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Search for Squarks and Gluinos with the D0 detector

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We report on D0 searches for scalar quarks ($\tilde{q}$) and gluinos ($\tilde{g}$), the superpartners of quark and gluons, in topologies involving jets and missing transverse energies. Data samples obtained with D0 detector from $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV corresponding to an intergrated luminosities of 1–4 fb^{-1} were analyzed. No evidence for the production of such particles were observed and lower limits on squarks and gluino masses were set.

1. Introduction

Supersymmetric (SUSY) extensions of the standard model (SM) assign a bosonic superpartner to every SM fermion and vice-versa. The theory that consider only the SM particles, their corresponding superpartners, and two Higgs doublets is known as the minimal supersymmetric standard model (MSSM) [1]). The MSSM Lagrangian depends on 105 parameters that makes it difficult to apply for searches involving complex production and decay of the SUSY particles. Analyses described in section 3 were done in the the minimal supergravity model with a reduced set of the parameters (mSUGRA [2]). In mSUGRA the sparticles masses and couplings are defined by a set of only five parameters: m_0 and $m_{1/2}$, respectively the universal scalar mass and the universal gaugino mass at Λ_{GUT}; A_0, the universal trilinear coupling at Λ_{GUT}; tan β the ratio of the vacuum expectation value of the two Higgs fields; and μ, the sign of Higgs-mixing mass parameter. Searches for stop and sbottom quarks (section 4) do not depend on SUSY parameters other then the masses of the sparticles. In all presented analysis R-parity is assumed conserved and thus the lightest supersymmetric particle (LSP) is stable and all SUSY particles are produced in pairs.

2. The D0 experiment

The D0 experiment was proposed in 1983 to study high mass states and large p_T phenomena in proton-antiproton collisions at the Fermilab Collider Complex. During 1996-2001 both the Tevatron and the D0 detector [3] were significantly upgraded. In Run II (which started March 2001) the Fermilab collider operates at an increased center-of-mass energy of 1.96 TeV and at higher instantaneous luminosity (in range from 1.6×10^{32} cm^{-2}s^{-1} in the beginning of Run II up to 2.8×10^{32} cm^{-2}s^{-1} after 2006). The D0 detector upgrade included new central tracking and new forward muon systems and an improved central muon system. In 2006 the D0 tracking system was upgraded and the trigger system was improved. This report describes the analyses of the Run II D0 data sets collected between April 2002 and December 2008.

3. Searches for squarks and gluinos

These searches were done using the mSUGRA model ignoring the production of scalar top quarks. Thus below the "squark mass" is the average of all other squarks.

3.1. Search for squarks and gluinos in the jets plus $\not\!\!E_T$ final state

A search was made in 2.1 fb^{-1} of data for the $\tilde{q}\bar{\tilde{q}}/\tilde{q}\tilde{q}/\tilde{q}\tilde{g}/\tilde{g}\tilde{g} \rightarrow jets + \not\!\!E_T$. The analysis explored $(m_0, m_{1/2})$ plane of mSUGRA parameters with fixed values of $A_0 = 0$, tan β=3 and $\mu < 0$.

The minimum number of jets in the final state could be two ($p\bar{p} \rightarrow \tilde{q}\bar{\tilde{q}} \rightarrow q\tilde{\chi}_1^0\bar{q}\tilde{\chi}_1^0$, $p\bar{p} \rightarrow \tilde{q}\tilde{q} \rightarrow q\tilde{\chi}_1^0 q\tilde{\chi}_1^0$), if the squark mass is less then the mass of the gluino; three ($p\bar{p} \rightarrow \tilde{q}\tilde{g} \rightarrow q\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$), at $m_{\tilde{q}} \approx m_{\tilde{g}}$; or four ($p\bar{p} \rightarrow \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$), if $m_{\tilde{q}} > m_{\tilde{g}}$. For the dijet analysis events were required to pass an acoplanar dijet trigger, and a multijet and $\not\!\!E_T$ trigger was used for selection of events with higher number of jets. The jets transverse energies were required to be $E_T > 35$ GeV for the first three leading jets and $E_T > 20$ GeV for the fourth jet. In addition, the $\not\!\!E_T > 40$ GeV, the leading jet acoplanarity $< 165°$, the azimutal angles between the $\not\!\!E_T$ and first jet $\Delta\phi(\not\!\!E_T, jet_1) > 90°$ and between the $\not\!\!E_T$ and second jet were $\Delta\phi(\not\!\!E_T, jet_1) > 50°$ were required in all analyses. A veto on isolated electrons or muons with $p_T > 10$ GeV was also applied in all analyses to reject backrounds events with a lepton from W boson decay. In the dijet analysis a cut on the minimum azimutal angle $\Delta\phi_{min}(\not\!\!E_T, jets) > 40^o$ between the $\not\!\!E_T$ and any jet with $E_T > 15$ GeV was applied to suppress the QCD background. The two final cuts on $\not\!\!E_T$ and $H_T = \sum_{jets} E_T$ were optimized for each of the analyses by minimizing the expected upper limit on the cross section in the absence of signal.

