Novel signatures of heavy quarks at the CERN S$\bar{p}p$S and Fermilab Tevatron colliders

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(Received 24 February 1992)

New heavy quarks with $m_Q < M_Z$, if they exist, are produced rather copiously at existing hadronic colliders. If they predominantly decay via unusual modes, thus giving rise to novel signatures, they could have so far evaded detection. The fourth-generation b' quark, with its diverse decay modes, is studied as an illustration. We focus on the signatures $ee+2j$, $\not{p}_T+2j$, and $\gamma+3j$, while more intriguing signatures are also discussed. Exotic quarks, such as vectorlike quarks, possess signatures that form a subset of these. However, the possible existence of the γ+jets mode is unique to b'. Such quarks, if they exist in the appropriate mass range, could constitute a source of large background to the signals for supersymmetric particles, the Higgs boson, technipartides, etc. We find that existing hadronic colliders should be able to discover these new heavy quarks if they fall inside the $M_Z/2 \lesssim m_Q \lesssim M_Z$ range, and $m_Q < M_{H^0}$.

PACS number(s): 14.80.Dq, 13.85.Qk

I. INTRODUCTION

The search for new particles, in particular, new quarks, is one of the main themes of high-energy physics. As each new energy threshold is reached, one tries to set limits (in the hope of making a discovery) to the best of one's ability. At present, the CERN e^+e^- collider LEP sets an unequivocal bound of $m_Q \gtrsim M_Z/2$ [1] that is valid for practically any new heavy quark. On the other hand, hadronic machines such as the CERN S$\bar{p}p$S or Fermilab Tevatron colliders hold the higher-energy frontier, with the Tevatron giving the most stringent limit on the top quark, i.e., $m_t > 91$ GeV [2]. This bound relies, however, on the semileptonic decay mode and hence the assumption that its branching ratio (B) is as given by the standard model (SM), i.e., $B(t \to l\bar{\nu}X) \simeq \frac{1}{9}$. It would *not* be valid for other heavy quarks if $B(Q \to l\nu X)$ is very different. Although a number of different particles are on the search agenda at hadronic colliders, little effort has so far gone into establishing or ruling out the possible existence of heavy quarks other than the top quark. As we have argued in the past [3], and wish to emphasize again in this paper, because there could be rather interesting implications coming from their existence, the search for new particles at colliders must cover heavy quarks beyond the top quark.

Are there any new heavy quarks ($m_Q \gtrsim M_Z/2$) beyond the top? The standard model is presently unsurpassed in simplicity and power to explain experimental data. In fact, aside from the top quark, it does not call for any additional heavy quarks. However, beyond the simple "why not?", there are still many reasons for continuing our quest for new quarks. A sequential fourth generation is not completely ruled out, while more exotic, nonsequential quarks (for example, vectorlike quarks or mirror fermions) often appear in many extensions of the SM [4]. These heavy quarks can have richer decay properties, with significant branching ratios in many more modes than the top quark. This would make such quarks very interesting in their own right. On the other hand, the existence of new quarks with decay channels very different from the top may have implications for the search for other very interesting particles, e.g., the Higgs boson, techniparticles (such as the techni-ρ and techni-ω), or supersymmetric particles. Since quarks are produced through strong interaction, the production cross section is about the largest for any new interesting phenomena. If they subsequently decay via some unusual mode(s), *different* from what one has assumed so far (i.e., SM expectations), they may quite easily constitute a source of large background and wash out the signal for some interesting particle (or physics) that hitherto has been believed to be straightforward. An example is the threat of $Q \to qZ$ decays [if $B(Q \to qZ)$ is substantial] to the search for the Higgs boson through the standard $H \to ZZ$ channel [3]. Thus, on the phenomenological or practical side, the search for new heavy quark has a twofold purpose: to find new phenomena and to be sure that current expectations for other important new physics at supercollider energies will not be hampered.

Let us be more specific about the types of heavy quarks that may exist in nature. The possibility of the existence of a fourth, sequential generation was supposedly ruled out by the observation of only three light-neutrino families at LEP [5]. However, this is only true if, taking the cue from the three known neutrino species, one imposes the condition that all neutrinos (i.e., neutral leptons that form left-handed doublets with some charged lepton in the standard way) be close to massless. If, for some reason, the fourth neutrino (call it ν_σ) is simply heavier than $M_Z/2$, it would not show up in the "neutrino counting" at LEP, although one then faces the question of why

m_{ν_σ} should be so different from the known neutrinos. The physics community's reluctance to accept this is understandable; however, the possibility is there. One should recall that fermions *do* come in three repetitive families, distinguished only by their masses. However, family replication as well as fermion mass generation cannot be explained (only described) within the context of the SM. Given that the top is rather heavy, it may well be that fourth-generation fermions (quarks *and* leptons) belong to fermionic "energy levels" that are of order 1 times the weak symmetry-breaking scale (v). From the perspective of past experience with dynamical systems (e.g., QCD and the hadronic spectrum), they would in fact look more natural, while presently known fermions would appear to be the more peculiar "zero modes" of the theory. It should be noted that there is some circumstantial evidence suggesting the existence of a sequential fourth family. In the so-called "τ consistency problem" [6], the measured $B(\tau\rightarrow l\bar{\nu}\nu)$ differs (by 2σ) from the predictions of the SM when one scales up $\Gamma(\mu\rightarrow e\bar{\nu}\nu)$ from universality. If this turns out to be true, then either m_τ or the τ lifetime has been mismeasured. Otherwise the simplest explanation would be that the τ couples to ν_σ via the charged current with a strength of $\sim 15\%$, but $\tau\rightarrow l\bar{\nu}\nu_\sigma$ is kinematically forbidden. The idea of a fourth generation has also been contemplated very recently from a number of different perspectives: e.g., the scenario of dynamical electroweak symmetry breaking due to heavy-quark (beginning with the top) condensation [7], or the SM upper bound on the mass of the top quark [8]. We therefore think that fourth-generation quarks should continue to be searched for until ruled out by rigorous means.

Given our ignorance of the larger picture of fermion family replication and the question of fermion mass generation, one should also contemplate the existence of "exotics," i.e., nonsequential fermions that come in representations that differ from the standard left-handed doublet, right-handed singlet structure. Well-known examples are the so-called vectorlike fermions [9], where left- and right-handed quarks come under the same representation structure of the $SU(2)\times U(1)$ gauge group, or mirror fermions [10], where one has left-handed singlets and right-handed doublets (we shall view mirror fermions as some special kind of vectorlike quarks, since the phenomenology of concern to us is rather similar). These quarks typically appear in (superstring-inspired) E_6 grand unified models [11], which suggests that they ought to be very heavy. From the low-energy point of view, this is also true, since in principle vectorlike fermions could have arbitrary Dirac masses (not generated by Yukawa couplings after spontaneous $SU(2)\times U(1)$-symmetry breaking), e.g., of order 1 eV or 1 MeV. But we see no exotic fermions (that carry color or electroweak charges) below $M_Z/2$; hence, they are only natural if their masses are well above the SM scale v. It is not inconceivable, however, that for some unknown reason their masses are of order v or slightly below. In any case, in addition to further sequential repetition, these are the simplest extensions of the SM. They may also have some bearing on the above-mentioned "τ consistency problem."

If all these new quarks decay predominantly via the charged current (CC), then one could use the exact machinery that has been used so far in the search for the top to establish bounds. However, as is known, even the top may decay via other means if there is physics beyond the SM (e.g., $t\rightarrow bH^+$ [12], where $H^\pm$ is a physical charged scalar, or $t\rightarrow ch^0$ [13], where h^0 is a nonstandard Higgs boson), and thereby invalidate the Collider Detector at Fermilab (CDF) limit. For new heavy quarks, it is therefore of interest to ask how they might decay. For the fourth-generation b' quark, it has been pointed out [14] that the CC $b'\rightarrow t$ transition may be kinematically forbidden if $m_{b'}<m_t$, while the $b'\rightarrow c$ transition is expected to be rather Cabibbo-Kobayashi-Maskawa (CKM) suppressed since $V_{cb'}$ crosses two generations. Thus, *loop-induced* flavor-changing neutral-current (FCNC) $b'\rightarrow b$ transitions, such as $b'\rightarrow bg$, $b\gamma$, bl^+l^-, $b\nu\bar{\nu}$, $bq\bar{q}$, and bH^0, may well be dominant, in which case the CDF limit will be circumvented. We shall focus on this scenario for the b' quark because of the many available decay channels that may lead to potentially useful signatures. For nonsequential quarks, since the Glashow-Iliopoulos-Maiani (GIM) mechanism does not hold, QqZ and QqH^0 (but not $Qq\gamma$) couplings exist at *tree level* at some prescribed strength. However, unlike the case of the b' quark, there are always significant branching ratios for the CC decay modes, and the CDF limit is at best compromised, not eliminated. On the other hand, there would always be sizable branching ratios into FCNC transitions, and one should search for these modes whenever a new quark is discovered.

