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Searches for SUSY at LHC

For the CMS Collaboration

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Abstract

One of the main motivations of experiments at the LHC is to search for SUSY particles. The talk is based on recent analyses, performed by CMS Collaboration, within the framework of the Supergravity motivated minimal SUSY extension of the Standard Model. The emphasis is put on leptonic channels. The strategies for obtaining experimental signatures for strongly and weakly interacting sparticles productions, as well as examples of determination of SUSY masses and model parameters are discussed. The domain of parameter space where SUSY can be discovered is investigated. Results show, that if SUSY is of relevance at Electro-Weak scale it could hardly escape detection at LHC.

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1. Introduction

The Standard Model (SM), despite its phenomenological successes, is most likely a low energy effective theory of spin-1/2 matter fermions interacting via spin-1 gauge bosons. A good candidate for the new physics beyond the SM is the Supersymmetry (SUSY). In the minimal version it doubles the number of known particles, introducing scalar (fermion) partners to ordinary fermions (bosons) with the same couplings. These provide cancellation of divergences in the radiative corrections of the SM, but necessarily, the masses of super-partners should be of the order of Electro-Weak (EW) scale, i.e. $\lesssim 1$ TeV.

As a framework we have chosen the minimal Supergravity (mSUGRA), which is the most fully investigated model [1], where only five extra parameters need to be specified: the universal scalar (m_0), gaugino ($m_{1/2}$) masses and trilinear term (A_0) which are fixed at the gauge coupling unification scale; the ratio of the vacuum expectation values of the two Higgs fields (tanβ) and the sign of the Higgsino mixing parameter ($sign(\mu)$). Sparticle masses and couplings at the EW scale are then evolved via the renormalization group equations. Obtained SUSY mass spectrum is dependent most strongly on m_0 and $m_{1/2}$. In the following we limit ourselves to the choice of tan$\beta = 2$, $A_0 = 0$ and $\mu < 0$. Fig.1 shows the isomass contours for gluinos ($\tilde{g}$), charginos ($\tilde{\chi}^{\pm}$), neutralinos ($\tilde{\chi}^0$), sleptons ($\tilde{l}$) in (m_0, $m_{1/2}$) parameter space.

In R-parity conserving SUSY models sparticles are produced in pairs and a stable Lightest Supersymmetric Particle (LSP; which is the $\tilde{\chi}_1^0$ in mSUGRA) appears at the end of each sparticle decay chain. It is weakly interacting and escapes detection thus leading to a classical E_T^{miss} signature. Due to the escaping LSP's the masses of sparticles cannot be reconstructed explicitly. Usually, one characterizes the SUSY signal significance (S) by an excess of events (N_S) over the SM background expectation (N_B): $S = N_S/\sqrt{N_S + N_B}$. In some cases, the background to a particular SUSY channel is SUSY itself.

The goal of the current analysis is to evaluate the domain of (m_0, $m_{1/2}$) parameter space in which SUSY can be discovered, estimate the reach in gluino, squark, slepton, chargino, neutralino masses in various channels, develop methods to determine SUSY masses and model parameters, understand the instrumental limiting factors and contribute to detector optimization before the design is frozen [2].

In the following the SM backgrounds are generated with PYTHIA and mSUGRA processes with ISAJET. The CMS detector performances are parameterized on the basis of detailed simulations [3].

2. Gluino/Squark Production

At LHC energies, the total SUSY particles production cross-section are largely dominated by strongly interacting sparticles. Thus a typical high mass SUSY signal has squarks and/or gluinos which decay through a number of steps to quarks, gluons, charginos, neutralinos, W, Z, Higgses and ultimately to a stable $\tilde{\chi}_1^0$. For instance, the branching ratios of $\tilde{g}$, $\tilde{q}$ decays into $\tilde{\chi}_1^{\pm}$ ($\tilde{\chi}_2^0$) are complementary in (m_0, $m_{1/2}$) parameter space and exceed 30÷50%. Furthermore, at values of m_0, $m_{1/2} \gtrsim 200$ GeV the decays $\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$ are dominant, giving an isolated lepton (μ or e from W) in about 20% of cases. In the region of m_0, $m_{1/2} \lesssim 200$ GeV the leptonic branching ratios are even higher (here, also B($\tilde{\chi}_2^0 \to l^+l^- + invisible$) may reach 10÷20% being an additional important source of isolated leptons). The final state has thus a number of hard jets, missing energy ($2\tilde{\chi}_1^0$ + neutrinos) and a variable number of leptons, depending on the decay chain. The SM backgrounds considered are: $t\bar{t}$, W+jets, Z+jets, WW, ZZ, ZW, Z$b\bar{b}$, QCD ($2 \to 2$ processes, including $b\bar{b}$).

