LHC/ILC interplay for challenging SUSY scenarios

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Combined analyses at the Large Hadron Collider and at the International Collider are important to unravel a difficult region of supersymmetry that is characterized by scalar SUSY particles with masses around 2 TeV. Precision measurements of masses, cross sections and forward-backward asymmetries allow to determine the fundamental supersymmetric parameters even if only a small part of the spectrum is accessible. Mass constraints for the heavy particles can be derived.

1 Introduction

Supersymmetry (SUSY) is one of the best-motivated candidates for physics beyond the Standard Model (SM). If experiments at future accelerators, the Large Hadron Collider (LHC) and the International Linear Collider (ILC), discover SUSY they will also have to determine precisely the underlying SUSY-breaking scenario. Scenarios where the squark and slepton masses are very heavy (multi-TeV range) as required, for instance, in focus-point scenarios (FP) [2], are particularly challenging. It is therefore of particular interest to verify whether the interplay of an LHC/ILC analysis [3] could unravel such models with very heavy sfermions. Here we combine only results from the LHC with results from the 1st stage of the ILC with $\sqrt{s} \leq 500$ GeV.

Methods to derive the SUSY parameters at collider experiments have been worked out, for instance in [4, 5]. In [6, 7, 8] the chargino and neutralino sectors have been exploited at the ILC to determine the MSSM parameters. However, in most cases only the production processes have been studied. Furthermore, it has been assumed that the masses of the virtual scalar particles are already known. Exploiting spin effects in the whole production-and-decay process in the chargino/neutralino sector [9], it has been shown in [10] that, once the chargino parameters are known, useful indirect bounds for the mass of the heavy virtual particles could be derived from forward–backward asymmetries of the final lepton $A_{\mathrm{FB}}(\ell)$.

Here a FP-inspired scenario is discussed that is characterized by a ~ 2 TeV scalar particles sector [11]. The analysis is performed entirely at the EW scale, without any reference to the underlying SUSY-breaking mechanism.

2 Case study at LHC and ILC

We study chargino production $e^- + e^+ \to \tilde{\chi}_1^+ + \tilde{\chi}_1^-$ with subsequent leptonic $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + \ell^\pm + \nu$ and hadronic decays $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + \bar{q}_d + q_u$, where $\ell = e, \mu$, $q_u = u, c$, $q_d = d, s$. The production process contains contributions from γ- and Z^0-exchange in the s-channel and

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$m_{\tilde{\chi}^{\pm}_{1,2}}$	$m_{\tilde{\chi}^{0}_{1,2,3,4}}$	$m_{\tilde{\nu}_e,\tilde{e}_{\mathrm{R,L}}}$	$m_{\tilde{q}_{\mathrm{R,L}}}$	$m_{\tilde{t}_{1,2}}$	$m_{\tilde{g}}$
117, 552	59, 117, 545, 550	1994, 1996, 1998	2002, 2008	1093, 1584	416

Table 1: Masses of the SUSY particles [in GeV].

from $\tilde{\nu}$-exchange in the t-channel. The decay processes are mediated by $W^{\pm}$, $\tilde{\ell}_{\mathrm{L}}$, $\tilde{\nu}$ or by $\tilde{q}_{d\mathrm{L}}$, $\tilde{q}_{u\mathrm{L}}$ exchange. The masses and eigenstates of the neutralinos and charginos are determined by the fundamental SUSY parameters: the $U(1)$, $SU(2)$ gaugino mass parameters M_1, M_2, the Higgs mass parameter μ and the ratio of the vacuum expectation values of the two neutral Higgs fields, $\tan\beta = \frac{v_2}{v_1}$. In our case study the MSSM parameters at the EW scale are given by: $M_1 = 60$ GeV, $M_2 = 121$ GeV, $M_3 = 322$ GeV, $\mu = 540$ GeV, $\tan\beta = 20$. The derived masses of the SUSY particles are listed in Table 1.

2.1 Expectations at the LHC

All squarks in this scenario are kinematically accessible at the LHC. The largest squark production cross section is for $\tilde{t}_{1,2}$. However, with stops decaying mainly to $\tilde{g}t$ (with $BR(\tilde{t}_{1,2} \to \tilde{g}t) \sim 66\%$), where background from top production will be large, no new interesting channels are open in their decays.

