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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 has been performed using the data taken by the DELPHI experiment at energies from 130 to 183 GeV. The Cherenkov light detected in the Ring Imaging Cherenkov and the ionization loss measured in the Time Projection Chamber are used to identify heavy particles from masses of 2 to nearly 89 GeV/c^2.
Upper limits at 95% confidence level 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.

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1 Introduction

A search has been made for stable and long-lived [1]heavy charged particles in *all* final states using the data taken by the DELPHI experiment at energies from 130 till 183 GeV. The results presented here extend the results published 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 is commonly believed to be neutral and stable. In most of the searches it is therefore assumed that the supersymmetric particles decay promptly. It is, however, possible that a stable or long-lived heavy charged susy-particle exists. In Minimal Supersymmetric Standard Model (MSSM) where the neutralino is assumed to be the LSP [3], the chargino can get a sufficiently long lifetime to be observed as stable in the detector, if the mass difference between the chargino and neutralino becomes small. 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) can obtain a long lifetime in a very natural way for large values of the SUSY-breaking scale [5]. This is possible for sleptons if e.g. the stau is the NLSP. In certain variations of the minimal model the squark can be the NLSP and become long-lived [6].

Also other SUSY and non-SUSY models predict stable and long-lived heavy charged leptons, quarks and hadrons not present in the Standard Model. Further, it is possible that free (s)quarks exist.

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 [7]. However, the upper limits on the production cross-section of squarks, where the squark dresses up and becomes a charged or neutral s-hadron 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 $\sim$15 to 45 GeV/^{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, 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 s-hadrons. No search will be done for free squarks of charge q $pm\frac{1}{3}e$, because it is not certain that the tracking system will be 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 s-hadrons 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.

Heavy stable particles are selected by looking for high momentum charged particles with either anomalous ionization loss dE/dx 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 TPC and RICH detectors

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

and kinematical cuts provides 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.[8], with more details on the Barrel RICH in ref. [9]. Charged particles were selected if their impact parameter was less than 5 cm in the azimuthal and less than 10 cm in the longitudinal plane, and their polar angle lies between 20 and 160 degrees. The relative error on the measured momentum was required to be less than 100 % and the track length larger than 30 cm. The energy of a charged particle was evaluated from its momentum [2] 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. It was required that the total energy in one hemisphere was larger than 10 GeV and the total energy of the charged particles in the other hemisphere was larger than 10 GeV. It was further demanded that at least one charged particle had a momentum above 5 GeV/c reconstructed by the TPC and was inside the acceptance of the Barrel RICH $|\cos\theta| < 0.68$, where θ is the polar angle. The event should have at least two reconstructed charged particle tracks.

Cosmic muons were removed by putting tighter cuts on the impact parameter with respect to the average 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 azimuthal plane was required to be less than 0.15 cm, and in the longitudinal plane less than 1.5 cm.

Only the highest momentum (leading) charged particle in a given hemisphere was selected and identified using a combination of the following signals (where the sensitive mass range for 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) the TPC high ionization loss: measured normalized energy loss was above 2 units i.e. twice the energy loss for a minimum ionizing particle (m>70 GeV/c^2)
- (4) the TPC low ionization loss: measured normalized energy loss was below that expected for protons (m=1-50 GeV/c^2)

The particle identification using the RICH is described in detail in ref. [10].

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 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 wires were required for the measurement of the normalized energy loss in the TPC.

[2] 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.

Two sets of cuts selected sleptons or squarks. One set for 'leptonic topologies' for which the number of charged particles is less than four and another set for 'hadronic topologies' or all other events. The cuts were optimized using slepton and squark events generated with SUSYGEN [11] and passed through the detector simulation program [8]. 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-momentum distribution including initial state radiation was generated by SUSYGEN. The JETSET parton shower model was used to fragment the squark-anti-squark string [12]. 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 [13]. A s-hadron was given the mass of the squark plus 150 or 300 MeV/c^2 for resp. a s-meson or s-baryon. In the fragmentation process approximately 9% s-baryons were formed and 40% of the s-hadrons were charged, 60 % neutral. In the detector simulation program a charged s-hadron was given the properties of a heavy muon, a neutral s-hadron of a K^0_l. 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 pair has often a low multiplicity.

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)·(2)+(1)·(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)·(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))·((1)+(3))+(4)·(4)).

For hadronic topologies the following kinematical quantities were used to select events were a large fraction of the energy is taken by a heavy particle. The energy fraction F_c, 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 a minimum energy fraction F, because s-hadrons carry most of the energy in a given hemisphere.

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 60% in both hemispheres and in one of the hemispheres above 90%. The selected charged particle had to be identified by a Gas Veto or a high or a low ionization loss ((1)+(3)+(4)).

