

Large Jet Multiplicities and Natural Supersymmetry at the LHC

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We consider a search strategy for new physics at the Large Hadron Collider which focuses on the signature of many jets and missing transverse energy, but no charged leptons. We show that this signature can be useful in probing a wide class of models, including natural supersymmetry, in which dark matter is produced in conjunction top quarks. As an example, we apply this strategy to a simplified supersymmetric model with a light gluino, light stop and light neutralino. The efficacy of this strategy is comparable to (and in some cases better than) that of other strategies which require charged leptons and/or b -tagged jets.

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1. Introduction

There are several scenarios for new physics containing heavy QCD-charged particles which are also charged under a new unbroken discrete symmetry and which couple mostly to 3rd generation Standard Model matter [1]. The new heavy particles can be produced copiously at the Large Hadron Collider (LHC), and will necessarily decay to top/bottom quarks (due to $SU(3)$ gauge-invariance) and to the lightest particle charged under the discrete symmetry (which is a dark matter candidate).

An example which has drawn recent interest is *natural supersymmetry* [2], in which a top squark is relatively light, while other squarks are heavy. Natural supersymmetry is one way of reconciling relatively small fine-tuning with LHC constraints on the mass of 1st generation squarks. A characteristic feature of natural supersymmetry would be the pair-production of color-charged particles through QCD processes, with each new particle decaying to top quarks and missing transverse energy. It is thus vital to consider methods of probing these models with LHC data.

We consider a search strategy which selects events with a large number of jets (not necessarily b -tagged) and missing transverse energy, but no charged leptons [3] (see also [4, 5]). We will find that our search strategy is advantageous for this scenario of new physics. In particular, the charged lepton veto will remove Standard Model events where the missing transverse energy arises from W production followed by the leptonic decay $W \rightarrow l\nu$. After this veto, the dominant Standard Model background satisfying the jet and missing transverse energy cuts is top pair-production; since the background also contains b -jets, b -tagging is unnecessary. There are two main kinematic regimes, in which the energy of the new pair-produced particles emerges either with the visible particles, or as \cancel{E}_T . In the latter case, an elevated \cancel{E}_T -cut is useful.

2. An Example Supersymmetric Model

To implement our search strategy, we will consider an example model in which there is minimal flavor violation and the only light particles of the MSSM spectrum are the lightest neutralino (\tilde{N}_1), the lightest stop (\tilde{t}_1) and the gluino (\tilde{g}). In this case, the dominant sparticle production processes at the LHC are $pp \rightarrow \tilde{g}\tilde{g}$ and $pp \rightarrow \tilde{t}_1^*\tilde{t}_1$. Since all of couplings in the Feynman diagrams for these processes are determined by $SU(3)$ gauge-invariance, both production cross-sections are determined by the masses of the lightest stop ($m_{\tilde{t}_1}$) and the gluino ($M_{\tilde{g}}$). We will assume $m_{\tilde{t}_1} > m_t + M_{\tilde{N}_1}$, $M_{\tilde{g}} > 2m_t + M_{\tilde{N}_1}$.

Similarly, the sparticle decay chains are entirely determined by gauge-invariance, R-parity conservation, and minimal flavor violation. The allowed decay chains are $\tilde{t}_1 \rightarrow t\tilde{N}_1$ and $\tilde{g} \rightarrow \tilde{t}_1 \rightarrow \tilde{t}_1\tilde{N}_1$, where the decay rates are again entirely determined by the masses of the sparticles. Each hadronic top decay will produce three partons. Stop pair-production will nominally result in six jets, while gluino pair-production will nominally result in twelve jets.¹

For any point in our low-energy parameter space, a complete supersymmetric model is generated using SuSpect 2.41 [6]. Signal and background events are generated with MadGraph/MadEvent 5 and Pythia [7, 8]. PGS [9] is used to simulate detector effects. NLO corrections to the signal production cross-section are computed using Prospino [10], while NLO corrections to background cross-sections are estimated from results in the literature [11].

¹In conventional parlance, twelve jets constitutes a squadron.

