PROSPECTS OF SUPERSYMMETRY SEARCHES AT LEP/LHC

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Abstract

We present a Monte-Carlo study of the signal coming from sleptons and squarks produced via supersymmetric leptoproduction in the ep collisions of the LHC. We show how the supersymmetric signal can be extracted from the background due to standard processes and particularly the important background due to the heavy top quarks produced via weak boson and gluon fusion and the background due to the production of single W bosons.

1 Introduction and model

The LHC has the unique feature of being able to run not only in the pp or in the ion-ion collider mode but, also in the ep collider mode with 50 GeV electrons and 8 TeV protons at a luminosity of $10^{32}cm^2s^{-1}$ i.e. 1000 pb$^{-1}$ for a one year running. The standard and exotic physics potentials of this LEP/LHC collider are large [1] and in the following we discuss the possibilities of searching for supersymmetry assuming these machine parameters.

Selectron-squark and sneutrino-squark productions, $eq \to \tilde{e}q, \tilde{\nu}q$ are the most probable supersymmetric processes that can occur in the ep collisions of LEP/LHC. The Feynmann diagrams and the formulae for the cross sections are known from the literature, see references in [2].

The study of the signals coming from the sleptons $\tilde{l}$ and squarks $\tilde{q}$ and the study of the background reduction are performed with the help of Monte Carlo simulations. We present the analysis according to the three following steps.

In a first step we have chosen to look at supersymmetric leptoproduction for one example of the equal masses case $m_l = m_\tilde{q}$ in two different points of the parameter space $M$, $\mu$ (which are respectively the mass parameter of the SU(2) gauginos and the mass parameter of the higgsino, both taken from minimal low energy supergravity theories MLES) consistent with the present LEP excluded region [3], see table 1.

The choice of these two points is motivated by the fact that they are leading to two different phenomenologies, i.e. gauginos masses, cross sections (resp. tables 1,2) and, above all, decays of scalars and fermions [2] which determine the signature of the supersymmetric events.

As far as the decays are concerned, for the point 1 of the mass parameter space, the scalars have the simplest decay into their fermionic partners and the lightest supersymmetric particle LSP whereas for the point 2 cascade decays can occur [2]. In this example, the choice of the masses of $\tilde{e}$, $\tilde{\nu}$, $\tilde{u}$ and $\tilde{d}$ is 250 GeV which is typical for the LEP/LHC accessible range.

The study of this example will allow us to find a simple set of cuts that reduces the background at a reasonable level. Moreover, the study of the cascade decays for one example of $m_l$ and $m_\tilde{q}$ is instructive enough to show that these decays are actually complicating the signatures and the detection of the supersymmetric processes.
In a second step, in order to find the detection limits, we extend the study to a wider range of selectrons and squarks masses in the equal masses case \( m_{\tilde{e}} = m_{\tilde{q}} \), but assuming only the simplest decay: \( \tilde{e}, \tilde{q} \rightarrow e, \nu \chi_1^0 \) with a 100\% branching ratio and \( \chi_1^0 \) being the lightest neutralino considered as the LSP.

The study of the detection limits of the supersymmetric signal for a wide range of \( m_{\tilde{t}} \) and \( m_{\tilde{q}} \) in the case of cascade decays is more complicated because the channels and the branching ratios are changing with \( m_{\tilde{t}} \) and \( m_{\tilde{q}} \) and with the different parameters of the previous parameter space, see [2]. Implementing and working out the present example for the cascade decays at \( m_{\tilde{t}} = m_{\tilde{q}} = 250 \text{ GeV} \) taught us that this study can be a tedious and very long one. Nevertheless, such a study remains to be done.

In a third step, we examine the case of unequal masses \( m_{\tilde{t}} < m_{\tilde{q}} \). The study of the detection limits for \( m_{\tilde{e}} \) and \( m_{\tilde{q}} \) in this case is done assuming once again only the simplest decay. The same previous arguments can be here repeated for the study of the unequal masses case with cascade decays. One additional feature of the unequal masses case is that a slepton can also be produced in the cascade decay of a squark and this slepton can have in turn its own cascade decay.

