

Search for Scalar Top and Scalar Bottom Quarks in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV

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We have searched for direct pair production of scalar top and scalar bottom quarks in  $88 \text{ pb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  with the CDF detector. We looked for events with a pair of heavy

flavor jets and missing energy, consistent with scalar top quark decays to a charm quark and a neutralino, or scalar bottom quark decays to a bottom quark and a neutralino. The numbers of events that pass our selection for each process show no deviation from Standard Model expectations. We compare our results to next-to-leading order calculations for the scalar quark production cross sections to exclude regions in scalar quark-neutralino parameter space.

PACS numbers: 14.80.Ly, 13.85.Rm

Supersymmetry (SUSY) [1] assigns to every fermionic Standard Model (SM) particle a bosonic superpartner and to every bosonic SM particle a fermionic superpartner. Therefore, the SM quark helicity states  $q_L$  and  $q_R$  acquire scalar partners  $\tilde{q}_L$  and  $\tilde{q}_R$ . SUSY models usually predict that the masses of the first two generations of scalar quarks are approximately degenerate. The scalar top quark ( $\tilde{t}$ ) mass, however, may be lower than that of the other scalar quarks due to a substantial Yukawa coupling resulting from the large top quark mass. In addition, mixing between  $\tilde{t}_L$  and  $\tilde{t}_R$  can cause a large splitting between the mass eigenstates  $\tilde{t}_1$  and  $\tilde{t}_2$  [2]. If the Yukawa coupling strength or the mixing is strong enough (or both) then the mass eigenstate  $\tilde{t}_1$  can be lighter than the top quark. We note that many baryogenesis models require a light stop quark [3].

The bottom quark mass is much smaller than the top quark mass, therefore the effect of the Yukawa coupling on the scalar bottom quark ( $\tilde{b}$ ) mass is small. However, in some regions of SUSY parameter space a large mixing between  $\tilde{b}_L$  and  $\tilde{b}_R$  can still occur, leading to a significant splitting between mass eigenstates and a low mass value for the lighter mass eigenstate ( $\tilde{b}_1$ ) [4].

At the Tevatron, third generation scalar quarks are expected to be produced in pairs via  $gg$  fusion and  $q\bar{q}$  annihilation. In this Letter, we describe two analyses looking for processes in a Minimal Supersymmetric Standard Model framework: (i) a scalar top analysis, searching for the process  $p\bar{p} \rightarrow \tilde{t}_1\bar{\tilde{t}}_1 \rightarrow (c\tilde{\chi}_1^0) (\bar{c}\tilde{\chi}_1^0)$ , and (ii) a scalar bottom analysis, searching for the process  $p\bar{p} \rightarrow \tilde{b}_1\bar{\tilde{b}}_1 \rightarrow (b\tilde{\chi}_1^0) (\bar{b}\tilde{\chi}_1^0)$ . We do not assume a gaugino unification hypothesis. We assume the lightest neutralino  $\tilde{\chi}_1^0$  is the lightest supersymmetric particle and stable. This leads to experimental signatures with appreciable missing transverse energy. The decay  $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ , as in process (i), dominates via a one-loop diagram in the absence of flavor-changing neutral currents if  $m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^\pm}$  and  $m_{\tilde{t}_1} < m_W + m_b + m_{\tilde{\chi}_1^0}$  [2]. For process (ii) we assume  $m_{\tilde{b}_1} > m_b + m_{\tilde{\chi}_1^0}$  and  $m_{\tilde{b}_1} < m_b + m_{\tilde{\chi}_2^0}$  [4]. Here,  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  are the lightest chargino and next-to-lightest neutralino. Therefore, the signature of both processes is a pair of acolinear heavy flavor jets,  $\cancel{E}_T$ , and no leptons in the final state.

