Search for bottom squarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV

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B. Abbott,[43] M. Abolins,[40] V. Abramov,[18] B.S. Acharya,[11] I. Adam,[42] D.L. Adams,[52] M. Adams,[27] S. Ahn,[26] V. Akimov,[16] G.A. Alves,[2] N. Amos,[39] E.W. Anderson,[33] M.M. Baarmand,[45] V.V. Babintsev,[18] L. Babukhadia,[19] A. Baden,[36] B. Baldin,[26] S. Banerjee,[11] J. Bantly,[49] E. Barberis,[20] P. Baringer,[34] J.F. Bartlett,[26] A. Belyaev,[17] S.B. Beri,[9] I. Bertram,[29] V.A. Bezzubov,[18] P.C. Bhat,[26] V. Bhatnagar,[9] M. Bhattacharjee,[45] N. Biswas,[31] G. Blazey,[28] S. Blessing,[24] P. Bloom,[21] A. Boehnlein,[26] N.I. Bojko,[18] F. Borcherding,[26] C. Boswell,[23] A. Brandt,[26] R. Breedon,[21] G. Briskin,[49] R. Brock,[40] A. Bross,[26] D. Buchholz,[29] V.S. Burtovoi,[18] J.M. Butler,[37] W. Carvalho,[2] D. Casey,[40] Z. Casilum,[45] H. Castilla-Valdez,[14] D. Chakraborty,[45] S.V. Chekulaev,[18] W. Chen,[45] S. Choi,[13] S. Chopra,[24] B.C. Choudhary,[23] J.H. Christenson,[26] M. Chung,[27] D. Claes,[41] A.R. Clark,[20] W.G. Cobau,[36] J. Cochran,[23] L. Coney,[31] W.E. Cooper,[26] D. Coppage,[34] C. Cretsinger,[44] D. Cullen-Vidal,[49] M.A.C. Cummings,[28] D. Cutts,[49] O.I. Dahl,[20] K. Davis,[19] K. De,[50] K. Del Signore,[39] M. Demarteau,[26] D. Denisov,[26] S.P. Denisov,[18] H.T. Diehl,[26] M. Diesburg,[26] G. Di Loreto,[40] P. Draper,[50] Y. Ducros,[8] L.V. Dudko,[17] S.R. Dugad,[11] A. Dyshkant,[18] D. Edmunds,[40] J. Ellison,[23] V.D. Elvira,[45] R. Engelmann,[45] S. Eno,[36] G. Eppley,[52] P. Ermolov,[17] O.V. Eroshin,[18] V.N. Evdokimov,[18] T. Fahland,[22] M.K. Fatyga,[44] S. Feher,[26] D. Fein,[19] T. Ferbel,[44] H.E. Fisk,[26] Y. Fisyak,[46] E. Flattum,[26] G.E. Forden,[19] M. Fortner,[28] K.C. Frame,[40] S. Fuess,[26] E. Gallas,[50] A.N. Galyaev,[18] P. Gartung,[23] V. Gavrilov,[16] T.L. Geld,[40] R.J. Genik II,[40] K. Genser,[26] C.E. Gerber,[26] Y. Gershtein,[49] B. Gibbard,[46] B. Gobbi,[29] B. Gómez,[5] G. Gómez,[36] P.I. Goncharov,[18] J.L. González Solís,[14] H. Gordon,[46] L.T. Goss,[51] K. Gounder,[23] A. Goussiou,[45] N. Graf,[46] P.D. Grannis,[45] D.R. Green,[26] H. Greenlee,[26] S. Grinstein,[1] P. Grudberg,[20] S. Grünendahl,[26] G. Guglielmo,[48] J.A. Guida,[19] J.M. Guida,[49] A. Gupta,[11] S.N. Gurzhiev,[18] G. Gutierrez,[26] P. Gutierrez,[48] N.J. Hadley,[36] H. Haggerty,[26] S. Hagopian,[24] V. Hagopian,[24] K.S. Hahn,[44] R.E. Hall,[22] P. Hanlet,[38] S. Hansen,[26] J.M. Hauptman,[33] C. Hebert,[34] D. Hedin,[28] A.P. Heinson,[23] U. Heintz,[37] R. Hernández-Montoya,[14] T. Heuring,[24] R. Hirosky,[27] J.D. Hobbs,[45] B. Hoeneisen,[6] J.S. Hoftun,[49] F. Hsieh,[39] Tong