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*Dark Matter Prospects in 2HDM model at
CEPC: a Comparative Study of Scalar and
Pseudoscalar Portals*

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ABSTRACT

This work compares the prospects for Dark Matter (DM) searches at the CEPC ($\sqrt{s} = 250$ GeV) in the 2HDM+ a (pseudoscalar portal) and 2HDM+ S (scalar portal) models. A 2D scan of the cross section for $e^+e^- \rightarrow Zh_1 \rightarrow \mu^+\mu^- + 4\chi$ is performed over $m_{h_1} = 80\text{--}160$ GeV and $m_{\text{med}} = 20\text{--}80$ GeV using MadGraph5. Both models are studied at equally weak couplings ($\sin\theta = 0.03$, $\lambda_{HHS} = 0.05$). A kinematic boundary at $m_{h_1} = 2m_{\text{med}}$ is observed, and an artefact at $m_{\text{med}} = 20$ GeV is excluded. 2HDM+ S yields a baseline cross section of 6–8 fb (2–3 times higher than 2HDM+ a) and remains stable up to $m_{h_1} = 160$ GeV, while 2HDM+ a drops sharply above 140 GeV. Hence, 2HDM+ S is a more promising scenario for CEPC.

INTRODUCTION

The Standard Model of particle physics successfully describes all known elementary particles and three of the four fundamental interactions (electromagnetic, weak, and strong). Its predictions have been confirmed by numerous experiments, and the discovery of the Higgs boson in 2012 was an important confirmation of the theory [1]. However, the Standard Model has several limitations. It does not explain the nature of dark matter, whose existence is firmly established by astrophysical and cosmological observations: galaxy rotation curves, gravitational lensing, and the anisotropy of the cosmic microwave background. Ordinary matter makes up only about 5% of the total energy density of the Universe [2], while dark matter accounts for about 27%. In addition, the Standard Model does not answer questions about the baryon asymmetry of the Universe, neutrino masses, anomalies in B-meson decays, or the muon magnetic moment. These problems indicate the need for physics beyond the Standard Model.

One of the most popular dark matter candidates is WIMPs [3] (Weakly Interacting Massive Particles). They have masses in the range from GeV to TeV and interact with ordinary matter with a strength of the order of the electroweak interaction. Such particles can be produced at colliders. At the LHC, searches are performed using mono-X signatures: a visible particle (photon, jet, Z or W boson) is detected together with missing transverse energy associated with unregistered dark matter particles. The ATLAS and CMS collaborations have analysed data from the second run of the LHC (centre-of-mass energy 13 TeV, integrated luminosity 137 fb^{-1}) within the 2HDM+ a model [4]. No signal was observed, and limits on the masses of new particles were obtained. However, the high-mass region remains open for further studies.

The future electron-positron collider CEPC (China) is designed for precision studies of the Higgs boson. At an energy of 240 GeV and an integrated luminosity of 5.6 ab^{-1} , about one million ZH events are expected. The absence of the strong interaction and the recoil method allow the invisible width of the Higgs boson to be measured with a sensitivity of less than 0.26%, which is an order of magnitude better than the capabilities of the LHC [5]. This makes CEPC a promising tool for searching for dark matter interacting with the Higgs boson.

In this work, two models are considered — 2HDM+ a and 2HDM+ s . Both are extensions of the two-Higgs-doublet model and are recommended by the LHC Dark Matter Working Group for dark matter searches. In the 2HDM+ a model, a pseudoscalar singlet is added, and the decay of the light scalar into two mediators

is controlled by the mixing angle $\sin\theta$. In the 2HDM+ s model, a scalar singlet is added, and the corresponding decay is controlled by the portal coupling λ_{HHS} . The difference in the nature of the mediator leads to different phenomenology, which makes a comparative study of these models an interesting task.

The aim of this work is to compare the prospects for dark matter detection in the 2HDM+ a and 2HDM+ s models at the CEPC with an energy of 250 GeV. For this purpose, a two-dimensional scan of the cross sections for the process $e^+e^- \rightarrow Zh_1 \rightarrow \mu^+\mu^- + 4\chi$ is performed as a function of the masses of h_1 and the mediator particle. The model parameters are fixed with equally weak couplings to allow a fair comparison. Kinematic boundaries, artefacts, and differences in the cross-section behaviour are analysed.