The supersymmetric events generator used is described in [4]. It has been upgraded in order to include all the previous masses and cross sections as well as the full description of the decays especially the cascade decays. The events generators for the background study is described in [5].

Finally a detector is crudely simulated by:

- beam pipe 100 mrad
- Hadron energies are fluctuating with a dispersion \( \frac{0.5}{\sqrt{E}} + 0.02 \)
- Electron energies are fluctuating with a dispersion \( \frac{0.1}{\sqrt{E}} + 0.01 \)

\section{The equal mass case at 250 GeV}

\subsection{Point 1 of the parameter space: simple decays}

In the point 1 of the parameter space previously defined, the \( \tilde{t} \) and \( \tilde{q} \) have the following 100\% branching ratio simple decay:

\[ \tilde{e}, \tilde{\nu}, \tilde{q} \rightarrow e, \nu, q \tilde{\chi}_1^0 \]

for the scalar partners of both left and right handed fermions.

In consequence, for the charged current supersymmetric process \( \bar{C}C \) where \( \tilde{\nu}, \tilde{q} \) are produced (see the cross section in table 2), the signature of the event is jets and large missing energy due to the two undetected LSPs and the neutrino.

The main background is due to the charged current deep inelastic scattering (CC DIS) process which has the same signature.

By looking at the distribution of the missing transverse momentum \( P_{T}^{\text{mis}} \) w.r.t the beam axis for both kinds of events showed in fig. 1, we conclude that \( CC \) and \( \bar{C}C \) processes cannot be distinguished. With the simplest decay yielding no isolated charged lepton in the signature, the detection of \( \bar{C}C \) is hopeless.
In the supersymmetric neutral current case $\tilde{N}C$, where $\tilde{c}, \tilde{q}$ are produced (see the cross sections in table 2), the signature is one electron, jets and a large amount large missing energy due to the two undetected LSPs.

One of the most serious background is likely to be the production of a single heavy top quark $t$ with the decays $t \to W b$, where the $W$ is real, and $W \to e \nu$ giving rise to the same signature. Single tops are produced via the fusion of a $W$ and a gluon going into $t$ and $b$ quarks. The cross sections have been computed for various top masses by J.v.d Bij and G. Schuler from the heavy flavour working groups [6] and we concentrated here on three top masses namely 100, 150 and 200 GeV.

Fig. 2a to Fig. 5a show respectively the pseudorapidity $\eta$ of the electron, the accompanying energy $E_{acc}$ as defined in [7] (i.e. the total transverse energy within a cone around the electron momentum defined in the azimuthal angle and $\eta$ space), the transverse momentum of the electron w.r.t the beam axis $P_t^e$ and $P_t^{mis}$ of the $\tilde{N}C$ events whereas Fig. 2b to Fig. 5b show respectively the same quantities for the previous $tb$ background events for a top mass of 150 GeV.

The two electrons coming from the $\tilde{N}C$ signal and from the $tb$ background are equally well isolated i.e. more than 80 % of the events have $E_{acc} < 1 GeV$, and they have comparable pseudorapidities.

With $E_{acc} < 1 GeV$ (electron isolation), $P_t^{mis} > 50 GeV$ and $P_t^e > 80 GeV$ we obtain 60 events for $\tilde{N}C$ with the cross section of table 2 and of the order 10 $tb$ of background events for the 3 previous top masses considered.

The most efficient cut is $P_t^e > 80 GeV$ which helps to reduce the $tb$ background at an acceptable level. Going to a lower $P_t^e$ cut, affects drastically the signal to background ratio.

The same previous set of cuts reduces completely the other possible sources of background, such as NC DIS, CC DIS with an electron coming from a secondary decay and and production with one electron in the signature.

