Agreement of theoretical calculations with the observed production rate of bottom quarks at hadron colliders is improved by the introduction of a contribution from pair-production of light gluinos, of mass 12 to 16 GeV, having two-body decays into bottom quarks and light bottom squarks with mass $\sim 2$ to 5.5 GeV. Predictions are made for hadronic and radiative decays of the Upsilon states. In the limit of large $\tan \beta$, the dominant decay mode of the light scalar Higgs boson is into a pair of light bottom squarks that materialize as jets of hadrons.

1. INTRODUCTION

The cross section for bottom-quark $b$ production at hadron collider energies exceeds the central value of predictions of next-to-leading order (NLO) perturbative quantum chromodynamics (QCD) by about a factor of two or three [1]. The NLO contributions are large, and a combination of further higher-order effects in production and/or fragmentation may eventually reduce the discrepancy [2]. In Ref. [3], my collaborators and I propose a contribution from physics beyond the standard model (SM). In this paper, I summarize the proposal in Ref. [3] of light gluinos $\tilde{g}$ and light bottom squarks $\tilde{b}$, as well as subsequent work [4–8]. In this scenario the $\tilde{b}$ is the lightest supersymmetric (SUSY) particle, and the masses of all other SUSY particles are arbitrarily heavy, i.e., of order the electroweak scale or greater. The lifetime of the $\tilde{b}$ is assumed to be less than the cosmological time scale so that these squarks make no contribution to the dark matter density. References to an extensive body of other recent theoretical papers can be found in [7]. Various experimental constraints and phenomenological implications are examined in Ref. [5].

There are important restrictions on couplings of the $\tilde{b}$ from precise measurements of $Z^0$ decays. A light $\tilde{b}$ would be ruled out unless its coupling to the $Z^0$ is very small. The squark couplings to the $Z^0$ depend on the mixing angle $\theta_b$. The lowest-order (tree-level) coupling to the $Z^0$ can be arranged to be small [9] if $\sin^2 \theta_b \sim 1/6$. The couplings of the heavier bottom squark $\tilde{b}^2$ survive. A careful phenomenological analysis is needed of expected $\tilde{b}^2$ decay signatures, along with an understanding of detection efficiencies and expected event rates, before one knows the admissible range of its masses consistent with LEP data.

In the first paper of Ref. [10] it is argued that one-loop contributions may render the light $\tilde{g}$ and light $\tilde{b}$ scenario inconsistent with data, unless the mass of the $\tilde{b}^2$ is less than about 125 GeV. The possibility that $\tilde{b}^2$ lies in this mass range is not excluded. In the second paper, the mass bound is relaxed to about 180 GeV, and in the third, the constraint is further relaxed if $CP$-violating phases are present.

2. HADRON COLLIDERS

The light gluinos are produced in pairs via standard QCD subprocesses, dominantly $g + g \rightarrow \tilde{g} + \tilde{g}$ at Tevatron and Large Hadron Collider (LHC) 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 $p_T$ distribution, and the CDF measurement [11] of $B^0 - \bar{B}^0$ mixing are three features of the data that help to estab-
lish the preferred masses of the $\tilde{g}$ and $\tilde{b}$. Values of $m_{\tilde{b}} \simeq 12$ to 16 GeV are chosen because the resulting $\tilde{g}$ decays produce $p_{Tb}$ spectra that are enhanced primarily in the neighborhood of $p_{Tb}^{\text{min}} \simeq m_{\tilde{b}}$ where the data show the most prominent enhancement above the QCD expectation. Larger values of $m_{\tilde{b}}$ 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.

After the contributions of the NLO QCD and SUSY components are added, the magnitude of the bottom-quark cross section and the shape of the integrated $p_{Tb}^{\text{min}}$ distribution are described well. The SUSY process produces $b$'s in a four-body final state. Nevertheless, the angular correlations between $b$'s in the SUSY case are nearly indistinguishable from those of QCD once experimental cuts are applied. The energy dependence of the $b$ cross section is a potentially important constraint on models in which new physics is invoked. Since the assumed $\tilde{g}$ mass is larger than the mass of the $b$, the $\tilde{g}$ pair process will turn on more slowly with energy than pure QCD production of $b\bar{b}$ pairs. The new physics contribution will depress the ratio of cross sections at 630 GeV and 1.8 TeV from the pure QCD expectation. An explicit calculation with CTEQ4M parton densities and the $b$ rapidity selection $|y| < 1$, yields a pure NLO QCD prediction for the ratio of 0.17 $\pm$ 0.02 for $p_{Tb}^{\text{min}} = 10.5$ GeV, and 0.16 $\pm$ 0.02 after inclusion of the $\tilde{g}$ pair contribution. Either of these numbers is consistent with data [12].

