

95 GeV excesses in the $\mathbb{Z}_3$ -symmetric next-to-minimal supersymmetric standard model

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Recent analyses by CMS and ATLAS suggest a deviation in the diphoton channel at approximately 95 GeV, alongside a previously observed excess in $b\bar{b}$ signals at a similar mass by the Large Electron-Positron collider, potentially hinting at a new scalar particle. This study explores this possibility within the framework of the $\mathbb{Z}_3$ -symmetric next-to-minimal supersymmetric standard model. A comprehensive parameter scan was conducted, integrating constraints from dark matter relic density, direct detection experiments, and the properties of the observed 125 GeV Higgs boson. The results demonstrate that the model can accommodate the observed excesses with a singlet-dominated CP -even scalar boson near 95 GeV. The model accurately predicts signal strengths of the diphoton and $b\bar{b}$ channels at a level of 1σ . Furthermore, it accounts for the measured dark matter relic abundance through bino-dominated neutralinos coannihilation with winolike electroweakinos, all while remaining consistent with existing Large Hadron Collider (LHC) constraints. These findings pave the way for future validation at the high-luminosity LHC and linear colliders, which may offer crucial tests of the model's predictions.

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I. INTRODUCTION

The Higgs boson plays a pivotal role in the standard model (SM) of particle physics, serving as the primary agent responsible for electroweak symmetry breaking. It is intimately connected to a multitude of fundamental inquiries concerning the nature of the Universe. Beyond the SM (BSM), various well-motivated theories necessitate expanded scalar sectors to grapple with unresolved issues inherent to the SM, such as neutrino mass, dark matter (DM) origin, and baryon number asymmetries. These extended scalar sectors, while offering potential resolutions to existing SM enigmas, may concurrently introduce notable disparities compared to SM predictions. Following the landmark discovery of the Higgs boson with a mass of approximately 125 GeV at the Large Hadron Collider (LHC) by the ATLAS and CMS Collaborations [1,2], the relentless search for additional scalar bosons has been a primary objective of the collider's scientific agenda. Although conclusive evidence of BSM remains elusive, the persisting

uncertainty within the measurements of Higgs boson couplings, fluctuating by less than approximately 20%, affords an intriguing margin for the exploration of BSM explanations [3].

In the pursuit of new scalar bosons at the LHC, the diphoton signal stands prominently as the “golden channel,” esteemed for its capacity to provide precise measurements and clean experimental signatures. In a recent update, the CMS Collaboration has released their latest analysis focused on the search for a light Higgs boson. This investigation reaffirms a previously reported excess observed at $m_{\gamma\gamma} = 95.4$ GeV with a local significance of 2.9σ by using advanced analysis techniques to 13 TeV data amassed over the first, second, and third years of Run-2 [4]. Besides, the ATLAS Collaboration has also published an analysis of the full Run-2 LHC dataset amounting to 140 fb^{-1} targeting the diphoton signals within the mass range of 66 GeV to 110 GeV [5]. This analysis uncovers an excess at an invariant mass around 95 GeV with a local significance of 1.7σ . Notably, the renormalized diphoton production rates, as observed independently by both collaborations, align within uncertainties for the same mass value, suggesting the plausible emergence of the excesses from the production of a singular new particle. If it is further validated, this could signify the inaugural hint of new physics in the Higgs-boson sector. The combined signal strength yields a 3.1σ local excess [6],

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$$\mu_{\gamma\gamma}^{\text{exp}} = \mu_{\gamma\gamma}^{\text{ATLAS+CMS}} = \frac{\sigma(pp \rightarrow \phi \rightarrow \gamma\gamma)}{\sigma_{\text{SM}}(pp \rightarrow H_{\text{SM}} \rightarrow \gamma\gamma)} = 0.24_{-0.08}^{+0.09}, \quad (1.1)$$

where ϕ represents a hypothetically nonstandard scalar with a mass of $m_\phi = 95.4$ GeV responsible for the diphoton excess, and σ_{SM} denotes the cross section for a hypothetical SM-like Higgs boson H_{SM} at the same mass. Moreover, the existence of a light ϕ finds additional support from the measurement of bottom quark pair events at the Large Electron-Positron (LEP) collider. The combined data hinted at the production of a scalar particle ϕ with an invariant mass of approximately 98 GeV through the process $e^+e^- \rightarrow Z\phi \rightarrow Z(b\bar{b})$, with a signal strength of $\mu_{b\bar{b}}^{\text{exp}} = 0.117 \pm 0.057$ and a local significance of 2.3σ [7–9]. Given the limited mass resolution for dijets at LEP, this $b\bar{b}$ excess might correspond to the same particle responsible for the diphoton excess. Furthermore, the scalar around 95 GeV is also supported by an excess in the di- τ channel observed by CMS [10] and in the WW channel, as discussed in Ref. [11]. Collectively, these observations strengthen the hypothesis that the 95 GeV scalar could be a crucial piece in the quest for new physics.

The conjecture surrounding the observed excesses has ignited a flurry of investigations into the plausibility of interpreting both phenomena within BSM theories [6,12–38]. This intellectual fervor finds a particularly rich ground in the low-energy supersymmetric (SUSY) extensions of the SM as they provide a versatile platform for accommodating various particle sectors, allowing for nuanced examinations of their interplay and potential collective contributions to the observed phenomena [9,39–58]. Among these, the next-to-minimal supersymmetric standard model (NMSSM) [59] has attracted considerable attention in recent years. Distinguishing itself from the well-known minimal supersymmetric standard model (MSSM), the NMSSM augments the latter by introducing a gauge-singlet Higgs field. The allure of this model lies not only in the natural solution to the so-called μ -problem inherent in the MSSM but also in its capacity to furnish more viable DM candidates [60–62]. In the context of elucidating the observed excesses, especially within the scenario involving a light CP -even Higgs, the model's distinctive features contribute to a sizeable lift in the mass of the SM-like Higgs boson. This elevation is attributed to the combined effects of an additional tree-level contribution and the singlet-doublet mixing [63–65], effectively mitigating the need for substantial radiative corrections from top/stop loops. Such alleviation is crucial for aligning with the experimental measurement of the SM-like Higgs boson mass at approximately 125 GeV, thus enhancing the model's explanatory power.

The NMSSM with a $\mathbb{Z}_3$ discrete symmetry ($\mathbb{Z}_3$ -NMSSM) remains a popular framework due to its economical structure. Numerous investigations into the Higgs sector phenomenology of this model have largely focused on collider measurements without considering other experimental constraints [42,43,45,51–53]. These studies demonstrate that the $\mathbb{Z}_3$ -NMSSM can accommodate a resonant production of a light scalar boson near 95 GeV in the diphoton channel based on preceding data, as well as a possible resonance in the $b\bar{b}$ channel. Moreover, it is capable of simultaneously fitting a heavier resonance at either ~ 400 GeV [51] or ~ 650 GeV [53]. However, when the excesses are analyzed in combination with DM constraints, previous works, such as [9,39,44,56,58], encounter difficulties in predicting both signal strengths while satisfying DM experimental bounds. For instance, the study in [9] reports that the $\mathbb{Z}_3$ -NMSSM struggles to produce elevated diphoton rates at the 1σ level after accounting for correct relic density and direct detection constraints. Furthermore, recent results in [56] indicate challenges in reproducing the central values or 1σ ranges for $\mu_{\gamma\gamma}^{\text{exp}}$ and $\mu_{b\bar{b}}^{\text{exp}}$ simultaneously (see Table 4 for benchmark points and compare Figs. 1 and 2 of [56]).¹ Besides, the study in [58] explores a compressed Higgsino-like triplet scenario, which only predicts diphoton rates of less than 0.1 (see Table 4 and Fig. 2 of [58]).

In essence, the $\mathbb{Z}_3$ -NMSSM manifested a distinct trait by employing six input parameters for both the Higgs sector and the neutralino sector. Among these parameters, λ , κ , $\tan\beta$, and μ were shared between both sectors, engendering an inherent entanglement between the theory's Higgs and DM physics. This entanglement introduced a notable complexity, exerting an influence on the maximal reach of the diphoton signal rate. Though efforts to disentangle the intricacies of the theoretical framework, including extensions of the $\mathbb{Z}_3$ -NMSSM with seesaw mechanism [46] and the general version of the NMSSM with $\mathbb{Z}_3$ -symmetry breaking [48,54,66], have proven promising in addressing the complexity, there remains merit in conducting a comprehensive reinvestigation into the capacity of the popular $\mathbb{Z}_3$ -NMSSM to fully accommodate the observed excesses while adhering to various experimental constraints. This reexamination becomes particularly pertinent in light of the decrease in the diphoton rate as indicated by recent reports and the notable improvement in sensitivities of DM direct detection experiments by more than one order of magnitude compared to prior studies. Through utilization of analytic expressions and a novel sampling strategy, the present study endeavors to

¹This difficulty may arise from assumptions or sampling strategies emphasized in the present work. In addition, their findings suggest a preference for electroweakinos with masses not far above 100 GeV, which could face stringent constraints from ongoing SUSY searches at the LHC.

demonstrate that the central values of both signal rates can be simultaneously accommodated in this cost-effective model. Under the circumstances, the DM relic abundance is entirely accounted for by the binolike neutralinos, while the electroweakinos exhibit sufficient mass to be discernible by the LHC experiments.²

The paper is organized as follows. Section II briefly recapitulates the basics of the $\mathbb{Z}_3$ -NMSSM framework and the formulas of the two excesses. In Sec. III, a sophisticated scan over the model parameter space is performed, and the numerical results are presented in both figures and tables. Finally, the conclusion and comments are made in Sec. IV.

II. THEORETICAL PRELIMINARIES

A. Basics of the $\mathbb{Z}_3$ -NMSSM

The NMSSM is known as a straightforward extension of the MSSM with the inclusion of a gauge-singlet chiral superfield. Upon imposing a discrete $\mathbb{Z}_3$ symmetry, the scale-invariant superpotential and its associated soft SUSY-breaking terms of the Higgs scalars can be expressed as follows [59]:

$$W = W_{\text{Yukawa}} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3, \quad (2.1)$$

$$-\mathcal{L}_{\text{soft}} = \left(A_\lambda \lambda S H_u \cdot H_d + \frac{1}{3} A_\kappa \kappa S^3 + \text{H.c.} \right) + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2. \quad (2.2)$$

Here, $SU(2)_L$ indices are disregarded here for the sake of brevity. W_{Yukawa} includes all Yukawa coupling terms identical to those in the MSSM. $\hat{H}_u = (\hat{H}_u^+, \hat{H}_u^0)^T$, $\hat{H}_d = (\hat{H}_d^0, \hat{H}_d^-)^T$ represent the usual $SU(2)_L$ doublet Higgs superfields. $\hat{S}$ is the superfield that transforms as a singlet under the SM gauge group.

The Higgs sector of the NMSSM comprises the scalar components of the Higgs superfields, denoted by H_u , H_d , and S as expressed in Eq. (2.2). The interactions of these Higgs fields are parametrized by the dimensionless coefficients λ and κ in Eq. (2.1), along with the soft-breaking trilinear coefficients A_λ and A_κ in Eq. (2.2). The SUSY-breaking mass parameters $m_{H_u}^2$, $m_{H_d}^2$, m_S^2 in Eq. (2.2) can be determined by solving the conditional equations for minimizing the scalar potential and expressed in terms of the vacuum expectation values (vevs) of the Higgs fields, namely, $\langle H_u^0 \rangle = v_u/\sqrt{2}$, $\langle H_d^0 \rangle = v_d/\sqrt{2}$, and $\langle S \rangle = v_s/\sqrt{2}$,

with $v = \sqrt{v_u^2 + v_d^2} \simeq 246$ GeV. Consequently, the Higgs sector is characterized by the following six input parameters:

$$\lambda, \kappa, A_\lambda, A_\kappa, \tan \beta, \mu, \quad (2.3)$$

where $\tan \beta$ is defined as the ratio of the vevs, $\tan \beta \equiv v_u/v_d$, and μ is generated dynamically by $\mu \equiv \lambda v_s/\sqrt{2}$. Throughout this work, all of these parameters are treated as real numbers, as the CP conservation is assumed.

