Higgs Boson Decays to Neutralinos
in Low-Scale Gauge Mediation

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Abstract

We study the decays of a standard model-like MSSM Higgs boson to pairs of neutralinos, each of which subsequently decays promptly to a photon and a gravitino. Such decays can arise in supersymmetric scenarios where supersymmetry breaking is mediated to us by gauge interactions with a relatively light gauge messenger sector ($M_{\text{mess}} \lesssim 100$ TeV). This process gives rise to a collider signal consisting of a pair of photons and missing energy. In the present work we investigate the bounds on this scenario within the minimal supersymmetric standard model from existing collider data. We also study the prospects for discovering the Higgs boson through this decay mode with upcoming data from the Tevatron and the LHC.
1 Introduction

Supersymmetry (SUSY) is an attractive mechanism to stabilize the scale of electroweak symmetry breaking against large quantum corrections from unknown high-energy physics. However, to be phenomenologically viable SUSY must be broken at low energies. One class of models that can achieve this in an acceptable manner are theories of gauge-mediated supersymmetry breaking (GMSB) where supersymmetry breaking occurs in a hidden sector, and is communicated to the visible sector containing the supermultiplets of standard model (SM) particles through gauge interactions with a set of gauge messenger particles [1, 2, 3].

Gauge mediation leads to experimental signatures that are very different from other forms of SUSY breaking, such as gravity and anomaly mediation, when the gauge messengers are very light relative to the Planck scale. In this case, the lightest superpartner particle (LSP) is generally the gravitino, and is stable in the presence of \( R \)-parity (which we assume in the present work). The lightest standard model superpartner will then decay to a gravitino and one or more SM states. For example, if the lightest SM superpartner is a mostly-Bino neutralino, it can decay to a photon and gravitino. Such decays can be prompt on collider time scales for gauge messenger masses below about 100 TeV. The distinctive photon-rich collider signatures of this scenario have been studied in a number of works such as Refs. [4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

These previous studies of low-scale gauge mediation focused mainly on a minimal class of GMSB models. However, more recent investigations of GMSB scenarios have illustrated that a much broader range of superpartner spectra are possible within more general realizations of this mechanism [14, 15, 16, 17, 18, 19]. With the Tevatron running and the LHC about to start up, it is therefore interesting to consider new and unusual collider signatures that can emerge in this context [20]. In the present work we investigate a novel Higgs boson signature within the minimal supersymmetric standard model (MSSM) that can potentially arise in generalized GMSB models, but is impossible in minimal GMSB scenarios.

The signature that we discuss arises from the decays of a SM-like Higgs boson to pairs of the lightest neutralinos. Each neutralino is assumed to subsequently decay promptly to a photon and a stable gravitino, \( \chi_0^0 \rightarrow \gamma \tilde{G} \), giving rise to a collider signature consisting of two photons and missing energy (\( E_T \)). This decay mode does not occur in standard scenarios of gravity-mediated supersymmetry breaking because in that case the lightest neutralino is (meta-)stable and can only produce an invisible Higgs signature [21, 22, 23]. This decay channel is also impossible in minimal MSSM GMSB models since the lightest neutralino is constrained to be heavier than half the mass of the SM-like Higgs boson. However, Higgs boson decays to pairs of unstable neutralinos can potentially arise in generalized GMSB constructions. To the best of our knowledge, this decay mode has not been studied previously, although related work has treated the decays of the heavier non-SM-like Higgs bosons through this channel [24]. Let us also mention that decays of Higgs bosons directly to a gravitino and a neutralino have been investigated in Ref. [24], while Higgs decays to a heavier and a lighter neutralino were studied in Ref. [26]. Non-standard Higgs decays in

\( R \)-parity is one simple way to forbid dangerous operators that can lead to rapid proton decay.
generalized GMSB scenarios within singlet extensions of the MSSM have also been discussed in Refs. [27, 28, 29].

The layout of this paper is as follows. In Section 2 we investigate the constraints on this scenario from previous searches at LEP as well as direct GMSB searches at the Tevatron. We estimate the prospects of discovering this Higgs boson decay mode at the Tevatron in Section 3. In Section 4 we undertake a similar analysis for the LHC. Finally, Section 5 is reserved for our conclusions.

2 LEP and Tevatron Bounds on Light Neutralinos

We begin by investigating the bounds on light neutralinos that decay promptly to a photon and a gravitino from existing particle collider data. Motivated by recent progress in non-minimal GMSB models, we consider very general low-energy superpartner spectra (with a light gravitino) that do not necessarily fit into the paradigm of minimal GMSB. The strongest parameter bounds are found to come from the LEP experiments and the Tevatron searches for direct neutralino and chargino production in low-scale GMSB. We also study the maximal size of the branching fraction of the SM-like Higgs boson to neutralino pairs subject to these constraints. No dark matter constraints are imposed as the dominant dark matter component may come from a different sector – examples include axions [30, 31] or dark matter in the supersymmetry-breaking sector [32, 33, 34, 35, 36]. Furthermore, the very light gravitino masses considered here need not induce any cosmological difficulties [37].

