Observability of inert scalars at the LHC

Majid Hashemi\textsuperscript{1,a}, Saereh Najjari\textsuperscript{2,b}

\textsuperscript{1} Physics Department, College of Sciences, Shiraz University, Shiraz 71946-84795, Iran
\textsuperscript{2} Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

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Abstract In this work we investigate the observability of inert doublet model scalars at the LHC operating at the center of mass energy of 14 TeV. The signal production process is $pp \rightarrow AH^\pm \rightarrow ZH W^{\pm}H$ leading to two different final states of $\ell^+\ell^-HjjH$ and $\ell^+\ell^-H\ell^\pm_vH$ based on the hadronic and leptonic decay channels of the W boson. All the relevant background processes are considered and an event selection is designed to distinguish the signal from the large Standard Model background. We found that signals of the selected search channels are well observable at the LHC with an integrated luminosity of 300 fb\textsuperscript{-1}.

1 Introduction

The Inert Doublet Model (IDM) is a special type of Two Higgs Doublet Model (2HDM); it respects a discrete $Z_2$ symmetry under which the Standard Model (SM) fields are even while the inert doublet additional $SU(2)$ scalar doublet $\Phi_D$ is odd, therefore the neutral component of $\Phi_D$ could be a dark matter candidate [1–7]. Only the SM Higgs doublet acquires a non-zero vacuum expectation value and hence is a source of electroweak symmetry breaking (EWSB). The inert doublet does not couple with the fermions of the SM. After EWSB in the scalar sector this model has five physical states: the SM-like Higgs boson $h$ as well as two charged scalars, $H^\pm$, and two neutral ones, $H$ and $A$.

The inert doublet scalars have been studied in [8], aiming at their mass reconstruction at a linear collider. A detailed study recently presented in [9] shows that all inert scalars can well be identified and their masses can be measured up to a reasonable accuracy at a future linear collider. The observation of inert scalars at the LHC has also attracted attention. For a list of recent work one may refer to [10–15]. These studies have been done mostly based on the production of $H^+H^-, HA, HH^+$ and $AH^+$ followed by the $H^+ \rightarrow W^+H$ and $A \rightarrow ZH$ assuming $H$ as the dark matter candidate. In one of the most recent works in the list [14] a di-jet plus missing transverse energy signature of the inert doublet model events has been studied. The studied benchmark points (which are different from ours) are shown to be observable at a minimum integrated luminosity of 3000 fb\textsuperscript{-1}. There has also been a study of IDM tri-lepton [16] and multi-lepton [17] signals at LHC at an integrated luminosity of 300 fb\textsuperscript{-1}. The analysis in [16] is based on a search for opposite-sign same-type di-lepton signature. However, single electroweak gauge boson production ($W+$jets and Drell–Yan $Z/\gamma+$jets) has not been considered. Furthermore, most parameter space points which were studied in [16] are already excluded by the analysis of LHC RUN-1 data. The benchmark points introduced in this work are set to dominate $H^\pm \rightarrow W^\pm H$ and $A \rightarrow ZH$, while in [17] other decay channels are also considered leading to four-lepton final states. The same signal as in [16] is covered by the current work. However, the aim of this paper is to perform a search near the recent excluded area of the LHC. This analysis is completely independent and benefits from a topological event study based on the flight angle of final state leptons.

In most analyses mentioned earlier, the neutral scalar, $H_0$, is assumed to be the dark matter candidate. Although this is not a requirement, we consider the scalar $H$ to be lighter than the pseudoscalar $A$, hence the dark matter candidate. The focus will be on the parameter space close to the LHC excluded region to investigate the phenomenology and observability of the inert scalars at the LHC. We propose a new set of benchmark points which satisfy all the recent experimental and theoretical constraints. The analysis is performed in two categories: di-lepton plus di-jet and tri-lepton final states, all of them produced through $A^0H^\pm$ at the center of mass energy of 14 TeV. The lepton denoted by $\ell$ is either an electron or a muon. Therefore signal events include both electrons and muons in the final states. The following processes are considered as the signal in our studies:

\begin{itemize}
  \item $pp \rightarrow AH^\pm \rightarrow ZH W^{\pm}H$
  \item $pp \rightarrow HH^+H^-$
  \item $pp \rightarrow AH^\pm HjjH$
  \item $pp \rightarrow H\ell\ell H$
  \item $pp \rightarrow H\ell\ell\nu H$
  \item $pp \rightarrow HH^+H^+$
  \item $pp \rightarrow AH^\pm H\ell\ell$
  \item $pp \rightarrow H\ell\ell\nu H$
  \item $pp \rightarrow HH^+H^+H^-$
\end{itemize}
Concerning the decay channels, $H^\pm$ decays to $W^\pm H$ and $A$ decays to $ZH$, however, at all the benchmark points under study, $M_{H^\pm} < (M_W + M_H)$ and $M_A < (M_Z + M_H)$, therefore those decays can only occur via a virtual $W^\pm$ and $Z^*$ boson whose masses are set to $m_{W^\pm} = m_{H^\pm} - m_H$ and $m_{Z^*} = m_A - m_H$. This setting implies that the distributions of the di-muon invariant mass from decays of off-shell $Z^*$ bosons shows a resonance at $m_A - m_H$. The dominant source of the width of such a resonance is the experimental smearing of the muon four momentum which is taken into account.

