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Top Channel for Early SUSY Discovery at the LHC

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Arguably the best-motivated channel for early LHC discovery is events including a high multiplicity of third generation quarks, such as four top quarks. For example generic string theories compactified to four dimensions with stabilized moduli typically have light gluinos with large branching ratios to t and b quarks. We analyze signals and background at 7 TeV LHC energy for 1 fb^{-1} integrated luminosity, suggesting a reach for gluinos of about 650 GeV. A non-Standard Model signal from counting bs and leptons is robust, and provides information on the gluino mass, cross section, and spin.

I. INTRODUCTION

The Large Hadron Collider (LHC) is likely to accumulate significant amounts of data in 2011. While the detector groups will be sensitive to many ways new physics could appear, it is not possible to focus equally on all possible interesting signatures, so it is valuable to examine well-motivated channels that may yield results at the initial LHC energies and luminosities. It has increasingly been recognized that considerations of new physics point toward top-quark and bottom-quark rich final states.

Supersymmetry implies the existence of a top partner that cancels quadratic divergences, and introduces a partner for the gluon, the gluino, in the low energy spectrum. At proton colliders pair production of gluinos, and consequently their decay products, typically become the main channel of supersymmetric signals. Models with light top partners are common and they imply that a typical signature of production of the gluino will be multiple top quarks in the final states [1].

Here we will study this signature of low energy supersymmetry with light gluinos, focusing on the well-motivated spectrum in which the squarks are considerably heavier than the gluino and the third generation squarks are lighter than those of the first two generations. In this case, the gluino will dominantly decay into top and/or bottom quarks. Earlier some of us, along with Acharya, Grajek, and Suruliz [2] studied such processes for the 14 TeV LHC. In this paper we update the study for early LHC at 7 TeV, and focus on the significant reach and robustness of a signal with the number of events from 1 fb^{-1}.

Many models lead to multi-top final states [3], and corresponding analysis approaches have been studied [4] (See Ref. [2] for a more extensive list.). When embedding low energy supersymmetry into a string theory, moduli stabilization and cosmological constraints imply that moduli masses and gravitno mass, and consequently scalar masses [5], are larger than about 20 TeV [6]. Then, standard renormalization group (RG) running of scalar masses from the unification scale down to the electroweak scale will push the third generation squark masses significantly lower than those of the other generations.

The gluino decays via virtual squarks to $q\bar{q}\tilde{\chi}_1^0$ or $q\bar{q}\tilde{\chi}_1^{\pm}$. Since the rate for a given diagram scales as the virtual squark mass to the -4 power from the propagator, the lightest squarks dominate. Therefore, we are led to consider decay channels $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$, $\tilde{g} \to t\bar{b}\tilde{\chi}_1^-$, and $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$. Decays of multiple top quarks lead to b-rich and lepton rich final states, and give excellent potential for early discovery. In fact, we show that significant excesses can be observed at the early LHC-7 TeV. For example, gluino masses larger than 600 GeV can be discovered in the single-lepton plus 4 b-jets channel.

We carry out our study on several benchmark models. To study the reach of gluino pair production, with decays into third generation squarks, a detailed scan of the parameter space involving the gluino mass and LSP mass, for different branching ratios, is performed. We emphasize that the goal of this study is to demonstrate that gluino pair production with decays via third generation squarks provides an ideal channel for early discovery at the LHC, since it leads to lepton and b-quark rich final states.

II. BENCHMARK MODELS

Three benchmark models are considered which will form the basis for the numerical scan discussed below. The model parameters and relevant decay branching ratios are shown in Table I. Model A is a simple example of multi-top physics. The spectrum would have a stop much lighter than the other squarks, and therefore gluino pair production always produces four tops in the final state. Model B is designed to include the decay channel $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$, which will result if the sbottom is also lighter than the first two generation squarks, and $m_{\tilde{t}} \sim m_{\tilde{b}}$. Model B is observably different than Model A, while somewhat more difficult to discover. These models have a Bino-like LSP. In Model C, the Wino is the LSP, and is approximately degenerate with the lightest chargino, which is also Wino-like. It is designed to further include a chargino in the decay chain, which allows

