The Complementary Roles of the LHC and the LC in Discovering Supersymmetry

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If weak scale SUSY exists, then it almost certainly should be discovered at the CERN LHC, where a variety of signatures occur as a result of sparticle production and subsequent cascade decays[1]. In Ref. [2], several case studies within the mSUGRA model have been performed. Although model independent sparticle mass measurements are not typically possible in a hadron collider environment, many mass *differences* can be measured, some with very high precision. It was shown that a fit of masses and mass differences from an mSUGRA case study to mSUGRA model parameters will allow a determination of model parameters to relatively high precision.

A possible problem is that mSUGRA may not be a valid description of nature. In this note, we adopt instead a case study based on a SUSY $SO(10)$ GUT with a high degree of Yukawa coupling unification[3]. The $SO(10)$ parameters considered for our case study, as well as a sample of mass spectra, are shown in TABLE I. The signatures of the model are very much mSUGRA-like, since R parity is conserved, and the gravitino decouples. However, D-term splitting of scalar masses, M_D, due to the breakdown of $SO(10)$ GUT symmetry destroys universality within the generations, and leads to a somewhat different spectrum than is predicted by the mSUGRA model. In this case, while LHC may discover SUSY, it will remain for a LC to provide model independent mass measurements which will reflect the true nature of the underlying model.

In our case study, the lightest Higgs scalar h should be discovered at the Fermilab Tevatron $p\bar{p}$ collider if sufficient integrated luminosity is achieved. In addition, clean trileptons from $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to 3\ell$ will occur at the 0.65 fb level using cuts SC2 of Ref. [4]; this is just above the 3σ level for 25 fb^{-1} of integrated luminosity, and would give an indication of the mass difference $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$.

1. Mass measurements at the LHC

The main results for the reconstruction of sparticle decay chains, and the extraction of certain mass differences, were summarized in Ref. [2]. We rely on these results when estimating the precision of the determination of mass differences at the LHC.

We envision a scenario in which initially certain mass differences and later the lightest Higgs mass will be measurable at the LHC, providing partial information on the SUSY mass spectrum. In particular, based on the $SO(10)$ model, we assume that three mass differences are in the reach of the LHC: $\delta_1 = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$, $\delta_2 = m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0}$, and $\delta_3 = m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$. In the following we assess the potential precision of these measurements.

An inspection of the SUSY production cross sections, plotted in Figure 1a, shows that at the LHC the $\tilde{b}_1$ pair production rate is the highest, with $\sigma(\tilde{b}_1\tilde{b}_1) \sim 1.9 \times 10^4$ fb, followed by gluino pair production, with $\sigma(\tilde{g}\tilde{g}) \sim 3.4 \times 10^3$ fb. In our case study, gluinos decay at $\sim$ 100% to $b\tilde{b}_1$. Furthermore, since $\tilde{b}_1$ decays only to $\tilde{\chi}_i^0 b$, $i = 1, 2, 3$, and in a proportion 1:1:2 roughly, and $\tilde{\chi}_{2,3}^0 \to \tilde{\chi}_1^0 \ell^+\ell^-$ branching ratio is a few percent, the opposite sign same flavor $\ell^+\ell^-$ invariant mass distribution will have two sharp upper edges. Indeed in Fig. 1b (although with a rather poor

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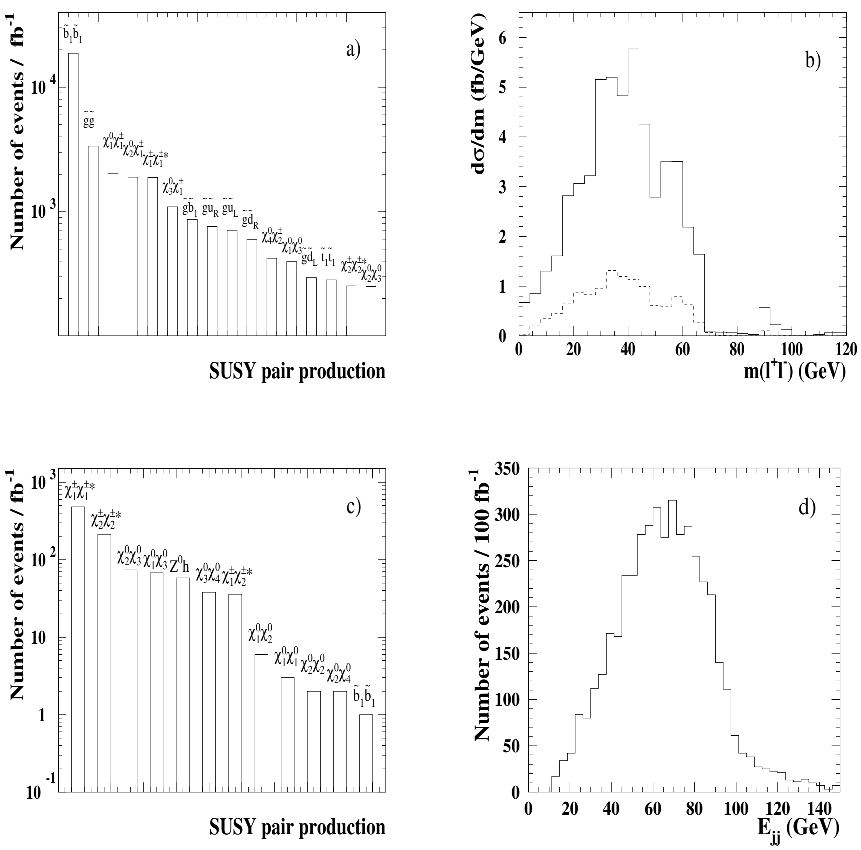

Figure 1:

statistics), one can see two distinct end-points: the first (second) indicates $m_{\tilde{\chi}^0_{2(3)}} - m_{\tilde{\chi}^0_1} = 46.1$ (71.5) GeV. The solid (dashed) histogram contains 1049 (961) all SUSY (gluino) pair production events with the final state n jets $+\ell^+\ell^- + \not{E}_T$, with $n \geq 4$, $E_T^{jet} > 30$ GeV and $\not{E}_T > 100$ GeV.