We have searched data corresponding to a total integrated luminosity of  $88.0 \pm 3.6 \text{ pb}^{-1}$  collected using the CDF detector during the 1994-95 Tevatron run. CDF is a general purpose detector and is described in detail elsewhere [5]. Here we give a brief description of the components relevant to this analysis. The innermost part of CDF, a four-layer silicon vertex detector (SVX'), allows a precise measurement of a track's impact parameter with respect to the primary vertex in the plane transverse to the beam direction [6]. A time projection chamber determines the position of the primary vertex along the beam direction. The central drift chamber, located inside a 1.4-T superconducting solenoidal magnet, measures the momenta of the charged particles. Outside the drift chamber there is a calorimeter, which is organized into electromagnetic and hadronic components, with projective towers covering the pseudo-rapidity range  $|\eta| < 4.2$ . The muon system is located outside the calorimeter and covers the range  $|\eta| < 1$ . Events for this analysis were collected using a trigger which required missing transverse energy  $\cancel{E}_T > 35 \text{ GeV}$ .  $\cancel{E}_T$  is the energy imbalance in the directions transverse to the beam direction using the raw energy deposited in calorimeter towers with  $|\eta| < 3.6$ .

After removing events with large  $\cancel{E}_T$  from accelerator-induced and cosmic ray sources, we select events with two or three jets that have transverse energy  $E_T \geq 15 \text{ GeV}$  and  $|\eta| \leq 2$  (hard jets) and no jets with  $7 \leq E_T < 15 \text{ GeV}$  and  $|\eta| \leq 3.6$  (soft jets). These requirements efficiently reject  $t\bar{t}$  events (which have more than 3 hard jets) and QCD multijet events (which have soft jets due to gluon radiation). Jets are found from calorimeter information using a fixed cone algorithm [7] with a cone radius of 0.4 in  $\eta$ - $\phi$  and jet energies are calculated using the raw energy deposition in calorimeter towers. The angle  $\phi$  is the angle in the plane normal to the beam direction. To reduce systematic effects from the trigger, we require events to have  $\cancel{E}_T > 40 \text{ GeV}$ , and to reject events with fake missing energy arising from jet energy mismeasurements we require that the missing transverse energy direction is neither parallel to any jet( $j$ ) nor anti-parallel to the leading  $E_T$  jet :  $\Delta\phi(\cancel{E}_T, j) > 45^\circ$  and  $\Delta\phi(\cancel{E}_T, j_1) < 165^\circ$  where the jet indices are ordered by decreasing  $E_T$ . Moreover, to reduce the QCD background, we require the angle between the two leading jets to be  $45^\circ < \Delta\phi(j_1, j_2) < 165^\circ$ . We reject events with one or more identified electrons (muons) with  $E_T (P_T) > 10 \text{ GeV}$  ( $\text{GeV}/c$ ).

After applying these requirements, the data sample (which we call the pretag sample) contains 396 events. The largest source of background in the pretag sample is the production of  $W$ +jets, where the  $W$  decays to a neutrino (leading to missing energy) and either an electron or muon that is not identified or a tau which decays hadronically.

The pretag sample also contains QCD multijet events where the large  $\cancel{E}_T$  is due to jet energy mismeasurement.

