CMS Conference Report

November 7, 1997

Search for SUSY at LHC : Discovery and Inclusive Studies

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Abstract

We discuss the expected discovery potential of the LHC in sparticle searches. The study is done within the framework of the mSUGRA-MSSM model. The domain of parameter space where SUSY can be discovered in squark/gluino, $h \rightarrow b\bar{b}$, slepton, chargino-neutralino searches is investigated. The results show that LHC will be capable to detect sparticles in the domain of parameter space where SUSY would be relevant at the electro-weak scale.

Presented at *International Europhysics Conference on High Energy Physics*, Jerusalem, Israel, August 19-26, 1997

1 Introduction

Supersymmetry (SUSY) is a possible scenario for new physics beyond the Standard Model (SM), allowing to relieve difficulties with quadratic divergence of SM Higgs mass [1]. The minimal extension of the SM, MSSM [2] implies the existence of supersymmetric partners to all the ordinary particles, with masses of the order of electro-weak scale. Since exact mechanism for SUSY breaking is unknown, in MSSM some “soft-breaking” terms are introduced by hand to parameterize the effects of supersymmetry breaking in a more fundamental theory. A general parameterization of SUSY breakings in MSSM introduces about 100 free parameters [1]. This hampers a phenomenological analysis. The studies presented here are carried out in the framework of a minimal Supergravity model (mSUGRA) [3], which implies the simplest symmetry breaking at a GUT scale and leads to only 5 extra parameters : a common gaugino mass ($m_{1/2}$), a common scalar mass (m_0), a common trilinear interaction amongst the scalars (A_0), the ratio of the vacuum expectation values of the Higgs fields at M_Z ($\tan\beta$), and a Higgsino mixing parameter $\text{sign}(\mu)$. Using these parameters one can derive via renormalization group equations the physical masses and couplings of the complete SUSY particles spectrum at electro-weak scale. Masses of sparticles depend mainly on m_0 and $m_{1/2}$. Fig.1a shows isomass contours for gluinos, squarks, CP-even (h) and CP-odd (A) Higgs bosons. Fig.1b shows isomass contours for lightest neutralinos and left and right charged sleptons. The regions of parameter space excluded either by theory (TH) or experiment data up to now (EX) are indicated by shaded regions.

Models with R-parity conservation imply pair production of sparticles and the existence of a Lightest Supersymmetric Particle (LSP) which is $\tilde{\chi}_1^0$ in mSUGRA. It appears at the end of the decay chain of each sparticle and reveals itself, escaping detection, through a missing E_T . Since masses of sparticles cannot be reconstructed, the detection of these sparticles relies on the observation of an excess of events over SM expectations, characterized by a signal significance expressed as $S = N_S / \sqrt{N_S + N_B}$, where N_S is a number of particular SUSY signal events, and N_B is the number of background events. Background can be a mixture of both SM and SUSY events.

The purpose of this study is to evaluate the LHC discovery potential in sparticle searches, in particular to determine the domain of mSUGRA parameter space where SUSY reveals itself in squark/gluino, scalar Higgs, sleptons, chargino-neutralino searches. The simulation of mSUGRA signal events is performed with ISAJET [4] and of SM backgrounds with PYTHIA [5]. The CMS detector performance is simulated with a fast Monte-Carlo program CMSJET [6], which is based on detailed simulation parameterizations. The use of a fast simulation is due to the necessity to process large samples of both SM background (e.g. $t\bar{t} \approx 10^7$ ev., QCD $\approx 10^8$ ev.) and mSUGRA signal (up to 10^6 ev. in some parameter space points).

