Sparticle searches with CMS at LHC

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In this paper a review of recent studies made to understand the capability to detect and reconstruct strongly interacting squarks and gluinos with the CMS detector is presented. The detection of these sparticles relies on the observation of an excess of events over Standard Model background expectations. The results for inclusive searches of squarks and gluinos are presented as 5σ discovery contours in the framework of a minimal SU(5) mSUGRA model.
A new study devoted to the scalar bottom quark ($\tilde{b}$) and gluino ($\tilde{g}$) reconstruction, through the process $\tilde{g} \rightarrow \tilde{b}b$, will be discussed extensively and the expected resolutions on sbottom and gluino masses are presented.

1 Introduction

One of the main purposes of the LHC collider is to search for the physics beyond the Standard Model. The discovery of superpartners of ordinary particles, as expected in Supersymmetric extension of SM (SUSY) [1], would be a proof of the existence of new physics. If supersymmetry exists at the electroweak scale, it could hardly escape detection at LHC. Thanks, in fact, to the centre of mass energy of 14 TeV, which will be available at LHC, it will be possible to extend the searches of SUSY particles up to masses of 2.5 – 3 TeV. SUSY, if it exists, is expected to reveal itself at LHC via excess of multijet+$\mathrm{E}_{\mathrm{T}}^{miss}$+(multilepton) final states compared to SM expectations [2]. Determining masses of supersymmetric particles, however, is more difficult. The main goal of this paper, is to show the potential of the CMS detector [3] to find evidence for SUSY and to reconstruct SUSY particles. Since the production cross section for gluinos and squarks dominates the total SUSY cross section over a wide region of the parameter space, this paper will deal with squark and gluino discovery potential and especially will be focused on the reconstruction capabilities of sbottom and gluino masses. After a brief description of the MSSM-mSUGRA model used, first a review of the inclusive squark and gluino searches is described in terms of the reach obtainable with the CMS detector. The second part of the paper will be dedicated to the description of a new strategy to select and reconstruct sbottoms and gluinos and the resolution achievable on their masses.

2 Model employed

The large number of SUSY parameters even in the framework of Minimal extension of the SM (MSSM) makes it difficult to evaluate the general reach. Therefore, these studies are performed in the framework of the Minimal Supergravity (mSUGRA) model [4], a constrained version of the MSSM model. mSUGRA is the $N = 1$ Supergravity theory with the "soft" SUSY breaking naturally performed by universal gravitational interactions in the "hidden" sector. At the Grand Unification (GUT) scale ($\approx 10^6$ GeV) gauginos and scalars have common masses and couplings. The low-energy phenomenology is then evolved using Renormalization Group Equations [5] from the GUT scale to the Electroweak scale. The independent parameters of the model are: the common gaugino mass $m_{1/2}$, the common scalar mass m_0, the common trilinear scalar coupling A_0, the ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta$ and the sign of the Higgsino mixing parameter μ.

An additional requirement is the R-parity conservation. As a consequence of this assumption, sparticles can be produced only in pairs and the Lightest Supersymmetric Particle (LSP) produced at the end of decay chain of every sparticle is stable. In mSUGRA models the LSP is always the lightest neutralino $\tilde{\chi}_1^0$.

Sparticle masses strongly depend on $m_{1/2}$ and m_0 and only moderately on the other parameters, so it is natural to present the results in the mSUGRA parameter plane ($\mathrm{m_0}$,$\mathrm{m_{1/2}}$) for fixed values of other parameters. The trilinear scalar coupling has a small effect and we set it to zero in our study. In Fig. 1 the total mSUGRA production cross section, as obtained with ISAJET 7.37 [6], for $A_0 = 0$, $\mu > 0$, $\tan\beta = 2$ (left panel) and $\tan\beta = 35$ (right panel) is shown [7] (the $\mu < 0$ case is very similar and is omitted). The overall SUSY production cross section (continuous line) is compared with the total cross section for processes with at least one strongly interacting sparticle (dashed line). The total cross section for different values of $\tan\beta$ and μ, but for the same values of $\mathrm{m_0}$, $m_{1/2}$ differs slightly. The bulk of the total cross section for low values of $m_{1/2}$ is made of $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production, whereas in the domains with extremely high masses of $\tilde{g}$ and $\tilde{q}$ the contribution of production of squarks or gluinos associated with charginos and neutralinos may dominate.

