The Z+photon and diphoton decays of the Higgs boson as a joint probe of low energy SUSY models (Postprint)

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Abstract

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Full Text

The Z+photon and Diphoton Decays of the Higgs Boson as a Joint Probe of Low Energy SUSY Models

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Abstract

In light of recent remarkable progress in Higgs searches at the LHC, we study the rare decay process $h \to Z\gamma$ and show its correlation with the decay $h \to \gamma\gamma$ in low energy SUSY models such as the CMSSM, MSSM, NMSSM, and nMSSM. Under various experimental constraints, we scan the parameter space of each model and present in the allowed parameter space the SUSY predictions on the $Z\gamma$ and $\gamma\gamma$ signal rates in Higgs production at the LHC and future e^+e^- linear colliders.

We have the following observations: (i) Compared with the SM prediction, the $Z\gamma$ and $\gamma\gamma$ signal rates in the CMSSM are both slightly suppressed; (ii) In the MSSM, both the $Z\gamma$ and $\gamma\gamma$ rates can be either enhanced or suppressed, and in the optimal case, the enhancement factors at the LHC can reach 1.1 and 2, respectively; (iii) In the NMSSM, the $Z\gamma$ and $\gamma\gamma$ signal rates normalized by their SM predictions are strongly correlated, and at the LHC the rates vary from 0.2 to 2; (iv) In the nMSSM, the $Z\gamma$ and $\gamma\gamma$ rates are both greatly reduced. Since the correlation behavior between the $Z\gamma$ signal and the $\gamma\gamma$ signal is so model-dependent, it may be used to distinguish the models in future experiments.

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Introduction

Based on measurements of the $\gamma\gamma$ and ZZ^* channels, the ATLAS and CMS collaborations have independently provided compelling evidence for a bosonic resonance around 125-126 GeV [**?**, **?**]. This is a great triumph for particle physics, but it also leads to a host of new questions about the nature of the boson. So far, there exist large uncertainties in determining the rates of the two channels, and meanwhile, observation of the boson through other signals such as $b\bar{b}$ and $\tau^+\tau^-$ channels is still far from becoming significant [**?**]. Although the preliminary data from the LHC indicate that the boson closely resembles the Higgs boson in the Standard Model (SM), the deficiencies of the SM itself, such as the gauge hierarchy problem, suggest a new physics explanation of the boson. Obviously, in order to determine the correct underlying theory, the LHC should exhaust its potential to measure the decay channels of the boson as accurately as possible in its high-luminosity phase.

Among the decay modes of the Higgs-like boson h, the diphoton channel plays a very important role in determining its mass, spin, and parity [**?**]. At the same time, since the diphoton channel is mediated by loops of charged particles, it also serves as a sensitive probe of new physics. This feature has been widely utilized to explain the results of the ATLAS and CMS collaborations on the inclusive diphoton signal in 2012 \cite{5-14}, which were 1.9 ± 0.5 and 1.56 ± 0.43, respectively, for the signal rate normalized by its SM prediction [**?**, **?**].

In this note, we concentrate on another decay mode, $h \to Z\gamma$. In the SM, the branching ratio of this decay is about two-thirds of that for the diphoton decay, and just like the diphoton signal, it can provide a clean final-state topology for determining the properties of the boson, such as its mass, spin, and parity [**?**]. Moreover, since new charged particles affecting the diphoton decay can also contribute to the $Z\gamma$ decay, the two decay modes should be correlated, and therefore studying them jointly can reveal more details about the underlying physics. Despite these advantages, in contrast to the diphoton decay which has been intensively studied, the $Z\gamma$ decay received little attention in the past. For example, since the discovery of the boson, only several works have been devoted to this decay in new physics models such as the type-II seesaw model [**?**], the Georgi-Machacek model [**?**], extensions of the SM by charged scalars in different $SU(2)_L$ representations [**?**], and the SM with extra colored scalars [**?**], and until very recently have the CMS and ATLAS collaborations set an upper limit on the ratio $\sigma_{Z\gamma}/\sigma_{Z\gamma}^{\mathrm{SM}} < 10$ [**?**]. Note that although the $Z\gamma$ signal suffers from a large irreducible background at the LHC [?], the Higgs event from the process $e^+e^- \to Zh \to ZZ\gamma$ can be easily reconstructed at the next-generation linear collider with center-of-mass energy around 250 GeV [?], which is very helpful in suppressing the background for such a signal. Therefore, there is good prospects to precisely measure this decay in the future.

In the following, we focus on the $Z\gamma$ decay channel of the SM-like Higgs boson h in low-energy supersymmetric models such as the Constrained Minimal Supersymmetric Standard Model (CMSSM) [?], the Minimal Supersymmetric Standard Model (MSSM) [?, ?], the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [?], and the Nearly Minimal Supersymmetric Standard Model (nMSSM) [?]. We investigate the $Z\gamma$ signal of Higgs production at the LHC and future e^+e^- linear colliders, and especially, we study its correlations with the $\gamma\gamma$ signal. As we will show below, the $Z\gamma$ signal rate may be either enhanced or suppressed in SUSY, and its correlation behavior is so model-dependent that it may be utilized to distinguish the models in the high-luminosity phase of the LHC.

This work is organized as follows. In Section II we introduce the basic features of the SUSY models and present some formulae relevant to our calculation. In Section III we first discuss the effects of new charged SUSY particles on the partial decay widths of $h \to Z\gamma$, then we study in a comparative way the $Z\gamma$ and $\gamma\gamma$ signal rates of Higgs production at different colliders. Finally, we draw our conclusions in Section IV. Various couplings used in the calculation are given in the Appendix.

II. The Models and Analytic Formulae

In a low-energy supersymmetric gauge theory, the explicit form of its Lagrangian is determined by the gauge symmetry, superpotential, and soft breaking terms. As for the four models considered in this work, their differences mainly come from the superpotential, which is the source for the Yukawa interactions of fermions and self-interactions of scalars.

