Search for Gluino-Mediated Sbottom Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report on a search for the supersymmetric partner of the bottom quark produced from gluino decays in data from 2.5 fb^{-1} of integrated luminosity collected by the Collider Detector at Fermilab at $\sqrt{s} = 1.96$ TeV. Candidate events are selected requiring two or more jets and large missing transverse energy. At least two of the jets are required to be tagged as originating from a b quark to enhance the sensitivity. The results are in good agreement with the prediction of the standard model processes, giving no evidence for gluino decay to sbottom quarks. This result constrains the gluino-pair-production cross section to be less than 40 fb at 95 % credibility level for a gluino mass of 350 GeV/c^2.

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The standard model (SM) of elementary particles and fundamental interactions, however successful, is incomplete, since it does not explain the origin of electroweak symmetry breaking or the gauge hierarchy problem [1]. A proposed extension of the SM, supersymmetry (SUSY) [2], solves these problems by introducing a symmetry that relates particles of different spin. The theory assigns a SUSY boson partner for each SM fermion and vice versa. R-parity [2] conserving SUSY models also provide a prime candidate for the dark matter in the cosmos [3], namely the stable lightest supersymmetric particle (LSP). In these models, 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 ($\tilde{b}$) significantly lighter than other squarks. In proton-antiproton ($p\bar{p}$) collisions at the Tevatron's center-of-mass energy of $\sqrt{s} = 1.96$ TeV, the gluino ($\tilde{g}$, the spin-1/2 superpartner of the gluon) pair-production cross section is almost an order of magnitude larger than that of a sbottom of similar mass [5]. Therefore, if sufficiently light, sbottom quarks could be copiously produced through the $\tilde{g} \to \tilde{b}b$ decays 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 the lightest neutralino ($\tilde{\chi}^0$), which is often assumed to be the LSP. Previous searches for direct sbottom [6, 7] or gluino production [8, 9] at the Tevatron placed lower limits on the masses of these particles.

In this Letter, we report the search for $\tilde{g} \to \tilde{b}b$ decays in $p\bar{p}$ collision data from 2.5 fb^{-1} of integrated luminosity collected between March 2003 and April 2008 by the upgraded Collider Detector at Fermilab (CDF II) at the Tevatron. Assuming R-parity conservation, $\tilde{g}$'s are produced in pairs. We consider a scenario where the branching fractions $\tilde{g} \to b\tilde{b}$ and $\tilde{b} \to b\tilde{\chi}^0$ are 100%. If these conditions are satisfied the analysis is largely independent of the $\tilde{\chi}^0$ mass, as long as the $m(\tilde{b}) - m(\tilde{\chi}^0)$ is larger than 25 GeV/c^2, due to b-jet energy cut (discuss later). For our calculations we assume a $\tilde{\chi}^0$ mass of 60 GeV/c^2, which is above the current limits from LEP [10]. The final state contains four b jets from the hadronization of the b quarks and an imbalance in momentum in the transverse plane to the beam ("missing transverse energy" or $\not\!\!E_T$ [11]) from the two undetected LSPs.

CDF II is a multipurpose detector, described in detail elsewhere [12]. The charged-particle tracking system consists of silicon microstrip detectors [13] and a cylindrical open-cell drift chamber [14] in a 1.4 T solenoidal magnetic field coaxial with the beam line. The silicon detectors provide coverage in the pseudorapidity [11] range $|\eta| \leq 2$ and are used to identify events with long-lived particle decays. The drift chamber surrounds the silicon detectors and has maximum efficiency up to $|\eta| = 1$. Segmented sampling calorimeters, arranged in a projective tower geometry, surround the tracking system, and measure the energy of interacting particles for $|\eta| \leq 3.6$. Muons are identified by drift chambers, which extend to $|\eta| = 1.5$, and are located outside the calorimeter volume. Jets are reconstructed from the energy depositions in the calorimeter cells using an iterative cone jet-clustering algorithm [15], with a cone size of radius $R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ [11]. Energy corrections [16] are applied to account for effects that distort the measured jet energy, such as non-linear calorimeter response, underlying event, and the position of the primary vertex.

Candidate events used for this search are selected by an on-line event selection system, a (trigger) requiring $\not\!\!E_T \geq 45$ GeV. Further selections remove accelerator-produced and detector-related backgrounds as well as cosmic-ray events. After off-line event reconstruction, the events are required to have $\not\!\!E_T \geq 70$ GeV, and at least two jets with $|\eta| \leq 2.4$ and $E_T \geq 25$ GeV. The highest-E_T jet is required to have $E_T \geq 35$ GeV and at least one of the selected jets is required to have $|\eta| \leq 0.9$. The B hadrons in jets coming from b quark fragmentation have an average flight path of about 500 microns, yielding secondary vertices relative to the interaction point (primary vertex). We require the events to have at least two jets identified as b jets by the CDF secondary-vertex b-tagging algorithm [17]. The double b-tagging requirement effectively enhances the sensitivity. Exclusive single-tagged events were used to cross-check the results.

