Low-Energy Supersymmetry and the Tevatron Bottom-Quark Cross Section

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A long-standing discrepancy between the bottom-quark production cross section and predictions of perturbative quantum chromodynamics is addressed. We show that pair production of light gluinos, of mass 12 to 16 GeV, with two-body decays into bottom quarks and light bottom squarks, yields a bottom-quark production rate in agreement with hadron collider data. We examine constraints on this scenario from low-energy data and make predictions that may be tested at the next run of the Fermilab Tevatron collider.

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The measured cross section for bottom-quark production at hadron collider energies exceeds the expectations of next-to-leading order calculations in perturbative quantum chromodynamics (QCD) by about a factor of 2 [1]. The next-to-leading order (NLO) corrections are large, and it is not excluded that higher order effects in production or fragmentation may resolve the discrepancy. However, this long-standing discrepancy has so far resisted satisfactory resolution within the standard model (SM) of particle physics [2]. The disagreement is surprising because the relatively large mass of the bottom quark sets a hard scattering scale at which perturbative QCD computations of other processes are generally successful. In this Letter we explore an explanation of the discrepancy within the context of the minimal supersymmetric standard model (MSSM) [3]. We postulate the existence of a relatively light gluino $\tilde{g}$ (mass $\simeq 12-16$ GeV) that decays into a bottom quark and a light bottom squark $\tilde{b}$ (mass $\simeq 2-5.5$ GeV). The $\tilde{g}$ and the $\tilde{b}$ are the spin-1/2 and spin-0 supersymmetric partners of the gluon (g) and bottom quark (b). In our scenario the $\tilde{b}$ is either long-lived or decays hadronically. We obtain good agreement with hadron collider rates of bottom-quark production. Several predictions are made that can be tested readily with forthcoming data from run II of the Fermilab Tevatron collider.

Our assumptions are consistent with all experimental constraints on the masses and couplings of supersymmetric particles [4–12]. An analysis of four-jet data by the ALEPH Collaboration disfavors a $\tilde{g}$ with mass $m_{\tilde{g}} <$ 6.3 GeV [4] but does not cover the mass range considered in this Letter. An analysis by the UA1 Collaboration [5] of the mass range $4 < m_{\tilde{g}} < 53$ GeV does not apply to our scenario because they assume that the gluino decays into two quarks plus large missing energy. However, a new comparison to the UA1 data [2] does see an excess in the b-quark cross section, as would be expected in our model.

If the light $\tilde{b}$ is an appropriate admixture of left-handed and right-handed bottom squarks, its tree-level coupling to the neutral gauge boson Z can be small, leading to good agreement with the Z-peak observables [6]. Bottom squarks make a tiny contribution to the inclusive cross section for $e^+e^- \rightarrow$ hadrons, in comparison to the contributions from quark production, and $\tilde{b}\bar{\tilde{b}}$ resonances are likely to be impossible to extract from backgrounds [7,8]. One can study the angular distribution of hadronic jets produced in e^+e^- annihilation in order to bound the contribution of scalar-quark production. Spin-1/2 quarks and spin-0 squarks emerge with different distributions, $(1 \pm \cos^2\theta)$, respectively. We refit the angular distribution measured by the CELLO Collaboration [9] and find it is consistent with the production of a single pair of charge-1/3 squarks along with five flavors of quark-antiquark pairs. The exclusion by the CLEO Collaboration [10] of a $\tilde{b}$ with mass 3.5 to 4.5 GeV does not apply since that analysis focuses on the decays $\tilde{b} \rightarrow cl\tilde{\nu}$ and $\tilde{b} \rightarrow cl$ [11]. Thus, measurements at e^+e^- colliders do not significantly constrain $\tilde{b}$ masses in the region of interest.

A long-lived $\tilde{b}$ is not excluded by conventional searches at hadron and lepton colliders, but an analysis similar to that of Ref. [12] should be done to verify that there are no additional constraints on the allowed range of $\tilde{b}$ masses and lifetimes. Alternately, the $\tilde{b}$ could decay hadronically via a baryon-number- and R-parity-violating interaction into soft light hadrons which will fall within the cone of the b jet. The main constraint is that the $\tilde{b}$ does not decay into hard leptons or leave a large missing energy. The $\tilde{b}$ and $\tilde{g}$ masses we consider are also compatible with theoretical constraints which require the absence of color and charge breaking minima in the scalar potential [13].

