PROCEEDINGS OF SCIENCE

Searching for dark matter in 2HDM + complex singlet at future (lepton) colliders

Juhi Dutta,[a,b] **Jayita Lahiri,**[c,*] **Cheng Li,**[d] **Gudrid Moortgat-Pick,**[c,e] **Sheikh Farah Tabira**[c] **and and Julia Anabell Ziegler**[c]

[a] *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA*

[b] *The Institute of Mathematical Sciences, 4th Cross St, CIT Campus, Tharamani, Chennai, Tamil Nadu, India, 600113*

[c] *II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*

[d] *School of Science, Shenzhen Campus of Sun Yat-Sen University, Gongchang Road 66, 518107 Shenzhen, China*

[e] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*

E-mail: juhidutta@imsc.res.in, jayita.lahiri@desy.de, gudrid.moortgat-pick@desy.de, lich389@mail.sysu.edu.cn, sheikh.farah.tabira@desy.de, julia.ziegler@desy.de

We investigate the phenomenological prospects of the Two Higgs Doublet and Complex Singlet Scalar Extension (2HDMS) in the context of dark matter (DM) and Higgs phenomenology. The 2HDMS provides an enlarged Higgs sector along with a DM candidate. In this work, we perform an exhaustive scan to find representative benchmarks which are consistent with all theoretical and experimental constraints. We choose benchmarks with light, intermediate and massive DM masses and in some cases, also accommodate the 95 GeV excess in $b\bar{b}$ and $\gamma\gamma$ channels observed at the Large Electron-Positron Collider (LEP) and Large Hadron Collider (LHC). We investigate and compare different DM signal topologies for different DM mass regions and focus on the relevant signatures at all current and future colliders such as the LHC and at proposed future lepton colliders including electron-positron and muon colliders. Using a cut and count analysis, we show that while the High Luminosity LHC (HL-LHC) may hint towards new physics, future lepton colliders prove to be efficient discovery probes for dark matter searches at colliders.

The European Physical Society Conference on High Energy Physics (EPS-HEP2025)
7-11 July 2025
Hamburg, Germany

*Speaker

PoS(EPS-HEP2025)044

1. Introduction

The Standard Model (SM) of particle physics has established itself on strong grounds over time. At the same time, indirect evidence of dark matter (DM) via gravitational interaction has been found in galaxy rotation curves [1], the Bullet cluster data [2] as well as the cosmic microwave background [3]. Yet, the SM does not provide a suitable DM candidate. The most recent discovery of a 125 GeV Higgs boson, on the one hand, solidified the viability of the SM, on the other hand, it opened up the possibility of an extended scalar sector. Therefore the Higgs boson and its properties have become a crucial sector to probe New Physics. Furthermore, searches for extra scalars are ongoing at the collider experiments. The extended scalar sector where extra doublets and singlets are appended to the SM Higgs sector, can also provide an answer to the DM problem. In this context, we have considered a complex singlet extension of the two Higgs doublet model (2HDMS) [4]. Such a scenario can provide a scalar DM candidate if suitable symmetries are imposed on the scalar potential.

