The mass-degenerate SM-like Higgs and anomaly of $(g - 2)_\mu$ in $\mu$-term extended NMSSM

Liangliang Shang, XiaoFeng Zhang and Zhaoxia Heng

School of Physics, Henan Normal University, Xinxiang 453007, China

E-mail: shangliangliang@htu.edu.cn, xiaofeng_z1@126.com, zxheng@htu.edu.cn

ABSTRACT: We chose the $\mu$-term extended next-to-minimal supersymmetric standard model ($\mu$NMSSM) for this work, and we perform a phenomenological study based on the assumption that the observed Standard Model (SM)-like Higgs is explained by the presence of a double overlapping resonance and in light of the recent $(g - 2)_\mu$ result. The study also takes into account a variety of experimental results, including Dark Matter (DM) direct detections and results from sparticle searches at the Large Hadron Collider (LHC). We study the properties of DM confronted with the limits from DM direct detections. As a second step, we focus our attention on the properties of the mass-degenerate SM-like Higgs bosons and on explaining the anomaly of $(g - 2)_\mu$. We conclude that the anomaly of $(g - 2)_\mu$ can be explained in the scenario with two mass-degenerate SM-like Higgs, and there are samples that meet the current constraints and fit $1 - \sigma$ anomalies of Higgs data.

KEYWORDS: Multi-Higgs Models, Supersymmetry

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1 Introduction

The publication of the latest data by the Fermi National Accelerator Laboratory (FNAL) and Brookhaven National Laboratory (BNL) show a 4.2σ discrepancy from the Standard Model (SM) prediction [1–38]. When the experimental accuracy is further improved, the measurement of the muon anomalous magnetic moment \((g - 2)_{\mu}\) is likely to become a breakthrough of new physics [39–42]. So the interpretation of \((g - 2)_{\mu}\) anomaly has also become an important task of new physics. For examples, low-energy supersymmetry (SUSY) can naturally explain the anomaly of \((g - 2)_{\mu}\) [43–131].

SUSY models have been widely studied due to its multiple theoretical advantages, such as the explanation of the gauge hierarchy problem, the unification of gauge coupling, and natural solutions to the Dark Matter (DM) mystery. As the most economical realization of SUSY, the minimal supersymmetric standard model (MSSM) [132] with R-parity conservation can provide a viable candidate of DM, which is lightest neutralino as the lightest supersymmetric particle (LSP). However, considering the constraints from DM relic density and DM direct detections, MSSM is strongly restricted, and there are also some problems in the MSSM, such as the \(\mu\)-problem and little hierarchy problem, which can be solved in
the next-to-minimal supersymmetric standard model (NMSSM) [133, 134]. NMSSM extends the MSSM by one singlet Higgs superfield $\hat{S}$, which develops a vacuum expectation value (VEV) to generate an effective $\mu$-term. Furthermore, because of the enlarged Higgs sector, the SM-like Higgs boson mass can be easily interpreted [135]. In the NMSSM with a $Z_3$ symmetry ($Z_3$-NMSSM), to realize a singlino-dominant DM, $2|\kappa|/\lambda$ must be less than 1 [136]. However, the situation is different in the general NMSSM (GNMSSM). We consider a simplified version of GNMSSM, i.e., the $\mu$-term extended $Z_3$-NMSSM ($\mu$NMSSM) [137]. In the $\mu$NMSSM, the mass ratio of singlino and higgsino is no longer equal to $2|\kappa|/\lambda$, so the values of $\kappa$ have a wider range compared to the case in the $Z_3$-NMSSM [138]. The parameter $\kappa$ has an important effect on the singlet fields’ self-interactions, which can be entirely responsible for the DM density. Therefore, considering the latest DM experimental constraints, the $\mu$NMSSM has a wider parameter space than the $Z_3$-NMSSM.

In July 2012, both the ATLAS and CMS collaborations announced a scalar with mass near 125 GeV [139, 140]. Combined measurements of Higgs boson production cross sections and decay branching fractions show no significant deviations from Standard Model (SM) predictions. However, for the Higgs production process in association with a top quark pair followed by the decay mode to vector boson ($H \rightarrow WW$) or photon ($H \rightarrow \gamma\gamma$) [141–145], there is a discrepancy between the SM prediction and the experimental data. Many theories attempt to interpret the observed data at the LHC. In the $\mu$NMSSM, either the lightest CP-even Higgs boson $H_1$ or the next-to-lightest CP-even Higgs boson $H_2$ can be SM-like with mass near 125 GeV. In fact, it is also possible to have $H_1$ and $H_2$ nearly degenerate with mass near 125 GeV [146–150], so that the observed signal at the LHC is actually a superposition of two individual peaks, and these two peaks cannot be independently resolved. In our work we focus on the scenario with two mass-degenerate Higgs boson with mass near 125 GeV in the $\mu$NMSSM considering various constraints including the DM relic density and DM direct detection limits. Furthermore, we try to explain the anomaly of $(g - 2)_\mu$ in this scenario.

The paper is structured as follows. In section 2, we briefly introduce the basic properties of $\mu$NMSSM including the Higgs, neutralino and chargino sectors. Then we study the observables of the 125 GeV Higgs boson at the LHC, DM and $(g - 2)_\mu$ in the $\mu$NMSSM. We also describe our scanning strategy. In section 3, we investigate the properties of DM confronted with DM direct detection limits. In section 4, we show the numerical results in the scenario with two mass-degenerate Higgs boson and explain the anomaly of $(g - 2)_\mu$. Finally, we give a summary in section 5.

2 Theoretical preliminaries

2.1 Basics of $\mu$NMSSM

To address a number of flaws in MSSM, such as the $\mu$ problem, we consider the next-to-minimal extension. Compared with MSSM, NMSSM introduces a singlet Higgs field $\hat{S}$. The superpotential of the general NMSSM (GNMSSM) is given by

$$W_{\text{GNMSSM}} = W_{\text{Yukawa}} + (\mu + \lambda \hat{S}) \hat{H}_u \cdot \hat{H}_d + \xi_F \hat{S} + \frac{1}{2} \mu' \hat{S}^2 + \frac{\kappa}{3} \hat{S}^3$$

(2.1)
where the Yukawa terms $W_{\text{Yukawa}}$ are as follows [134],

$$W_{\text{Yukawa}} = h_u \hat{Q} \cdot \hat{H}_u \hat{U}_R^c + h_d \hat{H}_d \cdot \hat{Q} \hat{D}_R + h_e \hat{H}_d \cdot \hat{L} \hat{E}_R^c$$

Among them, $\lambda$ and $\kappa$ are dimensionless couplings, $\mu$ and $\mu'$ are supersymmetric mass terms, and $\xi_F$ is the supersymmetric tadpole term of mass square dimension.

