Supersymmetry Explanation for the Puzzling Bottom Quark Production Cross Section

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Abstract. It has been known for a long time that the cross section for bottom-quark $b$ production at hadron collider energies exceeds theoretical expectations. An additional contribution from pair-production of light gluinos $\tilde{g}$, of mass 12 to 16 GeV, with two-body decays into bottom quarks and light bottom squarks $\tilde{b}$, helps to obtain a $b$ production rate in better agreement with data. The masses of the $\tilde{g}$ and $\tilde{b}$ are restricted further by the ratio of like-sign to opposite-sign leptons at hadron colliders. Constraints on this scenario from other data are examined, and predictions are made for various processes such as Upsilon decay into $\tilde{b}'s$.

INTRODUCTION

The cross section for bottom-quark 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 [1, 2]. This longstanding discrepancy has resisted fully satisfactory resolution within the standard model [3]. The NLO contributions are large, and it is not excluded that a combination of further higher-order effects in production and/or fragmentation may resolve the discrepancy. However, the disagreement is surprising because the relatively large mass of the bottom quark sets a hard scattering scale at which fixed-order perturbative QCD computations of other processes are generally successful. The photoproduction cross section at DESY’s HERA [4] and the cross section in photon-photon reactions at CERN’s LEP [5] also exceed NLO expectations. The data invite the possibility of a contribution from "new physics".

SUPERSYMMETRY INTERPRETATION

The properties of new particles that can contribute significantly to the bottom quark cross section are fairly well circumscribed. To be produced with enough cross section the particles must interact strongly and have relatively low mass. They must either decay into $b$ quarks or be close imitators of $b$'s in a variety of channels of observation. They must evade constraints based on precise data from measurements of $Z^0$ decays at CERN’s LEP and SLAC’s SLC, and from many lower-energy $e^+ e^-$ collider experiments. The minimal supersymmetric standard model (MSSM) is a favorite candidate in many quarters for physics beyond the standard model. It offers a well-motivated theoretical framework and is reasonably well-explored phenomenologically. An explanation within the context of the MSSM [6] can satisfy all of the stated criteria.
In Ref. [6], the existence is assumed of a relatively light color-octet gluino $\tilde{g}$ (mass $\simeq 12$ to 16 GeV) that decays with 100% branching fraction into a bottom quark $b$ and a light color-triplet bottom squark $\tilde{b}$ (mass $\simeq 2$ to 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. In this scenario the $\tilde{b}$ is the lightest SUSY particle, and the masses of all other SUSY particles are arbitrarily heavy, i.e., of order the electroweak scale or greater. The $\tilde{b}$ is either long-lived or decays via R-parity violation into a pair of hadronic jets. Improved agreement is obtained with hadron collider rates of bottom-quark production, and several predictions are made that can be tested readily with forthcoming data.

**Differential Cross Section**

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 $p_{Tb}$ distribution, and the CDF measurement [7] 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 $\tilde{b}$. In Ref. [6], contributions are included from both $q + \bar{q} \rightarrow \tilde{g} + \tilde{g}$ and $g + g \rightarrow \tilde{g} + \tilde{g}$. The subprocess $g + b \rightarrow \tilde{g} + \tilde{b}$ contributes insignificantly. Shown in Fig. 1 is 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 next-to-leading order (NLO) perturbative QCD and CTEQ4M parton distribution functions (PDF’s) [8], with $m_b = 4.75$ GeV, and a renormalization and factorization scale $\mu = \sqrt{m_b^2 + p_{Tb}^2}$. SUSY-QCD corrections to $bb$ 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, the $\tilde{g}$-pair cross section is computed from the leading order (LO) matrix element with NLO PDF’s [8], $\mu = \sqrt{m_{\tilde{g}}^2 + p_{T\tilde{g}}^2}$, and a two-loop expression for the strong coupling $\alpha_s$. To account for NLO effects, this $\tilde{g}$-pair cross section is multiplied by 1.9, the ratio of inclusive NLO to LO cross sections [9].

