General Neutralino Parameter Spaces

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I. MOTIVATION

In this note, we will outline several simple MSSM scenarios where the neutralino is the next-to-lightest superpartner (NLSP) [1, 2] within the context of General Gauge Mediation (GGM) [3, 4] including the special case of Gauge Mediation with Split Messengers (GMSM). The lightest neutralino decays to its superpartner (photon, Z, or Higgs) plus a gravitino

$$\chi_1^0 \to (\gamma \ , \ Z \ , \ h \ ) + \tilde{G}$$

In this note we focus on final states where the neutralino decays to a photon or Z. The scenarios we present can be used to explore the discovery potential in early LHC running for final states with photons arising directly from neutralino decay and/or leptons from Z bosons arising from neutralino decay, all with missing energy. The Tevatron constraints on general neutralino NLSPs were studied in Ref. [5].

In General Gauge Mediation, the MSSM soft parameters are essentially free at the messenger scale, subject to the following requirements: flavor universality, two sum rules for the sfermion masses, zero A terms, and gravitino LSP. In particular, there is not necessarily a hierarchy between colored states (squarks, gluinos) and uncolored states (wino, bino, higgsinos, sleptons). Thus there is no theoretical constraint on how light the colored states can be. So within GGM relatively large production cross sections from compressed spectra provide the possibility of discovery even with very early LHC data. This should be contrasted with the more restrictive framework of Minimal Gauge Mediation (MGM) where colored states are always much heavier than the uncolored states, and therefore largely out of reach in early LHC running.

A simple framework in which light colored states and compressed spectra can arise is Gauge Mediation with Split Messengers (GMSM). In this straightforward generalization of MGM, the superpartner spectra are generally grouped in mass roughly into strongly and weakly interacting sets of superpartners. Over much of the parameter space the masses of both these groups can be comparable, yielding relatively compressed spectra with colored

	Bino	Wino	Higgsino (Z-rich)
M_1	vary	1.5 TeV	1 TeV
M_2	1.5 TeV	vary	1 TeV
μ	1.5 TeV	1.5 TeV	vary, $\mu > 0$
$\tan\beta$	2	2	2
$c\tau_{NLSP}$	0.1 mm	0.1 mm	0.1 mm

TABLE I: Benchmark scenarios for the three types of neutralino NLSPs. Other soft parameters depend on the specific scenario for the rest of the superparter spectrum. Soft parameters for states which are decoupled may be set to 1.5 TeV. The Higgs sector may also be taken to be in the decoupling regime with $M_{A^0} = 1.5$ TeV, and with the light Higgs boson mass set to a canonical value such as $M_{h^0} = 120$ GeV.

states not much heavier than weakly interacting states.

For each type of neutralino NLSP there is an huge multi-dimensional parameter space characterizing the remainder of the superpartner spectrum. Defining useable benchmarks within tractable parameter spaces therefore requires additional simplifying assumptions. The main motivation and focus here for early LHC searches is on compressed spectra with significant production cross section from strongly interacting superpartners. In the following sections, we will describe various interesting benchmark scenarios of this type. A script to generate the benchmarks defined here (as well as a wider class of generalizations) is described in section IV.

II. BENCHMARK PARAMETER SPACES

A. Minimal Benchmarks

For inclusive early LHC searches, it is useful to formulate the minimal parameter spaces necessary for producing the signature of interest. For general neutralino NLSPs, these minimal parameter spaces are quite simple indeed: they consist of the neutralino NLSP and the gluino, with all other superpartners decoupled. The neutralino mass is given by M_1, M_2, or μ in the Bino, Wino, or Higgsino case respectively (depending on the neutralino scenario) and gluino mass by M_3. All other soft parameters may be set to some large value such as 1.5 TeV. Specific choices of the parameters are exhibited in Table I. We emphasize that these minimal parameter spaces do correspond to physical models, since the entire GGM parameter space was covered by a perturbative messenger model in [4].