The SVX' information is used to tag heavy-flavor jets. We associate tracks to a jet by requiring that the track is within a cone of 0.4 in  $\eta$ - $\phi$  space around the jet axis. We require tracks to have  $P_T > 1.0$  GeV/ $c$ , positive impact parameter, and a good SVX' hit pattern. A good SVX' hit pattern consists of three or four hits in the SVX' detector with no hits shared by other tracks. We take the sign of a track's impact parameter to be the sign of the scalar product of the impact parameter and jet  $E_T$  vectors. We then define the impact parameter significance to be the impact parameter divided by its uncertainty. For tracks originating from the primary vertex the impact parameter significance distribution is symmetric around zero with a shape determined by the SVX' resolution, while decay products of long lived objects tend to have large positive impact parameter significances. We therefore use the negative impact parameter significance distribution to define the detector resolution function. For each track, we determine the probability that the track comes from the primary vertex using this resolution function. We call this probability *track probability*. By construction, the *track probability* distribution is flat for tracks originating from the primary vertex, and peaks near zero for tracks from a secondary vertex. We combine the track probabilities for all tracks associated to a jet to form the *jet probability* ( $\mathcal{P}_{jet}$ ) [8], the probability that all the tracks in the jet come from the primary vertex. The distribution of  $\mathcal{P}_{jet}$  is flat for jets originating from the primary vertex by construction, while for bottom and charm jets it peaks near zero.  $\mathcal{P}_{jet}$  is a continuous variable and the  $\mathcal{P}_{jet}$  requirement is easily optimized for the scalar top and scalar bottom searches separately. This motivates the choice of the  $\mathcal{P}_{jet}$  tagging algorithm over other tagging algorithms developed at CDF [9].

We select events for the scalar top analysis by requiring the event to have at least one taggable jet with a  $\mathcal{P}_{jet} \leq 0.05$ . A taggable jet has at least two SVX' tracks as defined above. The distribution of the minimum jet probability ( $\mathcal{P}_{jet}^{min}$ ) of the taggable jets in the pretag sample is shown in Figure 1. The expected background and scalar top/bottom signal distributions are overlaid. This requirement, chosen to optimize the expected signal significance, rejects approximately 97% of the background while its efficiency for the signal is 25%. For the scalar bottom analysis the expected signal significance is optimized by requiring that the event has at least one taggable jet with a  $\mathcal{P}_{jet}^{min} \leq 0.01$ . This requirement rejects approximately 99% of the background while retaining 45% of the scalar bottom signal.

Backgrounds (other than QCD multijet events) and the expected signal are estimated using a number of Monte Carlo programs followed by a full CDF detector simulation. Single vector boson production and decay is simulated using a tree-level calculation as implemented in the VECBOS [10] package, with HERWIG [11] routines used for subsequent parton hadronization. Vector boson pair production and decay is implemented in ISAJET [12]. Top pair production and decay is simulated using HERWIG. Signal events are modeled using the PYTHIA [13] generator. The PYTHIA Monte Carlo generator includes production and decay of SUSY particles [14]. The next-to-leading order (NLO) cross section for the scalar quark production is calculated using the PROSPINO [15] program with CTEQ3M parton distribution functions [16]. Simulated events are analyzed using the same procedure as the selected data sample. We check the single vector boson normalization with data by reversing the lepton veto requirement in the pretag sample.

We estimate the number of QCD multijet events in the tagged samples using a combination of Monte Carlo and data samples. We attribute the excess of data events above electroweak sources in the pretag data sample to QCD multijet sources. The total expected electroweak background in the pretag sample is  $270.1 \pm 76.2$  which gives us an estimate of  $125.9 \pm 83.4$  expected QCD multijet events in the pretag sample. We then apply a  $\mathcal{P}_{jet}$  mistag matrix to this excess to estimate the QCD multijet background after tagging. The  $\mathcal{P}_{jet}$  mistag matrix, which parameterizes the probability that a jet has  $\mathcal{P}_{jet} \leq 0.05$  as a function of jet  $E_T$  and the number of SVX' tracks, is derived from data and verified in several control data samples.