3 Inclusive searches

As discussed earlier, the highest cross section for R-parity conserving SUSY at hadron colliders is due to squarks and/or gluinos which decay through a number of steps to quarks, gluons, charginos, neutralinos, sleptons, W, Z, Higgses and ultimately a stable LSP, which is weakly interacting and escape detection. The final state has missing energy (2 LSP's + neutrinos), a number of jets, and a variable number of leptons, depending on the decay chain. The sparticle production and decay characteristics lead to a number of specific event topologies which should allow the discovery of SUSY in general, and

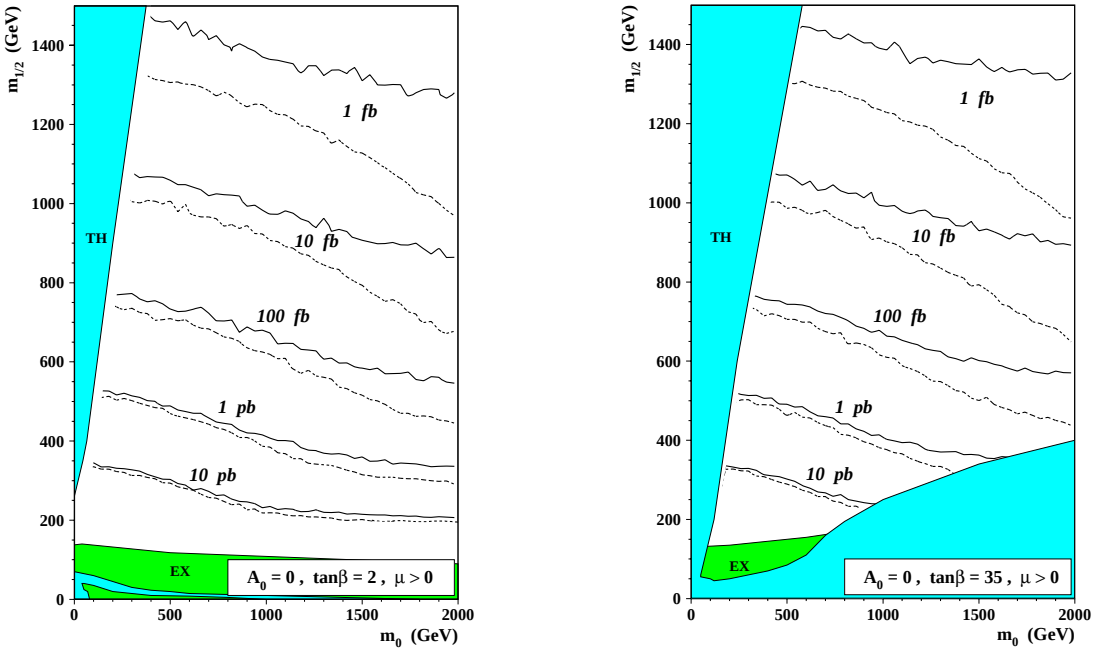

Figure 1: Total mSUGRA sparticle production cross section as a function of m_0 and $m_{1/2}$ for $A_0 = 0$, $\mu > 0$ and $\tan\beta = 2$ (left panel) and $\tan\beta = 35$ (right panel) [7].

specifically the separation of certain SUSY sparticles and processes from SM and other SUSY processes. The inclusive searches are based indeed on these peculiar features. Since the identification of specific processes is not required with this approach a high tagging efficiency can be achieved. The most peculiar features of squark and gluino decays can be summarized as:

- high E_T hadron jets from squark and gluino decays ($\tilde{q} \to q\tilde{\chi}_i^0$, $\tilde{q} \to q'\tilde{\chi}_i^{\pm}$, $\tilde{g} \to q\tilde{q}$);
- large missing transverse momentum due to the LSP's which do not interact with the detector;
- large number of b quarks (from decays of $\tilde{t}, \tilde{b}, h, t$) and τ leptons (specially at high $\tan\beta$);
- large number of isolated leptons produced by $\tilde{\chi}_2^0 \to \ell\tilde{\ell}, \ell\tilde{\ell}^*$, $\tilde{\ell} \to \ell\tilde{\chi}_1^0$ decays.

