

Boosting searches for natural supersymmetry with R -parity violation via gluino cascadesZhenyu Han,¹ Andrey Katz,² Minh Son,^{3,4} and Brock Tweedie⁵¹*Institute of Theoretical Science, University of Oregon, Eugene, Oregon 97403, USA*²*Center for the Fundamental Laws of Nature, Jefferson Physical Laboratory, Harvard University, Cambridge, Massachusetts 02138, USA*³*Department of Physics, Yale University, New Haven, Connecticut 06511, USA*⁴*Dipartimento di Fisica, Università di Roma “La Sapienza” and INFN Sezione di Roma, I-00185 Rome, Italy*⁵*Physics Department, Boston University, Boston, Massachusetts 02215, USA*

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In the presence of even minuscule baryonic R -parity violation (RPV), the stop can be the lightest superpartner and evade LHC searches because it decays into two jets. In order to cover this interesting possibility, we here consider new searches for RPV stops produced in gluino cascades. While typical searches for gluinos decaying to stops rely on same-sign dileptons, the RPV cascades usually have fewer hard leptons, less excess missing energy, and more jets than R -parity conserving cascades. If the gluino is a Dirac fermion, same-sign dilepton signals are also often highly depleted. We therefore explore search strategies that use single-lepton channels, and combat backgrounds using H_T , jet counting, and more detailed multijet kinematics or jet substructure. We demonstrate that the stop mass peaks can be fully reconstructed over a broad range of spectra, even given the very high jet multiplicities. This would not only serve as a “double-discovery” opportunity, but would also be a spectacular confirmation that the elusive top partner has been hiding in multijets.

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I. INTRODUCTION

We are currently at a very interesting crossroads for particle physics. The Higgs boson, or something very much like it, has recently been discovered at the LHC [1,2]. At the same time, the LHC experiments have been engaging in a large variety of searches for the physics that stabilizes the Higgs potential, so far without any signs of new phenomena. According to the usual logic, this is somewhat perplexing. Cancellation of the top loop without fine-tuning requires the existence of a top partner at the few hundred GeV scale, and in most models this is accompanied by many other new colored particles. The LHC is extremely efficient at producing colored particles, so if this scenario is correct, then the LHC is already creating top partners and other new particles in abundance. Where are they?

The nonobservation of new physics has in particular made a major dent in the available parameter space for one of our best-motivated and well-defined stabilization mechanisms, supersymmetry (SUSY) (for summaries of experimental searches see Refs. [3,4]). SUSY typically produces complicated cascade decay chains with copious production of jets, leptons, and—it is usually assumed—missing energy from an invisible lightest supersymmetric particle (LSP). One escape route for SUSY is to simply push up the masses of all superparticles beyond the LHC reach, though at the penalty of re-introducing the fine-tuning that it was invented to alleviate. A more attractive option from the perspective of naturalness is what has come to be called “natural SUSY” or “effective SUSY” [5,6] (see also Refs. [7,8]), where sleptons and first/second generation squarks are assumed to be very heavy, but the

particles necessary to avoid Higgs sector fine-tuning remain relatively light. Because of its reduced particle content, natural SUSY can more easily evade constraints from generic SUSY searches [9–11]. But while, for example, relatively light stops and sbottoms can still be accommodated by the LHC data, targeted searches for these scenarios are gaining ground [12–16].

As our standard approaches to SUSY have thus far proven unrealized by nature, it is becoming clear that we must cast a wider net both in terms of our SUSY models and our strategies for searching for them. This does not entail particularly baroque model-building, as even modest modifications to minimal SUSY models can radically change their phenomenology. One of the simplest and well known ways to do this is to turn on the baryon-number violating and R -parity violating (RPV) superpotential operator $W \sim u^c d^c d^c$. If this operator has even a tiny nonvanishing coefficient, all supersymmetric decay chains are fated to end in jets instead of the usual missing energy. This turns the LHC’s virtue of copious colored particle production into a curse, as these signals can easily become lost in the noise of QCD multijet backgrounds. Nonetheless, the LHC detectors are already proving themselves quite reliable for reconstructing detailed kinematic features using jets. RPV signals are uniquely well-suited to this because they can contain multijet resonances, and more generally jet-lepton resonances. Several papers have pointed out how some of these resonances might be uncovered [17–20], and searches are already underway [21,22].

R -parity violation is a well-motivated possibility from the perspective of natural SUSY [10]. Completely

eliminating the sleptons and first/second generation squarks from the theory, we can view the remaining particle content as an effective field theory, and allow for a wide range of ignorance about physics above a scale beyond the LHC's direct reach, e.g., $\mathcal{O}(10 \text{ TeV})$. The theory's UV completion may not even be supersymmetric, as in Ref. [23]. The main argument for exact R -parity conservation, and the ensuing vanishing of all of the dimension-four RPV superpotential operators, is that it automatically ensures proton stability. However, in a natural SUSY effective theory, there are no longer any guarantees that higher-dimensional R -parity conserving (RPC) operators are suppressed by a very high supersymmetric GUT scale, and we must impose additional symmetries such as exact baryon- or lepton-number conservation. The requirement of R -parity conservation then becomes redundant, and we can consider turning on RPV couplings consistent with the more fundamental proton-stabilizing symmetries. The size of these couplings is still constrained by flavor physics measurements (see Ref. [24] for review) and other indirect constraints that we briefly review below, but they are capable of mediating prompt decays at the LHC as long as they are larger than $\mathcal{O}(10^{-7})$.

While various aspects of the impact of RPV on SUSY phenomenology at the LHC are being studied, perhaps the simplest scenario, highly motivated by naturalness yet very difficult to find at a hadron collider, is a stop LSP that decays directly to two jets. Seemingly the most straightforward way to search for these particles is to pair produce them and look for pairs of dijet resonances within four-jet events. Searches of this type have been carried out by Refs. [25,26] (and can be re-interpreted in terms of stop limits). However, these searches are far too background dominated to conclusively find or rule out stops. Depending on the flavor structure of the $u^c d^c d^c$ superpotential operator, the decay may include a taggable b -jet that could be exploited in future four-jet searches, but this is far from guaranteed.

A search for $\tilde{t} \rightarrow jj$ in sbottom decays was proposed in Ref. [19], capitalizing on the presence of extra leptons from real or virtual W emission in the $\tilde{b} \rightarrow \tilde{t}$ transition. There it was shown that the stop may be visible as a dijet invariant mass peak rising above the backgrounds. Nonetheless, the coverage is spectrum dependent, and many additional possible search options remain open for investigation.

In this paper, we turn our attention to searches for RPV stops produced in gluino decays. If we take naturalness as a guide, then the gluino cannot be much heavier than a TeV, and should be within reach of the LHC [10,11]. Producing stops in this way is potentially very useful for three reasons. First, gluino cross sections can be large and they tend to produce a lot of activity in their decays, making the stops easier to spot against background. Second, gluino decays most directly produce stops in association with top quarks.

Since the stops lose their top quantum number in their RPV decay, becoming a fairly anonymous-looking dijet resonance, this may be one of the cleanest ways to establish that the resonance is in fact a top partner. Third, the gluino itself is an independent target in our searches for supersymmetry. Of course, if this turns out to be the first search of this kind that yields a positive result, the impact of such a double discovery would be quite dramatic.

Recently, there has been a study of gluino cascades into top quarks and RPV stops [27] that utilizes the same-sign dileptons that can result when a pair of gluinos decays into tops with equal charge. Searches with same-sign dileptons are a classic way to look for gluinos, and exploit the fact that they are Majorana particles with no intrinsic sense of charge, as well as the fact that there are usually multiple chances for lepton production in their cascade decays. Standard Model (SM) backgrounds to same-sign dilepton production are quite modest, allowing for a very clean search.