Secondly, an event was selected if the energy fraction F in one of the hemispheres was above 60%. In that case the momenta of the charged particles in both hemispheres had to lie above 15 GeV/c and both leading charged particles had a Gas Veto, or both had a high ionization loss, or a low ionization loss ((1)·(1)+(3)·(3)+(4)·(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 ± 0.3 events. In Figure 1 the data taken at 183 GeV are shown for leptonic topologies. The measured normalised ionization loss and the measured Cherenkov angle in the liquid radiator are shown after applying the Gas Veto.

In the hadronic topology 3 events were selected: one at 130 GeV, one at 161 GeV and one at 183 GeV. The expected background was estimated to be 3.5 ± 1.5 events using the real data assuming that the background is from Standard Model processes, in which the RICH or TPC misidentifies 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. These characteristics are compatible with the background expectation. In Figure 2 the data taken at 183 GeV are shown 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%. The one candidate event can be observed in 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 Figures 3a to 6a. The efficiency approaches zero at masses below 1 GeV/^{2}, where the Gas Veto becomes inefficient. The lowest upper limit on the mass is therefore 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 s-hadrons, the response of the calorimeter to a neutral s-hadron and the fragmentation function. In the simulation the fraction of neutral s-hadrons is 60%. This was changed to 50% and an efficiency increase of 15% was found. In the simulation it was assumed that a neutral s-hadron behaves like a K^0_L. If one assumes that a neutral s-hadron deposits only 20% of the energy of a K^0_L and the rest escapes, the efficiency is only reduced by 10%. Finally the fragmentation function was softened assuming a linear dependence on the squark mass for $\epsilon = 0.003\,(5./m)$. The efficiency at a centre-of-mass energy of 183 GeV increased by 20% around a squark mass of 45 GeV/^{2} and decreased by 15% around 70 GeV/^{2}. From these studies it was concluded that the efficiencies for squarks are sufficiently stable under these large changes.

The observed number 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 additional 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 Figure 7. The resulting distribution doesnot show clear bumps at the masses of 21, 30 and 48 GeV/c^2, because the observed charged multiplicity modifies the shape. The upper limit on the number of events at 95 % confidence level is derived from this distribution by adding 3 to it and scaling it with a scale factor. Zero probability in this figure would 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. This is known to be approximate but 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].

Figures 3 and 4 summarize the results for the leptonic topology for stable and long-lived sleptons, charginos and free squarks. Figure 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.

Figure 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.

Figures 5 and 6 summarize the results for the hadronic and leptonic topologies for stable and long-lived squarks. Figure 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 up-type squarks are excluded in the range from 2 to 81 (85) GeV/c^2.

Figure 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 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 the previous published result [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. In Table 1 the excluded mass region at 95% confidence level for different stable and long-lived supersymmetric particles is summarized.

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 $\tilde{q}_R$	2-84
$\tilde{t}_L$ or up-type $\tilde{q}_L$	2-86
hadronic and leptonic topologies	
hadronizing squarks	
$\tilde{t}$ mixed	2-80
$\tilde{t}_R$ or up-type $\tilde{q}_R$	2-81
$\tilde{t}_L$ or up-type $\tilde{q}_L$	2-85
$\tilde{b}$ mixed	5-38
$\tilde{b}_R$ or down-type $\tilde{q}_R$	5-40
$\tilde{b}_L$ or down-type $\tilde{q}_L$	2-83

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

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References

[1] P. Abreu et al. (DELPHI collaboration), Phys. Lett. **B396** (1997) 315.
[2] R. Barate et al. (ALEPH Collaboration), Phys. Lett. **B405** (1997) 379;
M. Acciari et al. (L3 Collaboration), Phys. Lett. **B412** (1997) 189;
K. Ackerstaff et al. (OPAL Collaboration), CERN-EP/98-039, submitted to Phys. Lett. B.
[3] H. P. Nilles, Phys. Rep. **110** (1984) 1;
H.E. Haber and J.L. Kane , Phys. Rep. **117** (1985) 75;
W. de Boer et al., Z. Phys. **C71** (1996) 415.
[4] H. Dreiner, hep-ph/9707435.
[5] M. Dine et al., Phys. Rev. Lett. **76** (1996) 3484;
S. Dimopoulos et al., Nucl. Phys. B Proc Supl **52A** (1997) 38.
[6] G.F. Giudice and R. Rattazzi, hep-ph/9801271.
[7] P. Abreu et al. (DELPHI collaboration), CERN-PPE/90-167;
D. Buskulic et al. (ALEPH Collaboration), Phys. Lett. **B303** (1993) 198;
R. Akers et al. (OPAL Collaboration), Zeit. Phys. **C67** (1995) 203.
[8] P. Aarnio et al., Nucl. Instr. Meth. **A 303** (1991) 233;
P. Abreu et al., Nucl. Instr. Meth. **A 378** (1996) 57.

[9] W. Adam et al., Nucl. Instr. Meth. **A343** (1994) 1.

