

# Constraining the pMSSM with Gluino-Squark Simplified Models

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**ABSTRACT:** After the Run 1 at the Large Hadron Collider (LHC), the ATLAS collaboration analysed the constraints on a 19-parameters realisation of the phenomenological Minimal Supersymmetric Standard Model (pMSSM) using the results of the many searches for new physics. A large portion of the parameter space excluded by the ATLAS collaboration can also be efficiently constrained using directly the simplified model results, which became the standard method employed for the interpretation of searches for Beyond the Standard Model (BSM) physics. Moreover the still uncovered part could be potentially covered by a new class of simplified model stemming from gluino-squark associated production, producing a 3 jets + missing energy signature in the LHC detectors. This work aims at demonstrating that it is possible to extend significantly the coverage of the pMSSM-19 parameter space by means of such simplified models results.

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## 1 Introduction

Simplified models spectra (SMS) have become the standard method for the LHC collaborations to interpret the results of their searches for Beyond the Standard Model (BSM) particles, as in the case of Supersymmetry (SUSY). The most notable benefit is the drastic reduction of the large parameter spaces of full theories to a handful of new states. SMS serve not only as a useful benchmark to design and optimize the searches, but also they can easily highlight the specific strength of each search. Each SMS is characterized by a few SUSY particles, while all the remaining are too massive to be produced at the LHC energy due to very small cross section production, and they can not appear as intermediate on-shell states in cascade decays.

In the case of SUSY, the masses of the particles, their production cross section and their decay modes are sufficient to fully characterise each SMS. Once these parameters are fixed, it is straightforward to estimate the exclusion provided by the LHC searches with SMS. The interpretation of searches with SMS started back at the early LHC era, with the data collected at a centre-of-mass energy of 7 TeV (see e.g. [1] by the CMS Collaboration).

The choice of specific SMS relies on their simple experimental signatures and kinematic properties of the particles captured by the detectors. It is to be particularly stressed how the kinematics of the events is determined mainly by the mass scale of the SUSY particles involved, rather than the specific quantum or gauge numbers of the theory. Using SMS to re-interpret the results of the searches in the context of complete theory is however challenging. The main difficulty comes from considering the full particle spectra appearing in general theories. In fact, considering for example the R-parity conserving Minimal Supersymmetric Standard Model (MSSM), the kinematics of the cascade decays to the lightest supersymmetric particles (LSP) might differ significantly from the one of the simplified case. The SMS commonly used for the interpretation of searches normally include up to three SUSY particles masses in the case of cascade decays, i.e. models where the produced SUSY particle decay to intermediate on-shell particles, or in the case of the production of two distinct SUSY particles.

For the task of re-interpretation of searches with SMS results in the context of general models, dedicated tools such as **FastLim**[2] and **SModelS**[3] were developed. They can decompose BSM signals into its SMS, and check the constraints provided by the LHC searches, contained in a dedicated database of results. In particular, **SModelS** was used in [4] to study the coverage of the pMSSM-19[5] with SMS with respect to the full recast analyses performed by the ATLAS collaboration. The set of pMSSM points considered were made public by the ATLAS collaboration on the **HepData** website[6]. The sensitivity of the ATLAS searches for a selection of BSM searches on the pMSSM was presented in [7]. They re-run their analyses on thousands of pMSSM model points, and characterised the constraints offered by a selection of the searches performed during the LHC Run 1, with proton-proton collisions at 8 TeV centre-of-mass energy.

The same model points were then tested with **SModelS** v1.1[8], obtaining a total coverage of roughly 55%-63% for the Bino and Higgsino-like LSP case, respectively<sup>1</sup>. It was shown that by means of efficiency maps (EM) results, that can be produced by phenomenologists outside the experimental collaborations, it was possible to increase significantly the number of excluded point with respect to using upper limit (UL) results only. In fact, from one side, the LHC collaborations provide results only for a limited set of SMS, and many interesting model, to which existing searches are sensitive to, are left unexplored, so EM enables phenomenologists to produce results for arbitrary SMS. From the other side, EM results can combine several signals together and obtain more stringent limits.

The comparison between the **SModelS** approach and the re-interpretation performed by the ATLAS collaboration showed that the usage of simplified model could be potentially improved by including results for simple signatures, such as the  $3jets + \text{missing energy}$  ( $E_T^{miss}$ ). This signature can arise, for example, from gluino-squark associated production, where the gluino decays preferentially to an on-shell lighter squark, in turn decaying to a quark (that is reconstructed by the analysis as a jet of hadrons) and the LSP. It was found that this simplified model, for which experimental results are not available, possesses on

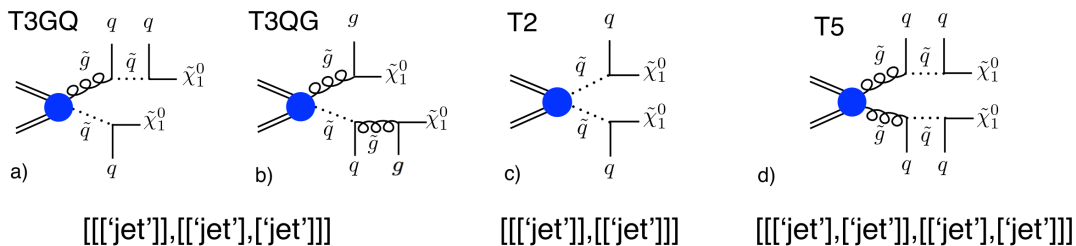
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<sup>1</sup>The Wino-like LSP dataset was neglected since most of the model pointed included long-lived charged particles, a signature which could not be handled by the v1.1 used.

average the largest  $\sigma \times BR$  (production cross section times branching ratio).

The idea at the basis of this work is to extend the previous study of the coverage of the pMSSM, and concretely show how the inclusion of newly created EM for the  $3jets + E_T^{miss}$  signature increases the coverage of the pMSSM. This can be efficiently achieved by combining the information obtained with **SModelS** regarding the important missing topologies, and the usage of analyses recasting tools to produce EMs results for arbitrary simplified models, to be implemented in the database of experimental results. For this purpose, this paper is structured as follows. Section 2 summarises the main characteristics of the  $3jets + E_T^{miss}$  signature arising from gluino-squark production. In Section 4 the set up of the **SModelS** analysis is described: the details regarding the production of the EMs for the gluino-squark model are discussed, and the set of pMSSM points used for the study are provided. Section 5 summarises the improved constrained obtained with the newly added EMs, in particular discussing the benefit of the signal combination from EM results. A brief analysis of the current state of the art simplified model results at 13 TeV is discussed in Chapter 6. Finally an outlook about future extensions of the procedure is given in the conclusive Chapter 7.

## 2 The 3 jets + $E_T^{miss}$ Signature in the pMSSM-19



**Figure 1:** Diagrams for the simplified models used for the extension of the database. Models  $T3GQ(a)$  and  $T3GQ(b)$ , corresponding to the two different mass hierarchies  $m_{\tilde{g}} > m_{\tilde{q}}$  and  $m_{\tilde{q}} > m_{\tilde{g}}$ , are identified by the  $3jets + E_T^{miss}$  experimental signature. Light quarks and gluons are included in the definition of ‘jet’. Diagrams c) and d) represent the  $T2$  and  $T5$  models, mapping to the  $2jets + E_T^{miss}$  and  $4jets + E_T^{miss}$  signatures respectively. Note that the insertion of the final state particles in the vertices of each topology uniquely identifies a given simplified model. Below each mode, the bracket notation used by the `SModelS` tool is reported as a reference.