It is known that the $b'\rightarrow bH^0$ mode would be the single predominant FCNC mode [15] if it is kinematically allowed in the mass range $M_Z/2<m_{b'}<M_Z$. For vectorlike quarks, this could also occur if $M_{H^0}<M_W$. Since $Q\rightarrow qH^0$ decays (followed by $H^0\rightarrow b\bar{b}$) do not lead to good signatures, we shall assume that $m_Q<M_{H^0}$; therefore, $Q\rightarrow qH^0$ is forbidden. As the LEP limit on M_{H^0} improves, this assumption can be checked for almost the entire range of $M_Z/2\lesssim m_Q\lesssim M_Z$.

Because of richer and different decay properties, generally speaking, the signatures of the b' quark and vectorlike quarks could be quite different from the top quark. However, bounds coming from e^+e^- colliders, e.g., from LEP, are not significantly affected. This is because the clean production environment permits one to set limits on new flavor thresholds by looking only at event topology, such as event shape. Even here, if it is observed (as LEP energy goes up) that a new threshold has been crossed, the specific signatures would have to be searched for to identify the particle being produced. We believe that this is relatively easy to do at e^+e^- colliders [16], and we shall only briefly comment on it in Sec. IV. For $p\bar{p}$ colliders, however, because of the "underlying event," one has to look at specific decay products just to discern that something new is being produced. This makes the discovery of a heavy quark at hadronic colliders much more dependent on its decay modes. For the top quark, the most useful SM signatures are "isolated $e^\pm\mu^\mp$" and "isolated $e^\pm(\mu^\pm)$ + multijets" coming from charged-current decays. It is clear that, if FCNC decays are predominant for b' or vectorlike quarks, the novel signatures could have evaded the top search strategy employed by CDF and UA1/UA2, and one would need additional effort to cover these possibilities.

In this paper we shall study the means one has at one's disposal to search for or rule out the existence of new quarks beyond the top at hadronic colliders. We focus on the mass range $M_Z/2 \lesssim m_Q \lesssim M_Z$, where the lower bound corresponds to the LEP limit. Beyond M_Z the signatures change considerably. This mass range corresponds to sizable strong production cross sections and can be studied with existing data. Our conclusion is in the positive: With some work, existing hadronic colliders should be able to discover these new heavy quarks if they fall inside this mass range. In Ref. [16], the signatures in this mass range were analyzed for e^+e^- colliders. The case of $m_Q \gtrsim M_Z$ was considered in Ref. [4]. In Sec. II we discuss specific novel signatures of the b' quark and vectorlike quarks in more detail. In Sec. III we determine the most useful signatures of the b' quark by computing the signal-to-background ratio for various signatures. Results are given for both the Tevatron and the CERN $Sp\bar{p}S$ colliders. Some discussion is given in Sec. IV and our conclusions are presented in the final section.

II. SIGNATURES

Signatures of a particle depend on its decay modes. Some of these decay modes may not be useful for the purpose of identifying these particles in a noisy environment. Good signatures at a particular collider should satisfy the following criteria: (a) the number of events is large, (b) the signal-to-background ratio is favorable, and (c) the signal can be looked for in the foreseeable future. Of course, these conditions are not independent of each other. For the $M_Z/2 \lesssim m_Q \lesssim M_Z$ range, production cross sections at hadronic colliders are so large that good signatures may be searched for with *existing* data.

To ascertain the useful signatures of the b' quark, we first determine the *relative importance* of its various decay modes. In Table I we display the branching ratios for the decay modes of the b' quark. These branching ratios are for the "extreme" case where CC modes are completely suppressed. Here we have chosen $m_t = 100$ and $m_{t'} = 200$ GeV, so the $b' \to t$ transition is kinematically forbidden, while we set $V_{cb'} = 0$ so the $b' \to c$ mode is CKM forbidden. In Sec. IV, we will discuss the implications of varying these parameters. We see that the channel $b' \to bg$ has the largest branching ratio in the mass range of interest, followed by the modes $b' \to bq\bar{q}$, $b' \to b\gamma$, $b' \to b\nu\bar{\nu}$, and $b' \to bl^+l^-$. Here l is a charged lepton.

These branching ratios were first computed in Refs. [14] and [17]. The gluonic and photonic penguin diagrams contribute to the decay modes $b' \to bg$ and $b' \to b\gamma$, respectively. The main contribution to the decay modes $b' \to bq\bar{q}$, $b' \to bl^+l^-$, and $b' \to b\nu\bar{\nu}$ come from Z-penguin diagrams where the Z is virtual. However, box diagrams also make important contributions [17]. They enhance the decay rate for the $b' \to b\nu\bar{\nu}$ mode, while the rate for the $b' \to bl^+l^-$ mode is slightly reduced. For $b' \to bq\bar{q}$ modes, for $q = u,d,s,c$, one could include the box-diagram contribution by adapting the box contribution for $b' \to b\nu\bar{\nu}, l^+l^-$ decays. However, the box-diagram contribution to $b' \to bb\bar{b}$ has so far not been calculated. For our purpose of making estimates, we shall use only the Z-penguin diagram contribution for the three-body modes. We notice that one of the most interesting features of these branching ratios is that the $b' \to b\gamma$ decay mode is quite substantial. In fact, this mode is unique for the b' quark, and will thus give rise to a very distinctive signature. Other exotic heavy quarks, e.g., vectorlike quarks, do not have this decay mode. The decay mode $b' \to bg$ is also unique to the b' quark. Although one cannot identify gluon jets, as we shall see, the presence of a significant $b' \to bg$ mode facilitates the detection of b'. The decay modes for vectorlike quarks are discussed below.

Based on these decay modes we see that these heavy quarks will give rise to rather diverse signatures even if CC modes are completely suppressed. To date, these novel signatures have *not* been specifically searched for at $p\bar{p}$ colliders. We shall primarily focus on three signatures that may be potentially most useful, and comment briefly on other signatures. These novel signatures are (1) "isolated e^+e^-+multijet," (2) "$\not{p}_T$+multijet," and (3) "isolated γ+multijet." In our discussions, any e^+e^- pair can be replaced by a $\mu^+\mu^-$ pair. Other even more unconventional (and very distinctive) signatures coming from combinations of the b' decay modes mentioned above are (in rough decreasing order of overall weight) (a) "isolated $\gamma + \nu\bar{\nu}(\not{p}_T)$+two jets," (b) "isolated 2γ+two jets," (c) "isolated $e^+e^- + \nu\bar{\nu}(\not{p}_T)$+two jets," and (d) "isolated $\gamma + e^+e^-$+two jets." The signature "$\nu\bar{\nu}$ $\nu\bar{\nu}$+two jets" has a decent branching ratio. However, its signature is not very distinct from $\nu\bar{\nu}$+two jets, except in the high end of the $\not{p}_T$ distribution. The signature "isolated $e^+e^-e^+e^-$+two jets" seems very good; however, it has a hopelessly small branching ratio (less than 0.1%). The multijet (four to six jets) signature is excluded as a good signature in a hadronic production environment because it would be overwhelmed by the direct production

TABLE I. Branching ratios for various FCNC decay channels of the b' quark with $m_t = 100$, $m_{t'} = 200$ GeV, and $V_{cb'} = 0$.

$m_{b'}$	$B(b' \to b\gamma)$	$B(b' \to bg)$	$B(b' \to be^+e^-)$	$B(b' \to b\nu\bar{\nu})$	$B(b' \to bq\bar{q})$
50	0.138	0.546	0.012	0.069	0.234
60	0.136	0.540	0.012	0.071	0.240
70	0.132	0.534	0.012	0.074	0.248
80	0.126	0.521	0.013	0.078	0.262

of multijet events. The background cross section here is typically several orders of magnitude larger than the signal.

For the three signatures that we study, one can look for one or more accompanying jets. The maximum number of jets are produced in the processes $p\bar{p} \to b'\bar{b}'X \to b\bar{b}\gamma q\bar{q}X$, $b\bar{b}l^+l^-q\bar{q}X, b\bar{b}\nu\bar{\nu}q\bar{q}X$. However, the processes $p\bar{p} \to b'\bar{b}'X \to b\bar{b}\gamma gX, b\bar{b}l^+l^-gX, b\bar{b}\nu\bar{\nu}gX$ turn out to be more important since two of the jets are produced through two-body decays and thus have relatively larger p_T, jet-jet pair mass, etc. This feature will help in reducing the background. It also singles out the b' quark as particularly easy to establish or rule out.