In the above formula, the $\mu$, $\mu'$ and $\xi_F$ terms break the $Z_3$-symmetry, and the $\xi_F$ term conserves the $Z_3$-symmetry while breaking the PQ-symmetry. Some articles use the terms $\mu$ and $\xi_F$ to explain the tadpole problem [151] and the cosmological domain-wall problem [152–154]. To maintain the purpose of our research without sacrificing generality, we set $\mu' = \xi_F = 0$. This is known as the $\mu$-term extended NMSSM ($\mu$NMSSM). The extra $\mu$-term is related to the non-minimal supergravity coupling $\chi$ via the gravitino mass as $\mu = \frac{3}{2} m_{3/2} \chi$, where $m_{3/2}$ denotes the gravitino mass [155]. The superpotential and soft supersymmetry-breaking terms of $\mu$NMSSM are given below [156, 157],

$$W_{\mu\text{NMSSM}} = W_{\text{Yukawa}} + (\lambda \hat{S} + \mu) \hat{H}_u \cdot \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3,$$

$$- \mathcal{L}_{\text{soft}} = \left[ A_\lambda \lambda \lambda \hat{S} H_u \cdot H_d + \frac{1}{3} A_\kappa \kappa \hat{S}^3 + B_\mu \mu H_u \cdot H_d + \text{h.c.} \right]$$

$$+ m^2_{H_u} |H_u|^2 + m^2_{H_d} |H_d|^2 + m_s^2 |S|^2 + \cdots .$$

The breaking of electroweak symmetry allows Higgs field to obtain non-zero vacuum expected values (vevs) $< H^0_u > = v_u / \sqrt{2}$, $< H^0_d > = v_d / \sqrt{2}$, $< H^0_s > = v_s / \sqrt{2}$. The expression of the Higgs fields can be written as

$$H_u = \begin{pmatrix} h_u^+ \\ h_u^- \end{pmatrix} = \begin{pmatrix} \eta_u^+ \\ \frac{1}{\sqrt{2}} (v_u + \sigma_u + i \phi_u) \end{pmatrix}, \quad H_d = \begin{pmatrix} h_d^+ \\ h_d^- \end{pmatrix} = \begin{pmatrix} \eta_d^+ \\ \frac{1}{\sqrt{2}} (v_d + \sigma_d + i \phi_d) \end{pmatrix},$$

$$S = \frac{1}{\sqrt{2}} (v_s + \sigma_s + i \phi_s).$$

The ratio of the two Higgs doublet vevs defines the parameter $\tan \beta = v_u / v_d$ with $v = \sqrt{v_u^2 + v_d^2} = 246$ GeV, and the effective $\mu$-term $\mu_{\text{eff}}$ is generated by $\mu_{\text{eff}} = \lambda v_s / \sqrt{2}$.

We set $B_u = 0$ in the soft breaking term since it plays a minor role in our work, then we get a Higgs potential as follows,

$$V_{\text{Higgs}} = \left( m^2_{H_d} + (\mu + \lambda S)^2 \right) |H_d|^2 + \left( m^2_{H_u} + (\mu + \lambda S)^2 \right) |H_u|^2$$

$$+ \left( \kappa S^2 + \lambda \lambda \lambda \dot{H}_u \cdot H_d \right)^2 + \frac{g^2_3}{2} |H_d^+ H_u|^2 + \frac{3 g^2_3 + g^2_2}{8} \left( |H_d|^2 - |H_u|^2 \right)^2$$

$$+ m_S^2 S^2 + 2 \lambda A_\lambda S H_u \cdot H_d + \frac{2}{3} \lambda A_\kappa \hat{S}^3$$

For convenience, we use the field combinations $H_{\text{SM}} \equiv \sin \beta \Re (H_u) + \cos \beta \Re (H_d)$, $H_{\text{NSM}} \equiv \cos \beta \Re (H_u) - \sin \beta \Re (H_d)$, and $A_{\text{NSM}} \equiv \cos \beta \Im (H_u) - \sin \beta \Im (H_d)$, then the mass matrix of CP-even Higgs bosons in the basis $(H_{\text{NSM}}, H_{\text{SM}}, \Re (S))$ can be written as
follows,
\[
\mathcal{M}_{S,11}^2 = \frac{2\mu_{\text{eff}}(\lambda A_\lambda + \kappa_{\text{eff}})}{\lambda \sin 2\beta} + \frac{1}{2} \left(2m_Z^2 - \lambda^2 v^2\right) \sin^2 2\beta
\]
\[
\mathcal{M}_{S,12}^2 = -\frac{1}{4} \left(2m_Z^2 - \lambda^2 v^2\right) \sin 4\beta
\]
\[
\mathcal{M}_{S,13}^2 = -\frac{1}{\sqrt{2}} \left(\lambda A_\lambda + 2\kappa_{\text{eff}}\right) v \cos 2\beta
\]
\[
\mathcal{M}_{S,22}^2 = m_Z^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta
\]
\[
\mathcal{M}_{S,23}^2 = \frac{v}{\sqrt{2}} (2\lambda_{\text{eff}} + 2\lambda_\mu - (\lambda A_\lambda + 2\kappa_{\text{eff}}) \sin 2\beta),
\]
\[
\mathcal{M}_{S,33}^2 = \frac{\lambda A_\lambda \sin 2\beta}{4\mu_{\text{eff}}} \lambda v^2 + \frac{\mu_{\text{eff}}}{\lambda} \left(\kappa A_\kappa + \frac{4\kappa^2_{\text{eff}}}{\lambda}\right) - \frac{\lambda_\mu}{2\mu_{\text{eff}}} \lambda_\nu v^2
\]
and those for CP-odd Higgs bosons in the basis \(A_{\text{NSM, Im}(S)}\) are as follows
\[
\mathcal{M}_{P,11}^2 = \frac{2\mu_{\text{eff}}(\lambda A_\lambda + 2\kappa_{\text{eff}})}{\lambda \sin 2\beta}, \quad \mathcal{M}_{P,12}^2 = \frac{v}{\sqrt{2}} (\lambda A_\lambda - 2\kappa_{\text{eff}})
\]
\[
\mathcal{M}_{P,22}^2 = \frac{(\lambda A_\lambda + 4\kappa_{\text{eff}}) \sin 2\beta}{4\mu_{\text{eff}}} \lambda v^2 - \frac{3\mu_{\text{eff}}}{\lambda} \kappa A_\kappa - \frac{\lambda_\mu}{2\mu_{\text{eff}}} \lambda_\nu v^2
\]

By diagonalizing the mass matrix \(\mathcal{M}_S^2\) and \(\mathcal{M}_P^2\) using the unitary rotations \(V\) and \(V_P\), we can get the mass eigenstates \(H_i(i = 1, 2, 3)\) and \(A_i(i = 1, 2)\). The mass of the charged Higgs bosons \(m_{H^\pm}\) can be written as follows
\[
m_{H^\pm}^2 = m_W^2 - \mu^2 \lambda^2 + \frac{\mu_{\text{eff}}}{\cos \beta \sin \beta} \left(\frac{\kappa}{\lambda} \mu_{\text{eff}} + A_\lambda\right)
\]

The neutralino sector in the \(\mu\)NMSSM consists of Bino field \(\tilde{B}^0\), Wino field \(\tilde{W}^0\), Higgsino fields \(\tilde{H}_d^0, \tilde{H}_u^0\) and Singlino field \(\tilde{S}^0\). In the basis \(\psi^0 = (-i\tilde{B}^0, -i\tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0, \tilde{S}^0)\), the mass matrix can be given by [156]
\[
M_{\tilde{\chi}^0} = \begin{pmatrix}
M_1 & 0 & -m_Z \sin \theta_W \cos \beta & m_Z \sin \theta_W \sin \beta & 0 \\
\cdot & M_2 & m_Z \cos \theta_W \cos \beta & -m_Z \cos \theta_W \sin \beta & 0 \\
\cdot & \cdot & 0 & -(\mu + \mu_{\text{eff}}) & -\lambda v \sin \beta \\
\cdot & \cdot & \cdot & 0 & -\lambda v \cos \beta \\
\cdot & \cdot & \cdot & \cdot & 2\sqrt{2} \mu_{\text{eff}}
\end{pmatrix}
\]

where \(\theta_W\) denotes the Weinberg angle, \(M_1\) and \(M_2\) denote the gaugino soft breaking masses. By a rotation matrix \(N\), we can get the mass eigenstate \(\tilde{\chi}_i^0(i = 1 - 5)\), which are labeled in mass-ascending order. It can clearly see that the higgsino mass in the \(\mu\)NMSSM is determined by the parameter \(\mu_{\text{tot}} = \mu + \mu_{\text{eff}}\), and the singlino mass mainly depends on \(2\sqrt{2} \mu_{\text{eff}}\).