The pMSSM-19 is a 19 parameters realization of the phenomenological R-parity conserving Minimal Supersymmetric Standard Model (MSSM). This model was taken as a benchmark by the ATLAS[7] and CMS[9] collaboration to analyse the impact of their Run 1 searches on a full SUSY model. The pMSSM is in fact more complex than simplified models but still possesses a reasonably small number of free parameters. With respect to the MSSM, the parameters are reduced by excluding new sources of CP violation and neutral currents producing large flavour violation. The former are avoided by imposing that all the elements in the soft SUSY breaking potential are real; the latter, by requiring that the matrices of the sfermions and the trilinear couplings are diagonal in flavour space.

These assumptions are anyhow mostly motivated by a pure phenomenological point of view and theoretical simplicity. Looking at the coloured sector, the pMSSM offers a rich phenomenology.

In generic pMSSM-19 model points, the squark mass parameters are:

$$m_{\tilde{u}_L} = m_{\tilde{d}_L} = m_{\tilde{c}_L} = m_{\tilde{s}_L}$$

$$m_{\tilde{u}_R} = m_{\tilde{c}_R}$$

$$m_{\tilde{d}_R} = m_{\tilde{s}_R},$$

where the subscripts  $R$  and  $L$  denote the right and left handedness respectively, resulting in three free mass parameters for the squarks. The third generation squarks, i.e. stops and sbottoms, are set to a high mass scale and will not be considered. Since the mass of the gluinos is another free parameter, there are two possible mass hierarchies of interest in the context of SMS. When considering for simplicity the lightest of the squark masses with  $m_{\tilde{g}} > \min(m_{\tilde{q}})$ , gluinos will decay almost entirely to an on-shell intermediate squark, followed by the decay of the squark to the LSP and the corresponding Standard Model quark:

$$pp \rightarrow \tilde{g}\tilde{q}, \tilde{g} \rightarrow \tilde{q}q, \tilde{q} \rightarrow q\tilde{\chi}_1^0 \quad (2.1)$$

However, for the alternative hierarchy where the squark considered is now heavier than the gluino,  $\min(m_{\tilde{q}}) > m_{\tilde{g}}$  the squarks will decay to an on-shell intermediate gluino. The gluino will then decay either via radiative decay to the LSP as

$$pp \rightarrow \tilde{g}\tilde{q}, \tilde{q} \rightarrow \tilde{g}q, \tilde{g} \rightarrow g\tilde{\chi}_1^0 \quad (2.2)$$

or, for small  $\Delta(\min(m_{\tilde{q}}), m_{\tilde{g}})$ , via a three-body decay from off-shell squark:

$$pp \rightarrow \tilde{g}\tilde{q}, \tilde{q} \rightarrow \tilde{g}q, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0. \quad (2.3)$$

The focus of this work is the simplified model that produces a  $3jet + E_T^{miss}$  final state as formulated in the Decays 2.1 and 2.2. This experimental signature can be obtained by considering two different mass hierarchies, visualized by the diagrams a) and b) in Fig. 1. The first, labelled  $T3GQ$  represents the case where the gluinos are heavier than the squarks, and the latter, labelled  $T3QG$  represents the alternative case. Each specific pMSSM model point considered includes one of the two alternative mass hierarchies.

MadGraph5_aMC@NLO processes	Mass Planes
<b><i>T2</i></b> : $pp \rightarrow \tilde{q}\tilde{q}$ define Q = dl dr dl~dr~ul ur ul ~ur~ generate p p > Q Q add process p p > Q Q j	up to $m_{\tilde{q}} - m_{\tilde{\chi}_1^0} = 5$ GeV
<b><i>T5</i></b> : $pp \rightarrow \tilde{g}\tilde{g}$ generate p p > go go add process p p > go go j	x=(0.05,0.50,0.95) $\Delta M(\tilde{q}, \tilde{\chi}_1^0) = 5$ GeV
<b><i>T3GQ</i></b> : $pp \rightarrow \tilde{g}\tilde{q}$ define Q = dl dr dl~dr~ul ur ul~ur~ generate p p > go Q \$ go Q add process p p > go Q j \$ go Q	$m_{\tilde{g}} = 200, \dots, 1200$ 50 GeV bin $m_{\tilde{g}} = 1300, \dots, 2000$ 100 GeV bin $m_{\tilde{q}}$ up to $m_{\tilde{q}} - m_{\tilde{\chi}_1^0} = 5$ GeV      50 GeV bin

**Table 1:** MadGraph5\_aMC@NLO processes for the production of the Monte Carlo samples, and mass plane parametrization used for the EMs production of the *T2*, *T3GQ* and *T5*. See the text for details.

**Previous Results** As stated in the introduction, the  $3jet + E_T^{miss}$  final state was previously found to be the most important missing result in the case of the pMSSM-19, originating from both the hierarchies here described. In the context of the **SModelS** tool (which will be briefly described in Section 4.1), this means that the SMS producing this particular signature, for which no experimental are available, were found to be the most frequent. This is quantified by looking at the weight  $\sigma \times BR$  that could was mapped onto this signature. However, one important consideration concerns other complementary simplified model results, namely the so called *T2* and *T5* models, represented by plots c) and d) of Fig. 1, i.e. by the decays

$$pp \rightarrow \tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0 \quad (2jet + E_T^{miss}) \quad (2.4)$$

and

$$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0 \quad (4jet + E_T^{miss}) \quad (2.5)$$

respectively. We will show here the impact of these two SMS results on the pMSSM-19, and in particular of the improvement in the constraining power when the three signals are combined together.

### 3 Production of the Efficiency Maps

In this Section we describe the necessary steps to produce the SMS results, in terms of signal efficiency maps, for the SMS of interest. Monte Carlo events at parton level were generated using MadGraph5\_aMC@NLO[10], and then showered and hadronized using Pythia 6.4[11]. The processes and the MadGraph5\_aMC@NLO syntax used for the production of the samples for the simplified model are described in the left columns of Tab. 1. We included the additional emission of up to one extra parton. The syntax \$go Q is used to avoid the presence

of on-shell resonances, represented by intermediate gluino or squarks, that would lead to double counting when performing the merging between matrix-element and parton-shower. The merging between the matrix elements and parton-shower formalisms was performed adopting the  $k_T$  jet MLM scheme [12, 13]. The analysis recasting was performed with **MadAnalysis 5** [14, 15], using the codes for the analysis ATLAS-SUSY-2013-02 [16, 17] and CMS-SUS-13-012 [18, 19]. The tuned version of **DELPHES 3** integrated in the **MadAnalysis 5** framework was used to take into consideration the detector efficiency on the particles. Jets were clustered using **FastJet** [20].