For vectorlike quarks, except in extreme cases, CC $Qq'W$ and FCNC QqZ couplings are usually comparable; hence, the standard CC search strategy for heavy quarks is quite applicable. However, to be certain of the actual type of quark flavor that is produced, one should search for the additional FCNC signatures. Since FCNC decays in general never dominate in this case, it would probably be necessary to combine CC and FCNC signatures.

We note that a combination of CC and FCNC decay channels will give rise to even more diversity in the type of events. They may in turn constitute backgrounds that could further complicate the search for new physics in unexpected ways. One of the more interesting types of events would be multileptonic events, e.g., $\mu e^+e^- + \not{p}_T +$multijet. However, such events will have rather small cross sections and will not be of immediate interest. Our main focus in the following shall be signatures due to FCNC decay modes alone.

III. SIGNAL AND BACKGROUND

To see whether a signature satisfies our criteria for a good signature, one has to calculate the number of events due to the signal as well as the background. Because of the limited available luminosity, the first issue of concern is the number of events. It is clear that to maximize the number of events in a given signature, one should look for as few accompanying jets as possible. Otherwise the experimental cuts on each additional jet and smaller detection efficiency for lower-p_T jets will reduce the number of events with the specific signature. However, one has to keep in mind the second condition of our criteria. The smaller the number of jets one observes in an event, the larger the background will be. In the case of $b'\bar{b}'$ pair production, we get up to four accompanying jets for free. One will have to judge in the particular situation the number of jets one needs to optimize detection prospects.

Our goal is to point out the good signatures that one must see in order to verify, or rule out, the existence of some heavy quarks. We therefore treat the production and decay processes for heavy quarks independently. The correlations of the two processes will not affect our conclusions. For the computation of the background, we use the code of Hagiwara and Zeppenfeld [18], which has been applied by the Wisconsin group in calculating V^*+ multijet ($V=\gamma, W, Z$) cross sections [19,20]. We have used the Duke-Owens structure functions, set 1 [21], for the results presented in the tables below. In each case, we first apply a generic set of cuts to mimic usual experimental cuts. Then, to improve the signal-to-background ratio we shall apply further cuts as specified below.

A. Signature 1: isolated e^+e^-+multijet

This particular signature is the easiest of all signatures to reconstruct. However, the number of signal events is relatively small. We focus on the $be^+e^-\bar{b}g$ signal events. As discussed above, although the signal contains three or four jets, for the sake of having a respectable number of events, we demand only two jets for the Drell-Yan background (in the case of clearly identified three-jet events, one selects the two more energetic ones), and apply the following set of generic cuts for the case of the Tevatron:

$$\begin{aligned} &p_T^{j,l^\pm} > 15 \text{ GeV}, \quad |\eta^{j,l^\pm}| < 2.5 , \\ &R(j_1,j_2), \quad R(j,l^\pm) > 0.6 , \end{aligned} \tag{1}$$

where η is the pseudorapidity variable, $\eta = \ln \cot\theta/2$, and $R=\sqrt{(\Delta\eta)^2+(\Delta\phi)^2}$ is the jet-jet or jet-lepton angular separation variable. To mimic experimental resolution limitations we smear jet energies with Gaussian fluctuations with a width of 5 GeV. For the CERN $Sp\bar{p}S$ collider, we demand that $p_T^{j,l^\pm} > 10$ GeV.

The results for the total signal (SG) and background (BG) cross sections are displayed in the first column of Table II. We have applied a cut $M(e,e) > 10$ GeV to eliminate the Drell-Yan pole at vanishing q^2 due to QED. At first sight, it appears that the BG dominates over the SG. However, the signal process provides further handles for background suppression. In Figs. 1(a) and (b) we display the $M(e,e)$ and $M(j,j)$ distributions. For the signal distribution, the two most energetic jets (out of three) are paired together. From the $M(e,e)$ plot, one sees, as expected, that the background peaks at 0 and M_Z. For the signal, since the e^+e^- pair comes from $b' \to be^+e^-$, we have $M(e,e) < m_{b'}$, but it peaks at some nonvanishing value. This is in part a consequence of the flatness of the

TABLE II. Cross sections (pb) for $b'\bar{b}' \to e^+e^- + 2j + X$ at the Tevatron with $\sqrt{s} = 1800$ GeV, $m_t = 100$, $m_{t'} = 200$ GeV, $V_{cb'} = 0$, and with the kinematic cuts as specified in the text.

	No mass cut		$M(j,j)$ cut		$M(e,e)$ cut		Both mass cuts	
$m_{b'}$ (GeV)	Signal	BG	Signal	BG	Signal	BG	Signal	BG
50	5.3	7.5	2.4	0.92	4.7	0.45	2.1	0.05
60	4.3	7.5	1.9	0.76	4.0	0.56	1.8	0.06
70	3.0	7.5	1.3	0.63	2.9	0.67	1.3	0.06
80	2.0	7.5	0.9	0.49	2.0	0.82	0.9	0.06

invariant $q^2=M^2(e,e)$ spectrum in the $b'\to be^+e^-$ process [17], and in part due to the generic cuts of Eq. (1). The upshot is that, for the b' mass range of interest, the signal distribution lies just in the low region between the two Drell-Yan background peaks. A cut on $M(e,e)$ against the background peaks will therefore enhance SG/BG. For the $M(j,j)$ distribution, the signal again shows a peaking effect that is different from and sharper than the Drell-Yan background (recall that jet energies have already been smeared by 5 GeV). This is because of the presence of a substantial $b'\to bg$ component in b' decays, where the b and gluon jets (on average the two more energetic ones in a $p\bar{p}\to b'\bar{b}'\to e^+e^-b\bar{b}g$ event) tend to form a jet-jet mass peak at $m_{b'}$. This again suggests a cut in $M(j,j)$. We therefore adopt the following two additional event-defining cuts:

$$20 \text{ GeV} < M(e,e) < m_{b'}, \quad |M(j,j)-m_{b'}| < 5 \text{ GeV} . \qquad (2)$$

The effects of the separate mass cuts on the total cross sections are displayed again in the second and third column of Table II. It is clear that applying either cut, the SG/BG ratio becomes greater than 1, which is of course already apparent in Figs. 1(a) and 1(b) but is further displayed in Figs. 1(c) and 1(d) in the respective $M(e,e)$ and $M(j,j)$ distributions that were not subject to the specific mass cut. Applying both cuts simultaneously, SG/BG becomes greater than 10, which means the background has practically been eliminated (note that the background stays roughly constant because of the compensating effects of the two mass cuts with the increase in $m_{b'}$). The cross sections are, however, quite reduced and only a handful of events would appear with existing data (of order 4 pb^{-1}).

Similar results are obtained for the CERN S$p\bar{p}$S collider. We make an initial cut of $M(e,e)>5$ GeV to eliminate the QED pole for the background. The total cross sections are displayed in Table III. With generic cuts, SG/BG is worse than in the Tevatron case [in part because of the lower $M(e,e)$ cut], as seen in the first column of Table III. This point is further displayed in Figs. 2(a) and 2(b). However, applying one of the cuts of Eq. (2), Figs. 2(c) and 2(d) indicate that the events should begin to stand out. With both mass cuts, one again gets good SG/BG, but not as good as in the Tevatron case, and