Five final states, called 0l, 1l, 2lOS, 2lSS, 3l, based on the requirements of no leptons, at least one lepton, two opposite charge leptons, two same charge leptons and three leptons, respectively, have been investigated. Besides, the final state with only missing transverse momentum (E_T^{miss}) has also been studied. The basic requirements of $E_T^{miss} > 200$ GeV and at least 2 jets with $E_T^{jet} > 40$ GeV and $|\eta^{jet}| < 3$ are common to all the analyses.

Several different strategies have been adopted for the different analyses [7] and for each of them the region of sensitivity of the CMS experiment is calculated. The ISAJET

7.37 generator [6] has been used for mSUGRA signal generation, whereas the PYTHIA 5.7 generator [8] has been used to generate all the SM backgrounds. The CMSJET [10] fast MC package has been used to model the CMS detector response. For each set of SUSY parameters investigated the selection cuts have been optimized in order to achieve the best sensitivity. The chosen criterion of the mSUGRA signal observability is $S/\sqrt{S+B} > 5$, where S means the number of mSUGRA signal events, while B is the number of background events.

Fig. 2a shows the 5σ discovery contours for an integrated luminosity $\int \mathcal{L}dt = 100$ fb^{-1} and $A_0 = 0$, $\mu > 0$ and $\tan\beta = 35$. The neutralino relic density contours from ref.[9] are also shown for Ωh^2 =0.15, 0.4 and 1.0. It is a rather general situation that for all investigated sets of mSUGRA parameters the best reach can be obtained with the E_T^{miss} signature. The contribution of each analysis is also shown. It is worth noticing that the cumulative reach of several signatures, like 0l+1l+2l+3l+... (in descending order of contribution) can be even better than the most promising single E_T^{miss} contribution. We show this with the cumulative 0l+1l+2l OS signature curve in Fig. 2a.

To show how the possible reach in the E_T^{miss}+jets final states increases with increasing integrated luminosities, in Fig. 2b, the 5σ reach contours for 1 fb^{-1}, 10 fb^{-1}, 100 fb^{-1} and the ultimate high luminosity of 300 fb^{-1} are shown.
Even with only 1 fb^{-1} of integrated luminosity, the CMS detector should be able to discover squarks and gluinos if their masses do not exceed about 1.3 TeV. With 10 fb^{-1} the search extend to $\approx 1.6-2.0$ TeV for gluinos and $1.8-2.0$ TeV for squarks depending on m_0, with 100 fb^{-1} the reach can be extended up to masses $m_{\tilde{q}} \sim m_{\tilde{g}} \sim 2.5$ TeV. This means that, within this mSUGRA scenario, the entire plausible domain of EW-SUSY parameter space for most probable value of $\tan\beta$ can be probed.

A first attempt to study the ability of CMS to discover SUSY using a less constrained model than mSUGRA, the pMSSM, has also been done. Details of this analysis can be found in ref. [11]. The main conclusion of this study is that there are very little difference between mSUGRA scenario and the pMSSM one. The limit of discovery corresponds to the limit of the cross section (2.7 TeV at CMS). The only difference appears for some points having a specific mass hierarchy. As an example, in the case of compact hierarchy of masses, the limit we expect is about $m_{\tilde{q}} \sim m_{\tilde{g}} \sim 1.5$ TeV.

