Simultaneous enhancement in $\gamma\gamma$, $b\bar{b}$ and $\tau^+\tau^-$ rates in the NMSSM with nearly degenerate scalar and pseudoscalar Higgs bosons

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Abstract

We propose an experimental test of a scenario in the Next-to-Minimal Supersymmetric Standard Model in which both the lightest scalar and the lightest pseudoscalar Higgs bosons have masses around 125 GeV. The pseudoscalar can contribute significantly to the $\gamma\gamma$ rate at the LHC due to light Higgsino-like charginos in its effective one-loop coupling to two photons. Such charginos are obtained for small values of the $\mu_{\text{eff}}$ parameter which also results in enhanced $b\bar{b}$ and $\tau^+\tau^-$ rates compared to those expected for a Standard Model Higgs boson. This scenario should result in a clear discrepancy between the observed rates in these three decay channels and those in the $WW$ and $ZZ$ channels, since the pseudoscalar does not couple to the $W$ and $Z$ bosons. However, in the dominant gluon fusion production mode the pseudoscalar will stay hidden behind the SM-like scalar Higgs boson and in order for it to be observable the associated $b\bar{b}h$ production mode has to be considered, the cross section for which is tiny in the Standard Model but $\tan\beta$-enhanced in supersymmetry. We analyze the constrained NMSSM with non-universal Higgs sector parameters and identify regions of its parameter space where the lightest pseudoscalar with mass around 125 GeV and strongly enhanced $\gamma\gamma$ (up to 60%), $b\bar{b}$ and $\tau^+\tau^-$ rates in the $b\bar{b}h$ mode can be obtained.

1 Introduction

Since its discovery at the LHC in July 2012 [1, 2], the CMS and ATLAS collaborations have accumulated more data and updated their results on the Higgs boson. In the early results, a considerable enhancement in the $\gamma\gamma$ and $ZZ$ rates compared to the Standard Model (SM) prediction was noted near $\sim 125$ GeV at the ATLAS detector. According to the CMS data, the signal strength, $\sigma/\sigma_{\text{SM}}$, was consistent with the SM prediction in the $ZZ$ channel but an enhancement in the $\gamma\gamma$ channel was observed there as well. However, the figures from both experiments have changed in the latest results released after the collection of $\sim 20$/fb of data [3, 4]. The signal strengths measured

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by the CMS have now fallen down to SM-like values, 0.78 ± 0.27 and 0.91±0.30 in the γγ and ZZ
decay channels, respectively, with the mean value of the boson being 125.6 ± 0.64 GeV.

The ATLAS collaboration, on the other hand, still reports sizable excesses, σ/σ_{SM} = 1.65±0.35
in the γγ channel with the mass measurement yielding 126.8 ± 0.73 GeV, and σ/σ_{SM} = 1.7 ± 0.5
in the ZZ channel with mass at 124.3±0.4 GeV. Moreover, broad peaks consistent with a 125 GeV
boson have now also been observed in the \( H \to WW \to 2l2\nu \) channel in the two detectors. Importantly, the best-fit signal strength in this channel is SM-like according to both CMS and ATLAS, with a measured value of 0.76 ± 0.21 at the former and of 1.01 ± 0.31 at the latter. In the \( bb \) decay channel, although no significant excess has been observed above the SM background at
either CMS or ATLAS, fitted signal strength values at \( m_h = 125 \) GeV have been obtained by the
two collaborations for some individual Higgs boson production modes. The best-fit values provided
by the CMS collaboration read 0.7 ± 1.4 for vector boson fusion (VBF), 1.0±0.5 for Higgs-strahlung
off a vector boson (\( Wh/Zh \)) and 0.74±1.34 for associated production off top quarks (\( t\bar{t}h \)). The
ATLAS collaboration has recently provided a fitted value of 0.2 ± 0.64 for the \( Wh/Zh \) production
mode only. In the \( \tau^+\tau^- \) channel an excess of events over a broad \( m_h \) range was reported by the
CMS collaboration with a best-fit \( \sigma/\sigma_{SM} = 1.1 ± 0.4 \) at 125 GeV. At ATLAS, however, no excess
has so far been observed in this channel also and a fitted value at \( m_h = 125 \) GeV, which is SM-like
but with a very large error, can be noted in [5]. We should point out here that neither of the two
 collaborations have provided any measurements of the signal strength in the \( bb \) and \( \tau^+\tau^- \) decay
channels for associated Higgs boson production off bottom quarks (\( bbh \)).

Since the first announcements of the discovery of the boson, there have been many attempts to
interpret the observed data in light of various supersymmetric (SUSY) extensions of the SM [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. In the context of the Minimal Supersymmetric Standard Model (MSSM)
the observed signal can be interpreted as being due to the lightest Higgs boson of the model, \( h \). In
the MSSM constrained at the grand unification theory (GUT) scale, referred to as the CMSSM [16],
\( h \) can attain a mass around the measured central value only if the SUSY-breaking scale, \( M_{\text{SUSY}} \), is
close to or larger than 1 TeV, while also satisfying other important phenomenological constraints.
In the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [17, 18] (see, e.g., [19, 20] for
recent reviews) it has been shown that either of the two lightest CP-even Higgs bosons, \( h_1 \) and \( h_2 \),
can easily be SM-like with mass around 125 GeV [21, 22]. In fact in this model it is possible to have
\( h_1 \) and \( h_2 \) almost degenerate in mass around 125 GeV [10], so that the observed signal is actually a
superposition of two individual peaks due to each of these, which cannot be independently resolved.

In the GUT-constrained version of the NMSSM (CNMSSM) [18, 23, 24, 25], in analogy with the
CMSSM, it has been found that in order to obtain \( h_1 \) as heavy as 125 GeV, \( M_{\text{SUSY}} \) at or above 1 TeV
is needed even with relevant phenomenological constraints imposed [14]. Alternatively, a SM-like
\( h_2 \) with mass \( \sim 125 \) GeV is easily achievable [14]. Relaxing slightly the universality conditions by
disunifying the masses of the scalar Higgs doublets \( m_{H_u} \) and \( m_{H_d} \) from the scalar mass parameter
\( m_0 \) and the soft Higgs trilinear coupling parameters \( A_\lambda \) and \( A_\kappa \) from the unified soft Yukawa
coupling \( A_0 \), makes it relatively easy to obtain SM-like \( h_1 \) or \( h_2 \) around 125 GeV [26]. Here we refer
to such a model with non-universal Higgs sector parameters as CNMSSM-NUHM. The scenario
with mass degenerate \( h_1 \) and \( h_2 \) satisfying also other phenomenological constraints has also been
pursued with much interest in the CNMSSM-NUHM [10, 12].

Even though the latest results from CMS seem to favor a SM-like Higgs boson, those from
ATLAS do so only partially and it is still possible for the observed boson to be a non-standard one. The
inconsistencies between the various measurements and fluctuations in the data leave ample
room for speculation in this regard. Therefore, in this article, we propose an experimental test of a
scenario, not investigated hitherto, in which the lightest pseudoscalar, \( a_1 \), of the NMSSM is almost
degenerate in mass with the lightest $\sim$125 GeV scalar, $h_1$. Such $a_1$ can have a sizeable one-loop effective coupling to $\gamma\gamma$ in the presence of a light Higgsino-like chargino in the loop. Thus with decreasing mass of such a chargino one should expect a rise in the signal rate defined, for a general Higgs boson $h_i$, as

$$R_X^V(h_i) = \frac{\sigma(Y \to h_i)}{\sigma(Y \to h_{\text{SM}})} \times \frac{BR(h_i \to X)}{BR(h_{\text{SM}} \to X)},$$

(1)

where $h_{\text{SM}}$ is a SM Higgs boson with the same mass as $h_i$ and $X$ denotes any one of its allowed SM decay channels. $Y$ stands for the various possible Higgs boson production modes at the LHC, which include gluon fusion ($ggh$), VBF, $Wh/Zh$ and $tth/bbh$. However, for $X = \gamma\gamma$, despite the non-negligible size of the second term in the product on the right hand side of Eq. (1), no net enhancement in the $\gamma\gamma$ rate of $a_1$ with decreasing chargino mass would be visible in the $ggh$ production mode. The reason is that the first term in the product always has a very small magnitude due to a highly reduced effective coupling of $a_1$ to two gluons compared to that of a SM Higgs boson, which is dominated by the top quark loop, thus nullifying the overall effect.