It is advantageous to define the combinations of Higgs fields: $H_{\text{SM}} \equiv \sqrt{2} \text{Re}(\sin \beta H_u^0 + \cos \beta H_d^0)$, $H_{\text{NSM}} \equiv \sqrt{2} \text{Re}(\cos \beta H_u^0 - \sin \beta H_d^0)$, and $A_{\text{NSM}} \equiv \sqrt{2} \text{Im}(\cos \beta H_u^0 - \sin \beta H_d^0)$. Here, H_{SM} has the same couplings to SM particles as a SM Higgs boson, while H_{NSM} and A_{NSM} represent non-SM-like CP -even and CP -odd states respectively. The singlet field is left unrotated, denoted by $\sqrt{2}S \equiv H_S + iA_S$. With this definition, H_{SM} would acquire the total SM-like Higgs field vev, i.e., $\langle H_{\text{SM}} \rangle = v$ and $\langle H_{\text{NSM}} \rangle = 0$. In the basis $(H_{\text{NSM}}, H_{\text{SM}}, H_S)$, the elements of the CP -even Higgs boson mass matrix $\mathcal{M}_S^2$ can be written as [59,67]

$$\begin{aligned} M_{11}^2 &= M_A^2 + \left(m_Z^2 - \frac{1}{2} \lambda^2 v^2 \right) \sin^2 2\beta, \\ M_{12}^2 &= -\frac{1}{2} \left(m_Z^2 - \frac{1}{2} \lambda^2 v^2 \right) \sin 4\beta, \\ M_{13}^2 &= \sqrt{2} \lambda \mu v (1 - \delta) \cot 2\beta, \\ M_{22}^2 &= m_Z^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta, \\ M_{23}^2 &= \sqrt{2} \lambda \mu v \delta, \\ M_{33}^2 &= \frac{\lambda^2 v^2 A_\lambda \sin 2\beta}{4\mu} + \frac{\mu}{\lambda} \left(\kappa A_\kappa + 4\kappa^2 \frac{\mu}{\lambda} \right), \end{aligned} \quad (2.4)$$

where $M_A^2 \equiv \frac{2\mu}{\sin 2\beta} (A_\lambda + \frac{\kappa}{\lambda} \mu)$ is the typical definition of the squared mass of the doublet-dominated pseudoscalar Higgs boson in the S decoupling limit. It is commonly employed to substitute the soft-breaking coefficients A_λ as an input parameter. Inspired by the theoretically well-motivated scenario in the alignment without decoupling limit [51,68], this work introduces a δ factor, defined as

$$\delta \equiv 1 - \left(\frac{M_A}{2\mu/\sin 2\beta} \right)^2 - \frac{\kappa}{2\lambda} \sin 2\beta, \quad (2.5)$$

to simplify the expression and allow for direct manipulation of the mixings of H_S with H_{SM} and H_{NSM} . As illustrated in Sec. III, adopting the δ factor instead of M_A^2 as an input parameter proves beneficial in obtaining solutions consistent with the observed excesses. Moreover, the equation for

²Note that the analyses of DM annihilation mechanisms in [56,58] focus primarily on the singlinolike neutralino. Additionally, in [56], the mass of the binolike lightest supersymmetric particle (LSP) is predicted to be relatively light, approximately 100 GeV. These aspects differ significantly from those explored in the present work.

M_{22}^2 in Eq. (2.4) implies that the mass of the H_{SM} -dominated Higgs boson can be increased by an additional contribution $\frac{1}{2}\lambda^2 v^2 \sin^2 2\beta$ compared to that in the MSSM. Additionally, the mixing between H_{SM} and H_S can further augment the H_{SM} -dominated boson's mass when $M_{22}^2 > M_{33}^2$. These increments facilitate the attainment of a SM-like Higgs boson with a mass around 125 GeV, mitigating the need for substantial radiative corrections originating from stop loops.

The model under consideration predicts the existence of three CP -even Higgs mass eigenstates, denoted as $h_i = \{h, H, h_s\}$, which arise from the mixings of the interaction eigenstates ($H_{\text{NSM}}, H_{\text{SM}}, H_S$),

$$h_i = V_{h_i}^{\text{NSM}} H_{\text{NSM}} + V_{h_i}^{\text{SM}} H_{\text{SM}} + V_{h_i}^S H_S. \quad (2.6)$$

Here, the mixing angles $V_{h_i}^j$ constitute a unitary matrix that diagonalizes the squared mass matrix delineated in Eq. (2.4). In addition, the imaginary components A_S and A_{NSM} mix into two CP -odd Higgs mass eigenstates $a_i = \{A_s, A_H\}$, while the charged components give rise to a pair of charged Higgs bosons $H^\pm$. Current experimental limitations provide crucial insights into the characteristics of the Higgs sector:

- (i) The CP -even mass eigenstate h aligns with the 125 GeV SM-like Higgs boson observed at the LHC. This state is predominantly composed of the H_{SM} component, with contributions from H_{NSM} and $\text{Re}[S]$ components restricted to be less than about 10% [69,70], i.e., $\sqrt{(V_h^{\text{NSM}})^2 + (V_h^S)^2} \lesssim 0.1$ and $|V_h^{\text{SM}}| \sim 1$.
- (ii) The heavy CP -even boson H exhibits a nearly degenerate mass with the CP -odd boson A_H and the charged Higgs bosons $H^\pm$. Searches for additional Higgs bosons at the LHC, coupled with indirect constraints from B physics, strongly suggest substantial masses for these bosons, e.g., $m_H \gtrsim 0.5$ TeV [10,71].
- (iii) Collider data currently available allow the singlet-dominated scalar states to possess moderate masses while retaining significant doublet components [72]. This particular characteristic forms the cornerstone of the present study.

The neutralino sector within the NMSSM framework is composed of the bino field $\tilde{B}$, the wino field $\tilde{W}$, the Higgsino fields $\tilde{H}_d^0$ and $\tilde{H}_u^0$, and the singlino field $\tilde{S}$. In the basis $\psi \equiv (\tilde{B}, \tilde{W}, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S})$, the symmetric neutralino mass matrix is formulated as follows [59]:

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -m_Z \sin \theta_W \cos \beta & m_Z \sin \theta_W \sin \beta & 0 \\ & M_2 & m_Z \cos \theta_W \cos \beta & -m_Z \cos \theta_W \sin \beta & 0 \\ & & 0 & -\mu & -\frac{1}{\sqrt{2}} \lambda v \sin \beta \\ & & & 0 & -\frac{1}{\sqrt{2}} \lambda v \cos \beta \\ & & & & \frac{2\kappa}{\lambda} \mu \end{pmatrix}, \quad (2.7)$$

where θ_W represents the weak mixing angle, and M_1 and M_2 denote the soft-breaking masses of the bino and wino fields, respectively. Diagonalizing $\mathcal{M}$ by a rotation matrix N results in five mass eigenstates,

$$\tilde{\chi}_i^0 = N_{i1}\psi_1^0 + N_{i2}\psi_2^0 + N_{i3}\psi_3^0 + N_{i4}\psi_4^0 + N_{i5}\psi_5^0. \quad (2.8)$$

Here, $\tilde{\chi}_i^0$ ($i = 1, 2, 3, 4, 5$) are labeled in a mass-ascending order, and the matrix element N_{ij} parametrizes the component of the field ψ_j^0 in $\tilde{\chi}_i^0$. Under the assumption of R -parity conservation, the lightest neutralino $\tilde{\chi}_1^0$ emerges as a viable DM candidate if it also serves as the lightest supersymmetric particle (LSP). To reconcile the total measured DM relic density with the absence of direct detection signals, the composition of $\tilde{\chi}_1^0$ typically necessitates a dominance of either the $\tilde{B}$ component or the $\tilde{S}$ component [62,73]. Indeed, the $\tilde{B}$ -dominated $\tilde{\chi}_1^0$ in the NMSSM bears a clear resemblance to that in

the MSSM.³ The $\tilde{\chi}_1^0$ DM in this case can annihilate through various channels, including the SM-like Higgs funnel, Z funnel, or coannihilation with electroweakinos, squarks, sleptons, and gluinos. Unfortunately, due to strong constraints from current LHC searches for SUSY particles, only coannihilation with winolike electroweakinos becomes the dominant mechanism to achieve the correct relic abundance. Regarding the $\tilde{S}$ -dominated $\tilde{\chi}_1^0$, the typical annihilation channels, $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow t\bar{t}$, $h_s A_s$, and $h A_s$ (where t represents the top quark) cannot fully account for the measured abundance. This limitation arises because a relatively large value of λ is disfavored by the null results

³One distinction lies in the fact that within the NMSSM framework, the $\tilde{B}$ -dominated $\tilde{\chi}_1^0$ s may coannihilate with $\tilde{S}$ -dominated neutralinos to obtain the observed abundance. Nevertheless, this scenario is confined to a rather narrow parameter space characterized by $|M_1| \simeq |2\kappa\mu/\lambda|$, necessitating sufficiently large values of λ , κ , and μ .

from direct detection experiments [62]. Consequently, the $\tilde{\chi}_1^0$ -dominated $\tilde{\chi}_1^0$ is more likely to attain the correct abundance through coannihilation with electroweakinos. However, within the context of the $\mathbb{Z}_3$ -NMSSM, this scenario suffers from a suppressed Bayesian evidence due to the fine-tuning required in a narrow region of parameter space, e.g., $|\kappa| \leq \lambda/2$ with $\lambda \lesssim 0.06$ [74]. Furthermore, the specific conditions for $V_{h_s}^{\text{SM}}$ and $V_{h_s}^{\text{NSM}}$ to match the central values of the 95 GeV excesses would constrain the model's capability to predict compatible $\tilde{\chi}_1^0$ -nucleon cross sections. In summary, as demonstrated later in this work, the interpretation of the combined excess favors the neutralino DM being dominated by the $\tilde{B}$ component.

B. $\gamma\gamma$ and $b\bar{b}$ signals

The observed $\gamma\gamma$ excess can be attributed to either a CP -even or CP -odd Higgs boson, or a combination of both. However, explaining the $b\bar{b}$ excess specifically requires the involvement of a CP -even Higgs boson, as CP -odd Higgs bosons lack couplings to the Z boson, precluding them from contributing significantly to this signal. Given this, the present study focuses on the resonant production of the lightest singlet-dominated CP -even Higgs, h_s , to fully account for both the $\gamma\gamma$ and $b\bar{b}$ excesses. In the narrow width approximation, the signal strengths normalized to their SM predictions are calculated as follows [54]:

$$\mu_{\gamma\gamma}|_{m_{h_s}=95.4 \text{ GeV}} = \frac{\sigma_{\text{SUSY}}(pp \rightarrow h_s)}{\sigma_{\text{SM}}(pp \rightarrow h_s)} \times \frac{\text{Br}_{\text{SUSY}}(h_s \rightarrow \gamma\gamma)}{\text{Br}_{\text{SM}}(h_s \rightarrow \gamma\gamma)} \simeq |C_{h_s gg}|^2 \times |C_{h_s \gamma\gamma}|^2 \times R_{\text{width}}, \quad (2.9)$$

$$\mu_{b\bar{b}}|_{m_{h_s}=95.4 \text{ GeV}} = \frac{\sigma_{\text{SUSY}}(e^+e^- \rightarrow Zh_s)}{\sigma_{\text{SM}}(e^+e^- \rightarrow Zh_s)} \times \frac{\text{Br}_{\text{SUSY}}(h_s \rightarrow b\bar{b})}{\text{Br}_{\text{SM}}(h_s \rightarrow b\bar{b})} \simeq |C_{h_s VV}|^2 \times |C_{h_s b\bar{b}}|^2 \times R_{\text{width}}, \quad (2.10)$$

where the mass of h_s is fixed at 95.4 GeV. The production rate $\sigma(pp \rightarrow h_s)$ and the decay branching ratio $\text{Br}(h_s \rightarrow \gamma\gamma)$ labeled with the subscript “SUSY” refer to the predictions from the model, whereas those with the subscript “SM” assume SM couplings for h_s . As the gluon fusion process is the primary contributor to Higgs production, the ratio of production rates, $\sigma_{\text{SUSY}}(pp \rightarrow h_s)/\sigma_{\text{SM}}(pp \rightarrow h_s)$, can be approximately expressed as $|C_{h_s gg}|^2$ at leading order. Here, $C_{h_s gg} \equiv \mathcal{A}_{\text{SUSY}}^{h_s gg}/\mathcal{A}_{\text{SM}}^{h_s gg}$ represents the ratio of the coupling strength between h_s and gluons predicted by the SUSY model $\mathcal{A}_{\text{SUSY}}^{h_s gg}$ to the corresponding coupling in the SM $\mathcal{A}_{\text{SM}}^{h_s gg}$.⁴ Similarly, the normalized coupling strength of h_s to photons, denoted by $C_{h_s \gamma\gamma}$, is defined in a comparable manner, including additional contributions from loops involving the W boson, charged Higgs bosons, and charginos [75]. However, the SUSY contributions to $C_{h_s gg}$ and $C_{h_s \gamma\gamma}$ are not significant in this study. Specifically, given the substantial masses of the squarks, their contributions to these couplings are typically negligible, amounting to just a few thousandths of the SM contributions. The contribution from the charged Higgs boson to $C_{h_s \gamma\gamma}$ is even smaller, typically on the order of 0.001%, again owing to the large mass. The contribution from charginos to $C_{h_s \gamma\gamma}$ may reach up to 10% under optimal conditions, particularly when the Higgsino mass is relatively light and λ is sufficiently large [82]. Overall, while the ratios $C_{h_s gg}$ and $C_{h_s \gamma\gamma}$ are key to understanding the production and decay processes of the singlet-dominated CP -even Higgs, the contributions from squarks and charged Higgs bosons generally have a limited impact in this context. The chargino loops might emerge as a slight effect when comparing distinctive scenarios.

