# DISCOVERY POTENTIAL FOR SUGRA/SUSY AT CMS

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We describe the expected SUSY discovery potential of the CMS experiment at LHC, both in the framework of mSUGRA and in other MSSM models, with emphasis on inclusive searches, the MSSM Higgs sector, and one example of complete reconstruction of a SUSY decay chain.

## 1 Introduction

The search for supersymmetry (SUSY) is one of the main goals of 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 center of mass energy of the pp collisions at LHC will be 14 TeV, with a design luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$, 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$^{-1}$ before reaching the design value; the results which will be presented in this article will often refer to this as the "low luminosity" scenario, whereas the design luminosity is sometimes referred to as "high".

The typical SUSY signature is that of events with many high transverse momentum ($p_t$) jets, missing transverse energy ($E_t$) and possibly the presence of high-$p_t$ leptons. The experimental requirements are therefore a good jet and missing-$E_t$ resolution, hermetic calorimetry, efficient b-tagging and tau identification and precise lepton and energy scales.

SUSY searches 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 extension of the Standard Model which contains SUSY is the Minimal Supersymmetric Standard Model (MSSM), which contains two Higgs doublets and and has more than 100 free parameters. A great reduction in the number of parameters is obtained by introducing unification of masses and couplings at the grand unification (GUT) scale. This model is usually referred to as the *constrained MSSM.* Under the assumption that SUSY breaking is communicated by gravitation, one obtains the model called minimal supergravity (mSUGRA), which is determined by only five parameters: $m_{1/2}$, 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, sign($\mu$), the sign of the Higgsino mixing parameter and $A_0$, the common trilinear scalar coupling at GUT scale. mSUGRA is often chosen as a convenient model to evaluate the potentials for discovery of

Table 1. Definition of the 6 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 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 |

new experiments, as is done in the rest of this paper.

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 parameters space, Section 4 contains some results related to the Higgs sector of some MSSM models and Section 5 describes the reconstruction of the full decay chain of a specific SUSY channel.

## 2 SUSY Triggers in CMS

The most common SUSY models have the feature of conserving R-parity ($R_p$), a symmetry which distinguishes between standard particles and their supersymmetric partners. In these models the lightest SUSY particle (LSP) is stable and weakly interacting (to explain its non-observation), leading to missing $E_t$, together with the presence of many high-$p_t$ jets coming from the SUSY decay chain. The case of $R_p$ violation is more challenging because it allows the decay of the LSP, predominantly to jets. The design of trigger algorithms which will allow an effective search for SUSY signals, must therefore take into account both cases of conservation and violation of $R_p$, relying differently on the multijets and missing $E_t$ signatures. CMS has recently presented results of optimisations of Level 1 (L1) and High Level Trigger (HLT) using GEANT simulation and fully realistic reconstruction software [1].

The SUSY trigger has been optimised at six benchmark mSUGRA 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 Tab. 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, relative to the low-luminosity scenario, lie just above the mass reach of the Tevatron, with relatively small sparticle masses and therefore with small missing $E_t$ and small jet $E_t$. For the high luminosity case, points 7, 8 and 9 are chosen to test the ability to probe high sparticle masses, with correspondingly very low

Table 2. The HLT cut values and efficiencies for six mSUGRA points defined in Tab. 1 and their corresponding $R_p$ violating versions (denoted with R next to the point number). The cuts are based on missing $E_t$($\mathrm{E}_t^m$) and on $E_t$ of the jets. The table shows efficiencies of the separate selections and, in parentheses, the cumulative efficiencies.

| Low luminosity | | | High luminosity | | |
|---|---|---|---|---|---|
| Point | 1 jet $>$ 180 GeV<br>$\mathrm{E}_t^m > 123$ GeV | 4 jets, $E_t$>113 GeV | Point | $\mathrm{E}_t^m > 239$ GeV | 4 jets, $E_t$>185 GeV |
| | 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) |

cross sections.

The results of the optimisation of the HLT are reported in Tab. 2, together with the corresponding cuts; both $R_p$ conservation and $R_p$ violation are considered. Selections are based on the combination of two trigger strategies, one based on missing $E_t$ and the other based purely on the presence of high-$E_t$ jets, the latter being very effective for the $R_p$-violating scenario. The overall HLT efficiencies are very high, even in the more challenging case of $R_p$ violation, showing that CMS is expected to trigger on SUSY events with a satisfactory efficiency in a very large region of the mSUGRA parameter space.

