Light Strange-beauty Squarks

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We summarize a study on the production, decay, and detection of the strange-beauty squark as light as 200 GeV at hadronic and $e^+e^-$ colliders. It was motivated by nearly maximal mixing between strange and beauty squarks.

I. INTRODUCTION

The SM predicts that the mixing-dependent CP violation measured in $B \rightarrow \phi K_S$ should be the same as in $B \rightarrow J/\psi K_S$. Belle, however, has found an opposite sign in $B \rightarrow \phi K_S$ for two consecutive years [1]. The current discrepancy with SM prediction stands at a 3.5σ level. Although Belle result is not consistent with BaBar, the combined result still has a 2.7σ deviation from SM expectation. It was pointed out [2] that a light strange-beauty squark, resulted from near-maximal mixing between the second and third right-handed (RH) squarks, provides all necessary ingredients to account for the discrepancy. It provides (1) a large $s-b$ flavor mixing, (2) a unique new CP violating phase, and (3) right-handed dynamics. The latter is needed for explaining why similar “wrong-sign” effects are not observed in the modes such as $B \rightarrow K_S\pi^0$ and $t/\bar{t}K_S$. This near-maximal mixing is motivated by a combination of Abelian flavor symmetry (AFS) and SUSY. Such a near-maximal mixing allows one state to be considerably lighter than the common squark mass scale $m$. A detailed study of various $B$ decays suggested [3] that $m_{\tilde{b}_1} \sim 200$ GeV and $m_{\tilde{g}} \sim 500$ GeV are needed, while the squark mass scale $\tilde{m}$ can be well above 1 TeV.

It is clear that a squark as light as 200 GeV is of great interest at the Tevatron. One should independently pursue the search for such a light $\tilde{b}_1$, even if the $B \rightarrow \phi K_S$ CP violation discrepancy evaporates in the next few years. We note that a strange-beauty squark, carrying $\sim 50\%$ in strange and beauty flavor, would lead to a weakening of bounds on beauty squark search based on $b$-tagging. The SUSY scenario that we have is that (i) the generic soft SUSY scale is at TeV, (ii) a RH strange-beauty squark as light as 200 GeV, (iii) a relatively light gluino $\sim 500$ GeV that goes together with the squark in the gluino-squark loop. We summarize our work [4] on strange-beauty squark-pair production, and various decay scenarios of the squark at the Tevatron.

II. HADRONIC PRODUCTION

We focus only on the $2 \times 2$ right-handed strange and beauty squarks, whose mass matrix is given by,

$$\mathcal{L} = - (\tilde{\nu}_R^* \tilde{b}_R^*) \left( \begin{array}{cc} m_{12}^2 & m_{13}^2 e^{-i\sigma} \\ m_{13}^2 e^{i\sigma} & m_{33}^2 \end{array} \right) \left( \begin{array}{c} \tilde{s}_R \\ \tilde{b}_R \end{array} \right),$$

which can be diagonalized by the transformation

$$\left( \begin{array}{c} \tilde{s}_R \\ \tilde{b}_R \end{array} \right) = R \left( \begin{array}{c} \tilde{sb}_1 \\ \tilde{sb}_2 \end{array} \right) = \left( \begin{array}{cc} \cos \theta_m & \sin \theta_m \\ -\sin \theta_m \cos \theta_m e^{i\sigma} & \cos \theta_m e^{i\sigma} \end{array} \right) \left( \begin{array}{c} \tilde{sb}_1 \\ \tilde{sb}_2 \end{array} \right).$$

The relevant gluino-quark-squark interactions in the mass eigenbasis are

$$\mathcal{L} = -\sqrt{2} g_s T_{i1} \left[ -\bar{g}_a P_{Rj} \tilde{s}_b \tilde{s}_1 \tilde{b}_k \tilde{b}_1^* \cos \theta_m + \bar{g}_a P_{Rj} \tilde{b}_k \tilde{s}_b \tilde{s}_1^* \sin \theta_m e^{-i\sigma} \\ -\bar{g}_a P_{Rj} \tilde{s}_b \tilde{s}_2 k \sin \theta_m - \bar{g}_a P_{Rj} \tilde{b}_k \tilde{s}_b \tilde{s}_2^* \cos \theta_m e^{-i\sigma} + \text{h.c.} \right]$$

$$-ig_\mu A_{ij}^\mu T_{ij} \left( \bar{\tilde{sb}}_{1i} \partial_\mu \tilde{sb}_{1j} + \bar{\tilde{sb}}_{2i} \partial_\mu \tilde{sb}_{2j} \right)$$

$$+g_s^2 (T^a T^b)_{ij} A_{\mu}^{ai} A_{\mu}^{bj} \left( \bar{\tilde{sb}}_{1i} \tilde{sb}_{1j} + \bar{\tilde{sb}}_{2i} \tilde{sb}_{2j} \right).$$

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The production of the strange-beauty squark can proceed via

\[ q\bar{q}, gg \rightarrow \tilde{s}_b \tilde{s}_b^* \]
\[ ss, sb, bb \rightarrow \tilde{s}_b \tilde{s}_b \]
\[ q\bar{q}, gg \rightarrow \tilde{g}\tilde{g} \text{ followed by gluino decay, and} \]
\[ sg, bg \rightarrow \tilde{s}_b\tilde{g} \text{ followed by gluino decay}. \]

The gluino so produced will decay into a strange or beauty quark plus the strange-beauty squark \( \tilde{s}_b \).

