

Hide and seek with natural supersymmetry at the LHC

B.C. Allanach^a and Ben Gripaios^b

^a*Department of Applied Mathematics and Theoretical Physics,
Centre for Mathematical Sciences, University of Cambridge,
Wilberforce Road, Cambridge CB3 0WA, U.K.*

^b*Cavendish Laboratory, University of Cambridge,
JJ Thomson Avenue, Cambridge CB3 0HE, U.K.*

E-mail: B.C.Allanach@damp.cam.ac.uk, gripaios@hep.phy.cam.ac.uk

ABSTRACT: Gluinos that result in classic large missing transverse momentum signatures at the LHC have been excluded by 2011 searches if they are lighter than around 800 GeV. This adds to the tension between experiment and supersymmetric solutions of the naturalness problem, since the gluino is required to be light if the electroweak scale is to be natural. Here, we examine natural scenarios where supersymmetry is present, but has hidden from 2011 searches due to violation of R -parity and the absence of a large missing transverse momentum signature. Naturalness suggests that third generation states should dominate gluino decays and we argue that this leads to a generic signature in the form of same-sign, flavour-ambivalent leptons, without large missing transverse momentum. As a result, searches in this channel are able to cover a broad range of scenarios with some generality and one should seek gluinos that decay in this way with masses below a TeV. We encourage the LHC experiments to tailor a search for supersymmetry in this form. We consider a specific case that is good at hiding: baryon number violation, and estimate that the most constraining existing search from 2011 data implies a lower bound on the gluino mass of 550 GeV.

KEYWORDS: Supersymmetry Phenomenology

ARXIV EPRINT: [1202.6616](https://arxiv.org/abs/1202.6616)

Contents

| | | |
|----------|--|-----------|
| 1 | Introduction | 1 |
| 2 | Natural supersymmetry at the LHC | 3 |
| 3 | Same-sign dilepton searches | 6 |
| 3.1 | Tops and stops | 7 |
| 3.2 | Bottoms and sbottoms | 7 |
| 3.3 | Bottom tagging | 9 |
| 3.4 | Same sign di-taus | 9 |
| 4 | Current searches | 10 |
| 4.1 | Test point | 12 |
| 4.2 | ATLAS di-muon search | 13 |
| 4.3 | ATLAS same-sign di-lepton, jets and missing transverse momentum search | 13 |
| 4.4 | CMS same-sign di-lepton, jets and missing transverse momentum search | 14 |
| 4.5 | Model exclusion limits | 15 |
| 5 | Suggestions for future searches | 17 |
| 6 | Summary | 20 |

1 Introduction

Softly-broken supersymmetry (SUSY) has long provided an elegant dogma for natural electroweak symmetry breaking, providing a mechanism by which the electroweak scale may be stabilised in the presence of radiative corrections from new physics at arbitrarily large mass scales. But even fervent disciples have seen their faith in SUSY shaken in recent times by the lack of evidence therefor.

Indeed, a generic, natural, supersymmetric theory predicts superpartners with masses liberally sprinkled around the weak scale (measured by, say, m_Z) and so negative searches for direct production of superparticles at LEP (and for the Higgs boson) already put strong constraints on generic supersymmetric theories. In a given theory, these constraints can be avoided by pushing up the mass scale of superparticles and carefully choosing the parameters to obtain the observed value of m_Z , but this is in itself nothing other than a fine tuning, corresponding to a residual “little hierarchy” between m_Z and the mass scale of superpartners.¹

¹Alternatively, one might imagine that a baroque theory exists in which the measured fine tuning, according to some definition, turned out to be small. But then one would be left wondering why Nature would choose such a theory apparently solely for the purpose of hiding physics beyond the Standard Model (SM) from our current generation of experiments.

The situation has worsened with the advent of the 7 TeV LHC, where a suite of negative searches [1–5] has pushed lower bounds on superpartner masses, in certain scenarios, beyond a TeV; though fine tuning is inherently a subjective notion, many of us no doubt feel that a psychological Rubicon has been crossed when bounds on superpartner masses reach the terascale.

As such, now would seem to be a good point to re-assess our agenda for future SUSY searches. Should searches be abandoned? Should we continue with existing searches, ratcheting up the luminosity and beam energy, and interpret the results in terms of the same models? Or should we pluck new models that purport to solve the hierarchy problem up to high scales out of the swamp of possibilities and design new searches for these? None of these strategies seems especially appealing.

A different suggestion has recently been put forward in ref. [6]. There, it is argued that, since the LHC directly probes energy scales well beyond the weak scale (up to a cut-off, Λ , less than a few TeV or so), we should try to discern whether there are any superparticles present below Λ that stabilise the dynamics up to Λ , without regard for what further dynamics might be required, beyond the reach of the LHC, to solve the ‘big’ hierarchy problem. This would seem to be a laudable goal from the point of view of the legacy of the LHC: if such superparticles are found at the LHC, then detailed investigation of them will become a priority for the next generation of experiments; if such superparticles are not found and if we can be reasonably confident that they are not there, then this will be a strong indicator that supersymmetric naturalness is not a good guide for predicting what (if any) physics may lie within our future reach.

This goal of ruling out supersymmetric naturalness within the reach of the LHC would, moreover, seem to be achievable, by and large, if we make the assumption of “minimality” [6]: that only those degrees of freedom that are required by naturalness are present in the low energy spectrum (with perhaps just a few other, auxiliary, states). This assumption is motivated not only phenomenologically (after all, we have yet to see *any* substantial evidence for superparticles and indeed the many direct and indirect constraints on TeV- scale dynamics are most easily alleviated by positing as few new TeV-scale particles as possible), but also by the existence of theoretical models whose dynamics is such that the lightest superparticles are automatically those that couple most strongly to the Higgs sector [7–10]. (For other models giving rise to such dynamics, see [11–17].) The experimental implications of the minimality assumption are that we are left with a relatively small number of possible final states on which to focus LHC searches.

Happily, many of these final states are already being sought and much effort is being put into interpreting those searches in terms of a generic exclusion of supersymmetric models. But it is important that searches cover *all* feasible scenarios and that we strive to obtain the best possible sensitivity in each case.

Here, we wish to focus on a generic scenario that is not currently under examination, as far as we are aware. The scenario involves light gluinos, which are required by naturalness and in consequence have significant production cross-section at the LHC. The scenario differs from canonical ones in that R -parity conservation (which is not required by naturalness) is not assumed, such that conventional searches based on large missing transverse

momentum ($|\vec{p}_T^{\text{miss}}|$) signatures fail. Nevertheless, there is sensitivity at the LHC, because pairs of Majorana gluinos sometimes decay into pairs of same-sign leptons (plus hadrons). The reasons that we arrive at leptons are two-fold. Firstly, naturalness and flavour physics constraints suggest that third generation quarks and squarks are lightest and that their couplings are largest, meaning that top quarks are often present in gluino decays. A significant fraction of these further decay into isolated leptons. Secondly, the R -parity violating couplings by which superpartners ultimately decay frequently involve either leptons or (again by naturalness and flavour arguments) top-quarks. So a search for same-sign leptons (which should include τ leptons) should cover many of the possible gluino decays. In fact we find only one, rather special, case in which a significant fraction of same-sign leptons from gluino decays is not automatic: for that to happen, the gluino must decay into a left-handed bottom squark. This decay is unlikely to overwhelmingly dominate, given that the gluino couples with equal strength to left-handed top and bottom squarks and given that, at tree-level, the difference in the squared masses of these squarks is only $m_{\tilde{t}_L}^2 - m_{\tilde{b}_L}^2 = M_W^2 \cos 2\beta$. Even if the decay to a left-handed sbottom does predominate, the decay of the latter must proceed via a charged Higgs boson to a virtual right-handed top squark, which in turn must decay via the superpotential operator $W \supset U_3 D_i D_j$ into light quark jets. Then, the only possible source of an isolated lepton comes from the charged Higgs decay. This decay will not result in a source of leptons only if the charged Higgs is below threshold to decay to $t\bar{b}$ and only if the CKM-suppressed decay to $c\bar{b}$ dominates over the decay to $\tau\bar{\nu}_\tau$. This last condition requires that $\tan\beta \ll \frac{m_t}{m_\tau} V_{cb} \approx 3$, which seems unlikely, at least in the context of the minimal supersymmetric SM (MSSM), due to higgs constraints from LEP.

The outline of the paper is as follows. In the next section, we review the arguments for which superparticles should be light and catalogue the possible LHC scenarios, showing that many are already being covered. In section 3, we consider the case of gluino pair-production followed by R -parity-violating decays in detail, showing that most cases can be covered by a search for a pair of same-sign e , μ or τ appearing in any flavour combination. In section 4, we argue that existing LHC searches for low-scale quantum gravity and canonical, R -parity-conserving SUSY in final states involving same sign leptons give the best current sensitivity and provide a rough estimate of the resulting bounds on the gluino mass from three such searches, in a scenario where the gluino decays via a top squark which subsequently decays via a baryon-number-violating operator. We then argue, in section 5, that dedicated searches could provide significantly stronger bounds and we encourage the LHC collaborations to carry them out.

2 Natural supersymmetry at the LHC

Which states then, ought to be within reach of the LHC? The largest contribution to the quadratic divergence in the Higgs mass parameter comes from a loop of top quarks via the Yukawa coupling. To cancel this using supersymmetric dynamics, we need both the right-handed top squark, \tilde{u}_R^3 , and the left-handed $SU(2)_L$ doublet containing top and bottom squarks, \tilde{Q}_R^3 , to be light.

The next largest quadratic divergences come from one-loop diagrams involving W -bosons and the Higgs itself, but already the couplings involved are small enough that one can imagine them being cancelled by superpartners that are beyond the reach of the LHC. This is especially true when one takes into account the fact that these are colour-singlet states with commensurately small direct production cross-sections in pp collisions.