1 Two-Higgs-Doublet Model and Its Extensions

1.1 Standard Two-Higgs-Doublet Model (2HDM)

The Standard Model (SM) contains one scalar doublet, which after spontaneous electroweak symmetry breaking gives rise to one physical scalar — the Higgs boson. The simplest extension of the scalar sector is the addition of a second doublet. This model is called the Two-Higgs-Doublet Model (2HDM). It preserves the main properties of the SM but predicts the existence of five physical scalar particles: two CP-even neutral scalars (usually denoted h and H), one CP-odd neutral pseudoscalar (A), and two charged scalars (H^+ and H^-) [6].

After symmetry breaking, the two doublets acquire vacuum expectation values v_1 and v_2 , with $v = \sqrt{v_1^2 + v_2^2} \approx 246$ GeV. Their ratio is denoted $\tan\beta = v_2/v_1$. An important parameter is the mixing angle α between the two CP-even states. The combination $\sin(\beta - \alpha)$ determines how SM-like the light scalar h is. In the so-called alignment limit, $\sin(\beta - \alpha) = 1$, and h behaves like the Standard Model Higgs boson with a mass of 125 GeV. This case is used in the present work.

1.2 2HDM+ a Model (Pseudoscalar Portal)

The 2HDM+ a model extends the two-Higgs-doublet model by adding a pseudoscalar singlet field a . This field has no electric charge and is CP-odd.

The interaction of the pseudoscalar singlet a with a dark matter fermion χ is given by the Lagrangian [7]:

$$\mathcal{L}_\chi = -iy_\chi a \bar{\chi} \gamma_5 \chi, \tag{1}$$

where y_χ is the coupling constant. The factor γ_5 indicates the pseudoscalar nature of the interaction, which has important consequences for decay properties and cross sections.

The scalar potential of the model consists of three parts:

$$V = V_{2\text{HDM}} + V_a + V_{a2\text{HDM}}. \quad (2)$$

The standard two-doublet potential $V_{2\text{HDM}}$ can be written as:

$$\begin{aligned} V_{2\text{HDM}} = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) \\ & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) \\ & + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left(\frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right). \end{aligned} \quad (3)$$

The singlet potential V_a contains only a mass term:

$$V_a = \frac{1}{2} m_a^2 a^2. \quad (4)$$

The interaction between the singlet and the doublets is given by:

$$V_{a2\text{HDM}} = a \left(i b_a \Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + a^2 \left(\lambda_{P1} \Phi_1^\dagger \Phi_1 + \lambda_{P2} \Phi_2^\dagger \Phi_2 \right). \quad (5)$$

These terms provide mixing between the doublet pseudoscalar A and the singlet a . The mixing angle is denoted θ . The parameter $\sin \theta$ controls the coupling of the light scalar h to a pair of pseudoscalars a . Thus, at small $\sin \theta$, the decay $h \rightarrow aa$ is strongly suppressed. This effect is crucial for understanding the differences in the phenomenology of the 2HDM+ a and 2HDM+ s models at lepton colliders.

Therefore the main parameters of the 2HDM+ a model include the ratio of vacuum expectation values $\tan \beta = v_2/v_1$, the mixing angle $\sin(\beta - \alpha)$ which determines how SM-like the light scalar h is, the mixing angle $\sin \theta$ between the doublet and singlet pseudoscalars, the mass of the pseudoscalar singlet m_a , the dark matter fermion mass m_χ , the coupling constant y_χ between a and χ , and the potential constants $\lambda_3, \lambda_{P1}, \lambda_{P2}$ which affect the $h \rightarrow aa$ coupling.

1.3 2HDM+ s Model (Scalar Portal)

The 2HDM+ s model is an alternative extension of the two-Higgs-doublet model, in which a scalar singlet field s (CP-even) is added.

The interaction of the scalar singlet s with a dark matter fermion χ is given by the Lagrangian [8]:

$$\mathcal{L}_\chi = -y_\chi s \bar{\chi} \chi, \quad (6)$$

where y_χ is the coupling constant. Unlike the pseudoscalar case, there is no γ_5 factor, i.e., the interaction is scalar. This difference has important phenomenological consequences.