The overall enhancement in $R_X^V(a_1)$ due to a light chargino should instead be visible in the $bbh$ production mode since, as we shall see, the conditions necessary to obtain a light chargino also result in an enhanced coupling of $a_1$ to $bb/\tau^+\tau^-$. In fact, one should thus obtain a simultaneous enhancement in the signal rates of the three channels, $\gamma\gamma$, $bb$ and $\tau^+\tau^-$ (collectively referred to as $X$ henceforth). We point out here that, while the enhancement in the $bb$ and $\tau^+\tau^-$ channels only is in principle possible even with a light MSSM-like scalar Higgs boson for large $\tan\beta$, the above ‘triple enhancement’ should be a clear signature of our proposed scenario. For this reason we shall investigate $bbh$ Higgs production mode here, emphasizing the importance of a measurement of the signal rate in this mode, which is very subdominant for a SM Higgs boson and is therefore generally considered to be of less interest. In contrast, in SUSY it is enhanced by $\tan^2\beta$ [27] and can therefore be potentially very interesting.

In the $bbh$ channel, the $a_1$ could be partially responsible for a net enhancement in the signal rate, $R_{X}^{bb}(\text{obs})$, in the $X$ decay channels measured at the LHC. However, being a pseudoscalar, it would not contribute to the $WW$ and $ZZ$ channels (denoted collectively by $V$), so that, assuming $h_1$ to be exactly SM-like,

$$R_{X}^{bb}(\text{obs}) \equiv \frac{\sigma_{bb}^{X}(\text{obs})}{\sigma_{bb}(h_{\text{SM}})} = R_{X}^{bb}(h_1) + R_{X}^{bb}(a_1) \simeq 1 + R_{X}^{bb}(a_1) \quad \text{and} \quad R_{V}^{bb}(\text{obs}) = R_{V}^{bb}(h_1) \simeq 1.$$  

(2)

Furthermore, a difference in the mass measurements in the $X$ and $V$ modes would also provide a hint for mass degenerate $h_1$ and $a_1$. Such a degeneracy would imply that the signal observed in the $X$ channels should in fact be interpreted as the ‘sum’ of two individual peaks due to $h_1$ and $a_1$, while the peaks in the $V$ modes correspond to $h_1$ alone. $h_1$ is still SM-like in this scenario due to a significant singlet component even though $\tan\beta$ can take fairly large values [28]. Since this scenario is compatible with a SM-like scalar Higgs boson, it is also not in conflict with the recent CMS measurements in the $ZZ$ mode which disfavor the pure pseudoscalar hypothesis [29, 30].

We identify regions of the CNMSSM-NUHM parameter space where both $h_1$ and $a_1$ with masses around 125 GeV can be obtained, expecting that a discrepancy between $X$ and $V$ rates will be seen by CMS and ATLAS collaborations in a focussed analysis of the $bbh$ production mode. We further confine ourselves only to the regions where the above mentioned triple enhancement can be obtained, serving as a clear signature of this scenario. We investigate the impact of other important experimental constraints on these regions. These include the limits from direct SUSY

\[1\text{We note here that the VBF and } Wh/Zh \text{ production modes are irrelevant for a pseudoscalar Higgs boson.} \]
searches released by ATLAS with \( \sim 20/\text{fb} \) of data as well as from the dark matter (DM) relic density measurements. We also require the corresponding parameter space to satisfy the recently announced positive BR (B\(_s \rightarrow \mu^+\mu^-\)) measurement by the LHCb collaboration.

The article is organized as follows. In Sec. 2 we discuss the possibility of observing an enhancement in the \( \gamma\gamma \) and \( bb/\tau^+\tau^- \) rates at the LHC due to a \( \sim 125 \) GeV pseudoscalar Higgs boson. In Sec. 3 we define the model’s parameter space. In Sec. 4 we describe the experimental constraints applied in our scans, present our numerical results and discuss their salient features. We summarize our findings in Sec. 5.

## 2 Enhancement in the observed \( \gamma\gamma \) rate due to a light pseudoscalar

In this section we present some analytical details of the mentioned NMSSM scenario in which the correlation between the \( \gamma\gamma \) and \( WW/ZZ \) rates can be altered. One way to achieve this is with mass degenerate lightest doublet-like scalar Higgs, \( h_1 \), and lightest singlet-like pseudoscalar, \( a_1 \).

### 2.1 The pseudoscalar mass

We first discuss the conditions that are necessary to obtain a \( \sim 125 \) singlet-like \( a_1 \) which couples to two photons through loops of fermions and charginos only. Starting from the 2×2 pseudoscalar mass matrix (after rotating away the Goldstone mode) \([19]\), one can obtain the approximate expression,

\[
m_{a_1}^2 \simeq -3\kappa s A^{\text{SUSY}}_{\kappa} - \frac{M_{P,12}^4}{M_{P,11}^2}.
\]

In the above equation \( M_{P,12}^2 \simeq \lambda (A^{\text{SUSY}}_\lambda - 2\kappa s) v \) is the off-diagonal entry of the pseudoscalar mass matrix, where \( v \equiv \sqrt{v_u^2 + v_d^2} \simeq 174 \) GeV, with \( v_u \) and \( v_d \) being the vacuum expectation values (vevs) of the \( u \)-type and \( d \)-type Higgs doublets, respectively, and \( A^{\text{SUSY}}_{\lambda/\kappa} \) denoting \( A_{\lambda/\kappa} \) at \( M_{\text{SUSY}} \). \( M_{P,11}^2 \simeq \mu_{\text{eff}} B_{\text{eff}} \tan \beta \), with \( \mu_{\text{eff}} \equiv \lambda s \) (\( s \) being the vev of the singlet field \( S \)), \( B_{\text{eff}} \equiv A^{\text{SUSY}}_\lambda + \kappa s \) and \( \tan \beta \equiv v_u/v_d \), is the diagonal term corresponding to the mass-squared of the doublet-like heavy pseudoscalar, \( a_2 \). The leading term in Eq. (3) implies that, for positive \( \kappa \), which we will assume here, the condition of the positivity of \( m_{a_1}^2 \) depends predominantly on the relative signs of \( \mu_{\text{eff}} \) and \( A_{\kappa} \) at \( M_{\text{SUSY}} \). This condition thus has some important repercussions when \( A_{\kappa} \) and \( A_\lambda \) are taken as input parameters at the GUT scale. Assuming the leading term to be positive so that the correct \( m_{a_1} \) is achieved by adjusting the free parameters in it, the negative contribution from the second term should be kept close to zero. This would require \( M_{P,11}^2 \gtrsim M_{P,12}^2 \). We explain how this can be achieved for negative and positive \( \mu_{\text{eff}} \) in the following.