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 $m_{\tilde{g}} \simeq 12$ to 16 GeV are chosen because the resulting $\tilde{g}$ decays produce $p_{Tb}$ spectra that are enhanced primarily in the neighborhood of $p_{Tb}^{\text{min}} \simeq m_{\tilde{g}}$ 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 $p_{Tb}^{\text{min}}$, 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.

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
FIGURE 1. Bottom-quark cross section in $p\bar{p}$ collisions at $\sqrt{S} = 1.8$ TeV for $p_T b > p_T^{\min}$ 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 SUSY processes. The solid curve is the sum of the QCD and SUSY components. The shaded band represents an uncertainty of roughly ±30% associated with variations of the renormalization and factorization scales, the $b$ mass, and the parton densities. The rapidity cut on the $b$'s is $|y_b| \leq 1$. Data are from Ref. 1.

are described well. Very good agreement is obtained also with data from the UA1 experiment (not shown) [2]. 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 [7, 10]. 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 bottom cross section is a potentially important constraint on models in which new physics is invoked to interpret the observed excess bottom quark yield. 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 QCD prediction at NLO of 0.17 +/- 0.02 for $p_T^{\min} = 10.5$ GeV, and 0.16 +/- 0.02 after inclusion of the gluino pair contribution. Either of these numbers is consistent with forthcoming data from CDF on
Same-sign to Opposite-sign Leptons

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 \( \bar{b}b \) final states that appear in QCD production. 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 intermediate \( p_T \) region, however, the like-sign suppression is reduced. The cuts chosen in current hadron collider experiments for measurement of the ratio of like-sign to opposite-sign muons 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 therefore to an increase of like-sign leptons in the final state after semi-leptonic decays of the \( b \) and \( \tilde{b} \) 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 \( \chi = f_d\chi_d + f_s\chi_s \), where \( f_d \) and \( f_s \) are the fractions of \( B^0_{d(S)} \) and \( B^0_{s(S)} \) hadrons in the sample of semi-leptonic \( B \) decays, and \( \chi_f \) is the time-integrated mixing probability for \( B^0_f \). Conventional \( b\bar{b} \) pair production determines the quantity \( LS_c = 2\chi(1-\chi) \), the fraction of \( b\bar{b} \) pairs that decay into like-sign leptons. The SUSY mechanism leads to a new expression

\[
LS = \frac{1}{2} \frac{\sigma_{\tilde{g}\tilde{g}}}{\sigma_{\tilde{g}\tilde{g}} + \sigma_{\text{qcd}}} + LS_c \frac{\sigma_{\text{qcd}}}{\sigma_{\tilde{g}\tilde{g}} + \sigma_{\text{qcd}}} = 2\chi_{\text{eff}}(1-\chi_{\text{eff}}).
\]

The factor \( 1/2 \) arises because \( N(bb + \bar{b}b) \sim N(b\bar{b}) \) in the SUSY mechanism for the selections on \( p_T b \) made in the CDF run I analysis. Defining \( G = \sigma_{\tilde{g}\tilde{g}}/\sigma_{\text{qcd}} \), the ratio of SUSY and QCD bottom-quark cross sections after cuts, and solving for the effective mixing parameter, one obtains

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

The CDF measurement is interpreted in Ref. [8] as a determination of \( \chi_{\text{eff}} = 0.131 \pm 0.02 \pm 0.016 \) [9]. This number is marginally larger than the world average value \( \chi = 0.118 \pm 0.005 \) [10], assumed to be the contribution from the pure QCD component only.