The scalar potential also consists of three parts:

$$V = V_{2\text{HDM}} + V_s + V_{s2\text{HDM}}. \quad (7)$$

The singlet potential includes a mass term and a quartic self-coupling:

$$V_s = \frac{1}{2} m_s^2 s^2 + \frac{\lambda_s}{4} s^4. \quad (8)$$

The interaction between the singlet and the doublets contains linear and quadratic portal couplings:

$$V_{s2\text{HDM}} = \lambda_{S1} (\Phi_1^\dagger \Phi_1) s + \lambda_{S2} (\Phi_2^\dagger \Phi_2) s + \lambda_{S12} (\Phi_1^\dagger \Phi_2 + \text{h.c.}) s + \lambda'_{S1} (\Phi_1^\dagger \Phi_1) s^2 + \lambda'_{S2} (\Phi_2^\dagger \Phi_2) s^2. \quad (9)$$

The key parameter controlling the decay of the light scalar h into two singlets is the portal coupling λ_{HHS} .

Therefore the main parameters of the 2HDM+ s model include the ratio of vacuum expectation values $\tan \beta = v_2/v_1$, the mixing angle $\sin(\beta - \alpha)$ which determines how SM-like the light scalar h is, the portal coupling λ_{HHS} controlling the $h \rightarrow ss$ decay, the mass of the scalar singlet m_s , the dark matter fermion mass m_χ , the coupling constant y_χ between s and χ , and the singlet quartic self-coupling λ_s .

2 The CEPC Collider and Its Detector

2.1 CEPC as a Higgs Factory

The Circular Electron Positron Collider (CEPC) is a future e^+e^- collider proposed by the Chinese high-energy physics community. It will operate mainly at $\sqrt{s} = 240$ GeV as a Higgs factory, providing an integrated luminosity of 5.6 ab^{-1} and about one million ZH events via the Higgsstrahlung process $e^+e^- \rightarrow ZH$. The clean e^+e^- environment, free from QCD backgrounds, allows precise model-independent measurements of the Higgs boson. In particular, the recoil method

enables a direct measurement of the invisible branching ratio with a sensitivity $\text{BR}(H \rightarrow \text{inv}) < 0.26\%$ at 95% CL, an order of magnitude better than LHC limits.

2.2 Detector Concepts

The CEPC detector is designed for excellent jet energy resolution, lepton identification, and missing transverse energy reconstruction. Two main concepts are considered: the baseline detector and the IDEA detector [5].

The baseline detector follows a particle flow approach. It includes a silicon vertex detector, a large time projection chamber (TPC), a silicon outer tracker, a 3 T superconducting solenoid, fine-granularity ECAL and HCAL, and a muon detector based on scintillator strips with SiPM readout. The muon system was developed with contributions from JINR (Dubna) and provides high efficiency for muon identification.

The IDEA detector, also proposed for FCC-ee, features a five-layer MAPS vertex detector, a 4 m drift chamber with 112 layers, an outer silicon wrapper, a thin 2 T solenoid ($0.74X_0$, 0.16λ), a preshower, a dual-readout calorimeter (simultaneous Cherenkov and scintillation light), and a μ -RWELL muon system.

For dark matter searches, both detectors provide clean $Z \rightarrow \mu^+\mu^-$ reconstruction and precise missing transverse energy measurement, giving a clear signature $e^+e^- \rightarrow Zh_1 \rightarrow \mu^+\mu^- + \text{MET}$.

2.3 Relevance for This Work

In this study, we assume CEPC at $\sqrt{s} = 250$ GeV (close to 240 GeV) with 5.6 ab^{-1} . The signal process $e^+e^- \rightarrow Zh_1$ with $h_1 \rightarrow h_4h_4$ (or $h_1 \rightarrow s_1s_1$) and $h_4/s_1 \rightarrow \chi\bar{\chi}$ is simulated using baseline detector parameters. The clean environment and high luminosity allow us to explore a wide range of mediator masses and to compare the 2HDM+ a and 2HDM+ s models in a realistic experimental setting.

