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Higgs and Z -boson Signatures of Supersymmetry

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Abstract

In supersymmetric theories of nature the Higgsino fermionic superpartner of the Higgs boson can arise as the lightest standard model superpartner depending on the couplings between the Higgs and supersymmetry breaking sectors. In this letter the production and decay of Higgsino pairs to the Goldstone fermion of supersymmetry breaking and the Higgs boson, h , or gauge bosons, Z or γ are considered. Relatively clean di-boson final states, hh , $h\gamma$, hZ , $Z\gamma$, or ZZ , with a large amount of missing energy result. The latter channels provide novel discovery modes for supersymmetry at high energy colliders since events with Z bosons are generally rejected in supersymmetry searches. In addition, final states with real Higgs bosons can potentially provide efficient channels to discover and study a Higgs signal at the Fermilab Tevatron Run II.

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1 Introduction

Supersymmetry (SUSY) provides perhaps the best motivated extension of the Standard Model. Spontaneous SUSY breaking leads naturally to radiative electroweak symmetry breaking with masses of order the electroweak scale for the superpartners of the Standard Model (SM) particles. If the messenger interactions which couple the SM superpartners to the SUSY breaking sector are stronger than gravity, the lightest supersymmetric particle (LSP) is the Goldstone fermion of supersymmetry breaking, the Goldstino \tilde{G} . The next to lightest supersymmetric particle (NLSP) is generally the lightest SM superpartner. If the intrinsic scale of supersymmetry breaking is below $\sim 10^3$ TeV the NLSP can decay to its SM partner and the Goldstino on laboratory length scales [1]. This has an important impact on experimental SUSY signatures at high energy colliders. Since superpartners are generally produced in pairs, these decays give rise to final states with two hard partons and missing energy (\cancel{E}_T) carried by the Goldstino pair, and with possibly other partons in the final state from cascade decays to the NLSP [1, 2, 3].

The identity of the NLSP determines the type of final states which arise from decay to the Goldstino [3]. A neutralino NLSP, $\tilde{\chi}_1^0$, which is gaugino-like, can decay by $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, leading to final states with $\gamma\cancel{E}_T$. A slepton NLSP, $\tilde{\ell}$, can decay by $\tilde{\ell} \rightarrow \ell\tilde{G}$, giving $\ell\cancel{E}_T$ final states. In this letter we consider in detail the possibility of a fermionic Higgsino-like neutralino NLSP. Because it is the superpartner of the Higgs boson, h , a Higgsino NLSP can decay by $\tilde{\chi}_1^0 \rightarrow h\tilde{G}$. In addition, since the longitudinal component of the Z boson mixes with the Goldstone mode of the Higgs field, $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$ can also result. Because of a strong phase space suppression of the h and Z final states near threshold, decay to a photon can also be important for Higgsinos not too much heavier than the Z boson. Pair production of Higgsinos which decay to Goldstinos can then give rise to the di-boson final states $(hh, h\gamma, hZ, Z\gamma, ZZ)\cancel{E}_T$ [4].

Di-boson signatures which include Higgs and Z bosons and \cancel{E}_T are quite novel discovery modes for supersymmetry in the mass range accessible to the current generation of high energy

collider experiments. In conventional SUSY signatures, in which the lightest neutralino, $\tilde{\chi}_1^0$, is assumed to escape the detector without decay to the Goldstino, the mass splittings between supersymmetric particles required in order for h or Z to arise in a cascade decay, typically imply the superpartners are too heavy to be produced in sufficient numbers at present colliders. For this reason events with reconstructed Z bosons are in fact generally rejected in present SUSY searches. However, since the Goldstino is essentially massless, sufficient phase space is available for the $h\tilde{G}$ and $Z\tilde{G}$ modes for a Higgsino somewhat heavier than h or Z . And this mass range will be accessible at the upcoming Run II at the Fermilab Tevatron. The Higgs final states also present the exciting possibility of discovering and studying the Higgs boson in association with supersymmetry.