The ratio \( G \) is determined in the region of phase space where the measurement is made [7], with both final \( b \)'s having \( p_T b \geq 6.5 \) GeV and rapidity \( |y_b| \leq 1 \). With \( m_b = 3.5 \) GeV, \( G = 0.37 \) and \( 0.28 \) for gluino masses \( m_{\tilde{g}} = 14 \) and \( 16 \) GeV, respectively. The predictions are \( \chi_{\text{eff}} = 0.17 \pm 0.02 \) for \( m_{\tilde{g}} = 14 \) GeV, and \( \chi_{\text{eff}} = 0.16 \pm 0.02 \) with \( m_{\tilde{g}} = 16 \) GeV. Additional theoretical uncertainties arise because there is no fully differential NLO calculation of gluino production and subsequent decay to \( b \)'s. The choice \( m_{\tilde{g}} > 12 \) GeV leads to a calculated \( \chi_{\text{eff}} \) that is consistent with the data within experimental and theoretical uncertainties. With \( \sigma_{\tilde{g}\tilde{g}}/\sigma_{\text{qcd}} \sim 1/3 \), the mixing data and the magnitude and \( p_T \) dependence of the \( b \) production cross section can be satisfied.
An early study by the UA1 Collaboration [13] excludes $\tilde{g}$’s in the mass range $4 < m_{\tilde{g}} < 53$ GeV, but it starts from the assumption that there is a light neutralino $\tilde{\chi}_1^0$ whose mass is less than the mass of the gluino. The conclusion is based on the absence of the expected decay $\tilde{g} \rightarrow q + \bar{q} + E_T$, where $E_T$ represents the missing energy associated with the $\tilde{\chi}_1^0$. In the scenario discussed above, this decay process does not occur since the bottom squark is the LSP, the SUSY particle with lowest mass, and the $\tilde{\chi}_1^0$ mass is presumed to be large ($i.e.$, $> 50$ GeV). An analysis of 2- and 4-jet events by the ALEPH collaboration [14] disfavors $\tilde{g}$’s with mass $m_{\tilde{g}} < 6.3$ GeV but not $\tilde{g}$’s in the mass range relevant for the SUSY interpretation of the bottom quark production cross section. A similar analysis is reported by the OPAL collaboration [15]. A light $\tilde{b}$ is not excluded by the ALEPH analysis. The exclusion by the CLEO collaboration [16] of a $\tilde{b}$ with mass 3.5 to 4.5 GeV does not apply since their analysis focuses only on the decays $\tilde{b} \rightarrow c \ell \bar{\nu}$ and $\tilde{b} \rightarrow c \ell$. The $\tilde{b}$ need not decay leptonically nor into charm. On the other hand, these data might be reinterpreted in terms of a bound on the R-parity violating lepton-number violating decay of $\tilde{b}$ into $c \ell$. It would be interesting to study the hadronic decays $\tilde{b} \rightarrow c q$, with $q = d$ or $s$, and $\tilde{b} \rightarrow u s$ with the CLEO data. The DELPHI collaboration’s [17] search for long-lived squarks in their $gg$ event sample is not sensitive to $m_{\tilde{b}} < 15$ GeV.

There are important constraints on couplings of the bottom squarks 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 $\theta_b$. As described in Ref. [18], if the light bottom squark ($\tilde{b}_1$) is an appropriate mixture of left-handed and right-handed bottom squarks, its lowest-order (tree-level) coupling to the $Z^0$ can be arranged to be small if $\sin^2 \theta_b \sim 1/6$. The couplings $Z_{\tilde{b}_1} b_2$ and $Z_{\tilde{b}_2} b_2$ survive, where $\tilde{b}_2$ is the heavier bottom squark. However, as long as the combination of the masses $m_{\tilde{b}_1} + m_{\tilde{b}_2}$ is less than the maximum center-of-mass energy explored at LEP, these couplings present no difficulty. This condition roughly implies $m_{\tilde{b}_2} > 200$ GeV. However, much lower masses of $\tilde{b}_2$ might be tolerated. 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 masses consistent with LEP data. At higher-order, unless the $\tilde{b}_2$ mass is of order 100 GeV, contributions from loop processes in which light gluinos are exchanged may produce significant deviations from measurements of the ratios $A_b$, the forward-backward $b$ asymmetry at the $Z^0$, and $R_b$, the hadronic branching ratio of the $Z^0$ into $b$ quarks [19, 20].

Bottom squarks make a small contribution to the inclusive cross section for $e^+ e^- \rightarrow$ hadrons, in comparison to the contributions from quark production, and $\tilde{t} \tilde{t}$ resonances are likely to be impossible to extract from backgrounds [21]. The angular distribution of hadronic jets produced in $e^+ e^-$ annihilation can be examined 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. The angular distribution measured by the CELLO collaboration [22] is consistent with the production of a single pair of charge-1/3 squarks along with five flavors of quark-antiquark pairs. A new examination of the angular distribution with greater statistics would be valuable.