## 3 Inclusive SUSY Reach

If SUSY turns out to be the right description of physics at the TeV scale, the LHC will be the ideal place to detect the new particles. In particular, cross sections will be high for the production of strongly-interacting sparticles, such as squarks and gluinos. In the $R_p$-conserving scenario, studies of the inclusive discovery reach of CMS have been performed [2], by exploiting the already mentioned signatures: missing energy due to the escape of the LSP, high-$p_t$ jets from squark and gluino decays and a variable number of isolated leptons, depending on the decay chains. In the case of high $\tan\beta$, the events will also contain a large number of b quarks and $\tau$ leptons.

Besides the common requirements of missing $E_t$ ($>$ 200 GeV) and of at least 2 jets with $E_t >$ 40 GeV, the following final-state topologies are 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

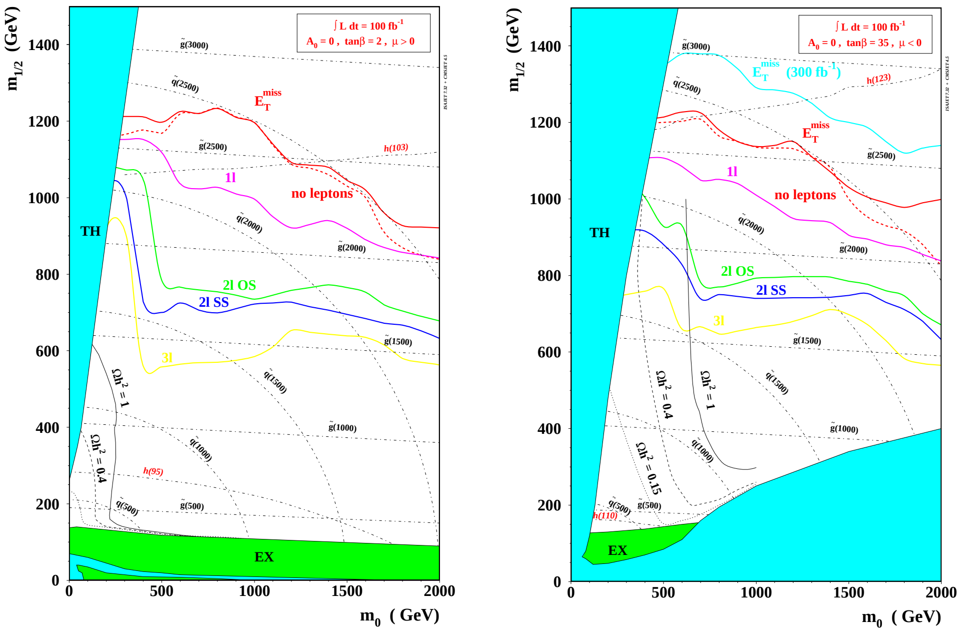

Figure 1. $5\sigma$ discovery reach of CMS in the mSUGRA $m_0$-$m_{1/2}$ plane with $A_0$=0, $\tan\beta$=2, $\mu > 0$ (left) and $A_0$=0, $\tan\beta$=35, $\mu < 0$ (right) and for 100 $fb^{-1}$ of integrated luminosity. The full lines correspond to different final states, as defined in the text. Dashed-dotted lines are isomass contours for squarks and gluinos. Filled areas correspond to regions excluded either theoretically or experimentally.

the detector response. 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($\mu$) and scanning the $m_0$-$m_{1/2}$ plane. As an example, Fig. 1 shows the discovery reach contours of CMS with an integrated luminosity of 100 $fb^{-1}$, for $A_0$=0, $\tan\beta$=2 and $\mu > 0$ (on the left) and $A_0$=0, $\tan\beta$=35 and $\mu < 0$ (on the right). The criterion for discovery was defined as $S/\sqrt{S+B} > 5$, where S is the number of SUSY signal events and B the number of background events.

It is clear from these plots that the missing-$E_t$ signature is very powerful in identifying an excess of mSUGRA events over the SM background. Similar results can be obtained for different integrated luminosities. As an example in Fig. 1 (right) the discovery contour for the missing $E_t$ final state for 300 $fb^{-1}$ integrated luminosity (expected in about 3 years of running at high luminosity) is also reported. In summary, for most of the mSUGRA parameter space

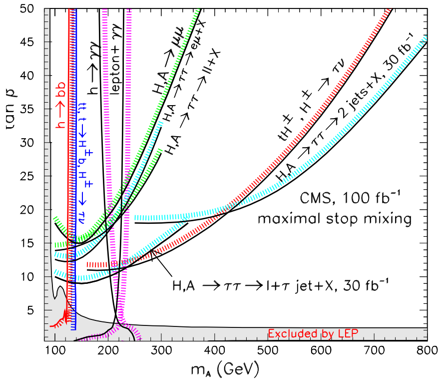

Figure 2. $5\sigma$ discovery contours for the MSSM Higgs sector in CMS for 100 $fb^{-1}$ of integrated luminosity.