In the current work, we investigate DM searches at future colliders in the context of 2HDMS, as a reference model. We perform an exhaustive study of the model parameter space, identifying regions that are allowed by existing data and at the same time are interesting from the point of view of DM phenomenology. We further mention that a new excess has been observed both at the former Large Electron-Positron Collider (LEP) [5] in the $b\bar{b}$ mode as well as in the $\gamma\gamma$ final state at the Large Hadron Collider (LHC) experiments CMS and ATLAS [6, 7]. We incorporated this excess in some of our chosen benchmarks. Furthermore, we focus on choosing benchmarks for our collider study, that can be probed at future colliders. In this regard, we intend to perform a comparative analysis, in order to establish a complementarity between various proposed future colliders such as High Luminosity LHC (HL-LHC), International Linear Collider (ILC) [8], Future Circular Collider in electron-positron mode (FCC-ee [9],CEPC [10]), Compact Linear Collider (CLIC) [11] and muon collider [12], in terms of detection prospects. We thereby identify regions of parameter space that can be probed at certain colliders and also point out the relevant channels that are most sensitive to each benchmark scenario. The SM backgrounds at various colliders and their effects are considered in detail. We explore the potential at the HL-LHC via the gluon fusion (GGF), vector boson fusion (VBF) and $b\bar{b}$ associated Higgs production (BBH) channels in mono-jet, di-jet and two b-jet along with missing transverse energy (MET) final states. We concentrate on the mono-photon, mono-Z, $b\bar{b}$ and $t\bar{t}$ + MET final states, at e^+e^- and muon colliders. $b\bar{b}$ and $t\bar{t}$ associated production channels have not previously been considered in the context of DM searches at high energy lepton colliders. We identify, via a detailed collider study the most sensitive channels for discovery of 2HDMS at both electron-positron and muon colliders and provide a guideline for future experiments. This contribution summarizes the results presented in [13].

2. The 2HDMS Framework

The scalar potential consists of the 2HDM Type-II sector with softly broken Z_2 symmetry, supplemented by a complex singlet charged under a Z_2' symmetry. Under the aforesaid symmetries, the scalar potential can be written as:

$$V = V_{2\text{HDM}}(\Phi_1, \Phi_2) + V_S(\Phi_1, \Phi_2, S) \tag{1}$$

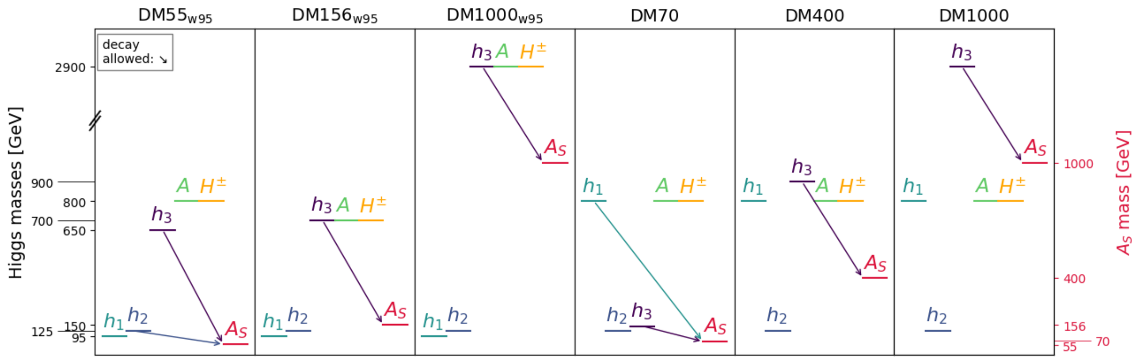

Figure 1: Chosen benchmarks and mass hierarchies in them.

where Φ_1 and Φ_2 are the two $SU(2)$ doublets and S is the $SU(2)$ singlet field. Explicit expressions for $V_{2\text{HDM}}(\Phi_1, \Phi_2)$ and $V_S(\Phi_1, \Phi_2, S)$ can be found in [13]. The vacuum expectation values (vev) of the fields are as follows.

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ v_i + \rho_i + i\eta_i \end{pmatrix}, \quad \langle \Phi_i \rangle = \begin{pmatrix} 0 \\ v_i \end{pmatrix}$$

$$S = \frac{1}{\sqrt{2}}(v_S + \rho_S + iA_S), \quad \langle S \rangle = v_S$$

After electroweak symmetry breaking, the physical spectrum includes three neutral scalars h_1, h_2, h_3, a pseudoscalar A, charged Higgs bosons $H^\pm$, and the DM candidate A_S. One scalar (here assumed to be h_2) is SM-like ($\approx$ 125 GeV). The DM candidate interacts with SM particles through the Higgs portal couplings.