In the basis \(\psi^\pm = (\tilde{W}^+, \tilde{H}_u^+, \tilde{W}^-, \tilde{H}_d^-)\), the chargino mass matrix is written as
\[
M_{\tilde{\chi}^\pm} = \begin{pmatrix}
M_2 & \sqrt{2} m_W \sin \beta \\
\sqrt{2} m_W \cos \beta & \mu + \mu_{\text{eff}}
\end{pmatrix}
\]

By rotation matrix \(U^c\) and \(V^c\), we can get the chargino mass eigenstate \(\tilde{\chi}_i^\pm(i = 1, 2)\).
Table 1. Rows represent the Higgs boson production modes: gluon fusion (ggH), vector boson fusion (VBF), associated production with a Z or W boson (VH), and associated production with a top quark pair (ttH). Columns represent Higgs boson decay modes.

For convenience, we have selected the following independent parameters as input parameters

\[ \lambda, \kappa, A_\lambda, A_\kappa, \mu, \mu_{\text{tot}}, \tan\beta \]  

(2.11)

2.2 Observables of the 125 GeV Higgs bosons

The ATLAS and CMS collaborations discovered a 5\(\sigma\) signal for a Higgs-like resonance with mass around 125 GeV [139, 140]. However, these signal channels deviate by 1–2\(\sigma\) from the SM prediction. Of course, as the experiment’s precision improves, we will be able to confirm the true nature of the discovered Higgs boson. But firstly, we need to see if the two mass-degenerate Higgs hypothesis can provide a better explanation for the current experiment. The enhancement of final state \(\gamma\gamma\) under the production modes of gluon fusion (ggH) and vector boson fusion (VBF) is one of the deviations between the current experimental data and the SM prediction.

We usually focus on the product of the production cross section \(\sigma_i\) and the decay branching ratio \(B_f\), so we define the observable \(O_{ij}\),

\[ O_{ij} = \sum_\alpha O_{ij}^\alpha \]

\[ O_{ij}^\alpha = \sigma_i^{H_\alpha} B_f^{H_\alpha} \]  

(2.12)

where \(i\) denotes the production modes: gluon fusion (ggH), vector boson fusion (VBF), associated production with a Z or W boson (VH), and associated production with a top quark pair (ttH), \(f\) denotes the decay modes: \(\gamma\gamma\), WW, \(\tau\tau\), bb, etc., \(\alpha\) denotes the index of the resonance. Eq. (2.12) is in general case, with a sum over the index of the resonance, and we can specify it to the case of a single resonance. We list major \(O_{ij}\) in table 1 and we could arbitrarily expand the table based on the process discovered at the LHC experiment, or we can empty the table that was not discovered at the LHC experiment. The error size of these data varies greatly due to the number of collider events and other factors.

We can select any part of interest or with high experimental precision to study. For example, when we choose the intersection of the first two rows and the first two columns, the determinant of this 2 \(\times\) 2 matrix is zero if there is only one Higgs resonance,

\[ O_{ggH,\gamma\gamma} O_{VBF,WW} - O_{VBF,\gamma\gamma} O_{ggH,WW} = 0 \]
In general case, the equation should be slightly modified as
\[(1 + \delta)O_{ggH,\gamma\gamma}O_{\gamma\gamma H,WW} - O_{VBF,\gamma\gamma}O_{ggH,WW} = 0\]  \hspace{1cm} (2.13)
here \(\delta\) is a factor, representing the degree of deviation. For clarity, this formula can be transformed as follows,
\[
\frac{O_{VBF,\gamma\gamma}}{O_{\gamma\gamma H,WW}} = \frac{O_{ggH,WW}}{O_{ggH,WW}} = 1 + \delta
\]  \hspace{1cm} (2.14)
This means that if there is only one Higgs resonance, this type of double ratio is strictly equal to 1, and \(\delta = 0\). Whereas, if there are two or more Higgs resonance, the ratio deviates from one, and \(\delta \neq 0\). Note that the observable \(O_{ij}\) is defined in eq. (2.12), and we should sum over the index of the resonance if there are two or more Higgs resonance. In our work, we focus on the scenario with two mass-degenerate Higgs bosons in the \(\mu\)NMSSM considering various constraints.

\section*{2.3 Dark matter in the \(\mu\)NMSSM}

We have two requirements for DM in the \(\mu\)NMSSM in our work. Firstly, we suppose that there was a large amount of DM in the early universe, and they reached the current Planck observation \(\Omega_{DM}h^2 = 0.120 \pm 0.01\) as they freezed out [158–160]. In this case, the relic density of DM \(\chi^0_1\) in the \(\mu\)NMSSM is required to be less than the central value 0.12. Note that the \(Z_3\)-NMSSM employs four parameters: \(m_{\tilde{\chi}^0_1}\), \(\lambda\), \(\kappa\) and \(\tan\beta\) to describe the properties of DM, but the properties of DM in the \(\mu\)NMSSM are described by five parameters: \(m_{\tilde{\chi}^0_1}\), \(\lambda\), \(\kappa\), \(\tan\beta\) and \(\mu_{tot}\) [136]. We can change \(\kappa\) to use the \(\chi^0_1\chi^0_1 \rightarrow h_sA_s\) process to achieve the correct relic density. Besides, DM based on higgsino in the \(\mu\)NMSSM has obvious advantages since that higgsino-dominated DM is different from the SU(2) singlet dominated DM which does not interact with Z bosons, such as \(\tilde{B}, \tilde{W},\) and \(\tilde{S}\). And the coupling of Z boson with higgsino-dominated DM \(C_{Z\chi^0_1\chi^0_1}\) in the \(\mu\)NMSSM is [161, 162],
\[
C_{Z\chi^0_1\chi^0_1} = -\frac{i}{2} (g_1 \sin \theta_W + g_2 \cos \theta_W) \left(N_{13}^2 - N_{14}^2\right) \frac{\gamma_\mu P_L}{\gamma_\mu P_R}
\]  \hspace{1cm} (2.15)
where \(\left|N_{13}^2 - N_{14}^2\right|\) is called ‘higgsino asymmetry’.