B. GMSM Inspired Benchmarks

For early LHC searches it is also useful to utilize parameter spaces that reproduce the important features of superpartner spectra that arise from simple underlying models. Here we formulate some benchmarks of this type inspired by GMSM.

The first GMSM inspired benchmark is defined to be a neutralino NLSP, a gluino, and (nearly) degenerate squarks, with all other superpartners decoupled. The neutralino mass is given by M_1, M_2, or μ in the Bino, Wino, or Higgsino case respectively, and gluino mass by M_3. The squark soft masses are taken to be degenerate with value $m_{\tilde{q}}$ related to the gluino mass by

$$m_{\tilde{q}} = 0.8 \ M_3$$

The squark mixing is also defined to vanish. This approximates the small mixing that is obtained in almost all theories of low scale gauge mediation. All other soft parameters may be set to some large value such as 1.5 TeV. With both squarks and gluinos in the spectrum, the dominant strong production modes at the LHC are $pp \to \tilde{q}\tilde{q}, \tilde{q}\tilde{g}$ with a small fraction of $\tilde{g}\tilde{g}$. The total strong production cross section for the Tevatron and LHC is shown in Fig. 1.

A final GMSM inspired benchmark for use with the Bino NLSP scenario described below that gives rise to di-photons + MET signatures is defined to the Bino-like neutralino NLSP, degenerate right-handed sleptons, a Wino-like second neutralino and first chargino, degenerate squarks, and a gluino. The inclusion of all these states gives a parameter space that interpolates between weak and strong production - this feature allows a comparison between existing Tevatron bounds (which are based on weak production) and early reach at the LHC from strong production. The Wino and gluino masses given by M_2 and M_3 respectively may be taken to be independent masses for a two parameter parameterization of this benchmark. The Bino, right-handed slepton, and degenerate squark masses may be related to these by

$$m_{\tilde{q}} = 1.3 \ M_3$$

$$m_{\tilde{\ell}_R} = 0.65\ M_2$$

$$M_1 = 0.5\ M_2$$

These ratios are very close to those of minimal gauge mediation with $N = 1$ messenger family. All other soft parameters may be set to some large value such as 1.5 TeV. Keeping M_2 and M_3 independent allows for compressed spectra with strong production.

III. SIGNATURES

In the following subsections, we will describe the promising final states for early LHC running (7 TeV, $\lesssim 1\ \mathrm{fb}^{-1}$). We consider a final state "promising" if it contains at least one photon or two leptons coming from NLSP decay, and if it is not utterly suppressed by branching fractions.

A. Bino NLSP

For bino NLSP, since the bino has a small direct production cross-section, the dominant production for the minimal benchmark is gluino pair production (with cross-section determined by the gluino mass) and for the GMSM inspired benchmarks in addition qluino-squark and squark-squark production, as well as Wino pair production for the final benchmark described above with weak production. The produced states always cascade decay down to the bino NLSP, which then decays to either $\gamma + \tilde{G}$ or $Z + \tilde{G}$. For $m_{\tilde{B}} \gg m_Z$, this happens in a 0.77 : 0.23 ratio. The final states which contain either one photon or two leptons are: $\gamma + X + \not{E}_T$, $Z(\ell\ell) + X + \not{E}_T$, $\gamma\gamma + \not{E}_T$, $\gamma Z(\ell\ell) + \not{E}_T$, $Z(\ell\ell)Z(\ell\ell) + \not{E}_T$. The last has too small of a branching fraction to be useful, so we will ignore it (however, the Higgsino NLSP will populate this final state, see below). We also lump the hadronic and invisible decays of the Z into the inclusive "X" category. The $\sigma \times \mathrm{Br}$ for the minimal benchmark in the above final states is given in Figure 2.

