Large Jet Multiplicities and New Physics at the LHC

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Abstract

A broad class of scenarios for new physics involving additional strongly-interacting fields generically predict signatures at hadron colliders which consist solely of large numbers of jets and substantial missing transverse energy. In this work, we investigate the prospects for discovery in such scenarios using a search strategy in which jet multiplicity and missing transverse energy are employed as the primary criteria for distinguishing signal from background. We examine the discovery reach this strategy affords in an example theory (a simplified supersymmetric model whose low-energy spectrum consists of a gluino, a light stop, and a light neutralino) and demonstrate that it frequently exceeds the reach obtained via other, alternative strategies.

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I. INTRODUCTION

Determining how to identify and interpret signals of new physics within a rapidly accumulating store of LHC data has become one of the primary challenges for particle phenomenology of late. Particular attention has been focused on those signals which can be resolved within the first few fb$^{-1}$ of integrated luminosity. For example, a great deal of attention has been focused on signals which arise in the presence of new particles charged under the Standard-Model (SM) gauge group $SU(3)_c$. Such particles can be produced copiously at hadron colliders via strong interactions, and once produced, each is required by $SU(3)_c$ invariance to decay down to a final state including one or more SM quarks or gluons. As a result, theories which predict new strongly-interacting particles frequently lead to excesses in multi-jet events — excesses which can only be resolved above the sizeable SM QCD background via the application of astutely chosen event-selection criteria.

One commonly employed search strategy for resolving signals of new physics in multi-jet events at hadron colliders is to search for multi-jet resonances arising from the decay of new strongly-interacting particles. Indeed, the utility of this strategy has been demonstrated in a variety of beyond-the-Standard-Model (BSM) contexts \cite{1-3}, and has recently been implemented, for example, in the trijet searches conducted by the CDF \cite{4} and CMS \cite{5} collaborations.

Another strategy which can assist in resolving signals of new physics in multi-jet events is to search for events with substantial missing transverse energy $\not{E}_T$. This strategy is relevant for extensions of the SM which include not only additional fields charged under $SU(3)_c$, but also a stable massive particle which can serve as a dark-matter candidate. In traditional single-particle dark-matter models, the stability of the dark matter particle is frequently guaranteed by charging that particle under some additional symmetry, such as R-parity in supersymmetric theories, KK-parity \cite{6} in models with universal extra dimensions \cite{7-9}, or T-parity \cite{10} in little-Higgs theories \cite{11}. When other, heavier particles charged under the same symmetry are produced at colliders, each of these particles ineluctably decays to a final state including one or more dark-matter particles; hence dark-matter models of this sort generically predict signatures involving a substantial amount of missing transverse energy. By contrast, only a minute fraction of events produced by pure QCD processes, which provide the dominant SM background for multi-jet events, include substantial $\not{E}_T$. Missing transverse energy therefore provides a useful discriminant between signal and background for multi-jet events in extensions of the SM which include both new strongly-interacting fields and a stable dark-matter candidate. Indeed, a variety of new physics models (see, \textit{e.g.}, Ref. \cite{10,12}) involving such a dark-matter candidate predict signatures involving high-$p_T$ jets plus $\not{E}_T$, and searches in these channels have been performed both at the Tevatron \cite{13,14} and at the LHC \cite{15,16}. Moreover, even in alternative dark-matter scenarios which do not include a single, stable dark-matter candidate \cite{19}, the jets + $\not{E}_T$ channel can still play an important role as a probe of new physics.

It is important to recognize, however, that while a broad class of new-physics models generically give rise to signals involving multiple high-$p_T$ jets and $\not{E}_T$, the optimal strategy for identifying such signals may differ — even qualitatively — from model to model. One notable example of a situation for which typical search strategies are not the most efficacious and for which the limits obtained with such strategies are not directly applicable is one in which the additional strongly-interacting fields in the theory decay preferentially to SM states involving third-generation quarks — and in particular top quarks. Such “top-rich”
scenarios give rise to a variety of distinctive signatures involving not only substantial $E_T$, but also large jet multiplicities, and can therefore be probed quite effectively by selecting events based on the observed number of jets appearing in the final state. We note, however, that top-rich scenarios also exist for which the characteristic event topologies involve large numbers top quarks, but no $E_T$. For such models, alternative search strategies [20] are required.

A number of recent studies have assessed the prospects for detecting signals of new physics in top-rich scenarios which give rise to the specific event topologies $t\bar{t} + E_T$ [21, 22] and $tt\bar{t} + E_T$ [23–25]. Most of these studies have focused on the case where at least one of the top quarks decays leptonically, in which case the presence of one or more charged leptons in the final state may be used to differentiate signal events from events associated with the SM QCD background. This approach has been fruitful in other extensions of the SM which give rise to large-jet-multiplicity events as well. For example, many general supersymmetry (SUSY) searches are based on the production of color-charged superpartners which have complex decay chains, producing leptons in addition to substantial numbers of jets and missing energy.

In this paper, we examine an alternative possibility for resolving signals of new physics from the SM background in scenarios characterized by large jet multiplicities. We focus on the fully hadronic channel (i.e., on events in which no high-$p_T$ charged leptons appear in the detector), and select events primarily on the basis of two criteria: the number $N_j$ of high-$p_T$ jets in the event and the total missing transverse energy $E_T$. There are many advantages to this approach. Focusing on hadronic events permits the imposition of a charged-lepton veto which can significantly suppress the sizeable SM backgrounds from $t\bar{t} +$ jets and $W +$ jets events involving one or more leptonically-decaying $W$ bosons. These events often contain substantial missing transverse energy, due to the presence of one or more neutrinos in the final state, and consequently a substantial number of such events survive the stringent $E_T$ cut designed to eliminate the QCD background. Focusing on jet number as the primary discriminant between signal and background is advantageous as it does not rely on top reconstruction, $b$-tagging, or other techniques for top-quark identification whose efficiency factors result in a sizable suppression in signal-event count. Furthermore, the theoretical implications of searches in purely hadronic channels are generally less ambiguous than those in channels including charged leptons, simply because conclusions drawn from hadronic searches usually require fewer assumptions about the electroweak couplings of new particles appearing in the decay chains initiated by the decay of the strongly-interacting particles initially produced. Indeed, charged leptons can be produced in such decay chains in a variety of ways, and reconstructing the structure of such decay chains is notoriously difficult.

For these reasons and others, we claim that searching for events with large jet multiplicities and substantial $E_T$ is generically one of the most promising methods for identifying new physics which gives rise top-rich event topologies at hadron colliders. Precedents for an analysis of this sort do exist in the literature in the context of particular models which give rise to top-rich event topologies, and it is encouraging to note that our claim is borne out in these cases. In Ref. [22], for example, the authors investigated the discovery potential for new physics in a model containing an exotic quark $T'$ which decays directly to a top quark and a dark-matter particle with a branching fraction of effectively unity. They showed that the best prospects for resolving a signal from the characteristic $t\bar{t} + E_T$ event topology which results from the pair-production of such an exotic quark were indeed obtained in the fully hadronic channel when minimum cuts on $E_T$ and the number of jets $N_j$ in any particular
event were used as the primary event-selection criteria. This approach is likewise supported by the results of Ref. [26, 27], in which it was demonstrated that the fully hadronic channel provides the best prospects for observing signs of new physics in the context of no-scale $\mathcal{F} - SU(5)$ models after stringent cuts on $N_j$ and $E_T$ are imposed. We observe that many of the analysis techniques pioneered in these works for obtaining signals of new physics in these models are in fact applicable to a broad class of BSM theories which predict signatures with large jet multiplicities and substantial missing transverse energy.

