Slepton–Squark Production and Decay in ep Collisions

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1 Introduction

In ep collisions the most promising processes to search for supersymmetric particles are [1,2,3]

$$e+p \;\rightarrow\; \tilde{e}_{L,R}+\tilde{q}_{L,R}+X \tag{1}$$

$$e+p \;\rightarrow\; \tilde{\nu}_L+\tilde{q}_L+X, \tag{2}$$

where $\tilde{e}_{L,R}$, $\tilde{\nu}_L$, and $\tilde{q}_{L,R}$ are the selectron, sneutrino and squark, respectively. These processes proceed via t-channel neutralino (chargino) exchange (Feynman diagrams in Fig. 1). The produced particles $\tilde{e}_{L,R}$, $\tilde{\nu}_L$, and $\tilde{q}_{L,R}$ decay in the following way:

$$\tilde{e}_{L,R} \;\rightarrow\; e+\tilde{\chi}^0_i,\ \tilde{e}_L \rightarrow \nu+\tilde{\chi}^-_k \tag{3}$$

$$\tilde{\nu}_L \;\rightarrow\; \nu+\tilde{\chi}^0_i, e^- + \tilde{\chi}^+_k \tag{4}$$

$$\tilde{q}_{L,R} \;\rightarrow\; q+\tilde{\chi}^0_i,\ \tilde{q}_L \rightarrow q'+\tilde{\chi}^-_k, \tag{5}$$

where $\tilde{\chi}^0_i$, $i=1,\ldots 4$, are the neutralinos and $\tilde{\chi}^\pm_k$, $k=1,2$ are the charginos. (Here we assume that the gluinos are heavier than the squarks.)

The neutralinos and charginos are the mass eigenstates of the gauge and Higgs fermion system. The lightest neutralino $\tilde{\chi}^0_1$ is usually assumed to be the lightest supersymmetric particle and gives rise to missing energy in experiment. The charginos and the neutralinos decay in various modes until $\tilde{\chi}^0_1$ is reached:

$$\tilde{\chi}^0_i \rightarrow Z^0+\tilde{\chi}^0_k,\ W^\pm+\tilde{\chi}^\mp_k,\ H^0_l+\tilde{\chi}^0_k,\ H^\pm+\tilde{\chi}^\mp_k \tag{6}$$

$$\tilde{\chi}^\pm_i \rightarrow Z^0+\tilde{\chi}^\pm_k,\ H^0_l+\tilde{\chi}^\pm_k,\ W^\pm+\tilde{\chi}^0_k,\ H^\pm+\tilde{\chi}^0_k, \tag{7}$$

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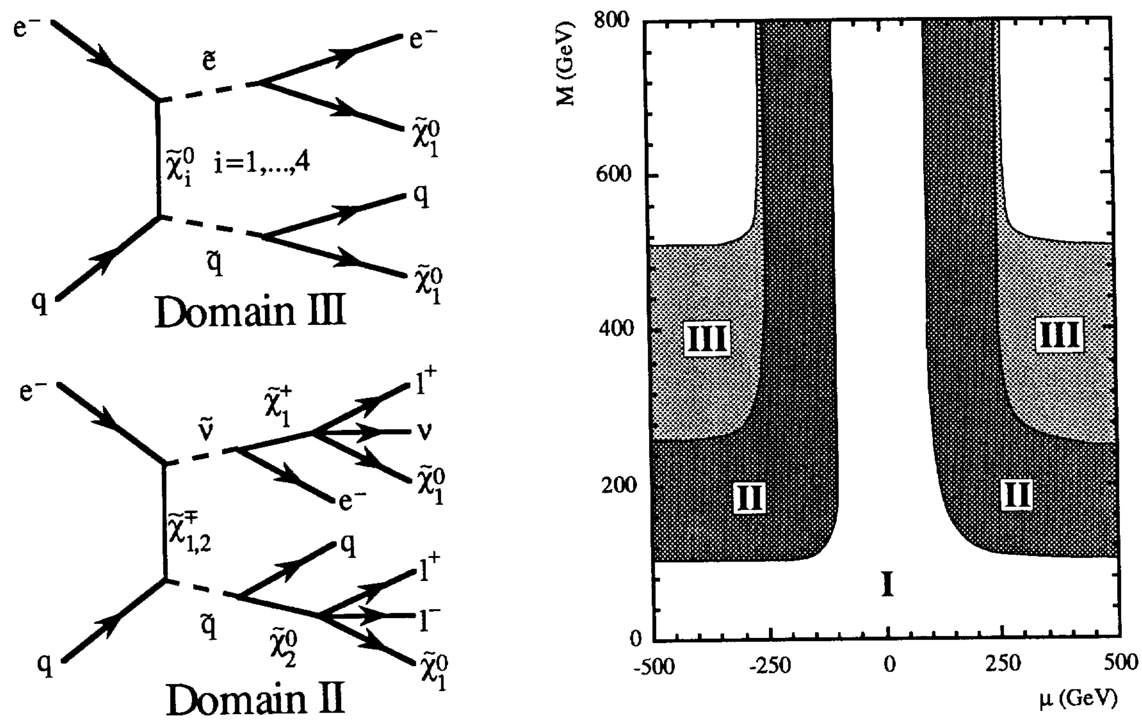