The coefficient R_{width} appearing in Eqs. (2.9) and (2.10) is derived as the ratio of the SM prediction for the total decay width of h_s to its width in the SUSY model. The reciprocal of this ratio has the following expression [54]:

$$1/R_{\text{width}} = |C_{h_s b\bar{b}}|^2 \times \text{Br}_{\text{SM}}(h_s \rightarrow b\bar{b}) + |C_{h_s \tau\bar{\tau}}|^2 \times \text{Br}_{\text{SM}}(h_s \rightarrow \tau\bar{\tau}) + |C_{h_s c\bar{c}}|^2 \times \text{Br}_{\text{SM}}(h_s \rightarrow c\bar{c}) + |C_{h_s gg}|^2 \times \text{Br}_{\text{SM}}(h_s \rightarrow gg) + \dots, \simeq 0.801 \times |C_{h_s b\bar{b}}|^2 + 0.083 \times |C_{h_s \tau\bar{\tau}}|^2 + 0.041 \times |C_{h_s c\bar{c}}|^2 + 0.067 \times |C_{h_s gg}|^2, \quad (2.11)$$

⁴The SUSY coupling strength $\mathcal{A}_{\text{SUSY}}^{h_s gg}$ is contributed by the loops mediated by quarks and squarks [75]. It is computed in the SPheno-4.0.5 code [76,77] using the following formula:

$$\mathcal{A}_{\text{SUSY}}^{h_s gg} = \sum_q C_{h_s q\bar{q}}^{\text{tree}} \times \frac{m_q(Q)}{m_q(\text{pole})} \times \mathcal{A}_{\text{SM}}^{h_s gg, q} + \sum_{\tilde{q}} \mathcal{A}_{\text{SUSY}}^{h_s gg, \tilde{q}},$$

where $\mathcal{A}_{\text{SUSY}}^{h_s gg, q}$ and $\mathcal{A}_{\text{SUSY}}^{h_s gg, \tilde{q}}$ represent the contributions to the $h_s gg$ coupling from quark loops and squark loops, respectively [78]. $\mathcal{A}_{\text{SM}}^{h_s gg, q}$ denotes the quark loop contribution in the SM with the formulation available in Ref. [79]. $C_{h_s q\bar{q}}^{\text{tree}}$ is the tree-level coupling between h_s and quarks. $m_q(Q)$ and $m_q(\text{pole})$ represent the running mass of the quark at scale $Q \approx m_{h_s}$ and the quark pole mass, respectively. Higher-order QCD corrections are applied to these calculations based on the methods detailed in Refs. [80,81].

where $C_{h_s f \bar{f}}$ ($f = b, \tau, c$) are the normalized couplings of h_s to the fermion pairs $f \bar{f}$. $\text{Br}_{\text{SM}}(h_s \rightarrow f \bar{f})$ are the corresponding SM branching ratios for h_s , obtained from the LHC Higgs Cross Section Working Group, which incorporates all known higher-order QCD corrections [83].

$$\begin{aligned} C_{h_s t \bar{t}} &= V_{h_s}^{\text{SM}} + V_{h_s}^{\text{NSM}} \cot \beta \simeq V_{h_s}^{\text{SM}}, & C_{h_s b \bar{b}} &= V_{h_s}^{\text{SM}} - V_{h_s}^{\text{NSM}} \tan \beta, & C_{h_s V V} &= V_{h_s}^{\text{SM}}, \\ C_{h_s c \bar{c}} &= C_{h_s t \bar{t}}, & C_{h_s \tau \bar{\tau}} &= C_{h_s b \bar{b}}, & C_{h_s g g} &\simeq C_{h_s t \bar{t}}, & C_{h_s \gamma \gamma} &\simeq V_{h_s}^{\text{SM}}. \end{aligned} \quad (2.12)$$

Based on these relations, one can derive values for V_j^i required to obtain the central values of $\mu_{\gamma\gamma}$ and $\mu_{b\bar{b}}$: $V_{h_s}^{\text{SM}} \simeq 0.36$ and $(V_{h_s}^{\text{SM}} - V_{h_s}^{\text{NSM}} \tan \beta) \simeq 0.70 \times V_{h_s}^{\text{SM}} \simeq 0.25$. These lead to the branching ratios $\text{Br}_{\text{SUSY}}(h_s \rightarrow \gamma\gamma) \simeq 1.86 \times \text{Br}_{\text{SM}}(h_s \rightarrow \gamma\gamma) \simeq 2.58 \times 10^{-3}$ and $\text{Br}_{\text{SUSY}}(h_s \rightarrow b\bar{b}) \simeq 0.90 \times \text{Br}_{\text{SM}}(h_s \rightarrow b\bar{b}) \simeq 72.6\%$. However, given the use of the exact formulas for $C_{h_s g g}$ and $C_{h_s \gamma \gamma}$ through out this study, these values could deviate slightly from $C_{h_s t \bar{t}}$ by about 4% and 14%, respectively. Consequently, the updated values for the Higgs mixing angles would be $V_{h_s}^{\text{SM}} \simeq 0.35$, $(V_{h_s}^{\text{SM}} - V_{h_s}^{\text{NSM}} \tan \beta) \simeq 0.83 \times V_{h_s}^{\text{SM}} \simeq 0.291$. As a result, the corresponding branching ratios would change to $\text{Br}_{\text{SUSY}}(h_s \rightarrow \gamma\gamma) \simeq 1.81 \times \text{Br}_{\text{SM}}(h_s \rightarrow \gamma\gamma) \simeq 2.52 \times 10^{-3}$, and $\text{Br}_{\text{SUSY}}(h_s \rightarrow b\bar{b}) \simeq 0.96 \times \text{Br}_{\text{SM}}(h_s \rightarrow b\bar{b}) \simeq 76.9\%$. These results underscore the importance of achieving an appropriate balance between the coupling $C_{h_s t \bar{t}}$ and a relatively suppressed $C_{h_s b \bar{b}}$ for adequately explaining the observed excesses [9,84]. Notably, small deviations in $C_{h_s g g}$ and $C_{h_s \gamma \gamma}$ from $C_{h_s t \bar{t}}$ can significantly reduce the required value of $V_{h_s}^{\text{NSM}} \tan \beta$ to match the central values of the observed signals while having little effect on $V_{h_s}^{\text{SM}}$. Additionally, the approximations indicate that reducing $V_{h_s}^{\text{NSM}} \tan \beta$ can enhance $C_{h_s b \bar{b}}$ resulting in a higher $\mu_{b\bar{b}}$ and a lower $\mu_{\gamma\gamma}$ assuming other couplings remain constant [9].

The explanation for the observed diphoton and $b\bar{b}$ excesses relies heavily on the parameters in the Higgs sector. By using eigenvalue equations of the mass eigenstates h and h_s and recognizing that $m_{h_s}, m_h \ll m_A$ indicates minor mixings of H_{NSM} with H_{SM} and H_S , the following tree-level approximations can be derived:

$$m_B^2 \equiv M_{33}^2 \simeq m_{h_s}^2 |V_{h_s}^S|^2 + m_h^2 |V_{h_s}^{\text{SM}}|^2, \quad (2.13)$$

$$V_{h_s}^{\text{SM}} \simeq \frac{\sqrt{2} \delta \lambda \mu v}{m_h^2 - m_B^2} V_{h_s}^S, \quad (2.14)$$

$$V_{h_s}^{\text{NSM}} \simeq \frac{\sqrt{2}(\delta - 1) \lambda \mu v \cot 2\beta}{m_A^2 - m_{h_s}^2} V_{h_s}^S. \quad (2.15)$$

Here, m_B^2 denotes the squared mass element of the singlet field. These expressions suggest that the observed excesses

In the absence of significant SUSY contributions, the normalized couplings of h_s to fermions and W or Z boson pairs can be expressed in terms of the rotation matrix elements V_j^i as defined in Eq. (2.6) [59],

constrain m_B within a narrow range (approximately 100 GeV, as discussed later). The relations also imply that the following condition must be met to achieve the central values of the observed excesses:

$$\frac{1}{\delta} = 1 + \frac{m_A^2 - m_{h_s}^2}{m_h^2 - m_B^2} \times \frac{2}{5(\tan^2 \beta - 1)}. \quad (2.16)$$

This condition suggests $\tan \beta \lesssim 10$ for $m_A \simeq 2$ TeV and $m_B \simeq 100$ GeV when δ is required to be smaller than 0.3. Additionally, the following approximation can be inferred:

$$\delta \lambda \simeq 0.03 \times \left(\frac{\mu}{200 \text{ GeV}} \right)^{-1}, \quad (2.17)$$

to predict $V_{h_s}^{\text{NSM}} \tan \beta \simeq 0.07$. Given that LHC searches for electroweakinos have established $\mu_{\text{tot}} \gtrsim 200$ GeV [85], the explanation points toward $\delta \lambda \lesssim 0.03$.

III. EXPLANATION OF THE EXCESSES

This section introduces the sampling strategy and presents detailed numerical results that interpret the observed diphoton and $b\bar{b}$ excesses while respecting constraints from other experiments, especially those related to DM detections. The numerical analysis comprises several key steps. First, the process begins with utilizing the package SARAH-4.14.3 [86–89] to build the model routines of the $\mathbb{Z}_3$ -NMSSM. Second, the codes SPheno-4.0.5 [76,77] and FlavorKit [90] are employed to generate particle spectrum and compute low energy flavor observables, respectively. Subsequently, the DM physics observables are calculated with the package micrOMEGAS-5.0.4 [91–100]. Finally, resulting samples are analyzed using both Bayesian inference, focusing on the posterior probability density function (PDF), and frequentist statistics, emphasizing the profile likelihood (PL) [101]. These statistical approaches allow for a comprehensive understanding of the parameter space, facilitating a nuanced interpretation of the experimental results.

A. Strategy in scanning the parameter space

To investigate the properties of Higgs bosons within the present framework, this study employs a specialized parameter scan strategy. The scan focuses on the parameters defined in Eq. (2.3), but substitutes A_λ and A_κ with δ and m_B^2 , respectively. This reconfiguration streamlines the sampling process without compromising the key aspects of the investigation. The soft trilinear coefficients for the third-generation squarks, A_t and A_b , are also considered free parameters due to their significant influence on the SM-like Higgs boson mass via radiative corrections. Additionally, the scan examines the soft-breaking masses for bino and wino $M_{1/2}$ to accommodate the possibility of a bino-dominated $\tilde{\chi}_1^0$ as the DM candidate. In total, the scan explores a nine-dimensional parameter space as delineated in Table I. The MultiNest algorithm is employed for this multidimensional scan with a high number of live points $n_{\text{live}} = 8000$ to ensure a comprehensive survey of the parameter space.⁵

The likelihood function that guides the scan process is constructed as $\mathcal{L} \equiv \mathcal{L}_{\gamma\gamma+b\bar{b}} \times \mathcal{L}_{\text{Res}}$. The term $\mathcal{L}_{\gamma\gamma+b\bar{b}} = \exp(-\frac{1}{2}\chi_{\gamma\gamma+b\bar{b}}^2)$ quantify the compatibility with the experimental observations of $\gamma\gamma$ and $b\bar{b}$ excesses at 95 GeV by defining the following χ^2 function:

$$\chi_{\gamma\gamma+b\bar{b}}^2 = \left(\frac{\mu_{\gamma\gamma} - 0.24}{0.08} \right)^2 - \left(\frac{\mu_{b\bar{b}} - 0.117}{0.057} \right)^2. \quad (3.1)$$

The $\mathcal{L}_{\text{Res}}$ term represents additional restrictions from relevant experiments on the theory, defined such that $\mathcal{L}_{\text{Res}} = 1$ if conditions are met, and $\mathcal{L}_{\text{Res}} = \exp[-100]$ otherwise. These restrictions include the following:

- (i) *Mass of the light Higgs*: The mass of h_s is expected to be around 95.4 GeV to account for the excesses. Considering theoretical and experimental uncertainties of 1 GeV, the acceptable range is $94.4 \text{ GeV} \leq m_{h_s} \leq 96.4 \text{ GeV}$.
- (ii) *Higgs data fit*: The properties of h that corresponds to the discovered Higgs boson at the LHC must align with measurements by the ATLAS and CMS Collaborations at the 95% confidence level. This condition is validated using the code HiggsSignals-2.6.2 [104–107], with a criterion for acceptance being a p-value greater than 0.05, indicating compatibility between observed data and theoretical predictions.
- (iii) *Extra Higgs searches*: The signal rates for additional Higgs bosons must comply with cross-section limits based on experimental data at LEP, Tevatron, and

TABLE I. Ranges of specific input parameters. All parameters are assigned a flat prior probability distribution due to their well-defined physical interpretation. To streamline the analysis, the soft trilinear coefficients for the third-generation squarks are unified such that $A_t = A_b$. Dimensional parameters not directly relevant to this study are fixed to specific values for simplicity and alignment with experimental constraints. The gluino mass is set to $M_3 = 3 \text{ TeV}$, and a common value of 2 TeV is assigned to other unspiced parameters to ensure consistency with limits from LHC searches for new physics. All parameters are defined at the renormalization scale $Q_{\text{input}} = 1 \text{ TeV}$. The parameter space is acquired based on the analysis in the previous section and validated through multiple trial scans over much broader ranges to ensure comprehensive coverage and effective exploration of the potential regions of interest.

Parameter	Prior	Range	Parameter	Prior	Range
μ/TeV	Flat	$0.3 \sim 1.0$	λ	Flat	$0.001 \sim 0.5$
m_B/GeV	Flat	$80 \sim 120$	κ	Flat	$-0.5 \sim 0.5$
A_t/TeV	Flat	$2.0 \sim 5.0$	δ	Flat	$0.0 \sim 0.3$
M_1/TeV	Flat	$-1.0 \sim -0.3$	$\tan\beta$	Flat	$1.0 \sim 10$
M_2/TeV	Flat	$0.3 \sim 1.0$			

LHC. This requirement is implemented using the HiggsBounds-5.10.2 code [108–112] and further refined through the HiggsTools code [113].

