

- **What about the Dark Doublet and Dark Singlet phases? For these two phases, the situation is different: DDP and DSP minima can coexist, and neither is *a priori* deeper than the other!**

*** At least against tunelling to other neutral minima, but the possibility of charge breaking for all these phases also has to be taken into account.**

- In fact, the bilinear formalism applied to Dark Doublet and Dark Singlet stationary points yields

$$V_{DSP} - V_{DDP} = \frac{1}{4}(v_2^S)^2 (m^2_{H_D})^D - \frac{1}{4}(v_s^D)^2 (m^2_{H_D})^S\,.$$

- Notice how the difference in depths of the potential depends on the difference between a combination of vevs and masses computed at each extremum.

- Unlike previous expressions, the sign of this potential difference is not fixed when either the DDP or DSP are a minimum.

- The phases can in fact coexist in the potential as minima of different depths, and different regions of parameter space will have either of them as the global minimum of the model.

- Thus in order to ensure the stability of a DDP or DSP minimum one will have to compute the tunneling time to an eventual deeper vacuum, and verify whether it is larger than the current age of the Universe.

Thus, to summarise:

- **If a minimum of the Broken Phase exists, it is the global minimum of the model – extrema of all other phases wil lie above it and be saddle points. Conversely, if a minimum of any of the other phases exists, any Broken Phase extremum lies above it and is a saddle point.**

- **Similarly, if the Fully Dark Phase is a minimum it is the global minimum. But if any other phase is a minimum, the FDP is a saddle point necessarily lying above it.**

- **There can be coexisting minima of the Dark Doublet and Dark Singlet phases. Either phase can be the global minimum of the theory, depending on the choice of parameters.**

A numerical study of the properties of each of the phases reveals interesting aspects of each of them.

IN ALL NUMERICAL ANALYSES PRESENTED, BASIC CONSTRAINTS WERE TAKEN INTO ACCOUNT VIA THE *SCANNERS* CODE.

- **The scalar potential must be *BOUNDED FROM BELOW* and preserve *UNITARITY*.**

- **Any phase must reproduce ALL the SM's experimental results. In particular, they must comply with *ELECTROWEAK PRECISION DATA*.**

- **Substantial constraints to multiscalar models' parameter space comes from requiring compliance with B-physics data (the $b \to s\gamma$ measurements, for instance) and the existence of a scalar with mass equal to 125 GeV and properties very similar to those of the SM (*ALIGNMENT LIMIT*).**

- **HIGGSBOUNDS and HIGGSSIGNALS were also used to account for all current experimental results for the scalar sector.**

- **Dark Matter constraints, namely, the relic density and direct detection cross sections are calculated using MicrOMEGAs. The relic density is required not to oversaturate the observed relic abundance by more than 2σ and the Xenon1T direct detection bound is imposed.**

Is it Possible to Distinguish These Phases Experimentally?

- **The discovery of a charged Higgs boson through its fermionic decays would immediately exclude the Dark Doublet and the Fully Dark phases, given that in those phases the charged scalar would be one of the "dark" particles, without fermionic interactions. The Fully Broken and Dark Singlet phases would still be allowed, of course.**

- **Likewise, the discovery of three extra neutral scalars in the visible sector would *exclude all phases except the broken phase*.**

- **Precision measurementes of the discovered Higgs boson, however, could also provide hints as to the existence of these phases, and help in distinguishing them.**