Hu,[30] A.S. Ito,[26] S.A. Jerger,[40] R. Jesik,[30] T. Joffe-Minor,[29] K. Johns,[19] M. Johnson,[26] A. Jonckheere,[26] M. Jones,[25] H. Jöstlein,[26] S.Y. Jun,[29] C.K. Jung,[45] S. Kahn,[46] D. Karmanov,[17] D. Karmgard,[24] R. Kehoe,[31] S.K. Kim,[13] B. Klima,[26] C. Klopfenstein,[21] W. Ko,[21] J.M. Kohli,[9] D. Koltick,[32] A.V. Kostritskiy,[18] J. Kotcher,[46] A.V. Kotwal,[42] A.V. Kozelov,[18] E.A. Kozlovsky,[18] J. Krane,[41] M.R. Krishnaswamy,[11] S. Krzywdzinski,[26] S. Kuleshov,[16] Y. Kulik,[45] S. Kunori,[36] F. Landry,[40] G. Landsberg,[49] B. Lauer,[33] A. Leflat,[17] J. Li,[50] Q.Z. Li,[26] J.G.R. Lima,[3] D. Lincoln,[26] S.L. Linn,[24] J. Linnemann,[40] R. Lipton,[26] A. Lucotte,[45] L. Lueking,[26] A.L. Lyon,[36] A.K.A. Maciel,[28] R.J. Madaras,[20] R. Madden,[24] L. Magaña-Mendoza,[14] V. Manankov,[17] S. Mani,[21] H.S. Mao,[4] R. Markeloff,[28] T. Marshall,[30] M.I. Martin,[26] K.M. Mauritz,[33] B. May,[29] A.A. Mayorov,[18] R. McCarthy,[45] J. McDonald,[24] T. McKibben,[27] J. McKinley,[40] T. McMahon,[47] H.L. Melanson,[26] M. Merkin,[17] K.W. Merritt,[26] C. Miao,[49] H. Miettinen,[52] A. Mincer,[43] C.S. Mishra,[26] N. Mokhov,[26] N.K. Mondal,[11] H.E. Montgomery,[26] P. Mooney,[5] M. Mostafa,[1] H. da Motta,[2] C. Murphy,[27] F. Nang,[19] M. Narain,[37] V.S. Narasimham,[11] A. Narayanan,[19] H.A. Neal,[39] J.P. Negret,[5] P. Nemethy,[43] D. Norman,[51] L. Oesch,[39] V. Oguri,[3] N. Oshima,[26] D. Owen,[40] P. Padley,[52] A. Para,[26] N. Parashar,[38] Y.M. Park,[12] R. Partridge,[49] N. Parua,[7] M. Paterno,[44] B. Pawlik,[15] J. Perkins,[50] M. Peters,[25] R. Piegaia,[1] H. Piekarz,[24] Y. Pischalnikov,[32] B.G. Pope,[40] H.B. Prosper,[24] S. Protopopescu,[46] J. Qian,[39] P.Z. Quintas,[26] R. Raja,[26] S. Rajagopalan,[46] O. Ramirez,[27] S. Reucroft,[38] M. Rijssenbeek,[45] T. Rockwell,[40] M. Roco,[26] P. Rubinov,[29] R. Ruchti,[31] J. Rutherfoord,[19] A. Sánchez-Hernández,[14] A. Santoro,[2] L. Sawyer,[35] R.D. Schamberger,[45] H. Schellman,[29] J. Sculli,[43] E. Shabalina,[17] C. Shaffer,[24] H.C. Shankar,[11] R.K. Shivpuri,[10] D. Shpakov,[45] M. Shupe,[19] H. Singh,[23] J.B. Singh,[9] V. Sirotenko,[28] E. Smith,[48] R.P. Smith,[26] R. Snihur,[29] G.R. Snow,[41] J. Snow,[47] S. Snyder,[46] J. Solomon,[27] M. Sosebee,[50] N. Sotnikova,[17] M. Souza,[2] G. Steinbrück,[48] R.W. Stephens,[50] M.L. Stevenson,[20] F. Stichelbaut,[46] D. Stoker,[22] V. Stolin,[16] D.A. Stoyanova,[18] M. Strauss,[48] K. Streets,[43] M. Strovink,[20] A. Sznajder,[2] P. Tamburello,[36] J. Tarazi,[22] M. Tartaglia,[26] T.L.T. Thomas,[29] J. Thompson,[36] T.G. Trippe,[20] P.M. Tuts,[42] V. Vaniev,[18] N. Varelas,[27] E.W. Varnes,[20] A.A. Volkov,[18] A.P. Vorobiev,[18] H.D. Wahl,[24] G. Wang,[24] J. Warchol,[31] G. Watts,[49] M. Wayne,[31] H. Weerts,[40] A. White,[50] J.T. White,[51] J.A. Wightman,[33] S. Willis,[28] S.J. Wimpenny,[23] J.V.D. Wirjawan,[51] J. Womersley,[26] D.R. Wood,[38] R. Yamada,[26] P. Yamin,[46] T. Yasuda,[38] P. Yepes,[52] K. Yip,[26] C. Yoshikawa,[25] S. Youssef,[24] J. Yu,[26] Y. Yu,[13] B. Zhang,[4] Z. Zhou,[33] Z.H. Zhu,[44] M. Zielinski,[44] D. Zieminska,[30] A. Zieminski,[30] V. Zutshi,[44] E.G. Zverev,[17] and A. Zylberstejn[8]

