PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 69, No. 5
November 2007
pp. 843–847

Testing the supersymmetric QCD Yukawa coupling in a combined LHC/ILC analysis

A FREITAS[1,*] and P Z SKANDS[2]
[1]Institut für Theoretische Physik, Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich
[2]Theoretical Physics, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500, USA
[*]E-mail: afreitas@physik.unizh.ch

Abstract. In order to establish supersymmetry (SUSY) at future colliders, the identity of gauge couplings and the corresponding Yukawa couplings between gauginos, sfermions and fermions needs to be verified. A first phenomenological study for determining the Yukawa coupling of the SUSY-QCD sector is presented here, using a method which combines information from LHC and ILC.

Keywords. Supersymmetry; quantum chromodynamics.

PACS Nos 11.30.Pb; 14.80.Ly; 13.85.-t

One of the fundamental relations in softly broken supersymmetric theories is the equality between the Yukawa coupling $\hat{g}$ of a gaugino interacting with a fermion and an sfermion and the corresponding standard model (SM) gauge coupling g of a gauge boson and two (s)fermions, $g = \hat{g}$. At colliders, this relation can be investigated through the production cross-sections for SUSY particles. Within the minimal supersymmetric standard model (MSSM), it has been shown [1–4] that the SUSY Yukawa couplings in the electroweak sector can be precisely tested at the per cent level at a high-energy e^+e^- collider (ILC).

However, the analysis of the SUSY Yukawa coupling $\hat{g}_{\rm s}$ in the QCD sector is much more difficult. At the ILC this interaction could be studied in the process $e^+e^- \to q\tilde{q}^*\tilde{g}$, $\bar{q}\tilde{q}\tilde{g}$ [5], but suffers from very low rates and large backgrounds. At the LHC on the other hand, squarks and gluinos with masses below 2–3 TeV are abundantly produced, and their pair production cross-sections depend directly on $\hat{g}_{\rm s}$. However, measurements of total cross-sections are exceedingly difficult at hadron colliders, with typically only one or two specific decay channels of the squarks and gluinos experimentally accessible [6].

In this contribution, a combination of ILC and LHC measurements is considered, where the relevant branching ratios are to be determined at ILC and combined with exclusive cross-section measurements in selected channels at the LHC.

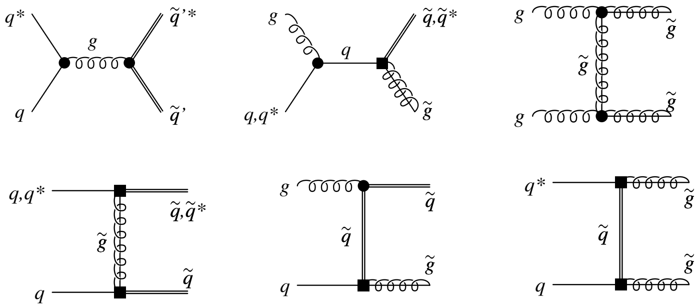

Figure 1. Examples for Feynman diagrams for partonic squark and gluino production in pp collisions. Dots indicate the gauge coupling $g_{\rm s}$, squares the Yukawa coupling $\hat{g}_{\rm s}$.

In pp collisions, squarks and gluinos can be produced in various combinations (see figure 1). The production of same-sign squarks ($\tilde{u}_{\rm L}\tilde{u}_{\rm L}, ...$) is especially interesting, since it only proceeds through the diagram in the lower left of figure 1, and thus depends solely on the SUSY Yukawa coupling $\hat{g}_{\rm s}$. In pp collisions this process dominantly produces $\tilde{u}$ and $\tilde{d}$ squarks, in direct proportion to the quark content of the proton.

While the typically lighter $\tilde{q}_{\rm R}$ almost exclusively decays directly into the lightest neutralino and a quark jet, thus not allowing charge tagging, for the heavier $\tilde{q}_{\rm L}$ the charge of the squark can be tagged through a chargino decay chain,

$$\tilde{u}_{\rm L} \to d\tilde{\chi}^+_1 \to dl^+\nu_l\tilde{\chi}^0_1, \quad \tilde{d}_{\rm L} \to u\tilde{\chi}^-_1 \to ul^-\bar{\nu}_l\tilde{\chi}^0_1. \tag{1}$$

The production of same-sign squarks with this decay channel will thus lead to two same-sign leptons, two hard jets and missing transverse energy in the final state. Other direct squark production processes on the other hand will tend to produce opposite-sign leptons.

A very problematic background can come from gluino pair and mixed gluino-squark production if $m_{\tilde{g}} > m_{\tilde{q}_{\rm L}}$. In this case, gluinos can decay into quarks and squarks, $\tilde{g} \to q\tilde{q}_{\rm L}$, generating a component of two same-sign squarks plus additional jets. This background is very challenging if the mass difference $m_{\tilde{g}} - m_{\tilde{q}_{\rm L}}$ is small, since then the additional jets from the gluino decay will be soft. In the following we will only consider a scenario where the mass difference $m_{\tilde{g}} - m_{\tilde{q}_{\rm L}}$ is sufficiently large to allow a veto on additional jets for gluino background reduction. We use a modification of the SPS1a scenario [7], where the gluino mass is raised to 700 GeV.