Figure 1: Domains in (M, μ) plane for typical decay patterns of a squark or slepton with a mass of 250 GeV, for $\tan\beta = 4$. Domain I: Explored by LEP 200. Domain II: Cascade decays possible. Domain III: Only decays into $\tilde{\chi}_1^0$ possible. Also shown typical Feynman diagrams for $e + q \to \tilde{e}\,(\tilde{\nu}) + \tilde{q}$ and subsequent decays.

where H_a^0, $a = 1, 2, 3$, and $H^\pm$ represent the neutral and charged Higgs bosons, respectively. If these two-body decays are kinematically forbidden, then the following three-body decays will be important:

$$\tilde{\chi}_i^\pm \to l + \bar{l} + \tilde{\chi}_k^\pm,\; q + \bar{q} + \tilde{\chi}_k^\pm,\; l^\pm + \overset{(-)}{\nu} + \tilde{\chi}_k^0,\; q + \bar{q}' + \tilde{\chi}_k^0. \tag{8}$$

$$\tilde{\chi}_i^0 \to l + \bar{l} + \tilde{\chi}_k^0,\; q + \bar{q} + \tilde{\chi}_k^0,\; l^\mp + \overset{(-)}{\nu} + \tilde{\chi}_k^\pm,\; q + \bar{q}' + \tilde{\chi}_k^\pm. \tag{9}$$

We shall work within the minimal supersymmetric extension of the standard model based on $N = 1$ supergravity [4,5]. The parameters describing the basic production process $e + q \to \tilde{l} + \tilde{q}$ and the slepton and squark decays, Eqs. (3 – 5), are the masses of the sleptons and squarks, $m_{\tilde{l}}$ and $m_{\tilde{q}}$, the mass paramters of the $SU(2)$ gauge and Higgs fermions, M and μ, and the ratio of the vacuum expectation values of the two Higgs doublets, $v_2/v_1 (\equiv \tan\beta)$. We shall fix the mass parameter of the $U(1)$ gauge fermion by $M'/M = (5/3)\tan^2\theta_W$. The mass of the charged Higgs boson $m_{H^\pm}$ is also a parameter for the decays of the neutralinos and charginos [6], Eqs. (6 – 7).

In this article we shall study slepton and squark production and decay in ep collisions at $\sqrt{s} = 1.4$ TeV, the CMS energy of LEP/LHC. At LEP/LHC the masses of the produced slepton and squark can be as large as several hundred GeV. For such a heavy sfermion