The background coming from the single $W$ production $ep \to eWX$, with one electron in the signature of the event, is a possible source of background. From [8], the number of single $W$ events, with one electron in the signature, passing the previous cuts on $P_e^t$ and on $P_t^{mis}$ is expected to be small i.e. of the order of 3 events. The case of the single $W$ production $ep \to \nu WX$ followed by the decay $W \to e \nu$ is also a source of background. From [9], after applying the previous set of cuts, the number of background events is found to be of the order of 25. Nevertheless, more detailed simulations are needed for the study of this source of background.

### 2.2 Point 2 of the parameter space: cascade decays

In the point 2 of the parameter space, cascade decays occur. $\tilde{t}$ and $\tilde{q}$ have decays into $l$ and $q$ respectively plus heavy neutralinos or charginos. These neutralinos and charginos have in turn their own decays into quarks or leptons and lighter neutralinos or charginos. These cascade decays continue until the LSP is produced. The signature for this type of events will be multi-(charged)leptons, jets, and missing energy.

In our particular example, 6 different decay channels are possible for each $\tilde{e}_L, \tilde{\nu}_L, \tilde{t}_L$ and $\tilde{d}_L$. The dominant ones are [2]:

\[
\begin{align*}
\tilde{e}_L & \to e\tilde{\chi}_1^0 \quad 0.5168 \quad \tilde{u}_L \to d\tilde{\chi}_1^+ \quad 0.5793 \\
\tilde{\nu}_L & \to e\tilde{\chi}_1^- \quad 0.4713 \quad \tilde{d}_L \to u\tilde{\chi}_2^\pm \quad 0.3306
\end{align*}
\]
Where the numbers correspond to the branching ratios. The partners of the right handed
fermions have the simplest decay with 100 % branching ratio. Then, afterwards, the
decays of the charginos and the heavy neutralinos occur (in our example, 10 channels for
$\tilde{\chi}_1^\pm$, 8 for $\tilde{\chi}_2^\pm$, 10 for $\tilde{\chi}_2^0$, 24 for $\tilde{\chi}_3^0$, and 23 for $\tilde{\chi}_4^0$). The dominant ones for $\tilde{\chi}_1^\pm$ are \[2\]:

$$
\tilde{\chi}_1^\pm \rightarrow \nu e \tilde{\chi}_1^0 \quad 0.0966
$$

$$
\tilde{\chi}_1^\pm \rightarrow q\bar{q} \tilde{\chi}_1^0 \quad 0.7062
$$

where $q, q' = u, d$ and $c, s$. The numbers correspond to the branching ratios. For our
particular example, the following observations can be made:

- $\tilde{c}$ still decays dominantly into $e$ and the LSP.
- $\tilde{\nu}$ dominantly decays into $e$ and chargino $\tilde{\chi}_1^\pm$. This is very different from the
  situation in point 1 in which $\tilde{\nu}$ decays into $\nu$ and the LSP, both being undetected. Now, the
  presence of a charged lepton in the decay of $\tilde{\nu}$ allow us to detect the $\tilde{C}\tilde{C}$ processes.
  $\tilde{C}\tilde{C}$ can also be detected through cascade decays on the $\tilde{q}$ side.
- $\tilde{q}$ has also dominant decays into $q \tilde{\chi}^\pm$.
- $\tilde{\chi}_1^\pm$ decays dominantly into quarks and LSP. The branching ratio of its decay into
  charged leptons $e, \mu$ and LSP is of the order of 19 %.
- $\tilde{\chi}_2^\pm$ has three comparable dominant decays into higgs $H_2^0$ or $W$ and neutralinos.
- $\tilde{\chi}_2^0$ decays dominantly into $q$ or $\nu$ pairs and the LSP.
- $\tilde{\chi}_3^0$ and $\tilde{\chi}_4^0$ decay dominantly into the $H_2^0$ higgs and $\tilde{\chi}^0$.

It follows that, in our example, when all the channels of the cascade decays are taken
into consideration, the dominant signature for both $\tilde{N}\tilde{C}$ and $\tilde{C}\tilde{C}$ processes is again one
electron, jets and missing energy. Due to the cascade decay, $\tilde{C}\tilde{C}$ processes can now be
detected but, in this example, they do not distinguish from $\tilde{N}\tilde{C}$.