4 Exclusive searches: sbottom and gluino reconstruction

If SUSY exists at the electroweak scale, then, as we have shown, it should be discovered at the LHC. Determining masses of supersymmetric particles, however, is more difficult because each SUSY event contains two LSP's, and there are not enough kinematic constraints to determine the momenta of these. In order to reconstruct sparticle masses a different strategy with respect to the one developed for the inclusive analysis should be used. In this section we present the results of a new study aimed at the reconstruction of the strongly interacting gluinos and sbottoms. In order to perform this mass reconstruc-

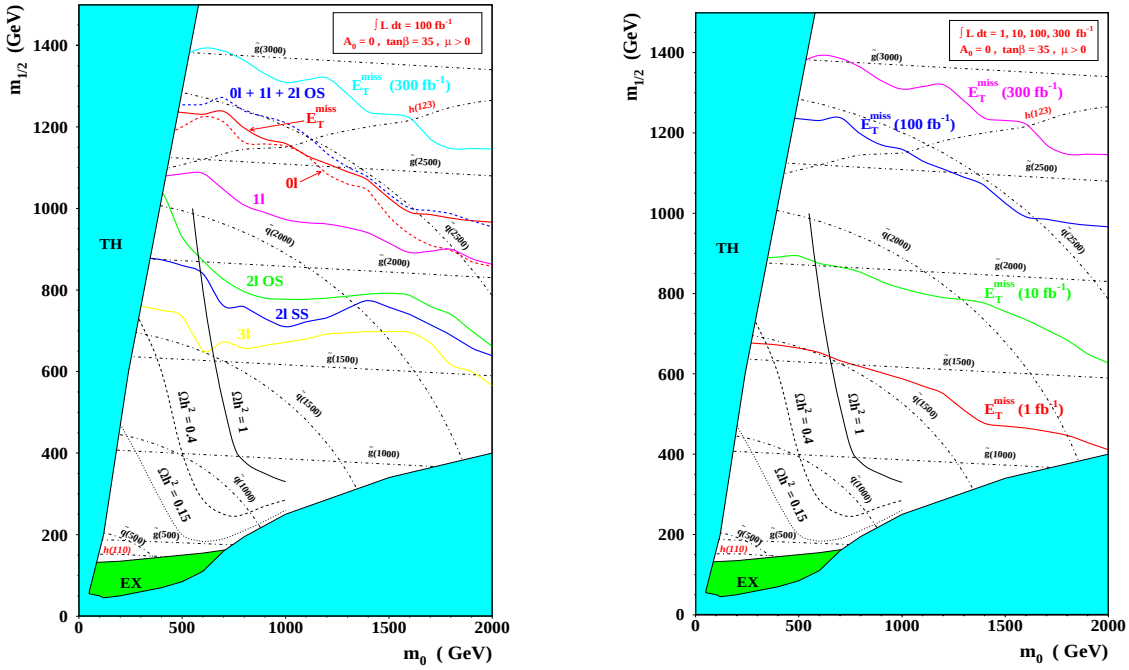

Figure 2: (a): 5σ reach contours for various final states, as described in the text, for $\tan\beta = 35$, $A_0 = 0$, $\mu > 0$ (left panel). (b): 5σ reach contours for E_T^{miss}+jets final state for $\tan\beta = 35$, $A_0 = 0$, $\mu > 0$ for various assumed integrated luminosities.

tion, the decay chain $\tilde{g} \to \tilde{b}b$, $\tilde{b} \to \tilde{\chi}_2^0 b$, $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0 \ell^+\ell^-$, where $\ell = e, \mu$, has been considered. In this decay two b-jets, two same flavour and opposite charge isolated leptons and large missing transverse momentum due to the escaping $\tilde{\chi}_1^0$ are produced. Leptons from the $\tilde{\chi}_2^0$ decay exhibit a peculiar $\ell^+\ell^-$ invariant mass distribution with a sharp edge, as shown in Fig. 3. If $m_{\tilde{\chi}_2^0} < m_{\tilde{\ell}} + m_{\ell}$ the $\tilde{\chi}_2^0$ decay would be a three body decay mediated by a virtual slepton and the edge would be placed at $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. In the opposite case, when $m_{\tilde{\chi}_2^0} > m_{\tilde{\ell}} + m_{\ell}$, the neutralino decay is a two body decay and the edge would be placed at

$$M_{\ell^+\ell^-}^{max} = \frac{\sqrt{\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2\right)\left(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2\right)}}{m_{\tilde{\ell}}} \qquad (1)$$

