Higgs boson production in association with squark pairs in the MSSM at the LHC

A. Dedes and S. Moretti
Rutherford Appleton Laboratory,
Chilton, Didcot, Oxon, OX11 0QX, UK

We study neutral and charged Higgs boson production in association with stop and sbottom squarks at the Large Hadron Collider (LHC), within the so-called M-SUGRA scenario, i.e., the Supergravity (SUGRA) inspired Minimal Supersymmetric Standard Model (MSSM). For low values of \( \tan \beta \) only the cases \( \tilde{t}_1 \tilde{t}^*_1 H \), \( \tilde{t}_1 \tilde{t}^*_1 h \) and \( \tilde{t}_1 \tilde{t}^*_2 h \) give detectable rates while for \( \tan \beta \gtrsim 30 \) a variety of signals involving all Higgs bosons can be accessed, at high collider luminosity. The dependence of these reactions on the M-SUGRA parameters might further allow one to pin down the actual structure of the underlying Supersymmetric (SUSY) model.

1 Squark-squark-Higgs boson production at the LHC

1.1 Introduction

We have considered elementary processes of the type

\[
g + g \rightarrow \tilde{q}_\chi + \bar{\tilde{q}}_{\chi'} + \Phi,
\]

where \( q^{(l)} = b, t, \chi^{(l)} = 1, 2 \) and \( \Phi = H, h, A, H^\pm \), in all possible combinations, within the theoretical M-SUGRA framework, at the leading order (LO) in QCD. That is, we have considered \( gg \)-induced final states involving any possible Higgs state produced in conjunction with both heavy sbottom and stop squarks. The phenomenological relevance at the LHC of such reactions is in fact twofold:

- They furnish new production mechanisms of Higgs bosons of the MSSM, both neutral and charged.
- They yield production rates, for particular combinations of \( q^{(l)}, \chi^{(l)} \) and \( \Phi \), strongly dependent on the fundamental M-SUGRA parameters: i.e., \( M_0, M_{1/2}, \text{sign}(\mu), A_0 \) and \( \tan \beta \).

As for previous literature on the subject, we should mention that the case \( gg \rightarrow \tilde{t}_1 \tilde{t}^*_1 h \) was first considered in Ref.\(^3\) in the so-called ‘decoupling’ limit. Adopting the M-SUGRA scenario, associated production of CP-odd Higgs bosons and squark pairs was then addressed by the authors in Ref.\(^4\). Furthermore, in Ref.\(^5\) (see also\(^6\)) light CP-even Higgs boson production in association with light stop squarks was reanalysed in the M-SUGRA scenario at both Tevatron and LHC\(^7\). Finally, the study of all final states of the type (\( \Box \)) was completed (again, in the M-SUGRA scenario) in Ref.\(^7\). A general consensus on the possible detectability at the LHC

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\(^{\ddagger}\)The same final state, but produced in \( e^+e^- \) annihilations at the TeV scale, has been considered in Refs.\(^7\).
of squark-squark-Higgs events emerged from Refs. 1 to 5, particularly in the case of light stop squarks, not too heavy Higgs bosons and/or large trilinear couplings.

1.2 Calculation

Our procedure for calculating the cross sections of the various processes was the following.

- We derived an analytical expression of the corresponding $2 \rightarrow 3$ matrix elements (MEs), which can be found in Ref. 2.
- Their integration over the three-body phase spaces was performed by means of VEGAS and their convolution with gluon Parton Distribution Functions (PDFs) was provided by the fit CTEQ(4L), at the scale $Q = E_{cme}$ (at the partonic level).
- The evolution of the strong coupling constant, $\alpha_s$, was done at two-loop order with all relevant (s)particle thresholds taken into account through the $\theta$-function approximation.
- In order to prevent the MEs from becoming singular, finite widths were inserted in the (anti)squark propagators, as computed from the program ISAJET/ISASUGRA 7.40.

2 Results

2.1 Small $\tan \beta$ region

In the small region, e.g., $\tan \beta \sim 2$, the following cross sections exceed the 1 $fb$ level, value which we adopt as threshold of observability for a annual luminosity $L = 100 fb^{-1}$. These are:

$$gg \rightarrow \tilde{t}_1 \tilde{t}_1^* H,$$
$$gg \rightarrow \tilde{t}_1 \tilde{t}_1^* h,$$
$$gg \rightarrow \tilde{t}_1 \tilde{t}_2^* h.$$

In fact the largest cross sections are in general those associated to the last two processes, in decreasing size. These are both strongly dependent upon $A_0$, the (common) trilinear coupling of the M-SUGRA model. In the case of heavy CP-even Higgs boson production in the first channel, though the cross sections are typically smaller, it is possible to distinguish the sign of the M-SUGRA Higgsino mass, $\mu$, since the production rates corresponding to the two opposite signs can differ by up to two orders of magnitude. As for the other combinations of squarks and Higgs bosons in (1), their cross sections are always below detection level.