The description of the grid of mass points defined for the production of the efficiency maps is provided in the right columns of Tab. 1. The analyses chosen for the recasting search for SUSY events in the “all hadronic” final state, vetoing the presence of isolated leptons. In particular the two above analyses are sensitive to events with small jet multiplicity, as generated by the simplified models considered. Although official EM results for the  $T2$  model were made public by the collaborations, part of the parameter space with small mass gap between the squark and the LSP is below 50 GeV is not properly covered. For this reason, EMs were produced to replace the official results, up to a mass difference as small as 5 GeV between the squarks and the LSP. In addition, also the results for the  $T5$  model were extended to cover scenarios with small mass difference between the gluino-squark and squark-LSP. The parameter  $x$  is defined so that

$$m_{\tilde{q}} = x \cdot m_{\tilde{g}} + (1 - x) \cdot m_{\tilde{\chi}_1^0}. \quad (3.1)$$

For the  $T3GQ$  model, the gluino mass reaches the value of 2 TeV, with a binning of 50 GeV for  $200 \leq m_{\tilde{g}} < 1200$ , and a binning of 100 GeV for  $1200 \leq m_{\tilde{g}} \leq 2000$  GeV. The squark masses for the  $T3GQ$  have a 50 GeV binning, and reach the maximum value of 1 TeV. For a better coverage of the parameter space in the case of small mass differences, additional mass planes parametrized with

$$\Delta(m_{\tilde{q}}, m_{\tilde{\chi}_1^0}) = (5, 10, 15) \text{ GeV} \quad (3.2)$$

were produced. Note that the values of the maximum values of the gluinos and squarks were chosen arbitrarily, since a priori there is no possibility to determine the efficiency of the analysis and of the cross section upper limit. For the gluino-squark model we chose the hierarchy  $m_{\tilde{g}} > m_{\tilde{q}}$ , i.e.  $T3GQ$  model was chosen to constrain the  $3jet + E_T^{miss}$  signature. Under simplified model assumptions, these results will be used to constrain as well the alternative hierarchy. Small differences can indeed arise when considering the hadronisation and the clustering of jets originating from gluons or quarks so that the jets momentum and multiplicity, and linked kinematics variables such as the hadronic transverse energy, might differ. However the analysis efficiency should not be very sensitive to such differences, and will not be discussed in this work. It is important to stress that **SModelS** does not distinguish between gluon and light quarks in the final states, both generically identified as “jet”. This happens with the  $T3GQ$  model as drawn in diagrams a) and b) of Fig. 1, where both quark and gluon jets appear. Consequently also the  $T2$  and  $T5$  results can be

used to constrain the alternative models  $pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{g}\chi_1^0$  and  $pp \rightarrow \tilde{q}\tilde{q}, \tilde{q} \rightarrow \tilde{g}q, \tilde{g} \rightarrow g\tilde{\chi}_1^0$ . The EMs here discussed are now publicly available in the release v.2.0 of **SModelS**.

## 4 Simplified Model Analysis Setup

We describe in this Section the setup at the basis of our analysis of the pMSSM: we introduce the basic features of the **SModelS** tool, we describe the experimental results considered and then selection of the pMSSM-19 points.

### 4.1 SModelS Workflow

To explore the constraining power of the plenty of SMS results produced both by the LHC collaboration and by groups of phenomenologists, the tool **SModelS**[8, 21, 22] offers an efficient interface between the theory predictions for arbitrary BSM models and the experimental data. While up to version 1.1 the BSM models were assumed to satisfy a  $\mathcal{Z}_\epsilon$  symmetry resulting in a missing energy signature in the detectors, the most recent version v.2.0 extends its capabilities to more exotic models, containing for example long lived charge particles. However, these are not the interest of this work, where it is assumed that each SMS has a pair production of SUSY particles forming two branches, each of them terminating with a  $\tilde{\chi}_1^0$  as LSP responsible of the missing energy signature. The two main steps at the basis of the **SModelS** workflow are the decomposition of the input BSM model into a spectrum of simplified models, and the comparison of the theory prediction associated with each simplified model to the experimental cross section UL. The UL can be provided directly by the LHC collaborations, under the form of UL maps, or they can be calculated using a the simplified CLs prescription (see e.g. [23, 24]) starting from the analyses efficiency, for each separate signal region, and the experimental information of the number of expected background events  $n_{exp}$ , its related uncertainty  $\Delta n_{exp}$  and the number of observed events  $n_{obs}$ . The values of the UL for distinct SMS cannot be combined, and can only be compared individually to each theory prediction. For these reasons, efficiency maps results often offer stronger limits compared to UL results; however, it is not possible to exploit the full power of signal regions (SRs) combination, either because they are overlapping and events might fall in more than one SR, or because of lack of the correlation matrices, not available for the LHC Run 1 results. This forces to consider only separate SRs, and the limit considered is the one provided by the "best" SR, defined as the SR giving the strongest expected limit (obtained by setting  $n_{obs} \equiv n_{exp}$ ). This should avoid biases in the SR selection due to statistical fluctuations in the experimental data; finally, the observed UL of the best SR is calculated. The parameter:

$$r \text{ value} = \frac{\sigma_{Theo}}{\sigma_{UL}} \quad (4.1)$$

is then extracted for each result. The quantity  $\sigma_{Theo}$  corresponds to the weight  $\sigma \times BR$  of each simplified model (multiplied by the efficiency values in the case of EM results). A model point is excluded if, for at least one experimental result, the corresponding theory prediction exceeds the value of the UL. **SModelS** does not currently perform any statistical analysis



of the  $r$  value. Note that also the ATLAS collaboration makes use of the CLs prescriptions and the choice of best SR to calculate the 95% CL exclusion of the pMSSM points tested, without performing SR combination as done in the case of the SMS interpretation.

## 4.2 Selection of the pMSSM-19 Model Points

The setup for the analysis with **SModelS** follows closely what described originally in [4], that is here summarized. The pMSSM-19 model points considered represent a subset of the dataset originally used by the ATLAS collaboration in the re-interpretation study[7], and made available on **HepData**[6] in the form of SLHA[25] files. The details regarding the production of the model points and the selection criteria can be found in the original phenomenological papers [26–29]. The model points are divided according to the nature of the LSP, i.e. the lightest of the four neutralinos, into Bino, Higgsino and Wino-like nature, as:

- **Bino-like LSP** for  $N_{11}^2 > \max(N_{12}^2, N_{13}^2 + N_{14}^2)$  [103,410];
- **Wino-like LSP** for  $N_{12}^2 > \max(N_{11}^2, N_{13}^2 + N_{14}^2)$  [80,233];
- **Higgsino-like LSP** for  $(N_{13}^2 + N_{14}^2) > \max(N_{11}^2, N_{12}^2)$  [126,684],

where  $N_{ij}$  are the entries in the neutralino mixing matrix (see e.g. [30]). In square brackets, the total numbers of parameters points tested in the ATLAS study is reported. For these more than 300k model points, the ATLAS collaboration produced Monte Carlo samples and re-run a selection of Run 1 searches for BSM physics (mostly SUSY). The **SModelS** coverage study investigated only the subset of points which could at least be excluded by at least one classical SUSY search based on missing energy signature. The goal was to quantify the coverage of the pMSSM by means of simplified model results. Consequently, the model points that could be excluded only by searches for resonant heavy Higgs bosons, or by searches for exotic charged particle that give origin to signatures such as displaced vertices, were not considered. This reduced the original number of points tested by ATLAS from 103,410 to 38,575 (Bino-like LSP dataset) and from 126,684 to 45,594 (Higgsino-like LSP dataset). These surviving points were passed through **SModelS** and analysed, and constitute the same dataset for the new analysis presented in this work, aiming at showing the improvement in the coverage thanks to the newly added EM results.