The analysis has been performed in a mSUGRA scenario, considering two different benchmark points, the so called point B($m_{1/2} = 250$, $m_0 = 100$, $\tan\beta = 10$, $\mu > 0\, and\, A_0 = 0$) and G($m_{1/2} = 375$, $m_0 = 120$, $\tan\beta = 20$, $\mu > 0\, and\, A_0 = 0$) of ref. [12], which are characterized both by relative low value for m_0 and $m_{1/2}$ (higher production cross section for strongly interacting sparticles) and different values of $\tan\beta$. Indeed, the branching ratios of $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\ell^+\ell^-$ ($\ell = e, \mu$) decays, due to the τ Yukawa coupling increase with increasing $\tan\beta$, leading to a larger $\tilde{\chi}_2^0 \to \tau^+\tau^-\tilde{\chi}_1^0$ branching ratio, are strongly dependent on the $\tan\beta$ parameter. This effect is of fundamental importance for our analysis.

The signal events are generated using ISASUGRA 7.51[6], whereas background events ($t\bar{t}$, Z+jets, W+jets and QCD jets) are generated with PYTHIA 6.152[8]. The detector response has been evaluated using the fast MC package CMSJET[10]. The study has been realized for several different integrated luminosities. In order to perform the sbottom and gluino reconstruction, events with at least 2 same flavour opposite sign (SFOS) isolated leptons having $p_T > 15$ GeV and $|\eta| < 2.4$, corresponding to the acceptance of the muon system, and at least 2 jets tagged as b-jets, having $p_T > 20$ GeV and $|\eta| < 2.4$, are selected.

The $\tilde{b}$ reconstruction proceeds in two steps. First the $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\ell^{\pm}\ell^{\mp}$ decay chain is considered. As mentioned before, this decay is characterized by a sharp end-point in the dilepton invariant mass distribution. In Fig. 3 the SFOS dilepton pair invariant mass distribution is shown for SUSY events superimposed over the SM background. The $t\bar{t}$ component, which represents the main background, gives a wide distribution, while the Z+jets channel is visible for the Z peak which lies quite close to the end-point of the SUSY distribution.

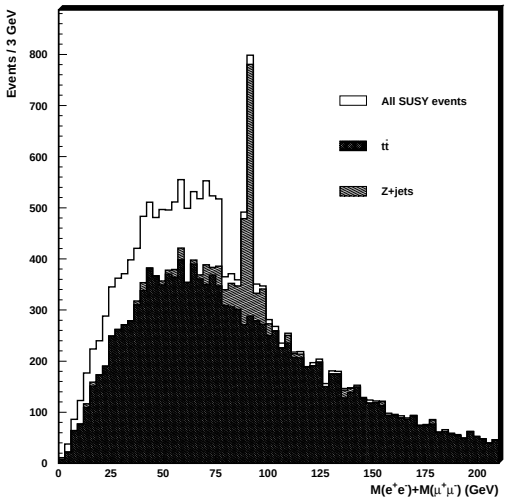

Figure 3: Invariant mass distribution of same flavour opposite sign isolated leptons for SUSY events, superimposed on the SM background. The contributions of $t\bar{t}$ and Z+jets events are shown.

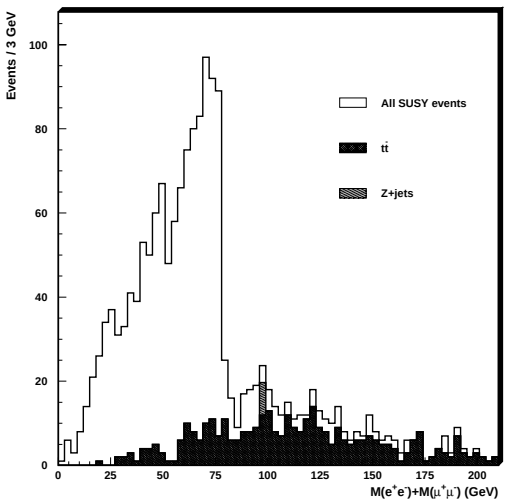

Figure 4: Same as in Fig. 3 with $E_T^{miss} > 150$ GeV and $E_{ll} > 100$ GeV cuts.