The Yukawa and gauge couplings of the lightest MSSM neutralino $\chi_1^0$ to the lightest CP even Higgs boson $h^0$ and the electroweak gauge bosons are given (in two-component notation) by [38, 39]

$$-\mathcal{L} \supset Y_{h^0\chi^0_{1\chi_1^0}} h^0_1 \chi_1^0 + Y_{Z^0\chi^0_{1\chi_1^0}} Z^0_1 \chi_1^0 \bar{\sigma}^{\mu} \chi_1^0$$

$$+ Y_{W_-\chi^0_{1\chi_1^0}} W^-_{\mu} \chi_{1j}^0 \bar{\sigma}^{\mu} \chi_{1j}^0 + Y_{W_+\chi^0_{1\chi_1^0}} W^+_{\mu} \chi_{1j}^0 \bar{\sigma}^{\mu} \chi_{1j}^0 + \text{h.c.,}$$

where

$$Y_{h^0\chi^0_{1\chi_1^0}} = (\cos \alpha N_{14}^* + \sin \alpha N_{13}^*) (g' N_{11}^* - g N_{12}^*),$$

$$Y_{Z^0\chi^0_{1\chi_1^0}} = \frac{g}{2\cos \theta_W} (|N_{13}|^2 - |N_{14}|^2),$$

$$Y_{W_-\chi^0_{1\chi_1^0}} = g \left( \frac{1}{\sqrt{2}} N_{14} V_{j2}^* - N_{12} V_{j1}^* \right),$$

$$Y_{W_+\chi^0_{1\chi_1^0}} = g \left( \frac{1}{\sqrt{2}} N_{13} U_{j2}^* + N_{12} U_{j1}^* \right).$$

Here the unitary matrix $N$ satisfies the relation $N^* \mathcal{M}^0 N^\dagger = \text{diag}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}, m_{\chi_4^0})$ where $\mathcal{M}^0$ is the neutralino mass matrix in the basis ($\tilde{B}_0$, $\tilde{W}^3$, $\tilde{H}_d$, $\tilde{H}_u$). Similarly, the matrices $U$ and $V$ bi-diagonalize the chargino mass matrix according to $U^* \mathcal{M}^\pm V^\dagger$ relative to the basis ($\tilde{W}^\pm$, $\tilde{H}^\pm$), and the angle $\alpha$ describes CP-even Higgs boson mass mixing. See [40] and [41] for further discussion and four-component versions of these formulae.
The results of LEP I and II and the Tevatron place bounds primarily on the couplings of neutralinos and charginos to the electroweak gauge bosons. These constraints imply that in order for the lightest MSSM neutralino to be light enough to allow superpartner Higgs decays, it must be mostly Bino since significant Higgsino or Wino components lead to overly large gauge boson couplings (and unacceptably light charginos). The Bino, coming from $U(1)_Y$, avoids such couplings due to its Abelian nature. This is reflected in the absence of $N_{11}$ in the gauge boson couplings listed in Eq. (2). However, for the lightest neutralino to couple to the Higgs, it must have at least some Higgsino content. From the expressions for Higgs-neutralino and neutralino-gauge boson couplings, one sees that two Higgsino (or Wino) mixing factors are required for a mostly Bino state to couple to a $Z^0$ gauge boson, whereas only one is needed to couple to the SM-like Higgs boson. It is this feature that will allow the Higgs to decay significantly to a Bino-like neutralino in the MSSM without contradicting LEP constraints.

2.1 Bounds from LEP and the Tevatron

The most constraining LEP searches for a light neutralino decaying promptly to a photon are those looking for di-photon final states. LEP II has searched for di-photons and missing energy up to $\sqrt{s} \sim 209$ GeV, which limits $\sigma(e^+e^- \rightarrow \gamma\gamma + E_T) \lesssim 10^{-2} \text{pb}$ \cite{42}. LEP I running on the $Z^0$ pole also bounds the branching fraction for $Z^0$ decays to di-photons and missing energy as $BR(Z^0 \rightarrow \gamma\gamma + E_T) \lesssim 3 \times 10^{-6}$ \cite{43}. The $Z^0$ decay bound was derived assuming $Z^0 \rightarrow \nu\bar{\nu}Z'$ with $Z' \rightarrow \gamma\gamma$ and $m_{Z'} = 60$ GeV. We expect the acceptance for $\gamma\gamma + E_T$ to be similar for $Z^0 \rightarrow \chi_1^0\chi_1^0$ with $\chi_1^0 \rightarrow \gamma\tilde{G}$, and we therefore apply the same bound here. In addition to bounds on the neutralino, the lightest chargino must typically be heavier than $m_\chi^+ \gtrsim 103$ GeV to be consistent with the LEP data \cite{44,45}.