The minimal dynamics, then, contains only left- and right-handed top squarks, together with the left-handed bottom squark. Search strategies for these depend on when and how they decay. If they are sufficiently long-lived to reach the detector before decaying (perhaps because of some symmetry, like R -parity, either approximate or exact)² then the exotic ‘ R -hadrons’ into which they are confined may be detected either by their interactions with the detector or by their eventual decays [18]. Existing searches, though subject to large uncertainties due to our poor understanding of the properties of R -hadrons, already exclude masses up to around 500 GeV [19], so there is hope that the TeV Rubicon will eventually be crossed. On the other hand, stops and sbottoms may decay promptly. For the lightest state to decay, R -parity must be violated. We write the R -parity violating part of the renormalisable MSSM superpotential [20] (in the basis where the superfields have been rotated such that the quarks contained within are in the mass basis)

$$W_{\mathcal{R}p} = \frac{1}{2}\lambda_{ijk}L_iL_jE_k + \lambda'_{ijk}L_iQ_jD - \kappa^iL_iH_2 + \frac{1}{2}\lambda''_{ijk}U_iD_jD_k, \quad (2.1)$$

where we have suppressed the gauge indices, i, j, k are flavour indices, and L_i, Q_i, U_i, D_i, E_i are chiral superfields containing left-handed fermions: lepton doublets, quark doublets, anti up-quarks, anti down quarks and positrons, respectively. The $U_iD_jD_k$ operators break baryon number, whereas the others break lepton number. We do not expect both sets of operators to be present simultaneously, since proton decay would be predicted to be much faster than is observed. However, several discrete gauge symmetries have been proposed which may ban one set of operators [23, 24] as alternatives to R -parity. As has long been known [21, 22], and has been re-stressed in [6], R -parity itself does not forbid dimension-five operators in the superpotential, such as $W \supset \frac{Q_iQ_jQ_kL_l}{\Lambda}$, by which the proton may decay. So R -parity does not seem to be well-motivated in the context of an effective theory in which we profess ignorance of the dynamics beyond the reach of the LHC, such that the cut-off Λ is just a few TeV.

If stops or sbottoms do decay promptly, they will presumably do so via the R -parity violating operators in the superpotential of lowest dimension, *viz.* either via λ'_{3jk} or λ''_{3mn} . The couplings λ'_{3jk} or λ''_{3mn} endow the squarks with leptoquark or diquark properties, respectively, and the final states of interest then depend on the values of the remaining indices. In the case of leptoquark-like states, only couplings to the third-generation are likely to be sizable if constraints coming from flavour physics are to be satisfied [25], leading to final states which are pairwise combinations of $t\tau$, $t\nu_\tau$, $b\tau$, and $b\nu_\tau$. The LHC sensitivities for such leptoquarks are studied in [26], but are unlikely to rise beyond a few hundred GeV. A search in the $2b2\nu_\tau$ final state was recently performed in [27]. In the

²We do not concern ourselves here with potential cosmological issues arising from stable or long-lived coloured particles.

case of diquark-like states, it was shown in [28] that for a right-handed top squark (which couples antisymmetrically in flavour indices to a pair of down quarks) any one of the three couplings λ''_{3mn} could be sizable. This opens up the possibility of single production (leading to sensitivity in di-jet resonance searches) or pair production followed by decay into four jets (possibly with heavy-flavour), for which existing searches may be found in [29, 30].

We next ask what may happen if (a small number of) additional superparticles are present. For the purposes of LHC phenomenology, it is easiest to classify these by their colour charges. Colour singlets have low production cross section and are most likely to affect phenomenology through their appearance in decays of the produced top and bottom squarks. Perhaps the most likely such particles are Higgsinos, whose masses may arise from the R -parity conserving superpotential term $W \supset \mu H_u H_d$. This term also contributes to the Higgs scalar potential and thus is partly responsible for setting the weak scale, via $\frac{m_Z^2}{2} \simeq -|\mu|^2 - m_{H_u}^2$, where $m_{H_u}^2$ is a soft SUSY breaking mass term. Thus, unless μ is of order m_Z (implying a Higgsino mass of order m_Z) an apparently unnatural fine tuning between supersymmetric and SUSY-breaking terms is required. However, this argument for the existence of a light Higgsino cannot be considered watertight, even putting aside the subjectivity of naturalness considerations: in an effective theory with low cut-off Λ , Higgsinos may also receive contributions to their masses from higher-dimensional, SUSY-breaking terms, for example from the Kähler potential term $K \supset \frac{X^\dagger X}{\Lambda^3} D_\alpha H_u D^\alpha H_d$, where $X \supset F\theta^2$ is a SUSY-breaking spurion.

If Higgsinos or other colour singlets are present, then we have the possibility of top and bottom squark decays to these charged- or electrically-neutral states, together with top and bottom quarks. In the case that these are long-lived, we must look either for $|\vec{p}_T^{\text{miss}}|$ in final states or charged tracks in the detector; if they decay promptly via R -parity-violating operators, we may expect various combinations of jets, leptons and $|\vec{p}_T^{\text{miss}}|$.

In all cases without charged tracks of new, heavy particles, it seems unlikely that we will ever get sensitivity to squark masses much above several hundred GeV, the reason being that the production cross section for individual squarks is too low in the region in which signals have a clean kinematic separation from backgrounds. As an example, the cross section to pair-produce a top squark with mass equal to the mass of the top quark is reduced by a factor of around eight, compared to the $t\bar{t}$ production cross section, due to spin and threshold effects. The problem is compounded by the fact that the $|\vec{p}_T^{\text{miss}}|$ final states, like $2\tilde{t} \rightarrow 2(t + \chi^0)$, are kinematically very similar to backgrounds from SM $t\bar{t}$ production. As a result, the current limits on squark masses in such scenarios are extremely low, below m_t even [31–33].³

Adding more coloured particles may help to increase the LHC cross-section. Adding colour triplets (i.e. squarks) is, however, proscribed by existing LHC searches in final states with jets, $|\vec{p}_T^{\text{miss}}|$ [1, 5], and possibly leptons, which put strong (around a TeV) bounds on both gluino and squark masses when all squarks are assumed to have common mass. These bounds can be avoided either by relaxing the assumption of common squark mass, keeping

³An exclusion of up to a few hundred GeV can be obtained if more than one squark is light [6, 33]. Another possible loophole to this argument is that, for rather heavy squarks, one can hope to compensate for the reduced cross section by use of jet substructure techniques applied to the boosted decay products of the squarks.

only the third generation squarks light for naturalness reasons (excluding perhaps \tilde{b}_R) or by invoking violation of R -parity.

One may also add a colour octet in the form of a light gluino and in fact this is desirable from the naturalness viewpoint: as several authors have stressed recently [6, 33–35], light, third-generation squarks are themselves natural only if the gluino is relatively light, since the former receive large corrections to their masses at one-loop from the latter via the strong interaction. (Equivalently, there are sizable contributions to Higgs mass parameters at two-loop level from contributions involving the gluino.) As always, it is hard to argue in absolute terms that naturalness requires the gluino to be within reach of the LHC. Nevertheless, it has been argued that the gluino should not be more than a couple of times heavier than the lightest third-generation squark [6].

If the gluino is within reach, then a significant boost to the squark production cross-section can be obtained, via pair production of gluinos followed by decay to top or bottom quarks and squarks. The enhancement is such that there is already sensitivity at the LHC, with an ATLAS search [36] reporting preliminary bounds on the gluino mass of up to around: 900 GeV, for $\tilde{g} \rightarrow \tilde{b}b \rightarrow 2b + \tilde{\chi}^0$; 650 GeV, for $\tilde{g} \rightarrow \tilde{t}t \rightarrow tb + \tilde{\chi}^\pm$; and 750 GeV for $\tilde{g} \rightarrow 2t + \tilde{\chi}^0$.

These searches for gluino production followed by decays to third-generation squarks have become a priority for the experimental collaborations. However, the searches focus on R -parity conserving scenarios, relying on the presence of significant $|\vec{p}_T^{\text{miss}}|$ in the final state. It is clear from the arguments above, however, that the naturalness-based theoretical ideas which motivate these searches do not motivate the additional assumption of R -parity conservation. Thus, searches that probe scenarios that feature R -parity violation, but are otherwise similar in terms of their spectra, would seem to be just as much of a priority, if they can be carried out.

Some of the final states that would arise in such a scenario seem to be hopeless. Imagine, for example, pair production of gluinos followed by decays to top squarks and quarks, followed by hadronic decays of the top quarks and hadronic decays of the stop quarks via the R -parity violating operator $W \supset U_3 D_j D_k$. Such ten jet final states will *a priori* be very difficult to disentangle from a background that we are currently unable to compute accurately.⁴ But other final states seem much more promising. Indeed, the presence of pair-produced gluinos not only boosts the cross section, but also, due to the Majorana nature of the gluino, implies an equal proportion of particle and antiparticle states, on average, in each gluino decay. The gluinos decay to third generation quarks and squarks, whose decays often involve leptons, leading to the possibility of final states involving same-sign di-leptons, for which the SM backgrounds are manageable. In the next section, we consider the various possibilities in more detail, showing that most can be covered by a single, same-sign-di-lepton search.

3 Same-sign dilepton searches

In considering the final states of interest, it is useful to divide the possibilities according to two criteria: (i) whether the gluino decays predominantly to stops or sbottoms (and

⁴Refs. [3, 37, 38] suggest a variety of interesting ways in which this hurdle may be overcome.

indeed whether these are predominantly left- or right-handed), and (ii) whether the subsequent decay of the stop or sbottom proceeds via the $U_i D_j D_k$ operator or the $Q_i L_j D_k$ superpotential operator.⁵ Furthermore, though the right-handed bottom squark need not be light for naturalness, it may plausibly be present to make up a full third generation of light squarks and so we include it in our general discussion, distinguishing between cases in which it is, or is not, present.

3.1 Tops and stops

Let us begin by analysing the case in which gluino decays produce top quarks. If they do, then we expect same-sign tops (or anti-tops) in half of the $\tilde{g}\tilde{g}$ events and even in the worst case scenario, we expect same sign e or μ from top quark decays in roughly 3.3 % of events and to same sign e , μ , or τ_h in roughly 5.5 % events. Though these fractions are small, one must bear in mind that the cross section for gluino production is relatively large compared to the SM and detector backgrounds in this channel.

This worst case scenario corresponds to the lightest squark being predominantly \tilde{t}_R , decaying via $U_3 D_i D_j$ operators to two jets, one of which may be a b jet, illustrated in figure 1a. Thus, there are no additional, isolated leptons arising from the squark decay.