Here, we will be pursuing a different strategy. While same-sign dilepton searches can be expeditious for setting limits, it is not immediately clear that they are actually optimal when baryonic RPV decays are involved. A standard R -parity conserving gluino decay via stop produces two top quarks (on or off shell), providing four opportunities for lepton production in a $\tilde{g} \tilde{g}$ pair event. The overall branching ratio for same-sign dileptons is $\mathcal{O}(10\%)$. The RPV cascade $\tilde{g} \rightarrow t\tilde{t}^* \rightarrow t(jj)$ instead provides one top quark from each side of the event, so the overall dilepton branching fraction is the same as in SM $t\bar{t}$, and only half of the dileptons are same sign. The same-sign dilepton branching fraction then shrinks to 2.5%. Some gain could be made by switching to an inclusive dilepton search strategy, combining same sign and opposite sign, with $t\bar{t} + \text{jets}$ becoming the major limiting background for the latter. However, as pointed out in Ref. [28], searches in the $l + \text{jets}$ channel with high jet multiplicity also face $t\bar{t} + \text{jets}$ as their leading background, but with much higher branching fractions (30%). Effectively, for the price of roughly doubling the relative background, we gain a factor of six in signal rate, and the latter is far more important when working near the edge of discovery or exclusion reach. To capitalize on this, we therefore do not pursue dilepton-based searches, but focus on what might be possible with the far more plentiful $l + \text{jets}$.

There is also another reason to consider searches that do not rely on the presence of a low-background, same-sign dilepton component of the signal: the gluino may be a Dirac fermion instead of a Majorana fermion. This possibility, pointed out in Refs. [29–31], is well motivated because it relaxes stringent constraints from low-energy tests such as flavor-changing neutral currents [32] and neutron-antineutron oscillation [10]. It also allows the gluino to be somewhat heavier (up to about $4m_{\tilde{t}}$) while still keeping the Higgs potential natural [31]. From the

perspective of super-QCD, Dirac gluinos carry a well-defined fermion number, and can only be produced in gluino-antigluino pairs. Their subsequent decays into tops and stops then depend sensitively on the exact spectrum. In the limit where one species of purely-chiral stop dominates, gluinos will only decay into one specific sign of top quark, and antigluinos will decay into the other sign. The subset of events where both tops decay leptonically will then be entirely *opposite* sign. More general spectra can lead to a more mixed composition of same sign and opposite sign, though an imbalance in favor of opposite sign is generally preferred. Our $l + \text{jets}$ searches will be insensitive to such details, and therefore also uniquely suited to covering a broad range of possible spectra with Dirac gluinos.

Both Dirac and Majorana gluinos decaying to RPV stops will contribute an excess of $t\bar{t} + \text{jets}$, and can be revealed with high purity by placing stringent cuts on the total activity of these events. The simplest version of such a search would demand a single hard, isolated lepton produced in association with a large number of jets and a large amount of scalar-summed jet p_T (H_T), as was pursued in Ref. [28]. However, the signal also contains within it two dijet resonances. These could be revealed if we can manage the combinatoric confusion presented by the additional jets from the top quark decays and from hard radiation. Being able to explicitly reconstruct the $\tilde{t} \rightarrow jj$ peak is crucial to establish that we are producing a new particle in association with top quarks, a strong indication that it is indeed an RPV stop. Having an additional highly-featured handle on the signal will also further improve S/B and help reduce uncertainties associated with background modeling. These are important benefits even from the perspective of just setting limits.

We will pursue two approaches to reconstructing the stop peak, which allow us to reliably combat combinatorics over a wide range of kinematics. If the mass gap between the gluino and the stop is small, the top quarks receive little kinetic energy and the jets from the stop decays are usually amongst the hardest ones in the event. We can then attempt a “best pair of pairs” approach similar to what is currently being used in searches for direct production of pairs of dijet resonances [25,26]. If the mass gap is instead large, then the tops and stops are both produced with fairly large boost. This reduces combinatorial uncertainties and renders the events suitable for analysis with jet substructure techniques (see Refs. [33,34] for reviews). We will see that there is a sizable overlap between the regions of parameter space where either technique is effective, and that there are no “weak spots” in the sensitivity. The combination of the two methods allows discovery-level sensitivity to roughly 1 TeV gluinos by the end of the 2012 run, for almost any LSP stop mass.

Our paper is organized as follows. In the next section we will briefly review our assumption about RPV as well as

existing constraints on baryon-number violation, coming from flavor physics, other precision tests and cosmological considerations. We then go in detail through the relevant existing searches for SUSY and estimate the LHC constraints on our scenario. In Sec. III, we describe our search strategies and estimate their discovery potential. Finally, in Sec. IV we conclude. The Appendix contains details of our simulations.

II. CONSTRAINTS

Throughout this paper we assume that lepton number is perfectly conserved, thus preventing proton decay, while baryon number is violated by the RPV superpotential operator

$$W = \lambda_{ijk} u_i^c d_j^c d_k^c. \quad (1)$$

Note that λ is antisymmetric in indices j and k . A stop LSP can then decay into two down-type jets through, e.g., $t^c s^c d^c$ or $t^c s^c b^c$. We will not make any assumptions about the flavor structure, and therefore do not attempt to capitalize on the possible presence of a b -jet in the decay.¹

Although proton decay is automatically prevented by lepton-number conservation, the presence of baryon-number violation induces several other effects that are highly constrained. One of the simplest is $n - \bar{n}$ oscillation (see Ref. [39] for review). This would bound $\lambda \lesssim 10^{-5}$, but the constraint is easily avoided if the gluino mass is mostly Dirac. There are also bounds from $K - \bar{K}$ mixing, which would require $\lambda \lesssim 10^{-2}$ if we assume mostly universal flavor structure. Other indirect constraints from low-energy experiments tend to be weaker [24].²

At high-energy colliders, direct production of stops can be identified most simply by looking for pairs of dijet resonances. The decays can be considered prompt as long as $\lambda \gtrsim 10^{-7}$, a bound which can accommodate the above indirect constraints. The LEP experiments searched for this process (which is quite analogous to $e^+e^- \rightarrow W^+W^- \rightarrow 4j$), placing a limit of $m_{\tilde{t}} > 90$ GeV for pure \tilde{t}_R [43], with a small allowed region at $m_{\tilde{t}} \simeq m_W$. Similar searches have been done at the LHC [25,26], but there multijet production backgrounds swamp the signal.³

Hadron collider searches for gluinos decaying via stops usually make a set of implicit assumptions that lead to

¹However, we note that some theories can favor this, especially those motivated by minimal flavor violation [35,36]. Constraints on these scenarios might therefore be augmented by direct searches that have additional b -tagging demands, such as Refs. [15,37,38].

²Cosmologically, baryon-number violation can potentially wash out the baryon asymmetry produced in the early Universe. This is avoided if the coupling is less than $\mathcal{O}(10^{-6})$. However, one can also use (1) as a mechanism of electroweak-scale baryogenesis, requiring more sizable values of λ [40–42].

³No search of this type has been performed at the Tevatron, though it would likely be capable of making substantial gains.

leptons produced in association with at least four jets of $p_T > 50$ GeV and 150 GeV of \cancel{E}_T . In a simplified RPC model with a gluino decaying via an off-shell stop into two tops and a light LSP neutralino, gluinos of mass less than 920 GeV are ruled out.