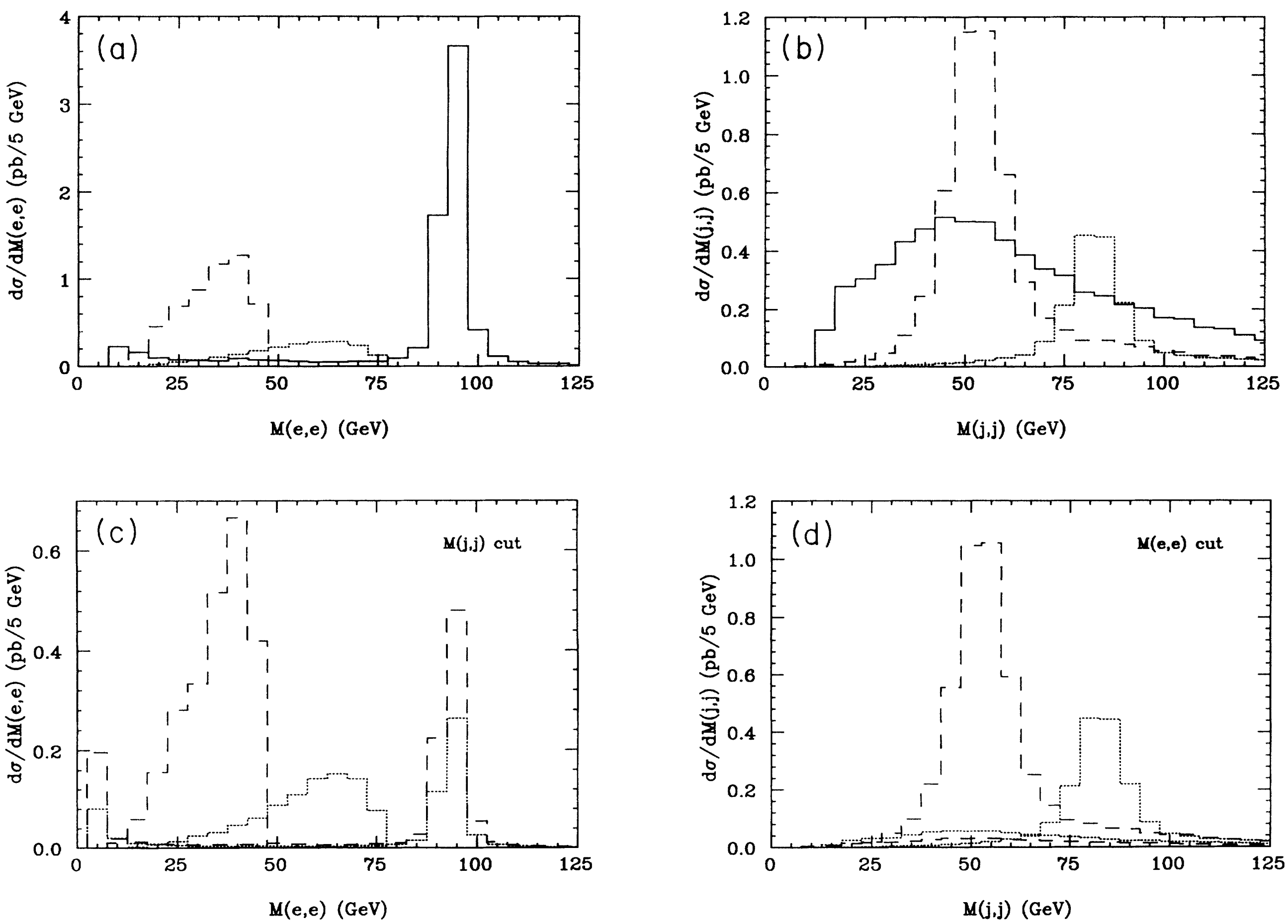

FIG. 1. (a) Differential cross section (pb/GeV) vs $M(e,e)$ with a 5-GeV bin size at the Tevatron for the signal $p\bar{p}\to b'\bar{b}'X\to e^+e^-+$two jets $+X'$ for $m_{b'}=50$ GeV (dashed line), 80 GeV (dotted line), and for the background $p\bar{p}\to e^+e^-+$two jets $+X$ (solid line). (b) Same as (a) but for $M(j,j)$ instead of $M(e,e)$. (c) Same as (a) but with an additional cut on $M(j,j)$ as specified in the text. The background now also depends on the target $m_{b'}$ value and is thus indicated. (d) Same as (b) but with an additional cut on $M(e,e)$ as specified in the text.

TABLE III. Cross sections (pb) for $b'\bar{b}' \to e^+e^- + 2j + X$ at the S$p\bar{p}$S Collider with $\sqrt{s} = 630$ GeV, $m_t = 100$, $m_{t'} = 200$ GeV, $V_{cb'} = 0$, and with the kinematic cuts as specified in the text.

	No mass cut		$M(j,j)$ cut		$M(e,e)$ cut		Both mass cuts	
$m_{b'}$ (GeV)	Signal	BG	Signal	BG	Signal	BG	Signal	BG
50	0.89	2.47	0.43	0.25	0.76	0.46	0.38	0.04
60	0.42	2.47	0.20	0.16	0.38	0.50	0.19	0.03
70	0.20	2.47	0.09	0.09	0.18	0.45	0.09	0.02
80	0.09	2.47	0.05	0.06	0.09	0.49	0.05	0.01

deteriorating faster with $m_{b'}$. Cross sections are an order of magnitude smaller than in the Tevatron case, and falling off much more rapidly in $m_{b'}$. However, with the existing 20 pb^{-1} or so integrated luminosity, the number of events that could show up is comparable to that at the CDF with 4 pb^{-1} for $m_{b'}$ up to about 60 GeV.

Note that SG/BG can be enhanced further by adjusting our cuts, usually at the expense of the total remaining cross section. For example, the lower cut on $M(e,e)$ can certainly be raised with $m_{b'}$.

B. Signature 2: $\not{p}_T$ + multijet

The main source of background comes from the direct production of "$Z^*(\to \nu\bar{\nu})$+multijet" events. We assume that "τ jets" can be identified; therefore, we can ignore the background from the process $p\bar{p} \to W^*(\to \tau\nu_\tau)$ +multijet. We would like to note that this particular signature is a benchmark signature for supersymmetry [22], and has been analyzed from this perspective in the literature. We apply the following generic set of cuts for the Tevatron:

$$p_T^j > 15 \text{ GeV}, \quad \not{p}_T > 20 \text{ GeV} , \qquad |\eta^j| < 2.5, \quad R(j_1, j_2) > 0.6 . \tag{3}$$

Again, to mimic experimental resolution we smear the jet energies and the components of $\not{p}_T$ with Gaussian fluctuations of width 5 GeV. For CERN S$p\bar{p}$S, we use $p_T^j > 10$ GeV and $\not{p}_T > 15$ GeV.

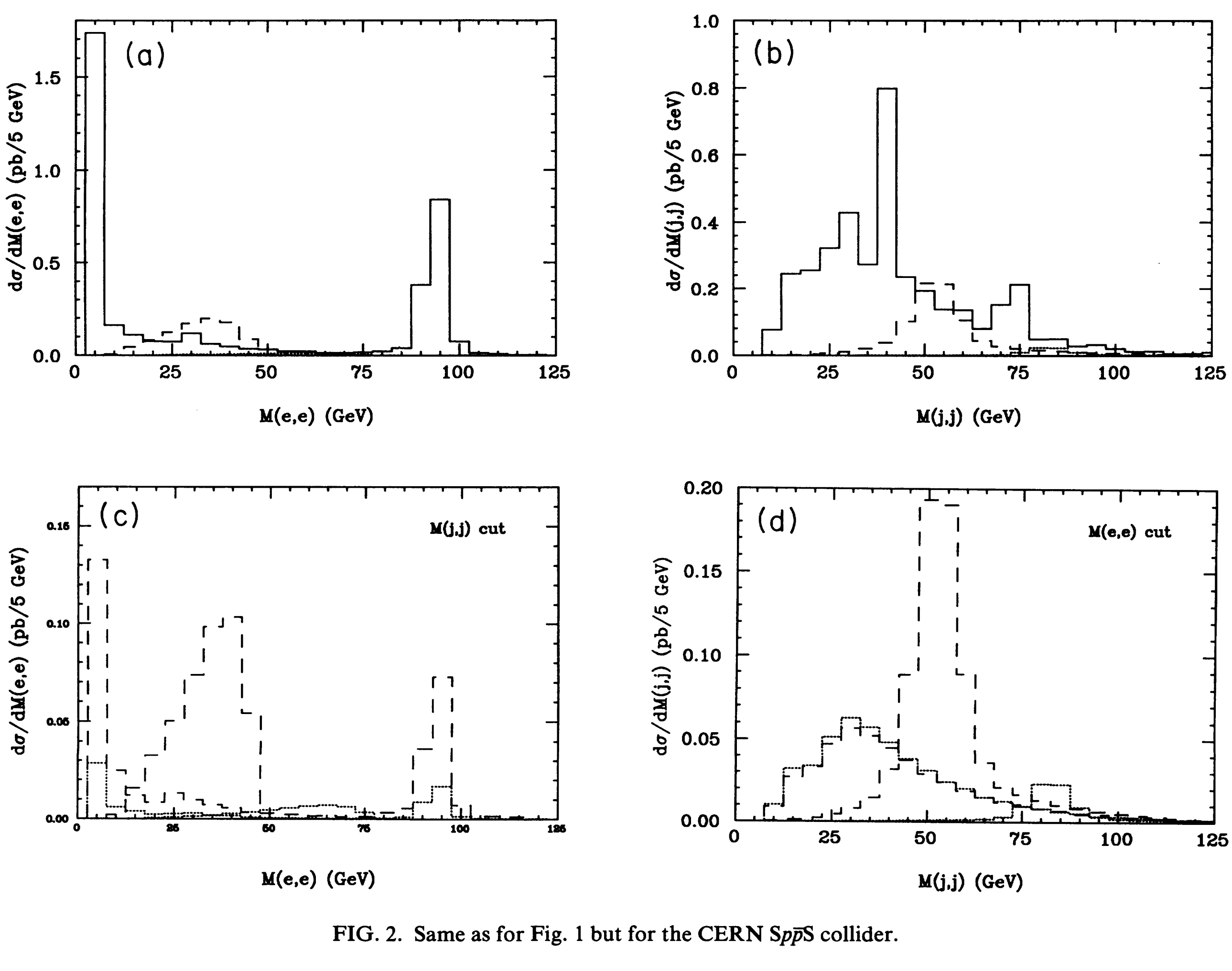

FIG. 2. Same as for Fig. 1 but for the CERN S$p\bar{p}$S collider.

