Single B Production through R-Parity Violation

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Supersymmetry without R–parity predicts tree level quark flavor violation. We present a potential signal of single bottom production at electron–positron colliders with energies in the range 6 to 20 GeV. Taking into account rare decay limits, it should be detectable with the current BaBar and Belle data samples.

I. INTRODUCTION

The Minimal Supersymmetric Standard Model \cite{1} (MSSM) without R–parity \cite{2} predicts Yukawa interactions that violate baryon and/or lepton number without violating Standard Model gauge symmetries or supersymmetry. The superpotential for these interactions is

\[ W_R = \frac{1}{2} \lambda_{ijk} (L_i)_a \epsilon_{ab} (L_j)_b E_k^c + \lambda'_{ijk} (L_i)_a \epsilon_{ab} (Q_j)_b D_k^c \]

\[ + \mu' (L_i)_a \epsilon_{ab} (H_u)_b + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c \]

where \( i, j \) and \( k \) are generational indices and \( a \) and \( b \) are \( SU(2) \) indices. Color indices have been suppressed. \( L \) is the lepton doublet, \( E^c \) is the charged anti–lepton singlet, \( Q \) is the quark doublet, \( D^c \) is the down–type anti–quark singlet, \( U^c \) is the up–type anti–quark singlet and \( H_u \) is the Higgs doublet which generates mass for up-type quarks. The factor of \( \frac{1}{2} \) before the \( \lambda \) term is conventional: we see that \( \lambda_{ijk} = -\lambda_{jik} \) by relabelling \( a \) to \( b \) and vice–versa in the first term of the superpotential, hence the extra factor of \( \frac{1}{2} \) sets the coupling of the \( \nu_i e_j E_k^c \) term to be \( \lambda_{ijk} \), rather than \( 2 \lambda_{ijk} \). Likewise \( \lambda''_{ijk} \) is antisymmetric in \( j \) and \( k \) (the color indices in the final term are combined with an antisymmetric tensor), hence its factor of \( \frac{1}{2} \).

The combination of \( \lambda' \) and \( \lambda'' \) leads to proton decay and is thus constrained by searches for proton decay into a positron and a pion \cite{3} and also by invisible neutron disappearance searches \cite{4}. Requiring \( \lambda''_{ijk} = 0 \) is sufficient to guarantee perturbative proton stability while leaving the possibility of non–zero lepton–number violating couplings. These couplings introduce a new channel for flavor violation.

So far, there is no direct evidence for supersymmetry or R–parity violation. The non–observation of single sparticle production puts constraints on a combination of their masses and couplings \cite{5}. Most of the tightest bounds on individual couplings come from charged current universality \cite{6}, as single sfermion exchange generally interferes with weak boson exchange. Meson and \( \tau \)–lepton rare decay data typically provide tighter bounds on products of R–parity violating (RPV) couplings than the product of individual bounds \cite{2}.

In an era of high–precision flavor physics the obvious question is whether for example B physics observables can be used to further probe the RPV parameter space. We present a potential signal of single B production at electron–positron colliders with energies in the range 6 to 20 GeV, with special attention given to the case of a center–of–mass energy of 10.58 GeV, at which BaBar and Belle currently run. The lower limit is chosen slightly above the threshold for creating a \( BK \) meson pair.

This paper is arranged as follows. First, the potential signal through RPV couplings is calculated for two cases: that in which only an on–shell quark—anti–quark pair is produced, and that in which an on–shell quark—anti–quark pair and a photon are produced. The hadronization of the quarks and the experimental signature are then briefly discussed. Next, the background to the signal is considered: the SM contribution is calculated and the signal from the R–parity–conserving sector of the MSSM is estimated. Finally, the conclusions are presented.

II. SINGLE b PRODUCTION

The Standard Model predicts quark flavor violation through CKM mixing, but the cross–sections for \( e\bar{e}\to b\bar{s} \) or \( b\bar{d} \) are extremely small. Detection of flavor violation in significant excess to the Standard Model prediction would be an exciting signal of new physics.

