In this talk, I describe a supersymmetric solution to the long-standing discrepancy between the bottom-quark production cross section and predictions of perturbative quantum chromodynamics. Pair production of light gluinos, of mass 12–16 GeV, with two-body decays into bottom quarks and bottom squarks, of mass 2–5.5 GeV, yields the correct normalizations and shapes of the measured bottom-quark distributions. One prediction of this scenario is that like-sign $B$ mesons, $B^+B^+$ and $B^-B^-$, should be produced with a measurable rate at the next run of the Fermilab Tevatron Collider.

1 Introduction

The cross section for bottom-quark production is measured at hadron and photon colliders to be about a factor of 2 above the expectations of next-to-leading order (NLO) calculations in perturbative quantum chromodynamics (QCD). Despite more than ten years of effort, this discrepancy has resisted satisfactory resolution within the standard model (SM) of particle physics. This is surprising because the mass of the bottom quark sets a scale at which other perturbative QCD calculations are reliable. While additional higher-order QCD effects in production or fragmentation may solve part or all of the puzzle, a reasonable question to ask is whether this anomaly is a hint of “new physics”.

In a recent Letter, we explore an explanation of the discrepancy within the context of the minimal supersymmetric standard model (MSSM). We postulate the existence of a light bottom squark $\tilde{b}$ (mass $\simeq 2–5.5$ GeV) and a relatively light gluino $\tilde{g}$ (mass $\simeq 12–16$ GeV) that decays with 100% branching fraction to $b$ and $\tilde{b}$. The masses of these particles are constrained by fits to several different experiments as described below. The $\tilde{b}$ may either be long-lived or it may decay via R-parity-violating interactions into a pair of hadronic jets. We obtain good agreement with the magnitude and shape of the measured distributions of bottom-quark production at UA1 and
the Fermilab Tevatron. We also make several predictions, and point out a “golden channel” of like-sign $B$ mesons, $B^+ B^+$ or $B^- B^-$, that may either be observed, or whose absence will rule out this scenario, at run II of the Tevatron.

Our assumptions are consistent with all experimental constraints on the masses and couplings of supersymmetric particles.\textsuperscript{4–7} The tree-level coupling of the light $b_1$ to the $Z$ boson $g_{Zb_1b_2} \sim (T_3 \sin^2 \theta_b - Q_b \sin^2 \theta_W)$. Hence, if $\sin \theta_b \simeq 0.38$, $b_1$ approximately decouples from the $Z$, which leads to good agreement with the $Z$-peak observables.\textsuperscript{7} The couplings $g_{Zb_1b_2}$ and $g_{Zb_2b_2}$ survive, but are irrelevant as long as $m_{b_2} \gtrsim 200$ GeV. Production of $b_1$ pairs via virtual photons is a factor of 2–4 smaller than the best bound from LEPI\textsuperscript{8} Bottom squarks make a tiny ($\sim 2\%$) contribution to $e^+ e^- \rightarrow$ hadrons. Thus, despite the improved 6–10\% measurement of $R$ by the BES Collaboration\textsuperscript{9} presented at this meeting, there is no sensitivity to this resonance. Spin-1/2 quarks are produced in $e^+ e^-$ annihilations with an angular distribution of $(1 + \alpha \cos^2\theta)$ and $\alpha = 1$. The bottom squark appears as an effective $\alpha \simeq 0.92$. We refit the angular distribution measured by the CELLO Collaboration\textsuperscript{10} 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.

2 Comparison with Data

Because the excess production rate is observed in all bottom-quark decay channels and distributions, any solution will necessarily involve additional production of bottom quarks. In our scenario, light gluinos are dominantly produced by gluon fusion ($gg \rightarrow \tilde{g}g$) at Tevatron energies. As long as $m_{\tilde{g}} > m_b + m_{\tilde{b}}$, the $\tilde{g}$ decays promptly to $b + \tilde{b}$. In Fig. 1 we show the integrated $p_{Tb}$ distribution of the $b$ quarks as measured at UA1\textsuperscript{11} and the Tevatron.\textsuperscript{12} For comparison we plot the NLO cross section with CTEQ4M PDF’s, $m_b = 4.75$ GeV, scale $\mu = \sqrt{m_b^2 + p_{Tb}^2}$. We show separately the effect of $\tilde{g}$ production, followed by $\tilde{g} \rightarrow b + \tilde{b}$, for $m_{\tilde{b}} = 14$ GeV and $m_{\tilde{b}} = 3.5$ GeV. We compute the $\tilde{g}$-pair cross section from the leading order (LO) matrix element with NLO PDF’s, $\mu = \sqrt{m_{\tilde{g}}^2 + p_{T\tilde{g}}^2}$, a two-loop $\alpha_s$, and use a $K$-factor of 1.9\textsuperscript{13}

The SUSY-QCD corrections to $b\tilde{b}$ production are not yet available\textsuperscript{14}