- (iv) *DM relic density*: The central value for the DM relic density, $\Omega h^2 = 0.120$, is derived from the Planck-2018 data [114]. To account for a theoretical uncertainty of 20%, the acceptable range $0.096 \leq \Omega h^2 \leq 0.144$ is applied.
- (v) *DM detections*: The spin-independent (SI) and spin-dependent (SD) DM-nucleon scattering cross sections must be below the upper bounds imposed by the LZ experiments [115].⁶ The constraints of DM indirect searches from Fermi-LAT on gamma-ray emissions are not considered, as they do not impose restrictions for $|m_{\tilde{\chi}_1^0}| \gtrsim 100 \text{ GeV}$ [118].
- (vi) *B-physics observables*: The branching ratios of $B_s \rightarrow \mu^+\mu^-$ and $B \rightarrow X_s\gamma$ should be consistent with their experimental measurements at the 2σ level [119]. Note that the current measurement results [120] show no significant deviations from the values used in the present work. It has been verified that using the 2024 limits would not change the number of surviving samples or the parameter regions that can explain the diphoton and $b\bar{b}$ excesses at the 1σ level.
- (vii) *Vacuum stability*: The vacuum state of the Higgs potential must be stable or long lived [121]. This

⁵In the context of nested sampling algorithms like MultiNest, n_{live} refers to the number of active or live points that is utilized in each iteration to define the iso-likelihood contour [102,103]. A larger n_{live} value translates to a more detailed scan of the parameter space.

⁶The LZ Collaboration has recently reported the latest 2024 results [116]. The preliminary combined results will be displayed against the 2022 limits used in the likelihood function, along with the projected sensitivity for future studies [117] in Fig. 3.

TABLE II. Experimental analyses of the electroweakino production processes considered in this study categorizing by the topologies of the SUSY signals.

Scenario	Final state	Name
$\tilde{\chi}_1^0 \tilde{\chi}_1^\pm \rightarrow W Z \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$	$n\ell(n \geq 2) + nj(n \geq 0) + E_T^{\text{miss}}$	CMS-SUS-20-001 (137 fb ⁻¹) [131] ATLAS-2106-01676 (139 fb ⁻¹) [85] CMS-SUS-17-004 (35.9 fb ⁻¹) [132] CMS-SUS-16-039 (35.9 fb ⁻¹) [133] ATLAS-1803-02762 (36.1 fb ⁻¹) [134] ATLAS-1806-02293 (36.1 fb ⁻¹) [135]
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow W h \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$	$n\ell(n \geq 1) + nb(n \geq 0) + nj(n \geq 0) + E_T^{\text{miss}}$	ATLAS-1909-09226 (139 fb ⁻¹) [136] CMS-SUS-17-004 (35.9 fb ⁻¹) [132] CMS-SUS-16-039 (35.9 fb ⁻¹) [133] ATLAS-1812-09432 (36.1 fb ⁻¹) [137] CMS-SUS-16-034 (35.9 fb ⁻¹) [138] CMS-SUS-16-045 (35.9 fb ⁻¹) [139]
$\tilde{\chi}_1^\mp \tilde{\chi}_1^\pm \rightarrow W W \tilde{\chi}_1^0 \tilde{\chi}_1^0$	$2\ell + E_T^{\text{miss}}$	ATLAS-1908-08215 (139 fb ⁻¹) [140] CMS-SUS-17-010 (35.9 fb ⁻¹) [141]
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow Z W \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow W W \tilde{\chi}_1^0 \tilde{\chi}_1^0$	$2j(\text{large}) + E_T^{\text{miss}}$	ATLAS-2108-07586 (139 fb ⁻¹) [142]
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow (h/Z) W \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$ $\tilde{\chi}_2^0 \tilde{\chi}_3^0 \rightarrow (h/Z) Z \tilde{\chi}_1^0 \tilde{\chi}_1^0$	$j(\text{large}) + b(\text{large}) + E_T^{\text{miss}}$	ATLAS-2108-07586 (139 fb ⁻¹) [142]
$\tilde{\chi}_2^0 \tilde{\chi}_1^\mp \rightarrow h/Z W \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \gamma/Z\tilde{G}$ $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow W W \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \gamma/Z\tilde{G}$	$2\gamma + n\ell(n \geq 0) + nb(n \geq 0) + nj(n \geq 0) + E_T^{\text{miss}}$	ATLAS-1802-03158 (36.1 fb ⁻¹) [143]
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow Z W \tilde{\chi}_1^0 \tilde{\chi}_1^\pm, \tilde{\chi}_1^0 \rightarrow h/Z\tilde{G}$ $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow W W \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow h/Z\tilde{G}$ $\tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow Z \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow h/Z\tilde{G}$ $\tilde{\chi}_1^\mp \tilde{\chi}_1^0 \rightarrow W \tilde{\chi}_1^0 \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow h/Z\tilde{G}$	$n\ell(n \geq 4) + E_T^{\text{miss}}$	ATLAS-2103-11684 (139 fb ⁻¹) [144]
$\tilde{\chi}_i^{0,\pm} \tilde{\chi}_j^{0,\mp} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm + \chi_{\text{soft}} \rightarrow Z Z/H\tilde{G}\tilde{G}$	$n\ell(n \geq 2) + nb(n \geq 0) + nj(n \geq 0) + E_T^{\text{miss}}$	CMS-SUS-16-039 (35.9 fb ⁻¹) [133] CMS-SUS-17-004 (35.9 fb ⁻¹) [132] CMS-SUS-20-001 (137 fb ⁻¹) [131]
$\tilde{\chi}_i^{0,\pm} \tilde{\chi}_j^{0,\mp} \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm + \chi_{\text{soft}} \rightarrow H H\tilde{G}\tilde{G}$	$n\ell(n \geq 2) + nb(n \geq 0) + nj(n \geq 0) + E_T^{\text{miss}}$	CMS-SUS-16-039 (35.9 fb ⁻¹) [133] CMS-SUS-17-004 (35.9 fb ⁻¹) [132]
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow W^* Z^* \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$	$3\ell + E_T^{\text{miss}}$	ATLAS-2106-01676 (139 fb ⁻¹) [85]
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \rightarrow Z^* W^* \tilde{\chi}_1^0 \tilde{\chi}_1^\pm$	$2\ell + nj(n \geq 0) + E_T^{\text{miss}}$	ATLAS-1911-12606 (139 fb ⁻¹) [145] ATLAS-1712-08119 (36.1 fb ⁻¹) [146] CMS-SUS-16-048 (35.9 fb ⁻¹) [147]
$\tilde{\chi}_2^0 \tilde{\chi}_1^\pm + \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp + \tilde{\chi}_1^\pm \tilde{\chi}_1^0$	$2\ell + nj(n \geq 0) + E_T^{\text{miss}}$	ATLAS-1911-12606 (139 fb ⁻¹) [145] ATLAS-1712-08119 (36.1 fb ⁻¹) [146] CMS-SUS-16-048 (35.9 fb ⁻¹) [147]

condition is tested using Ve- VACIOUSPLUSPLUS [122] (the C++ version of VEVACIOUS [123]).

Given the heavy mass ranges specified in Table I, constraints from LHC searches for electroweakinos are expected to have no significant impact on the scan results, as suggested by recent statistical combination of ATLAS Run 2 searches in [124]. To substantiate this, the obtained samples are evaluated using the code SModelS-2.1.1, which encoded various event-selection efficiencies by analyzing topologies of SUSY signals [125]. Moreover, the benchmark points presented in Tables III and IV undergo further

investigated through simulation analyses listed in Table II using package CheckMATE-2.0.26 [126–128] which is validated in a manner similar to the method described in [129]. The R values defined as $R \equiv \max\{S_i/S_{i,\text{obs}}^{95}\}$ are calculated for all the involved analyses, where S_i represents the simulated event number in the i th signal region (SR), and $S_{i,\text{obs}}^{95}$ denotes the corresponding 95% confidence level upper limit. An R value exceeding 1 indicates experimental exclusion, while an R value below 1 suggests consistency with experimental analyses, assuming negligible uncertainties [130].

B. Numerical results

The scan process yields more than 28,000 samples that are consistent with the experimental restrictions, among which about 21,000 samples can explain both the $\gamma\gamma$ and $b\bar{b}$ excesses at a level of 2σ . All samples prefer bino-dominated $\tilde{\chi}_1^0$ s as DM candidates. They achieve the measured relic abundance primarily by coannihilating with the winolike electroweakinos.

Figure 1 presents the statistical distributions of the nine input parameters listed in Table I, including one-dimensional profile likelihoods (PL, delineated as green lines) and marginal posterior probability density functions (PDF, plotted as black lines).⁷ The violet and orange bands represent the 1σ and 2σ confidence intervals, respectively, while the green dots mark the best points corresponding to $\chi^2_{\gamma\gamma+b\bar{b}} \simeq 0$. The yellow and golden bands denote the 1σ and 2σ credible regions and the black dots denote the modes of the posterior probability density function. The PL distributions indicate that the parameter space outlined in Table I can readily account for the diphoton and $b\bar{b}$ excesses at a level of 2σ while satisfying other experimental constraints. The results support the previous analysis in Sec. II B and exhibit the following features:

- (i) The signal rates of the excesses require the Higgs mixing angles $V_{h_s}^{\text{SM}}$ in Eq. (2.14) and $V_{h_s}^{\text{NSM}}$ in Eq. (2.15) to be sizeable enough. Thus, δ should have a relatively small value, hence a prior range of $\delta \lesssim 0.3$. Consequently, Eqs. (2.5) and (2.13), together with $V_{h_s}^{\text{SM}} \simeq 0.35$ and $V_{h_s}^{\text{NSM}} \simeq 0.012$, impose limits on λ and κ , i.e., $\lambda \lesssim 0.42$ and $|\kappa| \lesssim 0.3$, and constrain m_B within a narrow range.
- (ii) The trilinear coefficient A_t affects the SM-like Higgs boson mass m_h , the mixing angles $V_{h_s}^{\text{SM}}$, and the $h_s g g$ and $h_s \gamma\gamma$ coupling strengths via $\tilde{t}$ -mediated loops.

⁷The profile likelihood is the most significant likelihood value in a specific parameter space [101]. Given a set of input parameters $\Theta \equiv (\Theta_1, \Theta_2, \dots)$, one can acquire the one-dimensional PL by changing the other parameters to maximize the likelihood function, i.e.,

$$\mathcal{L}(\Theta_A) = \max_{\Theta_1, \dots, \Theta_{A-1}, \Theta_{A+1}, \dots} \mathcal{L}(\Theta).$$

The PL reflects the preference of a theory on the parameter space. For a given point Θ_A , it represents the capability of the point in the theory to account for experimental data. By contrast, the one-dimensional marginal posterior probability density functions (PDF) of parameter Θ_A is obtained by integrating the posterior PDF from the Bayesian theorem, $P(\Theta)$, over the rest of the model inputs,

$$P(\Theta_A) = \int P(\Theta) d\Theta_1 d\Theta_2 \cdots d\Theta_{A-1} d\Theta_{A+1} \cdots.$$

It represents the updated belief about the parameter values after taking the observed data into account.

Given that the soft-breaking masses of the squarks are fixed at 2 TeV, A_t in the whole range of (2 TeV, 5 TeV) can render the theory capable of explaining the excesses.

- (iii) The lower boundary of $\mu \gtrsim 450$ GeV arises from the LZ experimental constraint [62] as the $\tilde{B}$ -dominated DM-nucleon scattering cross sections are inversely proportional to μ^2 [62]. To suppress the SI scattering cross sections, M_1 is assigned an opposite sign to μ *ab initio* to form a “blind spot” scenario where different contributions counteract each other [148–151].

Besides, the posterior PDF lines may significantly deviate from the PL lines. This occurs because the PL function evaluates the likelihood at the best fit value of other parameters and reflects how well different values of the parameter fit the data. In contrast, the posterior PDFs depend not only on the likelihood function but also involve integration over the prior volume. Hence, the narrow peaks of posterior PDF lines represent the most credible region under the current experimental data, whereas the lower regions reflect the parameter space suppression due to a certain degree of fine tuning.