For \( \mu_{\text{eff}} < 0 \) (and therefore negative \( s \), assuming positive \( \lambda \)), the first term in Eq. (3) is positive if \( A_\kappa > 0 \) at \( M_{\text{SUSY}} \). In the second term \( M_{P,12}^2 \) is positive definite and \( M_{P,11}^2 \) must be positive for a non-tachyonic \( a_2 \), which requires \( B_{\text{eff}} < 0 \). For given \( \tan \beta \) and \( \mu_{\text{eff}} \), \( M_{P,11}^2 \) is driven by the magnitude of \( B_{\text{eff}} \), in order to enhance which \( A_\lambda \) should take smaller values (note that \( A_\lambda \) is bounded from above by \( \kappa |s| \)). However, \( A_\lambda \) at \( M_{\text{SUSY}} \) runs upwards from its GUT value with falling negative \( A_0 \) owing to the contribution from the relevant term in its renormalization group equation (RGE) \([19]\). Hence increasing negative \( A_0 \) diminishes the difference between the two terms in \( B_{\text{eff}} \), reducing its size and in turn driving \( M_{P,11}^2 \) closer to zero. At the same time \( M_{P,12}^2 \), which is a sum of \( 2\kappa |s| \) and \( A_\lambda \), grows as \( A_\lambda \) increases, as opposed to \( M_{P,11}^2 \). Consequently, the ratio \( \frac{M_{P,12}^2}{M_{P,11}^2} \) in Eq. (3) grows with decreasing \( A_0 \) and, for large negative values of the latter, can result in negative \( m_{a_1}^2 \).
Note also that the running of $A_\kappa$ in turn depends dominantly on $A_\lambda$. $A_\kappa$ runs upwards with $A_\lambda$ as long as the latter is negative. When $A_\lambda$ turns positive $A_\kappa$ runs in the opposite direction, owing to its RGE. Thus $A_\kappa$ in the leading term in Eq. (4) will have somewhat constrained GUT scale values that can yield correct $m_{a_1}$. On the other hand, for $\mu_{\text{eff}} > 0$, the two terms in $B_{\text{eff}}$ are both positive and the cancellation described above does not occur.

In summary, the net effect of the interplay between various Higgs sector parameters is that for negative $\mu_{\text{eff}}$ the values of $A_0$ at the GUT scale are bounded from below by the condition of the physicality of $a_1$. This constraint on $A_0$ causes a slight tension between $m_{h_1}$ and $m_{a_1}$, since it is well known that in order to obtain $h_1$ which is SM-like with mass $\sim 125$ GeV large negative values of $A_0$ are required for $M_{\text{SUSY}} \sim 1$ TeV. For positive $\mu_{\text{eff}}$ there is no such tension because $A_0$ is relatively free to take values that give large negative $A_t$ at $M_{\text{SUSY}}$, as long as the correct $a_1$ mass can be achieved by adjusting other free parameters.

### 2.2 $\gamma\gamma$ decay of the pseudoscalar

Besides a singlet-like $a_1$ with mass similar to that of the experimentally observed boson, this scenario also requires a low mass, $m_{\chi^\pm_1}$, of the lightest chargino. The effective coupling of a pseudoscalar $a_i$, with $i = 1, 2$, to two photons (see, e.g., [31, 32]), is dominated by a light chargino in the loops and can be approximated by

$$C_{\text{eff}}(\gamma\gamma) \simeq \frac{g_{a_1\chi^\pm_1\chi^\pm_1}}{\sqrt{2}G_F m_{\chi^\pm_1}} A_{1/2}^{a_1}(\tau_i),$$

where $\tau_i = \frac{m_{\chi^\pm_1}^2}{4m_{\chi^\pm_1}^2}$. For $\tau_i \leq 1$, which is applicable here, with $m_{a_i} \simeq 126$ GeV and the light chargino obeying the lower limit, $m_{\chi^\pm_1} > 94$ GeV [33], the form-factor $A_{1/2}^{a_i}(\tau_i) = \frac{1}{\tau_i} \arcsin^2 \sqrt{\tau_i}$ [34] in the above equation lies in the range

$$1 < A_{1/2}^{a_i}(\tau_i) \lesssim 1.2.$$  

The coupling of $a_i$ to charginos in Eq. (4) can be written, following the notation of [19], as

$$g_{a_1\chi^\pm_1\chi^\pm_1} = \frac{i}{\sqrt{2}} \left[ \lambda \frac{P_{13} \sin \theta_U \sin \theta_V - g_2 \sqrt{2} (P_{12} \cos \theta_U \sin \theta_V + P_{11} \sin \theta_U \cos \theta_V) - \sqrt{2} P_{14} \sin \theta_\beta \cos \theta_U \sin \theta_V}{\sqrt{2} \cos \theta_V} \right],$$

where $\theta_U$, $\theta_V$ are the mixing angles for rotating the chargino interaction states to mass eigenstates, and $P_{ij}$ are the entries of the mixing matrix that diagonalizes the pseudoscalar mass matrix. When the pseudoscalar weak eigenstates $A_i^{\text{weak}}$ are expressed in the basis $(H_{u1}, H_{u1}, S_I)$ [19], $P_{11}$ corresponds to $H_{u1}$, $P_{12}$ to $H_{u1}$ and $P_{33}$ to $S_I$, respectively.

The first term in Eq. (4) implies that $\sin \theta_{U,V} \simeq 1$ (yielding a Higgsino-like $\chi_1^\pm$), $P_{13} \simeq 1$ and that larger values of $\lambda$ are needed in order to enhance $C_{a_1}^{\text{eff}}(\gamma\gamma)$ for the singlet-like $a_1$. On the other hand, for the doublet-like pseudoscalar, $a_2$, an enhancement in $C_{a_2}^{\text{eff}}(\gamma\gamma)$ requires either $\cos \theta_U \sin \theta_V$ or $\sin \theta_U \cos \theta_V$ to be non-negligible. This can be realized only in a very limited region of the parameter space where $M_2 \simeq \mu_{\text{eff}}$ and not too large in order to keep $m_{\chi^\pm_1}$ low. Moreover, in this case, the mixing angles in the chargino sector read

$$\theta_{U,V} \simeq \arctan \left[ \frac{\pm 2M^2_{W} \frac{1-\tan^2 \beta}{1+\tan^2 \beta} - 2 \sqrt{(M^2_{W} + \mu^2_{\text{eff}})^2 - \mu^4_{\text{eff}}} \sqrt{2} M_{W} \mu_{\text{eff}}(1 + \tan \beta)}{\sqrt{2} M_{W} \mu_{\text{eff}}(1 + \tan \beta)} \right],$$

where $M_W$ is the mass of $W$ boson. The sign of the first term implies that the enhancement can only be seen when $a_2$ has a leading $H_{u1}$ component so that the term in Eq. (7) proportional to
\[
\sin \theta_V \cos \theta_V \text{ is dominant. Evidently, in this case the } a_2b\bar{b} \text{ coupling, and in turn } \text{BR}(a_2 \to b\bar{b}), \text{ will also get enhanced. Consequently, a contribution from } a_2 \text{ will provide no significant excess in the } \gamma\gamma \text{ signal rate, defined in Eq. (1).}
\]

The above explanation also precludes such a scenario in the MSSM, where the pseudoscalar, \( A \), is doublet-like. Besides, as noted in [33, 34], in the MSSM in order to obtain the lightest CP-even Higgs boson, \( h \), with mass around 125 GeV, \( m_A \) is required to be \( \gtrsim 300 \) GeV, which is the so-called decoupling regime of the model. On the other hand, while it is also possible to have a \( \sim 125 \) GeV \( H \), the heavier CP-even Higgs boson of the MSSM, this can only be achieved for \( 95 \) GeV < \( m_A < 110 \) GeV, in a tiny portion of the ‘non-decoupling regime’. This region is, moreover, disfavored by the constraints from flavor physics [37, 38].

