DESY SUMMER STUDENT PROJECT

STUDY OF SIGNAL SIGNIFICANCE FOR SUSY HIDDEN VALLEY MODELS SEARCHES AT LHC

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Abstract

Current searches at LHC has not found hints for SUSY yet. Despite the fact that could be there but we haven't enough luminosity to see it, SUSY could be stealth by some extensions which should completely change the MET signature we are looking for. We will present in this paper the Hidden Valley model extension of SUSY and we will underline how its phenomenology could hide SUSY, leading current searches to be uneffective. After that we will explain how we have simulated this model, how we have analyzed it for different analyses and mass spectra. We will present a systematic study of signal significance and which counclusions we should deduce from that.

Contents

1 The SUSY Hidden Valley Scenarios

1.1 HV Theory

The basic idea behind the *Hidden Valley* (HV) models is an extension of a model, for example Standard Model (SM) with gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y = G_{SM}$, by a new non-abelian group, G_v. The latter introduces new light particles that are charged under G_v but neutral under G_{SM}. On the other hand, the SM particles are neutral under G_v. The valley sector has its own matter, v-quarks, and its own gauge bosons, v-gluons.
To let the sectors talk each other, an interaction between SM and the v-sector has to be added: it is carried out by higher dimensional operators at the TeV scale, for example by heavy particles with both G_{SM} and G_v charges or Z' loop. This interaction is represented by the barrier in Fig. 1(a)
This scheme can be developed and implemented in most of the theories beyond SM, SUSY in our case, that solve hierarchy problem, producing significant signals at colliders. For a review of general phenomenologies associated with these scenarios, see [1]. The important fact to underline is that the phenomenology usually associated with those beyond SM theories can drastically change with a hidden sector.

Concerning SUSY, the standard searching approach involves missing energy signal. In fact, if R-parity is conserved[1], in every vertex there must be a pair of superpartners and in the final state we should expect two Lightest Supersymmetric Particles (LSsP), both stable and neutral.
However, even with R-parity conservation, this signal could be significantly reduced if these particles are not stable and decay into hidden valley particles: this decay will participate in whatever dynamics occurs in that sector. In particular, if the Lightest Superstmmetric v-Particle (LSvP) is lighter that the LSsP, the LSsP would decay to an LSvP plus one or more v-hadrons, some of which could decay visibly, Fig. 1(b). In this case, the real stable particle is the LSvP.
Moreover, If SUSY is broken at a low scale, it is natural for the hidden sector to have a spectrum approximately supersymmetric, with a small amount of SUSY breaking first introduced by interactions with SM fields.

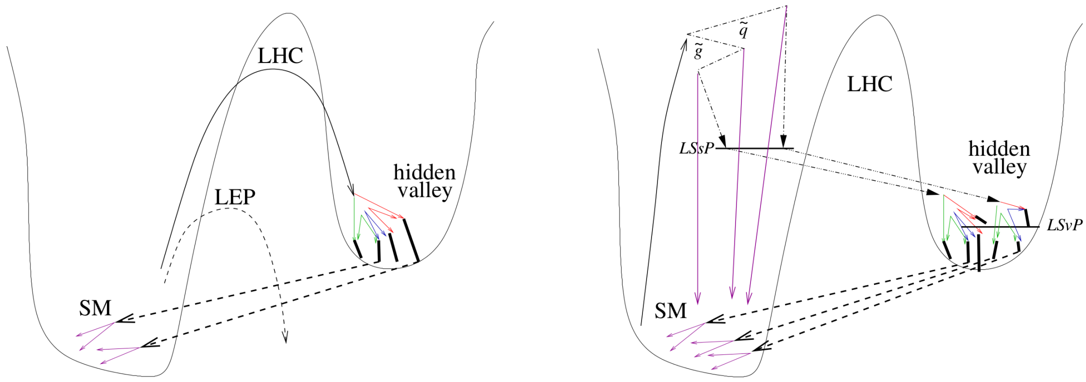
1.2 HV Phenomenology

In the following, we will consider a Minimal Supersimmetric model extended with a minimal hidden sector, which contain a singlet scalar S and its fermionic superpartner $\tilde{S}$ the singlino, which is also the LSvP [3]. We will require the LSsP, $\tilde{H}$, to decay as $\tilde{H} \to S\tilde{S}$ and $S \to gg$. The dacay chain is shown in Fig. 2.
The mass spectrum of this model is summarized in Fig. 3: the mass splits among $\tilde{H}$, S and $\tilde{S}$ are of the order of ten to hundreds GeV, variable with the masses of the particles. It is also set the kinematic limit $m_{\tilde{S}} + m_S < m_{\tilde{H}}$. The limit on the higgsino

[1] R-parity is defined as

$$P_R \overset{def}{=} (-1)^{2s+3(B-L)}.$$

In particular it is requested to avoid proton decay with a too short lifetime.