3. Benchmark Scenarios and Constraints

We chose benchmark points (BPs) spanning the following parameter regions:

- Low DM mass ($\sim$ 55–70 GeV),
- Intermediate DM mass ($\sim$ 150–400 GeV),
- Heavy DM mass ($\sim$ 1 TeV).

Our benchmark choices are motivated by the prospect of detecting them in the future colliders, which is why different mass ranges are focussed on. We are interested in the final state topology DM+X ($X = \gamma, Z$), where a DM pair is produced in the onshell decay of one of the scalars (h_1, h_2, h_3) via $h_i \to A_S A_S$.

Each BP satisfies:

- theoretical constraints: stability, perturbativity, unitarity,
- collider constraints from Higgs signal strengths and direct searches,

- dark matter constraints: relic density [14], LZ direct detection [15], indirect detection [16] limits.

The selected benchmarks and the mass hierarchies therein are presented in Fig. 1. Scenarios involving the 95 GeV excess are shown with the subscript w95. Out of the benchmarks we analyzed, $\mathbf{DM156_{w95}}$ is under-abundant, while all other benchmarks are fully relic-abundant. We study $\mathbf{DM156_{w95}}$, because although relic-underabundant, this benchmark is collider-friendly due to having large dark-portal couplings.

4. Collider Analysis

Having chosen benchmarks from interesting regions of parameter space, we probe the benchmark scenarios at the future colliders, namely HL-LHC, e^+e^- collider and muon collider. In this section we present the collider analysis.

4.1 Prospect at the HL-LHC

We explore the possibility of probing low and intermediate mass DM at the HL-LHC in the following final states.

- Gluon fusion process with mono-jet + MET,
- VBF production with two forward jets + MET,
- $b\bar{b}$ + MET.

We present the Feynman diagrams corresponding to the aforementioned final states in Fig. 2. Z+jets, $t\bar{t}$, QCD multijets are the major backgrounds at the LHC. After choosing suitable kinematical observables (for details we refer to [13]) for signal-background separation, we obtain the following signal significance values, presented in Table 1.

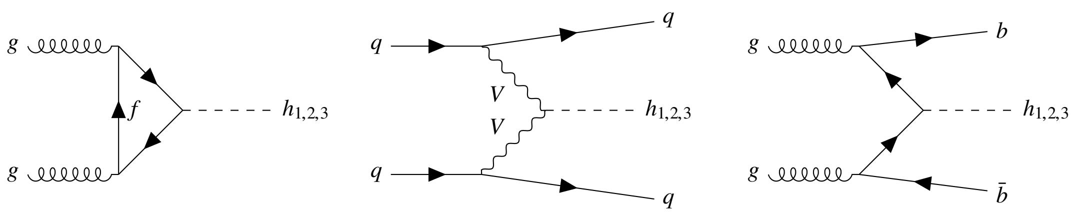

Figure 2: Feynman diagrams pertaining to GGF, VBF and $b\bar{b}$-associated production.

Certain conclusions can be drawn from Table 1. While $\mathbf{DM55_{w95}}$ remains difficult to probe at the HL-LHC (primarily due to relatively small invisible branching fraction of the 125 GeV Higgs in this BP), **DM70** and $\mathbf{DM156_{w95}}$ achieve a significance of order 2σ. Overall, the HL-LHC can provide mere hints for DM (upto a 2σ excess) for certain benchmarks, but not a clear, observed signal, for which we need a higher signal significance. For this purpose, we explore the lepton colliders.

Benchmark	m_χ (GeV)	m_{h_i} (GeV)	$BR(h_i \to \chi\chi)$	channel	Significance
$\mathbf{DM55_{w95}}$	55 GeV	125 GeV	2%	GGF	0.33 σ
DM70	70 GeV	150 GeV	100%	VBF	1.94 σ
$\mathbf{DM156_{w95}}$	156 GeV	700 GeV	69%	$b\bar{b}h_i$	1.95 σ

Table 1: Signal significance of $\mathbf{DM55_{w95}}$, **DM70** and $\mathbf{DM156_{w95}}$ at the HL-LHC. The results are shown for the channels in which the best signal significance is obtained.