Dominant SM backgrounds are top-quark pair-production and single top-quark production, electroweak boson and diboson production, heavy-flavor (HF) multijet production, and light-flavor jets falsely tagged as b jets (mistags). The latter two background contributions are estimated from data. The PYTHIA event generator [18] is used to estimate the remaining backgrounds. For the event generation the CTEQ5L [19] parton distribution functions were used. Events are passed through

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the GEANT3-based [20] CDF II detector simulation [21] and weighted by the probability that they would pass the trigger as determined in independent data samples. The single top-quark and diboson event yields are normalized to the theoretical cross sections [22–24]. The event yields for the electroweak boson samples are normalized to the leading order cross section provided by PYTHIA, scaled by a factor of 1.4 to account for higher order corrections. We use the top-quark pair production cross section of $\sigma_{t\bar{t}} = 7.3 \pm 0.8$ pb [25].

Mistags are estimated from inclusive jet-sample data by computing a mistag rate [17] which is parametrized by the jet E_T, $|\eta|$, secondary-vertex track-multiplicity, the number of primary vertices in the event, primary vertex z-position, and the scalar sum of E_T of all jets in the event. To estimate the HF multijet background from data, we have developed a multijet tag rate estimator (MUTARE). The estimator is based on a tag-rate matrix applied to each jet in an event following a parametrization of E_T, $|\eta|$ and the scalar sum of E_T of all jets in the event. Each element of the matrix is computed in a reference sample as the ratio between the number of b-tagged jets minus the number of mistags over the number of "taggable" jets, where "taggable" jets are defined as jets with tracks passing the CDF secondary-vertex b-tagging algorithm requirements [17]. The final prediction is obtained after subtracting the HF contribution coming from non-multijet production processes. The amount of non-multijet HF contribution is computed by applying the MUTARE matrix to each non-multijet background sample described above.

To avoid potential biases when searching for new physics, we test the various background contributions in distinct control regions that are defined *a priori*. The three control regions used to check the SM prediction are denoted as multijet, lepton, and pre-optimization regions. The multijet control region is defined to have the second leading E_T jet ($\vec{j}_2$) aligned with the $\vec{\not{E}}_T$ [11], where aligned means $\Delta\phi(\vec{\not{E}}_T, \vec{j}_2) \leq 0.4$ rad. This HF multijet enriched region is used to build the MUTARE matrix to predict the HF multijet background in the other control and signal regions. The lepton control region is defined to have $\vec{j}_2$ not aligned with the $\vec{\not{E}}_T$ ($\Delta\phi(\vec{\not{E}}_T, \vec{j}_2) \geq 0.7$ rad) and at least one isolated lepton with $p_T \geq 10$ GeV/c. This lepton region is used to check the top quark and electroweak W/Z boson backgrounds. The pre-optimization control region is defined to have the leading and second-leading E_T jets not aligned with the $\vec{\not{E}}_T$ and to have no identified leptons. Predicted total numbers of events and distributions of kinematic variables such as jet E_T, the track multiplicity, and the $\not{E}_T$ have been studied and found to be in agreement with observations in the three control regions. As an example, the $\not{E}_T$ distributions for the pre-optimization region are shown in Fig. 1. The background contributions to the number of expected inclusive double b-tagged events and the observed events in the control regions are summarized in Table I.

TABLE I: Comparison of the total number of expected events with total uncertainties and observed double b-tagged events in the control regions.

	Multijet Region	Lepton Region	Pre-optimization Region
Electroweak bosons	10 ± 7	21 ± 14	33 ± 22
Top-quark	19 ± 6	111 ± 34	146 ± 45
Light-flavor jets	225 ± 49	8 ± 2	57 ± 12
HF Multijets	839 ± 419	25 ± 12	270 ± 135
Total expected	1093 ± 422	165 ± 39	506 ± 144
Observed	1069	159	451