2 Gluinos and squarks at LHC

Since the total SUSY production is dominated by strongly interacting sparticles, a typical signal contains squarks and gluinos decaying through a number of steps to quarks, gluons, charginos, neutralinos, W, Z, Higgs bosons and ultimately a stable $\tilde{\chi}_1^0$. The final state has thus a number of jets, missing energy (2 LSP + neutrinos) and a variable number of leptons, depending on the decay chain. Among the final states discussed here are : one lepton (1l), two leptons of opposite sign (2l OS), two leptons of same sign (2l SS), three leptons (3l), four leptons (4l) and five leptons (5l). The SM background considered are : $t\bar{t}$, W+jets, Z+jets, WW, ZZ, ZW, QCD ($2 \rightarrow 2$, including $b\bar{b}$). The study of Baer *et al.* [7] carried out with a generic LHC detector description and with fixed kinematical cuts shows that a significant signal can be obtained in a wide range of mSUGRA parameters. Here we summarize the results of a detailed study [8]. The following kinematical variables are most useful ones for the SM backgrounds suppression : E_T^{miss} , number of jets (N_j), jet E_T^j , scalar transverse energy sum $E_T^{sum} = E_T^{miss} + \Sigma E_T^j + \Sigma E_T^l$. In some cases cuts on lepton p_T^l , *Circularity* (C) and transverse angle between hardest lepton and E_T^{miss} ($\delta\varphi$) are also used. The cuts are optimized for each mSUGRA domain (kinematics of the signal) and final state topology and are typically : $E_T^{miss} > 100 \div 600$ GeV, $N_j \geq 2 \div 6$, $E_T^j > 40 \div 300$ GeV, $E_T^{sum} > 500 \div 1200$ GeV, $p_T^l > 10 \div 50$ GeV, $C > 0.1$, $\delta\varphi > 10 \div 20$ degrees. Electrons are always isolated to be unambiguously identified. It is shown [8] that taking into account non-isolated muons (which come from decays of abundantly produced b-jets) allows one to improve significantly the reach in some cases. Figs. 2a and 2b show the 5σ discovery contours in various final states in $\tilde{q}, \tilde{g}$ searches for two sets of mSUGRA parameters. The regions of parameter space excluded either by theory (TH) or experimental data up to now (EX) are indicated by shaded regions. The upper limit of neutralino relic density [9] corresponding to the $\Omega h = 1$ contour is fully contained in the explorable region.

3 Possibility to observe $h \rightarrow b\bar{b}$ in $\tilde{q}, \tilde{g}$ decays.

The most general way to detect the lightest CP-even Higgs of MSSM is to search for the inclusive channel $h \rightarrow \gamma\gamma$, which, with 10^5 pb^{-1} , would allow to explore a domain approximately given by $m_A \geq 250 \text{ GeV}$, $\tan\beta \geq 3$ [10]. We can expect a signal on a top of a large irreducible background with $S/B \leq 1/20$. Other production or decay modes of h have also some disadvantages or limitations. On the other hand, it is well known that the MSSM h can be abundantly produced in decays of charginos and neutralinos (primarily $\tilde{\chi}_2^0$), see Fig.3. In turn, the $\tilde{\chi}_2^0$ is a typical decay product of squarks and gluinos, which are produced with large (strong-interaction) cross sections. The idea is thus to search the h in the $b\bar{b}$ mode in cascade decays of sparticles [11]. Fig.4 shows an example of signal observability at one representative point of mSUGRA parameter space, with cuts appropriate for high-mass range of $\tilde{q}, \tilde{g}$ and with the expected b-tagging performance of CMS [12]. The SM backgrounds considered are : $t\bar{t}$, Wb , QCD ($2 \rightarrow 2$ including $b\bar{b}$). We find that there is a significant part of the mSUGRA parameter space, where

Figure 3: $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h$ branching ratio as a function of $m_0, m_{1/2}$ for various values of $\tan\beta$ and $\text{sign}(\mu)$ with $A_0=0$.

Figure 4: Example of the $h \rightarrow b\bar{b}$ signal visibility in some representative point of mSUGRA parameter space with expected CMS b-tagging performance.

the $h \rightarrow b\bar{b}$ peak can be observed with $S/B \sim 1$, and in some points an observation would be possible already with a few fb^{-1} [13]. The influence of various instrumental factors on the signal visibility is also investigated [13]. The outcome of this study is shown in Fig.5 for two sets of mSUGRA parameters.