(a) SM HV extension. The barrier limits cross-sectors interactions and avoids production of v-hadrons by LEP

(b) SUSY HV extension. SUSY particles decay to SM plus LSsP. The LSsP then would decay to a LSvP plus some v-hadrons that decay in SM particles

Figure 1: Hidden valley extension for SM and SUSY

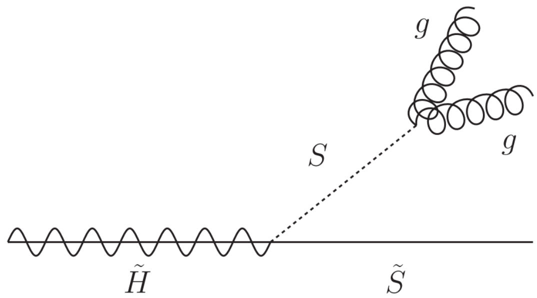


Figure 2: SUSY lighest particle decay through the hidden sector made by S and $\tilde{S}$

mass (around 300-400 GeV) is motivated by the fact that this mass typically contributes to the electroweak VEV at tree level. If one assumes that the electroweak scale is protected *purely by supersymmetry* then the lightest higgsino mass and the Higgs boson mass cannot be too far separated without fine tuning.
With this mass spectrum we can highlight two different possibilities:

1. if $m_{\tilde{S}} \to m_{\tilde{H}}$ and, as consequence, $m_S \to 0$ we would expect large MET without more jets: the hidden sector does not play any role from an experimental point of view;

2. if $m_S \to m_{\tilde{H}}$ and $m_{\tilde{S}} \to 0$ the MET signature may be completely absent and we expect more jets in the final state.

As shown in [3], it is clear that it has to be done a specific study on a multi-jets final state without presence of MET: this signature is only covered by a reinterpretation of micro Black Holes search [4], above all if gluino mass is heavier than 1 TeV. More details are given in appendix A.2 of [3].

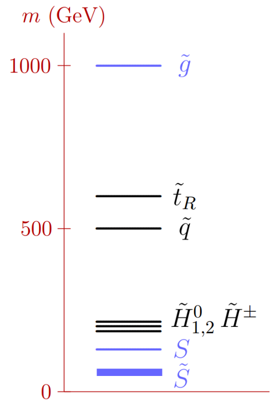


Figure 3: Mass spectrum for our minimal Hidden Valley model. Blue lines indicate variable masses.

2 Simulation Tools

To analyze this hidden valley model we have used three different tools that we are going to explain below. With these, we have completely explored the mass spectrum of the hidden sector, varying masses of $\tilde{g}$, S and $\tilde{S}$. More details on the simulation run will be given in the section 3.

2.1 `SoftSusy`

`SoftSusy` [6] is a tool which accurately calculates a complete SUSY spectrum in Minimal and Next-To-Minimal Supersymmetric Standard Model (MSSM and NMSSM). It creates a spectrum consistent with the Standard Model parameters taken from data, with or without R-parity, including flavour mixing and violations. It could calculate the spectrum with 2-loops or 3-loops correction to the mass of squarks and gluino. The program solves the renormalisation group equations with theoretical constraints on soft supersymmetry breaking terms provided by the user.
The spectrum produced is used to feed Pythia .

2.2 Pythia 8

Pythia [7][8] is a MonteCarlo generator that provides the simulations of the hard scattering process. It has a very simple interface and needs only some parameters to work properly: we can choose which kind of particles we want to collide, at which $\sqrt{s}$, which kind of processes we want to simulate (in our case are $\tilde{g}\tilde{g}$ production from an initial state of gg or $q\bar{q}$) and which "features" you want to take into account. Among these, there are MultiPartons Interaction and Initial/Final State Radiation of gluons and photons. It also takes into account the processes of fragmentation and hadronization to simulate completely how jets are created and behave.
Another nice feature of Pythia is that the hard scattering process and the decay chain desidered can be completly set by the user. Here, the spectrum calculated with `SoftSusy` plays its role: all the parameters of SUSY are set with the file generated

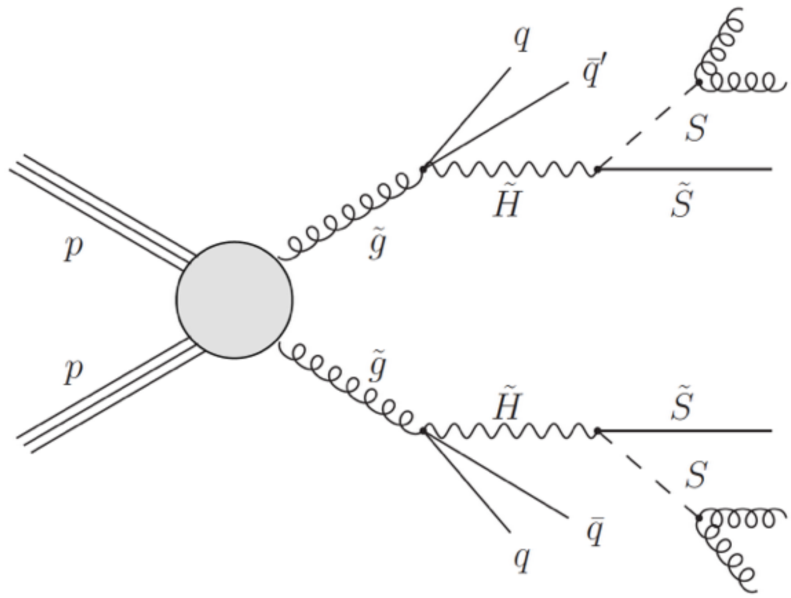


Figure 4: Full hard scattering process simulated by Pythia .

by the previous tool. The HV is encapsulated in this file with its masses and its cross sections. So, with changes in the masses into this file, we can explore the entire mass spectrum of Hidden Valley. The complete hard scattering process is shown in figure Fig. 4.