The following kinematical variables are the most useful ones for the SM backgrounds suppression: lepton p_T^l, jet E_T^j, E_T^{miss}, scalar transverse energy sum $E_T^{sum} = \sum p_T^l + \sum E_T^j + E_T^{miss}$ and $Circularity$. Depending on the mSUGRA domain under study and the final state topology, the cut values are optimized and are typically: $p_T^l > 10 \div 50$ GeV, $E_T^j > 50 \div 250$ GeV, $E_T^{miss} > 100 \div 500$ GeV, $E_T^{sum} > 500 \div 1200$ GeV and $C > 0.1$. Fig.2 shows the 5σ $\tilde{g}/\tilde{q}$ discovery contours in various final states with at least two jets, $E_T^{miss} > 100$ GeV and with one lepton ($1l$), two leptons of opposite sign ($2l$ OS), two leptons of same sign ($2l$ SS), etc. [4]. Clearly, at an integrated luminosity of $L_{int} = 10^5$ pb^{-1} the gluino/squark masses up to $2 \div 2.5$ TeV can be probed. The corresponding reach in the $\tilde{\chi}_1^0$ mass is ~350 GeV. This result is of particular importance as the $\tilde{\chi}_1^0$ could be a good candidate for cold dark matter of the Universe. The upper limit on neutralino relic density corresponds to $\Omega h^2 = 1$ contour (see Fig.2) [5], which is fully contained in the explorable domain.

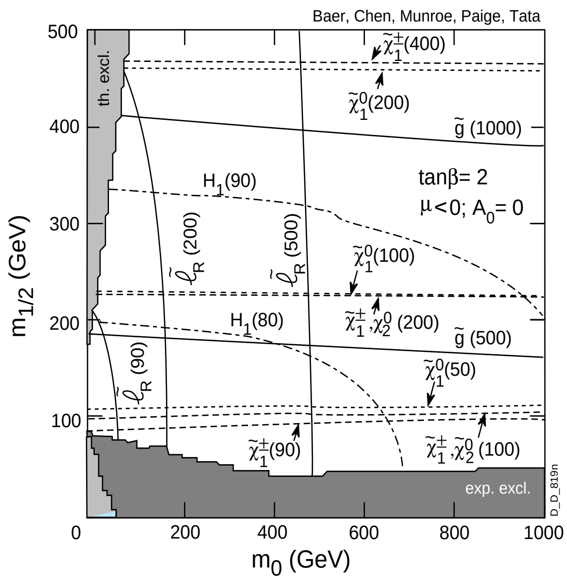

Figure 1: Sparticles isomass contours in (m_0, $m_{1/2}$) parameter space of mSUGRA.

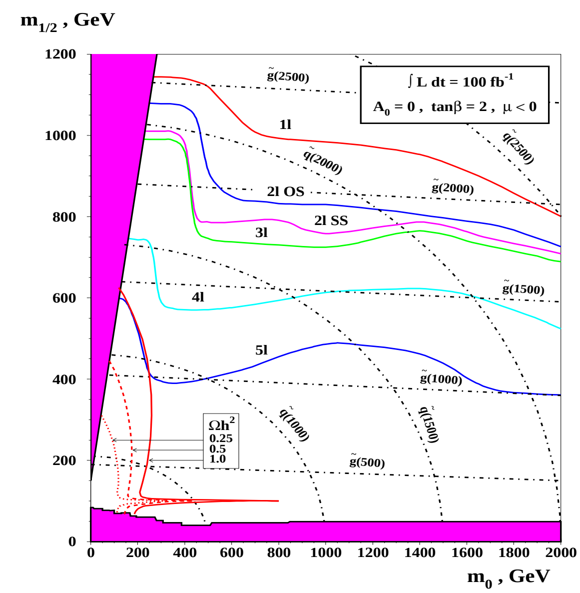

Figure 2: Explorable domain of (m_0, $m_{1/2}$) parameter space in $n \cdot l + m \cdot jets + E_T^{miss}$ final states at $L_{int} = 10^5$ pb^{-1}.