Light neutralinos that decay promptly to a photon and a gravitino are also strongly constrained by Tevatron searches for GMSB. These searches performed by the CDF and DØ experiments concentrate on $\gamma\gamma + E_T$ final states. Their results are presented in terms of bounds on the specific SPS8 GMSB Snowmass point \cite{46}, corresponding to minimal gauge mediation with $\tan\beta = 15$, $N_{mess} = 1$, $\Lambda = F/M$ a free parameter, and $M_{mess} = 2\Lambda$. Given their focus on this specific point, their results do not always apply to more general scenarios, but we expect their bounds to carry over to the present case. The dominant SUSY production mode for the SPS8 point at the Tevatron is direct electroweak chargino and neutralino creation. In our numerical scans below, we will effectively decouple all the superpartners other than the Bino and the Higgsinos, and electroweak production of charginos and neutralinos will again be the dominant Tevatron SUSY production mode. The primary significant difference between the spectrum we will study and that of SPS8 is that our lightest neutralino will be much lighter for a given Higgsino mass. This may change the decay cascades of the heavier chargino and neutralino states. However, since the Tevatron searches concentrate on the $\gamma\gamma + E_T$ signature, the nature of these cascades should not alter the bounds very much.

The latest CDF GMSB search makes use of $2.6 \text{fb}^{-1}$ of integrated luminosity \cite{47}. They demand well-identified photon pairs, where each photon has $p_T > 13$ GeV and $|\eta| < 1.1$. 

\[ \text{4} \]
In addition, they apply a cut on the event shape to remove jets mis-identified as photons (MetSig), they demand $H_T = \sum_i p_T^i + E_T > 200$ GeV where the sum runs over all hard photons, leptons, and jets (suitably defined) to reduce SM backgrounds, and they require $\Delta \phi(\gamma_1, \gamma_2) < \pi - 0.35$. After these cuts, the dominant background comes from electroweak gauge bosons producing genuine $E_T$ in the form of neutrinos. In this signal region, $1.2 \pm 0.4$ events are expected while none are observed, and we interpret this result as an upper bound on the total chargino and neutralino production cross-section of about $\sigma_{\chi_{\text{tot}}} < 20$ fb.

$D\phi$ has a similar but slightly different search based on $1.1 fb^{-1}$ of data $^{[18]}$. They require well-identified photon pairs such that each photon has $p_T > 25$ GeV and $|\eta| < 1.1$. Using this di-photon sample, they compare the $E_T$ distribution of observed events to the expected background. Using a likelihood analysis based on the signal shape, they find that the total chargino plus neutralino production in SPS8 must be less than about $80$ fb. Note that in contrast to the CDF analysis, they do not impose a cut on $H_T$.

### 2.2 Parameter Scans

To estimate the maximal size of the Higgs branching fraction to neutralinos in the MSSM, subject to the bounds from LEP and the Tevatron on light neutralinos and other superpartners, we have performed a numerical scan over MSSM parameters using a modification of NMSSMtools $^{[19]}$ and PYTHIA 6.4 $^{[50]}$. With NMSSMtools we compute the spectrum and check the LEP bounds on superpartners and the Higgs, while we use PYTHIA 6.4 to estimate Tevatron cross-sections. We have also cross-checked our results obtained in NMSSMtools at the qualitative level using CPSuperH $^{[51]}$. In our scans we fix

$$
M_2 = 700 \text{ GeV}, \quad M_3 = 800 \text{ GeV}, \quad m_{L_i} = 490 \text{ GeV}, \quad m_{E^c_i} = 600 \text{ GeV},
$$
$$
m_{Q_i} = m_{U^c_i} = 2000 \text{ GeV}, \quad m_{D^c_i} = 1970 \text{ GeV}, \quad A_i = 0 \text{ GeV}.
$$

We also scan over the ranges $M_i \in [0, 80]$ GeV, $\mu \in [-500, 500]$ GeV, $\tan \beta \in [3, 15]$, and $m_{A^0} \in [500, 2000]$ GeV. Since we restrict our attention to spectra with a light Bino and somewhat heavy scalars, these parameters do not obey the relations of minimal gauge mediation. However, they may be realized in more general GMSB scenarios where the gaugino masses can be taken as independent parameters $^{[14]}$. In addition, we have adjusted the scalar masses to satisfy the sum rules derived in Ref. $^{[16]}$, although deviations away from them can arise in even more general GMSB scenarios.$^{2}$ The large stop and pseudoscalar Higgs masses ensure that the lightest Higgs is SM-like and heavier than 114 GeV, even for smaller values of $\tan \beta$. We also take somewhat large slepton soft masses to suppress the $t$-channel selectron contribution to LEP neutralino production. We have also studied lower stop and Higgs masses, but as we will discuss below, this does not substantially increase the region of allowed parameters.