In the fully constrained version of the NMSSM, unification of \( A_\kappa \) and \( A_0 \) at the GUT scale introduces tension between the masses of \( h_1 \) and \( a_1 \), not allowing both to acquire values \( \lesssim 125 \) GeV simultaneously. There, in order to obtain the correct \( h_1 \) mass, large negative values of \( A_0 \) are necessary so that the mixing term \( \left( \frac{\lambda_X}{M_{\text{SUSY}}} \simeq \frac{A_t}{M_{\text{SUSY}}} \right) \) can be maximized. A light \( a_1 \), on the other hand requires small \( A_\kappa \) at \( M_{\text{SUSY}} \), which in turn implies small \( A_\kappa \) at the GUT scale, owing to the effects of running. Moreover, small values of \( \mu_{\text{eff}} \), necessary to obtain light Higgsino-like charginos, additionally limit the running of \( A_t \) in the CNMSSM [14]. Therefore, to obtain a SM-like \( \sim 125 \) GeV \( h_1 \) and a pseudoscalar with a similar mass and a non-negligible \( \gamma\gamma \) rate one has to look beyond the MSSM and the CNMSSM, hence we analyse the CNMSSM-NUHM here.

Through the mechanism explained above, a more precise measurement of the reduced effective coupling, \( C_{a_1}(\gamma\gamma) \equiv \frac{C_{a_1}^{\text{eff}}(\gamma\gamma)}{C_{h_{\text{SM}}}^{\text{eff}}(\gamma\gamma)} \), can yield an effective limit on the mass of the lighter chargino through\(^2\)

\[
C_{a_1}(\gamma\gamma) \simeq \lambda \times \left( \frac{130 \text{ GeV}}{m_{\chi_1^\pm}} \right), \tag{8}
\]

for \( m_{a_1} \simeq 125 \) GeV. The bound obtained on the mass of \( \chi_1^\pm \) is also an effective upper limit on the mass of the lightest neutralino, \( \chi (\equiv \chi_1^0) \).

Having described the mechanism for enhancing the \( \gamma\gamma \) decay rate of \( a_1 \), we now discuss the actual quantity used for comparison with the experimentally observed \( \gamma\gamma \) rate. In terms of the reduced effective couplings, \( C_{a_1}(\gamma\gamma) \) and \( C_{a_1}(dd) \), of \( a_1 \) to \( \gamma\gamma \) and \( b\bar{b} \), respectively, the signal rate, given in Eq. (1), can be rewritten for the \( bb \) production mode as

\[
P_{\gamma\gamma}^{bb}(a_1) = C_{a_1}^2(dd) C_{a_1}^2(\gamma\gamma) \frac{\Gamma_{\text{total}}^{h_{\text{SM}}}}{\Gamma_{a_1}^{\text{total}}} \simeq \left| P_{11}'' \right|^2 \lambda^2 \left( \frac{130 \text{ GeV}}{m_{\chi_1^\pm}} \right)^2 \left( \frac{1}{\Gamma_{a_1}^{\text{total}}/\Gamma_{h_{\text{SM}}}} \right), \tag{9}
\]

where \( \left| P_{11}'' \right| \simeq \left| \frac{\lambda(A_{\chi_{1}}}^{\text{SUSY}} - 2\kappa a)\mu}{\mu(A_{\chi_{1}}}^{\text{SUSY}} + \kappa a) \right| \) and \( \Gamma_{\text{total}}^{h_{\text{SM}}} \) and \( \Gamma_{\text{total}}^{h_{\text{SM}}} \) denote the theoretical values of the total widths of \( a_1 \) and a SM Higgs boson with the same mass as \( a_1 \), respectively. The dependence of the above expression on \( \tan \beta \) is not straightforward, since it only enters indirectly through \( \Gamma_{a_1}^{\text{total}}/\Gamma_{h_{\text{SM}}}^{\text{total}} \). Eq. (9) also shows that, as noted in the Introduction, the conditions necessary to enhance \( C_{a_1}(\gamma\gamma) \), i.e., large \( \lambda \) and small \( \mu \), also yield an enhanced \( |C_{a_1}(dd)| \sim |P_{11}''| \).

In Sec. 3 we will use Eqs. (8) and (9) to obtain an effective upper limit on \( m_{\chi_1^\pm} \) and the mass of \( \chi, m_{\chi} \), in our model under consideration.

\(^2\)Assuming a singlet-like \( a_1 \), which implies \( P_{13} \simeq 1 \), and a Higgsino-like \( \chi_1^\pm \) so that \( \sin \theta_{U,V} \simeq 1 \).
2.3 \( b\bar{b}/\tau^+\tau^- \) decay of the pseudoscalar

The signal rate in these decay modes can be written, following Eq. (9), as

\[
P_{b\bar{b}/\tau^+\tau^-}(a_1) \simeq \frac{|P^H_{11}|^4}{\Gamma_{a_1}^{\text{total}}/\Gamma_{hSM}^{\text{total}}},
\]

It should be noted in the above expression that both the \( b\bar{b} \) and \( \tau^+\tau^- \) decay rates scale with the same reduced coupling \( C_{a_1}(dd) \). Both these decay channels, therefore, show exactly the same behavior as far as their signal rates are concerned, despite the fact that \( \text{BR}(a_1 \to \tau^+\tau^-) \) is considerably smaller than \( \text{BR}(a_1 \to b\bar{b}) \). From an experimental point of view, the \( b\bar{b} \) decay mode will result in 4 \( b \)-jets which may be quite challenging to tag owing to the large hadronic background, although this mode has been visited in the past [3]. The \( \tau^+\tau^- \) decay mode, on the other hand, is subject to a much smaller leptonic background and is in fact the preferred mode for analysing possibly supersymmetric Higgs bosons.

3 The CNMSSM-NUHM

In the fully constrained NMSSM universality conditions are imposed on the dimensionful parameters at the GUT scale. This leads to a unified gaugino mass parameter, \( m_1/2 \), besides \( m_0 \) and \( A_0 \), with \( A_\lambda \) and \( A_\kappa \) also unified to the latter. Thus, given the correct value of the mass of Z boson, \( m_Z \), \( m_0 \), \( m_1/2 \), \( A_0 \) and \( \lambda \), taken as an input parameter at \( M_{\text{SUSY}} \), constitute the only free parameters in the CNMSSM.

In the partially unconstrained version of the model, the CNMSSM-NUHM, the soft masses of the Higgs fields, \( m_{H_u}, m_{H_d} \) and \( m_S \), as well as the soft trilinear coupling parameters \( A_\lambda \) and \( A_\kappa \) are taken as free parameters at the GUT scale, instead of assuming their unification with \( m_0 \) and \( A_0 \), respectively. Through the minimization conditions of the Higgs potential the three mass parameters \( m_{H_u}, m_{H_d} \) and \( m_S \) at the electroweak scale can be traded for the parameters \( \kappa, \mu_{\text{eff}} \) and \( \tan \beta \). The model is thus defined in terms of the following eight continuous input parameters:

\[
m_0, m_1/2, A_0, \tan \beta, \lambda, \kappa, \mu_{\text{eff}}, A_\lambda = A_\kappa.
\]

The unification of \( A_\lambda \) and \( A_\kappa \) at the GUT scale assumed above is in general not necessary in the CNMSSM-NUHM. In fact, one can argue that the restriction on \( A_0 \) for \( \mu_{\text{eff}} < 0 \) and the resultant tension between \( m_{h_1} \) and \( m_{a_1} \) discussed in the previous section can be relaxed by not imposing such a condition. In that case, the effect of large \( A_\lambda \) can be counter-balanced by increasing \( A_\kappa \) independently, thus still yielding physical \( a_1 \) solutions. However, this unification condition has minimal impact on the allowed parameter space of the model for our purpose, since, as we shall see later, we can still exploit the interesting phenomenology of the model while keeping the number of free parameters to a minimum. This is also consistent with the fully constrained version of the model that we studied earlier [14], where \( A_\kappa \) and \( A_\lambda \) were set equal to \( A_0 \) at the GUT scale, even though \( m_S \neq m_0 \).

