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Search for Scalar Bottom Quarks from Gluino Decays in $\bar{p}p$ Collisions at $\sqrt{s}$ = 1.96 TeV

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We searched for scalar bottom quarks in 156 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the Collider Detector at Fermilab II experiment at the Tevatron. Scalar bottom quarks can be produced from gluino decays in R-parity conserving models of supersymmetry when the mass of the gluino exceeds that of the scalar bottom quark. Then, a scalar bottom quark can decay into a bottom quark and a neutralino. To search for this scenario, we investigated events with large missing transverse energy and at least three jets, two or more of which were identified as containing a secondary vertex from the hadronization of b quarks. We found four candidate events, where 2.6 ± 0.7 are expected from standard model processes, and placed 95% confidence level lower limits on gluino and scalar bottom quark masses of up to 280 and 240 GeV/c^2, respectively.

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Despite its extraordinary success, the standard model of elementary particles and interactions (SM) is incomplete since it does not explain the origin of electroweak symmetry breaking and the gauge hierarchy problem [1] and some of its predictions violate unitarity when extended to the TeV scale. One proposed extension of the SM, supersymmetry (SUSY) [2], solves these problems. R-parity [2] conserving SUSY models also provide a prime candidate for the dark matter in the cosmos [3], the stable lightest supersymmetric particle (LSP). SUSY is a space-time symmetry that relates particles of different spin by introducing a boson SUSY partner for each SM fermion and vice versa. For example, the left-handed and right-handed quarks have scalar partners denoted $\tilde{q}_L$ and $\tilde{q}_R$ which can mix to form scalar quarks (squarks) with mass eigenstates $\tilde{q}_{1,2}$. Several models [4] predict that this mixing can be

substantial for the scalar bottom (sbottom), yielding a sbottom mass eigenstate ($\tilde{b}_1$) significantly lighter than other squarks. At the Tevatron center-of-mass energy of $\sqrt{s} = 1.96$ TeV, the predicted gluino ($\tilde{g}$, the spin-1/2 partner of the gluon) production cross section is almost an order of magnitude larger than that of a sbottom of the same mass [5]. Therefore, if sufficiently light, sbottom quarks could be copiously produced through the decay of the gluino into a sbottom and a bottom quark since the gluino preferentially decays into a squark-quark pair [2]. A sbottom in the mass range accessible at the Tevatron is expected to decay predominantly into a bottom quark and a lightest neutralino which is often assumed to be the LSP.

Previous searches for direct sbottom [6,7] or gluino production [8] at the Tevatron placed lower limits on the masses of these particles. In this Letter, we describe the first search for $\tilde{b}_1$ from $\tilde{g}$ decays in 156 pb^{-1} of data collected between July 2002 and September 2003 by the Collider Detector at Fermilab (CDF II) at the Tevatron. We assume R-parity conservation and, therefore, that $\tilde{g}$ are produced in pairs. We consider a scenario where the branching fractions $\tilde{g} \to b\tilde{b}_1$ and $\tilde{b}_1 \to b\tilde{\chi}_1^0$ are 100%. We assume a $\tilde{\chi}_1^0$ mass of 60 GeV$/c^2$, which is above the current limits from LEP [9]. The signature of our search is a final state with four b jets from the hadronization of the b quarks, an imbalance in energy in the transverse plane to the beam ("missing transverse energy" or $\not{E}_T$) from the two LSPs escaping detection, and no isolated leptons with large transverse momentum. We expect this signature in events with large $\not{E}_T$ in which at least three jets are detected, two of which are required to be consistent with b jets. After describing the experiment, we introduce our event selection, major backgrounds, systematic uncertainties, and results.

CDF II is a multipurpose detector described in detail elsewhere [10]. We use a cylindrical coordinate system around the beam axis in which θ and ϕ are the polar and azimuthal angles, respectively. The pseudorapidity η is defined as $\eta = -\ln(\tan(\frac{\theta}{2}))$. The transverse momentum and energy are defined as $p_T = p\sin\theta$ and $E_T = E\sin\theta$, respectively. The tracking system consists of a cylindrical open-cell drift chamber and silicon microstrip detectors in a 1.4 T magnetic field parallel to the beam axis. The silicon detectors provide precise tracking information for $|\eta| < 2$ and are used to detect displaced vertices [11]. The drift chamber [12] surrounds the silicon detectors and has maximum efficiency for $|\eta| < 1$. The energies of electrons and jets are measured in calorimeters which cover $|\eta| < 3.6$. Muons are identified by drift chambers located outside the calorimeter volume which extend to $|\eta| < 1.5$.