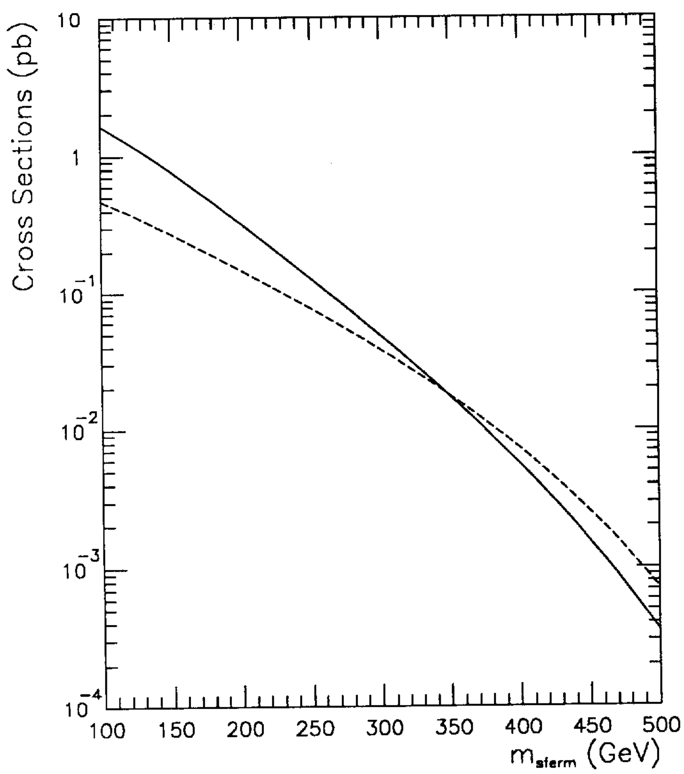

Figure 2: Cross sections for $e+p \to \sum(\tilde{l}+\tilde{q}+X)$ at $\sqrt{s} = 1.4$ TeV, where the sum goes over all slepton and squark species, as a function of $m_{\tilde{f}}$, for $m_{\tilde{e}} = m_{\tilde{\nu}} = m_{\tilde{q}} = m_{\tilde{f}}$, $\tan\beta = 4$, and $\mu = -400$ GeV. $M = 200$ GeV (——), $M = 800$ GeV (- - -).

the dominant decay will not necessarily be the simplest one, $\tilde{f} \to f + \tilde{\chi}_1^0$. In general, one has a more complex decay pattern due to cascade decays involving heavier neutralinos and charginos, Eqs. (3–9). A systematic analysis of the whole process of production and decay is necessary in order to work out suitable signatures. For illustration we show in Fig. 1 the domains in the (M, μ) plane (for $\tan\beta = 4$) where, for a squark or a slepton with a mass of 250 GeV, cascade decays are kinematically possible (domain II), or where only transitions into the lightest neutralino are allowed (domain III).

2 Numerical analysis and discussion

For simplicity, we assume in the following that the sleptons and squarks have the same mass, which is theoretically reasonable [5]. Due to the existing experimental bounds it is sufficient to consider the mass range $m_{\tilde{l}} = m_{\tilde{q}} > 150$ GeV. In the numerical examples we shall take $\tan\beta = 4$. We shall not consider the supersymmetry parameter region corresponding to a chargino mass lower than 100 GeV (see domain I in Fig. 1) as this will be explored by LEP.

We first discuss the production process, Eqs. (1– 2). The formulae for the cross sections are given in [1] and [2]. We show in Fig. 2 the cross section of $e+p \to \sum \tilde{l}+\tilde{q}+X$, summed over all possible pairs of sleptons and squarks, as a function of the sfermion mass for

