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A search for heavy stable and long-lived squarks and sleptons in e^+e^- collisions at energies from 130 to 183 GeV

DELPHI Collaboration

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Abstract

A search for stable and long-lived heavy charged particles used the data taken by the DELPHI experiment at energies from 130 to 183 GeV. The Cherenkov light detected in the Ring Imaging Cherenkov Detector and the ionization loss measured in the Time Projection Chamber identify heavy particles from masses of 2 to nearly 89 GeV/c^2. Upper limits are given on the production cross-section and masses of sleptons, free squarks with a charge of $q = \pm\frac{2}{3}e$ and hadronizing squarks.

1. Introduction

A search for stable and long-lived [3] heavy charged particles in *all* final states is reported using the data taken by the DELPHI experiment at energies from 130 to 183 GeV. These results extend those reported in [1] by including the 130–136 and 183 GeV data taken in 1997. The other LEP experiments have searched for stable and long-lived heavy charged particles in low multiplicity final states [2].

In most models of Supersymmetry (SUSY) the supersymmetric partners of standard particles are unstable and have short lifetimes, except the lightest supersymmetric particle (LSP) which could be neutral and stable. In most of the searches it is therefore assumed that the supersymmetric particles decay promptly. However, it is possible that a stable or long-lived heavy charged SUSY-particle exists. In the Minimal Supersymmetric Standard Model (MSSM) with the neutralino as the LSP [3], if the mass difference between the chargino and neutralino is small the chargino can have a sufficiently long lifetime to be observed as stable in the detector. In the MSSM with a very small amount of R-parity violation the LSP can be a charged slepton or squark and decay with a long lifetime into Standard Model particles [4].

In gauge mediated supersymmetric models the gravitino is the LSP and the next to lightest supersymmetric particle (NLSP) could have a long lifetime in a very natural way for large values of the SUSY-breaking scale [5]. This is possible for sleptons, for example when the stau is the NLSP. In certain variations of the minimal model the squark can be the NLSP and become long-lived [6].

Other SUSY and non-SUSY models predict stable and long-lived heavy charged leptons, quarks and hadrons not present in the Standard Model. Free (s)quarks might even exist [7].

The published analyses from DELPHI [1] and the other LEP experiments [2] covered masses, m, above 45 GeV/c^2. The present analysis has been further optimized for squarks and extended down to masses of 2 GeV/c^2. This extension is important for the stable and long-lived squark search. Stable long-lived free squarks of charge $\pm\frac{2}{3}e$ were excluded by the data taken at the Z^0 peak [8]. However, the upper limits on the production cross-section of squarks, where the squark dresses up and becomes a charged or neutral shadron in a hadronization or fragmentation process, are worse than those of free squarks. In particular, hadronizing stop and sbottom quarks with so-called typical mixing and down-type right-handed squarks are not ruled out in the mass region from ~ 15 to 45 GeV/c^2 due to the small production cross-section at Z^0 energies.

Limits on the production cross-section and masses will be given for stable and long-lived sleptons,

[3] Throughout the paper stable particles include long-lived particles decaying outside the detector.

charginos, free (not hadronizing) squarks of charge q $= \pm\frac{2}{3}e$ and hadronizing squarks (q $= \pm\frac{1}{3}e$ or $\pm\frac{2}{3}e$) forming shadrons. No search is made for free squarks of charge q $= \pm\frac{1}{3}e$, because the tracking system is not sensitive enough to record the ionization of these particles.

A dedicated simulation program was used for the hadronization of squarks. It is assumed that the sleptons, charginos, free squarks and shadrons decay outside the tracking volume of the detector, which extends to a typical radius of 1.5 m. It is further assumed that these particles do not interact more strongly than ordinary matter particles (protons or electrons) and reach the main tracking device.

Heavy stable particles are selected by looking for high momentum charged particles with either anomalous ionization loss $\mathrm{d}E/\mathrm{d}x$ measured in the Time Projection Chamber (TPC), or the absence of Cherenkov light in the gas and liquid radiators of the Barrel Ring Imaging CHerenkov (RICH). The combination of the data from the TPC and RICH detectors and kinematic cuts provide an efficient detection of new heavy particles with a small background for masses from 2 GeV/c^2 to the kinematic limit.