After introducing in Sect. 2 the model and setting up the notations, in Sect. 3 we provide the benchmark points for this study. The simulation tools used for the analysis are described in Sect. 4. The event generation and the analysis of our benchmark points are given in Sects. 5–7. Finally, we discuss and conclude in Sects. 9 and 10.

2 Inert Doublet Model

The IDM is the extension of the scalar sector of the SM by addition of scalar doublet $\Phi_D$ to the SM-like Higgs doublet ($\Phi_5$). The inert doublet is odd under the discrete $Z_2$ symmetry, whereas all of the SM fields are even. The two scalar doublets can be written as

$$\Phi_S = \frac{1}{\sqrt{2}} \left( \sqrt{2} G^\pm \right), \quad \Phi_D = \frac{1}{\sqrt{2}} \left( H + i A \right),$$

where $v = 246$ GeV denotes the vacuum expectation value of the SM-like Higgs doublet. The scalar potential for the IDM reads

$$V(\Phi_S, \Phi_D) = -\frac{1}{2} \left[ m_{11}^2 (\Phi^*_S \Phi_S) + m_{22}^2 (\Phi^*_D \Phi_D) \right] + \frac{\lambda_1}{2} (\Phi^*_S \Phi_S)^2 + \frac{\lambda_2}{2} (\Phi^*_D \Phi_D)^2 + \lambda_3 (\Phi^*_S \Phi_S) (\Phi^*_D \Phi_D) + \lambda_4 (\Phi^*_S \Phi_D) (\Phi^*_D \Phi_S) + \frac{\lambda_5}{2} (\Phi^*_S \Phi_D)^2 + (\Phi^*_D \Phi_S)^2.$$  

(3)

The masses and interactions of scalar section are fixed by parameters, $(m_{11,22}, \lambda_{1,2,3,4,5})$. After EWSB the physical masses of scalars are expressed as

$$m_h^2 = \lambda_1 v^2 = m_{11}^2,$$

$$m_{H^\pm}^2 = \frac{1}{2} (\lambda_3 v^2 - m_{22}^2).$$

(4)

with $\lambda_{L,S}$ defined as $\lambda_{L,S} = \frac{1}{2} (\lambda_3 + \lambda_4 \pm \lambda_5)$. The scalar and pseudoscalar mass splitting is related to $\lambda_5$:

$$m_{H^*}^2 - m_A^2 = \lambda_5 v^2.$$  

(5)

Note that if $\lambda_5 < 0$, the neutral scalar $H$ is the lightest scalar of dark sector (one which will be considered in our analysis) and if $\lambda_5 > 0$, the neutral scalar $A$ is the lightest scalar of dark sector.

The theoretical and experimental constraints on IDM reduce the parameter space considerably. In the following two subsections we outline these constraints and then in the next section we propose our benchmarks points which respect all the following constraints.

2.1 Theoretical constraints

We enlist below the theoretical constraints on the IDM parameters:

(i) Stability The tree-level vacuum stability constrains the potential quartic coupling parameters by

$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0, \quad \sqrt{\lambda_1 \lambda_2} + \lambda_3 > 0, \quad \sqrt{\lambda_1 \lambda_2} + 2 \lambda_5 > 0.$$  

(6)

(ii) Global minimum In order to have a global minimum of the inert potential, we impose the following bound on the mass parameters [18]:

$$\frac{m_{11}^2}{\sqrt{\lambda_1}} \geq \frac{m_{22}^2}{\sqrt{\lambda_2}}.$$  

(7)

(iii) Tree-level unitarity The constraints from the perturbative unitarity of $2 \to 2$ scattering of the vector bosons in the SM is taken into account.

(iv) Perturbativity We also require that all couplings remain perturbative, i.e. we take $4\pi$ as upper limits.

2.2 Experimental constraints

(i) SM-like Higgs We employ the SM-like Higgs boson mass $h$ to be $M_h = 125$ GeV [19] and its total width to be $\Gamma_h \leq 22$ MeV [20,21].