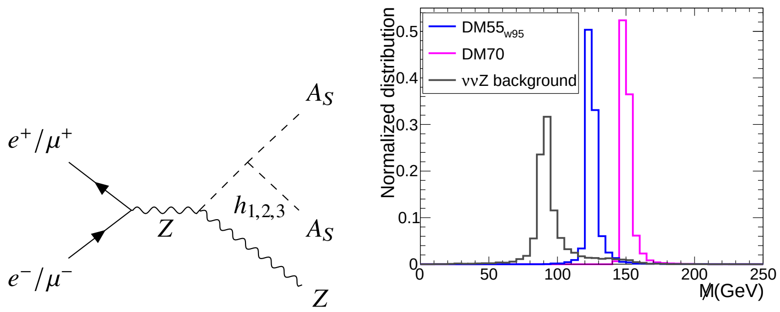

Figure 3: (left) Feynman diagrams for mono-Z+MET final state, (right) $\not{M}$ distribution for signal and background.

4.2 Prospect at the e^+e^- Colliders

In the low mass region, we take $\mathbf{DM55_{w95}}$ and **DM70** as representative BPs. At $\sqrt{s} = 250\,\text{GeV}$ (ILC, FCC-ee, CEPC), we study mono-photon, mono-Z, $b\bar{b}$-associated, and VBF-like channels. The mono-Z final state from Higgs-strahlung process $e^+e^- \to Zh_i$, $h_i \to A_S A_S$ provides the strongest sensitivity due to larger cross-section compared to the other processes.

We show the Feynman diagram for the dominant process pertaining to mono-Z + MET final state in Fig. 3 (left). The major background comes from SM $\nu\bar{\nu}Z$ final state. For signal-background separation we chose an observable called missing mass ($\not{M}$) which is defined as follows.

$$\not{M}^2 = (p_{in} - p_{out})^2. \tag{2}$$

Benchmark	$\sqrt{s}$ (GeV)	Collider	Channel	Cut	Significance
$\mathbf{DM55_{w95}}$	250 GeV	e^+e^-	mono-Z	$\not{M}$ > 100 GeV	11σ(1 ab^{-1})
DM70	250 GeV	e^+e^-	mono-Z	$\not{M}$ > 130 GeV	3σ(3 ab^{-1})

Table 2: Signal significance of $\mathbf{DM55_{w95}}$ and **DM70** at the e^+e^- collider. Suitable final states and kinematical cuts are also presented.

The missing mass distribution for the signal and background is shown in Fig. 3 (right). The signal significances that can be achieved for the two low mass BPs considered, are presented in Table 2 along with the relevant kinematical cuts.

4.3 Prospect at the Muon Collider

We now discuss the prospect of the intermediate and heavy mass benchmarks at the muon collider. The muon collider is proposed to run at $\sqrt{s}$ = 3 TeV and 10 TeV.

For the intermediate mass benchmark **DM156$_{\mathbf{w95}}$**, at $\sqrt{s}$ = 3 TeV, $b\bar{b}$+MET final state (Feynman diagrams shown in Fig. 4 (left)) provides the largest event yield. The SM processes $t\bar{t}$ and $b\bar{b}\nu\bar{\nu}$ are the dominant backgrounds in this case. After using invariant mass of the $b\bar{b}$ pair (m_{bb}) as discriminant between signal and background (see Fig. 4(right)), we obtain the signal significance of 6.3 σ at 3 ab^{-1} integrated luminosity (see Table 3).

