DARK MATTER AND 125 GEV HIGGS FOR IDM

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We discuss a scalar Dark Matter candidate from the Inert Doublet Model in light of discovery of a 125 GeV SM-like Higgs boson at the LHC. We explore the possibility of using the recent and future data from LHC experiments, namely the Higgs diphoton decay measurements, to constrain the properties of Dark Matter particles.

1 Introduction

According to the standard cosmological model around 25% of the Universe is made of cold, non-baryonic, neutral and very weakly interacting particles. The Inert Doublet Model (IDM) is one of the simplest extensions of the Standard Model (SM) that can provide such Dark Matter (DM) candidate. The scalar sector in the IDM is extended with respect to the SM-like Higgs doublet \( \Phi^S \) by a second \( SU(2) \) doublet, \( \Phi^D \), which is odd under a \( D (Z_2) \) symmetry:

\[ \Phi^S \rightarrow \Phi^S, \Phi^D \rightarrow -\Phi^D, \text{SM fields} \rightarrow \text{SM fields}. \]

The IDM can provide a viable DM candidate in agreement with collider constraints and relic density measurements in three regions of DM mass: \( M_{DM} \sim 10 \text{ GeV}, 40 \text{ GeV} \lesssim M_{DM} \lesssim 160 \text{ GeV} \) and \( M_{DM} \gtrsim 500 \text{ GeV} \). Further constraints for the DM candidate can come from direct and indirect detection experiments. However, as for now there is no agreement how to consistently interpret various reported signals and the exclusion limits.

In this work we set constraints on scalar DM from the IDM by using the LHC Higgs data and WMAP relic density measurements. Combining the \( h \rightarrow \gamma \gamma \) data for the SM-like Higgs with the WMAP results excludes a large part of the IDM parameter space, setting limits on DM that are stronger or comparable to these obtained by the DM detection experiments.

2 The Inert Doublet Model

The IDM is defined as a 2HDM with a \( D \)-symmetric potential and vacuum state:

\[
V = -\frac{1}{2} \left[ m_1^2 (\Phi^S_1 \Phi^S_2) + m_2^2 (\Phi^D_1 \Phi^D_2) \right] + \lambda_1 (\Phi^S_1 \Phi^S_2)^2 + \lambda_2 (\Phi^D_1 \Phi^D_2)^2 \\
+ \lambda_3 (\Phi^S_1 \Phi^S_2) (\Phi^D_1 \Phi^D_2) + \lambda_4 (\Phi^S_1 \Phi^D_2) (\Phi^D_1 \Phi^S_2) + \frac{\lambda_5}{2} \left( (\Phi^S_1 \Phi^D_2)^2 + (\Phi^D_1 \Phi^S_2)^2 \right),
\]

\[
\langle \Phi^S \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \Phi^D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad v = 246 \text{ GeV},
\]

and Yukawa interaction set to Model I.\(^1_2\)

In the IDM only one doublet, \( \Phi^S \), is involved in the EW symmetry breaking. It provides a SM-like Higgs boson \( h \), which has tree-level couplings to fermions and gauge bosons like in the SM with possible deviation from the SM in loop couplings. The second doublet, \( \Phi^D \), is inert and

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contains four dark scalars \( H, A, H^\pm \), that have no couplings to fermions. The lightest particle coming from this doublet is stable, being a good DM candidate.

The IDM can be described by the masses of scalar particles and their physical couplings: \( \lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5 \) is related to \( hHH \) and \( hhHH \) vertices, while \( \lambda_3 \) gives \( hH^+H^- \) and \( \lambda_2: HHHHH \). Parameters of the IDM are constrained by various theoretical and experimental conditions. In our analysis we use vacuum stability constraints, that ensure the potential is bounded from below. We also demand, that the state (1) is the global, and not just a local minimum. Parameters of the potential should also fulfill perturbative unitarity bounds.

The value of the Higgs boson mass, \( M_h = 125 \text{ GeV} \), and above conditions provide the following constraints for the parameters of the potential: \( \lambda_1 = 0.258, m_{22}^2 \lesssim 9 \cdot 10^4 \text{ GeV}^2, \lambda_3, \lambda_{345} > -\sqrt{\lambda_1\lambda_2} \geq -1.47, \lambda_5^{\text{max}} = 8.38 \).