The same version v1.1.1 of **SModelS** was employed in this work. The cross section calculator module, which provides a useful interface with **Pythia 8**(v.8.226)[31], **Pythia 6**[11] and **NLLFast** [32–39] was used to compute the production cross sections, up to NLO+NLL order for strong production, and LO for electroweak processes; **Pythia 6** was instead used for slepton production. The other two relevant parameters selected in the configuration file **parameters.ini** are the **sigmacut**= 0.03 fb, that controls the minimum allowed weight  $w = \sigma \times BR$  for each simplified model appearing in the decomposition, and **minmassgap** = 5 GeV, i.e. the minimum mass gap for which the SM products appearing in the decay chain are considered visible. We refer to the extended online user manual[?] for more details.

### 4.3 SModelS Database

We used the complete set of SMS results available for 8 TeV centre-of-mass energy of the release 1.1.1 of the database. These include official results in the form of upper limits and efficiency maps from the ATLAS and CMS collaborations, EMs results produced by the **FastLim** collaboration available at [40] and adapted to the **SModelS** infrastructure, and the set of EM results recast by **SModelS** collaboration. The complete description of the database of v1.1.1 can be consulted in [4]). In addition we added the EM results specifically produced for this work described in Section 3. To summarise, the additional EMs results are:

- ATLAS-SUSY-2013-02:  $T2$  (which replaces the maps officially provided by ATLAS),  $T5$  and  $T3GQ$  results;
- CMS-SUS-13-012  $T2$  (which replaces the maps officially provided by CMS) and  $T3GQ$  results.

The replacement of the  $T2$  results was done in order to cover smaller mass gaps between the squarks/gluinos and the LSP, as described in Tab. 1. The new EMs were made available with the database release 1.2.2. All the versions of **SModelS** databases can be consulted at [41]. For convenience, all the EMs results that will be discussed when presenting the extended pMSSM-19 coverage are summarised in Tab. 2.

Note that the discussion will focus on the ATLAS-SUSY-2013-02 EMs, mainly for two reasons. The first one is the availability of a direct comparison with the full recast performed by the ATLAS collaboration. The second one is that, on average, the results from this analysis are more constraining with respect to the CMS counterpart. This is due to the specific design of the analysis: the signal regions in the ATLAS search are very inclusive hence the efficiency can capture a large portion of the SUSY signals within the same signal region. On the contrary, the CMS analysis defines 36 non-overlapping signal regions, so that the SUSY signal is split into several bins. Since the combination of signal regions is not possible, only the best signal region is used to calculate the limits, that in general result weaker than the ATLAS search.

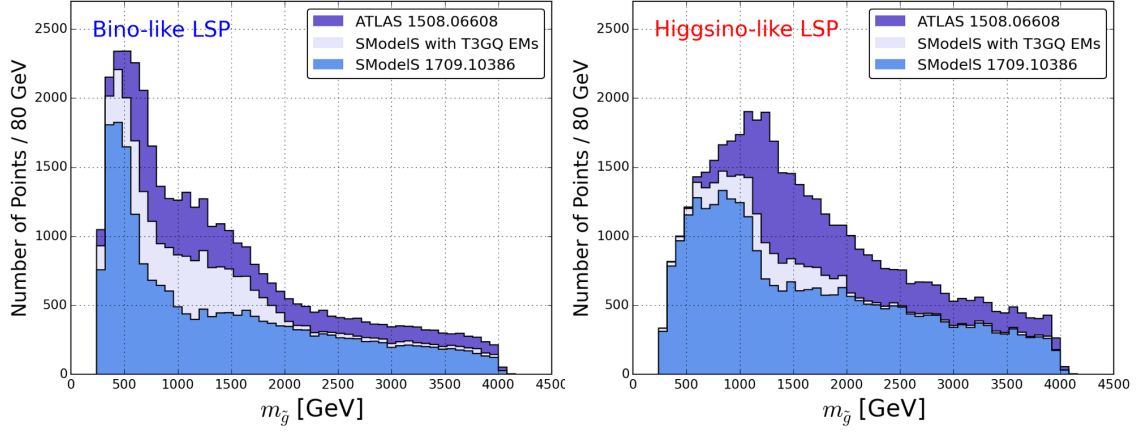
ATLAS-SUSY-2013-02 , CMS-SUS-13-012		
SMS	Decay	Source
$T1$	$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	Official
$T2$	$pp \rightarrow \tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	Recast
$T5$	$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{q}q, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	Recast
$T3GQ$	$pp \rightarrow \tilde{g}\tilde{q}, \tilde{g} \rightarrow \tilde{q}q, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	Recast

**Table 2:** Summary of the EMs considered in the extension of the pMSSM-19 coverage.

## 5 Extending the pMSSM Coverage

In this Section we study the improvements in the pMSSM coverage provided by the additional EMs for the  $T3GQ$  gluino-squark model, in combination with the  $T2$  and  $T5$  model.

Table 3 shows the new total exclusion of the pMSSM points, 21,151 and 28,669 points for the Bino and Higgsino-like case, covering the 74 and 71 % of the total points tested. With



**Figure 2:** Distributions of the points excluded by ATLAS (purple), by **SModelS** with the inclusion of the newly home-grown maps (light blue), and by the previous work [4] (slate blue), for the Bino(top) and Higgsino-like LSP (bottom).

	ATLAS	SModelS(EM+UL)
<b>Bino LSP</b>	38527	28765 (74 %)
<b>Higgsino LSP</b>	45345	32358 (71 %)

**Table 3:** **SModelS** constraints for the Bino and Higgsino-like LSP after the addition of the newly implemented EMs results for the models  $T2$ ,  $T5$  and  $T3GQ$ .

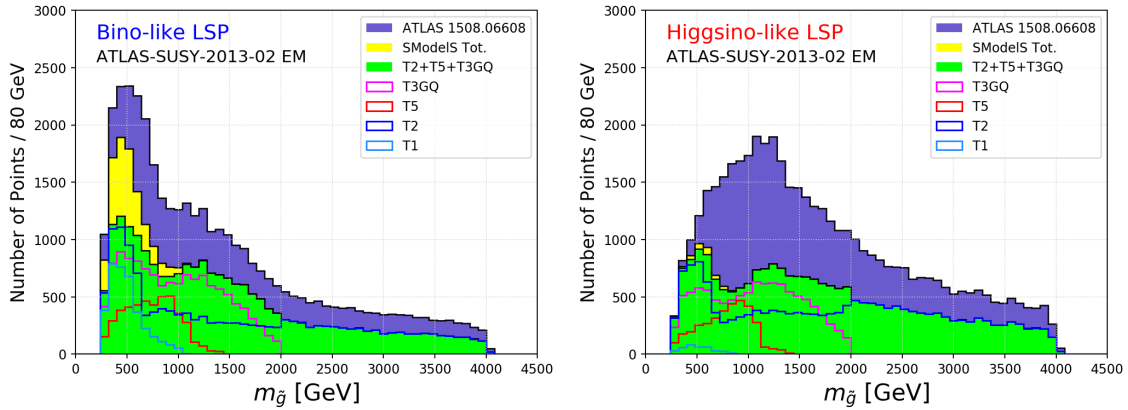
respect to the previous coverage detailed in [4], an improvement in the coverage of +19% and +8% respectively is obtained. The major improvement appears in the Bino-like LSP case, as noticeable also in the gluino and squark mass coverage distributions in Fig. 2. Due to the choice of the parametrisation of the mass planes for the sample production, the bulk of the improvement is found for  $m_{\tilde{g}} \leq 2$  TeV.