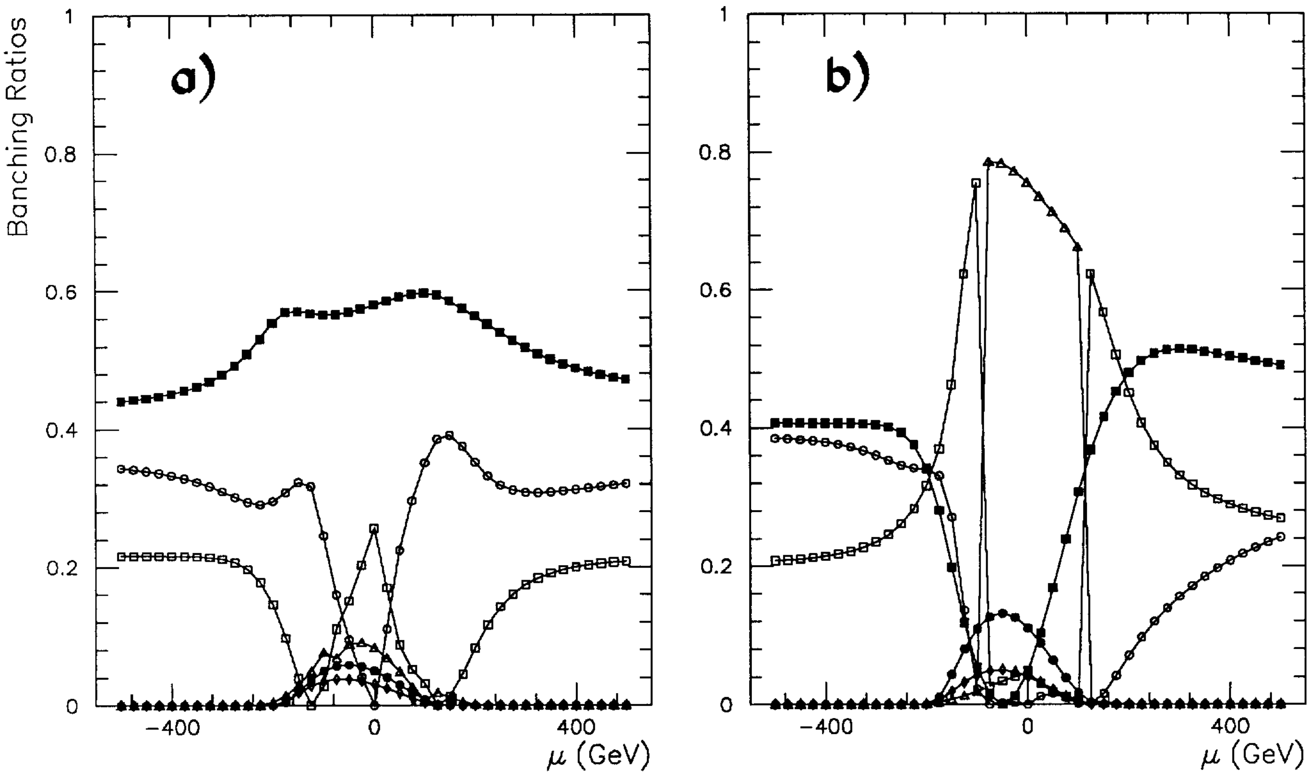

Figure 3: Branching ratios for **a:** $\tilde{\nu}_L \rightarrow \tilde{\chi}^0_i + \nu,\ e + \tilde{\chi}^+_k$; **b:** $\tilde{e}_L \rightarrow \tilde{\chi}^0_i + e,\ \nu + \tilde{\chi}^-_k$, for $m_{\tilde{e}} = m_{\tilde{\nu}} = 250$ GeV, $M = 200$ GeV, $\tan\beta = 4$. Decays into $\tilde{\chi}^\pm_1$ (■), $\tilde{\chi}^\pm_2$ (●), $\tilde{\chi}^0_1$ (○), $\tilde{\chi}^0_2$ (□), $\tilde{\chi}^0_3$ (△), and $\tilde{\chi}^0_4$ (◇).

$\mu = -400$ GeV, $M = 200$ GeV and $M = 800$ GeV. This cross section is larger than 0.1 pb for $m_{\tilde{f}} \leq 300$ GeV. Assuming an integrated luminosity of 500 pb^{-1}, this would give between 50 and 1000 events per year. The cross section shows almost no variation with μ and depends moderately on M. However, the individual production cross sections for different slepton and squark species are very different from each other. Since in general the charginos couple more strongly to the sleptons and squarks than the neutralinos, $e + p \rightarrow \tilde{\nu}_L + \tilde{d}_L + X$ has the largest cross section. Moreover, in a wide range of the parameters M, μ and $\tan\beta$ the cross section depends essentially on the sum $m_{\tilde{l}} + m_{\tilde{q}}$, and not on $m_{\tilde{l}}$ and $m_{\tilde{q}}$ seperately.

