Supersymmetric Particle Reconstruction with the CMS detector

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A method to reconstruct squark and gluino signals through the decay chain $\tilde{g} \rightarrow \tilde{b} \rightarrow \tilde{c}^0 q q \rightarrow \tilde{\chi}_1^0 q q \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- q q$ is described. The sbottom is reconstructed exploiting the expected b-tagging performance of the CMS detector in the chain $\tilde{g} \rightarrow \tilde{b} \rightarrow \tilde{\chi}_1^0 q q \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- q q$. The study is performed in three different mSUGRA scenarios. With favourable parameters the mass peaks can be reconstructed with $10 \text{ fb}^{-1}$ of integrated luminosity. The main source of error on the measurements of the signal masses arises from the $\tilde{\chi}_1^0$ mass uncertainty.

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Key words: Supersymmetric Spectroscopy, CMS, mSUGRA, gluino, squark

1 Introduction

Past simulation studies have shown that for an integrated luminosity of $100 \text{ fb}^{-1}$ the CMS detector is capable to observe squarks and gluinos with masses up to $\sim 2 \text{ TeV}$ [1] through events in excess over SM expectations in jets+$E_T$ final states. However the “excess” over the Standard Model alone is not yet a proof of Supersymmetry. It is reasonable to demand a more complete evidence: if new particles are observed, it is necessary to measure, in a second stage, their masses and eventually other quantities such as couplings, widths or spins.

Such a kind of spectroscopic studies on supersymmetry have not been performed previously by the CMS collaboration. In this paper the work done to evaluate the detector capability to detect signals from squarks and gluinos and to reconstruct their mass peaks is presented. A detailed description can be found in [2]. This kind of analysis is based on a different approach when compared to the ones used in previous studies in CMS: the aim is not the determination of some regions of observability in parameter space, but rather testing the detector performances for a specific set of SUSY parameters. Three points in the mSUGRA parameter space have therefore been chosen among the ones suggested in Ref. [3] and each of them has been analysed in detail. They have been selected among the points with relatively low values of $m_0$ and $m_{1/2}$ in order to have low mass spectrum and hence a high production cross section for squarks and gluinos, thus possibly allowing early observation. Three different values of $\tan \beta$ have been considered, since this parameter strongly influences the branching ratios of the decays considered for this study. The selected points are the following:

“Point B”: $m_0 = 100 \text{ GeV}$, $m_{1/2} = 250 \text{ GeV}$, $\tan \beta = 10$, $A_0 = 0$, and $\mu > 0$;

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“Point G”: $m_0 = 120 \text{ GeV}, m_{1/2} = 375 \text{ GeV}, \tan \beta = 20, A_0 = 0, \text{ and } \mu > 0$;

“Point I”: $m_0 = 180 \text{ GeV}, m_{1/2} = 350 \text{ GeV}, \tan \beta = 35, A_0 = 0, \text{ and } \mu > 0$.

The decay chain we are investigating is $\tilde{g} \to \tilde{q} \chi_1^0 \to \tilde{q}^0 \ell^+ \ell^- \chi_1^0$. The aim is the reconstruction of the gluino and the squark signals starting from the $\chi_1^0 \to \ell^+ \ell^- \chi_1^0$ decay, with $\ell = e, \mu, \tau \text{'s are not considered in this study. Exploiting the expected performances of the CMS tracker, allowing the tagging of b jets with high efficiency, it is possible to observe separately the mass peaks of the supersymmetric partners of the light quarks (which are generally called squarks in this paper) and of the sbottoms, reconstructed through the decay: $\tilde{g} \to \tilde{b} b \to \chi_2^0 b b \to \ell^+ \ell^- \chi_1^0 \to \ell^+ \ell^- \chi_1^0$.