[10] W. Adam et al., Nucl. Instr. Meth. **A343** (1994) 240;
M. Battaglia and P. M. Kluit, *Particle Identification using the RICH detectors based on the RIBMEAN package*, DELPHI note 96-133 RICH 90.

[11] S. Katsanevas and S. Melanchroinos in *Physics at LEP2*, CERN 96-01 (Vol.2) 328.

[12] T. Sjöstrand, Comp. Phys. Comm. **39** (1986) 347;
T. Sjöstrand, *PYTHIA 5.6 and JETSET 7.3*, CERN-TH/6488/92.

[13] W. Beenhakker et al., Phys. Lett. B 349 (1995) 463.

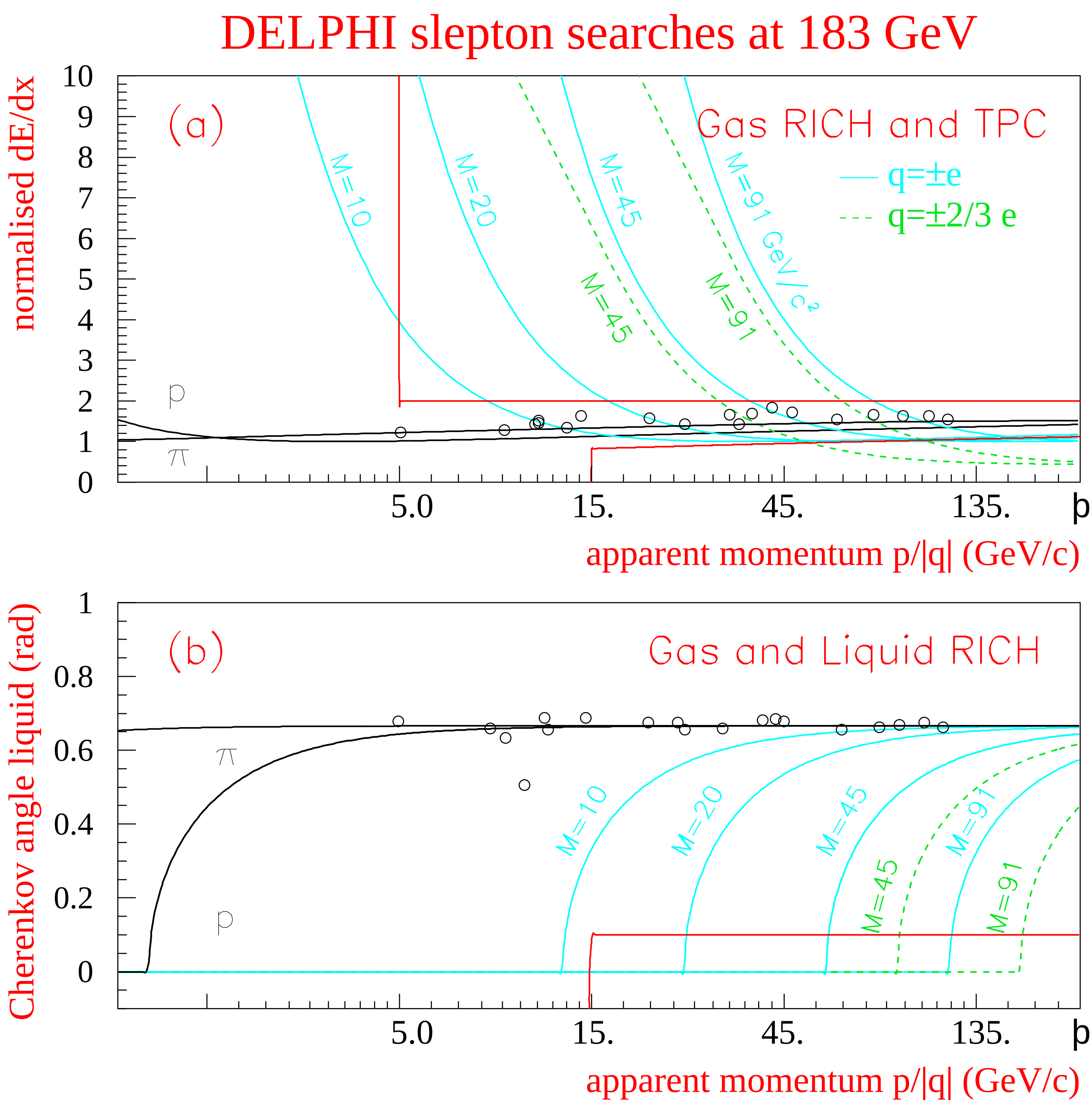

Figure 1: For leptonic topologies. (a) Normalised energy loss as a function of the apparent momentum $p/|q|$ after the Gas Veto for the 183 GeV data. (b) Measured Cherenkov angle in the liquid radiator as a function of the apparent momentum after the Gas Veto: if four photons or less were observed in 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 rectangular areas in (a) indicate selections (3) and (4), and that in (b) shows selection (2). The selection criteria are explained in section 2.