The most serious background of such events is the same as the previous one i.e. $t\bar{b}$
events with one electron coming from the top side and the single $W$ production $ep \rightarrow \nu W X$
followed by the decay $W \rightarrow ev$.

And for example, Figs. 6a-6d show the distributions of $P_t^e$, $\eta$, $E_{acc}$ of the electron and
the $P_{t_{\text{mis}}}$ distribution of the $\tilde{N}\tilde{C}$ process with the dominant decay for $\tilde{c}$, with $\tilde{q} \rightarrow q\tilde{\chi}_1^\pm$,
and with the dominant decay for the $\tilde{\chi}_1^\pm$ giving rise to a signature with one electron.

Figs. 7a-7d show the distribution of the same quantities for $\tilde{C}\tilde{C}$ process with the
dominant decay for $\tilde{\nu}$ and the same decays for $\tilde{q}$ and $\tilde{\chi}_1^\pm$ as above giving also rise to a
signature with one electron.

Due to slightly lower $P_t^e$ and $P_{t_{\text{mis}}}$, this $\tilde{C}\tilde{C}$ process is more affected by the the previous
set of cuts than the $\tilde{N}\tilde{C}$ process. Consequently, the sample of supersymmetric events is
simply enhanced by the contribution of the $\tilde{C}\tilde{C}$ process.

Taking both $\tilde{N}\tilde{C}$ and $\tilde{C}\tilde{C}$ processes with the cross sections of table 2, taking also
into consideration all the channels of the cascade decays and considering the previous
signature with one electron, we obtain of the order of 45 events with the same previous
set of cuts (the background remains off course unchanged).

Cascade decays of supersymmetric particles are also responsible for signatures with
multi (charged)leptons (plus jets and missing energy). In our present example, the signa-
ture with multi-leptons is not the dominant one. Nevertheless $\tilde{N}\tilde{C}$ and $\tilde{C}\tilde{C}$ events with,
for example, the signature in 2e, jets and missing energy or with the signature in e, μ, jets and missing energy (in which the charged leptons may come not only from sleptons but also from charginos or neutralinos of the cascade decay) may have less background. The most serious background is likely to be again tb events in which 2e or e,μ are coming from the t and b.

With \( E_{\text{acc}} < 1 \text{ GeV} \) and \( P_t^l > 5 \text{ GeV} \) for charged leptons and requiring \( P_t^l > 45 \text{ GeV} \) for the hardest charged lepton, and with \( P_t^{\text{miss}} > 50 \text{ GeV} \), we obtain less than 1 event of tb background for a top mass of 150 GeV for each of the two signatures.

Taking our example of cascade decays, without making any distinctions between \( \bar{N}C \) and \( C\bar{C} \) (with the cross section of table 2), considering events with the signature in 2e or in e,μ, we obtain of the order of 10 events.

3 Detection limits in the equal mass case

The total cross section for \( m_\tilde{\nu} = m_\tilde{q} = 325 \text{ GeV} \) is of the order of \( 2.5 - 3.0 \times 10^{-2} \text{ pb} \), see [2].

We assume the simplest decays for \( \tilde{e}, \tilde{q} \) into e, q and the LSP \( \tilde{\nu}_1 \) giving the signature e, jets and missing energy.

Fig. 8a. shows the percentage of events that pass the set of cuts defined in 2.1 for two different masses of \( \tilde{\nu}_1 \). For \( m_\tilde{\nu} + m_\tilde{q} > 600 \text{ GeV} \) this percentage reaches a plateau at a value of the order of 70 - 75 % with few differences between the two LSP masses considered. The attainable mass is limited by the cross sections around 325 GeV. Above this limit, the ratio \( \text{signal}/\sqrt{\text{background}} \) begins to be smaller than 3.

4 Detection limits in the unequal mass case

\( \tilde{q} \) may have a higher mass than the \( \tilde{\nu} \). We take the cross sections from [2] and we assume again the simplest decays for \( \tilde{e}, \tilde{q} \) into e, q and the LSP.