MSSM and CMSSM

The MSSM [?, ?] contains two Higgs doublets H_u, H_d and predicts five physical Higgs bosons, of which two are CP-even, one is CP-odd, and two are charged. Its superpotential takes the following form:

$$W_{\text{MSSM}} = W_F + \mu \hat{H}_u \cdot \hat{H}_d,$$

where W_F denotes the Yukawa interaction, given by:

$$W_F = \hat{u} Y_u \hat{Q} \cdot \hat{H}_u - \hat{d} Y_d \hat{Q} \cdot \hat{H}_d - \hat{e} Y_e \hat{L} \cdot \hat{H}_d.$$

After considering appropriate soft breaking terms, one can write down the Higgs potential:

$$V_{\rm MSSM} = (|\mu|^2+m_{H_u}^2)|H_u^0|^2+(|\mu|^2+m_{H_d}^2)|H_d^0|^2-(B\mu H_u^0 H_d^0+\text{h.c.})+\frac{g^2+g'^2}{8}(|H_u^0|^2-|H_d^0|^2)^2,$$

where m_{H_u}, m_{H_d}, and B are all soft parameters with mass dimension, terms proportional to $|\mu|^2$ come from the F-term of the superpotential, and the last term comes from gauge symmetry (the so-called D-term). This potential indicates that after electroweak symmetry breaking, the μ-parameter is related to the Higgs vacuum expectation value (vev) and therefore should be $\mathcal{O}(100\text{ GeV})$. However, since μ is the only parameter with mass dimension that appears in the superpotential, its value should naturally take the SUSY-preserving scale. Such a tremendously large scale gap is usually referred to as the μ-problem [**?**].

The theoretical framework of the CMSSM [**?**] is exactly the same as that of the MSSM, and the only difference between them comes from the fact that in the general MSSM, all soft breaking parameters are independent [**?**], while in the CMSSM they are correlated. Explicitly, the CMSSM assumes the following universal soft breaking parameters at the SUSY breaking scale (usually chosen at the Grand Unification scale) [**?**]: $M_{1/2}$, M_0, A_0, $\tan\beta$, sign(μ), with $M_{1/2}$, M_0, and A_0 denoting gaugino mass, scalar mass, and trilinear interaction coefficient, respectively, and evolves these four parameters down to the weak scale to obtain all the soft breaking parameters of the MSSM. In this sense, the parameter space of the CMSSM should be considered as a subset of that for the MSSM, and so is its phenomenology.

NMSSM and nMSSM

In order to solve the μ-problem in the MSSM, various singlet extensions of the MSSM were proposed historically, and among them the most well-known models include the NMSSM and the nMSSM. The superpotentials of these two models are respectively given by [**?**, **?**]:

$$W_{\rm NMSSM} = W_F + \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3}\hat{S}^3,$$

$$W_{\rm nMSSM} = W_F + \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \xi_F M_n^2 \hat{S},$$

where λ, κ, and ξ_F are dimensionless parameters of order 1, and the dimensionful parameter M_n may be naturally fixed at the weak scale in certain basic frameworks where the parameter is generated at a high loop level [**?**].

One attractive feature of both models comes from the fact that after the real scalar component of $\hat{S}$ develops a vev $\langle S\rangle$, an effective μ parameter is generated by $\mu_{\rm eff} = \lambda\langle S\rangle$, and its value may be as low as about 100 GeV without conflicting with current experiments [**?**] (in contrast, the μ parameter in the MSSM must be larger than about 200 GeV [**?**]). Another attractive feature of the models is that the Z boson mass may be obtained with less fine-tuning than in the MSSM

[?]. In SUSY models, after minimization of the Higgs potential, the Z boson mass is given by [?]:

$$M_Z^2 = \frac{m_{H_d}^2 + \Sigma_d - (m_{H_u}^2 + \Sigma_u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2,$$

where $m_{H_u}^2$ and $m_{H_d}^2$ represent the soft SUSY breaking masses of the Higgs fields, and Σ_u and Σ_d arise from radiative corrections to the Higgs potential with the dominant contribution to Σ_u given by:

$$\Delta_{\rm rad} m_{H_u}^2 \simeq \frac{3y_t^2}{8\pi^2} \times m_{\tilde{t}}^2 \ln\left(\frac{Q^2}{m_{\tilde{t}}^2}\right).$$

These equations indicate that if the individual terms on the right-hand side of the M_Z^2 equation are comparable in magnitude so that the observed value of M_Z is obtained without resorting to large cancellations, relatively light stops and μ of $\mathcal{O}(100$ GeV) are preferred. As far as the NMSSM and the nMSSM are concerned, due to the Higgs self-interactions, the squared mass of the SM-like Higgs boson gets an additional contribution $\lambda^2 v^2 \sin^2 2\beta$ (compared with its MSSM expression), and further it can be enhanced by the doublet-singlet mixing [?, ?]. Consequently, predicting a 125 GeV Higgs boson does not necessarily require heavy scalar top quarks [?]. This is very helpful in reducing the tuning. For example, it has been shown that the fine-tuning parameter Δ, defined by $\Delta = \mathrm{Max}\{|\partial \ln m_Z / \partial \ln p_{\rm GUT}|\}$ with $p_{\rm GUT}$ denoting SUSY parameters at the GUT scale [?], may be as low as 4 in the two models, while in the MSSM it usually exceeds 100 [?].

Regarding the nMSSM, one should note that the tadpole term only affects the Higgs masses and the minima of the scalar potential, so the interactions in the Higgs and neutralino sectors of the nMSSM are identical to those in the NMSSM with $\kappa = 0$. This enables us to modify the package NMSSMTools [?] and use it to study the phenomenology of the nMSSM [?]. Also note that the singlino mass vanishes at tree level and the lightest neutralino, as the dark matter candidate, acquires its mass through mixing of the singlino with Higgsinos and gauginos. In this case, the dark matter is light and singlino-dominated, and it must annihilate through exchanging a resonant light CP-odd Higgs boson to obtain the correct relic density [?]. As a result, the SM-like Higgs boson will decay dominantly into light neutralinos or other light Higgs bosons, suppressing the branching fractions of visible decay channels like $h \to \gamma\gamma$, $b\bar{b}$, $ZZ^*(4l)$, and $\tau^+\tau^-$ [?]. This is strongly disfavored by current LHC data, as shown in [?]. In this work, we take the nMSSM only as an example to show its peculiar behaviors in Higgs physics (in comparison with other new SUSY models).