Secondly, spin-independent (SI) and spin-dependent (SD) DM-nucleon cross sections are required to meet experimental limits [163–165]. When the squarks are heavy, the SI nucleon scattering is primarily the t-channel process of exchanging Higgs bosons with the cross-section given as [166, 167],
\[
\sigma^{SI}_N = \frac{4\mu^2_r}{\pi} \left|f^{(N)}\right|^2, \quad f^{(N)} = \sum_{i} f^{(N)}_{H_i} = \sum\frac{C_{\chi^0_1\chi^0_1 H_i} C_{NNH_i}}{2m_{H_i}^2}
\]  \hspace{1cm} (2.16)
where \(\mu_r = m_N m_{\tilde{\chi}^0_1}/(m_N + m_{\tilde{\chi}^0_1})\) is the reduced mass of nucleus and \(\tilde{\chi}^0_1\), and \(C_{NNH_i}\) is the coupling of Higgs boson \(H_i\) with nucleon,
\[
C_{NNH_i} = -\frac{m_N}{v} \left[ F^{(N)}_d (V_{i2} - \tan \beta V_{i1}) + F^{(N)}_u (V_{i2} + \frac{1}{\tan \beta} V_{i1}) \right]
\]  \hspace{1cm} (2.17)
In the above formula, \( F_d^{(N)} = f_d^{(N)} + f_s^{(N)} + \frac{2}{27} f_G^{(N)} \) and \( F_u^{(N)} = f_u^{(N)} + \frac{4}{27} f_G^{(N)} \) with form factor \( f_q^{(N)} = m_N^{-1} \langle N | q \bar{q} | N \rangle \) (\( q = u, d, s \)) and \( f_G^{(N)} = 1 - \sum_{q=u,d,s} f_q^{(N)} \). In our case that mass of the heaviest neutral CP-even Higgs is larger than 1.5 TeV, the dominant contributions to the SI cross-section are from the two light Higgs bosons and the relevant couplings \( C_{\chi_1 \chi_1^0 H_i} \) is given by [138],

\[
C_{\chi_1 \chi_1^0 H_i} \simeq \frac{\mu + \mu_{\text{eff}}}{v} \left( \frac{\lambda v}{\mu + \mu_{\text{eff}}} \right)^2 \frac{N_{15}^2 V_{12} (m_{\chi_1^0}/(\mu + \mu_{\text{eff}}) - \sin 2\beta)}{1 - (m_{\chi_1^0}/(\mu + \mu_{\text{eff}}))^2} \\
+ \frac{\lambda}{2\sqrt{2}} \left( \frac{\lambda v}{\mu + \mu_{\text{eff}}} \right)^2 \frac{N_{15}^2 V_{13} \sin 2\beta}{1 - (m_{\chi_1^0}/(\mu + \mu_{\text{eff}}))^2} \\
- \sqrt{2} \kappa N_{15}^2 V_{13} \left[ 1 + \left( \frac{\lambda v}{\sqrt{2}(\mu + \mu_{\text{eff}})} \right)^2 \frac{1}{1 - (m_{\chi_1^0}/(\mu + \mu_{\text{eff}}))^2} \frac{\mu_{\text{eff}}}{\mu + \mu_{\text{eff}}} \right]
\]

(2.18)

Then the SD cross section takes the following simple from [168, 169],

\[
\sigma_{SD}^N \simeq C_N \times 10^{-4} \times \left( \frac{N_{13}^2 - N_{14}^2}{0.1} \right)^2 \\
\simeq C_N \times 10^{-2} \times \left( \frac{\lambda v}{\sqrt{2}(\mu + \mu_{\text{eff}})} \right)^4 \left( \frac{N_{15}^2 \cos 2\beta}{1 - (m_{\chi_1^0}/(\mu + \mu_{\text{eff}}))^2} \right)^2
\]

(2.19)

where \( C_N = C_p \simeq 4.0 \) pb for the proton and \( C_N = C_n \simeq 3.1 \) pb for the neutron and these equations could be helpful for understanding our numerical results in the following sections.

### 2.4 \((g-2)_\mu\) in the \(\mu\)NMSSM

In supersymmetry, the correction for the muon anomalous magnetic moment \( a_{\mu}^{\text{SUSY}} \) in the \(\mu\)NMSSM is almost the same as the case in MSSM, the difference is that \( \mu \) in MSSM is replaced by \( \mu_{\text{tot}} \) in the \(\mu\)NMSSM. Although at one loop there is also the possibility of a singlino insertion contribution, this contribution is never large when DM constraints are considered, at least for the singlino-dominated DM case [137].

We list the loop contribution items of \( a_{\mu}^{\text{SUSY}} \) [40, 170],

\[
a_{\mu}^{\text{SUSY}} = \left[ a_{\mu}^{1L(a)} + a_{\mu}^{2L(a)} + a_{\mu}^{2L(b)} + a_{\mu}^{2L(c)} \right] \tan \beta + \cdots 
\]

(2.20)

Referring to ref. [43], Feynman diagrams for \( a_{\mu}^{1L}, a_{\mu}^{2L(a)}, a_{\mu}^{2L(b)}, a_{\mu}^{2L(c)} \) are given in figure 1 and figure 2, respectively. The subscript \( \tan \beta \) means that each n-loop term is proportional to the \((\tan \beta)^n\) term, which leads to a 10% correction for higher-order terms if \( \tan \beta \) is greater than 50 [51]. If \( \tan \beta \) tends to infinity, even if all SUSY particle masses are above TeV scale, there can keep a large correction [74].
Figure 1. The one-loop contributions arise from Feynman diagrams where the muon lepton number is carried by $\tilde{\mu}$ or $\tilde{\nu}_\mu$. The external photon can couple to each charged particle.

Figure 2. The two-loop $a^{2L(a)}_\mu$ (left) with closed stop loop inserted into an SM-like one-loop diagram with Higgs and photon exchange, $a^{2L(b)}_\mu$ (middle) or $a^{2L(c)}_\mu$ (right) corresponding to SUSY one-loop diagrams with additional photon loop, or with fermion/sfermion-loop insertion. The external photon can couple to each charged particle.

It can be seen from figure 1 that the correction of one-loop diagram mainly comes from two parts, one part is the exchange of neutralinos $\tilde{\chi}^0_i$ and smuon $\tilde{\mu}$, and the other part is the exchange of charginos $\tilde{\chi}^\pm_i$ and sneutrino $\tilde{\nu}_\mu$:

\[
a^{\text{1L}}_\mu = a^{0\tilde{\mu}} + a^{\tilde{\nu}_\mu}_\mu,
\]

\[
a^{0\tilde{\mu}}_\mu = \frac{m_\mu}{16\pi^2} \sum_{i,l} \left\{ - \frac{m_\mu}{12m_{\tilde{\mu}_i}} \left( |n^L_{il}|^2 + |n^R_{il}|^2 \right) F^N_{1l} (x_{il}) + \frac{m_{\tilde{\chi}^0_i}}{3m_{\tilde{\mu}_i}} \text{Re} \left( n^L_{il}n^R_{il} \right) F^N_{2l} (x_{il}) \right\},
\]

\[
a^{\tilde{\nu}_\mu}_\mu = \frac{m_\mu}{16\pi^2} \sum_{i,l} \left\{ - \frac{m_\mu}{12m_{\tilde{\nu}_\mu}} \left( |c^L_k|^2 + |c^R_k|^2 \right) F^C_{1l} (x_k) + \frac{2m_{\tilde{\chi}^\pm_i}}{3m_{\tilde{\nu}_\mu}} \text{Re} \left( c^L_kc^R_k \right) F^C_{2l} (x_k) \right\},
\]

where $i = 1, \ldots, 5$, $l = 1, 2$, $k = 1, 2$ are the neutralino, smuon and chargino index, respectively. $n^L_{il}, n^R_{il}, c^L_k, c^R_k$ are expressed as follows:

\[
n^L_{il} = \frac{1}{\sqrt{2}} (g_2 N_{i2} + g_1 N_{i1}) X^*_{i1} - y_\mu N_{i3} X^*_{i2}, \quad n^R_{il} = \sqrt{2} g_1 N_{i1} X_{i2} + y_\mu N_{i3} X_{i1},
\]

