SIGNATURES OF THE INERT DOUBLET MODEL AT THE LHC

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Abstract

It's easy to add on to the Standard Model and account for dark matter. The Inert Doublet Model is a simple way to do that, too (DM). Under a Z2 symmetry, it says that the vacuum is always the same. This means that it's odd, while all of the particles in the Standard Model are even. It also introduces a new scalar field with the same gauge quantum numbers as the Standard Model Higgs boson, which is a new particle. This new field has the same gauge quantum numbers. When you look at 1 and 2, they're like the Scalar Sector in the IDM, which is like the SM's Scalar Sector. Two SUs are in the IDM (2)scalar doublets. It has a Z2 symmetry because one of the scalar doublets (in our case, 2) is odd, but all the other SM fields (like 1) are even. In our paper, we use a new set of realistic BPs that are consistent with more recent and stronger limitations to see how likely these signals are. More important, we didn't just study BPs alone. We've found places in the APS that are likely to be sensitive to the predicted signals in future LHC experiments as and when it's possible. In part because of the structure of the DM's clumpy structure, it may be possible to figure out how dense it is in the cosmologically small area around the Earth, which hasn't been done yet extremely low.

Keywords: Signature, Inert, Doublet, Model, LHC, etc

1. INTRODUCTION

The It's easy to add on to the Standard Model and account for dark matter. The Inert Doublet Model is a simple way to do this (DM). Under a Z2 symmetry, it says that the vacuum is always the same. This means that it's odd, while all of the particles in the Standard Model are even. It also introduces a new scalar field with the same gauge quantum numbers as the Standard Model Higgs boson, which is a new particle. This new field has the same gauge quantum numbers. There are many different ways that a simple assumption like this one can go wrong. The Z2 symmetry makes sure that the doublet has a DM candidate particle that is very stable. It also doesn't interact with any fermions from the Standard Model when it's on top of a tree. This is why it's called "inert." This, however, doesn't mean that it isn't connected to our visible part of the business. Gauge interactions and the Higgs portal, on the other hand, are two ways that the observable world communicates with the non-observable world. For example, in the potential, terms like ()(),, which is the Standard Model Higgs doublet, are used. If you choose the right parameters, you could explain why the DM abundance DMh2 = 0.1199 0.0027 is so high. These interactions with Standard Model particles could also send DM signals in both direct and indirect ways.

Relics are everywhere: The freeze-out method is one of the most common ways to make DM. If you look at this framework, DM particles should interact with Standard Model particles in pairs, with a strength that affects how many DM particles are made and how many of them are destroyed. In addition, it's thought that the At high enough temperatures, DM particles and Standard Model particles were in thermal equilibrium, which means they were in the same state. This means that the rate at which they were born and killed was the same. This is how it worked: The DM mass went down in temperature when the temperature fell below that point particles kept annihilating, but they couldn't be made again because the Standard Model particles couldn't be made again because they were too hot lacked the kinetic energy to produce DM particles. When a result, as the Universe cooled, the number of DM particles reduced exponentially. This process would have continued in a static world Because of the expansion of the Universe, the number of DM particles became so low at some point that annihilations were no longer possible. The amount of DM per volume of movement "froze-out" after this era and stayed roughly stable until the present epoch.

1.1 Signatures of Inert Doublet model at Future e+e Colliders

It's If you want to add more information and find a dark matter (DM) candidate, this is one of the easiest ways. Inert Doublet Model: This model is called that because it doesn't have any extra parts (IDM). Another Higgs doublet is called a "inert or dark doublet" in this model. In addition, the scalar sector has a so-called "SM Higgs doublet S." D is the name of this two-piece (the only field odd under Z2 symmetry). The SM Higgs boson h and four dark scalars, two of which are neutral and two of which are charged, are formed, as shown in the figure. When it comes to both theory and experiments, there had to be two sets of benchmark points that had to be met. They looked at all possible signs at e + e colliders with IDM particle masses up to 1 TeV, and they looked at them all. The scalar mass distributions for each of the IDM tests. H is the scalar that is the lightest and the most stable in the benchmark cases that were looked at. It could be a good DM option.