In order to demonstrate the potency of this technique for uncovering new physics, we investigate prospects for observing a signal of new physics in the context of a simplified model [28] whose field content includes a color-octet fermion, a color-triplet scalar, and a color-singlet fermion which plays the role of the dark-matter particle. The canonical context in which such a simplified model arises is that of supersymmetric models in which the only sparticles light enough to be accessible at the LHC include the gluino $\tilde{g}$, a single, predominately right-handed stop $\tilde{t}_1$, and a bino-like neutralino $\tilde{N}_1$. For this reason, in the remainder of this work we refer to the color-octet fermion as the gluino $\tilde{g}$, the color-triplet scalar as the lighter stop $\tilde{t}_1$, and the color-singlet fermion as the lightest neutralino $\tilde{N}_1$. However, we emphasize that this analysis is applicable to any scenario for new physics whose low-energy effective description involves the same field content. Our results can also be readily adapted to a wide variety of qualitatively similar models via an appropriate rescaling of the pair-production cross-sections and decays widths of the particles involved.

The outline of this paper is as follows. In Sect. II we review the production and decay properties of the gluino and lightest stop in our simplified model and discuss the top-rich event topologies to which the model gives rise. In Sect. III we discuss the current limits on stop and gluino masses from Tevatron and LHC data, taking care to distinguish between those bounds which apply only when the masses of the first- and second-generation squarks are light and those which apply even in the limit in which those masses are taken to infinity. In Sect. V we enumerate the Standard Model backgrounds for a high-jet-multiplicity signal with substantial $E_T$, and outline the program of event-selection criteria we employ in distinguishing such a signal from those backgrounds. In Sect. VI we present our results for the LHC detection prospects for our simplified model and discuss how these results may be extended to other, related scenarios which likewise give rise to top-rich event topologies. Finally, in Sect. VII we conclude.

II. LARGE JET MULTIPlicITIES FROM TOP-RICH EVENT TOPOLOGIES

As discussed in the introduction, the primary purpose of this paper is to examine the prospects for observing signals of new physics in extensions of the SM which give rise to final states involving large numbers of high-$p_T$ jets plus missing transverse energy. The search strategies employed here should be applicable to a broad class of models. However, in order to assess the detection prospects afforded by these search strategies within the first few $fb^{-1}$ of integrated luminosity at the LHC and to compare them to those afforded by other, alternative strategies, we choose to focus on a particular toy theory involving a subset of the field content of the minimal supersymmetric Standard Model (MSSM) as an example. In this simplified supersymmetric model, the only strongly-interacting particles light enough to be relevant for LHC physics are the gluino $\tilde{g}$ and a single, effectively right-handed stop $\tilde{t}_1 \approx \tilde{t}_R$. In other words, this simplified model represents the limit in which all of the other squarks (hereafter collectively referred to here as $\tilde{q}$) are taken to be heavy
and decoupled. The only other particle in the low-energy spectrum of the theory is a light, bino-like neutralino $\tilde{N}_1 \approx \tilde{B}$. We take this neutralino to be the LSP in what follows — i.e., we assume that $M_{\tilde{g}}, m_{\tilde{t}_1} > m_{\tilde{N}_1}$.

One of the primary advantages of adopting this toy scenario as an arena in which to study large-jet-multiplicity physics is that the decay behavior of both $\tilde{g}$ and $\tilde{t}_1$ is particularly simple. Under the assumption of minimal flavor violation, $\tilde{t}_1$ decays almost exclusively via $\tilde{t}_1 \rightarrow t\tilde{N}_1$ as long as this channel is kinematically open. Similarly, $\tilde{g}$ decays almost exclusively through $\tilde{g} \rightarrow \tilde{t}_1 t \rightarrow t\tilde{N}_1$ and the conjugate process, where the stop may be real or virtual, depending on the relationship between $M_{\tilde{g}}$ and $m_{\tilde{t}_1}$. As a consequence of this simple decay phenomenology, each production process which contributes to the signal event rate in the jets + $E_T$ channel is characterized by a distinctive distribution of jet multiplicities. This toy model therefore provides an excellent venue in which to assess the merits and drawbacks of any given event-selection strategy for a variety of qualitatively different production and decay scenarios by scanning over the model-parameter space. Thus the results we obtain here should be applicable in a wide variety of models for BSM physics.

This notwithstanding, it is important to emphasize that the collider phenomenology of supersymmetric models in which the $\tilde{q}$ are heavy and decoupled (and their phenomenology in the fully hadronic channel in particular) differs from that in which the $\tilde{q}$ have TeV-scale masses in a number of aspects — even in scenarios which involve the the same sparticle-mass hierarchy $m_{\tilde{q}} > M_{\tilde{g}}, m_{\tilde{t}_1} > M_{\tilde{N}_1}$ on which we focus in this analysis. As we shall stress in Sect. 111 many of the extant bounds on sparticle masses (and on $M_{\tilde{g}}$ in particular) do not apply — or are at least considerably weakened — in situations in which the first- and second-generation squark masses lie well above the TeV scale. It therefore behooves us, before we move on to address $\tilde{q}$ and $\tilde{t}_1$ production and decay in our toy theory, to highlight the differences between theories with and without light squarks from the perspective of multi-jet collider phenomenology.

The first significant distinction to be drawn between these two classes of models lies in the types of production processes which contribute non-trivially to the total event rate in the jets + $E_T$ channel. In models in which the $\tilde{q}$ are decoupled, there are only two such processes $pp \rightarrow \tilde{q}\tilde{q}$ and $pp \rightarrow \tilde{t}_1 \tilde{t}_1^*$. Indeed, the only other contributions are those from $pp \rightarrow \tilde{g}\tilde{t}_1$ and its conjugate process. Under the assumption of minimal flavor violation, these contributions are suppressed by small off-diagonal elements in the Cabibbo-Kobayashi-Maskawa (CKM) matrix and may be safely neglected. By contrast, in models with light $\tilde{q}$, additional pair-production processes such as $pp \rightarrow \tilde{q}\tilde{q}$ and $pp \rightarrow \tilde{q}\tilde{q}^*$ also contribute. As a result, the $N_j$ and $E_T$ distributions which result from such models can differ significantly from those which result from models in which the $\tilde{q}$ are decoupled.

A second difference between these two classes of models arises from the effect of the light $\tilde{q}$ on the cross-sections for those multi-jet-production processes which occur in both sorts of models. In models in which the $\tilde{q}$ are heavy and decoupled (again assuming minimal flavor violation), only a limited number of Feynman diagrams contribute to $pp \rightarrow \tilde{q}\tilde{q}$ and $pp \rightarrow \tilde{t}_1 \tilde{t}_1^*$. These diagrams are displayed in Fig. 1. By contrast, in models in which one or more of the first- and second-generation squarks are light, additional diagrams involving the $t$-channel exchange of such squarks also contribute, and the inclusion of these additional diagrams results in an often significant modification of the production cross-section for $pp \rightarrow \tilde{g}\tilde{g}$ relative to that obtained in the decoupled-squark limit.