A gluino of mass $m_{\tilde{g}} \simeq 12–16$ GeV is necessary give the correct magnitude of the cross section. The $\tilde{g}$ decays produce $p_{Tb}$ spectra that are enhanced primarily in the neighborhood of $p_{Tb}^{\min} \simeq m_{\tilde{g}}$, exactly 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, but are not ruled

![Figure 1: Bottom-quark cross section at UA1 ($\sqrt{s} = 630$ GeV) and the Tevatron ($\sqrt{s} = 1.8$ TeV) for $p_{Tb} > p_{Tb}^{\min}$ with $m_{\tilde{b}} = 14$ GeV and $m_{\tilde{b}} = 3.5$ GeV (solid); NLO QCD prediction (dashed); SUSY contribution (dotted).](image-url)
out. The interesting values of \( m_{\tilde{b}} \) and \( m_{\tilde{g}} \) are correlated; after selections on \( p_{Tb} \), large values of \( m_{\tilde{b}} \) reduce the cross section and lead to shapes of the \( p_{Tb} \) distribution that agree less well with the data.

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 \( p_{Tb} \) 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 \( b \)'s in the SUSY case we find they are nearly indistinguishable from those of QCD once experimental cuts are applied.

### 3 Effects on \( B^0-\bar{B}^0 \) Mixing

Since the \( \tilde{g} \) is a Majorana particle, its decay can yield either quarks or antiquarks. Given the kinematic cuts applied at hadron colliders, gluino pair production and subsequent decay to \( b \)'s will generate a number of \( bb \) and \( \bar{b}\bar{b} \) pairs equal to the number of \( bb \) final states. This leads to the “golden signature” of like-sign \( B \) mesons, \( B^+B^+ \) and \( B^-B^- \). If these do not appear in the run II data, then this scenario may be ruled out.

We predict there will be 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 \( \tilde{B}^0-\bar{B}^0 \) mixing. Time-integrated mixing analyses of lepton pairs determine the quantity \( \bar{\chi} = f_d\chi_d + f_s\chi_s \), where \( f_d \) and \( f_s \) are the fractions of \( B^0_d \) and \( B^0_s \) hadrons, respectively, in the sample of semi-leptonic \( B \) decays, and \( \chi_f \) is the time-integrated mixing probability for \( B^0_f \). The quantity \( 2\bar{\chi}(1-\chi) \) is the fraction of \( bb \) pairs that decay as like-sign \( b \)'s. Our SUSY mechanism can be incorporated by introducing \( \bar{\chi}_{\text{eff}} \) such that \( 2\bar{\chi}_{\text{eff}}(1-\bar{\chi}_{\text{eff}}) = [2\bar{\chi}(1-\chi) + G/2]/(1+G) \), where \( G \) is the ratio of SUSY and QCD bottom-quark cross sections after cuts. Hadron colliders measure

\[
\bar{\chi}_{\text{eff}} = \frac{\bar{\chi}}{\sqrt{1+G}} + \frac{1}{2} \left[ 1 - \frac{1}{\sqrt{1+G}} \right].
\]

To estimate \( \bar{\chi}_{\text{eff}} \), we assume that the world average value \( \bar{\chi} = 0.118 \pm 0.005 \) represents the contribution from only the pure QCD component. We determine \( \bar{\chi}_{\text{eff}} \) in the region of phase space where the measurement is made with both final \( b \)'s having \( p_T \) of at least 6.5 GeV and rapidity \( |y_b| \leq 1 \). For gluino masses of \( m_{\tilde{g}} = 14 \) and 16 GeV, we obtain \( \bar{\chi}_{\text{eff}} = 0.17 \pm 0.02 \) and \( 0.16 \pm 0.02 \), respectively. There is an additional uncertainty of \( \pm 0.02 \) from the lack of a NLO calculation of \( \tilde{g} \to bb \) distributions. Our expectations may be compared with the CDF Collaboration’s published value \( \bar{\chi}_{\text{eff}} = 0.131 \pm 0.02 \pm 0.016 \). Values of \( m_{\tilde{g}} > 12 \) GeV lead to a calculated \( \bar{\chi}_{\text{eff}} \) that is consistent with the measured value within experimental and theoretical uncertainties.

### 4 Additional Implications

In the standard model, a global fit to all observables provides an indirect measurement of \( \alpha_s(M_Z) \approx 0.119 \pm 0.006 \). A light \( \tilde{g} \) with mass about 15 GeV and a light \( \tilde{b} \) modify the QCD \( \beta \) function. Thus, experiments performed below \( m_{\tilde{g}} \) would predict \( \alpha_s(M_Z) = 0.125 \). This is within the range of experimental uncertainty, and in better agreement with some measurements at LEP. Light gluinos are also helpful in improving gauge coupling unification by providing a light threshold in the evolution of \( \alpha_s \). 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 \( \alpha_s(M_Z) \approx 0.127 \), in agreement with the measured value.