In the left panel of Fig. $^{[11]}$ we show the values of the branching fraction $B(h^0 \to \chi^0_1 \chi^0_1)$ obtained in our scan, both before and after imposing bounds from the Tevatron ($\sigma_{\chi_{\text{tot}}} < 20$ fb). $^{3}$

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$^2$ We do not specify here the origin of the $\mu$ term, but it is important to keep in mind that mechanisms to generate it may induce violations of the sum rules in the third generation or contribute to $A$-terms $^{[52]}$.

$^3$Note that the Higgs mass predicted by NMSSMtools has a theoretical uncertainty of a few GeV.
20 fb). With only the LEP bounds, branching fractions as large as 0.45 are possible for $m_{\chi_0^1} \gtrsim M_Z/2$. For lighter masses, the constraint from $Z^0$ decays limits the Higgsino content of the light neutralino, and in turn its coupling to the SM-like Higgs boson. As a result, the allowed branching ratio of the Higgs to neutralinos falls rapidly when $m_{\chi_0^1} < M_Z/2$. When the additional bounds from Tevatron GMSB searches are included, the maximal Higgs branching fraction to neutralinos is reduced to about 0.15. Branchings of this size are too small to significantly affect the LEP-II limits on the SM Higgs mass of about 114 GeV derived from searches for Higgs-strahlung off a $Z^0$ boson with $h^0 \rightarrow b\bar{b}$ [53].

In the right panel of Fig. 1 we show the (unboosted) decay lengths $c\tau$ of the product neutralinos as a function of the neutralino mass for a supersymmetry-breaking scale of $\sqrt{|F|} = 50$ TeV. We show only points for which $BR(h^0 \rightarrow \chi_1^0 \chi_1^0) > 0.1$. These decay lengths were obtained using the standard result for minimal gauge mediation [54, 55]

$$c\tau = 48\pi \frac{m_{3/2}^2 M_{Pl}^2}{m_{\chi_1^0}^5 |P_1^\gamma|^2},$$

where $|P_1^\gamma| = |N_{11} c_W + N_{12} s_W|$, and $m_{3/2} = |F|/\sqrt{3} M_{Pl} \simeq 0.6$ eV [4]. This value of $m_{3/2}$ is cosmologically safe [37], but still large enough that direct $Z^0$ and Higgs decays to gravitinos are negligible [25, 56]. Note that the boosts here are typically of order unity because, for regions of parameter space where $BR(h^0 \rightarrow \chi_1^0 \chi_1^0) > 0.1$, $m_{\chi_0^0}$ can not be significantly lighter than $m_h/2$ due to the bound from $Z^0$ decays. Among the allowed points shown in Fig. 1, we find that they all have decay lengths less than 2 cm, about the limit of what $D_0$ can detect using electromagnetic calorimeter (ECAL) pointing. The resolution (based on timing) at CDF is somewhat worse. In both cases the small decay length before the photon is emitted is not large enough to interfere with the photon reconstruction algorithms. We concentrate on such “prompt” photons in the present work, but it would also be interesting to look at the case of displaced photons.

To see the origin of the reduction in the neutralino branching fraction when the Tevatron bounds are included, we show in Fig. 2 the values of $\mu$ and $\tan\beta$ for the LEP-allowed scan points with $BR(h^0 \rightarrow \chi_1^0 \chi_1^0) > 0.1$ as well as the range of Tevatron production rates. The constraint imposed on the Higgs branching ratio restricts the set of points appearing in the $\mu$-$\tan\beta$ plane. Tevatron bounds require larger $\mu$ and $\tan\beta$. However, lower values of $\mu$ and smaller values of $\tan\beta$ are needed to obtain a significant Higgs-neutralinos coupling. Let us also point out that our scans include both positive and negative values of $\mu$, but only positive values generate a significant Higgs branching fraction, greater than 0.1. This arises because, having fixed $M_1 > 0$, positive $\mu$ leads to more Bino-Higgsino mixing. From Fig. 2 we also see that the Tevatron direct production cross-sections of neutralinos and charginos become unacceptably large for $\mu \lesssim 250$ GeV. This is simply the result of the charginos and heavier neutralinos derived from the Higgsinos becoming light enough to be produced at the Tevatron without too much kinematic suppression.

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4 The precise values of $c\tau$ and $m_{3/2}$ will differ in more general GMSB scenarios, but we expect their values to be qualitatively similar in many cases.
Figure 1: Higgs boson branching fraction into neutralinos $h^0 \to \chi_1^0 \chi_1^0$ (left) and neutralino decay length to photon plus gravitino (right) as functions of the neutralino mass. The green points in both plots are consistent with LEP bounds while the red points are also consistent with the Tevatron search bounds for neutralinos that decay promptly to photons. All points in the plot on the right have $BR(h^0 \to \chi_1^0 \chi_1^0) > 0.1$.