Masses of dark particles are constrained by the LEP measurements and EWPT to be: \( M_{H^\pm} + M_H > M_W \), \( M_{H^\pm} + M_A > M_W \), \( M_H + M_A > M_Z \), \( 2M_{H^\pm} > M_Z \), \( M_{H^\pm} > 70 \text{ GeV} \) with an excluded region where simultaneously \( M_H < 80 \text{ GeV} \), \( M_A < 100 \text{ GeV} \) and \( M_A - M_H > 8 \text{ GeV} \).

### 3 The diphoton decay rate \( R_{\gamma\gamma} \) in the IDM

\( R_{\gamma\gamma} \) is the ratio of the diphoton decay rate of the Higgs particle \( h \) observed at the LHC to the SM prediction. The current measured values of \( R_{\gamma\gamma} \) are \( R_{\gamma\gamma} = 1.65 \pm 0.24 \text{ (stat)}^{+0.25}_{-0.15} \text{ (syst)} \) for ATLAS and \( R_{\gamma\gamma} = 0.79^{+0.28}_{-0.26} \) for CMS\(^{10,11} \). They are in 2\( \sigma \) agreement with the SM value \( R_{\gamma\gamma} = 1 \), however a deviation from that value is still possible and would be an indication of physics beyond the SM.

The ratio \( R_{\gamma\gamma} \) in the IDM is given by:

\[
R_{\gamma\gamma} := \frac{\sigma(pp \to h \to \gamma\gamma)^{\text{IDM}}}{\sigma(pp \to h \to \gamma\gamma)^{\text{SM}}} \approx \frac{\Gamma(h \to \gamma\gamma)^{\text{IDM}}}{\Gamma(h \to \gamma\gamma)^{\text{SM}}} \frac{\Gamma(h)^{\text{SM}}}{\Gamma(h)^{\text{IDM}}},
\]

where \( \Gamma(h)^{\text{SM/IDM}} \) are the total decay widths of \( h \) in the SM and the IDM, while \( \Gamma(h \to \gamma\gamma)^{\text{SM/IDM}} \) are the respective partial decay widths for \( h \to \gamma\gamma \). In the IDM two sources of deviation from \( R_{\gamma\gamma} = 1 \) are possible. First is a \( H^\pm \) contribution to the partial decay width:\(^{12,13} \)

\[
\Gamma(h \to \gamma\gamma)^{\text{IDM}} = \frac{G_F\alpha^2 M_h^3}{128\sqrt{2}\pi^3} |\mathcal{M}^{\text{SM}} + \delta\mathcal{M}^{\text{IDM}}(M_{H^\pm}, \lambda_3)|^2,
\]

where \( \mathcal{M}^{\text{SM}} \) is the SM amplitude and \( \delta\mathcal{M}^{\text{IDM}} \) is the \( H^\pm \) contribution. The interference between \( \mathcal{M}^{\text{SM}} \) and \( \delta\mathcal{M}^{\text{IDM}} \) can be either constructive or destructive. The second source of deviations are possible invisible decays \( h \to HH, AA \), which can strongly augment the total decay width \( \Gamma^{\text{IDM}}(h) \) with respect to the SM case. If \( h \) can decay invisibly then \( R_{\gamma\gamma} \) is always below 1\(^{14,13} \). For \( M_H > M_h/2 \) and \( M_A > M_h/2 \) the invisible channels are closed, and \( R_{\gamma\gamma} > 1 \) is possible. \( R_{\gamma\gamma} \) depends only on the masses of the dark scalars and \( \lambda_{345} \) (or \( \lambda_3 \)), so setting a lower bound on \( R_{\gamma\gamma} \) leads to upper and lower bounds on \( \lambda_{345} \) as functions of \( M_{H,A,H^\pm} \).\(^{15} \)