B. Wino NLSP

Here production arises from both colored states that decay to the Wino and directly from Wino pair production, so the production cross-section is controlled by both the gluino mass and the wino mass. The wino chargino and neutralino are nearly mass degenerate and form co-NLSPs, so we have to keep track of which -ino the colored states decay into. When the squarks are heavier than the gluino, as in the minimal benchmark, each gluino decays to a charged wino with branching fraction $\sim 60\%$ and a neutral wino the remaining $\sim 40\%$. The CC case leads to $W^+(\ell\nu)W^-(\ell\nu) + \not{E}_T$. The CN case leads to $\gamma + X + \not{E}_T$, $W^+(\ell\nu)\gamma + \not{E}_T$, $Z(\ell\ell) + X + \not{E}_T$, or $W(\ell\nu)Z(\ell\ell) + \not{E}_T$. The NN case leads to the same final states as bino NLSP, except now with the reversed ratio of $\gamma + \tilde{G}$ to $Z + \tilde{G}$. The $\sigma \times$ Br of the above final states for the minimal benchmark is given in Figure 3.

C. Z-rich Higgsino NLSP

Here as for the winos, the Higgsinos can be directly produced, or produced in decays of colored states, so the overall cross-section is controlled by both the gluino and Higgsino masses. For all the benchmarks defined here we choose parameters such that the heavier Higgsino states always decay down to the lightest Higgsino neutralino. That is, there is no co-NLSP, just a single Higgsino NLSP. In particular, we choose to change the gravitino mass with the Higgsino mass such that the Higgsino decay length is fixed ~ 0.1 mm. For this decay length, the charged Higgsino always decays first to the neutral Higgsino. The NLSP in turn can decay either to photon, Z or Higgs. For the Z-rich case (low $\tan\beta$, $\mu > 0$), the branching ratio to Higgs is negligible, and the branching ratio to photon is negligible except when the NLSP is very light and the Z decay mode is squeezed. Thus for Z-rich Higgsino NLSPs, the available final states are $Z(\ell\ell) + X + \not{E}_T$ and $Z(\ell\ell)Z(\ell\ell) + \not{E}_T$. The $\sigma \times$ Br of the above final states for the minimal benchmark is given in Figure 4.

IV. MONTE CARLO SIMULATIONS

Monte Carlo event simulation can be performed using PYTHIA in conjunction with a SUSY Les Houches Accord file containing a mass spectrum and decay table. Before generating events, the user needs to specify that PYTHIA should read information in from a SUSY Les Houches Accord file by setting the switch `IMSS(1)=11` and by pointing `IMSS(21-22)` to the relevant file. Additionally, for the GMSB scenario it is absolutely crucial that the user turns on gauge mediation and specifies the gravitino mass using the following PYTHIA switches:

$$\texttt{IMSS(11)=1}$$
$$\texttt{RMSS(21)=}m_{\tilde{G}}$$

where $m_{\tilde{G}}$ is the gravitino mass in units of eV. For a prompt decay of the NLSP to the gravitino and its partner particle a canonical value of the supersymmetry breaking scale is 30 TeV which is equivalent to a gravitino mass of 0.2 eV. Setting `IMSS(11)=1` instructs PYTHIA that the lightest neutralino $\tilde{\chi}_1^0$ should be taken to be the NSLP and that the gravitino $\tilde{G}$ should be taken to be the LSP.

To generate a mass spectrum and decay table in SUSY Les Houches Accord format for the the benchmark scenarios described above , we have included a package containing scripts that run the SuSpect supersymmetric spectrum generator with the SDecay branching fraction calculator. The package can be downloaded from the following location

http : //www.physics.rutgers.edu/ q1park/GMSBSLHA.tar.gz

Once the package has been downloaded, the user should unzip the package by typing the following into the command line:

```
tar -zxvf GMSBSLHA.tar.gz
```

The user should then enter the folder `/GMSBSLHA/susylha/` and type `make` into the command line. This will produce all of the machinery necessary to generate the SUSY Les Houches Accord files.