2.2 Large $\tan \beta$ region

If $\tan \beta$ is as large as 30 or more, a larger variety of squark-squark-Higgs processes can be accessed at the LHC, at least for some specific combinations of M-SUGRA parameters, when both the gaugino and squark masses are not too heavy at the Plank scale (say, $M_0 < 500$ GeV and $M_{1/2} < 220$ GeV) and the trilinear couplings are negative, $A_0 < 0$ GeV. These modes are:

$$gg \rightarrow \tilde{t}_1 \tilde{t}_1^* H,$$
$$gg \rightarrow \tilde{b}_1 \tilde{b}_1^* H,$$
$$gg \rightarrow \tilde{t}_1 \tilde{t}_1^* h,$$
$$gg \rightarrow \tilde{t}_1 \tilde{t}_2^* H,$$
$$gg \rightarrow \tilde{b}_1 \tilde{b}_1^* H,$$
$$gg \rightarrow \tilde{t}_1 \tilde{t}_2^* A.$$
Figure 1: The largest squark-squark-Higgs cross sections at large tan \( \beta \) (left) and the values of the masses in the final states (right), as a function of \( M_{1/2} \). Shaded regions indicate areas excluded by direct squark/Higgs searches. The choice of the other M-SUGRA parameters is also shown.

\[
\begin{align*}
gg & \rightarrow \tilde{b}_1 \tilde{b}_2^* H, \\
gg & \rightarrow \tilde{t}_1 \tilde{b}_2^* H^-.
\end{align*}
\]

Their production rates are displayed in Fig. 1 (left), alongside the masses of the three final state particles (right).

### 2.3 Possible signatures and backgrounds

Many decay channels of the particles in the final states of processes of the type \( \bar{\tilde{t}}_1\bar{\tilde{t}}_2^*A \) were considered in Refs. [1,2]. Here, we only show one example: for the case of CP-odd Higgs boson production in association with stop pairs, i.e., \( gg \rightarrow \tilde{t}_1 \tilde{t}_2^*A \). The choice of M-SUGRA parameters is the following: \( M_0 = M_{1/2} = 125 \text{ GeV}, A_0 = 0 \text{ GeV}, \tan \beta = 40 \) and \( \mu < 0 \). One can have the decay pattern:

\[
\sigma(gg \rightarrow t_1t_2^*A) = 96 \text{ fb} \quad (2)
\]

\[
\begin{array}{c}
\bar{\tilde{t}}_1 \\
\downarrow \\
\chi^+_1 + b \\
\downarrow \\
\tilde{\tau}^+_1 + \nu + b \\
\downarrow \\
\tau^+ + \nu + b + \chi^0_1
\end{array}
\]

\[
\begin{array}{c}
\bar{\tilde{t}}_2^* \\
\downarrow \\
\chi^-_1 + \bar{b} \\
\downarrow \\
\tilde{\tau}^-_1 + \bar{\nu} + \bar{b} \\
\downarrow \\
\tau^- + \bar{\nu} + \bar{b} + \chi^0_1
\end{array}
\]

\[
4b + \tau^+\tau^- + E_{\text{miss}} \quad (3)
\]
which leads to 528 detectable events every 100 \( fb^{-1} \), after multiplying by \( \varepsilon_b^4 \) (the efficiency to tag four \( b \)-quarks, where \( \varepsilon_b \) is taken to be 70\%) and accounting for all relevant branching fractions. Standard backgrounds would come from ‘\( Z + 4b \)’ production. However, from one pair of \( b \)-quarks one could reconstruct the \( A \) mass, at around 114 GeV, thus reducing such a QCD noise. Besides, the large amount of missing energy, \( E_{\text{miss}} \), building up because of the four neutrinos and two neutralinos, could prove to be a further good handle against non-SUSY processes. Here, typical stop masses are around 380 and 240 GeV, for \( \tilde{t}_2 \) and \( \tilde{t}_1 \), respectively.

As for irreducible SUSY backgrounds, notice the poor decay rate \( \text{BR}(\tilde{t}_2 \to \tilde{t}_1 Z) \approx 7\% \).

### 3 Conclusions

In summary, we have studied neutral and charged Higgs boson production in association with all possible combinations of stop and sbottom squarks at the LHC, in the context of the SUGRA inspired MSSM. We have found that the cross sections of many of these processes should be detectable at high collider luminosity for not too small values of \( \tan\beta \) (except for the case of light and heavy CP-even Higgs boson being produced in association with light stops, which can be detected also in the very low \( \tan\beta \) regime). Furthermore, the strong dependence of these cross sections on \( M_0, M_{1/2}, \text{sign}(\mu), A_0 \) and/or \( \tan\beta \), would also help to pin down the actual values of these fundamental parameters defining the M-SUGRA scenario \[ \text{1}. \] Finally, we have given one representative example of a possible squark-squark-Higgs signature and a brief discussion of how to suppress the dominant backgrounds. As outlook for the future, we should mention the inclusion of the CP-violating phases \[ \text{12}, \] which can strongly affects the squark-squark-Higgs vertices here involved, as already shown in Refs. \[ \text{13} \] for MSSM (neutral) Higgs production via (s)quark loops in gluon-gluon fusion.

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