In the following discussion of the decays of sleptons and squarks we shall take $m_{\tilde{e}_L} = m_{\tilde{e}_R} = m_{\tilde{\nu}_L} = m_{\tilde{q}_L} = m_{\tilde{q}_R} = 250$ GeV. The formulae for the decay widths are taken from [2]. For $M < 250$ GeV, in a wide range of μ, the masses of the second lightest neutralino $\tilde{\chi}^0_2$ and the lighter chargino $\chi^\pm_1$ are in this case smaller than the mass of the sfermions. Then each sfermion can decay in several modes (domain II in Fig. 1). In Fig. 3a and b the branching ratios of $\tilde{\nu}_L$ and $\tilde{e}_L$ are shown as a function of μ. The most important decay modes of $\tilde{\nu}_L$ and $\tilde{e}_L$ are those into the lighter chargino (except $|\mu| \leq 100$ GeV for $\tilde{e}_L$). In Fig. 3a and b the branching ratios become practically independent of μ for $|\mu| \geq 500$ GeV. Also $\tilde{u}_L$ and $\tilde{d}_L$ most dominantly decay into lighter charginos [7,8]. It should be noted that for all left scalar particles the direct decay into the lightest neutralino, $\tilde{f}_L \rightarrow f + \tilde{\chi}^0_1$, is