Jets are reconstructed from the energy depositions in the calorimeter cells using an iterative cone jet clustering algorithm [13], with a cone size of radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$. Energy corrections are applied to account for effects that can distort the measured jet energy such as nonlinear calorimeter response, underlying events, or the position of the primary vertex. The $\not{E}_T$ is defined by, $\not{E}_T = -\sum_i E_T^i \hat{\mathbf{n}}_\mathbf{i}$, where $\hat{\mathbf{n}}_\mathbf{i}$ is a unit vector perpendicular to the beam axis and pointing at the ith calorimeter tower, and E_T^i the transverse energy therein. Candidate electrons must have a track associated with a cluster in the electromagnetic calorimeter with $E_T >$ 10 GeV, an electromagnetic to hadronic energy ratio, and shower shape compatible with an electron [14]. Candidate muons are identified with $p_T > 10$ GeV$/c$ tracks reconstructed in the tracking system which extrapolate to a track segment in the muon chambers, and leave an energy consistent with a minimum ionizing particle in the calorimeter [14]. To increase the lepton efficiency (including τ), candidate leptons are also identified as isolated tracks with $p_T > 10$ GeV$/c$.

The data used for this search are selected by a three-level trigger system. The Level 1 trigger requires $\not{E}_T \geq 25$ GeV, where the $\not{E}_T$ is estimated using trigger towers with more than 1 GeV of total E_T. The Level 2 trigger selects events with two jet clusters with $E_T > 10$ GeV. At Level 3, the $\not{E}_T$ is required to be larger than 35 GeV. After selections [14] to remove accelerator-produced and detector-related background, and cosmic ray events, 418 304 events remain. The position of the primary vertex along the beam axis, z_0, is found by a weighted fit of each track's z position at the closest approach to the beam axis, and must satisfy $|z_0| <$ 60 cm. If there are multiple vertices in the event, we use the vertex with the largest $\sum(p_T)$ of associated tracks. The events are required to have $\not{E}_T > 35$ GeV, and at least three jets with $|\eta| < 2$ and $E_T \geq 15$ GeV. Events where the $\not{E}_T$ is aligned with any of the three highest E_T jets are rejected by requiring $\Delta\phi(\not{E}_T, 1\text{–}3\text{jet}) > \frac{2\pi}{9}$ where $\Delta\phi$ is the azimuthal angle between the $\not{E}_T$ and each of the jets. The last selection criterion reduces backgrounds with $\not{E}_T$ resulting from jet mismeasurements or from semileptonic b decays. The long lifetime of B hadrons yields secondary vertices which have a large positive decay distance L_{xy} [15] relative to the primary vertex. We require the events to have at least one jet identified (inclusive single b-tagged) as a b jet by the CDF b-tagging algorithm [16]. After applying these selections, 332 events are observed in the data.

Dominant SM backgrounds are multijet, top, and electroweak production, which includes electroweak bosons (W and Z) produced with additional partons or electroweak diboson production. The multijet background includes jets from heavy flavor (HF) such as b and c production and light jets misidentified by the b-tagging algorithm. The latter are estimated from data using secondary vertices with negative L_{xy}. The PYTHIA event generator [17] is used to estimate the HF and top background. The top production is normalized to theoretical predictions [18] while the HF contribution is scaled to the data [14] in sidebands of the search region. The electroweak background is generated in ALPGEN [19], with the cross section at next-to-leading order (NLO) calculated by the MCFM [20] program and the showering of partons with the

TABLE I. Comparison of the total number of expected and observed inclusive single b-tagged events in the control regions. Only statistical uncertainties are quoted.