3 Methodology and Simulation Tools

3.1 MadGraph5_aMC@NLO Event Generator

For the theoretical calculations and event simulation in this work, the MadGraph5_aMC@NLO package was used [9]. This tool is widely employed in mod-

ern high-energy physics for the automatic computation of matrix elements and event generation within arbitrary theoretical models. The package allows calculations at leading order (LO) as well as next-to-leading order (NLO), and provides interfaces to parton shower and hadronisation programs (Pythia, Herwig), making it a universal solution for the full chain of event simulation.

In this work, all calculations were performed at leading order (LO) using the UFO files [10] of the 2HDM+*a* and 2HDM+*s* models. The main task was to simulate the associated production of a Z boson and a light scalar h_1 with subsequent decays into dark matter:

$$e^+e^- \rightarrow Zh_1, \quad h_1 \rightarrow h_4h_4 \text{ (or } s_1s_1), \quad h_4/s_1 \rightarrow \chi\bar{\chi}, \quad Z \rightarrow \mu^+\mu^-. \quad (10)$$

The final signature includes two opposite-sign muons and missing transverse energy (MET) associated with the undetected dark matter particles.

3.2 Model Loading and Process Definition

Work with MadGraph5 begins with loading the required theoretical model. For the 2HDM+*a* model, the following command is used:

```
import model Pseudoscalar_2HDM
```

After successful model loading, the process can be defined. The process definition syntax is close to standard physical notation. For the studied process, the command is:

```
generate e+ e- > z h1, (h1 > h4 h4, h4 > xd xd~), z > mu+ mu-
```

In this command: **e+** **e-** denote the initial state particles (positron and electron); **z h1** is the final state of the first stage (Z boson and light scalar); the decays are specified in parentheses: **h1 > h4 h4** is the decay of the scalar into two pseudoscalar mediators; **h4 > xd xd~** is the decay of each mediator into a dark matter particle-antiparticle pair (denoted as **xd**); finally, **z > mu+ mu-** is the decay of the Z boson into a muon pair. For the 2HDM+*s* model, the command is similar with **h4** replaced by **s1**:

```
generate e+ e- > z h1, (h1 > s1 s1, s1 > xd xd~), z > mu+ mu-
```

After entering the command, MadGraph automatically computes all Feynman diagrams contributing to the process and displays their number. The user is prompted to confirm generation, after which a directory with process files is created.

3.3 Setting Model Parameters

Model parameters are set using the `set param_card` command. The fixed parameters common to all calculations are set as follows:

```
set param_card mxd 10
set param_card tanbeta 1
set param_card sinbma 1
set param_card gPXd 1
set param_card lam3 3
set param_card laP1 3
set param_card laP2 3
```

Here, `mxd` is the dark matter particle mass $m_\chi = 10$ GeV; `tanbeta` is the ratio of vacuum expectation values $\tan\beta = 1$; `sinbma` is the mixing angle $\sin(\beta-\alpha) = 1$ (the alignment limit, where the light scalar h_1 is SM-like); `gPXd` is the coupling constant of the mediator to dark matter; `lam3`, `laP1`, `laP2` are quartic couplings in the scalar potential that affect the $h_1 \rightarrow h_4 h_4$ coupling.

The parameters controlling the coupling between the visible and dark sectors differ for the two models. For 2HDM+ a , the mixing angle is set as:

```
set param_card sinp 0.03
```

For 2HDM+ s , the portal coupling λ_{HHS} is set instead (the exact parameter name depends on the UFO implementation, e.g., `lambdaHHS`):

```
set param_card lambdaHHS 0.05
```

The scanned parameters — the light scalar mass and the mediator mass — are set in a loop. An example for specific values:

```
set param_card mh1 125
set param_card mh4 50
```

3.4 Energy and Event Number Configuration

The beam energy is set with:

```
set ebeam 125
```

A value of 125 GeV per beam corresponds to a centre-of-mass energy of $\sqrt{s} = 250$ GeV, which is close to the CEPC design energy (240 GeV). The number of generated events for each parameter space point is set by:

```
set nevents 10000
```

3.5 Automatic Decay Width Calculation

To correctly account for decay probabilities, MadGraph must automatically compute the widths of the h_1 and h_4 (or s_1) particles given the current model parameters. This is achieved with:

```
set width 25 Auto
set width 55 Auto
compute_widths 25 55
```

Here, 25 and 55 are the PDG codes for h_1 and h_4 , respectively. The `compute_widths` command triggers the width recalculation, after which MadGraph uses the computed values in propagators and branching ratios.