Figures 2 and 3 display scattering plots for all samples that meet the applied constraints and explain the $\gamma\gamma$ and $b\bar{b}$ excesses at a level of 1σ , i.e., $\chi^2_{\gamma\gamma+b\bar{b}} \lesssim 2.3$. The left panel in Fig. 2 demonstrates that explaining these excesses imposes an upper limit on the product of δ and λ . Specifically, neglecting cases with substantial deviations from the central values of the excesses, $\delta\lambda \lesssim 0.03$ is required for most samples, as indicated by Eq. (2.17). The middle panel illustrates a rather small discrepancy between $m_{\tilde{\chi}_1^0}$ and M_2 , indicating that $\tilde{\chi}_1^0$ achieves the measured relic abundance by co-annihilating with the winolike electroweakinos. The largest contribution to the abundance could come from the channel $\tilde{\chi}_2^0 \tilde{\chi}_1^- \rightarrow d_i \bar{u}_i$ ($i = 1, 2, 3$, represents the i th quark generation), denoted as Case-I, and the channel $\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow W^+ W^-$, denoted as Case-II, corresponding to Bayesian evidence of 79% and 20.4% respectively.⁸ Case-I samples are marked with cyan squares, and Case-II samples are marked with green squares. There are only less than 1% of samples predicting other channels as largest contribution, e.g., $\tilde{\chi}_1^+ \tilde{\chi}_1^+ \rightarrow W^+ W^+$ and $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow t\bar{t}$. Based on this analysis, several key inferences can be made:

- (i) In Case-II, the coannihilation process $\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow W^+ W^-$ proceeds mainly through t/u -channel exchanging $\tilde{H}$ -dominated charginos. This process becomes significant at higher mass thresholds for the Higgsino and $\tilde{\chi}_1^0$, specifically when $\mu \gtrsim 780$ GeV and $|m_{\tilde{\chi}_1^0}| \simeq 520$ GeV.

⁸For most samples, the total contribution from channels with $d_i \bar{u}_i$ final states for three generations usually dominate the coannihilation cross section. The phrase of “the largest contribution” from a certain channel refers to the single channel with the highest weight among all channels.

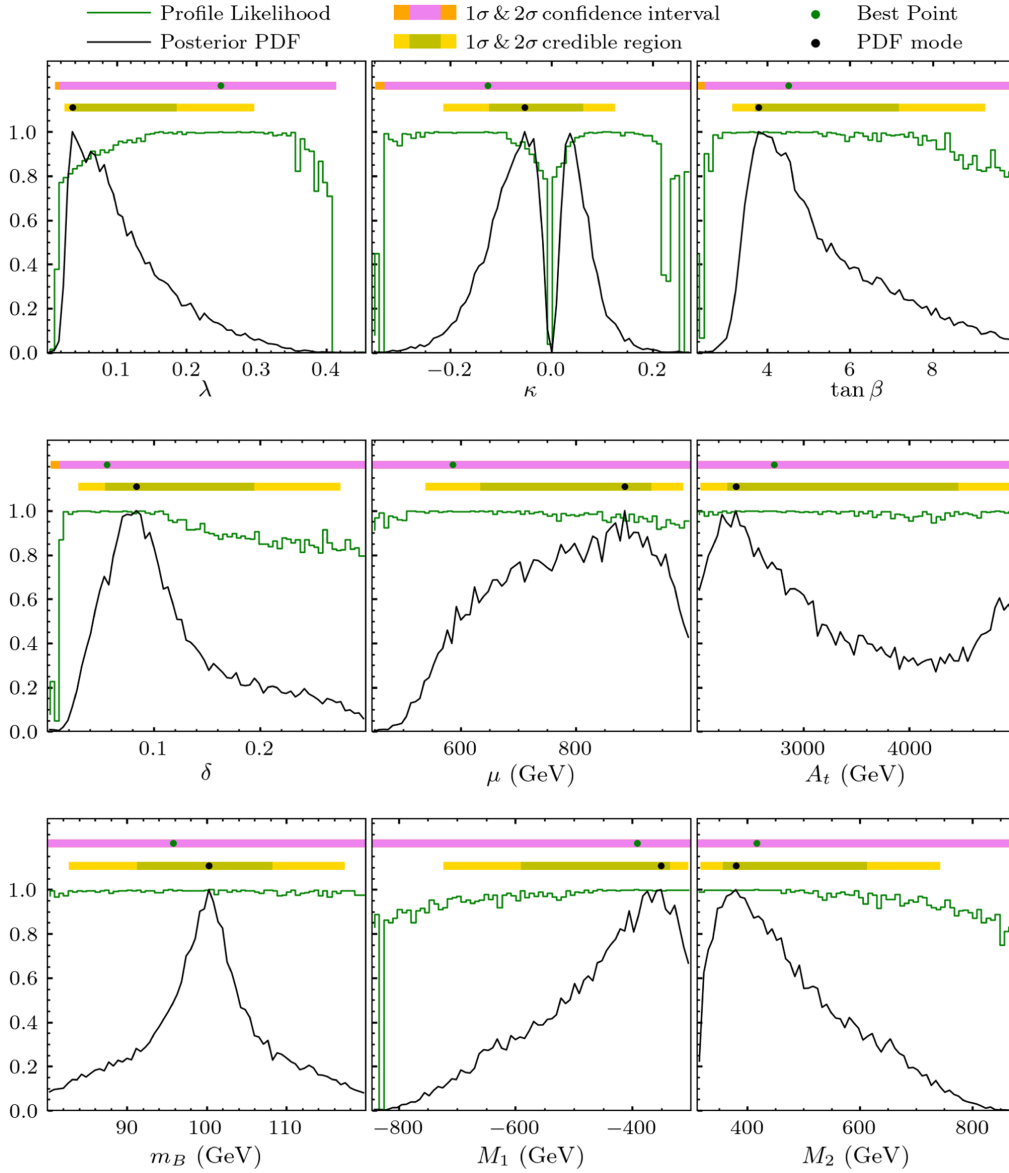


FIG. 1. One-dimensional profile likelihoods (green line) and marginalized posterior probability density functions (black line) of the input parameters λ , κ , $\tan \beta$, δ , μ , A_t , m_B , M_1 , and M_2 . The violet and orange bands show the 1σ and 2σ confidence intervals, respectively, and the green dot marks the best point corresponding to $\chi^2_{\gamma\gamma+b\bar{b}} \simeq 10^{-5}$. The yellow and golden bands denote the 1σ and 2σ credible regions, and the black dot denotes the PDF mode [101].

- (ii) Given that $\tan \beta$ is lower bounded around 2.3, the largest value of $-m_{\tilde{\chi}_1^0}/\mu$ for blind spot condition is $\sin 2\beta \simeq 0.72$. This explains why μ can reach a minimum value of 450 GeV for Case-I and 520 GeV for Case-II when $-m_{\tilde{\chi}_1^0}/\mu \simeq 0.72$.
- (iii) As shown in the left panel in Fig. 2, Case-I can exhibit a larger $\delta\lambda$ compared to Case-II. This is because that the former case favors a lower range of μ and therefore requires an increased $\delta\lambda$ to predict the appropriate Higgs mixing angles $V_{h_s}^{\text{SM}}$, as indicated by Eq. (2.14).
- (iv) For the same reason, Case-I can predict a larger $C_{h_s\gamma\gamma}$ compared to Case-II since the contribution from chargino loops is proportional to $\frac{\lambda v}{\mu}$. Under optimal

conditions, the chargino's contribution in Case-I can reach 0.041, whereas it is limited to 0.02 in Case-II.

The last two panels in Fig. 2 also suggest that the current LHC searches for electroweakinos pose minimal constraints on the presented samples. It is crucial to recognize that LHC constraints on the SUSY particle (sparticles) spectrum depend on the mass differences between the particles produced at the collider and the DM candidate. In scenarios with a compressed spectrum, bino-wino coannihilation could be probed through the wino-pair productions at the LHC. However, this approach proves ineffective in this study. As illustrated in Fig. 16 of Ref. [85], there are

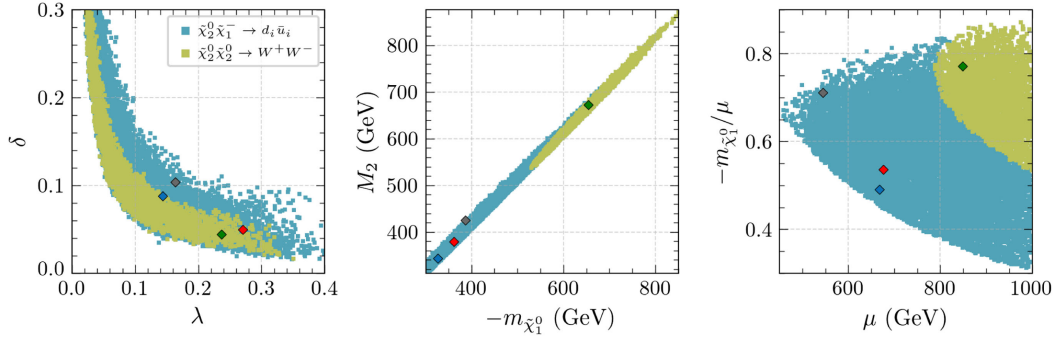


FIG. 2. Scattering plots of samples satisfying the applied constraints and $\chi^2_{\gamma\gamma+b\bar{b}} \leq 2.3$, projected onto (λ, δ) , $(-m_{\tilde{\chi}_1^0}, M_2)$, and $(\mu, -m_{\tilde{\chi}_1^0}/\mu)$ planes, respectively. The left panel shows that $\delta\lambda \lesssim 0.03$ is required for most cases to predict the excesses according to Eq. (2.17). The middle panel indicates that the DM achieves the measured relic abundance by coannihilating with the wino-like electroweakinos. The cyan squares represent samples where the coannihilation process is dominated by the channel $\tilde{\chi}_2^0 \tilde{\chi}_1^- \rightarrow d_i \bar{u}_i$ (with $i = 1, 2, 3$ denoting the quark generations), while the green squares indicate samples where the contribution from the channel $\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow W^+ W^-$ is significant. The right panel implies that a lower limit of $\mu \gtrsim 450$ GeV for $|m_{\tilde{\chi}_1^0}| \simeq 300$ GeV is imposed by the DM-nucleon scattering cross sections from LZ results. The colored diamonds represent four benchmark points whose properties are given in Tables III and IV.

no restrictions on the coannihilation region for $m_{\tilde{\chi}_1^0} \gtrsim 220$ GeV. For scenarios with significant mass splitting, Higgsino-pair production might be considered as a viable detection approach. However, this method is also inefficient here, as inferred from Fig. 12 in Ref. [142], because both Higgsino and $m_{\tilde{\chi}_1^0}$ are predicted to be heavy. To solidify this conclusion, simulations of electroweakino production were performed for four benchmark points using the package CheckMATE-2.0.26 [126–128]. The simulations consistently yielded low R values, indicating weak signals at the LHC. The essential reason for these weak restrictions is that explaining the excesses in this study mainly hinges on the Higgs mixings rather than the presence of light sparticles needed to make significant SUSY contributions to $C_{h_s g g}$ and $C_{h_s \gamma \gamma}$.

In Fig. 3, the SD and SI DM-nucleon scattering cross sections as a function of the LSP mass $m_{\tilde{\chi}_1^0}$ are plotted on the left panel and the right panel, respectively. These cross sections are derived from the samples identified in Fig. 2. For comparison, the figure also includes the upper limits from the 2022 results of the LZ experiment at a 90% confidence level [115], the latest preliminary 2024 limits combined with the 2022 limits [116], the projected sensitivities for future LZ runs [117], and the neutrino background expected in the experiment [152]. From the left panel, it is evident that numerous samples fall well below the current upper constraints and the projected limits for the SD scattering cross sections. The right panel reveals that the SI scattering cross sections are subject to stronger restrictions compared to the SD scattering cross sections,

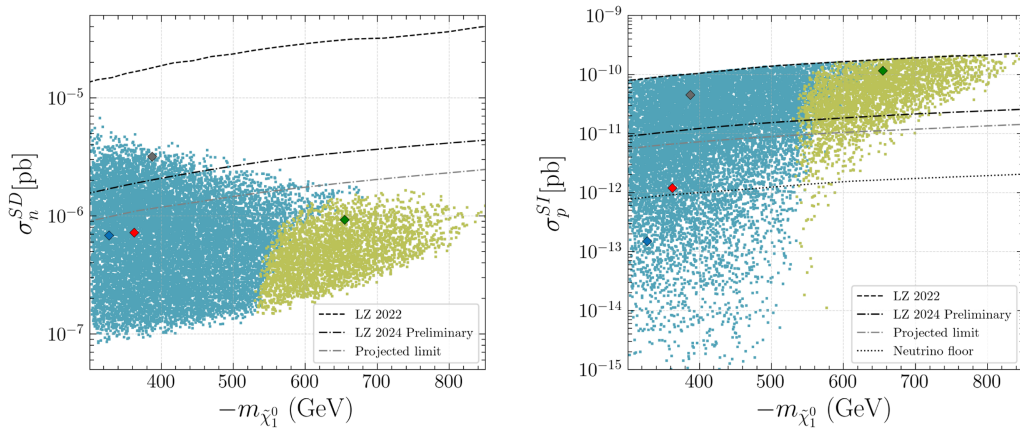


FIG. 3. σ_n^{SD} and σ_p^{SI} as functions of $m_{\tilde{\chi}_1^0}$ for points in Fig. 2. The dashed black lines denote the upper limits at 90% confidence level from the 2022 results of the LZ experiment [115]. The dashed-dotted black lines represent the preliminary 2024 limits combined with the 2022 results [116]. The dashed-dotted gray lines indicate the projected LZ sensitivity for future runs [117]. The dotted lines correspond to the neutrino floor [152].