	Branching ratios		
	$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	$\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$	$\tilde{g} \to t\bar{b}\tilde{\chi}_1^+ + h.c.$
A	1	0	0
B	0.5	0.5	0
C	.08	0.22	0.7

TABLE I. Relevant branching ratios for the benchmark models considered in this paper. The models A and B have bino LSP. In Model C, the lightest neutralino and lightest chargino are both winos. In all models the first two generation squark masses are taken to be 8 TeV. The third generation is taken to be somewhat lighter and is chosen to generate the required branching ratios of the model.

the decay $\tilde{g} \to t\bar{b}\tilde{\chi}_1^+$. Since the charged Wino is approximately degenerate with the wino LSP, it appears only as missing energy; though if one focuses on the signal events the chargino stub [7] can probably be seen in the vertex detector.

The three models are taken as a basis for 3 separate numerical scans, where $m_{\tilde{g}}$ and m_{LSP}, are varied while the branching ratios are fixed, as shown in Table I. In particular, scans in model A and model B varied $m_{\tilde{g}}$ and $m_{\rm LSP} = m_{\tilde{\chi}_1^0}$, while scan in model C varied $m_{\tilde{g}}$ and $m_{\rm LSP} = m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm}$.

III. SIGNAL ISOLATION AND BACKGROUNDS

The relatively large b-jet and lepton multiplicity associated with multiple top production provide for potentially striking signatures that are easily distinguishable above the expected SM background. By requesting multiple b-tagged jets and at least one lepton, it is possible to achieve signal significance $S/\sqrt{B} > 5$ for 1 fb^{-1} of integrated luminosity.

The most significant backgrounds from the SM for final states with many b-jets, several isolated leptons and missing energy, are from top pair production, $t\bar{t}$. The expected cross-section at the LHC for 7-TeV center-of-mass energy is $\sigma = 164$pb (NLO) [8]. Also included in the analysis are a set of SM backgrounds involving associated production of gauge bosons with third generation quarks. These contribute less significantly to the backgrounds than $t\bar{t}$, but can contribute to signals with high lepton multiplicity. All background sources considered, and their respective cross sections are given in Table II. With the exception of the $t\bar{t}$ cross section, we increased all SM background cross sections by a factor of 2, to account for possible K-factor from NLO corrections. Since the relevant backgrounds for the channels considered end up small (Table II), uncertainties in the cross section are not important.

Background event samples were produced with Madgraph v.4 [9], while the parton shower and hadronization used Pythia 6.4 [10]. Additional hard jets (up to three) were generated via Madgraph, while the MLM [11] matching scheme implemented in Madgraph was used to match these jets to the ones produced in the Pythia showers. The events were then passed through the PGS-4 [12] detector simulators with parameters chosen to mimic a generic ATLAS type detector. The b-tagging efficiency was changed to more closely match the expected efficiencies at ATLAS [13]. For b-jets with 50 GeV $\lesssim p_T \lesssim$ 200 GeV, which is typical of the b-jets in the signal, the efficiency is approximately 60% for tagging a b-quark, roughly 15% for mistagging a charm-jet.

Process	σ [fb]	σ_{L1}	σ_1	σ_2	σ_{1l3b}	σ_{1l4b}
$b\bar{b} + \gamma/Z$	4.69×10^5	1.41×10^4	34.0	107.8	0	0
$b\bar{b} + W^\pm$	2.41×10^4	5.39×10^2	7.71	13.3	0	0
$t\bar{t} + \gamma/Z$	1.54×10^3	7.69×10^2	42.3	95.4	1.2	0.2
$t\bar{t} + W^\pm$	2.25×10^2	1.31×10^2	14.3	27.6	0.8	0.1
$t\bar{b} + \gamma/Z$	1.34×10^3	8.09×10^2	7.37	26.6	0.3	0
$b\bar{b} + VV$	1.14×10^3	2.33×10^2	1.45	3.94	0.1	0
$t\bar{t}$	1.60×10^5	6.60×10^4	2076.7	5905.6	38.0	0.8
$t\bar{t}b\bar{b}$	1.2×10^3	5.36×10^2	31.5	73.8	0.4	0.7
$t\bar{t}t\bar{t}$	0.80	0.60	0.22	0.25	0	0
VV	1.03×10^5	1.03×10^5	108.6	377.7	1.0	0
Model A	1.19×10^3	9.48×10^2	403.8	508.1	39.3	19.3
Model B	1.19×10^3	1.03×10^3	505.2	703.1	26.9	13.8
Model C	1.19×10^3	5.80×10^2	300.5	420.5	14.4	7.4