The sparticle mass spectra and decay branching ratios in all the scenarios have been evaluated using ISASUGRA 7.51 [4]. The SUSY events have been generated using PYTHIA 6.152 [5], and the CMS detector response has been simulated with CMSJET 4.801 [6]. Table 1 summarizes the supersymmetric particle masses given by ISASUGRA 7.51 at Point B, G and I. The main Standard Model backgrounds, $t\bar{t}$, $W$+jets, $Z$+jets and QCD jets, have been generated with PYTHIA 6.152 and simulated with CMSJET 4.801.

### Table 1: Spectra at point B, G and I as given by ISASUGRA 7.51.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (GeV/c²)</th>
<th>Point B</th>
<th>Point G</th>
<th>Point I</th>
</tr>
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<tbody>
<tr>
<td>$\tilde{u}_L, \tilde{c}_L$</td>
<td>537.0</td>
<td>773.9</td>
<td>738.4</td>
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</tr>
<tr>
<td>$\tilde{d}_L, \tilde{s}_L$</td>
<td>542.8</td>
<td>778.0</td>
<td>742.7</td>
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<tr>
<td>$\tilde{b}_L$</td>
<td>496.0</td>
<td>701.9</td>
<td>640.3</td>
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<td>$\tilde{u}_R, \tilde{c}_R$</td>
<td>519.1</td>
<td>747.9</td>
<td>714.9</td>
<td></td>
</tr>
<tr>
<td>$\tilde{d}_R, \tilde{s}_R$</td>
<td>520.9</td>
<td>745.8</td>
<td>713.2</td>
<td></td>
</tr>
<tr>
<td>$\tilde{b}_R$</td>
<td>524.0</td>
<td>748.4</td>
<td>713.3</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\tau}_R, \tilde{\mu}_R$</td>
<td>136.2</td>
<td>183.2</td>
<td>221.3</td>
<td></td>
</tr>
<tr>
<td>$\tilde{\tau}_L, \tilde{\mu}_L$</td>
<td>196.6</td>
<td>278.9</td>
<td>295.7</td>
<td></td>
</tr>
<tr>
<td>$\tilde{g}$</td>
<td>595.1</td>
<td>860.8</td>
<td>809.8</td>
<td></td>
</tr>
<tr>
<td>$\chi_1^0$</td>
<td>95.6</td>
<td>150.0</td>
<td>139.8</td>
<td></td>
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<tr>
<td>$\chi_2^0$</td>
<td>174.7</td>
<td>277.1</td>
<td>257.9</td>
<td></td>
</tr>
</tbody>
</table>

2 Reconstructions at Point B

At $\sqrt{s} = 14 \text{ TeV}$, the total SUSY cross section at Point B is 57.77 pb. The dominant contributions are squark-gluino, gluino-gluino and squark-squark processes: 86% of SUSY events come from these three production mechanisms. Direct production cross section of sbottoms is much lower and only sbottoms arising from gluinos are important for the reconstruction. A sketch of the decay chain under

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study is given in Fig. 1; the same decay chain with light quarks replacing bottoms is used for the squark reconstruction. The events are selected requiring at least two

\[ p \rightarrow \bar{b} \bar{b} \rightarrow \chi_0^0 \ell \bar{\ell} \rightarrow \chi_0^0 \ell \bar{\ell} \bar{b} \bar{b}. \]

Fig. 1. : Sketch of the decay $\tilde{g} \rightarrow \tilde{b}_1 \tilde{b}$, with $\chi_0^0$ and $\tilde{b}_1$.