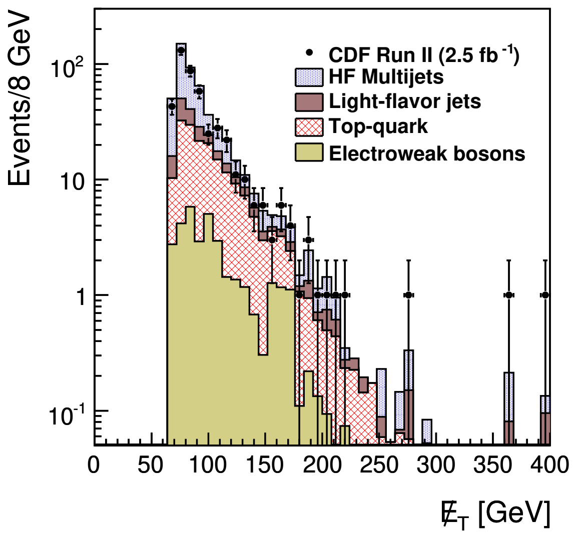

FIG. 1: Distribution of $\not{E}_T$ in the pre-optimization region in which leading E_T and second-leading E_T jets are not aligned with the $\not{E}_T$, and isolated leptons are vetoed. SM prediction (stacked histograms) and observed distribution (dots) are shown, where HF multijets and light-flavor jets are predicted from data as an integrated estimation.

We optimize the sensitivity to sbottom production from gluino decays by using two Neural Networks (NN) trained with the TMVA package [26]. One of them is optimized to remove the HF multijet background (multijet-NN) and the other to remove the top-quark pair background (top-NN). The training is based on jet variables using, jet E_T, $\Delta\phi(\vec{\not{E}}_T, \vec{j}_i)$, $\not{E}_T$, and the summed E_T of all the jets in the event. We choose two reference signal points based on values of $\Delta m \equiv m(\tilde{g}) - m(\tilde{b})$ and perform the same optimization procedure. We refer to large Δm optimization with $m(\tilde{g}) = 335$ GeV/c^2 and $m(\tilde{b}) = 260$ GeV/c^2 and to small Δm optimization with $m(\tilde{g}) = 335$ GeV/c^2 and $m(\tilde{b}) = 315$ GeV/c^2. These two signal points represent two different kinematic regions. For the large Δm optimization three or more jets are required before applying the NN procedure. For the small Δm optimization two or more jets are required

TABLE II: Number of expected and observed events in the signal regions. Predictions for the two corresponding signal optimization points are also shown. Correlated and uncorrelated uncertainties in the total background and expected signal were treated separately in the analysis although they are combined here.

	Large Δm Optimization	Small Δm Optimization
Electroweak bosons	0.17 ± 0.05	0.5 ± 0.3
Top-quark	1.9 ± 1.0	0.6 ± 0.4
Light-flavor jets	1.0 ± 0.3	0.6 ± 0.1
HF Multijets	1.6 ± 0.8	0.7 ± 0.3
Total expected SM	4.7 ± 1.5	2.4 ± 0.8
Observed	5	2
Optimized $\tilde{g}$ signal	14.9 ± 5.0	8.5 ± 2.8

since the E_T spectrum of the b jets is much softer. The signal predictions are obtained by computing the acceptance using the PYTHIA event generator normalized to the NLO production cross section determined with PROSPINO event generator [5] and the CTEQ6M [27, 28] parton distribution functions. The uncertainty of the NLO production cross section varies from 20% ($m(\tilde{g}) \simeq 200$ GeV/c^2) to 30% ($m(\tilde{g}) \simeq 400$ GeV/c^2).

The systematic uncertainties on the signal and the background predictions, taking into account correlated and uncorrelated uncertainties, are studied. Correlated uncertainties, affecting both the background prediction and signal acceptance, are dominated by the jet energy scale (16% (25%) for the large (small) Δm optimization region), the different b-tagging efficiency between data and simulation (4.4% (4.9%) for the large (small) Δm optimization region), and the luminosity (6%). Uncorrelated systematic uncertainties on the background predictions are dominated by the HF multijet b-tag rate (50%), the mistag rate (16% for light-flavor multijets), the top-quark pair-production cross section (11%), the single top-quark production cross section (13%), and the diboson production cross section (10% for WW/WZ and 20% for ZZ). Due to the limited ability of PYTHIA to simulate multijet environments, a 40% uncertainty [29] is assigned for the extracted yields of events with a W or Z boson and jets. Correlated and uncorrelated uncertainties are evaluated separately and combined in quadrature.

The signal region is analyzed after the background predictions are determined. We find 0.8 as an optimal value for the selection cut for both multijet-NN outputs and 0.6 (0.8) for the top-NN outputs in the large (small) Δm optimization within an interval of -1 to 1, where the background peaks at -1 and the signal peaks at 1. We observe 5 (2) events for the large (small) Δm optimization region, where 4.7 ± 1.5 (2.4 ± 0.8) are expected from background, as summarized in Table II. The contributions of each SM process are listed as well as the predicted gluino signal for the two optimized points.