\[
c^L_k = -g_2 V^c_{k1}, \quad c^R_k = y_\mu U^c_{k2}.
\]

where $y_\mu = g_2 m_\mu / (\sqrt{2} m_W \cos \beta)$ is the muon Yukawa coupling, $X$ is the smuon mass rotation matrix. The kinematic loop functions $F(x)$ depending on the variables $x_{il} \equiv
$m^{2}_{\tilde{\chi}^{0}_{i}}/m^{2}_{\mu}$ and $x_{k} \equiv m^{2}_{\tilde{\chi}^{k}_{L}}/m^{2}_{\tilde{\mu}_{\mu}}$ are given by:

$$F_{1}^{N}(x) = \frac{2}{(1-x)^{2}} \left[ 1 - 6x + 3x^{2} + 2x^{3} - 6x^{2} \ln x \right]$$

$$F_{2}^{N}(x) = \frac{3}{(1-x)^{2}} \left[ 1 - x^{2} + 2x \ln x \right]$$

$$F_{1}^{C}(x) = \frac{2}{(1-x)^{2}} \left[ 2 + 3x - 6x^{2} + x^{3} + 6x \ln x \right]$$

$$F_{2}^{C}(x) = -\frac{3}{2(1-x)^{2}} \left[ 3 - 4x + x^{2} + 2 \ln x \right]$$

(2.23)

It can be seen that $a_{1L}^{H}$ depends essentially on the bino(wino) masses $M_{1}(M_{2})$, the higgsino mass $\mu$, the left(right) smuon mass $m_{L_{\mu}}, m_{E_{\mu}}$ and $\tan \beta$, and it hardly depends on $A_{t}, A_{\kappa}$ or $A_{\lambda}$. There is a simple relationship, $a_{1L}^{H}$ is proportional to $\tan \beta/M^{2}_{SUSY}$, where $M^{2}_{SUSY}$ refers to the general SUSY mass [53, 55, 127].

The two-loop correction to $a_{\mu}^{SUSY}$ has three types shown in figure 2. The correction from the left diagram mainly depends on Higgs boson masses and stop masses. The term $a_{\mu}^{2L(a)}$ can be large in certain regions of parameter space but decouples as the masses of SUSY particles or heavy Higgs increase [43]. The term $a_{\mu}^{2L(b)}$ has an additional negative factor, which usually results in a $(-7 \ldots -9)\%$ correction according to the literature [52, 171]. The contribution of the fermion/sfermion-loop is introduced in the right diagram, which includes the each generation squarks and sleptons. The peculiarity of this diagram is that if the mass of the fermions (sfermions) is very large, it does not decouple, but increases logarithmically. When the squark mass is lower than the TeV scale, the $a_{\mu}^{2L(c)}$ term can achieve a positive or negative correction of about 10% [53, 54].

2.5 Parameter space and scanning method

We start with a random scan to find the initial point in the parameter space, and then use the Markov chain Monte Carlo (MCMC) scan in EasyScan-1.0.0 [172] to explore the high-dimensional parameter space as follows,

$$|M_{1}| \leq 2.5 \text{ TeV}, \quad 100 \text{ GeV} \leq M_{2} \leq 2 \text{ TeV},$$

$$0 \leq \lambda \leq 0.5, \quad |\kappa| \leq 0.5, \quad 1 \leq \tan \beta \leq 60, \quad 2 \text{ TeV} \leq |A_{t}| \leq 5 \text{ TeV},$$

$$10 \text{ GeV} \leq \mu \leq 1 \text{ TeV}, \quad 100 \text{ GeV} \leq \mu_{\text{tot}} \leq 1 \text{ TeV}, \quad |A_{\kappa}| \leq 1 \text{ TeV},$$

$$100 \text{ GeV} \leq m_{L_{\mu}} \leq 2 \text{ TeV}, \quad 100 \text{ GeV} \leq m_{E_{\mu}} \leq 3 \text{ TeV},$$

(2.24)

We set $A_{\lambda}$ and other supersymmetric parameters of the first and third generation sleptons, all squarks and gluinos to 2 TeV. We use SARAH-4.14.3 [173–176] to generate the model files in the $\mu$NMSSM and then use SPheno-4.0.4 [177, 178] to generate spectrums, which includes the masses of the particles, mixing angles between mass eigenstates and interaction fields and other physical observables. In order to improve the sampling efficiency, we only require that the spectrums should satisfy the following conditions during scanning, whereas we will discuss the effects of DM direct detection limits and the $(g-2)_{\mu}$ anomaly on the parameter space in section 3 and section 4, respectively.
• There are two mass-generate Higgs bosons with mass in 123–128 GeV. The package HiggsBounds-5.3.2 \cite{179} is used to check non-SM-like Higgs bosons against the published exclusion bounds from Higgs boson searches at the LEP, Tevatron and LHC experiments. While the package HiggsSignals-2.2.3 \cite{180} evaluates a $\chi^2$ measure to provide a quantitative answer to the statistical question of how compatible the Higgs data is with predictions. Spectrums with p-values less than 0.05 are excluded at the 95% confidence level. SPheno writes the spectrum file and the input interface files for HiggsBounds and HiggsSignals.\footnote{The interface files include BR\_t.dat, BR\_H\_NP.dat, BR\_Hplus.dat, effC.dat, MH\_GammaTot.dat, MHplus\_GammaTot.dat. With these files as input, we can run HiggsBounds and HiggsSignals by issuing the following commands, respectively:}

```
./HiggsBounds LandH effC 5 1
```

“LandH” indicates that LEP, Tevatron and LHC analyses will be considered by HiggsBounds, “effC” stands for the input format for HiggsBounds, “5” stands for the number of neutral Higgs bosons and “1” stands for the number of charged Higgs boson in the model.

```
./HiggsSignals latestresults peak 2 effC 5 1
```

“peak” specifies that the peak-centered $\chi^2$ method should be used by HiggsSignals, “2” selects the Gaussian parametrization for the Higgs mass uncertainty. “latestresults” has the same meaning as “LandH”, “effC”, “5” and “1” have the same meaning as described for HiggsBounds.

• DM relic density $\Omega h^2 = 0.120 \pm 0.01$. We assume the LSP $\chi^0_1$ is one of the DM candidates, so the DM relic density is required to be less than 0.120, i.e., $\Omega h^2 < 0.120$. The Spin-independent (SI) DM cross section $\sigma_{SI}$ and spin-dependent (SD) cross section $\sigma_{SD}$ should be scaled by a factor $\Omega h^2 / 0.120$. We use the package MicrOMEGAs-5.0.4 \cite{181–186} to calculate $\Omega h^2$, $\sigma_{SI}$ and $\sigma_{SD}$.

• Results from sparticle searches at the LHC. SModelS-1.2.3 \cite{187–192} is used to determine whether a sample is excluded or not by decomposing spectrum and converting it into Simplified Model topologies and then comparing it with these simplified model results interpreting from the LHC. We consider these typical processes $pp \rightarrow \tilde{\chi}^0_{1,2} \tilde{\chi}^\pm_1, \tilde{\chi}^+_1 \tilde{\chi}^-_1, \tilde{\mu}^+ \tilde{\mu}^-$ and use the package Prospino2 \cite{193–196} to generate the next-to-leading order cross sections of these processes as inputs for SModels.