The data taken during the period from 1995 to 1997 corresponds to an integrated luminosity of 11.9 pb^{-1} at an energy of 130–136 GeV (including 6 pb^{-1} taken in 1997) 9.8 pb^{-1} at an energy of 161 GeV, 9.9 pb^{-1} at an energy of 172 GeV, and 54.0 pb^{-1} at an energy of 183 GeV.

2. Event selection

A description of the DELPHI apparatus and its performance can be found in Ref. [9], with more details on the Barrel RICH in Ref. [10] and particle identification using the RICH in Ref. [11].

Charged particles were selected if their impact parameter with respect to the mean beam-spot was less than 5 cm in the xy plane (perpendicular to the beam), and less than 10 cm in z (the beam direction), and their polar angle (θ) was between 20 and 160 degrees. The relative error on the measured momentum was required to be less than 1 and the track length larger than 30 cm. The energy of a charged particle was evaluated from its momentum [4] assuming the pion mass. Neutral particles were selected if their deposited energy was larger than 0.5 GeV and their polar angle was between 2 and 178 degrees.

The event was divided into two hemispheres using the thrust axis. The total energy in one hemisphere was required to be larger than 10 GeV and the total energy of the charged particles in the other hemisphere to be larger than 10 GeV. The event must have at least two reconstructed charged particle tracks including at least one charged particle with momentum above 5 GeV/c reconstructed by the TPC and also inside the acceptance of the Barrel RICH, $|\cos\theta| < 0.68$.

Cosmic muons were removed by putting tighter cuts on the impact parameter with respect to the mean beam-spot position. When the event had two charged particles with at least one identified muon in the muon chambers, the impact parameter in the XY plane was required to be less than 0.15 cm, and below 1.5 cm in Z.

The highest momentum (leading) charged particle in a given hemisphere was selected and identified using a combination of the following signals (where the typical sensitive mass range for pair produced sleptons at an energy of 183 GeV is shown in brackets):

(1) the Gas Veto: no photons were observed in the Gas RICH ($m > 1$ GeV/c^2)

(2) the Liquid Veto: four or less photons were observed in the Liquid RICH ($m > 65$ GeV/c^2)

(3) high ionization loss in the TPC: measured ionization was above 2 units i.e. twice the energy loss for a minimum ionizing particle ($m > 70$ GeV/c^2)

(4) low ionization loss in the TPC: measured ionization was below that expected for protons ($m =$ 1–50 GeV/c^2) Selections (1) till (3) are identical to those used in our previous publication [1].

For the Gas and Liquid Vetoes it was required that the RICH was fully operational and that for a selected track photons from other tracks or ionization hits were detected inside the drift tube crossed by the

[4] In the following, 'momentum' means the apparent momentum, defined as the momentum divided by the charge $|q|$, because this is the physical quantity measured from the track curvature in the 1.23 T magnetic field.

track. Due to tracking problems electrons often passed a Gas or Liquid Veto. Therefore it was required that particles that deposit more than 5 GeV in the electromagnetic calorimeter, had either hits included in the outer tracking detector or associated RICH ionization hits. At least 80 from a maximum of 160 wires were required for the measurement of the ionization in the TPC.

Two sets of cuts selected sleptons or squarks. One set was defined for ‘leptonic topologies’ for which the number of charged particles is less than four and another set for ‘hadronic topologies’ for all other events. The cuts were optimized using slepton and squark events generated with SUSYGEN [12] and passed through the detector simulation program [9]. Samples with different masses for smuons, free squarks with a charge of $\pm\frac{2}{3}e$ and hadronizing sbottom and stop squarks were studied in detail.

The hadronization of squarks was implemented in the following way. The initial squark four-momenta including initial state radiation were generated by SUSYGEN. The JETSET parton shower model was used to fragment the squark-anti-squark string [13]. In the fragmentation process the Peterson fragmentation function was used with a value for $\epsilon = 0.003\,(5/m)^2$, where m is the mass of the squarks in GeV/c^2 [14]. A shadron was given the mass of the squark plus 150 MeV/c^2 for a smeson or plus 300 MeV/c^2 for a sbaryon. In the fragmentation process, approximately 9% sbaryons were formed and 40% of the shadrons were charged, 60 % neutral. In the detector simulation program a charged shadron was given the properties of a heavy muon, a neutral shadron those of a K^0_L [5]. Due to the hard fragmentation function the charged multiplicity decreases as a function of the mass of the squark. At very high masses a squark-antisquark pair often produces a low multiplicity final state.