TABLE IV. Cross sections (pb) for $b'\bar{b}' \to \not{p}_T + 2j + X$ at the Tevatron with $\sqrt{s} = 1800$ GeV, $m_t = 100$, $m_{t'} = 200$ GeV, $V_{cb'} = 0$, and with the kinematic cuts as specified in the text.

	No mass cut		$M(j,j)$ cut	
$m_{b'}$ (GeV)	Signal	BG	Signal	BG
50	144	42	47.8	4.5
60	75	42	26.4	4.1
70	39	42	14.5	3.5
80	22	42	8.4	2.7

TABLE V. Cross sections (pb) for $b'\bar{b}' \to \not{p}_T + 2j + X$ at the S$p\bar{p}$S Collider with $\sqrt{s} = 630$ GeV, $m_t = 100$, $m_{t'} = 200$ GeV, $V_{cb'} = 0$, and with the kinematic cuts as specified in the text.

	No mass cut		$M(j,j)$ cut	
$m_{b'}$ (GeV)	Signal	BG	Signal	BG
50	10.8	7.7	4.4	0.72
60	4.1	7.7	1.7	0.46
70	1.7	7.7	0.8	0.29
80	0.8	7.7	0.4	0.18

In Table IV we present the results for the signal and the background. The signal is already rather respectable against background without further cuts, with SG/BG falling below 1 only for $m_{b'} > 70$ GeV. Compared to signature 1, the good SG/BG is mainly because of the absence of a photonic contribution in the background. Figure 3 compares the $M(j,j)$ distributions for signal and background. When one applies the $M(j,j)$ cut as in Eq. (2), with the slight modification that here we pair the two highest-p_T jets together, the effect is given in the second column of Table IV. The background is suppressed by an order of magnitude or more, while the loss in the signal is less than a factor of 3. We see that the CDF at the Tevatron should be able to explore the full $M_Z/2 \lesssim m_{b'} \lesssim M_Z$ range with this signature using *existing* data.

The situation for the CERN S$p\bar{p}$S is given in Table V. SG/BG is more critical here. From Fig. 4, it is clear that there should be no problem for $m_{b'} \lesssim 70$ GeV, since the signal cross sections peak at $M(j,j) \sim m_{b'}$. This is demonstrated by applying the $M(j,j)$ cut of Eq. (2), where the result is given in the second column of Table V. Folding in accumulated luminosities, one also concludes from cross sections that the UA1/UA2 Collaborations can probably probe up to roughly 70 GeV in the b' mass.

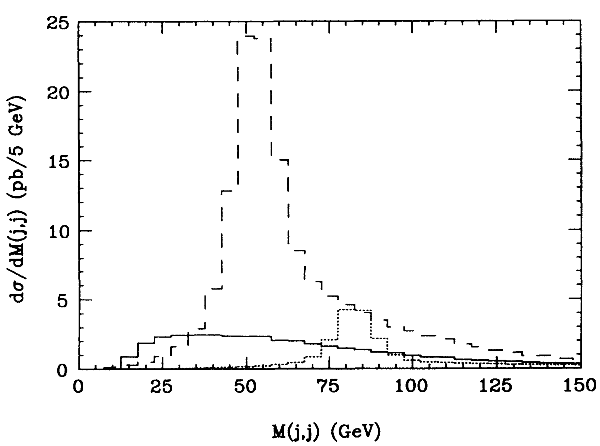

FIG. 3. Differential cross section (pb/GeV) vs $M(j,j)$ with a 5-GeV bin size at the Tevatron for the signal $p\bar{p} \to b'\bar{b}'X \to \not{p}_T +$ two jets $+X'$ for $m_{b'} = 50, 80$ GeV, and for the background $p\bar{p} \to \not{p}_T +$ two jets $+X$.

C. Signature 3: isolated γ + multijet

For this signature, the main source of background is the direct production of "γ + multijet" (through Compton-like scattering). The signature is of special interest because, if identified, it could confirm the scenario of Ref. [14]. This is because it is not easy for heavy quarks to decay via a photon: there must be a loop effect (or else an effect of "structure," i.e., compositeness). Experimentally, the identification of energetic photons at hadronic colliders is rather challenging.

We shall focus again on signatures that follow from an accompanying $b' \to bg$ decay, so the basic signature that we look for is actually γ + three jets. The following set of general cuts were applied for the Tevatron:

$$p_T^{j,\gamma} > 15 \text{ GeV}, \quad |\eta^j| < 2.5, \quad |\eta^\gamma| < 1 , \qquad R(j_1,j_2), \quad R(j,\gamma) > 0.6 . \tag{4}$$

Note that we demand that the photon be central, that is, $|\eta^\gamma| < 1$. This leads to a substantial reduction in the signal events, but we do so because of the difficulties involved in detecting noncentral photons. To mimic experimental resolution limitations we smear the jet and photon energies with Gaussian fluctuations with widths of 5 and 2 GeV, respectively. For the CERN S$p\bar{p}$S collider we retain the same cuts as given above, since the cross section is not so much a problem for this mode.

For the Tevatron, we display in Table VI the number

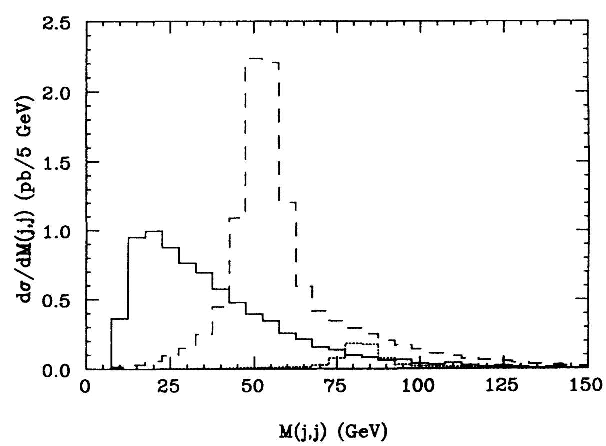

FIG. 4. Same as for Fig. 3 but for the CERN S$p\bar{p}$S collider.

TABLE VI. Cross sections (pb) for $b'\bar{b}' \to \gamma + 3j + X$ at the Tevatron with $\sqrt{s} = 1800$ GeV, $m_t = 100$, $m_{t'} = 200$ GeV, $V_{cb'} = 0$, and with the kinematic cuts as specified in the text.

	No mass cut		Level-1 cut		Level-2 cut	
$m_{b'}$ (GeV)	Signal	BG	Signal	BG	Signal	BG
50	111	570	95	267	70	26
60	64	570	54	267	42	19
70	34	570	29	267	24	10
80	18	570	15	267	12	6

of events for the signal as well as the background with three jets accompanying the photon. With the generic cuts, the remaining background cross section is around 570 pb, quite a bit larger than signal cross sections. Further cuts are necessary. Note that, for $b'\bar{b}' \to \gamma b\bar{b}g$, the photon pairs with one of the (b) jets, while the remaining two jets are also paired together. Each pair is the decay product of a b' quark; therefore the two pairs should have a similar pair mass up to experimental resolutions. Being generous regarding the smearing effect of jet energies, we impose the level-1 cut

$$|M(\gamma,j_1) - M(j_2,j_3)| < 10 \text{ GeV}, \quad j_1,j_2,j_3 \text{ permuted}. \tag{5}$$

The signal is not much affected, but the background comes down by a factor of 2 as seen from Table VI. The cut is not very efficient because we have not been very stringent on pair mass correlations; hence, combinatorics become a problem. With better jet energy resolution, permitting a more stringent level-1 cut, the BG will drop more drastically. With the level-1 cut one may make a meaningful $M(\gamma,j)$ plot [the corresponding $M(j,j)$ cannot differ by too much], which is given in Fig. 5. One sees that, although the signal would probably stand out for low $m_{b'}$, for higher $m_{b'}$, not only is the signal cross section smaller, but it tends to get submerged in the broad background peak at roughly 50 GeV. Some further cuts are still needed.