Because the excess production rate is observed in all bottom-quark decay channels, an explanation in terms of "new physics" is guided towards hypothesized new particles that decay either like bottom quarks or directly to bottom quarks. The former is difficult to implement successfully in the MSSM, as explained in the discussion of alternative scenarios at the end of the Letter. We adopt the latter. In our scenario, light gluinos are produced in pairs via standard QCD subprocesses, dominantly $g + g \rightarrow \tilde{g} + \tilde{g}$ at Tevatron energies. The $\tilde{g}$ has a strong color coupling to b's and $\tilde{b}$'s and, as long as its mass satisfies $m_{\tilde{g}} > m_b + m_{\tilde{b}}$, the $\tilde{g}$ decays promptly to $b + \tilde{b}$. The magnitude of the b cross section, the shape of the b's transverse momentum p_{Tb} distribution, and the CDF measurement [14] of $B^0 - \bar{B}^0$ mixing are three features of the data that help to establish the preferred masses of the $\tilde{g}$ and $\tilde{b}$.

Including contributions from both $q + \bar{q} \rightarrow \tilde{g} + \tilde{g}$ and $g + g \rightarrow \tilde{g} + \tilde{g}$ [15], we show in Fig. 1 the integrated p_{Tb} distribution of the b quarks that results from $\tilde{g} \rightarrow b + \tilde{b}$, for $m_{\tilde{g}} = 14$ GeV and $m_{\tilde{b}} = 3.5$ GeV. The results are compared with the cross section obtained from NLO perturbative QCD [16] and CTEQ4M parton distribution functions (PDF's) [17], with $m_b = 4.75$ GeV, and a renormalization and factorization scale $\mu = \sqrt{m_b^2 + p_{Tb}^2}$. SUSY-QCD corrections to $b\bar{b}$ production are not included as they are not available and are generally expected to be somewhat smaller than the standard QCD corrections. A fully differential NLO calculation of $\tilde{g}$-pair production and decay does not exist either. Therefore, we compute the $\tilde{g}$-pair cross section from the leading order (LO) matrix element with NLO PDF's [17], $\mu = \sqrt{m_{\tilde{g}}^2 + p_{T\tilde{g}}^2}$, a two-loop α_s, and multiply by 1.9, the ratio of inclusive NLO to LO cross sections [18].

A relatively light gluino is necessary in order to obtain a bottom-quark cross section comparable in magnitude to the pure QCD component. Values of $m_{\tilde{g}} \simeq 12-16$ GeV are chosen because the resulting $\tilde{g}$ decays produce p_{Tb} spectra that are enhanced primarily in the neighborhood of $p_{Tb}^{\min} \simeq m_{\tilde{g}}$ where the data show the most prominent enhancement above the QCD expectation. Larger values of $m_{\tilde{g}}$ yield too little cross section to be of interest, and smaller values produce more cross section than seems tolerated by the ratio of like-sign to opposite-sign leptons from b decay, as discussed below. The choice of $m_{\tilde{b}}$ has an impact on the kinematics of the b. After selections on $p_{Tb}^{\min}$, large values of $m_{\tilde{b}}$ reduce the cross section and, in addition, lead to shapes of the p_{Tb} distribution that agree less well with the data. The values of $m_{\tilde{b}}$ and $m_{\tilde{g}}$ are correlated; similar results to those shown in Fig. 1 can be obtained with $m_{\tilde{g}} \simeq 12$ GeV, but $m_{\tilde{b}} \simeq m_b$.