Included in the package is a script called GMSBneut which interactively takes user inputs, runs SuSpect and SDecay, then saves the information in SUSY Les Houches Accord format. To run the script, the user should simply enter the `/GMSBSLHA/` directory and type:

```
./GMSBneut
```

The user will then be prompted to enter a file name for the SUSY Les Houches Accord file. Three more input lines prompt the user to enter the Bino, Wino, and Gluino masses, the Higgsino mass μ-parameter and $\tan\beta$, the right and left handed slepton and squark masses for the first and second generation, and the third generation slepton and squark soft masses.

General neutralino and chargino mixing is calculated based on the input parameters. All masses are entered in units of GeV, and multiple entries after an input prompt should be separated by a single space. All right and left handed sleptons and squark soft parameters are set equal to the input slepton and squark masses respectively internally in the script. Left-Right mixing for third generation sleptons and squarks is fixed internally to vanish. This feature allows a smooth decoupling of the Higgsino mass μ-parameter while leaving squark and slepton spectra unaffected. With these assumptions all right handed sleptons are degenerate as are all left handed sleptons, and all squarks are effectively degenerated except for the top squarks which have a mass squared given by $m_{\tilde{t}}^2 = m_{\tilde{q}}^2 + m_t^2$. From these inputs and the assumptions detailed above, an slha output file is then created in `/GMSBSLHA/` for use with PYTHIA. The slha file contains masses for all MSSM particles and branching ratios for the important decay processes except for the neutralino decays which are commented out. With the neutralino decay modes commented out, Pythia calculates the branching ratios for neturalino decays to the gravitino internally.

The following is an example of the command line prompts and how the commands should be formatted:

```
% ./GMSBneut
Input the name of the slha file to be generated, followed by [ENTER]:
testfile
Input M1, M2, M3 (Bino, Wino and Gluino masses) separated by single space,
followed by [ENTER]:
120 240 500
Input Mu (Higgsino mass) and TANBETA, separated by single space, followed
by [ENTER]:
1000 2
Input MeR, MeL, and MQ (Left and Right Handed Slepton and Squark Masses)
separated by single space, followed by [ENTER]:
156 1000 650
Input MtauR, MtauL, MBR, MTR, MQ3 (Left and Right Handed Stau, Right handed
Sbottom and Stop, and Sbottom-Stop doublet masses) separated by single
spaces, followed by [ENTER]:
```

```
156 1000 650 650 650
```

This will produce a file called `testfile.slha` according to all of the above inputs.

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[1] S. Dimopoulos, M. Dine, S. Raby and S. D. Thomas, "Experimental Signatures of Low Energy Gauge Mediated Supersymmetry Breaking," Phys. Rev. Lett. **76**, 3494 (1996) [arXiv:hep-ph/9601367].

[2] R. L. Culbertson *et al.* [SUSY Working Group Collaboration], "Low scale and gauge mediated supersymmetry breaking at the Fermilab Tevatron Run II," arXiv:hep-ph/0008070.

[3] P. Meade, N. Seiberg and D. Shih, "General Gauge Mediation," Prog. Theor. Phys. Suppl. **177**, 143 (2009) [arXiv:0801.3278 [hep-ph]].

[4] M. Buican, P. Meade, N. Seiberg and D. Shih, JHEP **0903**, 016 (2009) [arXiv:0812.3668 [hep-ph]].

[5] P. Meade, M. Reece and D. Shih, JHEP **1005**, 105 (2010) [arXiv:0911.4130 [hep-ph]].