Formula in Calculation

In order to study the $h \to Z\gamma$ decay and its correlation with the $h \to \gamma\gamma$ decay in SUSY, we define the following normalized rates at the LHC and the

International Linear Collider (ILC) [?]:

$$R_{Z\gamma} \equiv \frac{\sigma(pp \to h \to Z\gamma)}{\sigma_{\rm SM}(pp \to h \to Z\gamma)} \simeq \frac{{\rm Br}(h \to Z\gamma)}{{\rm Br}_{\rm SM}(h \to Z\gamma)} \simeq \frac{\Gamma_{Z\gamma}(h)}{\Gamma^{\rm SM}_{Z\gamma}(h)} \frac{\Gamma^{\rm SM}_{\rm tot}(h)}{\Gamma_{\rm tot}(h)}, \quad (9)$$

$$R_{\gamma\gamma} \equiv \frac{\sigma(pp \to h \to \gamma\gamma)}{\sigma_{\rm SM}(pp \to h \to \gamma\gamma)} \simeq \frac{{\rm Br}(h \to \gamma\gamma)}{{\rm Br}_{\rm SM}(h \to \gamma\gamma)} \simeq \frac{\Gamma_{\gamma\gamma}(h)}{\Gamma^{\rm SM}_{\gamma\gamma}(h)} \frac{\Gamma^{\rm SM}_{\rm tot}(h)}{\Gamma_{\rm tot}(h)}, \quad (10)$$

$$K_{Z\gamma} \equiv \frac{\sigma(e^+e^- \to Zh \to ZZ\gamma)}{\sigma_{\rm SM}(e^+e^- \to Zh \to ZZ\gamma)} \simeq \frac{C^2_{hZZ}}{C^{\rm SM2}_{hZZ}} \frac{\Gamma_{Z\gamma}(h)}{\Gamma^{\rm SM}_{Z\gamma}(h)} \frac{\Gamma^{\rm SM}_{\rm tot}(h)}{\Gamma_{\rm tot}(h)}, \quad (11)$$

$$K_{b\bar{b}} \equiv \frac{\sigma(e^+e^- \to Zh \to Zb\bar{b})}{\sigma_{\rm SM}(e^+e^- \to Zh \to Zb\bar{b})} \simeq \frac{C^2_{hZZ}}{C^{\rm SM2}_{hZZ}} \frac{\Gamma_{b\bar{b}}(h)}{\Gamma^{\rm SM}_{b\bar{b}}(h)} \frac{\Gamma^{\rm SM}_{\rm tot}(h)}{\Gamma_{\rm tot}(h)}, \quad (12)$$

where Higgs production at the LHC is dominated by the gluon fusion process, while at the ILC with $\sqrt{s} \sim 250$ GeV, it is dominated by the Zh associated production. Here C_{hgg} and C_{hZZ} are the couplings of the Higgs boson to gluons and Z bosons, respectively, and $\Gamma_{Z\gamma}(h)$, $\Gamma_{\gamma\gamma}(h)$, and $\Gamma_{b\bar{b}}(h)$ are the partial widths for the decays $h \to Z\gamma$, $h \to \gamma\gamma$, and $h \to b\bar{b}$, respectively. In deriving these formulae, we neglect SUSY radiative corrections to the signals. Those corrections are expected to be at the few percent level, given that heavy sparticles are preferred by current LHC experiments.

In SUSY, the decays $h \to Z\gamma$ and $h \to \gamma\gamma$ receive new contributions from loops mediated by charged Higgs bosons, sfermions (including stops, sbottoms, and staus), and charginos. Consequently, the formulas for $\Gamma_{Z\gamma}$ and $\Gamma_{\gamma\gamma}$ are modified:

$$\Gamma_{Z\gamma}(h) = \frac{G_F m_h^3 \alpha}{64\sqrt{2}\pi^4} \left(1 - \frac{m_Z^2}{m_h^2}\right)^3 \left| A_W^{Z\gamma} + A_t^{Z\gamma} + A_{\tilde{f}}^{Z\gamma} + A_{H^\pm}^{Z\gamma} + A_{\chi^\pm}^{Z\gamma} \right|^2,$$

$$\Gamma_{\gamma\gamma}(h) = \frac{G_F m_h^3 \alpha^2}{128\sqrt{2}\pi^4} \left| A_W^{\gamma\gamma} + A_t^{\gamma\gamma} + A_{\tilde{f}}^{\gamma\gamma} + A_{H^\pm}^{\gamma\gamma} + A_{\chi^\pm}^{\gamma\gamma} \right|^2,$$

where A_i ($i = W, t, \tilde{f}, H^\pm, \chi^\pm$) denote the contributions from particle i mediated loops, and their explicit expressions are listed in the Appendix. Note that our expressions differ from those presented in [?] in two aspects. One is that we have an overall minus sign for the new contributions $A_{H^\pm}$, $A_{\tilde{f}}$, and $A_{\chi^\pm}$, and an additional factor of 2 for the sfermion contributions. This sign difference was also observed recently in [?]. The other difference is that we have included in a neat way the contributions from loops with two particles (such as $\tilde{f}_1$ and $\tilde{f}_2$ or $\chi_1^\pm$ and $\chi_2^\pm$) running in them. Such contributions were considered to be negligibly small [?], but our results indicate that sometimes they may play a role. Also note that in the SUSY package FeynHiggs [?], the decay $h \to Z\gamma$ is not calculated. In the package NMSSMTools [?], this decay is calculated only by considering the contributions from SM particles and the charged Higgs boson. We improve these packages by inserting our codes for $h \to Z\gamma$.

III. Numerical Calculation and Discussions

In our calculation, we first perform a random scan over the parameter space of each model by considering various experimental constraints. Then for the surviving samples we investigate the $h \to Z\gamma$ and $h \to \gamma\gamma$ decays. Since each unconstrained SUSY model involves too many free parameters in the calculation, we make some assumptions to simplify our analysis.

Our treatment of the MSSM and the NMSSM is as follows. First, we note that the first two generation squarks change little the properties of the Higgs boson, and LHC searches for SUSY particles imply that they should be very heavy. Therefore, in our scan we fix all soft masses and trilinear parameters in this sector to be 2 TeV. We have checked that our conclusions are not affected by this specific choice. Second, since the third-generation squarks affect the Higgs sector significantly, we set free all soft parameters in this sector except that we assume $m_{U_3} = m_{D_3}$ and $A_t = A_b$ to reduce the number of free parameters. Third, considering that the muon anomalous magnetic moment is sensitive to the spectrum of scalar muons and the decay $h \to Z\gamma$ may receive significant contributions from the scalar tau (stau) sector, we assume $A_\tau = A_\mu = A_e = 0$, $M_{L_3} = M_{L_2} = M_{L_1}$ and $M_{E_3} = M_{E_2} = M_{E_1}$, and treat M_{L_3} and M_{E_3} as free parameters. We have checked that for our considered cases, the decay $h \to Z\gamma$ is insensitive to A_τ. Finally, since our results are insensitive to the gluino mass, we fix it at 2 TeV. We also assume the grand unification relation $3M_1/5\alpha_1 = M_2/\alpha_2$ for electroweak gaugino masses.