Control region	C0	C1	C2
$\not{E}_T$	35–50 GeV	35–50 GeV	>50 GeV
Isolated high-p_T lepton	required	vetoed	required
W/Z + jets/diboson	3.9 ± 0.8	10.9 ± 1.2	9.6 ± 1.2
Top	11.7 ± 0.2	8.2 ± 0.1	35.0 ± 0.3
Multijet	19.1 ± 4.1	128.9 ± 17.3	10.9 ± 4.5
Total predicted	34.7 ± 4.2	148.0 ± 17.3	55.5 ± 4.7
Observed	36	121	63

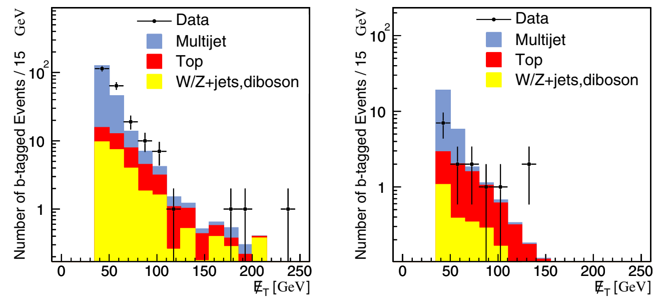

FIG. 2 (color online). $\not{E}_T$ spectrum after vetoing events with high-p_T isolated leptons, for single b-tagged events (left) and double b-tagged events (right).

HERWIG [21] program. The CTEQ5L [22] parton distribution functions are used in the generation of all background samples. Events are passed through the standard simulation [23] of the CDF II detector and weighted by the probability that they would pass the trigger as determined in independent data samples.

To avoid potential bias when searching for new physics, we test the SM background in control regions that are defined *a priori*. The data are divided into four regions having different $\not{E}_T$ and high-p_T isolated lepton multiplicity. The signal region contains events with $\not{E}_T > 50$ GeV (80 GeV) before (after) optimization and no high-p_T isolated leptons. The three control regions used to check the SM prediction, denoted as C0, C1, and C2, are defined in Table I. C0 and C1 are sensitive to the predictions of the multijet background. Control region C2 with high-p_T isolated leptons and $\not{E}_T > 50$ GeV is used to check the top and electroweak backgrounds. Predicted total numbers of events and distributions of kinematic variables such as the jet E_T, the track multiplicity and the $\not{E}_T$ have been studied and found to be in agreement with observations [14] in the control regions. As an example, Fig. 1 shows $\Delta\phi(\not{E}_T$, 1st jet), the azimuthal angle between the $\not{E}_T$ and the highest E_T jet in the event (1st jet) if this jet is b-tagged. The distributions show satisfactory agreement between data and prediction. Table I summarizes the background contributions to the number of expected inclusive single b-tagged events and the observed events in the control regions.

We optimize the sensitivity to sbottom production from gluino decays by maximizing the ratio of $N_{\rm SUSY}/\sqrt{N_{\rm SM}}$ where $N_{\rm SUSY}$ and $N_{\rm SM}$ are the sbottom and SM background events expected in the signal region [14], respectively. The signal predictions are obtained by computing the acceptance using the ISAJET [24] event generator normalized to the NLO production cross section determined with PROSPINO [5] and the CTEQ5M [22] parton distribution functions. Figure 2 shows the $\not{E}_T$ spectrum for events with a single b-tagged jet (exclusive single b-tagged) and at least two b-tagged jets in the event (inclusive double b-tagged) when high-p_T isolated leptons are vetoed. The best sensitivity is achieved by requiring inclusive double b-tagged events with $\not{E}_T > 80$ GeV. The double b-tag requirement is very effective at suppressing the background. Exclusive single tagged events were used to cross-check the results. Since the efficiency of tagging a b jet is about 30% [16], and there are four b jets in the signal final state, the signal acceptance for single and double tag events are similar and vary between 5% and 12% as a function of the sbottom and the gluino masses.

The systematic uncertainty on the signal and the background predictions is studied in detail in Ref. [14]. Correlated uncertainties, affecting both the background prediction and the signal, are dominated by the jet energy scale (25% for multijet and electroweak, 14.5% for top, 10% for the signal), b-tagging efficiency (12%), and the luminosity (6%). Uncorrelated systematic uncertainties on the background predictions are dominated by the heavy flavor Monte Carlo scale factor (20%), the misidentified b-tag rate (16% for light flavor multijets), the top cross section (15%), and the electroweak cross section (11.5%). Correlated and uncorrelated uncertainties are evaluated separately and combined in quadrature [14]. The total systematic uncertainties are 35%, 31%, and 25% for the multijet, electroweak and top background predictions, respectively, and 18% on the signal.