A third significant difference between the collider phenomenologies associated with decoupled and non-decoupled scenarios arises from differences in the decay properties of the
FIG. 1: Feynman diagrams associated with the processes relevant for \( \tilde{g} \) and \( \tilde{t}_1 \) pair-production in the limit in which all other squarks are taken to be heavy and decoupled.

gluino in these two scenarios. In the limit in which the \( \tilde{q} \) are decoupled, all decay chains initiated by \( \tilde{g} \) decay necessarily involve \( \tilde{t}_1 \) (which can be either real or virtual, depending on the relationship between \( M_{\tilde{g}} \) and \( m_{\tilde{t}_1} \)), and hence lead to the production of a top-antitop pair. Consequently, all fully hadronic final states resulting from the \( pp \to \tilde{g}\tilde{g} \) process will necessarily include at least twelve “jets” (i.e., quarks or gluons) at the parton level. However, this is generally not the case for models in which one or more of the \( \tilde{q} \) are light enough to affect the decay phenomenology of \( \tilde{g} \). In particular, in those scenarios in which \( m_{\tilde{t}_1} > M_{\tilde{g}} \), and thus no two-body decay channels are open for the gluino, the branching fractions for three-body gluino-decay processes involving virtual \( \tilde{q} \) (such as \( \tilde{g} \to q\tilde{q}'N_1 \), where \( q \) denotes any light quark) can be significant. As a consequence, the expected jet multiplicities from the \( pp \to \tilde{g}\tilde{g} \) process in the fully hadronic channel can often be substantially lower in these scenarios than in those in which the \( \tilde{g} \) are decoupled. Furthermore, as discussed above, other processes such as \( pp \to \tilde{g}\tilde{q} \) and \( pp \to \tilde{q}\tilde{q}^* \) also contribute to the overall event rate in the jets + \( E_T \) channel in such models, and therefore must be taken into account when assessing their discovery potential via the search strategies outlined here.

On a related note, it is also worth reiterating that while we refer to the BSM fields in our toy theory as the gluino, stop, and neutralino, we adopt this terminology only for sake of convenience and to make contact with experimental limits extant in the literature. Indeed, this scenario may simply be viewed as a model whose additional field content consists of a fermionic \( SU(3)_c \) octet, a scalar \( SU(3)_c \) triplet, and a neutral, color-singlet fermion which plays the role of the dark-matter particle (assuming that all three are charged under a new unbroken symmetry). Indeed, in any such model, gauge-invariance and the assumption that the new particles couple dominantly to top quarks mandate that the decay phenomenology of the model be essentially the same. Our analysis therefore applies to any theory with the same field content and charge assignments, whether or not that theory arises in the context of supersymmetry.

Having highlighted some of the salient differences between our example model and other, similar models, let us now turn to examine its multi-jet phenomenology. As discussed above, the only contributions to the total event rate in the jets + \( E_T \) channel in this model arise due to gluino-pair and stop-pair production. The cross-sections for the partonic gluino-
production processes $gg \rightarrow \tilde{g}\tilde{g}$ and $q\bar{q} \rightarrow \tilde{g}\tilde{g}$ are given at leading order (LO) by [29, 30]

$$
\hat{\sigma}_{q\bar{q} \rightarrow \tilde{g}\tilde{g}}(\hat{s}) = \frac{8\pi\alpha_s^2}{9\hat{s}} \left( 1 + \frac{2M_g^2}{\hat{s}} \right) R
$$

$$
\hat{\sigma}_{gg \rightarrow \tilde{g}\tilde{g}}(\hat{s}) = \frac{3\pi\alpha_s^2}{4\hat{s}} \left[ 3 \left( 1 + \frac{4M_g^2}{\hat{s}} - \frac{4M_g^2}{\hat{s}^2} \right) \ln \left( \frac{1 + R}{1 - R} \right) - \left( 4 + \frac{17M_g^2}{\hat{s}} \right) R \right], \tag{1}
$$

where

$$
R \equiv \sqrt{1 - \frac{4M_g^2}{\hat{s}}}. \tag{2}
$$

Similarly, the partonic cross-sections for the corresponding stop-pair production processes are given by [29]

$$
\hat{\sigma}_{q\bar{q} \rightarrow \tilde{t}_1\tilde{t}_1^*}(\hat{s}) = \frac{2\pi\alpha_s^2}{27\hat{s}} \hat{s}^3
$$

$$
\hat{\sigma}_{gg \rightarrow \tilde{t}_1\tilde{t}_1^*}(\hat{s}) = \frac{\pi\alpha_s^2}{6\hat{s}^2} \left[ \left( \frac{5}{8} + \frac{31m_{t_1}^2}{4\hat{s}} \right) \hat{s} S - \left( 4 + \frac{m_{t_1}^2}{\hat{s}} \right) m_{t_1}^2 \ln \left( \frac{1 + S}{1 - S} \right) \right], \tag{3}
$$

where

$$
S \equiv \sqrt{1 - \frac{4m_{t_1}^2}{\hat{s}}}. \tag{4}
$$

In Fig. [2], we indicate how the total (LO) cross-sections $\sigma_{pp \rightarrow \tilde{g}\tilde{g}}$ and $\sigma_{pp \rightarrow \tilde{t}_1\tilde{t}_1^*}$ for gluino- and stop-pair production at the $\sqrt{s} = 7$ TeV LHC behave as functions of $M_g$ and $m_{t_1}$. The curves appearing in this figure were obtained by convolving the partonic cross-section formulae in Eqs. [1] and [3] with the CTEQ6L1 [31] parton-distribution function (PDF) set and approximating the running of $\alpha_s$ using the relation

$$
\alpha_s(Q) = \alpha_s(M_Z) \left[ 1 + \frac{\alpha_s(M_Z)}{12\pi} \left[ 23 - 2\Theta(Q^2 - m_{t_1}^2) \ln \left( \frac{Q^2}{m_{t_1}^2} \right) - 6\Theta(Q^2 - M_g^2) \ln \left( \frac{Q^2}{M_g^2} \right) \right] \right]^{-1}, \tag{5}
$$

where $\Theta(x)$ is the Heaviside theta function, $Q$ is the energy scale at which the coupling is being evaluated, and $m_t$ is the top-quark mass (taken here to be $m_t = 172$ GeV). The fiducial value $\alpha_s(M_Z) = 0.130$ assigned to $\alpha_s$ at the weak scale was chosen to accord with the definition in the CTEQ6L1 PDF set.

Since next-to-leading order (NLO) corrections to the cross-sections for both $pp \rightarrow \tilde{g}\tilde{g}$ and $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$ production can be quite significant, it is important to account for the effects of such corrections. In this analysis, we approximate these effects by scaling our leading-order results for $\sigma_{pp \rightarrow \tilde{g}\tilde{g}}$ and $\sigma_{pp \rightarrow \tilde{t}_1\tilde{t}_1^*}$ by the overall multiplicative factors $K_{\tilde{g}\tilde{g}}^{\text{NLO}}$ and $K_{\tilde{t}_1\tilde{t}_1^*}^{\text{NLO}}$, which incorporate the effects of both NLO modifications. The NLO K-factors $K_{\tilde{g}\tilde{g}}^{\text{NLO}}$ and $K_{\tilde{t}_1\tilde{t}_1^*}^{\text{NLO}}$ were evaluated for each combination of $M_g$ and $m_{t_1}$ included in our analysis using the Prospino package [32]. While the K-factor formalism employed here does not account for
FIG. 2: Total LO cross sections $\sigma_{pp\rightarrow \tilde{g}\tilde{g}}$ (solid curve) and $\sigma_{pp\rightarrow \tilde{t}_1\tilde{t}_1}$ (dashed curve) at the $\sqrt{s} = 7$ TeV LHC in the limit in which all other squark masses are taken to infinity.