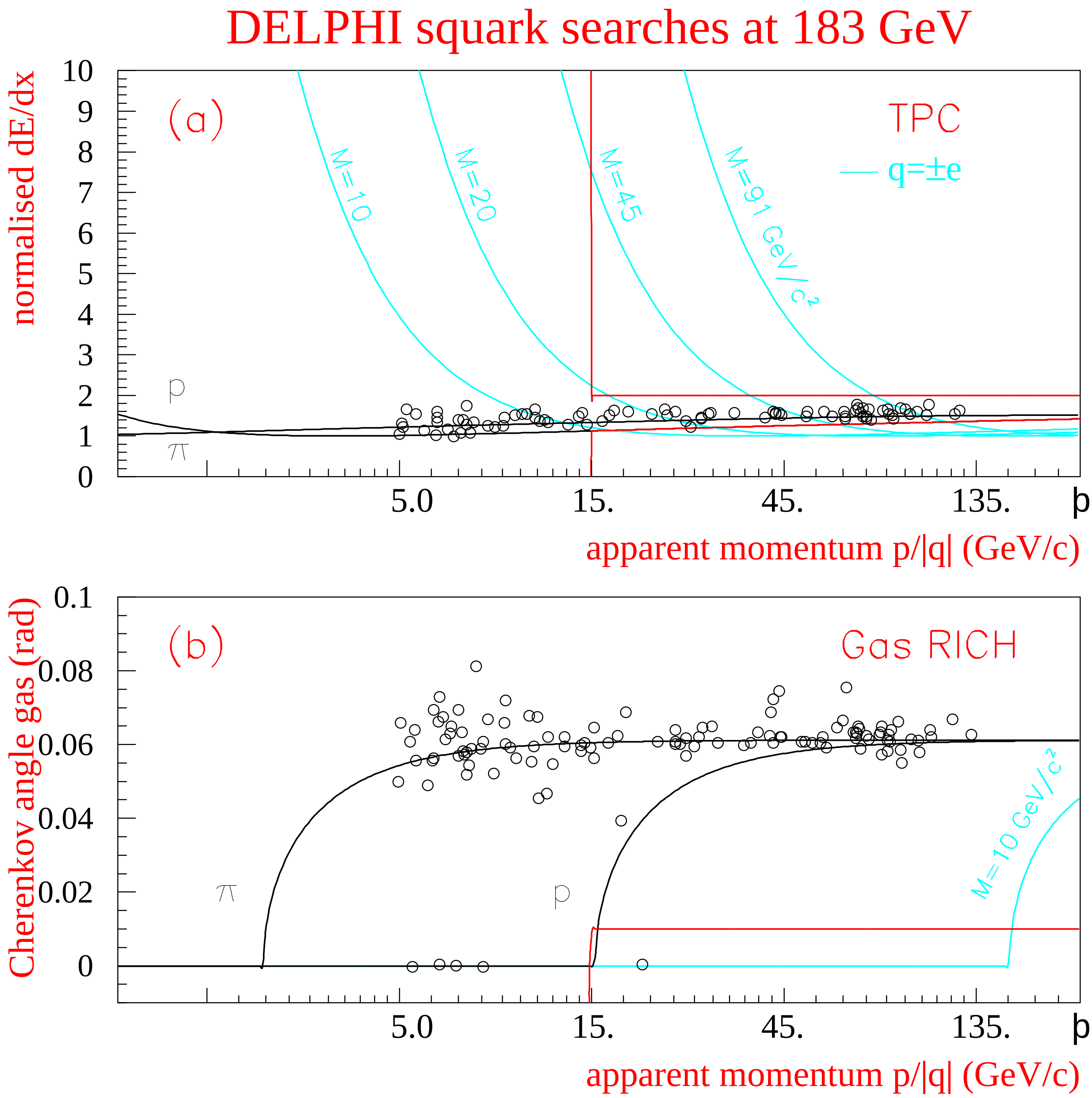

Figure 2: For hadronic topologies after the kinematic selection described in the text. (a) Normalised energy loss as a function of the apparent momentum p/$|q|$ for the 183 GeV data. (b) Measured Cherenkov angle in the gas radiator as a function of the apparent momentum: if zero photons were observed 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 rectangular areas in (a) indicate selections (3) and (4), and that in (b) shows selection (2). The selection criteria are explained in section 2.