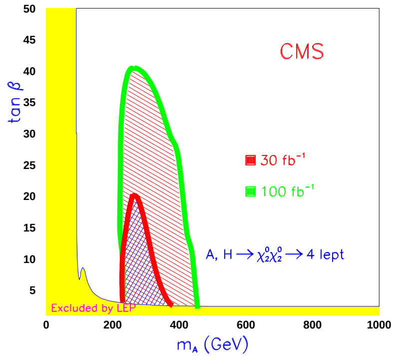

Figure 3. $5\sigma$ discovery contours for integrated luminosity of 30 and 100 $fb^{-1}$ for the channel A, H $\rightarrow \chi_2^0 \chi_2^0 \rightarrow 4\ell + X$.

the discovery reach of CMS for squarks and gluinos is between 2.6 and 3.0 TeV.

## 4 The MSSM Higgs Sector

The Higgs sector of the MSSM consists of two complex SU(2) doublets, 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 the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$ and the mass of the A boson, $M_A$. The discovery potential for the MSSM Higgs states is summarised in Fig. 2, where contours of $5\sigma$ 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 generation become smaller and therefore the decays of charged Higgs containing one $\tau$ and of H, A to $\tau$ pairs cannot be exploited. Some parts of this region can be covered by the decays of heavy Higgs to pairs of neutralinos or charginos, when kinematically allowed [5]. Particularly interesting is the channel A, H $\rightarrow \chi_2^0 \chi_2^0 \rightarrow 4\ell + X$, 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 $5\sigma$ discovery contours for an integrated luminosity of 30 and 100 $fb^{-1}$ are shown in Fig. 3, for a given choice of MSSM parameters ($M_1 = 60$ GeV, $M_2 = 120$ GeV, $\mu = -500$ GeV, $M_{\tilde{l}} = 250$ GeV,

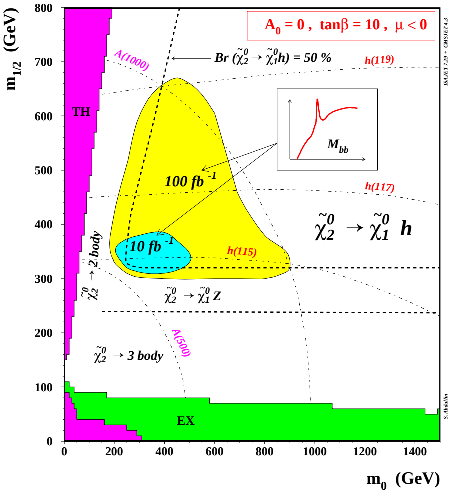

Figure 4. Discovery contours ($5\sigma$) in CMS for the lightest SUSY Higgs boson h, produced in SUSY cascades and decaying in the mode h$\rightarrow b\bar{b}$. The other mSUGRA parameters are chosen as: $A_0$=0, $\tan\beta$=10 and $\mu < 0$. Results are given for integrated luminosities of 10 and 100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

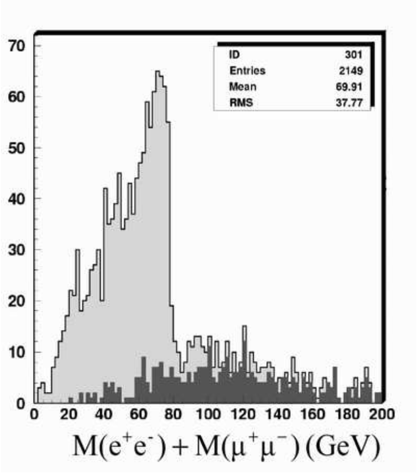

Figure 5. The dimuon and dielectron invariant mass distribution obtained after requiring missing $E_t>$ 150 GeV, for the gluino-sbottom decay chain described in the text. The dark histogram represents the remaining SM background, the light one is the SUSY signal. The plot is based on an integrated luminosity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

$M_{\tilde{q},\tilde{g}} = 1000$ GeV).

Besides SUSY Higgs decays, SUSY Higgs production has also been studied in CMS. In particular 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 a very promising discovery channel for this particle. Results of a study [6] performed in the framework of mSUGRA are shown in Fig. 4 as $5\sigma$ discovery contours for integrated luminosities of 10 and 100 $fb^{-1}$. The signal can be observed in a b-tagged di-jet effective mass distribution in multijet plus missing $E_t$ 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 up to about 1.5 TeV, with 100 $fb^{-1}$.