3 Properties of DM confronted with direct detection limits

We project the surviving samples obtained during scanning in figure 3. In the left plot, the green samples above the red dashed line are excluded by the XENON-1T SI limit in 2018 \cite{163} and the green samples below the red dashed line are excluded by the XENON-1T SD limit in 2019 \cite{164}. While in the right plot, the cyan samples above the red dashed line are excluded by the XENON-1T SD limit in 2019, but the cyan samples below the red dashed line are excluded by the XENON-1T SI limit in 2018. The samples with red points in the left plot and magenta points in the right plot are the surviving samples considering the limits from DM direct detections. So, we can see that the SI and SD constraints are
Figure 3. SI (left plot) and SD (right plot) cross section for DM-nucleon experiments versus the mass of DM in the scenario with two mass-degenerate Higgs bosons. The red dashed line on the left plot stands for the XENON-1T SI limit in 2018, the red dashed line (magenta dash-dotted) on the right plot stands for the XENON-1T SD limit in 2019 (LUX SD limit in 2017). Samples above these lines are excluded, and samples with red and magenta points are the surviving samples considering the limits from DM direct detections. The black solid line stands for the neutrino floor.

Figure 4. The projection of samples on the $\lambda - \kappa$ plane, $\lambda - \tan \beta$ plane and $\mu_{\text{tot}} - M_2$ plane. Samples represented by green points indicate ones excluded by DM direct detection limits and those represented by red points are surviving samples confronted with these limits.

complementary in limiting the parameter space of $\mu$NMSSM. We notice that there are a few of samples whose SI cross section can be lower than the neutrino floor, and consequently these DM may never be probed in DM direct detections. In the following discussion, we will focus on the parameter space tightly limited by DM direct detection limits in the $\mu$NMSSM.

Figure 4 shows the samples on the $2\kappa/\lambda - \mu_{\text{tot}}/\mu_{\text{eff}}$ plane, $\lambda - \tan \beta$ plane and $\mu_{\text{tot}} - M_2$ plane. Samples with red (green) points are allowed (excluded) by DM direct detection
limits. In the scenario with two mass-degenerate SM-like Higgs bosons, the DM is higgsino-dominated, which is easier to meet the constraints from DM direct detections compared with the scenario with singlino-dominated DM. To avoid the singlino-dominated DM in the $\mu$NMSSM, $2\kappa/\lambda$ should be far greater than $\mu_{\text{tot}}/\mu_{\text{eff}}$, which can be seen clearly from figure 4(a). This is significantly different from the case in the $Z_3$-NMSSM, which only requires $2\kappa/\lambda$ to be greater than 1. In figure 4(b), we find that a large $\tan\beta$ greater than about 20 is accompanied with a small $\lambda$ less than about 0.05, which guarantee to realize two mass-degenerate Higgs boson with mass about 125 GeV. In figure 4(c), we can see that a larger $M_2$ is required since that it can avoid the wino-dominated neutralino as the LSP.

To consider the DM direct detection limits, we try to find the factor that affect the variation of SI and SD cross section. We find that $m_{\tilde{\chi}_1^0}$ is around 50–200 GeV, which is much greater than the neutron mass. So $\mu_r$ in eq. (2.16) change little for different $m_{\tilde{\chi}_1^0}$, $\sigma_{SI}$ is primarily influenced by the couplings $C_{\tilde{\chi}_1^0\tilde{\chi}_1^0H_1}$ and $C_{N_iH_1}$. We propose that the factor $A_X$ derived from eq. (2.18) has a powerful influence on $\sigma_{SI}$:

$$A_X = \frac{m_{\tilde{\chi}_1^0}/\mu_{\text{tot}}}{1 - \left(m_{\chi_1^0}/\mu_{\text{tot}}\right)^2}$$

In figure 5 we show the effect of $A_X$ on $\sigma_{SI}$ on the left plot, and the effect of higgsino asymmetry $N_{ha} = |N_{13}^2 - N_{14}^2|$ on $\sigma_{SD}$ on the right plot. As the size of the cross section decreases, the color of the surviving sample shows a gradient change, which shows that the SI and SD cross sections depend on the variation of $A_X$ and $N_{ha}$.

We project samples on $\tan\beta$ - $A_X$ plot and $M_2$ - $A_X$ plot in figure 6. The trend that $\sigma_{SI}$ decreases with increasing $A_X$ holds true for all samples as shown on the right plot. In the horizontal band $A_X = 0 \sim 1$, a large number of samples are excluded because they have higher DM relic densities leading to higher $\sigma_{SD}$ and $\sigma_{SI}$. This can be seen from the green samples in the horizontal band $A_X = 0 \sim 1$ on the left plot. $\Omega h^2$ of samples in this
Figure 6. All samples in figure 3 are projected on $\tan \beta - A_X$ plot and $M_2 - A_X$ plot. The colorbar represents the common logarithm of DM relic density in the left plot. Black samples in the right plot are excluded by DM direct detection limits, and the others are surviving samples. For surviving samples, the colorbar in the right plot represents the common logarithm of $\sigma_{SI}$, samples close to green color are much safer, samples close to red color are near DM direct detection limits.

Figure 7. The projection of all samples in figure 3 on $N_{13}/N_{14} - m_{\tilde{\chi}_1^0}/\mu_{tot}$ plot and $N_{13} - N_{14}$ plot. Black samples in each plot are excluded by DM direct detection limits, and the others are surviving samples. For surviving samples, the colorbar in each plot represents $\sigma_{SD}$, samples close to green color are much safer, samples close to red color are near DM direct detection limits.

band are much higher than the surrounding ones and so they are excluded by DM direct detection limits.

We project samples on $N_{13}/N_{14} - m_{\tilde{\chi}_1^0}/\mu_{tot}$ plot and $N_{13} - N_{14}$ plot in figure 7. When $N_{13}$ is less than $N_{14}$, $m_{\tilde{\chi}_1^0}/\mu_{tot}$ is proportional to $N_{13}/N_{14}$. When $N_{13}$ is relatively large, however, the relationship between $m_{\tilde{\chi}_1^0}/\mu_{tot}$ and $N_{13}/N_{14}$ is inversely proportional. We can see that the samples with $N_{13}/N_{14}$ close to one on the left plot of figure 7 correspond to the samples with smaller higgsino asymmetry on the right plot of figure 5, and they all have safer $\sigma_{SI}$. The horizontal band $m_{\tilde{\chi}_1^0}/\mu_{tot} = 0.7 - 0.9$ is severely excluded by DM direct detection limits because it corresponds to a larger higgsino asymmetry. When $N_{13}/N_{14}$
Figure 8. All surviving samples in figure 5 are projected on plots of $R_{VBF,\gamma\gamma}^h - R_{VBF,WW}^h$, $R_{VBF,\tau\tau}^h - R_{ggH,ZZ}^h$, $B_{WW}^b - B_{bb}$. The colorbar represents $\sum_i \sigma_i^H / \sum_i \sigma_i^h$. Samples with green (red) color indicate that $\sigma_i^h$ mainly comes from the contribution of $H_1$ ($H_2$), and samples with golden color indicate that $\sigma_i^h$ comes from contributions of both $H_1$ and $H_2$. The pink line stands for one standard deviation observed by ATLAS and CMS. The blue star represents the SM prediction.

is smaller or larger, the surviving samples reappear because $N_{13}$ and $N_{14}$ themselves are much small. This corresponds to the green samples in the left-bottom corner on the right plot in figure 7. The right plot supports our conclusion that the samples satisfying DM direct detection limits must have a smaller higgsino asymmetry.

