Discovery Potential for SUGRA/SUSY at CMS

Stefano Villa

University of California, Riverside, CA 92521, USA

Abstract

The expected SUSY discovery potential of the CMS experiment at LHC is described, both in the MSSM and in the more constrained framework of mSugra, with emphasis on inclusive searches, the MSSM Higgs sector, and one example of complete reconstruction of a SUSY decay chain.

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1 Introduction

Searches for supersymmetry (SUSY) will be actively carried out with the CMS detector, one of the two general purpose experiments which will start collecting data at the LHC proton proton collider at CERN in the year 2007. The centre-of-mass energy will be 14 TeV, allowing the study of physics in the TeV range, where most theories predict a breakdown of the Standard Model (SM) and the appearance of new physics. The LHC will probably run for some time at a luminosity of about $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ (called low luminosity in the following) before reaching the design value of $10^{34}$ cm$^{-2}$ s$^{-1}$ (called high luminosity).

The typical SUSY signatures are high transverse momentum ($p_T$) jets, missing transverse energy ($E_T^{miss}$) and possibly high-$p_T$ leptons. The experimental requirements are therefore a good jet and $E_T^{miss}$ resolution, hermetic calorimetry, efficient b tagging and tau identification and precise lepton and jet energy scales.

Searches for SUSY have to deal with models with a relatively large set of free parameters, all consistent with the low-energy data and with constraints coming from cosmology. The minimal supersymmetric extension of the Standard Model (MSSM) contains two Higgs doublets and has more than 100 free parameters. A great reduction in the number of parameters is obtained with the unification of masses at the GUT scale and the conservation of R parity ($R_p$). With, in addition, the requirement of a dynamic (radiative) electroweak symmetry breaking, only five parameters survive: $m_{1/2}$, the common gaugino mass at GUT scale, $m_0$, the common scalar mass at GUT scale, $\tan \beta$, the ratio of the vacuum expectation values of the two Higgs doublets, $\text{sign}(\mu)$, the sign of the Higgsino mixing parameter and $A_0$, the common trilinear scalar coupling at GUT scale. This very constrained and very predictive model is called Minimal Supergravity (mSugra) and is often chosen as a guideline to evaluate the potentials for discovery of new experiments, as is done in most of this note.

In the following the expected SUSY discovery potential of the CMS detector is described. Section 2 reports results of a study of dedicated SUSY triggers, Section 3 describes the expected inclusive discovery reach in the mSugra parameter space, Section 4 contains some results related to the Higgs sector and Section 5 describes the reconstruction of the full decay chain of a specific SUSY channel.
2 SUSY Triggers in CMS

If R parity is conserved, as is the case in mSugra, the lightest supersymmetric particle (LSP) is stable, and the decay chains of all other sparticles end up to the LSP. The LSP is often chosen to be the lightest neutralino or sneutrino, weakly interacting for cosmological reasons. It therefore escapes detection and leads to large $E_T^{miss}$, together with many high-$p_T$ jets or leptons coming from the SUSY decay chain of the produced sparticles (mostly squarks and gluinos at LHC). If $R_p$ is violated, the LSP may also decay exclusively to jets, in the case of a dominant UDD coupling considered in the following.

The design of trigger algorithms for an effective search for SUSY signals must therefore rely differently on the multijets and $E_T^{miss}$ signatures. Trigger optimizations at Level 1 (L1) and High Level (HLT) using GEANT simulation and fully realistic reconstruction software have recently been performed by CMS [1].

The SUSY trigger has been optimised at six benchmark mSugra-inspired points, three for the low-luminosity case and three for the high-luminosity scenario; in all cases $R_p$ conservation and violation are considered. The parameters corresponding to the six points are reported in Table 1. The points are chosen to represent the most challenging scenarios, from the point of view of triggering, which CMS might face in the search for SUSY. The first three points lie just above the mass reach of the Tevatron, with relatively small sparticle masses and therefore with small $E_T^{miss}$ and small jet $E_T$. Points 7, 8 and 9 are chosen to test the ability to probe large sparticle masses, with correspondingly very low cross sections.

Table 1: Definition of the six mSugra benchmark points used for the trigger studies. The other parameters were chosen as: $A_0=0$, $\tan \beta=10$ and $\mu > 0$. The corresponding production cross sections are reported in the last column.

| Point | $m_0$ (GeV/c^2) | $m_{1/2}$ (GeV/c^2) | $\sigma$ (pb) |
|-------|-----------------|---------------------|--------------|
| 4     | 20              | 190                 | 181          |
| 5     | 150             | 180                 | 213          |
| 6     | 300             | 150                 | 500          |
| 7     | 250             | 1050                | 0.017        |
| 8     | 900             | 930                 | 0.022        |
| 9     | 1500            | 700                 | 0.059        |

Table 3: Inclusive SUSY Reach

The LHC is an ideal place to detect strongly-interacting particles (squarks and gluon) because of the large production cross section in proton-proton collisions. In the $R_p$-conserving scenario, studies of the inclusive discovery reach of CMS have been performed [2], by exploiting the already mentioned signatures, i.e., missing energy, high-$p_T$ jets from squark and gluino decays and a number of isolated leptons, depending on the decay chains. In the case of high $\tan \beta$, the events also contain a large number of $b$ quarks and $\tau$ leptons.