For leptonic topologies an event was selected if the momentum of the charged particle was above 15 GeV/c and the Gas Veto (1) was confirmed by a Liquid Veto (2) or a low ionization loss (4) (in boolean notation $(1)\cdot(2)+(1)\cdot(4)$) or if the momentum of the charged particle was above 5 GeV/c and the Gas Veto was confirmed by a high ionization loss ($(1)\cdot(3)$). The event was also accepted if both hemispheres had charged particles with momenta above 15 GeV/c and both leading charged particles had a Gas Veto or a high ionization loss or both a low ionization loss ($((1)+(3))\cdot((1')+(3'))+(4)\cdot(4')$), where the primed selections refer to the opposite hemisphere.

For hadronic topologies the following kinematic quantities were used to select events where a large fraction of the energy is taken by a heavy particle. The energy fraction, F_c, is defined as the momentum of the identified charged particle divided by the total energy in a given hemisphere, and F_n the ratio of the neutral energy with respect to the total energy in a hemisphere. The energy fraction F is the maximum of F_c and F_n. The background from normal $q\bar{q}$ events was greatly reduced by requiring a minimum energy fraction F, because heavy shadrons take most of the energy.

An event in a hadronic topology was selected if the momentum of the leading charged particle was above 15 GeV/c, the energy fraction F was above 0.6 in one hemisphere and above 0.9 in the other. The selected charged particle had to be identified by a Gas Veto or a high or a low ionization loss ($(1)+(3)+(4)$).

An event was also selected if the energy fraction F in one hemisphere was above 0.6. In this case the momenta of the charged particles in both hemispheres had to be above 15 GeV/c and both leading charged particles had a Gas Veto, or both had high ionization, or both low ionization ($(1)\cdot(1')+(3)\cdot(3')+(4)\cdot(4')$).

3. Analysis results

No event was selected in the leptonic topology. The expected background was evaluated from the data and estimated to be 0.7 $\pm$ 0.3 events. In Fig. 1 the data taken at 183 GeV are shown for leptonic topologies. The measured ionization and the measured Cherenkov angle in the liquid radiator are shown after applying the Gas Veto.

Three events were selected in the hadronic topology: one at 130 GeV, one at 161 GeV and one at 183 GeV. The expected background was estimated to be

[5] It was only required that a charged shadron leaves a track as for a particle with unit charge, and that a neutral shadron deposit most of its energy in the hadron calorimeter.

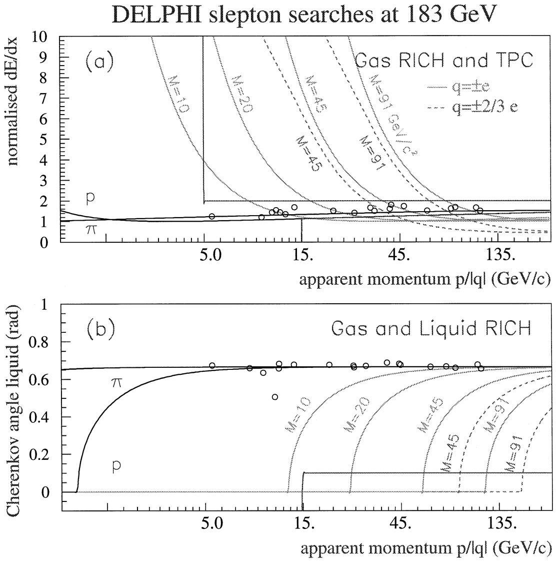

Fig. 1. For leptonic topologies after the Gas Veto. (a) Ionization as a function of the apparent momentum $p/|q|$ for the 183 GeV data. (b) Measured Cherenkov angle in the liquid radiator as a function of the apparent momentum; if four photons or less were observed in the liquid radiator, the Cherenkov angle was set equal to zero. The expectation curves for charge $\pm e$ particles for pions, protons and heavy particles with masses of 10, 20, 45 and 91 GeV$/c^2$ are given, as well as the dashed curves for charge $\pm\frac{2}{3}e$ particles with masses of 45 and 91 GeV$/c^2$. The areas bounded by straight lines in (a) indicate selections (3) and (4), and that in (b) shows selection (2). The selection criteria are explained in Section 2.