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We obtain the differential cross–sections shown in Fig. 1.

The sneutrino mediated diagram is proportional to \( \nu_1 \nu_3 \) (\( \nu_1 \nu_3 \) vertex) multiplied by either \( \lambda_{g11} \) (\( \nu_1 \nu_3 \) vertex) or \( \lambda'_{g11} \) (\( \nu_1 \nu_3 \) vertex). The squark mediated diagram is proportional to \( \nu_3 \nu_3 \) (\( \nu_3 \nu_3 \) vertex) multiplied by either \( \lambda_{g12} \) (\( \nu_3 \nu_3 \) vertex) or \( \lambda'_{g12} \) (\( \nu_3 \nu_3 \) vertex). We write \( \nu_1 \) and \( \nu_2 \) instead of \( \nu_3 \) and \( \nu_4 \), and guide — in all cases the sneutrino is implicitly of generation \( g \), and associated with the left–handed chirality of its superfield partner.

Because the sneutrinos are constrained to be heavy, \( m_{\tilde{\nu} L, R} \gtrsim 100 \text{ GeV} \), we approximate their propagators as static \( 1/m_{\tilde{\nu} L, R} \). Moreover, we assume that one sneutrino dominates the signal process, either because it is lighter than the others or because it has a larger coupling product.

If we sum over the \( b \) and \( \bar{b} \) final states and allow for only one of the two \( R \)–parity violating processes to dominate we obtain the differential cross–sections

\[
\frac{d\sigma}{d\Omega} = \frac{|p_b|}{|p_c|} \frac{3}{128\pi^2} \left( s - m_b^2 - m_{\tilde{\nu}}^2 \right) \frac{|\lambda_{g11}|^2 |\lambda'_{g23}|^2}{m_{\tilde{\nu}}^4}
\]

for the \( s \)–channel sneutrino exchange, and

\[
\frac{d\sigma}{d\Omega} = \frac{|p_b|}{|p_c|} \frac{3}{128\pi^2 s} \left( t - m_b^2 \right) \left( t - m_{\tilde{\nu}}^2 \right) \frac{|\lambda_{g12}|^2 |\lambda'_{g13}|^2}{m_{\tilde{\nu}}^4}
\]

for the \( t \)–channel squark. \( p_b \) is the 3–momentum of the \( b \) quark. We have ignored the electron mass compared to the rest of the masses and energies. The case of a final–state down quark can be obtained by the appropriate changes of indices. The current limits on these combinations of couplings from experimental data \[22\] are given in Tab. I.

In calculating the signal, we assume that the values of the couplings are equal to their current bounds. Performing the angular integrations (restricted to \(|\cos(\theta)| \leq 0.9\)) leads to the cross–sections presented in Fig. 5 and Fig. 6 with the numerical values for \( \sqrt{s} = 10.58 \text{ GeV} \) given in Tab. II.

### A. Single \( b \) Production With A High–Energy Photon

As is discussed in Sec. III the production of a single \( B \) meson — light meson pair is not necessarily a clean signal. \( B \) mesons are often misidentified, and an accurate reconstruction of the kinematics may reduce the detection efficiency substantially. Here we consider the cases of an additional final–state photon for the signals considered above, which may prove to be a cleaner signal as the energy of the \( B \) meson does not have to be measured — for a sufficiently energetic photon, \( BB \) pair production is kinematically excluded (in analogy to using radiative return to measure...
hadronic cross-sections for lower energies than those at which an experiment runs \(^{11}\)). The Feynman diagrams are the same as in Fig. \(\text{I}\) but with an external photon emitted by any of the external particles. An emission by the virtual squark suppresses the matrix element by another power of \(m_{\tilde{q}}^2\).