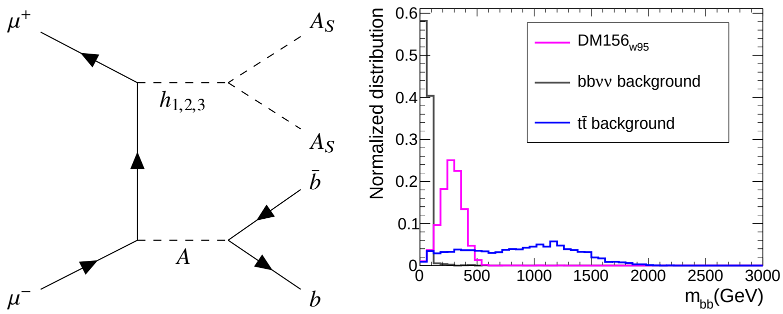

Figure 4: (left) Feynman diagrams for $b\bar{b}$+MET final state, (right) m_{bb} distribution for signal and background.

The muon collider benefits from an enhanced Yukawa coupling of muons relative to electrons, leading to significantly larger (~ 4 orders of magnitude) mono-photon (Feynman diagram in Fig. 5(left)) and mono-Z cross sections at the muon collider compared to the e^+e^- collider. Owing to the enhanced cross-section, it is possible to probe the intermediate mass BP **DM156$_{\mathbf{w95}}$** in the mono-photon final state at the muon collider at $\sqrt{s}$ = 1 TeV, which is significantly lower than the design energy of 3 TeV. We present missing mass distribution of signal and $\nu\bar{\nu}\gamma$ background in Fig. 5(right) and the corresponding signal significance in Table 3. Therefore, our results indicate a stronger physics case for a 1 TeV $\mu^+\mu^-$ collider compared to high energy e^+e^- colliders namely, 1 TeV ILC or even 3 TeV CLIC for probing an intermediate mass DM.

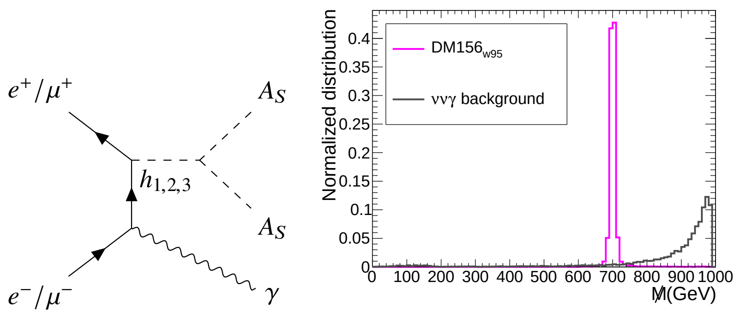

Figure 5: (left)Feynman diagram for mono-photon+MET final state at the e^+e^- and muon collider, (right) $\not{M}$ distribution for signal and background in the mono-photon + MET final state at $\sqrt{s}$ = 1 TeV muon collider.

For DM mass near ~ 1 TeV, which we call the heavy mass benchmark, only multi-TeV muon collider can provide adequate reach. At $\sqrt{s}$ = 10 TeV, the $t\bar{t}$ + MET final state (Feynman diagram in Fig. 6

Benchmark	$\sqrt{s}$ (GeV)	Collider	Channel	Cut	Significance
$\mathbf{DM156_{w95}}$	3 TeV	$\mu^+\mu^-$	$b\bar{b}$+MET	100 GeV < m_{bb} < 500 GeV	$6.3\sigma(3\ \text{ab}^{-1})$
$\mathbf{DM156_{w95}}$	1 TeV	$\mu^+\mu^-$	mono-photon	690 GeV < $\not{M}$ < 710 GeV	$3\sigma(3\ \text{ab}^{-1})$, 5.3σ $(10\ \text{ab}^{-1})$

Table 3: Signal significance of $\mathbf{DM156_{w95}}$ at the muon collider. Suitable final states and kinematical cuts are also presented.