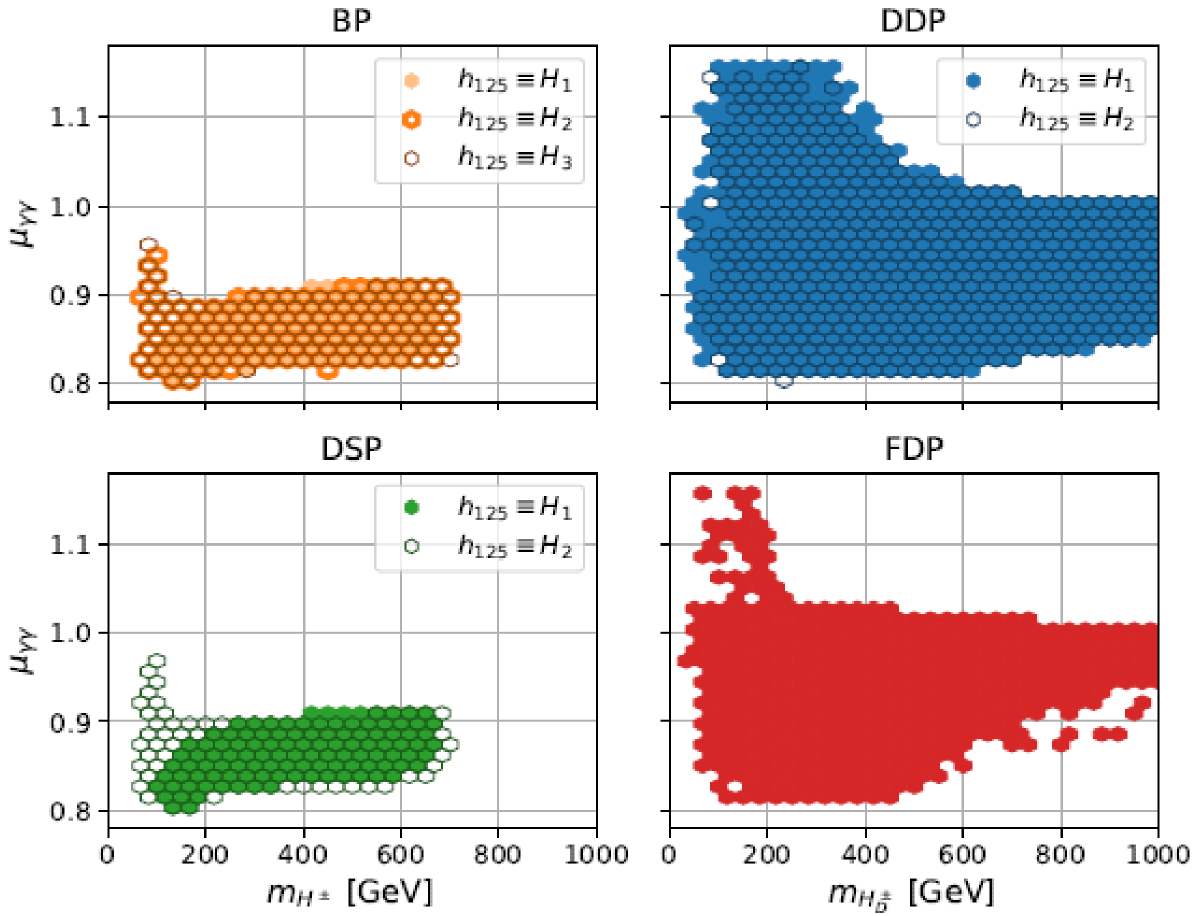
- **An obvious starting point in the Higgs diphoton decay, which gets contributions from the charged scalar, whether it is "dark" or "visible". This could show on the diphoton signal strength measured at LHC,**

$$\mu_{\gamma\gamma} = \frac{\sigma^{N2HDM}(pp \to h)\, BR^{N2HDM}(h \to \gamma\gamma)}{\sigma^{SM}(pp \to h)\, BR^{SM}(h \to \gamma\gamma)}$$

Higgs Diphoton Signal Strength for the Four N2HDM Phases

The existence of several CP-even states opens the possibility that the 125 GeV state is not necessarily the lightest one.

Several possibilities are explored here.