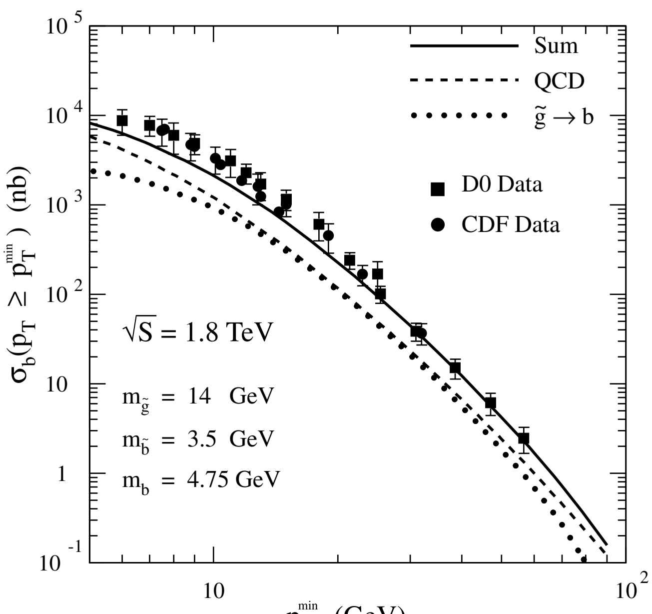

FIG. 1. Bottom-quark cross section in $p\bar{p}$ collisions at $\sqrt{S} = 1.8$ TeV for $p_{Tb} > p_{Tb}^{\min}$ with a gluino of mass $m_{\tilde{g}} = 14$ GeV and a bottom squark of mass $m_{\tilde{b}} = 3.5$ GeV. The dashed curve is the central value of the NLO QCD prediction. The dotted curve shows the p_T spectrum of the b from the supersymmetry (SUSY) processes. The solid curve is the sum of the QCD and SUSY components. Data are from Ref. [1].

After the contributions of the NLO QCD and SUSY components are added (solid curve in Fig. 1), the magnitude of the bottom-quark cross section and the shape of the integrated $p_{Tb}^{\min}$ distribution are described well. A theoretical uncertainty of roughly $\pm 30\%$ may be assigned to the final solid curve, associated with variation of the b mass, the scale, and the parton distributions.

The SUSY process produces bottom quarks in a four-body final state and thus their momentum correlations are different from those of QCD. Angular correlations between muons that arise from decays of b's have been measured [14,19]. Examining the angular correlations between b's in the SUSY case we find they are nearly indistinguishable from those of QCD once experimental cuts are applied.

Since the $\tilde{g}$ is a Majorana particle, its decay yields both quarks and antiquarks. Gluino pair production and subsequent decay to b's will generate bb and $\bar{b}\bar{b}$ pairs, as well as the $b\bar{b}$ final states that appear in QCD production.

We perform an exact matrix-element calculation of the four-body cross section for like-sign and opposite-sign bottom quarks from $\tilde{g}$-pair production and decay. When a gluino is highly relativistic, its helicity is nearly the same as its chirality. Therefore, selection of $\tilde{g}$'s whose transverse momentum is greater than their mass will reduce the number of like-sign b's. In the limit of either massless $\tilde{g}$'s or very high p_T cuts, the like-sign to opposite-sign ratio reduces to $y/(1 - y)$, where $y = \frac{1}{2}\sin^2 2\theta_{\tilde{b}}$ and $\sin\theta_{\tilde{b}}$ is the left-handed component of the lightest bottom-squark mass eigenstate. There is a strong suppression of like-sign b's if the mixing angle is small. For the case under consideration, the mixing of the bottom squark is determined by the condition that the $\tilde{b}$ coupling to the Z boson is small [6], namely, $\sin\theta_{\tilde{b}} \simeq 0.38$. In the intermediate p_T region, however, the like-sign suppression is reduced. The cuts chosen in hadron collider experiments for measurement of the like-sign to opposite-sign muon ratio result in primarily unpolarized $\tilde{g}$'s, and, independent of the $\tilde{b}$ mixing angle, an equal number of like-sign and opposite-sign b's is expected at production.