2. REVIEW OF THE LITERATURE

Fa-Xin Yang, Zhi-Long Han, and Yi Jin (2021) in this study, we examine in more detail, the same-sign dilepton signature in the inert double model Randomly, we look through the right parameter space, focusing on the low dark matter mass area. As a result of a number of limitations, viable samples are found, and twenty benchmark sites are chosen for more research into collider signatures. If you have hadron colliders, the same-sign dilepton signature can be made by the leptonic decay mode, which is called $ H pm to H W pm (to l pm nu)$. The $ppto W pm *W pm *JJ to H pm H pm jj$ is also used, where H is the candidate for dark matter. We look at how well the signal can be tested at the 27 TeV high-energy level energy LHC (HL-LHC) and the high-luminosity LHC (HL-LHC) (HE-LHC). The HL-LHC with $mathcalL=3ab-1$ can hardly investigate this signal, according to our simulation. Meanwhile, when $250textGeVlesssim m Hpm-m Hlesssim 300$ GeV with dark matter mass $m Hsim 60$ or 71 GeV is used with the HE-LHC with $mathcalL=15ab-1$, a $5sigma$ significance is expected.

Adil Jueid, Jinheung Kim, Soojin Lee, Adil Jueid, et al (2020) The inert doublet model is a simple dark matter model with strong theoretical underpinnings. In this model, dark matter is stabilised by enforcing Z2 parity, which keeps dark matter from moving away. Making Z2 parity into a global U(1) symmetry is something we look into. Both CP-even and CP-odd neutral inerts h1 and h2 can be possible DM candidates in this picture. Model parameters are one less than with Z2, which has more parameters. There are tests for LEP, electroweak precision, Higgs precision, theoretical stability and the density of dark matter relics. There are also tests for direct detection and experiments that look for dark matter relics that can be found. This is true even when the model is used to explain at least 10% of the relic density. There is a lot of dark matter that has a mass of about 70 GeV. The charged Higgs boson is also very light. At the LHC, we figure out the production cross sections of almost all the possible mono-X and mono-XX′ processes. We only look at a small set of parameters to figure this out. In this way, mono-W can be shown to be a good way to find new things. To make it more likely that a model for mono W signals will be found, search techniques are used at both the HL-LHC and the FCC-hh to look for them. It's thought that the best ETmiss/HT cut to make a signal more important is around 0.76 at the HL-LHC and around 7.5 at the FCC-hh. This is what people think.

Aleksander Zarnecki, Jan Kalinowski, Jan Klamka, et al (2019) There are many things that can be added to the Standard Model, but one of them is a candidate for dark matter. There are a lot of them, and the Inert Doublet model is just one of them, Second doublet: This two-Higgs doublet model says that the second doublet has more Higgs bosons scalars (inert scalars) don't connect with fermions from the Standard Model, which keeps the lightest of them from colliding with each other, keeping the model as stable as possible. A lot of different Inert Doublet Model scenarios are looked at to see if XENON1most T's recent limits, as well as collider and low-energy limits, are in line with what we know now. When we build future colliders, we look at a group of places that we think will show up when they're used as benchmarks. It looks at how each inert scalar pair is made. Then, the decays of Hpm and A into the final states, which are the lightest and most stable neutral scalar dark matter candidate H and Hpm, are looked at. For center-of-mass energies up to 3 TeV, this is the best way to get the best picture.the significance of expected data is looked into for a variety of benchmark models and different operating scenarios. Signal signatures with two muons in the final state or an electron and a muon are shown in numbers. Qualitative conclusions can also be drawn for semi-leptonic signatures.