In other cases, we expect same-sign leptons in a larger fraction of events. For example if the gluino decays to a \tilde{t}_L that eventually decays via the $U_i D_j D_k$ operator, then the \tilde{t}_L may decay in one of three ways, depending on the Yukawa couplings and on which of the other third-generation squarks is lightest. Firstly, it may decay to a (virtual, since it is heavier) \tilde{t}_R and a neutral Higgs boson as in figure 1b, in which case the extra number of leptons (coming from h^0 decay) is expected to be negligible. Secondly, it may decay to a \tilde{b}_L and a W boson (followed by decay of the \tilde{b}_L as described in the next subsection), in which case extra leptons come from the W decay. Thirdly, if the \tilde{b}_R is not too heavy, the \tilde{t}_L may decay via an off-shell \tilde{b}_R and a charged Higgs boson, as in figure 2a. Then there will be an additional source of leptons coming from the decay of the \tilde{b}_R , since flavour constraints on λ'_{lmn} suggest that the up-type quark produced will be a top quark [28]. Moreover, the charged Higgs is also likely to generate a source of leptons, as we shall shortly discuss.

Finally, the proportion of same sign leptons will be rather higher again in all cases where the superpartner decay chains terminate via the $W \supset Q_i L_3 D_j$ operator. (Again, on the basis of flavour constraints upon the couplings, we expect that only the λ'_{ijk} coupling involving the τ , i.e. $j = 3$ is likely to be sizable, as discussed in [25].) In such cases, same-sign stops lead to same-sign (τ) leptons, and even opposite-sign stops will lead to same-sign di-leptons if at least one top decays leptonically. Approximating t decays such that they decay to each flavour of lepton with a probability of $\frac{1}{9}$, we obtain same sign leptons in roughly $\frac{7}{9}$ of gluino pair production events.

3.2 Bottoms and sbottoms

If gluinos instead decay predominantly to bottom quarks, similar arguments apply. On the one hand, if the eventual R -parity-violating decay arises via the $Q_i L_j D_k$ operator, then we expect same-sign di-leptons (most likely τ) in at least half of events.

⁵It is also possible, in other scenarios, that cascade decay chains will terminate via the $L_i L_j E_k$ or $L_i H_2$ superpotential operators. Evidently these *also* result in large rates for same-sign leptons in the final states.

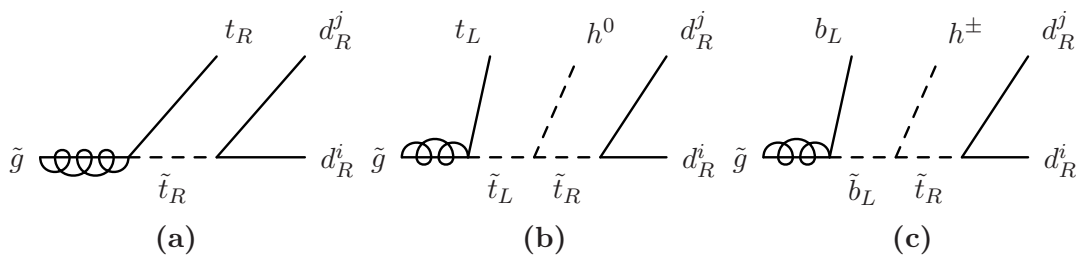


Figure 1. Gluino decays without right-handed bottom squarks in the presence of $W \supset U_3 D_i D_j$, via (a) right-handed top, (b) left-handed top, and (c) left-handed bottom. Same sign leptons are obtained in (c) only if the charged Higgs subsequently decays to $t\bar{b}$ or to leptons.

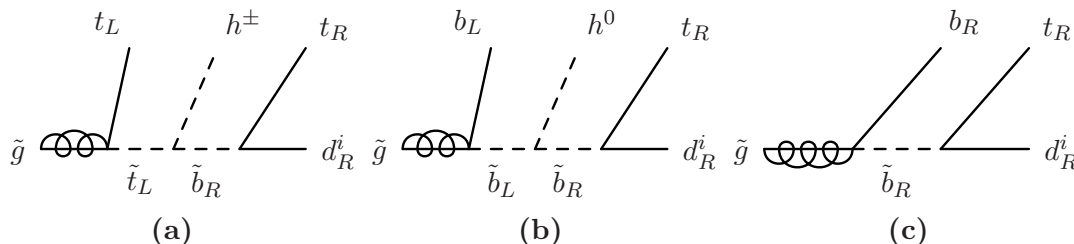


Figure 2. Gluino decays with right-handed bottom squarks in the presence of $W \supset U_3 D_i D_3$, via (a) left-handed top squark, (b) left-handed bottom squark, and (c) right-handed bottom squark.

On the other hand, if the dominant R -parity violating operator is $W \supset U_3 D_i D_3$, then a \tilde{b}_L produced in a gluino decay must first decay to either a charged Higgs or a W -boson and a (virtual) \tilde{t}_R or \tilde{t}_L , respectively. The relative branching fractions for these decays depend on the unknown masses of the \tilde{t}_R or \tilde{t}_L , as well as on the top Yukawa coupling. The decay involving a W can obviously lead to leptons, but this is not obviously the case for a decay involving the charged Higgs, illustrated in figure 1c. This, in a sense, represents a potentially dangerous scenario, since the \tilde{t}_R will decay to two anti down-type quarks, meaning that the only possible source of isolated leptons comes from charged Higgs decays. Thus, in this one case out of all those we consider, a significant source of same-sign leptons is not automatic, depending on the details of the charged Higgs decays. However, for $m_{H^\pm} > m_t + m_b$, decays to $t\bar{b}$ will dominate, while for lower charged Higgs masses, decays to $\tau\nu_\tau$ will dominate, unless $\tan\beta$ is so small that the CKM suppressed decay to $c\bar{b}$ becomes competitive. This requires that $\tan\beta \ll \frac{m_t}{m_\tau} V_{cb} \approx 3$, which seems highly unlikely, at least in the context of the MSSM, because of higgs constraints from LEP.

If we follow the non-minimal possibility of a light \tilde{b}_R , then the \tilde{b}_R may be dominantly produced in the gluino decay (as in figure 2c), in which case flavour arguments [28] suggest that a top quark (and hence leptons) will be produced in the R -parity-violating decay. Alternatively, the gluino may first decay to a lighter \tilde{b}_L , which may then decay to a top quark via a virtual \tilde{b}_R and a neutral Higgs state, as in figure 2b.

Thus we see that in this broad range of scenarios with gluino pair production followed by decays to top and bottom quarks and squarks (on- or off-shell), with one R -parity

violating coupling dominating, same-sign di-lepton signatures are guaranteed in all but one case, *viz.* when gluinos decay predominantly to \tilde{b}_L , which in turn decay via \tilde{t}_R and the $U_3 D_i D_j$ operator. Even then, the resulting charged Higgs decay is likely to proceed via top quarks or a τ lepton.

Before going further, we pause to discuss complications that may arise when even more states are present in the effective theory at the weak scale. Consider what would happen, for example, if Higgsinos were present in the scenario where gluinos decay predominantly to top quarks and squarks, with the latter able to decay via the λ''_{3jk} coupling. Depending on the size of this coupling and the precise spectrum, it might prove preferential for the top squark to first decay via the supersymmetric Yukawa coupling (to a top quark and a neutralino or a bottom quark and a chargino). But the resulting charginos or neutralinos cannot decay via the λ''_{3jk} coupling and would be forced to decay back through to the Yukawa coupling to a virtual top squark, which in turn would decay via the R -parity-violating coupling. For those decay chains involving neutralinos an extra $t\bar{t}$ pair would be present in each gluino decay, yet further increasing the probability of a same-sign di-lepton event.⁶ In the most favourable case of an event with six top quarks in the final state, the probability of a same-sign ee , $\mu\mu$ or $e\mu$ rises to roughly one in four.

3.3 Bottom tagging

The same-sign di-lepton final states we have been discussing involve at least two b quarks and as many as six, so further leverage of the signal compared to the background may be obtained by requesting some number of b tags. (Roughly, for a signal containing n b jets, and with b -tagging efficiency of order fifty *per cent*, requesting $\frac{n}{2}$ b tags keeps the signal efficiency of order a half). The most effective course of action may be to search for different numbers of b tags: up to, say, three.

3.4 Same sign di-taus

The procedure of measuring the charges of electrons and muons and the associated uncertainties are relatively well understood. But many of the scenarios mentioned above involve production of τ s. Indeed, in cases where the R -parity violating decay is via the $Q_i L_j D_k$ operator, we have argued, on the basis of constraints from flavour physics, that the lepton involved is likely to be a τ (i.e. the dominant coupling has $j = 3$). The latter decays to e or μ roughly one-third of the time, meaning that eight out of nine signal events will be lost if we only search for same-sign pairs of electrons and muons. Similarly, when decays occur via the $U_3 D_i D_j$ operator, a lepton that comes from a top quark decay will be a τ roughly a third of the time, so same-sign electrons or muons arise in just over half of di-leptonic decays. Thus, an important question is whether we are able to reliably measure the signs of the charges of hadronically decaying τ s in LHC events. An answer in the affirmative is given by a recent CMS analysis [39] doing just that. The CMS selection employs an algorithm (described in more detail in [39]) in which the individual hadronic decay modes are explicitly identified, with an efficiency that asymptotes to 34% for momenta above 80 GeV.

⁶This increase must be weighed against the fact that the branching ratio for the chargino chain exceeds that for the neutralino chain, assuming approximate chargino/neutralino degeneracy.

However, it is important to note that the CMS analysis requires significant amounts of $|\vec{p}_T^{\text{miss}}|$ in events with one or more hadronically-decaying τ s, both for triggering and for the baseline event selection (*viz.* $|\vec{p}_T^{\text{miss}}| \gtrsim 35$ GeV and > 80 GeV, respectively). But in scenarios in which the R -parity violating decay proceeds via the $Q_i L_3 D_j$ operator, there may not be sufficient, isolated $|\vec{p}_T^{\text{miss}}|$ in events to pass these thresholds: whilst $|\vec{p}_T^{\text{miss}}|$ is always present in τ decays due to the presence of neutrinos, it may either be too small or too closely aligned to the hadronic jet coming from a τ decay.