Taking the set of cuts of 2.1, fig. 8b shows the contours in the \( m_{\tilde{\nu}}, m_{\tilde{q}} \) plane inside which we obtain more than 20 events (i.e. \( \text{signal}/\sqrt{\text{background}} \) greater than 3) for two different masses for the LSP.

The attainable masses in the domain \( m_{\tilde{\nu}}, m_{\tilde{q}} \) above 250 GeV is limited by the cross sections.

Although the cross sections are higher for smaller \( m_{\tilde{\nu}} \) and \( m_{\tilde{q}} \) (respectively of the order of 150 GeV and 200 to 300 GeV), the cut on \( P_t^{\text{sc}} \) affects the accessible \( \tilde{\nu} \) mass region below 200 GeV, in the case of a LSP mass of 100 GeV.

5 Conclusion

The detection of the supersymmetric signal that comes from the production of \( \tilde{l} \) and \( \tilde{q} \) at the LEP/LHC looks promising.

In one example at \( m_{\tilde{\nu}} = m_{\tilde{q}} = 250 \text{ GeV} \) of the equal masses case, assuming the simplest decay, we obtain of the order of 60 events for the signal and 10 events for the tb events, with top masses between 100 and 200 GeV, and 25 events for the \( ep \rightarrow \nu WX \) events. Assuming the cascade decays in this particular example, we obtain of the order of 45 events for the dominant signature with one electron.

Nevertheless, detailed simulations are needed for the study of the background coming from the single W production \( ep \rightarrow \nu WX \) followed by the decay \( W \rightarrow ev \).
Cascade decays allow signatures with more than one charged leptons. In our example, although the signature with, for example, 2 electrons is not the dominant one, we expect very little background from tb events i.e.: less than 1 event for $m_t = 150 \text{ GeV}$.

As far as the detection limits are concerned, the equal masses case assuming the simplest decay would allow to set a limit of the order of 650 GeV for the sum of the masses. This limit is 550 - 600 GeV in the case of unequal $\hat{c}$ and $\hat{q}$ masses, assuming the simplest decay into a light LSP.

Acknowledgements

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References

[1] R.Rückl and also J. Feltesse these proceedings.


The numerical values for the masses of the charginos and neutralinos, cross sections and branching ratios for the two points of the parameter space considered have been provided by this group.


[9] J.Vermaseren, private communication. See also these proceedings.
Table 1
The gaugino masses

<table>
<thead>
<tr>
<th>$v_2/v_1 = 2$</th>
<th>Point 1</th>
<th>Point 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>250 GeV</td>
<td>200 GeV</td>
</tr>
<tr>
<td>$\mu$</td>
<td>-600 GeV</td>
<td>-150 GeV</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}^\pm}$</td>
<td>255.0 GeV</td>
<td>155.3 GeV</td>
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<tr>
<td>$m_{\tilde{\chi}^0_1}$</td>
<td>608.7 GeV</td>
<td>226.8 GeV</td>
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<tr>
<td>$m_{\tilde{\chi}^0_3}$</td>
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<td>143.9 GeV</td>
</tr>
<tr>
<td>$m_{\tilde{\chi}^0_4}$</td>
<td>609.2 GeV</td>
<td>225.7 GeV</td>
</tr>
</tbody>
</table>