2.3 Delphes 3

Delphes [9] is a framework that performs fast detector response simulation. The simulation includes a tracking system, embedded into a magnetic field, calorimeters and a muon system. The framework could be interfaced with event generator (like Pythia MC) and the output observables are completely chosen by the user: from those, we can perform dedicated analyses.
The simulation of the detector response takes into account the effect of magnetic field, the granularity of the calorimeters, sub-detector resolutions and efficiencies, the momentum smearings. It also reconstructs jets event with the `FastJet` library[10], which uses an anti-k_{T} algorithm. Visualization of the final state particles is also built-in using the corresponding ROOT library.
Also this tool is completely configurable, but we use the default card that describes ATLAS.

3 Analysis and Results

3.1 Simulations

We have completely explored the mass spectrum of the hidden sector, varying masses of $\tilde{g}$, S and $\tilde{S}$. In particular, we have generated 10k events for:

- three different gluino masses: 1 TeV, 1.5 TeV, 2 TeV

- a fixed Higgsino mass: $m_{\tilde{H}} = 300\,\text{GeV}$
- a fixed mass step of 5 GeV to explore $m_{\tilde{S}}$ and m_S from 5 GeV to 290 GeV

The number of simulations that have to be run are around 5400 and a full simulation, for a set of mass parameters and made of 10k events, including generation and reconstruction, takes three minutes and half. So we have faced, and solved, the problem of running these simulations in parallel on many processors (18-20 cores) to reduce the computational time needed from 13 days to 16 hours.

3.2 Analysis

All the events generated are analyzed with many different cuts.
In order to remove jets that could be badly reconstructed by ATLAS we always apply these "object definition" cuts:

- $p_{\mathrm{T}}^{jet} > 40\,\text{GeV}$[2]
- $|\eta^{jet}| < 2.5$[3]

In the following, we will call "Inclusive" the analysis with only these two cuts.

After this first selection, we performed many analyses to be sensitive to different kind of final state signatures. We will call "Exclusive" these analyses. Events are filtered through more tight cuts concerning Missing Transverse Energy (MET), Hadronic Transverse Energy (HT), and jet multiplicity. Shortly, MET is defined as the energy that is missing in the transverse plane due to, hopefully, undetected particles like the singlino $\tilde{S}$; HT, instead, is defined as the sum of the $|p_{\mathrm{T}}|$ belonging to hadronic objects. The analyses made are shown in the Table 1. Every exclusive analysis requests also that $\Delta\phi(jet, \text{MET}) > 0.5$ for the three leading p_{T} jets.

	MET	*HT (1)*	*HT (2)*	*MET & HT (1)*	*MET & HT (1)*
MET [GeV]	> 300	-	-	> 100	> 200
HT [GeV]	-	> 1400	> 2100	> 700	> 500
Jet Multipl	≥ 4 or 8	≥ 4 or 8	≥ 4 or 8	≥ 4 or 8	≥ 4 or 8

Table 1: ten different exclusive analyses are performed

All the following plots are normalized with a luminosity of $30\,\text{fb}^{-1}$ and the cross section for $\tilde{g}\tilde{g}$ production at 13 TeV[11]. The σ values are shown in Table 2.

[2]The subscript T stays for Transverse: in hadronic colliders, we don't know which is the boost of center of mass along interaction axis because of compositeness of proton; the only unboosted quantities belong to the plane transverse to interaction axis. Moreover, in this plane the sum of all energies must be equal to zero.

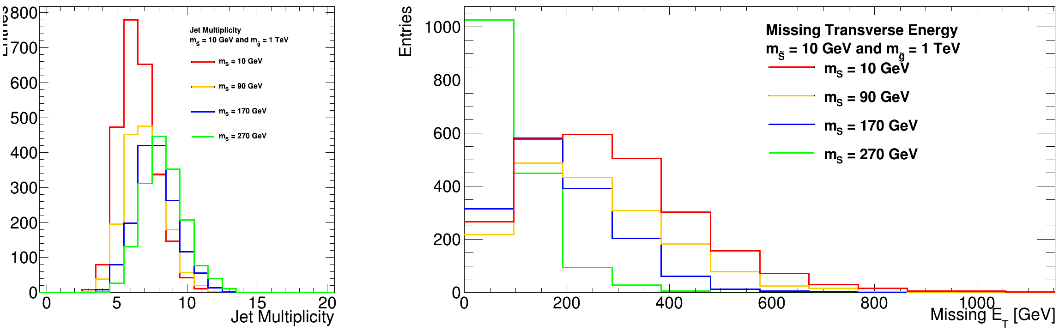
[3]η is defined as $-\ln\left(\tan\frac{\theta}{2}\right)$, where θ is azimuthal angle with regards to beam line.

