Searching for Bottom Squarks at Luminosity Upgrades of the Fermilab Tevatron

Howard Baer\(^1\), P. G. Mercadante\(^2\), and Xerxes Tata\(^2\)

\(^1\)Department of Physics, Florida State University, Tallahassee, FL 32306-4350 USA
\(^2\)Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822 USA

Abstract

Because of their Yukawa interactions, third generation squarks may be substantially lighter than those of the first two generations. Assuming that \(\tilde{b}_1 \rightarrow b \tilde{Z}_1\) and \(\tilde{Z}_1\) escapes experimental detection, we show that experiments at the Main Injector upgrade (integrated luminosity of 2 \(fb^{-1}\)) of the Tevatron should be sensitive to \(b\)-squark masses up to 210 GeV for \(m_{\tilde{Z}_1} \leq 120\) GeV. For integrated luminosities of 10 \(fb^{-1}\) (25 \(fb^{-1}\)) the sbottom mass reach increases by 20 GeV (35 GeV). If the channel \(\tilde{b}_1 \rightarrow b \tilde{Z}_2\) is also accessible, the reach becomes model-dependent and may be degraded relative to the case where only the decay to \(\tilde{Z}_1\) is allowed. In models with gaugino mass unification and \(\mu\) much larger than gaugino masses, we argue that this degradation is unlikely to be larger than 30-40 GeV.

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It is well known that third generation squarks, on account of their large Yukawa couplings, can be significantly lighter than their first and second generation cousins, even in models where soft supersymmetry (SUSY) breaking squark masses are universal at some scale. The large value of the top quark Yukawa coupling has prompted several theoretical and experimental investigations of possible signals via which a light $t$-squark might be detectable at the Tevatron, under the assumption that all other squarks as well as the gluino are heavier. It should, however, be remembered that electroweak gauge invariance requires that the soft SUSY breaking masses of $\tilde{t}_L$ and $\tilde{b}_L$ are identical since these are members of an $SU(2)_L$ doublet; moreover, whereas the diagonal entries in the top squark mass squared matrix include a contribution $m_t^2$ (from electroweak symmetry breaking), the corresponding contribution to the sbottom mass matrix is essentially negligible. It is, therefore, not unreasonable to consider the possibility that $\tilde{b}_1$, the lighter of the two $b$-squark eigenstates, may be much lighter than other squarks. Moreover, in models (such as mSUGRA) with universal squark masses at some high scale, it is reasonable to suppose that $\tilde{b}_1 \approx \tilde{b}_2$ as long as the bottom Yukawa coupling is small relative to its top counterpart. Experiments at LEP have obtained lower limits of about 70 GeV on the sbottom mass. These limits have been obtained assuming that the $b$-squark mixing angle $\theta_b$ vanishes. More generally, the LEP limit depends on $\theta_b$, and even disappears if this angle is fine tuned so that the $Z$ exchange amplitude exactly cancels the corresponding photon exchange. The purpose of this paper is to examine signals via which such a light sbottom may be searched for at future runs of the Tevatron collider, and to delineate the reach of experiments at the Main Injector (MI) and its luminosity upgrades that may be possible in the future.

The signals depend on how the sbottom decays. In our analysis, we assume that the gluino is heavy so that the decay $\tilde{b}_1 \to \tilde{g}$ is kinematically forbidden, and further, that the lightest neutralino $\tilde{Z}_1$ is the lightest SUSY particle (LSP), so that the decay $\tilde{b}_1 \to \tilde{b}\tilde{Z}_1$ is always allowed. The other possible two-body decay modes are $\tilde{b}_1 \to \tilde{b}\tilde{Z}_i$ and $\tilde{b}_1 \to \tilde{t}\tilde{W}_i$. Searches at LEP 2 exclude charginos lighter than $\sim 85$ GeV and so preclude the latter decays unless $\tilde{b}_1$ is heavier than 260 GeV. We will see that such heavy sbottoms are beyond the reach of the Tevatron upgrades; it is, therefore, sufficient to focus on the case where only the neutralino decays of $\tilde{b}_1$ are accessible.