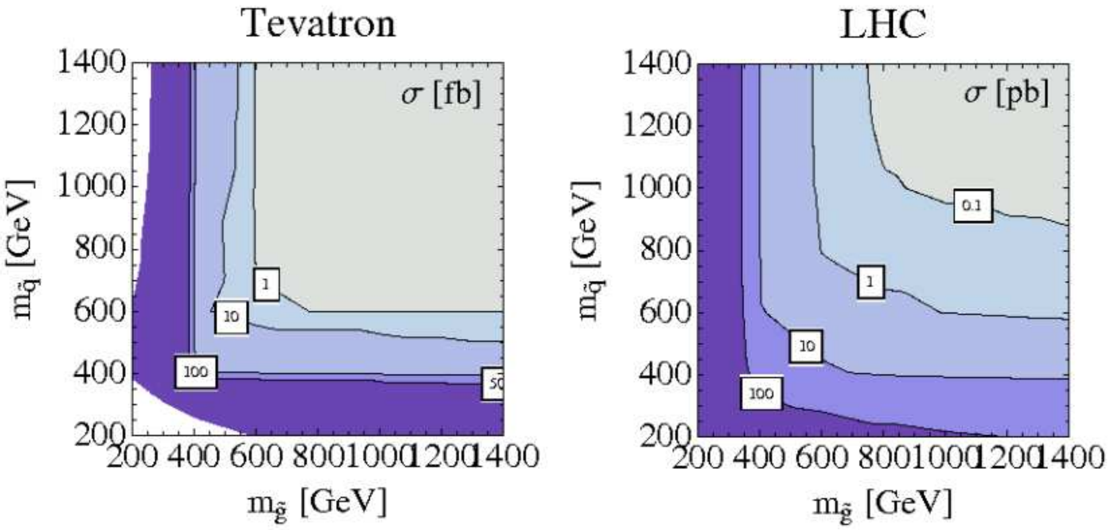

FIG. 1: σ_{tot} for strong production at the Tevatron and LHC at 7 TeV.