We restrict the photon to have 10% or more energy above this value for a possibility that it was emitted through the radiative decay of a \(B\) meson. Since there is an upper bound to the energy that the radiated photon can have for a \(B\) meson with a given momentum in the beam center–of–momentum frame, we restrict the photon to have 10% or more energy above this value for a \(B\) meson with half the beam energy, \(i.e.\)

\[
E_{\gamma} \geq 1.1 \frac{m_{\tilde{b}}^2}{2((\sqrt{s}/2) - \sqrt{4 - m_{\tilde{b}}^2})}
\]  

In doing this, we eliminate the background of misidentified \(B\bar{B}\) pair production.

The cross–sections for this process are also presented in Fig. \(\text{I}\) and Fig. \(\text{I}\) with the numerical values for \(\sqrt{s} = 10.58\) GeV given in Tab. \(\text{I}\) The signal begins at 10.56 GeV as below this it is kinematically impossible to produce a \(B\bar{B}\) pair, hence the advantage of the additional photon is non–existent, while still suffering from the \(\alpha\) suppression of the signal. The restriction on the photon energy cuts out much of the phase space, and cuts out more as \(\sqrt{s}\) increases, until around \(\sqrt{s} = 13.8\) GeV, where the entire phase space is excluded. Unfortunately, even in the best case, close to the special value \(\sqrt{s} = 10.58\) GeV, the best signal is less than 0.1 ab.

\section*{III. BACKGROUND}

We identify three sources of background to the signal: direct SM \(e\bar{e} \rightarrow MB\) production, and \(R\)–parity conserving MSSM \(\bar{e}e \rightarrow b\bar{s}\) or \(bd\).

\subsection*{A. Standard Model Background}

As mentioned in the introduction, there is a Standard Model background to the processes \(e\bar{e} \rightarrow b\bar{s}, bd\). However, its leading order contribution is at one–loop level and is Cabbibo suppressed. Ignoring Feynman diagrams with an electron–Higgs Yukawa coupling, there are five classes of diagrams, shown in Fig. \(\text{I}\) (in these diagrams the photon may be replaced by a \(Z\) boson, though this suppresses the matrix element by a further factor of \(s/m_{\tilde{b}}^2\)).

Using FeynArts \(\text{I}\) and FormCalc \(\text{I}\), which utilize FORM \(\text{I}\) and LoopTools \(\text{I}\), we obtain the cross–sections presented in Fig. \(\text{I}\) and Fig. \(\text{I}\) with the numerical values for \(\sqrt{s} = 10.58\) GeV given in Tab. \(\text{I}\).

Considering the two–particle final states, the SM background is completely negligible compared to the squark–mediated signal for \(bd\) production. However, it is within an order of magnitude of the other three potential signals. Unfortunately, detecting such cross–sections of \(10^{-4}\) fb is well beyond the reach of current colliders.

There are related processes, where four quarks are created in the hard process. They can then hadronize into two mesons, either a charged pair or a neutral pair. The diagrams for the production of a charged pair are those in Fig. \(\text{I}\).

\begin{table}[h]
\begin{center}
\begin{tabular}{|c|c|c|}
\hline
\(bd\) via \(\bar{\nu}\) & \(3.4 \times 10^{-6}\) fb & \(bd\gamma\) via \(\bar{\nu}\) & \(1.6 \times 10^{-9}\) fb \\
\hline
\(bs\) via \(\bar{\nu}\) & \(6.2 \times 10^{-6}\) fb & \(bs\gamma\) via \(\bar{\nu}\) & \(2.9 \times 10^{-9}\) fb \\
\hline
\(bd\) via \(\bar{u}\) & 0.13 fb & \(bd\gamma\) via \(\bar{u}\) & 5.7 \times 10^{-9} fb \\
\hline
\(bs\) via \(\bar{u}\) & \(1.0 \times 10^{-6}\) fb & \(bs\gamma\) via \(\bar{u}\) & \(4.3 \times 10^{-9}\) fb \\
\hline
\end{tabular}
\end{center}
\caption{The cross–sections for \(e\bar{e} \rightarrow b\bar{s}/bd/db/bs\gamma/bs\gamma/bd\gamma/db\gamma\) at \(\sqrt{s} = 10.58\) GeV.}
\end{table}
FIG. 2: SM background single $b$ production.