3 Di-photon Searches at the Tevatron

To investigate the prospects for discovering a SM-like Higgs boson at the Tevatron through neutralino decays leading to prompt photons, we have generated parton-level (but including initial- and final-state radiation) events in PYTHIA 6.4 [50] for a particular MSSM sample point. The parameter values for this point are

$$M_1 = 50 \text{ GeV}, \quad \mu = 300 \text{ GeV}, \quad \tan \beta = 5.5, \quad m_{A^0} = 1000 \text{ GeV},$$

(5)

with all other soft parameter taken as in our previous parameter scans. For these values we find $BR(h^0 \to \chi_1^0 \chi_1^0) \approx 0.11$, $m_h \approx 114.7$ GeV, $m_{\chi_1^0} \approx 46.6$ GeV, as well as a total leading-order chargino/neutralino Tevatron production cross-section of $\sigma_\chi \approx 7.2 \text{ fb}$. This point appears to satisfy all current experimental bounds (not including the DM density).

Very significant SM backgrounds to the signals we are interested in come from jets and electrons mis-identified as photons. We do not attempt to model this detector-dependent background. Instead, we simulate signal events while applying cuts and scaling by efficiency factors to allow for direct comparisons to the backgrounds tabulated in the most recent published $D\phi$ searches for $h^0 \to \gamma\gamma$ [57] and GMSB [48]. Both searches select events containing a pair of photons, each with $p_T^\gamma > 25$ GeV and $|\eta| < 1.1$. In addition, the candidate photons must be isolated and pass a set of photon identification requirements which differ slightly between the two analyses. The $D\phi$ GMSB analysis also considers cuts on missing transverse energy ($E_T$) [48].

The scaling factors we apply consist of a K-factor to account for higher-order corrections to the cross-section, as well as a detection efficiency factor $\varepsilon$. For Higgs production, we choose the K-factors such that the cross-sections in PYTHIA agree with published $N^nLO$ results. We consider production through gluon fusion (GF) [58, 59], W/Z-associated modes [60, 61],
and vector boson fusion (VBF) \cite{62}, and we obtain scaling factors of $K_{GF} : K_{W/Z} : K_{VBF} = 4.7 : 1.2 : 1.0$. The K-factor we use for chargino/neutralino production at the Tevatron is $K_\chi = 1.1$ \cite{48}.

The efficiency factors $\varepsilon$ quoted in Refs. \cite{57, 48} include both the acceptance probability $A$ that the signal passes the given cuts, as well as the reduced efficiency $\tilde{\varepsilon}$ to reconstruct the fraction of signal events passing the cuts. We assume that these factorize according to

$$\varepsilon = A \tilde{\varepsilon}. \quad (6)$$

While the acceptance $A$ clearly depends on the process under study, we assume further that the reduced efficiency $\tilde{\varepsilon}$ is constant for all events that pass the cuts. To extract the reduced efficiencies $\tilde{\varepsilon}$, we estimate the signal acceptances for di-photons from a 120 GeV Higgs boson or from the SPS8 GMSB Snowmass point ($\Lambda = 100$ TeV) by simulating these signals and imposing the relevant cuts within PYTHIA. We find $A_{h} \approx 0.42$ and $A_{GMSB} \approx 0.53$. Given the $D\phi$ values $\varepsilon_h \approx 0.20$ for di-photons from a 120 GeV Higgs \cite{57}, and $\varepsilon_{GMSB} \approx 0.20$ for the SPS8 point \cite{18}, we deduce that $\varepsilon_h \approx 0.47$ and $\varepsilon_{GMSB} \approx 0.38$. Presumably the difference between these values is due to the slightly different photon identification requirement used in the two $D\phi$ analyses.

In Fig. 3 we show the di-photon invariant mass distribution of Tevatron events originating from the $h^0$ Higgs, both with and without a cut on missing energy. We also show in this figure the di-photon mass distribution from the endpoints of chargino and neutralino cascades. All events are required to have at least two photons with $p_T^\gamma > 25$ GeV and $|\eta| < 1.1$. The distributions for which a $E_T$ cut was not imposed have been scaled to be directly comparable to the backgrounds tabulated in the $D\phi$ di-photon Higgs search in Ref. \cite{57}, while the distributions with $E_T > 30$ GeV are scaled to be comparable with the $D\phi$ GMSB
Figure 3: Di-photon signal events at the Tevatron from the Higgs boson and chargino/neutralino cascade decays. The distributions without a $E_T$ cut are scaled by K-factors and efficiencies to allow for direct comparison with the backgrounds of Ref. [57], while the distributions with the imposed cut $E_T > 30$ GeV are scaled to make them comparable to the backgrounds in Ref. [48].

No detector smearing effects have been included in this plot.