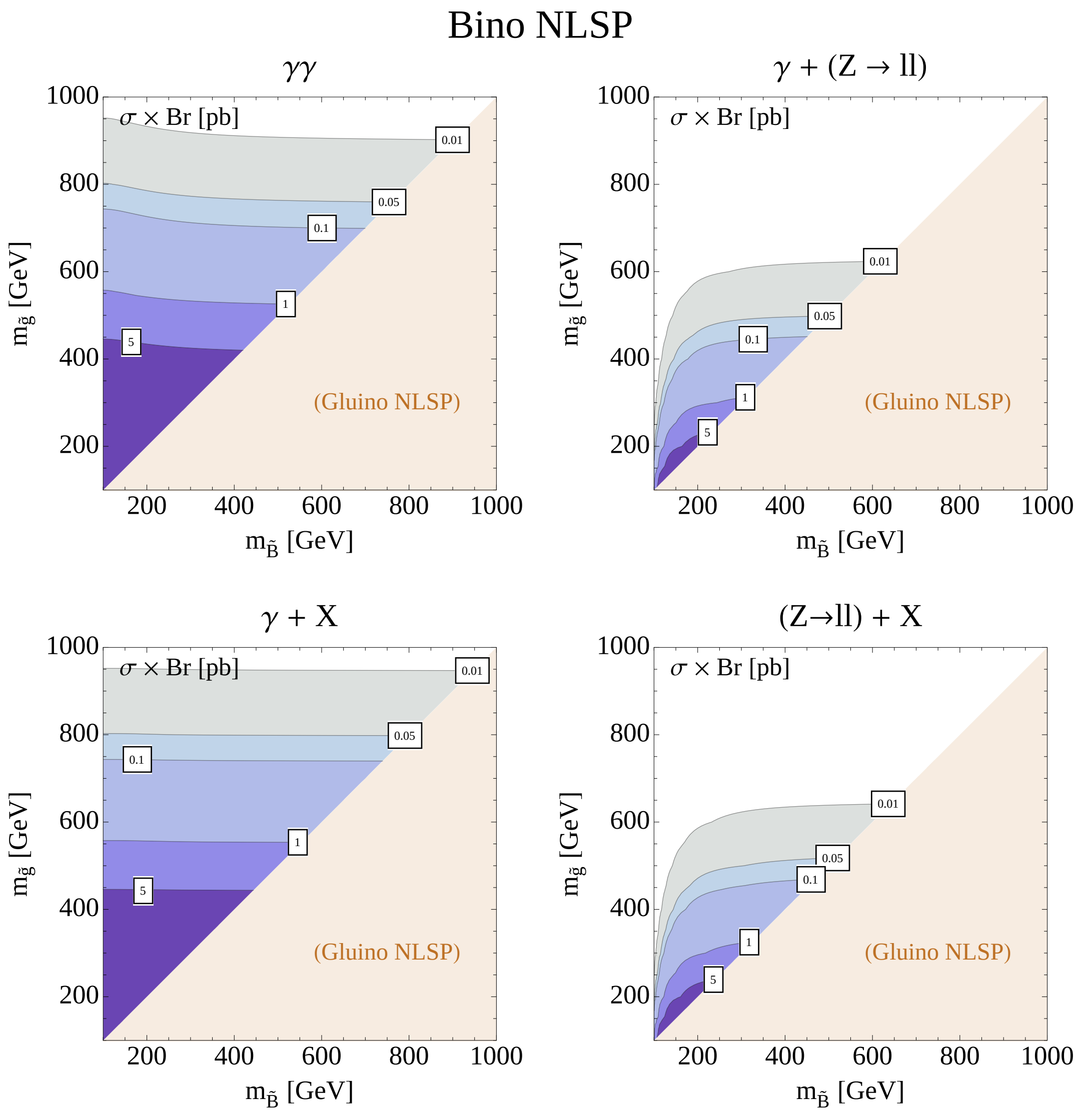

FIG. 2: $\sigma \times$ Br of some promising final states with a bino-like NLSP.