Although our case study is somehow different from the five points studied in Ref. [2], we assume here that based on the dilepton mass distribution in Fig. 1b similar analysis can be performed and $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$ can be expected to be measured with a precision of about 500 MeV. Moreover, we estimate the precision of the measurements $\Delta(\delta_2) = \pm 10$ GeV, and $\Delta(\delta_3) = \pm 20$ GeV. We also assume that after these mass differences are extracted, the mass of the lightest Higgs boson will also be determined with a precision of 3 GeV.

2. Global fit of mSUGRA parameters

If the LHC determined the above masses to the outlined precision, then it is possible to perform a global fit to a model to determine the basic parameters of the underlying theory. Since the signatures are mSUGRA-like, it is natural to first fit to that particular model. Using ISAJET 7.58, we begin by generating 1.6×10^5 mSUGRA models, uniformly distributed in the parameter space:

$$0 < m_0 < 2000 \text{ GeV}, \quad 0 < m_{1/2} < 1000 \text{ GeV}, \quad -2m_0 < A_0 < 2m_0, \quad 3 < \tan\beta < 50, \tag{1}$$

for both signs of μ. Then, for each of the above models we form

$$\chi^2 = \sum_{i=1}^{4} \left(\frac{|\delta_i^{ex}| - |\delta_i^{th}|}{\Delta(\delta_i)} \right)^2, \tag{2}$$

Table I

	SO(10)	Fit 1	Fit 2	Fit 3	Fit 4
Parameters fitted	–	$\delta_{1,3}$	$\delta_{1,2}$	$\delta_{1,2,3}$	$\delta_{1,2,3,4}$
χ^2	–	1	76	181	228
$m_{16}(m_0)$	1022.0	1050.0	150.0	150.0	150.0
m_{10}	1315.0	–	–	–	–
M_D	329.8	–	–	–	–
$m_{1/2}$	250.0	257.5	167.5	167.5	167.5
A_0	-1325.0	630.0	270.0	270.0	210.0
$\tan\beta$	48.0	46.5	39.4	39.4	37.1
μ	-143.2	-148.3	-208.1	-208.1	-210.0
$m_{\tilde{g}}$	649.0	644.9	420.7	420.7	421.0
$m_{\tilde{t}_1}$	530.7	768.0	306.6	306.6	303.6
$m_{\tilde{b}_1}$	239.5	829.8	302.3	302.3	310.3
$m_{\tilde{\chi}_1^0}$	85.3	85.1	62.4	62.4	62.5
$m_{\tilde{\chi}_2^0}$	131.4	130.9	109.2	109.2	109.8
$m_{\tilde{\chi}_1^\pm}$	119.0	118.4	108.9	108.9	109.5
m_h	119.5	113.8	91.9	91.9	106.9

with δ_i, for $i = 1, 2, 3$ being the three measured mass differences and $\delta_4 = m_h$. The superscript "ex" ("th") stands for the quantities within $SO(10)$ case study (fitted mSUGRA models). Finally, we select the mSUGRA model with the lowest χ^2. To simulate a situation in which only partial information is available from the LHC experiments, we perform four different fits (Fit 1, ..., Fit 4). It is probable that initially only two of the mass differences will be available, so Fit 1 and 2 are only two parameter fits to $\{\delta_1, \delta_3\}$ and $\{\delta_1, \delta_2\}$ respectively. Fit 3 fits all three mass differences simultaneously, and Fit 4 fits the mass differences and the lightest Higgs mass.

The results of the four fits are displayed in TABLE I. We can see that even with only two mass differences measured, the χ^2 is low only in Fit 1, which does not depend on the scalar masses. This is somehow expected since the D-term present in the $SO(10)$ case is responsible for the difference in the scalar sector between this model and mSUGRA. With more information accumulating, it will become obvious that the model is not mSUGRA, but the vital point is that it would be difficult for the LHC to narrow the masses such that the $SO(10)$ model can be singled out.

3. The role of the LC

In our scenario the LHC discovers SUSY, and moreover after years of running can give information on mass differences of supersymmetric particles. Although LHC cannot uniquely determine the nature of supersymmetry breaking, the combinations of some mass differences measured can distinguish our case study $SO(10)$ model from an mSUGRA model.

In order to obtain more information on supersymmetric particle masses, a precision machine such as a high energy linear collider (LC) will be required. In Fig. 1c we show the dominant cross sections within our case study at a 500 GeV LC. In particular, the process $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ leading to 2–jet + ℓ+ $\not{E}_T$ can give a very accurate estimates of $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\chi}_1^\pm}$ through the 2-jet energy distribution [5], as shown in Fig. 1d. With the use of $\tilde{\chi}_1^0$ mass information the LHC data can be re-analyzed and the correct mass values of the second and third lightest neutralinos, gluino and lightest squarks can be obtained. In principle all the neutralino and chargino masses can be measured at a LC, however to measure the complete SUSY mass spectra the complementary role of the two colliders is necessary. *Acknowledgments: We thank X. Tata for discussions.*

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