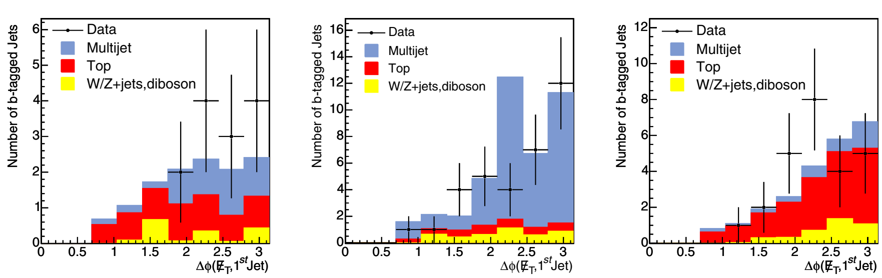

FIG. 1 (color online). Distributions of $\Delta\phi$ ($\not{E}_T$, 1st jet), the azimuthal angle between the $\not{E}_T$ and the highest E_T jet in the event, if it is b-tagged in control region C0 (left), C1 (middle), and C2 (right).

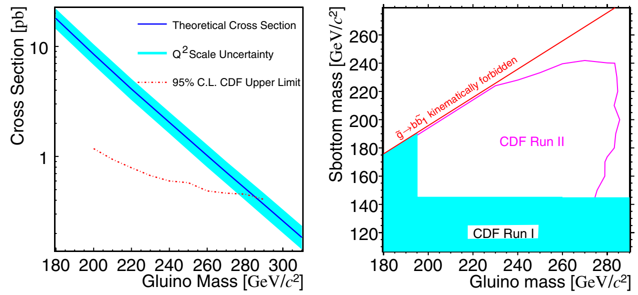

FIG. 3 (color online). The 95% C.L. cross section upper limit as a function of the gluino mass for a 60 GeV$/c^2$ mass difference between the gluino and sbottom (left). The 95% C.L. limit curve in the $m(\tilde{g})$-$m(\tilde{b}_1)$ plane for inclusive double b-tagged events (right).

The signal region is analyzed after all the background predictions and selection cuts are determined. Requiring at least two b-tagged jets we observed four events, where 2.6 ± 0.7 are expected from background, as summarized in Table II. We observe 21 exclusive single b-tagged events, which is in agreement with SM background expectations of 16.3 ± 3.6 events.

Since no evidence for gluino pair production with $\tilde{g} \to b\tilde{b}_1$ is found, a cross section upper limit at 95% confidence level (C.L.) is computed and an exclusion limit set using the Bayesian likelihood method [25] with uniform prior probability density function for the signal cross section, up to an arbitrary cutoff to which the observed limit is insensitive, and Gaussian priors for the uncertainties on acceptance and backgrounds. An example cross section upper limit is shown in Fig. 3. The contour exclusion limit shown in Fig. 3 is computed using the inclusive double b-tag analysis. The $\tilde{\chi}_1^0$ mass has a minor impact [14] on this limit, as long as the $\tilde{\chi}_1^0$ is sufficiently lighter than the $\tilde{b}_1$, so that its decay produces a taggable b jet.

In conclusion, we have searched for sbottom quarks from gluino decays in 156 pb^{-1} of CDF Run II data. We observe four inclusive double b-tagged candidate events, which is in agreement with SM background expectations of 2.6 ± 0.7 events. No evidence for sbottom quarks from gluino decays is observed and we exclude a significant region in the gluino and sbottom mass plane at 95% confidence level. Gluino masses below 270 GeV$/c^2$ for $\Delta m = m(\tilde{g}) - m(\tilde{b}_1) > 6$ GeV$/c^2$ and $m(\tilde{b}_1) < 220$ GeV$/c^2$ are excluded.

TABLE II. Number of expected and observed events in the signal region. Correlated and uncorrelated uncertainties in the total predicted background were treated separately and combined as described in Ref. [14].

Process	Excl. single b tag	Incl. double b tag
W/Z + jets/diboson	5.6 ± 1.8	0.6 ± 0.3
Top	6.1 ± 1.5	1.9 ± 0.5
Multijet	4.6 ± 1.7	0.2 ± 0.1
Total predicted	16.3 ± 3.6	2.6 ± 0.7
Observed	21	4

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