Since the gluino is rather light in this scenario, several gluino decay channels can be exploited. The largest branching ratio for the gluino decay in our scenario is a three-body decay into neutralinos, $BR(\tilde{g} \to \tilde{\chi}^0_2 b\bar{b}) \sim 14\%$, followed by a subsequent three-body leptonic neutralino decay $BR(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+\ell^-)$, $\ell = e, \mu$ of about 6%. In this channel the dilepton edge will be clearly visible [3]. The mass difference between the two light neutralino masses can be measured from the dilepton edge with an uncertainty of about $\delta(m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}) \sim 0.5$ GeV [12]. The gluino mass can be reconstructed in a manner similar to the one proposed in [13] and a relative uncertainty of $\sim 2\%$ can be expected.

2.2 Expectations at the ILC

At the first stage of the ILC, $\sqrt{s} \leq 500$ GeV, only light charginos and neutralinos are kinematically accessible. However, in this scenario the neutralino sector is characterized by very low production cross sections, below 1 fb, so that it might not be fully exploitable [11]. Only the chargino pair production process has high rates and we use $\sqrt{s} = 350$ and 500 GeV. The chargino mass can be measured in the continuum, with an error of about 0.5 GeV [14]. This can serve to optimize the ILC scan at the threshold which, can be used to determine the light chargino mass very precisely, to about [14]:

$$m_{\tilde{\chi}^{\pm}_1} = 117.1 \pm 0.1 \text{ GeV}. \tag{1}$$

The mass of the lightest neutralino $m_{\tilde{\chi}^0_1}$ can be derived, either from the lepton energy distribution $(BR(\tilde{\chi}^-_1 \to \tilde{\chi}^0_1 \ell^- \bar{\nu}_\ell) \sim 11\%)$ or from the invariant mass distribution of the two jets $(BR(\tilde{\chi}^-_1 \to \tilde{\chi}^0_1 q_d \bar{q}_u) \sim 33\%)$. We take [14]

$$m_{\tilde{\chi}^0_1} = 59.2 \pm 0.2 \text{ GeV}. \tag{2}$$

Together with the information from the LHC a mass uncertainty for the second light neutralino of about

$$m_{\tilde{\chi}_2^0} = 117.1 \pm 0.5 \text{ GeV} \qquad (3)$$

can be assumed.

We identify the chargino pair production process in the fully leptonic and semileptonic final states and estimate an overall selection efficiency of 50%. The W^+W^- production is the dominant SM background. For the semileptonic (slc) final state, this background can be efficiently reduced from the reconstruction of the hadronic invariant mass. In Table 2, we list cross sections multiplied by the branching fraction $B_{slc} = 2 \times BR(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \bar{q}_d q_u) \times BR(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell^- \bar{\nu}) + [BR(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell^- \bar{\nu})]^2 \sim 0.34$ (first two families) including a selection efficiency of $e_{slc} = 50\%$. The error includes the statistical uncertainty of the cross section and A_{FB} (see [11]) based on $\mathcal{L} = 200 \text{ fb}^{-1}$ in each polarization configuration, $(P_{e^-}, P_{e^+}) = (-90\%, +60\%)$ and $(+90\%, -60\%)$, and a relative uncertainty in the polarization of $\Delta P_{e^\pm}/P_{e^\pm} = 0.5\%$ [15].
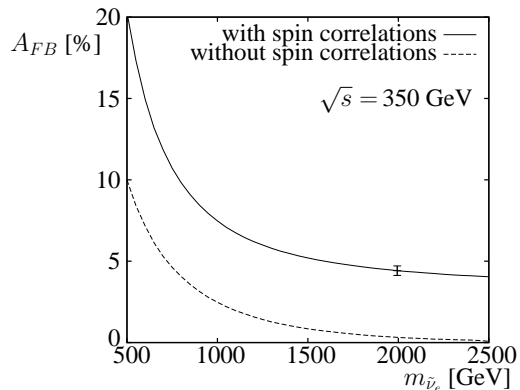

Figure 1: Forward–backward asymmetry of the final e^- [11] as a function of $m_{\tilde{\nu}_e}$. For nominal value of $m_{\tilde{\nu}_e} = 1994$ GeV the expected experimental errors are shown.

3 Parameter determination

We determine the underlying SUSY parameters in several steps:

3.1 Analysis without A_{FB}

Only the masses of $\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and the chargino pair production cross section, including the fully leptonic and the semileptonic decays have been used as observables. A four-parameter fit for the parameters M_1, M_2, μ and $m_{\tilde{\nu}}$ has been applied, for fixed values of $\tan\beta = 5$, 10, 15, 20, 25, 30, 50 and 100. Due to the strong correlations among parameters [11], fixing of $\tan\beta$ is necessary. We perform a χ^2 test and obtain the following 1σ bounds for the SUSY parameters:

$$59.4 \leq M_1 \leq 62.2 \text{ GeV}, \quad 118.7 \leq M_2 \leq 127.5 \text{ GeV},$$
$$450 \leq \mu \leq 750 \text{ GeV}, \quad 1800 \leq m_{\tilde{\nu}_e} \leq 2210 \text{ GeV}.$$

3.2 Analysis including leptonic A_{FB}

We now extend the fit by using as an additional observable the leptonic forward–backward asymmetry, which is sensitive to $m_{\tilde{\nu}}$. Proper account of spin correlations is crucial, see Fig. 1. The $SU(2)$ relation between the two virtual masses $m_{\tilde{\nu}}$ and $m_{\tilde{e}_\text{L}}$ has been assumed.