Our gluino pair production signal produces two top quarks in association with four hard jets from the RPV stop decays. It can contribute to the SS dilepton signal if both tops have the same charge and both decay semileptonically. This is guaranteed to occur if the gluino is Majorana, since it then has no sense of fermion number, and can decay with equal probability into $t\bar{t}^*$ and $\bar{t}t$. The branching fraction of a complete event into SS dileptons is nonetheless quite small, as we pay the usual penalty of 5% for dileptonic tops, times an extra factor of 1/2 to account for the probability that the tops have the same charge. Subsequently, the requirement of four hard jets is almost trivially satisfied. The \cancel{E}_T requirement is most easily met if the stop is somewhat light relative to the gluino, so that the tops can pick up a large fraction of the available energy in the decay and boost up the leptonically-decaying W bosons.

The upper limit on a new physics signal is 6.3 events. For a Majorana gluino with $m_{\tilde{g}} = 600$ GeV and $m_{\tilde{t}} = (100, 200, 400)$ GeV, we estimate that ATLAS would have observed (25,22,3) extra events.⁴ The smallest allowed $m_{\tilde{t}}$ is roughly 350 GeV for this gluino mass. Note that the limits become weaker for heavier stops, since then the energy apportioned to the top quark is squeezed out.

The same channel for the same RPV model was also studied in Ref. [27], re-interpreting SS dilepton searches from LHC7 with up to 2 fb^{-1} of data. They found gluino mass limits of 550 GeV, roughly independent of the stop mass, in the case where the RPV coupling is unity and mainly in regions of parameter space where the top or stop is off shell.⁵ The fully on-shell region which we have checked, with a more recent analysis from ATLAS, extend these results.

⁴We have validated our own Monte Carlo with respect to ATLAS by studying predicted kinematic distributions and event counts for their simplified RPC model.

⁵We point out one subtlety here. The behavior in the region $m_{\tilde{t}} < m_{\tilde{g}} < m_{\tilde{t}} + m_t$ may be highly dependent on the RPV coupling strength. For very small RPV coupling (e.g., $\lesssim 10^{-5}$), such as we are implicitly assuming to avoid precision constraints, the top will almost always be off shell, and the stop on shell. The energy available to the lvb system will therefore completely shut off as $m_{\tilde{g}} \rightarrow m_{\tilde{t}}$ from above, eliminating the leptonic part of the signal and making limit setting impossible. However, for $\mathcal{O}(1)$ RPV coupling, such as it was assumed in Ref. [27], the stop can also go off shell with appreciable rate, allowing the lepton to still carry some energy and nontrivial limits to be set. When $m_{\tilde{g}} < m_{\tilde{t}}$, this subtlety is sidestepped as the stop is then *forced* off shell, and the lepton can be energetic regardless of the coupling. However, since we are assuming a stop LSP for naturalness reasons, this case formally falls outside the scope of our paper.

B. Opposite-sign dileptons

CMS has an OS dilepton search for generic RPC SUSY with 5 fb^{-1} of LHC7 data [45]. This analysis further requires two hard jets, and places a small variety of H_T and \cancel{E}_T cuts defining four signal regions. (H_T is defined by summing over jets.) For our purposes, the “high H_T ” region is the most constraining, as our signal easily produces large amounts of H_T , but not necessarily large amounts of \cancel{E}_T . The cuts are $H_T > 600$ GeV and $\cancel{E}_T > 200$ GeV.

This analysis places some constraints on Majorana gluinos with RPV stops, but they are much weaker than those from SS dilepton searches. For Majorana gluinos, the rates in OS and SS are identical, but the backgrounds in the latter are significantly smaller. Dirac gluinos, on the other hand, might only contribute to OS. Assuming its decay is dominated by a single species of mostly left-handed or mostly right-handed stop, an approximate fermion number can be defined that is conserved throughout both the production and decay. The sensitivity is also much better for Dirac than Majorana, for two reasons. First, Dirac production cross sections are twice as big. Second, we assume that dileptonic Dirac gluino pairs are always OS, whereas for Majorana they are only OS half of the time. The total OS cross section for Dirac is therefore four times larger than for the equivalent Majorana model.

CMS places an upper limit of 23 new physics events in its high H_T signal region. For a Dirac gluino with $m_{\tilde{g}} = 600$ GeV and $m_{\tilde{t}} = (100, 200, 400)$ GeV, we estimate that CMS would have observed (24,18,1.2) extra events. The smallest allowed $m_{\tilde{t}}$ is therefore close to 100 GeV for this gluino mass.

C. Single lepton

Searches for SUSY in single-lepton channels can be nontrivial to interpret for our models. Our signal essentially looks like $t\bar{t}$ + jets, which occurs plentifully in the SM and serves as one of the dominant SUSY backgrounds. SUSY searches therefore tend to craft cuts that either efficiently eliminate $t\bar{t}$ + jets from the outset or attempt to fit it away using control regions. Most of the ATLAS searches fall into the former category, by demanding that $m_T(l, \cancel{E}_T) > 100$ GeV. Since this severely degrades our signal along with the SM $t\bar{t}$ + jets, we do not study these searches in detail. However, CMS has four recent searches which do not place such a cut.

Of all of these, probably the most robust for our purposes is [46]. The strategy is to normalize the backgrounds in a low- H_T , low- \cancel{E}_T control region, extrapolate to high- H_T and high- \cancel{E}_T using Monte Carlo, and count. For this analysis, the control region should indeed be more highly purified in backgrounds relative to the signal regions, at least for $m_{\tilde{g}} \gtrsim 400$ GeV. The final analysis cuts demand at least three hard jets, $H_T > 750$ or 1000 GeV, $\cancel{E}_T > 250, 350, \text{ or } 450$ GeV, and various numbers of b -tags. We find

the best sensitivity in the signal regions with either of the two H_T cuts, the smallest \cancel{E}_T cut, and no requirements on b -tags. The strongest constraints are obtained for Dirac gluinos, due to their higher cross section. However, the search proves to be strictly weaker than the OS dilepton.

The other three searches are likely incapable of placing stronger limits. One search [47] uses an artificial neural network trained on the RPC model LM0, for which $m_T(l, \cancel{E}_T)$ is actually the most powerful individual discriminating variable. Another [48] looks for deviations in the $\cancel{E}_T/\sqrt{H_T}$ spectrum, again normalizing backgrounds using control regions. However, these include a high- H_T and low- $\cancel{E}_T/\sqrt{H_T}$ control region, which would actually be more signal-pure than their high- H_T and high- $\cancel{E}_T/\sqrt{H_T}$ signal region. Even ignoring this issue completely, the final sensitivity would still be weaker than Ref. [45]. Finally, the most recent search [49] attempts to exploit differences in the relationship between the lepton and \cancel{E}_T in SM backgrounds versus RPC SUSY signals. For example, in $t\bar{t} + \text{jets}$, harder \cancel{E}_T tends to be associated with harder leptons. Exactly the same relationships occur for our signal. But again completely ignoring this issue, and just checking the counts in the signal regions, we expect sensitivity at most comparable to the OS dilepton search above.

D. Black hole searches

If TeV-scale black holes exist, they should be produced at the LHC and decay into high-multiplicity final states of jets, leptons, photons, and neutrinos. Two of the most recent such searches are Refs. [50,51]. Neither of these searches places stringent requirements on \cancel{E}_T , and only the second requires the presence of a lepton. They can therefore be fairly efficient at capturing the gluino signal, even in the all-hadronic mode in the former case.