Alexander Belyaev, Giacomo Cacciapaglia, Igor Ivanov, Felipe Rojas, and Marc Thomas (2016) It's called the inert Two Higgs Doublet Model (i2HDM), and it's a well-thought-out example of a minimal Dark Matter (DM) model that makes monojet, monoZ, monoHiggs, and VBFusion+Missing Transverse Momentum signatures at the LHC, which are also backed up by signals from direct and indirect DM search experiments. It talks about what kinds of things we know about i2HDM's full 5D parameter space. These things include perturbativity, unitarity, electroweak precision data, Higgs data from the LHC, like the density of Higgs relics, how direct or indirect detection works, and how monojet analysis works. Limitations: In this section, we show how the limitations above work together and give estimates for future LHC data as well as direct DM detection studies that will help us look into the i2HDM parameter space even more. In the CalcHEP and micrOMEGAs programmes, the model has been added to them. The HEPMDB database can help you find both of these programmes. If you want to find out what's going on at the LHC or find out how many relics are there, this can help the future.

3. OBJECTIVES

- To study Signatures of Inert Doublet model at Future e+e Colliders.
- To investigate The IDM's restrictions and their ramifications and multilepton signatures at the LHC.

4. RESEARCH METHODOLOGY

4.1 Description of the Model

The IDM has two SU(2) scalar doublets, Φ1 and Φ2, which are a straightforward extension of the SM's scalar sector. One of the scalar doublets (in our case Φ2) is odd, whilst all other SM fields (including Φ1) are even, resulting in a discrete Z2 symmetry. Φ 2 does not produce any VEV if this additional Z2 symmetry is not spontaneously destroyed. As a result, the other Z2 even scalar doublet Φ1 resembles the SM Higgs doublet quite closely. At the tree level, the renormalizable CP-conserving Z2 symmetric scalar potential is provided by

$$\begin{aligned} V(\Phi_1,\Phi_2) &= \mu_1^2|\Phi_1|^2 + \lambda_1|\Phi_1|^4 + \mu_2^2|\Phi_2|^2 + \lambda_2|\Phi_2|^4 \\ &\quad + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right] \end{aligned} \quad (1)$$

Where $\mu_{1,2}$ and λ_i (i = 1, 2, 3, 4, 5) are actual variables. The following is a list of the two scalar doublets:

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

Where v is the VEV of the Φ_1, $G^\pm$ and G^0 are Goldstone bosons. The Z_2 symmetry is unbroken, ensuring that

- ✓ Because there is no mixing between these two scalar doublets, h acts as the SM Higgs field. The doublet Φ_2 produces four new scalar states: a CP even neutral scalar H, a CP odd neutral scalar A, and a pair of charged scalar fields $H^\pm$.
- ✓ Because these new scalars have no interaction with the SM fermions, they are referred to as "inert."
- ✓ Only colliders can produce non-standard scalar fields in pairs.
- ✓ Because the lightest scalar neutral field (H or A) is absolutely stable, it could be a DM candidate.

The scalar potential provided in eq. (1) looks like this after the spontaneous breakdown of the EW symmetry.

$$\begin{aligned} V(h,H,A,H^\pm) &= \frac{1}{4}\left[2\mu_1^2(h+v)^2 + \lambda_1(h+v)^4 + 2\mu_2^2(A^2 + H^2 + 2H^+H^-) \right. \\ &\quad \left. + \lambda_2(A^2 + H^2 + 2H^+H^-)^2\right] \\ &\quad + \frac{1}{2}(h+v)^2\left[\lambda_3 H^+H^- + \lambda_S A^2 + \lambda_L H^2\right] \end{aligned} \quad (2)$$

Where

$$\lambda_{L,S} = \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5) \quad (3)$$

Masses of these scalars are given by,

$$m^2_h = \mu^2_1 + 3\lambda_1 v^2$$

$$m^2_H = \mu^2_2 + \lambda_L v^2$$

$$m^2_A = \mu^2_2 + \lambda_S v^2$$

$$m^2_{H\pm} = \mu^2_2 + 1/2\, \lambda_3 v^2$$

For $\lambda_4 - \lambda_5 < 0$ and $\lambda_5 > 0$ ($\lambda_4 + \lambda_5 < 0$ and $\lambda_5 < 0$), A (H) is the Z_2 odd particle that is the lightest (LOP). In this paper, we consider A to be the LOP and hence a valid DM candidate. Choosing H as the LOP will have similar outcomes. We define them as follows for subsequent convenience because the mass difference between A and $H^\pm$ commonly appears in computations.