(DØ Collaboration)

[1] *Universidad de Buenos Aires, Buenos Aires, Argentina*
[2] *LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[3] *Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[4] *Institute of High Energy Physics, Beijing, People's Republic of China*
[5] *Universidad de los Andes, Bogotá, Colombia*

[6]Universidad San Francisco de Quito, Quito, Ecuador
[7]Institut des Sciences Nucléaires, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France
[8]DAPNIA/Service de Physique des Particules, CEA, Saclay, France
[9]Panjab University, Chandigarh, India
[10]Delhi University, Delhi, India
[11]Tata Institute of Fundamental Research, Mumbai, India
[12]Kyungsung University, Pusan, Korea
[13]Seoul National University, Seoul, Korea
[14]CINVESTAV, Mexico City, Mexico
[15]Institute of Nuclear Physics, Kraków, Poland
[16]Institute for Theoretical and Experimental Physics, Moscow, Russia
[17]Moscow State University, Moscow, Russia
[18]Institute for High Energy Physics, Protvino, Russia
[19]University of Arizona, Tucson, Arizona 85721
[20]Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
[21]University of California, Davis, California 95616
[22]University of California, Irvine, California 92697
[23]University of California, Riverside, California 92521
[24]Florida State University, Tallahassee, Florida 32306
[25]University of Hawaii, Honolulu, Hawaii 96822
[26]Fermi National Accelerator Laboratory, Batavia, Illinois 60510
[27]University of Illinois at Chicago, Chicago, Illinois 60607
[28]Northern Illinois University, DeKalb, Illinois 60115
[29]Northwestern University, Evanston, Illinois 60208
[30]Indiana University, Bloomington, Indiana 47405
[31]University of Notre Dame, Notre Dame, Indiana 46556
[32]Purdue University, West Lafayette, Indiana 47907
[33]Iowa State University, Ames, Iowa 50011
[34]University of Kansas, Lawrence, Kansas 66045
[35]Louisiana Tech University, Ruston, Louisiana 71272
[36]University of Maryland, College Park, Maryland 20742
[37]Boston University, Boston, Massachusetts 02215
[38]Northeastern University, Boston, Massachusetts 02115
[39]University of Michigan, Ann Arbor, Michigan 48109
[40]Michigan State University, East Lansing, Michigan 48824
[41]University of Nebraska, Lincoln, Nebraska 68588
[42]Columbia University, New York, New York 10027
[43]New York University, New York, New York 10003
[44]University of Rochester, Rochester, New York 14627
[45]State University of New York, Stony Brook, New York 11794
[46]Brookhaven National Laboratory, Upton, New York 11973
[47]Langston University, Langston, Oklahoma 73050
[48]University of Oklahoma, Norman, Oklahoma 73019
[49]Brown University, Providence, Rhode Island 02912
[50]University of Texas, Arlington, Texas 76019
[51]Texas A&M University, College Station, Texas 77843
[52]Rice University, Houston, Texas 77005
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We report on a search for bottom squarks ($\widetilde{b}$) produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the DØ detector at Fermilab. Bottom squarks are assumed to be produced in pairs and to decay to the lightest supersymmetric particle (LSP) and a b quark with a branching fraction of 100%. The LSP is assumed to be the lightest neutralino and stable. We set limits on the production cross section as a function of $\widetilde{b}$ mass and LSP mass.