"Visible" H^+ in these two phases

⇓

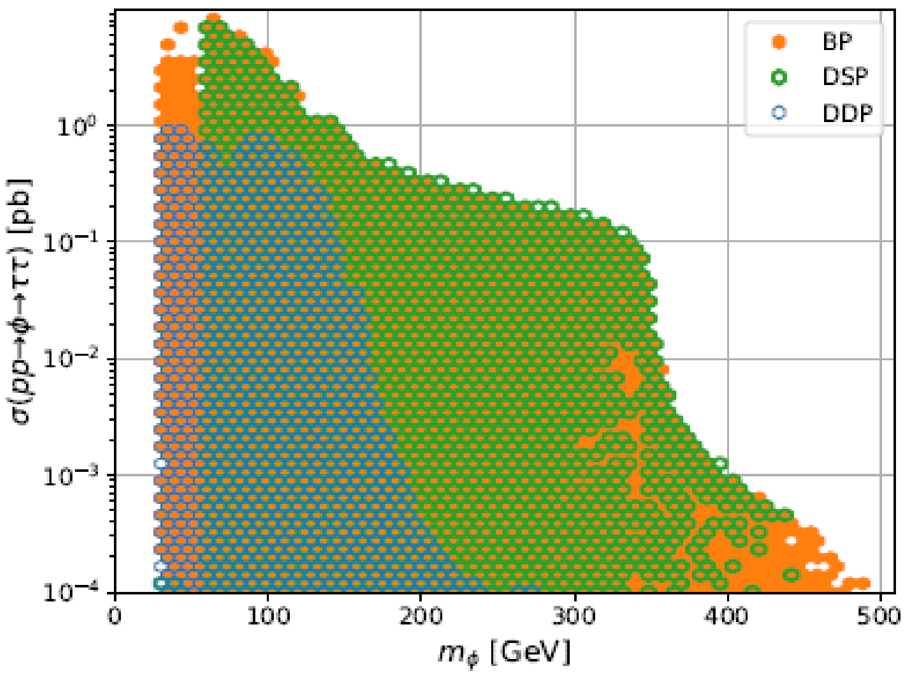
$\mu_{\gamma\gamma}$ suppressed

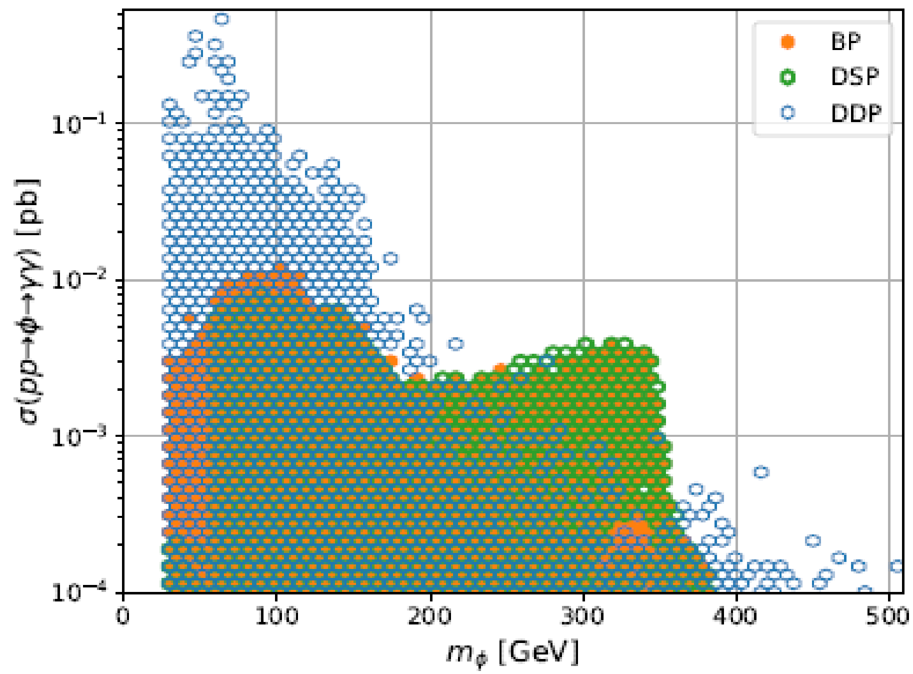
"Dark" H^+ in these two phases

⇓

Greater freedom, $\mu_{\gamma\gamma}$ can even be enhanced

Extra Scalars' Behaviour in Different Phases

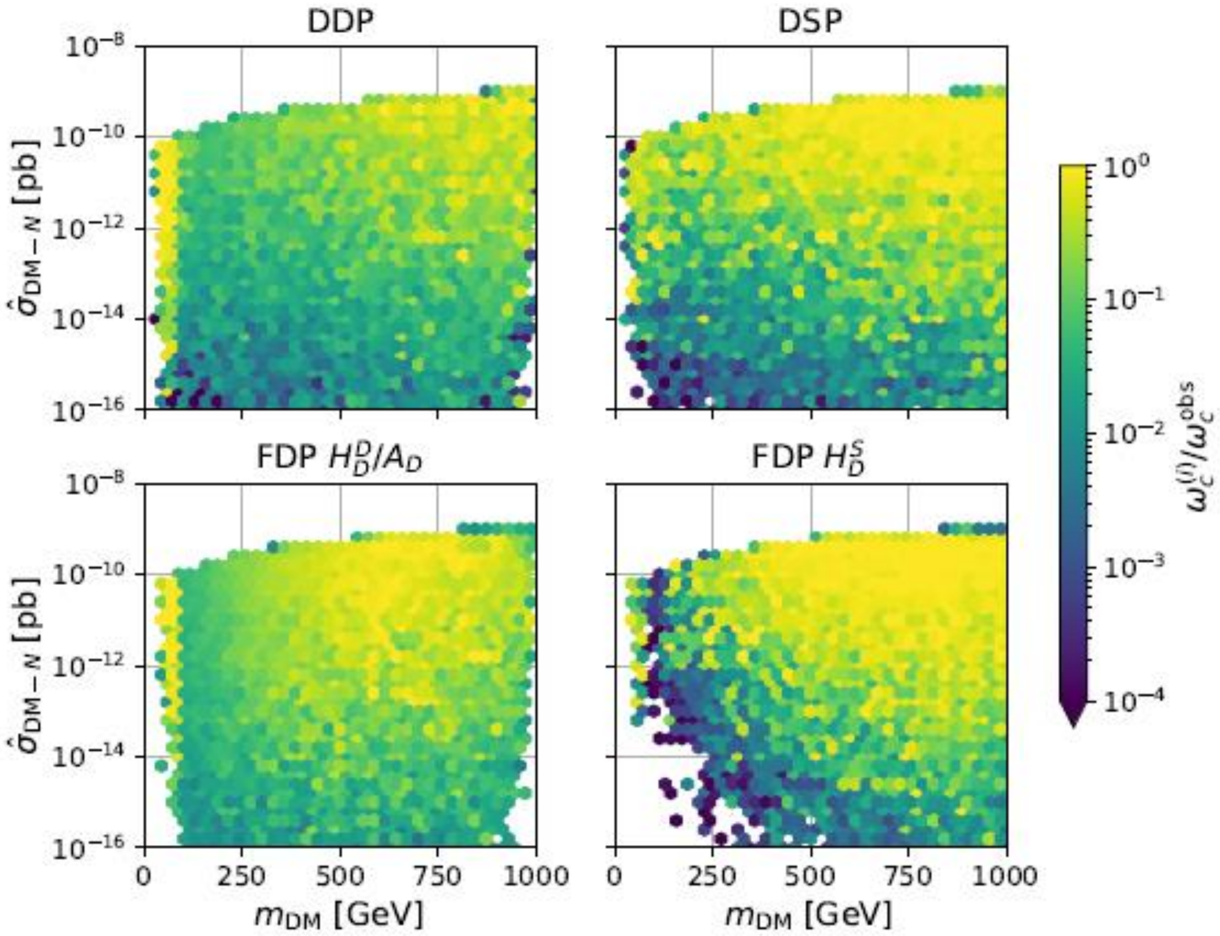




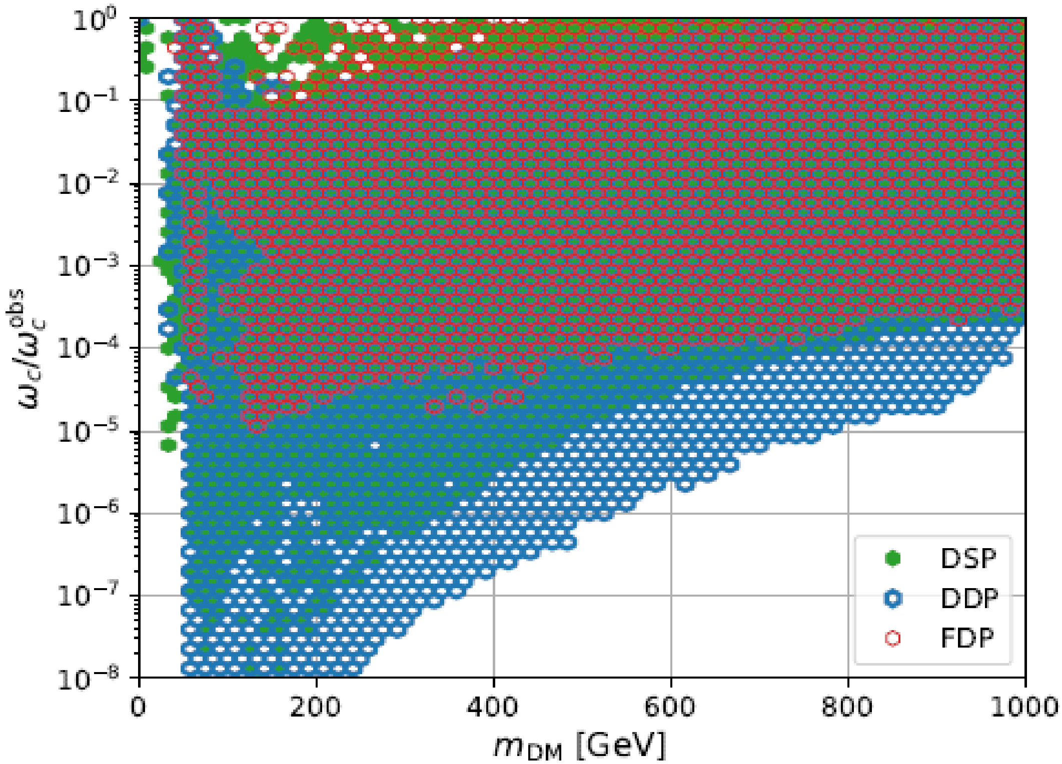
For the phases for which one could have extra visible scalars (not FDP, of course), decays to tau or photon pairs could, for some regions of parameter space, distinguish between several of the phases.

The DDP, for instance, would have enhanced diphoton decays for the extra neutral scalar for masses below 150 GeV, much more than what occurs for the other phases. Di-tau decays, however, would be suppressed for the DDP above that same mass.

Dark Matter Constraints for all Phases



The Nucleon-Dark Matter direct detection cross section can have values well below 10^{-12} (the *neutrino floor*) for all phases, and as such current experimental limits can be easily satisfied, even saturating the relic density bound. Notice how the FDP has contributions from two Dark Matter particles.



All phases, except for the DDP, have regions of parameter space for which the relic density is saturated – and so Dark matter is fully explained within the N2HDM for that phase – for all values of Dark Matter mass above $m_h/2$.

The DDP has a DM mass region between about 100 and 500 GeV where it is not possible to find parameters such that the relic density is saturated, and therefore and extra DM candidates would be needed. Remember that the DDP is anaalog of the IDM, and it has been reported that for the Inert doublet Model, the relic density cannot be saturated for DM masses between about 75 and 500 GeV.

CONCLUSIONS

- **With two discrete symmetries applied, the N2HDM can have several different vacua yielding Dark matter candidates.**
- **An analytical calculation revealed that minima of two of the possible phases would be absolutely stable, two others wouldn't.**
- **All phases can conform to existing LHC and Dark Matter experimental constraints.**
- **Higgs precision measurements, and new scalars' properties, could in principle help distinguish between the several phases.**