To perform our reconstruction a precise knowledge of the edge is necessary. In order to reduce the SM background contribution, the high missing energy content of SUSY events has been exploited. A cut on $E_T^{miss} > 150$ GeV permits to drastically reduce the SM background. This, combined with a cut on the dilepton energy, $E_{\ell\ell} > 200$ GeV, which suppresses other SUSY background sources, gives a very clean dilepton edge, as can be seen in Fig. 4. In order to extract the value of the end-point, a fit with a Jacobian function can be performed on the clean $M(e^+e^-) + M(\mu^+\mu^-) - M(e^+\mu^-) - M(\mu^+e^-)$ distribution, which, according to Eq. 1, returns the value $M_{\ell^+\ell^-}^{max} = (78.9 \pm 2.1)$GeV, in good agreement with the true value of 78.16 GeV.

To reconstruct the sbottom, opposite charge leptons in a window of about 15 GeV around the edge are selected. This requirement allows to select a kinematical condition in which the leptons are emitted back-to-back in the $\tilde{\chi}_2^0$ rest frame, with the $\tilde{\chi}_1^0$ at rest. In this condition and under the assumption $m_{\tilde{\chi}_2^0} \sim 2m_{\tilde{\chi}_1^0}$, which is usually valid in mSUGRA scenarios, the $\tilde{\chi}_2^0$ momentum is reconstructed through the relation:

$$\vec{p}_{\tilde{\chi}_2^0} = \left(1 + \frac{m_{\tilde{\chi}_1^0}}{M_{\ell^+\ell^-}}\right) \vec{p}_{\ell^+\ell^-}. \tag{2}$$

At this stage of reconstruction, we use the generated value for $m(\tilde{\chi}_1^0)$; similar results are obtained if the mass of the $\tilde{\chi}_1^0$ is approximated with the end-point value. We will come back to this point later.

The $\tilde{\chi}_2^0$ momentum is then summed with the momentum of the highest E_T b-tagged jet and the $\tilde{b}$ is hence reconstructed. To reduce combinatorial background coming from wrong b jets association, further kinematical cuts have been used. As shown in Fig. 5a, with an integrated luminosity of 10 fb^{-1}, a well visible sbottom mass peak, with a resolution better than 10%, can be reconstructed. The result of the fit, $M_{\tilde{b}} = 500 \pm 7$, $\sigma = 42 \pm 5$ GeV, is in good agreement with the generated values of the two sbottoms $(\tilde{b}_1, \tilde{b}_2)$, $M_{\tilde{b}_1} = 496\,GeV, M_{\tilde{b}_2} = 524$ GeV, even if at this stage of the study the CMS detector doesn't seem able to resolve the two separate peaks. Further studies are in progress to understand if it is possible to disentangle the two contributions.

The gluino is reconstructed from the sbottom momentum and that of the closest b-tagged jet. As shown in Fig. 5b, a resolution better than 10% is achieved also in this case and the fitted mass value, $M_{\tilde{g}} = 600 \pm 12$, $\sigma = 33 \pm 11$ GeV, is in agreement with the generated value, $M_{\tilde{g}} = 595$ GeV.

All the results shown so far are derived for point B and for an integrated luminosity of 10 fb^{-1}. The same kind of analysis was repeated also for point G. In this case, however, as mentioned before, the higher value of $\tan\beta$ reflects into higher branching ratio for the decay $\tilde{\chi}_2^0 \to \tau^+\tau^-\tilde{\chi}_1^0$ and so to a lower signal $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\ell^+\ell^-$, $\ell = e, \mu$. In this case, in order to reconstruct a clean mass peak for sbottom and gluino, not only the cuts should be tightened but also a greater integrated luminosity is needed. Only with an integrated luminosity of 300 fb^{-1} it is possible to reconstruct the two mass peaks ($\tilde{b}$, $\tilde{g}$) and perform the fits, nonetheless in this case a worse mass resolution is obtained. An attempt was made also to repeat the analysis at point I of ref. [12], which is characterized by a still higher value of $\tan\beta$ ($\tan\beta = 35$), but for that point, also with an integrated luminosity of 300 fb^{-1}, it is not possible to reconstruct sbottoms and gluinos with this method.
In Table 1 the results obtained for the reconstructed masses and resolutions at point B and G, in the hypothesis of a known $\tilde{\chi}_1^0$ mass and at different integrated luminosity, are summarized.

