Increased Yield of $t\bar{t}b\bar{b}$ at Hadron Colliders in Low-Energy Supersymmetry

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(Received 20 February 2002; published 16 May 2002)

Light bottom squarks and gluinos have been invoked to explain the b quark pair production excess at the Fermilab Tevatron. We investigate the associated production of $t\bar{t}b\bar{b}$ at hadron colliders in this scenario, and find that the rates for this process are enhanced over the standard model prediction. If light gluinos exist, it may be possible to detect them at the Tevatron, and they could easily be observed at the CERN Large Hadron Collider.

DOI: 10.1103/PhysRevLett.88.221801 PACS numbers: 12.60.Jv, 14.80.Ly

The bottom quark pair production cross section measured at the Fermilab Tevatron exceeds the theoretical prediction by about a factor of 2 [1]. The state-of-the-art theoretical prediction is currently next-to-leading order (NLO) in QCD. While the NLO corrections are large, it is possible that the measured excess is due to new physics [2].

Berger *et al.* [3] proposed a solution to this puzzle based on low-energy supersymmetry (LESS) [4]. In particular, they proposed the existence of a light gluino, $\tilde{g}$, with mass $m_{\tilde{g}} \approx$ 12-16 GeV, which decays to a bottom quark and light bottom squark, $\tilde{b}_1$, of mass $m_{\tilde{b}_1} \approx$ 2-5.5 GeV. The bottom squark is either long lived or decays hadronically. It is argued that this scenario is not yet ruled out by other experiments [5,6].

One way to test the above scenario is via observation of the final state $t\bar{t}b\bar{b}$. With LESS, there is the new production channel $t\bar{t}\tilde{g}\tilde{g}$, with the gluinos decaying immediately to $b\tilde{b}_1$. If the bottom squark decays hadronically, the decay products are typically merged with those of the associated b quark jet. If instead the bottom squarks are long lived, the event signature is still two additional bottom quarks in top quark pair production. One would expect the rate for this new channel to be larger than the standard model (SM) $t\bar{t}b\bar{b}$ rate due to the large Casimir. Looking for LESS in this manner has many nice properties. Unlike for Υ [7] or B [8] meson decays, we do not need to worry about nonperturbative physics. Furthermore, the scale dependence for top quark pair associated production is much smaller than for bottom quark pair production. Finally, unlike many supersymmetric searches, with this production channel there is almost no model dependence. Since the production coupling involved is that of QCD, α_s, to a first approximation the only LESS model parameter which enters at leading order is the gluino mass, $m_{\tilde{g}}$ (inclusion of top squarks leads to additional diagrams, but these are suppressed primarily due to the additional heavy propagators). One could also choose to examine other associated production processes, such as $Z\tilde{g}\tilde{g}$. The larger scale uncertainty could be compensated by the comparatively larger cross section, but the processes are not purely QCD, so we do not consider them here.

We perform leading order, parton level Monte Carlo calculations of the SM $t\bar{t}b\bar{b}$ and LESS $t\bar{t}\tilde{g}\tilde{g}$ production cross sections, for gluino masses in the range $m_{\tilde{g}} =$ 12-16 GeV. Cross sections are calculated for both $p\bar{p}$ collisions relevant to Run II of the Fermilab Tevatron, $\sqrt{s} = 2.0$ TeV and for pp collisions at the CERN Large hadron Collider (LHC), $\sqrt{s} = 14.0$ TeV. Decay of the top quarks is included at the matrix element level, to determine the efficiency of realistic kinematic cuts that would be imposed in such a search. We apply those efficiencies to the inclusive $t\bar{t}\tilde{g}\tilde{g}$ rate, but we treat the gluinos as final state particles, impose a minimum transverse momentum cut on the gluinos, and assume that their decay leads to an observable hadronic jet with the vertex tag from the daughter bottom quark. Kinematic cuts used at the Tevatron (LHC) are as follows:

$$\begin{aligned} p_T(j) &> 15(20)\ \text{GeV}, \qquad |\eta(j)| < 3.0(4.0)\,, \\ p_T(b) &> 20(20)\ \text{GeV}, \qquad |\eta(b)| < 2.0(2.5)\,, \\ p_T(l) &> 15(15)\ \text{GeV}, \qquad |\eta(l)| < 2.0(2.5)\,, \\ \not{p}_T &> 30(30)\ \text{GeV}, \qquad \Delta R_{mn} > 0.4(0.4)\,. \end{aligned} \tag{1}$$

where m, n are leptons, bottom quarks, gluinos, or light jets.