same-flavour opposite-sign isolated leptons with $p_T > 15$ GeV/c and $|\eta| < 2.4$, and two jets with $p_T > 20$ GeV/c and $|\eta| < 2.4$. For the sbottom reconstruction, b-tagging on the jets is required. The first step of the reconstruction procedure is the identification of the $\chi_0^0$ from its decay products. It is well known that the invariant mass distribution of the two leptons produced in the $\chi_0^0$ decay shows a sharp end-point (2 out of 3 phase space distribution with vertical asymptote at upper edge), corresponding to the kinematic situation in which, in the $\chi_0^0$ rest frame, the two leptons are emitted back-to-back. Figure 2 shows the inclusive dilepton invariant mass distribution of SUSY events only, together with the content of the sample. Leptons coming from $\chi_0^0$ decays dominate, and are slightly contaminated by leptons arising from decays of $\tau$’s, W’s or Z’s. Figure 3 shows the dilepton invariant mass for the squark decay chain, superimposed over the SM background for 1 fb$^{-1}$ of integrated luminosity, which should correspond to the first weeks of LHC running. The SM background can be reduced applying a cut on the transverse missing energy: the dilepton edge is well visible with $E_T^{miss} > 50$ GeV. For the sbottom decay chain, larger statistics is needed to observe a good edge, due to the lower production cross section of the sbottom and to the effect of the b-tagging efficiency. The edge can be observed with 10 fb$^{-1}$, expected to be collected in the first year of LHC running. At the specific kinematical conditions of the end-point, the following relation is valid:

\[ \vec{p}_\chi^0 = \left( 1 + \frac{m_{\chi^0}}{M_{\ell^+ \ell^-}} \right) \vec{p}_{\ell^+ \ell^-}. \]  

Fig. 2. : Invariant mass distribution of same-flavour opposite-sign isolated lepton pairs for the SUSY events passing the selection criteria at Point B.

The momentum of the $\chi_0^0$ can hence be reconstructed through the momenta of the two leptons. A knowledge of the $\chi_0^0$ mass is however necessary. At this stage, it is taken from the Monte Carlo, and the dependence of the results on it is discussed in the following. Lepton pairs in a window of 15 GeV/c$^2$ at the edge are selected, and the $\chi_0^0$ from the dilepton distribution can be associated to one of the jets (b jets) in the event to reconstruct the squark (sbottom). The most energetic one is
Fig. 3.: Invariant mass distribution of same-flavour opposite-sign isolated lepton pairs for the SUSY events superimposed over the SM background for two different $E_T^{\text{miss}}$ cuts at Point B. The integrated luminosity is 1 fb$^{-1}$.

Fig. 4.: Invariant mass peaks of squark (left), sbottom (middle) and gluino in the sbottom chain (right) at Point B. The integrated luminosity is 1 fb$^{-1}$ for the squark and 10 fb$^{-1}$ for the others.

chosen since quarks (b quarks) coming from the squark (sbottom) have a harder spectrum than the others.

Figure 4 shows the reconstructed squark mass distribution, for an integrated luminosity of 1 fb$^{-1}$. The peak can be fitted with a Gaussian superimposed over a polynomial, which takes into account SUSY and SM backgrounds. The measured squark mass is $M(\tilde{q}) = 536 \pm 10$ GeV/c$^2$; the width of the peak is $\sigma = 60 \pm 9$ GeV/c$^2$. This mass value is in good agreement with the generated values of the left component of the squarks shown in Table 1. The right components give a negligible contribution to the peak since the $\tilde{q}_R$ decays into $\tilde{\chi}_1^0$ with a branching ratio smaller than 1%.

In the same figure, the sbottom mass peak is also shown, for an integrated lu-
minosity of 10 fb$^{-1}$. $E_{\text{b}_{1}} > 250$ GeV is required to reduce SUSY and combinatorial backgrounds (see Ref. [2] for details of the cuts). The measured sbottom mass is $M(\tilde{b}_{2}^{0}) = (500 \pm 7)$ GeV/c$^{2}$, and the width $\sigma = (42 \pm 5)$ GeV/c$^{2}$. Since both $\tilde{b}_{1}$ and $\tilde{b}_{2}$ can decay into $\chi_{1}^{0}\ell^{\pm}\ell^{\mp}$, the peak should be considered as the superposition of two unresolved peaks. The measured mass has to be compared to the mean of the two sbottom masses weighted by the corresponding $\sigma \times \text{BR}$'s:

$$< M(\tilde{b}_{1}) > = \frac{M(\tilde{b}_{1}) \cdot \sigma \times \text{BR}(\tilde{b}_{1}) + M(\tilde{b}_{2}) \cdot \sigma \times \text{BR}(\tilde{b}_{2})}{\sigma \times \text{BR}(\tilde{b}_{1}) + \sigma \times \text{BR}(\tilde{b}_{2})} = 503.9 \text{ GeV/c}^{2} \quad (2)$$

where $\sigma \times \text{BR}(\tilde{b}_{1})$ is $\sigma(\text{pp} \rightarrow \tilde{g}) \times \text{BR}(\tilde{g} \rightarrow \tilde{b}_{1} \rightarrow \tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{R}^{\pm} \ell^{\mp} \rightarrow \chi_{1}^{0} \ell^{\pm} \ell^{\mp}) + \sigma(\text{pp} \rightarrow \tilde{b}_{1}) \times \text{BR}(\tilde{b}_{1} \rightarrow \chi_{1}^{0} \rightarrow \tilde{\ell}_{R}^{\pm} \ell^{\mp} \rightarrow \chi_{1}^{0} \ell^{\pm} \ell^{\mp})$.

Once the squark (bottom) mass peak has been reconstructed, a second jet (b jet) can be associated to it to reconstruct the gluino mass. This second jet is chosen as the jet closest in angle to the reconstructed squark (sbottom). In the squark channel the large SUSY background in the gluino mass distribution is due to the large number of squark-squark and squark-gluino events, which result in fake associations. These combinatorial background sources can be partially reduced applying an upper cut to the energy of the second selected jet. The reconstructed gluino mass is $M(\tilde{\chi}_{1}^{0}q\bar{q}) = 392 \pm 7$ GeV/c$^{2}$, and the width $\sigma = 75 \pm 5$ GeV/c$^{2}$. The gluino reconstructed in the sbottom chain has a better resolution thanks to the cleaner environment; it is shown in Fig. 4 for an integrated luminosity of 10 fb$^{-1}$. The measured mass value is $M(\tilde{\chi}_{1}^{0}bb) = (594 \pm 7)$ GeV/c$^{2}$, $\sigma = (42 \pm 7)$ GeV/c$^{2}$. Both measurements are in agreement with the generated value $M(\tilde{g}) = 595$ GeV/c$^{2}$.

### 3 Dependence on the $M(\tilde{\chi}_{1}^{0})$

All the results shown in the previous section have been obtained in the hypothesis of a known $\tilde{\chi}_{1}^{0}$ mass. In real experimental conditions, however, CMS will not be able to directly detect $\tilde{\chi}_{1}^{0}$, this being a weakly interacting particle which escapes the detector. It is worth noticing that as both $M(\tilde{b})$ and $M(\tilde{g})$ depend on the $\tilde{\chi}_{1}^{0}$ mass, their difference $M(\tilde{g})-M(\tilde{b})$ does not: this measurement can thus be performed without any assumption on the $\tilde{\chi}_{1}^{0}$ mass

Of course a $M(\tilde{\chi}_{1}^{0})$ measurement from any other analysis could allow a determination of gluino, squark and sbottom masses separately. To evaluate the dependence of the mass measurements on the assumed accuracy of the $\tilde{\chi}_{1}^{0}$ mass value, the reconstruction procedure has been repeated changing the $\tilde{\chi}_{1}^{0}$ mass value while keeping unchanged the rest of the sparticle spectrum. The dependence of $M(\tilde{b})$ has been measured to be

$$\Delta M(\tilde{\chi}_{2}^{0}b) = (1.60 \pm 0.03) \Delta M(\tilde{\chi}_{1}^{0}) \quad (3)$$

with similar results for squark and gluino.