If supersymmetry is broken at a low scale, as required for the di-boson signatures discussed here, it is very likely that the SM gauge interactions play some role in coupling the SUSY breaking sector to the SM superpartners [2]. However, such gauge-mediated SUSY breaking requires additional interactions between the Higgs and SUSY breaking sectors in order to break certain Higgs sector global symmetries and obtain acceptable electroweak symmetry breaking [3]. These interactions can modify the Higgsino mass from minimal expectations, and allow for a Higgsino NLSP. So searches for di-boson signatures of a Higgsino NLSP within theories of low scale gauge-mediated SUSY breaking are very well motivated as possible indirect probes for the existence of these additional couplings.

2 Higgsino decays and production

The Higgsinos \tilde{H}_u and \tilde{H}_d are fermionic superpartners of the Higgs boson fields H_u and H_d . The neutral Higgsinos mix with the gaugino superpartners of the γ and Z gauge bosons, while the charged Higgsino mixes with the gaugino superpartner of the W gauge boson. In the limit relevant here, in which the gauginos are heavier than the Higgsinos, the two lightest neutralinos and lightest chargino, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, are predominantly Higgsino and approximately

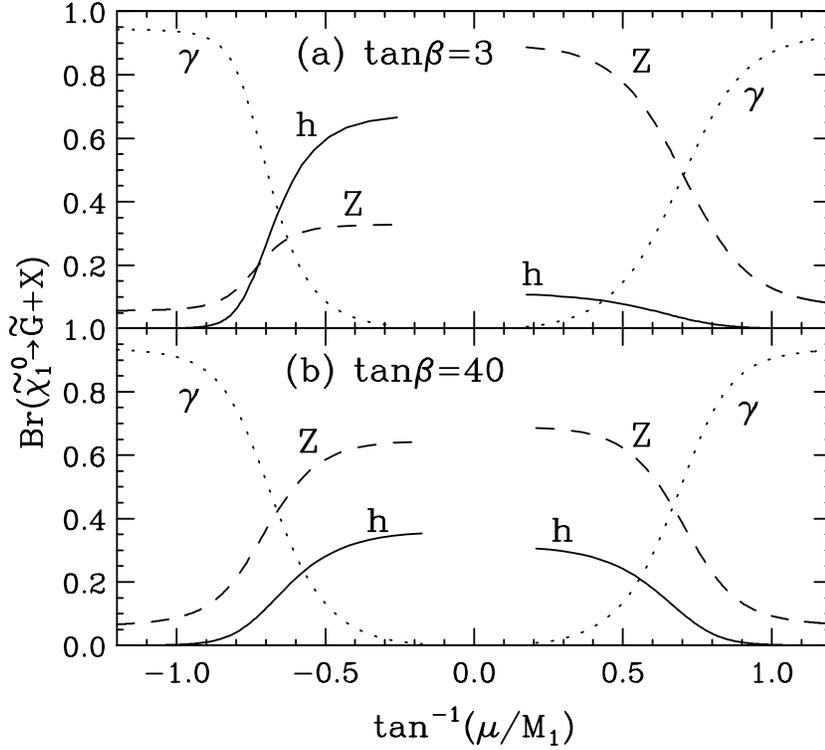


Figure 1: Branching ratios of the lightest neutralino $\text{Br}(\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma, h, Z)$ as a function of the neutralino mixing angle $\tan^{-1}(\mu/M_1)$, for a fixed mass $M_{\tilde{\chi}_1^0} = 160$ GeV and $m_h = 105$ GeV for (a) $\tan \beta = 3$ and (b) $\tan \beta = 40$.

degenerate. The splitting between these states is on the order of 10-15 GeV for masses in the range 120-250 GeV discussed below. If the $U(1)_Y$ and $SU(2)_L$ gaugino mass parameters, M_1 and M_2 , have the same sign, $\text{sgn}(M_1 M_2) = +$ then $\tilde{\chi}_1^0$ is the NLSP. For $\text{sgn}(M_1 M_2) = -$ it is however possible in certain regions of parameter space that $\tilde{\chi}_1^\pm$ is the NLSP. In this letter only a $\tilde{\chi}_1^0$ NLSP, which leads to the interesting di-boson signatures, will be considered.