FIG. 3: The NLO $K$-factors for gluino-pair production (left panel) and stop-pair production (right panel) at a $\sqrt{s} = 7$ TeV LHC, shown as a function of the gluino mass $M_{\tilde{g}}$ and stop mass $m_{\tilde{t}_1}$, respectively. The results shown assume that all other squarks $\tilde{q}$ are infinitely heavy and decoupled. The different curves in the right panel correspond to different choices of $M_{\tilde{g}}$.

changes in kinematical distributions of the decay products of the gluino, some information on how these distributions are affected at NLO can be found in Ref. [34]. In this analysis, we do not include the effect of next-to-leading-log (NLL) corrections to these process from soft-gluon radiation, but we note that these corrections can provide an additional contribution as high as $O(20\%)$ [33] to the total production cross-section in some cases.
III. CURRENT CONSTRAINTS

A variety of new-physics searches both at the Tevatron and at the LHC place constraints on extensions of the SM involving new strongly-interacting fields in general and on supersymmetric models in particular. However, it should be stressed that many of these constraints are predicated on particular assumptions about the field content, mass spectrum, etc., of the scenario in question. For this reason, many oft-quoted bounds on the masses of new strongly-interacting fields are not directly applicable to scenarios in which those fields decay primarily to states involving top quarks. For example, the ATLAS collaboration has searched for evidence of squark and gluino production in final states involving one isolated charged lepton, at least three high-\(p_T\) jets (with no \(b\)-tagging requirement) and missing energy \[35\]. The results of this search, interpreted in the context of the constrained minimal supersymmetric Standard Model (CMSSM) with \(A_0 = 0\), \(\mu > 0\) and \(\tan \beta = 3\), yield the constraint \(M_{\tilde{g}} \geq 700\) GeV. However, the results of this analysis are not directly applicable to the simplified supersymmetric model introduced in Sect. II. First of all, a number of additional decay channels are open for squarks and gluinos in the CMSSM which yield final-state leptons beyond those produced from top decay. Moreover, the \(\tilde{q}\) generally play a significant role in the collider phenomenology of CMSSM models, whereas in this simplified model, such squarks play no role whatsoever in collider phenomenology by construction.

In addition to this ATLAS study, results from a number of searches conducted at both the Tevatron and the LHC in the jets + \(E_T\) channel can be used to constrain the parameter space of the supersymmetric models. A recent CDF study \[14\], performed at an integrated luminosity of 2 \(fb^{-1}\), used the results of such a search to constrain the parameter space of minimal supergravity (mSUGRA). In the \(m_{\tilde{q}} \gg m_{\tilde{g}}\) limit (in which only gluino-pair production dominates the signal rate in this channel) with the mSUGRA parameter assignments \(\mu < 0\), \(A_0 = 0\), and \(\tan \beta = 5\), the results of this study place a lower bound \(M_{\tilde{g}} > 280\) GeV on the gluino mass. A DØ search performed at a similar integrated luminosity \[13\] and with similar mSUGRA parameter choices obtained a similar bound \(M_{\tilde{g}} > 308\) GeV. An analogous study has also been performed by the CMS collaboration \[15\] at \(L_{\text{int}} = 35\) \(pb^{-1}\). Once again, these results are not directly applicable to the simplified model on which we focus here, since the sparticle-mass spectra and decay phenomenologies of these constrained models differ considerably from those obtained for \(M_{\tilde{g}}, m_{\tilde{t}_1} > \tilde{N}_1\), with all additional sparticles heavy and decoupled.

It should be noted that squark and gluino searches which do not assume a CMSSM or mSUGRA sparticle spectrum have also been performed at the LHC. Such a search was recently performed by the ATLAS collaboration in the jets + \(E_T\) channel with 165 \(pb^{-1}\) of integrated luminosity \[17\]. In this analysis, the third-generation squarks were taken to be extremely heavy, while the first- and second-generation squarks were permitted to be sufficiently light so as to be potentially accessible at the LHC. For simplicity, the lightest neutralino was treated as massless. For the case in which the squarks of the first two generations are also reasonably heavy, with masses of around 2 TeV, a lower bound \(M_{\tilde{g}} \geq 725\) GeV on the gluino mass was obtained. However, this result is not directly applicable to the simplified model considered here either. As discussed in Sect. II, the production rates and decay properties of first- and second-generation squarks differs considerably from that of \(\tilde{t}_1\). Thus, in scenarios in which such squarks are light, the decay phenomenology of the gluino in such scenarios is considerably different.

A number of new-physics searches are directly applicable to top-rich scenarios of this sort,
however, and the results of these searches meaningfully constrain $M_\tilde{g}$ and $m_{\tilde{t}_1}$ in our example scenario. One example is the recent search performed by the ATLAS collaboration [36] at an integrated luminosity of 35 pb$^{-1}$. The results of the analysis, which focused on events containing one lepton and two high-$p_T$ jets (one of which was required to be $b$-tagged), serve to constrain $M_\tilde{g}$ in supersymmetric models in which stop- and gluino-pair production are the only signal processes relevant in early running. For stop masses in the range $130$ GeV $\lesssim m_{\tilde{t}_{1,2}} \lesssim 300$ GeV, the collaboration obtained a limit $M_\tilde{g} \geq 520$ GeV on the gluino mass. An experimental bound on $m_{\tilde{t}_1}$ can likewise be derived from the results of a recent CDF search [37] for an exotic color-triplet fermion $\psi$ which decays preferentially to a top quark and a scalar dark-matter candidate $\chi$. That the collaboration found no evidence of $pp \rightarrow \psi \overline{\psi} \rightarrow t\overline{t} + E_T$ production in the semileptonic channel implies a bound $m_\psi \geq 360$ GeV on the mass of such a fermion, assuming $m_\chi \leq 100$ GeV. By taking into account the difference between the pair-production cross-sections for scalars and fermions, one can translate this bound into a rough lower limit $m_{\tilde{t}_1} \gtrsim 260$ GeV on the mass of the lightest stop (or indeed any color-triplet scalar with similar decay properties), under the same assumption about $m_\chi$. A similar search performed by the Atlas collaboration [38] (also in the semileptonic channel) at an integrated luminosity of 35 pb$^{-1}$ implies the constraints $m_\psi \geq 275$ GeV and $m_\psi \geq 300$ GeV for $m_\chi = 50$ GeV and $m_\chi = 10$ GeV, respectively. Again accounting for the difference in production cross-section between scalars and fermions, these bound can be translated into the rough limits $m_{\tilde{t}_1} \gtrsim 190$ GeV and $m_{\tilde{t}_1} \gtrsim 215$ GeV for the corresponding choices of $m_\chi$. A recent update with 1.04 fb$^{-1}$ of integrated luminosity [39] has elevated this lower limit to $m_{\tilde{t}_1} \gtrsim 270$ GeV for $m_\chi = 10$ GeV.