The SUSY mechanism leads to an increase of like-sign leptons in the final state after semileptonic decays of the b and $\bar{b}$ quarks. This increase could be confused with an enhanced rate of $B^0 - \bar{B}^0$ mixing. Time-integrated mixing analyses of lepton pairs observed at hadron colliders determine the quantity $\bar{\chi}$, expressed conventionally as $\bar{\chi} = f_d \chi_d + f_s \chi_s$, where f_d and f_s are the fractions of B_d^0 and B_s^0 hadrons, respectively, in the sample of semileptonic B decays, and χ_f is the time-integrated mixing probability for B_f^0. The quantity $2\bar{\chi}(1 - \bar{\chi})$ is the fraction of $b\bar{b}$ pairs that decay as like-sign b's. Our SUSY mechanism can be incorporated by introducing $\bar{\chi}_{\rm eff}$ such that $2\bar{\chi}_{\rm eff}(1 - \bar{\chi}_{\rm eff}) = [2\bar{\chi}(1 - \bar{\chi}) + G/2]/(1 + G)$, where G is the ratio of SUSY and QCD bottom-quark cross sections after cuts. The effective mixing parameter constrains G:

$$\bar{\chi}_{\rm eff} = \frac{\bar{\chi}}{\sqrt{1 + G}} + \frac{1}{2}\left[1 - \frac{1}{\sqrt{1 + G}}\right]. \qquad (1)$$

To estimate $\bar{\chi}_{\rm eff}$, we assume that the world average value $\bar{\chi} = 0.118 \pm 0.005$ [20] represents the contribution from only the pure QCD component. We determine the ratio G in the region of phase space where the measurement is made [14], with both final b's having p_T of at least 6.5 GeV and rapidity $|y_b| \leq 1$. The ratio is computed with LO matrix elements, NLO PDF's, α_s at two loops, and $\mu = m_x$, where x is b or $\tilde{g}$. The SUSY and QCD cross sections are multiplied by 1.9 and 2.3, respectively, to account for NLO effects [16,18]. For gluino masses of $m_{\tilde{g}} = 14$ and 16 GeV, we obtain $G = 0.37$ and 0.28, respectively, with $m_{\tilde{b}} = 3.5$ GeV. We compute $\bar{\chi}_{\rm eff} = 0.17$ for $m_{\tilde{g}} = 14$ GeV, and $\bar{\chi}_{\rm eff} = 0.16$ with $m_{\tilde{g}} = 16$ GeV.

To estimate the uncertainty on G, we vary the scale at which the cross sections are evaluated between $\mu = m_x/2$ and $\mu = 2m_x$. Uncertainties of $\pm 50\%$ are obtained and lead to uncertainties in the determined values of $\delta\bar{\chi}_{\rm eff} \simeq \pm 0.02$. Additional uncertainties arise because there is no fully differential NLO calculation of gluino production and subsequent decay to b's.

Our expectations may be compared with the CDF Collaboration's published value $\bar{\chi}_{\rm eff} = 0.131 \pm 0.02 \pm 0.016$ [14]. Values of $m_{\tilde{g}} > 12$ GeV lead to a calculated $\bar{\chi}_{\rm eff}$ that is consistent with the measured value within experimental and theoretical uncertainties.

The effects of light gluinos and bottom squarks on the strong gauge coupling α_s are potentially very significant. In the SM, a global fit to all observables provides an indirect measurement of α_s at the scale of the Z boson mass M_Z. The value $\alpha_s(M_Z) \simeq 0.119 \pm 0.006$ describes most observables properly [21]. QCD induced processes such as jet cross sections at hadron colliders and the top-quark cross section are consistent with this value of $\alpha_s(M_Z)$. A light $\tilde{g}$ with mass about 15 GeV and a light $\tilde{b}$ modify $\alpha_s(M_Z)$, determined by extrapolation from experiments performed at energies lower than $m_{\tilde{g}}$. The result is a shift of 0.007 in α_s derived from these experiments, to $\alpha_s(M_Z) = 0.125$. The value of $\alpha_s(M_Z)$ obtained from the Z hadronic width is modified by the presence of light $\tilde{b}$'s and light $\tilde{g}$'s, but the effect is slight because these superpartners approximately decouple from the Z. In the presence of light $\tilde{g}$'s, all values of $\alpha_s(M_Z)$ still fall within the range of experimental uncertainty, with a slight preference for the upper edge of the range. We do not attempt a global fit to the data.