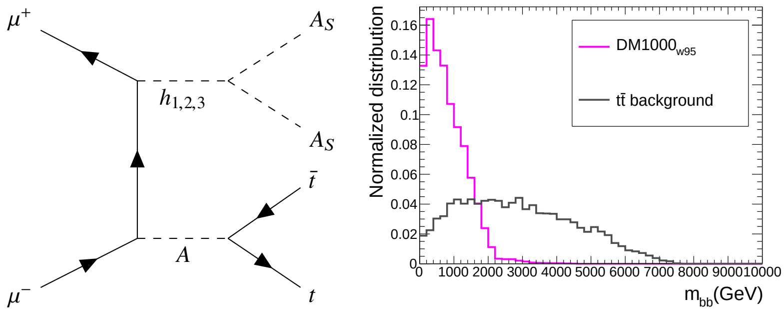

Figure 6: (left) Feynman diagrams for $t\bar{t}$+MET final state, (right) m_{bb} distribution for signal and background at $\sqrt{s}$ = 10 TeV muon collider.

(left)) is most sensitive. We note that, for heavy $h_i(\sim 3$ TeV), the largest BR to $t\bar{t}$ causes overall enhanced signal rate in this final state.

Benchmark	$\sqrt{s}$ (GeV)	Collider	Channel	Cut	Significance
$\mathbf{DM1000_{w95}}$	10 TeV	$\mu^+\mu^-$	$t\bar{t}$ + MET	m_{bb} < 2 TeV	$3\sigma(10\ \text{ab}^{-1})$

Table 4: Signal significance of $\mathbf{DM1000_{w95}}$ at the muon collider. Suitable final states and kinematical cuts are also presented.

The major background in this case is the SM $t\bar{t}$ process. We use the invariant mass of $b\bar{b}$ pair (m_{bb}) in order to enhance the signal over background. The distributions of m_{bb} for the signal and background are shown in Fig. 6(right). After applying suitable cut on this observable we obtain 3σ signal significance at the 10 TeV muon collider with integrated luminosity of 10 ab^{-1}. We present the results in Table 4.

4.4 Challenges and Complementarity

We found, that there are scenarios among our chosen benchmarks, namely, **DM400**, **DM1000** in Fig. 1, that are allowed by all constraints, and account for the total observed relic density of the universe. Furthermore, the branching fraction of the heavier scalar to DM pair can be very large in these benchmarks. This is because, in the aforementioned benchmark scenarios, the heavier scalar that decays on-shell into a pair of dark matter particles, is predominantly singlet-like and therefore has negligible couplings to the SM states. Due to the same reason, their production becomes challenging, even at the 10 TeV muon collider. In this context, FCC-hh may be helpful. Being a hadron machine, it will offer enhanced cross-section in GGF process as well as $b\bar{b}$-associated production processes. We provide a comparison between the production cross-sections at 14 TeV

LHC and 100 TeV FCC-hh in the gluon fusion process for **DM400** and **DM1000** in Table 5. However, we have not performed a full signal-background analysis for FCC-hh case and leave it for future studies.

Collider	Process	Production cross-section (fb)	
		DM400	**DM1000**
LHC($\sqrt{s}$ = 14 TeV)	GGF	0.016	1.27×10^{-4}
FCC-hh($\sqrt{s}$ = 100 TeV)	GGF	1.456	0.117

Table 5: The production cross-sections at leading order (LO) at $\sqrt{s}$ = 14 TeV at LHC and $\sqrt{s}$ = 100 TeV at FCC-hh.

5. Conclusion

The purpose of our study is to explore the possibility of detecting DM at future (lepton) collider experiments, when the DM pair comes from an on-shell heavy scalar. In this context, we consider 2HDM + a complex singlet model. However, we emphasize that our findings will be valid for a broad class of models. We found that, in general, the benchmarks that are under-relic, are easier to probe at the collider, due to larger portal coupling and large invisible branching. We also showed that DM mass above a few hundred GeV will be difficult to probe at the HL-LHC. Whereas a hint for dark matter can be obtained at the HL-LHC, for higher signal significance one would need to go to the future lepton colliders. Low mass DM $\lesssim \frac{m_{h_2}}{2}$ can be best probed at the mono-Z final state, at a e^+e^- collider with $\sqrt{s}$ $\approx$250 GeV. Intermediate and heavy mass regions are best probed at the muon-collider. We also noticed an interesting fact, that a 1 TeV muon collider can have stronger physics case compared to a 1 TeV ILC or even 3 TeV CLIC due to enhanced muon-Yukawa coupling. On another note, the conventional VBF channel may not be useful in a broad class of models, due to suppressed couplings of non-standard scalars to the gauge bosons in the alignment limit (The assumption that the observed 125 GeV Higgs is SM-like). In such scenarios, associated $b\bar{b}/t\bar{t}$ can be important channels to look for. However, there are still regions of the parameter space, where the heavy scalar that decays into DM pair, is singlet-like, and therefore difficult to produce even at a high-energy muon collider. A hadron machine FCC-hh can be useful to probe such scenarios. In the end, we hope that this work provides a thorough and exhaustive road map for future collider experiments aiming at discovering DM.