In Ref. [50], a purely data-driven search by CMS using 3.7 fb^{-1} at LHC8, the only discriminating variables are the inclusive number N of reconstructed objects (jets, leptons, and photons) with $p_T > 50 \text{ GeV}$, and the S_T formed by summing all of these p_T 's (also adding \cancel{E}_T if it exceeds 50 GeV). They consider events with $N \geq 3-8$ and $S_T > 1800 \text{ GeV}$. The S_T shape is assumed to be independent of N , and is fit using $N = 2$, which is mainly dijets. The predictions for $d\sigma/dS_T$ for the different N cuts are then independently normalized using the data observed in the range $S_T = [1800, 2200] \text{ GeV}$. Model-independent results are presented for the total allowed $\sigma \times (\text{acceptance})$ of any new physics contribution as a function of N and S_T cuts. The strongest bounds on our signal would come from the $N \geq 8$ region. For example, an 800 GeV Dirac gluino with 300 GeV stop would contribute about 30 events, or 8 fb, for $S_T > 2200 \text{ GeV}$. The upper limit is about 6 fb, suggesting that gluinos up to 800 GeV may already be ruled out. However, we point out an important caveat to this

interpretation. Like the SM, the gluino signal is a steeply-falling function in this region of high- S_T , and would contribute to the shape template normalization. In our example model, the signal contribution in the CMS control region would be 70 events, whereas the number observed is roughly 150. We therefore do not feel that the claimed cross section limits can be robustly applied to this gluino model, as the signal highly contaminates the control region. Heavier gluinos could be easier to discriminate in shape, but contribute much smaller rates. A more careful S_T shape analysis in high-multiplicity events could be useful here.

In Ref. [51], a search by ATLAS using 1 fb^{-1} of LHC7 data, the signal region requirements are at least one lepton with $p_T > 100 \text{ GeV}$, at least two other jets or leptons with $p_T > 100 \text{ GeV}$, and lower bounds on the scalar-summed p_T over all jets and leptons varying from 700 to 1500 GeV. Backgrounds are normalized in low- p_T control regions. The modest requirements on the number of reconstructed objects makes this search less sensitive than it otherwise might be for gluinos, but it can still place a nontrivial limit. For 600 GeV gluinos with $m_{\tilde{t}} < 300 \text{ GeV}$, we predict more than 30 events with summed $p_T > 1200 \text{ GeV}$, whereas ATLAS places an upper limit of 33 events. This search is therefore stronger than CMS's 5 fb^{-1} OS dilepton search.

E. ATLAS b' search

Interestingly, ATLAS's fourth generation down-type fermion search [52] puts one of the most stringent existing constraints on Dirac gluinos. This search looks for pair-produced b' fermions, each of which decays into a top and W . Four W 's are ultimately produced from the two $b' \rightarrow Wt$ and $t \rightarrow Wb$ decays. The search considers the channel where exactly one of these W 's produces an observable, isolated lepton, and the others decay hadronically (or into taus or otherwise unobserved leptons). Since the missing energy in signal events is coming only from a neutrino, this analysis imposes very mild cuts on \cancel{E}_T and m_T .

The nominal signal is one lepton plus eight jets, six of which can in principle be clustered into on-shell W 's. In practice, the hadronic W 's, which are somewhat boosted in the heavy b' decay, are identified by looking for pairs of jets with $\Delta R(j, j) < 1.0$ and $m(jj) = [70, 100] \text{ GeV}$. The events are binned according to the number of jets and the number of identified hadronic W 's. We find that our gluino signal is most efficiently captured by the tightest bin, demanding at least eight jets and at least two W 's reconstructed out of these jets. For the bulk of the parameter space constrained by this search, the acceptance is $\mathcal{O}(20\%)$. (For $m_{\tilde{t}} \approx 100 \text{ GeV}$, the search can even pick up the stops as “ W 's”.)

We show the exclusion of this search in Fig. 1 (along with all of the most relevant searches discussed above). The resulting constraints are strong, excluding Dirac gluinos up to almost 690 GeV for a light stop. We note

that the search has only been carried out up to a luminosity of 1 fb^{-1} at 7 TeV. However, any improvement of these bounds will probably be very moderate as more data is added. This is because the error is already largely dominated by systematics, mainly from the theoretical uncertainty on $t\bar{t}$ + jets production.

The b' search shares some similarities with the dedicated $\tilde{g} \rightarrow t\bar{t}$ searches that we propose in the next section. Some differences are that we will also take advantage of the high- H_T of gluino events and actively search for the stop mass peaks. We will also replace the simple hadronic “ W tagging” with more sophisticated hadronic “top tagging.” As can already be seen in Fig. 1, even our simplest dedicated search can in principle make major gains.

III. SEARCH STRATEGIES AND RESULTS

While each LSP stop from a gluino pair always decays to two jets, the associated top can either decay semileptonically or hadronically. We will focus on events where one top decays semileptonically, providing us a clean trigger and suppressing multijet backgrounds, while maintaining a high branching fraction. A simple search strategy is then to perform a survey over jet multiplicity, N_j , and event H_T , where we define the latter as

$$H_T \equiv p_T(l) + \sum_i p_T(j_i). \quad (2)$$

The main backgrounds are $t\bar{t}$ + jets and W + jets. These tend to occupy low (N_j, H_T) , whereas the signal occupies high (N_j, H_T) : N_j tends to be larger than six, and H_T is strongly correlated with $2m_{\tilde{g}}$. Therefore, our first approach will be to simply choose N_j and H_T cuts to maximize the significance, very similar to what was proposed in Ref. [28]. As we will show, gluinos up to roughly 1 TeV are discoverable at the 8 TeV LHC using this simple method, neglecting possible systematic errors.

We will then show that it is possible to reconstruct the $\tilde{t} \rightarrow jj$ peaks in the signal, despite the nontrivial combinatorics in a high- N_j environment. The appropriate strategy depends on the mass hierarchy between the gluino and the stop. When the masses are comparable, the stop is fairly heavy and the top quark receives fairly little kinetic energy in the gluino decay. The jets from the stop decay then tend to be well separated and higher in energy than the jets from top quark decay (or additional radiation jets). We will apply a traditional jet reconstruction strategy to this case, and break the combinatoric ambiguities by identifying the two dijet subsystems that are closest in mass to each other, choosing only amongst the hardest handful of jets in the event. When the stop mass is instead much smaller than the gluino mass, possibly even smaller than the top quark mass, both the stop and the top quark will be produced with appreciable boost. A strategy based on jet substructure then becomes appropriate to identify “stop jets” and

distinguish these from top jets. Picking the best of these two procedures, and supplementing our (N_j, H_T) cuts with a mass window cut centered on the stop mass, we obtain similar naive discovery potential as with (N_j, H_T) alone. However, this comes with better shape discrimination, enhanced S/B , and of course a much clearer picture of what is being produced.

Below, we will mainly work in a simplified model where $\text{BR}(\tilde{g} \rightarrow t\bar{t}) \equiv 1$. The details of our Monte Carlo simulations and event reconstruction can be found in the Appendix. Note that we do not utilize any detector simulation, since a large amount of irreducible physics noise is already induced by combinatoric uncertainties and showering effects. (Introducing a detector model does not change our results.) We also find that our results are fairly insensitive to whether we are working with a Majorana or Dirac gluino, up to the fact that the latter cross section is 2 times larger than the former.

A. (N_j, H_T) cut-and-count analysis

We show the jet multiplicity distribution of high- H_T events for several different gluino masses and for SM backgrounds in the left panel of Fig. 2. The SM background samples consist of $t\bar{t}$ + jets matched up to two jets, and W + jets matched up to four jets, as described in the Appendix. As expected, the signal events occupy a higher N_j region than the backgrounds. We also see that the N_j distribution is insensitive to $m_{\tilde{g}}$, and it turns out that the cut $N_j \geq 7$ allows us to optimize the search significance over the entire range of gluino masses and stop masses that we consider. Therefore, we first fix the cut on jet multiplicity to be $N_j \geq 7$. After fixing this cut, we show the H_T distributions in the right panel of Fig. 2, where we see that a cut on H_T will further increase the signal/background ratio. For simplicity, we fix the H_T cut such that $\sim 80\%$ of the signal events are kept (after the $N_j \geq 7$ cut). One can further optimize the set of (N_j, H_T) cuts, but we will not pursue it in this work.