Fig. 3 illustrates that di-photons from the Higgs dominate strongly over those from chargino and neutralino cascades in the low $m_{\gamma\gamma}$ region. Di-photons from Higgs decays to neutralinos are very spread out relative to direct di-photon decays, which appear as the sharp spike around $m_{\gamma\gamma} \simeq 115$ GeV. The broad distribution of di-photon events from Higgs decays to neutralinos is also seen to fall off sharply near 90 GeV. This arises from a kinematic endpoint in the invariant mass distribution,

$$m_{\gamma\gamma} \leq \frac{2 m_{\chi_1^0}^2}{m_h - \sqrt{m_h^2 - 4 m_{\chi_1^0}^2}}.$$  \hspace{1cm} \text{(7)}$$

with equality occurring when both photons are emitted parallel to the direction of the outgoing neutralinos. In principle, a measurement of this endpoint together with an independent determination of the Higgs boson mass from the location of the diphoton resonance would yield the neutralino mass.

Note that the QCD background in the Higgs search is estimated from a sideband analysis that cuts out the window $m_h \pm 15$ GeV. Di-photons from $h^0 \rightarrow \chi_1^0 \chi_1^0$ will also contribute in this sideband region. However, the signal is much smaller than the background within any one bin, so this effect will be tiny.
Comparing our simulation to the background estimate in Ref. [57], the signal from $h^0 \rightarrow \chi^0_1 \chi^0_1$ appears to be too small to be observable. From a pure counting perspective, there are about $S = 7$ signal events with $50 \text{ GeV} < m_{\gamma\gamma} < 90 \text{ GeV}$ relative to about $B = 8000$ expected for background (3 and 2000 for $70 \text{ GeV} < m_{\gamma\gamma} < 90 \text{ GeV}$), yielding a significance $S/\sqrt{B} < 0.08$ (0.07) for 1 $fb^{-1}$ of data.\footnote{Our background estimates are based on the very rough parametrization $\frac{d\sigma}{dm_{\gamma\gamma}} \approx (10 \text{ fb/GeV})(\frac{m_{\gamma\gamma}}{150 \text{ GeV}})^{-3.7}$ of the background given in Fig. 3 of Ref. [57].} Increasing the integrated luminosity to 10 $fb^{-1}$ is still not enough to yield a visible signal. Even with much more luminosity, the very small value of $S/B$ in this channel will likely make it impossible to observe.

To reduce the SM background, a simple option is to impose a cut on missing energy $E_T$, as considered in the $D\Theta$ searches for gauge mediation with prompt photons [48]. Adding a cut of $E_T > 30 \text{ GeV}$ to the signal detection requirements described above, we find a reduction in the $h^0 \rightarrow \chi^0_1 \chi^0_1 \rightarrow \gamma\gamma \tilde{G}\tilde{G}$ signal by more than a factor of 2. In comparison, the SM background is reduced by a much larger factor, as can be seen in Fig. 1 of Ref. [48], which is based on an integrated luminosity of 1.1 $fb^{-1}$. For a fiducial integrated luminosity of 1 $fb^{-1}$, we find 2.7 signal events with $m_{\gamma\gamma} < 100 \text{ GeV}$ relative to an expected background of $9.8 \pm 1.0$ (see Table I of Ref. [48]), corresponding to a statistical significance of $S/\sqrt{B} = 0.86$. Scaling up to an integrated luminosity of 10 $fb^{-1}$, this yields a statistical significance close to 3, enough for a 95% exclusion and nearly enough for preliminary evidence. This is comparable to or better than estimates for the combined Tevatron reach for a SM Higgs boson with mass below $m_h < 130 \text{ GeV}$, even with improvements in detection efficiency [63].

Our simple significance estimate based on counting will be degraded once systematic uncertainties and the small number of total events are factored in. On the other hand, there is a great deal of shape information we have not used. The di-photon spectrum from Higgs decays to neutralinos is peaked towards $m_{\gamma\gamma} \sim 70 \text{ GeV}$, whereas our expectation is that the SM backgrounds will fall off quickly with $m_{\gamma\gamma}$. Therefore modifying the cuts within the $m_{\gamma\gamma}-E_T$ plane and fitting to a signal shape in this plane using a two-dimensional log-likelihood analysis has an excellent chance of improving the signal significance. This technique would also reduce the sensitivity to systematics. We illustrate the distribution of di-photon events passing the basic photon identification requirements discussed above ($p_T^\gamma > 25 \text{ GeV}, |\eta| < 1.1$, and photon identification) in Fig. 4. We should also mention that somewhat relaxing the requirements on $p_T^\gamma$ may also help improve the signal significance. Our results suggest that this channel would benefit from further study by the experimental collaborations. Note that the CDF GMSB search technique as presented in Ref. [47] is less useful for finding this Higgs mode since their cut of $H_T > 200 \text{ GeV}$ removes nearly all of this signal.