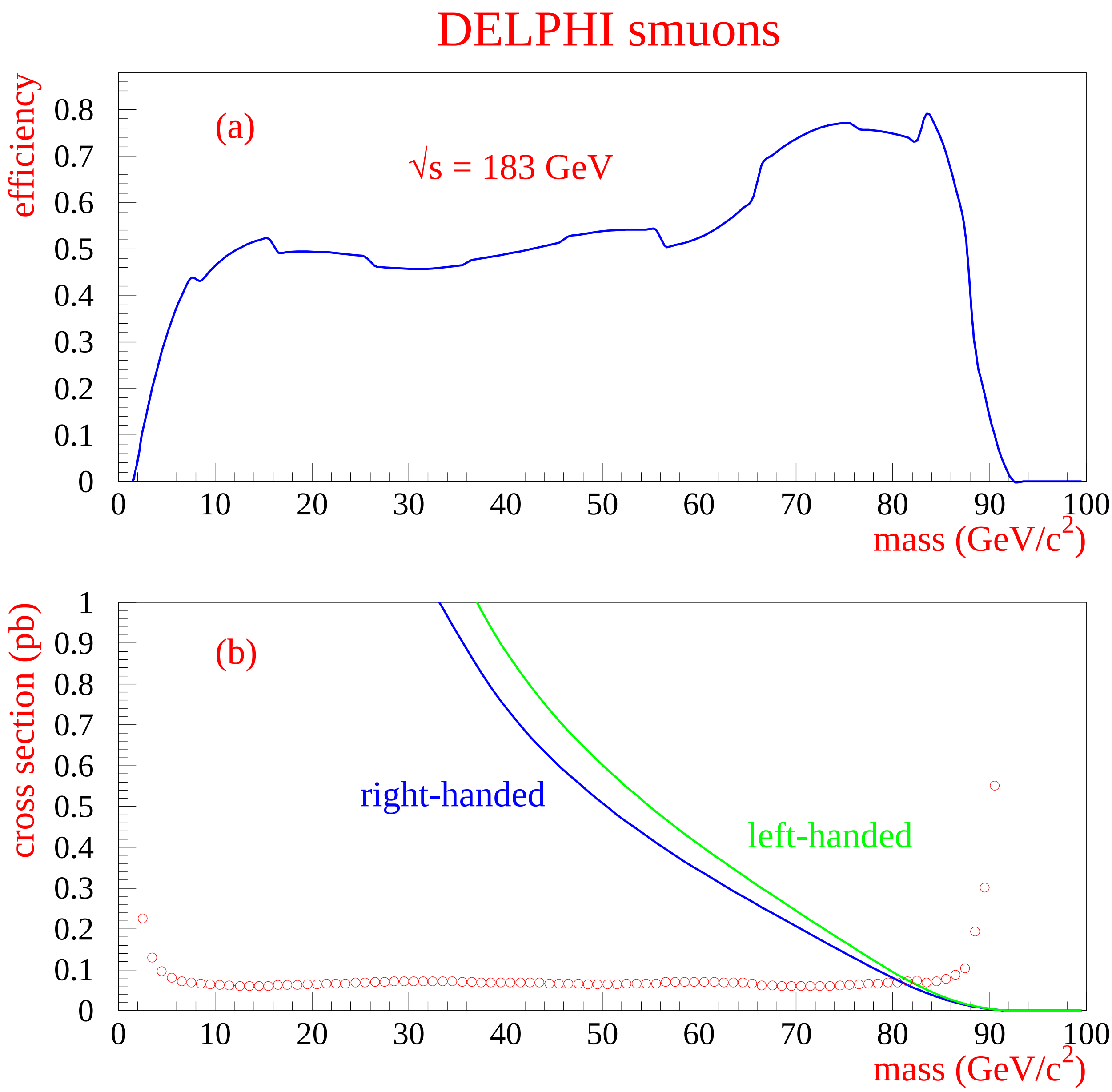

Figure 3: (a) Efficiency for detecting stable and long-lived smuons (staus) as a function of the smuon mass at a centre-of-mass energy of 183 GeV. (b) Production cross-section from SUSYGEN as a function of the smuon (stau) mass for right- and left-handed smuons at 183 GeV (solid curves). The circles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