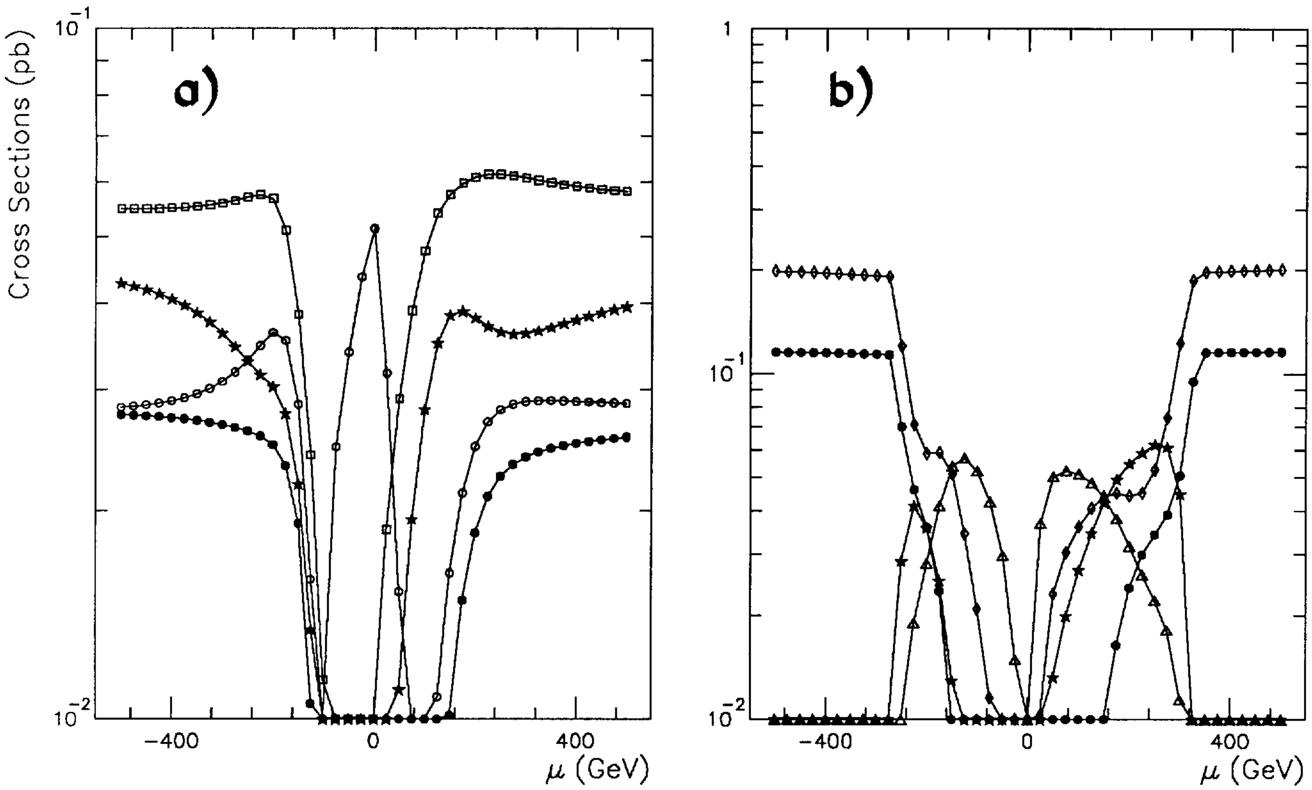

Figure 4: Cross sections (at $\sqrt{s} = 1.4$ TeV) for various final states for $m_{\tilde{l}} = m_{\tilde{q}} = 250$ GeV and $\tan\beta = 4$ **a:** $M = 200$ GeV; **b:** $M = 300$ GeV. The curves correspond to the following processes: $ep \to eu\tilde{\chi}_1^0\tilde{\chi}_1^0X + ed\tilde{\chi}_1^0\tilde{\chi}_1^0X$ ($\bullet$), $ep \to \nu u\tilde{\chi}_1^0\tilde{\chi}_1^-X$ ($\star$), $ep \to ed\tilde{\chi}_1^+\tilde{\chi}_2^0X$ ($\circ$), $ep \to eu\tilde{\chi}_1^+\tilde{\chi}_1^-X$ ($\square$), $ep \to \nu d\tilde{\chi}_1^0\tilde{\chi}_1^0X$ ($\diamond$), and $ep \to ed\tilde{\chi}_1^+\tilde{\chi}_1^0X$ ($\triangle$).

not the dominant one. For $\tilde{\nu}_L \to \nu + \tilde{\chi}_1^0$ and $\tilde{e}_L \to e + \tilde{\chi}_1^0$ the branching ratio is between 20 and 40 percent. For $\tilde{u}_L$ and $\tilde{d}_L$ the branching ratio into $\tilde{\chi}_1^0$ is less than 10 percent, and in the region $|\mu| \geq 100$ GeV it is even much smaller than that into $\tilde{\chi}_2^0$. Among the decays of the right scalar fermions $\tilde{e}_R$, $\tilde{u}_R$, and $\tilde{d}_R$, the decay into $\tilde{\chi}_1^0$ has the largest branching ratio, $B(\tilde{f}_R \to f + \tilde{\chi}_1^0) \sim 1$, except for $|\mu| \leq 100$ GeV. For $M > 250$ GeV, only the lightest neutralino has a mass smaller than 250 GeV in a wide range of μ (domain III of Fig. 1), yielding $B(\tilde{f}_{L,R} \to f + \tilde{\chi}_1^0) = 1$.

For discussing the signatures it is necessary to perform a combined analysis of the individual production processes together with the various decay modes of the produced particles. In Fig. 4a and b we show the sum of the cross sections for $ep \to \sum \tilde{e}_a\tilde{u}_bX \to eu\tilde{\chi}_1^0\tilde{\chi}_1^0$ and $ep \to \sum \tilde{e}_a\tilde{d}_bX \to ed\tilde{\chi}_1^0\tilde{\chi}_1^0$, where both the slepton and the squark directly go into the lightest supersymmetric particle $\tilde{\chi}_1^0$. This would give rise to large missing energy in the final state, the "classical" signature for supersymmetry. For $M = 200$ GeV and $|\mu| \geq 200$ GeV (Fig. 4a), this cross section is $0.02 - 0.03$ pb, mainly due to the reactions $ep \to \tilde{e}_R\tilde{q}_RX$ and $\tilde{f}_R \to f\tilde{\chi}_1^0$. It is smaller than the total cross section $\sigma(ep \to \sum \tilde{e}\tilde{q}X)$ by one order of magnitude. As also shown in Fig. 4a the largest cross section in this parameter region is obtained for the process $ep \to \tilde{\nu}_L\tilde{d}_LX \to eu\tilde{\chi}_1^+\tilde{\chi}_1^-X$. Also $\sigma(ep \to \tilde{\nu}_L\tilde{d}_LX \to ed\tilde{\chi}_1^+\tilde{\chi}_2^0X)$ is equal to or even larger than $\sigma(ep \to eu\tilde{\chi}_1^0\tilde{\chi}_1^0X + ed\tilde{\chi}_1^0\tilde{\chi}_1^0X)$. Since both $\tilde{\chi}_1^\pm$