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Table I shows the number of data and background events after all selections. The background is dominate by W/Z+jets and $t\bar{t}$ processes. No excess of data events were found against the SM predictions in all three analysis and the 95% C.L. limits on squark-gluino production cross-section were set. The QCD contribution was found to be small and was not accounted in the limit calculations.

Table I Number of data and background events after all selections for each of the analyses.

Analysis	(H_T,$\not\!\!E_T$) GeV	Data	Background
>=2 jets	(325,225)	11	$11.1\pm1.2^{+2.9}_{-2.3}$
>=3 jets	(375,175)	9	$10.0\pm0.9^{+3.1}_{-2.1}$
>=4 jets	(400,100)	20	$17.7\pm1.1^{+5.5}_{-3.3}$

Figure 1(a) show the excluded regions in the squark-gluino mass plane. The observed 95% C.L. limits on squark and gluino masses of 392 GeV and 327 GeV are the most constraining direct limits to date. Figure 1(b) shows the excluded regions in the $(m_0, m_{1/2})$ mSUGRA parameter plane. The limits from LEP2 SUSY searches are improved for m_0 in the range 70–300 GeV and for $m_{1/2}$ values between 125 and 65 GeV.

3.2. Search for squarks production in the jets+tau leptons+$\not\!\!E_T$ final state

A search explored the region of mSUGRA parameter space (tan β=15, $A_0 = -2m_0$, $\mu < 0$, m_0 and $m_{1/2}$ are varied) where squark and gluino cascade decays could lead to final state with at least one τ leptons, two or more jets and large missing transverse energy from the undetected neutralino. The complex cascade decays giving such a signature are only possible within a narrow region of (m_0,$m_{1/2}$) parameter space and have not previously been studied at SUSY searches at Tevatron. The data sample corresponds to an integrated luminosity of 1 fb^{-1}.

The event selection are similar to the inclusive search and were optimized for "tau-dijet" or "tau-multijet" signatures depending on whether a dijet or multijet trigger were required. The analysis tuned to hadronically decaying tau leptons, which appear in the detector as narrow isolated jets. Jets with transverse energy greater then 15 GeV were considered as tau-candidates if they were not already identified as one of the two highest p_T jets. A neural net trained on simulated $Z \to \tau\bar{\tau}$ signal was used to separate tau candidates from quark and gluon jets. The signal selection was optimized (against the expected upper limit on the cross section) with cuts on $\not\!\!E_T$ and $S_T = p_T^{jet_1} + p_T^{jet_2} + E_T^{tau}$. After all selections 3 events were observed in data in good agreement with the SM prediction of $2.3 \pm 0.4(stat) \pm 0.3(syst)$. The background is dominated by top quark production and $W(\to l\nu)$+jets events. The QCD multijet backround contribution was found to be negligible. Because the hadronic tau lepton can be reconstructed as a jet the obtained result was combined with the 2.1 fb^{-1} dijet and multijet searches for squark production in the $\not\!\!E_T$+jets topology.