3. Slepton Production

Slepton pairs produced in a Drell-Yan process and decaying leptonically lead to the final states characterized by two hard, same-flavor, opposite-sign isolated leptons, E_T^{miss} and no jet activity, except from the initial state radiation. The issue here is to understand and keep under control the SM and internal SUSY backgrounds in the many processes involved. The following SM processes may contribute to 2 leptons final state: WW, WZ, $t\bar{t}$, Wtb, $\tau\tau$, $b\bar{b}$. A typical set of cuts allowing to extract the signal is: 2 isolated leptons of $p_T^l > 30$ GeV, $E_T^{miss} > 80$ GeV, veto on jets with $E_T^j > 30$ GeV in $|\eta| < 4$, relative azimuthal angle between the leptons and $E_T^{miss} > 160°$ [6]. Depending on mSUGRA domain under study the cuts are optimized. The dominant backgrounds are: reducible $t\bar{t}$ and irreducible WW, $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$. Other SUSY backgrounds are largely reduced by vetoing the central jets. Fig.3 shows mSUGRA points for which the slepton signal visibility has been investigated in the $2l + no\ jets + E_T^{miss}$ final states along with a 5σ significance contour for an integrated luminosity of $L_{int} = 10^5$ pb^{-1}. The slepton mass domain that can be explored extends up to ~400 GeV.

4. Chargino-Neutralino Pair Production

There are 21 different reactions ($8\tilde{\chi}^{\pm}_{\imath}\tilde{\chi}^{0}_{\jmath}$, $3\tilde{\chi}^{\pm}_{\imath}\tilde{\chi}^{\mp}_{\jmath}$ and $10\tilde{\chi}^{0}_{\imath}\tilde{\chi}^{0}_{\jmath}$; $\imath = 1,\ 2$; $\jmath = 1 \div 4$) for chargino-neutralino pair production via Drell-Yan processes, among which $\tilde{\chi}^{\pm}_{1}\tilde{\chi}^{0}_{2}$ production has the largest cross-section. The easiest way to extract the signal is to exploit $\tilde{\chi}^{\pm}_{1}\tilde{\chi}^{0}_{2}$ leptonic decays resulting to the $3l{+}no\,jets{+}E_T^{miss}$ final states. The SM backgrounds considered are: WZ, ZZ, $t\bar{t}$, Wtb, Z$b\bar{b}$, $b\bar{b}$. The SUSY processes, that may lead to 3 leptons in final states are also taken into account: strong production ($\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$), associated production ($\tilde{g}\tilde{\chi}, \tilde{q}\tilde{\chi}$), chargino-neutralino pair production ($\tilde{\chi}\tilde{\chi}$, other than $\tilde{\chi}^{\pm}_{1}\tilde{\chi}^{0}_{2}$) and slepton pair production ($\tilde{l}\tilde{l}, \tilde{l}\tilde{\nu}, \tilde{\nu}\tilde{\nu}$). The SUSY background is dominated by strong production, but the jet veto requirement is very efficient in reducing $\tilde{g}/\tilde{q}$ events which in their cascade decays produce many jets. The typical set of cuts to extract the signal is: 3 isolated leptons with $p_T^l > 15$ GeV; veto on jets with $E_T^j > 25$ GeV in $|\eta| < 3.5$; a Z mass window cut $M_Z - 10$ GeV $< M_{l^+l^-} < M_Z + 10$ GeV, which significantly reduces the dominant SM WZ contribution.

The signal observability contours at various integrated luminosities are shown in Fig.4 [7]. At low integrated luminosity, $L_{int} = 10^4$ pb^{-1}, the direct production of $\tilde{\chi}^{\pm}_{1}\tilde{\chi}^{0}_{2}$ can be extracted up to $m_{1/2} \lesssim 150$ GeV for all m_0. A further increase of luminosity up to $L_{int} = 10^5$ pb^{-1} extends the explorable region only by about $10 \div 20$ GeV for $m_0 \gtrsim 120$ GeV because of $\tilde{\chi}^0_2 \to l^+l^-\tilde{\chi}^0_1$ 3-body decays are overtaken by "spoiler" modes $\tilde{\chi}^0_2 \to$ h$\tilde{\chi}^0_1$, Z$\tilde{\chi}^0_1$, which are now kinematically allowed. However, for $m_0 \lesssim 120$ GeV the gain in parameter space is much larger, up to $m_{1/2} \lesssim$ 420 GeV, due to $\tilde{\chi}^0_2 \to l^+\tilde{l}^-_{R,L} \to l^+l^-\tilde{\chi}^0_1$ 2-body decays.