Having already utilized the level-1 cut, i.e., by demanding that $M(\gamma,j)$ and $M(j,j)$ be similar for at least one combination, we make a further stringent cut, called level-2:

$$|M(\gamma,j_1) - m_{b'}| < 5 \text{ GeV},$$
$$|M(j_2,j_3) - m_{b'}| < 5 \text{ GeV}, \quad \text{no longer permuted}. \tag{6}$$

Note that we demand that the pair masses be close to the target $m_{b'}$ for *both* the γj and jj systems that satisfied the level-1 cut. The results are given in Table VI, where now SG/BG for the total cross section is greater than 2 for the entire $m_{b'}$ range. We also display the p_T distribution of the photon (the p_T distribution of the jet in the γ-jet pair is only slightly different), in Fig. 6 for the two masses $m_{b'} = 50$ and 80 GeV. In general, the signal distribution has a longer high-p_T tail, becoming more prominent with an increase in b' mass. Enlarging the range for $\eta(\gamma)$, we also plot (in Fig. 7) the photon rapidity distribution for these two b' masses, where all cuts up to level 2 (demanding, in addition, that $p_T^\gamma > m_{b'}/3$) have been applied. The signal is seen to be more central than the background, and the range $|\eta^\gamma| < 1$ seems to be quite optimal, both for SG/BG and for experimental reasons.

For the CERN S$p\bar{p}$S collider, applying both the generic cuts (recall that $p_T^{\gamma,j} > 15$ GeV is retained) and the level-1

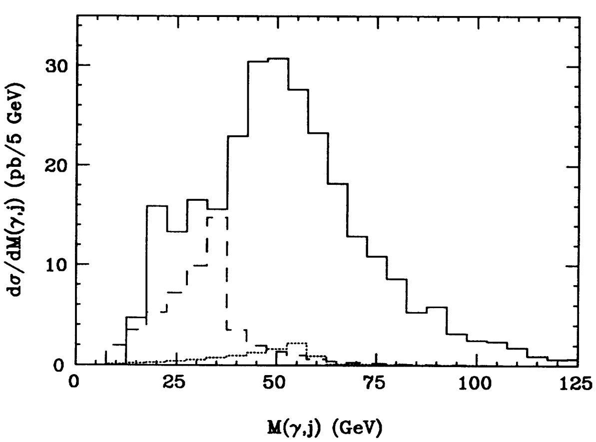

FIG. 5. Differential cross section (pb/GeV) vs $M(\gamma,j)$ with a 5-GeV bin size at the Tevatron for the signal $p\bar{p} \to b'\bar{b}'X \to \gamma +$three jets $+X'$ for $m_{b'} = 50,80$ GeV, and for the background $p\bar{p} \to \gamma +$three jets $+X$ with a level-1 mass cut.

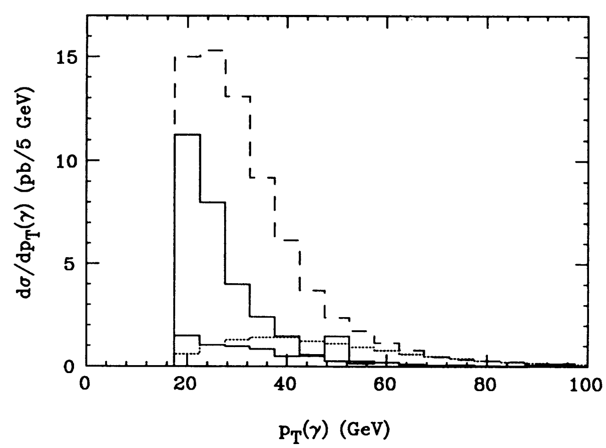

FIG. 6. Differential cross section (pb/GeV) vs $p_T(\gamma)$, with a 5-GeV bin size at the Tevatron for the signal $p\bar{p} \to b'\bar{b}'X \to \gamma +$three jets $+X'$ for $m_{b'} = 50,80$ GeV, and for background $p\bar{p} \to \gamma +$three jets $+X$ with a level-1 mass cut.

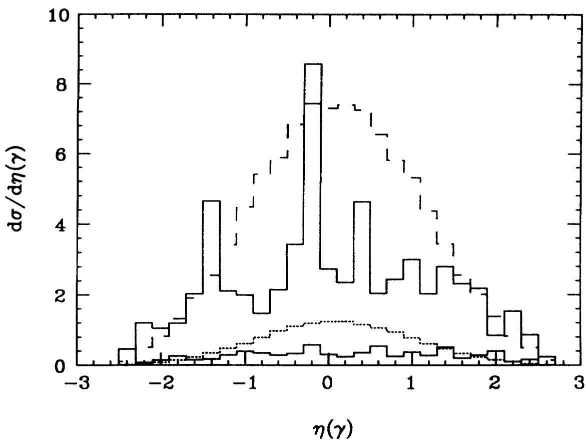

FIG. 7. Differential cross section (pb) vs $\eta(\gamma)$ at the Tevatron for the signal $p\bar{p}\to b'\bar{b}'X\to\gamma+$three jets $+X'$ for $m_{b'}=50, 80$ GeV, and for the background $p\bar{p}\to\gamma+$three jets $+X$ with level-1 and level-2 mass cuts (and $p_T^j > m_{b'}/3$).

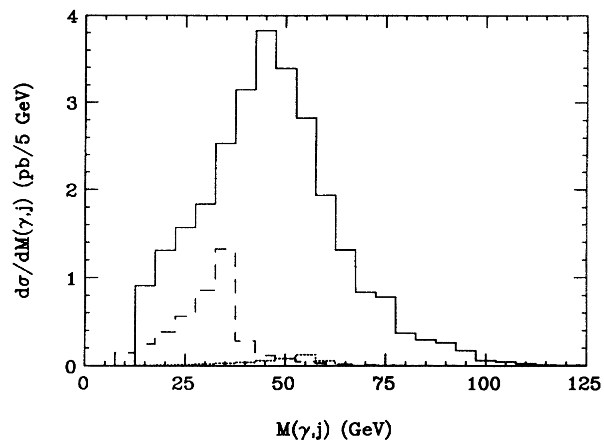

FIG. 8. Same as for Fig. 5 but for the CERN $Sp\bar{p}S$ collider.

cut, the SG/BG ratio is rather poor, as is seen both in Table VII and the $M(\gamma,j)$ distribution displayed in Fig. 8. Again, one has to invoke the rather stringent level-2 cut. Applying this, the results are displayed in Table VII, where one sees that SG/BG is now not bad but, in fact, better for larger $m_{b'}$. This is partly due to the rapidly falling (with $m_{b'}$) total cross section, because of which one can perhaps only search for b' up to about 70 GeV. Figure 9 displays the photon p_T distribution after all cuts up to level-2 have been applied. They are qualitatively similar to the Tevatron case (except in event rate) since similar cuts were made. The photon rapidity distribution, analogous to Fig. 7, is displayed in Fig. 10.

Note that we have not included the possibility of π^0's faking a photon. Although this would be quite an experimental problem for raw $\gamma+$three jet data (say, passing our level-0 cuts), it should be clear that little of this type of background should survive the level-1 and -2 cuts.

D. Other signatures

After demonstrating the efficacy of searching for e^+e^-+two jets, $\not{p}_T+$two jets, and $\gamma+$three jets, we again remark that with more jets (in each case there could be three to four well-separated jets) one could play further with the cuts to see the relative gains in SG/BG versus losses in total event rate. For instance, one could demand more jets that are well separated, but weaken the jet p_T cut. One could also place a cut on the total accompanying hadronic mass (outside of the beam direction), etc. We believe that this kind of fine-tuning is best left for the experimenter since it would depend on detector details. What we have provided is a set of standard cuts that could help isolate events resulting from FCNC decays of some new heavy quark. One specific handle of the b' quark has been used, viz., the existence of a substantial $b'\to bg$ mode.

Let us discuss now other plausible distinct signatures listed in Sec. II.

(a) Isolated $\gamma+\nu\bar{\nu}(\not{p}_T)+$two jets: this $b'\bar{b}'$ decay mode has a combined branching ratio of roughly 2%, and is in fact quite stable against varying m_t, $m_{t'}$, and $m_{b'}$ since the changes in $B(b'\to b\gamma)$ and $B(b'\to b\nu\bar{\nu})$ mutually compensate each other. The signal cross section is about a factor of 3–5 below that of $\nu\bar{\nu}+$three jets or $\gamma+$three jets; however, the signature is quite different and, hence, the background is also quite different. The background cross section should be roughly $\alpha/\alpha_s\sim\frac{1}{10}$ down from $\nu\bar{\nu}+$three jets. One can further utilize cuts on, say, $M(\gamma,j)$. Although we have not actually computed the background cross section, judging from the sources of signatures 2 and 3, we believe that $\gamma+\nu\bar{\nu}+$two jets would also be a viable and perhaps even more distinct signature.