To sum up, for the MSSM we scan the parameters in the following regions:

$$1 \le \tan\beta \le 60, \quad 100 \text{ GeV} \le \mu \le 1 \text{ TeV}, \quad 100 \text{ GeV} \le M_A \le 1 \text{ TeV},$$
$$100 \text{ GeV} \le (M_{Q_3}, M_{U_3}) \le 2 \text{ TeV}, \quad 100 \text{ GeV} \le (M_{L_3}, M_{E_3}) \le 1 \text{ TeV},$$
$$-3 \text{ TeV} \le A_t \le 3 \text{ TeV}, \quad 50 \text{ GeV} \le M_1 \le 500 \text{ GeV}.$$

Note that in actual calculations, λ and μ_{eff} in the NMSSM are usually treated as independent input parameters, and for any given value of μ_{eff}, the phenomenology of the NMSSM is identical to that of the MSSM with $\mu = \mu_{\text{eff}}$ in the limit $\lambda, \kappa \to 0$ [?]. This enables us to use the package NMSSMTools [?], which calculates various observables and also considers various experimental constraints in the framework of the NMSSM, to study the phenomenology of the MSSM (note that the validity of this method has been justified by the authors of NMSSM-Tools [?]). In our calculation we use NMSSMTools-3.2.4 to perform the scan for the MSSM by setting $\lambda = \kappa = 10^{-4}$ and $A_\kappa = -10$ GeV. Here the value of A_κ is actually irrelevant to our calculation for the MSSM as long as it is negative and satisfies $|A_\kappa| < 4\kappa\mu/\lambda$ (in order to guarantee the squared masses of the singlet scalars to be positive) [?].

For the NMSSM, we use NMSSMTools-3.2.4 to scan the region in Eq. (15) and also the following ranges for additional parameters:

$$0.5 \leq \lambda \leq 0.7, \quad 0 \leq \kappa \leq 0.7, \quad |A_\kappa| \leq 1 \text{ TeV}.$$

Note that in our scan we only consider relatively large λ. The reason is that in the NMSSM, the properties of the SM-like Higgs boson are expected to deviate significantly from the MSSM prediction only for sizable λ [?], and in particular, for $\lambda \gtrsim 0.5$, the Higgs mass at tree level is maximized at $\tan\beta \sim 1$, instead of at large $\tan\beta$ as in the MSSM.

As for the nMSSM, our assumptions are the same as those for the MSSM except that, in order to explain the muon anomalous magnetic moment at the 2σ level, we assume all soft SUSY breaking parameters in the slepton sector to be 100 GeV [?].$Suchasleptonmassisallowedbythe LEPIIbounds, whichare 99.9 GeV forthefirsttwogenerationsand 93.2 Ge$ Although the LHC also gave a bound on slepton mass by searching for the decay $\tilde{l} \to l\tilde{\chi}_1^0$, the result is not applicable to the nMSSM. The reason is that in the nMSSM, the LSP is singlino-like and the NLSP is usually a bino-like neutralino $\tilde{\chi}_2^0$. As a result, the dominant decay chain of a slepton is $\tilde{l} \to l\tilde{\chi}_2^0 \to l\tilde{\chi}_1^0 b\bar{b} \to l +$ missing energy + jets [?]\$. Other parameters in this model are scanned in the following ranges:

$$0.1 \leq \lambda \leq 0.7, \quad |A_\lambda| \leq 1 \text{ TeV}, \quad 0 \leq \tilde{m}_S \leq 200 \text{ GeV},$$

where $\tilde{m}_S$ is the soft breaking mass for the singlet Higgs field. In our calculation, we adapt the code of NMSSMTools to the nMSSM case as done in [?]\$.

For the CMSSM, we use the package NMSPEC [?]\$ to scan the following parameter space:

$$100 \text{ GeV} \leq (M_0, M_{1/2}) \leq 2 \text{ TeV}, \quad 1 \leq \tan\beta \leq 60, \quad -3 \text{ TeV} \leq A_0 \leq 3 \text{ TeV},$$

and we take the sign of μ to be positive. Similar to the MSSM scan, we set $\lambda = \kappa = 10^{-4}$ and $A_\kappa = -10$ GeV at the GUT scale (note that the validity of NMSPEC to study the phenomenology of the CMSSM was emphasized by the authors of the package [?]\$). Since in the CMSSM different soft breaking parameters at the electroweak scale are correlated, it is expected that its phenomenology is only a subset of the MSSM.

In our scan we have considered various constraints on the models, which come from vacuum stability, LEP and LHC searches for SUSY particles and Higgs bosons, electroweak observables ϵ_i and R_b, B physics observables such as the branching ratio of $B \to X_s\gamma$ and the mass difference ΔM_s, the dark matter relic density, and direct detection experiments. When imposing the constraint from a certain observable that has an experimental central value, we require SUSY to explain the observable at the 2σ level. These constraints are described in detail in [?]$ and have been implemented in the package NMSSMTools-3.2.4 [?]. $Inparticular, thedarkmatterrelicdensityiscalculatedbythepackageMicrOMEGAs$[?], which now acts as an important component of NMSSMTools.

Compared with the constraints in [?]$, we have the following improvements in this work. First, we require 123 GeV $\leq m_h \leq$ 127 GeV. This mass range is favored by the LHC search for Higgs bosons after considering theoretical uncertainties [?, ?]. $Second, weutilizethelatestresultoftheXENON100experimenttolimitthemodels(at90.$ We calculate the scattering cross-section of dark matter with nucleons using the formula presented in [?]$, and we set $f_{T_s} = 0.020$, with f_{T_s} denoting the strange quark content in the nucleon. Third, we consider the constraints from the recent LHCb measurement of $B_s \to \mu^+\mu^-$, which gives $\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$ [?]$. The agreement of the measurement with its SM prediction strongly limits the combination $\tan^6\beta/M_A^4$ in the MSSM [?]$. Fourth, we also consider the constraint from the CMS search for non-SM Higgs bosons in the channel $H/A \to \tau^+\tau^-$ [?]$. This search, like $B_s^0 \to \mu^+\mu^-$, is very powerful in limiting the $\tan\beta - M_A$ plane in the MSSM.

Finally, we emphasize that in our scan we require the MSSM, NMSSM, and nMSSM to explain the muon $g-2$ at the 2σ level, i.e., $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (25.5 \pm 8.0) \times 10^{-10}$ [?]$. As for the CMSSM, it has long been noticed that there exists tension in predicting a 125 GeV SM-like Higgs boson while simultaneously explaining the muon $g-2$ \cite{50-52}$. In our calculation we consider the latest LHC bounds on the $M_0 - M_{1/2}$ plane of the CMSSM and find that under such bounds the CMSSM cannot explain the muon $g-2$ at the 2σ level. Therefore, we do not require the CMSSM to explain the muon $g-2$ at the 2σ level in our analysis.