Mass [TeV]	σ (pb)	Events 30 fb^{-1}
1	0.325388	$\sim$ 9700
1.5	0.0141903	$\sim$ 420
2	0.000981077	$\sim$ 30

Table 2: cross section for $\tilde{g}\tilde{g}$ production

3.3 Results

If we fix two out of three masses and vary the third one, we will obtain one dimensional distributions for jet multiplicity and MET. They are useful to understand which type of signature we will expect in the final state. These plots are shown in Fig.5 for $m_{\tilde{g}} = 1$ TeV and $m_{\tilde{S}} = 10$ GeV.



(a) (b)

Figure 5: jet multiplicity(a) and MET(b) for a fixed configuration of $m_{\tilde{g}}$ and $m_{\tilde{S}}$

It is clearly visible from these plots that when the singlet mass increases, the jet multiplicity peak shifts around 8 jets. In fact, the gluons in Fig.2 have an increasing invariant mass and the jets generated are more and more energetic. Instead, when the singlet mass is low, the gluons could produce high energetic jet only if singlet is very boosted.
On the other hand, it happens the opposite for MET plot: when singlet mass increases, distribution peaks moves to the left. This is expected because the singlino has less and less phase space to produce significantly high MET. Notice also that if a standard SUSY analysis cut around 200 GeV is applied, it would cut the signal for $m_S = 270$ GeV almost completely.
The plots for different gluino masses are shown in appendix A.

3.3.1 Signal significance

In this section we will show and comment some signal significance plots. Because of the large number of these (three gluino mass times ten analyses), all the plots are presented in the Appendix B without comments: the reader is invited to analyze

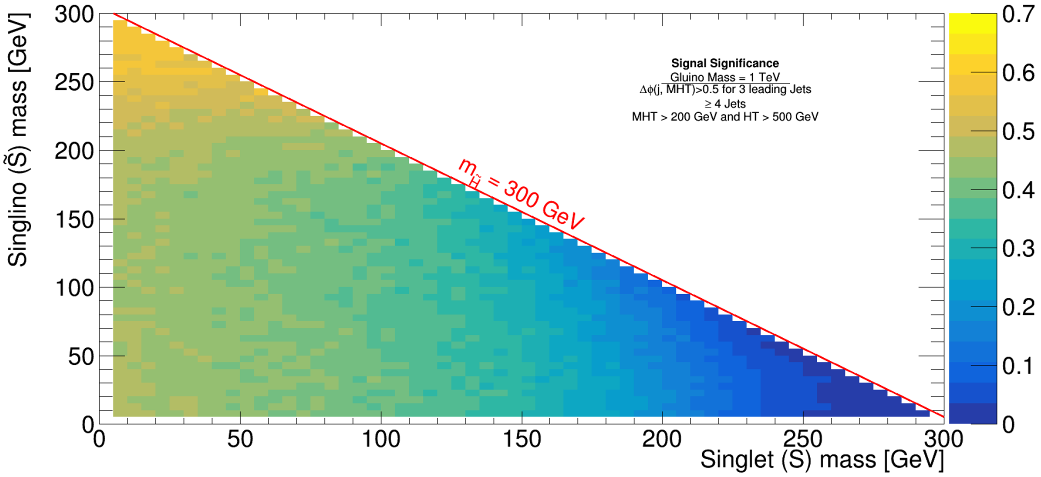


Figure 6: ξ for a standard SUSY analysis. Kinematic limit is shown with the red line. Whole low left corner is missed by current searches

those plots after having read this section.

First of all, the signal significance ξ is defines as

$$\xi = \frac{\text{events Exclusive}}{\text{events Inclusive}},$$

where Exclusive is intended for whatever analysis type.
In Fig. 6, the distribution of the signal significance is shown for the whole hidden sector spectrum. In this case the analysis applied has both MET and HT cut and requests at least 4 jets. It is quite similar to a standard SUSY LHC search. Different behaviours are visible:

- in the high left corner, ξ is around $50 - 60$ %: even if $\tilde{S}$ passes easily the MET cut, the gluino is not very massive and most of the jets produced in the decay chain don't pass the Inclusive selection. However, the efficiency is high;
- in the low right corner, ξ is null: the MET selection cuts this part away completely. It is clear that with current analyses we have no possibilities to discover this signature;
- in the central part, ξ oscillates beetween 30 and 50%: moving from right to left the HT cut is less and less effective; the same happens for MET cut moving from bottom to top.

In Fig. 7, it is performed the same analysis of Fig. 6 but, now, gluino mass is raised to 1.5 TeV. The plot shows a trend to lighter colours. This is easily explained considering that with a higher gluino mass all the particles in the decay chain are more boosted, hence they pass cuts more probably.