(b) Isolated $2\gamma+$two jets: this signal comprises roughly 0.5–1.5 % of the signal cross section, i.e., roughly 1%, but is sensitive to the heavy-quark masses. The signal cross section is therefore one order of magnitude below signature 3. However, the background cross section is

TABLE VII. Cross sections (pb) for $b'\bar{b}'\to\gamma+3j+X$ at the $Sp\bar{p}S$ Collider with $\sqrt{s}=630$ GeV, $m_t=100$, $m_{t'}=200$ GeV, $V_{cb'}=0$, and with the kinematic cuts as specified in the text.

	No mass cut		Level-1 cut		Level-2 cut	
$m_{b'}$ (GeV)	Signal	BG	Signal	BG	Signal	BG
50	7.1	45.4	6.4	26.2	4.9	3.1
60	3.4	45.4	3.1	26.2	2.4	1.6
70	1.5	45.4	1.4	26.2	1.2	0.7
80	0.7	45.4	0.6	26.2	0.5	0.3

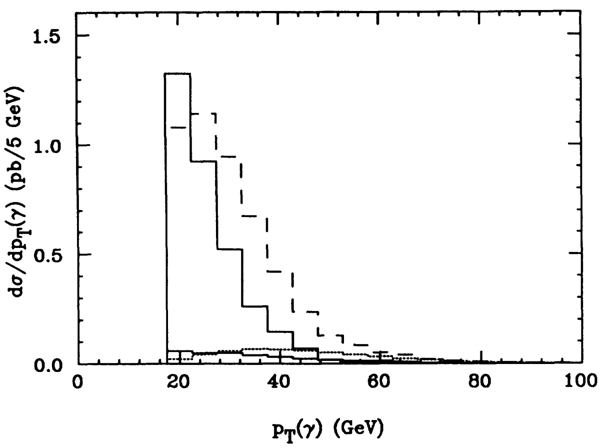

FIG. 9. Same as for Fig. 6 but for the CERN S$p\bar{p}$S collider.

roughly down by $\alpha/\alpha_s \sim \frac{1}{10}$ from γ + three jets, while cuts such as Eqs. (5) and (6) should also work, and suffers less from the combinatorics background. We therefore think that this very distinctive signature should have a SG/BG as good as signature 3.

(c) Isolated $e^+e^- + \nu\bar{\nu}(\not{p}_T)$ + two jets: the effective branching ratio is slightly less than that of e^+e^- + three jets. It is not easy, however, to estimate the background. But given the good SG/BG of signature 1, even before more refined cuts, we think this mode should have a very respectable SG/BG, although it will suffer in event rate. The *WW* pair-production background cannot compete with a strong production process.

(d) Isolated $\gamma + e^+e^-$ + two jets: this mode has a combined branching ratio around 0.3%, and again is rather stable with respect to varying heavy-quark masses. The signal cross section is down by roughly factor of 3 from signature 1, but the background cross section is again down by roughly an order of magnitude from e^+e^- + three jets. The cuts employed in signature 1 are not very applicable, but those analogous to signature 3 (coincidence in group masses) should be effective. The SG/BG is therefore clearly very good; however, this mode probably suffers in event rate.

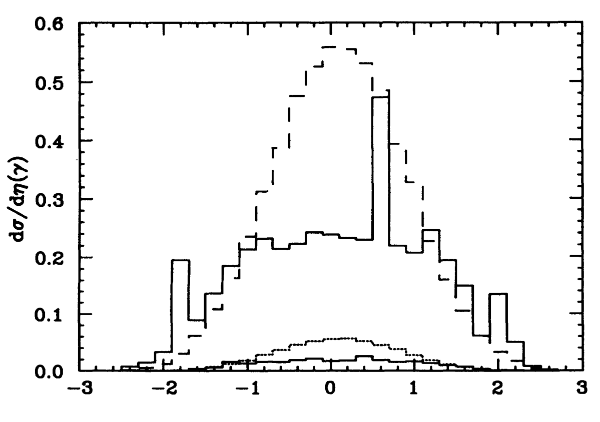

FIG. 10. Same as for Fig. 7 but for the CERN S$p\bar{p}$S collider.

IV. DISCUSSION

The three signatures discussed more extensively in the previous section were the most illustrative, and the background cross section, subject to uncertainties that can be estimated, are readily evaluated. They all turned out to be quite promising at existing hadronic colliders even with *existing* data.

In this respect, it is of interest to see what has been done so far by the experimental collaborations. In general, b' limits have sometimes been quoted together with limits on m_t. However, this is done always with the (tacit) assumption that b' decays via CC channels. To the best of our knowledge, direct searches for FCNC signatures of heavy quarks have not yet been carried out at hadronic machines, in contrast with the case at e^+e^- machines [23]. However, something of relevance has appeared recently. The CDF Collaboration has published a measurement of the inclusive $M(e,e)$ distribution [24], i.e., without demanding the identification of accompanying jets. From our own simulations of Drell-Yan production, without knowing the true detector efficiencies of CDF, we agree with the statement [24] that the inclusive $M(e,e)$ spectrum can be accounted for by SM Drell-Yan production. In Fig. 11 we give our results with the cuts

$$p_T^{e_1} > 15 \text{ GeV}, \quad p_T^{e_2} > 7 \text{ GeV} ,$$
$$|\eta^e| < 2.5, \quad R(e_1,e_2) > 0.4 , \tag{7}$$

and with the electron energy smeared by Gaussian fluctuations with a width of 1.5 GeV. We have multiplied by an integrated luminosity of 4 pb^{-1} for the event rate. The $M(e,e)$ distribution from b' pair production, followed by $b' \to be^+e^-$ for one of the b', is also displayed. Note that the Drell-Yan background effectively disappears below 25 GeV with the cuts of Eq. (7). This is be-

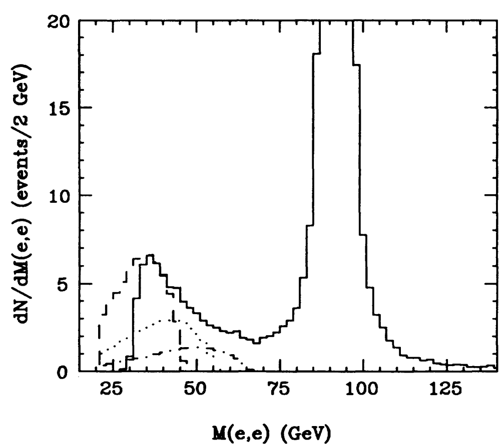

FIG. 11. Histogram illustrating $M(e,e)$ distributions with a 2-GeV bin size at the Tevatron for the signal $p\bar{p} \to b'\bar{b}X \to e^+e^- + X$ for $m_{b'} = 50$ (dashed line), 60 (dotted line), 70 GeV (dot-dashed line), and for Drell-Yan background $p\bar{p} \to e^+e^- + X'$ (solid line) with the cuts specified in the text. The Z peak rises to 140 pb/2 GeV with electron energies smeared by a Gaussian fluctuation of $\sigma = 1.5$ GeV.

cause Drell-Yan production peaks in the forward (backward) direction. In contrast, since the e^+e^- pair is produced more isotropically, the signal survives down to 20 GeV or so. From Fig. 11, we believe that even with existing data on inclusive $M(e,e)$ distribution, a bound can be placed on the branching ratios in the FCNC channels. However, as is clear from Table II, observation of the jets is necessary to get a good signal-to-background ratio, which is even more important due to the small data sample. Furthermore, the data sample on $M(e,e)$ is probably not sufficient to say anything meaningful for $m_{b'} \gtrsim 60$ GeV.

Let us turn to some miscellaneous remarks. For the sake of consistency in event generation, the branching ratios that are given in Table I do not include the contribution from the box diagrams. As discussed in Sec. II, the inclusion of the box diagrams tend to [17] increase the branching ratios of the decay modes $b' \to bq\bar{q}, b\nu\bar{\nu}$, while decreasing the branching ratios of the modes $b' \to be^+e^-$, bg, and $b\gamma$. This will lead to a decrease of about 20–30 % in the signal for the signatures "isolated e^+e^- + two jets" and "isolated γ + three jets." The contribution of the signal to the signature $\not{p}_T$ + two jets is largely unaffected, due to compensating effects in the $b' \to b\nu\bar{\nu}$ and $b' \to bg$ modes. In all three cases the signal-to-background ratio would remain favorable even if box diagrams are included. We have also used $\mu = m_{b'}$ as the scale for the QCD running coupling constant for the process $b' \to bg$. This tends to enhance the $b' \to bg$ mode compared to taking, e.g., $\mu = M_W$, for the $m_{b'}$ range we considered.

In estimating the signal, we have not included the contribution from $b' \to bq\bar{q}$ (as compared with $b' \to bg$). This decay mode is not expected to enhance the signal significantly, and the issue has been discussed in Sec. II. However, the events with this decay mode will modify the $M(j,j)$ and $M(\gamma,j)$ distributions, and increase the signal modestly.