(ii) Gauge boson width bound The width of the SM gauge bosons W and Z put the following constraint on the mass parameter [22]:

$$m_1^2 \geq \lambda_1 v^2 = m_{11}^2,$$

$$m_{H^\pm}^2 = \frac{1}{2} (\lambda_3 v^2 - m_{22}^2).$$

(4)
\begin{align*}
& m_H + m_A \geq m_Z, \quad 2m_{H^\pm} \geq m_Z, \\
& m_A + m_{H^\pm} \geq m_W, \quad m_H + m_{H^\pm} \geq m_W.
\end{align*}

(iii) **Dark matter** We take into account the following DM search bounds:

- We consider $2\sigma$ LUX2016 experimental direct searches exclusion bound on the dark matter scattering cross section [23].
- We also employ the Planck measurement $2\sigma$ limits on dark matter relic density, $\Omega h^2 = 0.1197 \pm 0.0022$ [24].

(iv) **Charged scalar**

- LEP limit on the charged scalar mass of $m_{H^\pm} \geq 70$ GeV [25] is taken into account. Moreover, the exclusion bounds from SUSY searches at LHC and LEP [13,26] are also considered.
- Limit on the charged scalar total width, $\Gamma_{tot} \geq 6.58 \times 10^{-18}$ GeV, to avoid bounds from long lived charged particle searches [10].

(v) **EWPO** Electroweak precision observables (EWPO) bound at $2\sigma$ level is also considered [27–30].

3 Benchmark points

The IDM has seven free parameters, out of which two ($m_{11}$ and $\lambda_1$) are fixed to get the electroweak vacuum expectation value, $v = 246$ GeV, and the SM-like Higgs mass $m_h = 125$ GeV. The remaining five parameter $m_{22}, \lambda_{2,3,4,5}$ can be traded for the physical parameters namely, $m_H, m_A, m_{H^\pm}, \lambda_2$ and $\lambda_L$. Taking into account all the above mentioned theoretical and experimental bounds, we propose the following benchmark points (BP) which have the potential for observation at the LHC:

BP1: $m_H = 60$ GeV, $m_A = 111$ GeV, $m_{H^\pm} = 123$ GeV,
BP2: $m_H = 75$ GeV, $m_A = 120$ GeV, $m_{H^\pm} = 115$ GeV,
BP3: $m_H = 70$ GeV, $m_A = 110$ GeV, $m_{H^\pm} = 130$ GeV.

Figure 1 shows our benchmark points and the LHC excluded region from RUN-1 as well as the high luminosity run prediction for an integrated luminosity of 300 fb$^{-1}$. The LHC contours are taken from [13]. It is expected that LHC exclusion extends up to the larger area denoted by “300 fb$^{-1}$” when high luminosity data is available. However, these results are based on a di-lepton plus missing transverse energy search which is different from the search channel proposed in this paper.

Note that the above BPs only fix the inert scalar masses, whereas the two parameters $\lambda_2$ and $\lambda_L$ are free. However, as noted above, there are theoretical and experimental bounds constraining the parameters $\lambda_2$ and $\lambda_L$. Considering the perturbativity and the tree-level unitarity constraints $\lambda_2 \leq 4.2$. There is also a lower bound on $\lambda_2$ from positivity (6), $\lambda_2 = [0, 42]$. Note that the parameter $\lambda_L$, quartic self coupling of the inert scalars, does not affect the value of relic density because the annihilation to the SM is mostly mediated through the SM-like Higgs boson and the parameter $\lambda_L$. Therefore $\lambda_2$ does not enter to this study and the effect of that will only appear at one loop level. Parameter $\lambda_L < -0.5$ is excluded from the bounds on positivity. We fix the parameter $\lambda_L$ in a way that the dark matter candidate $H$ provide the correct dark matter relic density in the universe, i.e. $\Omega_c h^2 \approx 0.1241$. We compute the relic density of dark matter ($H$) as a function of $\lambda_L$, our result for the benchmark points are summarized in Fig. 2a. The direct detection exclusion from the LUX experiment is shown as a function of $\lambda_L$ in Fig. 2b. We note that $\lambda_L \simeq 0.001$ for BP1, $\lambda_L \simeq -0.01$ for BP2 and $\lambda_L \simeq 0.01$ for BP3 fixes the right dark matter relic abundance and is not excluded by the LUX experiment. We used *micrOMEGAs 4.1* [31] for the LUX bound and relic density.