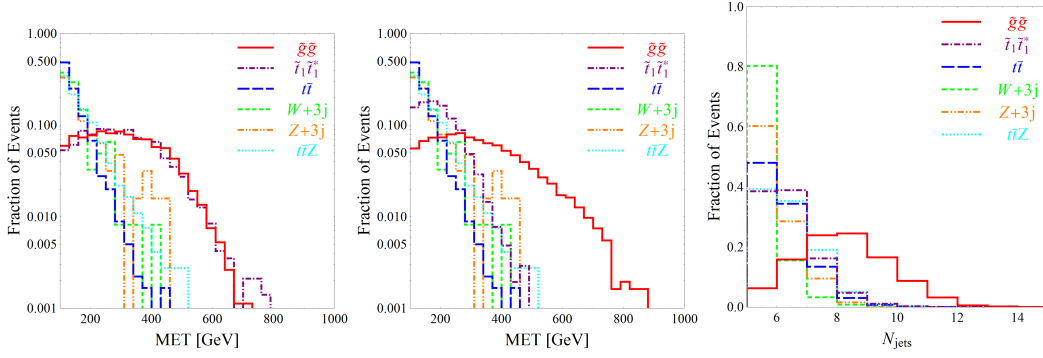


Figure 1: \cancel{E}_T -distribution (left and center) and jet distribution (right) for background and signal events (as labeled) passing the precuts. We assume $M_{\tilde{N}_1} = 100$ GeV, and either $M_{\tilde{g}} = 800$ GeV, $m_{\tilde{t}_1} = 600$ GeV (left), $M_{\tilde{g}} = 1200$ GeV, $m_{\tilde{t}_1} = 400$ GeV (center) or $M_{\tilde{g}} = 1000$ GeV, $m_{\tilde{t}_1} = 600$ GeV (right).

3. Event Selection

We begin with an initial set of cuts applied to all selected events

- No isolated e^\pm or μ^\pm in the final state, and at least five isolated jets ($p_T > 40$ GeV for each jet, $\Delta R_{jj} > 0.4$ for each pair of jets).
- At least 11.5° angular separation between the missing momentum direction and the 3 leading jets (this cut serves to remove QCD background events where missing transverse energy arises from jet mismeasurement [12]).
- $\cancel{E}_T > 100$ GeV

The leading contribution to Standard Model events passing these cuts are from W, Z +jets and $\bar{t}t$ (with either a mistagged lepton or a hadronically decaying τ). The $\bar{t}tZ$ background is also calculated, but is negligible.

In figure 1 we plot the \cancel{E}_T -distribution for signal and background events which satisfy these precuts. We assume $M_{\tilde{N}_1} = 100$ GeV and either $M_{\tilde{g}} = 800$ GeV, $m_{\tilde{t}_1} = 600$ GeV (left panel) or $M_{\tilde{g}} = 1200$ GeV, $m_{\tilde{t}_1} = 400$ GeV (center panel). We also plot the distribution of isolated jets for signal and background (right panel) in the case $M_{\tilde{g}} = 1000$ GeV, $m_{\tilde{t}_1} = 600$ GeV, $M_{\tilde{N}_1} = 100$ GeV. These distributions illustrate the key features which can be used in distinguishing signal from background. As the right panel shows, one expects many more jets from gluino pair-production than stop pair-production; gluino production is a prototype for models wherein the decay of new particles produces more than two t 's, and an elevated jet cut will be useful in distinguishing signal from background for such models.

The major remaining uncertainty lies in the kinematics of the heavy particle decay, which can yield energy mostly in the tops (and thus, the visible jets), or in \cancel{E}_T . The case $M_{\tilde{g}} = 800$ GeV, $m_{\tilde{t}_1} = 600$ GeV provides one example; the decay of the gluino produces a stop which is nearly at rest, but the stop decay produces an energetic neutralino. The case $M_{\tilde{g}} = 1200$ GeV, $m_{\tilde{t}_1} = 400$ GeV provides a different example; gluino production and subsequent decay produces a boosted stop and leads to a boosted neutralino, but stop production and subsequent decay produces a top and a neutralino nearly at rest.

A general feature which can be inferred is that larger mass splittings between particles in the decay chain lead to larger \cancel{E}_T , but the particular \cancel{E}_T -distribution is model-dependent. We thus find that, in addition to the precuts, it can be useful to elevate the cut on the number of jets (to search for models producing more than two tops) and/or elevate the \cancel{E}_T cut (to search for models whose decay chains produce boosted dark matter).