3.5 $\pm$ 1.5 events using the real data and assuming that the background is from Standard Model processes, when the RICH or TPC misidentifies a particle known to be a pion (electron, muon, kaon or proton) as a heavy particle. The misidentification probability was evaluated from the data and used to estimate the expected background. The procedure was cross-checked by simulation studies. The three candidate events have total charged multiplicities of 6, 4 and 5. The masses of the hypothetical squarks were estimated from a constrained fit using energy and momentum conservation and found to be 48, 21 and 30 GeV$/c^2$ with typical uncertainties of about $\pm$10 GeV$/c^2$. The mass is also correlated to the charged multiplicity. The most likely squarks masses based both on these masses and the observed charged multiplicities are 41, 30 and 42 GeV$/c^2$. The resulting probability density distribution is not very gaussian. The characteristics of the candidate events are compatible with the background expectation. Fig. 2 shows the data taken at 183 GeV for hadronic topologies. The data are shown after the kinematic cut (see Section 2) requiring that the energy fraction F was above 60% in both hemispheres and in one of the hemispheres above 90%. One candidate event passes the Gas Veto (Fig. 2b).

The efficiency for selecting an event was evaluated as a function of the mass at different energies for right-handed smuons, mixed free stop quarks of charge q $= \pm\frac{2}{3}e$, mixed hadronizing stop quarks and mixed hadronizing sbottom quarks. The term ‘mixed’ refers to a typical mixing angle between left- and right-handed particles for which the cross-section is minimal. The angle is $\sim$60 degrees for stop quarks and $\sim$70 degrees for sbottom quarks. The efficiency curves for a centre-of-mass energy of 183 GeV are shown in Figs. 3a to 6a. The efficiency approaches

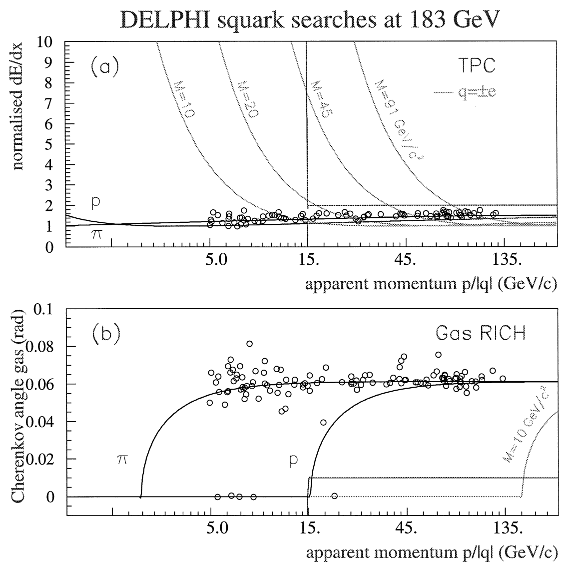

Fig. 2. For hadronic topologies after the kinematic selection described in the text. (a) Ionization as a function of the apparent momentum $p/|q|$ for the 183 GeV data. (b) Measured Cherenkov angle in the gas radiator as a function of the apparent momentum: if zero photons were observed the Cherenkov angle was set equal to zero. The expectation curves for charge $\pm e$ particles for pions, protons and heavy particles with masses of 10, 20, 45 and 91 GeV$/c^2$ are given. The areas bounded by straight lines in (a) indicate selections (3) and (4), and that in (b) shows selection (1). The selection criteria are explained in Section 2. Only one candidate is in the 183 GeV data, the other two being at 130 GeV and 161 GeV.

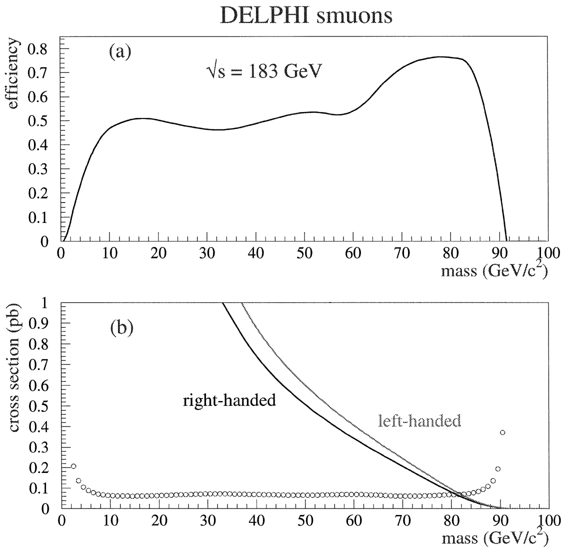

Fig. 3. (a) Efficiency for detecting stable and long-lived smuons (staus) as a function of the smuon mass at a centre-of-mass energy of 183 GeV. (b) Production cross-section from SUSYGEN as a function of the smuon (stau) mass for right- and left-handed smuons at 183 GeV (full curves). The circles indicate the experimental 95% confidence level upper limit for the combined 130–136, 161, 172 and 183 GeV data.