4 Methodology and results

We perform scans of the parameter space of CNMSSM-NUHM requiring both \( h_1 \) and \( a_1 \) to have masses near 125 GeV. We impose the latest 95% confidence level (CL) exclusion limit on the \((m_0, m_1/2)\) space of mSUGRA/CMSSM obtained by the ATLAS collaboration from two same-sign
leptons and jets in the final state at $\sqrt{s} = 8\,\text{TeV}$ with 20.7/fb of data. It has been verified in [33] that such a limit, obtained originally for the CMSSM, generally has negligible dependence on the Higgs sector parameters and is, therefore, applicable to any $R$-parity conserving SUSY model with unified $m_0$ and $m_{1/2}$. We also impose the lower limit, $m_{\chi_1^+} > 94\,\text{GeV}$ [33], on the lightest chargino mass in our scans. Furthermore, we include Gaussian likelihoods for the most significant $b$-physics observables, with their measured mean values and errors taken as:

- $\text{BR}(B_s \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2} \pm 0.32) \times 10^{-9}$,
- $\text{BR}(B_s \rightarrow \tau\nu) = (1.66 \pm 0.66 \pm 0.38) \times 10^{-4}$,
- $\text{BR}(B \rightarrow X_s\gamma) = (3.43 \pm 0.22 \pm 0.21) \times 10^{-4}$ and
- $\Delta M_{B_s} = (17.72 \pm 0.04 \pm 2.4)\,\text{ps}^{-1}$.

For testing the compatibility of the regions of interest against the dark matter direct detection cross section, $\sigma_p^{\text{SI}}$, we use the XENON100 90% CL exclusion limits. Note that we neglect the $a_\mu$ constraint here since it is well known that the regions where correct $a_\mu$ can be obtained in the parameter spaces of SUSY models with unification of squark and slepton soft masses are strongly disfavored by the direct SUSY searches at the LHC [41, 14, 8]. However, in order to minimize the deviation from experimental value of $a_\mu$ and also to release the tension between $m_{h_1}$ and $m_{a_1}$, as discussed at the end of Sec. 2.1 we shall use $\mu_{\text{eff}} > 0$, unless stated otherwise. We also note here that no likelihood function was implemented in our scans for the relic density constraint. However, in all our results below we only show points with neutralino relic density, $\Omega h^2$, lying in the $\pm 2\sigma$ range, $0.087 < \Omega h^2 < 0.137$, around the central experimental value (again, unless stated otherwise), after taking into account 10% error on the theoretical calculation. We use a slightly extended range of the allowed Higgs boson mass, $122\,\text{GeV} < m_{h_1,a_1} < 130\,\text{GeV}$, compared to the mass measurements of the observed boson at the LHC in order to take into account large theoretical and experimental errors. Finally, for all the points considered, $h_1$ is always SM-like, with $R^{bb}_{X/V}(h_1) \simeq 1$.

The numerical analysis was performed using the BayesFITS package which engages several external, publicly available tools: MultiNest [42] for sampling of the CNMSSM-NUHM parameter space; NMSSMTools v3.2.4 [43] for computing SUSY mass spectrum, Higgs BRs and reduced couplings, as well as $\Delta M_{B_s}$ for a given NMSSM point; SuperIso v3.3 [44] for calculating $\text{BR}(B \rightarrow X_s\gamma)$, $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ and $\text{BR}(B_u \rightarrow \tau\nu)$. DM observables such as the relic density and $\sigma_p^{\text{SI}}$ are calculated with MicrOMEGAs v2.4.5 [45].

### 4.1 $\gamma\gamma$ rate enhancement

As noted in Sec. 2, the scenario under consideration requires low values of $\mu_{\text{eff}}$, giving a light Higgsino-like $\chi_1^\pm$ and correspondingly a $\chi$ with significant Higgsino component. Under these conditions the upper limit on $m_{\chi_1^\pm}$ and $m_{\chi}$ can be obtained in the CNMSSM-NUHM from Fig. 11, where $C_{a_1}(\gamma\gamma)$ and $R^{bb}(a_1)$ are shown as functions of $m_{\chi_1^\pm}$ in (a) and (b), respectively. For all points in the plots we assume $122\,\text{GeV} < m_{h_1,a_1} < 130\,\text{GeV}$.

The parameter space of the CNMSSM-NUHM giving an enhancement in the $\gamma\gamma$ rate due to a $\sim 125\,\text{GeV}$ $a_1$ can in fact be divided into three main regions depending on the composition of $\chi$:

- i) the singlino-Higgsino region,
- ii) the Higgsino region, and
- ii) the focus-point (FP) region.

Below we discuss the results for each of these regions separately.
4.1.1 Singlino-Higgsino region

This region is defined by \( \chi \) being a mixture of a large Higgsino component and a smaller but important singlino component. Owing to the significant singlino component (20\%–30\%) the neutralino will interact very weakly with matter and will thus result in large relic abundance unless it has a small mass and consequently large annihilation cross-section. In Fig. 2a we see the distribution of this region in the \( (m_0, m_{1/2}) \) plane. Light blue squares correspond to points with 1 < \( R^{bb}(h_1 + a_1) \) ≤ 1.15, green squares to points with 1.15 < \( R^{bb}(h_1 + a_1) \) ≤ 1.3, red squares to points with 1.3 < \( R^{bb}(h_1 + a_1) \) ≤ 1.45 and green squares to points with \( R^{bb}(h_1 + a_1) > 1.45 \). Also shown in the figure is the current 95\% CL exclusion limit from ATLAS obtained with 20/fb of data.

While \( m_0 \) is widely distributed, intermediate-to-large values of \( m_{1/2} \) are favored for allowing a neutralino with a negligible bino component for small positive \( \mu_{\text{eff}} \). In Fig. 2b, the favored ranges of \( \tan \beta \) and \( A_0 \) parameters are shown. We see that the enhancement in \( R^{bb}(h_1 + a_1) \) decreases as \( \tan \beta \) increases. The reason for this is as follows. The enhancement in \( R^{bb}(a_1) \) grows with \( \lambda \), according to Eq. (9). However, large values of \( \lambda \) can only give correct \( m_{h_1} \) for not too large values of \( \tan \beta \). This is because larger values of \( \tan \beta \) result in an enhanced Yukawa coupling of \( h_1 \) to \( b \bar{b} \) and \( \tau \bar{\tau} \). This will make \( A_\lambda \) run upwards faster from its GUT scale value, which in turn causes \( A_\kappa \) to run downwards to larger negative values. That will result in a decrease in \( m_{h_1} \), since it has a significant singlet component, while \( m_{a_1} \) increases. \( A_0 \) almost always takes large negative values, in order to maximize \( m_{h_1} \). We, therefore, hardly see any points corresponding to positive \( A_0 \).

In Fig. 2c: we show the distribution of points in the \( (A_0, A_\kappa) \) plane. The interdependence of \( A_0 \) and \( A_\lambda = A_\kappa \) is further illustrated by this figure. \( A_\kappa \) can take quite large positive values at the GUT scale, even though it ought to be negative at \( M_{\text{SUSY}} \). The reason is that, for large negative \( A_0 \) values, \( A_\lambda \) which is also positive, makes \( A_\kappa \) run downwards. In Fig. 2d, the \( (\lambda, \kappa) \) plane is shown.
Figure 2: (a)-(d) Ranges of CNMSSM-NUHM parameters corresponding to the singlino-Higgsino region. (e) $\sigma_{SI}$ obtained for this region as a function of $m_\chi$. (f) Ranges of $m_{h_1}$ and $m_{a_1}$ obtained in this region. See text for details.
The allowed range of $\lambda$ for a given region is subject to a three-way tension. Large $\lambda$ is favored in order to obtain an enhancement in the coupling of $a_1$ to $\chi_1^\pm$ but the condition to obtain a SM-like $h_1$, on the other hand, prefers smaller values. The small-to-intermediate range of $\lambda$ seen in the figure is then a result of the compromise between these two conditions and, additionally, of the requirement to achieve the desired $m_{a_1}$ by generating $s (= \mu_{\text{eff}}/\lambda)$ of the correct size. We note also in the the figure small-to-intermediate values of $\kappa$ which are required to maximize the singlino component of $\chi_1$, as the $5 \times 5$ term in the neutralino mass matrix is equal to $2\kappa s$ ($\equiv 2\kappa p_{\text{eff}}/\lambda$). Hence the smallness in $\kappa$ has to be compensated by large values of $A_\chi$, as noted in Fig. 2b, for obtaining the correct $m_{a_1}$. Finally, over the entire allowed ranges of $\lambda$ and $\kappa$ a large enhancement in $R_{\gamma\gamma}^{bb}(h_1 + a_1)$ is observed, although this region corresponds to more fine-tuned values of these two parameters compared to the other two regions, as we shall see later.