### CONCLUSIONS FROM OTHER DATA

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PREDICTIONS AND IMPLICATIONS

\( Y \) Decay into Bottom Squarks

If the bottom squark mass 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 experimental observation or exclusion of a light bottom squark. In Ref. [23], the expected rate for \( Y \to \tilde{b}\tilde{b}^* \) is computed as a function of the masses of the bottom squark and the gluino. The mass of the gluino enters because the \( \tilde{g} \) is exchanged in the decay subprocesses. The electronic width of the \( Y \) is used as the source of absolute normalization.

The data sample is largest at the \( \Upsilon(4S) \). For a fixed gluino mass of 14 GeV, the branching fraction into a pair of bottom squarks is about \( 10^{-3} \), for \( m_{\tilde{b}} = 2.5 \text{ GeV} \), and about \( 10^{-4} \) for \( m_{\tilde{b}} = 4.85 \text{ GeV} \). A sample as large as \( 10^6 \) may be available in current data from runs of the CLEO detector.

The predicted decay rates for the \( \Upsilon(nS) \), \( n = 1, 3 \) are shown in Fig. 2 These curves can be read as predictions of the width for the corresponding values of \( m_{\tilde{b}} \) and \( m_{\tilde{g}} \), or as lower limits on the sparticle masses given known bounds on the branching fractions. The current experimental uncertainties on the hadronic widths of the \( \Upsilon \)'s are compatible with the range of values of \( m_{\tilde{b}} \) and \( m_{\tilde{g}} \) favored in the work on the bottom quark production cross section in hadron reactions described above. The analysis of \( \Upsilon(nS) \) decays shows nevertheless that tighter experimental bounds on the bottom squark fraction are potentially powerful for the establishment of lower bounds on \( m_{\tilde{b}} \) and \( m_{\tilde{g}} \).

The hadronic width of the \( Y \) is calculated in conventional QCD perturbation theory from the three-gluon decay subprocess, \( Y \to 3g \), and \( \Gamma_{3g} \propto \alpha_s^3 \). The SUSY subprocess adds a new term to the hadronic width from \( Y \to \tilde{b} + \tilde{b} \). If this new subprocess is present but ignored in the analysis of the hadronic width, the true value of \( \alpha_s(\mu = m_b) \) will be smaller than that extracted from a standard QCD fit by the factor \( \left( 1 - \frac{1}{\Gamma_{SUYSY}/\Gamma_{3g}} \right)^{\frac{1}{3}} \). For a contribution from the \( \tilde{b}\tilde{b} \) final state that is 25% of \( \Gamma(1S) \) (i.e., a ratio \( R_{\tilde{b}\tilde{b}} = 10 \) in Fig. 2), the value of \( \alpha_s \) extracted will be reduced by a factor of 0.9, at the lower edge of the approximately 10% uncertainty band on the commonly quoted value of \( \alpha_s(\mu) \) [24]. A thorough analysis would require the computation of next-to-leading order contributions in SUSY-QCD to both the \( 3g \) and \( \tilde{b}\tilde{b} \) amplitudes and the appropriate evolution of \( \alpha_s(\mu) \) with inclusion of a light gluino and a light bottom squark.

Direct observation of Upsilon decay into bottom squarks requires an understanding of the ways that bottom squarks may manifest themselves, discussed in more detail below. Possible baryon-number-violating R-parity-violating decays of the bottom squark lead to \( u + s; c + d; \) and \( c + s \) final states. These final states of four light quarks should be distinguishable from conventional hadronic final states mediated by the three-gluon intermediate state. If the \( \tilde{b} \) lives long enough, it will pick up a light quark and turn into a \( B \)-mesino, \( \tilde{B} \). Charged \( B \)-mesino signatures in \( Y \) decay include single back-to-back equal momentum tracks in the center-of-mass; measurably lower momentum than lepton pairs (\( < 4 \text{ GeV/c} \) vs. \( \simeq 5 \text{ GeV/c} \) for muons and electrons); \( 1 + \cos^2 \theta \) angular distribution; and ionization, time-of-flight, and Cherenkov signatures consistent with a particle whose
FIGURE 2. Loci in the $m_{\tilde{b}} - m_{\tilde{g}}$ plane for which the rate for Upsilon decay into a pair of bottom squarks is either 10 times $\Gamma_{\ell\ell}$ for each $\Upsilon(nS)$, with $n = 1 - 3$ (lower set of curves) or equal to $\Gamma_{\ell\ell}$ (upper set). Above the curves, the rate would be less. Within each set of curves, the order is (bottom to top) 1S, 2S, 3S.