### 5.1 Breakdown of the SMS Results

As detailed in Section 2, the  $T2$ ,  $T5$  and  $T3GQ$  can be combined to reconstruct more comprehensively the signals from  $\tilde{g}\tilde{g}$ ,  $\tilde{q}\tilde{q}$  and  $\tilde{g}\tilde{q}$  production channels. Here we wish to analyse how the newly excluded points benefit from such combination, using the ATLAS-SUSY-2013-02 results. The following results include also EMs for the  $T1$  model

$$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0, \quad (5.1)$$

i.e. gluino decay to the LSP via off-shell light squarks (provided by the ATLAS collaboration). The experimental signature is a  $4jet + E_t^{miss}$ , same as the  $T5$  model, where the intermediate squarks is on-shell. The exclusions from each model and from the combination of the ( $T1 + T2 + T3GQ$ ) are drawn in Fig. 3. Note that points can be excluded by more than one results, e.g. points with both light squarks and gluinos, with  $m_{\tilde{g}} > m_{\tilde{q}}$ , might be excluded by both the  $T2$  and  $T5$  results; for this reason, the histogram relative to each

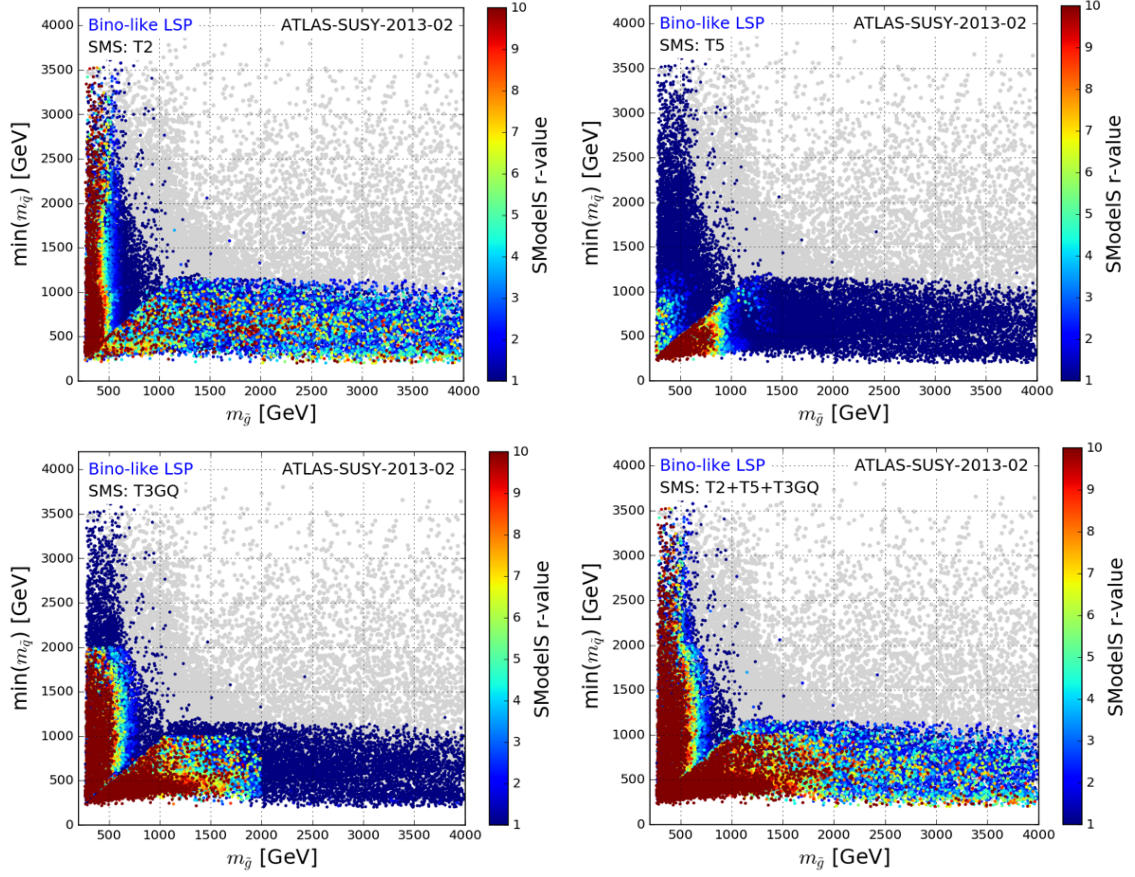


**Figure 3:** Contribution of the  $T1$ ,  $T2$ ,  $T5$  and  $T3GQ$  simplified model results and their combination for the analysis ATLAS-SUSY-2013-02, as a function of  $m_{\tilde{g}}$ .

SMS cannot be stacked together. A major difference between the Bino and the Higgsino-like LSP case concerns the exclusion from the  $T1$  results, which are significant in the former case, but almost irrelevant in the latter. The model is considered for completeness since such result is available. However, this signal cannot be in general combined with the other signatures of interest, they assume mutually excluding decays to either on- or off-shell decay to intermediate squarks. Other SUSY configuration can still result in the  $T1$  signature, for example the production of charginos and neutralinos decaying hadronically to off-shell vector bosons, but they are scarcely relevant due to the small  $\sigma \times BR$ . As already stressed, EMs allow for the combination of different SUSY signals, map onto the decomposed SMS of the model tested. In Table 4 the number of points that can be excluded only by the specific model listed is provided. This means that, for example, the  $T1$  model results can exclude 3,175 model points of the Bino-like LSP dataset, so that the individual  $r$  value for this results exceeds unity. On the opposite, the  $r$  value of the sum of remaining results is insufficient to exclude the point. We see that, in this sense, the most powerful results is certainly the  $T2$ ; at the same time, around 3.000 points can only be excluded by the sum of ( $T2 + T5 + T3GQ$ ) results. Finally, in Fig. 4 the distribution for the  $r$ -values for the  $T2$ ,  $T5$ ,  $T3GQ$  models and their combination is shown, for the Bino and Higgsino-like LSP cases respectively. The contribution from the  $T1$  model is not considered. Note that the plots are projected onto the  $(m_{\tilde{g}}, \min(m_{\tilde{q}}))$  mass plane. This highlights the contribution from the two alternative mass hierarchies  $m_{\tilde{g}} > \min(m_{\tilde{q}})$  or  $\min(m_{\tilde{q}}) > m_{\tilde{g}}$ , clearly indicated by the points distributed around the diagonal of the plots.

