Machine Learning in the 2HDM2S model for Dark Matter

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PIC1 Project: Scalar Dark Matter: Vacuum Structure and Parameter Scan with Machine Learning

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Scalar extensions of the SM provide:

- **A source for scalar CP violation;**
- **Dark matter candidates:** Requires a stable, non-baryonic, electrically neutral and cold particle to account for observed dark matter abundance;
- **Large portions of parameter space testable at LHC.**

Our model with 2 Higgs doublets and 2 singlets:

- **Type II 2HDM:** down- type quarks and charged leptons couple to the SM doublet and up-type quarks couple to the second doublet;
- **Dark matter candidates:** Singlets inert and protected by a global symmetry.

The vacuum

$$\langle\Phi_1\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix}, \quad \langle\Phi_2\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}, \quad \langle S\rangle_0 = 0, \quad \langle P\rangle_0 = 0$$

Apply Z2xZ'2 symmetry

$$\mathbb{Z}_2: \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2, \quad S \to S, \quad P \to P,$$

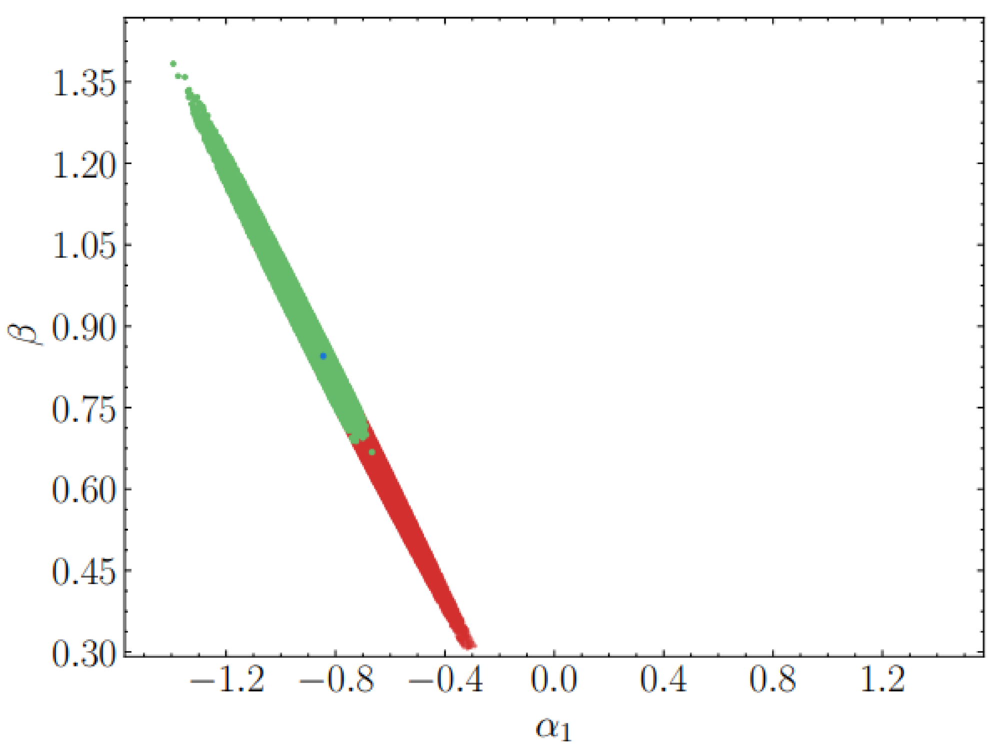
$$\mathbb{Z}_2': \quad \Phi_1 \to \Phi_1, \quad \Phi_2 \to \Phi_2, \quad S \to -S, \quad P \to -P.$$