The branching ratios $\text{Br}(\tilde{\chi}_1^0 \rightarrow \tilde{G} + (\gamma, h, Z))$ are determined by the Higgsino and gaugino content of $\tilde{\chi}_1^0$ [3, 5]. This is illustrated in Fig. 1 as a function of the neutralino mixing angle $\tan^{-1}(\mu/M_1)$ for fixed $\tilde{\chi}_1^0$ mass, where μ is the Higgsino mass parameter, and $\tan \beta = v_u/v_d$ is the ratio of Higgs expectation values. For definiteness the Higgs decoupling limit in which decays to the heavy scalar and pseudoscalar Higgs bosons, H and A , are kinematically blocked is employed throughout. For gaugino-like $\tilde{\chi}_1^0$ the γ mode dominates, but for Higgsino-like $\tilde{\chi}_1^0$

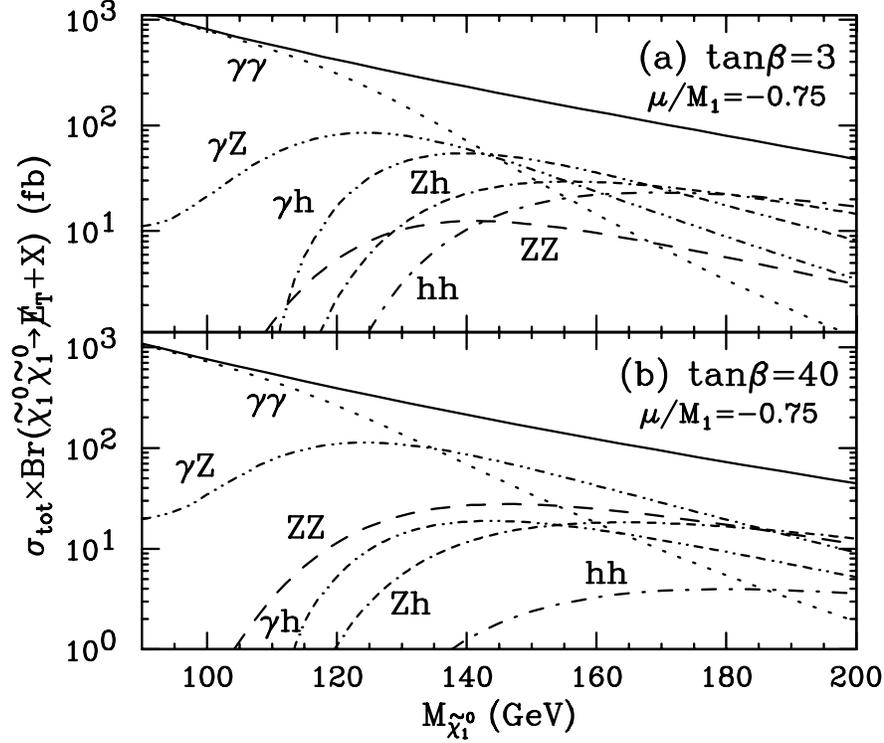


Figure 2: Total cross-section $\sigma_{tot}(p\bar{p} \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-)$ in fb for $i, j = 1, 2$ times the branching ratio into various di-boson final states as a function of the lightest Higgsino mass $M_{\tilde{\chi}_1^0}$, for a fixed ratio $\mu/M_1 = -3/4$, with (a) $\tan\beta = 3$ or (b) $\tan\beta = 40$. The center of mass energy is 2 TeV and $m_h = 105$ GeV. The solid line indicates the total cross section.

the h and Z modes become important. The dependence on $\text{sgn}(\mu)$ and $\tan\beta$ apparent in Fig. 1 can be understood in terms of the $\tilde{\chi}_1^0$ quantum numbers and couplings and will be presented elsewhere.