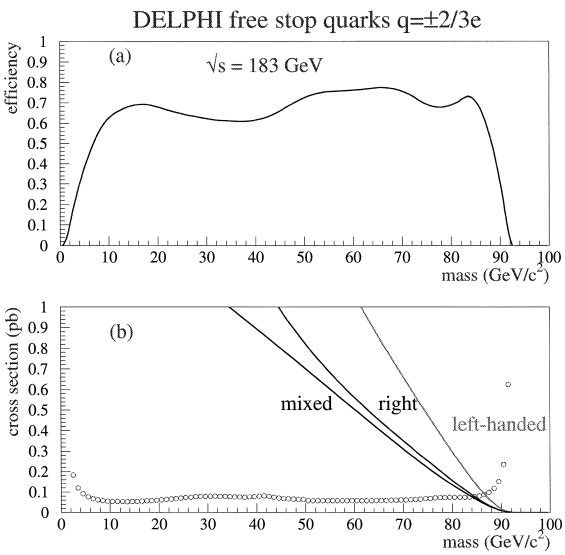

Fig. 4. (a) Efficiency for detecting free stop quarks as a function of the stop mass at a centre-of-mass energy of 183 GeV. (b) Production cross-section from SUSYGEN as a function of the stop mass for typical mixing, right- and left-handed stop quarks at 183 GeV (full curves). The circles indicate the experimental 95% confidence level upper limit for the combined 130–136, 161, 172 and 183 GeV data.

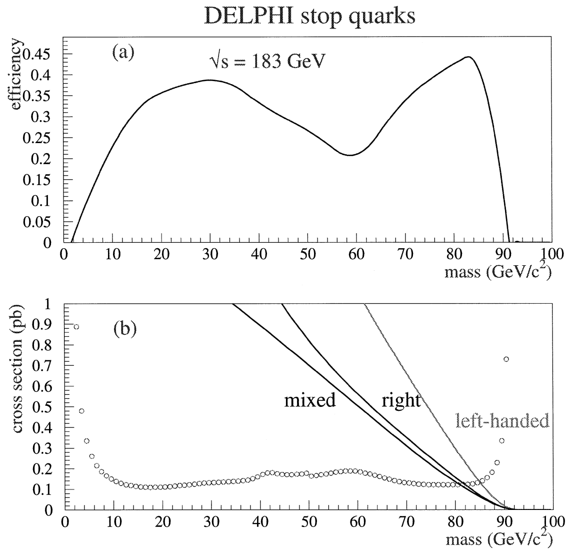

Fig. 5. (a) Efficiency for detecting hadronizing stop quarks as a function of the stop mass at a centre-of-mass energy of 183 GeV. (b) Production cross-section from SUSYGEN as a function of the stop mass for typical mixing, right- and left-handed stop quarks at 183 GeV (full curves). The circles indicated the experimental 95% confidence level upper limit for the combined 130–136, 161, 172 and 183 GeV data.

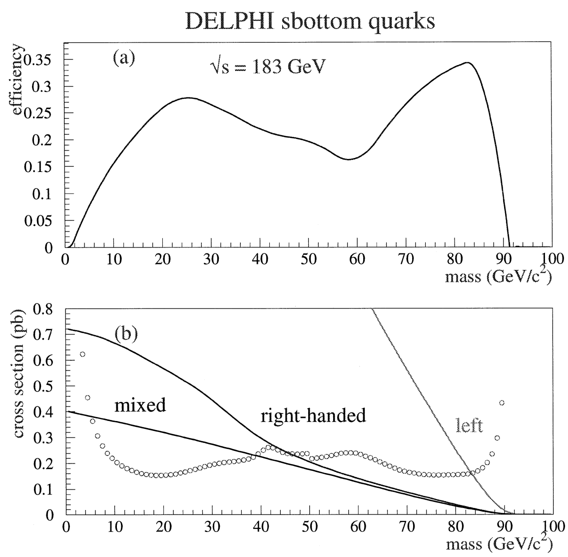

Fig. 6. (a) Efficiency for detecting hadronizing sbottom quarks as a function of the sbottom mass at a centre-of-mass energy of 183 GeV. (b) Production cross-section from SUSYGEN as a function of the sbottom mass for typical mixing, right- and left-handed sbottom quarks at 183 GeV (full curves). The circles indicate the experimental 95% confidence level upper limit for the combined 130–136, 161, 172 and 183 GeV data.

zero at masses below 1 GeV/c^2, where the Gas Veto becomes inefficient. Therefore the lowest upper limit on the mass is put at 2 GeV/c^2.