In Fig. 1 we project the surviving samples onto the plane of the $Z\gamma$ signal rate at the LHC versus the SM-like Higgs boson mass in the four SUSY models. We also show the CMS bound on the rate in the figure [?]$. From the left panel we see that compared with its SM prediction, the $Z\gamma$ rate in the MSSM and the NMSSM can be either enhanced or suppressed, with maximal deviations reaching 20% and 60%, respectively. In contrast, as shown in the right panel, the $Z\gamma$ rate is always slightly suppressed (by less than 5%) in the CMSSM and severely suppressed (by more than 90%) in the nMSSM. We have checked that for the CMSSM and MSSM, the suppression is mainly due to the increase of the $h \to b\bar{b}$ partial width [?, ?]$. For the nMSSM, however, it is due to the opening of new decays $h \to \chi^0\chi^0, a_1 a_1$ (χ^0 and a_1 denote the dark matter and lightest CP-odd Higgs boson, respectively), which significantly enlarges the total width of the Higgs boson and leads to severe suppression for all visible decay channels.

[Figure 1: see original paper]

For the samples shown in Fig. 1, we also compare their predictions on the $\gamma\gamma$ and ZZ^* signal rates of the Higgs boson with the corresponding experimental data. We find that for most of the samples in the MSSM and the NMSSM, and for all samples in the CMSSM, their theoretical predictions on the $\gamma\gamma$ and ZZ^* rates agree with the data at the 3σ level, while for samples in the nMSSM, their predictions always lie outside the 3σ regions (see Fig. 1 and Fig. 2 in [?]$). Moreover, we have checked that the branching ratio of $h \to b\bar{b}$ in the MSSM, NMSSM, and CMSSM varies in the ranges [57%, 69%], [32%, 67%], and [60%, 63%], respectively (in the SM its value is about 57% for $m_h \simeq 125.5$ GeV), and the signal strength for the process $pp \to Vh \to Vb\bar{b}$ normalized by its SM value varies from 0.97 to 1.12, 0.55 to 1.05, and 1.00 to 1.02, respectively. Considering that so far the only way to detect the $h \to b\bar{b}$ decay at the LHC is through the Vh associated production, whose signal strength is $\mu_{Vb\bar{b}} = -0.4 \pm 1.0$ from ATLAS [?]$ and $\mu_{Vb\bar{b}} = 1.0 \pm 0.49$ from CMS [?]$, one can conclude that such alterations of $b\bar{b}$ signal rates are allowed by current experimental data at the 2σ level.

Next we focus on the MSSM and the NMSSM. In Fig. 2 we exhibit the contributions of different sparticles to the amplitude of the $h \to Z\gamma$ decay. Since sbottoms and charged Higgs bosons have little effect on the amplitude, we do not show their contributions. This figure shows the following features: (1) In the MSSM, the potentially largest contribution comes from stau loops, which can alter the SM amplitude by about 10%. In contrast, the stop contribution is small, typically changing the amplitude by less than 3%. This feature can be well understood from the formulae listed in the Appendix. Explicitly, in order to obtain a significant sfermion contribution, one necessary condition is that $Y_{hLR} \sin 2\theta_{\tilde{f}}/m^2_{\tilde{f}_1}$ should be as large as possible, where Y_{hLR} denotes the chiral-flipping coupling of the Higgs to sfermions, $\theta_{\tilde{f}}$ is the chiral mixing angle, and $m_{\tilde{f}_1}$ represents the lighter sfermion mass. As far as the stop sector is concerned, a relatively light $\tilde{t}_1$ is always accompanied by a heavy $\tilde{t}_2$ in order to predict $m_h \simeq 125$ GeV. Although A_t in this case may be very large, the chiral mixing angle $\theta_{\tilde{t}}$ is usually small, and consequently the stop contribution can never be significantly enhanced. In the stau sector, however, both parameters M_{L_3} and M_{E_3} are unlimited, and one can choose light staus and an appropriate $\theta_{\tilde{\tau}}$ to maximize the contribution. In this process, the value of $\mu \tan\beta$ and the splitting between M_{L_3} and M_{E_3} play an important role. It is worth noting that a light stau with mass close to the dark matter may co-annihilate with the dark matter, which helps avoid overabundance of dark matter in today' s universe [?, ?]$.

(2) In the MSSM, the chargino contribution is small and can only reach 3% and 0.5% for the $R_{\gamma\gamma} < 1$ case and $R_{\gamma\gamma} > 1$ case, respectively. The reason is that in the MSSM, the $H_i^0 \tilde{H}^{\pm} \tilde{W}^{\mp}$ coupling (where $i = u, d$ and $\tilde{H}$ and $\tilde{W}$ denote Higgsino and Wino, respectively) is induced by the $H_i^0 \bar{H} W$ interaction, and this coupling strength is maximized when both the Higgsino and Wino components of $\chi_1^{\pm}$ are sizable. We have checked that for most of the $R_{\gamma\gamma} > 1$ samples, $M_2 \leq 700$ GeV and $\mu > 800$ GeV (a large μ is needed for the stau contribution to enhance the diphoton rate [?]$), so that $\chi_1^{\pm}$ is basically Wino-like. Consequently, its coupling to the

Higgs boson is weak.

(3) In the NMSSM, the largest SUSY contribution to the $Z\gamma$ decay comes from chargino loops, with the correction reaching 6% in the optimal case, while the magnitude of the stau contribution is always smaller than 1%. This is because in the NMSSM with large λ, μ is preferred to vary from 100 GeV to 250 GeV and $\tan\beta$ is usually smaller than 10 [?]$. As a result, the $h\bar{\chi}_1^\pm\chi_1^\pm$ coupling is relatively large, while the $h\tilde{\tau}_L^*\tilde{\tau}_R$ coupling cannot be pushed up by moderate $\mu\tan\beta$. Due to the singlet component of h in the NMSSM, the $hb\bar{b}$ coupling can be greatly suppressed (reaching 40% according to our results), so that the total width of h is reduced by about 50% in extreme cases [?]$. Consequently, even when the SUSY contributions to the decay width are small, $R_{Z\gamma}$ can still be quite large. As mentioned before, such a suppressed $hb\bar{b}$ coupling can reduce the normalized strength of the process $pp \to Vh \to Vb\bar{b}$ down to 0.55, which, however, is still compatible with current LHC data due to the large uncertainty of the measured signal strength ($\mu_{Vb\bar{b}} = -0.4 \pm 1.0$ from ATLAS [?]$ and $\mu_{Vb\bar{b}} = 1.0 \pm 0.49$ from CMS [?]$).