As a result, developing a search strategy for these scenarios is likely to require a careful study of triggering issues and perhaps a dedicated trigger. One possibility would be to focus on events where only one τ decays hadronically, using the e or μ from the other τ to trigger, possibly in tandem with a requirement on H_T or other jet activity.

4 Current searches

We use three current LHC searches to constrain the gluino and stop masses, under the assumption that the stop or gluino decays dominantly via the \mathcal{R}_p couplings λ''_{3ij} . The searches all involve same-sign di-leptons, which provides a good opportunity to find natural SUSY,⁷ since backgrounds are low. The SUSY signal is several times larger in W +jets type final states, where the W decays leptonically, and one could potentially use recent measurements [43, 44] of the properties of such final states to bound the new physics models. However, the SM backgrounds are expected to be much larger such that the model coverage would be smaller than for same-sign di-lepton signatures. Moreover, W +jets searches may not provide coverage of scenarios where the leptons arise from the $Q_i L_j D_k$ operator instead of from top quark decays.

The dominant backgrounds to like-sign di-lepton production include $t\bar{t}W$ production, and “fake leptons”, where jets can yield isolated leptons from unidentified photon conversions, muons from meson decays in flight, heavy flavour decays, or other detector effects [19, 45]. We do not simulate such backgrounds, since the experimental publications have already taken them into account and have provided bounds on new physics contributions to the cross section after cuts. Since we do not make use of any b tags, our re-interpretation of the searches does not depend upon how many of the λ''_{3ij} are non-zero, nor on the values of i and j . For the simulations, we have explicitly chosen only one non-zero weak-scale baryon-number violating coupling, with $i = 2$ and $j = 3$.

We shall approximate experimental searches by simulating the signal events with HERWIG++-2.5.2 [46–48] and reconstructing jets with fastjet-3.0.1 [49], using cuts identical to those used in the experimental analyses. For the most constraining search, we include detector corrected efficiencies, whereas for the others, these effects are neglected, since they are expected to only weaken the exclusion. We calculate the MSSM spectrum with SOFTSUSY2.4.3 [20, 50], passing the information on to the event generator via the SUSY Les Houches Accord [51]. Sparticle decays are calculated using PYTHIA6.4.25 [52].

⁷Supersymmetric like-sign di-lepton signatures have received much attention in the literature for the more usual large \vec{p}_T^{miss} searches [40, 41]. Ref. [42] also mentions the possibility of using them in an R -parity violating context.

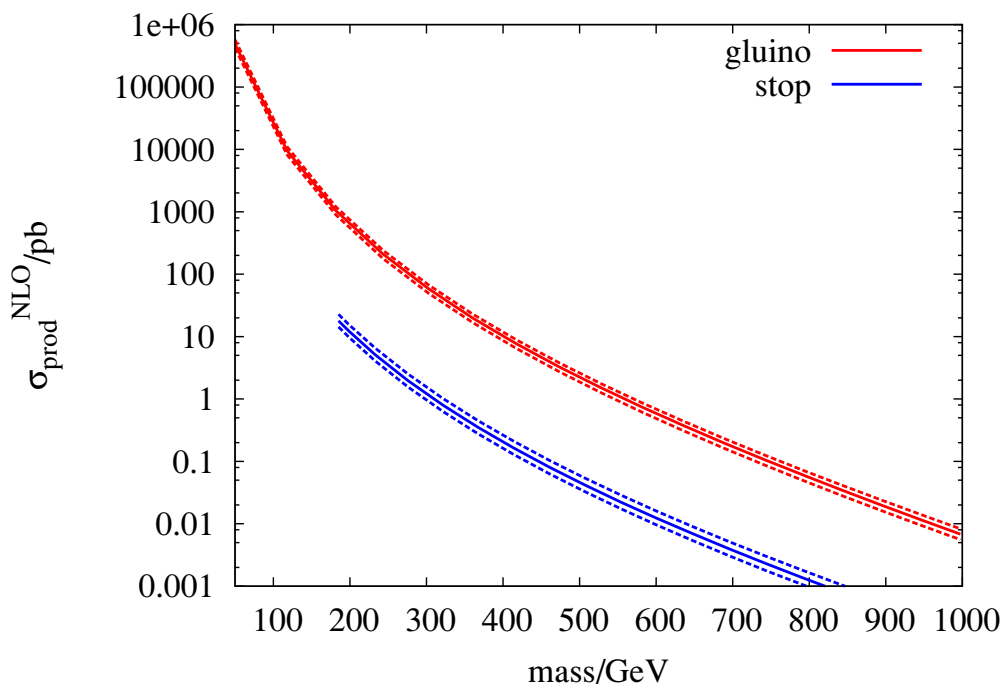


Figure 3. Stop and gluino total production cross-sections at a 7 TeV LHC calculated at NLO by PROSPINO2.1. The dashed curves show the variations due to changes in the renormalisation scale by a factor of two.

Our simplified model has all sparticles other than the right-handed stops and gluinos being heavy. The only SUSY production processes at the 7 TeV LHC are then di-stop production and di-gluino production. We plot the total production cross-sections of di-gluinos and di-stops in figure 3, calculated to next-to-leading order in QCD with PROSPINO2.1 [53, 54]. We use the central next-to-leading order (NLO) production cross-sections for our estimates of the exclusion power of various searches. We see large cross-sections for light gluinos, and expect that current LHC data of $\sim 5000 \text{ pb}^{-1}$ of 7 TeV pp collisions should constrain them.

We show the gluino lifetime for a particular value of $\lambda''_{323} = 1$ in figure 4, as calculated by PYTHIA6.4.25 [52]. This ignores decays through an off-shell top and finite-width effects (these should be negligible, however, except very close to the broken line in figure 4. To a good approximation, the gluino lifetime above the broken line (where $\tilde{g} \rightarrow t^*\tilde{t}$, $t\tilde{t}^*$ and both the stop and top are on-shell) is insensitive to the value of λ''_{3ij} , because the decay is mediated by a SUSY gauge interaction. The lifetime is then governed by the strong coupling α_s and by the masses of the gluino, top and stop. Below the broken line, $\tilde{g} \rightarrow t\bar{s}\bar{b}$ through an off-shell stop (plus conjugate decay products). In this case, $\tau_g \propto 1/|\lambda''_{323}|^2$. The largest lifetime of $\sim 10^{-15}$ seconds corresponds to a decay length of $c\tau_{\tilde{g}} = 3 \times 10^{-7} \text{ m}$, so all decays are prompt in the parameter region shown in the figure. If, however, λ''_{323} were to be reduced by a couple of orders of magnitude, one would obtain gluinos that would form millimetre length (or longer) R -hadron tracks [55], terminating in a decay into jets or jets and a lepton. We do not consider this interesting possibility further here.

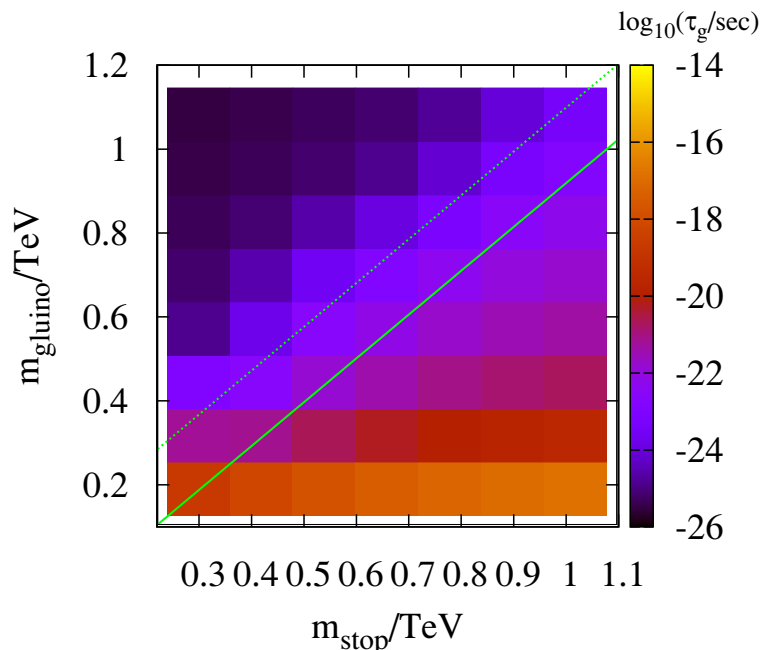


Figure 4. Gluino lifetime τ_g for $\lambda''_{323} = 1$. The green unbroken contour displays the line of equal mass, where the broken line shows $m_{\tilde{g}} = m_t + m_{\tilde{l}}$.

It is important to consider the lepton isolation criteria, since they are the main tool used to reduce the fake lepton backgrounds. For some test lepton l , each of the three searches we consider defines a quantity p_T^{cone} , which must satisfy the following inequality in order for a lepton in the fiducial region of the detector to be considered isolated:

$$p_T^{\text{cone}}(p_T^{\text{min}}, \Delta R) < \max(I_{\text{iso}} p_T(l), M_{\text{iso}}), \tag{4.1}$$

where p_T^{cone} is defined as the sum of p_T of all tracks with $p_T > p_T^{\text{min}}$ in a cone around the lepton axis described by $\Delta R = \sqrt{(\eta - \eta(l))^2 + (\phi - \phi(l))^2}$, where η is the pseudo-rapidity and ϕ the azimuthal angle, measured in radians.

4.1 Test point

We shall define a specific point in parameter space to illustrate various properties of signal events in LHC collisions. Our point has $m_{\tilde{l}_R} = 500$, $M_3 = 478$ GeV, $\lambda''_{323} = 1$ and all other sparticles heavy. For convenience, we will set other λ'' couplings to zero in our simulations, but our results would be identical were we to include them.⁸ This point yields

$$m_{\tilde{g}} = 588 \text{ GeV}, \quad m_{\tilde{t}_1} = 581 \text{ GeV}. \tag{4.2}$$

Gluinos then promptly decay through off-shell stops into tsb or $\bar{t}\bar{s}\bar{b}$, with an equal branching ratio for each channel. We summarise the sparticle decays in table 1. The total cross-section for production of supersymmetric particles before cuts is $\sigma_{NLO} = 681$ fb for the default renormalisation scale.