TABLE II. Cross sections, in femtobarns [fb], for production of signal and backgrounds. All processes include additional hard jets. The first column gives the total production cross section. The second gives the cross section after the L1 triggers defined in PGS-4 (see text). The next two columns give the cross section after selection cuts in Eq. 1 and Eq. 2, with an additional missing energy (MET) requirement, $\not{E}_T \geq 100$ GeV. The final two columns give the cross section after requiring 1 lepton and either 3 or 4 tagged b-jets. The $b\bar{b}$ + jets and $b\bar{b}b\bar{b}$-inclusive backgrounds have been considered, and after the applying the selection cuts in Eqs. 1-2 and requiring at least one lepton, the number of events are negligible in the $\{b, \ell\}$ channels considered here. In this table, we set $m_{\tilde{g}} = 500$ GeV and $m_{LSP} = 100$ GeV.

The signal event samples for gluino pair production and decay were produced using Pythia 6.4 and have been passed through the same PGS-4 detector simulation. Basic lepton isolation was applied to all samples. To reduce backgrounds, events are required to pass the L1-triggers defined by PGS. We also display the effect of two possible additional selection cuts, together with the additional requirement $\not{E}_T \geq 100$ GeV,

$$\textit{cut-1} : n_j(p_T \geq 50\,\text{GeV}) \geq 4 \qquad (1)$$

$$\textit{cut-2} : n_j(p_T \geq 30\,\text{GeV}) \geq 4 \qquad (2)$$

in the last two columns of Table II. The second cut (weaker than the first) is optimal for discovery signatures, such as the same-sign dilepton signature, that have

Number of Background Events (B)

Standard Model

	$2b$	$3b$	$4b$
1ℓ	289.6	42.2	1.74
OS	32.8	5.65	0.007
SS	0.3	0.06	0
$3L$	0.14	0.007	0

Number of Signal Events (S)

	Model A				Model B				Model C		
	$2b$	$3b$	$\geq 4b$		$2b$	$3b$	$\geq 4b$		$2b$	$3b$	$\geq 4b$
$1L$	47.1	39.3	19.3	$1L$	33.5	26.9	13.8	$1L$	18.0	14.4	7.4
OS	12.4	9.9	3.9	OS	6.4	5.0	1.7	OS	2.0	0.9	0.6
SS	6.6	5.1	2.3	SS	2.3	1.2	0.2	SS	0.7	0.6	0.2
$3L$	3.0	2.1	0.7	$3L$	0.7	1.0	0.3	$3L$	0	0.1	0.1

Significance ($\mathbf{S/\sqrt{B+1}}$)

	Model A				Model B				Model C		
	$2b$	$3b$	$\geq 4b$		$2b$	$3b$	$\geq 4b$		$2b$	$3b$	$\geq 4b$
$1L$	2.76	5.97	10.4	$1L$	1.96	4.01	7.5	$1L$	1.06	2.19	4.0
OS	2.13	3.83	3.88	OS	1.10	1.93	1.69	OS	0.34	0.34	0.40
SS	5.75	4.95	2.30	SS	2.00	1.16	0.20	SS	0.58	0.58	0.20
$3L$	2.80	2.09	0.70	$3L$	0.65	0.99	0.30	$3L$	0	0.10	0.10

TABLE III. Number of SM events, number of signal event, and signal significance, with 2, 3, or 4 b-tagged jets and OS, SS, or 3 leptons at the early LHC-7, for 1 fb^{-1} integrated luminosity. For the 1-lepton counts, *cut-1* was applied, while for the other lepton counts *cut-2* was applied. These numbers were found for $m_{\tilde{g}} = 500$ GeV and $m_{LSP} = 100$ GeV.

relatively small SM backgrounds.