Supersymmetry (SUSY) is a hypothetical fundamental space-time symmetry relating bosons and fermions [1]. Supersymmetric extensions to the standard model (SM) feature as yet undiscovered supersymmetric partners for every SM particle. The scalar quarks (squarks) $\widetilde{q}_L$ and $\widetilde{q}_R$ are the partners of the left-handed and right-handed quarks, respectively. These are weak eigenstates, and can mix to form the mass eigenstates, with $\widetilde{q}_1 = \widetilde{q}_L\cos\theta + \widetilde{q}_R\sin\theta$ for the lighter squark, and the orthogonal combination for the heavier squark $\widetilde{q}_2$. In most SUSY models, the masses of the squarks are approximately degenerate. But in some models, the lighter top and bottom squarks could have a lower mass than the other squarks because of the high mass values of the top and bottom quarks. In particular, lighter bottom squarks could arise for large values of $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs fields in the minimal supersymmetric standard model.

We report the results of a mixing-independent search for bottom squarks produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. Squarks are produced in pairs by QCD processes with the production cross section depending on the mass of the squark but not on the mixing angle θ. We search for events where both squarks decay to the lightest neutralino $\widetilde{\chi}_1^0$ via $\widetilde{b} \rightarrow \widetilde{\chi}_1^0 + b$ and assume that the $\widetilde{\chi}_1^0$ is the lightest supersymmetric particle (LSP) and stable. This should be the dominant decay channel provided that the mass of the squark ($m_{\widetilde{b}}$) is larger than the combined masses of the b quark and LSP ($m_{\rm LSP}$); therefore we assume its branching fraction is 100%. This yields a final state consisting of two b quarks and two unobserved stable particles resulting in missing transverse energy ($\not\!\!E_T$) in the detector. In this paper, we give limits on the squark pair production cross section for different values of $m_{\widetilde{b}}$ and $m_{\rm LSP}$. Limits on the cross section are used to exclude a region in the ($m_{\rm LSP}$, $m_{\widetilde{b}}$) plane. Limits [2] from the CERN e^+e^- collider (LEP) experiments depend on the Z/γ-to-squark coupling, which is a function of the mixing angle. For maximal coupling, the LEP exclusion region can extend to the kinematic maximum; for example, to about 85 GeV/c^2 at $\sqrt{s} = 183$ GeV.

The data used for our analysis were collected during 1992–1996 by the DØ detector [3] at the Fermilab Tevatron Collider. The DØ detector is composed of three major systems: an inner detector for tracking charged particles, a uranium/liquid argon calorimeter for measuring electromagnetic and hadronic energies, and a muon spectrometer consisting of a magnetized iron toroid and three layers of drift tubes. The detector measures jets with an energy resolution of approximately $\sigma/E = 0.8/\sqrt{E}$ (E in GeV) and muons with a momentum resolution of $\sigma/p = [(\frac{0.18(p-2)}{p})^2 + (0.003p)^2]^{1/2}$ (p in GeV/c). $\not\!\!E_T$ is determined by summing the calorimeter and muon transverse energies, and is measured with a resolution of $\sigma = 1.08$ GeV + $0.019\cdot(\Sigma|E_T|)$ [4].

Four channels are combined to set limits on the production of bottom squarks. The first required a $\not\!\!E_T$ and jets topology. This channel was previously used to set limits on the mass of the top squark, which was assumed to decay $\widetilde{t} \rightarrow \widetilde{\chi}_1^0 + c$ [5]. The other three channels in addition required that at least one jet has an associated muon, thereby tagging b quark decay, and were used to set limits on a charge 1/3 third generation leptoquark for the decay $LQ \rightarrow \nu_\tau + b$ [6]. We use identical data samples and event selections for the bottom squark limits presented in this paper. For all channels, the presence of significant $\not\!\!E_T$ is used to identify the non-interacting LSPs. Figure 1 shows the expected $\not\!\!E_T$ distribution for two values of $m_{\widetilde{b}}$ and different $m_{\rm LSP}$ [7]. Our requirement that $\not\!\!E_T > 35 - 40$ GeV reduces the acceptance for small values of the mass difference $m_{\widetilde{b}}$–$m_{\rm LSP}$. Backgrounds arise from events where neutrinos produce significant $\not\!\!E_T$; for example, in W+jets events, where $W \rightarrow l\nu$.

