IMPLICATIONS OF THE 125 GeV HIGGS FOR THE INERT DARK MATTER

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The impact of the LHC results for the decay of the Higgs boson to two photons on the properties of the inert dark matter (DM) is analysed. The results are combined with the Planck constraints on DM relic density. Constraints on the DM mass are derived, that are stronger or comparable to the XENON and LUX results.

1 Introduction

With the Higgs data available thanks to the LHC experiments, we can learn a lot not only about the Higgs boson, but also about new, still undiscovered particles. The aim of this work is to constrain the properties of a DM candidate in the Inert Doublet Model (IDM), with the use of the measurements of the Higgs boson properties. We refer the reader to the original papers\(^1\)\(^2\) for more details.

The IDM\(^3\) is a special type of two-Higgs doublet model (2HDM) with the interaction of the two\(\text{SU}(2)\) scalar doublets \(\phi_S\) and \(\phi_D\) described by the following potential

\[
V = -\frac{1}{2} \left[ m_{11}^2 (\phi_S^\dagger \phi_S) + m_{22}^2 (\phi_D^\dagger \phi_D) \right] + \frac{1}{2} \left[ \lambda_1 (\phi_S^\dagger \phi_S)^2 + \lambda_2 (\phi_D^\dagger \phi_D)^2 \right] \\
+ \lambda_3 (\phi_S^\dagger \phi_S)(\phi_D^\dagger \phi_D) + \lambda_4 (\phi_S^\dagger \phi_D)(\phi_D^\dagger \phi_S) + \frac{1}{2} \lambda_5 \left[ (\phi_S^\dagger \phi_D)^2 + (\phi_D^\dagger \phi_S)^2 \right].
\]

Important feature of this potential is that it possesses a global discrete symmetry called \(D\), such that: \(\Phi_D \xrightarrow{D} -\Phi_D\), \(\Phi_S \xrightarrow{D} \Phi_S\). The Yukawa interactions are chosen in such a way as to respect this symmetry as well, i.e., only \(\phi_S\) couples to fermions (type I), making the whole lagrangian of the IDM \(D\)-symmetric. Furthermore, we take a vacuum state which also preserves the symmetry, i.e., \(\langle \phi_S \rangle = \frac{v}{\sqrt{2}}, \langle \phi_D \rangle = 0\). This way the IDM is exactly \(D\)-symmetric. This symmetry renders the lightest \(D\)-odd particle stable and provides a viable DM candidate.

The particle spectrum of the model includes a SM-like Higgs boson, which originates from the \(\phi_S\) doublet. It has all tree-level couplings to fermions and gauge bosons like the SM Higgs. However, deviations from the properties predicted by the SM may appear at the loop level.

From the \(\phi_D\) doublet come four so-called dark (\(D\)-odd) scalars which do not couple to fermions at the tree level: the scalar \(H\), the pseudoscalar \(A\), and a pair of charged scalars \(H^\pm\). We choose \(H\) to be the DM candidate, so \(M_H < M_{H^\pm}, M_A\).

2 Higgs phenomenology in the IDM

The Higgs boson in the IDM is SM-like, however some of its properties are different than in the SM, due to the existence of the dark scalars. We consider two phenomena in which the presence
of the new scalars can manifest itself: the invisible and two-photon decays of the Higgs boson.

2.1 Invisible decays of the Higgs boson

In general the Higgs boson $h$ can decay into $HH$ or $AA$ pairs. As $H$ particles are stable and do not interact with fermions, they cannot be observed at detectors. Thus in the IDM invisible decays of the Higgs, which augment the total width of the Higgs boson, can be present. The partial decay width of $h \to HH$ depends on two parameters: the mass of the DM and the coupling of the Higgs boson to two DM particles, $\lambda_{345}$, where $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$. Thus the LHC constraints on the invisible Higgs branching ratios $^4 (Br(h \to inv) < 37\%, \text{ see the contribution of P. Meridiani})$, and total Higgs width $^5 (\Gamma(h)/\Gamma(h)^{SM} < 4.2, \text{ see the contribution of N. De Fillippis})$, as well as fits to LHC data $^6 (Br(h \to inv) \lesssim 20\%)$ can constrain these two parameters, see Fig. 1.