An other LHC study [7] has shown that the $\tilde{\chi}_{1}^{0}$ mass can be deduced from measurements of a set of end-points similar to the one observed for the two leptons

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coming from the $\chi^0_1$ and discussed here. With favourable parameters, this method would allow to determine the $\chi^0_1$ mass with an uncertainty of the order of 10% with an integrated luminosity of 300 fb$^{-1}$, as could be expected for the first three to four years of data taking at LHC. In Table 2 is given a summary of the measured masses for integrated luminosities of 10 fb$^{-1}$ and 300 fb$^{-1}$. With 300 fb$^{-1}$ of integrated luminosity the gluino, sbottom and squark masses can be measured with a statistical uncertainty of the order of 1±3 GeV/c$^2$. The main sources of systematics are on the jet energy scale from the calorimeters, which has been evaluated to contribute for 2±3 GeV/c$^2$, and the uncertainty on the mass of the $\chi^0_1$. Assuming a 10% error on $M(\chi^0_1)$ as quoted above and the dependence of the measured gluino, sbottom and squark masses on $M(\chi^0_1)$ of Eq.3, this error is of the order of 15 GeV/c$^2$ at point B.

Table 2: Sparticle masses and resolutions in sbottom and squark decay chains. All the results are expressed in GeV/c$^2$. The quoted errors are statistical.

<table>
<thead>
<tr>
<th></th>
<th>M(b)</th>
<th>$\sigma$(b)</th>
<th>M(\tilde{g})</th>
<th>$\sigma$(\tilde{g})</th>
<th>M(\tilde{g})-M(b)</th>
<th>$\sigma$(\tilde{g}-b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 fb$^{-1}$</td>
<td>500 ± 7</td>
<td>42 ± 5</td>
<td>594 ± 7</td>
<td>42 ± 7</td>
<td>92 ± 3</td>
<td>17 ± 4</td>
</tr>
<tr>
<td>300 fb$^{-1}$</td>
<td>497 ± 2</td>
<td>36 ± 3</td>
<td>591 ± 3</td>
<td>39 ± 3</td>
<td>90 ± 2</td>
<td>23 ± 2</td>
</tr>
<tr>
<td></td>
<td>M(\tilde{q})</td>
<td>$\sigma$(\tilde{q})</td>
<td>M(\tilde{g})</td>
<td>$\sigma$(\tilde{g})</td>
<td>M(\tilde{g})-M(\tilde{q})</td>
<td>$\sigma$(\tilde{g}-\tilde{q})</td>
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<tr>
<td>10 fb$^{-1}$</td>
<td>535 ± 3</td>
<td>57 ± 3</td>
<td>592 ± 7</td>
<td>75 ± 5</td>
<td>57 ± 3</td>
<td>9 ± 3</td>
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<tr>
<td>300 fb$^{-1}$</td>
<td>536 ± 1</td>
<td>31 ± 1</td>
<td>590 ± 2</td>
<td>59 ± 2</td>
<td>44 ± 2</td>
<td>11 ± 2</td>
</tr>
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</table>

4 Reconstructions at Point G

At Point G the total SUSY cross section at $\sqrt{s}$ is 8.25 pb, much lower than at Point B. The branching ratios of the decays of the gluino into squark and sbottom are also slightly lower. In addition the branching ratio of the decay $\chi^0_2 \rightarrow \tilde{\ell}\ell$, which is the starting point of the procedure, is only 2.26%, while other decays producing leptons from W’s, τ’s or Z’s, and which can hence be considered as SUSY backgrounds, have larger branching ratios. The dilepton invariant mass for the selected SUSY sample is shown in Fig. 5. It is therefore more difficult to observe the end-point in the dilepton mass distribution and to separate SUSY from SM: larger statistics and harder cuts are needed. Figure 6 shows the peaks obtained at point G for squark, sbottom and gluino in the sbottom chain for an integrated luminosity of 300 fb$^{-1}$. All the results summarized in Table 3 are in agreement with generated values within the errors. Larger statistical errors affect the measurements at the same integrated luminosity, and also the resolutions of the peaks are worse because a wider window around the dilepton edge needs to be selected to collect a sufficient statistics. Even in this case the uncertainty coming from the $M(\chi^0_1)$ measurement is the main systematics.
Fig. 5.: Invariant mass distribution of same-flavour opposite-sign isolated lepton pairs for the SUSY events passing the selection criteria at Point G (left) and Point I (right).