4 Simulation Results

4.1 Scan Parameters and Methodology

To perform a comparative analysis of the prospects for dark matter detection in the 2HDM+ a and 2HDM+ s models at the CEPC collider, a two-dimensional scan of the cross section for the process

$$e^+e^- \rightarrow Zh_1 \rightarrow \mu^+\mu^- + 4\chi \quad (11)$$

was carried out as a function of the light scalar mass m_{h_1} and the mediator mass m_{med} (denoted h_4 in the 2HDM+ a model and s_1 in the 2HDM+ s model). The scan was performed in the following ranges:

- m_{h_1} from 80 to 160 GeV in steps of 5 GeV;
- m_{med} from 20 to 80 GeV in steps of 2 GeV.

For each point, the total cross section was calculated using the MadGraph5_aMC@NLO event generator (version 2.9.2) at leading order (LO). Event generation was performed with fixed parameters common to both models:

- centre-of-mass energy $\sqrt{s} = 250$ GeV;
- dark matter particle mass $m_\chi = 10$ GeV;
- ratio of vacuum expectation values $\tan\beta = 1$;
- mixing angle $\sin(\beta - \alpha) = 1$ (alignment limit, where h_1 is SM-like);
- dark matter coupling constants $g_{PXd} = 1$ (for 2HDM+ a) and $y_\chi = 1$ (for 2HDM+ s);
- scalar potential constants for 2HDM+ a : $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$.

The parameters controlling the coupling between the visible and dark sectors were chosen to be equally weak to allow a fair comparison:

- for 2HDM+ a : mixing angle $\sin \theta = 0.03$;
- for 2HDM+ s : portal coupling $\lambda_{HHS} = 0.05$.

For each point in the parameter space, 10,000 events were generated. The decay widths of h_1 and h_4/s_1 were automatically recalculated using the `compute_widths` command, ensuring that all open decay channels were taken into account for the given masses and coupling constants.

4.2 Kinematic Constraints

When processing the results, two kinematic conditions necessary for the existence of the signal were taken into account. First, the decay $h_1 \rightarrow h_4 h_4$ is only possible when $m_{h_1} > 2m_{h_4}$. On the two-dimensional plots, this boundary appears as a diagonal below which the signal is completely absent. Second, the decay $h_4 \rightarrow \chi \bar{\chi}$ is only possible when $m_{h_4} > 2m_\chi = 20$ GeV. At $m_{h_4} = 20$ GeV, the decay width vanishes, leading to a computational artefact (a sharp cross section peak) with no physical meaning. This point was excluded from the final analysis.

4.3 Results for the 2HDM+ a Model

Figure 1 shows the two-dimensional colour map of the cross section (in femtobarns) for the 2HDM+ a model as a function of m_{h_1} and m_{h_4} .