4 LHC Searches

For a Higgs boson of mass less than 125 GeV, the most promising search mode at the LHC is inclusive production followed by a decay to di-photons. In the mass region $115 < m_h < 125 \text{ GeV}$, both ATLAS and CMS should be able to discover a SM-like Higgs with about
Figure 4: Distribution of di-photon events from \( h^0 \rightarrow \chi^0_1 \chi^0_1 \) in the \( m_{\gamma\gamma}-E_T \) plane subject to the \( D\phi \) photon requirements discussed in the text (\( p_T^\gamma > 25 \text{ GeV}, |\eta| < 1.1 \), and photon ID). The z-axis units are \( fb/(10 \text{ GeV})^2 \) after applying the rescalings relevant for the \( D\phi \) GMSB search.

15 \( fb^{-1} \) of data. Here, we attempt to extrapolate these analyses to the broader di-photon spectrum expected from Higgs decays to unstable neutralino pairs.

The ATLAS inclusive \( h^0 \rightarrow \gamma\gamma \) analysis presented in Ref. [64] requires two well-reconstructed photons with \( p_T^\gamma > 40 \text{ GeV} \), 25 GeV and \( 0 < |\eta| < 1.37 \) or \( 1.52 < |\eta| < 2.37 \). The total detection efficiency for di-photons from a 120 GeV Higgs after applying these cuts (along with photon ID requirements) is \( \varepsilon \approx 0.36 \) in the absence of pile-up. As in our Tevatron analyses, we assume that \( \varepsilon = A\tilde{\varepsilon} \), where \( A \) is the probability that the signal passes the \( p_T^\gamma \) and \( \eta \) cuts, and that the reduced efficiency \( \tilde{\varepsilon} \) is effectively constant. Simulating \( h^0 \rightarrow \gamma\gamma \) events in PYTHIA, we deduce \( \tilde{\varepsilon} \approx 0.59 \), which is consistent with the general photon detection efficiencies discussed in Ref. [64]. When simulating signal events from \( h^0 \rightarrow \chi^0_1 \chi^0_1 \), we consider GF, \( W/Z \)-associated production, and VBF, and scale the production cross-sections by factors of \( K_{GF} = 3.2 \) [58, 59], \( K_{W/Z} = 1.3 \) [60, 61], and \( K_{VBF} = 1 \) [65], where the particular values are chosen to rescale the PYTHIA values to higher-order estimates.

In Fig. 5 we show the expected Higgs boson signal for the MSSM sample point described in the previous section after imposing the cuts and scalings discussed above. In this figure we also show the di-photon signal from SUSY cascade events. The dominant contribution in this case comes from gluino production (\( M_3 = 800 \text{ GeV} \)), but electroweak neutralino and chargino production is also significant. The SUSY signal with \( m_{\gamma\gamma} < m_h \) is seen to be subleading relative to the Higgs contribution. To evaluate the significance of the \( h^0 \rightarrow \chi^0_1 \chi^0_1 \) di-photon
signal, we estimate the SM background by making a power-law extrapolation to the inclusive di-photon background in Ref. [64]. We find that the statistical signal significance $S/\sqrt{B}$ is optimized if we require $60 \text{ GeV} < m_{\gamma\gamma} < 90 \text{ GeV}$, yielding about 224 total signal events and 44000 background events, corresponding to $S/\sqrt{B} \simeq 1.1$ with 1 $fb^{-1}$ of data. Scaling up by luminosity, a discovery in this inclusive channel based on statistics alone would require at least 20 $fb^{-1}$ of data. This number will be strongly degraded by pile-up and systematics given the very low value of $S/B$, but it should also be improvable with a more clever analysis, possibly using a mild $\not{E}_T$ cut. At this point let us also mention that we have focused on ATLAS searches here because the CMS di-photon search has a slightly harder photon $p_T$ requirement of $p_T^{\gamma} > 40 \text{ GeV}$, 35 GeV [65] which significantly reduces the signal acceptance.

Both ATLAS and CMS also plan to perform di-photon Higgs searches in the exclusive vector boson fusion (VBF) and associated $W/h$ and $Z/h$ channels. These modes have lower production cross-sections, but the extra products in the events, a pair of forward tagging jets or a lepton, allow for a significant reduction in background. To illustrate the potential power of these channels, we focus on the proposed CMS search for di-photons from $W/h$ and $Z/h$ associated production [65, 66]. Their strategy is to look for a photon pair together with at least one lepton ($e$ or $\mu$). Both photons are required to have $p_T^{\gamma} > 35$, 20 GeV, and $|\eta| < 2.5$.