Besides the common requirements of $E_T^{miss}$ (> 200 GeV) and of at least two jets with $E_T > 40$ GeV, the following final-state topologies were investigated: events with no leptons (0$\ell$), at least one lepton (1$\ell$), two opposite-charge leptons (2$\ell$OS), two same-charge leptons (2$\ell$SS) and three leptons (3$\ell$). The study was based on SM background samples generated with PYTHIA 5.7 [3] and SUSY signals generated with ISAJET 7.32 [4] and fast simulation of the detector response (CMSJET 4.51 [5]). The optimisation of the selection strategies was performed on each of the above final-state categories and on the final state with only missing transverse energy, in the mSugra framework, for a few values of $A_0$, $\tan \beta$ and sign($\mu$). A scan of the ($m_0$, $m_{1/2}$) plane allows the discovery reach of CMS to be determined. For example, Fig. 1 shows the corresponding contours for an integrated luminosity of 100 fb$^{-1}$, for $A_0=0$, $\tan \beta=2$ and $\mu > 0$ (left) and $A_0=0$, $\tan \beta=35$ and $\mu < 0$ (right).
Table 2: The HLT cut values and efficiencies for six mSugra points defined in Table I and their corresponding $R_p$ violating versions (denoted with R next to the point number). The cuts are based on $E_T^{miss}$ and on $E_T$ of the jets. The table shows the efficiencies of the separate selections and, in parentheses, the cumulative efficiencies.

| Point | 1 jet $> 180$ GeV, $E_T^{miss} > 123$ GeV | 4 jets, $E_T^{miss} > 113$ GeV | Low luminosity | 4 jets, $E_T^{miss} > 239$ GeV | 4 jets, $E_T > 185$ GeV | High luminosity |
|-------|------------------------------------------|-------------------------------|----------------|-------------------------------|---------------------|---------------|
|       | efficiency (%)                          | efficiency (%) (cum. eff.)    |               | efficiency (%)                | efficiency (%) (cum. eff.) |               |
| 4     | 67                                       | 11 (69)                       | 7             | 85                            | 18 (85)              |               |
| 5     | 65                                       | 14 (68)                       | 8             | 90                            | 28 (92)              |               |
| 6     | 37                                       | 16 (44)                       | 9             | 72                            | 28 (76)              |               |
| 4R    | 27                                       | 28 (46)                       | 7R            | 70                            | 75 (90)              |               |
| 5R    | 17                                       | 30 (41)                       | 8R            | 58                            | 78 (88)              |               |
| 6R    | 9                                        | 20 (26)                       | 9R            | 41                            | 52 (64)              |               |

Similar results can be obtained for different integrated luminosities. As an example in Fig. I(right) the discovery contour for the $E_T^{miss}$ final state for 300 fb$^{-1}$ integrated luminosity (expected in about three years of running at high luminosity) is also reported. In summary, for most of the mSugra parameter space the ultimate discovery reach of CMS for squarks and gluinos is between 2.6 and 3.0 TeV/$c^2$.

4 The MSSM Higgs Sector

The Higgs sector of the MSSM consists of two SU(2) doublets of complex scalar fields, which after symmetry breaking yield five physical states, two CP-even bosons, h and H, one CP-odd boson A and two charged states $H^{\pm}$. At tree level, the Higgs sector is completely determined by two parameters, usually chosen to be $\tan \beta$ and $m_A$. The discovery potential for the MSSM Higgs states is summarised in Fig. [2] where contours of 5σ significance are outlined for several decay modes of the Higgs particles in the case of maximal stop mixing and for 100 fb$^{-1}$ of integrated luminosity. The lighter state, h, can be discovered by CMS in the full parameter space.

A more challenging task is the search for the heavy states ($H, A, H^{\pm}$) in the region of low and moderate $\tan \beta$, where the couplings to the third fermion generation are not large enough for the decays $H^+ \rightarrow \tau^+ \nu_\tau$ and $H, A \rightarrow \tau^+ \tau^-$ to be exploited. Some parts of this region can be covered by the decays of H and A to pairs of neutralinos or charginos, when kinematically allowed [6]. Particularly interesting is the channel $A, H \rightarrow \chi_1^0 \chi_2^0$ with $\chi_2^0 \rightarrow \chi_1^0 \ell^+ \ell^-$, due to the very clear signature of four isolated leptons in the final state. The main backgrounds are ZZ production and a few SUSY channels. For this channel, the 5σ discovery contours for an integrated luminosity of 30 and 100 fb$^{-1}$ are shown in Fig. 3 for a choice of MSSM parameters corresponding to $M_{\chi_1^0} = 60$ GeV/$c^2$ and $M_{\chi_2^0} = 120$ GeV/$c^2$.