4 Software setup

The generation of signal events starts with implementing the inert doublet model Lagrangian in *LanHEP-3.2.0* [32,33]. The *LanHEP* output (model files) are used in *CompHEP-4.5.2* [34,35] for event generation. The hard processes generated by *CompHEP* are then passed to *PYTHIA-8.2.15* [36] for final state showering and multi parti-
particle interactions. There are alternative packages, however, we use the LanHEP-CompHEP chain, which provides a user-friendly graphical user interface. The performance of our software setup has been verified by calculating cross sections of benchmark points of other analyses such as [16,37], which use different software setups. Reasonable agreement has been observed.

The background events are all generated by PYTHIA. The jet reconstruction is performed using FASTJET-2.8 [37, 38] based on an anti-\(k_T\) algorithm with a cone size of 0.4. The analysis is carried out using ROOT-5.34.30 [39].

5 Signal and background processes

The signal processes are categorized into two main channels. These channels have been selected carefully with the aim of a reasonable background suppression. The di-lepton plus di-jet channel benefits from a tool which we call “\(W/Z\) veto” and is powerful against Drell–Yan and any other SM background which has a genuine \(W\) boson in the event. The tri-lepton channel benefits from “jet veto” and three-lepton requirement which suppresses the Drell–Yan background and any other SM background with jets involved, except for the irreducible \(WZ\) process. In what follows, the above two channels are described in detail.

5.1 \(AH^\pm \rightarrow \ell^+\ell^-HjjH\)

The di-lepton plus di-jet channel proceeds through \(AH^\pm\) production followed by the \(A \rightarrow ZH\) and \(H^\pm \rightarrow W^\pm H\) decays. The \(H\) escapes the detector and can only be seen as missing (transverse) energy. The off-shell bosons decay through \(W^\pm \rightarrow jj\) and \(Z \rightarrow \ell\ell\) thus producing a final state consisting of two jets and two leptons. Figure 3a illustrates the signal production chain. The main difference between the signal and the SM background events is the virtuality of gauge bosons, which results in low values of di-lepton and di-jet invariant mass distributions far from SM peaks corresponding to the \(Z\) and \(W\) bosons at roughly 90 and 80 GeV. A reasonable background suppression is achieved by requiring missing transverse energy threshold and exactly two leptons and two jets in the event. The two jets should be light (\(u, d, s\)) for \(t\bar{t}\) suppression and should not have an invariant mass near the \(W\) boson mass to reject the SM gauge boson pair or single production. The \(W/Z\) boson “veto” suppresses both \(W+\)jets and Drell–Yan \(Z^{(\gamma^*)+}\)jets dramatically.

Possible sources of \(t\bar{t}t\bar{t}, t\bar{t}Z\) and \(b\bar{b}Z\), as discussed in [17], can be suppressed to a reasonable level by a \(b\)-jet veto, cuts on lepton impact parameter to veto displaced leptons from \(b\)-jets, and the cut on the number of jets and \(Z\) boson mass. The \(b\bar{b}Z\) events are unlikely to pass the \(b\)-jet veto as none of the two \(b\)-jets in such events should be identified as a \(b\)-jet to pass the selection cuts. A detector simulation of background events may provide a better understanding of the power of our selection cuts. While a simulation of large samples of background processes is needed to make a reasonable comparison between the current results and a detector based simulation, the signal shapes from di-muon invariant mass distributions are obtained using Delphes 3.3.2 [40] and compared in the next steps. The overall results show reasonable agreement.
5.2 $AH^\pm \rightarrow \ell\ell H\nu H$

The tri-lepton channel is produced through $AH^\pm$ process with $A \rightarrow ZH$ and $H^\pm \rightarrow W^\pm H$ decays. Both $Z$ and $W$ bosons decay leptonically in this case. Therefore the final state consists of three leptons, two of which are expected to give an invariant mass near the off-shell $Z^*$ boson mass in the signal. Figure 3b shows the signal production chain. Since there are no jets in the signal process, SM background events, such as $t\bar{t}$, $W+$ jets, $Z/\gamma+$ jets, are well suppressed by the jet veto and one requires exactly three leptons in the event. Since the final aim in this channel is the distribution of the di-lepton from the $Z^*$ boson, the Drell–Yan background should be suppressed down to a reasonable level. It is, in fact, dramatically suppressed by requiring three leptons in the event. The main background will then be the irreducible $WZ$ production, which produces the same type of final state particles. This background is also shown to be well under control by requiring hard leptons above a reasonable threshold ($E_T > 30$ GeV).

6 Signal and background cross sections

The signal cross section is calculated at leading order using CompHEP at event generation time. Tables 1 and 2 show cross sections of the signal process ($AH^\pm$) as well as the branching ratios of relevant decays for three benchmark points. The cross sections of background processes are also presented in Table 3.