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7Our very approximate background estimate is $\frac{d\sigma}{dm_{\gamma\gamma}} \simeq (100 \text{ fb/Gev}) \left( \frac{m_{\gamma\gamma}}{150 \text{ GeV}} \right)^{-3.7}$ based on Fig. 6 of the $h^0 \rightarrow \gamma\gamma$ analysis of Ref. [64].
As above, we deduce a reduced efficiency $\varepsilon$ for the subset of events with photons passing these cuts by simulating direct Higgs boson decays to di-photons in PYTHIA. We obtain $\varepsilon = 0.56, 0.33$ for $W/h$ and $Z/h$, respectively, along with a $K$-factor of 1.3 for the production cross-section to match onto higher-order estimates [60, 61]. Combining these factors, we estimate a total of 6.7 signal events per $fb^{-1}$ of data in the di-photon invariant mass window of $20 \text{ GeV} < m_{\gamma\gamma} < 90 \text{ GeV}$. The estimated background rates listed in Tables 10.26 and 10.27 of Ref. [65], without restricting $m_{\gamma\gamma}$, is about 28 $fb$, yielding a statistical significance of $S/\sqrt{B} \simeq 1.26$ with 1 $fb^{-1}$ of data. This corresponds to a 5 $\sigma$ discovery with about 16 $fb^{-1}$ of data, and the prospects will improve even further once the backgrounds are restricted to lie within the signal acceptance window. Note that this is considerably better than the estimated significance for the direct di-photon channel [65] due to the larger signal rate. More generally, we expect that any search channel that uses relatively weak photon $p_T$ requirements along with an additional handle to remove backgrounds will be effective for searching for di-photons from $h^0 \rightarrow \chi^0_1 \chi^0_1$. Other examples include VBF and $t\bar{t}h$ associated production.

One additional strategy that could prove useful is to make use the ability of ATLAS to reconstruct photon “tracks”. Using the ECAL alone, the primary di-photon vertex can be identified to within about 1.5 cm along the beam axis [64]. However, a significant fraction of hard photons interact with material in the trackers and convert to an $e^+e^-$ pair. A converted photon can therefore give rise to charged tracks allowing for a very precise determination of the primary photon vertex position. Estimates in Ref. [64] suggest this determination could be as good as $5 \times 10^{-3}$ cm. This is useful in regular Higgs searches for determining the location of primary interaction vertex. In the case of neutralino decays to gravitinos and photons in low-scale gauge mediation, vertexing the products of double photon conversions might allow for a measurement of the neutralino lifetime, even when the neutralino decays are otherwise “prompt”.

5 Conclusions

Decays of a SM-like Higgs boson to a pair of neutralinos, each of which subsequently decays to a photon and a gravitino, can arise in generalized gauge-mediated supersymmetric scenarios. This channel leads to a signal consisting of a di-photon pair plus missing energy at high energy colliders. In the present work we have investigated this possibility within the MSSM, and we find that neutralino branching fractions of the Higgs as large as 0.15 can be consistent with existing collider bounds. For branching fractions not too far below this upper bound, both the Tevatron and the LHC can potentially observe the Higgs boson through this non-standard decay channel.

The most promising Tevatron searches for this Higgs mode look for di-photon events with a small amount of missing energy, much like in the existing $D\phi$ searches for GMSB. Our preliminary analysis suggests that evidence for the Higgs boson can be obtained with $10 \text{ fb}^{-1}$ of data. Improvements in detection efficiencies and optimized analysis techniques making use of shape information in the $m_{\gamma\gamma} - E_T$ plane could potentially lead to a discovery,
although a more careful analysis by the collaborations is needed before a firm conclusion can be drawn.

At the LHC, this unusual Higgs boson decay channel can be probed efficiently in associated production channels that use relatively mild cuts on the photon momenta. Inclusive production with a mild $E_T$ cut may also be useful for probing this decay mode, though in this case a more careful study of the backgrounds is required. In principle, the neutralino mass can be determined from the endpoint of the di-photon mass distribution in this channel once the Higgs boson mass is known. Photon conversions may also provide information about the lifetime of the unstable neutralino and the mass of the gravitino.

In the present work we have focused on Higgs decays to neutralinos in the MSSM, but even more possibilities can arise in extensions with additional singlets \[67, 68\]. In this case the Higgs boson can potentially have significant branching ratios to any neutralinos that are mostly bino or singlino. Depending on the precise spectrum and pattern of mixing angles, various signatures involving photons and missing energy are possible. Another interesting possibility occurs if the spectrum also contains a light pseudoscalar $a_1$, allowing for example the decays $h^0 \rightarrow \chi_1^0 \chi_1^0$ with $\chi_1^0 \rightarrow a_1 \tilde{G}$. This could lead to collider signatures similar to those considered in Ref. \[69\], but with modified kinematics and missing energy. We hope to study these possibilities in a future work \[70\].

Finally, we would like to emphasize the importance of searching broadly for new physics in upcoming collider data. In the present analysis we have found that in many cases cuts imposed while optimizing searches for new physics in other channels also cut out the majority of the signal in the non-standard Higgs channel we are interested in. Given the wide variety of possibilities for new physics beyond the standard model, we feel that it is most prudent to cast our experimental nets as widely as practicable.

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