We use ISAJET 7.37 [4] for our simulation. To model the experimental conditions at the Tevatron, we use the toy calorimeter simulation package ISAPLT. We simulate calorimetry covering $-4 < \eta < 4$ with cell size $\Delta\eta \times \Delta\phi = 0.1 \times 5^\circ$. We take the hadronic (electromagnetic) energy resolution to be $50\%/\sqrt{E}$ ($15\%/\sqrt{E}$). Jets are defined as hadronic clusters with $E_T > 15$ GeV within a cone with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.7$. We require that $|\eta_j| \leq 3.5$. Muons and electrons are classified as isolated if they have $p_T > 10$ GeV, $|\eta(\ell)| < 2$, and the visible activity within a cone of $R = 0.3$ about the lepton direction is less than 5 GeV. For SVX tagged $b$-jets, we require a jet (using the above jet requirement) to have in addition $|\eta_j| < 1$ and to contain a $B$-hadron with $p_T > 15$ GeV. Then the jet is tagged as a $b$-jet with a 50% efficiency.

We begin by considering the simplest case, where we assume that $m_{\tilde{Z}_2} > m_{\tilde{b}_1} - m_b$ so that $\tilde{b}_1 \to \tilde{b}\tilde{Z}_1$ with a branching fraction of essentially 100%. In this case, the signal naively consists of two $b$-jets recoiling against $E_T$ from the two neutralinos that escape detection. The dominant Standard Model backgrounds come from $W + j$, $Z \to \nu\nu + j$, $Z \to \tau\tau + j$, and $t\bar{t}$ production. We consider the signal to be observable above background if, for a given
integrated luminosity, (i) the signal exceeds “5σ”; i.e. $S \geq 5\sqrt{B}$, where $S$ and $B$ are the expected number of signal and background events, respectively, and (ii) $S \geq 0.2B$. We also require a minimum of 5 signal events. To enhance the signal relative to the SM background, we impose the following requirements, hereafter referred to as the basic cuts:

1. at least two jets with $p_T(j_1) > 30$ GeV, $p_T(j_2) > 20$ GeV;
2. at least one jet in $|\eta_j| < 1$;
3. $E_T > 50$ GeV;
4. $\delta\phi(\vec{E}_T, \vec{p}_{Tj}) > 30^\circ$;
5. for di-jet events only, $\delta\phi(\vec{p}_{Tj1}, \vec{p}_{Tj2}) < 150^\circ$;
6. at least one SVX tagged B;
7. no isolated leptons ($e$ or $\mu$).

The SM backgrounds at a 2 TeV $p\bar{p}$ collider, with these basic cuts, are shown in the first row of Table 1. We use CTEQ3L structure functions [7] for all our calculations, and take $m_t = 175$ GeV. Except in the case of the $t\bar{t}$ background the tagged $b$-jet comes from QCD radiation. For an integrated luminosity of 2 $fb^{-1}$ expected to be accumulated at the MI upgrade of the Tevatron, the $5\sigma$ level falls just short of our $S \geq 0.2B$ requirement. To see how to further enhance the signal, we note that $t\bar{t}$ events form the dominant background. Because of the lepton veto, much of this background comes when one of the tops decays into a tau lepton that decays hadronically, while the other top decays completely hadronically. These events are, therefore, likely to have large jet multiplicity, in contrast to the signal (as well as the other backgrounds in the Table). We are, therefore, led to impose the additional requirement,

8. $n_j = 2, 3$

designed to further reduce the top background with relatively modest loss of signal. The corresponding background levels are shown in the second row of Table 1. The entry +8 in the first column denotes the cuts over and above the basic cuts 1-7. Indeed, we see that the top background is reduced by a factor 5, and no longer dominates.