Since no significant deviation from the SM prediction is observed, the results are used to calculate an exclusion limit for the cross section of the described gluino process. We use a Bayesian method to determine the 95% credibility level (C.L.) upper limit on the $\tilde{g}\tilde{g}$ cross section, assuming a uniform prior probability density. We treat the various correlated uncertainties as nuisance parameters, which we remove by marginalization, assuming a Gaussian prior distribution. The obtained limit is such that no more than 8.0 (5.4) events are observed in the large (small) Δm signal region. Figure 2 shows the expected and observed limits as a function of $m(\tilde{g})$ for two values of the $\tilde{b}$ quark mass. The expected limit is computed by assuming that the observed number of events matches the expectation from the backgrounds in each signal region.

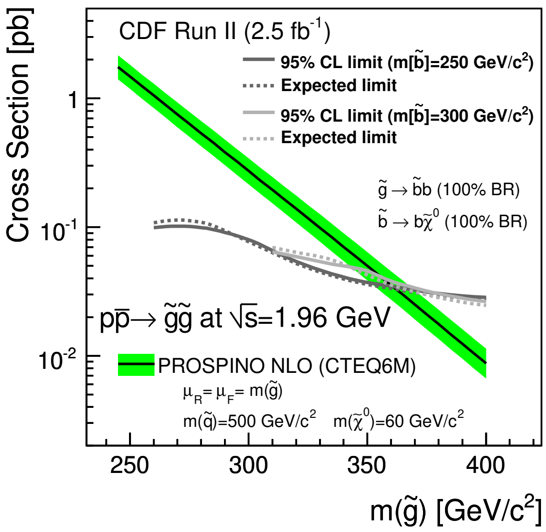

FIG. 2: Observed (solid lines) and expected (dashed lines) 95% C.L. upper limit on the gluino cross section (solid line with band) as a function of the gluino mass for two assumed values of the sbottom mass. The shaded band denotes the uncertainty on the NLO $\tilde{g}\tilde{g}$ production due to the truncated higher-order terms and the parton distribution functions.

The gluino production cross section limit is nearly independent of the sbottom mass between 250 and 300 GeV/c^2 , and is around 40 fb for $m(\tilde{g}) =$ 350 GeV/c^2 . In addition, using the assumed model, a 95% C.L. limit is obtained in the parameter plane of the model. Figure 3 shows the excluded region in the gluino-sbottom mass plane, compared with the expectation from the analysis sensitivity and with the results from previous analyses [6–9]. The limit obtained with the present analysis improves the results of previous searches using similar topology and also, under the assumptions discussed above, sets a more stringent limit on the sbottom and gluino production than dedicated sbottom searches.

In conclusion, we have searched for sbottom quarks from gluino decays in 2.5 fb^{-1} of CDF Run II data. We

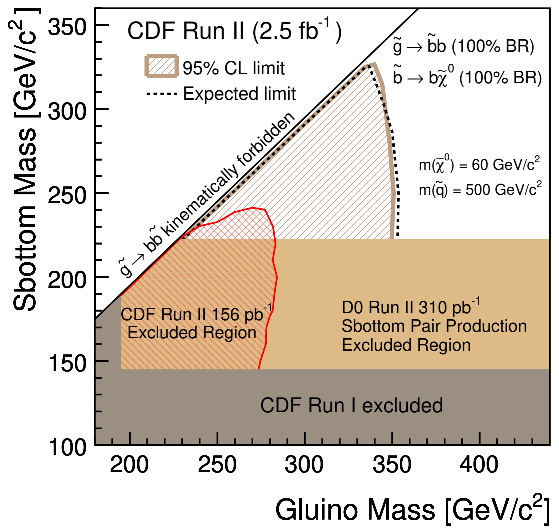

FIG. 3: Excluded region at 95% C.L. in the $m(\tilde{g})$-$m(\tilde{b})$ plane for a $m(\tilde{\chi}^0) = 60$ GeV$/c^2$, $m(\tilde{q}) = 500$ GeV$/c^2$. The result is compared to the previous results from CDF in Run I [8], and Run II [9] and direct sbottom production by D0 [7].

observe 5 (2) inclusive double b-tagged candidate events for the large (small) Δm optimization region, which is in agreement with SM background expectations of 4.7 ± 1.5 (2.4 ± 0.8) 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% C.L. For the assumed model, the limit is nearly independent of the sbottom mass and the cross section limit is around 40 fb for $m(\tilde{g}) = 350$ GeV$/c^2$.

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