4. Discovery Potential

The discovery potential of this search strategy is shown in figure 2. Here we show signal significance contours in the $(m_{\tilde{t}_1}, M_{\tilde{g}})$ plane with 10 fb^{-1} of 7 TeV LHC data (we again assume $M_{\tilde{N}_1} = 100 \text{ GeV}$). The orange and red contours refer to 3σ and 5σ Gaussian equivalent significance, respectively. In the dark gray hashed region, there are fewer than 5 signal events. In the upper left panel, only the precuts are imposed. In the upper right panel, an additional $\cancel{E}_T > 300 \text{ GeV}$ cut is imposed. In the lower left panel, an additional cut on the number of jets, $N_j \geq 8$ is imposed. Finally, in the lower right panel, both additional cuts $\cancel{E}_T > 300 \text{ GeV}$ and $N_j \geq 8$ are imposed.

The general features of these cuts are evident from figure 2. In regions of parameter space where one can pair-produce particles whose decays yield more than two tops (i.e., when gluinos are accessible to the LHC), the elevated jet cut improves signal significance. In regions of parameter space where the decays of new particles yield energy in \cancel{E}_T ($M_{\tilde{g}} \gg m_{\tilde{t}_1} \gg M_{\tilde{N}_1}$), an elevated \cancel{E}_T is effective in distinguishing signal from background.

One can compare the detection prospects for this search strategy with those of other strategies [13, 14]. For example, a search for gluino pair-production using the channel with 1 charged lepton and 4 b -tagged jets was estimated to produce a 5σ -sensitivity for $M_{\tilde{g}}$ as large as 650 GeV with 1 fb^{-1} of data at 7 TeV [14]. For the same luminosity and center-of-mass energy, the search strategy discussed here is estimated to provide 5σ -sensitivity for $M_{\tilde{g}}$ as large as 720 GeV, thus indicating that this search strategy can be at least comparable to other strategies.

For an analysis involving a broad distribution of jets, one must worry about systematic uncertainties in the estimation of the background. This concern can be addressed by requiring that the ratio of signal events (S) to background events (B) be large enough. For all of the elevated cuts imposed in figure 2, we find $S/B > 0.1$. However, this constraint is not satisfied for the light stop mass region in the case where only the precuts are imposed. To control systematic uncertainties, it thus may be desirable to impose an additional cut to reduce background.

Our choices of elevated cuts ($N_j \geq 8$ and/or $\cancel{E}_T > 300 \text{ GeV}$) are optimized for a 7 TeV 10 fb^{-1} LHC run. For gluino pair-production, an even higher jet cut will improve S/B , but will reduce the number of signal events dramatically. For an LHC run with higher luminosity, a more elevated jet cut may be desirable. Similarly, for a run at higher energy, a more elevated \cancel{E}_T cut may be desirable.

5. Conclusion

Although this search strategy has been applied to the MSSM with minimal flavor violation and a particular mass spectrum (the only light sparticles are the gluino, lightest stop and lightest neutralino), its applicability is more general. This strategy can be effective for any model in which one can pair-produce new particles which decay primarily to tops and dark matter. The signature