Turning to the signal, we use ISAJET to generate $\tilde{b}_1\tilde{b}_1$ events where $\tilde{b}_1 \rightarrow b\tilde{Z}_1$, and pass these through our simulation with the cuts discussed above. With these assumptions, the cross section is completely determined by $m_{\tilde{b}_1}$ and $m_{\tilde{Z}_1}$. The reach of a 2 TeV $p\bar{p}$ collider is shown in the $m_{\tilde{b}_1} - m_{\tilde{Z}_1}$ plane in Fig. 1. The diagonal solid line marks the boundary of the region where $m_{\tilde{b}_1} \geq m_{\tilde{Z}_1} + m_b$. With our assumptions, we are required to be below this line, since otherwise, $\tilde{b}_1$ would be the LSP. The dot-dashed contour shows the reach that should be attainable (using cuts 1-8) with an integrated luminosity of 2 $fb^{-1}$ corresponding to the anticipated data sample expected at the MI. The dotted lines denote signal cross sections after these cuts.

It is possible that larger data samples might be accumulated after several years of MI operation, or at TeV33, a proposed luminosity upgrade of the Tevatron. Here, we analyse
the $b$-squark reach for integrated luminosities of 10 $fb^{-1}$ and 25 $fb^{-1}$. The background, which now dominantly comes from $Z \rightarrow \nu \nu + j$ events, has to be further reduced in order to satisfy our $S/B$ requirement. It is reasonable to suppose that both the radiated jets that recoil against the high in $p_T Z$ boson these events are frequently on the opposite side as the $Z$ in the transverse plane. We are thus led to impose, in addition to cuts 1-8, a further requirement,

9. $\Delta \phi_{j_1, j_2} \geq 90^\circ$,

which significantly reduces the vector boson backgrounds, as can be seen from the third row in Table 1. For an integrated luminosity of 10 $fb^{-1}$, the $5\sigma$ level is just below the 20% requirement of 15.4 $fb$ which we take to be the observability level for this case. This is shown as the dashed contour in Fig. 1.

For the yet higher integrated luminosity of 25 $fb^{-1}$, the high event rate makes it possible to require double $b$-tagging,

10. $n_b \geq 2$,

to greatly reduce the vector boson background. As before, the top quark background is reduced by cut 8 on the jet multiplicity. The background levels corresponding to just the $n_b \geq 2$ cut (over and above the basic cuts), as well as this cut in conjunction with the cut on jet multiplicity, are shown in the next two rows of Table 1. Note that even after these stringent cuts, the $5\sigma$ cross section which determines the observable level implies that there should be more than 100 signal events in the data sample. The corresponding reach is shown as the solid contour in Fig. 1.

Several comments are in order.

- The reach of the MI extends to $m_{\tilde{b}_1} = 210$ GeV as long as the LSP is not too close in mass to $\tilde{b}_1$; for 70 GeV $\leq m_{\tilde{b}_1} \leq 160$ GeV, the signal is observable for $m_{\tilde{Z}_1} \lesssim 0.8 m_{\tilde{b}_1}$. For heavier $\tilde{b}_1$ the signal is observable up to 200 GeV as long as the LSP is lighter than 135 GeV. This result is model-independent as long as $\tilde{b}_1 \rightarrow b\tilde{Z}_1$ and $\tilde{Z}_1$ escapes detection in the experimental apparatus.

- With the cuts suggested, typically $\geq 100$ signal events are expected in the region where we claim an observable signal, for all three integrated luminosity cases studied here.

- There is a considerable increase in the region of the $m_{\tilde{b}_1} - m_{\tilde{Z}_1}$ plane that can be probed with larger integrated luminosity. Assuming that the detectors and other systems function the same way in a high luminosity environment, a data sample of 25 $fb^{-1}$ would enable us to detect $\tilde{b}_1$ as heavy as 240 GeV for an LSP up to 160 GeV.

- If $m_{\tilde{Z}_1}$ is close to $m_{\tilde{b}_1}$, the solid contour is actually slightly inside the dashed one. This is because the $b$-jet then tends to be soft so that the efficiency for double $b$-tagging is considerably reduced.