## 5.2 Estimation of the Uncertainties

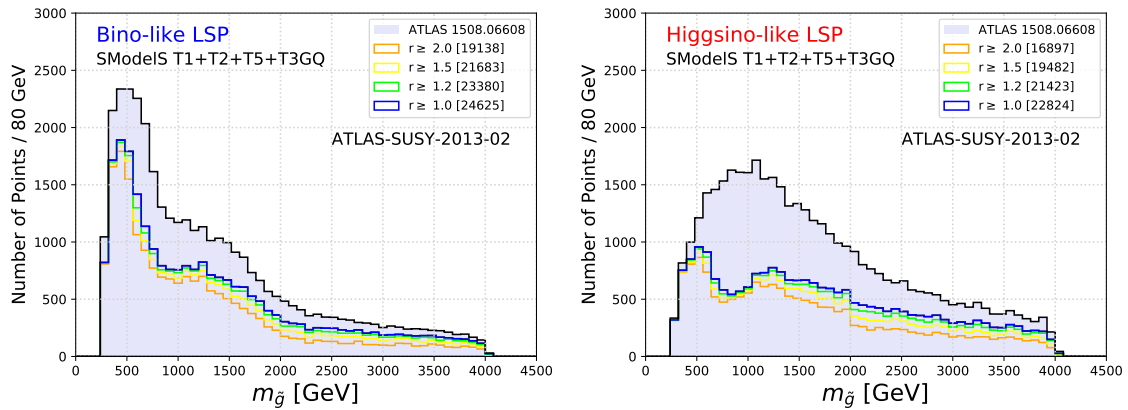
In this section we provide a rough yet qualitative estimation of the uncertainties of the whole procedure. These are very challenging to estimate reliably due to the complexity of the procedure itself, which involves at first the production of the Monte Carlo events for the generation of the event files, then the analyses recast. The validation documents provided



**Figure 4:** Distributions of the  $r$  value for  $T2$ ,  $T5$ ,  $T3GQ$  and their combination for the points excluded by the ATLAS-SUSY-2013-02 results (Bino-like LSP dataset). Grey points have a total  $r$  value  $\leq 1$ . A large portion of points excluded by  $T2$  lies in the  $m_{\tilde{g}} < 500$  GeV mass, due to the gluino loop decay  $\tilde{g} \rightarrow g\tilde{\chi}_1^0$ . A similar argument holds for the  $T5$  model, in the region where the result constrains the  $\tilde{q} \rightarrow q\tilde{g}, \tilde{g} \rightarrow g\tilde{\chi}_1^0$  decay. The  $T3GQ$  model results can efficiently constrain the two alternative mass hierarchies  $m_{\tilde{g}} > m_{\min(\tilde{q})}$  or  $m_{\min(\tilde{q})} > m_{\tilde{g}}$ . In particular it shows that the EMs should be extended to cover  $m_{\tilde{g}}$  masses larger than the 2 TeV values.

SMS	Bino	Higgsino
$T1 : pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	3174	204
$T2 : pp \rightarrow \tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	7221	11180
$T5 : pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	191	160
$T3GQ : pp \rightarrow \tilde{q}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	3259	2792
$T2 + T5 + T3GQ$	3320	299

**Table 4:** Number of points that can be excluded only by including each individual result for  $T1$ ,  $T2$ ,  $T5$ ,  $T3GQ$ , or their combination. See the text for details.



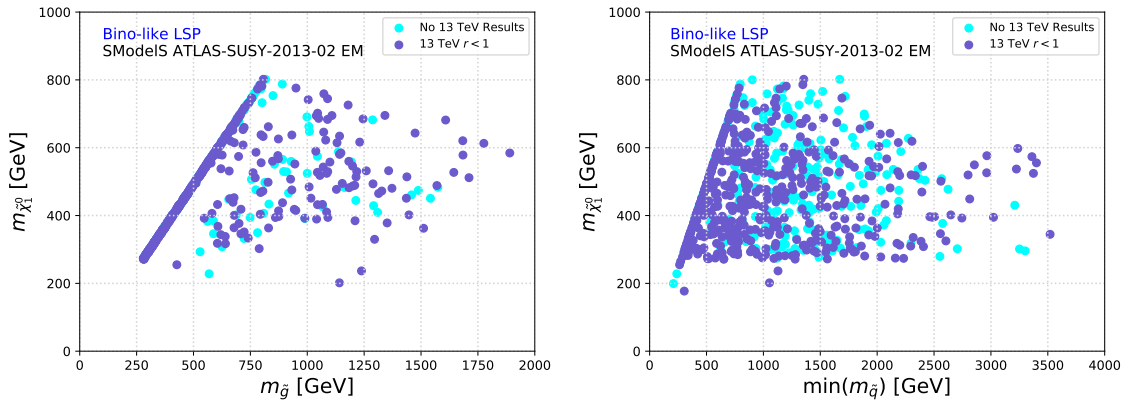
**Figure 5:** Distribution of the excluded points, as a function of  $m_{\tilde{g}}$ , for different requirements of  $r$  value  $> 1.0, 1.2, 1.5, 2.0$ . Only the EM results for the analysis ATLAS-SUSY-2013-03 are used, for the SMS T1 (official results from ATLAS) and  $T2$ ,  $T5$ ,  $T3GQ$  (homegrown SModelS results). On top, the total number of points excluded by the official ATLAS study only the aforementioned analysis is shown.

with the analyses recasting code is a valid proof that the choice of the simulation parameters allows to reproduce well the analyses efficiency. While the generation of a sufficient amount of events keeps the statistics uncertainty under reasonable control, systematic effects are more difficult to be accounted for. Last but not least, the entire assumptions at the basis of the simplified model spectra idea inevitably introduces approximations, for example since the exact production mechanisms of the SUSY particles considered are neglected, as well as any kinematic effects due to the specific quantum numbers of the particles. If the analysis efficiency is strongly affected by these two aspects, then the full recast approach is certainly more indicated. All these aspects add up together and cannot be easily quantified. As formulated in the definition of SModelS  $r$  value in Eq. 4.1, a model point is considered excluded at 95% CL if the  $r$  value exceeds unity. Tightening this condition by requiring that the theory predictions exceeds higher value can mimic the inclusion of uncertainties on the theory level concerning e.g. on the reference cross section calculation, the recasting procedure and/or the SMS approach assumptions. In Fig. 5 the distribution of the excluded points, as a function of  $m_{\tilde{g}}$ , is plotted for different  $r$  value requirements of  $r$  value  $> 1$  which is the standard exclusion limit, and  $r$  value  $> 1.2, 1.5, 2.0$ ; these last values correspond to a decrease in the theory predictions of 20%, 50%, 100%, so that the exclusion become more conservative. The total number of points excluded considering each separated value is reported in the legend. It is comforting to note that even for the pessimistic case of the largest uncertainty, the number of points does not differ for more than 25% with respect to the standard criterion. There is also no sign of higher impact which depends on  $m_{\tilde{g}}$ , so any systematic effect dependent on this mass parameter should be unlikely.

## 6 A Look at 13 TeV Results

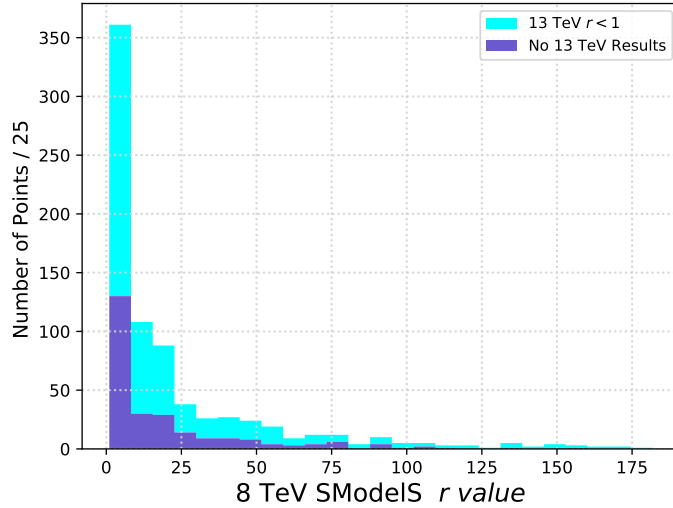
We discuss in this Section some results obtained with recent SMS results from LHC Run 2 searches. Due to the larger production cross section, it is expected that the coverage of the pMSSM-19 for the same dataset of points designed for 8 TeV results increases considerably. In fact, this was already shown in [42]: by using SMS results for a selection of 13 TeV analyses, with collision data adding up to around  $36 \text{ fb}^{-1}$ , almost all the entire set of pMSSM-19 points considered by ATLAS could be excluded, including the ones out of the of 8 TeV searches. The aim of the present discussion is to demonstrate that certain regions of the parameter space cannot be covered even by more recent results.