7 Event selection and analysis

In this section, the event selection strategy and details of the analysis are presented. Before proceeding to the details, it should be mentioned that all leptons and jets four momenta are smeared according to LHC results reported in [41,42]. The smearing is based on a gaussian distribution with a width of 15% of the jet energy and 2% of the lepton transverse momentum. These values are equivalently the jet (lepton) energy (transverse momentum) resolutions.

7.1 The di-lepton plus di-jet channel

This signal consists of two leptons and two jets. Equation 9 shows the kinematic cut applied on all leptons and jets in the event. Therefore all leptons and jets are required to pass a threshold of 30 GeV applied on their transverse momenta and they are required to be in the central barrel and endcap regions and not outside the $|\eta| < 3$ region. Here $\eta$ is defined as $\eta = -\ln\tan(\theta/2)$ with $\theta$ being the polar angle.

$$E_T^{\text{jet/lepton}} > 30 \text{ GeV}, \quad |\eta| < 3. \quad (9)$$
This requirement is basically useful for SM background suppression when an event involves soft leptons or jets like in a single or pair production of gauge bosons. If a lepton or jet passes this requirement, it is counted.

The $b$-tagging is also performed based on a simple spatial matching between the $b$-jet and the true $b$ or $c$ quark in the event. If a $b$-jet lies in the vicinity of a $b$ or $c$ quark, i.e., $\Delta R(b\text{-jet}, b/c \text{ quark}) < 0.4$, it is accepted by 60 or 10% probability, respectively. If a jet is not identified as a $b$-jet, it is taken as a light jet. An event is required to have exactly two light jets and two leptons passing the requirement in Eq. (9) to be selected for further analysis.

The next step is the missing transverse energy (MET) calculation. The MET is calculated by a negative vectorial sum of particles momenta in the transverse plane ignoring neutral particles. The MET is calculated by a negative vectorial sum of MET in signal and background events. As seen in Fig. 4, a cut on MET is applied as in Eq. (10). The lower cut is useful for Drell–Yan background suppression and other SM background processes, and the other pair (di-lepton) can finally be used as a clue to reject the Drell–Yan and other SM background processes.

Before proceeding to the di-lepton invariant mass calculation, we benefit from a feature of signal events which is the fact that there are two pairs in the event. One pair (di-jet) can be used as a clue to reject the Drell–Yan and other SM background processes, and the other pair (di-lepton) can finally be used as the signal signature.

The di-jet invariant mass distribution at this step shows a reasonable separation between the signal and background processes. Figure 6 shows the distribution of di-jet events in both signal and background events. The single $W$ has been suppressed to a negligible level at this point and is not shown on this plot. The Drell–Yan case has to involve a $Z/\gamma \rightarrow \ell\ell$ decay to be selected by the di-lepton requirement. Therefore the accompanying jets in the event produce a flat distribution of di-jet invariant mass. The only background events showing peaks near the $W$ or $Z$ are $WZ$ and $ZZ$. Demanding two jets plus two leptons in these events requires $W \rightarrow jj$ and $Z \rightarrow \ell\ell$ in the first case and $Z_1 \rightarrow jj$ and $Z_2 \rightarrow \ell\ell$ in the second case. Therefore the di-jet invariant mass shows a peak at $\sim 80$ GeV in $WZ$ events but a peak at $\sim 90$ GeV in $ZZ$ events. A cut on di-jet invariant mass is applied as a “$W/Z$ veto” as in Eq. (12):

$$15 \text{ GeV} < \text{MET} < 50 \text{ GeV}$$

$$\Delta\phi(\text{di-jet}) < 1 \text{ and } \Delta\phi(\text{di-lepton}) < 1.$$
selection efficiencies and the total efficiency of event selection. It should be mentioned that background events have been generated in a final state which is closest to the signal. For example the Drell–Yan efficiency quoted in Table 5 has been obtained from a sample of $Z/\gamma$+jets $\rightarrow \ell\ell$+jets. Therefore the number of events at a certain luminosity is obtained by taking the cross section in Table 3 multiplied by the $\text{BR}(Z \rightarrow \ell\ell) \simeq 0.066$, luminosity (300 fb$^{-1}$) and the total efficiency. All Drell–Yan events fall at either very low di-lepton invariant mass values or near the SM $Z$ boson mass at $\simeq 90$ GeV. The signal region around 40–50 GeV is thus almost free from the SM background.

Having applied all cuts (Eqs. (9), (10), (11), and (12), the remaining events are used for the di-lepton invariant mass calculation. Figure 7 shows the distribution of the di-lepton invariant mass in signal and background events. As is seen, signal events are well observable at a high luminosity of 300 fb$^{-1}$ and SM background processes are well under control.