The systematic uncertainties on the expected number of signal events apply for both  $\tilde{t}_1$  and  $\tilde{b}_1$ . The NLO cross section for third generation scalar quarks depends weakly on other masses and parameters ( $\sim 1\%$ ) [15]. The dominant NLO uncertainties are due to the choice of QCD renormalization scale ( $\mu$ ) and the choice of parton distribution function. The theoretical uncertainty on the NLO scalar quark production cross section is a function of the scalar quark mass and ranges from 11% to 22% for the mass range 30 GeV/ $c^2$  to 150 GeV/ $c^2$ . Gluon radiation from the initial state (ISR) or final state (FSR) partons is the largest source of systematic uncertainty. We determine its effect on our acceptance by turning off ISR or FSR in the signal Monte Carlo and comparing the efficiency with the default Monte Carlo which has ISR and FSR turned on. The combined ISR/FSR systematic uncertainty is 23%. We determine the jet energy systematic uncertainty, which is 10%, by varying the jet energies by  $\pm 5\%$ . The trigger efficiency systematic uncertainty, which is 10%, is determined by varying the trigger efficiency curve (which is derived from data) by  $\pm 1\sigma$  of its fitted values. The detection efficiency estimates are derived from Monte Carlo that has exactly one primary vertex. The dominant effect of multiple primary vertices is to reduce the efficiency for a requirement of no extra jets with  $E_T \geq 7$  GeV and  $|\eta| \leq 3.6$ . We account for the loss in efficiency due to the extra jet veto by combining the Monte Carlo with a minimum-bias data sample (consistent with the number of primary vertices found during

the 1994-95 Tevatron run), measuring the relative loss in efficiency of the “no extra jet” requirement, and degrading the signal efficiency by this factor. The efficiency scale factor due to multiple primary vertices is  $0.93 \pm 0.03$ . We use data samples enriched in charm(bottom) jets to determine the systematic uncertainty on the charm (bottom) tagging efficiency. The systematic uncertainty is 10% for both charm and bottom tagging. Including the systematic uncertainties due to the integrated luminosity measurement (4.1%) and finite Monte Carlo statistics (5–15%), the total systematic varies from 31% to 36% as a function of the squark mass.

In the scalar top analysis we observe 11 events, which is consistent with  $14.5 \pm 4.2$  events expected from SM processes (see Table I). We interpret the null result in the scalar top search as an excluded region in  $m_{\tilde{\chi}_1^0} - m_{\tilde{t}_1}$  parameter space using a background subtraction method [17]. The 95% C.L. excluded region is shown in Figure 2. The maximum  $m_{\tilde{t}_1}$  excluded is  $119 \text{ GeV}/c^2$  for  $m_{\tilde{\chi}_1^0} = 40 \text{ GeV}/c^2$ . The maximum excluded value of the neutralino mass is  $51 \text{ GeV}/c^2$  which corresponds to the scalar top mass of  $102 \text{ GeV}/c^2$ . The reach in  $m_{\tilde{t}_1}$  is limited by the statistics, while the gap between the kinematic limit and the excluded region is mostly determined by the  $\cancel{E}_T$  cut which is effectively fixed by the  $\cancel{E}_T$  trigger threshold. Also shown in Figure 2 are the results from the DØ experiment, based on  $7.4 \text{ pb}^{-1}$  [18], and from the OPAL experiment for  $\sqrt{s} = 189 \text{ GeV}$  at LEP [19].

In the scalar bottom analysis five events are observed with an expected background of  $5.8 \pm 1.8$  (see Table I). Similarly, we interpret the null result as an excluded region in  $m_{\tilde{\chi}_1^0} - m_{\tilde{b}_1}$  parameter space as shown in Figure 3. For  $m_{\tilde{\chi}_1^0} = 40 \text{ GeV}/c^2$  the maximum  $m_{\tilde{b}_1}$  excluded is  $146 \text{ GeV}/c^2$ . Also plotted are the latest results from DØ [20] and OPAL [19].

In summary, we have performed a search for  $\tilde{t}_1/\tilde{b}_1$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  using  $88 \text{ pb}^{-1}$  of data. We looked for events with significant missing energy, no high  $P_T$  lepton(s), and two or three jets. We required that at least one jet is consistent with originating from a heavy flavor jet using a technique called jet probability. After applying all selection criteria, we observed no excess of events above Standard Model predictions, and we set 95% C.L. exclusion regions in the  $m_{\tilde{\chi}_1^0} - m_{\tilde{q}_1}$  plane.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science and Culture of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the A. P. Sloan Foundation; and the Swiss National Science Foundation.