4 The mass-degenerate SM-like Higgs bosons and the explanation of muon $g - 2$ anomaly

4.1 The mass-degenerate SM-like Higgs bosons

To show the deviation of Higgs signal ($h$) observed by the ATLAS and CMS collaborations from the SM prediction, we define

$$R_{ij}^h = \frac{\sigma(i \rightarrow H_\alpha) \times B(H_\alpha \rightarrow f)}{\sigma(i \rightarrow h_{SM}) \times B(h_{SM} \rightarrow f)}$$

$$\mu_i^{H_\alpha} = \frac{\sigma_i^{H_\alpha}}{\sigma_i^{h_{SM}}}$$

$$B_{bb/WW}^i = \sum_\alpha \left[ B(H_\alpha \rightarrow bb/WW) \times \frac{\sigma_i^{H_\alpha}}{\sum_i \sigma_i^{H_\alpha}} \right]$$

where $\alpha = 1, 2$, $i$ denotes the production modes: gluon fusion ($ggH$), vector boson fusion ($VBF$), associated production with a Z or W boson ($VH$), and associated production with a top quark pair ($ttH$), $f$ denotes the decay modes: $\gamma\gamma$, $WW$, $\tau\tau$, $bb$, etc. We can simply have $\sigma_i^h = \sigma_i^H_1 + \sigma_i^H_2$ and $R_{ij}^h = R_{ij}^{H_1} + R_{ij}^{H_2}$. In the calculations we ignore the interference effect between the two mass degenerate Higgs bosons in the $\mu$NMSSM because the mass difference between most of the two Higgs bosons in our collected samples is greater than 50MeV.

We project the surviving samples on plots of $R_{VBF,\gamma\gamma}^h - R_{VBF,WW}^h$, $R_{VBF,\tau\tau}^h - R_{ggH,ZZ}^h$, $B_{WW}^b - B_{bb}$ in figure 8. From figure 8, we can see that $R^b$ and $B_{bb(WW)}$ predicted by SM are
different from that measured by ATLAS and CMS. \( B_{bb(WW)} \) predicted by SM even deviates beyond the experimental 1\( \sigma \) error. But Samples in the scenario with two mass-degenerate Higgs bosons are much more consistent with measured data than the SM prediction.

To quantify the degree of agreement with the measured data totally, we define

\[
\chi^2_{ij} = \frac{1}{2} \left( \frac{R_{ij}^h - R_{ij,ob}^h}{R_{ij,er}^h} \right)^2
\]

(4.3)

where \( R_{ij,ob}^h \) is the measured central value and \( R_{ij,er}^h \) is one standard deviation. When \( \chi^2 \) is zero, samples are perfectly aligned with measured data. Besides, to compare with the SM prediction conveniently, we define \( C_{ij} = \chi^2_{ij}/(\chi^2_{ij})_{SM} \). If \( C_{ij} \) is smaller than one, the scenario with two mass-degenerate Higgs bosons is more consistent with the measured data. Referring to ref. [149], we also use the double ratios:

\[
D_1 = \frac{R_{VBF,\tau\tau}^h}{R_{ggH,\tau\tau}^h}, \quad D_2 = \frac{R_{VBF,\gamma\gamma}^h}{R_{ggH,\gamma\gamma}^h}, \quad D_3 = \frac{R_{VBF,WW}^h}{R_{ggH,WW}^h}
\]

(4.4)

We project surviving samples in figure 5 on plots of \( \mu_{VBF}^H + \mu_{VBF}^H C_{VBF,\tau\tau} \), \( D_3 - C_{ttH,WW} \) and \( \kappa - C_{ggH,\gamma\gamma} \) in figure 9. It is clear that there is a strong correlation between \( \sum_i \sigma_i^h / \sum_i \sigma_i^h \) and \( C_{ij} \). When the contribution on \( \sum_i \sigma_i^h \) mainly comes from \( H_1 \) or \( H_2 \), the values of \( C_{ij} \) are close to 1, as the samples with red or green shows. That is to say, these samples are consistent with the SM prediction. But there are lots of samples with \( C_{ij} \) smaller than 1, which means that the assumption with two mass-degenerate Higgs bosons may be true. For example, in figure 9(a), when \( \mu_{VBF}^H + \mu_{VBF}^H \) is around the experimental measured value \( \mu_{VBF}^x = 1.18 \), samples have the lowest \( C_{VBF,\tau\tau} \). Figure 9(b) shows that \( C_{ttH,WW} \) decreases obviously when \( D_3 \) is less than 1. In figure 9(c), we can see that the SM prediction is better than samples in the scenario with two mass-degenerate Higgs bosons for \( C_{ggH,\gamma\gamma} \). The reason is that the cross section of \( VBF \) in the scenario with two
mass-degenerate Higgs bosons is raised compared to SM, but that of $ggH$ is not. When we take into account the total contribution $C_{tot} \equiv \sum_{i,j} C_{ij}$ including the high precision processes $(i,j) = (ggH, \gamma\gamma), (ggH, ZZ), (ggH, WW), (VBF, \gamma\gamma), (VBF, WW), (VBF, \tau\tau), (ttH, WW) \ [141, 143, 144]$, there exist some samples with $C_{tot} < 1$, which are more consistent with the measured Higgs data than the SM prediction. We list the relevant parameters of two benchmark points in table 2. For the DM mechanism that yields a relic density compatible with the observed upper bound, we find that the leading contribution is from the process $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow W^+W^-$, the contribution rate of this process is 49% and 51% for P1 and P2, respectively. For P1, the subleading contribution with 27% rate is from the coannihilation process $\tilde{\chi}_1^0 \tilde{\chi}_1^\pm \rightarrow f f'$ due to the mass splitting between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ at 11%, here $f, f'$ are the SM quarks. The other contribution is from the process $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow ZZ$. For P2, the other contributions are from the processes $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow ZZ, H_iA_j, H_iH_j$, here $H_i, A_j$ are the CP-even and CP-odd neutral Higgs, respectively. The main annihilation Feynman diagrams for the two benchmark points are presented in figure 10.

4.2 $(g-2)_\mu$ in the scenario with two mass-degenerate SM-like Higgs bosons

The muon anomalous magnetic $(g-2)_\mu$ predicted by our collected samples are labeled as $a^\text{SUSY}_\mu$. We use SPheno-4.0.4 to calculate $(g-2)_\mu$, which only the BSM contributions are calculated (at the one-loop level), the SM-part is not calculated. The likelihood function $\mathcal{L}$ is defined as an indicator of the degree of conformity between $a^\text{SUSY}_\mu$ and the experiment [137]:

$$\mathcal{L} = \exp \left[ -\frac{1}{2} \left( \frac{a^\text{SUSY}_\mu - 2.51 \times 10^{-9}}{5.9 \times 10^{-10}} \right)^2 \right] \quad (4.5)$$
**Figure 10.** The Feynman diagrams for the main DM annihilation processes. In the first row, \( V \) stands for \( W \) boson or \( Z \) boson, \( H_1 \) stands for the neutral Higgs bosons, \( \tilde{\chi} \) stands for the charginos when \( V = W \) and for the neutralinos when \( V = Z \). Besides, the s-channel propagator can also be \( Z \) boson when \( V = W \). In the second row, \( H^\pm \) is the charged Higgs bosons, \( f, f' \) are the SM fermions and \( \tilde{f}' \) are their SUSY partners.