Figure 2(a) shows the expected and observed excluded regions in the $(m_0, m_{1/2})$ plane for the combination of all squark analysis. The result extends the exclusion region from LEP SUSY searches. The highest excluded squark mass at 95% C.L. limits is 410 GeV, as illustrated in Figure 2(b).

4. Searches for pair production of the top and bottom squarks

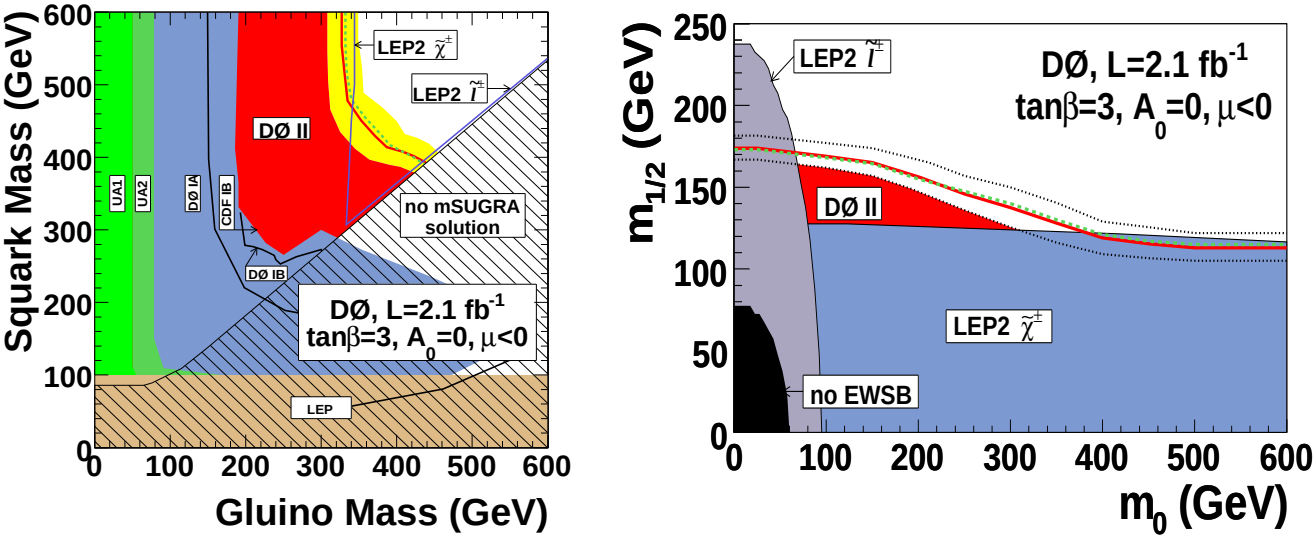
The supersymmetric quarks (squarks) are mixtures of the superpartners $\tilde{q}_L$ and $\tilde{q}_R$ of the SM quark helicity states q_L and q_R. The theory permits a mass difference between squark mass eigenstates $\tilde{q}_1$ and $\tilde{q}_2$ that gives the possibility that the lightest states of the stop and sbottom quarks are lighter than the first two generation squarks and thus have the largest production cross section. The presented analysis also assumes that the sneutrino (stop search) or the neutralino (sbottom analysis) is the LSP.

4.1. Search stop pairs in 2 b-jets+$e\mu$+$\not\!\!E_T$ events

A search was performed for three body decays of top squark pairs when each stop decays leptonically, $\tilde{t} \to b + \tilde{\nu} + l^{\pm}$ with a 100% branching fraction. Thus the stop pair production final state corresponds to the $e^{\pm} + \mu^{\mp} + 2b + \not\!\!E_T$ topology. The analysis studied 3.1 fb^{-1} of data.

The events were required to have an isolated electron and a muon of the opposite charge with p_T greater then 15 GeV and 8 GeV respectively, accompanied by jets with transverse energy $E_T > 15$ GeV and $\not\!\!E_T$. No explicit trigger requirements were applied, as the trigger efficiency is high for this combination of lepton p_T. The largest backrounds are $Z \to \tau\bar{\tau}$, QCD, WW, and top quark pairs. Cuts on angular differences between leptons and $\not\!\!E_T$ and $\not\!\!E_T > 18$ GeV were applied to remove Z and QCD events.