[Figure 2: see original paper]

In Fig. 3 we show the correlation of the amplitudes for $h \to Z\gamma$ and $h \to \gamma\gamma$. This figure indicates that in both the MSSM and the NMSSM, the top squark contribution to the amplitude of $h \to Z\gamma$ correlates roughly linearly with that of $h \to \gamma\gamma$, as does the chargino contribution. Fig. 3 also indicates that the correlation is spoiled for the stau contribution in the MSSM. We have checked that this is because θ_τ in the MSSM can vary over a broad range and the dependence of the two amplitudes on θ_τ is quite different. For example, in the case $M_{L_3} \simeq M_{E_3}$, $\theta_\tau \simeq \pi/4$ and both $Z\tilde{\tau}_1^*\tilde{\tau}_2$ and $h\tilde{\tau}_i^*\tilde{\tau}_i$ couplings approach zero by accidental cancellation. As a result, the stau contribution to the decay $h \to Z\gamma$ is suppressed. In contrast, the contribution to the decay $h \to \gamma\gamma$ is maximized since it is proportional to $\sin 2\theta_\tau$. On the other hand, if $|M_{L_3}^2 - M_{E_3}^2| \gg m_\tau\mu\tan\beta$ so that $\theta_\tau \to 0$, the contributions are suppressed for both decays because the dominant contribution to $Z\tilde{\tau}_1^*\tilde{\tau}_2$ coupling and that to $h\tilde{\tau}_i^*\tilde{\tau}_i$ coupling are both proportional to $\sin 2\theta_\tau$.

[Figure 3: see original paper]

Since $R_{Z\gamma}$ is mainly determined by the partial width of $h \to Z\gamma$ and the total width of the SM-like Higgs boson, we present in Fig. 4 the ratio of $\Gamma_{Z\gamma}^{\rm SUSY}$ versus the total width ratio for the two models. The left panel indicates that for almost all MSSM samples, the $Z\gamma$ partial width and the total width of the SM-like Higgs boson are larger than the corresponding SM predictions. These features originate from the constructive contributions of SUSY particles to $h \to Z\gamma$ and the enhanced width of $h \to b\bar{b}$, respectively. Interestingly, the largest increase of $\Gamma_{Z\gamma}$ occurs when $\Gamma_{\rm tot}^{\rm SUSY} \simeq \Gamma_{\rm tot}^{\rm SM}$. The right panel indicates that in order to enhance the $Z\gamma$ signal in the NMSSM with large λ (note that in this model

$R_{Z\gamma}$ correlates roughly linearly with $R_{\gamma\gamma}$, see Fig. 5), the SM-like Higgs boson tends to have a sizable singlet component to suppress the total width. In this case, $\Gamma_{Z\gamma}$ is suppressed too, but we have $\Gamma_{Z\gamma}^{\rm SUSY} > \Gamma_{Z\gamma}^{\rm SM}$. Moreover, as mentioned before, $\Gamma_{Z\gamma}$ can be slightly enhanced by the chargino contribution.

[Figure 4: see original paper]

Now we investigate the correlation of the $Z\gamma$ rate with the $\gamma\gamma$ rate in different SUSY models, which is shown in Fig. 5. From this figure we draw the following conclusions: (a) In the MSSM, although the partial width of $h \to Z\gamma$ can be enhanced by 20% (see Fig. 4), due to the increase of the Higgs total width and also the suppression of the hgg coupling [**?**]\$, the maximal value of $R_{Z\gamma}$ is only 1.1 (in comparison, $R_{\gamma\gamma}$ may be as large as 2), and only when $R_{\gamma\gamma} \gtrsim 1.25$ can $R_{Z\gamma} > 1$ be possible. Among the sparticle contributions to $R_{Z\gamma}$ and $R_{\gamma\gamma}$, the stau loops play the dominant role. The difference between the two signals comes from their dependence on θ_τ: when $\theta_\tau \simeq \pi/4$, $R_{\gamma\gamma}$ is maximized while $R_{Z\gamma}$ is suppressed. Our numerical results also indicate that for the surviving samples of the MSSM, the branching ratio of the invisible decay $h \to \chi^0\chi^0$ is usually smaller than 6% and 3% for the $R_{\gamma\gamma} < 1$ and $R_{\gamma\gamma} > 1$ cases, respectively, and the branching ratio of $h \to b\bar{b}$ varies from 57% to 69%.

(b) In the NMSSM with large λ, the sparticle corrections to the amplitudes of $h \to Z\gamma$ and $h \to \gamma\gamma$ are usually below 10%, and the main mechanism to alter $R_{Z\gamma}$ and $R_{\gamma\gamma}$ is through the suppression of the $hb\bar{b}$ and hW^+W^- couplings by the singlet component of h. As a result, $R_{Z\gamma}$ and $R_{\gamma\gamma}$ are highly correlated and both vary from 0.2 to 2. We have checked that the branching ratios of the exotic decays $h \to \chi^0\chi^0$, a_1a_1 may reach 22% and 45%, respectively (these extreme cases correspond to some of the squared points in Fig. 5 of [**?**]\$), and the branching ratio of the decay $h \to b\bar{b}$ varies in a large range, from 32% to 67%.

(c) In the CMSSM and nMSSM, $R_{Z\gamma}$ and $R_{\gamma\gamma}$ are slightly and strongly suppressed, respectively. As discussed before, in the CMSSM the suppression is due to the increase of the $h \to b\bar{b}$ partial width, while in the nMSSM it is due to the opening of the exotic decay channels $h \to \chi^0\chi^0$, a_1a_1.

Note that the opening of exotic decays $h \to \chi^0\chi^0$, a_1a_1 will generally lead to suppression of visible signal rates such as $R_{\gamma\gamma}$ and R_{ZZ^*}, and as analyzed in [**?**], $thelatestHiggsdatarequirethatthetotalbranchingratioofexoticdecaysshouldbelessthan28$). For the decay $h \to a_1a_1$ in the NMSSM, we have checked that m_{a_1} varies from about 20 GeV to 60 GeV, and a_1 mainly decays to $b\bar{b}$ (with a branching ratio of about 90%) and $\tau\bar{\tau}$ (with a branching ratio of about 9%). Therefore, in this case the decay product of the Higgs boson is four b-jets, or four τ leptons, or two b-jets plus two τ leptons, which is an interesting but challenging signal in Higgs searches at the LHC [**?**]\$. Since m_{a_1} is usually heavier than Υ, the constraint from the decay $\Upsilon \to a_1\gamma$ [**?**]\$ is irrelevant here. Also note that generally speaking, constrained models such as the CMSSM tend to predict strong correlations among observables due to the unified nature of their parameters. This is clearly shown in Fig. 5 for the CMSSM in comparison with the other three models.