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Sample	$N_{exp} (\mathcal{P}_{jet}^{min} \leq 0.05)$	$N_{exp} (\mathcal{P}_{jet}^{min} \leq 0.01)$
$W^\pm(\rightarrow e^\pm\nu_e)+ \geq 2$ jets	$0.3\pm 0.3\pm 0.1$	-
$W^\pm(\rightarrow \mu^\pm\nu_\mu)+ \geq 2$ jets	$0.9\pm 0.5\pm 0.3$	-
$W^\pm(\rightarrow \tau^\pm\nu_\tau)+ \geq 1$ jets	$7.6\pm 1.6\pm 2.2$	$3.0\pm 1.0\pm 0.9$
$Z^0(\rightarrow \nu\bar{\nu})+ \geq 2$ jets	$1.2\pm 0.4\pm 0.4$	$0.8\pm 0.3\pm 0.2$
$t\bar{t}$	$0.7\pm 0.2\pm 0.4$	$0.5\pm 0.2\pm 0.2$
<i>Diboson</i> ( $WW, WZ, ZZ$ )	$0.4\pm 0.1\pm 0.1$	$0.2\pm 0.1\pm 0.1$
Total $W/Z/t\bar{t}/Diboson$	$11.1\pm 1.8\pm 3.3$	$4.5\pm 1.1\pm 1.2$
Total <i>QCD</i>	$3.4\pm 1.7$	$1.3\pm 0.7$
Total Expected from SM	$14.5\pm 4.2$	$5.8\pm 1.8$
Total Observed	11	5

TABLE I. The number of observed data and expected background events. For  $W/Z/t\bar{t}/Diboson$ , the first uncertainty is statistical, the second is systematic. For *QCD* and Total Expected from SM, the uncertainty is statistical plus systematic.