The signal final state kinematic is determined by the size of the mass difference between squark and sneutrino $\Delta(m_{\tilde{t}_1}, m_{\tilde{\nu}})$. Events with a large $\Delta(m_{\tilde{t}_1}, m_{\tilde{\nu}})$ have more missing energy, higher jets energies and high charge leptons p_T, while signals with $\Delta(m_{\tilde{t}_1}, m_{\tilde{\nu}})$ have softer kinematics. The "hard" and "soft" signal efficiencies after the $\not\!\!E_T$ cut are 15% and 3% respectively. To prevent futher losses of the signal accep-



(a) (b)

Figure 1: The 95% C.L. excluded regions in the gluino and squark mass plane in the mSUGRA framework with tan β=3, A_0=0, μ <0 in the (a) gluino and squark mass plane and (b) in the $(m_0, m_{1/2})$ plane. The thick (dotted) line is the limit of the observed (expected) excluded region for signal cross section calculated with renormalization and factorization scale μ= Q, with Q equal $m_{\tilde{q}}$, $m_{\tilde{g}}$, $(m_{\tilde{q}}+m_{\tilde{g}})/2$ for $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{\bar{q}}/\tilde{q}\tilde{q}$ and $\tilde{g}\tilde{g}$ production, respectively. The yellow band and the band delimited the two dotted lines correspond to the parton distribution functions and μ uncertainties. Red shading represent the D0 Run II results. Light shaded regions are excluded by previous experiments.

tances, a technique that isolates the remaining background was applied: signal and backround events were distributed into a two dimensional histogram in the H_T (the scalar sum of the p_T of the jets) and the S_T (the scalar sum of $\not\!\!E_T$, the electron p_T and the muon p_T) plane. The bin edges were selected such that the background events are concentrated into a few bins while the remaining bins have a significant signal to background ratio. This method allows use of the same set of selections for the signals with different $\Delta(m_{\tilde{t}_1}, m_{\tilde{\nu}})$.

Table II shows the number of data, backgrounds and signal events after all selections. No significant excess above the standard model predictions were found. Figure 3 shows the 95% C.L. exclusion limits in the $(m_{\tilde{t}_1}, m_{\tilde{\nu}})$ mass plane. Stop masses up to 200 GeV were excluded for signals with $\Delta(m_{\tilde{t}_1}, m_{\tilde{\nu}}) > 30$ GeV and $m_{\tilde{\nu}} < 110$ GeV.

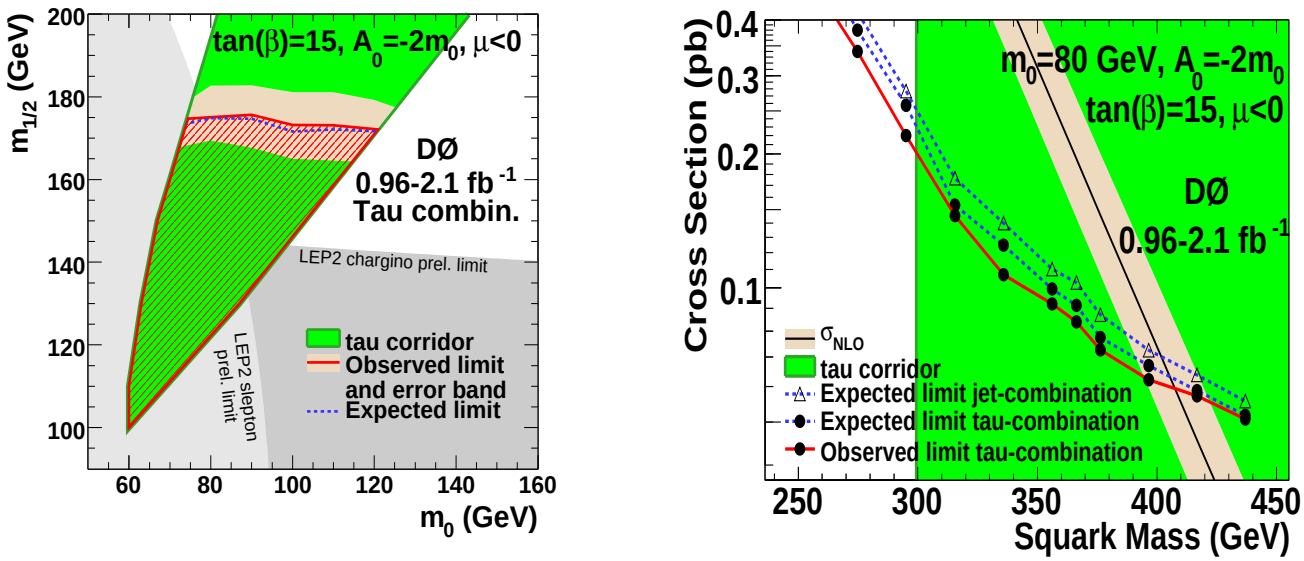
Table II Number of data, background and signal events after all selections for different stop signals.