⁸We note that even if only one λ''_{ijk} coupling were non-zero in the interaction eigenbasis, rotations to the quark mass eigenbasis will induce others.

| Decay | Branching ratio | Decay | Branching ratio |
|---|-----------------|--------------------------------|-----------------|
| $\tilde{g} \rightarrow \bar{t}\bar{s}\bar{b}$ | 0.5 | $\tilde{g} \rightarrow tsb$ | 0.5 |
| $\tilde{t}_1 \rightarrow \bar{s}\bar{b}$ | 1 | $\tilde{t}_1^* \rightarrow sb$ | 1 |

Table 1. Decays of stops and gluinos for the test point.

4.2 ATLAS di-muon search

We first consider an ATLAS search [56], which uses prompt like-sign muon pairs. This search does not require large $|\vec{p}_T^{\text{miss}}|$, and is quite inclusive. This fits our expectations for signal events, which do not contain a stable, lightest, supersymmetric particle to carry off $|\vec{p}_T^{\text{miss}}|$. ATLAS looked at 1.61 fb^{-1} worth of integrated luminosity at the 7 TeV LHC, requiring two isolated muons with identical charges and $p_T > 20 \text{ GeV}$. Since the data were found to agree well with SM backgrounds, upper limits were placed on new physics cross-sections leading to like-sign di-muons. For this analysis, a muon with $p_T(\mu)$ is defined to be isolated if eq. 4.1 is satisfied, with $p_T^{\text{min}} = 1 \text{ GeV}$, $\Delta R = 0.4$, $I_{\text{iso}} = 0.08$ and $M_{\text{iso}} = 5 \text{ GeV}$. In our simulations, the p_T^{min} cut is implemented for any charged hadron in the final state (i.e. all charged hadrons are assumed to form a track). The fiducial region for muons is $|\eta| < 2.4$. Four different signal regions were defined, each by a different lower cut on $m_{\mu\mu}$. ATLAS places upper bounds on isolated like-sign di-muon production above backgrounds and within the cuts $\sigma_{SS\mu\mu}^{95}$ as shown in the final column of table 2. As can be seen from the table, the acceptance A of signal events is very low, due mainly to the small branching ratios of top pairs into isolated di-leptons. We simulate SUSY signal events, calculating the proportion of gluino pairs that yield isolated like-sign di-muon pairs past the ATLAS cuts. We find that this search does not yield the most restrictive bounds upon the parameter space, and so we do not complicate the analysis and further weaken the bounds by performing a detector simulation, or by correcting for muon efficiencies.⁹ While simulating same-sign di-muon signals, we force the tops to decay via e, μ or τ in order to get better Monte Carlo statistics, taking the associated correction factor into account. For each point considered in parameter space, we simulate 10 000 SUSY signal events.

4.3 ATLAS same-sign di-lepton, jets and missing transverse momentum search

In this search, the ATLAS experiment analysed 2.06 fb^{-1} of integrated luminosity of LHC collisions collected at 7 TeV centre of mass energy [45], looking for events with same-sign leptons (electrons or muons) each with $p_T > 20 \text{ GeV}$, large missing transverse momentum $|\vec{p}_T^{\text{miss}}| > 150 \text{ GeV}$, and at least four jets, each with transverse momenta exceeding 50 GeV . Electrons were required to be within $|\eta| < 2.47$ and the isolation criteria followed eq. 4.1 with $M_{\text{iso}} = 0$, $I_{\text{iso}} = 0.1$, $\Delta R = 0.2$ $p_T^{\text{min}} = 0$. For muons, $|\eta| < 2.4$, $M_{\text{iso}} = 1.8 \text{ GeV}$, $I_{\text{iso}} = 0$, $\Delta R = 0.2$ and $p_T^{\text{min}} = 0$. Jets were defined using the anti- k_T algorithm with

⁹Muon efficiencies are high: from Z -boson decays, they range from 87% to 97% [56], depending upon p_T . However, the muon p_T spectra depend upon the new physics model and the ATLAS publication does not parametrise the efficiencies as a function of p_T , thus we are not able to reliably take them into account.

| Signal Region | $m_{\mu\mu}/\text{GeV}$ | $\sigma_{SS\mu\mu}^{\text{test}}/\text{fb}$ | $A/10^{-3}$ | $\sigma_{SS\mu\mu}^{95}/\text{fb}$ |
|------------------|-------------------------|---|-------------|------------------------------------|
| ATLAS $\mu\mu$ 1 | >15 | 12 | 1.3 | 58 |
| ATLAS $\mu\mu$ 2 | >100 | 7.5 | 0.86 | 16 |
| ATLAS $\mu\mu$ 3 | >200 | 2.1 | 0.29 | 8.4 |
| ATLAS $\mu\mu$ 4 | >300 | 0.41 | 0.077 | 5.3 |

Table 2. The ATLAS same-sign di-muon analysis search regions. The expected signal cross-section past cuts predicted our test model $\sigma_{SS\mu\mu}^{\text{test}}/\text{fb}$ is shown, as well as the acceptance of the selection A . A is defined to be the number of simulated supersymmetric events past cuts divided by the total number of simulated supersymmetric events. In the last column, we show the [56] 95% CL_s upper bound on non-SM cross section past cuts found by ATLAS $\sigma_{SS\mu\mu}^{95}/\text{fb}$.

| Signal Region | $ \vec{p}_T^{\text{miss}} /\text{GeV}$ | $m_T(l_1)/\text{GeV}$ | $\sigma_{SSll}^{\text{test}}/\text{fb}$ | $A/10^{-3}$ | $\sigma_{SSll}^{95}/\text{fb}$ |
|---------------|--|-----------------------|---|-------------|--------------------------------|
| ATLAS ll 1 | > 150 | > 0 | 0.67 | 1.0 | 1.6 |
| ATLAS ll 2 | > 150 | > 100 | 0.40 | 0.6 | 1.5 |

Table 3. ATLAS same sign-di lepton analysis search regions. We show the cuts, and the expected cross-section past cuts predicted by our test point over SM backgrounds $\sigma_{SSll}^{\text{test}}$, as well as the acceptance of the selection A . A is defined to be the number of simulated supersymmetric events past cuts divided by the total number of simulated supersymmetric events. In the last column, we show the [45] 95% CL_s upper bound on the cross-section past cuts surplus to those from the SM coming from the search, σ_{SSll}^{95} .

distance parameter $R = 0.4$, requiring $p_T > 20 \text{ GeV}$ and $|\eta| < 4.5$. \vec{p}_T^{miss} was defined to be the vector sum of the transverse momenta of jets and leptons, plus calorimetric energy clusters not belonging to reconstructed objects. The analysis defines one signal region which had an additional cut on the transverse mass $M_T = \sqrt{2 |\vec{p}_T^{\text{miss}}| \cdot p_T(l) \cdot [1 - \cos \Delta\phi(l, \vec{p}_T^{\text{miss}})]}$ of the hardest lepton l of the same-sign pair. No events past cuts were observed for either signal region, allowing ATLAS to place a 95% CL_s upper limit on an extra component of cross-section past cuts as shown in table 3. While simulating these ATLAS same-sign lepton signals, we force the tops to decay via leptons (or anti-leptons) of any flavour in order to get better Monte Carlo statistics, taking the associated correction factor into account in the efficiencies. For each point considered in parameter space, we simulate 100 000 SUSY signal events. It turns out that these searches also did not yield the most stringent bounds upon our model.

4.4 CMS same-sign di-lepton, jets and missing transverse momentum search

The CMS experiment analysed 0.98 fb^{-1} of integrated luminosity of LHC collisions collected at 7 TeV centre of mass energy [39]. The leptons were required to be within $|\eta| < 2.4$ and the isolation criteria followed eq. 4.1 with $M_{\text{iso}} = 0$, $I_{\text{iso}} = 0.15$, $\Delta R = 0.3$, $p_T^{\text{min}} = 0$. The

| Signal Region | H_T/GeV | $ \vec{p}_T^{\text{miss}} /\text{GeV}$ | N_{ll}/fb | $A \times \epsilon/10^{-3}$ | N_{ll}^{95} |
|---------------|------------------|--|--------------------|-----------------------------|---------------|
| CMS $ll1$ | >400 | >120 | 2.4 | 3.5 | <3.7 |
| CMS $ll2$ | >400 | >50 | 4.6 | 6.8 | <8.9 |
| CMS $ll3$ | >200 | >120 | 2.5 | 3.7 | <7.3 |

Table 4. Number of events past cuts for the CMS same sign-di lepton analysis N_{ll} predicted by our test point over SM backgrounds, and acceptance A times efficiency ϵ of the signal selection, for the test point. In the last column, we show the [39] 95% CL_s upper bound on the number of events surplus to those from the SM quoted by CMS, N_{ll}^{95} . The quoted acceptance A is defined to be the expected number of supersymmetric events past cuts divided by the total number of supersymmetric events for the test point. The efficiency ϵ is calculated as described in the text.

inclusive di-leptons search used here was defined to have a baseline selection of electron $p_T > 10$ GeV and muon $p_T > 5$ GeV. Jets were defined using the anti- k_T algorithm with distance parameter $R = 0.5$, requiring $p_T > 40$ GeV and $|\eta| < 2.5$. Lower cuts were placed on H_T , defined to be the scalar sum of jet p_T s that have $\Delta R > 0.4$ to the closest isolated lepton passing all other requirements. Lower cuts were also placed upon $|\vec{p}_T^{\text{miss}}|$, which the experiment defines using the particle flow technique. In our signal simulation, we define \vec{p}_T^{miss} to be the vector sum of jet and isolated lepton transverse momenta. CMS defined several search regions for their analysis, based on different cuts. The search regions for the inclusive di-leptons baseline selection (for which a description of the detector efficiencies were given) are displayed in table 4. CMS give approximate fitted formulæ for the efficiencies $\epsilon_e(p_T^e)$, $\epsilon_\mu(p_T^\mu)$, $\epsilon_{H_T}(H_T)$, $\epsilon_{|\vec{p}_T^{\text{miss}}|}(|\vec{p}_T^{\text{miss}}|)$ of the detection of electrons, the detection of muons, the H_T cut, and the $|\vec{p}_T^{\text{miss}}|$ cut, respectively. We take these into account for each of our signal events by recording an efficiency for each event of $\epsilon_{H_T}(H_T) \times \epsilon_{|\vec{p}_T^{\text{miss}}|}(|\vec{p}_T^{\text{miss}}|)$ multiplied by the two relevant lepton efficiencies, if the event yields like-sign isolated leptons within the fiducial region, and $H_T > 200$ GeV and $|\vec{p}_T^{\text{miss}}| > 30$ GeV, i.e. where the CMS parametrisation applies. This procedure should take detector effects into account at the 10% level. This is sufficient for our purposes, despite the fact that it misses possible correlations between the different variables. While simulating same-sign di-muon signals, we force the tops to decay via leptons (or anti-leptons) of any flavour in order to get better Monte Carlo statistics, taking the associated correction factor into account. For each point considered in parameter space, we simulate 10 000 SUSY signal events.

