SUSY-P5: Chargino / Neutralino Analysis in the Fully Hadronic Final State

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The fully hadronic final states of two signal processes from an mSUGRA inspired scenario (SUSY-P5) are studied within a full simulation of the LDC’ detector model. These are chargino pair and neutralino pair production, i.e. $e^+e^- \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$ and $e^+e^- \to \tilde{\chi}^0_2 \tilde{\chi}^0_2 \to q\bar{q} \tilde{\chi}^0_1$. Both processes have to be separated sufficiently from all background to measure the respective production cross sections and extract the masses of the involved bosinos, $m(\tilde{\chi}^\pm_1)$, $m(\tilde{\chi}^0_2)$ and $m_{LSP} = m(\tilde{\chi}^0_1)$. This is achieved by fitting the energy spectra of the reconstructed gauge bosons while taking into account the finite width of the boson mass. From simulation data corresponding to 500 fb$^{-1}$ of luminosity, a mass resolution of about 0.5 GeV seems to be achievable.

1 Introduction

Due to the clean environment and precisely known initial state at the ILC, it will be possible to measure very small signal cross sections and extract the masses of SUSY particles even from fully hadronic final states. As an example, from the SUSY-P5 scenario [2], pair production of charginos ($\tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$) and neutralinos ($\tilde{\chi}^0_2 \tilde{\chi}^0_2$) and their subsequent hadronic decays ($q\bar{q} \tilde{\chi}^0_1$) are studied. To successfully extract the masses of intermediate SUSY particles from a fully hadronic final state, it is mandatory to reduce the background to a minimum. Especially difficult is the mutual separation of both signal processes. Four jets need to be assigned to two gauge bosons, either two $W$ or two $Z$ bosons, depending on whether they originated from a decaying chargino or neutralino. In addition, a considerable amount of missing energy and momentum carried away by two of the lightest supersymmetric particles (LSPs) impede a complete reconstruction of the final state.

All Monte Carlo samples are part of the DESY mass production [3]. The events are generated with Whizard [4], run through the full simulation of the LDCPrime detector model and finally reconstructed with MarlinReco [5] using Pandora Particle Flow (PFlow) [6].

2 Selection strategies and kinematic fits

This study concentrates on the reduction of SM background using a few very basic requirements and a kinematic fit to improve separation of the chargino from the neutralino signal. A rough background scan as depicted in Fig. 1 (a) shows $WW$ and $WWZ$ production to be the dominant source of SM background. Especially, 6-fermion final states from $WWZ$ production, with an invisible $Z$-decay, i.e. $q\bar{q}q\bar{q}\nu\bar{\nu}$, constitute a nearly irreducible background component. However, the processes shown in Fig. 1 are not normalised to the same luminosity. While the SUSY signal processes correspond to 500 fb$^{-1}$, background samples were only available for $\approx 20-50$ fb$^{-1}$ for QCD multijet production ($qq$, $qqqq$ final states) and

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1 fb\(^{-1}\) for \(\gamma\gamma/e\gamma\) processes. Background from other SUSY processes has also not yet been considered, but it is expected to not render the preliminary results of this study obsolete.

Some very basic requirements reduce leptonic events and events from multijet QCD production (see caption of Fig. 1), while the very similar neutralino signal is hardly affected. To separate the chargino and neutralino signals from each other, two hypotheses are compared for the invariant di-jet masses, which can either form a 3\(^{\text{rd}}\)-order polynomial (4+2 par. to describe the edge positions) convoluted with a Gaussian (see text). The resulting \(\chi^2\)-values for each hypothesis are plotted against each other, so that the final selection criterion for chargino events results in:

\[
\begin{align*}
\chi^2(W, j_1j_2) + \chi^2(W, j_3j_4) &< 2 \quad \text{with} \quad \chi^2(W, j_kj_l) = (m_W - m(j_k, j_l))^2/(5 \text{ GeV})^2 \\
\chi^2(Z, j_1j_2) + \chi^2(Z, j_3j_4) &> 4 \quad \text{with} \quad \chi^2(Z, j_kj_l) = (m_Z - m(j_k, j_l))^2/(5 \text{ GeV})^2.
\end{align*}
\]

A more detailed description of the entire procedure is given in [7]. After the above selection of chargino-type events, the energy spectrum of di-jet masses in Fig. 1 (b) largely resembles that of the \(W\) boson\(^a\). The spectrum is fitted with an empirical function consisting of a 3\(^{\text{rd}}\)-order polynomial (4+2 par. to describe the edge positions) convoluted with a Gaussian (2 par.) yielding the following values for the bosino masses:

\[
\begin{align*}
m(\tilde{\chi}_1^+) &= 219.7 \pm 1.54 \text{ GeV} \quad \rightarrow \quad 216.5 \text{ GeV} \quad \text{(nominal chargino mass)} \\
m(\tilde{\chi}_1^0) &= 121.2 \pm 0.59 \text{ GeV} \quad \rightarrow \quad 115.7 \text{ GeV} \quad \text{(nominal neutralino/LSP mass)}.
\end{align*}
\]

The central fit values differ rather much from the nominal bosino masses in the SUSY-P5 scenario. However, for an analysis of real data, such a shift can be compensated by tuning the MC distribution such that the experimental data is well reproduced.

A different approach postpones the reduction of events from SM background in favour of a slightly better separation of chargino and neutralino signals with the help of a 2-dim. cut in the \((V_1, V_2)\) mass plane, with \(V\) being a \(W\) or \(Z\) boson (see Fig. 2). The cut is tuned, but not yet optimised, for a high efficiency and purity of the chargino pair production \((\varepsilon \times \pi)\).