The production of the lightest state h in cascade decays of squarks and gluinos, observed in the decay mode $h \rightarrow b\bar{b}$, turns out to be also a very promising discovery channel for this particle. Results of a study [7] performed in the framework of mSugra are shown in Fig. 4 as 5σ discovery contours for integrated luminosities of 10 and 100 fb$^{-1}$. The signal can be observed in a b-tagged di-jet mass distribution in multi-jet-plus-$E_T^{miss}$ final states, yielding in large regions of the parameter space a signal-over-background ratio of order one. Discovery is possible for masses of squarks and gluinos in the range from 450 GeV/$c^2$ up to about 1.5 TeV/$c^2$, with 100 fb$^{-1}$.

5 SUSY Spectroscopy at CMS

Once supersymmetric particles are discovered, it is of prime importance to study the new particles by, e.g., measuring their masses and branching fractions, so as to compare with the predictions of the underlying theory. This section describes one possible procedure to follow in reconstructing completely a decay chain of a particle in a specific example. The framework is mSugra with $m_{1/2}=250$ GeV/$c^2$, $m_0=100$ GeV/$c^2$, $\tan \beta= 10$, $\mu > 0$ and $A_0=0$. The results expected with 10 fb$^{-1}$ are shown here.

The channel considered corresponds to the production of a gluino, which decays through the chain $\tilde{g} \rightarrow b\bar{b}$, $b \rightarrow \chi_2^0 b$, $\chi_2^0 \rightarrow \tilde{\ell}^\pm \tilde{\ell}^\mp \rightarrow \chi_1^0 \ell^+ \ell^-$. The signature of this channel is the presence in the final
Figure 1: 5σ discovery reach of CMS in the mSugra $m_{0}$-$m_{1/2}$ plane with $A_{0}=0$, $\tan \beta=2$, $\mu > 0$ (left) and $A_{0}=0$, $\tan \beta=35$, $\mu < 0$ (right) and for 100 fb$^{-1}$ of integrated luminosity. The full lines correspond to different final states, as defined in the text. Dashed-dotted lines are isomass contours for squarks and gluinos. Filled areas correspond to regions excluded either theoretically or experimentally.

Figure 6 shows that already with 10 fb$^{-1}$ the sbottom peak is very clearly visible over a small residual background. A fit of the peak yields a value of the sbottom mass in good agreement with the generated value, with a resolution better than 10%.

The final step of the analysis consists in associating the sbottom to the closest b jet to reconstruct the gluino. The result is shown in Fig. 7. The mass of the gluino is correctly extracted from the fit to the peak, again with a resolution of about 10%. The large systematic uncertainties arising from the approximation about the $\chi^{0}_{1}$ mass remain to be studied.
Figure 2: $5\sigma$ discovery contours for the MSSM Higgs sector in CMS for 100 fb$^{-1}$ of integrated luminosity.

Figure 3: $5\sigma$ discovery contours for integrated luminosity of 30 and 100 fb$^{-1}$ for the channel $A, H \rightarrow \chi^0_2 \chi^0_2 \rightarrow 4\ell + X$.

Figure 4: Discovery contours ($5\sigma$) in CMS for the lightest SUSY Higgs boson $h$, produced in SUSY cascades and decaying in the mode $h \rightarrow b\bar{b}$. The other mSugra parameters are chosen as: $A_0=0$, $\tan \beta=10$ and $\mu < 0$. Results are given for integrated luminosities of 10 and 100 fb$^{-1}$.

Figure 5: The dimuon and dielectron invariant mass distribution obtained after requiring $E_T^{\text{miss}} > 150$ GeV, for the gluino-sbottom decay chain described in the text. The dark histogram represents the remaining SM background, the light one is the SUSY signal. The plot is based on an integrated luminosity of 10 fb$^{-1}$.

6 Conclusions

Supersymmetry is a good candidate theory to describe physics at energies in the TeV range. The LHC therefore provides a unique opportunity to test its predictions. Detailed studies have been performed in CMS to evaluate the SUSY discovery potentials in the mSugra framework. The inclusive CMS SUSY reach, with an integrated luminosity of 300 fb$^{-1}$, will be of about 2.6-3.0 TeV/$c^2$ for squarks and gluinos, quite independently of the choice of parameters. The discovery potential in the MSSM Higgs sector has also been studied. An analysis of a gluino-sbottom decay chain in a specific point of the MSSM parameter space shows that the masses of squarks and gluinos can be measured with integrated luminosities of about 10 fb$^{-1}$ provided that the LSP mass is known.
Figure 6: The neutralino-$b$ invariant mass, corresponding to the sbottom reconstructed as described in the text. The light histogram represents the SM background. Cut values are reported as well.

Figure 7: The reconstructed gluino mass peak, obtained associating the sbottom and the closest $b$ jet. SM background is in black, SUSY signal in gray.

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