The results presented in the last section have theoretical uncertainties from a number of sources, in particular, the choice of the structure functions, the scale μ^2 that appears in the strong-interaction coupling $\alpha_s(\mu^2)$ and structure functions, and the smearing of the jet energy. We vary these variables in the case of one signature γ + three jets for $m_{b'} = 50$ GeV to make an estimate. To determine the structure function dependence, we tried Duke and Owens structure functions, set 2 [21], those of Glück, Hoffman, and Reya [25], Eichten, Hinchliffe, Lane, and Quigg (EHLQ) [26], and the more recent fits of Harriman, Martin, Roberts, and Stirling (HMRS) [27]. Among these, the older structure functions have a stiffer gluon distribution, which leads to a substantial increase in the signal, while the background is not significantly changed. For example, in the case of the Glück-Hoffmann-Reya functions, the signal-to-background ratio is enhanced by about 50%. However, the use of a fit of HMRS functions results in a reduction of signal of about 27%, but the background is also reduced by about 25%. We therefore see that the use of different sets of structure functions could perhaps enhance the signal-to-background ratio considerably, and in the worst case it would hardly affect the SG/BG ratio. It is hard to describe uncertainties due to the scale dependence of the signal-to-background ratio. Here the main concern is the scale for α_s in the scattering subprocess; usually different values of μ^2 are suitable for the signal versus the background. For the background, we have used $\mu^2 = \langle p_T^2 \rangle$, the average of the p_T^2 of final-state partons. For the signal we have used $\mu^2 = m_{b'}^2$. If one uses $\mu^2 = M_Z^2$ or $\hat{s}$, the background cross section is reduced by half. Varying the μ^2 by a factor of 2 ($\frac{1}{2}$) changes the signal events by -37% ($+69\%$). However, we shall expect the signal-to-background ratio to have a much weaker dependence on the scale μ^2. We probed the sensitivity to the smearing in jet energies by varying the width of Gaussian fluctuations. The use of $\sigma = 3$ GeV instead of 5 GeV increases the signal events by roughly 23%, while the use of $\sigma = 7$ GeV reduces the signal by about 20%. Therefore, this uncertainty can change the signal-to-background ratio by approximately $\pm 20\%$. The upshot is that these three theoretical uncertainties should not affect the viability of the three signatures in any significant way. Another source of uncertainty is the unknown parameters m_t and $m_{t'}$. If we take larger values for these parameters, the branching ratios for the channels $b' \to bq\bar{q}$, $b' \to b\nu\bar{\nu}$, and $b' \to be^+e^-$ are enhanced, but the branching ratios for the channels $b' \to bg$ and $b' \to b\gamma$ decrease. Since the mode $b' \to bg$ plays a crucial rule in the reduction of background for all three signatures, it results in a degraded signal-to-background ratio in each case. For example, if $m_t = 140$ and $m_{t'} = 240$ GeV, the signal in the signature "isolated γ + three jets" will be reduced by 60–70 %, the signal in the signature "isolated e^+e^- + two jets" will be reduced by 30–40 %, while the signal in the signature "$\not{p}_T$ + two jets" will be reduced by 20–30 %. If such is the case, it is clear from the results given in our tables that the signatures "$\not{p}_T$ + two jets" and "isolated e^+e^- + two jets" remain quite viable, but the signature "isolated γ + three jets" will not be as good.

One degrading effect which we have not taken into account is energy-momentum loss in b jets due to semileptonic b decays. This is compounded further by the subsequent semileptonic c decays, although the loss due to the nonobservation of neutrinos will be less serious as one goes down the decay chain. Such loss will also occur, but to a much lesser degree in the background events. We have only partially taken into account this degradation by smearing the parton energies. The effect of this loss can be quite significant on the SG/BG ratio for the signatures "$\not{p}_T$ + two jets" and "isolated γ + three jets" due to the importance of $M(j,j)$ or $M(\gamma,j)$ cuts. For example, demanding that both b's decay hadronically results in a reduction of signal events by 40%. However, studying the impact of this degrading effect will require a much more detailed analysis than that carried out here. One should note, however, that if b jets can be efficiently tagged at a hadronic collider, it would add enormously to the efficiency of isolating the signal events.

We also discussed in Sec. III D various other very distinctive and promising signatures. Clearly, if the scenario of Ref. [14] is realized in nature for the mass range we considered, there would indeed be many rather spectacular signals hidden in existing CDF and UA1/UA2 data waiting to be extracted. The multitude of signatures, if discovered, would serve as useful cross checks, and also provide information for the extraction of relevant physical parameters, e.g., $m_{b'}, m_t, m_{t'}$.

The extreme scenario presented above should be easily refutable by analyzing data. However, as one weakens the assumptions involved, i.e., if $V_{cb'}$ is not extremely small (for the mass range that we consider, $m_{b'} < m_t$ is a safe assumption), then CC $b' \rightarrow c$ transitions may exist at some level. If CC is predominant, as stated before, it is also easy and straightforward (and already studied by experimental groups). However, if the CC and FCNC are comparable, then the phenomenology is even richer, but every signal gets diluted. The CDF limit on $m_{b'}$ will have to be lowered according to the $B(b' \rightarrow l\bar{\nu}+X)$ that is being probed. One would have to do a more elaborate analysis for the remaining unexplored range of $M_Z/2 \lesssim m_Q \lesssim M_Z$ than is presented here. We leave this to our experimental colleagues. We have no doubt, however, from the experience gained above, that this combined analysis should also be able to cover the complete mass range. Thus, if b' exists within the mass range $M_Z/2 \lesssim m_Q \lesssim M_Z$, we believe that existing hadronic collider data should be able to find it, whichever way it decays. With almost ten times more integrated luminosity and the entrance of the D0 detector into the search in the near future, one could even study the more suppressed modes.

All three signatures that we have discussed can also be explored at the e^+e^- collider LEP II, where the considerations for signal versus background are completely different than for hadronic machines. In general, the background is much less severe. We have discussed the usefulness of the signature "isolated + three jets" in Ref. [16]. There we showed that with the appropriate cuts (against $e^+e^- \rightarrow \gamma Z^0 \rightarrow \gamma +$three jets) the SG/BG ratio can be made quite favorable. We expect the situation to be even better for the other two signatures, viz., isolated e^+e^-+multijet and $\not{p}_T+$multijet, although the former may suffer from event rate. Similar searches can also be conducted for the other heavy quarks as well. However, as we have emphasized above the CDF/D0 Collaborations should be able to verify or rule out the existence of the b' quark in the relevant mass range before LEP II becomes operational.

We have not focused much on vectorlike quarks, for their signatures due to FCNC decay modes are similar to those of the b' quark—except the signatures with photons. Since these quarks always have substantial branching ratios for the CC modes, it is clear from the tables that such quarks, if produced, are much more likely to show up in the signature e^+e^-+multijet than any other. This signal is particularly clean (one could imagine the multijets to contain even jets from CC decays, i.e., from W^*) and the $M(e,e)$ cut (or plot) should work. In any case, when a new heavy quark is detected, it will take some time to check its flavor, and we think that checking for FCNC modes should be an integral part of the experimental program.

V. CONCLUSION

In this paper, we have emphasized the need to look for heavy quarks beyond the top quark. Such quarks could not only have interesting decay properties, but could also lead to unsuspected backgrounds to the detection of particles that are expected to provide clues at the SSC/LHC about the symmetry-breaking sector of the standard model, e.g., the Higgs boson, techni-ρ, or techni-ω. The classic signal for supersymmetry, $\not{p}_T+$multijet, also receives additional background. If new heavy quarks exist in the $M_Z/2 \lesssim m_Q \lesssim M_Z$ range, production cross sections at hadronic colliders are large enough that they should have already been recorded in existing data. We have analyzed three signatures of these heavy quarks, viz., "isolated e^+e^-+two jets," "$\not{p}_T+$two jets," and "isolated $\gamma+$three jets," in particular for the b' quark. We show that with these novel signatures taken into account, the CDF/D0 Collaborations at the Tevatron should be able to discover such quarks if they exist with a mass below M_Z. Such an analysis should also be possible at the CERN $Sp\bar{p}S$ collider, but for a more restricted mass range. Any discovery of new heavy quarks will be very exciting in itself. (For example, the existence of b' would imply the existence of heavy charged and neutral leptons.) If not, one can put appropriate bounds on the possible parameters and, in the process, make sure that the main program at the SSC/LHC does not run into unexpected difficulties.

ACKNOWLEDGMENTS

We thank our many colleagues for useful discussions. In particular, we thank J. Huth, M. Shapiro, and J. Yoh for discussions on experimental aspects, and M. Gold and T. Nakada for clarifying discussions regarding Ref. [22]. P.A. would like to thank Professor S. Ellis for his suggestions. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada.

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