The branching ratios also depend on the $\tilde{\chi}_1^0$ mass through the phase space available to the h and Z modes which suffer a β^4 velocity suppression near threshold [3, 5]. So even a Higgsino-like $\tilde{\chi}_1^0$ decays predominantly by $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ for masses not too far above the h and Z masses. The mass dependence of the branching ratios is illustrated in Fig. 2 in which the $p\bar{p}$ signal cross section times branching ratio into the di-boson final states is given as a function of the $\tilde{\chi}_1^0$ mass for fixed Higgsino-neutralino mixing. With $\tilde{\chi}_1^0$ Higgsino-like the hh , ZZ , or hZ modes dominate for very large masses, while the $\gamma\gamma$ mode dominates for smaller masses.

However, because of the strong phase space suppression near threshold there is a transition region which extends over a significant range of mass between these limits in which the mixed final states γh and/or γZ (depending on $\text{sgn}(\mu)$ and $\tan\beta$) are important. These final states are particularly useful for masses in the transition region since the photon is quite hard.

The total cross section $\sigma_{tot}(p\bar{p} \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_1^+ \tilde{\chi}_1^-)$ for $i, j = 1, 2$ in Fig. 2, summed over all the Higgsino-like states, is the relevant signal cross section since these states are approximately degenerate, and can all be produced at similar rates. The heavier states cascade decay to $\tilde{\chi}_1^0$ through neutral and charged current interactions. The partons from these cascade decays are relatively soft and probably not particularly useful at the trigger level.

3 Z boson final states

The final states with a Z boson can be significant for large $\tan\beta$, or at small $\tan\beta$ with $\mu > 0$. The Z boson can decay invisibly, leptonically, or hadronically, $Z \rightarrow \nu\nu, \ell\ell, jj$, leading to many possible signatures. The ee and $\mu\mu$ leptonic decays allow the possibility of precise reconstruction of the Z invariant mass, but suffer from small branching ratio, $\text{Br}(Z \rightarrow ee, \mu\mu) \simeq 6.7\%$. In contrast, the invisible and hadronic decay modes can be useful because of larger branching ratios, $\text{Br}(Z \rightarrow \nu\nu) \simeq 20\%$, and $\text{Br}(Z \rightarrow jj) \simeq 70\%$.

The $\gamma Z \cancel{E}_T$ di-boson mode dominates the total cross section in the transition region of masses as shown in Fig. 2(b). Leptonic decay of the Z provides the cleanest final state, $\gamma\ell^+\ell^-\cancel{E}_T$, which is similar to existing SM $Z\gamma$ studies without \cancel{E}_T [6, 7]. For a Higgsino search, however, an additional large \cancel{E}_T cut, as well as a more stringent photon E_T cut should reduce the backgrounds to a negligible level. Our Monte Carlo estimates indicate that this channel is practically background free, but is limited by the small leptonic branching ratio of the Z boson. The Tevatron Run IIa with 2 fb^{-1} of integrated luminosity will have a reach at the 3σ discovery level for $\tilde{\chi}_1^0$ masses up to 155 GeV for the parameters of Fig. 2(b), while the reach in Run IIb with 30 fb^{-1} should approach 220 GeV.

Invisible decay of the Z gives rise to the signature $\gamma\cancel{E}_T$. This channel has been studied in Run I as a probe for anomalous γZ couplings [8, 9]. Backgrounds include γj and jj with one jet faking a photon *and* in each case the remaining jet energy mismeasured to be below the minimum pedestal. The largest background in Run I was from single W production with $W \rightarrow e\nu$ and the electron misidentified as a photon. This background can be substantially reduced by raising the photon E_T and \cancel{E}_T cuts above 50 GeV, beyond the Jacobian peak for $W \rightarrow \ell\nu$ [10]. This also reduces the hadronic background. The 3σ discovery reach in $\tilde{\chi}_1^0$ mass should then approach 150 (185) GeV in Run IIa (IIb) for the parameters of Fig. 2(b).