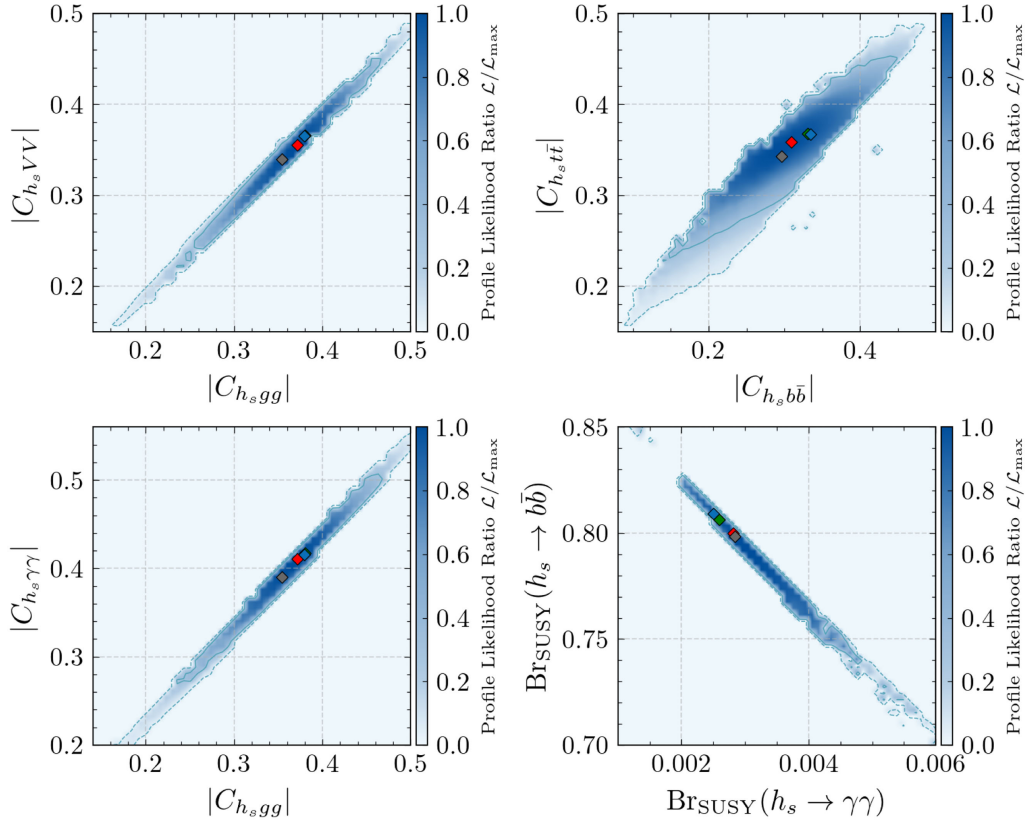


FIG. 4. Two-dimensional profile likelihoods for all samples, projected onto $|C_{h_s VV}| - |C_{h_s gg}|$, $|C_{h_s b\bar{b}}| - |C_{h_s t\bar{t}}|$, $|C_{h_s \gamma\gamma}| - |C_{h_s gg}|$, and $\text{Br}(h_s \rightarrow \gamma\gamma) - \text{Br}(h_s \rightarrow b\bar{b})$ planes, respectively. The contours for 1σ and 2σ confidence intervals correspond to $\chi^2_{\gamma\gamma+b\bar{b}} = 2.3$ and $\chi^2_{\gamma\gamma+b\bar{b}} = 6.18$, labeled as solid and dashed lines, respectively. The colored diamonds denote the four benchmark points in Figs. 2 and 3 with detailed information in Tables III and IV.

especially in the high mass region of $m_{\tilde{\chi}_1^0}$. Despite the tight constraint, a significant number of samples remain below the current and projected upper limits. A few of these samples fall within the neutrino background, posing a challenge for future detections. Overall, the plots indicate that the interpretation of the observed excesses are consistent with the current DM direct detection experiments.

Figure 4 presents the two-dimensional PL functions on the $|C_{h_s VV}| - |C_{h_s gg}|$, $|C_{h_s b\bar{b}}| - |C_{h_s t\bar{t}}|$, $|C_{h_s \gamma\gamma}| - |C_{h_s gg}|$, and $\text{Br}(h_s \rightarrow b\bar{b}) - \text{Br}(h_s \rightarrow \gamma\gamma)$ planes. The solid and dashed lines correspond to the contours for 1σ and 2σ confidence intervals, respectively. The figure reveals that $|C_{h_s VV}| \simeq |C_{h_s t\bar{t}}|$ and $|C_{h_s \gamma\gamma}| \gtrsim |C_{h_s gg}|$ (both slightly larger than $|C_{h_s t\bar{t}}|$). These relationships align with the predictions from Eq. (2.12) and the associated discussions. The figure also illustrates that explaining the excesses at the 1σ level requires the normalized couplings $|C_{h_s t\bar{t}}|$ to be within the range $0.23 \lesssim |C_{h_s t\bar{t}}| \lesssim 0.45$, $|C_{h_s b\bar{b}}|$ within $0.15 \lesssim |C_{h_s b\bar{b}}| \lesssim 0.45$, with a ratio $|C_{h_s t\bar{t}}|/|C_{h_s b\bar{b}}| \simeq 1.4$, $0.27 \lesssim |C_{h_s \gamma\gamma}| \lesssim 0.51$ and $0.23 \lesssim |C_{h_s gg}| \lesssim 0.45$. Additionally, the branching ratios for h_s are constrained to $2.0 \times 10^{-3} \lesssim \text{Br}_{\text{SUSY}}(h_s \rightarrow \gamma\gamma) \lesssim 4.15 \times 10^{-3}$ and $74\% \lesssim \text{Br}_{\text{SUSY}}(h_s \rightarrow b\bar{b}) \lesssim 83\%$.

Figure 5 depicts the normalized couplings (strengths of interaction) and branching ratios (decay probabilities) for the SM-like Higgs boson. As the figure shows, the normalized couplings $|C_{h_s VV}|$, $|C_{h_s t\bar{t}}|$, $|C_{h_s b\bar{b}}|$, $|C_{h_s gg}|$, and $|C_{h_s \gamma\gamma}|$ are centered around 0.926, 0.926, 0.952, 0.935, and 1.04, respectively, for a 1σ level interpretation of the excesses. These couplings agree well with the SM predictions within 10% uncertainties. The branching ratio $\text{Br}(h \rightarrow b\bar{b})$ ranges from 55.4% to 58.6%, closely matching the SM prediction of $(57.7 \pm 1.8)\%$ [83]. While $\text{Br}(h \rightarrow \gamma\gamma)$ varies from 3.02×10^{-3} to 3.20×10^{-3} , showing a significant deviation from the SM prediction of $(2.28 \pm 0.11) \times 10^{-3}$ [83], the diphoton signal of h remains comparable with LHC Higgs data since the samples predict relatively low branching ratios of $h \rightarrow gg$ ($C_{hgg} < 1$).

The left panel of Fig. 6 explores the compatibility of the diphoton and $b\bar{b}$ excesses within the $\mathbb{Z}_3$ -NMSSM. It displays the surviving parameter points (after applying all experimental constraints described in Sec. III A) plotted in the $\mu_{\gamma\gamma} - \mu_{b\bar{b}}$ plane. The dashed and dotted lines delineate the regions in which the two excesses can be accommodated at a level of 1σ and 2σ , respectively. This plot

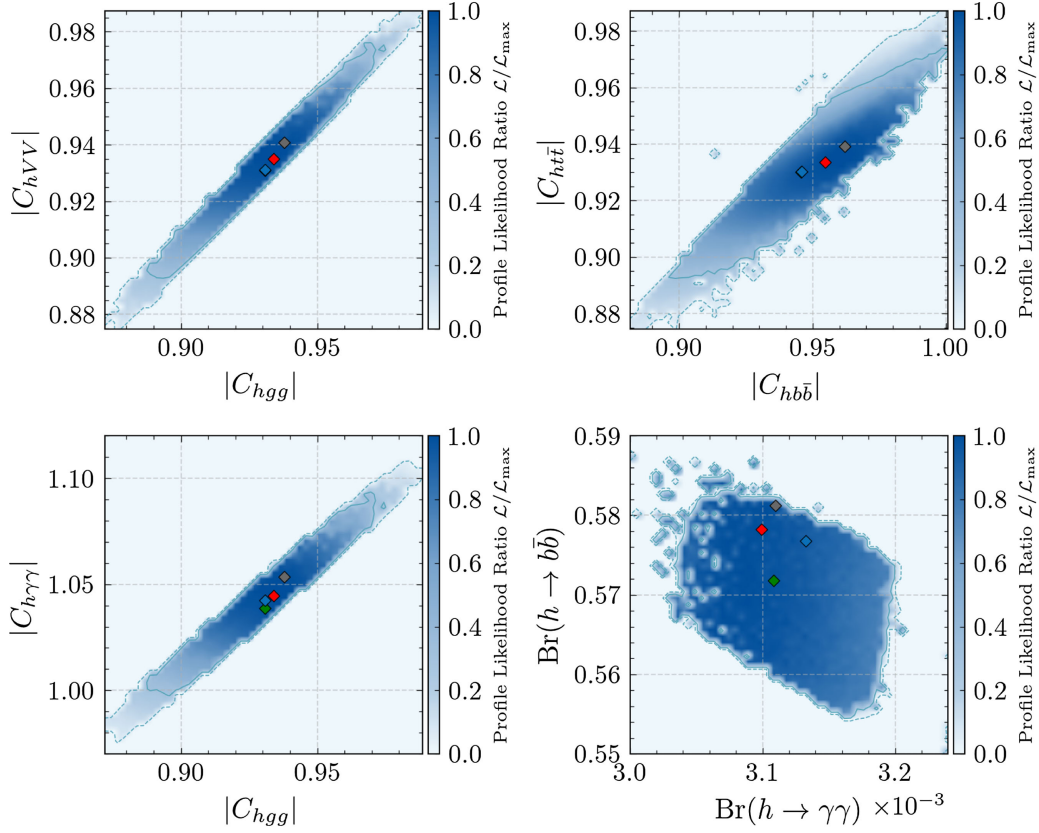


FIG. 5. Same as Fig. 4, but projected onto $|C_{hVV}| - |C_{hgg}|$, $|C_{hb\bar{b}}| - |C_{h\bar{t}t}|$, $|C_{h\gamma\gamma}| - |C_{hgg}|$, and $\text{Br}(h \rightarrow b\bar{b}) - \text{Br}(h \rightarrow \gamma\gamma)$ planes.

illustrates that the model can adequately explain both excesses at the 1σ level. The round and square points represent the dominant DM co-annihilation mechanisms. Notably, Case-I predicts signal strengths closer to the observed central values compared to Case-II. This can

be attributed to the larger contribution of charginos to the coupling $C_{h_s\gamma\gamma}$ in Case-I.

To ensure a robust analysis that encompasses the 13 TeV LHC Higgs data, the latest version of HiggsTools [113] is employed to compute a χ^2 value for each sample,

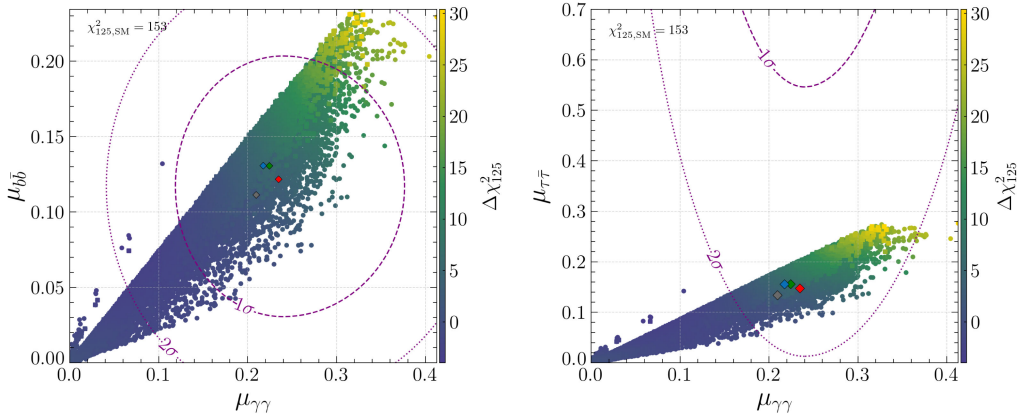


FIG. 6. Projection of the samples surviving the experimental restrictions onto the $\mu_{\gamma\gamma} - \mu_{b\bar{b}}$ plane (left) and $\mu_{\gamma\gamma} - \mu_{\tau\bar{\tau}}$ (right). $\mu_{\tau\bar{\tau}}$ is the signal rate of the di- τ channel for h_s near 95 GeV predicted by the samples. The central value and uncertainty of $\mu_{\tau\bar{\tau}}$ observed by CMS in [10] is taken as $\mu_{\tau\bar{\tau}}^{\text{CMS}} = 1.38^{+0.69}_{-0.55}$ [53]. The color coding indicates the value of $\Delta\chi^2_{125}$ that quantifies the Higgs data fit with respect to the SM result. The round and square points denote Case-I and Case-II, respectively. Points enclosed within the dashed and dotted purple lines can explain the two excesses at 1σ and 2σ levels, corresponding to $\chi^2_{\gamma\gamma+b\bar{b}(\tau\bar{\tau})} \leq 2.30$ and $\chi^2_{\gamma\gamma+b\bar{b}(\tau\bar{\tau})} \leq 6.18$, respectively.