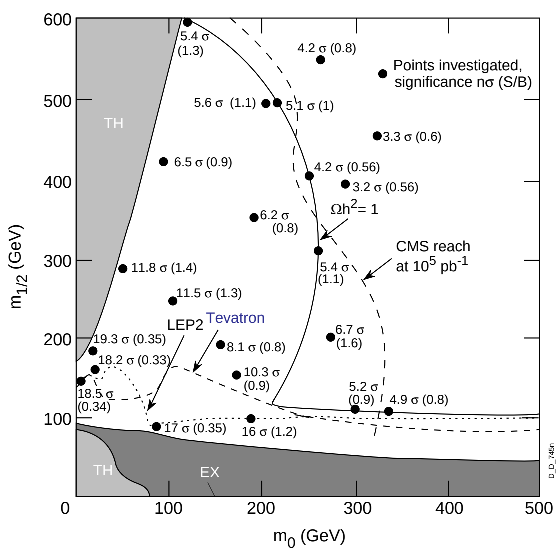

Figure 3: Explorable domain of (m_0, $m_{1/2}$) parameter space in slepton searches.

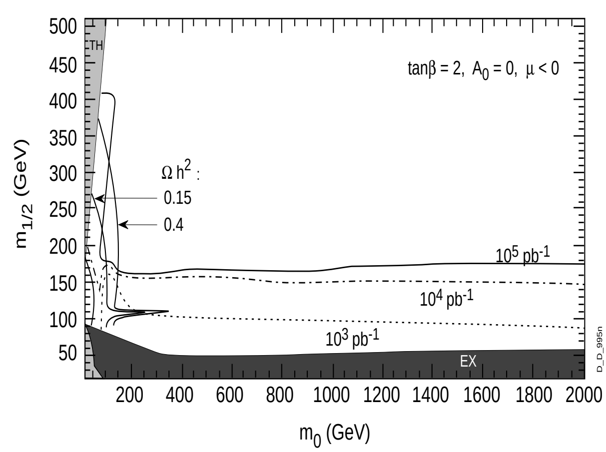

Figure 4: 5σ significance contours at various luminosities for Chargino-Neutralino direct production.

5. Search for the Next-to-Lightest Neutralino

The kinematical feature of $\tilde{\chi}^0_2$ leptonic decays which can be exploited is the l^+l^- invariant mass spectrum with its characteristic edge, as shown in Fig.5 for a representative mSUGRA point. In cascade decays of gluinos and squarks the production of $\tilde{\chi}^0_2$ is so abundant, that an "edge" in the dilepton mass spectrum can be observed in a significant part of (m_0, $m_{1/2}$) plane. Fig.6 shows the cross-section times branching ratio into leptons for $\tilde{\chi}^0_2$ inclusive production. The SM background can be easily suppressed, e.g. requiring a third lepton or/and E_T^{miss}, and with $L_{int} = 10^5$ pb^{-1} a detectable edge is seen as long as $\sigma{\cdot}$B $\gtrsim 10^{-2}$ pb [8].

There are domains of parameter space when both 2- and 3-body decays co-exist (or where both modes, $\tilde{\chi}_2^0 \to l^+\tilde{l}_R^-$ and $l^+\tilde{l}_L^-$ are present). For example, in Fig.7 the first edge at $M_{l^+l^-}^{max} = 52$ GeV corresponds to $\tilde{\chi}_2^0 \to l^+\tilde{l}_R^-$ decays, while the second edge at $M_{l^+l^-}^{max} = 69$ GeV to $\tilde{\chi}_2^0 \to l^+l^-\tilde{\chi}_1^0$ ones. In 3-body decays, the kinematical upper limit of the dilepton mass spectrum is $M_{l^+l^-}^{max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} \approx M_{\tilde{\chi}_1^0}$, as in mSUGRA $M_{\tilde{\chi}_2^0} \approx 2M_{\tilde{\chi}_1^0}$, thus providing the determination of the $\tilde{\chi}_1^0$ mass. Whether an edge corresponds to a 2- or 3-body decays can be deduced from the decay kinematics, e.g. lepton p_T-asymmetry $A = (p_T^{max} - p_T^{min})/(p_T^{max} + p_T^{min})$. This is illustrated in Fig.8, where several dotted histograms are obtained assuming, that the first edge in Fig.7 is due to the 3-body decays with $M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} = 52$ GeV.