Since the e^+e^- collider at $\sqrt{s} \sim 250$ GeV provides a clean environment to detect the decays $h \to Z\gamma$ and $h \to b\bar{b}$, we also investigate their rates at the ILC as defined in Eq. (11) and Eq. (12). The corresponding results are shown in Fig. 6. This figure exhibits the following features: (a) In the MSSM, a suppressed $Z\gamma$ signal (compared with its SM prediction) tends to correspond to an enhanced $b\bar{b}$ signal, and an enhanced $Z\gamma$ signal requires the $b\bar{b}$ signal rates to be roughly at their SM prediction. In any case, the enhancement factor for both signals is less than 1.2. Note that there exist a few cases where the $b\bar{b}$ signal rate is slightly suppressed. (b) In the NMSSM with large λ, the normalized $b\bar{b}$ signal rate is less than 1.1, and in some cases it may be significantly suppressed. In contrast, the $Z\gamma$ signal rate can be either greatly enhanced or severely suppressed. In the enhancement case, the $b\bar{b}$ signal rate is usually less than its SM prediction, and greater enhancement corresponds to stronger suppression. (c) In the CMSSM, both signal rates are roughly equal to their SM predictions. In the nMSSM, however, both rates are strongly suppressed.

Moreover, we have checked that the $\gamma\gamma$ signal rate at the ILC has similar dependence on the $b\bar{b}$ rate for the four models.

[Figure 5: see original paper]

[Figure 6: see original paper]

IV. Conclusion

In this work, we investigate the rare decay of the SM-like Higgs boson, $h \to Z\gamma$, and study its correlation with $h \to \gamma\gamma$ in the MSSM, NMSSM, nMSSM, and CMSSM. We perform a scan over the parameter space of each model by considering various experimental constraints and present our results on various planes. We have the following observations: (i) In SUSY models, the sparticle correction to the rare decay $h \to Z\gamma$ is usually several times smaller than that to $h \to \gamma\gamma$. (ii) In the MSSM, the net SUSY contribution to the amplitude of $h \to Z\gamma$ is constructive with the corresponding SM amplitude and can enhance the SM prediction by at most 10%. As a result, the $Z\gamma$ signal rates at the LHC and the ILC can be enhanced by at most 20%. In comparison, the $\gamma\gamma$ rate can be enhanced by a factor of 2 due to large stau contributions. (iii) In the CMSSM, due to the slightly enhanced total width of the SM-like Higgs boson, the $Z\gamma$ signal rates at the LHC and the ILC are both slightly below their SM predictions, as is the $\gamma\gamma$ signal. (iv) In the NMSSM with large λ, the SUSY corrections to the amplitudes for the decays $h \to Z\gamma$ and $h \to \gamma\gamma$ are at most 10%, and to obtain significant deviation of the two rates from their SM values, the total width of the SM-like Higgs boson must be moderately suppressed by the singlet component of h. In this model, the two rates are highly correlated and vary from 0.2 to 2. (v) In the nMSSM, the signal rates of $h \to Z\gamma$ and

$h \to \gamma\gamma$ are both greatly suppressed due to the opening of the exotic decays $h \to \chi^0\chi^0$, $a_1 a_1$.

Finally, we note that some strategies have been proposed in the literature to discriminate the considered models, e.g., via correlations between Higgs couplings [?]$, via enhanced Higgs pair production at the LHC$[?] and the ILC [?]$, or via direct dark matter detection$[?]. Compared with these existing strategies, the loop-induced $Z\gamma$ and $\gamma\gamma$ decay modes of the Higgs boson seem to be more sensitive to the nature of the models (some non-SUSY models predict rather different correlation behavior [?]\$). Therefore, the correlation between $Z\gamma$ and $\gamma\gamma$ rates analyzed in this work may play a complementary role in discriminating new physics models in the future.

Note added: After we finished this work, both the ATLAS and CMS collaborations updated their Higgs search results [?, ?]$. Among these new results, the CMS data on the diphoton signal rate ch$ Since in our analysis we did not use the diphoton data as a constraint (instead we just displayed the predictions for the diphoton signal rate in different SUSY models), our results and conclusions are not affected by the new data.

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Appendix

In SUSY, the decays $h \to Z\gamma$ and $h \to \gamma\gamma$ receive new contributions from loops mediated by charged Higgs bosons, sfermions (including stops, sbottoms, and staus), and charginos. Consequently, the formulas for $\Gamma_{Z\gamma}$ and $\Gamma_{\gamma\gamma}$ are modified:

$$\Gamma(h \to Z\gamma) = \frac{G_F m_h^3 \alpha}{64\sqrt{2}\pi^4}\left(1 - \frac{m_Z^2}{m_h^2}\right)^3 \left|A_W^{Z\gamma} + A_t^{Z\gamma} + A_{\tilde{f}}^{Z\gamma} + A_{H^\pm}^{Z\gamma} + A_{\chi^\pm}^{Z\gamma}\right|^2,$$

$$\Gamma(h \to \gamma\gamma) = \frac{G_F m_h^3 \alpha^2}{128\sqrt{2}\pi^4}\left|A_W^{\gamma\gamma} + A_t^{\gamma\gamma} + A_{\tilde{f}}^{\gamma\gamma} + A_{H^\pm}^{\gamma\gamma} + A_{\chi^\pm}^{\gamma\gamma}\right|^2,$$

where A_i $(i = W, t, \tilde{f}, H^\pm, \chi^\pm)$ denote the contributions from particle i mediated loops. The expressions for $A_i^{\gamma\gamma}$ are relatively simple and are given by:

$$A_W^{\gamma\gamma} = g_{hVV} A_1(\tau_W), \quad A_t^{\gamma\gamma} = g_{ht\bar{t}} N_c Q_t^2 A_{1/2}(\tau_t),$$

$$A_{H^\pm}^{\gamma\gamma} = g_{hH^+H^-} A_0(\tau_{H^\pm}), \quad A_{\tilde{f}}^{\gamma\gamma} = \sum_{\tilde{f}} g_{h\tilde{f}_i\tilde{f}_i} N_c Q_{\tilde{f}}^2 A_0(\tau_{\tilde{f}_i}),$$

$$A_{\chi^\pm}^{\gamma\gamma} = \sum_{i=1,2} g_{h\chi_i^\pm\chi_i^\pm} A_{1/2}(\tau_{\chi_i^\pm}),$$