$$\Delta M_H = m_H - m_A,$$

$$\Delta M_{H\pm} = m_{H\pm} - m_A$$

As a result, the IDM's independent set of parameters becomes $\{m_A, \Delta M_H, \Delta M_{H\pm}, \lambda_2, \lambda_S\}$. As A is the DM candidate, the Higgs portal coupling λ_S is chosen as a free parameter. We set $\lambda_2 = 0$ throughout this project because λ_2 have no bearing on the relic density computation.

5. RESULT AND DISCUSSION

5.1 The IDM's restrictions and their ramifications

According to theory, the model outlined in the previous section has a five-dimensional parameter space that is limited by things like the People talk about these things when they talk about stable vacuums, perturbativity, and a single scattering matrix. In addition to the precision of the EW, the LEP search limits, and the Higgs decay width found at the LHC, a few more restrictions are put on the experimental ground because of these three things: The most important restriction is that the IDM only fills up the measured density of DM relics in the universe. The first thing we do in this work is figure out the APS for three different scenarios with the given constraints:

A. mA = 70.0 GeV, λS = 0.005 (fig. 1)

mA = 70.0 GeV and S = 0.007 (fig. 2)

mA = 55.0 GeV, and S = 0.0035 (fig. 1)

(A) and (B) (B). Scenario (C), on the other hand, is a way to think about a parameter space where the decay of the Higgs isn't visible permitted. The free parameters ΔM_H and $\Delta M_{H\pm}$ outline the APS constrained by the aforesaid constraints in all three scenarios. These factors, combined with m_A, determine the potential LHC signatures in each of the scenarios that will be examined in the next sections. It should be observed that the constraint imposed by the undetectable decline width of h in scenario (C) necessitates λ_S to be ~ 10^{-3}. Larger λ_S might have been chosen in scenarios (A) and (B), as long as the choice is consistent with the measured DM relic density.

i. Bounds derived from the diphoton signal strength at the LHC

At one loop This is how it works: in the IDM, H makes extra contributions to the Higgs' diphoton decay process. The ATLAS collaborations found that = 1.170.27 and = 0.27. the CMS collaborations measured values of $\mu_{\gamma\gamma}=1.14^{+0.26}{}_{-0.23}$. These empirically determined values at 1.5σ levels are compatible with the BPs utilized in this work.