	Cross Section
$e+p\to Z+X+p_{\rm miss}$	$4.8\cdot 10^{-2}$ pb
$e+p\to W+X+p_{\rm miss}$	$2.2\cdot 10^{-1}$ pb
$e+p\to H_2^0+X+p_{\rm miss}$	$9.3\cdot 10^{-1}$ pb
$e+p\to (e)_{\rm l.s.}+X+p_{\rm miss}$	$6.1\cdot 10^{-2}$ pb
$e+p\to (e+{\rm jets})_{\rm l.s.}+X+p_{\rm miss}$	$7.4\cdot 10^{-2}$ pb
$e+p\to l^+l^-+X+p_{\rm miss}$	$3.9\cdot 10^{-2}$ pb

Table 1: Cross sections for various final states coming from $e+p\to\tilde{e}+\tilde{q}+X$ and $e+p\to\tilde{\nu}+\tilde{q}+X$ at $\sqrt{s}=1.4$ TeV for $M=200$ GeV, $\mu=-500$ GeV, $\tan\beta=4$. The subscript "l.s." means "lepton side".

and $\tilde{\chi}_2^0$ dominantly decay into two quarks and $\tilde{\chi}_1^0$, events with an electron and jets in the lepton hemisphere and jets in the hadron hemisphere provide another important signature for supersymmetry. As an example we give in Table 1 the cross sections for several final states for $M=200$ GeV and $\mu=-500$ GeV. (For the mass of the charged Higgs boson we have taken $m_{H^\pm}=500$ GeV, leading to $m_{H_2^0}=80$ GeV for $\tan\beta=4$.) Due to the large mass differences between $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ or $\tilde{\chi}_1^\pm$, the Z-boson, $W^\pm$-boson, and neutral Higgs boson H_2^0 are produced in the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ decays.

In Fig.4b we show the situation for $M=300$ GeV. For $|\mu|\geq 300$ GeV only decays into the lightest supersymmetric particle $\tilde{\chi}_1^0$ are kinematically allowed. The cross section of $ep\to eu\tilde{\chi}_1^0\tilde{\chi}_1^0X+ed\tilde{\chi}_1^0\tilde{\chi}_1^0X$ is ~ 0.1 pb, being higher than in the previous case for $M=200$ GeV. For $|\mu|<250$ GeV, also here cascade decays are possible.

3 Conclusions

We have studied the production of sleptons and squarks and their decays in ep collisions at LEP/LHC. If the sum of the masses of slepton and squark is smaller than 600 GeV, the production cross section (summed over all possible pairs) becomes larger than ~ 0.1 pb.

The signature of slepton and squark production decisively depends on the supersymmetry parameters. In a certain region, mainly $|\mu|>m_{\tilde{f}}$, $M>m_{\tilde{f}}$, $M'<m_{\tilde{f}}$, indicated as domain III in Fig. 1, the slepton (squark) can only decay into the lightest neutralino plus a lepton (quark). The signature in this case is an isolated electron (on the lepton side) and jets (on the hadron side) with large missing momentum in the final state.

If either M or $|\mu|$ is smaller than $m_{\tilde{f}}$ (domain II in Fig. 1), then many configurations are possible for the final state and some of them have cross sections larger than 10^{-1} pb. The final state containing an electron coming from the decay $\tilde{\nu}_L\to e+\tilde{\chi}_k^+$ has a cross section up to $\sim 10^{-1}$ pb. This electron is accompanied by jets or another charged lepton.

In order to decide which is the best signature for slepton and squarks it will, however, be necessary to perform detailed Monte Carlo studies taking into account the background [9].

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