TABLE III. Details of the benchmark points P1 and P2. Both of them can explain the diphoton and $b\bar{b}$ excesses at a 1σ level while satisfying the applied constraints. They correspond to the Case-I scenario and the Case-II scenario, respectively, and are represented as diamonds colored red and green in the previous figures. The notations d_i , u_i , and ℓ_i in the annihilation final state denote the i th generation of down-type quarks, up-type quarks, and leptons, respectively.

Benchmark point P1				Benchmark point P2			
μ	676.6 GeV	λ	0.271	μ	849.3 GeV	λ	0.237
m_B	97.39 GeV	κ	-0.192	m_B	98.47 GeV	κ	-0.129
A_t	2962 GeV	δ	0.049	A_t	2881 GeV	δ	0.044
M_1	-359.2 GeV	$\tan\beta$	3.737	M_1	-650.9 GeV	$\tan\beta$	4.221
M_2	378.8 GeV			M_2	672.1 GeV		
$m_{\tilde{\chi}_1^0}$	-362.5 GeV	m_{h_s}	95.02 GeV	$m_{\tilde{\chi}_1^0}$	-654.8 GeV	m_{h_s}	95.55 GeV
$m_{\tilde{\chi}_2^0}$	386.3 GeV	m_h	124.8 GeV	$m_{\tilde{\chi}_2^0}$	678.7 GeV	m_h	125.0 GeV
$m_{\tilde{\chi}_3^0}$	-683.3 GeV	m_H	2900 GeV	$m_{\tilde{\chi}_3^0}$	-847.9 GeV	m_H	3948 GeV
$m_{\tilde{\chi}_4^0}$	703.8 GeV	m_{A_s}	1655 GeV	$m_{\tilde{\chi}_4^0}$	885.1 GeV	m_{A_s}	1601 GeV
$m_{\tilde{\chi}_5^0}$	-961.7 GeV	m_{A_H}	2902 GeV	$m_{\tilde{\chi}_5^0}$	-939.4 GeV	m_{A_H}	3947 GeV
$m_{\tilde{\chi}_1^\pm}$	386.5 GeV	$m_{H^\pm}$	2903 GeV	$m_{\tilde{\chi}_1^\pm}$	678.9 GeV	$m_{H^\pm}$	3947 GeV
$m_{\tilde{\chi}_2^\pm}$	703.7 GeV			$m_{\tilde{\chi}_2^\pm}$	885.2 GeV		
Ωh^2		0.101		Ωh^2		0.113	
$\sigma_p^{SI}, \sigma_n^{SD}$		$1.2 \times 10^{-48} \text{ cm}^2, 7.2 \times 10^{-43} \text{ cm}^2$		$\sigma_p^{SI}, \sigma_n^{SD}$		$1.0 \times 10^{-46} \text{ cm}^2, 9.3 \times 10^{-43} \text{ cm}^2$	
$\mu_{\gamma\gamma}, \mu_{b\bar{b}}$		0.235, 0.121		$\mu_{\gamma\gamma}, \mu_{b\bar{b}}$		0.224, 0.130	
$V_{h_s}^S, V_{h_s}^{\text{SM}}, V_{h_s}^{\text{NSM}}$		0.935, -0.355, -0.012		$V_{h_s}^S, V_{h_s}^{\text{SM}}, V_{h_s}^{\text{NSM}}$		0.931, -0.365, -0.008	
$C_{h_s,gg}, C_{h_s,VV}, C_{h_s,\gamma\gamma}, C_{h_s,\bar{t}t}, C_{h_s,b\bar{b}}$		0.372, 0.355, 0.410, 0.358, 0.310		$C_{h_s,gg}, C_{h_s,VV}, C_{h_s,\gamma\gamma}, C_{h_s,\bar{t}t}, C_{h_s,b\bar{b}}$		0.381, 0.365, 0.417, 0.367, 0.331	
$C_{hgg}, C_{hVV}, C_{h\gamma\gamma}, C_{h\bar{t}t}, C_{hbb}$		0.934, 0.935, 1.044, 0.933, 0.955		$C_{hgg}, C_{hVV}, C_{h\gamma\gamma}, C_{h\bar{t}t}, C_{hbb}$		0.931, 0.931, 1.039, 0.930, 0.946	
$N_{11}, N_{12}, N_{13}, N_{14}, N_{15}$		0.997, 0.001, 0.074, 0.024, -0.009		$N_{11}, N_{12}, N_{13}, N_{14}, N_{15}$		-0.010, 0.044, -0.111, 0.110, -0.987	
$N_{21}, N_{22}, N_{23}, N_{24}, N_{25}$		-0.010, -0.976, 0.179, -0.129, -0.005		$N_{21}, N_{22}, N_{23}, N_{24}, N_{25}$		-0.025, -0.280, 0.680, -0.657, -0.162	
$N_{31}, N_{32}, N_{33}, N_{34}, N_{35}$		-0.070, 0.036, 0.693, 0.702, -0.142		$N_{31}, N_{32}, N_{33}, N_{34}, N_{35}$		-0.122, -0.050, -0.701, -0.702, -0.002	
$N_{41}, N_{42}, N_{43}, N_{44}, N_{45}$		0.035, -0.217, -0.685, 0.694, 0.013		$N_{41}, N_{42}, N_{43}, N_{44}, N_{45}$		0.008, -0.958, -0.167, 0.234, 0.002	
$N_{51}, N_{52}, N_{53}, N_{54}, N_{55}$		0.002, -0.003, -0.110, -0.091, -0.990		$N_{51}, N_{52}, N_{53}, N_{54}, N_{55}$		0.992, -0.006 - 0.068, -0.106, -0.000	
Coannihilations			Fractions [%]	Coannihilations			Fractions [%]
$\tilde{\chi}_2^0 \tilde{\chi}_1^- \rightarrow d_i \bar{u}_i / ZW^- / \nu_{\ell_i} \ell_i^- / \gamma W^-$			9.8/6.5/3.3/1.8	$\tilde{\chi}_2^0 \tilde{\chi}_1^- \rightarrow d_i \bar{u}_i / ZW^- / \nu_{\ell_i} \ell_i^- / \gamma W^-$			9.0
$\tilde{\chi}_2^0 \tilde{\chi}_2^- \rightarrow W^- W^+$			7.8	$\tilde{\chi}_2^0 \tilde{\chi}_2^- \rightarrow W^- W^+$			8.3/7.3/2.9/2.1
$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow W^\pm W^\pm$			7.6	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow W^\pm W^\pm$			8.4
$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow ZZ / W^\pm W^\pm / \gamma Z / u_i \bar{u}_i / d_i \bar{d}_i$			4.7/4.1/2.7/2.4/2.4	$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow ZZ / W^\pm W^\pm / \gamma Z / u_i \bar{u}_i / d_i \bar{d}_i$			5.4/4.8/3.2/2.1/2.0
Decays			Branching ratios [%]	Decays			Branching ratios [%]
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$			100	$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$			100
$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_2^0 Z / \tilde{\chi}_1^0 h / \tilde{\chi}_1^0 Z$			64.1/29.5/3.15/1.18	$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_2^0 Z / \tilde{\chi}_1^0 h / \tilde{\chi}_1^0 Z$			63.7/27.1/5.75/2.91
$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_2^0 h / \tilde{\chi}_2^0 h_s / \tilde{\chi}_1^0 Z$			66.3/20.8/7.04/3.75	$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_2^0 h / \tilde{\chi}_2^0 h_s / \tilde{\chi}_1^0 Z$			69.7/15.6/8.80/5.46
$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_2^\pm W^\mp / \tilde{\chi}_3^0 h / \tilde{\chi}_4^0 Z / \tilde{\chi}_1^\pm W^\mp$			37.8/20.3/17.6/12.8	$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_2^\pm W^\mp / \tilde{\chi}_3^0 h / \tilde{\chi}_4^0 Z / \tilde{\chi}_1^\pm W^\mp$			67.1/31.7/0.51/0.35

(Table continued)

TABLE III. (Continued)

Benchmark point P1		Benchmark point P2	
$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W^{++}$	100	$\tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 W^{++}$	100
$\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_2^0 W^+ / \tilde{\chi}_1^+ Z / \tilde{\chi}_1^+ h / \tilde{\chi}_1^+ h_s$	33.8/32.2/21.7/7.25	$\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_2^0 W^+ / \tilde{\chi}_1^+ Z / \tilde{\chi}_1^+ h / \tilde{\chi}_1^+ h_s$	36.2/32.7/15.9/8.95
$h_s \rightarrow b\bar{b} / \tau^+ \tau^- / gg / c\bar{c} / W^+ W^{*-} / \gamma\gamma$	79.9/8.85/5.38/5.07/0.48/0.28	$h_s \rightarrow b\bar{b} / \tau^+ \tau^- / gg / c\bar{c} / W^+ W^{*-} / \gamma\gamma$	80.6/8.93/5.02/4.70/0.41/0.26
$h \rightarrow b\bar{b} / W^+ W^{*-} / \tau^+ \tau^- / gg / ZZ^* / \gamma\gamma$	57.8/25.6/6.71/4.58/2.32/0.31	$h \rightarrow b\bar{b} / W^+ W^{*-} / \tau^+ \tau^- / gg / ZZ^* / \gamma\gamma$	57.2/26.2/6.63/4.61/2.39/0.31
$H \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^- / \tilde{\chi}_2^0 \tilde{\chi}_{3,4}^- / t\bar{t} / A_s Z$	39.2/18.2/17.3/6.52	$H \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^- / \tilde{\chi}_2^0 \tilde{\chi}_{3,4}^- / t\bar{t} / A_s Z$	36.7/13.5/15.0/4.93
$A_s \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^- / \tilde{\chi}_2^0 \tilde{\chi}_{3,4}^- / \tilde{\chi}_1^0 \tilde{\chi}_{3,4}^0 / \tilde{\chi}_1^+ \tilde{\chi}_1^-$	45.0/25.8/22.7/3.68	$A_s \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^- / \tilde{\chi}_2^0 \tilde{\chi}_{3,4}^- / \tilde{\chi}_1^0 \tilde{\chi}_{3,4}^0 / \tilde{\chi}_1^+ \tilde{\chi}_1^-$	53.7/26.8/7.91/6.81
$A_H \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^- / t\bar{t} / \tilde{\chi}_2^0 \tilde{\chi}_{4,3}^0 / h A_s$	35.5/17.4/16.4/5.36	$A_H \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^- / t\bar{t} / \tilde{\chi}_2^0 \tilde{\chi}_{4,3}^0 / h A_s$	29.0/13.8/8.96/7.23
$H^+ \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \tilde{\chi}_1^+ / t\bar{b} / A_s W^+$	20.6/19.6/18.6/18.1/6.6	$H^+ \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \tilde{\chi}_1^+ / t\bar{b} / A_s W^+$	20.6/19.7/15.3/14.8/4.99
R value: 0.32	Signal region: E-high-ee-30 in Ref. [145]	R value: 0.02	Signal region: SR-G05 in Ref. [133]

quantifying the agreement with experimental measurements. Samples satisfying the condition $\Delta\chi_{125}^2 \equiv \chi_{125}^2 - \chi_{125,\text{SM}}^2 \lesssim 6.18$ where $\chi_{125,\text{SM}}^2 = 153$ is the SM fit result, would be considered valid as they provide a good description of the Higgs data at an approximate 2σ CL (assuming Gaussian uncertainties) [153]. The analysis leads to the exclusion of about half of the samples that meet $\chi_{\gamma\gamma+b\bar{b}}^2 \leq 2.30$ while simultaneously satisfying other experimental constraints. The color coding in Fig. 6 indicates the value of $\Delta\chi_{125}^2$ and illustrates a strong tension between the interpretation of the 95 GeV excess with $\mu_{\gamma\gamma} \gtrsim 0.23$ and $\mu_{b\bar{b}} \gtrsim 0.11$ and the Higgs data fit. The four benchmark points with $\chi_{125}^2 \approx 159$ are thus facing stringent constraints from this. Consequently, the analysis restricts the normalized couplings of h_s to be $|C_{h_s t\bar{t}}| \lesssim 0.39$, $|C_{h_s b\bar{b}}| \lesssim 0.39$, $|C_{h_s gg}| \lesssim 0.40$, and $|C_{h_s \gamma\gamma}| \lesssim 0.43$. Meanwhile, the lower limit of the normalized couplings of h are raised to $|C_{h t\bar{t}}| \gtrsim 0.93$, $|C_{h b\bar{b}}| \gtrsim 0.93$, $|C_{h gg}| \gtrsim 0.92$ and $|C_{h \gamma\gamma}| \gtrsim 1.03$.

Additionally, the distribution of the samples are also projected onto the $\mu_{\gamma\gamma} - \mu_{\tau\tau}$ plane in the right panel of Fig. 6. $\mu_{\tau\tau}$ is the signal rate of the di- τ channel for h_s near 95 GeV predicted by the samples. The central value and uncertainty of $\mu_{\tau\tau}$ observed by CMS in [10] is taken as $\mu_{\tau\tau}^{\text{CMS}} = 1.38_{-0.55}^{+0.69}$ [53]. This plot illustrates that the diphoton and $\tau\tau$ excesses can only be simultaneously accommodated at a 2σ level. The primary reason for this limitation is that $\mu_{\tau\tau}$ approximates $\mu_{b\bar{b}}$ since the couplings of h_s to tau leptons and bottom quarks are predicted to be equal, i.e., $C_{h_s \tau\tau} = C_{h_s b\bar{b}}$. This finding aligns with the observation in Ref. [154] that the interpretation of the CMS di- τ excess as a CP -even scalar is excluded at the 1σ level by the ATLAS $t\bar{t} + \tau\tau$ search [155]. Moreover, the study in [29] has highlighted that the possibility of accommodating the di-tau excess for a CP -even scalar is ruled out model independently by CMS searches for di-tau resonances produced in association with top quarks [156].