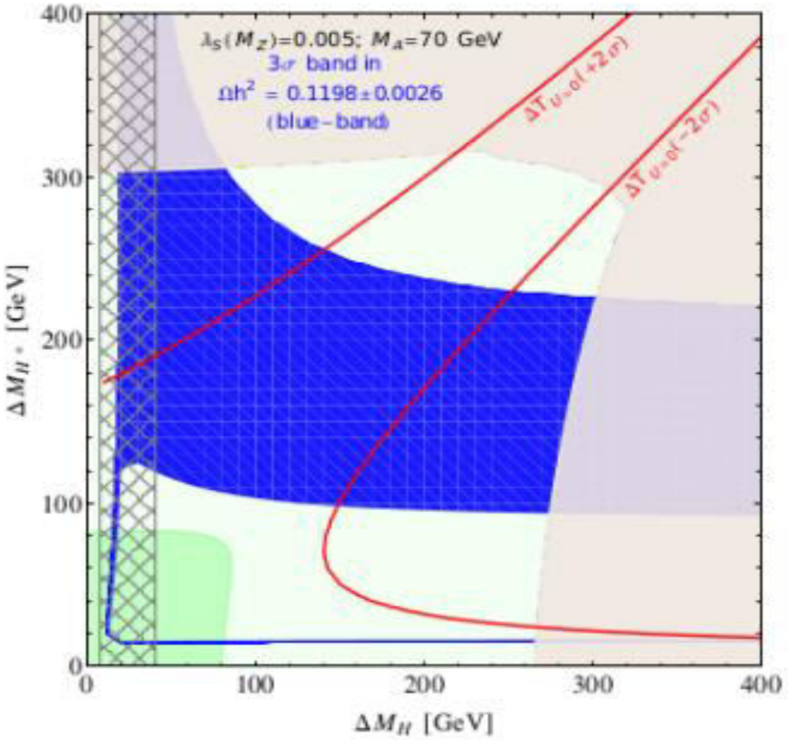

Figure 1: The allowed parameter space in the $\Delta M_H - \Delta M_{H\pm}$ plane for m_A = 70 GeV and λS = 0.005. Constraints coming from the T parameter allow only the area between the solid red lines. In the lower left corner of the green region, the unitarity bound is valid up to the Planck scale. In the light green region, the unitarity bound is valid up to 10 TeV. The blue regions are allowed by the DM constraint at the 3σ level and the relaxed unitarity constraint. The cross-hatched region is excluded from the LEP II data

ii. Invisible Higgs decay bounds from the LHC

The Higgs can decay into a pair of these particles if inert particles are lighter than $m_h/2$. When the Higgs can decay into a pair of LOPs, the invisible Higgs decay width as observed at the LHC places strict constraints on the parameter space of the IDM. The BR of the Higgs in the invisible channel is around 0.05 in scenario (C).

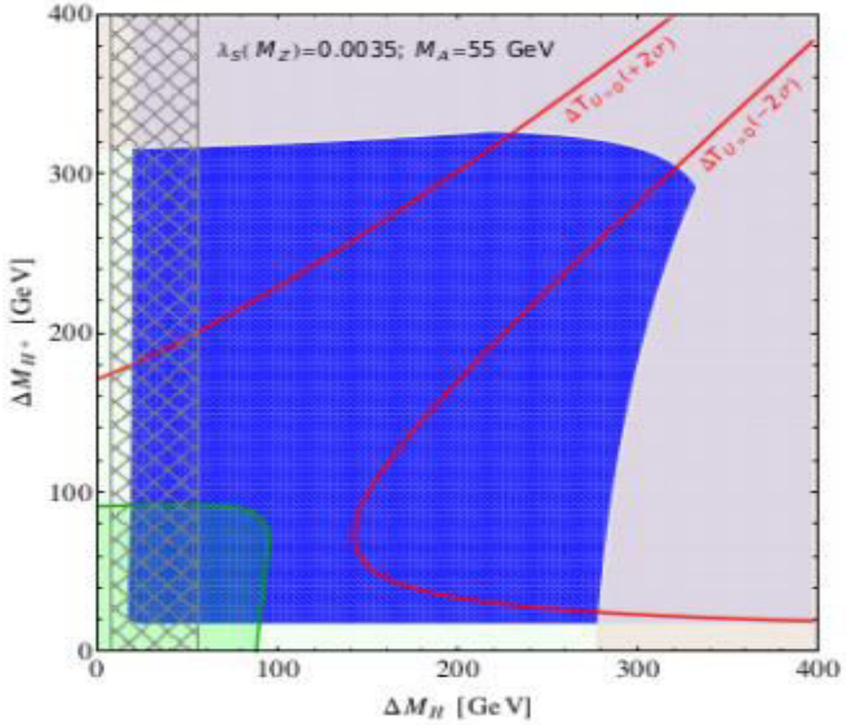

Figure 2: The allowed parameter space in the $\Delta M_H - \Delta M_{H^\pm}$ plane for mA = 55 GeV and λ_S = 0.0035. Constraints coming from the T parameter and the stronger unitarity condition are as in fig. 6.1. The blue region is allowed by the DM constraint at the 3σ level and the weaker unitarity condition. The cross-hatched region is excluded from the LEP II data