A mass window on this distribution could determine the signal significance inside the window. On the other hand, one can use a (Gaussian) fit performed on the signal plus background distributions to obtain the off-shell $Z^*$ boson mass which can be used to obtain information as regards the mass difference between the charged scalar and the $H$ dark matter candidate mass.

Table 6 shows the mass window position and the obtained signal significance in the mass window. The mass window position is obtained by searching for the lower and upper
Table 5 Background selection efficiencies and the total efficiency for each background. STS and STT denote the single top s and t channels, respectively.

| Selection cut      | SM background, $\ell \ell HjjH$ analysis |
|--------------------|-----------------------------------------|
|                    | $t\bar{t}$ | $WW$   | $WZ$ | $ZZ$ | STS  | STT  | $W$ | $Z\gamma$ |
| 2 jets Eq. (9)     | 0.022      | 0.046  | 0.22 | 0.19 | 0.013 | 0.04  | 0.015 | 0.006    |
| 2 leptons Eq. (9)  | 0.46       | 0.4    | 0.42 | 0.077| 0.017 | 0.0097| 0.0003| 0.28     |
| MET Eq. (10)       | 0.29       | 0.39   | 0.042| 0.037| 0.53  | 0.52  | 0.46  | 0.042    |
| $\Delta \phi$ Eq. (11) | 0.046   | 0.077 | 0.13 | 0.082| 0.064 | 0.053 | 0    | 0.10     |
| W/Z veto Eq. (12)  | 0.37       | 0.42   | 0.31 | 0.28 | 0.44  | 0.39  | 0    | 0.32     |
| Total eff.         | 5.02e−05   | 2.3e−4 | 1.5e−4|1.2e−05| 3.1e−06| 4.1e−06| 0    | 2.3e−06  |

Fig. 7 The distribution of di-lepton invariant mass in signal and background events.

cuts which maximize the signal significance. Based on these results, a 5σ discovery is possible in the area of 300 fb−1 integrated luminosity.

7.2 The tri-lepton channel

The tri-lepton channel is a signal process which involves three leptons in the event. The final goal in the analysis of this channel is to obtain a di-lepton invariant mass distribution like what was obtained in the previous section. There are, however, different combinations of leptons out of the three in each event.

The analysis starts with a kinematic threshold applied on transverse energies and flight directions of leptons and jets as in Eq. 13:

$$E_{T,\text{jet/lepton}} > 20 \text{ GeV}, \ |\eta| < 3.$$  

The signal cross section in this channel is small due to the small branching ratio of leptonic decays of gauge bosons. Therefore the lepton transverse energy has been set to 20 GeV to allow for more signal events to be selected. The jet transverse energy threshold has also been carefully reduced to 20 GeV to increase the number of selected jets. The final aim with the jet analysis is a jet veto. The jet veto may suppress some of signal events due to the initial/final state radiation appeared as jets, however, it suppresses the $t\bar{t}$ and single top backgrounds dramatically. Decreasing the jet energy threshold increases the chance of a jet to be selected. This results in a higher suppression of background events by the jet veto finally. An event is required to contain no jet and exactly three leptons satisfying the requirement in Eq. 13.

The missing transverse energy is also calculated with the approach as in the previous section. Figure 8 shows the MET distribution based on which a cut is applied as in Eq. 14. We have

$$\text{MET} > 20 \text{ GeV}.$$  

Table 6 Mass window cuts in GeV, the number of signal and background events in the mass window and the signal significance at 300 fb−1

| Signal | BP1 | BP2 | BP3 |
|--------|-----|-----|-----|
|        | Lower cut | Upper cut | Lower cut | Upper cut | Lower cut | Upper cut |
| $m(\ell_1, \ell_2)$ (GeV) | 50 | 52 | 44 | 46 | 39 | 41 |
| $N_s$  | 64 | 43 | 23 | 12 |
| $N_B$  | 16 | 16 | 9  | 14 |
The most powerful approach which can be used to identify the true pair of leptons which come from a $Z$ boson is the analysis of (azimuthal) angles between each pair as well as the angle between each lepton and the neutrino (MET) direction.

The underlying assumption in this approach is that $A$ and $H^\pm$ fly back-to-back after the hard scattering (Fig. 3b). When subsequent decays occur ($A \rightarrow ZH$ and $H^\pm \rightarrow W^\pm H$), the $Z$ and $W$ bosons will also be back-to-back and their decay products fly in the same directions as theirs. As is seen in Fig. 3b, the flight angle between each lepton from the $Z$ decay and the lepton from the $W$ decay tends to be large (near $\pi$). The lepton and neutrino from the $W$ decay are almost collinear and therefore the same argument applies to the angles between each $Z$ decay product and the missing transverse energy. All above arguments rely on the fact that there is a large Lorentz boost acquired by the $A$ and $H^\pm$ scalars in the hard scattering and is in turn transferred to the gauge bosons. Based on the above statements a search among the three leptons is performed to find the best combination satisfying the $\Delta \phi$ requirement as in Eq. (15). The labels are according to the following decay scheme: $Z \rightarrow \ell_1 \ell_2$ and $W \rightarrow \ell_3 \nu$.