Hadronic decay of the Z in the $\gamma Z\cancel{E}_T$ mode gives rise to the signature $\gamma jj\cancel{E}_T$. Backgrounds are similar to those of the $\gamma\cancel{E}_T$ channel. The $\gamma jj\cancel{E}_T$ channel has been studied in Run I in order to place limits on squark and gluino masses in very specific supersymmetric models [11]. Further background suppressions not included in the Run I study are possible with acoplanarity, sphericity and invariant dijet mass cuts to reconstruct the Z boson, and a lepton veto. In any case, the total background is expected to be smaller than for the $\gamma\cancel{E}_T$ channel, due to the presence of two additional hard partons. Given the significant Z hadronic branching ratio, the $\gamma jj\cancel{E}_T$ channel should provide somewhat better reach than the $\gamma\ell^+\ell^-\cancel{E}_T$ or $\gamma\cancel{E}_T$ channels in Run II.

The $ZZ\cancel{E}_T$ di-boson mode dominates at larger $\tilde{\chi}_1^0$ mass as shown in Fig. 2(b). Leptonic decay of each Z boson gives rise to the spectacular signature $\ell^+\ell^-\ell'^+\ell'^-\cancel{E}_T$, with the lepton pairs reconstructing the Z mass (in one choice of pairing for $\ell = \ell'$). This channel is expected to be essentially background free, but suffers from small leptonic branching ratio. Because of this Run IIb will not be sensitive to this channel for the parameters of Fig. 2. But for $\mu/M_1 = 1/3$ and $\tan\beta = 3$ with larger $\text{Br}(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})$ (c.f. Fig. 1), the 3σ discovery reach in Run IIb for the $\tilde{\chi}_1^0$ mass is 170 GeV. At the LHC $\ell^+\ell^-\ell'^+\ell'^-\cancel{E}_T$ would represent the gold plated channel for the $ZZ\cancel{E}_T$ di-boson mode from Higgsino decay.

Hadronic decay of one of the Z bosons gives the signature $\ell^+\ell^-\cancel{E}_T$. An important

background in this channel comes from $t\bar{t}$ production with $t \rightarrow Wb$ and $W \rightarrow \ell\nu$ with the $\ell^+\ell^-$ pair reconstructing the Z mass, and each b -jet not identified as a heavy flavor. Other backgrounds arise from ZZ and WZ in association with jets. In Run IIb the 3σ discovery reach in $\tilde{\chi}_1^0$ mass should approach 195 GeV for $\mu/M_1 = 1/3$ and $\tan\beta = 3$. Rejecting backgrounds for the other decay channels of the $ZZ\not{E}_T$ di-boson mode presents more serious challenges.

4 Higgs boson final states

The decay of Higgsinos to real Higgs bosons gives perhaps the most interesting di-boson final states because of the opportunity to study both supersymmetry and the Higgs sector. Higgs boson final states are important for small $\tan\beta$ and $\mu < 0$ or for large $\tan\beta$ with sufficiently large $\tilde{\chi}_1^0$ mass, as shown in Figs. 1 and 2.

In the transition region of $\tilde{\chi}_1^0$ mass, $\gamma h\not{E}_T$ is the most important di-boson mode. With the dominant decay $h \rightarrow bb$ this leads to the signature $\gamma bb\not{E}_T$. Backgrounds include $Z\gamma j$ and Zjj with $Z \rightarrow bb$ and $bb\gamma j$ and $bbjj$ with one jet misidentified as a photon *and* in each case the remaining jet energy mismeasured to be below the minimum pedestal. Based on the work presented here [4] it has been estimated [12] that with a single b -tag the 3σ discovery reach in $\tilde{\chi}_1^0$ mass should approach 210 (250) GeV in Run IIa (IIb) for the parameters of Fig. 2(a).