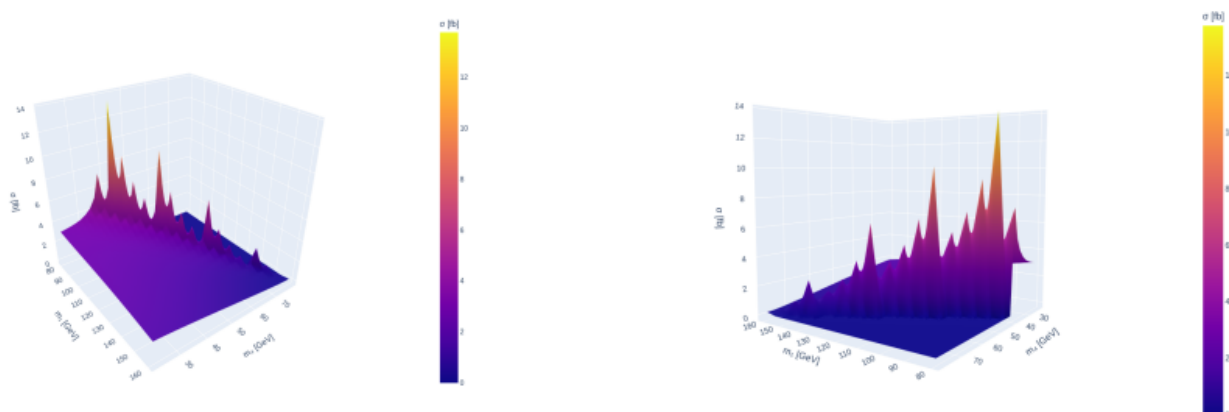


Figure 1. – Cross section for $e^+e^- \rightarrow Zh_1 \rightarrow \mu^+\mu^- + 4\chi$ in the 2HDM+ a model at $\sqrt{s} = 250$ GeV, $\sin \theta = 0.03$, $\tan \beta = 1$, $m_\chi = 10$ GeV.

The kinematic boundary at $m_{h_1} = 2m_{h_4}$ is clearly visible: below this diagonal the cross section is zero. In the allowed region, the cross section exhibits local

maxima corresponding to resonant conditions where the decay $h_1 \rightarrow h_4 h_4$ is most probable. The maximum cross section is 13.76 fb, achieved at $m_{h_1} = 85$ GeV, $m_{h_4} = 42$ GeV. The baseline cross section away from resonances is approximately 2–3 fb. When m_{h_1} exceeds 140 GeV, the cross section drops sharply to 0.15–0.5 fb.

4.4 Results for the 2HDM+ s Model

Figure 2 shows the analogous two-dimensional colour map of the cross section for the 2HDM+ s model.

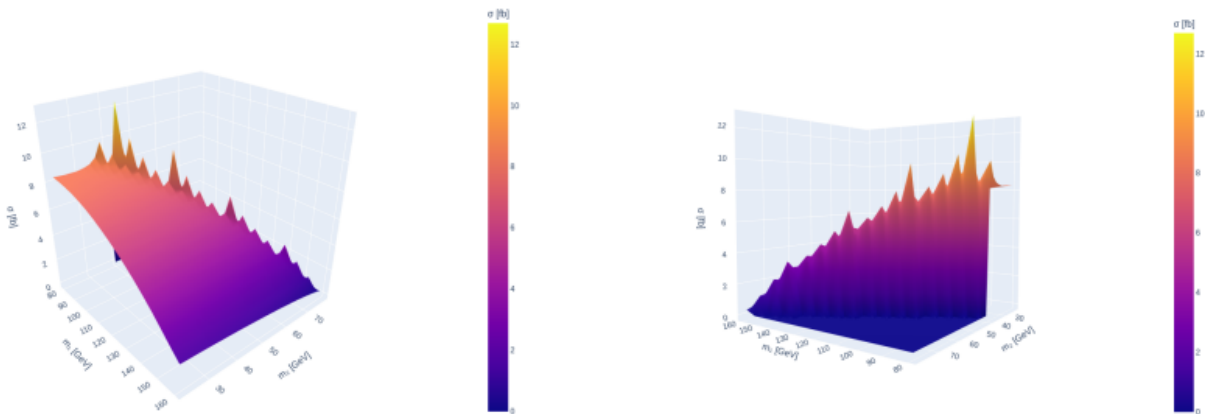


Figure 2. – Cross section for $e^+e^- \rightarrow Zh_1 \rightarrow \mu^+\mu^- + 4\chi$ in the 2HDM+ s model at $\sqrt{s} = 250$ GeV, $\lambda_{HHS} = 0.05$, $\tan\beta = 1$, $m_\chi = 10$ GeV.

The kinematic boundary $m_{h_1} = 2m_{s_1}$ is also clearly visible. The maximum cross section is 12.69 fb. However, the key difference from the 2HDM+ a model lies in the behaviour of the cross section at large m_{h_1} . The baseline cross section away from resonances is 6–8 fb, which is 2–3 times higher than in the 2HDM+ a model. As m_{h_1} increases to 160 GeV, the cross section remains at the level of several femtobarns, showing no sharp drop. This is explained by the fact that the scalar mediator s_1 couples to h_1 through a direct portal coupling λ_{HHS} , which is not suppressed by a small mixing angle, unlike the pseudoscalar case.