In Fig. 2 we show the $(m_\chi, \sigma_p^{\text{SI}})$ plane for this region. Also shown in the figure are the actual 90% CL exclusion limits from XENON100 as well as the 90% CL limits expected from the LUX [46] and XENON1T [47] experiments. A large number of points satisfying the XENON100 limit lies below the projected 90% CL XENON1T limit. Note also that since very small $m_\chi$ and consequently $m_{\chi_1^\pm}$ is favored by this region almost all the points below the XENON100 line have a highly enhanced $R_{\gamma\gamma}^{bb}(a_1)$, since $\chi_1^\pm$ also appears in the denominator of Eq. (9). This is also the reason why such points are achievable even with relatively small values of $\tan \beta$, as seen in Fig. 2b earlier. This region yields the maximum enhancement, up to $\sim 60\%$ or so, in $R_{\gamma\gamma}^{bb}(h_1 + a_1)$ out of the three regions discussed here and is, therefore, the most favorable of all.

In Fig. 2 we show the distribution of $m_{h_1}$ versus that of $m_{a_1}$. We note that this region can have fairly large $m_{h_1}$, which is due to the combined effects of large negative $A_0$ as well as larger allowed values of $\lambda$. Another important feature of this region is that $h_2$ can also be almost mass degenerate with $h_1$ and $a_1$, implying in that case a ‘triple degeneracy’ among the Higgses. Again, while mass degenerate $h_1$ and $h_2$ can explain the enhanced $\gamma\gamma$ rate in the $ggH$ production mode in the ATLAS data, in order to test the additional degeneracy with $a_1$ one will have to explore the associated production mode of Higgs with $bb$. In the $bbH$ production mode, such $h_2$ can further contribute $\sim 20\%$ of the measured $\gamma\gamma$ rate. Finally, $\text{BR}(B_s \to \mu^+\mu^-)$ in this region varies between $3 \times 10^{-9}$ and $3.8 \times 10^{-9}$ while $\text{BR}\left(\overline{B} \to X_s\gamma\right)$ lies in the $2.8 \times 10^{-4}$ to $3.3 \times 10^{-4}$ range.

### 4.1.2 Higgsino region

A nearly pure Higgsino-like neutralino can generate large enough $\Omega_\chi h^2$ only if $m_\chi \approx \mu_{\text{eff}} \sim 1 \text{ TeV}$, but such high values of $\mu_{\text{eff}}$ will not yield the desired enhancement in the $a_1 \to \gamma\gamma$ rate. Therefore, in order to obtain a sizeable enhancement one has to relax the condition on neutralino relic density (thereby allowing low $\mu_{\text{eff}}$ and, therefore, $\Omega_\chi h^2$ to be too low). One can assume that a neutralino contributes only partially to the relic abundance of the universe beside some other DM candidate, e.g., the axion. In that case $\Omega_\chi h^2 = \xi \Omega_{\text{total}} h^2$, where $\xi$ is the fraction of the total relic abundance produced by $\chi$ and $\Omega_{\text{total}} h^2 = 0.112$. Another possibility is that the entire relic abundance is due to an alternative DM candidate particle in the model. Often considered examples of such an additional/alternative DM candidate are gravitino (see, e.g., [48] for recent analyses in the MSSM) and/or axino [49]. The first (second) of these candidates is (not) tightly constrained by Big Bang Nucleosynthesis but both are likely to be allowed in this region due to the low neutralino yield at freeze-out.

In Fig. 3a we show the region in the $(m_0, m_{1/2})$ plane generating a light $a_1$ and a Higgsino-like $\chi$. The color assignment of the points is the same as in the singlino-Higgsino region. Large values of $m_0$ are preferred again in order to enhance $m_{h_1}$ through radiative corrections from the SUSY sector. $m_{1/2}$ also takes large values in order to minimize the bino component of $\chi$ with large
Figure 3: (a)-(d) Ranges of CNMSSM-NUHM parameters corresponding to the Higgsino region. (e) $\xi \sigma_p^{SI}$ obtained for this region as a function of $m_\chi$, where $\xi = \Omega_\chi h^2/\Omega_{\text{total}}h^2$. (f) Ranges of $m_{h_1}$ and $m_{a_1}$ obtained in this region. See text for details.
A light neutralino with mixed bino-Higgsino composition can generate correct DM relic density, $\Omega_\chi h^2$, in the so called focus-point (FP) region of minimal SUSY models in general [50]. Since this region satisfies the constraints from XENON100 and BR (B → X_sγ) measurement better when $\mu_{\text{eff}} < 0$ [51], we shall pursue this case here. In Fig. 4, we show the region in the ($m_0, m_{1/2}$) plane generating a light $a_1$ (122 GeV $\leq m_{a_1} \leq 130$ GeV) and $\chi$ with a dominant bino and a small Higgsino component. We see that while large values of $m_0$ are favored in order to enhance the mass of $h_1$, $m_{1/2}$ is typically low, which is necessary for producing a mixed bino-Higgsino $\chi$. This region, however, lies very close to the current 95% CL exclusion limit from ATLAS and should potentially be tested soon.

In Fig. 4b, we show the favored ranges of the $A_0$ and tan $\beta$ parameters. tan $\beta$ is almost always $\lesssim 5$ to allow enhancement in the $h_1bb$ coupling in our considered Higgs production mode, as noted

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4The figure assumes that $\chi$ is only responsible for a small portion of the observed relic abundance. For the points obtained in the scan $\xi \leq 0.05$. 

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$\mu_{\text{eff}}-m_{1/2}$ splitting. In Fig. 3b, we see that once again tan $\beta$ spans a fairly wide range but small to intermediate values are favored by $R_{\gamma\gamma}^{bb}(a_1)$, for the same reasons as in the singlino-Higgsino region. Larger values of negative $A_0$ are favored so that $m_{a_1}$ can be maximized.

In Fig. 3c we show $A_\kappa$ vs $A_0$. As in the singlino-Higgsino region, for the (comparatively smaller) positive $A_\kappa$ at the GUT scale only large negative $A_0$ values are allowed. However, in contrast with that region, a considerable number of points is visible for negative $A_\kappa$ and negative $A_0$ up to $\sim -2$ TeV. In this portion of the region negative $A_0$ makes $A_\lambda$ run upwards between the GUT scale and $M_{\text{SUSSY}}$ and, since the latter is negative, it also drives $A_\kappa$ upwards to smaller negative values. Naturally then, negative $A_0$ should not be very large or $A_\kappa$ at $M_{\text{SUSSY}}$ will be driven positive. Positive $A_0$ solutions are also possible, as long as they don’t yield positive $A_\kappa$ at $M_{\text{SUSSY}}$. In Fig. 3d the ranges of the parameters $\lambda$ and $\kappa$ favored by our scenario under consideration are shown for this region. A larger range of $\kappa$ is favored in this region compared to the singlino-Higgsino region since $s$ is more free to vary owing to the comparatively less constrained $A_\kappa$ (which does not need to be as large to give correct $m_{a_1}$) $\lambda$ can now take much smaller values than those allowed in the singlino-Higgsino region but cannot be as large as there. This is in fact the main feature distinguishing this region from the singlino-Higgsino region in terms of the parameter space of the model. Evidently, larger enhancement in the $\gamma\gamma$ rate is favoured by large values of $\lambda$.