4.5 Model exclusion limits

We present the model exclusion limits from the ATLAS di-muon and both di-lepton-jets- $|\vec{p}_T^{\text{miss}}|$ analyses in figure 5. One of the CMS di-lepton-jets- \vec{p}_T^{miss} search regions yields the strongest bounds upon our scenario, one of the search regions ruling out gluino masses less than 550 GeV. The CMS $ll2$ curve lies on top of the CMS $ll1$ exclusion curve, and so we do not display it in the figure. We have neglected some search regions either because they are weaker than the search regions shown for the particular search in question. We

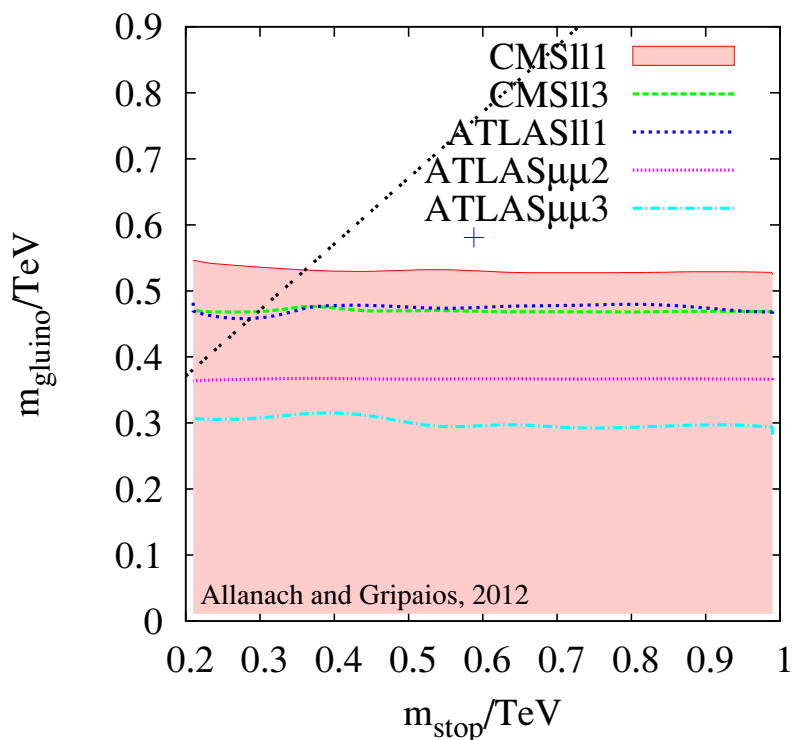


Figure 5. 95% exclusions from the CMS di-leptons \bar{p}_T^{miss} search (CMSII1,3), the ATLAS di-leptons \bar{p}_T^{miss} search (ATLASII1) and the ATLAS same-sign di-muons search (ATLAS $\mu\mu$ 2,3). The signal regions of each analysis, corresponding to the number are defined in tables 2, 3, 4. The cross shows the location of our test point. We have not combined the different exclusion regions, but have merely shaded the area excluded by the most constraining search. Above and to the left of the black dashed diagonal line, gluino decays are through on-shell stops, whereas underneath and to the right of it, gluino decays are through off-shell stops.

note that, in order to combine different search regions, one should apply the *expected* most constraining search region at each parameter point (not the observed most constraining search). This procedure removes the *a posteriori* statistical bias of just choosing the most restrictive limit in parameter space. However, not all of the searches supplied the expected limits from each signal region and so we were unable to combined the exclusion limits in this way. Instead, we just present the limits separately.

In figure 5, we see that the exclusion limits are approximately independent of the stop mass. This is expected, since the signal production cross-section for gluino pairs is insensitive to the stop mass. In the top-left hand portion of the plane, the gluino decays through on-shell tops, which could have a mild effect on acceptances for the di-lepton searches, where jet cuts are applied. On the other hand, the CMSII1 exclusion does show a mild, but non-trivial dependence upon the stop mass. To the extreme left of the curve, gluinos may decay through on-shell stops, but for $m_{\tilde{t}} > 400$ GeV, the gluino decays are three body. Three-body decays share the gluino’s mass energy between the tsb decay products, leading to differences in the jet kinematics and \bar{p}_T^{miss} . We see this effect upon the signal efficiency in figure 6. The signal efficiency is defined as the fraction of simulated

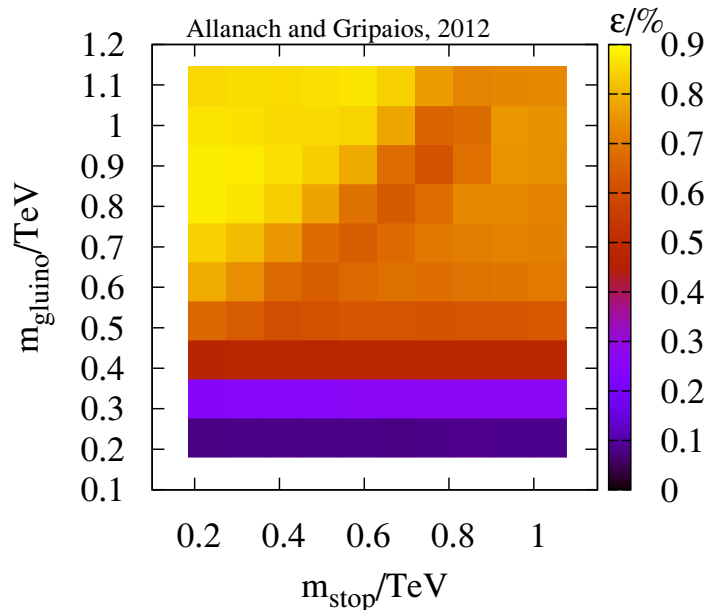


Figure 6. Signal efficiency for the the CMS di-lepton $|\vec{p}_T^{\text{miss}}|$ analysis.

SUSY events which yield like-sign isolated di-leptons in the fiducial region (where the leptons satisfy the basic minimum p_T requirements) and which also satisfy $H_T > 200$ GeV, $|\vec{p}_T^{\text{miss}}| > 30$ GeV, multiplied by the product of detection efficiencies defined in section 4.4. This definition includes the leptonic branching ratios of top pairs within the efficiency on the plot. The efficiency is rather low, less than a percent irrespective of gluino or stop mass. We suggest below how the efficiency may be improved. For the sake of brevity and because detector effects have not been included, we do not show the cut efficiencies for the other, less constraining searches. One sees that at low values of $m_{\tilde{g}}$, the efficiencies are low because of lower p_T jets (however here, the production cross-sections are extremely large, as figure 3 shows).

5 Suggestions for future searches

The searches we have considered were designed with rather different models of new physics in mind and it is of interest to consider ways in which they might be optimised for the models discussed here. While a definitive answer will also require dedicated background and full detector simulations, one can still obtain some ideas for directions for future study by examining properties of the signal. Thus, we begin by showing in figure 7 various distributions taken from our simulated 7 TeV LHC SUSY events for the test point described in section 4.1. Each quantity is defined to be at the generator level, i.e. detector effects are not taken into account. $p_T > 20$ GeV cuts on the anti- k_T ($R = 0.5$) jets are applied, as well as $p_T(e) > 10$ GeV, $p_T(\mu) > 5$ GeV, and fiducial volume cuts on jets and leptons, as in section 4.4.

We see from figure 7a that the majority of events do not have two isolated like-sign