A random selection of two leptons results in a $\Delta \phi$ distribution as shown in Fig. 9. The signal events clearly show two regions of interest. The region with $\Delta \phi < 1$ shows the true combination and the region with $\Delta \phi > 2$ is related to the wrong combinations. The ‘true’ or ‘wrong’ label here denotes whether the lepton pair under study are decay products of a $Z$ boson or not. We have

$$\Delta \phi(\ell_1, \ell_3) > 2, \quad \Delta \phi(\ell_2, \ell_3) > 2.$$  

If an event passes the cut on $\Delta \phi$ as in Eq. 15, a “$W$ veto” is applied by requiring the transverse mass of the lepton from the $W$ decay ($\ell_3$) and MET to be below the $W$ boson mass as in Eq. (16). This cut has been chosen to be hard enough to reject SM background samples such as $WZ$, which are important due to having the same final state as the signal.

$$\text{trans. mass}(\ell_3, \text{MET}) < 60 \text{ GeV}$$  

Now before proceeding to the final distribution which is the di-lepton invariant mass, selection efficiencies have to be calculated for a correct normalization of signal and background samples. Tables 7 and 8 show relative efficiencies in signal and background events, respectively.
Table 8 Background selection efficiencies and the total efficiency for each background. STS and STT denote the single top $s$ and $t$ channels, respectively.

| Selection cut | SM Background, $\ell\ell H\nu H$ analysis | $t\bar{t}$ | $WW$ | $WZ$ | $ZZ$ | STS | STT | $W$ | $Z/\gamma$ |
|---------------|---------------------------------|---------|-------|------|------|------|------|------|--------|
| 0 jets Eq. (13) | 0.011                           | 0.59    | 0.55  | 0.61 | 0.052| 0.067| 0.75 | 0.75  | 0.89   |
| 3 leptons Eq. (13) | 0.037                           | 0.0001  | 0.42  | 0.26 | 0.0005| 0.0001| 5.3e−07 | 1.5e−05 |
| MET Eq. (14) | 0.91                            | 0.82    | 0.86  | 0.005| 0.87  | 0.82 | 1    | 0.07  |        |
| $\Delta\phi$ Eq. (15) | 0.19                           | 0.36    | 0.23  | 0.14 | 0.27  | 0.16 | 1    | 0.3   |        |
| $W/Z$ veto Eq. (16) | 0.67                           | 0.62    | 0.77  | 0.97 | 0.63  | 0.71 | 0.5  | 1     |        |
| Total eff. | 4.8e−05                         | 1.5e−05 | 0.035 | 0.0001| 3.7e−06| 1e−06| 2e−07| 3e−07 |        |

Fig. 10 The distribution of di-lepton pair invariant mass in signal ($\ell\ell H\nu H$) and background events

Finally Fig. 10 shows the invariant mass of the lepton pair in signal and background events. As is seen, the signal is visible on top of the background events. The gauge boson pair production ($WZ$) is dominated mostly around the $Z$ boson peak at $\simeq 90$ GeV and the background distribution in the signal region at 40–50 GeV is almost flat making the signal well visible. The sharp signal peak proves that the $\Delta\phi$ cut has effectively selected the true combination of leptons as the off-shell $Z$ decay products. It should be noted that our results are based on setting $m_{Z^*} = m_A - m_H$ and the distribution of the di-muon invariant mass is narrower than in [16,17]. Table 9 presents the mass window cuts and number of signal and background events at 300 fb$^{-1}$ and the signal significance inside the mass window which corresponds to a $3\sigma$ evidence.

Although in this analysis four momenta of jets and leptons are smeared, a detector simulation based on Delphes 3.3.1 is performed on signal events to obtain the final distributions of di-muon invariant mass. The background simulation passed to Delphes takes some time as for each background sample 50 millions of events were simulated. It is, however, interesting to compare the signal distributions from different benchmark points in two channels as shown in Figs. 11 and 12. Replacing the signal distributions with those obtained with detector simulation, the signal significances for the di-lepton plus di-jet analysis are $13\sigma$, $8\sigma$ and $14\sigma$ to be compared with $16\sigma$, $9\sigma$ and $14\sigma$ without detector simulation. The tri-lepton analysis with signals passed through the detector simulation leads to significances of $\sim 2\sigma$ compared to $\sim 3\sigma$ without detector simulation.