$(m_{\tilde{t}_1}, m_{\tilde{\nu}})$ GeV	Data	Background	Signal(acpt,%)
(110,80)	288	303^{+16}_{-20}	89^{+11}_{-13} (3)
(150,50)	288	303^{+16}_{-20}	122^{+14}_{-16} (15)

4.2. Search sbottom pairs in 2 b-jets+$\not\!\!E_T$ events

A search considered the region of SUSY parameter space where the only possible decay of the sbottom quark's lightest state is $\tilde{b}_1 \to b\tilde{\chi}^0_1$, $m_{\tilde{b}_1} > m_b + m_{\tilde{\chi}^0_1}$ and $m_{\tilde{b}_1} < m_t + m_{\tilde{\chi}^{\pm}_1}$, where the neutralino $\tilde{\chi}^0_1$ and chargino $\tilde{\chi}^{\pm}_1$ are the lightest SUSY partners of the electroweak bosons. These requirements result in $b\tilde{\chi}^0_1\bar{b}\tilde{\chi}^0_1$ final state. The corresponding detector signature are two acoplanar b-jets from the scalar bottom quarks and the missing energy due to escaping neutralinos. The data sample was collected using jet plus missing energy triggers and corresponds to an integrated luminosity of 4 fb^{-1}.

Events with two or three jets with $E_T^{jet} > 20$ GeV and the $\not\!\!E_T > 40$ GeV were selected. For the two leading jets acoplanarity $< 165°$ was required. To reduce the contribution from $W \to l\nu$ decays, events with isolated electrons or isolated muons with $p_T > 15$ GeV were vetoed. To suppress the instrumental background events where the $\not\!\!E_T$ direction overlapped a jet in ϕ were removed. Also events where the direction of $\not\!\!E_T$ is not aligned with the missing track $\not\!\!p_T$, calculated as the negative of the vectorial sum of charged particles transverse momenta were removed. A neural net b-tagging tool was used to identify the heavy-flavor jets while significantly reducing the SM and QCD backgrounds which are dominated by light



(a) (b)

Figure 2: a) The 95% C.L. excluded regions in the $(m_0, m_{1/2})$ plane in the mSUGRA framework with tan β=15, $A_0 = -2m_0$, $\mu < 0$. The green region represents the $(m_0, m_{1/2})$ space in which the final states with tau's are possible with the shaded part excluded by the combination of all squark analysis. b) The 95% C.L. upper limits on squark and gluino pair production cross section for $m_0 = 80$ GeV.

flavor jets. As the final state consist of two high E_T b-jets, the $X_{jj} \equiv (E_T^{jet1} + E_T^{jet2})/(\Sigma_{jets} E_T)$ variable was used as a discriminant against top quark processes, requiring $X_{jj} > 0.9$. Finally the cuts on E_T^{jet1}, $\not\!\!E_T$ and H_T were optimized for the different $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ signals. These selections are tighter for the sbottom signals with large $\not\!\!E_T$. For the regions with a low $m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0}$, the $\not\!\!E_T$ and jet energies in the signal events are lower and relaxed thresholds were used.