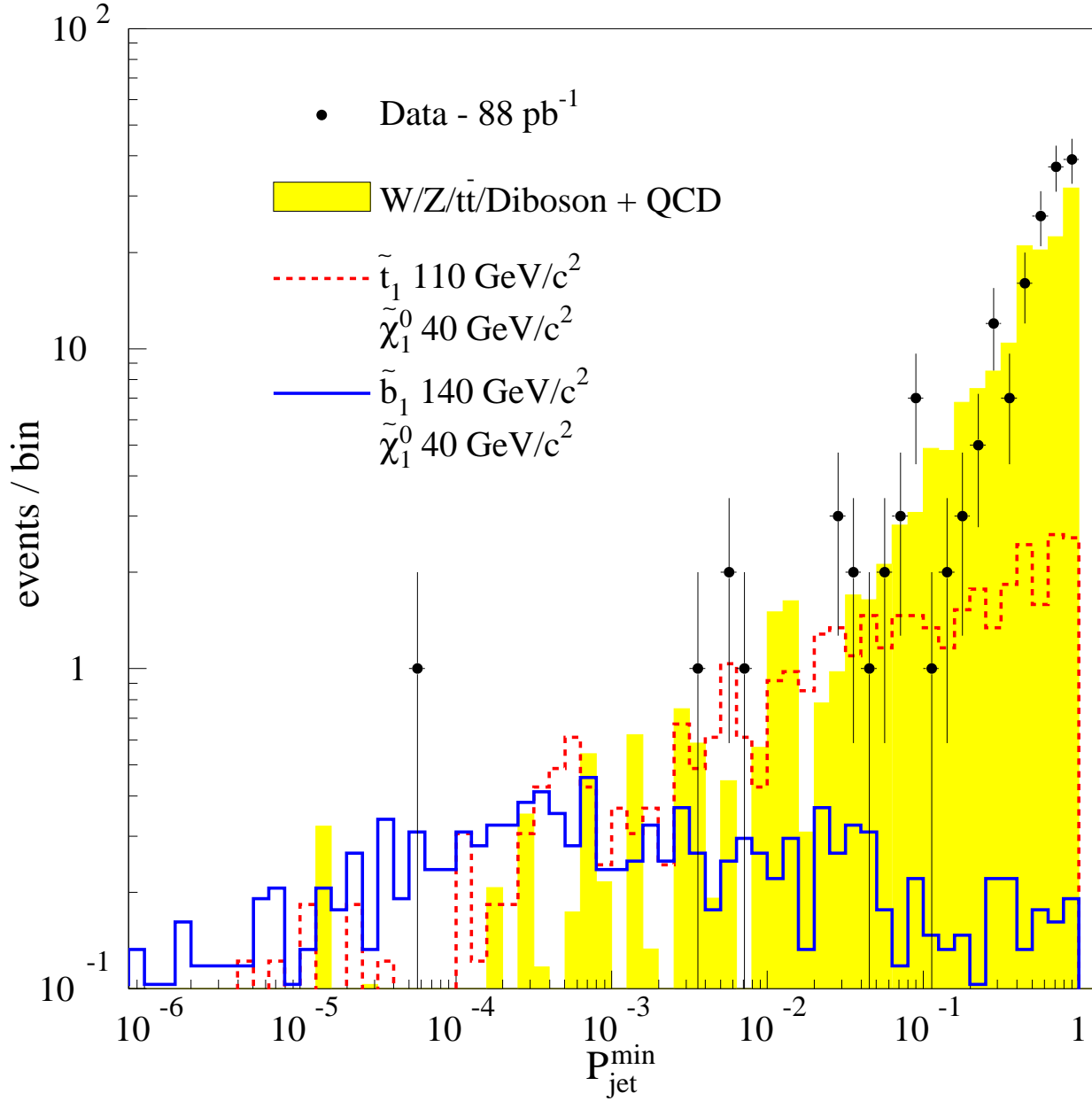


FIG. 1. The distribution of  $\mathcal{P}_{jet}^{min}$  - the lowest value of  $\mathcal{P}_{jet}$  for all taggable jets in an event. A requirement of  $\mathcal{P}_{jet}^{min} \leq 0.05$  (0.01) is applied to select charm (bottom) jets. Points are data, the shaded histogram is the sum of the predicted backgrounds, the solid line is the predicted signal for  $m_{\tilde{t}_1} = 110 \text{ GeV}/c^2$ ,  $m_{\tilde{\chi}_1^0} = 40 \text{ GeV}/c^2$ , and the dashed line is the predicted signal for  $m_{\tilde{b}_1} = 140 \text{ GeV}/c^2$ ,  $m_{\tilde{\chi}_1^0} = 40 \text{ GeV}/c^2$ . The background and signal are normalized to  $88 \text{ pb}^{-1}$ .