8 Toy experiments

In order to study the possibility of signal reconstruction using the signal shape in the di-lepton distribution, a set of toy experiments are generated using RooFit package implemented in ROOT.

To do so, the probability density functions of background and signal distributions are obtained and used to generate a set of pseudo-data. The di-lepton plus di-jet channel is taken as the example. A polynomial plus Gaussian fit is performed on the signal plus background pseudo-data to verify the possibility of mass reconstruction with a likelihood fit. The reconstructed mass is in fact the off-shell $Z$ boson or equivalently $m_A - m_H$.

Figure 13a–c show the pseudo-data of a typical LHC and the fit function and the fitted parameters. The fit function is $p_0 + p_1.x + p_2.x^2 + p_3.Gaus(p_4, p_5)$ where Gaus($p_4, p_5$) is a Gaussian function with the mean value at $p_4$ and the width $\sigma = p_5$. The $p_4$ values are thus the $m_A - m_H$ values which are well obtained from the fit.

9 Discussion

Comparing the results of the two analyses, i.e., the di-lepton plus di-jet channel ($\ell\ell HjjH$) and the tri-lepton channel
Table 9  Mass window cuts in GeV, the number of signal and background events in the mass window and the signal significance at $300 \text{ fb}^{-1}$

|         | Signal BP1 |         | Signal BP2 |         | Signal BP3 |
|---------|------------|---------|------------|---------|------------|
|         | Lower cut  | Upper cut| Lower cut  | Upper cut| Lower cut  | Upper cut  |
| $m(\ell_1, \ell_2)$ (GeV) | 50        | 52      | 44        | 46      | 39        | 41        |
| $N_S$   | 31         | 30      | 28        |         |           |           |
| $N_B$   | 86         | 99      | 104       |         |           |           |
| $\sqrt{N_S/N_B}$ | 3.3      | 3.0     | 2.7       |         |           |           |

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Fig. 11  The distribution of di-lepton pair invariant mass in signal ($\ell\ell jj HH$) with and without detector simulation (CMS) using Delphes.

Fig. 12  The distribution of di-lepton pair invariant mass in signal ($\ell\ell\ell\nu HH$) with and without detector simulation (CMS) using Delphes.

($\ell\ell H\ell\nu$), one may realize that the overall shape of the signal distribution is almost the same. However, there is less background in the di-lepton plus di-jet channel and more signal due to the use of the hadronic decay of the $W$ boson. These issues result in a higher significance.

The $WZ$ background plays the more important role in tri-lepton analysis. However, it has less effect in the di-lepton plus di-jet analysis. The reason is that the signal in di-lepton plus di-jet channel, has missing transverse energy from the dark matter candidate ($H$). The $WZ$ background should undergo $W \rightarrow jj$ and $Z \rightarrow \ell\ell$ decays to mimic the signal. There is no real missing transverse energy in such events and this background is well suppressed by the cut on the missing transverse energy.

On the other hand, in the tri-lepton analysis, the $WZ$ background has to experience $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ decays which produce a source of missing transverse energy through the $W$ leptonic decay. This feature of the $WZ$ background makes it difficult to suppress in the tri-lepton analysis resulting in a $3\,\sigma$ evidence of the signal in the best case.

Extrapolating the results back to an earlier time to obtain the needed luminosity for a $5\,\sigma$, one finds that in di-lepton plus di-jet channel, BP1, BP2 and BP3 will be observable at $5\,\sigma$ at an integrated luminosity of 30, 90 and 38 fb$^{-1}$, respectively. This means that such signals can already be visible at LHC if the same analysis is performed on the collected data.

The signal shape on top of the background can well be used in a likelihood fit to obtain the mass difference $m_A - m_H$ to a reasonable accuracy. Although a momentum/energy smearing was applied on signal and background leptons/jets, a detailed study has to include all sources of theoretical and experimental uncertainties and propagate them to the final signal distributions and its significance. A simple toy experiment, however, shows that the signal can be observable in a blind fit to the total distribution in the di-lepton plus di-jet channel.
10 Conclusions

We presented the LHC potential for a dark matter search by introducing an analysis based on inert double model framework. A set of benchmark points which respect all experimental and theoretical bounds were introduced as working points. The analysis was performed at center of mass energy of 14 TeV. Two main channels, i.e., the di-lepton plus di-jet and tri-lepton channels were analyzed. The results show that distinguishable signals can be obtained at LHC in the di-lepton plus di-jet channel with significances exceeding 5σ earlier than the area of 300 fb\(^{-1}\) integrated luminosity.

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