Finally, CDF [40] and DØ [41] have also performed searches for evidence of stop-pair production in the fully leptonic channel at an integrated luminosity of 1 fb$^{-1}$. The non-observation of a signal at either experiment implies a bound $m_{\tilde{t}_1} \geq 180$ GeV (assuming that the dark matter particle is lighter than 100 GeV). CDF has conducted another search [42] at $L_{\text{int}} = 2.7$ fb$^{-1}$ for $t\overline{t}^*$ production followed by the decay $t \rightarrow b\chi^\pm \rightarrow b\ell\nu\chi_1^\pm$. The results of this search imply a limit $m_{\tilde{t}_1} \geq 150 - 185$ GeV, depending both on the branching fractions involved and on the chargino and neutralino masses.

As the results quoted above attest, the bounds on $M_\tilde{g}$ and $m_{\tilde{t}_1}$ are far less severe in models with top-rich decay phenomenologies than in other supersymmetric scenarios — especially those in which the first- and second-generation squarks are light. Indeed, the oft-quoted bounds on squark and gluino masses derived in Refs. [13-17] are not directly applicable in such models. However, as we demonstrate below, the analysis we propose for the fully hadronic channel affords a substantial increase in sensitivity to such models at the LHC.

**IV. STANDARD MODEL BACKGROUNDS AND EVENT GENERATION**

We now characterize the SM backgrounds for top-rich new physics at the LHC. A number of SM processes yield events with large central-jet multiplicities, no charged leptons, and substantial missing transverse energy. The dominant contributions come from processes such as $t\overline{t}$ + jets and $W^\pm$ + jets, with all heavy particles decaying hadronically, and processes such as $Z$ + jets and $t\overline{t}Z$ + jets in which the $Z$ boson decays to a neutrino pair. In addition, a sizeable contribution arises from pure QCD processes in which the appearance of substantial $E_T$ arises due to jet-energy mismeasurement, and from $W \rightarrow \tau \nu_\tau$ decays where the $\tau$ is mistagged as a jet. We stress that these backgrounds are not particular to the simplified model which forms the focus of the present analysis, but are those generically relevant for
TABLE I: Leading-order cross-sections $\sigma_{\text{LO}}$ for each of the relevant SM background processes considered in this analysis after the application of the precuts discussed in Sect. V, as well as the NLO $K$-factor $K_{\text{NLO}}(\mu)$ associated with each processes. The factorization and renormalization scales at which each $K$-factor has been evaluated are taken to be $\mu_F = \mu_R = \mu$, where the value of $\mu$ for each process, along with the energy $\sqrt{s}$ for which each each $K$-factor appearing in this table has been derived, are also displayed.

| Process       | $\sigma_{\text{LO}}$ (precuts) | $K_{\text{NLO}}(\mu)$ | $\mu$ | $\sqrt{s}$ |
|---------------|-------------------------------|-------------------------|-------|------------|
| $t\bar{t}$ + jets | 267.2 fb                     | 1.40                    | $m_t$ | 14 TeV     |
| $W^\pm$ + jets  | 60.4 fb                      | 0.65                    | $M_W$ | 7 TeV      |
| $Z$ + jets      | 48.6 fb                      | 1.17                    | $M_Z$ | 7 TeV      |
| $t\bar{t}Z$ + jets | 0.7 fb                     | 1.35                    | $m_t + M_Z/2$ | 14 TeV |
conservative estimate of the overall signal significance, since $t\bar{t} + \text{jets}$ provides the dominant contribution to the SM background after a substantial cut on $N_j$ is applied, and since the $K$-factors for the subprocesses which contribute toward the inclusive cross-section for $t\bar{t} + \text{jets}$ tend to decrease as the number of jets involved increases. The NLO $K$-factors for several $Z + \text{jets}$ [49] and $W + \text{jets}$ [50] subprocesses have recently been computed for the LHC at a center-of-mass energy $\sqrt{s} = 7$ TeV. While corresponding results for the remaining processes included in our analysis are not yet extant in the literature for the same center-of-mass energy, $K$-factors for a number of $t\bar{t} + \text{jets}$ subprocesses [51, 52], as well as for $t\bar{t}Z + \text{jets}$ [53], have been computed at $\sqrt{s} = 14$ TeV. We estimate the $K$-factors for these processes by adopting these results. Numerical values for all $K$-factors used in this analysis are summarized in Table I, along with the center-of-mass energy and common factorization and renormalization scale $\mu$ at which each is evaluated. The LO cross-sections for the corresponding background processes (after the application of the precuts described in Sect. V below) are also included in the table.

Estimates of the SM backgrounds obtained from Monte-Carlo simulations should always be taken with a grain of salt, especially when those estimates apply to regimes (such as the large-jet-multiplicity regime) for which little experimental data exists to corroborate them. More accurate characterizations of the backgrounds relevant in these regimes will come as more experimental data is accumulated. However, preliminary studies based on simulations of this sort are frequently invaluable, as it is often in such regimes in which signals of new physics can be most readily resolved. Moreover, the primary results of our analysis (for example, the projected discovery reach for $M_{\tilde{g}}$ and $m_{\tilde{t}_1}$) are not particularly sensitive to these uncertainties.

V. SURVEYING THE PARAMETER SPACE

We have discussed in detail the processes which contribute to the total signal and background event rates in the jets + $E_T$ channel in the example scenario for top-rich new physics we have outlined above. We now outline the search strategy we adopt for differentiating signal from background events in this channel — a strategy in which the principal event-selection criteria are based on the total number of high-$p_T$ jets $N_j$ in a given event and the amount of missing transverse energy $E_T$ associated with that event. (More specifically, in this analysis, we define $N_j$ to be the number of jets in the event with $p_T > 30$ GeV.) As emphasized in the introduction, this strategy is one particularly well-suited for obtaining evidence of new physics in extensions of the SM which give rise to hadronic events with large jet multiplicities. Indeed, as we shall demonstrate, in many top-rich scenarios the adoption of such a search strategy actually renders the fully-hadronic channel even more auspicious for discovery than other, more conventional channels.

Our primary aim in this paper is to demonstrate the effectiveness of a search strategy based primarily on $N_j$ and $E_T$ for top-rich scenarios in general, and not to present a meticulous assessment of the LHC discovery potential for the particular simplified model we have chosen as an example. We therefore choose not to optimize our event-selection criteria for each combination of the model parameters $M_{\tilde{g}}$, $m_{\tilde{t}_1}$, and $\tilde{N}_1$; rather, we introduce a small number of representative cutting regimens, each of which is designed to resolve the signal from the SM background within a certain characteristic region of model parameter space.

It is worth noting that none of the cuts we impose as part of this program of event-selection criteria involve $b$-tagging or top reconstruction. The primary reason for this is that
the dominant contribution to the SM background at large jet multiplicities (i.e., after the application of a sizeable $N_j$ cut) is that from $t\bar{t} +$ jets. As a result, any further selection of events based on $b$-tagging or top reconstruction would reduce signal and background proportionally, and thus only serve to diminish signal significance. That the search strategy we outline here does not rely on these techniques is a distinct asset, since it significantly broadens the range of BSM scenarios for which it can be effective.