The efficiency curves for left- and right-handed squarks are slightly different due the different kinematical distributions, but this difference can be neglected because it has no influence on the quoted upper limits.

The efficiency curves have an overall systematic error of $\pm 5\%$ coming from the modelling of the detector. For the hadronization of squarks the following effects were studied using the simulation: a change in the fraction of neutral shadrons, the response of the calorimeter to a neutral shadron and the fragmentation function. In the simulation the fraction of neutral shadrons is 60%. This was changed to 50% and an efficiency increase of 15% was found. In the simulation it was assumed that a neutral shadron behaves like a K_L^0. If one assumes that a neutral shadron deposits only 20% of the energy of a K_L^0 and the rest escapes, the efficiency is only reduced by 10%. Finally the fragmentation function was softened assuming that ϵ is inversely proportional to the squark mass with $\epsilon = 0.003(5/m)$. The efficiency at a centre-of-mass energy of 183 GeV increased by 20% around a squark mass of 45 GeV/c^2 and decreased by 15% around 70 GeV/c^2. From these studies it was concluded that the efficiencies for squarks are sufficiently stable under these large changes.

The observed numbers of events in the leptonic and hadronic topologies are compatible with the expected background. Experimental upper limits at 95% confidence level are obtained on the cross-section in the leptonic and hadronic topologies. In the leptonic topology the 95% confidence level upper limit corresponds to 3 events. In the hadronic topology it corresponds to 5.4 events in the case of 3 observed events with 3 expected background events.

The masses and charged particle multiplicity distributions of the candidates are included in the experimental upper limit. From the simulation, the probability distribution as a function of the squark mass is obtained for each candidate and the sum of these 3 probability distributions is shown in Fig. 7. The upper limit on the number of events at 95% confidence level is derived from this distribution by scaling it and adding it to 3. Zero probability in this figure would thus correspond to an upper limit of 3 events. The scale factor is adjusted such that 3 observed events with a flat probability distribution would correspond to an upper limit of 5.4 events. It was cheked that this procedure is sufficiently precise for the present analysis. The experimental upper limit on the cross-section was derived from the upper limit on the number of events, the signal efficiencies, integrated luminosities and cross-section ratios at different energies as explained in footnote 6 of Ref. [1].

Figs. 3 and 4 summarize the results for the leptonic topology for stable and long-lived sleptons, charginos and free squarks while Figs. 5 and 6 summarize the results for the hadronic and leptonic topologies for stable and long-lived squarks.

Fig. 3b shows the expected production cross-section for right- and left-handed smuons (staus) as a function of the mass at a centre-of-mass energy of 183 GeV. The combined experimental upper limit at 95% confidence level on the cross-section varies between 0.06 and 0.5 pb in the mass range from 2 to 90 GeV/c^2. Right(left)-handed smuons or staus are excluded in their mass range from 2 to 80 (81) GeV/c^2. From the same data, stable and long-lived charginos are excluded in the mass region from 2 to 87.5 GeV/c^2 for sneutrino masses above 41 GeV/c^2. For sneutrino masses above 200 GeV/c^2 the excluded mass goes up to 89.5 GeV/c^2.

Fig. 4b shows the expected production cross-section for free mixed (right, left-handed) stop quarks as a function of the mass at an energy of 183 GeV. The combined experimental upper limit at 95% confidence level varies between 0.06 and 0.5 pb in the mass range from 2 to 90 GeV/c^2. Free mixed (right, left-handed) stop quarks are excluded in the mass range from 2 to 84 (84, 86) GeV/c^2. Similarly, free right(left)-handed up-type squarks of charge $\pm \frac{2}{3}e$ are excluded in the range from 2 to 84 (86) GeV/c^2.