The most important backgrounds from standard model sources are $W^\pm W^\pm jj$, where j is a light-flavor jet, and semi-leptonic $t\bar{t}$, with the second lepton coming from the decay of a b quark. Due to the large total $t\bar{t}$ cross-section, this can result in a sizable background.

We compute numerical results for expected signal and background levels including some simple estimates for the detector response and resolution (see [8] for details), but do not perform a real experimental analysis. In our scenario, the chargino mainly decays into scalar taus, which subsequently decay into taus. To trace the charge explicitly, here we only consider the leptonic tau branching fraction in the decay chain

Table 1. Signal and background cross-sections for progressive application of cuts.

Cross-sections $\sum_{q=u,d,s,c}\sigma$ (fb)	Signal $\tilde{q}_L\tilde{q}_L$	Backgrounds **Sum**	$t\bar{t}$	$W^\pm W^\pm jj$	$\tilde{q}_L\tilde{g}$	$\tilde{q}_L\tilde{q}_L^*$	$\tilde{g}\tilde{g}$
Total	2100	–	8×10^5	–	7000	1350	3200
Preselection	49.2	384.6	177.7	–	136.4	23.2	47.3
b-veto	17.1	31.4	13.0	–	10.3	7.1	1.0
$\not{E} > 150$ GeV	15.1	22.2	6.1	–	9.0	6.2	0.9
$p_{\mathrm{T},j_3} < 50$ GeV	7.8	5.9	2.4	N/A	1.0	2.5	0.03
$p_{\mathrm{T},j_1} > 200$ GeV	**7.0**	**<4.9**	1.0	<0.7	0.8	2.3	0.03

$$\tilde{u}_L \xrightarrow{65\%} d\,\tilde{\chi}_1^+ \xrightarrow{100\%} d\,\tau^+\,\nu_\tau\,\tilde{\chi}_1^0 \xrightarrow{35\%} d\,\ell^+ + \not{E}, \quad \ell = e,\,\mu, \tag{2}$$

and similarly for $\tilde{d}_L$. Both signal and top and gluino backgrounds were simulated with PYTHIA 6.326 [9], while the $WWjj$ background was generated with MADEVENT [10]. The cross-sections for squark, gluino and top production were normalized with the K-factors for next-to-leading order QCD corrections [11], while for the $W^\pm W^\pm jj$ background only leading order results are available.

As a first step, the following pre-selection cuts are applied: at least 100 GeV transverse missing energy, at least 2 jets with $p_{\mathrm{T},j} > 100$ GeV, and two isolated leptons $\ell = e,\mu$ with $p_{\mathrm{T},\ell} > 7$ GeV. At this level, most backgrounds are still larger than the signal (see table 1).

Using a b-veto is effective against the gluino and $t\bar{t}$ backgrounds. A high efficiency of $\epsilon = 90\%$ reduces the background substantially, at the price of a high mistagging $D = 25\%$ rate for the signal. The large SM backgrounds can be further suppressed by a cut on the missing transverse energy $\not{E}$, with $\not{E} > 150$ GeV. At this point, the gluino-related backgrounds dominate. They are reduced by a cut on hard additional jets. By rejecting all events with $p_{\mathrm{T},j3} > 50$ GeV, the ratio of the signal to gluino background is markedly improved. Finally, increasing the transverse momentum cut on the first jet to $p_{\mathrm{T},j1} > 200$ GeV, the top background is suppressed further, resulting in the cross-section estimate in table 1. The signal-to-background ratio is 1.4, sufficient to allow a meaningful measurement. With an integrated luminosity of 100 fb^{-1}, the statistical error on the same-sign squark cross-section is 4.9%.

In order to obtain from the measured rates at the LHC the total squark production cross-section, the individual branching ratios (BRs) in the decay chain (eq. (2)) must be determined. Here we explore, how these could be extracted from measurements at ILC.

The chargino BRs can be determined from chargino pair production. Due to the large cross-section for that process, all possible chargino decay channels can be easily separated from backgrounds, and the expected error on the BR is about 1%.

In the given scenario the L-squarks are slightly too heavy to be accessible at a 1 TeV linear collider. Here, we instead analyse the production of squarks for a hypothetical e^+e^- collider with a center-of-mass energy of about 1.5 TeV.

The L-squarks can decay into the whole spectrum of charginos and neutralinos. While in our scenario the light charginos and neutralinos decay into taus, the heavier

Table 2. Combination of statistical and systematic errors for the same-sign squark cross-section at the LHC and the derivation of the strong SUSY-Yukawa coupling.

	$\sigma(\tilde{q}_L\tilde{q}_L)$ (%)	$\hat{g}_s/g_s$ (%)
LHC signal statistics	4.9	1.3
SUSY-QCD Yukawa coupling in $\tilde{q}_L\tilde{g}$ background	2.4	0.6
PDF uncertainty	10	2.4
NNLO corrections	8	2.0
Squark mass $\Delta m_{\tilde{q}_L} = 9$ GeV	6	1.5
$\mathrm{BR}(\tilde{q}_L \to q'\,\tilde{\chi}_1^\pm)$	8.2	2.0
	17.3	4.1

states have large BRs into gauge bosons, and can be distinguished through these channels (see [8] for details). The tau leptons in the final state can be identified in their hadronic decay mode with roughly 80% tagging efficiency.