5.2 The multilepton signatures at the LHC

As previously stated, due to Z2, the inert scalars are formed in pairs because they are all the same. At the LHC, the most common ways to make things are HH, HA, and H+H. The heavier scalar H (H) breaks down into the SM gauge boson W(Z) and the stable inert scalar A leaves the detector, which results in T. According to the decay modes that W and Z have when they die, there can be a lot of different final states (e.g., jets +/-T; leptons +/-T; jets +/-T) that can be made. It isn't just m-leptons that we look at in our work. We also look at m-leptons and their signatures in future LHC experiments with m = 3, 4, or 5. FeynRules were used to make the IDM model file, and micrOMEGAs were used to find out how many relics there were in the IDM file. our analysis, considering A as the DM candidate. CalcHEP is used to produce signal events. PYTHIA uses the CalcHEP-PYTHIA interface to perform hadronization and showering. To minimize double counting of jets, Each background event is made with an extra jet at the parton level by using ALPGEN with MLM matching. The extra jet is then sent to the background event PYTHIA for hadronization and showering.

- **5l + $\notin_T$ signal:**

The 5l + $\notin_T$ + X signal's chances in future LHC experiments the key factor influencing the signal is

$$pp \rightarrow H^{\pm}H \text{ followed by } H^{\pm} \rightarrow W^{\pm}H,\ W^{\pm} \rightarrow l^{\pm}\nu \text{ and } H \rightarrow l^{+}l^{-}A$$

It's worth noting that H^+ pair formation (where both H^+ and H^- decay into W H) can theoretically lead to 5l + $\notin_T$ ultimate states. However, we have discovered that its contribution is insignificant. The SM backdrop is listed below.

- ✓ Production of ZZZ followed by leptonic decays of all three Z bosons, with one lepton not detected or failing to pass the cutoff.
- ✓ Production of $W^{\pm}$ ZZ, in which both $W^{\pm}$ and Z decay into leptons.
- ✓ $t\bar{t}Z$ production, where the corresponding decay occurs via $Z \rightarrow l^{+}l^{-}$, $t(\bar{t})\ b(\bar{b})W^{+}(W^{-})$, $W^{\pm} \rightarrow l^{\pm}\ v$, and one lepton is produced by b decay (b→ clv).

The background is considerably reduced by requiring 5 isolated leptons in the final state. The background can be effectively reduced to a negligible level with a $\notin_T$ cut of 80 GeV. Table 1 summarizes the findings.

Table 1: Number of 5l events (S) at $\sqrt{s}$ = 13 TeV for an integrated luminosity of 3000 fb^{-1} The SM background is negligible

Benchmark	**Signal events after cuts (S)**	**Benchmark points**	**Signal events after cuts (S)**
BP6	3.33	BP11	5.37
BP7	3.89	BP12	1.92
BP8	1.75		

The rest In table 1, some of the BPs may give clues about the IDM at the LHC until much more high luminosity (> 3000 fb-1) is accumulated. To help the LHC search for the IDM, BPs 1 through 11 can serve as hints until much more high luminosity (> 3000 fb-1) is collected. The chances of seeing multilepton (ml) signatures predicted by the IDM, a well-known DM model, in future LHC experiments for m = 3,4 have been looked at again. It's important to remember that the previous observability analyses used BPs that didn't work well in the post-Higgs era because of the strict LHC rules. It was very difficult to figure out how big the Higgs boson was and how small its decay width could be deserve special emphasis in this context. We also simulate the 5l + $\notin_T$ signal for the first time and investigate its observability.

6. CONCLUSION

Our work focuses on evaluating the likelihood these signals will now be shown using a new set of realistic BPs that are in line with more recent and stronger limitations. More important, we didn't just study BPs alone. We've found places in the APS that are likely to be sensitive to the predicted signals in future LHC experiments as and when it's possible. In part because of its shape, the density of the DM in the small area around Earth that hasn't been directly measured is very low. This is because of the DM's clumpy structure. This makes the idea of making and detecting DM at a high-energy collision like the LHC very appealing. Recent attention has been paid to the search for the DM at the LHC, which has made people talk. A lot of different theories have been put forward that are compatible with the relic density data, and their possible LHC fingerprints have been looked into. Completed: The discovery of the Higgs boson has made sure that the SM has a full spectrum. However, it must be said that the SM's scalar sector is the least limited. Since the scalar sector has been expanded, it's very likely that this particle comes from the DM particle.

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