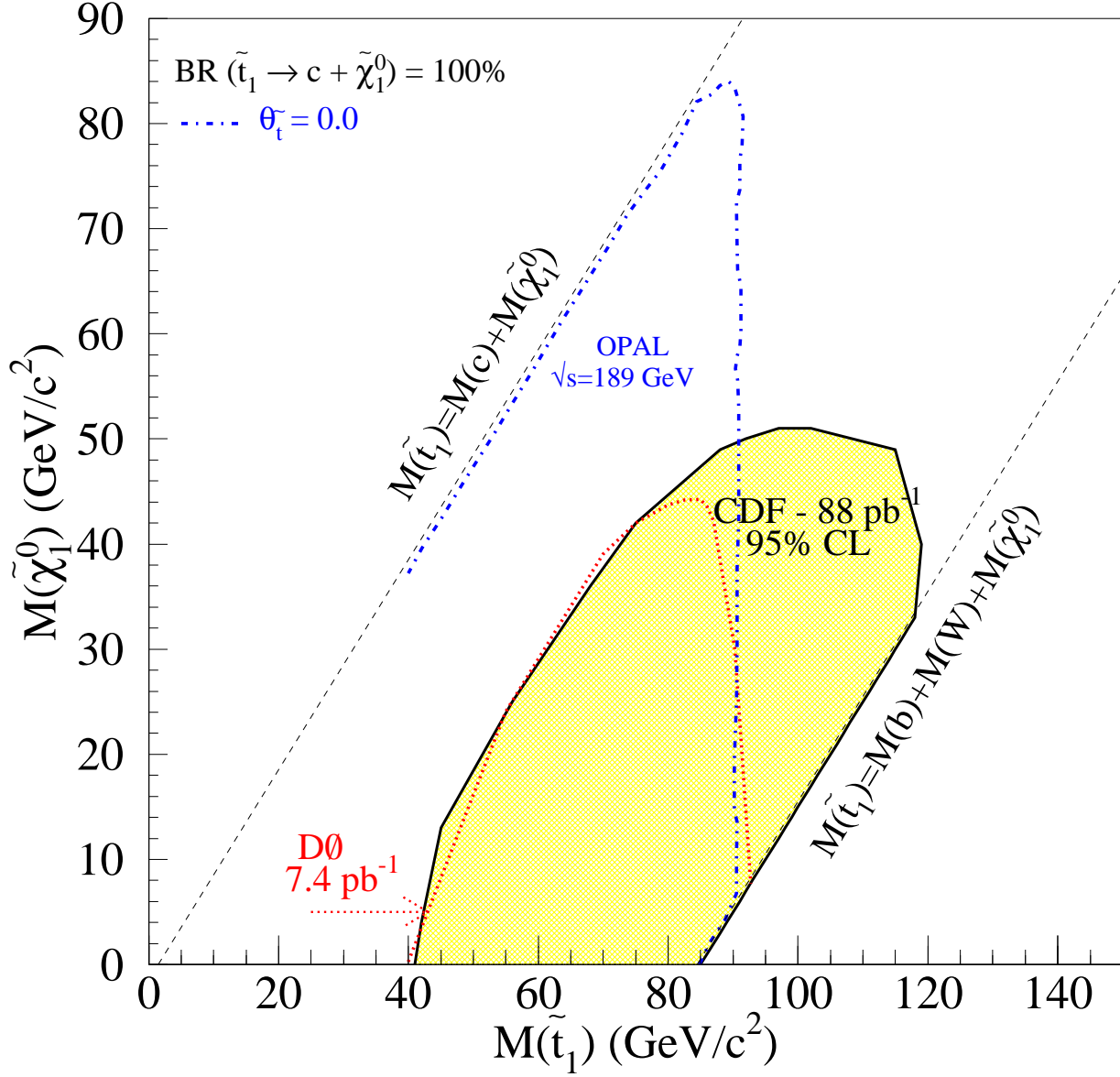


FIG. 2. 95% CL exclusion region (shaded region) in  $m_{\tilde{\chi}_1^0} - m_{\tilde{t}_1}$  plane for  $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ . Also shown are results from DØ [18] and OPAL [19].  $\theta_{\tilde{t}}$  parameterizes the mixing of the left/right scalar top gauge eigenstates to form the light/heavy mass eigenstates. Note that the results for both DØ and CDF are independent of  $\theta_{\tilde{t}}$ .