4.5 Comparison of the Models

Figure 3 shows a direct comparison of the cross sections for both models.

It is clearly seen that the cross section in the 2HDM+ s model is systematically higher, especially in the low mediator mass region. As the mediator mass increases, the difference decreases, but the 2HDM+ s model maintains its advantage.

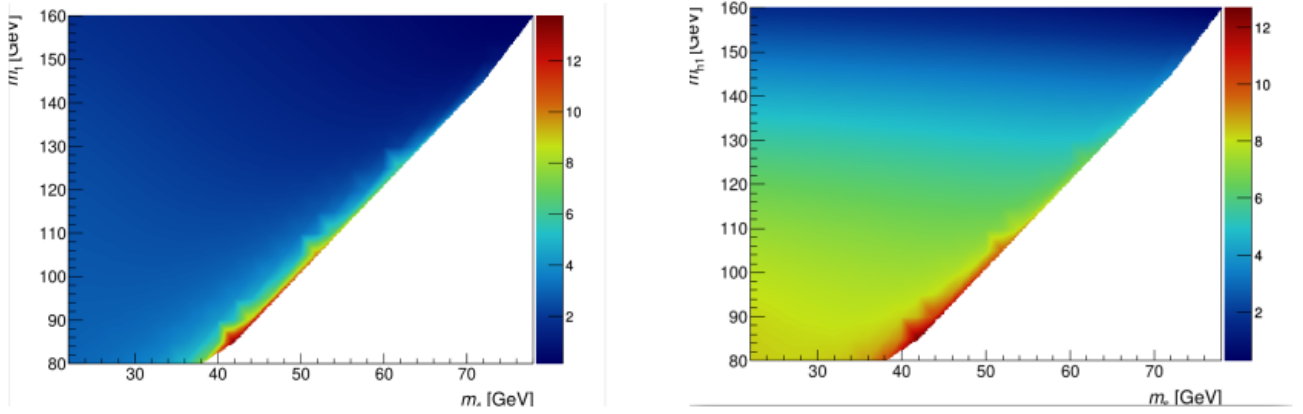


Figure 3. – Comparison of cross sections for the 2HDM+ a and 2HDM+ s models at $\sqrt{s} = 250$ GeV.

The two-dimensional cross section scan allows the following conclusions to be drawn:

1. Both models exhibit a clear kinematic boundary at $m_{h_1} = 2m_{\text{med}}$, below which the signal is absent.
2. The 2HDM+ s model has a significantly higher baseline cross section (6–8 fb) compared to the 2HDM+ a model (2–3 fb) at equally weak coupling.
3. In the 2HDM+ s model, the signal remains stable as m_{h_1} increases to 160 GeV, while in the 2HDM+ a model the cross section drops sharply for $m_{h_1} > 140$ GeV.
4. The maximum cross sections are comparable: 13.76 fb for 2HDM+ a and 12.69 fb for 2HDM+ s .

Thus, from the perspective of dark matter searches at CEPC, the 2HDM+ s model is more promising because it provides a higher and more stable signal over a wide mass range. The 2HDM+ a model requires a stronger coupling ($\sin \theta \sim 0.3$) to achieve comparable cross sections. The expected sensitivity of CEPC to invisible Higgs decays at the level of 1.2% [11] gives hope for the discovery of a signal in the 2HDM+ s model, which, as shown in our analysis, yields a cross section of 6–8 fb for weak coupling.

CONCLUSION

This work was devoted to a comparative study of the prospects for dark matter searches at the future electron-positron collider CEPC within the framework of two theoretically well-motivated extensions of the Standard Model — the 2HDM+ a (pseudoscalar portal) and the 2HDM+ s (scalar portal) models. Both models are recommended by the LHC Dark Matter Working Group for the interpretation of dark matter searches at colliders and provide a theoretically consistent description of a dark matter candidate. The relevance of this work is due to the fact that the Standard Model does not explain the nature of dark matter, while CEPC, with its clean e^+e^- environment and the recoil method, offers a unique opportunity to search for invisible Higgs decays with a sensitivity of $\text{BR}(H \rightarrow \text{inv}) < 0.26\%$, which is an order of magnitude better than current LHC limits.