If the \( \tilde{b} \) is relatively stable, the \( \tilde{b} \) could pick up a light \( \tilde{u} \) or \( \tilde{d} \) and become a \( \tilde{B}^- \) or \( \tilde{B}^0 \) “mesino” with \( J = 1/2 \). The mass of the mesino would be roughly 3–7 GeV for the interval of \( b \) masses
we consider. The charged mesino could fake a heavy muon if it punches through the hadron calorimeter, or perhaps act like a heavy $\bar{p}$—possibly detectable with a time-of-flight apparatus. A long-lived $\tilde{b}$ is not excluded by conventional searches at hadron and lepton colliders.

If $R$ parity is violated, the bottom squark can decay either promptly, or somewhere outside of the detector. The CLEO Collaboration has constrained a promptly decaying $\tilde{b}$ with mass 3.5–4.5 GeV with the decay chain $\tilde{b} \rightarrow cl\nu$ or $\tilde{b} \rightarrow cl$. Baryon-number-violating decays, however, are nearly unconstrained. In this case, the bottom squark decays to 2 jets with a width,

$$\Gamma(\tilde{b} \rightarrow jj) = \frac{m_{\tilde{b}}}{2\pi} \sin^2 \theta_{\tilde{b}} \sum_{j<k} |\lambda''_{ijj}|^2 .$$

If $m_{\tilde{b}} = 3.5$ GeV, $\Gamma(\tilde{b} \rightarrow ij) = 0.08|\lambda''_{ijj}|^2$ GeV. Unless all $\lambda''_{ijj}$ are extremely small, the $\tilde{b}$ will decay quickly and leave soft hadrons in the cone around the $b$-jet.

There appears to be roughly a factor of 2 difference between the QCD prediction and the $b$ production rate measured at the $ep$ collider HERA and in photon-photon collisions at LEP. Whether the existence of light bottom squarks and gluinos in the mass ranges we consider will produce enough of an excess to explain these experiments is unknown. A full NLO study is underway to determine the effect.

Acknowledgments

I am indebted to Ed Berger, Brian Harris, David E. Kaplan, Tim Tait, and Carlos Wagner for their collaboration and insight. This work is supported by the U.S. Department of Energy under Contract W-31-109-ENG-38.

References

1. CDF Collaboration, F. Abe et al., Phys. Rev. Lett. 71, 500 (1993); 79, 572 (1997); 75, 1451 (1995); D0 Collaboration, B. Abbott et al., Phys. Lett. B 487, 264 (2000); Phys. Rev. Lett. 85, 5068 (2000).
2. P. Nason et al., in Proceedings of the 1999 CERN Workshop on Standard Model Physics (and more) and the LHC, edited by G. Altarelli and M. L. Mangano (CERN, Geneva, 2000), p. 231; S. Frixione, M. L. Mangano, P. Nason, and G. Ridolfi, in Heavy Flavors II, edited by A. J. Buras and M. Linder (World Scientific, Singapore, 1997).
3. E. L. Berger, B. W. Harris, D. E. Kaplan, Z. Sullivan, T. M. P. Tait, and C. E. M. Wagner, Phys. Rev. Lett. 86, 4231 (2001).
4. M. Carena, S. Heinemeyer, C. E. M. Wagner, and G. Weiglein, Phys. Rev. Lett. 86, 4463 (2001).
5. DELPHI Collaboration, P. Abreu et al., Phys. Lett. B 444, 491 (1998).
6. BES Collaboration, J. Z. Bai et al., hep-ex/0102003; N. Wu, in this Proceedings.
7. CELLO Collaboration, H.-J. Behrend et al., Phys. Lett. B 183, 400 (1987).
8. UA1 Collaboration, C. Albajar et al., Phys. Lett. B 198, 261 (1987).
9. See Refs. 16–18 of Berger et al. (Ref. 3 above) for details and references.
10. Z. Sullivan, in production.
11. CDF Collaboration, F. Abe et al., Phys. Rev. D 55, 2546 (1997).
12. D0 Collaboration, B. Abbott et al., Phys. Lett. B 487, 264 (2000), and references therein.
13. Particle Data Group, D. E. Groom et al., Eur. Phys. Jour. C 15, 1 (2000).
14. CLEO Collaboration, V. Savinov et al., Phys. Rev. D 63, 051101 (2001).
15. E. L. Berger, B. W. Harris, and Z. Sullivan, Phys. Rev. Lett. 83, 4472 (1999); Phys. Rev. D 63, 115001 (2001).
16. H1 Collaboration, C. Adloff et al., Phys. Lett. B 467, 156 (1999); ZEUS Collaboration, J. Breitweg et al., Eur. Phys. Jour. C 18, 625 (2001); L3 Collaboration, M. Acciarri et al., Phys. Lett. B 503, 10 (2001); OPAL Collaboration, A. Csilling et al., hep-ex/0010060.