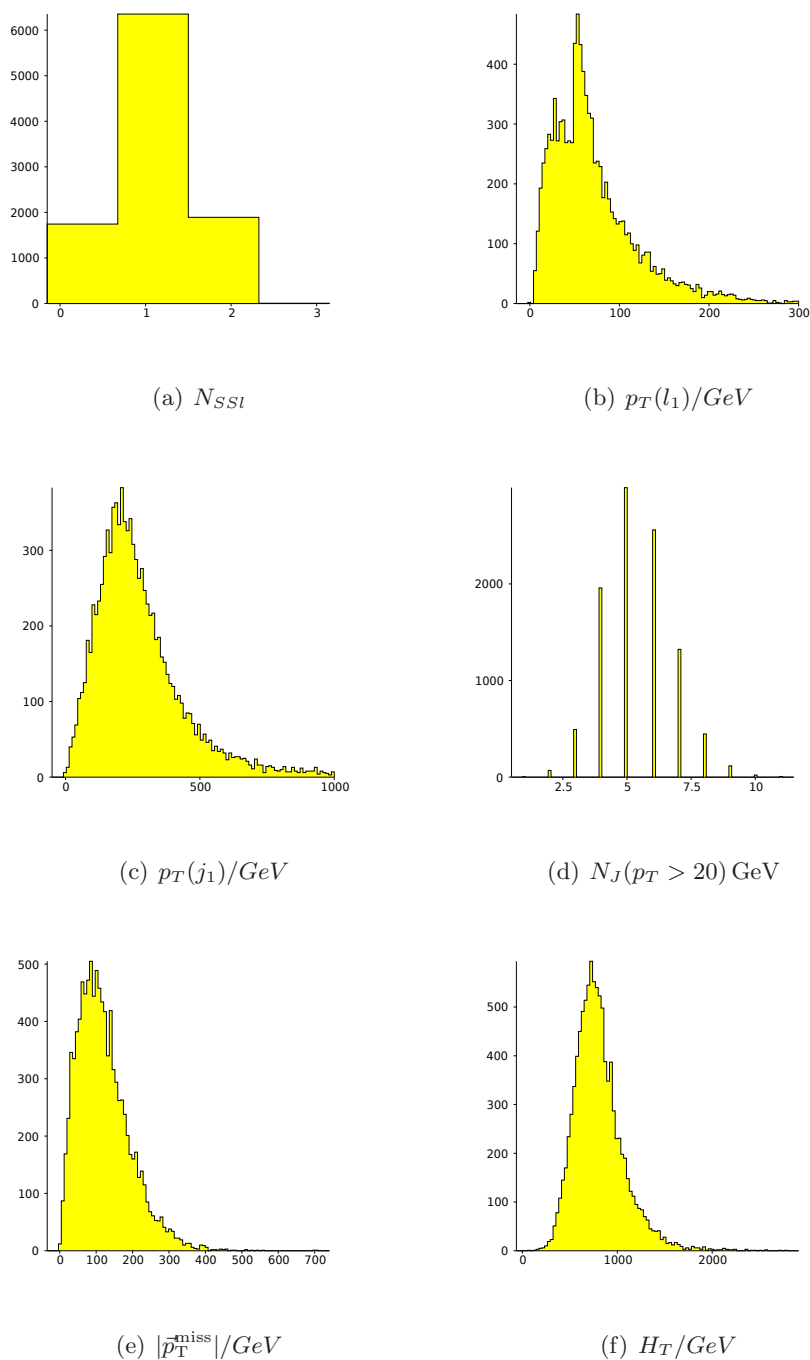


Figure 7. Distributions of quantities of interest for our test point $m_{\tilde{g}} = 588$ GeV, $m_{\tilde{t}_1} = 581$ GeV, for supersymmetric signal events. In (a), we show the number of *isolated* leptons passing minimum p_T cuts (where, if there are two, they must have the same sign). We use the CMS analysis' lepton isolation criteria. In (b), we show the hardest isolated lepton's p_T . Otherwise, the only cuts are that jets have $p_T > 20$ GeV, and jets and leptons lie within the fiducial region of the detector. Other detector effects are not taken into account.

di-leptons passing the p_T cuts: one lepton is often lost due to it not being isolated, or being outside the fiducial volume of the detector. The efficiency to select same-sign di-leptons could certainly be improved by lowering the lepton p_T cut and it is also possible that an improvement might be obtained by modifying the lepton isolation criterion.

Several of the existing searches also require a significant amount of missing energy in events. For the particular model and test point considered here, a significant amount of $|\vec{p}_T^{\text{miss}}|$ is present (see figure 7e), though a cut at 120 GeV nevertheless removes roughly half of the events. Unfortunately, the possible improvement in sensitivity that might be gained by lowering (or indeed increasing) the $|\vec{p}_T^{\text{miss}}|$ cut is difficult to gauge from the existing searches. The CMS search, for example, contains search regions which are identical except for the $|\vec{p}_T^{\text{miss}}|$ cuts applied, but one search region is subject to an over-fluctuation in the data whilst the other is subject to an under-fluctuation; without knowing the limit that CMS expected to set on a signal cross-section in each region, one cannot pinpoint the effect of varying the $|\vec{p}_T^{\text{miss}}|$ cut.

In any case, it is clear that there are scenarios in which a large amount of $|\vec{p}_T^{\text{miss}}|$ cannot be expected. In particular, in cases where superpartners eventually decay via the $Q_i L_j D_k$ operator, $|\vec{p}_T^{\text{miss}}|$ comes only from neutrinos from τ decays and these may not generate significant $|\vec{p}_T^{\text{miss}}|$ (or indeed $|\vec{p}_T^{\text{miss}}|$ that is sufficiently isolated from hadronic activity to be considered ‘clean’).

Lowering the $|\vec{p}_T^{\text{miss}}|$ and lepton p_T cuts does, of course, have the negative impact of increasing the background contribution. This could be mitigated by increasing the cuts on other quantities. For our test point, we see that the hadronic activity, as measured by the p_T of the hardest jet (figure 7c), by the number of jets with $p_T > 20$ GeV (figure 7d), or by H_T (figure 7f), is typically large in signal events. Then again, one can imagine scenarios in which the jets, though numerous, are rather soft. For example, this will be the case if the gluino decay proceeds via a long chain of (possibly virtual) states, such as when squarks first decay to charginos or neutralinos, which in turn decay via virtual squarks and an R -parity violating operator $U_i D_j D_k$.

Similar arguments apply to b tags. We have argued that one can expect between two and six b jets in signal events; the best strategy to exploit this could be to search in regions with differing numbers of required b tags, so as to give maximum coverage in model space.

Most of these effects should be relatively straightforward to analyse and implement. More challenging is the issue of how to optimise one’s searches for same-sign dilepton final states involving one or more hadronically-decaying τ . We have argued that these may be dominant in some models. The approach described in [39] acts as a proof-of-principle that searches using hadronic τ decays can be done, but is likely to have low sensitivity to certain models, since it requires significant $|\vec{p}_T^{\text{miss}}|$ as a trigger requirement. This would not appear to be a *sine qua non*, however: at least in cases where only one hadronically-decaying τ is present, one can exploit the other lepton for the trigger.

6 Summary

We have argued that LHC searches for same-sign di-leptons of all flavours provide a generic means by which one may discover supersymmetric scenarios without R -parity, which retain naturalness of the weak scale (by keeping gluinos and third-generation squarks light), but evade existing collider and flavour constraints. The constraints are avoided by a combination of two factors: (i) a reduction of $|\vec{p}_T^{\text{miss}}|$ in final states because of R -parity violating couplings; and (ii) heavy first- and second-generation quarks. The same-sign di-leptons are either provided by same-sign tops in decay chains, by lepton number violating couplings or by charged Higgs or W decays in decay chains.

We have shown that same sign di-lepton searches provide essentially guaranteed coverage of all but one scenario, in which the gluino decays predominantly into a left-handed bottom squark that decays via the charged Higgs into a virtual right-handed top squark, which in turn decays to down-type quark jets via the $U_3 D_i D_j$ superpotential operator(s). This exceptional case can only be missed in the small (and unlikely) part of parameter space where $\tan \beta \ll 3$ and the charged Higgs has no significant branching ratio for decay into either tau or top.

We have assessed the impact of existing searches for same-sign di-leptons, designed for other scenarios of new physics, in the case where pair-produced gluinos decay to light, right-handed stop quarks, which in turn decay to down-type quark jets via $U_3 D_i D_j$ operators. The most stringent search presents a bound of 550 GeV on the gluino mass, approximately independently of the stop mass. This approximation ought to be precise to a few tens of GeV, but some of the less stringent bounds are crude estimates, since then the detector simulation is crude. In some cases, we interpret the results of searches which have been applied to very different models of new physics, and systematic errors on the signal will be different to those assumed in the paper. Such changes in these signal systematic errors are neglected in our analysis.

We hope that our arguments regarding the importance of such supersymmetric models are sufficiently persuasive, and the results of our simulations sufficiently promising, as to convince the experimental collaborations to re-interpret the results of their existing same-sign di-lepton searches in the context of the models described here. The recently developed RECAST framework [57] would seem to be an ideal vehicle by which to facilitate such re-interpretations.

Existing searches were designed with rather different models of new physics in mind and it is clear that increased sensitivity could be obtained by optimising them for the models that we suggest. In particular a number of directions suggest themselves, namely by varying cuts on $|\vec{p}_T^{\text{miss}}|$, number of b tags, and jet activity. Finally, we have shown that a natural expectation in some scenarios is an excess of same-sign τ final states over SM backgrounds. These may occur in a sizable fraction of signal events (half of all events, for example, in decays via $Q_i L_3 D_j$ operators), which will more than offset the inevitable reduction in efficiency in this channel compared to that for pairs of e or μ . A priority for searches in this channel is the implementation of a τ (or di- τ) trigger which does not require large $|\vec{p}_T^{\text{miss}}|$.

Acknowledgments

This work has been partially supported by STFC. We would like to thank other members of the Cambridge SUSY Working Group, J. Butterworth, C. Campagnari, and R. Sundrum for useful discussions.

References

- [1] ATLAS collaboration, G. Aad et al., *Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions*, *Phys. Lett. B* **710** (2012) 67 [[arXiv:1109.6572](#)] [[INSPIRE](#)].
- [2] ATLAS collaboration, G. Aad et al., *Search for supersymmetry in final states with jets, missing transverse momentum and one isolated lepton in $\sqrt{s} = 7$ TeV pp collisions using 1 fb⁻¹ of ATLAS data*, *Phys. Rev. D* **85** (2012) 012006 [[arXiv:1109.6606](#)] [[INSPIRE](#)].
- [3] ATLAS collaboration, G. Aad et al., *Search for new phenomena in final states with large jet multiplicities and missing transverse momentum using $\sqrt{s} = 7$ TeV pp collisions with the ATLAS detector*, *JHEP* **11** (2011) 099 [[arXiv:1110.2299](#)] [[INSPIRE](#)].
- [4] ATLAS collaboration, G. Aad et al., *Searches for supersymmetry with the ATLAS detector using final states with two leptons and missing transverse momentum in $\sqrt{s} = 7$ TeV proton-proton collisions*, *Phys. Lett. B* **709** (2012) 137 [[arXiv:1110.6189](#)] [[INSPIRE](#)].
- [5] CMS collaboration, S. Chatrchyan et al., *Search for supersymmetry at the LHC in events with jets and missing transverse energy*, *Phys. Rev. Lett.* **107** (2011) 221804 [[arXiv:1109.2352](#)] [[INSPIRE](#)].
- [6] C. Brust, A. Katz, S. Lawrence and R. Sundrum, *SUSY, the third generation and the LHC*, *JHEP* **03** (2012) 103 [[arXiv:1110.6670](#)] [[INSPIRE](#)].
- [7] T. Gherghetta and A. Pomarol, *The standard model partly supersymmetric*, *Phys. Rev. D* **67** (2003) 085018 [[hep-ph/0302001](#)] [[INSPIRE](#)].
- [8] R. Sundrum, *SUSY splits, but then returns*, *JHEP* **01** (2011) 062 [[arXiv:0909.5430](#)] [[INSPIRE](#)].
- [9] M. Redi and B. Gripaios, *Partially supersymmetric composite Higgs models*, *JHEP* **08** (2010) 116 [[arXiv:1004.5114](#)] [[INSPIRE](#)].
- [10] T. Gherghetta, B. von Harling and N. Setzer, *A natural little hierarchy for RS from accidental SUSY*, *JHEP* **07** (2011) 011 [[arXiv:1104.3171](#)] [[INSPIRE](#)].
- [11] S. Dimopoulos and G. Giudice, *Naturalness constraints in supersymmetric theories with nonuniversal soft terms*, *Phys. Lett. B* **357** (1995) 573 [[hep-ph/9507282](#)] [[INSPIRE](#)].
- [12] A. Pomarol and D. Tommasini, *Horizontal symmetries for the supersymmetric flavor problem*, *Nucl. Phys. B* **466** (1996) 3 [[hep-ph/9507462](#)] [[INSPIRE](#)].
- [13] R. Barbieri, G. Dvali and L.J. Hall, *Predictions from a U(2) flavor symmetry in supersymmetric theories*, *Phys. Lett. B* **377** (1996) 76 [[hep-ph/9512388](#)] [[INSPIRE](#)].
- [14] A.G. Cohen, D. Kaplan and A. Nelson, *The more minimal supersymmetric standard model*, *Phys. Lett. B* **388** (1996) 588 [[hep-ph/9607394](#)] [[INSPIRE](#)].
- [15] R. Barbieri, E. Bertuzzo, M. Farina, P. Lodone and D. Pappadopulo, *A non standard supersymmetric spectrum*, *JHEP* **08** (2010) 024 [[arXiv:1004.2256](#)] [[INSPIRE](#)].