For this work, Monte-Carlo samples for squark pair production in the different squark decay channels have been generated at the parton level with the tools of ref. [4]. Also the most relevant backgrounds have been simulated, stemming from double and triple gauge boson production as well as $t\bar{t}$ production. It is assumed that an integrated luminosity of 500 fb^{-1} is spent for a polarization combination $P(e^+)/P(e^-) = +50\%/-80\%$, which enhances the production cross-section both for $\tilde{u}_L$ and $\tilde{d}_L$ production. Here $\mp$ indicates left/right-handed polarization. The BRs are obtained from measuring the cross-sections of all accessible decay modes of the squarks and identifying the fraction of decays into one specific decay mode out of these.

Since the squarks are produced in charge-conjugated pairs, it is *a priori* difficult to distinguish up- and down-squarks in the final state. However, assuming universality between the first two generations, a separation between up- and down-type squarks can be obtained through charm tagging. According to ref. [12], a c-tagging efficiency of 40% is achievable for a purity of 90%. By combining the different decay channels, the following final state signatures are identified as interesting: $jj(n\tau)\not{E}$ with $n \in \{1,2,3,4\}$, $cc(n\tau)\not{E}$ with $n \in \{2,4\}$, $jj\tau\tau(Z/W)\not{E}$, $cc\tau\tau Z\not{E}$, where j indicates an untagged jet, c a tagged charm jet, and Z/W a hadronically decaying gauge boson where the invariant mass of the two jets combines to the given gauge boson mass. Since several squark decay channels can contribute to most of the final states above, one has to solve a linear equation system in order to derive the individual contributions. With this procedure we estimate the precision for the BRs of the squarks into charginos to be $\mathrm{BR}(\tilde{u}_L \to d\tilde{\chi}_1^+) = (67.7 \pm 3.2)\%$ and $\mathrm{BR}(\tilde{d}_L \to u\tilde{\chi}_1^-) = (63.9 \pm 5.2)\%$.

Based on the simulations for squark production at the LHC and the ILC presented above, one can now derive an estimate for the precision for the determination of the strong SUSY Yukawa coupling $\hat{g}_s$. The statistical uncertainty is combined with the most important systematic error sources in table 2. We considered the following systematic error sources. The remaining background from gluino production at the LHC introduces a systematic error since it depends on $\hat{g}_s$, which is estimated by varying $\hat{g}_s$. The uncertainty from the proton parton distribution functions (PDFs) is evaluated by comparing results for different CTEQ PDFs [13]. The uncertainty of the missing $\mathcal{O}(\alpha_s^2)$ radiative corrections are estimated by varying the renormalization scale of the $\mathcal{O}(\alpha_s)$ corrected cross-section within a factor two. Furthermore, the cross-section depends on the values of the squark masses, which according to ref. [6] can be determined with an error better than $\Delta m_{\tilde{q}_L} = 9$ GeV. Finally, the expected error for the determination of the squark branching ratios at the linear collider must be included. Combining all error sources in quadrature, it is found that the SUSY-QCD Yukawa coupling $\hat{g}_s$ can be determined with an error 4.1% in the given scenario.

References

[1] J L Feng, M E Peskin, H Murayama and X Tata, *Phys. Rev.* **D52**, 1418 (1995)
[2] S Y Choi *et al*, *Euro. Phys. J.* **C14**, 535 (2000)
S Y Choi, J Kalinowski, G Moortgat-Pick and P M Zerwas, *Euro. Phys. J.* **C22**, 563 (2001)
[3] M M Nojiri, K Fujii and T Tsukamoto, *Phys. Rev.* **D54**, 6756 (1996)
H C Cheng, J L Feng and N Polonsky, *Phys. Rev.* **D57**, 152 (1998)
[4] A Freitas, A v Manteuffel and P M Zerwas, *Euro. Phys. J.* **C34**, 487 (2004); **C40**, 435 (2005)
[5] A Brandenburg, M Maniatis and M M Weber, hep-ph/0207278
[6] LHC/LC Study Group: G Weiglein *et al*, hep-ph/0410364
[7] B C Allanach *et al*, *Euro. Phys. J.* **C25**, 113 (2002)
[8] A Freitas and P Z Skands, hep-ph/0606121
[9] T Sjöstrand, L Lönnblad, S Mrenna and P Skands, hep-ph/0308153
[10] F Maltoni and T Stelzer, *J. High Energy Phys.* **0302**, 027 (2003)
[11] W Beenakker, R Höpker, M Spira and P M Zerwas, *Nucl. Phys.* **B492**, 51 (1997)
[12] S M Xella Hansen *et al*, LC-PHSM-2003-061, www-flc.desy.de/lcnotes/
[13] J Pumplin *et al*, *J. High Energy Phys.* **0207**, 012 (2002)