In a realistic scenario, however, CMS will not be able to detect $\tilde{\chi}_1^0$, this being a weakly interacting particle which escapes the detector. In order to evaluate the impact of

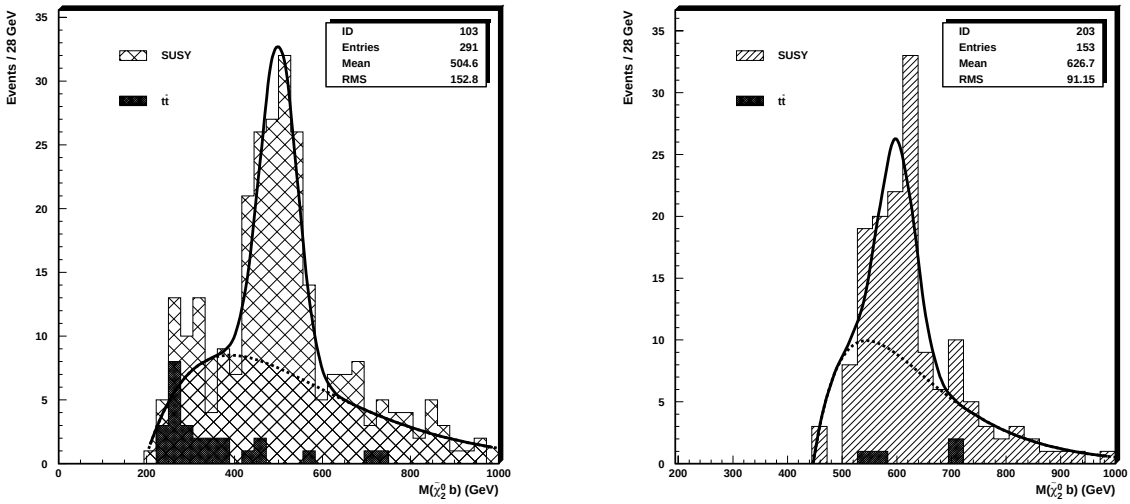

Figure 5: (a): $M(\tilde{\chi}_2^0 b)$; (b): $M(\tilde{\chi}_2^0 bb)$ mass distributions. In both plots results for mSUGRA point B are presented. Events in the mass window $65\,\text{GeV} < M_{\ell^+\ell^-} < 80\,\text{GeV}$ with $E_T^{miss} > 150\,\text{GeV}$, $E_{\ell\ell} > 100\,\text{GeV}$ and $E_T^b > 250\,\text{GeV}$ are considered.

		M($\tilde{b}$)	$\sigma(\tilde{b})$	M($\tilde{g}$)	$\sigma(\tilde{g})$	M($\tilde{g}$)-M($\tilde{b}$)	$\sigma(\tilde{g}$-$\tilde{b})$
Point B	10 fb^{-1}	500 ± 7	42 ± 5	600 ± 12	33 ± 11	91 ± 3	18 ± 3
		(470 ± 6)	(39 ± 4)	(555 ± 6)	(42 ± 4)		
	60 fb^{-1}	502 ± 4	39 ± 4	591 ± 4	44 ± 4	86 ± 2	21 ± 2
		(466 ± 4)	(32 ± 5)	(552 ± 4)	(38 ± 4)		
	300 fb^{-1}	498 ± 2	36 ± 3	590 ± 3	42 ± 4	90 ± 1	24 ± 1
		(469 ± 2)	(36 ± 2)	(552 ± 4)	(38 ± 4)		
Point G	300 fb^{-1}	720 ± 26	81 ± 18	858 ± 27	121 ± 34	125 ± 21	47 ± 22

Table 1: Sbottom and gluino mass resolution. All the results are expressed in GeV. In parenthesis the reconstructed sbottom and gluino masses for $\text{m}(\tilde{\chi}_1^0) \equiv \text{M}_{\ell^+\ell^-}^{max}$.