For larger $\tilde{\chi}_1^0$ masses the $hZ\not{E}_T$ and/or $hh\not{E}_T$ modes can become important, as shown in Fig. 2. The $hh\not{E}_T$ di-boson final state gives rise to the signature $bbbb\not{E}_T$. The sizeable QCD and electroweak backgrounds to this final state can be significantly reduced by requiring at least 3 tagged b -jets with large invariant mass for two b -jet pairs [4], as verified by Monte Carlo simulation [13]. Remaining backgrounds include ZZj with each $Z \rightarrow bb$, $bbjj$ with one jet misidentified as a b -jet, and $bbbbj$ with in each case the jet energy mismeasured to be below the minimum pedestal, and $t\bar{t}$ production with $t \rightarrow Wb$ and one hadronic decay $W \rightarrow jj$ with one jet misidentified as a b -jet, and one leptonic decay $W \rightarrow \ell\nu$ with ℓ not identified. Accounting for the $t\bar{t}$ background [13], the 3σ discovery reach in $\tilde{\chi}_1^0$ mass at Run IIb should

approach 240 GeV for the parameters of Fig. 2(a).

The $hZ\cancel{E}_T$ di-boson mode arising from Higgsino decay is similar to direct hZ production. Invisible decay of the Z gives the signature $bb\cancel{E}_T$, and would contribute slightly to searches for the SM Higgs boson in this channel. Leptonic decay of the Z gives the signature $\ell^+\ell^-bb\cancel{E}_T$. Unfortunately, the dominant background from $t\bar{t}$ production with $t \rightarrow Wb$ and $W \rightarrow \ell\nu$ with the $\ell^+\ell^-$ pair reconstructing the Z mass, is very similar to the signal. Because of this, Run II is not expected to be sensitive to this channel. Hadronic decay with $Z \rightarrow bb$ gives the signature $bbbb\cancel{E}_T$, similar to the $hh\cancel{E}_T$ mode. However, because of the smaller branching ratio, $\text{Br}(Z \rightarrow bb)/\text{Br}(h \rightarrow bb) \simeq 20\%$, Run II will just marginally not be sensitive to the $hZ\cancel{E}_T$ mode in this channel for the parameters of Fig. 2.

The Higgs boson final states of Higgsino decay discussed above present the possibility of collecting a relatively clean sample of events which contain real Higgs bosons. It is therefore interesting to consider the reach as a general function of both Higgsino and Higgs masses. The total cross section times branching ratio contours for the $\gamma bb\cancel{E}_T$ and $bbbb\cancel{E}_T$ channels as a function of the h and $\tilde{\chi}_1^0$ masses are shown in Fig. 3. These contours include $\text{Br}(\chi_1^0 \rightarrow (\gamma, h)\tilde{G})$ for $\tan\beta = 3$ and $\mu/M_1 = -3/4$ and SM values for $\text{Br}(h \rightarrow bb)$. The Run IIa 3σ discovery reach quoted above for the $\gamma bb\cancel{E}_T$ channel corresponds to a signal times branching ratio cross section of 5 fb. For the parameters of Fig. 3 this corresponds to a Higgs mass of up to at least 120 GeV for $\tilde{\chi}_1^0$ masses in the range 135-200 GeV, with a maximum reach in Higgs mass of just over 130 GeV. This is to be contrasted with the search for the SM Higgs from direct Wh and Zh production. These SM channels are background limited, and no sensitivity to a Higgs mass beyond current limits is expected in Run IIa [14]. So the $\gamma bb\cancel{E}_T$ channel presents the interesting possibility for Run IIa of a SUSY signal which contains real Higgs bosons. The Run IIb 3σ discovery reaches quoted above for the $\gamma bb\cancel{E}_T$ and $bbbb\cancel{E}_T$ channels correspond to signal times branching ratio cross sections of 1 fb and 4 fb respectively. For the parameters of Fig. 3 the maximum reach in Higgs mass then corresponds to just over 145 GeV and 115