- In addition to SVX tagging, the CDF collaboration had used soft lepton tags (SLT) to enhance the $b$ tagging efficiency for its top quark analysis. For the $b$-squark signal discussed in this paper, we found that attempting to include lepton tags leads to a
much bigger increase in the background relative to the signal and actually degrades the reach. This is because $W + j$ events where the lepton from a $W$ is accidently within the jet (which is then tagged as $b$) are a significant source of “fake” background events. This is not so for the top quark search since, in that case, in addition to the lepton to tag the $b$, another isolated lepton was required to be present.

- Finally, we stress that efficient SVX tagging of $b$-jets is crucial for this search. Our analysis may be somewhat optimistic in that we have not included the possibility that charm or light quark or gluon jets might fake the $b$ in our estimate of the SM backgrounds. While we do not expect these backgrounds to be overwhelmingly large, the reader can use the cross section contours in the figure to obtain a rough idea of how the reach would be altered at Run II once these backgrounds are included, or for that matter, if the $b$ tagging efficiency turns out to be different from the assumed 50%.

We should note that it may be possible to modify our cuts (for $\tilde{b}_1$ search at the MI) to search for $b$-squarks in the CDF Run I data sample. Because the SVX tagging efficiency seemed to be evolving as the run progressed, we have made no attempt to project the sbottom mass range that the CDF collaboration might be able to probe using the data that they have already collected.

Up to now we have assumed that $\tilde{b}_1 \to b\tilde{Z}_1$ and further that $\tilde{Z}_1$ escapes detection. It is reasonable to ask what happens if this is not the case: in particular, can the reach be substantially degraded from that shown in Fig. 1? We confine ourselves to models where $R$-parity is conserved, and where $\tilde{Z}_1$ is the (stable) LSP, noting only that the reach may be considerably degraded if $\tilde{Z}_1$ decayed hadronically via $\tilde{Z}_1 \to q\bar{q}$ (and its conjugate mode) via $R$-parity violating interactions. Since LEP constraints already preclude the decay $\tilde{b}_1 \to t\tilde{W}_1$, we are led to consider the possibility that $\tilde{b}_1 \to b\tilde{Z}_2$ is also allowed. The signal now depends on the branching fraction for this decay, as well as the decay pattern of $\tilde{Z}_2$. In other words, the signal depends both on the $b$-squark mixing angle as well as on the parameters of the neutralino mass matrix.

We have already argued that in many models it is reasonable to suppose that $\tilde{b}_1 \approx \tilde{b}_L$. To make our analysis tractable, we will assume that this is the case. We will further assume that $|\mu|$ is much larger than electroweak gaugino masses. Assuming gaugino mass unification, the two lighter neutralinos are approximately the hypercharge gaugino and the $SU(2)$-gaugino, with $m_{\tilde{Z}_2} \approx m_{\tilde{W}_1} \approx 2m_{\tilde{Z}_1}$. Note that these assumptions fix the branching fraction for $\tilde{b}_1 \to b\tilde{Z}_{1,2}$ decays in terms of the sparticle masses. It is also worth pointing out that if $\tilde{Z}_2 \simeq SU(2)$-gaugino, it essentially decouples from $\tilde{b}_R$, so that the maximum impact of the $\tilde{b}_1 \to b\tilde{Z}_2$ indeed occurs when $\tilde{b}_1 = \tilde{b}_L$.

Since we are interested in seeing how much the reach of the Tevatron may be reduced from what shown in Fig. 1, we consider extreme limits for how $\tilde{Z}_2$ might decay. If $\tilde{Z}_2$ dominantly decays to leptons via $\tilde{Z}_2 \to \ell\ell\tilde{Z}_1$, sbottom pair production would result in characteristic $bb + 4\ell + E_T$ and $bb + 2\ell + jets + E_T$ events for which the background is small, and the corresponding reach, presumably, larger than that in Fig. 1. If $\tilde{Z}_2 \to b\bar{b}\tilde{Z}_1$ it may be possible to reduce the background (and hence increase the reach) by requiring two (or more) $b$-tags. The worst case “realistic” scenario is when $\tilde{Z}_2$ decays into jets which are not amenable to any tagging. To simulate this situation, we have forced $\tilde{Z}_2$ to decay via
\( \bar{Z}_2 \to u\bar{u}\bar{Z}_1 \) and run these events through our simulation, and once again obtained the reach for the three choices of integrated luminosity in Fig. 1.