As a first step in our event-selection procedure, we apply a preliminary set of cuts, hereafter referred to as our “precuts,” to the signal and background events we obtain from Monte-Carlo simulation. These precuts are designed not only to mimic a realistic detector acceptance, but also to eliminate the sizable SM backgrounds from pure QCD processes, as discussed in Sect. IV, and from low-jet-multiplicity events in general. In particular, we require that all events satisfy the following criteria:

- No isolated charged leptons ($e$ or $\mu$) in the final state.
- At least five jets with $p_T > 40$ GeV.
- Each jet must be isolated in the sense that $\Delta R_{jj} > 0.4$ for every possible pairing of jets in the event, where $\Delta R_{jj}$ is the lego-plot-separation distance between a given pair of jets.
- An azimuthal-angle separation $\Delta \phi(p_T, \vec{p}_T) > 11.5^\circ$ between the missing-transverse-momentum vector and each of the leading three jets (ranked by $p_T$).
- $\slashed{E}_T > 100$ GeV.

This choice of cuts is guided by the features of the signal — namely, the presence of many jets and missing energy. For the SM backgrounds, the only significant sources of missing energy are neutrinos and jet-energy mismeasurement. The first of these is suppressed quite efficiently by the lepton veto, while the second is suppressed by the combination of the minimum $\slashed{E}_T$ cut and the requirement that the missing-transverse momentum vector $\vec{p}_T$ not be aligned (or anti-aligned) with any of the leading jets in a given event — the jets for which the potential for jet-energy mismeasurement is the greatest. It is worth noting that the $\Delta \phi(p_T, \vec{p}_T)$ cut employed here differs from the $\Delta \phi^*$ and $\alpha_T$ cuts employed in Refs. [18, 54] for a similar purpose. As was pointed out in Ref. [26, 27], these latter variables may not be optimal for searches involving large jet multiplicities due to the sheer number of jets involved. By contrast our $\Delta \phi(p_T, \vec{p}_T)$ cut, excludes events based on the proximity of the $\vec{p}_T$ vector to the three highest-$p_T$ jets (for which the potential for jet-energy mismeasurement is the greatest) rather than the nearest jet, and may therefore be a more reliable variable in the large-jet-multiplicity regime.

We now turn to consider the effect of imposing elevated cuts on $N_j$ and $\slashed{E}_T$ beyond those imposed as part of the precuts enumerated above. In order to illustrate the effect that such additional cuts will have on the statistical significance for discovery in this example model, we display the event distributions for all relevant signal and background processes as functions of $N_j$ and $\slashed{E}_T$ in Figs. 4 and 5 respectively. In both of these figures, each distribution shown has been normalized so that the total area under the distribution is unity.

The results displayed in Fig. 4 correspond to $M_{\tilde{g}} = 1000$ GeV and $m_{\tilde{t}_1} = 600$ GeV; however, the shapes of the $N_j$ distributions for the signal processes do not vary significantly over the range of parameter space surveyed, primarily because $N_j$ depends primarily on
FIG. 4: Event distributions for all relevant signal and background processes as functions of jet number $N_j$ corresponding to the parameter choice $M_{\tilde{g}} = 1000$ GeV and $m_{\tilde{t}_1} = 600$ GeV in our simplified supersymmetric model. Each distribution shown has been normalized so that the total area under it is unity.

The structure of the decay chain and is not particularly sensitive to the details of the kinematics involved. For example, as discussed in Sect. II, the characteristic number of “jets” at the parton level (i.e., final-state quarks or gluons) expected in the fully-hadronic channel from the $pp \rightarrow \tilde{g}\tilde{g}$ and $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$ signal processes is twelve and six, respectively. The characteristic jet multiplicity for $pp \rightarrow \tilde{g}\tilde{g}$ at the detector level is reduced somewhat because the sheer number of quarks and gluons in the final state makes it increasingly likely that multiple such partons will be clustered together into the same jet. Nevertheless, this process clearly still yields a substantial number of events with large jet multiplicities. By contrast, the largest contributions to the SM background from $t\bar{t} +$ jets and $W^\pm +$ jets after the application of the precuts are those from events in which a $W^\pm$ boson decays to a $\tau$ lepton, which is misidentified as a jet, and a neutrino. These backgrounds exhibit far lower characteristic jet multiplicities. Indeed, we see that only a minute fraction of background events surviving our precuts have jet multiplicities in the range $N_j \geq 8$, whereas roughly half of the $pp \rightarrow \tilde{g}\tilde{g}$ events contain at least this number of jets. This figure therefore attests to how effective an elevated $N_j$ cut can be in discriminating between signal and background in regions of parameter space in which gluino-pair production provides the largest contribution to the signal.

The results shown in Fig. 5 likewise motivate the application of an elevated $E_T$ cut in certain cases, although the utility of such a cut is more sensitive to the values of $M_{\tilde{g}}$ and $m_{\tilde{t}_1}$. The distributions displayed in the left panel of the figure correspond to the parameter assignments $M_{\tilde{g}} = 800$ GeV and $m_{\tilde{t}_1} = 600$ GeV. For this choice of parameters, as can be verified from Fig. 3, gluino-pair production provides the dominant signal contribution, and the $E_T$ distributions for both $pp \rightarrow \tilde{g}\tilde{g}$ and $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$ are sufficiently broad compared to those
FIG. 5: Event distributions for all relevant signal and background processes as functions of missing transverse energy $E_T$ for two illustrative combinations of the gluino mass $M_{\tilde{g}}$ and stop mass $m_{\tilde{t}_1}$ in our simplified supersymmetric model. The distributions shown in the left panel correspond to the parameter choice $M_{\tilde{g}} = 800$ GeV and $m_{\tilde{t}_1} = 600$ GeV, while those shown in the right panel correspond to $M_{\tilde{g}} = 1200$ GeV and $m_{\tilde{t}_1} = 400$ GeV. As in Fig. 4, each distribution appearing in each panel has been normalized such that the total area under each distribution is unity.

for the SM background processes so as to render an elevated $E_T$ cut an effective discriminant between signal and background. By contrast, the situation displayed in the right panel, which corresponds to the parameter assignments $M_{\tilde{g}} = 1200$ GeV and $m_{\tilde{t}_1} = 400$ GeV, is quite different. Since $\tilde{t}_1$ is quite light in this case, $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$ provides the dominant signal contribution. However, another consequence of $\tilde{t}_1$ being so light is that the $\tilde{N}_1$ produced by stop decay are not particularly energetic. As a result, the $E_T$ distribution for $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$ does not differ as significantly from that of the SM background. We therefore conclude that there is little to be gained by imposing an elevated $E_T$ cut in regions of parameter space in which $m_{\tilde{t}_1}$ is small. On the other hand, an elevated $E_T$ cut does enhance detection prospects for regions of parameter space in which the kinematics of stop- or gluino-decay is such that substantial kinetic energy is transferred to the $\tilde{N}_1$.