B. Bump hunting with traditional jets

Our traditional jet analysis is appropriate when the jets from the stop decay are well separated, and are the dominant jets in the event. Of the seven or more jets in the event, the chances of randomly picking two jets from the same stop decay are small. We therefore exploit the fact that there are two stops in the event, by searching for two pairs of jets with similar invariant masses and taking their average. Similar techniques were introduced in Ref. [53] and implemented in LHC searches for pair-produced dijet resonances [25,26].

Naively, one would conduct such a search over all available jets. However, we have found that very frequently, the pairs with the closest mass (either relatively or in GeV) are not the correct ones. Alternatively, we could

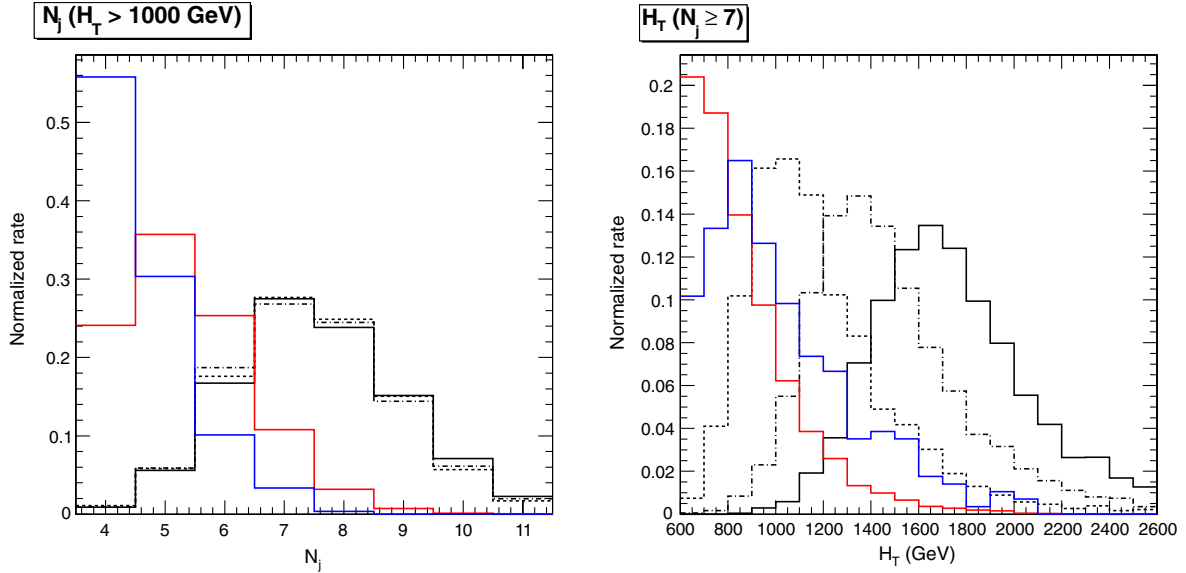


FIG. 2 (color online). Left panel: N_j distributions of signals for $m_{\tilde{g}} = 600$ GeV (black dotted line), 800 GeV (black dashed line), and 1000 GeV (black solid line) with $m_{\tilde{t}} = 1/2 \times m_{\tilde{g}}$, and backgrounds $t\bar{t} + \text{jets}$ (solid red line) and $W + \text{jets}$ (solid blue line). Right panel: H_T distributions of the corresponding signals and backgrounds. The gluinos used for these plots are Dirac, but we obtain equivalent distributions with Majorana.

restrict ourselves to only the hardest four jets. This works well in some cases, but not always. In fact, we have found that the appropriate number of jets to pick depends on the size of the hierarchy between $m_{\tilde{t}}$ and $m_{\tilde{g}}$. We illustrate the situation in Fig. 3. Here, we pick from amongst the hardest n leading jets, where $n = 4, 5, \text{ or } 6$. From amongst all partitionings into two pairs, we keep the one where the absolute difference in pair masses is the smallest, and take the average of the two masses. We see that for larger $m_{\tilde{t}}/m_{\tilde{g}}$, we obtain better results with smaller n , whereas the reverse trend occurs for smaller $m_{\tilde{t}}/m_{\tilde{g}}$. In order to minimize the amount of spurious reconstruction, we therefore recommend a search that uses a sequence of different n 's to cover different ranges of mass ratios. Note that, even though the choice of n also sculpts the background distributions of the average pair mass in different ways, the signal peak typically remains distinct in shape.

In the following, to estimate our possible reach, we always pick the n that optimizes our signal significance. To exploit the peak feature's ability to improve S/B , we apply a mass window cut of $\pm 20\%$ around the nominal stop mass.

C. Bump hunting with jet substructure

When the stop is light relative to the gluino, the stop and top quark can both be boosted in the decay, and our jet substructure analysis becomes appropriate. While it is somewhat rare to find tops or stops fully merged into small jets for the gluino masses accessible to LHC8, jet substructure methods very conveniently organize the large

amount of hadronic information in the event.⁶ In particular, these methods implicitly exploit the simplifications in combinatorics that occur when stops and tops become boosted, as each will typically beam all of its decay products into localized regions in the detector. It is also exactly in this regime that our traditional style search becomes least effective. When the stops are lighter, they take up a smaller fraction of the gluino decay's energy, and jets from the top decays become more difficult to disentangle by simply ranking all jets in p_T .

After applying our baseline (N_j, H_T) cuts described above, we recluster the event into $R = 1.5$ "fat-jets" using the Cambridge/Aachen algorithm [56,57]. Since stop decays are two prong, we can apply the common Butterworth-Davison-Rubin-Salam substructure algorithm [58], which first identifies two subjets within a fat jet, and then filters soft and diffuse radiation out of them. The mass of the remaining particles is our stop candidate mass.

At this stage, if we simply picked a random fat jet, we would have some chance of capturing a complete stop decay, a complete hadronic top decay, a part of a decay,

⁶At LHC14, jet merging will become an unavoidable issue. Techniques like the ones we discuss here will then become crucial. Searches in this regime may also benefit from a different jet counting criterion, or perhaps even a *subjet* counting criterion, though this is to some degree implicit in the taggers that we employ. We also comment that the relatively good parton separations at LHC8 allow us to continue to use traditional lepton isolation. Dedicated nonisolated lepton techniques [54,55] will be required for heavier gluinos.