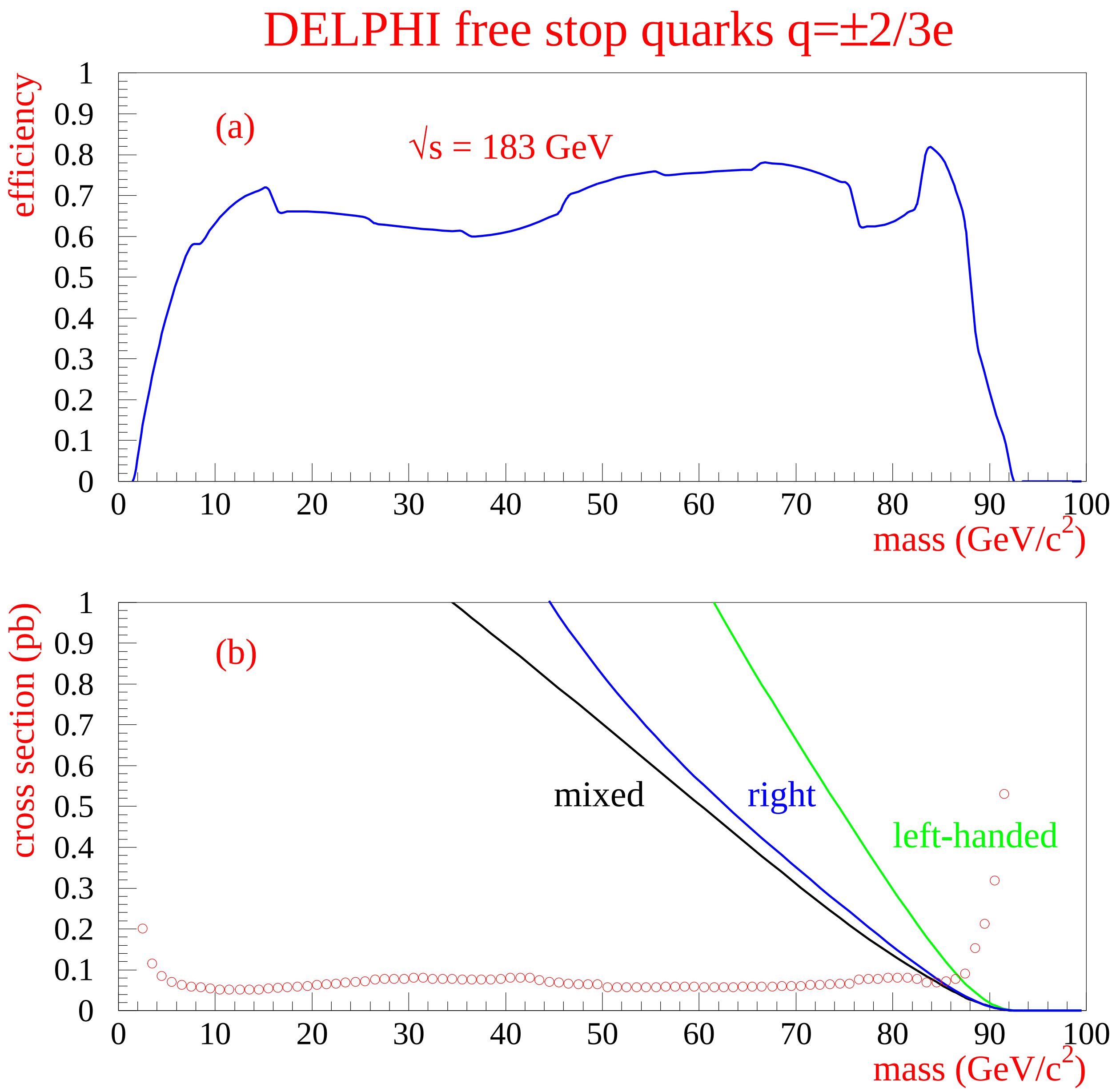

Figure 4: (a) Efficiency for detecting free stop quarks as a function of the stop mass at a centre-of-mass energy of 183 GeV. (b) Production cross-section from SUSYGEN as a function of the stop mass for typical mixing, right- and left-handed stop quarks at 183 GeV (solid curves). The circles indicate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