## 5 SUSY Spectroscopy at CMS

Provided that SUSY is the right theory to extend the SM in the TeV range, it will be important not only to detect signals of its existence, as described in Sec. 3, but also to study the new particles which will constitute its spectrum. This section describes one possible procedure to follow in reconstructing completely a decay chain of a sparticle in a specific example. The framework is mSUGRA with $m_{1/2}$=250 GeV, $m_0$=100 GeV, $\tan\beta$= 10, $\mu > 0$ and $A_0$=0, and we will show results obtained in the assumption of an integrated luminosity of 10 $fb^{-1}$.

The channel considered corresponds to the production of a gluino, which decays through the chain: $\tilde{g} \to \tilde{b}b$, $\tilde{b} \to \tilde{\chi}_2^0 b$, $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+ \ell^-$. The signature of this channel is the presence in the final state of two same-flavour opposite-sign isolated leptons (electrons and muons are considered), two b-jets and missing $E_t$. The main SM background is $t\bar{t}$, which is greatly reduced by cutting on the missing $E_t$ of the event. In Fig. 5 we show the dilepton invariant mass distribution for events with missing $E_t$ of at least 150 GeV. A sharp edge which is due to the kinematics of the decay is clearly visible. For events close to the kinematic endpoint, corresponding to the two leptons being emitted back-to-back in the $\tilde{\chi}_2^0$ rest frame, the $\tilde{\chi}_2^0$ momentum is given by:

$$\vec{p}_{\tilde{\chi}_2^0} = \left(1 + \frac{M_{\tilde{\chi}_1^0}}{M_{\ell^+\ell^-}}\right) \vec{p}_{\ell^+\ell^-}, \tag{1}$$

where $M_{\tilde{\chi}_1^0}$ is the mass of the $\tilde{\chi}_1^0$, $M_{\ell^+\ell^-}$ is the dilepton invariant mass and $\vec{p}_{\ell^+\ell^-}$ is the sum of the momenta of the two leptons. Selecting events with a dilepton invariant mass in a window of 16 GeV centered on the dilepton edge, and associating $\vec{p}_{\tilde{\chi}_2^0}$ with the momentum of the highest-$E_t$ b-jet in the event, the kinematics of the decaying sbottom can be reconstructed. The invariant mass is shown in Fig. 6. This analysis is obtained under the assumption that $M_{\tilde{\chi}_1^0}$ is known. Alternatively, in the mSUGRA framework, one can approximate it to the value of the dilepton edge, with little error. Fig. 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 of 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%.

## 6 Conclusions

Supersymmetry is considered by most physicists to be the best candidate theory to describe physics at energies higher than the ones we can access with present experiments. The LHC will be the machine which will provide us with the unique opportunity to test this theory. Detailed studies have been performed in CMS to evaluate the SUSY discovery potentials, both in the mSUGRA framework and in other MSSM models. The inclusive CMS SUSY reach, with an integrated luminosity of 300 $fb^{-1}$, will be of about 2.6-3.0 TeV for squarks and gluinos, quite independently of the choice of parameters. In this paper we have also briefly described some results relative to the CMS

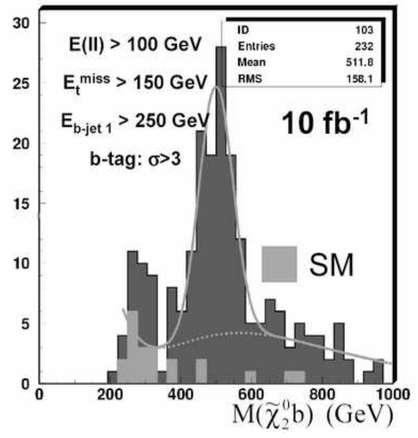

Figure 6. The neutralino-b invariant mass, corresponding to the sbottom reconstructed as described in the text. The light histogram represents the SM background. Cut values are reported as well.

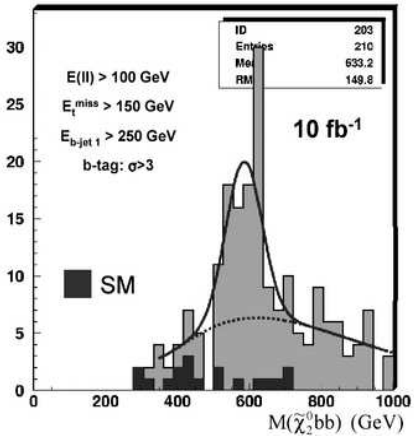

Figure 7. The reconstructed gluino mass peak, obtained associating the sbottom and the closest b-jet. SM background is in black, SUSY signal in gray.

discovery potential in the MSSM Higgs sector, in particular exploiting SUSY production and decay of the Higgs particles. 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 $fb^{-1}$.

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