TABLE III: SM background cross–sections for $e\bar{e}\rightarrow b\bar{s}/s\bar{b}/b\bar{d}/d\bar{b}$ at $\sqrt{s} = 10.58$ GeV.

| Process       | Cross–section |
|---------------|---------------|
| $bd$ in SM    | $7.3 \times 10^{-6}$ fb |
| $bs$ in SM    | $1.8 \times 10^{-4}$ fb |

Those for the production of a neutral pair are the same as for the charged pair, but with the down–type quarks combining to form a $B^0$ and the up–types combining to form a light neutral meson.

Generally, we expect the hard matrix element for the creation of four quarks to be of a similar size or less than the two–quark case. Even ignoring the suppression of the wavefunction overlap of these four quarks with the two–meson final state, we can therefore safely neglect this Standard Model background as well.

B. False Signal From $B\bar{B}$ Pair Production

Misidentification of $B$ mesons is an extremely important concern. Our signal must not be confused with that of a $b\bar{b}$ pair production with one unidentified $b$. Simply looking for events that contain only a single tagged bottom is (quantitatively) not feasible. Hence, we use kinematics to get rid of $b\bar{b}$ events. The direct production of a $B$ meson and a light meson of mass $m_M$ leads to, in the beam center–of–mass frame, the $B$ meson taking a fraction $(s + m^2_B - m^2_M)/(2s)$ of the center–of–mass energy $\sqrt{s}$. For the squark–mediated $bd$ signal with $\sqrt{s} = 10.58$ GeV, the $B$ meson will have energy between 6.56 GeV (where the light meson is an $\eta'$) to 6.61 GeV (where the light meson is a $\pi^0$). This is to be compared to the case of $BB$ production, where both have energy 5.29 GeV.

The high–energy tail of the electron–positron beam can create $b\bar{b}$ pairs with enough energy that the resulting $B$ mesons could present a false signal by both having the energy that a singly–produced $B$ meson would have (around 6.6 GeV for $\sqrt{s} = 10.58$ GeV), and one could decay into a high–energy light meson, with the radiated photon or particle missing the detector. BaBar produces $1.1 \times 10^6$ $b\bar{b}$ pairs per fb$^{-1}$, and has over 350 fb$^{-1}$ of integrated luminosity recorded [16]. This gives 385 million $b\bar{b}$ pairs. The beam energy spread we expect to be of the order of 5 MeV, estimated from the beam spread from 4.63 to 4.83 MeV on the $\Upsilon(4S)$ resonance [17]. For the false signal described, the $BB$–pair is required to have 2.6 GeV more than the mean beam energy. This is over 400 standard deviations away, if we assume that the beam energy has a Gaussian distribution. The expected number of events from this channel is then insignificant (less than $10^{-250}$).

Using the $\Upsilon(4S)$ resonance width of 20.7 MeV [17] as the spread, the cut is 125 standard deviations away from the mean, which still leads to an expected number of events less than $10^{-250}$. These brief estimates certainly allow us to neglect beam energy spread as a background source for our signal process.

This is also the source of any potential background to the case with an additional high–energy photon. For the range of energies considered, the false signal background of a $BB$ plus a high–energy photon requires between 1 and 2 GeV more than the mean beam energy. This is 200 to 400 standard deviations over the mean, and hence the expected number of events is less than $10^{-250}$. The false signal background of a $BB$ pair of sufficient energy that the radiative decay of one of the mesons produces a photon that passes the cut is also less than $10^{-250}$ events.
C. R–Parity Conserving MSSM Background

Any signal of flavor violation in significant excess of the SM prediction is an exciting signal for new physics. However, the thrust of this paper is that such a signal could come from RPV couplings. Backgrounds from the $R$–parity conserving part of the MSSM arise from two sources: flavor violation through $SU(2)_L$ and through non–minimal squark mixing, i.e. general soft SUSY breaking terms \[18\]. (Examples of both types are shown in Fig. 4.)