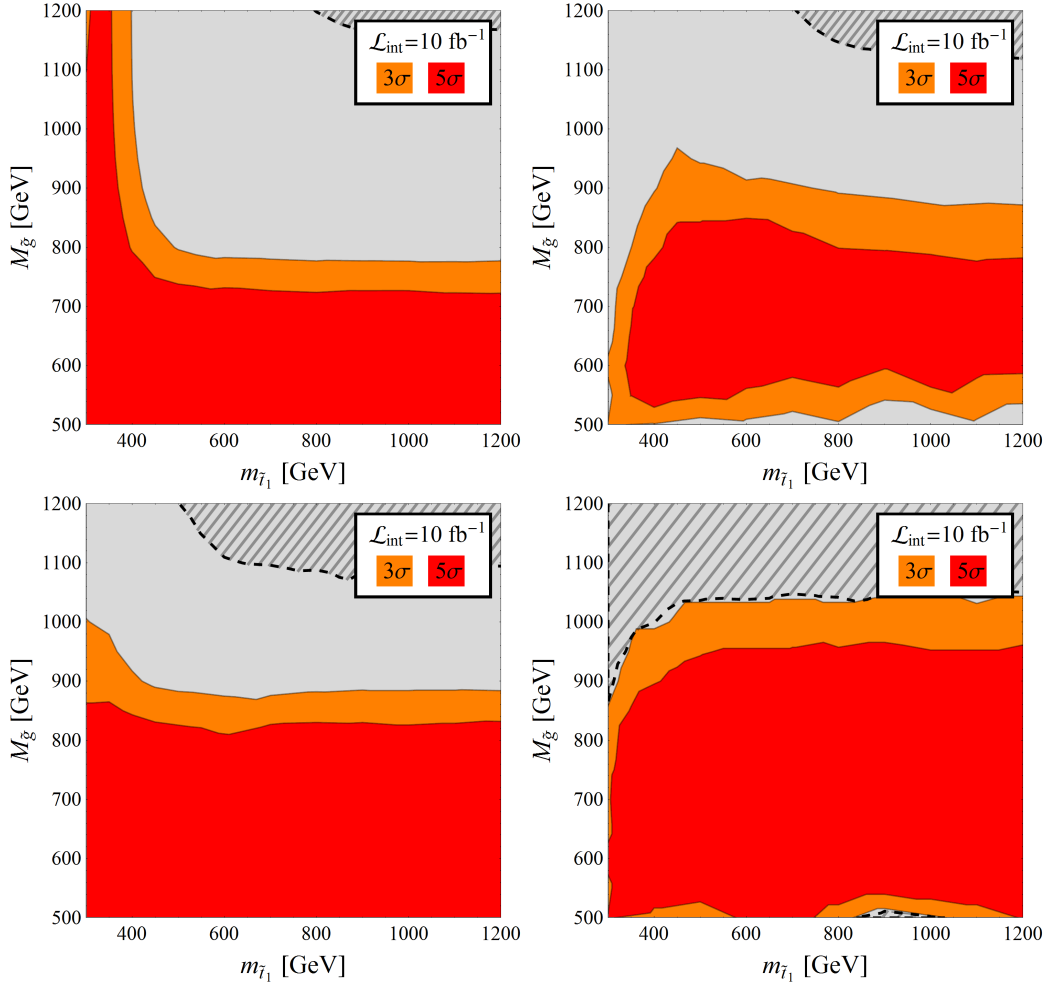


Figure 2: Signal significance contours (orange = 3σ , red = 5σ) in the $(m_{\tilde{t}_1}, M_{\tilde{g}})$ plane with $\mathcal{L}_{\text{int}} = 10 \text{ fb}^{-1}$ at the $\sqrt{s} = 7 \text{ TeV}$ LHC. For all panels, events must satisfy the precuts. Additional cuts which can be applied are $\cancel{E}_T > 300 \text{ GeV}$ (upper right), $N_j \geq 8$ (lower left), and $\cancel{E}_T > 300 \text{ GeV}$, $N_j \geq 8$ (lower right). In the dark gray hashed region bounded by the dashed contour, less than 5 signal events are expected.

is many jets, \cancel{E}_T , and no charged leptons. The charged lepton veto removes SM background events with \cancel{E}_T arising from $W \rightarrow l\nu$. An elevated cut on the number of jets can improve sensitivity to models which produce multiple tops from the decay of new heavy particles, while an elevated \cancel{E}_T cut can improve sensitivity to models wherein the kinematics of the decay chain favor the production of boosted dark matter. This strategy may be effective in natural SUSY searches.

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References

- [1] J. L. Feng and J. Kumar, Phys. Rev. Lett. **101**, 231301 (2008) [arXiv:0803.4196 [hep-ph]]; J. L. Feng, J. Kumar, and L. E. Strigari, Phys. Lett. B **670**, 37 (2008) [arXiv:0806.3746 [hep-ph]]; B. Dutta and