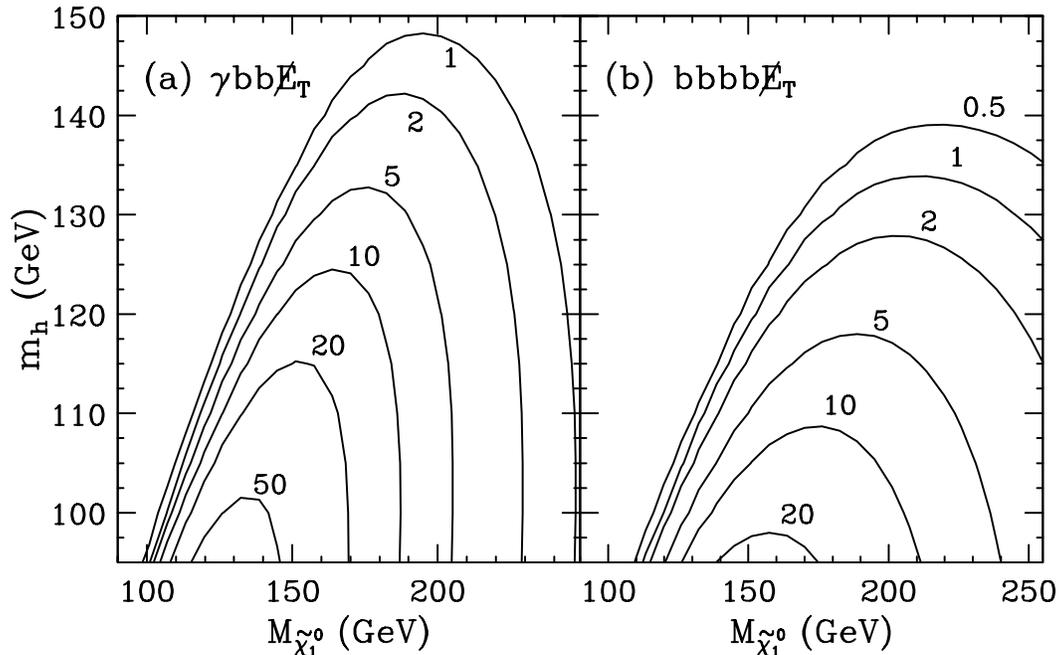


Figure 3: Signal cross-section times branching ratio contours in fb for the (a) $\gamma bb \cancel{E}_T$ and (b) $bbbb \cancel{E}_T$ channels, as a function of the neutralino mass $M_{\tilde{\chi}_1^0}$, and the Higgs mass m_h , for $\tan \beta = 3$ and $\mu/M_1 = -3/4$.

GeV respectively.

In order to identify the Higgs boson directly in a sample of events arising from Higgsino decays it is necessary to observe a peak in the bb invariant mass. The identifiable di-boson final states and large \cancel{E}_T carried by the Goldstinos render the supersymmetric Higgs boson final states discussed here relatively clean. Reconstructing the Higgs mass peak should be relatively straightforward compared to SM Wh and Zh production modes which suffer from much larger continuum bb backgrounds.

All the new signatures presented here involve hard photons, leptons, and/or b -jets, in association with significant missing energy. New triggers are therefore not required, but final state specific off line analysis should be implemented in order to search for supersymmetry and/or the Higgs boson in these interesting channels.

Finally, Higgsino decay with a measurable macroscopic decay length to the Goldstino would render all the di-boson final states discussed here essentially background free. A search for such final states requires a special analysis for displaced $\ell^+\ell^-$, jj , or bb with large invariant mass and approximately uniform angular distribution with respect to the beam axis [15].

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