After all selections the number of data events agreed with the expectations from the simulated SM processes (dominated by the $t\bar{t}$ production and W/Z+heavy flavor jets events) and the QCD estimation from data. The later is significant for the selections with soft requirement on $\not\!\!E_T$. Table III shows the number of data, backround and signal events after all selections applied in searches for the signals with low and high $\not\!\!E_T$.

Table III Number of data,background and signal events after all selections for low and high $\not\!\!E_T$ sbottom signals.

$(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ GeV	Data	Background	Signal(acpt,%)
(100,60)	483	493±12	610±29 (1.0)
(240,0)	7	7.1±0.4	11.4±0.2 (3.6)

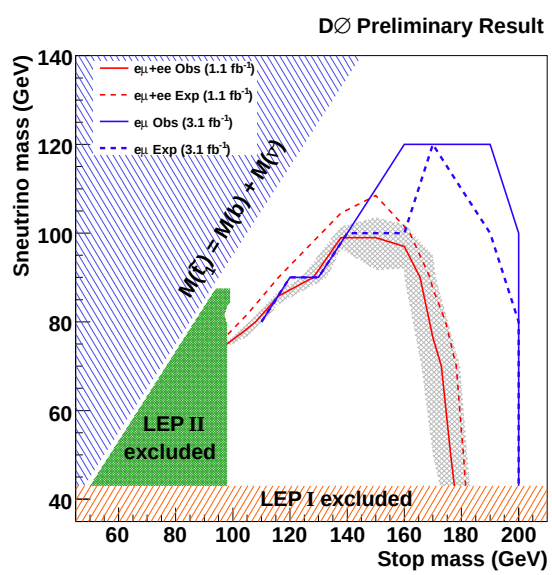


Figure 3: Excluded 95% C.L regions for the stop pair production in the dilepton plus $\not\!\!E_T$ events. Points below the blue lines are excluded by the presented 3.1 fb^{-1} analysis. Also shown the D0 1.1 fb^{-1} exclusion countour from the $e\mu$ and ee channels (the red line) and LEP I and LEP II excluded regions (shaded green and orange regions). Dashed lines represent the expected exclusion contours.

Figure 4 shows the 95% C.L. and excluded region in the sbottom mass versus neutralino mass plane. Production of sbottom quarks with $m_{\tilde{b}_1} < 253$ GeV is excluded for $m_{\tilde{\chi}_1^0} = 0$. The limits from previous Tevatron searches are improved and the exclusion region extends up $m_{\tilde{\chi}_1^0} = 95$ GeV for $m_{\tilde{b}_1}$ in the range 150–200 GeV.

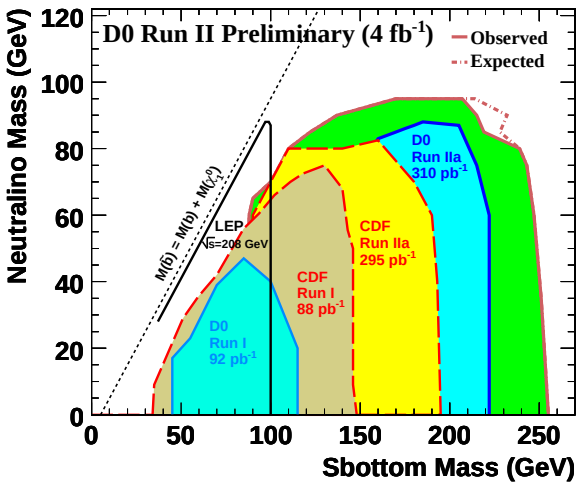


Figure 4: The 95% C.L. exclusion contour in $(m_{\tilde{b}_1}, m_{\tilde{\chi}_1^0})$ mass plane. Also presented results from previous searches at LEP and at the Tevatron.

5. Summary

Searches for squarks and gluinos are performed in 1–4 fb^{-1} D0 data samples for different regions of MSSM/mSUGRA parameter space. All presented analysis are in good agreement with the SM predictions. As no signs of SUSY were observed a set of 95% C.L. limits on squark and gluino masses and on mSUGRA parameters have been obtained improving previous Tevatron results. More details on the presented analyses can be found at [4].

References

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