![Figure 1 - Constraints in the $(M_H, \lambda_{345})$ plane in the IDM coming from the constraints on the invisible decays Br($h$ inv) $\lesssim 20\%$ (solid line), Br($h$ inv) $< 37\%$ (dashed line), and from the constraint on the total decay width of the Higgs boson $\Gamma(h)/\Gamma(h)^{SM} < 4.2$ (dotted line). Here we assume that the $h \to AA$ channel is closed.](image)

2.2 Decay of the Higgs boson to two photons

The two-photon decay of the Higgs boson is a loop-induced process, with fermions or $W^\pm$ propagating in the loop. In the IDM also the charged scalar $H^\pm$ can contribute to the process, interfering either constructively or destructively with the SM amplitudes. What is actually measured, is the signal strength $R_{\gamma\gamma}$, given (in the narrow width approximation) by the formula:

$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)^{IDM}}{\sigma(pp \to h \to \gamma\gamma)^{SM}} \approx \frac{\Gamma(h \to \gamma\gamma)^{IDM}}{\Gamma(h \to \gamma\gamma)^{SM}} \frac{\Gamma(h)^{SM}}{\Gamma(h)^{IDM}}. \quad (2)$$

In the IDM $R_{\gamma\gamma}$ can be modified with respect to the SM prediction, $R_{\gamma\gamma} = 1$, in two ways: either the total width can be modified, dominantly due to the existence of invisible decays, or the partial decay width of $h \to \gamma\gamma$ can be affected by the charged scalar. We stress that the effect of the charged scalar is most pronounced if the invisible channels are kinematically closed.

The current measurements of $R_{\gamma\gamma}$: $R_{\gamma\gamma} = 1.55^{+0.33}_{-0.28}$ (ATLAS), $R_{\gamma\gamma} = 0.78 \pm 0.27$ (CMS) motivate to analyse two cases: of enhanced and suppressed signal in the $h \to \gamma\gamma$ channel.

2.3 $R_{\gamma\gamma} > 1$ and the masses of the dark scalars

When $R_{\gamma\gamma} > 1$, some constraints on the masses of the charged scalar and the DM particle can be derived. In Fig. 2 (left panel) the allowed region in the $(m_{H^\pm}^2, M_{H^\pm})$ plane is presented. In the lightly coloured region $R_{\gamma\gamma} > 1$, and the lines represent constant values of $R_{\gamma\gamma}$. If $R_{\gamma\gamma}$ is to be substantially enhanced, then the allowed region is bounded. For example for $R_{\gamma\gamma} > 1.2$ only fairly light $H^\pm$ and $H$ are allowed, $M_{H^\pm}, M_H \lesssim 154$ GeV.

$^a$The $m_{H^\pm}^2$ parameter is important for the analysis, because the coupling of $H^\pm$ to the Higgs boson is proportional to $2M_{H^\pm} + m_{H^\pm}^2$. 

Figure 2 – Allowed region in the \((m_{\gamma\gamma}^2, M_H)\) plane in the IDM, light green (grey) – \(R_{\gamma\gamma} > 1\), purple lines – constant values of \(R_{\gamma\gamma}\) (left panel). Dependence of \(R_{\gamma\gamma}\) on \(M_H\) in the IDM (right panel).

From the right panel of Fig. 2 it can be seen that it is not possible to enhance \(R_{\gamma\gamma}\) if the DM is lighter than around 63 GeV, i.e. when the invisible decay \(h \to HH\) is allowed. Thus, if \(R_{\gamma\gamma} > 1\), then DM with \(M_H < 63\) GeV is excluded.

3 Inert DM and its interplay with the Higgs boson

3.1 \(R_{\gamma\gamma}\) and the DM relic density

The IDM is an example of the so-called “Higgs portal” model, i.e., the DM couples to fermions only through the Higgs boson. The relic density of DM was measured by WMAP and Planck experiments and its current value is \(0.1118 < \Omega_{DM}h^2 < 0.1280\), at 3\(\sigma\) level. It has been shown in previous works\(^7\) that inert DM can give correct relic density in three regions of masses: very light DM \((M_H \lesssim 10\) GeV\) with the coupling to the Higgs, \(\lambda_{345}\), at the level of 0.05, intermediate DM with masses \(40\) GeV \(\lesssim M_H \lesssim 160\) GeV and \(\lambda_{345} \sim \mathcal{O}(0.05)\), or heavy DM with \(M_H \gtrsim 500\) GeV and \(\lambda_{345} \sim \mathcal{O}(0.1)\).