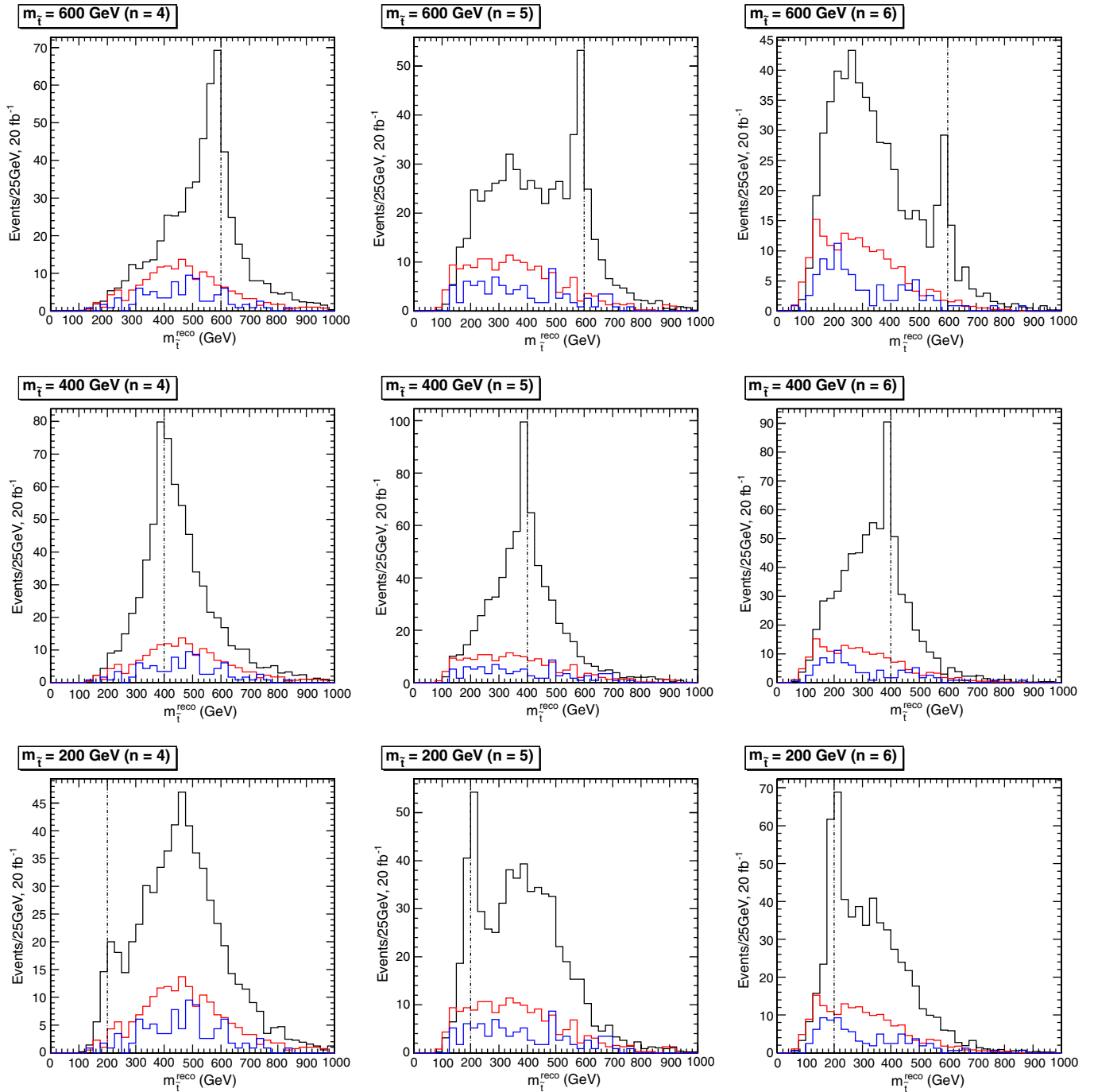


FIG. 3 (color online). Reconstructed stop mass distributions using our traditional jet analysis for 800 GeV Dirac gluinos with 20 fb^{-1} at LHC8. Black histograms are signal, red histograms are $t\bar{t} + \text{jets}$ background, and blue histograms are $W + \text{jets}$ background. We consider three different stop masses and three different choices for the number of jets used in the reconstruction. Rows correspond to 600 GeV stops (top row), 400 GeV stops (middle row), and 200 GeV stops (bottom row). Columns correspond to reconstructions using the n leading jets with $n = 4$ (left column), 5 (middle column), and 6 (right column). We restrict to events with $N_j \geq 7$ and $H_T > 1200 \text{ GeV}$. Vertical dashed lines represent the truth stop masses. (All plots are unstacked.)

or complete or partial decays contaminated by other hard jets. It is also rare, at least for the mass ranges that we consider, that both stops are completely caught in individual fat-jets, so we cannot reliably apply the nearby-mass trick used in the traditional jet analysis.

To increase our chances of picking a fat jet that actually corresponds to a fully contained stop, we therefore propose the following. First, we try to identify a fat jet corresponding to the hadronic top, characterized by a three-prong system with mass near m_t . To do so, we make a first pass

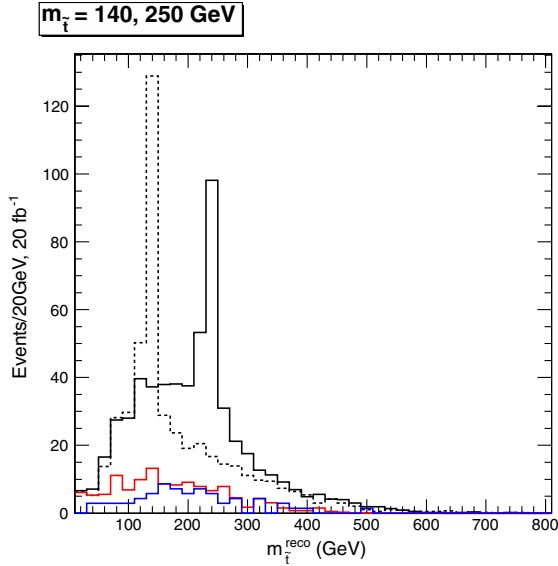


FIG. 4 (color online). Reconstructed stop mass distributions using jet substructure for 800 GeV Dirac gluinos with 20 fb^{-1} at LHC8. Black histograms are signals with 250 GeV (solid lines) and 140 GeV (dashed lines) stops, the red histogram is the $t\bar{t}$ + jets background, and the blue histogram is the W + jets background. We restrict to events with $N_j \geq 7$ and $H_T > 1200$ GeV. (The plot is unstacked.)

over all fat jets with the HEPTopTagger [59,60]. Amongst all fat jets passing this tagger (if any), we select the one whose mass is closest to m_t ,⁷ and remove it from the list of fat jets. Amongst the remaining fat-jets, we take the one with the highest p_T as a stop jet candidate. This is the most likely to consist of a fully-contained stop decay, rather than a fragment of a stop or top decay (either of which only acquires some fraction of the parent energy).

We run the Butterworth-Davison-Rubin-Salam procedure in the default setting on the selected stop jet candidate. In the rare cases where it fails the procedure, the event is discarded. The stop mass is then defined as the jet mass after filtering, which is plotted in Fig. 4 for some example signals and the SM backgrounds. While the rate of misreconstruction is not negligible, we nonetheless obtain very narrow stop peaks on top of fairly featureless backgrounds. As in the traditional analysis, we define a mass window within $\pm 20\%$ of the nominal stop mass, and run a refined counting experiment.

D. Comparison of methods and final results

With our methods and cuts now determined, we estimate the performance of the different analyses. We start with a

⁷We have checked that the chance of a stop jet being mischaracterized as a top jet is very small (at the percent level) even if $m_{\tilde{t}} \approx m_t$. The two-body decays of stops lack the additional substructure sought out by top taggers, such as the presence of a subjet doublet consistent with a hadronic W boson.

detailed look at the case of an 800 GeV gluino, which we used above to compare several kinematic distributions. In Fig. 5, we see the S/\sqrt{B} and S/B obtainable from all three analyses. While the basic (N_j, H_T) analysis tends to give somewhat better statistical significance, reconstructing the stops and adding in mass window requirements can improve S/B by as much as a factor of 3.5. We also see how the substructure based search nicely takes over at low stop masses, where the traditional jet analysis falls off in effectiveness. The crossover for this gluino mass occurs roughly at $m_{\tilde{t}} = 300$ GeV. We list a complete summary of our final signal and background cross sections for the 800 GeV gluino analysis in Table I.

In Fig. 6, we show the boundary in the $(m_{\tilde{g}}, m_{\tilde{t}})$ plane of models that would be discoverable by the end of 2012. Masses up to 1 TeV are attainable for Majorana gluinos, and beyond 1.1 TeV for Dirac gluinos. The results are not very sensitive to the stop mass, except as we approach the line $m_{\tilde{g}} = m_{\tilde{t}} + m_t$. In particular, we can again see the substructure-based search taking over at lower stop masses. The equivalent exclusion contours (not shown), would move up to roughly 1.1 and 1.2 TeV, respectively.