In Fig. 6 we consider a set of points which can be excluded with the new ATLAS-



**Figure 6:** Distribution of the points (Bino-like LSP dataset) excluded by the 8 TeV EM results for the analysis ATLAS-SUSY-2013-02, but not excluded by recent 13 TeV analyses published in v1.2.2 of the SModelS database. In cyan, the points fall outside the grid of results available for 13 TeV results; in purple, points for which the 13 TeV  $r$  value  $< 1$ . Note that most of the points lies in the region of small gluino/squark-LSP mass gap.

SUSY-2013-02 EMs, but cannot be excluded by the 13 TeV results available in v1.2 of the SModelS database. The points are divided into two categories. The first include points that do not map onto any of the available results. This is mainly due to the limitation in the mass grid for which results are available, that might not allow to cover the specific mass configuration of the model points tested. Another cause is the lack of relevant SMS results, since the variety of SMS used for the interpretation at 13 TeV is still rather small. The second category includes points for which 13 TeV results can indeed be applied, but the corresponding limits are too weak to exclude the point. The two different mass planes employed for the projections of the results show clearly that the majority of points falls in the region where the mass gap between the gluino-LSP or squark-LSP is small. We characterize the distribution of the  $r$  value of such points in Fig. 7, using the results for the 8 TeV ATLAS-SUSY-2013-02 analysis. For many model points, the  $r$  value reaches up to few tens, meaning that the points can efficiently be constrained by 8 TeV results.

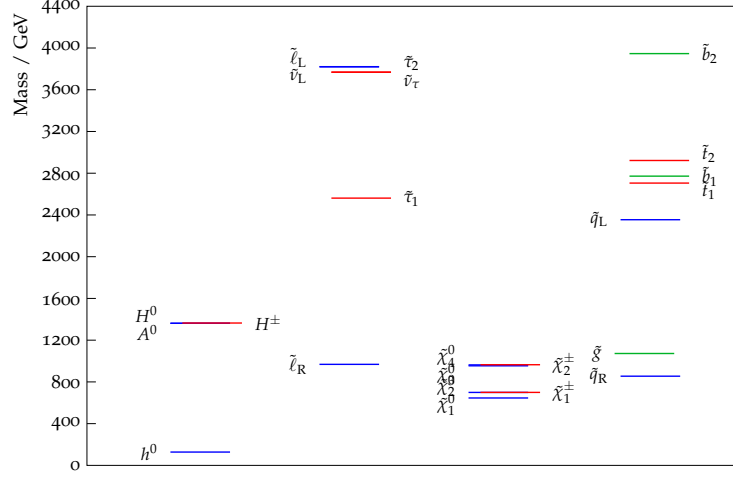


**Figure 7:** Distribution of the  $r$  value of the points excluded by 8 TeV results, that cannot be excluded by recent 13 TeV results.

On a side note, we observe that the recent Run 2 inclusive ATLAS 0 lepton, 2-6 jets search[43], that uses  $36\text{ fb}^{-1}$  of collision data, is interpreted with both gluino and squark pair productions, plus a gluino-squark model intended as a realisation of the pMSSM where only 1st and 2nd generation squarks and gluinos are light, and all the other sparticles are decoupled. They parametrized the mass planes by fixing the LSP mass (Bino-like, for  $m_{\tilde{\chi}_1^0} = (0, 695, 995)$ ) and considered a grid of gluino and squark masses. In order to use such results, an interpolation in the LSP mass of around 700 GeV, to cover the region  $m_{\tilde{\chi}_1^0} < 700\text{ GeV}$ , has to be performed, which is quite a large mass interval. Unfortunately the results are provided (on InspireHEP[44] only in the form of UL maps. It would be much appreciated if EMs for the gluino-squark model were also made available and allow for the combination with the published EMs for the  $T2$  model to exploit the full gluino-squark signal constraints.

Finally, we report in detail the results of one of such points, namely the SLHA file 59847871 from the Bino-like LSP dataset. Its mass spectrum, adapted from the tool pySLHA[45], is shown in Fig. 8. We see that, besides the light neutralinos/charginos  $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_1^\pm$  whose mass lies around 500 GeV, the lightest SUSY particles are down-type right-handed squark, with mass of 854 GeV. The gluino is slightly heavier, with a mass of 1.072 TeV. The up-type right-handed and the left-handed squarks have a mass of 1.763 and 2.353 TeV respectively. In Table 5 the results from the best 13 TeV analysis and the results from our recast EMs for the 8 TeV searches are shown. The only applicable 13 TeV results are in the form of  $T2$  SMS UL, coming from the decay of the down-type right-handed squarks to their corresponding Standard Model quark companion and the LSP. On the other hand, gluinos decay via one-step cascade to the intermediate lighter squarks; overall, this would produce the  $T5$  signature. The values of the cross section, listed in Tab. 6, show that indeed the three different production channels  $pp \rightarrow \tilde{g}\tilde{g}$ ,  $pp \rightarrow \tilde{g}\tilde{q}$  and  $pp \rightarrow \tilde{q}\tilde{q}$





**Figure 8:** Mass spectrum of the point 59847871, from the Bino-like LSP dataset. Right-handed squarks are the lightest coloured particles, opening the  $\tilde{g} \rightarrow q\tilde{q}$  decay channel. **FIX!!! right up and down squarks**

Point 59847871 Bino-like LSP dataset		
Analysis	$\sqrt{s}$ [TeV]	r value
ATLAS-SUSY-2013-02 (EM)	8.0	1.57
CMS-SUS-16-033 (UL)	13.0	0.79
CMS-SUS-16-036 (UL)	13.0	0.69

**Table 5:** SModelS results for the point 59847871 Bino-like LSP dataset, for the analyses providing the three largest  $r$  value.