Next, the signal is searched for in multi b-jet ($n_b = 2, 3, 4$) and multi lepton channels ($1\ell, SS, OS, 3\ell$). All objects are required to have a minimum p_T of 20 GeV. Same sign (SS) and opposite sign (OS) di-leptons are separated as they can have different origins and sizes. We will use the possible excess in these channels to assess the discovery potential. Table III shows the expected number of events from the SM background as classified according to the number of b-tagged jets and isolated leptons in the event.

Table III shows the expected number of signal events with b-tagged jets and isolated leptons for the three benchmark models. Model A, which is predominantly a four top signal, has significantly more multi-lepton and b-jet events passing selection cuts than Model B and Model C. In Table III, the signal significance achievable with 1 fb^{-1} integrated luminosity is shown. By requesting at least 4 b-tagged jets it is possible to observe signal significance $S/\sqrt{B}$ $\geq$5 for events with a single lepton. The one-lepton four-b-jet channel will prove to be robust and the best channel for discovery.

IV. SCAN AND RESULTS

For each model (a fixed $m_{\tilde{g}}$ and m_{LSP}), we simulated 1 fb^{-1} of data using Pythia and PGS. Then we searched for the models over the backgrounds for the selection cuts in Eqs. 1-2 in each of the b-jet and lepton ($\{b, l\}$) channels. A statistical significance in a $\{b, \ell\}$ channel is defined as $\sigma_{\{b,\ell\}} \equiv \frac{S_{\{b,\ell\}}}{\sqrt{B_{\{b,\ell\}}+1}}$ where $S_{\{b,l\}}(B_{\{b,\ell\}})$ is the number of signal(background) events expected to be in the $\{b, \ell\}$-channel for one of the two selection cuts in Eqs. 1-2. Thus, if for any of the significances, $\sigma_{cut_i,\{b,\ell\}} \geq 5$, the model can be considered discoverable at 1 fb^{-1}. In Figures 1 we plot $\sigma_{cut_1,\{b,\ell\}} = 5$ contours, for the channels

$$\{\geq 4b, 1\ell\} \quad \{3b, 1\ell\} \quad \{\geq 2b, SS\} \quad \{\geq 2b, OS\} \quad \{\geq 1b, 3\ell\}.$$

In the first two channels *cut-1* is used, and in the last three channels, the weaker *cut-2*, is used. As is evident from Table III, the backgrounds for $\{\geq 4b, 1\ell\}$ are significantly smaller than the backgrounds for $\{3b, 1\ell\}$, and therefore it is not beneficial to combine them into the inclusive channel $\{\geq 3b, 1\ell\}$. The channels we used in this study maximize the significance.

In all cases the $\{\geq 4b, 1\ell\}$- channel best for discovery. But, the SS-dilepton channel can be an equally competitive mode for discovery when the branching ratio to tops is large. It is important that the 4-top final state will give signatures in several channels if it appears in any. Finding a second predicted channel would be valuable confirmation. If two or more channels are present a combined significance would be a useful construct and facilitate a claim of discovery.