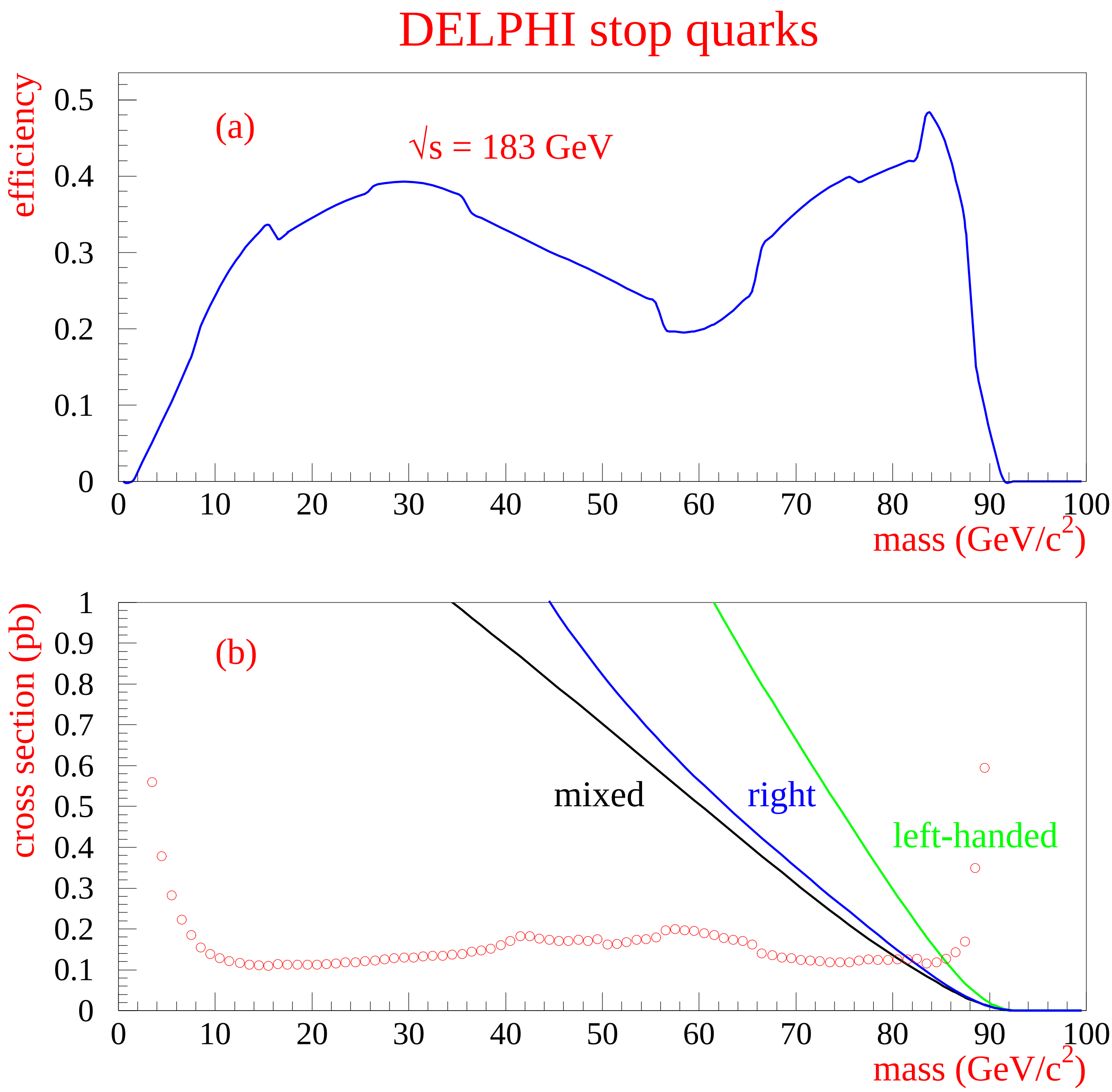

Figure 5: (a) Efficiency for detecting hadronizing stop quarks as a function of the stop mass at a centre-of-mass energy of 183 GeV. (b) Production cross-section from SUSYGEN as a function of the stop mass for typical mixing, right- and left-handed stop quarks at 183 GeV (solid curves). The circles indicated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