The results of our analysis for this case are illustrated in Fig. 2. The upper diagonal line is as in Fig. 1, while the lower line is where \( m_{\tilde{b}_1} = 2m_{\tilde{Z}_1} + m_b \approx m_{\tilde{Z}_2} + m_b \). In our analysis, we have adjusted \( A_b \) to cancel the off diagonal term in the sbottom mass matrix in order to make \( \tilde{b}_1 = \tilde{b}_L \). We have fixed \( \mu = 500 \text{ GeV} \) and \( \tan \beta = 2 \); this value of \( \mu \) is large enough for \( \tilde{b}_1 \) and \( \tilde{Z}_2 \) to be gauginos to a very good approximation.

When the decay \( \tilde{b}_1 \to b\tilde{Z}_2 \) is inaccessible, the reach should be as given by our analysis above; i.e., the reach illustrated by the dot-dashed, dashed and solid contours until just above this line, is identical to that in Fig. 1. The contours below this line are obtained as described shortly, and show the extent to which the reach might be reduced if the \( \tilde{b}_1 \) can also decay to \( \tilde{Z}_2 \). These contours in Fig. 2 turn inwards just slightly above this line precisely because the relation \( m_{\tilde{Z}_2} = 2m_{\tilde{Z}_1} \) is slightly violated by our finite choice of \( \mu \).

As before, the cuts have to be optimized for each value of integrated luminosity. Cut 8, which was so effective in reducing the \( t\bar{t} \) background in our analysis in Fig. 1 now leads to too large a signal loss because of the additional jets from \( \tilde{Z}_2 \) decay. For the case of 2 \( fb^{-1} \) we found that the best strategy was to simply use the basic cuts 1-7 for which the 20\% signal level is just a bit above the 5\( \sigma \) level. The dot-dashed contour in the Fig. 2 shows the corresponding reach for the MI. We see that even in this “worst case” scenario, the MI reach is diminished by no more than 25-30 GeV.

For an integrated luminosity of 10 \( fb^{-1} \), the analysis is more complicated. Just below the lower diagonal line, the jet multiplicity is still not large because the \( b \)-jet from \( \tilde{b}_1 \to b\tilde{Z}_2 \) tends to be soft and/or the branching fraction for the decay is still not large: in this case, the additional cuts 8+9 are still effective and the signal (presumably from events where at least one of the sbottoms decays directly to \( \tilde{Z}_1 \)) remains observable above background. However, for larger values of \( m_{\tilde{b}_1} - m_{\tilde{Z}_2} \), too much of the signal is eliminated by the jet multiplicity cut, and the reach in \( m_{\tilde{b}_1} \) is considerably reduced. In this case, however, it is possible to obtain an observable signal by requiring double \( b \)-tagging, without any restriction on jet multiplicity. For an integrated luminosity of 10 \( fb^{-1} \), we thus consider the signal to be observable if either it is observable using the additional cuts 8 and 9 (the signal is then still background-limited), or it is observable using the additional cut 10. The boundary of the plane that can be probed with 10 \( fb^{-1} \) is shown by the dashed contour in Fig. 2, where the kink merely reflects that this region is a composite of two such regions as we have just described.

Finally, for the 25 \( fb^{-1} \) case, as before we consider double-tagged events, for which the \( t\bar{t} \) background dominates. Since the top background sample (after the basic cuts) is expected to contain a pair of jets from the decay of a \( W \) boson, we further require

11. \( m_{j_1,j_2} \leq 60 \text{ GeV} \), where \( j_1 \) and \( j_2 \) are the two highest \( p_T \) untagged jets in the event. If an event has less than two untagged jets, we retain it as part of the signal.