**Figure 11.** All surviving samples in figure 5 are projected on the plane \( \mu_{\text{tot}} - m_{\mu} \). The color of samples represents the degree of \((g - 2)_\mu\) deviated from the experiment. Green samples represent deviations less than 1\( \sigma \), light green samples represent deviations of 1\( \sigma \) - 2\( \sigma \), and yellow samples represent deviations more than 2\( \sigma \).

We project surviving samples on plot of \( m_{L_\mu} - \mu_{\text{tot}} \) in figure 11. We can see that it is difficult to obtain samples satisfying the result of \((g - 2)_\mu\) experiment when \( m_{L_\mu} \) is greater than 1000 GeV. This is because that the loop contribution to \((g - 2)_\mu\) from smuon decreases sharply when smuon is much heavy.

We project surviving samples on plots \( m_{H_2} - m_{H_1} \) versus \( D_i \) (\( i = 1, 2, 3 \)) in figure 12. We can see that the double ratios \( D_i \) deviate from 1, indicating that there are different contributions from \( H_1 \) and \( H_2 \) on these ratios. And there are lots of samples in agreement with the recent experimental result of \((g - 2)_\mu\). But we note that the deviations are not very outstanding. The reason is that while the production cross sections of two mass-degenerate
Higgs bosons differ, the ratios are similar, i.e., $\frac{\sigma_{ggH_1}^{H_1}}{\sigma_{VBF}^{H_1}} \approx \frac{\sigma_{ggH_2}^{H_2}}{\sigma_{VBF}^{H_2}}$.

To achieve better results, we can take an aggressive approach and only consider the decay branching ratios instead of the production cross-section:

$$
B_{ZZ,\gamma\gamma} = (B_{ZZ}^{H_1} \times B_{\gamma\gamma}^{H_1}) + (B_{ZZ}^{H_2} \times B_{\gamma\gamma}^{H_2}) , \quad B_{ZZ,WW} = (B_{ZZ}^{H_1} \times B_{WW}^{H_1}) + (B_{ZZ}^{H_2} \times B_{WW}^{H_2})
$$

$$
B_{bb,\gamma\gamma} = (B_{bb}^{H_1} \times B_{\gamma\gamma}^{H_1}) + (B_{bb}^{H_2} \times B_{\gamma\gamma}^{H_2}) , \quad B_{bb,WW} = (B_{bb}^{H_1} \times B_{WW}^{H_1}) + (B_{bb}^{H_2} \times B_{WW}^{H_2})
$$

$$
D_B = \frac{B_{ZZ,\gamma\gamma}}{B_{bb,\gamma\gamma}/B_{bb,WW}}
$$

$D_B$ is used to describe similarity of decay of $H_1$ and $H_2$. If $D_B$ is around 1, it means that decay features of $H_1$ and $H_2$ are the same. If $D_B$ deviates from 1, it means that the decay features are different. We project surviving samples on plot $m_{H_2} - m_{H_1}$ versus $D_B$ in figure 13. We can see that the deviation is more obvious under the new variable $D_B$. There are some samples that typically deviate from 1. From the $(g - 2)_\mu$ deviation distribution, we find that the recent experimental result from $(g - 2)_\mu$ can be well explained in the scenario with two mass-degenerate Higgs bosons. Samples with $D_B$ around 1 deviate from the center value of $(g - 2)_\mu$, but some samples with $D_B$ deviation from 1 can satisfy the result of $(g - 2)_\mu$ much better.

5 Summary

In the $\mu$NMSSM with two mass-degenerate SM-like Higgs bosons, we investigate the properties of DM, the observation of two mass-degenerate Higgs bosons and the explanation of $(g - 2)_\mu$ anomaly. We first scan the parameter space under current experimental constraints including results of DM direct detection experiments and from LHC searches for sparticles. We find that,
Figure 13. Same as figure 12, but samples are projected on plot $m_{H_2} - m_{H_1}$ versus $D_B$.

- The SI and SD constraints are complementary in limiting the parameter space of $\mu_{\text{NMSSM}}$. The DM direct detection limits favor the DM is higgsino-dominated.

- The scenario with two mass-degenerate SM-like Higgs bosons is capable of explaining the $(g-2)\mu$ anomaly, that is, the scenarios we consider may be an explanation since they are compatible with the current measurements.

- Deviations defined by the double ratios $D_i (i = 1, 2, 3)$ are not very outstanding. The reason is that the ratio between the production cross section of $H_1$ and $H_2$ are similar. To achieve better results, we define a new variable $D_B$. Samples with $D_B$ deviation from 1 can satisfy the result of $(g-2)\mu$ much better.

- As far as the total contribution $C_{tot}$ is concerned, there exist some samples more consistent with the measured Higgs data than the SM prediction.

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A Double ratios and components of Higgs boson in the scenario with two mass-degenerate SM-like Higgs bosons

We project surviving samples on plots $m_{H_2} - m_{H_1}$ versus $\mu_{VBF}$, $m_{H_1}$ versus $\mu_{VBF}$, $m_{H_2}$ versus $\mu_{VBF}$ in figure 14. We can see that the value of $\mu_{VBF}^{H_1} + \mu_{VBF}^{H_2}$ can be raised to the measured value 1.18 in figure 14, but the single contribution $\mu_{VBF}^{H_1}$ or $\mu_{VBF}^{H_2}$ is all below 1. We also project surviving samples on plots of $m_{H_1} - S_{1X}$ and $m_{H_2} - S_{2X}$ in figure 15.
Figure 14. All surviving samples in figure 5 are projected on plots $m_{H_2} - m_{H_1}$ versus $\mu_{VBF}$, $m_{H_1}$ versus $\mu_{VBF}$, $m_{H_2}$ versus $\mu_{VBF}$. The red samples represent $\mu_{VBF}^{H_1} = \sigma_{VBF}^{H_1}/\sigma_{VBF}^{SM}$, the green samples represent $\mu_{VBF}^{H_2} = \sigma_{VBF}^{H_2}/\sigma_{VBF}^{SM}$, and the gold samples represent $\mu_{VBF}^{H_1} + \mu_{VBF}^{H_2}$.

Figure 15. All surviving samples in figure 5 are projected on the planes $m_{H_1} - S_{1X}$ and $m_{H_2} - S_{2X}$. $H_1 = S_{11}H_d + S_{12}H_u + S_{13}S$, $H_2 = S_{21}H_d + S_{22}H_u + S_{23}S$, $S_{1X}$ and $S_{2X}$ ($X = 1, 2, 3$) are proportions of each component $H_d$, $H_u$ and $S$. The light blue samples represent $S_{i1}$ ($i = 1, 2$), the yellow samples represent $S_{i2}$ and the blue samples represent $S_{i3}$.

Comparing figure 14(b) with figure 15(a) for $H_1$ and figure 14(c) with figure 15(b) for $H_2$, we can see that when $H_1$ or $H_2$ are dominated by $H_u$, its contribution on $\sigma_{VBF}$ is large. when $H_1$ or $H_2$ are dominated by $S$, its contribution on $\sigma_{VBF}$ becomes small. As a result, when the contribution on double ratios mainly comes from a single Higgs, the double ratios are around 1 according to eq. (4.4). Only if $H_1$ and $H_2$ are the mixing of $H_u$ and $S$, the double ratios can deviate from 1.

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