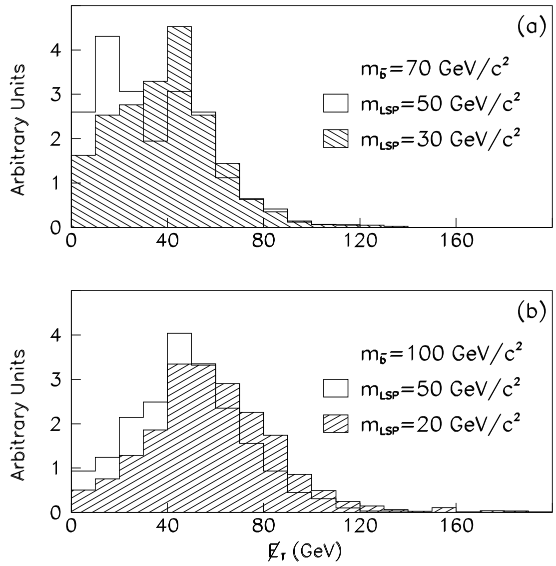

FIG. 1. The expected distributions of $\not\!\!E_T$ for $m_{\widetilde{b}}$ values of 70 (a) and 100 (b) GeV/c^2, for the indicated values of $m_{\rm LSP}$ [7].

Events for the $\not\!\!E_T$+jets channel were collected using a trigger that required $\not\!\!E_T > 35$ GeV. The offline analysis required two jets ($E_T^{\rm jet} > 30$ GeV), $\not\!\!E_T > 40$ GeV, and no isolated electrons or muons. Events had to have only one primary vertex to assure an unambiguous calculation of $\not\!\!E_T$. To eliminate QCD backgrounds, additional cuts were made on the angles between the two jets, and between jets and the direction of the $\not\!\!E_T$. Data with an integrated luminosity of 7.4 pb^{-1}, satisfying the above selection criteria, yielded three candidate events. Background was estimated to be 3.5 ± 1.2 events, with 3.0 ± 0.9 events from W boson decays and 0.5 ± 0.3 events from Z boson decays [5].

The trigger for the muon channels required either two low-p_T muons ($p_T^\mu > 3.0$ GeV/c), or a single low-p_T muon and a jet with $E_T > 10$ GeV, or a high-p_T muon ($p_T^\mu > 15$

GeV/c) and a jet with $E_T > 15$ GeV. Integrated luminosities of 60.1 pb^{-1}, 19.5 pb^{-1}, and 92.4 pb^{-1} respectively were collected using the three muon triggers. The offline analysis used muons in the pseudorapidity range $|\eta_\mu| < 1.0$ and $p_T^\mu > 3.5$ GeV/c, while jets were required to have $E_T > 10$ GeV. For events with two muons, each muon had to be associated with its own jet. In single muon events, the muon was required to be associated with a jet, and an additional jet with $E_T > 25$ GeV was also required. To remove QCD backgrounds, events were selected with $\not\!\!E_T > 35$ GeV and an azimuthal angular separation between the $\not\!\!E_T$ and the nearest jet of > 0.7 radians. For the single muon channels, backgrounds from W boson decays were reduced by cuts on muon-jet correlations, while background from top quark production was minimized by cuts on the scalar sum of jet E_T. After imposition of all selection criteria, two events remained in the data.

We considered background contributions to the muon channels from $t\bar{t}$ and W and Z boson decays [6]. Top quark events have multiple b quarks and $\not\!\!E_T$, and we estimated that 1.4 ± 0.5 $t\bar{t}$ events remained in our sample. W and Z events have $\not\!\!E_T$ from $W \to l\nu$ or $Z \to \nu\bar{\nu}$. They can also have muons near jets that can mimic b quark decays when a prompt muon overlaps a jet, or a jet fragments into a muon via a c quark or a π/K decay. We estimated there were 1.0 ± 0.4 W boson events and 0.1 ± 0.1 Z boson events in the sample. The total background for the muon channels was therefore 2.5 ± 0.6 events.

Combining the four channels yields five events, with a total estimated background of 6.0 ± 1.3 events. We set limits on the cross section by combining the detection efficiencies and integrated luminosities for the different channels. We calculate the detection efficiency using Monte Carlo (MC) generated acceptances [7], multiplied by trigger and reconstruction efficiencies obtained from data [5,6]. The total efficiencies for different squark and neutralino masses are summarized in Table I. Using a muon to tag b quark decays reduces the efficiency for those channels, but their higher integrated luminosities yield a sensitivity comparable to that of the $\not\!\!E_T$+jets channel. Including systematic errors and statistics for the MC, the total uncertainty on the combined efficiency varies between 8.6% and 29%, depending on the assumed masses. The jet energy scale dominates the systematic error for $m_{\tilde{b}} = 70$ GeV/c^2, while uncertainties on the muon trigger and reconstruction efficiency dominate at higher squark masses. The 95% confidence level (C.L.) upper limits on the pair production cross section are determined using Bayesian methods, and include the systematic uncertainty on the efficiency and a 5.3% uncertainty in the integrated luminosity. The resulting upper limits are given in Table I for different values of $m_{\tilde{b}}$ and $m_{\rm LSP}$.