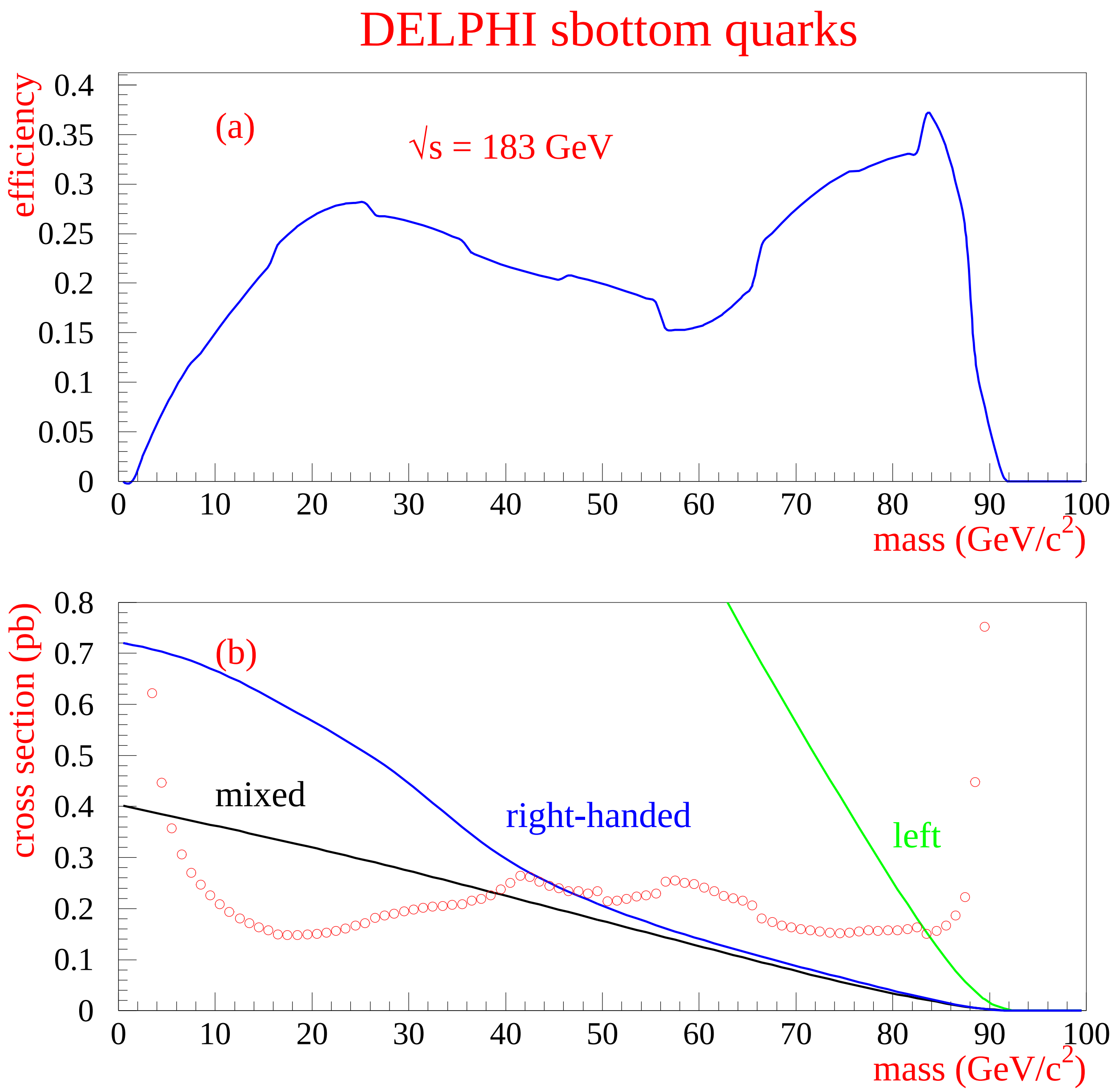

Figure 6: (a) Efficiency for detecting hadronizing sbottom quarks as a function of the sbottom mass at a centre-of-mass energy of 183 GeV. (b) Production cross-section from SUSYGEN as a function of the sbottom mass for typical mixing, right- and left-handed sbottom quarks at 183 GeV (solid curves). The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

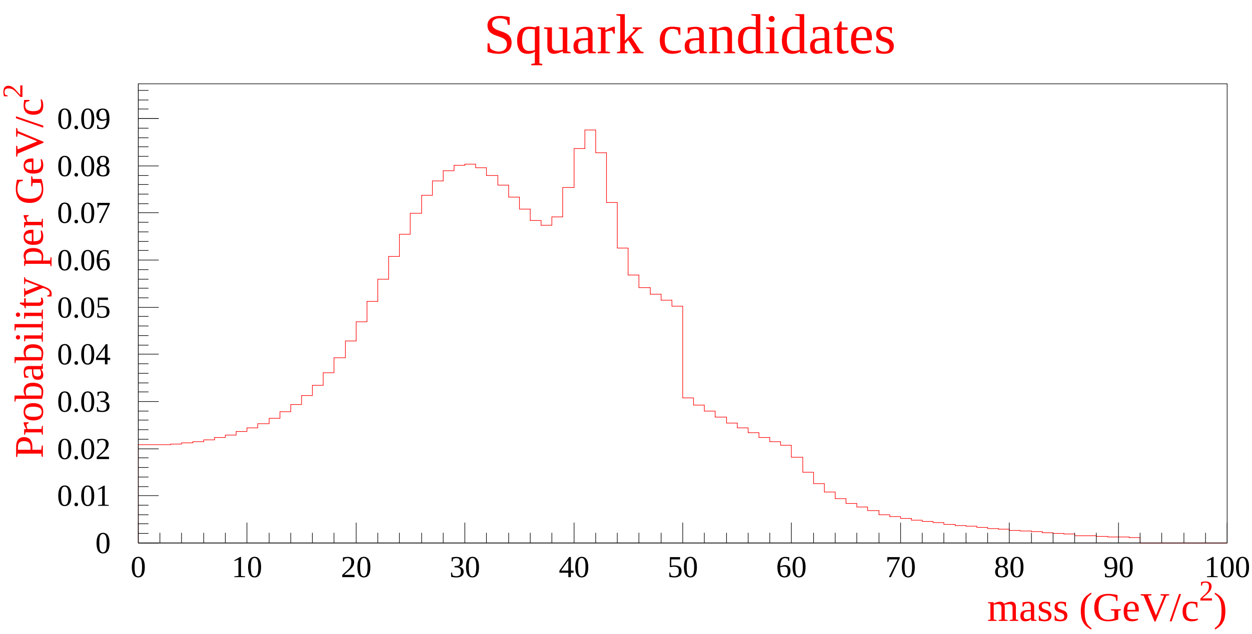

Figure 7: Probability density distribution per GeV/c^2 for the three squark candidates (normalised to three) as a function of the squark mass.