In Fig. 3e we show the distribution of the points in the $(m_\chi, \xi \sigma^{SI}_p)$ plane for this region. Almost all the points obtained in this region lie below the XENON100 line and a portion of these points even lies below the projected XENON1T line. Since $\chi$ is almost purely Higgsino here, the smaller its mass the bigger the enhancement in $R_{\gamma\gamma}^{bb}(a_1)$ is generated. Moreover, this region corresponds to large values of $m_0$ and $m_{1/2}$ so that the squarks and gluinos are always much heavier than the current LHC reach. Nevertheless, as discussed earlier, a more precise measurement of $R_{\gamma\gamma}^{bb}$ could still introduce limits on $m_\chi$ and $m_{\chi^\pm}$. Such derived upper limits are, therefore, especially interesting from the experimental point of view.

Finally, again as a result of large allowed values of negative $A_0$, $h_1$ as heavy as 129 GeV can be obtained in this region, as can be seen in Fig. 3c. $a_1$ mass is evenly distributed in the defined range, almost always showing a large enhancement in the $\gamma\gamma$ rate. Finally, a majority of points in this region show a big enhancement, up to $\sim 50\%$ above the SM expectation, in the $\gamma\gamma$ rate. We also note here that both BR (B → $\mu^+\mu^-$) and BR (B → X_sγ) always lie around their respective SM values.

### 4.1.3 Focus-point region

A light neutralino with mixed bino-Higgsino composition can generate correct DM relic density, $\Omega_\chi h^2$, in the so called focus-point (FP) region of minimal SUSY models in general [50]. Since this region satisfies the constraints from XENON100 and BR (B → X_sγ) measurement better when $\mu_{\text{eff}} < 0$ [51], we shall pursue this case here. In Fig. 4, we show the region in the ($m_0, m_{1/2}$) plane generating a light $a_1$ (122 GeV $\leq m_{a_1} \leq 130$ GeV) and $\chi$ with a dominant bino and a small Higgsino component. We see that while large values of $m_0$ are favored in order to enhance the mass of $h_1$, $m_{1/2}$ is typically low, which is necessary for producing a mixed bino-Higgsino $\chi$. This region, however, lies very close to the current 95% CL exclusion limit from ATLAS and should potentially be tested soon.

In Fig. 4b we show the favored ranges of the $A_0$ and tan $\beta$ parameters. tan $\beta$ is almost always $\lesssim 5$ to allow enhancement in the $h_1bb$ coupling in our considered Higgs production mode, as noted.
earlier. However, we see in the figure that for high positive $A_0 \tan \beta$ is limited to small values, $\lesssim 15$. The reason is that large $\tan \beta$ results in an enhanced Yukawa coupling of $h_1$ to $b\bar{b}$ and $\tau\tau$. Consequently $A_\lambda$ runs downwards rapidly from its GUT scale value (we shall see below that large positive $A_0$ coincides with negative $A_\lambda$) to more negative values at $M_{\text{SUSY}}$. This in turn causes $A_\kappa$ to run upwards from its GUT scale value, raising $m_{a_1}$ beyond the desired range. The effective upper bound on $\tan \beta$ is relaxed for lower $|A_0|$, when the running is slower. We point out here that the opposite effect of $\tan \beta$ was noted in the other two regions due to the fact that there $A_0$ was negative which made $A_\lambda$ and $A_\kappa$ run in the opposite directions to those here.

In Fig. 4c: we show the distribution of the parameters $A_0$ and $A_\kappa = A_\lambda$ at the GUT scale. We notice that $A_0$ stops at much smaller negative values than it would be expected to take in order to maximize $m_{h_1}$. This is due to the reason explained in Sec. 2. The main contribution to $m_{a_1}$ comes from the leading term in Eq. (3). Since in this region we assume $\mu_{\text{eff}} < 0$, $A_0$ is strongly bounded from below in order to minimize the effect of the second term there. Such negative $A_0$, by causing positive $A_\lambda$ to run upwards, also pushes $A_\kappa$ to somewhat large positive values at the GUT scale resulting in its small positive values at $M_{\text{SUSY}}$, since it runs in the opposite direction to $A_\lambda$. This is also the reason why no points are visible in the region with negative $A_\kappa$ and negative $A_0$ as opposed to the Higgsino region, but conversely one can see some points with positive $A_\kappa$ and positive $A_0$. Finally, for negative $A_\kappa$ large positive $A_0$ can be reached, since such values of $A_0$ drive positive $A_\lambda$ at the GUT scale downwards, which in turn causes $A_\kappa$ to run upwards to positive values at $M_{\text{SUSY}}$.

Fig. 4d shows the ranges of $\lambda$ and $\kappa$ corresponding this scenario. The distribution of these two parameters almost mimics that in the Higgsino region and as in there larger values of enhancement in $R_{\gamma\gamma}(h_1 + a_1)$ are obtained for large $\lambda$. In Fig. 4e: we show how the FP region fares against the XENON100 limits. Note that $m_{\chi^\pm}$ is bounded from below by the ATLAS limit on $m_{1/2}$ in this region as it is bino-dominated. We see that a majority of the allowed points with an enhanced $\gamma\gamma$ rate lie below the XENON100 line. Most of this region, however, lies above the LUX limit, while the XENON1T data should be able to test almost all of it. Fig. 4f shows the allowed masses of $h_1$ and $a_1$ in this region. We see that $m_{h_1}$ is always lighter than 124 GeV, which is a consequence of $\mu_{\text{eff}} < 0$ not allowing very large values of negative $A_0$ in this region, as discussed above. $a_1$, on the other hand, can easily have a mass greater than 125 GeV.

Overall, we notice only a relatively small enhancement, up to $\sim 25\%$ in the $\gamma\gamma$ rate compared to the SM expectation in this region of the CNMSSM-NUHM parameter space. The reason for this is that $m_{\chi^\pm}$ is not allowed to take values even as small as those possible in the Higgsino region due to the lower bound on the mass of $\chi$ discussed above ($m_{\chi^\pm} \sim \mu_{\text{eff}} > m_\chi$). BR ($B_s \to \mu^+\mu^-$) in this region varies between $2 \times 10^{-9}$ and $5.5 \times 10^{-9}$, which is within $2\sigma$ of the experimentally measured value $3.2 \times 10^{-9}$, taking into account the theoretical error (as in [14]). On the other hand, BR ($\bar{B} \to X_s \gamma$) takes values between $3.1 \times 10^{-4}$ and $3.7 \times 10^{-4}$ and hence is always close to the experimental value. This region, owing mainly to the facts that $m_{h_1}$ finds it difficult to reach the experimentally observed value and that the reduced $\gamma\gamma$ rate of $a_1$ barely exceeds 0.25, is the least favored of the three regions explored here.

To summarize, in Fig. 5a we show the range of $m_{\chi^\pm}$ across all the regions for which an enhancement in $R_{\gamma\gamma}(h_1 + a_1)$ was obtained in our CNMSSM-NUHM scan, and its compatibility with the current and expected limits on $\sigma^\text{SI}_p$. These regions are identified separately in Fig. 5b, again, in the $(m_{\chi^\pm}, \xi_0^\text{SI})$ plane, where the orange squares denote the FP region, dark green squares the Higgsino region and brown squares the singlino-Higgsino region.
Figure 4: (a)-(d) Ranges of CNMSSM-NUHM parameters corresponding to the FP region. (e) $\sigma_p^{SI}$ obtained for this region as a function of $m_\chi$. (f) Ranges of $m_{h_1}$ and $m_{a_1}$ obtained in this region. See text for details.
Figure 5: (a) The range of $\sigma_{p}^{SI}$ for giving an enhancement in $R_{bb}^{h} (h_1 + a_1)$ versus the neutralino mass $m_{\chi}$. Also shown are the 90% CL exclusion limits from XENON100 as well as the 90% CL limits expected from the LUX and XENON1T experiments. $\xi = \Omega_{\chi} h^2 / \Omega_{\text{total}} h^2$ when $\chi$ is almost purely Higgsino but 1 otherwise. (b) The $(m_{\chi}, \sigma_{p}^{SI})$ plane showing the three CNMSSM-NUHM regions where $R_{bb}^{h} (h_1 + a_1)$ is enhanced. Maroon squares denote the singlino-Higgsino region, green squares the Higgsino region and yellow squares the FP region. $\xi = \Omega_{\chi} h^2 / \Omega_{\text{total}} h^2$ in the Higgsino region, but 1 in the singlino-Higgsino and FP regions.