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\(^a\)SM background is multiplied by 10, since so far the luminosity is only about 50 fb\(^{-1}\) for most background processes. It is also not included in the fit, while the neutralino pair background is taken into account.
A simple kinematic 1C-fit, requiring equal di-jet masses (EMC), is applied to the three di-jet combinations of all events that can be clustered into 4 jets. The fit is meant to help find the correct jet-pairings, improve the mass and energy resolutions for the gauge bosons and thus, ultimately, the starting point for a fit to the $W$ ($Z$) boson energy spectra. The di-jet masses populating the $(V_1, V_2)$ mass plane in Fig. 2 correspond to the jet-pairings with the best fit probability and are assumed to be the correct ones.

![Figure 2: Selection of chargino-type events: all events between the middle (red) and the lower (orange) lines are assumed to originate from chargino decays, while events between the middle and upper lines are taken to be neutralino decays.](image)

### 3 Physics-driven fit to the energy spectrum of the $W$ boson

Having selected the events between the lower two lines in Fig. 2 as chargino events, the energy spectrum of the corresponding gauge boson is then fitted with the masses of the SUSY particles as free parameters. However, this time, not an empirical fit function is used but a physics-driven function. Firstly, the gauge boson’s energy and momentum are expressed in terms of the three relevant masses $m_2 = m(\tilde{\chi}_1^\pm, \tilde{\chi}_2^0)$, $m_1 = m(\tilde{\chi}^0_1) = m_{LSP}$, and $m_V = m_W, Z$:

$$E_V = \frac{1}{m_2} \left( m_2^2 - m^2 - m_1^2 \right) \quad \text{and} \quad |\vec{p}_V| = \frac{1}{m_2} \sqrt{ (m_2^2 - m^2 - m_1^2)^2 - 4 m_1^2 m_2^2}$$

From this the inverse expression has to be calculated for either the chargino (neutralino) mass. Next, the effect of the finite boson mass width is added by convolusion with a Breit-Wigner function $BW(m^0_V, \gamma, m_V - \Delta m^2, m_V + \Delta m^2)$ and, finally, some Gaussian smearing is added to the emerging fit function:

$$E_{\text{spec}}' = \text{bin}_i \cdot BW\left(m^0_V, \gamma, m_V - \frac{\Delta m^2}{2}, m_V + \frac{\Delta m^2}{2}\right) + \text{E-spec}$$

$$\text{bin}_i = \frac{1}{2} - \frac{a}{2} \left( \frac{x m_2 - E_b E_V}{\sqrt{E_b^2 - m_2^2 \cdot p_V}} \right) \cdot \left[ \Theta \left( \frac{a + 1}{\sigma_j} \right) - \Theta \left( \frac{a - 1}{\sigma_j} \right) \right] + \frac{a b}{2\pi} \left( e^{-\frac{(R-1)^2}{2(\sigma_j^2)^2}} - e^{-\frac{(R+1)^2}{2(\sigma_j^2)^2}} \right)$$

with: $b = \frac{m_2}{\sqrt{E_b^2 - m_2^2 \cdot p_V}}$, $R = \frac{x m_2 - E_b E_V}{\sqrt{E_b^2 - m_2^2 \cdot p_V}}$, $\sigma_j$: jet energy resolution.

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Figure 3: Fit to the energy spectrum of the $W$ boson (a) on generator level and (b) after reconstruction and a first rough chargino selection.

The fit values for the reconstructed bosino masses are actually quite close to the nominal generator level values:

$$m(\tilde{\chi}^\pm_1) = 215.3 \pm 2.45 \text{ GeV} \quad \leftrightarrow \quad 216.5 \text{ GeV} \quad \text{(nominal chargino mass)}$$

$$m(\tilde{\chi}^0_1) = 115.2 \pm 0.46 \text{ GeV} \quad \leftrightarrow \quad 115.7 \text{ GeV} \quad \text{(nominal neutralino/LSP mass)}.$$

Although the error on the chargino mass is still large, this is expected to be reduced by a more sophisticated selection (higher $\varepsilon \times \pi$) and a simultaneous fit to the cross sections of both signal processes, i.e. chargino and neutralino pair production. The cross sections could then serve as a further input to the fit of the gauge boson energy spectra.

While only the dominant SM background ($WWZ \rightarrow q\bar{q}q\bar{q}\nu\bar{\nu}$) is considered for the distributions in Fig. 3 (a,b), signal and background processes are normalised to the same luminosity of $500 \text{ fb}^{-1}$. This provides an estimate of the sensitivity of the chargino (neutralino) selection to a possible contamination from SM background.

4 Conclusions and outlook

Physics analyses using a full detector simulation play an important rôle in the ongoing optimisation effort for the ILC detector. This study, although performed on simulation data of a previous detector model (LDCPrime02Sc), constitutes one part of the general effort for the ILD detector concept. In cases where the gauge boson masses are reconstructed from 4-jet final states, the mass and energy resolution is expected to improve drastically due to the interplay between a highly segmented calorimeter with tracking ability for neutral particles and the new approach of Particle Flow algorithms. Together with more sophisticated fits to the resulting gauge boson energy spectra, mass resolutions of 0.5-1 GeV are achievable for those SUSY particles accessible to the ILC ($\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2$, and $\tilde{\chi}^0_1$).

Next steps will be to include all SM and relevant SUSY background, optimise the selection and fit procedures and utilise different polarisation scenarios to improve the S/B-ratio.
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