V. SUMMARY

We have studied the signatures of low energy supersymmetry in multi-top and/or multi-b production at 7 TeV LHC, and associated Standard Model backgrounds. Results are presented in terms of discovery reaches for 1 fb^{-1}. In recent years a number of models have been proposed that lead to such final states. The required spectrum, heavy squarks with the third generation somewhat lighter than the first two and light gluino, satisfies the existing experimental constraints better and can be motivated on very general theoretical grounds. In addition, it has been realized that generic string theories compactified to 4 dimensions and satisfying phenomenological constraints typically lead to such final states (as briefly described in the introduction). Thus such final states have emerged as an unusually well-motivated discovery channel at LHC. We focus on gluino pair production in supersymmetric theories both because of the strong theoretical motivations and because of the well defined nature of the such models. At 7 TeV LHC with 1 fb^{-1} the reach can be over 600 GeV (up to about 650 GeV) gluino mass. Discovery reach at higher luminosity can be scaled from our result straightforwardly. Precise discovery reach at a different energy requires a different full study, such as the case of $E_{\rm cm} = 14$ TeV studied in Ref. [2]. However, we can roughly estimate for $E_{\rm cm} = 8$ TeV, the reach in gluino mass can be enhanced by about a factor of 8/7. Top reconstruction was studied in [2] and is difficult, but counting leptons and b-jets excess for discovery is robust. The size of the counting signal provides information on the gluino cross section, which in turn is correlated with the gluino spin. Addition kinematical distributions could also help to enhance the discovery reach. More careful analysis, preferably with data driven approaches, will be necessary to understand the background distribution in detail.

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While this work was in preparation for posting [14] appeared which explores similar issues.

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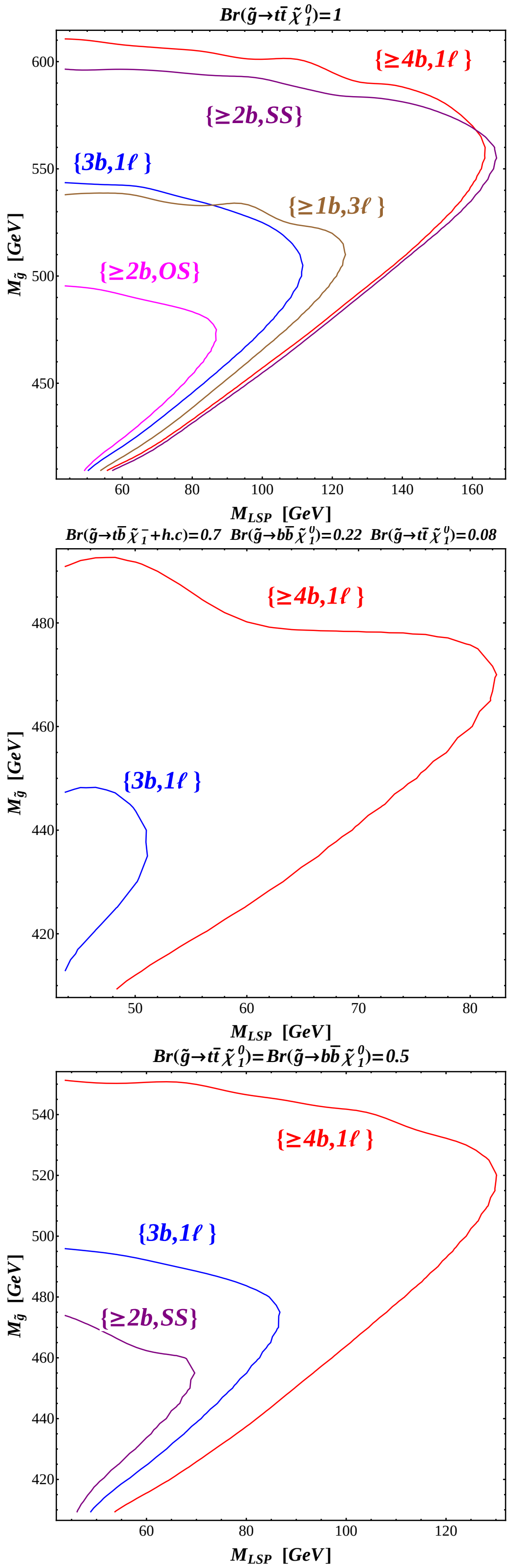

FIG. 1. $\sigma = 5$ contours $\{b, \ell\}$-channels at LHC-7 TeV for 1 fb^{-1} integrated luminosity of gluino pair production. In all Models, the $\{4b, 1\ell\}$- channel provides the best channel for discovery. In model A, where all events contain four tops, the SS-dilepton channel can be a competitive mode for discovery. In all models, there are other channels that will give a lower but noticeable excess, and will provide a valuable confirmation of a mutli-top signal.