- J. Kumar, Phys. Lett. B **699**, 364 (2011) [arXiv:1012.1341 [hep-ph]]; P. Fileviez Perez and M. B. Wise, Phys. Rev. D **82**, 011901 (2010) [Erratum-ibid. D **82**, 079901 (2010)] [arXiv:1002.1754 [hep-ph]]; T. R. Dulaney, P. Fileviez Perez, and M. B. Wise, Phys. Rev. D **83**, 023520 (2011) [arXiv:1005.0617 [hep-ph]].
- [2] M. Dine, A. Kagan and S. Samuel, Phys. Lett. B **243**, 250 (1990); A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Lett. B **388**, 588 (1996) [hep-ph/9607394]; H. Baer, S. Kraml, A. Lessa, S. Sekmen and X. Tata, JHEP **1010**, 018 (2010) [arXiv:1007.3897 [hep-ph]]; D. Feldman, G. Kane, E. Kuflik and R. Lu, Phys. Lett. B **704**, 56 (2011) [arXiv:1105.3765 [hep-ph]]; H. Baer, V. Barger, P. Huang and X. Tata, JHEP **1205**, 109 (2012) [arXiv:1203.5539 [hep-ph]].
- [3] J. Bramante, J. Kumar and B. Thomas, Phys. Rev. D **86**, 015014 (2012) [arXiv:1109.6014 [hep-ph]].
- [4] J. Alwall, J. L. Feng, J. Kumar, and S. Su, Phys. Rev. D **81**, 114027 (2010) [arXiv:1002.3366 [hep-ph]]; T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, arXiv:1103.4160 [hep-ph]; T. Li, J. A. Maxin, D. V. Nanopoulos, and J. W. Walker, arXiv:1108.5169 [hep-ph].
- [5] V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **660**, 449 (2008) [arXiv:0712.3805 [hep-ex]]; T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **102**, 121801 (2009) [arXiv:0811.2512 [hep-ex]]; T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **105**, 131801 (2010) [arXiv:0912.4691 [hep-ex]]; V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **698**, 196 (2011) [arXiv:1101.1628 [hep-ex]]; J. B. G. da Costa *et al.* [Atlas Collaboration], Phys. Lett. B **701**, 186 (2011) [arXiv:1102.5290 [hep-ex]]; ATLAS-COCONF-2011-086. ATLAS Collaboration, ATLAS-COCONF-2011-086; S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1109.2352 [hep-ex]; G. Aad *et al.* [Atlas Collaboration], JHEP **1111**, 099 (2011) [arXiv:1110.2299 [hep-ex]].
- [6] A. Djouadi, J. L. Kneur, and G. Moultaka, Comput. Phys. Commun. **176**, 426 (2007) [arXiv:hep-ph/0211331].
- [7] J. Alwall *et al.*, JHEP **0709**, 028 (2007) [arXiv:0706.2334 [hep-ph]].
- [8] T. Sjostrand, S. Mrenna, and P. Skands, JHEP **0605**, 026 (2006) [arXiv:hep-ph/0603175].
- [9] “PGS – Pretty Good Simulator”, <http://www.physics.ucdavis.edu/~conway/research/software/pgs/pgs4-general.html>
- [10] W. Beenakker, R. Hopker, M. Spira, and P. M. Zerwas, Nucl. Phys. B **492**, 51 (1997) [arXiv:hep-ph/9610490]; W. Beenakker, M. Kramer, T. Plehn, M. Spira, and P. M. Zerwas, Nucl. Phys. B **515**, 3 (1998) [arXiv:hep-ph/9710451].
- [11] J. M. Campbell, J. W. Huston, and W. J. Stirling, Rept. Prog. Phys. **70**, 89 (2007) [arXiv:hep-ph/0611148]; Z. Bern *et al.* [NLO Multileg Working Group], arXiv:0803.0494 [hep-ph]; A. Lazopoulos, T. McElmurry, K. Melnikov, and F. Petriello, Phys. Lett. B **666**, 62 (2008) [arXiv:0804.2220 [hep-ph]]; C. F. Berger *et al.*, Phys. Rev. D **80**, 074036 (2009) [arXiv:0907.1984 [hep-ph]]; C. F. Berger *et al.*, Nucl. Phys. Proc. Suppl. **205-206**, 92 (2010) [arXiv:1005.3728 [hep-ph]].
- [12] V. M. Abazov *et al.* [D0 Collaboration], Phys. Lett. B **638**, 119 (2006) [arXiv:hep-ex/0604029]; ATLAS Collaboration, ATL-PHYS-PUB-2009-084.
- [13] M. Toharia, J. D. Wells, JHEP **0602**, 015 (2006) [hep-ph/0503175]; P. Meade and M. Reece, Phys. Rev. D **74**, 015010 (2006) [arXiv:hep-ph/0601124]; T. Han, R. Mahbubani, D. G. E. Walker, and L. T. E. Wang, JHEP **0905**, 117 (2009) [arXiv:0803.3820 [hep-ph]]; B. S. Acharya, P. Grajek, G. L. Kane, E. Kuflik, K. Suruliz, and L. T. Wang, arXiv:0901.3367 [hep-ph].
- [14] G. L. Kane, E. Kuflik, R. Lu and L. -T. Wang, Phys. Rev. D **84**, 095004 (2011) [arXiv:1101.1963 [hep-ph]].