The impact of jets selection on ξ is illustrated in Fig. 8, where same $m_{\tilde{g}}$ and analysis of Fig. 6 are applied. The signal significance is greatly reduced in the whole left

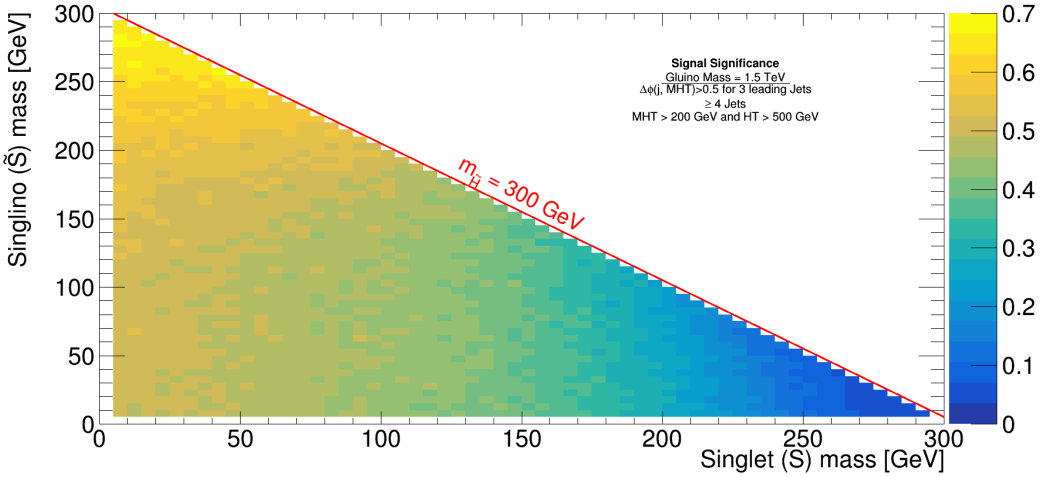


Figure 7: ξ as in Fig. 6 but with higher $m_{\tilde{g}}$

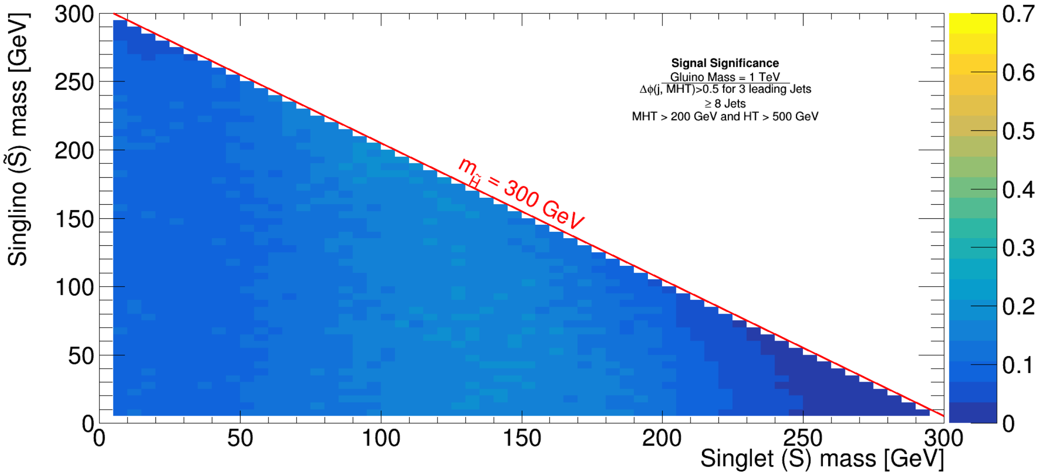


Figure 8: ξ as in Fig. 6 but with higher cut on jet multiplicity

part of the spectrum, because of low singlet mass that couldn't produce so many high p_{T} jets. Only in a middle band there is a significant ξ of 25%: in this part S and $\tilde{S}$ are not very massive, hence more boosted, and high jets could be produced by gluon emissions in quite every part of the decay chain, giving a higher number of jets. In appendix B the reader can find the plots for the same analysis but for higher gluino masses.

We have tried to remove the cut on MET and apply a higher cut on HT. The values of signal significance is pointed out in Fig. 9 for a $m_{\tilde{g}} = 1.5\,\mathrm{TeV}$. Removing or lowering the MET cut let us access to the low left corner, where current analyses don't look for. The ξ in this region is around $30 - 40\%$, therefore, according Tab. 2, around 160 events would be still present. The cuts applied are really tight and should greatly reduce background sources.