The diagrams for the former case are easily obtained by replacing the Standard Model particles in SM background loop diagrams with their supersymmetric partners. The $W$ boson mass ($m_W \gg m_B$) accounts for most of the suppression of the SM background. The sparticle masses are constrained to be (considerably) larger than $m_W$. The structure of the amplitude is similar, which means that we can expect the SUSY loops without a new flavor structure to contribute below the level of the SM backgrounds. If we increase the largest sparticle mass in the loop to three times the $W$ boson mass, these SUSY backgrounds drop below 10% to the already negligible Standard Model background rate.

There are potential enhancements in the large $\tan \beta$ region of the MSSM parameter space, but in the Higgs sector these destructively interfere with the SM amplitude \[19\], while any other enhancements are constrained by $b \to d\gamma$ to be at most close to the SM value.

The diagrams describing contributions from non–minimal flavor structure in squark sector are obtained by “supersymmetrizing” the virtual particles in the loops in the one–loop corrections to $e\bar{e} \to b\bar{b}$ (except for those diagrams without a virtual quark), and replacing the external $\tilde{b}$ with a $\bar{d}$ and the internal $\tilde{b}$ with the mass eigenstate mixtures of $\tilde{b}$ and $\tilde{d}$. These contributions are not easy to calculate, as the most significant pengluino diagram (shown in Fig. 4), is proportional to $\alpha_s \delta m_{\tilde{b}}^2/m_{\tilde{g}}^2$, where $\delta m_{\tilde{b}}^2$ is the difference in the squared masses of the squarks \[23\]. This, at least for $b\bar{d}$ mixing, is not well constrained \[20\]. However, we note that these diagrams would also contribute to $B\to \rho\gamma$, which is tightly constrained.

Altogether, we expect the $R$–parity conserving part of the RPV MSSM to contribute to the background at a rate comparable to the Standard Model contribution at most.
FIG. 5: Cross-sections for $e\bar{e}\to b\bar{d}/d\bar{b}/bd\gamma$ through $R$-parity violation and the SM background for $e\bar{e}\to b\bar{d}/d\bar{b}$.

IV. OUTLOOK

As far as we are aware, there have been no searches for single $B$ production. Currently BaBar has almost 400 fb$^{-1}$ of integrated luminosity [16] and Belle has almost 650 fb$^{-1}$ of data [21] available for analyses. Ignoring detector effects the maximum signal rate for single $b$ production allowed by current bounds comes from $t$-channel squark exchange and could be as large as 100 events.

A null result, while disappointing, would still improve the bound on $|\lambda_1'g_1|^2|\lambda_1'g_3|^2m_\tilde{u}^{-4}$. A 95% confidence limit non-observation corresponds to 95% confidence that less than three events occurred, leading to the deduction that the bound would be tightened by a factor of (expected events)/2, hence for a 0.13 fb signal with 1 ab$^{-1}$ of luminosity, which is 130 events with perfect detection efficiency, the bound on $|\lambda_1'g_1|^2|\lambda_1'g_3|^2m_\tilde{u}^{-4}$ would be tightened by a factor of 65.

We have shown that the backgrounds to this process are negligible, which makes single $b$ production a promising search channel for $R$ parity violation.

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FIG. 6: Cross-sections for $e\bar{e}\rightarrow b\bar{s}/b\bar{b}/b\bar{s}\gamma/b\bar{b}\gamma$ through R-parity violation and the SM background for $e\bar{e}\rightarrow b\bar{s}/b\bar{b}$.

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[23] This assumes that the gluino is more massive than the squarks, otherwise replace the gluino mass with the mass of the more massive squark.