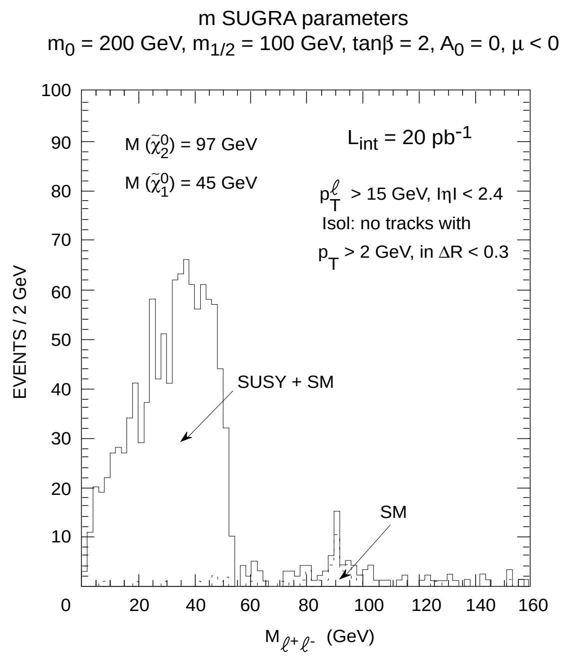

Figure 5: l^+l^- mass spectrum in 3-lepton final states.

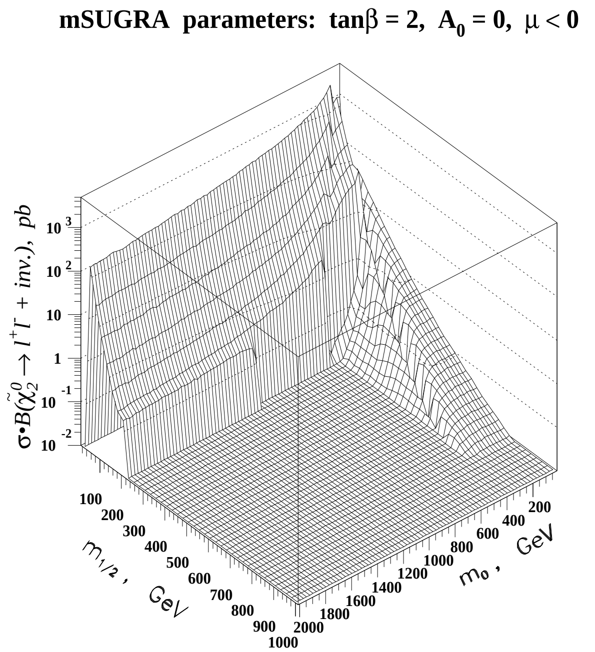

Figure 6: $\tilde{\chi}_2^0$ inclusive production cross-section times branching ratio into leptons.

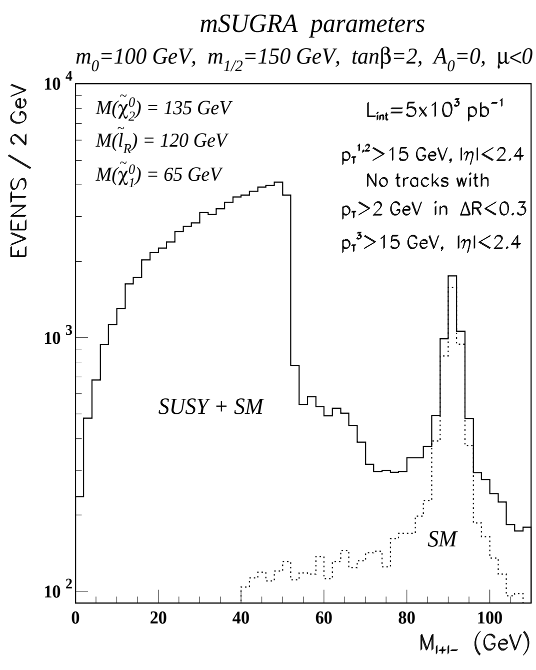

Figure 7: l^+l^- mass spectrum in 3-lepton final states.