The solid contour in Fig. 2, shows the reach for an integrated luminosity of 25 \( fb^{-1} \) with the additional cuts 10 and 11, for which the background level is just 23.3 \( fb \). We see that the reach may be diminished by about 40 GeV from that shown in Fig. 1. As with our earlier analysis, with our new cuts designed to pull out the signal when the \( \tilde{b}_1 \to b\tilde{Z}_2 \) might be accessible, we expect \( \geq 100 \) signal events (for all three cases of integrated luminosity) over
the entire region where the signal should be observable. We also stress that the degradation of the reach by 30-40 GeV that we have found is the largest it could be in a wide class of models. Most models will lead to a smaller reduction in the reach. In fact, in some scenarios, e.g. gauge-mediated models \cite{12} where $\tilde{Z}_1 \rightarrow \gamma \tilde{G}$, or $R$-parity violating models \cite{13} where $\tilde{Z}_1 \rightarrow \ell \ell' \nu$, the reach may even be larger than that shown in Fig. 1, because the presence of hard photons or leptons serves to greatly reduce the SM background.

While this may be obvious, it may be worth emphasizing that since we do not \textit{a priori} know whether $\tilde{b}_1 \rightarrow b \tilde{Z}_2$ is accessible, two separate analyses might be needed. If no signal is found with the analysis where it was assumed $\tilde{b}_1 \rightarrow b \tilde{Z}_1$, this means that either $(m_{\tilde{b}_1}, m_{\tilde{Z}_1})$ is outside the observable region in Fig. 1, or there is a sbottom signal with $\tilde{b}_1 \rightarrow b \tilde{Z}_2$ which is being effectively cut out, for instance, by the $n_j = 2, 3$ cut (cut 8) used in this analysis. To ensure that one is not throwing the baby out with the bathwater, it is thus important to reanalyse the data using the alternative set of cuts, specifically designed to retain the signal in this case.

We have also examined the case where $\tilde{Z}_2$ produced with exactly the same branching fraction as in Fig. 2 decays invisibly. In this case, there is a sharp reduction in the reach just below the kinematic boundary for the $\tilde{b}_1 \rightarrow b \tilde{Z}_2$ decay (since the daughter $b$ frequently fails to pass the cut on the second jet) but for lowest values of $m_{\tilde{Z}_2}$ in the figures, the reach contours lie within 10 GeV of the corresponding $m_{\tilde{b}_1}$ values in Fig. 1. Except for a tiny region very close to the $\tilde{b}_1 \rightarrow b \tilde{Z}_2$ decay boundary, the reach is more degraded in the case where $\tilde{Z}_2 \rightarrow u \bar{u} \tilde{Z}_1$ than in the case where $\tilde{Z}_2$ decays invisibly.

In summary, motivated by the fact that the $b$-squark may be lighter than other squarks we have attempted to assess the capability of the MI and possible future luminosity upgrades of the Tevatron to identify a SUSY signal from $\tilde{b}_1$ pair production. Assuming that $\tilde{b}_1 \rightarrow b \tilde{Z}_1$ and that $\tilde{Z}_1$ escapes detection, we have shown that it should be possible for experiments at the MI to detect $b$-squark signals over SM backgrounds for $m_{\tilde{b}_1} \leq 210$ GeV, even if the LSP is quite heavy. The capability of tagging $b$-jets in the central region with high efficiency and purity is crucial for this detection. Luminosity upgrades to 10 fb$^{-1}$ (25 fb$^{-1}$) should increase the reach to $\sim 230$ GeV ($\sim 245$ GeV). The reach may be somewhat degraded if sbottom can also decay into $\tilde{Z}_2$. We have argued that in many models (with $\tilde{Z}_1$ as a stable LSP) this degradation is typically smaller than 30-40 GeV, but could be larger if $\tilde{Z}_1$ is unstable and decays only to hadrons.