mass is heavier than that of a proton. At stake is discovery, or new limits on the mass, of the $\tilde{b}$ as well as measurement of or new limits on the R-parity violation couplings of the $\tilde{b}$.

Pseudoscalar $\eta_b$ decay into a pair of bottom squarks is forbidden, but the higher-order process of $\eta_b$ decay into a pair of $B$-mesinos can proceed. Decays of the $\chi_{b0}$ and $\chi_{b2}$ into a pair of bottom squarks are allowed.

**Hadron Reactions**

Among the predictions of this SUSY scenario, the most clearcut is pair production of like-sign charged $B$ mesons at hadron colliders, $B^+B^-$ and $B^-B^-$. To verify the underlying premise, that the cross section exceeds expectations of conventional perturbative QCD, a new measurement of the absolute rate for $b$ production in run II of the Tevatron is important. A very precise measurement of $\bar{\chi}$ in run II is desirable. Since the fraction of $b$’s from gluinos changes with $p_{Tb}$, a change of $\bar{\chi}$ is expected when the cut on $p_{Tb}$ is changed. The $b$ jet from $\tilde{g}$ decay into $b\bar{b}$ will contain the $\tilde{b}$, implying unusual material associated with the $\tilde{b}$ in some fraction of the $b\bar{b}$ data sample. The existence of light $\tilde{b}$’s
means that they will be pair-produced in partonic processes, leading to a slight increase (\(\sim 1\%\)) in the hadronic dijet rate.

The SUSY approach increases the \(b\) production rate at HERA and in \(\gamma\gamma\) collisions at LEP by a small amount, not enough perhaps if early experimental indications in these cases are confirmed \([4, 5]\). Full NLO SUSY-QCD studies should be undertaken. In these two cases, the apparent discrepancy may find at least part of its resolution in the fact that \(b\bar{b}\) production occurs very near threshold where fixed-order QCD calculations are not obviously reliable. Uncertain parton densities of photons may play a significant role.

**Running of \(\alpha_s\)**

The presence of a light gluino and a light bottom squark slow the running of the strong coupling strength \(\alpha_s(\mu)\). Above gluino threshold, the \(\bar{\beta}\) function of (SUSY) QCD is

\[
\bar{\beta}(\alpha_s) = \frac{\alpha_s^2}{2\pi} \left(-11 + \frac{2}{3}n_f + \frac{1}{6}n_s + 2\right).
\]  

The \(\tilde{b}\) (color triplet scalar) contributes little to the running, equivalent to that of 1/4'th of a new flavor, but the \(\tilde{g}\) (color octet fermion) is much more significant, equivalent to that of 3 new flavors of quarks. A precise determination of \(\bar{\beta}(\alpha_s)\) appears to be the best way to exclude the presence of a light gluino or to establish its possible presence.

In the standard model, a global fit to all observables provides an indirect measurement of \(\alpha_s\) at the scale of the \(Z\) boson mass \(M_Z\). The value \(\alpha_s(M_Z) \approx 0.1184 \pm 0.006\) describes most observables properly \([24]\). Extrapolation from \(M_Z\) to a lower scale \(\mu\) with inclusion of a light gluino reduces \(\alpha_s(\mu)\) from its pure QCD value. The presence of a light gluino, with or without a light bottom squark, also requires reanalysis of the phenomenological determinations of \(\alpha_s(\mu)\) at all scales to take into account SUSY processes and SUSY-QCD corrections to the amplitudes that describe the relevant processes. To date, a systematic study of this type has not been undertaken, but, as mentioned above, consistency is achieved for \(Y\) decays. A lesser value of \(\alpha_s(m_b)\) leads, under slower evolution, to the same \(\alpha_s(M_Z)\).