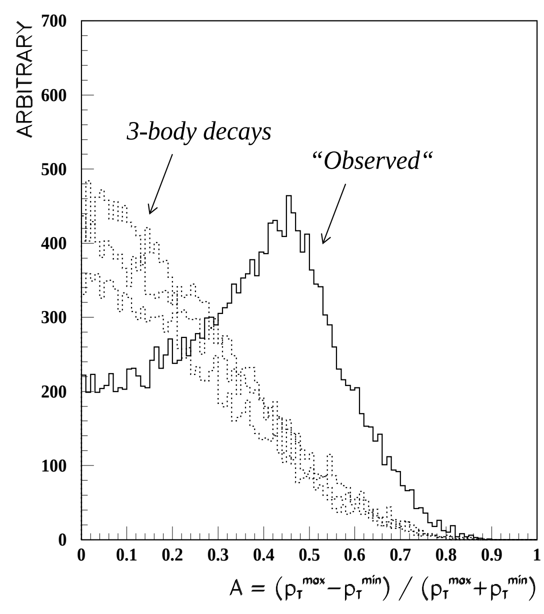

Figure 8: Leptons p_T asymmetry distributions in 3- and 2-body decays of $\tilde{\chi}_2^0$.

In 2-body decays the kinematical upper limit of the dilepton mass spectrum is $M_{l^+l^-}^{max} = \sqrt{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{l}}^2)(M_{\tilde{l}}^2 - M_{\tilde{\chi}_1^0}^2)}/M_{\tilde{l}}$, i.e. it is sensitive also to the slepton mass, which can be determined in the following way: i) assume $M_{\tilde{\chi}_2^0} = 2M_{\tilde{\chi}_1^0}$, ii) generate samples of $\tilde{\chi}_2^0$ 2-body sequential decays for various $M_{\tilde{\chi}_1^0}$ ($M_{\tilde{l}}$); note, that the slepton mass is constrained to provide the "observed" position of an edge, iii) ambiguity is then resolved statistically, by means of, e.g. a χ^2-test of the shape of the lepton p_T-asymmetry distributions. For the mSUGRA point ($m_0 = 100$ GeV, $m_{1/2} = 150$ GeV) this procedure provides the following precisions on masses: $\delta M_{\tilde{\chi}_1^0} \lesssim 5$ GeV, $\delta M_{\tilde{l}} \lesssim 10$ GeV. The use of both edges yields $\delta M_{\tilde{\chi}_1^0, \tilde{l}} \lesssim 1$ GeV.

Note, that the Z peak seen in Fig.5, 7 serves as an overall calibration signal; it allows to control the mass scale as well as the production cross-section.

6. Conclusions

At LHC/CMS SUSY will reveal itself easily by an excess of events over SM expectations in a number of characteristic signatures:

- The $n \cdot l + m \cdot jets + E_T^{miss}$ final states provide the maximal reach for SUSY via production of the strongly interacting sparticles. $\tilde{g}$ and $\tilde{q}$ masses can be probed up to ~2.5 TeV. The explorable $\tilde{\chi}_1^0$ mass extends up to ~350 GeV.
- The $2l + no\ jets + E_T^{miss}$ final states give access to slepton pair production. The explorable slepton mass range would extend up to ~400 GeV.
- The $3l + no\ jets + E_T^{miss}$ is the final state in which direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production in a Drell-Yan process should be looked for.
- The $l^+l^- +\ l^{\pm}/E_T^{miss}$ final states, with relatively modest demands on detector performance, may well be the first channel in which SUSY would reveal itself through $\tilde{\chi}_2^0$ inclusive production with subsequent decays – directly or via sleptons – into $l^+l^-\tilde{\chi}_1^0$. Characteristic dilepton invariant mass spectrum with a spectacular edge could provide a good handle to determine the sparticle masses.

What can be measured depends on a scenario Nature has chosen, but if SUSY is of relevance at EW scale it could hardly escape detection at LHC/CMS.

Acknowledgments

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