(P_{e^-}, P_{e^+})	$\sqrt{s} = 350$ GeV		$\sqrt{s} = 500$ GeV	
	$(-90\%, +60\%)$	$(+90\%, -60\%)$	$(-90\%, +60\%)$	$(+90\%, -60\%)$
$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)$	6195.5	85.0	3041.5	40.3
$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)\, B_{slc}\, e_{slc}$	1062.5±4.0	14.6±0.7	521.6±2.3	6.9±0.4
$A_{\mathrm{FB}}(\ell^-)/\%$	4.42±0.29	–	4.62±0.41	–
$A_{\mathrm{FB}}(\bar{c})/\%$	4.18±0.74	–	4.48±1.05	–

Table 2: Cross sections for the process $e^+ e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$ [in fb] and forward–backward asymmetries A_{FB} in the leptonic $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell^- \bar{\nu}$ and hadronic $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 s\bar{c}$ decay modes, for different beam polarization P_{e^-}, P_{e^+}. Concerning the errors, see text and [11].

The multiparameter fit strongly improves the results. No assumption on $\tan\beta$ has to be made. We find

$$59.7 \leq M_1 \leq 60.35 \text{ GeV}, \quad 119.9 \leq M_2 \leq 122.0 \text{ GeV}, \quad 500 \leq \mu \leq 610 \text{ GeV},$$
$$14 \leq \tan\beta \leq 31, \quad 1900 \leq m_{\tilde{\nu}_e} \leq 2100 \text{ GeV}.$$

The constraints for the mass $m_{\tilde{\nu}_e}$ are improved by a factor of about 2 and for gaugino mass parameters M_1 and M_2 by a factor of about 5. The masses of heavy chargino and neutralinos are predicted to be within the ranges

$$506 < m_{\tilde{\chi}_3^0} < 615 \text{ GeV}, \quad 512 < m_{\tilde{\chi}_4^0} < 619 \text{ GeV}, \quad 514 < m_{\tilde{\chi}_2^\pm} < 621 \text{ GeV}.$$

3.3 Analysis including hadronic and leptonic A_{FB}: test of $SU(2)$

In the last step both the leptonic and hadronic forward–backward asymmetries have been used. With the constraints for the squark masses from the LHC, the hadronic forward–backward asymmetry could be used to control the sneutrino mass. The leptonic forward–backward asymmetry provides constraints on the selectron mass and the $SU(2)$ relation between selectron and sneutrino masses could be tested. A six-parameter fit for the parameters M_1, M_2, μ, $m_{\tilde{\nu}}$, $m_{\tilde{e}_{\mathrm{L}}}$ and $\tan\beta$ has been applied, resulting in the following constraints:

$$59.45 \leq M_1 \leq 60.80 \text{ GeV}, \quad 118.6 \leq M_2 \leq 124.2 \text{ GeV}, \quad 420 \leq \mu \leq 770 \text{ GeV},$$
$$11 \leq \tan\beta \leq 60, \quad 1900 \leq m_{\tilde{\nu}_e} \leq 2120 \text{ GeV}, \quad 1500 \text{ GeV} \leq m_{\tilde{e}_{\mathrm{L}}}.$$

The limits are somewhat weaker comparing to the previous case, but we get now constraints for one additional parameter: the selectron mass.

4   Conclusions and outlook

Scenarios with heavy scalar particles are challenging for determining the MSSM parameters. A very powerful tool in this kind of analysis turns out to be the forward–backward asymmetry. This asymmetry is strongly dependent on the mass of the exchanged heavy particle. If the $SU(2)$ constraint is applied, the slepton masses can be determined to a precision of about 5% for masses around 2 TeV at the ILC running at 500 GeV. In addition powerful predictions for the heavier charginos/neutralinos can be made.

In future developments it will be crucial to add radiative corrections which are so far available separately for the production [16] and decays [17]. Full simulations of the whole production-and-decay process will be necessary for precision physics at the ILC.

Acknowledgements

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