Matrix elements were constructed with a LESS-modified version of MADGRAPH [9]. We used CTEQ5L parton distribution functions [10] with factorization scale $\mu_f = m_t + m_{jj}/2$, where m_{jj} is the invariant mass of the extra bottom quark or gluino pair. The renormalization scale was taken to be the same, $\mu_r = \mu_f$. We do not consider any additional contribution from $t\bar{t}\tilde{b}_1\bar{\tilde{b}}_1$ production, since, first, the rate is much lower than for gluinos and, second, this introduces additional model dependence: whether the bottom squarks are long lived or not; if not, whether they have sufficient mass to decay into bottom quarks.

In the LESS scenario, we take into account the altered running of the QCD coupling, α_s, which occurs due to the presence of the light gluino and bottom squark contributions to the beta function. This causes α_s to be considerably larger at the top quark mass scale. Since the cross

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sections are proportional to α_s^4, this effect increases the signal considerably. In calculating the signal cross section, we must also consider the effect of enhanced α_s on the SM $t\bar{t}b\bar{b}$ rate—an increase of 30%. We fix the value of the coupling to be $\alpha_s(m_b) = 0.205$, and use two-loop running with the bottom squark mass set to the bottom quark mass, $m_{\tilde{b}_1} = m_b$ [8]. We run the coupling from low-energy data, because if light gluinos and squarks exist, then the extraction of α_s from low-energy data would be unaffected by the LESS particle content. The value of α_s obtained at the Z mass scale is 0.127–0.128 for $m_{\tilde{g}} = 15$–12 GeV. Given the uncertainty on $\alpha_s(m_b)$, this result is within experimental errors, as discussed in Ref. [8].

We calculate the $t\bar{t}b\bar{b}$ cross section at the Tevatron to be 4.0 fb for $p_T(b) > 20$ GeV (applied to the additional bottom quarks only; no top decays). [Reference [11] imposed the same $p_T(b)$ cut but did not impose a cut on the rapidity of the b quarks.] We find a 25% efficiency for the kinematic cuts for both the semileptonic [branching ratio (BR) = 29%] and all-hadronic (BR = 46%) decay modes of the top quarks. We do not consider the all-leptonic channel (BR = 4.7%) as the rate is much less than one expected event for reasonable Run II luminosity. The LESS cross section for $t\bar{t}\tilde{g}\tilde{g}$ production varies from 11.2 fb at $m_{\tilde{g}} = 12$ GeV to 8.1 fb at 16 GeV, as shown in Fig. 1. The $t\bar{t}b\bar{b}$ rate is 5.8 fb with LESS α_s running. Assuming that the all-hadronic mode could be used (we do not assume that top quark reconstruction is necessary), which is somewhat optimistic, and with a bottom quark vertex tagging efficiency of $\epsilon_b = 50\%$ and demanding that all four bottom quarks be tagged, then with 30 fb^{-1} of integrated luminosity we estimate between 4.5 and 3.5 signal events on a SM background (calculated with SM running of the coupling) of 1.4 events. Using Poisson statistics, this corresponds to a 2.6 to 2.0 sigma effect. Alternatively, one may interpret this as the Tevatron having some capability to place 95% C.L. limits on this scenario.

We note that this analysis is different from the planned search for $t\bar{t}H$, which has the same final state signature, except for the lack of a mass peak in the extra bottom quark pair spectrum. The fact that this final state arising from light gluinos produces essentially identical kinematic distributions to the SM case makes our proposed channel search more difficult, but is mitigated by the much larger overall rate from light gluinos than from a Higgs boson. We speculate that this search could be improved at the Tevatron by requiring only three vertex tags, as in the analysis of Ref. [11]. This would increase the total sample by about a factor of 5, but would also approximately double the SM background by fake tags from $t\bar{t}gg$ events. Nevertheless, 22 signal events on a background of about 15 events is an $\approx 4.5\sigma$ effect. We feel that a more thorough investigation along these lines is warranted. It may also be useful to examine additional production channels at the Tevatron, such as $Z\tilde{g}\tilde{g}$, which will have larger cross sections but other complications in their analysis.