References

[1] V. C. Rubin and W. K. Ford, Jr., *Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions*, *Astrophys. J.* **159** (1970) 379–403.

[2] R. Barrena, A. Biviano, M. Ramella, E. E. Falco, and S. Seitz, *The dynamical status of the cluster of galaxies 1e0657-56*, *Astron. Astrophys.* **386** (2002) 816, [astro-ph/0202323].

PoS(EPS-HEP2025)044

[3] **Planck** Collaboration, N. Aghanim et al., *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* **641** (2020) A6, [arXiv:1807.06209]. [Erratum: Astron.Astrophys. 652, C4 (2021)].

[4] S. Baum and N. R. Shah, *Two Higgs Doublets and a Complex Singlet: Disentangling the Decay Topologies and Associated Phenomenology*, *JHEP* **12** (2018) 044, [arXiv:1808.02667].

[5] **LEP Working Group for Higgs boson searches, ALEPH, DELPHI, L3, OPAL** Collaboration, R. Barate et al., *Search for the standard model Higgs boson at LEP*, *Phys. Lett. B* **565** (2003) 61–75, [hep-ex/0306033].

[6] **CMS** Collaboration, *Search for a standard model-like Higgs boson in the mass range between 70 and 110* GeV *in the diphoton final state in proton-proton collisions at* $\sqrt{s}$ = 13 TeV, arXiv:2405.18149.

[7] **ATLAS** Collaboration, G. Aad et al., *Search for diphoton resonances in the 66 to 110 GeV mass range using pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *Journal of High Energy Physics* **2025** (Jan., 2025) [arXiv:2407.07546].

[8] **ILC** Collaboration, *The International Linear Collider Technical Design Report - Volume 2: Physics*, arXiv:1306.6352.

[9] M. Benedikt et al., *FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2. Future Circular Collider*, Tech. Rep. 2, CERN, Geneva, 2019.

[10] **CEPC Study Group** Collaboration, *CEPC Conceptual Design Report: Volume 1 - Accelerator*, arXiv:1809.00285.

[11] **CLICdp, CLIC** Collaboration, T. K. Charles et al., *The Compact Linear Collider (CLIC) - 2018 Summary Report*, arXiv:1812.06018.

[12] **International Muon Collider** Collaboration, C. Accettura et al., *Interim report for the International Muon Collider Collaboration (IMCC)*, arXiv:2407.12450.

[13] J. Dutta, J. Lahiri, C. Li, G. Moortgat-Pick, S. F. Tabira, and J. A. Ziegler, *Search for Dark Matter in 2HDMS at LHC and future Lepton Colliders*, arXiv:2504.14529.

[14] **Planck** Collaboration, N. Aghanim et al., *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* **641** (2020) A6, [arXiv:1807.06209].

[15] **LZ** Collaboration, J. Aalbers et al., *First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment*, *Physical Review Letters* **131** (July, 2023) [arXiv:2207.03764].

[16] **Fermi-LAT, DES** Collaboration, A. Albert et al., *Searching for Dark Matter Annihilation in Recently Discovered Milky Way Satellites with Fermi-LAT*, *Astrophys. J.* **834** (2017), no. 2 110, [arXiv:1611.03184].