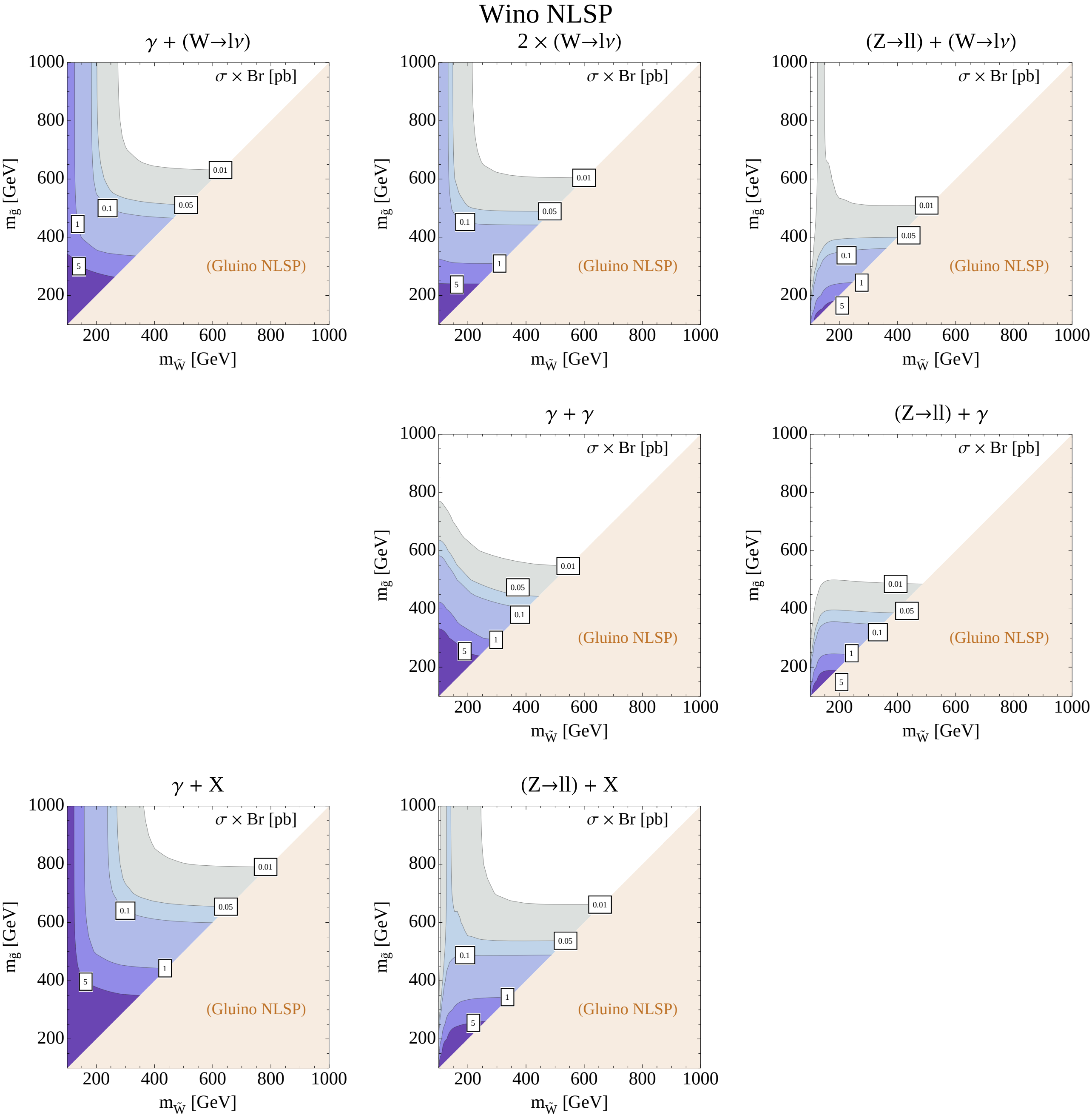

FIG. 3: $\sigma \times$ Br of some promising final states with a wino-like NLSP.

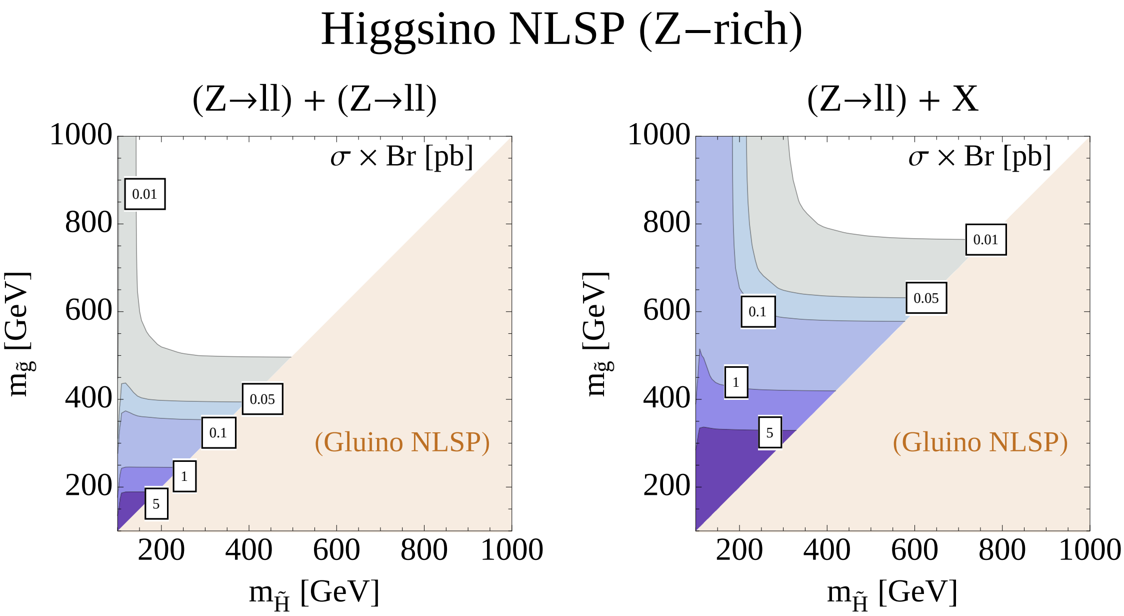

FIG. 4: $\sigma \times$ Br of some promising final states with a Higgsino-like NLSP.