Small values of $m_{\tilde{g}}$ and of the masses of the third generation squarks are helpful in supersymmetric solutions of the hierarchy problem of the SM. They reduce the fine-tuning needed, and avoid a color-breaking vacuum, in theories where SUSY is broken at the Planck scale [13,22]. Light gluinos are also helpful in improving gauge coupling unification by providing a light threshold in the evolution of α_s [23]. For gluinos of mass several hundred GeV, the strong coupling at M_Z predicted from unification is somewhat above 0.13. However, for gluinos of mass 15 GeV, this prediction becomes $\alpha_s(M_Z) \lesssim 0.127$, in agreement with the measured value. The upper limit is saturated when the masses of the weak gauginos are of the order of the weak scale.

Among the predictions of this SUSY scenario, the most clearcut is pair production of like-sign charged B mesons at the Tevatron collider. A very precise measurement of $\bar{\chi}$ in run II is obviously desirable. Since the fraction of b's from gluinos changes with p_{Tb}, we also expect a change of $\bar{\chi}$ with the cut on p_{Tb}. Possible bound states of bottom squark pairs are not expected to be prominent in e^+e^- annihilation [7] but could be seen as mesonic resonances in $\gamma\gamma$ reactions or as narrow states in μ pair production in hadron collisions. The existence of light $\tilde{b}$'s means that they will be pair produced in partonic processes, leading to a slight increase in the hadronic dijet rate. Our approach increases the b production rate at DESY ep collider HERA and in photon-photon collisions at CERN Large Electron-Positron Collider (LEP) by a small amount, not enough perhaps if early experimental indications in these cases are confirmed [24,25], but a full NLO study should be undertaken. Finally, to satisfy constraints from electroweak measurements, a light superpartner of the top quark, with mass about the top-quark mass should be present in the spectrum [6]. The lightest Higgs boson should be lighter than 123 GeV, and it should decay mainly into light $\tilde{b}$'s. A study of possible $\tilde{b}$ decay modes could be undertaken to see if our scenario can be made consistent with the Higgs-candidate events at LEP [26].

In our investigation, we consider and discard alternative scenarios. If only the $\tilde{b}$ is light, with $\tilde{b}$ decay products similar enough to those of the b quark, one can imagine that a light $\tilde{b}$ might be sufficient for a good description of the Tevatron b cross section. The cross section for pair production of light $\tilde{b}$'s becomes comparable to the bottom-quark rate for $m_{\tilde{b}} \simeq 3$ GeV. A $\tilde{b}$ with mass of about 3 GeV decaying through an R-parity violating process into a τ lepton and a charm quark could lead to an excess of the apparent b cross section. This scheme proves difficult to implement. Such a light $\tilde{b}$ cannot decay to a J/ψ and will therefore not reproduce the observed excess b cross section in this decay channel. Moreover, light $\tilde{b}$'s do not reproduce the observed p_T dependence of the b cross section.

If $m_{\tilde{b}} + m_b > m_{\tilde{g}}$, but $m_b < m_{\tilde{b}} < m_{\tilde{g}}$, the gluino can decay into a $\tilde{b}$ and a strange or down quark, followed by decay of the $\tilde{b}$ into a b and a light neutralino $\tilde{\chi}^0$. For this scenario, there must be a flavor violating coupling of $\tilde{g} - \tilde{b} - s$ of about 10^{-3} to suppress the branching ratio of the alternative $\tilde{g}$ decay channel: $\tilde{g} \to g\tilde{\chi}^0$. The problem is that a light $\tilde{b}$ proceeding from $\tilde{g}$ decay, and decaying into a b and missing energy, would lead to a $b\bar{b}$ plus missing energy cross section of order of 100 pb, so large that it should have been observed in the data from run I of the Tevatron collider [27].

In this Letter, we propose an interpretation of the excess bottom-quark production rate at the Tevatron that involves new physics and leads to several testable consequences. We show that pair production of low-mass gluinos that decay into bottom quarks and bottom squarks provides a good description of the b cross section and reproduces the measured ratio of like-sign to opposite-sign leptons. Our assumptions are consistent with all experimental constraints on SUSY particle masses.

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