In order to provide a more quantitative demonstration of the effects of $N_j$ and $E_T$ cuts on signal and background data, we provide a roster of cross-sections for the various signal and background processes considered in our analysis after the application of different combinations of such cuts in Table II. All cross-sections quoted in this table include the relevant NLO $K$-factors. In order to demonstrate how the effect of these cuts depends on $M_{\tilde{g}}$ and $m_{\tilde{t}_1}$, we present signal cross-sections for a pair of benchmark scenarios representative of the two principal types of multi-jet phenomenology to which our example model gives rise. For the first of these scenarios, for which $M_{\tilde{g}} = 1000$ GeV and $m_{\tilde{t}_1} = 350$ GeV, the cross-section for the $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$ production process is large enough that this process dominates the event rate in the jets + $E_T$ channel. For this scenario, moderate cuts on $N_j$ and $E_T$ similar to that imposed as part of the precuts offers the best prospects for discovery. For the second
TABLE II: Cross-sections (in femtobarns) for the signal processes $pp \to \tilde{g}\tilde{g}$ and $pp \to \tilde{t}_1\tilde{t}_1^*$ in a pair of illustrative benchmark scenarios with different values of the model parameters $M_{\tilde{g}}$ and $m_{\tilde{t}_1}$, as well as for the SM backgrounds from $t\bar{t}$, $W^+ +$ jets, $Z +$ jets, and $t\bar{t}Z +$ jets after the application of various cuts. For further details, see text.

benchmark scenario, for which $M_{\tilde{g}} = m_{\tilde{t}_1} = 800$ GeV, $pp \to \tilde{g}\tilde{g}$ production dominates, and the best prospects for discovery are obtained by imposing elevated $N_j$ and $E_T$ cuts on the order of $N_j \geq 8$ and $E_T \geq 300$ GeV.

VI. PROSPECTS FOR DISCOVERY

The effect of imposing elevated cuts on $N_j$ and $E_T$ on the statistical significance of discovery in different regimes of model-parameter space can be seen in Fig. [5] In this figure, we present a series of contour plots indicating the regions of $(M_{\tilde{g}}, m_{\tilde{t}_1})$ parameter space within which statistically significant evidence of new physics can be obtained at the $\sqrt{s} = 7$ TeV LHC after the application of several different sets of elevated $N_j$ and $E_T$ cuts. All results shown in these panels assume an integrated luminosity $L_{\text{int}} = 10$ fb$^{-1}$. Since the number of both signal and background events surviving the cuts we impose is often quite small, we calculate the confidence level for all values of $M_{\tilde{g}}$ and $m_{\tilde{t}_1}$ included in our parameter-space survey using Poisson statistics. The significance contours shown in each panel of Fig. [5] are those contours for which the equivalent confidence level for a Gaussian distribution would correspond to a 3$\sigma$ or 5$\sigma$ discovery. We also require that the signal is not event-count limited, in the sense that expected number of signal events at this luminosity which survive all cuts exceeds five. The gray region demarcated by the dashed contour indicates the region
of parameter space in which this event-count criterion is not satisfied.

FIG. 6: Contour plots illustrating the regions of $(M_{\tilde{g}}, m_{\tilde{t}_1})$ parameter space within which evidence for new physics can be obtained at the $3\sigma$ (orange) or $5\sigma$ (red) significance level with $L_{\text{int}} = 10 \text{ fb}^{-1}$ at the $\sqrt{s} = 7 \text{ TeV}$ LHC after the application of the various sets of cuts discussed in the text. The dark gray region bounded by the dashed contour in each panel demarcates the region within which the expected event count is less than five events at this luminosity. The contours displayed in the upper left panel correspond to the application of the precuts alone. Those in the upper right are obtained by imposing an additional $\not{E}_T \geq 300 \text{ GeV}$ cut on top of those precuts, those in the lower left panel are obtained by imposing an additional $N_j \geq 8$ cut on top of the precuts, and those in the bottom right panel are obtained by applying these two additional cuts in tandem.

The contours displayed in the upper left panel of Fig. 6 are obtained by imposing the precuts alone. In this case, we see that in the region of parameter space in which $m_{\tilde{t}_1} \lesssim 400 \text{ GeV}$, the signal contribution from $pp \to \tilde{t}_1 \tilde{t}_1^*$ is substantial, and the $N_j \geq 5$ and $p_T$ cuts imposed as part of the precuts are sufficient to resolve the signal from this process from the SM background. Likewise, for $M_{\tilde{g}} \lesssim 725 \text{ GeV}$, these same cuts alone are also sufficient to
resolve the signal from the $pp \rightarrow \tilde{g}\tilde{g}$ process.

The situation changes, however, when the minimum $E_T$ threshold is elevated, as is evident from the upper right panel of Fig. 6. This panel displays the results obtained by imposing an additional $E_T \geq 300$ GeV cut on top of the $E_T \geq 100$ GeV requirement included as part of the precuts. These results indicate that in regions of parameter space in which $M_{\tilde{g}} \gg 2m_t + M_{\tilde{N}_1}$, for which neutralinos produced via the $pp \rightarrow \tilde{g}\tilde{g}$ process tend to be quite energetic, $E_T$ serves as an extremely effective criterion for distinguishing signal from background, as we also saw in Fig. 5 (An exception occurs in cases in which $M_{\tilde{g}} \gg m_{\tilde{\chi}}$ and the top quarks receive a greater proportion of the mass energy of the decaying gluino.)

The same is true of neutralinos produced via the $pp \rightarrow \tilde{t}_1\tilde{\tau}_1^*$ process in regions of parameter space in which $m_{\tilde{\tau}} \gg m_t + M_{\tilde{N}_1}$. Conversely, when these conditions on $M_{\tilde{g}}$ and $m_{\tilde{\tau}}$ are not satisfied, $E_T$ serves as a poor discriminant between the respective $pp \rightarrow \tilde{g}\tilde{g}$ and $pp \rightarrow \tilde{t}_1\tilde{\tau}_1^*$ signal contributions and the SM background, and the significance of discovery afforded by the corresponding signal process decreases.

The lower right panel of Fig. 6 displays the results obtained by imposing an additional $N_j \geq 8$ cut in addition to the precuts. Events produced by $pp \rightarrow \tilde{g}\tilde{g}$, for which the characteristic jet multiplicity is quite high, tend to survive such a cut, which is quite efficient in eliminating events from the SM backgrounds. For this reason, the discovery potential afforded by this signal process is improved with each incremental increase in the $N_j$ requirement up to a reasonably high threshold — unless other considerations, such as the total expected number of signal events, become an issue. In accord with the results displayed in Fig. 4, we find that this threshold occurs for a cut in the $N_j \sim 8 - 10$ range. By contrast, events produced by $pp \rightarrow \tilde{t}_1\tilde{\tau}_1^*$ tend to involve far lower jet multiplicities; hence substantially elevating the $N_j$ cut results in a loss of significance in those regions of parameter space within which this process is responsible for the dominant signal contribution.

The bottom right panel of Fig. 6 displays the results obtained by imposing both a $N_j \geq 8$ cut and a $E_T \geq 300$ GeV cut in addition to the precuts. This set of cuts yields a $5\sigma$ significance throughout a broad region of parameter space within which $550$ GeV $\lesssim M_{\tilde{g}}$ $\lesssim 950$ GeV. This clearly constitutes a far greater reach than that obtained by imposing either an elevated $N_j$ cut or an elevated $E_T$ cut alone. As before, the elevated $N_j$ cut results in the signal rate being dominated by gluino-pair production, as expected. It is also evident from the results displayed in this panel that at $\mathcal{L}_{\text{int}} = 10$ fb$^{-1}$, the effect of the combined $E_T$ and $N_j$ cuts imposed here on the signal-event rate is quite severe. Indeed, we find that further increasing the jet-multiplicity threshold beyond $N_j \geq 8$ or substantially elevating the $E_T$ cut above $E_T \geq 300$ GeV does not result in a significant improvement in the reach, essentially because the signal becomes event-count limited.