**HH, AA decay channels open** In this region, the invisible decay channels have stronger influence on the value of \( R_{\gamma\gamma} \) than the contribution from \( H^\pm \) alone.\(^{14} \) If we demand that \( R_{\gamma\gamma} > 0.7 \), we get allowed values of \( \lambda_{345} \) that are small, typically in range \((-0.04, 0.04) \). For \( R_{\gamma\gamma} > 0.8 \) the allowed values of \( \lambda_{345} \) are smaller than for \( R_{\gamma\gamma} > 0.7 \). The condition \( R_{\gamma\gamma} > 0.9 \) strongly limits the allowed parameter space of the IDM. The allowed \( A, H \) mass difference is \( \delta_A \lesssim 2 \text{ GeV} \), and values of \( \lambda_{345} \) are smaller than in the previous cases. Requesting larger \( R_{\gamma\gamma} \) leads to the exclusion of the whole region of masses, apart from \( M_H \approx M_A \approx M_h/2 \).\(^{15} \)

**AA decay channel closed** When the AA decay channel is closed, the values of \( R_{\gamma\gamma} \) do not depend on the value of \( M_A \), while the charged scalar contribution becomes more relevant. If
$R_{\gamma\gamma} > 0.7$ then an exact value of $M_{H^\pm}$ is not crucial for the obtained limits on $\lambda_{345}$, and allowed values of $|\lambda_{345}|$ are of order 0.02. For $R_{\gamma\gamma} > 0.8$ the obtained bounds are different for $M_{H^\pm} = 70$ GeV and 120 GeV. Smaller $M_{H^\pm}$ leads to stronger limits, requiring $|\lambda_{345}| \sim 0.005$, while larger $M_{H^\pm}$ allow $|\lambda_{345}| \sim 0.015$. Larger value of $R_{\gamma\gamma}$ leads to smaller allowed values of $\lambda_{345}$. In the case of $R_{\gamma\gamma} > 0.9$ a large region of DM masses is excluded, as it is not possible to obtain the requested value of $R_{\gamma\gamma}$ for any value of $\lambda_{345}$ if $M_H \lesssim 45$ GeV.

**Invisible decay channels closed** If $M_A, M_H > M_h/2$, the invisible channels are closed and the only modification to $R_{\gamma\gamma}$ comes from the charged scalar loop (3). Enhancement in $R_{\gamma\gamma}$ is possible when $\lambda_3 < 0$\textsuperscript{13,14}. Unitarity and positivity limits on $\lambda_3$ and $\lambda_{345}$ constrain the allowed values of $M_{H^\pm}$ and $M_H$ for a given value of $R_{\gamma\gamma}$. For $R_{\gamma\gamma}^{\text{max}} = 1.01$ masses of $M_{H^\pm} \gtrsim 700$ GeV are excluded, and if $R_{\gamma\gamma}^{\text{max}} = 1.02$ this bound is stronger, forbidding $M_{H^\pm} \gtrsim 480$ GeV. Also, even a small deviation from $R_{\gamma\gamma} = 1$ requires a relatively large $\lambda_{345}$, if the mass difference $\delta_H$ is of the order $(50-100)$ GeV. Small values of $|\lambda_{345}|$ are preferred if $\delta_H$ is small\textsuperscript{15}.

4 Combining $R_{\gamma\gamma}$ and relic density constraints on DM

Here we compare the limits on the $\lambda_{345}$ parameter obtained from $R_{\gamma\gamma}$ with those coming from the requirement that the DM relic density is in agreement with the WMAP measurements: $0.1018 < \Omega_{DM} h^2 < 0.1234$. If this condition is fulfilled, then $H$ constitutes 100% of DM in the Universe. Values of $\Omega_{H} h^2 < 0.1018$ are allowed if $H$ is a subdominant DM candidate.

**Low DM mass** In the IDM the low DM mass region corresponds to masses of $H$ below 10 GeV, while the other dark scalars are heavier, $M_A \approx M_{H^+} \approx 100$ GeV. To obtain the proper relic density, the $HHh$ coupling ($\lambda_{345}$) has to be large, for example $|\lambda_{345}| = (0.35 - 0.41)$ for CDMS-II favoured mass $M = 8.6$ GeV. The coupling allowed by $R_{\gamma\gamma} \sim 0.7$, i.e. $|\lambda_{345}| \sim 0.02$, is an order of magnitude smaller than needed for $\Omega_{DM} h^2$ and thus we can conclude that the low DM mass region cannot be accommodated in the IDM with recent LHC results.