Table 2
The cross sections

| | Point 1 | | Point 2 |
|----------------------------------|---------|----------------|
| $\sigma(ep \rightarrow \tilde{\nu}_L \tilde{q}_L) = 2.111 \times 10^{-1} pb$ | $\sigma(ep \rightarrow \tilde{\nu}_L \tilde{q}_L) = 1.660 \times 10^{-1} pb$ |
| $\sigma(ep \rightarrow \tilde{\nu}_L \tilde{q}_L) = 8.811 \times 10^{-2} pb$ | $\sigma(ep \rightarrow \tilde{\nu}_L \tilde{q}_L) = 7.716 \times 10^{-2} pb$ |
| $\sigma(ep \rightarrow \tilde{\nu}_R \tilde{\nu}_R) = 3.377 \times 10^{-2} pb$ | $\sigma(ep \rightarrow \tilde{\nu}_R \tilde{\nu}_R) = 2.200 \times 10^{-2} pb$ |
| $\sigma(ep \rightarrow \tilde{\nu}_L \tilde{\nu}_R) = 9.493 \times 10^{-3} pb$ | $\sigma(ep \rightarrow \tilde{\nu}_L \tilde{\nu}_R) = 1.000 \times 10^{-2} pb$ |
| $\sigma(ep \rightarrow \tilde{\nu}_R \tilde{\nu}_L) = 3.224 \times 10^{-3} pb$ | $\sigma(ep \rightarrow \tilde{\nu}_R \tilde{\nu}_L) = 3.400 \times 10^{-3} pb$ |
Figure captions

Fig. 1a: $P_t^{\text{mis}}$ in GeV for $\tilde{C}C$ events for the point 1 of the parameter space.

Fig. 1b: $P_t^{\text{mis}}$ in GeV for CC DIS events.

Fig. 2a: Pseudorapidity of the electron from the $\tilde{c}$ decay for $\tilde{N}C$ events for the point 1 of the parameter space.

Fig. 2b: Pseudorapidity of electron from the real $W$ of the top decay for a top mass of 150 GeV.

Fig. 3a: $E_{\text{acc}}$ in GeV of the electron from the $\tilde{c}$ decay for $\tilde{N}C$ events for the point 1.

Fig. 3b: $E_{\text{acc}}$ in GeV of the electron from the real $W$ of the top decay for a top mass of 150 GeV.

Fig. 4a: $P_t^{\text{mis}}$ in GeV for $\tilde{N}C$ events for the point 1.

Fig. 4b: $P_t^{\text{mis}}$ in GeV of top events for a top mass of 150 GeV.

Fig. 5a: $P_t^{\tilde{e}}$ in GeV of the electron from the decay $\tilde{c}$ for the point 1.

Fig. 5b: $P_t^\nu$ in GeV from the real $W$ of the top decay for a top mass of 150 GeV.

Fig. 6a: $P_t^\nu$ in GeV of the electron from the $\tilde{c}$ decay for the point 2.

Fig. 6b: Pseudorapidity of the electron from the $\tilde{c}$ decay for the point 2 of the parameter space and one channel of the cascade decay.

Fig. 6c: $E_{\text{acc}}$ in GeV of the electron from the $\tilde{c}$ decay for the point 2.

Fig. 6d: $P_t^{\text{mis}}$ in GeV for $\tilde{N}C$ for point 2.

Fig. 7a: $P_t^\nu$ in GeV of the electron from the $\tilde{\nu}$ decay for the point 2.

Fig. 7b: Pseudorapidity of the electron from the $\tilde{\nu}$ decay for the point 2.

Fig. 7c: $E_{\text{acc}}$ in GeV of the electron from the $\tilde{\nu}$ decay for the point 2.

Fig. 7d: $P_t^{\text{mis}}$ in GeV for $\tilde{C}C$ events for point 2.

Fig. 8a: Percentage of events passing the set of cuts of section 2.1 vs $m_{\tilde{c}} + m_{\tilde{q}}$ in GeV assuming the simplest decays for $\tilde{c}$ and $\tilde{q}$ produced in $\tilde{N}C$, and assuming two LSP masses i.e. 0 GeV and 100 GeV.

Fig. 8b: Detection limits in the $m_{\tilde{c}}, m_{\tilde{q}}$ plane for $\tilde{N}C$ assuming the simplest decay ($m_{\tilde{q}}$ in GeV on the vertical axis and $m_{\tilde{c}}$ in GeV on the horizontal axis). Taking the set of cuts of section 2.1, the lines show the contours, for two LSP masses, in the $m_{\tilde{c}}, m_{\tilde{q}}$ plane inside which we obtain more than 20 events, i.e. $\text{signal}/\sqrt{\text{background}}$ greater than 3.