where $\tau_i = 4m_i^2/m_h^2$, g_{hXY} denotes the Higgs coupling with particles XY, and A_0, $A_{1/2}$, and A_1 are loop functions with scalars, fermions, and gauge bosons running in the loop. The explicit expressions of g_{hXY} and A functions are given by:

$$g_{hVV} = S_{h1}\sin\beta + S_{h2}\cos\beta, \quad g_{ht\bar{t}} = \frac{S_{h1}}{\sin\beta},$$

$$g_{h\tilde{f}_1\tilde{f}_1} = \sqrt{2}G_F^{1/2}(Y_{hLL}\cos^2\theta_{\tilde{f}} + Y_{hRR}\sin^2\theta_{\tilde{f}} + Y_{hLR}\sin 2\theta_{\tilde{f}}),$$

$$g_{h\tilde{f}_2\tilde{f}_2} = \sqrt{2}G_F^{1/2}(Y_{hLL}\sin^2\theta_{\tilde{f}} + Y_{hRR}\cos^2\theta_{\tilde{f}} - Y_{hLR}\sin 2\theta_{\tilde{f}}),$$

$$g_{hH^+H^-} = \sqrt{2}G_F^{1/2}\left[v_s(\Pi_{11}^{h_3} + \Pi_{22}^{h_3}) - v_u\Pi_{12}^{h_2} - v_d\Pi_{12}^{h_1}\right],$$

$$g_{h\chi_i^\pm\chi_i^\pm} = \sqrt{2}G_F^{1/2}(S_{h1}U_{i1}V_{i2} + S_{h2}U_{i2}V_{i1}),$$

where S is the 2×2 (3×3) rotation matrix of the MSSM (NMSSM) Higgs mass matrix under the basis (H_d^0, H_u^0, S), h in S_{h1} denotes the row index of the SM-like Higgs, Y_{hXY} denotes the SM-like Higgs coupling to sfermion interaction states, U and V denote the rotation matrices of the chargino mass matrix, and the loop functions are defined as:

$$A_0(x) = -x^2\left[x^{-1} - f(x^{-1})\right], \quad A_{1/2}(x) = 2x^2\left[x^{-1} + (x^{-1}-1)f(x^{-1})\right],$$

$$A_1(x) = -x^2\left[2x^{-2} + 3x^{-1} + 3(2x^{-1}-1)f(x^{-1})\right],$$

with $f(x) = \arcsin^2\sqrt{x}$.

As for $A_i^{Z\gamma}$, due to $m_Z \neq 0$ and the existence of ZXY $(X \neq Y)$ couplings, their expressions are rather complex:

$$A_W^{Z\gamma} = g_{hVV} c_W A_1(\tau_W, \lambda_W), \quad A_t^{Z\gamma} = g_{ht\bar{t}} N_c Q_t \hat{v}_t A_{1/2}(\tau_t, \lambda_t),$$

$$A_{H^\pm}^{Z\gamma} = g_{hH^+H^-} v_{H^\pm} A_0(\tau_{H^\pm}, \lambda_{H^\pm}),$$

$$A_{\tilde{f}}^{Z\gamma} = \sum_{\tilde{f}} g_{h\tilde{f}_i\tilde{f}_i} N_c Q_{\tilde{f}} v_{\tilde{f}_i} A_0(\tau_{\tilde{f}_i}, \lambda_{\tilde{f}_i}) - \sum_{\tilde{f}} g_{h\tilde{f}_1\tilde{f}_2} N_c Q_{\tilde{f}} v_{\tilde{f}_{12}} \left(A_0^{(1)} + A_0^{(2)}\right),$$

$$A_{\chi^\pm}^{Z\gamma} = \sum_{i=1,2} g_{h\chi_i^\pm\chi_i^\pm} v_{\chi_i^\pm} A_{1/2}(\tau_{\chi_i^\pm}, \lambda_{\chi_i^\pm}) + \sum_{i\neq j} g_{h\chi_i^\pm\chi_j^\pm} v_{\chi_{ij}^\pm} A_{1/2}^{(i,j)},$$

where $\lambda_i = 4m_i^2/m_Z^2$ and the coupling coefficients of h and Z are given by:

$$v_{\tilde{f}_i} = \frac{T_f^3 \cos^2\theta_{\tilde{f}} - Q_f s_W^2}{c_W}, \quad v_{\tilde{f}_{12}} = \frac{(Y_{hRR} - Y_{hLL})\sin 2\theta_{\tilde{f}} + Y_{hLR}\cos 2\theta_{\tilde{f}}}{2c_W},$$

$$\hat{v}_t = \frac{2T_t^3 - 4Q_t s_W^2}{c_W}, \quad v_{H^\pm} = \frac{c_W^2 - s_W^2}{c_W},$$

$$v_{\chi_i^\pm} = \frac{V_{i1}^2 + \frac{1}{2} - 2s_W^2}{2c_W}, \quad v_{\chi_{ij}^\pm} = \frac{V_{i1}V_{j1}}{2c_W},$$

with similar expressions for the U matrix elements. In the above formula, we have defined new functions:

$$A_0^{(1)} = 4m_{\tilde{f}_1} m_{\tilde{f}_2} C_{23}^{(1)}, \quad A_0^{(2)} = 4m_{\tilde{f}_1} m_{\tilde{f}_2} C_{23}^{(2)},$$

$$A_{1/2}^{(i,j)} = 2m_{\chi_i^\pm} m_{\chi_j^\pm} \left(2C_{23}^{(3)} + C_{23}^{(4)}\right),$$

where C_{ij} denote three-point loop functions introduced in [**?**]$, and the superscripts indicate different mass orderings. For the special cases considered here, these functions can be expressed in terms of standard Passarino-Veltman functions.

The other functions relevant to our calculation are defined by:

$$A_0(x,y) = I_1(x,y), \quad A_{1/2}(x,y) = I_1(x,y) - I_2(x,y),$$

$$A_1(x,y) = 4(3 - \tan^2\theta_W) I_2(x,y) + \left[(1 + 2x^{-1})\tan^2\theta_W - (5 + 2x^{-1})\right] I_1(x,y),$$

with:

$$I_1(x,y) = \frac{2}{x-y}\left[f(x^{-1}) - f(y^{-1})\right], \quad I_2(x,y) = \frac{1}{(x-y)^2}\left[g(x^{-1}) - g(y^{-1})\right] - \frac{1}{x-y}\left[f(x^{-1}) - f(y^{-1})\right],$$

and $g(z) = z^{-1} - 1 - f(z)$.

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