**Medium DM mass: invisible decay channels open** We first consider a case with $M_A = M_{H^\pm} = 120$ GeV and $M_h/2 > M_H > 50$ GeV. Red bound in the left panel of figure 1 denotes the WMAP-allowed range of $\Omega_{DM} h^2$. If we consider $H$ as a subdominant DM candidate with $\Omega_{H} h^2 < \Omega_{DM} h^2$ then also the regions below and above red bounds in figure 1 are allowed. This usually corresponds to larger values of $\lambda_{345}$. For a large portion of the parameter space limits for $\lambda_{345}$ from $R_{\gamma\gamma}$, even for the least stringent case $R_{\gamma\gamma} > 0.7$, cannot be reconciled with the WMAP-allowed region, where $|\lambda_{345}| \sim 0.1$, excluding $M_H \lesssim 53$ GeV.
Medium DM mass: invisible decay channels closed  Here we choose $\delta_{H^\pm} = \delta_A = 50$ GeV and $M_H$ varying between $M_h/2$ and 83 GeV. Figure 1 (central panel) gives the WMAP-allowed range with the corresponding values of $R_{\gamma\gamma}$. The absolute values of $\lambda_{345}$ that lead to the proper relic density are in general larger than in the case of $M_H < M_h/2$. From figure 1 it can be seen that this region of $M_H$ is consistent with $R_{\gamma\gamma} < 1$, and that $R_{\gamma\gamma} > 1$ and $\Omega_{DM} h^2$ constraints cannot be fulfilled for the middle DM mass region. If the IDM is the source of all DM in the Universe and $M_H \approx (63 - 83)$ GeV then the maximal value of $R_{\gamma\gamma}$ is around 0.98. A subdominant DM candidate, which corresponds to larger $\lambda_{345}$, is consistent with $R_{\gamma\gamma} > 1$.

Heavy DM mass: almost degenerated particle spectra  In this case it is possible to get $R_{\gamma\gamma} > 1$ and be in agreement with WMAP, as shown in right panel in figure 1 for $M_H \gtrsim 500$ GeV and $\delta_A = \delta_{\pm} = 1$ GeV, although deviation from $R_{\gamma\gamma} = 1$ is very small.

5 Summary

The DM candidate from the IDM is consistent with the WMAP results on the DM relic density and in three regions of masses it can explain 100% of the DM in the Universe. In a large part of the parameter space it can also be considered as a subdominant DM candidate. Measurements of the diphoton ratio $R_{\gamma\gamma}$ done at the LHC set strong limits on masses of the DM and other dark scalars, and their self-couplings.

We can exclude the low DM mass region in the IDM, i.e. $M_H \lesssim 10$ GeV, as values of $|\lambda_{345}|$ needed for the proper $\Omega_{DM} h^2$ are an order of magnitude larger than those allowed by assuming that $R_{\gamma\gamma} > 0.7$. In the medium mass region $R_{\gamma\gamma} > 1$ favours degenerated $H$ and $H^\pm$. When the mass difference is large, $\delta_{H^\pm} \approx 50$ GeV, then values of $|\lambda_{345}|$ that provide $R_{\gamma\gamma} > 1$ are bigger than those allowed by WMAP. We conclude it is not possible to have $R_{\gamma\gamma} > 1$ and all DM in the Universe explained by the IDM in the medium DM mass region. If $R_{\gamma\gamma} > 1$ then $H$ may be a subdominant DM candidate. If $R_{\gamma\gamma} < 1$ then $M_H \approx (63 - 80)$ GeV can explain 100% of DM in the Universe. For heavy DM particles it is possible to obtain $R_{\gamma\gamma} > 1$ and fulfill WMAP bounds, although deviation from $R_{\gamma\gamma} = 1$ is small.

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