2.1. Like/Unlike-sign $B$'s and Leptons

If, as in many scenarios, the $\tilde{g}$ is a Majorana particle, its decay yields both quarks and antiquarks. Pair production of Majorana gluinos 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. Therefore, a "gold-plated" prediction is production of $B^+B^+$ and $B^-\bar{B}^-$ pairs. For the cuts chosen in current hadron collider experiments, an equal number of like-sign and opposite-sign $b$'s is expected from the SUSY mechanism, leading to an increase of like-sign leptons in the final state after semi-leptonic 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 are interpreted in terms of the quantity $\chi$. The CDF measurement [11] of $\chi_{\text{eff}} = 0.131 \pm 0.01 \pm 0.016$ is marginally larger than the world average value $\chi = 0.118 \pm 0.005$ [13], assumed to be the contribution from the pure QCD component only. After the contribution from new physics is included, the predictions are $\chi_{\text{eff}} = 0.17 \pm 0.02$ for $m_{\tilde{b}} = 14$ GeV, and $\chi_{\text{eff}} = 0.16 \pm 0.02$ with $m_{\tilde{b}} = 16$ GeV. The calculated $\chi_{\text{eff}}$ is consistent with the data within uncertainties if $m_{\tilde{b}} > 12$ GeV. The published result is based on an analysis of only 20% of the run-I sample and only the $\mu\mu$ final state. It would be valuable to extend the analysis to the full sample in both the $e\mu$ and $\mu\mu$ modes.

With $\sigma_{bb}/\sigma_{qcd} \sim 1/3$, the mixing data and the magnitude and $p_T$ dependence of the $b$ production cross section can be satisfied.

3. $\Upsilon$ Decay

If $m_{\tilde{b}}$ is less than half the mass of one of the Upsilon states, then $\Upsilon$ decay to a pair of bottom squarks might proceed with sufficient rate for observation or exclusion of a light $b$. The rate for $\Upsilon(nS) \rightarrow bb^*$ is computed in Ref. [4] as a function of the masses of the $b$ and the $\tilde{g}$, and $\chi_{\Upsilon,b}$ decays are treated in Ref. [6]. The data sample is largest at the $\Upsilon(4S)$. For a fixed $\tilde{g}$ mass of 14 GeV, the branching fraction into a pair of $b$'s is about $10^{-4}$ for $m_{\tilde{b}} = 4.85$ GeV. A large sample may be available from the CLEO, BaBar, and BELLE experiments. Direct observation of $\Upsilon(nS)$ or $\chi_b$ decay into $b$'s requires an understanding of the ways that $b$'s may manifest themselves, discussed in Refs. [4–6]. Possible baryon-number-violating R-parity-violating decays of the $\tilde{b}$ lead to $u + s$; $c + d$; and $c + s$ final states.

It is possible that the $\tilde{b}$ is relatively stable and, hence, bound states of a bottom squark and bottom antiquark (bottomonium) could exist. These bound states could be produced in radiative decays of bottomonium states, such as $\Upsilon \rightarrow S\gamma$, where $S$ is the $S$-wave bound state of a $bb^*$ pair. In Ref. [8], a calculation is presented of the radiative decay of the $\Upsilon(nS)$ states into a
bound state of $\tilde{b}$'s. Predictions are provided of the branching fraction as a function of the masses $m_{\tilde{b}}$ and $m_{\tilde{g}}$. Branching fractions as large as several times $10^{-4}$ are obtained for SUSY particle masses in the range suggested by the analysis of the $b$ cross section. Provided that a bound state can be formed, the resonance search by the CUSB Collaboration [14] raises the allowed lower bounds on $m_{\tilde{b}}$ and $m_{\tilde{g}}$. Discovery of the $S$ bound states may be possible with the high-statistics 2002 CLEO-c data set, or a larger range of $\tilde{b}$ and $\tilde{g}$ masses may be disfavored [8].

4. HIGGS BOSON DECAY

Current strategies for discovery and measurement of the properties the neutral scalar Higgs particle $h$ with $m_h < 135$ GeV rely heavily on the presumption that the principal branching fractions are close to those predicted in the SM or in the usual minimal supersymmetric standard model (MSSM). For masses in this range, the decay width of the SM Higgs boson is dominated by its decay into bottom quarks, $b\bar{b}$. In Ref. [7], my collaborators and I show explicitly that these assumptions are not warranted if there are nonstandard light particles such as $b$'s in the spectrum. We analyze the possibility that the $h$ decays into new particles that manifest themselves as hadronic jets without necessarily significant bottom or charm flavor content. As an example of this possibility, we present the case of a light $\tilde{b}$, with mass smaller than about 10 GeV.

We work in the decoupling limit in which the mass of the pseudo-scalar Higgs boson ($m_A$) is large compared to $m_Z$, and we assume that the ratio of Higgs vacuum expectation values $\tan \beta$ is large. No assumption is made about the gluino mass; a light $\tilde{g}$ is not required. Under these conditions, the dominant decay of $h$ is into a pair of light $\tilde{b}$'s. The total decay width of the $h$ becomes several orders of magnitude larger than the width for decay into $b$'s. Branching fractions into SM decay channels are reduced from their SM values by a factor proportional to $\tan^{-2} \beta$. For values of the branching ratio $BR(h \rightarrow \tilde{b} \tilde{b}^*)$ larger than two to five times that into bottom quarks, the large QCD jet backgrounds will make observation of the $h$ very difficult in Tevatron and LHC experiments. Because they rely principally on the production process $e^+e^- \rightarrow hZ^0$, experiments at proposed $e^+e^-$ linear colliders remain fully viable for direct observation of the $h$ and measurement of its mass and some of its branching fractions [7].

REFERENCES