Slower running of \(\alpha_s(Q)\) also means a slower evolution of parton densities at small \(x\), an effect that might be seen in HERA data for \(Q > m_{\tilde{g}}\). Presence of a scalar \(\tilde{b}\) in the proton breaks the Callan-Gross relation and yields a non-zero leading-twist longitudinal structure function \(F_L(x, Q)\) at leading-order.

**\(\tilde{b}\)-onia**

Bound states of bottom squark pairs could be seen as \(J^P = 0^+, 1^-, 2^+, \ldots\) mesonic resonances in \(\gamma\gamma\) reactions and in \(p\bar{p}\) formation, with masses in the 4 to 10 GeV range. They could show up as narrow states in the \(\mu^+\mu^-\) invariant mass spectra at hadron colliders, between the \(J/\Psi\) and \(Y\). At an \(e^+e^-\) collider, the intermediate photon requires production of a \(J^{PC} = 1^{--}\) state. Bound states of low mass squarks with charge \(2/3\) were
studied with a potential model [21]. The small leptonic widths were found to preclude bounds for \( m_{\tilde{q}} > 3 \) GeV. For bottom squarks with charge \(-1/3\), the situation is more difficult.

\( \tilde{b} \) lifetime and observability

Strict R-parity conservation in the MSSM forbids \( \tilde{b} \) decay unless there is a lighter supersymmetric particle. R-parity-violating and lepton-number-violating decay of the \( \tilde{b} \) into at least one lepton is disfavored by the CLEO data [16] and would imply the presence of an extra lepton, albeit soft, in some fraction of \( b \) jets observed at hadron colliders. The baryon-number-violating R-parity-violating (\( R_p \)) term in the MSSM superpotential is \( W_{R_p} = \lambda''_{ijk} U^c_i D^c_j D^c_k \); \( U^c_i \) and \( D^c_i \) are right-handed-quark singlet chiral superfields; and \( i, j, k \) are generation indices. The limits on individual \( R_p \) and baryon-number violating couplings \( \lambda'' \) are relatively weak for third-generation squarks [25, 26], \( \lambda''_{ijk} < 0.5 \) to 1.

The possible \( R_p \) decay channels for the \( \tilde{b} \) are 123 : \( \tilde{b} \rightarrow u + s \); 213 : \( \tilde{b} \rightarrow c + d \); and 223 : \( \tilde{b} \rightarrow c + s \). The hadronic width is [26]

\[
\Gamma(\tilde{b} \rightarrow \text{jet + jet}) = \frac{m_{\tilde{b}}}{2\pi} \sin^2 \theta_{\tilde{b}} \sum_{j<k} |\lambda''_{ijk}|^2.
\]

If \( m_{\tilde{b}} = 3.5 \) GeV, \( \Gamma(\tilde{b} \rightarrow ij) = 0.08|\lambda''_{ij3}|^2 \) GeV. Unless all \( \lambda''_{ij3} \) are extremely small, the \( \tilde{b} \) will decay quickly and leave soft jets in the cone around the \( b \). \( b \)-jets with an extra \( c \) are possibly disfavored by CDF, but a detailed simulation is needed.

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 superpartner of the \( B \) meson. The mass of the mesino would fall roughly in the range 3 to 7 GeV for the interval of \( \tilde{b} \) masses we consider. The charged mesino could fake a heavy muon if its hadronic cross section is small and if it survives passage through the hadron calorimeter and exits the muon chambers. Extra muon-like tracks would then appear in a fraction of the \( b\bar{b} \) event sample, but tracks that leave some activity in the hadron calorimeter. The mesino has baryon number zero but acts like a heavy \( \tilde{p} \) – perhaps detectable with a time-of-flight apparatus. A long-lived \( \tilde{b} \) is not excluded by conventional searches at hadron and lepton colliders, but an analysis [27] similar to that for \( \tilde{g} \)'s should be done to verify that there are no additional constraints on the allowed range of \( \tilde{b} \) masses and lifetimes.

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