Production cross sections for direct \( \tilde{s}_b \tilde{s}_b^* \) pair production at the Tevatron are shown in Fig. 1(a). As expected, the production is dominated by \( q\bar{q} \) annihilation. For a gluino mass of 500 GeV the gluino-pair cross section is only a few fb, but, however, the feed-down from gluino becomes comparable to direct \( \tilde{s}_b \) pair production when \( m_{\tilde{s}_b} > \sim 300 \) GeV. Therefore, at high \( m_{\tilde{s}_b} \), the gluino contribution can help extending the sensitivity further.

The situation is different at the LHC, please refer to Ref. [4] for more details. Gluino pair production and squark pair production cross sections are both above 10 pb for \( m_{\tilde{s}_b} = 200 \) GeV and \( m_{\tilde{g}} = 500 \) GeV, and both contributions have to be taken into account. We also show the production cross sections at \( e^+e^- \) colliders in Fig. 1(b).

III. DECAY AND DETECTION OF THE STRANGE-BEAUTY SQUARK

We consider three scenarios for the decay of \( \tilde{s}_b \).

A. Strange-beauty Squark as the LSP

When the \( \tilde{s}_b \) is the LSP and \( R \)-parity is conserved, the \( \tilde{s}_b \tilde{s}_b^* \) pair so produced will hadronize into color-neutral hadrons by combining with some light quarks. Such objects are strongly-interacting massive particles, electrically either neutral or charged. If the hadron is electrically neutral, it will pass through the tracker with little trace. However, if it is electrically charged it will undergo ionization energy loss in the central tracking system, hence behaves like a “heavy muon”. We did a similar analysis as CDF search for stable charged particles [5] with the following selective cuts: \( p_T(\tilde{s}_b) > 20 \) GeV, \( |y(\tilde{s}_b)| < 2.0 \), \( 0.25 < \beta' \gamma < 0.85 \). In Ref. [4] we have shown the cross sections from direct \( \tilde{s}_b \) pair production with all the above acceptance cuts, for detecting 1 massive stable charged particle (MCP), 2 MCPs, or at least 1 MCPs in the final state. The sensitivity can reach up to almost \( m_{\tilde{s}_b} \sim 300 \) GeV with an integrated luminosity of 2 fb\(^{-1}\).
B. $\tilde{s}b_1$ as LSP but $R$-parity is violated

In this case the $\tilde{s}b_1$ pair so produced will decay via the $R$-parity violating couplings $\lambda' LQD^c$ or $\lambda'' U^c D c^c D^c$. For simplicity we only consider $\lambda'_{133}$, $\lambda'_{102}$ with $i = 1, 2$. The strange-beauty squark will decay into $e^- u$ or $\mu^- c$, and thus behaves like scalar leptoquarks of the first or second generation, respectively. The most stringent limit on leptoquarks comes from a combined analysis that pushes the first generation leptoquark limit to around 260 GeV [6]. Therefore, we believe that the limit that can be reached at the end of Run II (2 fb$^{-1}$) is very likely above 300 GeV. With an order more luminosity, the limit may be able to reach 350 GeV.

C. $\tilde{s}b_1$ is the NLSP

In this case the $\tilde{s}b_1$ so produced will decay into a strange or beauty quark plus the neutralino or the gravitino, depending on the SUSY breaking models. There are 2 quark jets in the final state of $\tilde{s}b_1 \tilde{s}b_1^*$ pair production, each of them either strange or beauty flavored, and with large missing energy due to the neutralinos or gravitinos. We performed an analysis with the following selective cuts and $b$-tagging and mistag efficiencies: $p_{Tj} > 15$ GeV, $|\eta_j| < 2.0$, $p_T > 40$ GeV, $\epsilon_{b\text{tag}} = 0.6$, $\epsilon_{\text{mis}} = 0.05$. Note that the branching ratio of the strange-beauty squark into a $b$ quark scales as $\sin^2 \theta_m$. With an integrated luminosity of 2 fb$^{-1}$ the sensitivity is around 300 GeV, if $\sin^2 \theta_m > 0.5$. If the integrated luminosity can go up to 20 fb$^{-1}$, then the sensitivity increases to 350 GeV. We also emphasize that the double-tag vs single-tag ratio contains information on $\sin^2 \theta_m$, while their sum, when compared with the standard $\tilde{b}$ squark pair production, provides additional consistency check on cross section vs mass.

In conclusion, the recent possible CP violation discrepancy in $B \to \phi K_S$ decay suggests the possibility of a light strange-beauty squark $\tilde{s}b_1$ that carries both strange and beauty flavors. Such an unusual squark can be searched for at the Tevatron Run II, with the precaution that $\tilde{s}b_1$ can decay into a beauty or strange quark, and the standard $\tilde{b}$ search should be broadened. Discovery up to 300 GeV is not a problem, and anomalous behavior in both production cross sections and the single versus double tag ratio may provide confirming evidence for the strange-beauty squark.

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