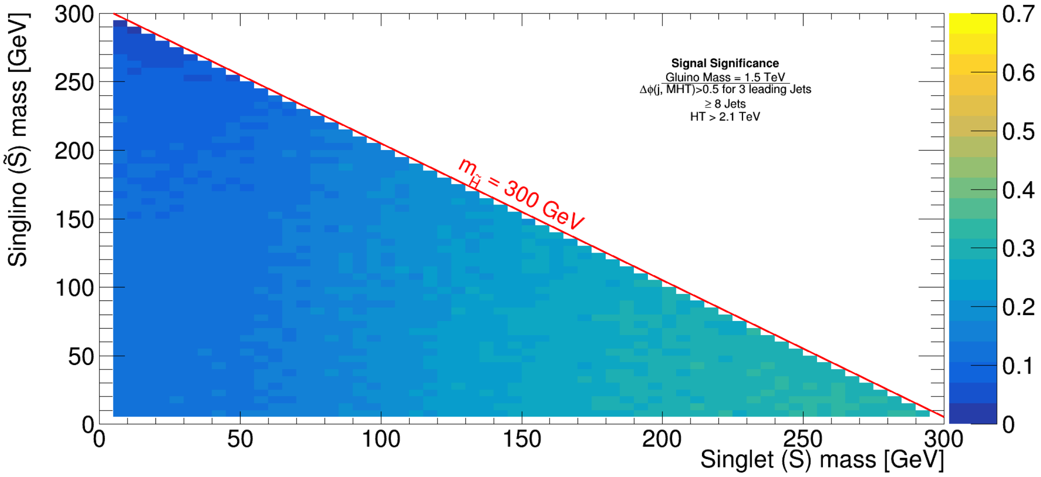


Figure 9: ξ for a feasible analysis sensitive to the hidden sector

4 Conclusions

We have dimostrated that current SUSY analyses at LHC could not be sensitive to a Stealth SUSY scenario, like for example our Minimal Hidden Valley extension. The latter could produce very high jets multiplicity in the final state without MET signature if HV spectrum has m_S near to the LSsP.
With our systematic study of signal significance ξ for different spectra and different kind of possible analyses, we have shown that:

- 0-lepton searches, with only jets+MET, can provide some sensitivity
- MET cut has to be lowered, and jet multiplicity has to be increased if we want to become sensitive to a larger fraction of Hidden Valley models

This work will be continued in the DESY ATLAS group. In the future, it is planned to change the hidden valley model presented here with another one, called Gauge Mediate SUSY Breaking (GMSB)[5]: this model produces the same identical signature of HV model but with a soft gravitino $\tilde{G}$ in the final state instead of $\tilde{S}$. This will solve the naturalness "problem" of the HV model, which has the mass of the superpartner $\tilde{S}$ larger than S.

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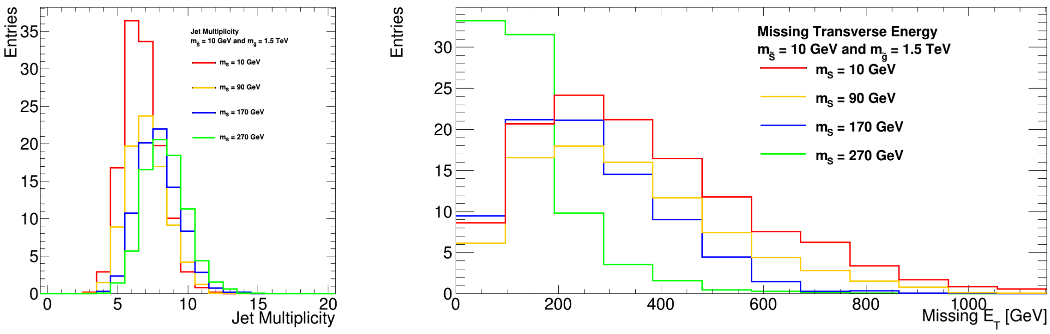
[11] `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections13TeVgluglu`

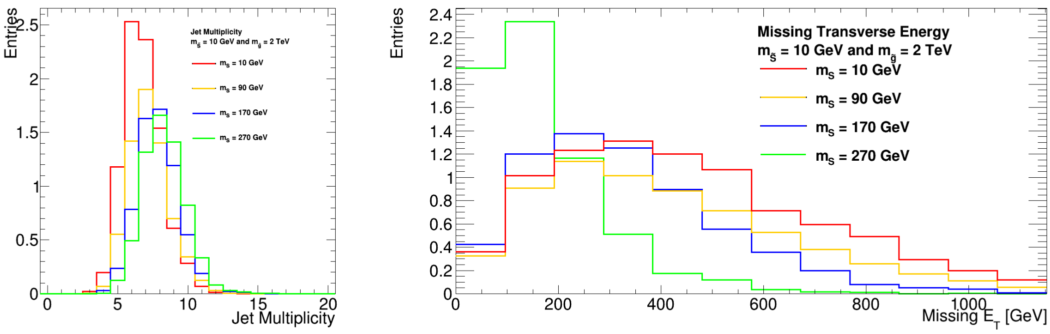
In this appendix the reader can find the plots for jet multiplicity and MET similar to Fig. 5 but for higher gluino masses. After these, in appendix B all the thirty plots for the signal significance are shown.