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[10] In the extreme case where the branching fraction for $\tilde{b}_1 \to b\tilde{Z}_2$ is 100% when this decay is allowed, and if $\tilde{Z}_2$ only decays invisibly, the reach can once again be read off from Fig. 1.

[11] We expect that this leads to a lower $E_T$ than in the case when it decays invisibly. We will return to this issue shortly.

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Figure Captions

**Fig. 1** The region of the $m_{\tilde{b}_1} - m_{\tilde{Z}_1}$ plane that can be probed at a 2 TeV $p\bar{p}$ collider, assuming that $\tilde{b}_1 \rightarrow b\tilde{Z}_1$ and that $\tilde{Z}_1$ escapes detection. The sbottom signal should be detectable with the observability criteria defined in the text in the region below the dot-dashed, dashed and solid contours for an integrated luminosity of 2 $fb^{-1}$, 10 $fb^{-1}$ and 25 $fb^{-1}$, respectively, with the set of cuts given in the text. These cuts have been optimized for each value of integrated luminosity. Also shown in the figure are contours of constant signal cross section after cuts 1-8 for the 2 $fb^{-1}$ case. The 34 $fb$ contour marks the $0.2B$ level that we require as a minimum for the signal. The diagonal line marks the boundary of the region beyond which $m_{\tilde{b}_1} > m_b + m_{\tilde{Z}_1}$.

**Fig. 2** The same as Fig. 1 except that the decay $\tilde{b}_1 \rightarrow b\tilde{Z}_2$ is also allowed when kinematically accessible below the lower diagonal line. To compute the branching fraction for this decay, we assume that $\tilde{b}_1 = \tilde{b}_L$, and that $\tilde{Z}_1$ and $\tilde{Z}_2$ are essentially hypercharge and $SU(2)$ gauginos, respectively, as discussed in the text, and that $m_{\tilde{Z}_2} \approx 2m_{\tilde{Z}_1}$. To illustrate the largest degradation of the reach in this scenario, we assume that $\tilde{Z}_2$ always decays via $\tilde{Z}_2 \rightarrow u\bar{u}\tilde{Z}_1$. The dotted lines are again contours of fixed cross section after the basic cuts 1-7 we use for the MI analysis. The dot-dashed contour that denotes our projection of the MI reach also corresponds to $S = 0.2B$. 
TABLE I. Standard Model background cross sections in fb to the $b$-squark signal after the basic cuts 1-7 described in the text, as well as after additional cuts designed to further reduce backgrounds. The “plus entries” in the first column refer to the cuts in addition to the basic cuts; for instance, the last row has cuts 1-8 together with cut 11. We take $m_t = 175$ GeV.

| CUT  | $W + j$ | $Z \rightarrow \nu \nu + j$ | $Z \rightarrow \tau \tau + j$ | $tt$  | Total |
|------|--------|----------------|----------------|------|-------|
| Basic| 65.5   | 92.4          | 2.6           | 195  | 356   |
| +8   | 51.6   | 80.6          | 2.1           | 36.7 | 172   |
| +8 + 9| 21.9   | 26.2          | 0.9           | 28.0 | 77    |
| +10  | 5.6    | 7.2           | 0.1           | 37.5 | 50.4  |
| +8 + 10| 3.8    | 6.6           | 0.1           | 6.7  | 17.2  |
| +8 + 11| 5.0    | 6.6           | 0             | 11.7 | 23.3  |
$b_1 \rightarrow b \tilde{Z}_1$

$m(\tilde{Z}_1) = m(\tilde{b}_1) - m(b)$

$\tilde{b}_1$ (GeV)

$\tilde{Z}_1$ (GeV)
\[ \tilde{b}_1 \rightarrow b \tilde{Z}_{1,2} \]

\[ \tilde{Z}_2 \rightarrow u \bar{u} \tilde{Z}_1 \]

\[ m(\tilde{Z}_1) = m(\tilde{b}_1) - m(b) \]

\[ m(\tilde{Z}_2) \approx 2m(\tilde{Z}_1) = m(\tilde{b}_1) - m(b) \]