Process	$\sigma(8 \text{ TeV})$ [pb]	$\sigma(13 \text{ TeV})$ [pb]
$pp \rightarrow \tilde{g}\tilde{g}$	$1.09 \cdot 10^{-2}$	$1.66 \cdot 10^{-1}$
$pp \rightarrow \tilde{g}\tilde{q}$	$1.01 \cdot 10^{-2}$	$2.9 \cdot 10^{-1}$
$pp \rightarrow \tilde{q}\tilde{q}$	$1.67 \cdot 10^{-2}$	$8.84 \cdot 10^{-2}$

**Table 6:** Cross section production [pb] for the processes  $pp \rightarrow \tilde{g}\tilde{g}, pp \rightarrow \tilde{g}\tilde{q}, pp \rightarrow \tilde{q}\tilde{q}$ . Cross sections values are calculated at NLL order.

have comparable size, and justifies why the combination of signals, possible with 8 TeV results, is necessary to exclude the point. **maybe move this to an appendix?**

## 7 Conclusion

While simplified models have become hugely popular among the experimental collaboration for the interpretation of their BSM searches, it is challenging to make use of such results to investigate complicated theories. Moreover, the question if the simplified approach is

sufficient to properly cover the a full model is always open. A concrete step forward was made in the previous **SModelS** analysis of the ATLAS pMSSM-19 coverage, showing that a large portion of the parameter space of such SUSY model can be efficiently constrained by means of SMS, without the computationally expensive procedure of analyses recasting. At the same time, despite the plenty available SMS results, there is a lot of room for improvement. The essence of SMS makes them inadequate in the presence of complicated mass spectra, that give rise to long decay patterns which are better, but not always, captured by full analyses recast. Fortunately the main outcome of the previous study showed clearly that for the majority of uncovered model points, most of the unconstrained  $\sigma \times BR$  was captured by a class of simplified models involving only three SUSY particles and short decay, arising from gluino-squark production. The associated  $3jets + E_T^{miss}$  signature is easily covered by inclusive all hadronic final state searches at the LHC, targeting specifically low jet multiplicity, such as ATLAS-SUSY-2013-02 and CMS-SUS-13-012. The results presented in this work show concretely that it is possible to produce such dedicated EM results, using available recasting tools, and significantly increase the coverage of the model up to 74% and 71% of the total ATLAS exclusion for the Bino and Higgsino like LSP dataset respectively. The workflow can be extended and implemented for other theories: once the most important missing simplified signatures are determined, recast EM can be produced only once, and the results can be re-used to constrain generic models. In addition to the possibility to produce customized SMS results, EMs have the advantage of allowing the combination of multiple signals. In particular, the combination of the  $T2 + T5 + T3GQ$  signals for the ATLAS-SUSY-2013-02 analysis is sufficient alone to cover around 70 % of the points covered by the full recast of the analysis, as performed by ATLAS. We note that this is obtained by neglecting most of the popular simplified model for gluino production, such as the direct decays of gluinos via off-shell top  $pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\chi_1^0$  and sbottom squarks  $pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\chi_1^0$ , and models for third generation squarks direct decay such as  $pp \rightarrow \tilde{b}\tilde{b}, \tilde{b} \rightarrow b\chi_1^0$  and  $pp \rightarrow \tilde{b}\tilde{b}, \tilde{b} \rightarrow b\chi_1^0$ , to which the search is expected to be sensitive to (see e.g. [46] for the top squark model). On another note, we are aware that the latest data, referring to proton collisions at 13 TeV centre-of-mass energy, give much better constraints on the same model due to the significant increase in the production cross section, and also in the larger amount of data, since the latest SUSY searches from the ATLAS and CMS collaborations are based on an integrated luminosity of around  $140 \text{ fb}^{-1}$ , already a factor 7 higher than the luminosity collected during Run 1. The impact on the pMSSM-19 was already estimated in [42]. There is however a substantial difference and outcome in the aim of the two works. With this study, we aimed at somehow give a concrete exemplification of systematic use of the tool **SModelS** in association with public recasting tool to improve what is the state of the art of the available SMS results. Stressing the importance of specific simplified models results, produced for specific SUSY searches, is valuable information for the future. In fact, still neither the  $T5$  nor the  $T3GQ$  models are available at higher centre-of-mass energy, being those official or recast results. This works constitute a solid starting point for building future updates of the databases of SUSY SMS results, and we invite both the experimental collaboration and our colleague phenomenologists to produce UL and/or EM results for the SMS here studied, ad a useful addition to the set of SMS

commonly used for the interpretation of searches.

## Acknowledgments

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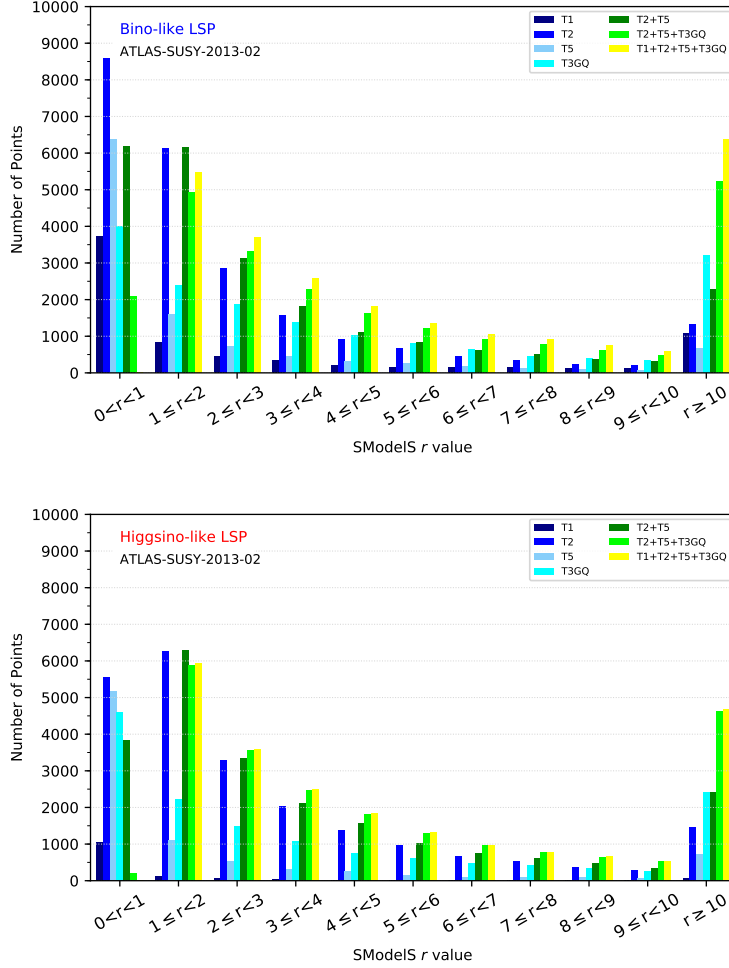
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## A Distributions of $r$ values

Fig.9 shows the distributions of the  $r$  values for each result of the analysis ATLAS-SUSY-2013-02 ( $T1, T2, T5$  and  $T3GQ$ ), the combinations of models ( $T2+T5$ ,  $T2+T5+T3GQ$  and the sum of all the available results  $T1+T2+T5+T3GQ$ ). Only the points excluded by the analysis are considered; this implies that the points in the first bin  $0 \leq r < 1$  can be excluded only by considering the sum of all the results, i.e. considering  $T1+T2+T5+T3GQ$ . For the bins with  $r \geq 1$ , each individual contribution might be sufficient to exclude the models tested. For large  $r$  value, the number of points decreases as expected, and the importance of the combinations of multiple results increases. The last bin refers to  $r$  value  $\geq 10$ , i.e. points that can be strongly excluded by the SMS results considered, in particular by the combination of the  $T1+T2+T5+T3GQ$  and  $T2+T5+T3GQ$  for the Bino and Higgsino-like LSP case respectively.



**Figure 9:** Distribution of the  $r$  values for excluded points, considering single SMS or combinations, for the analysis ATLAS-SUSY-2013-02. The points included in the first bin  $0 < r < 1$  can only be excluded by the combination of all the EMs results available for the ATLAS-SUSY-2013-02 analysis.