A MET and Jet Multipicity



(a) (b)

Figure 10: Jet Multiplicity(a) and MET(b) for $m_{\tilde{g}} = 1\,\text{TeV}$ and $m_{\tilde{S}} = 10\,\text{GeV}$



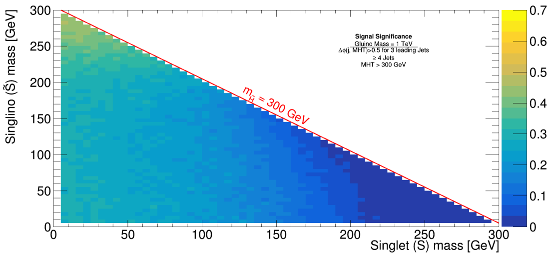
(a) (b)

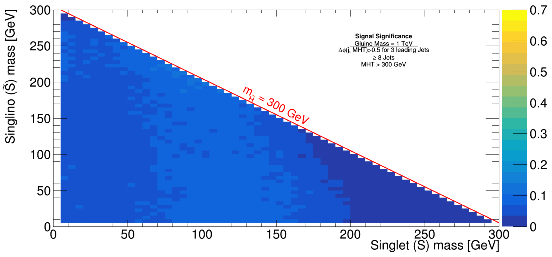
Figure 11: Jet Multiplicity(a) and MET(b) for a fixed configuration of $m_{\tilde{g}}$ and $m_{\tilde{S}}$

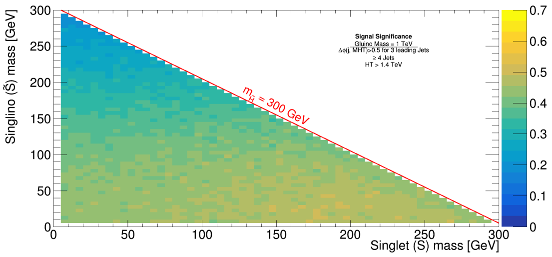
B Signal significance

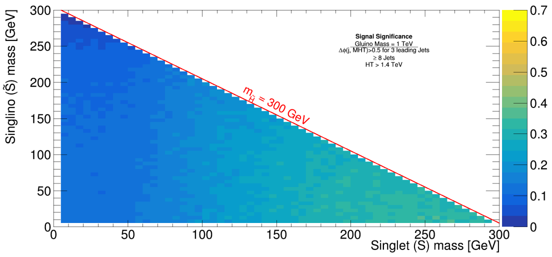
We have ordered plots by gluino masses and splitted in two columns: on the left there will be analyses with ≥ 4 jets, on the right with ≥ 8.