To achieve this goal, a two-dimensional scan of the cross section for the process $e^+e^- \rightarrow Zh_1 \rightarrow \mu^+\mu^- + 4\chi$ was performed as a function of the light scalar mass m_{h_1} and the mediator mass m_{med} . The scan was carried out in the range $m_{h_1} = 80\text{--}160$ GeV and $m_{\text{med}} = 20\text{--}80$ GeV with a step of 5 GeV, yielding 289 points in the parameter space. The calculations were performed using the MadGraph5_aMC@NLO event generator at leading order (LO) at a centre-of-mass energy of $\sqrt{s} = 250$ GeV, which is close to the CEPC design energy (240 GeV).

The fixed parameters common to both models included the ratio of vacuum expectation values $\tan\beta = 1$, the mixing angle $\sin(\beta - \alpha) = 1$ (the alignment limit, where the light scalar h_1 is SM-like), the dark matter particle mass $m_\chi = 10$ GeV, and the dark matter coupling constants $g_{PXd} = 1$ for the 2HDM+ a model and $y_\chi = 1$ for the 2HDM+ s model. For the 2HDM+ a model, the scalar potential constants were also fixed: $\lambda_3 = \lambda_{P1} = \lambda_{P2} = 3$. The parameters controlling the coupling between the visible and dark sectors were chosen to be equally weak to ensure a fair comparison: the mixing angle $\sin\theta = 0.03$ for the 2HDM+ a model and the portal coupling $\lambda_{HHS} = 0.05$ for the 2HDM+ s model.

The analysis of the obtained results shows that the 2HDM+ s model exhibits a baseline cross section of 6–8 fb away from resonances, which is 2–3 times higher than that of the 2HDM+ a model (2–3 fb). The maximum cross sections are comparable: 13.76 fb for the 2HDM+ a model (achieved at $m_{h_1} = 85$ GeV, $m_{h_4} = 42$ GeV) and 12.69 fb for the 2HDM+ s model. However, the key difference between the models appears at large light scalar masses. In the 2HDM+ a model, when m_{h_1} exceeds 140 GeV, the cross section drops sharply to 0.15–0.5 fb,

which is due to the reduced phase space and the dominance of competing decays $h_1 \rightarrow b\bar{b}$ and $h_1 \rightarrow \tau^+\tau^-$. In the 2HDM+ s model, in contrast, the signal remains stable up to $m_{h_1} = 160$ GeV, maintaining a cross section of several femtobarns.

This difference is explained by the nature of the interaction between the light scalar h_1 and the mediator particle. In the 2HDM+ a model, the $h_1 \rightarrow h_4h_4$ coupling is proportional to the small mixing angle $\sin\theta$, which leads to a strong suppression of the decay at $\sin\theta = 0.03$. In the 2HDM+ s model, the $h_1 \rightarrow s_1s_1$ coupling is determined by the direct portal constant λ_{HHS} , which does not suffer from such suppression. Thus, even with equally weak coupling parameters ($\sin\theta = 0.03$ and $\lambda_{HHS} = 0.05$), the 2HDM+ s model provides a higher probability for the decay of h_1 into the dark sector.

The obtained results allow the following conclusions to be drawn. The 2HDM+ s model is more promising for dark matter searches at the CEPC collider, as it provides a higher and more stable signal cross section over a wide range of m_{h_1} and m_{med} masses. The 2HDM+ a model with weak coupling ($\sin\theta = 0.03$) yields cross sections that are too small for confident detection, but its prospects may improve significantly if the mixing angle is increased to $\sin\theta \sim 0.3$. The clean environment of CEPC and its high design luminosity of 5.6 ab^{-1} allow the detection of cross sections at the level of several femtobarns, making the 2HDM+ s model an ideal candidate for first searches. Further research may be directed towards varying the mixing angle, extending the analysis to $\sqrt{s} = 360$ GeV, and including Standard Model background processes.

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