- [16] N. Craig, D. Green and A. Katz, *(De)constructing a natural and flavorful supersymmetric standard model*, *JHEP* **07** (2011) 045 [[arXiv:1103.3708](#)] [[INSPIRE](#)].
- [17] R. Barbieri, G. Isidori, J. Jones-Perez, P. Lodone and D.M. Straub, *U(2) and minimal flavour violation in supersymmetry*, *Eur. Phys. J. C* **71** (2011) 1725 [[arXiv:1105.2296](#)] [[INSPIRE](#)].
- [18] M. Fairbairn et al., *Stable massive particles at colliders*, *Phys. Rept.* **438** (2007) 1 [[hep-ph/0611040](#)] [[INSPIRE](#)].
- [19] CMS collaboration, *Search for heavy stable charged particles*, [PAS-EXO-11-022](#) (2011).
- [20] B. Allanach and M. Bernhardt, *Including R-parity violation in the numerical computation of the spectrum of the minimal supersymmetric standard model: SOFTSUSY*, *Comput. Phys. Commun.* **181** (2010) 232 [[arXiv:0903.1805](#)] [[INSPIRE](#)].
- [21] N. Sakai and T. Yanagida, *Proton decay in a class of supersymmetric grand unified models*, *Nucl. Phys. B* **197** (1982) 533 [[INSPIRE](#)].
- [22] S. Weinberg, *Supersymmetry at ordinary energies. 1. Masses and conservation laws*, *Phys. Rev. D* **26** (1982) 287 [[INSPIRE](#)].
- [23] L.E. Ibáñez and G.G. Ross, *Discrete gauge symmetries and the origin of baryon and lepton number conservation in supersymmetric versions of the standard model*, *Nucl. Phys. B* **368** (1992) 3 [[INSPIRE](#)].
- [24] B. Allanach, A. Dedes and H. Dreiner, *R parity violating minimal supergravity model*, *Phys. Rev. D* **69** (2004) 115002 [*Erratum ibid.* **D 72** (2005) 079902] [[hep-ph/0309196](#)] [[INSPIRE](#)].
- [25] B. Gripaios, *Composite Leptoquarks at the LHC*, *JHEP* **02** (2010) 045 [[arXiv:0910.1789](#)] [[INSPIRE](#)].
- [26] B. Gripaios, A. Papaefstathiou, K. Sakurai and B. Webber, *Searching for third-generation composite leptoquarks at the LHC*, *JHEP* **01** (2011) 156 [[arXiv:1010.3962](#)] [[INSPIRE](#)].
- [27] CMS collaboration, *Search for pair production of third-generation scalar leptoquarks using events produced in pp collisions at $\sqrt{s} = 7$ TeV*, [PAS-EXO-11-030](#) (2011).
- [28] G.F. Giudice, B. Gripaios and R. Sundrum, *Flavourful production at hadron colliders*, *JHEP* **08** (2011) 055 [[arXiv:1105.3161](#)] [[INSPIRE](#)].
- [29] CMS collaboration, *Search for new physics in the paired dijet mass spectrum*, [PAS-EXO-11-016](#) (2011).
- [30] ATLAS collaboration, G. Aad et al., *Search for massive colored scalars in four-jet final states in $\sqrt{s} = 7$ TeV proton-proton collisions with the ATLAS detector*, *Eur. Phys. J. C* **71** (2011) 1828 [[arXiv:1110.2693](#)] [[INSPIRE](#)].
- [31] CDF collaboration, T. Aaltonen et al., *Search for pair production of supersymmetric top quarks in dilepton events from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **104** (2010) 251801 [[arXiv:0912.1308](#)] [[INSPIRE](#)].
- [32] Y. Kats and D. Shih, *Light stop NLSPs at the Tevatron and LHC*, *JHEP* **08** (2011) 049 [[arXiv:1106.0030](#)] [[INSPIRE](#)].
- [33] M. Papucci, J.T. Ruderman and A. Weiler, *Natural SUSY endures*, [arXiv:1110.6926](#) [[INSPIRE](#)].
- [34] R. Essig, E. Izaguirre, J. Kaplan and J.G. Wacker, *Heavy flavor simplified models at the LHC*, *JHEP* **01** (2012) 074 [[arXiv:1110.6443](#)] [[INSPIRE](#)].

- [35] Y. Kats, P. Meade, M. Reece and D. Shih, *The status of GMSB after 1/fb at the LHC*, *JHEP* **02** (2012) 115 [[arXiv:1110.6444](#)] [[INSPIRE](#)].
- [36] ATLAS collaboration, *Search for supersymmetry in pp collisions at $\sqrt{s} = 7$ TeV in final states with missing transverse momentum and b-jets with the ATLAS detector*, *ATLAS-CONF-2012-003* (2012).
- [37] CMS collaboration, S. Chatrchyan et al., *Search for three-jet resonances in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. Lett.* **107** (2011) 101801 [[arXiv:1107.3084](#)] [[INSPIRE](#)].
- [38] A. Hook, E. Izaguirre, M. Lisanti and J.G. Wacker, *High multiplicity searches at the LHC using jet masses*, *Phys. Rev. D* **85** (2012) 055029 [[arXiv:1202.0558](#)] [[INSPIRE](#)].
- [39] CMS collaboration, *Search for new physics with same-sign isolated dilepton events with jets and missing energy*, *PAS-SUS-11-010* (2011).
- [40] H. Baer, X. Tata and J. Woodside, *Multi-lepton signals from supersymmetry at hadron super colliders*, *Phys. Rev. D* **45** (1992) 142 [[INSPIRE](#)].
- [41] R.M. Barnett, J.F. Gunion and H.E. Haber, *Discovering supersymmetry with like sign dileptons*, *Phys. Lett. B* **315** (1993) 349 [[hep-ph/9306204](#)] [[INSPIRE](#)].
- [42] C. Csáki, Y. Grossman and B. Heidenreich, *MFV SUSY: a natural theory for R-parity violation*, [arXiv:1111.1239](#) [[INSPIRE](#)].
- [43] CMS collaboration, S. Chatrchyan et al., *Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **10** (2011) 132 [[arXiv:1107.4789](#)] [[INSPIRE](#)].
- [44] ATLAS collaboration, G. Aad et al., *Study of jets produced in association with a W boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Phys. Rev. D* **85** (2012) 092002 [[arXiv:1201.1276](#)] [[INSPIRE](#)].
- [45] ATLAS collaboration, *Search for gluinos in events with two same-sign leptons, jets and missing transverse momentum with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV*, *ATLAS-CONF-2012-004* (2012).
- [46] M. Gigg and P. Richardson, *Simulation of beyond standard model physics in HERWIG++*, *Eur. Phys. J. C* **51** (2007) 989 [[hep-ph/0703199](#)] [[INSPIRE](#)].
- [47] M. Bahr et al., *HERWIG++ physics and manual*, *Eur. Phys. J. C* **58** (2008) 639 [[arXiv:0803.0883](#)] [[INSPIRE](#)].
- [48] M. Gigg and P. Richardson, *Simulation of finite width effects in physics beyond the standard model*, [arXiv:0805.3037](#) [[INSPIRE](#)].
- [49] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
- [50] B. Allanach, *SOFTSUSY: a program for calculating supersymmetric spectra*, *Comput. Phys. Commun.* **143** (2002) 305 [[hep-ph/0104145](#)] [[INSPIRE](#)].
- [51] P.Z. Skands et al., *SUSY Les Houches accord: interfacing SUSY spectrum calculators, decay packages and event generators*, *JHEP* **07** (2004) 036 [[hep-ph/0311123](#)] [[INSPIRE](#)].
- [52] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [53] W. Beenakker, R. Hopker, M. Spira and P. Zerwas, *Squark and gluino production at hadron colliders*, *Nucl. Phys. B* **492** (1997) 51 [[hep-ph/9610490](#)] [[INSPIRE](#)].

- [54] W. Beenakker, M. Krämer, T. Plehn, M. Spira and P. Zerwas, *Stop production at hadron colliders*, *Nucl. Phys. B* **515** (1998) 3 [[hep-ph/9710451](#)] [[INSPIRE](#)].
- [55] A. Kraan, J. Hansen and P. Nevski, *Discovery potential of R-hadrons with the ATLAS detector*, *Eur. Phys. J. C* **49** (2007) 623 [[hep-ex/0511014](#)] [[INSPIRE](#)].
- [56] ATLAS collaboration, G. Aad et al., *Search for anomalous production of prompt like-sign muon pairs and constraints on physics beyond the Standard Model with the ATLAS detector*, *Phys. Rev. D* **88** (2012) 032004 [[arXiv:1201.1091](#)] [[INSPIRE](#)].
- [57] K. Cranmer and I. Yavin, *RECAST: extending the impact of existing analyses*, *JHEP* **04** (2011) 038 [[arXiv:1010.2506](#)] [[INSPIRE](#)].