Constraints

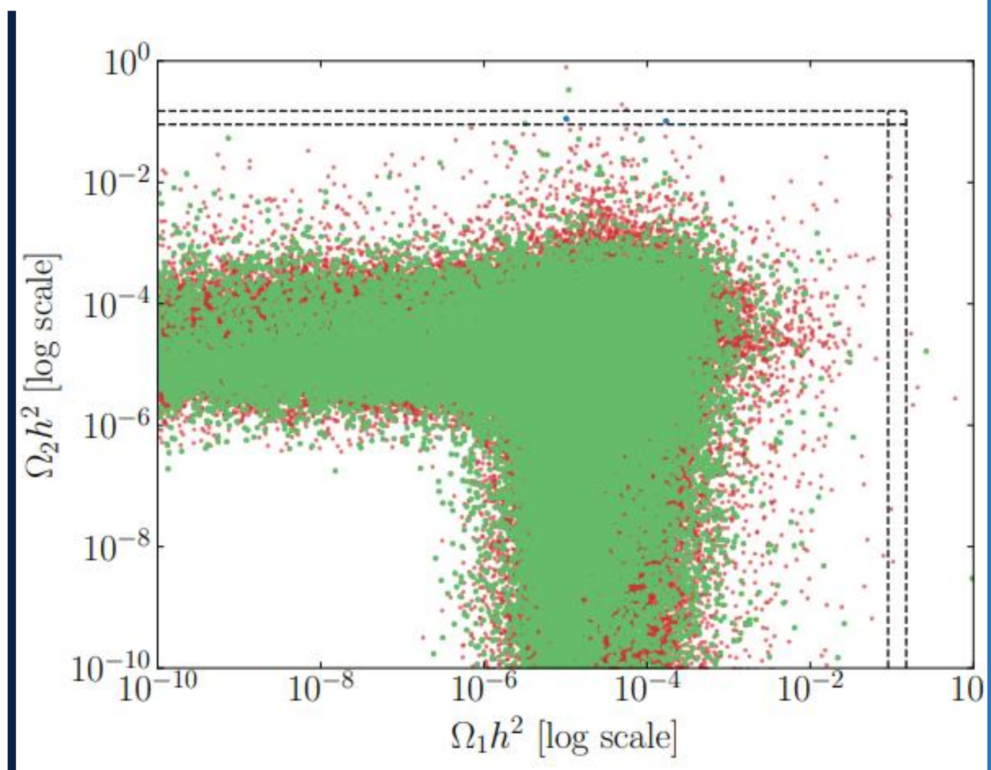
- **Boundedness From Below (Sufficient Conditions);**
- **Vacuum Stability and Global Minimum;**
- **Perturbative Unitarity;**
- **Precision Observables S, T, and U;**
- **Collider Constraints;**
- **Relic Density;**
- **Direct Detection;**
- **Indirect Detection.**

We developed a **parameterization** for the **2HDM2S** and a FORTRAN code to scan the 22 free parameters of the model with all known constraints. This parameter scan was done in three ways: **random sampling, imposing a 10% alignment limit and AI Black Box Optimization with and without Novelty Reward.**

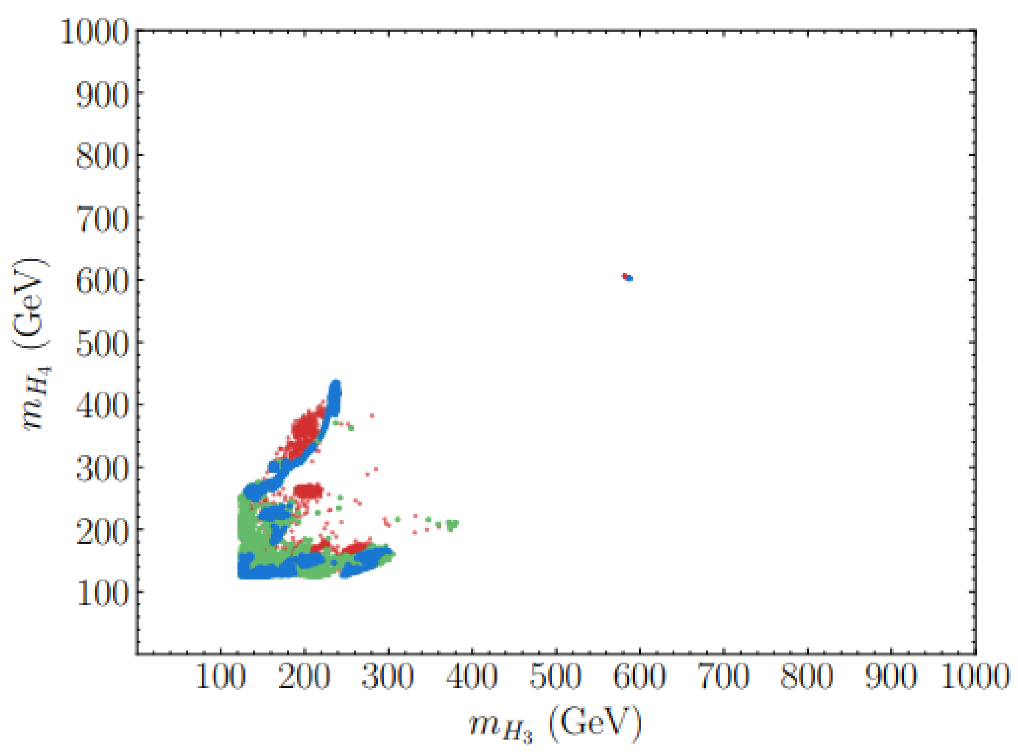
Sampling Methods:



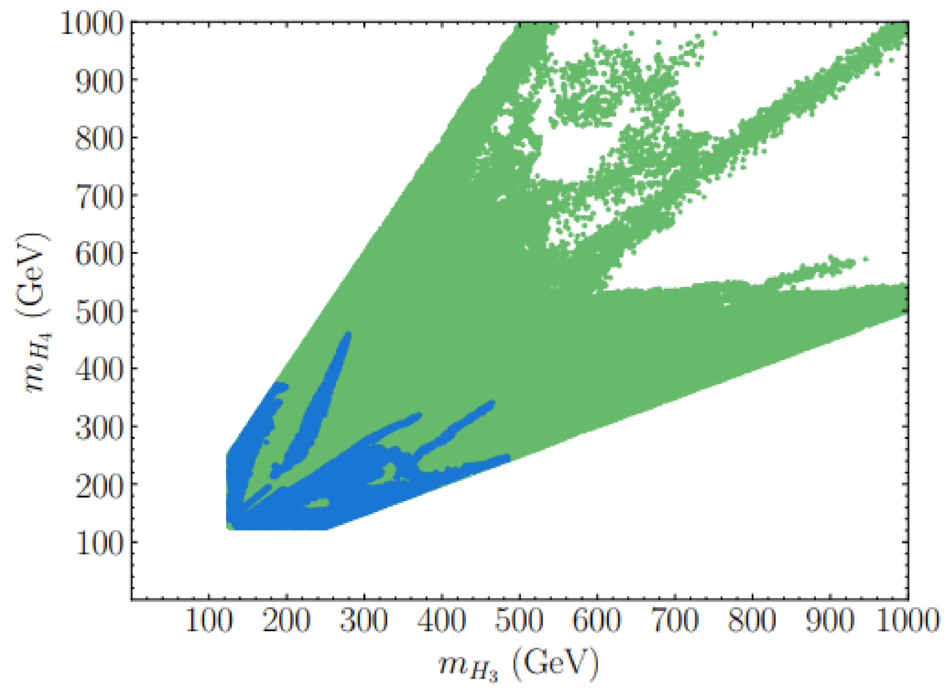
Points obtained near the alignment limit α=-β in the relic density plane



Points obtained with a random sampling in the α-β Plane



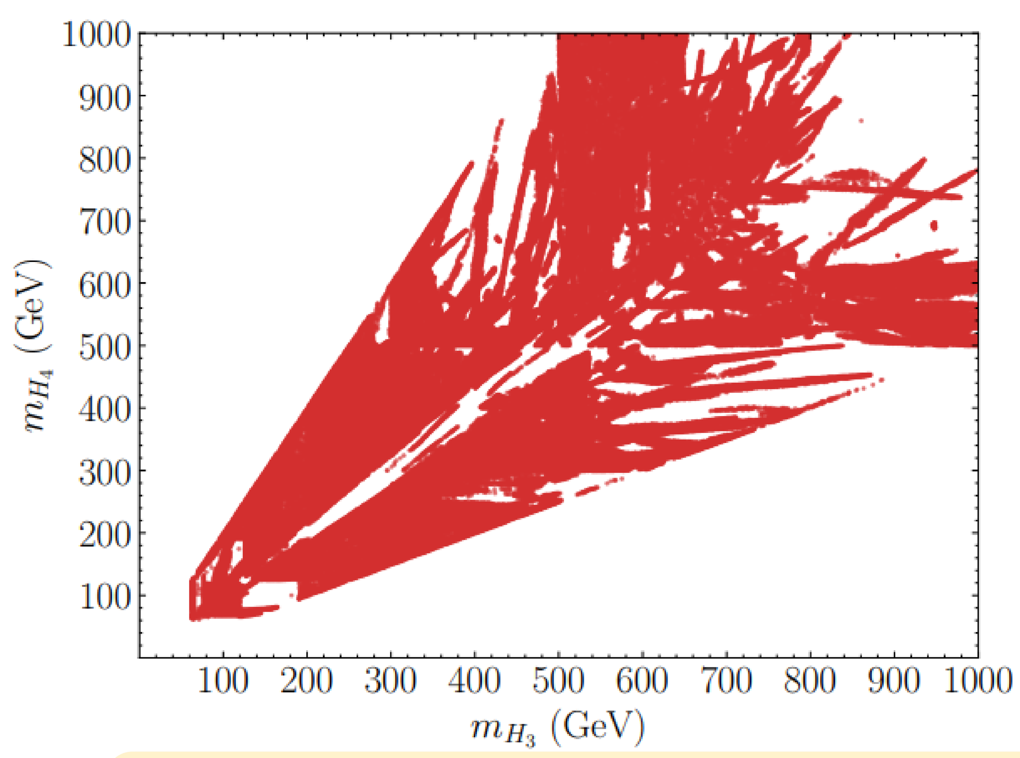
Points obtained with CMAES in the DM masses Plane



Points obtained with CMAES with Novelty Reward in the DM masses Plane

Passed HiggsTools-1.1.3
Green points that passed micrOMEGAs-6.2.3
Otherwise

We found that using the **ML method** in parameter scans **greatly improves its efficiency** and **provides a more complete exploration of the parameter space.**



Results from multiple runs of CMAES with Novelty Reward in the DM masses Plane. All points satisfy every constraint

We have found that current/projected **DD experiments do/will not exclude this model**. We have also studied current **indirect detection constraints**, and found that **they do not significantly affect those points already allowed by direct detection bounds and relic density.**

Funded by FCT under project 2024.01362.CERN, UIDB/00777/2020, UIDP/00777/2020, PRT/BD/152268/2021.