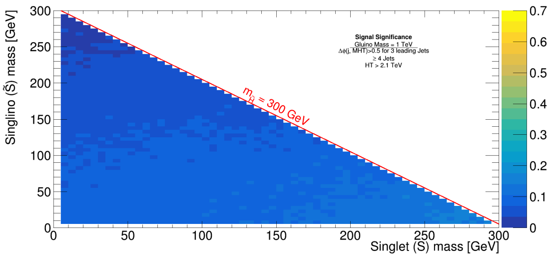
B.1 Gluino mass 1 TeV

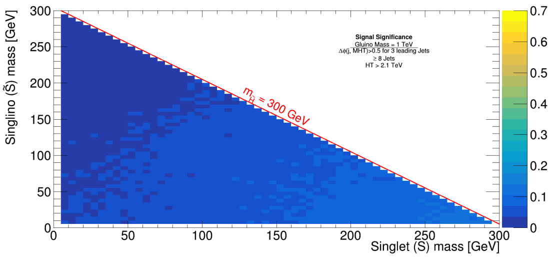


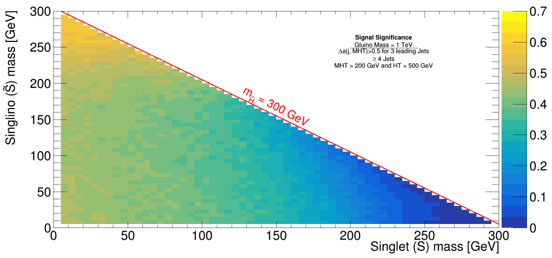


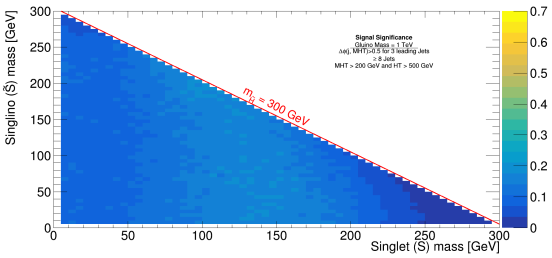


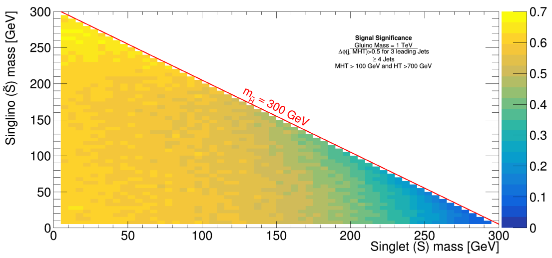


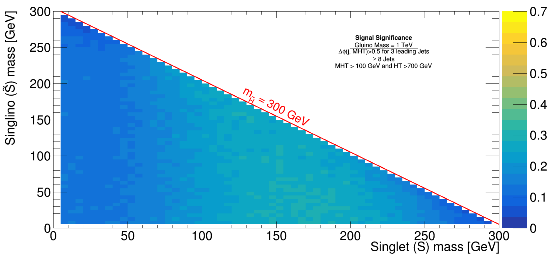




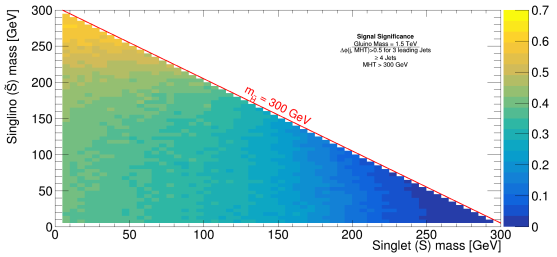


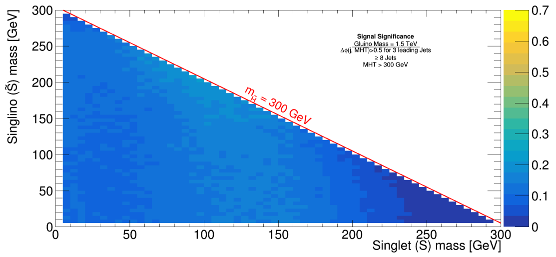


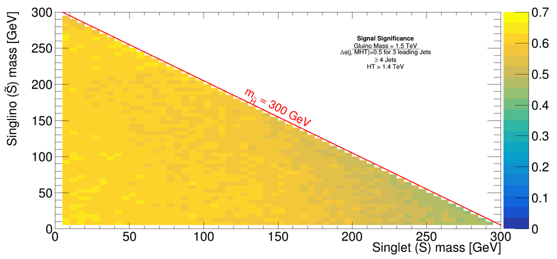


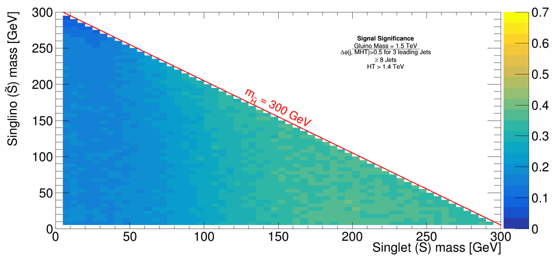


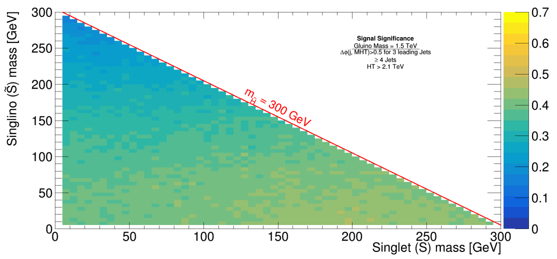
B.2 Gluino mass 1.5 TeV

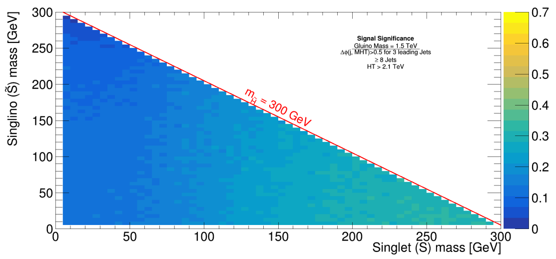


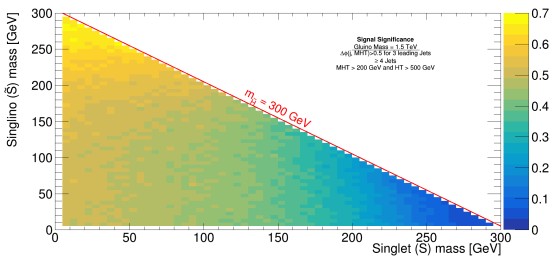


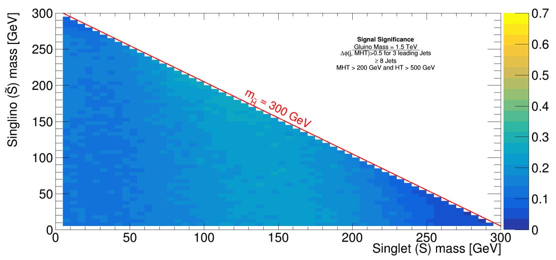


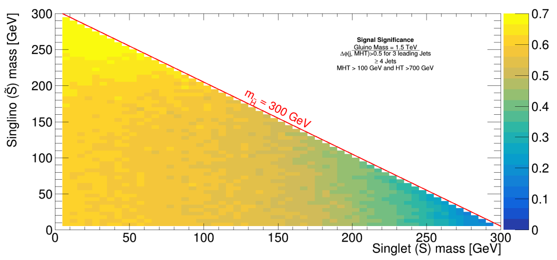


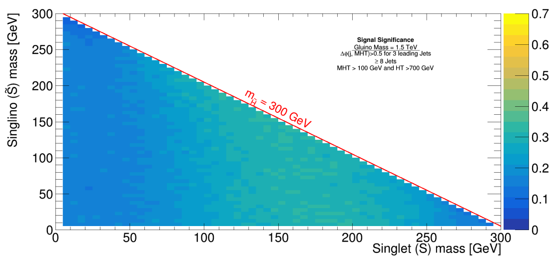












B.3 Gluino mass 2 TeV