The situation is much better at the LHC. We calculate the SM $t\bar{t}b\bar{b}$ total cross section [$p_T(b) > 20$ GeV, no top quark decays] to be 1.9 pb, a rate copious enough to allow one to examine the cleaner all-leptonic top quark decay channel as well as the semileptonic channel. We find cut efficiencies of 30% and 20%, respectively. The $t\bar{t}\tilde{g}\tilde{g}$ cross section varies from 9.0 pb for 12 GeV gluinos to 7.2 pb for 16 GeV gluinos, as shown in Fig. 1. The $t\bar{t}b\bar{b}$ rate is 2.8 pb with LESS α_s running. Again using $\epsilon_b = 50\%$ and demanding four tags, we estimate that each experiment would observe from 15 to 12 signal events in the all-leptonic channel alone, with only 2 fb^{-1} of data. Against the SM background of 3.3 events, this would yield a 5σ effect over the entire gluino mass range considered. In the semileptonic channel for the same amount of data, we estimate 61 to 54 signal events on a background of 18 events, potentially resulting in better than a 12σ observation.

One caveat is that of the long-lived bottom squark scenario: if the daughter bottom quark jets coming from the low-p_T portion of the gluino spectrum do not have sufficient energy to be identified as jets, this analysis could suffer. To compensate we also investigated the case where all b partons and gluinos were instead required to have $p_T > 50$ GeV. The rates fall by somewhat more than 50%, but the all-leptonic decay channel would need only 10 fb^{-1} and the semileptonic channel only 3 fb^{-1} each to

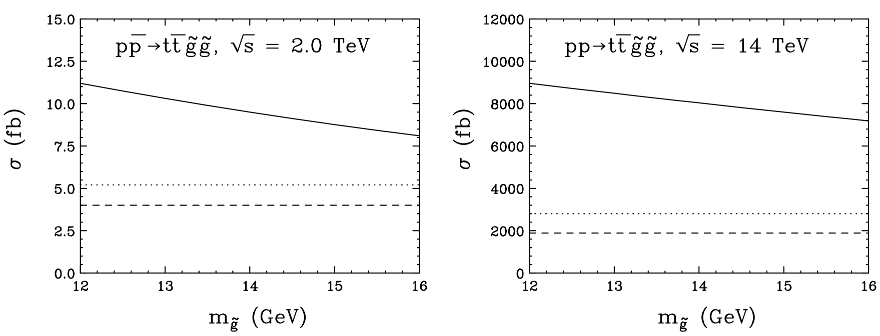

FIG. 1. $t\bar{t}\tilde{g}\tilde{g}$ cross section (solid lines) as a function of the gluino mass, $m_{\tilde{g}}$, at the Fermilab Tevatron (left) and CERN LHC (right) for $p_T(b) > 20$ GeV. Also shown are the SM $t\bar{t}b\bar{b}$ rates (dashed lines), and $t\bar{t}b\bar{b}$ rate with LESS-enhanced running of α_s (dotted lines).

reflect a 5σ observation of light gluinos. Thus, we feel that this analysis can easily be made model independent at the LHC.

A final point to consider is the scale uncertainty of the cross sections. We estimate this by first calculating the cross sections for $\mu_{f,r} = 2\mu_{f,r}$, $\mu_{f,r}/2$ and find about $+75\%/-45\%$ variation. We also find a 75% enhancement if we use μ_f as originally stated, but apply two factors of $\alpha_s(\mu_r = \mu_f)$ and two factors $\alpha_s(m_{jj})$. At LHC energies this results in an increase of about 75% in the rate. Since our signal cross sections are typically a factor of 4 larger than the SM background, we are safe in assuming that theoretical uncertainties on the cross section cannot be a limiting factor in this analysis.

We have presented an alternative production channel for light gluinos in a particular LESS model. It has the advantages of an extremely distinctive final state signature (four bottom quarks and two W bosons), scale uncertainties much smaller than the increase in rate due to non-SM particles, and the only model dependence is the gluino mass. The observable rate at the Tevatron, after kinematical cuts and approximate efficiencies, is unfortunately useful only to place probably 95% C.L. limits on the LESS scenario, and even then only with large integrated luminosity. However, the LHC can make a 5σ observation of light gluinos with only a few months of running at planned luminosity.

We thank Alex Kagan for useful discussions. Fermilab is operated by URA under DOE Contract No. DE-AC02-76CH03000.

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