Fig. 6.: Invariant mass peaks of squark (left), sbottom (middle) and gluino in the sbottom chain (right) at Point G for an integrated luminosity of 300 fb$^{-1}$.

Table 3.: Sparticle masses and resolutions in sbottom and squark decay chains. All the results are expressed in GeV/c$^2$. The quoted errors are statistical.

<table>
<thead>
<tr>
<th></th>
<th>M(b)</th>
<th>σ(b)</th>
<th>M(ġ)</th>
<th>σ(ġ)</th>
<th>M(ġ)-M(b)</th>
<th>σ(ġ-b)</th>
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<tbody>
<tr>
<td></td>
<td>720 ± 26</td>
<td>81 ± 18</td>
<td>852 ± 40</td>
<td>130 ± 43</td>
<td>127 ± 10</td>
<td>48 ± 11</td>
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<tr>
<td>M(ġ)</td>
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<td>774 ± 9</td>
<td>84 ± 9</td>
<td>853 ± 11</td>
<td>126 ± 11</td>
<td>82 ± 3</td>
<td>35 ± 3</td>
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</tbody>
</table>

5 Reconstructions at Point I

At Point I the total SUSY cross section is 10.14 pb. However $\chi^0_2$ decays into lepton pairs with a branching ratio of 0.25%. Figure 5 shows the invariant mass
distribution of same-flavour opposite-sign lepton pairs at point I for a sample corresponding to an integrated luminosity of 300 fb$^{-1}$. The solid line, representing the contribution from $\chi^0_2 \rightarrow \tilde{\tau}^\pm \ell^\mp \rightarrow \chi^0_1 \ell^\pm \ell^\mp$, which is the starting point of the procedure, is in competition with other lepton sources. In addition, the end-point of the distribution falls close to the $Z$ region and can hence be hardly identified.

This benchmark point is an example of a supersymmetric scenario for which the methods presented above cannot be applied to reconstruct squark and gluino mass peaks. It could be useful to exploit other chains: in particular, since the decay $\chi^0_2 \rightarrow \tilde{\tau}^\pm \tau^\mp \rightarrow \chi^0_1 \tau^\pm \tau^\mp$ has a branching ratio larger than 98% at Point I, tau-tagging techniques could be exploited to repeat the same reconstruction procedures adopted for electrons and muons. Dedicated studies are being performed by the LHC experiments to optimize the $\tau$-tagging algorithms for SUSY [8].

6 Conclusions

The capability of the CMS detector to reconstruct squark, sbottom and gluino mass peaks through the $\tilde{g} \rightarrow \tilde{q}q \rightarrow \chi^0_2 q\bar{q} \rightarrow \tilde{\ell}^\pm \ell^\mp q\bar{q} \rightarrow \chi^0_1 \ell^\pm \ell^\mp q\bar{q}$ decay has been evaluated in three different mSUGRA scenarios. At Point B the squark signal can be observed with $1$ fb$^{-1}$, i.e. within the first weeks of data taking at LHC; the sbottom and gluino mass peaks can be reconstructed within the first year ($10$ fb$^{-1}$). Statistical errors can be reduced down to $\sim 0.5\%$ with $300$ fb$^{-1}$. The main source of systematics is the uncertainty on the $\chi^0_1$ mass, which affects the measurements at a $2\pm 3\%$ level at high integrated luminosity, if $M(\chi^0_1)$ is taken from indirect measurements. At Point G the mass peaks can be observed only at high integrated luminosity, with larger errors when compared to Point B. At Point I it is not possible to perform a reconstruction with electrons and muons, but final-states with $\tau$'s are under investigation.

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References

[7] D. Tovey, these proceedings.