As both the relic density, and \(R_{\gamma\gamma}\) are affected by the value of the \(\lambda_{345}\) coupling, the two quantities are correlated. It has been shown,\(^2\) that setting a lower bound on \(R_{\gamma\gamma}\) constrains the \(\lambda_{345}\) parameter. In this work we set \(R_{\gamma\gamma} > 0.7\) in agreement with the CMS results\(^b\). These constraints in the \((M_H, \lambda_{345})\) plane can be combined with those coming from the Planck measurements.

In the light DM regime \((M_H \lesssim 10\) GeV\) the correct relic density is obtained for the coupling \(|\lambda_{345}| \sim \mathcal{O}(0.5)\). If this coupling is smaller, the DM does not annihilate efficiently enough leading to overclosing the Universe. On the other hand, if we demand that \(R_{\gamma\gamma} > 0.7\), then \(\lambda_{345}\) has to be small, \(|\lambda_{345}| < 0.04.\)\(^2\) This means that if \(R_{\gamma\gamma} > 0.7\) is confirmed, the light DM is excluded.

A map of values of \(R_{\gamma\gamma}\) in the \((M_H, \lambda_{345})\) plane for the DM with intermediate masses below 63 GeV is presented in Fig. 3 (left panel). The region in dark grey is excluded by the Planck results (the relic density of DM is too high), within the narrow band around the excluded region the relic density of DM is correct, and in the remaining part of the plot the relic density is too low, i.e., an additional source of DM should be present to satisfy the Planck constraints (then \(H\) would be a subdominant component of the DM). As can be seen from the plot, the limit \(R_{\gamma\gamma} > 0.7\) is in agreement with relic density measurement only for \(M_H > 53\) GeV.

The same type of plot for masses of \(H\) above 63 GeV is presented in Fig. 3 (middle panel). In this case all the points in the parameter space that are in agreement with Planck data, also correspond to \(R_{\gamma\gamma} > 0.7\). It is important to note, however, that in this case enhancement of \(R_{\gamma\gamma}\) is not possible (if agreement with Planck results is demanded). In the right panel of Fig. 3 analogous plot for heavy DM is presented. In this scenario also \(R_{\gamma\gamma} > 0.7\) agrees with the Planck

\(^b\)Other scenarios can be found in our paper.\(^2\)
data. Moreover, all the values of $R_{\gamma\gamma}$ are extremely close to 1, which is not strange, as we are in the decoupling limit.

### 3.2 $R_{\gamma\gamma}$ and direct detection of DM

The DM-nucleon scattering in the IDM appears through an exchange of the Higgs boson, and thus the scattering cross section for this process is proportional to $\lambda^2_{345}$. Therefore the bounds coming from the lower bound on $R_{\gamma\gamma}$ can be translated to the $(M_H, \sigma_{\text{DM,N}})$ plane and compared with the DM direct detection limits. It appears that the bounds obtained for $R_{\gamma\gamma} > 0.7$ are stronger than or comparable to the XENON100 results. As compared to the LUX results, they are stronger for $M_H > 10$GeV, and a bit weaker for other masses. They are also stronger than the constraints from LHC, derived on the basis of limits on Br($h \rightarrow \text{inv}$).

### 4 Summary

The Higgs phenomenology can teach us a lot about inert DM. The increasingly accurate constraints on the invisible Higgs decays and its total decay width leave less and less space for additional scalars. The measured value of $R_{\gamma\gamma}$ constrains the mass and coupling of the charged scalar (even stronger than the direct detection bounds), and when combined with the DM relic density measurements also excludes certain DM scenarios. Nonetheless, the IDM is still in agreement with the available experimental data and offers a viable DM candidate.

### Acknowledgments

BS would like to thank the organisers for the opportunity to present this work at the Rencontres de Moriond QCD and High Energy Interactions, and for the financial support. The work was partially supported by the grant NCN OPUS 2012/05/B/ST2/03306 (2012-2016).

### References