One can compare these results to those afforded by other, complementary strategies $[23, 25]$ for observing a signal of new physics from a pair of gluinos decaying into $t\bar{t}t\bar{t} + E_T$. From among those strategies, the the best reach is obtained by demanding one lepton and four $b$-tagged jets in the final state $[25]$, which permits a $5\sigma$ discovery for $M_{\tilde{g}}$ as high as 650 GeV at an integrated luminosity of 1 fb$^{-1}$. By contrast, with the search strategy we adopt here — and specifically by requiring that $N_j \geq 8$ and $E_T \geq 200$ GeV — we find that the LHC reach (at the same significance level and with the same luminosity) can be increased to roughly 730 GeV. This serves as just one example of how a search strategy focused on fully hadronic events with large jet multiplicities and substantial $E_T$ can be useful in identifying signals of new physics at the LHC.
VII. CONCLUSIONS

In this paper, we have outlined a search strategy for identifying signals of new physics in scenarios which give rise to large jet multiplicities and substantial missing transverse energy at the LHC. We have argued that this strategy, which focuses on the fully hadronic channel and uses \( N_j \) and \( \mathcal{E}_T \) as the principal criteria for resolving such signals from the SM background, can be an extremely effective one. To demonstrate the effectiveness of this search strategy, we have examined the prospects it offers for discovery in the context of an example scenario which gives rise to top-rich event topologies: a simplified supersymmetric model whose field content comprises a gluino \( \tilde{g} \), a light, right-handed stop \( \tilde{t}_1 \), and a bino-like neutralino \( \tilde{N}_1 \) with a mass hierarchy \( M_{\tilde{g}}, m_{\tilde{t}_1} > M_{\tilde{N}_1} \). We have shown that in such a model, the prospects for observing a signal of new physics in the jets + \( \mathcal{E}_T \) channel via the search strategy we have outlined here can actually be better than those obtained via other, more conventional channels for identifying new, top-rich physics at the LHC.

While in this paper, we have focused on one specific model in order to illustrate how effective a search strategy focused on \( N_j \) and \( \mathcal{E}_T \) can be in terms of discovery potential, it is worth reemphasizing that similar results can be expected for a broad class of scenarios for BSM physics whose field content includes both one or more new strongly-interacting states and a stable dark matter candidate. An important and oft-studied subclass of these scenarios are those which give rise to top-rich event topologies. These include models with additional fermion generations, supersymmetric models featuring a light stop and heavy first- and second-generation squarks (including certain string-theory-inspired scenarios \([26, 27]\)), and Little Higgs models with T-parity, UED models, and a variety of other new-physics scenarios.

The detection prospects in any given scenario will of course depend on the production rates for any new strongly-interacting fields involved, and hence on the masses, spins, and \( SU(3)_c \) representations of those fields. They will also depend quite sensitively on the structure of the decay chains initiated by those new strongly-interacting fields and on the kinematics of the final-state particles which result from each decay. Indeed, the decay phenomenology of the example model on which we have focused our attention in this paper is particularly simple and involves only a limited number of possible decay channels for \( \tilde{g} \) and \( \tilde{t}_1 \). By contrast, more involved models can exhibit far more complicated decay phenomenologies, the details of which in large part determine the optimal program of event-selection criteria (and in particular the optimal thresholds for \( N_j \) and \( \mathcal{E}_T \)) for resolving signal from background. For example, the effectiveness of using \( \mathcal{E}_T \) as an criterion for event selection in any particular scenario which includes both new strongly-interacting fields and a stable dark-matter particle depends largely on the decay phenomenology of those strongly-interacting fields. In particular, it depends on how much of the energy released by their decays emerges in the form of jets and how much emerges in the form of dark-matter particles. This balance depends sensitively on the structures and kinematics of the decay chains involved, and the more this balance is tilted toward dark-matter particles, the more effective a discriminant a \( \mathcal{E}_T \) cut will generally become.

It it worth remarking that the our analysis was conducted assuming an integrated luminosity of 10 fb\(^{-1}\) and a center-of-mass energy of 7 TeV, so as to be applicable to the present LHC run. At such an integrated luminosity, we found that there is no advantage to requiring more than eight energetic jets or \( \mathcal{E}_T \) significantly in excess of 300 GeV, since further elevating the cuts on these variables tends to reduce the expected number of signal events to
a negligible level. However, for higher luminosities or a larger center-of-mass energy (as can be expected after the planned LHC upgrade), further increasing the $N_j$ and $E_T$ thresholds cuts beyond those levels may indeed prove fruitful. Thus for any given model which predicts a jets $+$ $E_T$ signal, it may be necessary to reassess the optimal event-selection criteria for resolving that signal from the SM background.

On a final note, it is also worth remarking on another potentially interesting strategy which could be useful in identifying signals of new physics in certain top-rich scenarios, and which can be viewed in many ways as complementary to the strategy outlined here. This is to focus on final states involving bottom quarks plus $E_T$ alone. The utility of this approach was investigated in Ref. [55] in the context of a model with an additional pair of color-triplet fermions $T'$ and $B'$, which decay almost exclusively via the channels $T' \rightarrow tX$ and $B' \rightarrow bX$, where $X$ is a stable dark-matter particle. It was found that for $m_X \sim 1$ GeV, the $pp \rightarrow B'\bar{B}' \rightarrow b\bar{b} + E_T$ and $pp \rightarrow T'\bar{T}' \rightarrow t\bar{t} + E_T$ channels offered a comparable reach. Furthermore, it was argued that improved sensitivity in the $b\bar{b} + E_T$ channel can be expected as $m_X$ increases, provided that the $T'$ is reasonably light, since when this is the case, the jets produced from top decay tend to be reasonably soft. This scenario was analyzed in a recent study by the ATLAS collaboration at an integrated luminosity of 0.83 fb$^{-1}$ [56]. In this study, the collaboration searched for evidence of gluino pair-production followed by the decay $\tilde{g} \rightarrow b\bar{b}\tilde{N}_1$, assuming a branching fraction for this process of effectively unity. For $m_{\tilde{g}} < 600$ GeV and a neutralino mass set to $M_{\tilde{N}_1} = 60$ GeV, the results of this study place a bound $M_{\tilde{g}} \gtrsim 725$ GeV on the gluino mass, which is roughly comparable to the expected 5$\sigma$ sensitivity the search strategy we have outlined in this paper for models in which the primary decay channel for the gluino is $\tilde{g} \rightarrow t\bar{t}\tilde{N}_1$. It would be interesting to consider how the discovery prospects afforded by these two approaches compare in models in which both $\tilde{g} \rightarrow b\bar{b}\tilde{N}_1$ and $\tilde{g} \rightarrow t\bar{t}\tilde{N}_1$ channels have sufficient branching fraction — to wit, models which involve not only top-rich, but also bottom-rich event topologies.

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