4 Slepton production

Slepton pairs are produced in a Drell-Yan processes and decay leptonically into final states characterized by two hard, same flavour, opposite sign isolated leptons, E_T^{miss} and little jet activity. The sum of signal lepton transverse momenta and E_T^{miss} are mainly back-to-back. So lepton isolation and jet vetoing capability of the detector are essential issues to control the large backgrounds. Typical cuts applied are : 2 isolated leptons with $p_T^l > 30 \text{ GeV}$; veto on jets with $E_T^j > 30 \text{ GeV}$ in $|\eta| < 4$; $E_T^{miss} > 80 \text{ GeV}$; relative azimuthal angle between leptons and $E_T^{miss} > 160^\circ$. Cuts are optimized depending on the domain of mSUGRA parameter space. The dominant backgrounds are : reducible $t\bar{t}$ and irreducible $WW, \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$. Fig.6 shows the points of mSUGRA parameter space where slepton signal visibility is investigated in $2l + no \text{ jets} + E_T^{miss}$ final states and a 5σ significance contour for an integrated luminosity of 10^5 pb^{-1} [14]. The slepton mass reach is $\sim 400 \text{ GeV}$.

a)

b)

Figure 5: Domains of visibility of $h \rightarrow b\bar{b}$ peak with nominal CMS performance in mSUGRA-SUSY for two sets of the model parameters : a) $A_0=0, \tan\beta=2, \mu < 0$ and b) $A_0=0, \tan\beta=10, \mu < 0$.

Figure 6: Slepton search probed points, with expected signal significance and S/B ratio. The 5σ contour is shown by dashed line, the cosmological $\Omega h^2 = 1$ boundary is shown by solid line.

Figure 7: $\tilde{\chi}_i^\pm \tilde{\chi}_j^0 \rightarrow 3 \text{ leptons} + E_T^{miss} + \text{no jets}$ final states 5σ significance contours for various luminosities; relic neutralino matter density contours are indicated.

5 Chargino-neutralino pair production

There are 21 reactions for chargino-neutralino pair production through a Drell-Yan mechanism. The $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production has the largest cross section. The most promising experimental signature to detect the signal is $3l + no\ jets + E_T^{miss}$ [15]. The SM backgrounds considered are : WZ, ZZ, $t\bar{t}$, Wtb, Z $b\bar{b}$, $b\bar{b}$. The SUSY background is dominated by strong production, but the jet veto efficiently reduces $\tilde{q}, \tilde{g}$ multijet final state contribution. The typical set of cuts imposed is : 3 isolated leptons with $p_T^\ell > 15$ GeV; veto on jets with $E_T^j > 25$ GeV in $|\eta| < 3.5$; a Z mass window cut of ± 10 GeV. The signal observability contours at various integrated luminosities are shown in Fig.7 [16].

6 Characteristic shape of 2l OS SF effective mass as an evidence for SUSY

It has been known for some time that there is a “structure” in the l^+l^- invariant mass spectrum in exclusive $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production [15]. The question is how general is this observation. The edge in the invariant mass distribution originates from 3-body or 2-body cascade decays of $\tilde{\chi}_2^0$. In first case the maximum of the decay spectrum is at :

$$M_{l^+l^-}^{max} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0},$$

in the latter case at :

$$M_{l^+l^-}^{max} = m_{\tilde{\chi}_1^0} \cdot \sqrt{(1 - m_l^2/m_{\tilde{\chi}_2^0}^2) \cdot (1 - m_{\tilde{\chi}_1^0}^2/m_l^2)}.$$

Both cases can coexist in some domains of the parameter space thus leading to the appearance of two structures in the effective mass spectrum.

The studies [17] show that the “edge” can be visible in a significant part of parameter space in inclusive $\tilde{\chi}_2^0$ production. The SM background can be easily suppressed by requiring a third lepton or/and E_T^{miss} , as seen in Fig.8. An example of the explorable domain of the mSUGRA parameter space is shown in Fig.9.

Figure 8: Dilepton mass spectrum in an inclusive 3-lepton final state.

Figure 9: Explorable region of mSUGRA parameter space, where dilepton mass characteristic edge (Fig.8) is observed in 3 lepton (+ E_T^{miss}) final states.

7 Conclusion

At LHC supersymmetry will reveal itself by an excess production over SM expectations. LHC experiments will be able to test SUSY at electro-weak scale in a decisive way. The plausible part of mSUGRA-MSSM parameter space will be explored in a number of characteristic signatures. Expected mass reach is : for $\tilde{q}, \tilde{g} \sim 2$ TeV, for $\tilde{\chi}_1^0, \tilde{l} \sim 400$ GeV. The $h \rightarrow b\bar{b}$ may be much easier to observe in $\tilde{q}, \tilde{g}$ decays than $h \rightarrow \gamma\gamma$ in significant part of parameter space.

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