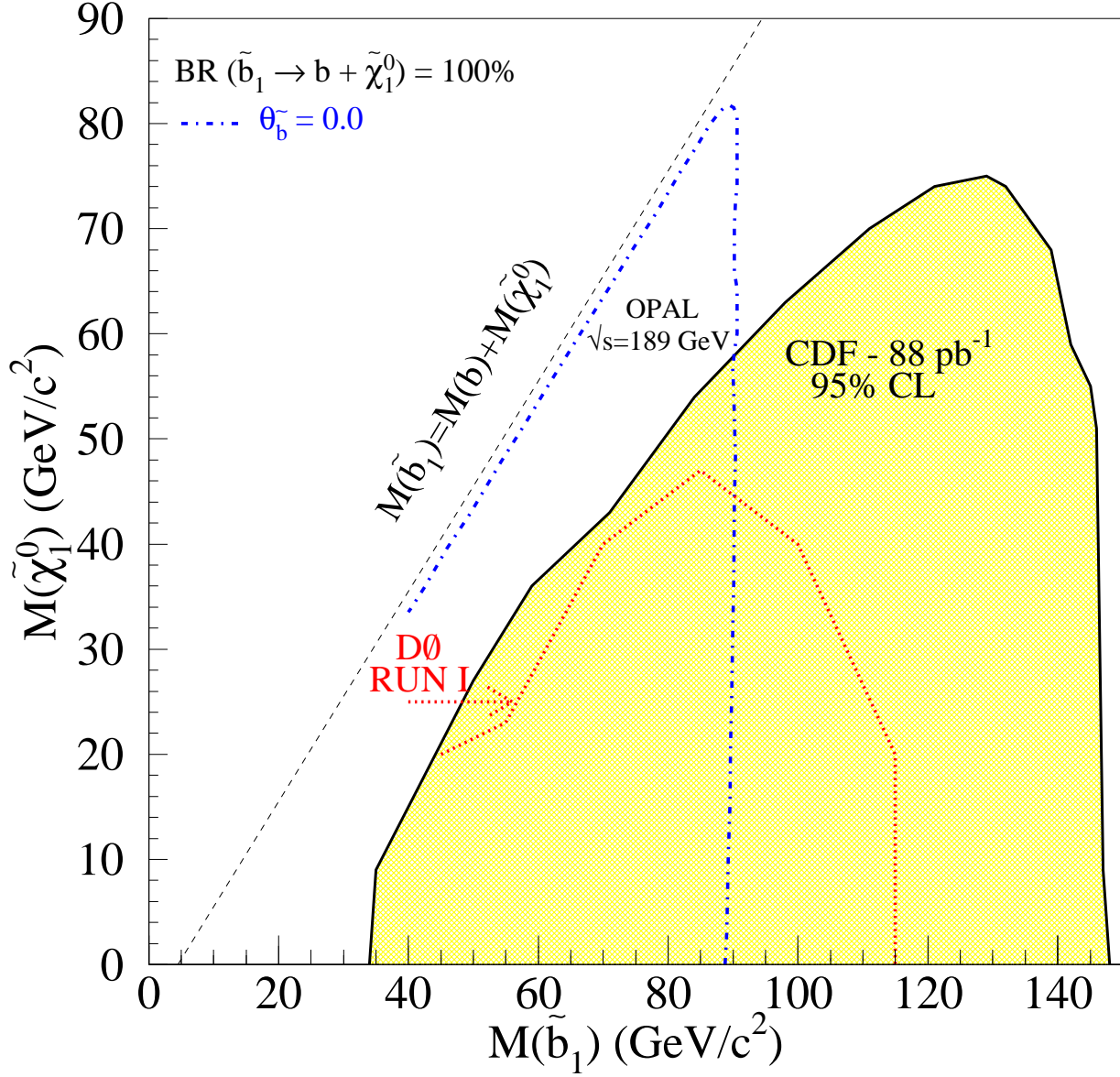


FIG. 3. 95% CL exclusion region (shaded region) in  $m_{\tilde{\chi}_1^0}$ - $m_{\tilde{b}_1}$  plane for  $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ . Also shown are the results from DØ [20] and OPAL [19].  $\theta_{\tilde{b}}$  parameterizes the mixing of the left/right scalar bottom gauge eigenstates to form the light/heavy mass eigenstates. Note that the results for both DØ and CDF are independent of  $\theta_{\tilde{b}}$ .