Figure 6: (a) Enhancement in $R_{bb}^{h} (h_1 + a_1)$ obtained in the Higgsino region as a function of the $\lambda$ and $\mu_{\text{eff}}$ parameters. (b) Enhancement in $R_{bb}^{h} (h_1 + a_1)$ obtained in the FP region as a function of $\kappa$ and ($A_{\chi}^{SUSY} + \kappa s$) from the denominator of $|P_{11}^\prime|$. See text for details.
4.2 \( b\bar{b}/\tau^+\tau^- \) rate enhancement

In this subsection we highlight only the important features corresponding to the \( b\bar{b} \) and \( \tau^+\tau^- \) decay channels of \( a_1 \) for the three regions discussed in detail above. As noted in Sec. 2.2, contrary to the case of a MSSM-like scalar Higgs boson, \( \tan \beta \) affects the \( b\bar{b}/\tau^+\tau^- \) rate of \( a_1 \) only indirectly through the term in the denominator of Eq. (10). Instead, a sizable \( R_{bb/\tau^+\tau^-}^{bb}(a_1) \) is an additional consequence of the conditions necessary to obtain an enhancement in \( R_{\gamma\gamma}^{bb}(a_1) \), i.e., large \( \lambda \) and small \( \mu_{\text{eff}} \). This is demonstrated in Fig. 6(a) for the Higgsino region, where one can see that the enhancement in \( R_{bb/\tau^+\tau^-}^{bb}(h_1 + a_1) \) rises with increasing \( \lambda \) and decreasing \( \mu_{\text{eff}} \). In the singlino-Higgsino region (not shown in the figure) \( R_{bb/\tau^+\tau^-}^{bb}(h_1 + a_1) \) is always larger than 1.6 for the entire range of \( \lambda \), seen in Fig. 2(d), and can be as high as 1.9. It will therefore result in a small blue region at the top left corner of Fig. 6(a).

In the FP region \( R_{bb/\tau^+\tau^-}^{bb}(a_1) \) can in fact have extremely large values, \( \sim 100 \). However, this should not be interpreted as a characteristic feature specific to the FP region, but as a result of negative \( \mu_{\text{eff}} \) assumed for this region. \( R_{bb/\tau^+\tau^-}^{bb}(a_1) \) increases as the denominator, \( A_3^{\text{SUSY}} + \kappa s \), of \( |P_{11}^{s}| \) in Eq. (10) approaches zero. For small negative \( \mu_{\text{eff}} \) and large positive \( \lambda \), resulting in small negative \( s \), the size of the denominator reduces as \( \kappa \) grows. In Fig. 6(b) we show how \( R_{bb/\tau^+\tau^-}^{bb}(h_1 + a_1) \) enhances with increasing \( \kappa \) and decreasing value of the above denominator term, and can acquire a huge value before the perturbative upper limit on the former is reached. Evidently a similar effect of negative \( \mu_{\text{eff}} \) should manifest in the other two regions also. However, since negative \( \mu_{\text{eff}} \) causes a tension between \( m_{a_1} \) and \( m_{h_1} \) and does not allow both of these to be around 125 GeV, as discussed in detail in Sec. 2.1 and as noted in the FP region, we retain \( \mu_{\text{eff}} > 0 \) in the singlino-Higgsino and the Higgsino regions. We thus expect the enhancement in the \( b\bar{b}/\tau^+\tau^- \) channels to be larger in these two regions also for \( \mu_{\text{eff}} < 0 \), but at the cost of \( m_{h_1} \) and \( a_\mu \) lying far from their respective experimentally measured values.

5 Summary

We have proposed an experimental test of a scenario in the NMSSM in which the lightest pseudoscalar of the model as well as a SM-like lightest scalar boson both have masses around \( \sim 125 \text{ GeV} \). The pseudoscalar could be distinguishable from the scalar at the LHC in the associated Higgs production mode with a \( b\bar{b} \) pair in the final state. This is because it will contribute significantly to the observed signal rate in the \( \gamma\gamma \) and \( b\bar{b}/\tau^+\tau^- \) channels but, since a pseudoscalar doesn’t couple to \( W \) and \( Z \) bosons, the measured rate in the \( WW/ZZ \) channels will be due only to the scalar and therefore SM-like. We have discussed the conditions necessary to obtain \( a_1 \) with the correct mass and noted that an observable enhancement in its \( \gamma\gamma \) decay rate is made possible by a light chargino entering in its one-loop effective coupling to two photons. We have also discussed in detail how the conditions to obtain such a light chargino in turn lead to an enhancement in the \( b\bar{b} \) and \( \tau^+\tau^- \) rates also. We have argued that, due to very specific requirements on the composition of \( a_1 \), which should be singlet-like, and of the light chargino, which should be almost purely Higgsino-like, such a scenario cannot be realized in the MSSM and is extremely unlikely in the fully constrained NMSSM.

We have, therefore, analyzed the CNMSSM with the universality conditions lifted in the Higgs sector to study the scenario at hand. We have scanned the parameter space of this model in order to look for regions that can allow both \( \chi_1^\pm \) and \( a_1 \) with the desired masses and compositions. We have found that these regions can be divided into three broad types based on the composition of the neutralino which, owing to the condition on \( \chi_1^\pm \), should also have a large Higgsino component.
These regions include the singlino-Higgsino region, where $\chi$ is Higgsino-dominated but with an admixture of the singlino, the Higgsino region, where it is almost purely Higgsino, and the FP region, where it is a bino-Higgsino mixture. The region showing least enhancement in the $\gamma\gamma$ rate of $a_1$ is the FP region, where it only reaches up to $\sim 25\%$, while the most favored one is the mixed Higgsino-singlino region, where the enhancement can be as high as $\sim 60\%$. However, we noted that for negative $\mu_{\text{eff}}$ the FP region satisfies the constraints from $\sigma_{p}^{\text{SI}}$ and $\text{BR}(B \to X_s \gamma)$ better and can also have very large enhancement in the $b\bar{b}$ and $\tau^+\tau^-$ rates, but cannot yield $m_{h_1}$ greater than 124 GeV.

We have also stressed the fact that such a singlet-like $a_1$ is likely to remain invisible at the LHC in the gluon-fusion production channel. The reason is that while the effective coupling of $a_1$ to the $\gamma\gamma$, $b\bar{b}$ and $\tau^+\tau^-$ pairs gets enhanced, the effective coupling to two gluons is still highly suppressed compared to a SM-like Higgs boson. We have, therefore, emphasized that a more focussed analysis of the associated Higgs boson production mode with $b\bar{b}$ pair, which is the least favorable production mode for a SM-like Higgs boson, is essential. By revealing such a pseudoscalar through the ‘triple enhancement’ in its decay rates, this production mode could provide a clear signature of our considered NMSSM scenario, in particular, and of beyond the SM physics, in general.

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CNMSSM-NUHM
 Singlino-higgsino $\chi_1^0$

$122 \, \text{GeV} < m_{h_1}, m_{a_1} < 130 \, \text{GeV}$

$1.6 < R_{\tau\tau,bb} < 1.9$