In all of our analyses, we have assumed a 100% branching ratio for the gluino decaying to a top-stop pair. If other decay channels are open, more dedicated reconstruction methods would help to maximize the discovery potential. Nevertheless, these decay channels can share similar features with the top-stop channel, and many of the strategies discussed above still apply with little or no modification. For example, if a sbottom is present below the gluino mass and above the stop mass, we obtain the same final state particles through the decay chain $\tilde{g} \rightarrow b\tilde{b} \rightarrow b(W\tilde{t})$. As an example, we have tested the mass point $(m_{\tilde{g}}, m_{\tilde{b}}, m_{\tilde{t}}) = (800, 300, 200)$ GeV and considered the case $\tilde{g}\tilde{g} \rightarrow t\bar{t}b\tilde{b}$. We let the W from the top decay hadronically and the one from the sbottom decay leptonically, and apply the same (N_j, H_T) cuts as in Table I. This results in only a slightly different signal efficiency of 31%, from 35% for the case when both gluinos decay to a top and a stop.

IV. CONCLUSIONS AND OUTLOOK

From the perspective of natural supersymmetry, it may not be surprising that superpartners have so far been elusive at the LHC. On the one hand, this framework places priority on light third generation squarks to maintain naturalness, while the other squarks and sleptons could simply be too heavy to produce. On the other hand, a fully general approach demands additional symmetries beyond R -parity to maintain proton stability, and makes R -parity violation a perfectly viable option. We should then take seriously the possibility that stops are light, and can decay directly to two jets via the $u^c d^c d^c$ superpotential operator. In this paper, we have approached the difficult task of finding $\tilde{t} \rightarrow jj$ in the context of gluino decays. We focused on the

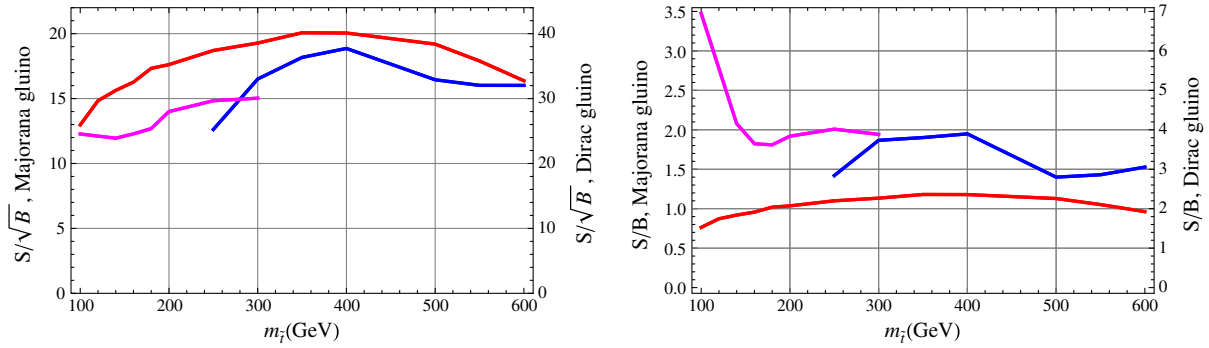


FIG. 5 (color online). The significance (S/\sqrt{B} , left) for 20 fb^{-1} integrated luminosity, and signal/background ratios (S/B , right), for an 800 GeV gluino and varying stop masses at LHC8. The red curves are the simple (N_j , H_T) analysis, the blue curves are with stop peaks reconstructed using traditional jets, and the pink curves use jet substructure. We have used the cuts given in Table I.

power of $l + \text{jets}$ searches with large jet multiplicity, and established the possibility of reconstructing the stop mass peaks despite the combinatoric challenges. In addition to the advantageous kinematic handles and the chance to discover two particles simultaneously, searching for stops in gluino production also provides a crucial opportunity to infer the stop's identity because it would be produced in association with top quarks.

Current searches for new physics are not optimized for this process. Nevertheless, nontrivial bounds can be inferred, and we have estimated the current allowed parameter space based on these existing searches. If we take the default assumption that the gluino is Majorana, then SS dilepton searches apply, and limits up to almost 800 GeV can be placed for stops lighter than about 350 GeV. If instead the gluino is Dirac, which would alleviate many low-energy constraints on RPV while potentially depleting the SS dilepton signal, then the most powerful limits actually come from the ATLAS black hole search. The

limit exceeds 600 GeV for $m_{\tilde{\tau}} \simeq 100 \text{ GeV}$, and becomes weaker for heavier stops.

In either case, we have found that even a simple cut-and-count based search for high- N_j , high- H_T $l + \text{jets}$ events would extend these limits. One could already exclude Majorana (Dirac) gluinos as heavy as 1.0 TeV (1.1 TeV) with this method, using an integrated luminosity of 5 fb^{-1} at LHC8. With 20 fb^{-1} , these masses are at the discovery boundary, and exclusions move out to 1.1 TeV (1.2 TeV).

To reconstruct the stop in gluino pair events, we proposed two approaches. The first uses traditional jets, and attempts to reconstruct both stops by studying pairs of pairings amongst the hardest 4, 5, or 6 jets in each event. This approach works well when $m_{\tilde{\tau}}/m_{\tilde{g}} \gtrsim 1/3$. Our second approach uses jet substructure. We identify fat-jets consistent with a two-body decay, and also reject fat-jets that look more consistent with three-body top decays. This approach works well when $m_{\tilde{\tau}}/m_{\tilde{g}} \lesssim 1/3$. We demonstrated that the two approaches facilitate reliable stop

TABLE I. LHC8 cross sections for an 800 GeV gluino and for backgrounds, after the different analysis cuts. The total cross section for the Majorana (Dirac) signal is 43 fb (86 fb) in the $l + \text{jets}$ channel before cuts. We assume $\text{BR}(\tilde{g} \rightarrow t\bar{t}) = 1$.

$m_{\tilde{g}} = 800 \text{ GeV}$, LHC8								
	$m_{\tilde{\tau}}$	100 GeV	150 GeV	200 GeV	250 GeV	300 GeV	400 GeV	600 GeV
Simple (N_j , H_T) $N_j \geq 7$ $H_T > 1200 \text{ GeV}$	Majorana	11 fb	13 fb	15 fb	16 fb	16 fb	17 fb	14 fb
	Dirac	22 fb	27 fb	30 fb	32 fb	33 fb	34 fb	28 fb
	$t\bar{t} + \text{jets}$				9 fb			
	$W + \text{jets}$				4.5 fb			
	n leading jets		...		$n = 6$	$n = 6$	$n = 5$	$n = 4$
$(N_j, H_T) + \text{traditional } m_{jj} \text{ reconstruction}$ $0.8m_{\tilde{\tau}} < m_{\tilde{\tau}}^{\text{reco}} < 1.2m_{\tilde{\tau}}$	Majorana		...		5.6 fb	7.5 fb	9.3 fb	8.6 fb
	Dirac		...		11 fb	15 fb	19 fb	17 fb
	$t\bar{t} + \text{jets}$...		2.4 fb	2.8 fb	3.0 fb	3.3 fb
	$W + \text{jets}$...		1.4 fb	0.9 fb	1.2 fb	1.8 fb
$(N_j, H_T) + \text{jet substructure}$ $0.8m_{\tilde{\tau}} < m_{\tilde{\tau}}^{\text{reco}} < 1.2m_{\tilde{\tau}}$	Majorana	3.2 fb	5.6 fb	6.0 fb	5.8 fb	5.0 fb		...
	Dirac	6.4 fb	10 fb	12 fb	12 fb	10 fb		...
	$t\bar{t} + \text{jets}$	0.9 fb	1.5 fb	1.6 fb	1.6 fb	1.3 fb		...
	$W + \text{jets}$	0.1 fb	0.7 fb	1.3 fb	0.8 fb	0.6 fb		...