We use the program PROSPINO [8] to calculate the bottom squark pair production cross section as a function of $m_{\tilde{b}}$. The cross section is evaluated assuming a renormalization scale $\mu = m_{\tilde{b}}$. The program includes next-to-leading order diagrams, and uses CTEQ4M parton distribution functions [9]. For any given $m_{\tilde{b}}$, we determine the value of $m_{\rm LSP}$ where our 95% C.L. limit intersects the theoretical cross section. The excluded region in the ($m_{\rm LSP}$,$m_{\tilde{b}}$) plane is shown in Fig. 2. We exclude values of $m_{\tilde{b}}$ below 115 GeV/c^2 for $m_{\rm LSP} < 20$ GeV/c^2. For $m_{\tilde{b}} = 85$ GeV/c^2, we exclude the region with $m_{\rm LSP} < 47$ GeV/c^2. Also shown are limits [2] from ALEPH for $\sqrt{s} = 181-184$ GeV. For most allowable values of $m_{\rm LSP}$, they exclude the region with $m_{\tilde{b}} < 83$ GeV/c^2, assuming maximal coupling ($\theta = 0^o$) [10].

In conclusion, we observe five candidate events consistent with the final state $b\bar{b}$+$\not\!\!E_T$. We estimate that 6.0 ± 1.3 events are expected from $t\bar{t}$ and W and Z boson production, and find no excess of events that can be

TABLE I. Total efficiencies for different $m_{\tilde{b}}$ and $m_{\rm LSP}$ values for the four channels, and 95% C.L. limits on the production cross section obtained by combining all channels.

$m_{\tilde{b}}$	$m_{\rm LSP}$	Total efficiency ($\times 10^{-3}$)				σ limit
(GeV/c^2)		$\not\!\!E_T$+ jets	dimuon	single muon low-p_T	single muon high-p_T	(pb)
70	30	18	0.13	2.2	0.3	32
70	50	4	0.02	0.6	0.1	245
85	40	29	0.20	3.9	0.6	18.8
85	60	11	0.04	1.0	0.1	84
100	20	43	0.50	9.5	1.9	9.3
100	40	34	0.27	7.0	1.3	12.6
100	50	30	0.30	5.8	1.0	14.7
115	40	51	0.54	10.9	2.0	8.0

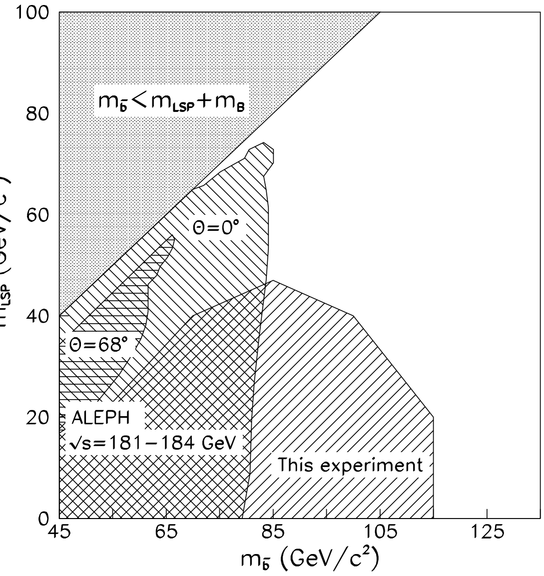

FIG. 2. The 95% C.L. exclusion contour in the ($m_{\rm LSP}$,$m_{\tilde{b}}$) plane. Also shown are the results from the ALEPH experiment at LEP for minimal ($\theta = 68^o$) and maximal ($\theta = 0^o$) coupling [2].

attributed to bottom squark production. We interpret our result as an excluded region in the (m_{LSP},$m_{\tilde{b}}$) plane. This result is independent of the mixing between $\widetilde{b}_L$ and $\widetilde{b}_R$.

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