To further elucidate the interpretation of the observed excesses, four benchmark points (P1, P2, P3, P4) are selected to exemplify distinct scenarios within the model. These points are denoted as diamonds colored red, green, blue, and gray, respectively, in the previous figures. Detailed information for these benchmarks is provided in Tables III and IV. Specifically, P1 and P2 correspond to the Case-I and Case-II scenarios, respectively. While P3 and P4 represent two rare scenarios where the largest contributions to the DM annihilation cross section arise from the channels $\tilde{\chi}_1^+ \tilde{\chi}_1^+ \rightarrow W^+ W^+$ and $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow t\bar{t}$, respectively. As illustrated in Fig. 3, P1 and P3 could evade DM direct detections due to their prediction of $\sin 2\beta + m_{\tilde{\chi}_1^0} / \mu \approx -0.03$, which aligns with the blind spot condition, thereby reducing the SI scattering cross section to values approaching or below the neutrino floor. In contrast, P2 and P4 do not exhibit this mitigating effect, and hence, they are

TABLE IV. Details of the benchmark points P3 and P4. They can also explain the diphoton and $b\bar{b}$ excesses at a 1σ level while satisfying the applied constraints. They correspond to two rare scenarios where the largest contributions to the DM annihilation cross section arise from the channels $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow W^+ W^-$ and $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{t}\bar{t}$, respectively.

Benchmark point P3		Benchmark point P4	
μ	668.1 GeV	λ	λ
m_B	91.59 GeV	κ	κ
A_t	2961 GeV	δ	δ
M_1	-324.6 GeV	$\tan\beta$	$\tan\beta$
M_2	342.9 GeV		
$m_{\tilde{\chi}_1^0}$	-327.5 GeV	m_{h_s}	m_{h_s}
$m_{\tilde{\chi}_2^0}$	343.7 GeV	m_h	m_h
$m_{\tilde{\chi}_3^0}$	352.6 GeV	m_H	m_H
$m_{\tilde{\chi}_4^0}$	-682.3 GeV	m_{A_s}	m_{A_s}
$m_{\tilde{\chi}_5^0}$	694.8 GeV	m_{A_H}	m_{A_H}
$m_{\tilde{\chi}_1^\pm}$	351.2 GeV	$m_{H^\pm}$	$m_{H^\pm}$
$m_{\tilde{\chi}_2^\pm}$	694.8 GeV		
Ωh^2		Ωh^2	
$\sigma_p^{SI}, \sigma_n^{SD}$		$\sigma_p^{SI}, \sigma_n^{SD}$	
$\mu_{\tilde{g}}, \mu_{b\bar{b}}$		$\mu_{\tilde{g}}, \mu_{b\bar{b}}$	
$V_h^S, V_{h_s}^{\text{SM}}, V_{h_s}^{\text{NSM}}$		$V_h^S, V_{h_s}^{\text{SM}}, V_{h_s}^{\text{NSM}}$	
$C_{h_s gg}, C_{h_s VV}, C_{h_s \gamma\gamma}, C_{h_s \tilde{t}\tilde{t}}, C_{h_s b\bar{b}}$		$C_{h_s gg}, C_{h_s VV}, C_{h_s \gamma\gamma}, C_{h_s \tilde{t}\tilde{t}}, C_{h_s b\bar{b}}$	
$C_{hgg}, C_{hVV}, C_{h\gamma\gamma}, C_{h\tilde{t}\tilde{t}}, C_{hb\bar{b}}$		$C_{hgg}, C_{hVV}, C_{h\gamma\gamma}, C_{h\tilde{t}\tilde{t}}, C_{hb\bar{b}}$	
$N_{11}, N_{12}, N_{13}, N_{14}, N_{15}$		$N_{11}, N_{12}, N_{13}, N_{14}, N_{15}$	
$N_{21}, N_{22}, N_{23}, N_{24}, N_{25}$		$N_{21}, N_{22}, N_{23}, N_{24}, N_{25}$	
$N_{31}, N_{32}, N_{33}, N_{34}, N_{35}$		$N_{31}, N_{32}, N_{33}, N_{34}, N_{35}$	
$N_{41}, N_{42}, N_{43}, N_{44}, N_{45}$		$N_{41}, N_{42}, N_{43}, N_{44}, N_{45}$	
$N_{51}, N_{52}, N_{53}, N_{54}, N_{55}$		$N_{51}, N_{52}, N_{53}, N_{54}, N_{55}$	
Coannihilations		Coannihilations	
$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow W^\pm W^\pm$		$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \tilde{t}\bar{t}/b\bar{b}$	Fractions [%]
$\tilde{\chi}_3^0 \tilde{\chi}_1^\mp \rightarrow d_i \bar{u}_i / ZW^- / \nu_e \ell_i^- / \gamma W^-$		$\tilde{\chi}_2^0 \tilde{\chi}_1^\mp \rightarrow d_i \bar{u}_i / ZW^- / \nu_e \ell_i^- / \gamma W^-$	26.7/1.2
$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow ZZ / W^\pm W^\pm / \gamma Z / u_i \bar{u}_i / d_i \bar{d}_i$		$\tilde{\chi}_2^0 \tilde{\chi}_3^0 \rightarrow W^\pm W^\pm$	6.6/3.9/2.2/1.2
$\tilde{\chi}_2^0 \tilde{\chi}_3^0 \rightarrow W^\pm W^\pm$		$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow ZZ / W^\pm W^\pm / \gamma Z / u_i \bar{u}_i / d_i \bar{d}_i$	5.1
Decays		Decays	
$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$		$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^*$	Branching ratios [%]
$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 Z^* / \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_2^0 Z^*$		$\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_2^0 Z$	100
$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_2^0 Z / \tilde{\chi}_2^0 h / \tilde{\chi}_1^0 h$		$\tilde{\chi}_4^0 \rightarrow \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_2^0 Z / \tilde{\chi}_1^0 h / \tilde{\chi}_1^0 h_s$	99.7/0.3
$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_3^0 h / \tilde{\chi}_2^0 h / \tilde{\chi}_1^0 Z$		$\tilde{\chi}_5^0 \rightarrow \tilde{\chi}_1^\pm W^\mp / \tilde{\chi}_2^0 h / \tilde{\chi}_2^0 h_s / \tilde{\chi}_1^0 Z$	66.4/27.1/3.84/1.67
$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^{+\mp}$		$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 W^{+\mp}$	76.7/11.3/6.12/5.03
			100

(Table continued)

TABLE IV. (Continued)

Benchmark point P3	Benchmark point P4
$\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_1^+ Z / \tilde{\chi}_3^0 W^+ / \tilde{\chi}_1^+ h / \tilde{\chi}_1^+ h_s / \tilde{\chi}_1^0 W^+$	$\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_2^0 W^+ / \tilde{\chi}_1^+ Z / \tilde{\chi}_1^+ h / \tilde{\chi}_1^0 W^+ / \tilde{\chi}_1^+ h_s$
$h_s \rightarrow b\bar{b} / \tau^+ \tau^- / gg / c\bar{c} / W^+ W^- / \gamma\gamma$	$h_s \rightarrow b\bar{b} / \tau^+ \tau^- / gg / c\bar{c} / W^+ W^- / \gamma\gamma$
$h \rightarrow b\bar{b} / W^+ W^- / \tau^+ \tau^- / gg / ZZ^* / \gamma\gamma$	$h \rightarrow b\bar{b} / W^+ W^- / \tau^+ \tau^- / gg / ZZ^* / \gamma\gamma$
$H \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^- / \tilde{\chi}_3^0 \tilde{\chi}_{4,5}^0 / \tilde{t}\tilde{t} / \tilde{\chi}_2^0 \tilde{\chi}_4^0$	$H \rightarrow \tilde{\chi}_1^+ \tilde{t}\tilde{t} / \tilde{\chi}_2^- / \tilde{\chi}_2^0 \tilde{\chi}_4^0 / \tilde{\chi}_4^0 \tilde{\chi}_5^0 / \tilde{\chi}_1^+ \tilde{\chi}_1^-$
$A_s \rightarrow \tilde{t}\tilde{t} / b\bar{b} / \tau\bar{\tau} / A_s Z / \gamma\gamma / gg$	$A_s \rightarrow \tilde{t}\tilde{t} / b\bar{b} / \tilde{\chi}_1^0 \tilde{\chi}_1^0 / \tilde{\chi}_1^+ \tilde{\chi}_1^- / Z h_s$
$A_H \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^- / \tilde{t}\tilde{t} / \tilde{\chi}_3^0 \tilde{\chi}_{5,4}^0 / \tilde{\chi}_5^0 \tilde{\chi}_2^0$	$A_H \rightarrow \tilde{t}\tilde{t} / \tilde{\chi}_1^+ \tilde{\chi}_2^- / \tilde{\chi}_1^+ \tilde{\chi}_1^- / \tilde{\chi}_2^+ \tilde{\chi}_2^- / \tilde{\chi}_1^0 \tilde{\chi}_1^0$
$H^+ \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \tilde{\chi}_1^+ / \tilde{\chi}_3^0 \tilde{\chi}_2^+ / t\bar{b} / \tilde{\chi}_1^0 \tilde{\chi}_2^+$	$H^+ \rightarrow t\bar{b} / \tilde{\chi}_2^0 \tilde{\chi}_2^+ / \tilde{\chi}_3^0 \tilde{\chi}_1^+ / \tilde{\chi}_4^0 \tilde{\chi}_1^+ / \tilde{\chi}_4^0 \tilde{\chi}_2^+$
R value: 0.54	R value: 0.12
Signal region: SR2-stop-3high-pt-1 in Ref. [147]	Signal region: SR-WZoff-high-njd in Ref. [85]

subject to exclusion by the projected sensitivity of the LZ experiment. Regarding constraints from the LHC experiments, given that all points predict compressed spectra and relatively large masses for the LSP, the LHC searches for SUSY would have no exclusion capability on them. Simulations of electroweakino productions using the package CheckMATE-2.0.26 indicate that their R values are all less than 0.6. The most significant signal regions and their experimental analyses are listed at the bottom row for each point.

IV. CONCLUSION

The recent analyses by CMS and ATLAS Collaborations have revealed a deviation in the diphoton channel at about 95 GeV with compatible signal strengths. The invariant mass of the diphoton signal coincides with that of the previously observed $b\bar{b}$ excess at LEP, suggesting they may originate from a same CP -even Higgs boson with its mass around 95 GeV. Given the significant decrease in the diphoton rate and the notable improvement in sensitivities of DM direct detection experiments, the present research conducts a comprehensive investigation into the capacity of the well-established $\mathbb{Z}_3$ -NMSSM to fully accommodate the observed excesses while adhering to various experimental constraints. By deriving analytic expressions and performing a specialized scan, the study demonstrates that the model can successfully explain the observed excesses through a singlet-dominated CP -even Higgs boson around 95 GeV. The investigation yields the following key insights:

- (1) The model could effectively explain the diphoton and $b\bar{b}$ excesses at the 1σ level, which requires the normalized couplings to be within the range $0.23 \lesssim |C_{h_s \tilde{t}\tilde{t}}| \lesssim 0.39$, $0.15 \lesssim |C_{h_s b\bar{b}}| \lesssim 0.39$, $0.27 \lesssim |C_{h_s \gamma\gamma}| \lesssim 0.43$, and $0.23 \lesssim |C_{h_s gg}| \lesssim 0.40$.
- (2) Case-I can predict signal strengths closer to the central values compared to Case-II due to larger contributions from chargino loops to $C_{h_s \gamma\gamma}$.
- (3) The interpretation favors the bino-dominated $\tilde{\chi}_1^0$ s as DM candidates. These particles achieve the measured relic abundance primarily by coannihilating with the winolike electroweakinos. This interpretation adheres to the constraints from DM direct detection experiments, with many parameter points predicting scattering cross sections below the current experimental limits and even within the neutrino background, rendering them challenging to detect.
- (4) Constraints from the LHC searches for electroweakinos have little impact on the compressed spectrum. Monte Carlo simulations for the four benchmark points consistently yield low R values (< 0.6), indicating weak signals at the LHC. This result is attributed to the heavy electroweakino masses pre-

dicted in the study, which reduce the production rates for these particles.

- (5) The diphoton and $\tau\bar{\tau}$ excesses can only be jointly explained at the 2σ level. This limitation arises because $\mu_{\tau\bar{\tau}}$ closely follows $\mu_{b\bar{b}}$, given the equality of $C_{h_s\tau\bar{\tau}}$ and $C_{h_sb\bar{b}}$ in this model.

These findings support the $\mathbb{Z}_3$ -NMSSM as a viable extension of the standard model that could accommodate the new scalar particle, motivating further experimental

investigations and more refined searches for potential signals in the upcoming collider experiments.

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