Fig. 5b shows the expected production cross-section for mixed (right, left-handed) stop quarks as a function of the mass at an energy of 183 GeV. The combined experimental upper limit at 95% confidence level on the cross-section varies between 0.1 and 0.5 pb in the mass range from 5 to 90 GeV/c^2. Hadronizing mixed (right, left-handed) stop quarks are excluded in the mass range from 2 to 80 (81, 85) GeV/c^2. Similarly, hadronizing right(left)-handed

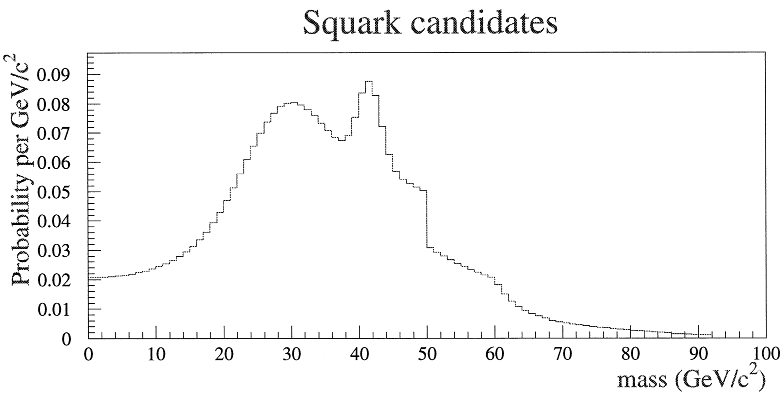

Fig. 7. Probability density distribution per GeV$/c^2$ for the three squark candidates (normalised to three) as a function of the squark mass.

up-type squarks are excluded in the range from 2 to 81 (85) GeV$/c^2$.

Fig. 6b shows the expected production cross-section for mixed (right, left-handed) sbottom quarks as a function of the mass at an energy of 183 GeV. The combined experimental upper limit at 95% confidence level on the cross-section is also shown. It varies between 0.15 and 0.5 pb in the mass range from 5 to 90 GeV$/c^2$. Hadronizing mixed (right, left-handed) sbottom quarks are excluded in the mass range from 5 (5, 2) to 38 (40, 83) GeV$/c^2$. Similarly, right(left)-handed down-type squarks are excluded in the range from 5 (2) to 40 (83) GeV$/c^2$.

These results supersede those previously published [1].

4. Conclusions

A search is made for stable and long-lived heavy charged particles in leptonic and hadronic final states at energies from 130 to 183 GeV, using particles identified by the Cherenkov light in the RICH and the ionization loss in the TPC.

No event is observed in the leptonic topology with an expected background of 0.7 $\pm$ 0.3 events. In the hadronic topology 3 events were observed with an expected background of 3.5 $\pm$ 1.5 events. The upper limit at 95% confidence level on the cross-section at a centre-of-mass energy of 183 GeV for sleptons and free squarks of charge $\pm\frac{2}{3}e$ varies between 0.06 and 0.5 pb in the mass range from 2 to 90 GeV$/c^2$. The upper limit for hadronizing squarks varies between 0.15 and 0.5 pb in the mass range from 5 to 90 GeV$/c^2$. Table 1 summarizes the excluded mass region at 95% confidence level for

Table 1
Excluded mass range at 95% confidence level for stable and long-lived particles

particle	excluded mass range GeV/c^2
leptonic topologies	
$\tilde{\mu}_R$ or $\tilde{\tau}_R$	2–80
$\tilde{\mu}_L$ or $\tilde{\tau}_L$	2–81
$\tilde{\chi}^{\pm}$ ($m_{\tilde{\nu}} > 41$ GeV$/c^2$)	2–87.5
$\tilde{\chi}^{\pm}$ ($m_{\tilde{\nu}} > 200$ GeV$/c^2$)	2–89.5
free squarks	
$\tilde{t}$ mixed	2–84
$\tilde{t}_R$ or up-type $\widetilde{q_R}$	2–84
$\tilde{t}_L$ or up-type $\widetilde{q_L}$	2–86
hadronic and leptonic topologies	
hadronizing squarks	
$\tilde{t}$ mixed	2–80
$\tilde{t}_R$ or up-type $\widetilde{q_R}$	2–81
$\tilde{t}_L$ or up-type $\widetilde{q_L}$	2–85
$\tilde{b}$ mixed	5–38
$\tilde{b}_R$ or down-type $\widetilde{q_R}$	5–40
$\tilde{b}_L$ or down-type $\widetilde{q_L}$	2–83

different stable and long-lived supersymmetric particles.

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