the uncertainty in $m(\tilde{\chi}_1^0)$ on the mass resolution of sbottom and gluino, we have repeated the analysis taking as an approximate value for $m(\tilde{\chi}_1^0)$ the dilepton end-point value. The values obtained are reported in Table 1 (numbers in parenthesis). In Fig. 6 the shift in the sbottom mass peak due to this effect is shown. The systematic error coming from this uncertainty is of the order of 5 –6%. This is an important information since for istance a future Linear Collider could permit to achieve a precision of the order of 1% in the determination of $m(\tilde{\chi}_1^0)$ and this could be used as an input for this kind of studies, eliminating the biggest source of systematic uncertainties.

It is worth noticing, that as both $M(\tilde{b})$ and $M(\tilde{g})$ depend on the $\tilde{\chi}_1^0$ mass, their difference $M(\tilde{g}) - M(\tilde{b})$ is on the contrary independent on $M(\tilde{\chi}_1^0)$. As shown in Fig. 7, CMS will be able to measure this difference with an error of few percents, independent of any assumption on the sparticle spectrum.

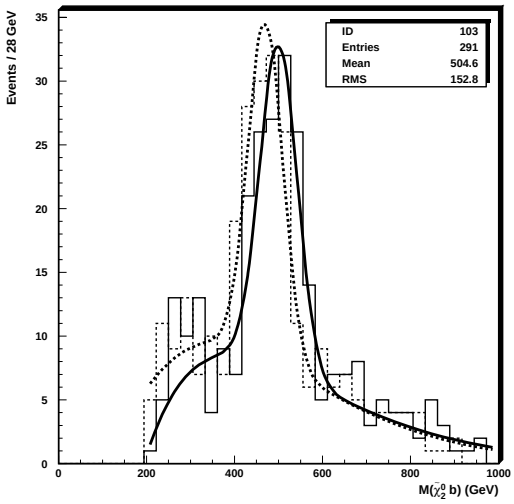

Figure 6: Shift in the sbottom mass distribution for $M(\tilde{\chi}_1^0) \equiv M_{\ell^+\ell^-}^{max}$

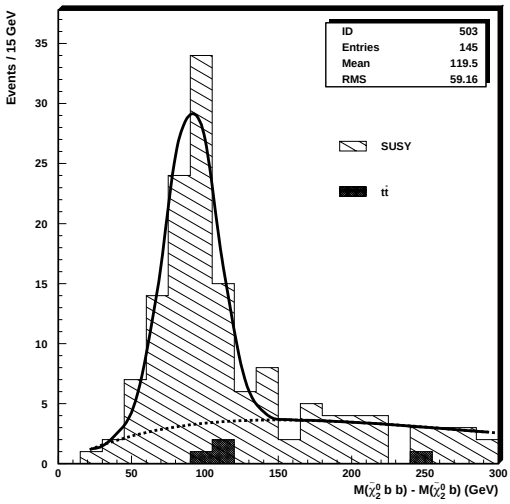

Figure 7: $M(\tilde{\chi}_2^0 bb) - M(\tilde{\chi}_2^0 b)$ distribution for the same events as in Fig. 5

5 Conclusions

If SUSY exists at the EW scale, the CMS detector will be able to discover it in a very large range of mSUGRA parameters. Squark and gluino decays present characteristic signatures to discriminate the SUSY processes from the Standard Model one. Inclusive studies have demonstrated that squarks and gluinos could be discovered already in the first months of data taking. With the ultimate high luminosity of 300 fb^{-1}, strongly interacting sparticles could be discovered up to masses of 2.5 – 3 TeV.

Altough sparticle reconstruction is more difficult, new analyses have shown that in many cases it will be possible to make exclusive reconstructions. This is the case, for istance, of the decay $\tilde{g} \to \tilde{b}b$ which allows to reconstruct both sbottom and gluino masses. Resolutions better than 10% will be attainable in the low $\tan\beta$ region, already after the first year of data taking. More work is in progress to evaluate the CMS capability to reconstruct SUSY sparticles.

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