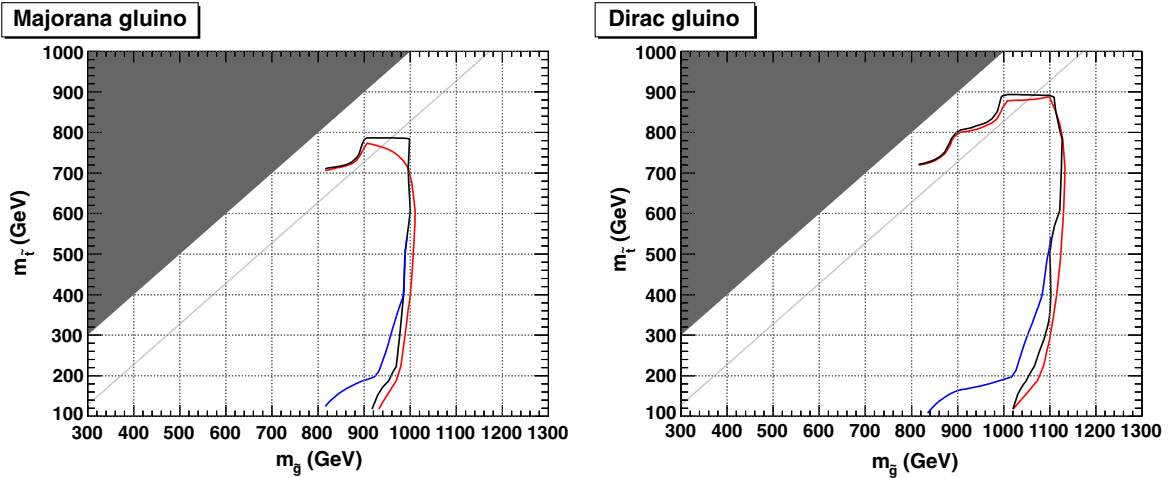


FIG. 6 (color online). Discovery potential ($S/\sqrt{B} \geq 5$) for a Majorana (left panel) and Dirac (right panel) gluino with 20 fb^{-1} at LHC8. The red line is our simple (N_j, H_T) cut-and-count style search. The black line is the better of our two searches using mass windows around the reconstructed stop peaks (traditional and substructure), which improve discrimination against backgrounds. The blue line is traditional only, without substructure. We do not consider regions with a \tilde{g} LSP, indicated with dark gray. The light gray line indicates $m_{\tilde{g}} = m_{\tilde{t}} + m_{\tilde{t}}$.

mass peak reconstruction in their respective regimes of validity, and that there is a healthy overlap between these regimes. The additional step of reconstructing the stop peak is not only useful for characterizing an excess in high- N_j , high- H_T events, but provides us with an important shape discriminant against the backgrounds and improves S/B . We expect that it will have an important role to play in controlling systematic uncertainties in these searches.

Assuming that such a dijet resonance bump is discovered, we can also immediately begin to understand whether it is indeed a top partner. The main goal would be to establish the presence of tops quarks in the signal. Such an endeavor would have to be undertaken with great care, since the main background is itself $t\bar{t} + \text{jets}$. However, we have seen that it is possible to achieve substantial S/B , making the model discrimination much easier. Of course, the presence of an accompanying leptonic W boson is easy to infer based on the transverse mass of the lepton and \cancel{E}_T . This could be used to rule out the presence of a new invisible particle produced in association with the dijet resonances, for example by showing that the resonance disappears for $m_T(l, \cancel{E}_T) > m_W$. It is somewhat more difficult to reconstruct the top quarks themselves, owing to the busy jet environment. Probably the best strategy is to try to find the leptonic top peak, reducing the combinatorics by demanding b -tags from the jets (or subjets) that were not used in stop reconstruction. Since the tops are typically at least somewhat boosted, combining the leptonic W with the closest b -tagged jet would likely be promising. A more global kinematic χ^2 style reconstruction, which attempts to reassemble every intermediate particle in the event, would also be interesting to explore.

Another useful way to further characterize the signal would be to fully reconstruct the gluino mass peaks. We already do this in an approximate way with H_T , and a slightly more careful analysis that uses H_T shape information would unambiguously tell us the gluino mass. However, it should also be possible to reconstruct one gluino at a time if we are able to also reconstruct top quarks in the event.

While we have found very similar kinematics for Majorana and Dirac gluinos, we point out that these may already be distinguishable based on total rate, though such a comparison would depend on $\text{BR}(\tilde{g} \rightarrow t\bar{t})$. A more definitive test would be a measurement of the relative rates of same-sign and opposite-sign dilepton signals, which becomes feasible with more data.

Naturalness suggests that gluinos are not much heavier than a TeV if they are Majorana, and can be just factor of $\mathcal{O}(2)$ heavier if they are Dirac. While our estimated LHC8 coverage only just reaches the TeV scale, the remaining parameter space will likely be covered at the higher energy run. The search strategies that we proposed in this paper should straightforwardly extend beyond a TeV, in particular the search based on jet substructure.

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APPENDIX: SIMULATION AND RECONSTRUCTION DETAILS

We generate all of our signal and background samples with MADGRAPH5 v1.4.7 [61]. The gluino pair signal samples are based on our own simplified UFO [62] models, which are in turn derived from the publicly available RPVMSSM model [63]. Gluinos can be either Majorana or Dirac, and we assume pure right-handed stops. We normalize LHC7 signal cross sections to their next-to-leading-order + next-to-leading-log (NLO + NLL) values [64], and assume $\text{BR}(\tilde{g} \rightarrow t\bar{t} \text{ or } \bar{t}t) = 1$. We apply a rescaling factor of 2 for Dirac gluinos, and extrapolate all cross sections to LHC8 by using leading-order ratios between LHC8 and LHC7. Our background samples, generated only for LHC8, consist of $t\bar{t}$ + jets matched up to two

jets and W + jets matched up to four jets. We use cone-MLM matching [65] with $R = 0.4$ and $p_T = 30$ GeV. For both backgrounds we apply an approximate K -factor of 2. While we would ideally match $t\bar{t}$ + jets up to four jets and W + jets up to seven or eight jets, these are too computationally intensive. However, we do compare our nominal samples to simulations requiring fewer numbers of matched jets, and obtain similar results. Backgrounds are automatically processed through PYTHIA6 [66]. The non-standard color structure of the RPV vertex requires us to instead use PYTHIA8 [67] for the signal, in order to obtain sensible showering and hadronization.⁸ We do not further process the hadron-level event using a detector model. Our basic event reconstruction proceeds as follows. We first demand exactly one isolated lepton with $p_T(l) > 20$ GeV and $|\eta(l)| < 2.5$. A lepton is considered isolated if the surrounding hadronic activity within a cone of size $R = 0.3$ satisfies $p_T(l)/(p_T(l) + p_T(\text{cone})) > 0.85$. We then cluster the rest of the particles in the event into $R = 0.5$ jets with the anti- k_T algorithm [68] using FASTJET [69], accepting only jets with $p_T(j) > 40$ GeV and $|\eta(j)| < 2.5$. At this stage, we simply count jets to define N_j and define the variable H_T as in equation [Eq. (2)].

⁸It is highly likely that the stops in fact hadronize before they decay, which effectively shields this color structure. However, we do not expect that these details have any impact on our results. We note that it is also possible to force the stop to decay to dijets within PYTHIA8 (and in principle in PYTHIA6), though we have not utilized this option.

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